Chapter 10: Asia

Coordinating Lead Authors: Rajib Shaw (Japan), Yong Luo (China), Tae Sung Cheong (Republic of Korea)

Lead Authors: Sharina Abdul Halim (Malaysia), Sanjay Chaturvedi (India), Masahiro Hashizume (Japan), Gregory E. Insarov (Russian Federation), Yoichi Ishikawa (Japan), Mostafa Jafari (Iran), Akio Kitoh (Japan), Juan Pulhin (Philippines), Chandni Singh (India), Kripa Vasant (India), Zhibin Zhang (China)

Contributing Authors: Rawshan Ara Begum (Bangladesh), Xi Chen (China), Rajarshi Dasgupta (India), Ronald C. Estoque (Philippines), Wanqin Guo (China), Garima Jain (India), Brian Johnson (USA), Tarek Katramiz (Syria), Pankaj Kumar (India), Xianbing Liu (China), Mythili Madhavan (India), Bijon Kumer Mitra (Bangladesh), Farah Mulyasari (Indonesia), Santosh Nepal (Nepal), Rekha Nianthi (Sri Lanka), Fereidoon Owfi (Iran), Gulsan Ara Parvin (Bangladesh), Shobha Poudel (Nepal), Atta-ur Rahman (Pakistan), Mihoko Sakurai (Japan), Amin Shaban (Lebanon), Dmitry Streletskiy (Russian Federation), Vibhas Sukhwani (India), Prabhakar S.V.R.K (India), Ai Tashiro (Japan), Tống Thị Mỹ Thi (Vietnam), Noralene Uy (Philippines) , Xinru Wan (China), Cunde Xiao (China)

Review Editors: Soojeong Myeong (Republic of Korea), Joy Jacqueline Pereira (Malaysia)

Chapter Scientist: Rajarshi Dasgupta (India), Yan Yang(China)

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Executive Summary

Observed surface air temperature has increased in the 20th century all over Asia *(high confidence[1])*. Significant warming has intensified the threat to social and economic sustainability in Asia (*medium confidence*). Rising temperature increases likelihood of the threat of heat waves across Asia, droughts in arid and semi-arid areas of West, Central and South Asia, delays and weakening of the monsoon circulation in South Asia, floods in monsoon regions in South, Southeast and East Asia, and glacier melting in the Hindu Kush Himalaya (HKH) region (*medium confidence*). {10.3.1; 10.3.3}

Asian countries are experiencing a hotter summer climate, resulting in increase of energy demand for cooling at a rapid rate, together with the population growth *(high confidence)*. Decrease in precipitation influences energy demand as well, as desalination, underground water pumping and other energy-intensive methods are increasingly used for water supply *(high confidence)*. More energy demands in summer seasons will exceed any energy savings from relatively lower heating demand due to warmer winter. Among thirteen developing countries with large energy consumption in Asia, eleven are exposed to high energy insecurity and industrial systems risk *(high confidence)*. {10.4.1}

Asian terrestrial ecosystems change is driven by global warming, precipitation and Asian monsoon alteration, permafrost thawing and extreme events like dust storms along with natural and human-related factors which are in interplay *(high confidence)*. Treeline position in North Asian mountains moves upward after 1990s, while in Himalaya treeline demonstrates a multidirectional shift, either moves upward, or does not show upslope advance or moves downward. This can be explained by site-specific complex interaction of positive effect of warming on tree growth, drought stress, change in snow precipitation, land use change, especially grazing, and other factors *(high confidence)*. The increased considerably changes in biomes in Asia are a response to warming *(medium confidence)*. Terrestrial and freshwater species, populations, and communities alter in line with climate change across Asia *(medium-to-high confidence)*. Climate change, human activity, and lightning determine the increase of wildfire severity and area burned in North Asia after 1990s *(medium confidence)*. Length of plant growth season increased in some parts of East and North Asia, while opposite trend or no change was observed in other parts *(high confidence)*. Observed biodiversity or habitat losses of animals or plants were linked to climate change in some parts of Asia *(high confidence)*. There are evidences that climate change can alter species interaction or spatial distribution of invasive species in Asia *(high confidence)*. Changes in ecosystems in Asia during the 21st century are expected to be driven by projected climatic, natural, and socioeconomic changes. Across Asia, under a range of RCPs and other scenarios rising temperature is expected to contribute to northward shift of biome boundaries and upward shift of mountain treeline *(medium confidence)*. {10.4.2}

Coastal habitats of Asia are diverse and the impacts of climate change including rising temperature, ocean acidification and sea level rise has brought negative effects to the services and the livelihood of people depending on it *(high confidence)*. The degree of bleaching of coral reefs was diverse among different presences of stress tolerant symbionts and higher thermal thresholds. The risk of irreversible loss of coral reefs, tidal marshes, seagrass meadows, plankton community and other marine and coastal ecosystems increases with global warming, especially at 2°C temperature rise or more *(high confidence)*. Mangroves in the region continue to face threats due to pollution, conversion for aquaculture, agriculture, in addition to climate based threats like SLR (Sea Level Rise) and coastal erosion. {10.4.3}

Both climatic and non-climatic drivers such as socio-economic changes have created water stress conditions in both water supply and demand in all sub-regions of Asia *(high confidence)*. These changes in space and time directly or indirectly affected water use sectors and services. By mid-21st Century, the international transboundary river basins of Amu Darya, Indus, Ganges and inter-state Sabarmati river basin in India could face severe water scarcity challenges with climate change acting as a stress multiplier *(high confidence)*. Due to global warming Asian countries could experience increase of drought conditions (5-20%) by the end of this century *(high confidence)*. {10.4.4}

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[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

The Asia glaciers are in minor area shrinkage and mass loss during 2006-2016, resulting in the instability of water resource supply *(high confidence)*. Glaciers in Asia are the water resources of about 220 million people in the downstream areas. The glacier meltwater in southern Tibetan Plateau has increased during 1998-2007, and will further increase till 2050. The glacier is *likely*[2] to disappear by nearly 50% in High Mountain Asia and about 70% in Central and Western Asia by the end of the 21st century under the medium scenario, and more under the high scenario. The total amount and area of glacier lakes were found increased during last decade *(high confidence)*. More glacier collapses and surges were found in western Tibet. Glacier lake outburst flood (GLOF) will threaten the securities of the local and downstream communities *(high confidence)*. Snowmelt water contributed 19% of the increase change in runoff of arid region's rivers in Xinjiang, China and 10.6% of the upper Brahmaputra River during 2003-2014 *(medium confidence)*. {10.4.4; Box 10.5}

Since IPCC AR5, more studies reinforce the earlier findings on the spatial and temporal diversity of climate change impacts on food production in Asia depending on the geographic location, agro ecology, and crops grown, recognizing that there are winners and losers associated with the changing climate across scales *(high confidence)*. Most of these impacts have been associated with drought, monsoon rain, and oceanic oscillations, the frequency and severity of which have been linked with the changing climate. Climate-related risks to agriculture and food systems in Asia will progressively escalate with the changing climate, with differentiated impacts across the region *(medium confidence)*. Major projected impacts of climate change in the agriculture and food sector include decline in fisheries, aquaculture, and crop production particularly in South and Southeast Asia, reduction in livestock production in Mongolia, and changes in crop, farming systems and crop areas in almost all regions with negative implications to food security *(medium confidence)*. In India, rice production can decrease from 10% to 30% whereas maize production can decrease from 25% to 70% assuming a range of temperature increase from 1º to 4°C. Similarly, rice production in Cambodia can decrease by 45% by 2080 under high emission scenario. Occurrence of pests such as the golden apple snail (Pomacea canaliculate), associated with the predicted increase in climatically suitable habitats in 2080, threatens the top Asian rice-producing countries including China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines and Japan. Increasing temperatures, changing precipitation levels, and extreme climate events like heat waves, droughts and typhoons will persist to be important vulnerability drivers that will shape agricultural productivity particularly in South Asia, Southeast Asia, and Central Asia. {10.4.5; Figure 10.6}

Asian urban areas are considered high risk locations from projected climate, extreme events, unplanned urbanisation, rapid land use change *(high confidence)* but also sites of ongoing adaptation *(medium confidence)*. Asia is home to the largest share of people living in informal settlements, with 332 million in Eastern and South-Eastern Asia, 197 million in Central and Southern Asia. By 2050, 64% of Asia's population will be urban. Coastal cities, especially in South and South East Asia are expected to see significant increase in average annual economic losses between 2005 and 2050 due to flooding, with very high losses in East Asian cities under high emission scenario *(high confidence)*. Climate change will amplify the urban heat island effect across Asian cities (especially South and East Asia) at 1.5°C and 2°C temperature rise, both substantially larger than under the present climate *(medium evidence, high agreement)*. Under high emission scenario, higher risks from extreme temperature and precipitation are projected for almost all cities *(medium confidence)*, with impacts on freshwater availability, regional food security, human health, and industrial outputs. By 2080, 940-1100 million urban dwellers in South and South East Asia could be affected by extreme heat lasting more than 30 days/year *(high confidence)*, with poorer populations affected the most. {10.4.6; Cross-Chapter Box URBAN in Chapter 6}

Climate change caused direct losses due to the damage in infrastructure, disruption in services and affected supply chains in Asia *(medium confidence)* and will increase risk to infrastructure as well as provide opportunities to invest in climate-resilient infrastructure and green jobs *(medium confidence)*.

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[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This Report also uses the term 'likely range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

At higher warming, key infrastructures such as power lines, transport by roads, railways, and built infrastructure such as airports and harbours are more exposed to climate-induced extreme events, especially in coastal cities *(medium confidence)*. Evidence on urban adaptation across Asia is growing with examples on infrastructural adaptation (e.g. flood protection measures, and climate resilient highways and power infrastructure); institutional adaptation (e.g. sustainable land use planning, zoning plans); nature ecosystem-based solutions (e.g. mangrove restoration, restoring and managing urban green spaces, urban farming); technological solutions (e.g. smart cities, early warning systems); and behavioural adaptation (e.g. improved awareness and preparedness measures). However, adaptation actions tend to be in initial stages and more reactive (57% urban adaptations focus on preparatory interventions such as capacity building and 43% cities report implemented adaptation interventions) *(medium confidence)*. The degree of implementation of urban adaptation is uneven with large cities receiving more funding and priority and smaller cities and towns and peri-urban spaces seeing relatively lower adaptation action *(medium confidence)*. {10.4.6}

Climate change is increasing vector-borne and water-borne diseases, undernutrition, mental disorders and allergic diseases in Asia by increasing the hazards such as heatwaves, flooding and drought, air pollutants, in combination with more exposure and vulnerability *(high confidence)*. Sub-regional diversity in socioeconomic and demographic context (e.g., ageing, urban vs agrarian society, increasing population vs reduced birth rate, high income vs low to middle income) and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia. Under the medium-high emissions scenario, rising temperature and extreme climate events will have an increasing impact on human health and wellbeing with varying types and magnitudes of impact across Asia *(high confidence)*. More frequent hot days and intense heat-waves will increase heat-related deaths in Asia. Increased floods and droughts will have adverse impact on food availability and prices of food resulting in increased undernourishment in South and Southeast Asia. Increases in heavy rain and temperature will increase the risk of diarrheal diseases, dengue fever and malaria in tropical and sub-tropical Asia. {10.4.7}

Increased climate variability and extreme events are already driving migration *(robust evidence, medium agreement)* and projecting longer-term climate change will increase migration flows across Asia *(medium confidence)*. One in three migrants comes from Asia and the highest ratio of outward migrants is seen from hazard-exposed Pacific countries. In 2019, Bangladesh, China, India and the Philippines each recorded more than 4 million disaster displacements. In South East and East Asia, cyclones, floods, and typhoons triggered internal displacement of 9.6 million people in 2019, almost 30% of total global displacements. {Box 10.2}

There is a small but growing literature highlighting the importance of behavioural aspects of adaptation in Asia *(high confidence)* but this is restricted primarily in agriculture and disaster risk reduction. Factors motivating adaptation actions include risk perception, perceived self-efficacy, socio-cultural norms and beliefs, previous experiences of impacts, levels of education and awareness *(high confidence)*. There is growing evidence on behavioural aspects of individual adaptation but lesser evidence on the socio-cognitive factors motivating governments and private sector actors to adapt. {10.5.3}

Climate change is already causing economic loss and damage across Asian regions and this will increase under higher warming *(medium confidence)*. Non-material losses and damages are reported to a lesser degree but this is due to underreporting and methodological issues with detection and attribution to climate change (*high confidence*). Loss and damage represents a key knowledge gap, especially in West, Central and North Asia. Insufficient literature differentiating loss and damage under future adaptation scenarios restricts a comprehensive assessment of residual damages and future loss and damage difficult. {Box 10.7}

Options such as climate smart agriculture, ecosystem-based disaster risk reduction, investing in urban blue-green infrastructure meet adaptation, mitigation, and sustainable development goals simultaneously, presenting opportunities for climate-resilient development (CRD) pathways in Asia *(high confidence)*. Climate risks, vulnerability and adaptation measures need to be factored into decision-making across all levels of governance (*high confidence*). To help achieve this, there is a need to advance the current understanding of climate impacts across sectors and spatiotemporal scales and improve on the current strategies in planning and budget allocation. More accurate forecasting of extreme events, risk awareness and prioritizing individual and collective decision choices are also need to be enhanced *(high confidence)*.

Options for Asian countries are transforming risks of climate change into opportunities for the advancement of projects in the energy sector – including promoting investment in non-fossil energies, securing local natural gas resources, enhancing water harvesting, adopting green building technologies, and encouraging multi-stakeholder partnerships. However, there are significant barriers to CRD such as fragmented, reactive governance; inadequate evidence on which actions to prioritise and how to sequence them; and finance deficits. Some Asia countries and regions offer solutions to overcome these barriers: Through use of advanced technologies (in-situ observation and remote sensing, a variety of new sensor technologies, citizen science, artificial intelligence, and machine learning tools); regional partnerships and learning; improved forecasting capabilities; and better risk awareness (*high confidence*). {10.5, 10.6}

10.1 Introduction

Asia is defined here as the land and territories of 51 countries/regions (**Figure 10.1**). It can be broadly divided into six sub-regions based on geographical position and coastal peripheries (IPCC, 2014b). These are, in alphabetical order, Central Asia (five countries), East Asia (seven countries/regions), North Asia (two countries), South Asia (eight countries), Southeast Asia (12 countries), and West Asia (17 countries). The population of Asia was reported to be about 4463 million in 2016, which is about 60% of the world population with an estimated density of 100 people per square kilometer (UNDESA, 2017). The highest life expectancy at birth is 84 (Japan) and the lowest is 52 (Afghanistan) (CIA, 2017). The gross domestic product (GDP) per capita ranged from US$587 (Afghanistan) to US$81,585 (Macao, PRC) (IMF, 2018).

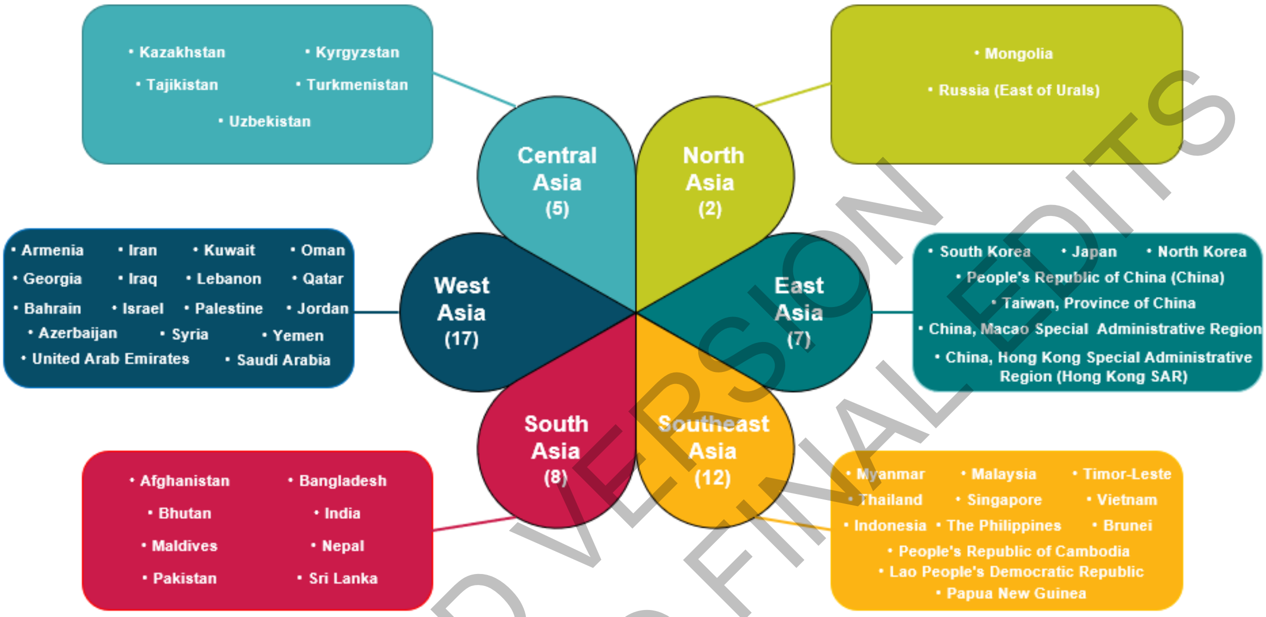


Figure 10.1: Countries and regions in Asia

[START BOX 10.1 HERE]

Box 10.1: What is New on Asia in AR6?

- Adaptation in energy sector is becoming increasingly crucial in the Asian region, which has been assessed in a new sub-section.
- Adaptation technology and innovations are also of high importance for the region. Classification of adaptation technology and its use in different systems are assessed.
- On the governance side, the nexus approach among several systems like food, energy, water is focused, and its importance is assessed.
- New concepts on decentralised and self-reliant society, such as the Circulating and Ecological Sphere (CES) are emerging for integrated adaptive governance.
- As a part of sustainable development pathway, interlinkages of climate change adaptation and disaster risk reduction is highlighted.

[END BOX 10.1 HERE]

10.2 Major Conclusions from Previous Assessments

As the most populous continent, Asia is faced with a unique set of challenges that vary across its climatic zones.

- The most perceptible change in climatic trends is observable in the increasing surface air temperature and rise in night time temperature, particularly during the season of winter. This is accompanied by monsoon rainfall variability, which is observable inter-seasonally, inter-annually and spatially.
- There is increasing evidence of an upward trend in the intensity and frequency of extreme weather events in Asia.
- The predictions for future climatic trends suggest an increase in warming along the higher latitudes of North Asia.
- Projections show that agricultural and food security will be impacted substantially, particularly in the area of cereal production by the end of the 21st century.
- Malnutrition among the poor and marginalised sections of the population in Asia remains a major concern that is further rendered complex by climate change.
- Projections of an increase in the incidence of pests and diseases impacts directly on the food security and health of vulnerable populations.
- Erosion will occur simultaneously with sea level rise; the projected rise could lead to large-scale flooding in low-lying areas, particularly South, Southeast and East Asia.
- The erosion of the major deltas of Asia may take place through a rise in sea levels, an increased frequency of extreme weather events, and the excessive withdrawal of groundwater.
- The priority areas for Asia include an enhancement of capabilities to collect social and biophysical data, information sharing, sectoral interactions, a mainstreaming of science and the identification of critical climate thresholds across regions and sectors.

Drawing upon a greater number of studies made possible by greater use of advanced research tools such as remote sensing as well as meticulous modelling of impacts, the Fifth Assessment Report could significantly expand its coverage of pertinent issues (IPCC, 2014c). For example, the discussion on the Himalayas was expanded to cover observed and projected impacts of climate change on tourism (see WGII AR5 Section 10.6.2); livelihood assets such as water and food (WGII AR5 Sections 9.3.3.1, 13.3.1.1, 18.5.3, 19.6.3); poverty (WGII AR5 Section 13.3.2.3); culture (WGII AR5 Section 12.3.2); flood risks (WGII AR5 Sections 18.3.1.1, 24.2.1); health risks (WGII AR5 Section 24.4.6.2); and ecosystems (WGII AR5 Section 24.4.2.2)(IPCC, 2014c).

- Over the past century, and across most of Asia, warming trends and increasing temperature extremes have been observed.
- Adequate supplies of freshwater resources are under considerable threat due to both the existing pattern of socio-economic growth and climate change.
- With a number of regions already close to the heat stress limits, most models, using a range of General Circulation Models (GCMs) and Special Report on Emission Scenarios (SRES) scenarios, suggest that higher temperatures will lead to shorter growing periods of rice cultivation resulting in lower rice yields.
- Climate change impacts have led to visible shifts on the terrestrial systems in many parts of Asia in the phenologies, growth rates, and the distributions of plant species.
- Coastal and marine systems in Asia are under increasing stress from both climatic and non-climatic drivers and mean sea level rise will contribute to upward trends in extreme coastal high water levels (WGI AR5 Section 3.7.6).(IPCC, 2014c) . Mangroves, salt marshes, and seagrass beds may decline unless they can move inland, while coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea levels. Damage to coral reefs will increase during the 21st century because of both warming and ocean acidification.
- Climate change will further compound multiple stresses caused due to rapid urbanisation, industrialisation, and economic growth. Development of sustainable cities in Asia with fewer fossil fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health.
- Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia.
- Local Knowledge and Indigenous Knowledge play an important role in the formulation of adaptation governance and related strategies (IPCC, 2007), and best quality, locality specific knowledge can help address serious lack of education on climate change and uncertainties surrounding quality, salience, credibility and legitimacy of available knowledge base.

Knowledge/research gaps identified in AR5 include, but are not limited to, an insufficient understanding of impacts, vulnerability and adaptation in urban settlements, under-researched linkages between local livelihoods, ecosystem functions, and land resources and a poor understanding of the impacts of projected climate changes on the vegetation of the lowland tropics.

10.3 Regional and Sub-regional Characteristics

10.3.1 Climatic Characteristics

Climate characteristics in Asia is diverse covering all climate zones from tropical to polar climate, including mountain climate. Monsoonal winds and associated precipitation are dominant in South, Southeast and East Asia. Annual mean surface air temperature averaged over the sub-region ranges from coldest North Asia (–3°C) to warmest Southeast Asia (25°C) based on JRA-55 (Kobayashi et al., 2015) climatology for 1981–2010. Most of North Asia and higher altitude is underlain by permafrost. West Asia is the driest and Southeast Asia is the wettest, with the annual precipitation averaged over the sub-region ranging about 10 times from 220 mm in West Asia to 2570 mm in Southeast Asia based on GPCC (Schamm et al., 2014) climatology for 1981–2010. Indonesia in Southeast Asia has the longest coastline in the world, causing this area (maritime continent) the wettest region (Yamanaka et al., 2018). The Hindu Kush-Himalaya (HKH) region is a biodiversity hotspot (Wester et al., 2019), and also has significant impacts on the Asian climate because of their orographic and thermodynamic effects (Wu et al., 2012).

Extreme precipitation events and related flooding occur frequently in monsoon Asia, i.e., Southeast, South and East Asia (Mori et al., 2021b). Tropical cyclones also affect East and South Asia with torrential rain, strong winds and storm surge. Floods and other weather-related hazards are causing thousands of casualty and millions of affected people each year (CRED/UNISDR, 2019). On the other hand, droughts have long-lasting effects on agriculture and livestock threatening water security in West Asia, Central Asia and northern China (Ranasinghe et al., 2021; Seneviratne et al., 2021). Adaptation to such extreme events was limited in Asia.

10.3.1.1 Observed climate change

Observations of past and current climate in Asia are assessed in IPCC WGI AR6 (IPCC, 2021a). Examples of observed impacts in Asia with attributed climatic impact-drivers (CIDs) are shown in **Figure 10.2.** Surface temperature has increased in the past century all over Asia (*very high confidence*). Elevation dependent warming, i.e. that the warming rate is different across elevation bands, is observed in high mountain Asia (*medium confidence*) (Krishnan et al., 2019) (Hock et al., 2019). While there is an overall trend of decreasing glacier mass in high mountain Asia, there are some regional differences and even areas with a positive mass balance due to increased precipitation (Wester et al., 2019). Rising temperature resulted in an increasing trend of growing season length. Number of hot days and warm nights continue to increase in the whole Asia (*high confidence*), while cold days and nights decrease except in the southern part of Siberia (Gutiérrez et al., 2021). Large increases in temperature extremes are observed in West and Central Asia (*high confidence*). Temperature increase is causing strong, more frequent, and longer heat waves in South and East Asia. East China 2013 heat waves case is such an example (Xia et al., 2016). Extreme warmth was observed in Asia in 2016 and 2018, for which event attribution study revealed that this would not have been possible without anthropogenic global warming (*medium confidence*) (Imada et al., 2018; Imada et al., 2019).

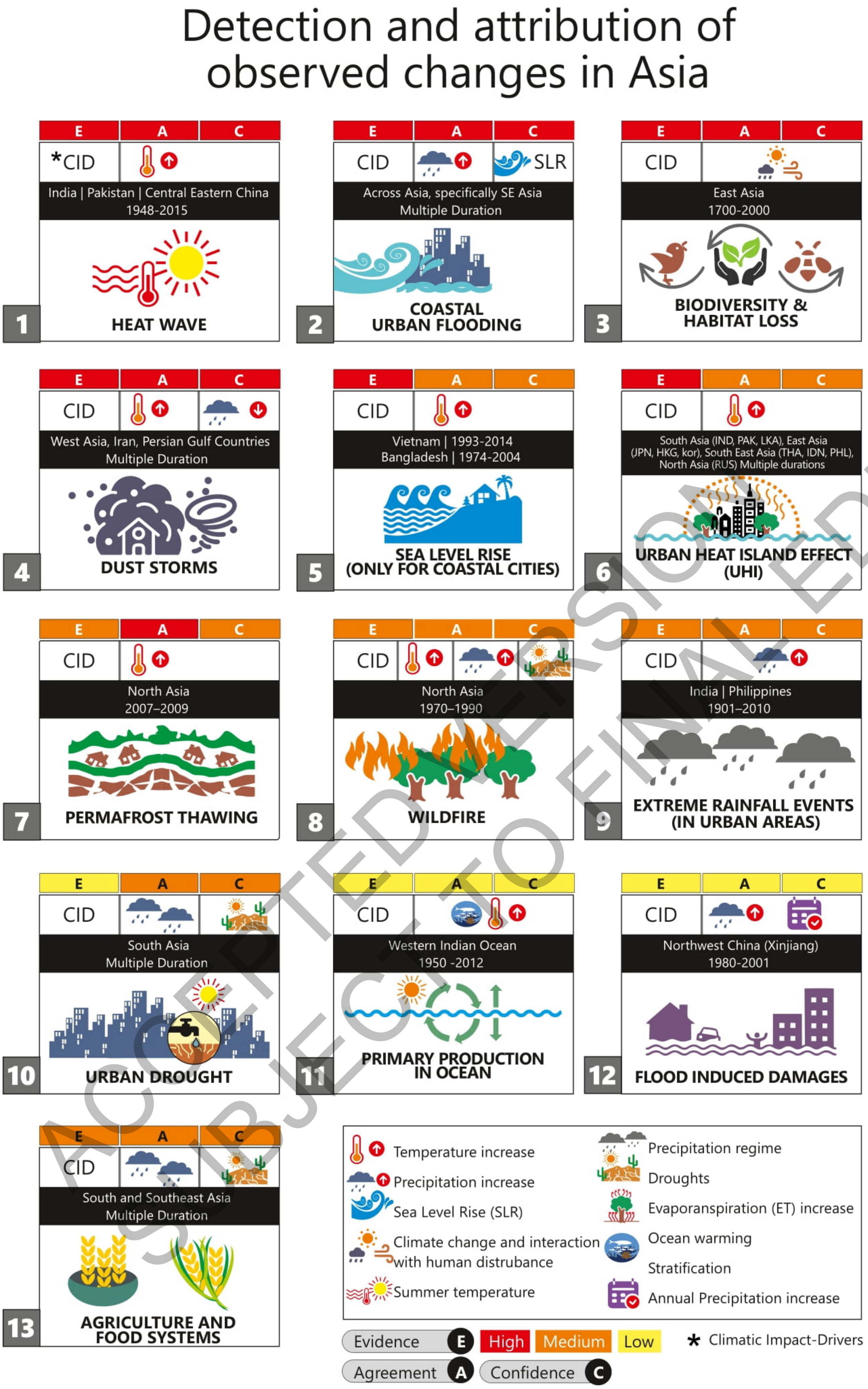


Figure 10.2: Detection and attribution of observed changes in Asia; Levels of Evidence (E), Agreement (A) and Confidence (C) are ranked by High (H), Medium (M) or Low (L). CID: Climatic Impact-Driver. References: (1) Heat waves, (Ross et al., 2018); (Mishra et al., 2015); (Rohini et al., 2016); (Panda et al., 2017); (Chen and Li, 2017). (2) Coastal urban flooding, (Dulal, 2019). (3) Biodiversity & habitat loss, (Wan et al., 2019). (4) Dust storms, (Alizadeh-Choobari et al., 2016); (Nabavi et al., 2016); (Yu et al., 2015); (Kelley et al., 2015). (5) Sea level rise (only for coastal cities),(Hens et al., 2018) (Brammer, 2014); (Shahid et al., 2016). (6) Urban heat island effect (UHI), (Kotharkar et al., 2018); (Choi et al.,

2014); (Estoque et al., 2017); (Santamouris, 2015); (Li et al., 2018a); (Ranagalage et al., 2017); (Hong et al., 2019c). (7) Permafrost thawing, (Biskaborn et al., 2019); (Shiklomanov et al., 2017a). (8) Wildfire, (Brazhnik et al., 2017); (Schaphoff et al., 2016). (9) Extreme rainfall events (in urban areas), (Ali et al., 2014). (10) Urban drought, (Pervin et al., 2020), (Gu et al., 2015). (11) Primary production in ocean, (Roxy et al., 2016). (12) Flood induced damages, (Fengqing et al., 2005). (13) Agriculture and food systems(Heino et al., 2018) (Prabnakorn et al., 2018)

There are considerable regional differences in observed annual precipitation trend (*medium confidence*). Observations show a decreasing trend of the South Asian summer monsoon precipitation during the second half of the 20th century (*high confidence*) (Douville et al., 2021). No clear trend in precipitation is observed in high mountain Asia (Nepal and Shrestha, 2015), while continuous shift toward a drier condition was observed since early 1980s in spring over the central Himalaya (Panthi et al., 2017). Increase in heavy precipitation occurred recently in South Asia (*high confidence*), and in Southeast and East Asia (*medium confidence*) (Seneviratne et al., 2021). In Japan, there is no significant long-term trend in the annual precipitation, while significant increasing trend is observed in the annual number of events of heavy precipitation (daily precipitation ≥ 400 mm) and intense precipitation (hourly precipitation ≥ 50 mm) (JMA, 2018). Decreased precipitation and increased evapotranspiration are observed in West and Central Asia, contributing to drought conditions and decreased surface runoff.

Annual surface wind speeds are decreasing in Asia since 1950s (*high confidence*) (Ranasinghe et al., 2021). The observed changes in the frequency of sand and dust storms vary from region to region in Asia (*medium confidence)*. The frequency and intensity of dust storms are increasing in some regions of Asia, such as West and Central Asia, due to land use and climate change (Mirzabaev et al., 2019). Significant decreasing trends of dust storms are observed in some part of Inner Mongolia and over the Tibetan Plateau (Ranasinghe et al., 2021). In contrast, West Asia has witnessed more frequent and intensified dust storms affecting Iran and Persian Gulf countries in the past decades (*medium confidence*) (Nabavi et al., 2016).

There is no significant long-term trend during 1951–2017 in the numbers of tropical cyclones (TCs) with maximum winds of 34 kt or higher forming in the western North Pacific and the South China Sea (*medium confidence*). There are substantial interdecadal variations in basin-wide TC frequency and intensity in the western North Pacific (Lee et al., 2020a). Numbers of strong TCs (maximum winds of 64 kt or higher) also show no discernible trend since 1977 when complete wind speed data near TC center becomes available (JMA, 2018). For TCs in the Philippines area, there are no significant trends in the annual number of TCs during 1951–2013 (Cinco et al., 2016). Their analysis showed that the Philippines have been affected by fewer TCs above 64 kt, but affected more by extreme TCs (above 81 kt). There is a significant northwestward shift in TC tracks since the 1980s, and a detectable poleward shift since the 1940s in the average latitude where TCs reach their peak intensity in the western North Pacific (Lee et al., 2020a) (*medium confidence*).

The oceans have warmed unabated since 2004, continuing the multi-decadal ocean warming trends (Bindoff et al., 2019). The report also summarised that there is increased agreement between coupled model simulations of anthropogenic climate change and observations of changes in ocean heat content (*high confidence*). Observed sea level rise around Asia over 1900–2018 is similar to the global mean sea level change of 1.7 mm/yr, but for the period 1993–2018, the sea level rise rate increased to 3.65 mm/yr in the Indo-Pacific region and 3.53 m/yr in the Northwest Pacific, compared to global value of 3.25 mm/yr (Ranasinghe et al., 2021). The extreme sea level has risen since 1980s along the coast of China (Feng et al., 2018b).

Ocean acidification continues with surface seawater pH values have shown a clear decrease by 0.01–0.09 from 1981–2011 along the Pacific coasts of Asia (*high confidence*) (Lauvset et al., 2015). For the western north Pacific along the 137°E line, the trend varies from –0.013 at 3°N to –0.021 at 30°N per decade during 1985–2017 (JMA, 2018). Ocean interior (about 150–800 m) pH also shows a decreasing trend with higher rates in the northern than the southern subtropics, which may be due to greater loading of atmospheric CO_2 in the former (JMA, 2018).

10.3.1.2 Projected climate change

Rising temperature increases likelihood of the threat of heat waves across Asia, droughts in arid and semi-arid areas of West, Central and South Asia, floods in monsoon regions in South, Southeast and East Asia, and glacier melting in the HKH region (*high confidence*) (Doblas-Reyes et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021). Confidence in direction of projected change in climatic impact-drivers in Asia are summarised in Table 12.4 of WGI AR6 Chapter 12 (Ranasinghe et al., 2021).

Projections of future annual mean surface air temperature change in Asia are qualitatively similar to those in the previous assessments with larger warming in higher latitudes, i.e. North Asia (*high confidence*) (Gutiérrez et al., 2021). Projected surface air temperature changes in the Tibetan Plateau, Central Asia and West Asia are also large (*high confidence*) (Gutiérrez et al., 2021). Highest levels of warming for extreme hot days are expected to occur in West and Central Asia with increased dryness of land (*high confidence*) (SR1.5). Over mountainous regions, elevation dependent warming will continue (*medium confidence*) (Hock et al., 2019). Glacier will generally shrink, but rates vary among region to region (*high confidence*) (Wester et al., 2019). Thawing permafrost presents a problem in northern areas of Asia, particularly Siberia (Parazoo et al., 2018). Temperature rise will be strongest in winter in most regions, while it will be strongest in summer in the northern part of West Asia and some parts of South Asia where desert climate prevails (*high confidence*) (Gutiérrez et al., 2021). The wet-bulb globe temperature (WBGT), which is a measure of heat stress, is *likely* to approach critical health thresholds in West and South Asia under the RCP4.5 scenario, and in some other regions such as East Asia under the RCP8.5 scenario (*high confidence*) (Lee et al., 2021a) (Seneviratne et al., 2021). Occurrence of extreme heat waves *very likely* increases in Asia. Projections show that a sizeable part of South Asia will experience heat stress conditions in the future (*high confidence*). It is *virtually certain* that cold days and nights become fewer (Ranasinghe et al., 2021).

Projections of future annual precipitation change are qualitatively similar to those in the previous SREX and AR5 assessments (IPCC, 2021a). *Very likely* large percent increase in annual precipitation is projected in South Asia and North Asia (*high confidence*) (Lee et al., 2021a) (Douville et al., 2021). Precipitation is projected to decrease over the north-western part of the Arabian Peninsula and increase over its southern part (*medium confidence*) (Gutiérrez et al., 2021). Both heavy precipitation and intense precipitation are projected to intensify and become more frequent in South, Southeast and East Asia (*high confidence*) (Seneviratne et al., 2021). There will be a large increase in flood frequency in these monsoon regions (Oppenheimer et al., 2019). This would lead to continuation to cause loss of lives and infrastructure without further mitigation efforts. SR1.5 assessed higher risk from heavy precipitation events at 2°C compared to 1.5°C of global warming in East Asia. A large ensemble modelling study shows that future warming is expected to further increase winter precipitation and extreme weather events such as rain-on-snow, result in the increase in extreme runoff in Japan (*low confidence*) (Ohba and Kawase, 2020). The earlier snowmelt will affect energy supply by hydropower.

Monsoon land precipitation *likely* increases in East, Southeast, and South Asia mainly due to increasing moisture convergence by elevated temperature (*high confidence*). However, there is *low confidence* in the magnitude and detailed spatial patterns of precipitation changes at sub-regional scale in East Asia (Doblas-Reyes et al., 2021). Increasing land-sea thermal contrast and resultant lower tropospheric circulation changes, together with increasing moisture, are considered to intensify the South Asian summer monsoon precipitation (*medium confidence*). Anthropogenic aerosols greatly modify sub-regional precipitation changes and their spatial and temporal changes are uncertain (Douville et al., 2021). Monsoonal winds will generally become weaker in future warming world with different magnitude across regions (*medium confidence*). Future changes in sand and dust storms are uncertain.

The global proportion of very intense TCs (category 4-5) will increase under higher levels of global warming (*medium-to-high confidence*). Mean global TC precipitation rate will increase (*medium-to-high confidence*). Models suggest a reduction of TC frequency, but an increase in the proportion of very intense TCs over the western North Pacific in the future. However, some individual studies project an increase in western North Pacific TC frequency (*medium confidence*) (Cha et al., 2020). In the western North Pacific, some models project a poleward expansion of the latitude of maximum TC intensity, leading to a future increase of intense TC frequency south of Japan (*medium confidence*) (Yoshida et al., 2017).

Relative sea level rise associated with climate change in Asia will range from 0.3 m–0.5 m in SSP1-2.6 to 0.7 m–0.8 m in SSP5-8.5 for 2081–2100 relative to 1995–2014 (Ranasinghe et al., 2021). In coastal region, evaluation of sea level rise is necessary in regional scale to assess the impacts on coastal sector. Liu et al. (2016c) investigates the regional scale sea level rise using dynamical downscaling from the three global climate models in western North Pacific. In their projection in the case following RCP 8.5 scenario, the regional sea level rises along Honshu Island in Japan during 2081–2100 relative to 1981–2000 are 6–25 cm higher than the global mean sea level rise due to the dynamical response of the ocean circulation. For the impact assessment of coastal hazard, the total sea level rise including extreme events due to the storm surge and high ocean wave, which are influenced by the changes of TCs (Seneviratne et al., 2021). Mori and Takemi (2016) summarised the characteristics of TCs in the western Pacific in the past and in the future, and the extreme value of significant wave height increase in several regions. There is considerable increase of the return levels along the China coast under 2.0°C warming compared with that under 1.5°C warming scenario (Feng et al., 2018b).

Ocean acidification will continue over the 21st century (*virtually certain*) (SROCC). Projected decrease in global surface ocean pH from 1986–2005 to 2081–2100 is about 0.145 under RCP4.5 (Lee et al., 2021a).

Diverse and complex climatic characteristics in Asia make the climate models' ability limited in reasonably simulating the current climate and projecting its future change (Gutiérrez et al., 2021).

10.3.2 Ecological Characteristics

Ecosystems in Asia are characterised by a variety of climate and topographic effects and can be divided into several distinct areas (Figure 10.3), and valuable ecosystem services provide vital support for human well-being and sustainable development (IPBES, 2018).

Boreal forests and tundra dominate in North Asia, deserts and xeric shrub-lands in Central and West Asia, and alpine ecosystems in the Hindu Kush-Himalaya, Tian Shan, Altai-Sayan, Ural and Caucasus mountain regions. Human-transformed landscapes occupies most parts of other sub-regions. Remained natural ecosystems in East Asia are temperate broadleaf and mixed forests and subtropical evergreen forests, and deserts and grasslands in the west. South Asia has tropical forests and semi-deserts in the northwest. Southeast Asia is covered mainly by tropical forests (Figure 10.3).

Ocean and coastal region in Asia have various ecological characteristics, such as high productivity in arctic/subpolar region, large biodiversity in tropical region, and unique system in marginal seas. In the atlas of WGI AR6, the ocean biomes in Asia is divided into 6 sub-regions (WGI AR6 Figure Atlas.4) (Gutiérrez et al., 2021). For the coastal region, the concept of the large marine ecosystem (e.g., (Sherman, 1994) provides the biological characteristics each marginal/semi-enclosed region and the regions characterised by boundary current system.

Biodiversity and ecosystem services play a critical role in socioeconomic development as well as the cultural and spiritual fulfilment of the population in the Asia (IPBES, 2018). For example, species richness reaches it maximum in the "coral triangle" of South-East Asia (central Philippines and central Indonesia) (IPCA, 2017) and the extent of mangrove forests in Asia is about 38.7% of the global total (Bunting et al., 2018). These coastal ecosystems provide multiple ecosystem services related to food production by fisheries/aquaculture, carbon sequestration, coastal protection, and tourism/Recreation (Ruckelshaus et al., 2013).

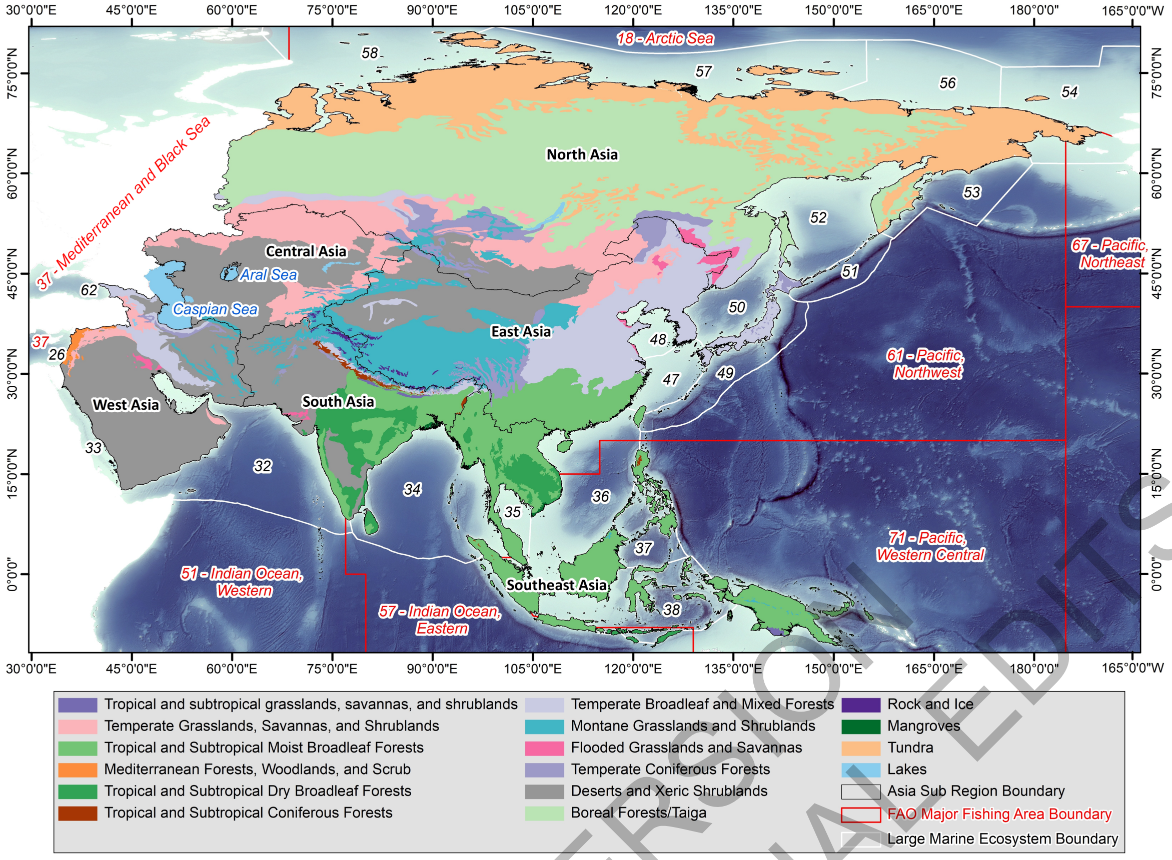


Figure 10.3: Terrestrial Ecoregions, Large Marine Ecosystems and Major Fishing areas of Asia. Large Marine Ecosystems (LMEs) of Asia: 26- Mediterranean Sea, 32- Arabian Sea, 33- Red Sea, 34- Bay of Bengal, 35- Gulf of Thailand, 36- South China Sea, 37- Sulu-Celebes Sea, 38- Indonesian Sea, 47- East China Sea, 48- Yellow Sea, 49- Kuroshio Current, 50- Sea of Japan, 51- Oyashio Current, 52- Sea of Okhotsk, 53- West Bering Sea, 54- Northern Bering - Chukchi Seas, 56- East Siberian Sea, 57- Laptev Sea, 58-Kara Sea, 62- Black Sea, developed after (Olson et al., 2001) (NOAA, 2010), (FAO, 2019)and made with Nature Earth. **Note**: The map is for illustrative purpose only. The boundaries and names shown and the designations used on this map are for the ecoregions and do not imply official endorsement or acceptance by the United Nations.

10.3.3 Demographics / Socio-economic Characteristics

In these six sub-regions of Asia, nature and biophysical impacts of climate change are observed in three climate change hot spots where strong climate signals and high concentrations of vulnerable people are present, namely in semi-arid, glacial fed river basins and mega deltas (Szabo et al., 2016b) (De Souza et al., 2015) (Kilroy, 2015). The impacts of global climate also have profound social implications, threatening human health and well-being, destabilising assets, coping capacities and response infrastructures and substantially increasing the number of socially, economically and psychologically vulnerable individuals and communities (Ford et al., 2015).

Vulnerability to climate change varies by geography and by the economic circumstances of the exposed population (Sovacool et al., 2017). The concentration of population growth in less developed regions means that an increasing number of people live in countries with the least ability to adapt to climate change (Auffhammer and Kahn, 2018). Bangladesh with 163 million people, an example, is one of the most vulnerable countries in the world to climate risks and natural hazards, faces severe floods, cyclones, droughts, heat waves and storm surges on a regular basis (Dastagir, 2015; Hossain et al., 2018; Roy and Haider, 2019).

Differential human vulnerability to environmental hazards results from a range of social, economic, historical, and political factors, all of which operate at multiple scales (Thomas, 2019) (De Souza et al., 2015). Climate change is expected to have serious impacts for people living within these hot spot areas, as observed from loss of food crop yields to disasters such as floods, fluctuations in seasonal water availability, or other systemic effects (De Souza et al., 2015). For instance in South Asia, extreme climatic conditions are threatening food security,thus agro-based economies like India and Pakistan are the most vulnerable to climate change in this regard (Mendelsohn, 2014; Ahmad, 2015; Kirby et al., 2016; Ali et al., 2017).

A broad-based understanding of gendered vulnerability as emerging from poverty and social discrimination as well social cultural practices in different political, geographical and historical settings, apart from climatic variability and environmental/natural risks is central to understanding people's capacities to cope with and adapt to change (Morchain et al., 2015; Yadav and Lal, 2018); (Rao et al., 2019). Studies highlight the fact that disasters do not affect people equally, mostly findings show that insufficient disaster education, inadequate protection measures, and powerful cultural issues, both pre- and post-disaster, increase women's vulnerability during and after disasters (Isik et al., 2015; Reyes and Lu, 2016; Hamidazada et al., 2019) . In particular, cultural issues play a role after disasters by affecting women's security, access to disaster aid, and health care (Raju, 2019). There must be more nuanced understanding and examination of gender, as well as poor, disadvantaged and vulnerable groups in vulnerability and risk assessments (Reyes and Lu, 2016; Reyer, 2017; Xenarios et al., 2019).

Based from the *World Economic Situation and Prospects as of mid-2019 Report*, the region has an estimated 400 million people living in extreme poverty below the threshold of $1.90 a day. At the higher international poverty line of $3.20 a day, the number of poor rises to 1.2 billion, accounting for more than a quarter of the region's total population (Holland, 2019). Beyond monetary measures, indicators of multidimensional aspects of poverty, most notably in Southern Asia indicate a large share of the population still lacks access to basic infrastructure and services (Bank, 2017b).

For instance, South Asia illustrates that on average it could lose nearly 2% of its GDP by 2050, rising to a loss of nearly 9% by 2100 under BAU (Business-as-Usual) scenario (Ahmed and Suphachalasai, 2014). The relationship between economic outcomes and cross-sectional climate variation is confounded by regional heterogeneity, including historical effects of settlement and colonisation (Dell et al., 2014; Newell et al., 2018). Climate change vulnerability may also depend on sufficient employment opportunities in the risk-prone areas, land holding size, gender, education level and family and community size, as observed in Nepal, Thailand, Vietnam (Baul and McDonald, 2015; Lebel L., 2015; Phuong et al., 2018a).

As poor households are constrained in their ability to receive nutrition, schooling and healthcare for their children, this is greatly dampening progress on human capital development and productivity growth, both of which are critical imperatives for sustainable development (Carleton and Hsiang, 2016; Schlenker and Auffhammer, 2018). Studies also have shown negative impacts of climate change on several essential components of people's livelihoods and well-being, such as water supply, food production, human health, availability of land and ecosystems (Roy and Haider, 2019) (Arnell et al., 2016);(Alauddin and Rahman, 2013).
Major population trends of urbanisation and urban area expansion are forecast to take place in Asia region has mentioned demographic change will make humanity more vulnerable to climate change particularly in places with high poverty rates and potentially prone to systemic disruptions in the food system (Puma et al., 2015; d'Amour et al., 2016; d'Amour et al., 2017).

The urban population of the world has grown rapidly from 751 million in 1950 to 4.2 billion in 2018. Asia, despite its relatively lower level of urbanisation, is home to 54% of the world's urban population (United Nations, 2019). Some cities have experienced population decline in recent years. Most of these are located in the low-fertility countries of Asia, where overall population sizes are stagnant or declining, as observed in a few cities in Japan and the Republic of Korea (for example, Nagasaki and Busan) have experienced population decline between 2000 and 2018 (United Nations, 2019). By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in developing regions. However, some of the fastest-growing urban agglomerations are cities with fewer than 1 million inhabitants, many of them located in Asia and Africa (United Nations, 2019). Challenges with water supply in many cases exist since decades (Dasgupta, 2015). Climate change increases these challenges (Hoque et al., 2016). As more people inhabit urban areas, the number of people vulnerable to heat stress is thus *likely* to rise, a problem that will be compounded by rising temperatures due to climate change (Acharya et al., 2018). Compared to rural areas, hot temperature risk is even higher in urban regions (Luo, 2018a; Ye, 2018; Setiawati Martiwi Diah, 2021).

The impact of heat in rural areas has been a blind spot so far, particularly for farmers and outdoor labourers who are increasingly exposed to high outdoor temperatures due to increase intensity in agriculture combined with changes in working hours (Tasgaonkar, 2018).

Farmers as a group have shown an increasing number of females over the years due to out-migration of male members in urban areas for employment, in which putting women at more severe risk in the context of climate variability (Singh, 2019). Women are required to acquire new capacities to manage new challenges, including risks from climate change, through capacity-building interventions to strengthen autonomous adaptation measures (Banerjee et al., 2019; James, 2019; Mishra, 2019). However, the overlapping crises of climate change and global public health crisis of COVID-19 represents a major challenge to gender equality and sustainable development (Katherine Brickell, 2020; Sultana, 2021).

For vulnerable populations, such as Indigenous Peoples, older and low-income groups, women, children, people with disabilities, and minorities, the health effects of climate change-related extreme weather events can be especially devastating (McGill, 2016). Such populations may be more susceptible to disease, have pre-existing health conditions or live in areas that do not promote good health or well-being, for instance loss of income and food supply shortages could lead children in rural households to nutritional deprivations that can have both immediate and lifelong impacts (Gleick, 2014; UNICEF, 2015). Children, already susceptible to age-related insecurities, face additional destabilising insecurities from questions about how they will cope with future climate change (Hansen et al., 2013).

[START BOX 10.2 HERE]

Box 10.2: Migration and Displacement in Asia

Migration and displacement in Asia: Migration is a key livelihood strategy across Asia and is driven by multiple factors such as socio-economic changes, increasing climate variability and disaster incidence, and changing aspirations. Displacement denotes a more involuntary movement in reaction to climatic or non-climatic factors. There is *robust evidence, medium agreement* that increased climate variability and extreme events are already driving migration (Gemenne et al., 2015; IDMC, 2020) (Rigaud et al., 2018; IDMC, 2019; Maharjan et al., 2020) (Jacobson et al., 2019; Siddiqui et al., 2019) and *medium evidence, medium agreement* projecting longer-term climate change will increase migration flows across Asia (Abubakar et al., 2018; Rigaud et al., 2018; Hauer et al., 2020; Bell et al., 2021).

Detection and attribution – does climate change drive migration? Ascertaining the role of climate change in migration is difficult and contested (see Cross-Chapter Box MIGRATE in Chapter 7 and RKR H in Chapter 16), with observation-based studies either linking extreme event incidence, weather anomalies, and environmental change with migration numbers or drivers (McLeman, 2014; Singh et al., 2019a; Kaczan and Orgill-Meyer, 2020) and projection studies looking at particular risks such as sea level rise or drought by linking increasing warming (often through RCPs) and population growth. Despite this methodological disagreement on detection and attribution of migration due to climate change, there is *medium evidence, medium agreement* that higher warming and associated changes in frequency and intensity of slow- and rapid-onset events are expected to increase forced migration in the future, especially under less optimistic development pathways (Dasgupta et al., 2014a; Davis et al., 2018; Rigaud et al., 2018; Hauer et al., 2020) but its role is smaller than non-climatic socio-economic drivers of migration (Wodon et al., 2014; Adger et al., 2021).

- *Current migration and displacement*: One in three migrants comes from Asia and the highest ratio of outward migrants is seen from hazard-exposed Pacific countries (Ober, 2019). In 2019, approximately 1,900 disasters triggered 24.9 million new displacements across 140 countries; in particular, Bangladesh, China, India and the Philippines each recorded more than 4 million disaster displacements (IDMC, 2019).Tajikistan, Kyrgyzstan and Russia see significant disaster-associated displacements: e.g. heavy rain-induced flooding in Khatlon (Tajikistan) triggered 5,400 new displacements; landslides in the Jalal-Abad (Kyrgyzstan) saw 4,700 new displacements, while floods in Altai, Tuva, and Khakassia (Russia) displaced 1,500 people. Iran reported highest sub-regional figures with > 520,000 new disaster-related displacements in 2019 (IDMC, 2019). In South East and East Asia, cyclones, floods, and typhoons triggered internal displacement of 9.6 million people in 2019, almost 30% of total global displacements (IDMC, 2019). With most migrants in the region being temporary migrant workers, loss of jobs and wages among them have been particularly severe due to adverse economic climate triggered by COVID-19 (ESCWA, 2020). It has also resulted in large-scale returns of migrant workers and remittances have declined drastically (Khanna, 2020; Li et al., 2021). Remittances to Eastern Europe and Central Asia are expected to decline 16.1 per cent from $57 billion in 2019 to $48 billion in 2020. Remittances in East Asia and the Pacific are estimated to fall 10.5 per cent over the same period, from $147 billion to $131 billion (United Nations, 2020). The COVID-19 pandemic has had significant impacts on migrants (Rajan, 2020) in the region and some countries have targeted migrants in economic stimulus packages or income support programmes; however, access to such support has been heterogenous.

- *Projected migration*: Regional variation is significant across Asia. By one estimate, in South Asia, internal climate migrants, i.e. those migrating due to climate change and associated impacts such as water scarcity, crop failure, sea-level rise, and storm surges, are projected to be 40 million by 2050 (1.8 percent of regional population) under high warming (Rigaud et al., 2018). While methodological critiques remain on projected migration estimates, what is certain is that some countries will be more affected that others; it is estimated that in south Bangladesh, sea level rise can displace 0.9-2.1 million people by direct inundation by 2050 (Jevrejeva et al.; Davis et al., 2018). In South Asia, migration hotspots include the Gangetic Plain and the Delhi–Lahore corridor, coastal cities such as Chennai, Chittagong, Dhaka, and Mumbai, which will be simultaneously exposed to climate change impacts and major migration destinations, and amplified rural–urban migration (Ober, 2019). Importantly, there is *low agreement* on projected numbers (see Boas et al. (2019)) with uncertainties around how local policies and individual behaviours will shape migration choices. Even in high-risk places, people might choose to stay or be unable to move, resulting 'trapped' populations (Zickgraf, 2019; Ayeb-Karlsson et al., 2020). There is currently inadequate evidence to ascertain the nature and numbers of trapped populations currently or in the future.

Implications of migration for adaptation: The evidence on migration and its impacts on adaptive capacity and risk reduction are mixed (Upadhyay, 2014; Banerjee et al., 2018; Szabo et al., 2018; Maharjan et al., 2020; Singh and Basu, 2020). Financial remittances help vulnerable households spread risk through better incomes, expanded networks, and improved assets such as housing, education, and communication technology (Jha et al., 2018; Szabo et al., 2018; Ober, 2019; Maharjan et al., 2020). Benefits from international remittances across the Asia Pacific region were approximately US$276 billion in 2017 (UN, 2018) and in countries such as Kyrgyzstan, Tajikistan, and Nepal remittances were ~25% of national GDP in 2015. However, migration requires a minimum level of resources and liquidity constraints impede internal migration by the poorest households often rendering them immobile (Ayeb-Karlsson et al., 2020; Maharjan et al., 2020). Further, migration does not necessarily mean people move out of risk and often might enter new risks. Notably, migrants in South and South East Asia were severely affected by the compounding crises of disasters and the COVID-19 pandemic and there is emerging evidence that inclusion of universal safety net provisions that embed adaptation planning can reduce vulnerabilities of migrants (Sengupta and Jha, 2020; Cundill et al., 2021; Sultana, 2021).

While there is *robust evidence (medium agreement)* that migration exacerbates gendered vulnerability and work burdens (Banerjee et al., 2019; Singh, 2019; Rao et al., 2020), it is well established that differential vulnerability of migrants intersects with ethnicity, age, and gender; political networks and social capital; and livelihoods in destination areas (Maharjan et al., 2020; Cundill et al., 2021). Across Asia, international and internal migration are changing social norms and household structures, with significant implications for local adaptive capacity (Singh, 2019; Evertsen and van der Geest, 2020; Porst and Sakdapolrak, 2020; Rao et al., 2020).

[END BOX 10.2 HERE]

10.4 Key Systems and Associated Impacts, Adaptation and Vulnerabilities

10.4.1 Energy Systems

10.4.1.1 Regional diversity

Energy consumption of Asia accounts for 36% of the global total at present. China, India and the ASEAN countries have largely contributed to the ever-growing global energy consumption. Asia is predicted to account for 80% of coal, 26% of natural gas and 52% of electricity consumption of the world by 2040 (IEA, 2018). The share of Asia in the global primary energy consumption will increase to 48% by 2050. China continues to be the world's largest energy consumer, and the combined consumption of India and ASEAN will be similar with that of China by that time (IEEJ, 2018).

The energy structure of Asia is dominated by fossil fuels so far. As the trend, the share of coal in China's primary energy consumption is forecasted to sharply decline from 60% in 2017 to around 35% in 2040 (BP, 2019). In contrast, India and ASEAN rely more on coal since coal may meet their soaring energy demand. Accordingly, more than 80% of the global coal will be consumed in Asia by 2050. China will surpass the U.S. in about 10 years to become the world's largest oil consumer. India will then replace the U.S. to be the second largest by late 2040s (IEEJ, 2018).

Around 60% of the incremental electricity demand globally, predicted to double in 2050, will occur in Asia. By that time, electrification rate in Asia will increase to 30% but 40% of electricity demand will be still covered by coal (IEEJ, 2018). Asia accounts for almost half of the growth in global renewable power generation. It is hardly for Japan and Korea to develop additional nuclear power plants as the planned. Whereas, nuclear generation continues to increase quickly in China and the scale will be similar to the entire of OECD by 2040 (BP, 2019). India and Russia's nuclear power sector is also growing fast, e.g., the recent launch of the Akademik Lomonosov offshore nuclear power in Russia.

The rapid growth of energy demand in Asia reinforces the region's position as the largest energy importer (BP, 2019). Around 80% of energy traded globally will be consumed in Asia and the rate of self-sufficiency will decrease from 72% to 63% by 2050. This tendency is especially remarkable for ASEAN, which will become a net importer in early 2020s. Self-sufficiency rate of coal will be maintained at a level of 80%, while that of oil and natural gas will decline significantly. The additional oil imports of the emerging Asian economies will be from North America, the Middle East and North Africa. The main players in Asia for the LNG imports will extend from Japan and Korea to China and India. ASEAN has been a net exporter of natural gas but starts to expand its import due to the increased consumption and resource depletion (IEEJ, 2018).

The increase in energy demand at a rapid rate in these countries cannot thus be attributed only to population growth and rising living standards, but also to increasingly extreme temperature variations. The decrease in precipitation influences energy demand as well, as countries are becoming more dependent on energy-intensive methods (e.g., desalination, underground water pumping) to supply water. Similarly, energy systems are influenced by the way the agriculture sector, mainly in Al Mashrek, relies increasingly on energy-intensive methods (e.g., more fertilisers, different irrigation and harvesting patterns) (Farajalla, 2013).

Climate change has direct and indirect impacts on energy and industrial systems. Climate change has a wide and profound impact on energy systems (energy development, transportation, supply, etc.). With global warming, the energy consumption for heating in winter decreases, while the energy consumption for cooling in summer significantly increases, but the overall energy demand shows an upward trend (Sailor, 2001; Szabo et al., 2018) (*High confidence*). Such demands in summer seasons will by far exceed any energy savings from the decrease in heating demand due to warmer winters. Higher demand for cooling due to hotter temperatures has become a major challenge in the energy sector in all countries. Furthermore, decreased water levels due to lower precipitation reduces hydroelectric output. This is particularly the case for countries such as Syria and Iraq with large hydroelectric capacity (Hamid and Raouf, 2009). Additionally, the decrease in water levels negatively affects low-carbon energy systems such as Concentrated Solar Power (SCP) and thermal generation plants that require regular cooling and cleaning.

Climate change adds extra pressure to current energy infrastructures in most countries where systems failures and blackouts are already common (Assaf, 2009). In the wake of extreme weather events (e.g., heat waves), energy infrastructures remain inadequate to cope. This is particularly the case for countries such as Lebanon, Syria, Jordan, and Palestine, with poor electricity infrastructures (Jordan, 2015). Extreme weather events could generate grave damage to power plants, most being located only a few meters above sea level, as well as power transmission towers and lines. In Lebanon, a small country where there are no Indigenous energy resources, the disruption of shipping of fuel supplies due to extreme weather events is a major risk. Other extreme weather events such as floods and sandstorms expose energy and industrial systems in the coastal areas due to a rise in sea level. Countries of the Arabian Peninsula are projected to experience significant inland flooding as sea levels rise (Hamid and Raouf, 2009). In East Asia wet snow accretion enhanced by global warming often cause damage to electric power lines (Sakamoto, 2000; Ohba and Sugimoto, 2020).

10.4.1.2 Key drivers to vulnerability, observed and projected impacts

The universal energy access is a big challenge for Asia (IEA, 2018). About 230 million Indian people lack access to electricity, and around 800 million still use the solid fuels for cooking (Sharma, 2019). The average electricity access rate in South Asia was 74%, an equivalent of 417 million people without electricity and accounting for more than a third of the global 1.2 billion lacking the access (Shukla et al., 2017). With a total population of nearly 640 million in ASEAN, an estimated 65 million people remain without electricity and 250 million rely on solid biomass as the cooking fuel (IEA, 2017). It is expected to achieve the universal access to electricity by 2030, while 1.6 billion people in Asia will still lack clean energy for cooking (UNESCAP, 2018b).

Asia faces energy security problem even with the rapid growth in production and trade (IEEJ, 2018). Among 13 developing countries with large energy consumption in Asia, 11 expose to high energy security risk (WEC, 2018). This will be a major challenge for the sustainable development of Asia due to the vulnerability to global energy supplies and price volatility (Nangia, 2019). Asia is lack of natural energy resources and has the smallest oil reserve, but largely relies on fossil fuels. The dependency of fossil fuels was as high as 88.3% in China, 72.3% in India, 89.6% in Japan and 82.8% in Korea in 2013 (BP, 2014). Many countries in south Asia rely on a single source to supply more than half of the electricity, i.e., 67.9% from coal for India, 99.9% from hydropower for Nepal, 91.5% from natural gas for Bangladesh and 50.2% from oil for Sri Lanka (Shukla et al., 2017). Additionally, it is still at a very preliminary stage for the cooperation in Asia to create the integrated energy systems for enhancing the overall security due to countries having different strategic plans and lack of cooperation among them on the common concern (Kimura and Phoumin, 2013).

Even energy efficiency is improving, the deployment of low carbon energy like renewables is not sufficient in Asia. To be consistent with the temperature goal of the Paris Agreement, the share of renewables in total energy consumption needs to reach 35% in Asia by 2030. The financing to deploy renewables presents another considerable challenge (UNESCAP, 2018b).

In order to cope with climate change, renewable energy has become the core of energy development and transformation. Since the 1960s, the total solar radiation on the ground in Asia has shown a downward trend as a whole, which is consistent with the change of global total solar radiation on the ground, and has experienced a phased change process of "first darkening and then brightening" (*high confidence*). This conclusion has been further confirmed by ground station observations, satellite remote sensing inversion data and model simulation research (Wang and Wild, 2016; Qin et al., 2018; Yang et al., 2018a).

However, wind speed over most Asian regions is obviously decreasing (*high confidence*). Based on meteorological observation records or reanalysis data, many studies have analysed the variation of near-surface average wind speed in Asia. It is generally found that the wind speed has declined since 1970s, although the declining trend is different (Yang et al., 2012c; Lin et al., 2013; Liu et al., 2014b; Zha et al., 2016; Guo et al., 2017a; Torralba et al., 2017; Wu et al., 2017a; Ohba, 2019). The decline of near-surface wind speed in Asia is consistent with the general decline of global land surface wind speed, among which the frequency of strong winds and the decline of wind speed are more prominent (McVicar et al., 2012; Jiang et al., 2013; Blunden and Arndt, 2017; Wu et al., 2018c). Since the early 2010' s, the average wind speed in the world and some parts of Asia has shown signs of increasing (Li et al., 2018d; Wu et al., 2018c; Zeng et al., 2019), which seems to be an interdecadal variability. Whether it means a change in its trend needs the support of longer observation data.

At the same time, with the increase of the proportion of renewable energy in the power system, the power system will be more vulnerable to climate change and extreme weather and climate events, and the vulnerability and risk of the power system will greatly increase (*medium confidence*).

10.4.1.3 Adaptation options

The overall solution would be to develop a resilient energy system and avoid the risk of unsustainable energy growth in developing Asia. This requires the strategic planning in consistent with the long term climate projection, impact and adaptation (EUEI-PDF, 2017). Although no single policy package would be applicable for all the countries across the region, several measures could be addressed as the common options, including to fortify energy infrastructure and diversify the sources by sufficient investment, to improve energy efficiency for the sector flexibility, and to promote regional cooperation and integration for increasing energy security (UNESCAP, 2018b). Adaptation also includes promoting renewable energy resources, securing local natural gas resources, enhancing water production, and adopting green building technologies. These adaptation measures may help increase the readiness for the anticipated impact of climate change.

The improvement of energy efficiency and demand side management can alleviate supply constraints and thus lower overall required energy capacity. Energy storage, smart grids for the electricity network as well as other flexibility management measures enable this energy demand shifting. Regional integration of energy markets drives productivity increase, cost reduction, new investment, human capability and diversity of energy sources (WEC, 2018). For example, better interconnection of natural gas supply networks among the ASEAN countries enhances gas security in the region. The development of the long planned regional power grid would make large scale renewable projects more viable, and aid the integration of rising shares of wind and solar power (IEA, 2017).

Providing enough investment in energy supply is a top priority to extend the connections to those without access to electricity and satisfy the soaring demand (IEA, 2017). The investment in non-fossil energies like renewables has been expanding to lever economic growth in China, India and Korea. According to the updated estimation of ADB, 14.7 trillion USD will be needed for the infrastructure development in power sector of developing Asia over the 15 years from 2016 to 2030 (ADB, 2017a). The cumulative investment needs of ASEAN for energy supply and efficiency up to 2040 is estimated at 2.7 to 2.9 trillion USD (IEA, 2017). Mobilising investment to such a scale requires significant participation from the private sector and international financial institutions.

Diversifying energy sources increases energy security and thus the resilience of the whole system. The deployment of renewable energy is widely recognised as a crucial measure enhancing energy access and diversity. There remains huge potential for renewable sources in Asia, i.e., India has the massive solar power potential (Shukla et al., 2017). Many renewable technologies, i.e., hydro, wind and solar PV, are becoming competitive and their lifecycle costs may fall below those of coal and natural gas in the near term. Great progresses have been made in Enhanced Geothermal Systems (EGS), and in conventional and unconventional fusion power that China is promoting. Conventional and underground pumped hydro level out supplies for intermittent renewable energy generation.

Substantial room may be fulfilled by increasing the share of renewable energy in overall energy consumption of this region (ADB, 2017a). Access to energy, particularly in rural areas, can reduce climate vulnerability of developing Asia. Due to the high cost of extending the electricity network to rural regions, an alternative way is to develop the off-grid renewable energy systems in these areas. The distributed instead of centralised energy systems can increase the energy access and resilience (EUEI-PDF, 2017).

Some countries in the Arabian Peninsula like the United Arab Emirates (UAE) are adopting an array of approaches to enhance the adaptive capacity of the energy infrastructure and diffuse the risk of climate change over a larger area (e.g., energy efficiency, demand management, storm planning for power plants). In Al Mashrek, building institutional capacity in the energy sector is a necessary first step to mainstream climate change adaptation. Countries such as Lebanon and Jordan have already made progress in mainstreaming climate change adaptation into electricity infrastructure. In the UAE, buildings account for more than 80% of the total electricity consumption. There are currently a set of measures and regulations on building conditions and specifications that are being applied to increase energy efficiency in buildings, but the rehabilitation and upgrading of old buildings still require further efforts (Environment, 2015). In Kuwait, one adaptation measure to dust storms is through the reduction of the proportion of open desert land from 75% to 51%, the increase of protected areas from 8% to 18%, and greenbelt projects in desert areas (Kuwait, 2015). Addressing climate change impact on energy systems in Lebanon, Jordan, Syria, Iraq, and Palestine needs to simultaneously consider other interlinked challenges of population growth, rapid urbanisation, refugee influx, conflict, and geopolitical location. To address these challenges and provide solutions for climate change adaptation, the promotion of multi-stakeholder partnerships is key to breaking the silo approach.

Climate change adaptation measures need to be broadened to fit the scope and depth of mitigation efforts by each country. Risk assessments and vulnerability assessments are in their early stages in the energy and industrial sectors and are not currently based on a comprehensive plan of action. The first step is to undertake comprehensive national assessments of the risks associated with climate change based on existing studies on climate impacts and risks and by making evidence-based decisions on adaptation actions.

10.4.2 Terrestrial and Freshwater Ecosystems

Sub-regional diversity of ecosystems is high in Asia, see 10.2.2. Climatic drivers of Asian terrestrial ecosystems (ATS) change are global warming, precipitation and Asian monsoon alteration, permafrost thawing and extreme events like dust storms. Observed and projected changes in ATS are affected by several interacting factors, which are in play. Non-climatic human-related drivers are change of land use, change of human use of natural resources including species and ecosystems overexploitation and other non-sustainable use, socioeconomic changes, direct impacts of rising GHGs. Ecosystem vulnerability resulted from complex interaction of climatic and non-climatic drivers, species interaction and natural variability of organisms, species and ecosystems is currently poorly understood, and much more work still needs to be done to unravel these multiple stressors (i.e. (Berner et al., 2013; Brazhnik and Shugart, 2015).

10.4.2.1 Observed Impacts

10.4.2.1.1 Biomes and mountain treeline

Changes in biomes in Asia are compatible with a response to regional SAT increase (Arias et al., 2021) (*medium agreement, medium evidence*). Expansion of the boreal forest and reduction of the tundra area is observed for about 60% of latitudinal and altitudinal sites in Siberia (Rees et al., 2020). In Central Siberia, the changes in climate and disturbance regimes are shifting the southern taiga ecotone northward (Brazhnik et al., 2017). In Taimyr, no significant changes in the forest boundary were observed during the last three decades (Pospelova et al., 2017). For the Japanese archipelago, it is suggested that tree community composition change along the temperature gradient is a response to past and/or current climate changes (Suzuki et al., 2015).

Alpine treeline position in Asian mountains in last decades either moves upward in North Asia, or demonstrate multidirectional shifts in Himalaya (*high confidence*). Since AR5, in North Asia new evidence appeared of trees expansion into mountain tundra and steppe, of intensive reproduction and increase of tree stands productivity in last 30-100 years at the upper treeline in Urals Mountains (Shiyatov and Mazepa, 2015; Zolotareva and Zolotarev, 2017; Moiseev et al., 2018; Sannikov et al., 2018; Fomin et al., 2020; Gaisin et al., 2020), in Russian Altai Mountains (Kharuk et al., 2017a; Cazzolla Gatti et al., 2019), in Putorana Mountains (Kirdyanov et al., 2012; Pospelova et al., 2017; Grigor'ev et al., 2019). Lower treelines in southernmost *Larix sibirica* forests in Saur Mountains, Eastern Kazakhstan, suffer from increased in last decades drought stress causing forest regeneration and tree growth decrease, and tree mortality increase (Dulamsuren et al., 2013). In Jeju Island, Korea, recent warming has enhanced *Quercus mongolica* growth at its higher distribution and has led to *Abies koreana* (ABKO) growth reduction at all elevations, except the highest locality. Thus, combination of warming, increasing competition, and frequent tropical cyclone disturbances can lead to population decline or even extinction of ABKO at Jeju Island (Altman et al., 2020). In Himalaya, treeline over recent decades either moves upward (Schickhoff et al., 2015; Suwal et al., 2016; Sigdel et al., 2018; Tiwari and Jha, 2018), or does not show upslope advance (Schickhoff et al., 2015; Gaire et al., 2017; Singh et al., 2018c), or moves downward (Bhatta et al., 2018). In Tibetan Plateau, treeline either shifted upwards or showed no significant upward shift (Wang et al., 2019c). This can be explained by site-specific complex interaction of positive effect of warming on tree growth, drought stress, change in snow precipitation, inter- and intraspecific interactions of trees and shrubs, land use change, especially grazing, and other factors (Liang et al., 2014; Lenoir and Svenning, 2015; Tiwari et al., 2017; Sigdel et al., 2018; Tiwari and Jha, 2018; Sigdel et al., 2020). It is largely unknown how broader scale climate inputs, as pre-monsoon droughts interact with local-scale factors to govern treeline response patterns (Schickhoff et al., 2015; Müller et al., 2016; Bhatta et al., 2018; Singh et al., 2019b).

10.4.2.1.2 Species ranges and biodiversity

Since AR5, new evidences appeared of terrestrial and freshwater species, populations and communities alterations in line with climate change (Arias et al., 2021) (*medium-to-high confidence*) across Asia. In North Asia, temperature increase and droughts promoted spread northward of the current silk moth outbreak (affected nearly 2.5 x 10^6 ha) in Central Siberia dark taiga since 2014 (Kharuk et al., 2017b; Kharuk et al., 2020). Climatic range of Colorado potato beetle, *Leptinotarsa decemlineata* in 1991–2010 expanded east- and northward in Siberia and Russian Far East compared with the 1951–1970 range (Popova, 2014). Climatic range of *Ixodes ricinus*, a vector of dangerous human diseases expanded into Central Asia and south of the Russian Far East (Semenov et al., 2020). A butterfly *Melanargia russiae* in the Middle Urals moved northward (Zakharova et al., 2017). Thrush birds in Western Siberia penetrated northward up to the limits of the sparse woodlands (Ryzhanovskiy, 2019a). Increase in the length of frost-free period observed in the Ilmen Nature Reserve, Middle Urals during the past decades is supposed to be interlinked with changes in the amplitude and frequency of population waves of bank vole (Kiseleva, 2020). In Katunskiy Biosphere Reserve, Russian Altai, in period 2005–2015, alpine plant species have shifted towards higher altitudes by 5.3 m on average (Artemov, 2018).Wild reindeer herds in Taimyr, north of the Central Siberia migrated northward up to the Arctic Sea coast in hot summers 1999–2003 and 2009–2016 because an earlier massive emergence of bloodsucking insects (Pospelova et al., 2017). In Yakutia, the ranges of red deer, elk and the northern pika are expanding, the winter survival of the mouse-like rodents has increased (Safronov, 2016). In the Chukchi Sea, in last decades the average duration polar bears spent onshore increased by 30 days (Rode et al., 2015b) in line with global warming and rapid declining of sea ice habitat (Derocher et al., 2013; Jenssen et al., 2015; Rode et al., 2015a).

In Central Kazakh Steppe, in line with warming, in 2018 there are more “southern” subarid species in the communities and fewer relatively “northern” boreal and polyzonal species of ground beetles (Carabidae) and black beetles (Tenebrionidae) than in 1976-78 (Mordkovich et al., 2020). Present distribution of Asian black birch, *Betula davurica* Pall. in East and North Asia was formed in result of northward expansion during post-Last Glacial Maximum global warming (Shitara et al., 2018). Both upper and low limits of avifauna of two New Guinean mountains, Mt. Karimui and Karkar Island shifted upslope over nearly a half-century since 1965 (Freeman and Freeman, 2014). In Korea, for the last 60 years, the northern boundary line of 63 southern butterfly species moved further north (Government, 2020). Change of butterflies’ occurrence in this period was influenced mostly by large-scale reforestation, not by climate change (Kwon et al., 2021). Warming-driven geographical range shift was recorded in 87% of 124 endemic plant species studied in Sikkim Himalaya in period 1849-1850 to 2007-2010 (Telwala et al., 2013). In Darjeeling district, India, significant change in lichen community structure was shown in response to climate change and anthropogenic pollution (Bajpai et al., 2016).

Observed biodiversity or habitat loss of animals or plants was linked to climate change in some parts of Asia (*high confidence*). Climate change, together with human disturbances, caused local extinction of some large- and medium-sized mammals during past three centuries in China (Wan et al., 2019). Climate change showed significant impacts on subalpine plant species at low altitudes and latitudes in Republic of Korea and may impose a big threat to these plant species (Adhikari et al., 2018; Kim et al., 2019c). Climate change has caused habitat loss of amphibians (Surasinghe, 2011), and extinction of some endemic species in Sri Lanka (Kottawa-Arachchi and Wijeratne, 2017).

There are evidences that climate change can alter species interaction or spatial distribution of invasive species in Asia (*high confidence*). Climate warming enhanced the competition ability of the native species (*Sparganium angustifolium*) against the invasive species (*Egeria densa*) in China under a mesocosm experiment in a greenhouse (Yu et al., 2018e). Climate warming increased the non-target effect on a native plant (*Alternanthera sessilis*) by a biological control beetle (*Agasicles hygrophila*) in China due to range expansion of the beetle and change of phenology of the plant (Lu et al., 2015). Climate warming expanded the distribution of invasive bamboos (*Phyllostachys edulis* and *P. bambusoides*) northward and upslope in Japan (Takano et al., 2017), while soil dry-down rates were a key driver of invasion of dwarf bamboo, *Sasa kurilensis* in central Hokkaido above and below treeline (Winkler et al., 2016).

Climate change along with land-use and land cover change influences soil organic carbon content, microbial biomass C, microbial respiration and soil carbon cycle in the Hyrcanian forests, Iran (Soleimani et al., 2019; Francaviglia et al., 2020). In fir forest ecosystems of Tibetan Plateau, winter warming affects the ammonia oxidising bacteria and archaea, thus alters N cycle (Huang et al., 2016). Ecosystem carbon pool in spruce forests of the north-eastern Tibetan Plateau was reduced by ca 25% by deforestation due to recent decades climate warming and wood pasture and logging (Wagner et al., 2015). In Mongolia's forest-steppe, recent decades drought- and land use-induced deforestation reduces ecosystem carbon stock density by c. 40 % (Dulamsuren et al., 2016). In Inner Mongolia, China, the predicted decreases in precipitation and warming for most of the temperate grassland region could lead to pH change, which contributes to a soil C-N-P decoupling that may reduce plant growth and production in arid ecosystems (Jiao et al., 2016).

In Central Asia, in Vakhsh, Kafirnigan, and Kyzylsu river basins, Tajikistan it was shown that temperature stimulate algal species diversity, while precipitation and altitude suppress it (Barinova et al., 2015). In line with warming of Lake Baikal, Russia since the 1990s in the lake's south basin there are shifts in diatom community composition towards higher abundances of the cosmopolitan *Synedra acus* and a decline in endemic species, mainly *Cyclotella minuta* and *Stephanodiscus meyerii* and to a lesser extent *Aulacoseira baicalensis* and *A. skvortzowii* (Roberts et al., 2018). In Gonghai Lake, North China diatom biodiversity increased remarkably from 1966, but began to decline after 1990 presumably in response to rapid climatic warming (Yan et al., 2018).

10.4.2.1.3 Wildfires

Climate change, human activity and lightning determine increase of wildfire severity and area burned in North Asia (*high detection, medium-to-low attribution to climate change*). In North Asia, the extent of fire-affected areas in boreal forest can be millions hectares in a single extreme fire year (Duane et al., 2021) and has nearly doubled between 1970 and 1990 (Brazhnik et al., 2017). During recent decades, number, area and frequency of forest fires increased in Putorana Plateau, north of Central Siberia; in larch-dominated forests of Central Siberia; and in Siberian forests as a whole. This increase is in line with increase of the average annual air temperature, air temperature anomalies, droughts and the length of fire season (Ponomarev et al., 2016; Kharuk and Ponomarev, 2017; Pospelova et al., 2017). The number of forest fires and damaged areas in Gangwon Province and the Yeongdong area in the 2000s increased by factors of 1.7 and 5.6, respectively, compared with the 1990s (Government, 2020). Climate change is not the sole cause of increase of forest fire severity (Wu et al., 2014; Wu et al., 2018d). Ignition is often facilitated by lightning (Canadell et al., 2021), and over 80% of fires in Siberia are *likely* anthropogenic in origin (e.g., (Brazhnik et al., 2017). Gas field development and Indigenous tundra burning practices that may get out of control contribute to fire frequency in forest-tundra of west Siberia (Adaev, 2018; Moskovchenko et al., 2020). Climate change in combination with socioeconomic changes has resulted in an increase of fire severity and area burned in southern Siberia, illegal logging acts to increase fire danger in forest–steppe Scots pine stands (Ivanova et al., 2010; Schaphoff et al., 2016).

10.4.2.1.4 Phenology, growth rate and productivity

In East and North Asia, satellite measurements and ground-based observations in last decades demonstrate either increase of the length of plant growth season over sub-regions or in some territories in line with climate warming, or do not show any significant trend in other territories (*high confidence*). In last decades in China, it was increasing trend in annual mean grassland net primary production (NPP), average Leaf Area Index (LAI) and lengthening of the local growing season (Piao et al., 2015; Zhang et al., 2017b; Xia et al., 2019). Nevertheless, phenology pattern vary across different studies, species and parts of China. In most regions of Northeast China (NEC), start date and length of land surface phenology from 2000 to 2015 had advanced by approximately 1.0 days year^{-1} except for the needle-leaf and cropland areas (Zhang et al., 2017d). For Inner Mongolia, it was shown that neither start of growing season (SOS) nor end of growing season (EOS) presented detectable progressive pattern at the regional level in 1998 – 2012, except for the steppe desert (6% of the total area) (Sha et al., 2016). In the Tianshan Mountains (TM) in China, NPP of only two out of 12 types of vegetation increased in spring, and NPP of only one type increased in autumn from 2000-2003 to 2012-2016 (Hao et al., 2019). In Republic of Korea, from 1970 to 2013 the SOS has been advanced by 2.7 days/decade and the EOS has been delayed by 1.4 day/decade (Jung et al., 2015), during the last decade leaf unfolding was accelerating 1.37 days/year, and the timing of leaf fall was delaying 0.34 day/year (Kim et al., 2019d), cherry blossoms is predicted to flower 6.3 days and 11.2 days earlier after 2090 according to scenarios RCP 4.5 and RCP 8.5, respectively (Government, 2020). On Tibetan Plateau (TP), it was found that the SOS has advanced and EOS has been delayed over the last 30-40 years (Yang et al., 2017). Using NDVI data sets and ground-based budburst data, (Wang et al., 2017c) found no consistent evidence that SOS has been advancing or delaying over the TP during the last two to three decades. The discrepancies in the trends of spring phenology over the TP among different studies could be largely attributed to the use of different phenology retrieval methods. An uncertainty exists with the relationship between land surface phenology and climate change estimated by satellite-derived NDVI because these indices are usually composite products of a number of days (e.g., 16-days) that could fail to capture more details. Besides, due to lack of in situ observations, SOS and EOS at large areas cannot be easy defined (Zhang et al., 2017d).

In North Asia, in the Middle Siberia and south of Western Siberia, growth index of Siberian larch based on tree rings width increased with the onset of warming and changed in antiphase with aridity in 1980s (Kharuk et al., 2018). In Mongolia and Kazakhstan, the last decade's temperature increase promoted radial stem increment of Siberian larch. However, the simultaneous influence of increased temperature, decreased precipitation and increased anthropogenic pressure resulted in widespread declines in forest productivity and reduced forest regeneration, and increased tree mortality (Dulamsuren et al., 2013; Lkhagvadorj et al., 2013b; Lkhagvadorj et al., 2013a; Dulamsuren et al., 2014; Khansaritoreh et al., 2017). In Eastern Taimyr, growing season, the number of flowering shoots, annual increment, success of seed ripening and vegetation biomass have increased considerably in last decades (Pospelova et al., 2017). In Vishera Nature Reserve, Northern Urals Mountains, annual temperature increased in last decades in parallel with summer temperature drop and increase of summer frost numbers. As result, trends of vegetation change are mostly unreliable (Prokosheva, 2017).

Date of arrival of migrant birds to nesting areas, and date of departure from winter areas in Asia are changing consistently with climate change (*medium confidence*). Time of arrival of the gray crow to the Lower Ob river region, northwest Siberia, shifted to earlier dates in period 1970–2017 in consistent with increase of daily average temperatures on the day of arrival (Ryzhanovskiy, 2019b). In Ilmen Nature Reserve, Urals, an earlier arrival of the majority of nesting bird species is not observed last decades. It is explained by the fact that other factors as weather of each spring month of particular years, population density in the previous nesting period, the seed yield of the main feeding plants, and migration of wintering species from adjacent areas determinate long-term dynamics of bird arrival (Zakharov, 2016; Zakharov, 2018). In Yokohama, Japan observations since 1986 revealed that arrival of six winter bird species became later and departure earlier than in the past in line with warmer temperatures (Kobori et al., 2012; Cohen et al., 2018). Part of papers analysed corroborate that earlier start and late end of phenological events in Asia are associated with global warming, however another part of papers does not confirm such a connection. Comparison and synthesis of results is impeded by usage of different metrics, measurement methods and models (e.g., (Hao et al., 2019)). Relative contribution of climatic stress and other factors to phenology and plant growth trends are poorly understood (e.g., (Andreeva et al., 2019)).

10.4.2.2 Projected Impacts

10.4.2.2.1 Biomes and mountain treeline

Across Asia, under a range of RCPs and other scenarios rising temperature is expected to contribute to northward shift of biome boundaries and upward shift of mountain treeline (*medium confidence*). Northward shift and area change of bioclimatic zones in Siberia (Anisimov et al., 2017; Torzhkov et al., 2019) and NE Asia (Choi et al., 2019) are projected. Projected changes in vegetation in China at the end of the 21st century revealed that the area covered by cold-dry potential vegetation decreases as the area covered by warm-humid potential vegetation increases (Zhao et al., 2017a). Forest expansion into mountain tundra of the Northern Urals is expected (Sannikov et al., 2018). In Republic of Korea, projected under RCP 4.5 and RCP 8.5 in 2070s suitable area loss of six subalpine tree species, namely, Korean fir, Khingan fir, Sargent juniper, Yeddo spruce, Korean yew, and Korean arborvitae range from 17.7% ± 20.1% to 65.2% ± 34.7%, respectively (Lee et al., 2021b). Korean fir forests would be replaced by temperate forests at lower elevations, while would continuously persist at the highest elevations on Mt. Halla, Jeju Island, Republic of

Korea (Lim et al., 2018). Himalayan birch at its upper distribution boundary either projected to move upward (Schickhoff et al., 2015; Bobrowski et al., 2018), or considered to downslope as a response to global-change-type droughts (Liang et al., 2014). Upward shift in elevation of bioclimatic zones, decreases in area of the highest elevation zones, large expansion of the lower tropical and sub-tropical zones can be expected by the year 2050 throughout the transboundary Kailash Sacred Landscape of China, India and Nepal, and *likely* within the Himalayan region more generally (Zomer et al., 2014).

In North Asia, it is projected a shift in the dominant biomes from conifers to deciduous species across Russia after 20 years of altered climate conditions (Shuman et al., 2015). In Southern Siberia, Brazhnik and Shugart (2015) projected shift from the boreal forest to the steppe biome. Rumiantsev et al. (2013) also project positive northward shift of vegetation boundaries for greater part of Western Siberia (WS) in line with warming, however no shift for the north of WS, and negative shift for Southern Urals and North-western Kazakhstan are projected for 2046-2065. The replacement of forest-steppe with steppe at the lower treeline in Southern Siberia is projected (Brazhnik and Shugart, 2015), and retreat of larch forests from the southernmost strongholds of boreal forest in the Eastern Kazakhstan is expected as part of a global process of forest dieback in semiarid regions (Dulamsuren et al., 2013). In North Asia, tree growth is intertwined with permafrost, snowpack, insect outbreaks, wildfires, seed dispersal and climate (e.g. (Klinge et al., 2018)). It is challenging to isolate the affects of individual factors, particularly since they can feedback on one another in unanticipated ways because underlined mechanisms are not understood well (Berner et al., 2013; Brazhnik and Shugart, 2015). The accuracy of treeline shift projections is limited because projections are based on vegetation models which do not consider all the factors (Tishkov et al., 2020). Regional vegetation model structure and parameterisation can affect model performance, and correspondent projections can differ significantly (Shuman et al., 2015).

10.4.2.2.2 Species ranges and biodiversity

Considerable changes of plant and animal species distribution under warming stress until 2100 are expected in Asia (*high confidence*). In East Asia, *Cunninghamia lanceolate*, a fast growing and wide distributed in China coniferous timber species, is projected to increase distribution, to decrease the establishment probability and to reduce total NPP by 2050s (Liu et al., 2014c). In monsoon Asia, by the end of the 21st century, NPP is projected to increase by 9–45 % (Ito et al., 2016). Under climate change in the Korean Peninsula (KP), potential habitat for *Abies nephrolepis* is the northern part of KP, *A. koreana* disappear from Jeju Island and shrink significantly in the KP (Yun et al., 2018), while evergreen forest would expand to the northern part of KP (Koo et al., 2018; Lim et al., 2018). It is expected that under projected warming fig species in China will expand to higher latitudes and altitudes (Chen et al., 2018c). In Japan, under AIB scenario 89% of the area currently covered by *Fagus crenata*-dominant forest type to be replaced in the future by *Quercus spp*.-dominant forest types (Matsui et al., 2018). Current trends of climate change will reduce distribution of tall, 2-2.5 m height herb communities in Japan, and will increase suitable for them area in the Russian Far East (Korznikov et al., 2019). A range expansion of *Lobaria pindarensis*, an endemic in HKH region epiphytic lichen, is projected to the north-east and to higher altitudes in response to climate change, although the species' low dispersal abilities and the local availability of trees as a substratum will considerably limit latitudinal and altitudinal shifts (Devkota et al., 2019).

Climatic range of Italian locust (*Calliptamus italicus* L.) under the RCP4.5 will expand north- and eastward to Siberia, Russian Far East and Central Asia (Popova et al., 2016). In Krasnoyarsk Krai, Siberia it is projected that the needle cast disease caused by fungi from the genus *Lophodermium* Chevall. in the Scots pine nurseries would shift northwards up to 2080 under A2 and B1 scenarios (Tchebakova et al., 2016). All four RCP scenarios showed northward expansion of vulnerable regions to pine wilt disease in China, Korea, Russian Far East, and Japan under future climate conditions in 2070 (Hirata et al., 2017), and in 2026-2050 in Japan (Matsuhashi et al., 2020). It should be noted that disease expansion depends not only on climatic factors, but also on the dispersal capacity of insect vectors, the transportation of infected logs to non-infected regions, and susceptibility of host trees (e.g. (Gruffudd et al., 2016)). Suitable habitat area of snow leopard *Panthera uncia* is projected to increase for 20% under the IPCC Scenario A1B by 2080: for the seven northernmost snow leopard range states (Afghanistan, Tajikistan, Uzbekistan, Kyrgyzstan, Kazakhstan, Russia, and Mongolia) the suitable habitat area will increase, while habitat loss is expected on the south slope of the Himalaya and the south-eastern Tibetan Plateau (Farrington and Li, 2016). Climate change projected under four RCP scenarios will not affect the distribution patterns of Turkestan Rock Agama *Paralaudakia lehmanni* (Nikolsky 1896) (Sancholi, 2018). In Iran, among 37 studied species of plants and animals, ranges of 30 species are expected to shrink and range of seven species are expected to increase by 2030-2099 under climate change stress (Yousefi et al., 2019).

Future climate change would cause biodiversity and habitat loss in many parts of Asia using modelling approaches (*high confidence*). Warren et al. (2018) projected that extirpation risks terrestrial taxa (plants, amphibians, reptiles, birds and mammals) from 2°C to 4.5°C global warming in 12 priority Places of Asia under the assumptions of without adaptation (dispersal) by 2080s is from 12.2-26.4% to 29-56% (Table 10.1, Figure 10.4).Under different scenarios, future climate change could reduce the extent of a suitable habitat for giant pandas (Fan et al., 2014), the moose (*Alces alces*) (Huang et al., 2016), black muntjac (*Muntiacus crinifrons*) (Lei et al., 2016), the Sichuan snub-nosed monkey (*Rhinopithecus roxellana*) (Zhang et al., 2019d) in China; Persian leopard (*Panthera pardus saxicolor*) in Iran (Ashrafzadeh et al., 2019a), Bengal tiger (Mukul et al., 2019), and four tree snail species (*Amphidromus*) in Thailand (Klorvuttimontara et al., 2017). However, climate change would have little impact on the habitats of Asian elephant, but would cause extinction of Hoolock gibbon in Bangladesh by 2070 (Alamgir et al., 2015). Climate change would increase the distribution of Mesopotamian spiny-tailed lizard (*Saara loricate*) in Iran (Kafash et al., 2016). Future climate change would reduce suitable habitat of protected plants (Zhang et al., 2014), *Polygala tenuifolia* Wild (Lei et al., 2016), relict species in East Asia (Tang et al., 2018), and tree *Abies* (Ran et al., 2018) in China; two threatened medicinal plants (*Fritillaria cirrhosa* and *Lilium nepalense*) in Nepal (Rana et al., 2017); a medicinal and vulnerable plant species *Daphne mucronata* (Abolmaali et al., 2018) and *Bromus tomentellus* in Iran (Sangoony et al., 2016); a valuable threatened tree species *Dysoxylum binectariferum* in Bangladesh (Sohel et al., 2016); plant diversity in Korea (Lim et al., 2018).

Impact of future climate change on invasive species may be species- or region-specific (*medium confidence*). Climate change would promote invasion of a highly invasive aquatic plant *Eichhornia crassipes* (You et al., 2014), *Ambrosia artemisiifolia* (Qin et al., 2014), alligator weed (*Alternanthera philoxeroides*) (Wu et al., 2016), invasive alien plant *Solidago canadensis* (Xu et al., 2014), three invasive woody oil plant species (*Jatropha curcas, Ricinus communis,* and *Aleurites moluccana*) (Dai et al., 2018), 90 of ~150 poisonous plant species (Zhang et al., 2017a) in China; six mostly serious invasive species (*Ageratum houstonianum* Mill., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Hyptis suaveolens* (L.) Poit*., Lantana camara* L*., Mikania micrantha* Kunth*,* and *Parthenium hysterophorus* L.) in Nepal (Shrestha et al. 2018), eleven invasive plant species in Western Himalaya (Thapa et al., 2018), alien plants in Georgia (Slodowicz et al., 2018), the invasive green anole (*Anolis carolinensis*) in Japan (Suzuki-Ohno et al., 2017), the Giant African Snail in India (Sarma et al., 2015), a major insect vector (*Monochamus alternatus*) of the pine wilt disease (Kim et al., 2016b) and melon thrips (*Thrips palmi* Karny) (Park et al., 2014) in Korea. In contrast, a few studies projected that the climate change would inhibit the invasion of one exotic species (*Spartina alterniflora*) (Ge et al., 2015), alien invasive weeds (Wan et al., 2017), invasive plant *Galinsoga parviflora* (Bi et al., 2019), an invasive species *Galinsoga quadriradiata* (Yang et al., 2018b) in China; two invasive plants (*Chromolaena odorata* and *Tridax procumben*s) in India (Panda and Behera, 2019).

Five of 15 endemic freshwater fish species in Iran will lose some parts of their current suitable range under climate change by 2070 (Yousefi et al., 2020). In line with projected large increases in mean water temperature, it is projected the strongest increase in exceeded frequency and magnitude of maximum temperature tolerance values for freshwater minnow (*Zacco platypus*) in East Asia for 2031 to 2100 (Van Vliet et al., 2013). Climate change under A1B scenario is projected to decrease diversity (-0.1%) along with increased local richness (+15%) and range size (+19%) of stream macroinvertebrates in the Changjiang River catchment, south-east China for the period 2021 to 2050, while land-use change was predicted to have the strongest negative impact (Kuemmerlen et al., 2015). Asian clam *Corbicula fluminea* (Müller, 1744), an invasive species native to southeast China, Korea, and south-eastern Russia, is projected to invade to South-east Asia under all four RCP scenarios for 2041–2060 and 2061–2080 periods (Gama et al., 2017). Projected sea level rise, related aquatic salinisation, and alteration in fish species composition may have a negative impact on poor households in Southwest Coastal Bangladesh (Dasgupta et al., 2017a).

10.4.2.2.3 Wildfires

Under regional projections for North Asia, warmer climate will increase forest fire severity by the late 21st century (*medium confidence*). For south taiga in Tuva Republic, central Siberia, in a warmer climate, both the annual area burned and fire intensity will increase by 2100. For middle taiga in Irkutsk Region, the annual area burned and the crown: ground fire fraction will increase by late 21st century against historical

(1960-1990) estimate. This moves forest composition toward greater contribution of hardwoods (*Betula* spp., *Populus* spp.) (Brazhnik et al., 2017). This shifting was also proved by observations in the Northern Mongolia, where boreal forest fires *likely* promote the relative dominance of *B. platyphylla* and threaten the existence of the evergreen conifers, *Picea obovata*, and *Pinus sibirica* (Otoda et al., 2013). For Tuva Republic, warming ambient temperatures increase the potential evapotranspiration demands on vegetation, but if no concurrent increase in precipitation occurs, vegetation becomes stressed and either dies from temperature-based drought stress or more easily succumbs to mortality from insects, fire, pathogens, or wind throw (Brazhnik et al., 2017). Although Torzhkov et al. (2019) also projected fire risk (FR) increase in Tuva Republic, they expect FR decrease in Irkutsk Region and Yakutia under RCP 8.5, and FR decrease in major part of central and eastern Siberia under RCP 4.5 for 2090-2099. This discrepancy is due to differences in models, climate projections, fire severity metrics and other assumptions. According to global projections, fire risk will increase in Central Asia, Russia, China and India under a range of scenarios (Sun et al., 2019).

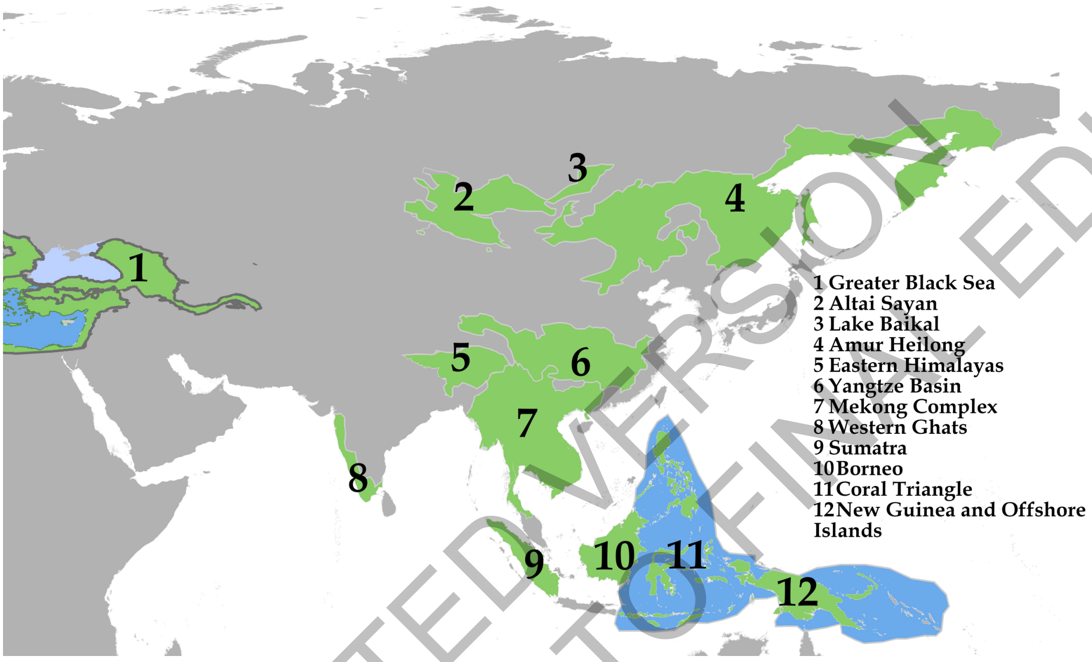


Figure 10.4. Location of Priority Places in Asia (modified from: Warren et al. (2018)

Table 10.1: Projected extirpation risks, % of taxa (plants, amphibians, reptiles, birds and mammals) for 2°C and 4.5°C global warming in Priority Places in Asia, without adaptation by 2080s (from: Warren et al. (2018))

Priority Places	**2°**	**4.5°**
Mekong	26.4	55.2
Baikal	22.8	49.5
Yangtze	20	42.6
Coral Triangle	19.2	41.8
W Ghats	18.8	41.67
New Guinea	19.8	41.2
Atlai-Syan	18.6	37
Sumatra	16.8	37
Borneo	17.6	36.8
Amur	14.2	35.6
Eastern Himalayas	12.2	29
Black sea	26.2	56

10.4.2.3 Vulnerabilities to Key Drivers

Both natural and managed ecosystems, ecosystem services and livelihoods in Asia will potentially be substantially impacted by changing climate (Wu et al., 2018d). There will be increased risk for biodiversity, particularly many endemic and threatened species of fauna and flora already under environmental pressure from land use change and other regional and global processes (Zomer et al., 2014; Rashid et al., 2015; Choi et al., 2019). Biomes shift not only serves as a signal of climate change but also provides important information for resources management and ecotone ecosystem conservation. A widespread upward encroachment of subalpine forests would displace regionally unique alpine tundra habitats and possibly cause the loss of alpine species (Schickhoff et al., 2015). In the North Asia, emissions from fires reduce forest ability to regulate climate. A warmer and longer growing season will increase vulnerability to fires, although fires can be attributed both to climate warming and to other human and natural influences. Recent field-based observations revealed that the forests in southern Siberia are losing their ability to regenerate post fire and other landscape disturbances under a warming climate (Brazhnik et al., 2017). Data support the hypothesis of climate-driven increase of fire frequency in boreal forests with the possible turning of boreal forests from carbon sink to a carbon source (Ponomarev et al., 2016; Schaphoff et al., 2016; Brazhnik et al., 2017; Ponomarev et al., 2018), however warming resulted from forest fire is partly compensated by cooling in response to increased surface albedo of burned areas in snow-on period (Chen and Loboda, 2018; Chen et al., 2018a; Jia et al., 2019; Lasslop et al., 2019).

10.4.2.4 Adaptation Options

Modelling of the interactions between climate-induced vegetation shifts, wildfire and human activities can provide keys to how people in Asia may be able to adapt to climate change (Kicklighter et al., 2014; Tian et al., 2020). Conservation and sustainable development would benefit from being tailored and modified considering the changing climatic conditions and shifting biomes, mountain belts and species ranges (Pörtner et al., 2021). Expanding the nature reserves would help species conservation; to facilitate species movements across climatic gradients, increase of landscape connectivity can be elaborated by setting up habitat corridors between nature reserves and along elevational and other climatic gradients (Brito-Morales et al., 2018; D'Aloia et al., 2019; United Nations Climate Change Secretariat, 2019). Assisted migration of species should be considered for isolated habitats as mountain summits or where movements are constrained by poor dispersal ability. Introducing seeds of the species to new regions will help to protect them from the extinction risk caused by climate change (Mazangi et al., 2016). In Asian boreal forest, a strategy and an integrated programmes should be developed for adaptation of forests to global climate change, including sustainable forest management, firefighting infrastructure and forest fuel management, afforestation, institutional, social, and other measures in line with SDG 15 ‘Life on Land’ (Isaev and Korovin, 2013; Kattsov and Semenov, 2014; Government, 2020). Improvements in forest habitat quality can reduce the negative impacts of climate change on biodiversity and ecosystem services (Choi et al., 2021). Adaptation options for freshwater ecosystems in Asia include increasing connectivity in river networks, expanding protected areas, restoring hydrological processes of wetlands and rivers, creating shade to lower temperatures for vulnerable species, assisted translocation and migration of species (Hassan et al., 2020; IPCC, 2021b). Reducing of non-climate anthropogenic impacts can enhance the adaptive capacity of ecosystems (Tchebakova et al., 2016).

[START BOX 10.3 HERE]

Box 10.3: Case Study on Sand and Dust Storm, Climate Change, in West Asia, Iran

West Asia Region, especially Tigris-Euphrates alluvial plain, has been recognised as one of the most important dust source areas in the world (Cao et al., 2015). The inhabitants of each of these settlements have experienced a decline in dust storms in recent decades, since the late 1980s at Nouakchott, since 2004 at Zabol, and since the late 1970s at Minqin. Iran is mostly arid or semiarid, with deserts making up at least 25 million hectares of the country’s area (NASA, 2018). Iran is experiencing unprecedented climate-related problems such as drying of lakes and rivers, dust storms, record-breaking temperatures, droughts, and floods (Vaghefi et al., 2019). There are three key factors responsible for the generation of sand and dust storms – strong wind, lack of vegetation and absence of rainfall (EcoMENA, 2020). It seems that it is closely related to the heating surface and the occurrence of local dry instabilities (Ghasem et al., 2012). According to

EcoMENA sand and dust storms cause significant negative impacts on society, economy and environment at local, regional and global scale (EcoMENA, 2020). The seasonality of the numbers of dusty days (NDD) in Iran shows the highest frequency for summer followed by the spring and autumn seasons (Modarres and Sadeghi, 2018). In the past decade, West Asia has witnessed more frequent and intensified dust storms affecting Iran and Persian Gulf countries (Nabavi et al., 2016). In terms of long-term frequency of dust events, observational analyses show an overall rising trend of the frequency of Iran's dust events in recent years (Alizadeh-Choobari et al., 2016). Results showed that there was a direct relationship between dust event and drought and years having intensive drought (Dastorani and Jafari, 2019). Compared to the period of 1980–2004, in the period of 2025–2049, Iran is *likely* to experience more extended periods of extreme maximum temperatures in the southern part of the country, more extended periods of dry (for ≥120 days: precipitation <2mm, Tmax ≥30°C) as well as wet (for ≤3 days: total precipitation ≥110mm) conditions, and higher frequency of floods (Vaghefi et al., 2019). The slope of precipitation, in West Asia region showed that during the period of 2016-2045 in January, February, July and August, precipitation would increase and decrease in other months of the year (Ahmadi et al., 2018). Temperatures in Central Asia have risen significantly within the last decades whereas mean precipitation remains almost unchanged (Haag et al., 2019). However, climatic trends can vary greatly between different sub-regions, across altitudinal levels, and within seasons (Haag et al., 2019).

[END BOX 10.3 HERE]

10.4.3 Ocean and Coastal Ecosystems

Coastal habitats of Asia are diverse and the impacts of climate change including rising temperature, ocean acidification and sea level rise has been known to affect the services and the livelihood of people depending on it. The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*) (IPCC, 2018b). In South China Sea coral growth and sea surface temperature (SST) showed regional long tern trends and inter-decadal variations while coral growth is predicted to decline by the end of this century (Yan et al., 2019). Increasing human impacts have also been found to reduce coral growth (Yan et al., 2019). In the SCS, nearly 571 coral species, have been severely impacted by global climate changes and anthropogenic activities (Huang et al., 2015a).

The 2014–2017 global-scale coral bleaching event (GCBE) resulted in very high coral mortality on many reefs, rapid deterioration of reef structures, and far-reaching environmental impacts (Eakin et al., 2019). The thermally tolerant Persian Gulf corals (Coles and Riegl, 2013) are facing an increasing frequency of mass bleaching (Riegl et al., 2018) and each event leaves a substantial long-term impact on coral communities (Burt, 2014) with low capacity for recovery indicating a bleak future for Persian Gulf reefs (Burt et al., 2019).

One of the probable results of global warming is rising high seas level. Scientists believe that increasing greenhouse gases (earth temperature controller) is the reason of this global warming and by using satellite measurements, have forecasted averagely 1-2 mm for rising high seas level (Jafari et al., 2016). The level of thermal stress (based on a degree heating month index, DHMI) at these locations during the 2015–2016 El Niño was unprecedented and stronger than previous ones (Lough et al., 2018) Persian Gulf the reef-bottom temperatures in 2017 were among the hottest on record, with mean daily maxima averaging 35.9 ± 0.10C across sites, with hourly temperatures reaching as high as 37.7o C (Riegl et al., 2018). About 94.3% of corals bleached, and two-thirds of corals suffered mortality in 2017 (Burt et al., 2019). In 2018 coral cover averaged just 7.5% across the southern basin of the Persian Gulf. This mass mortality did not cause dramatic shifts in community composition as earlier bleaching events had removed most sensitive taxa. An exception was the already rare Acropora which were locally extirpated in summer 2017 (Burt et al., 2019). During 2008-2011 also the coral communities of Musandam and Oman have shown changes depending on the stress tolerance levels of the species and the local environmental disturbance level (Bento et al., 2016).

Health and resilience of corals have been found to be associated with beneficial microorganisms of coral (BMC) which alter during environmental stress. Increased seawater temperature has been found to affect the functioning of symbiotic algae of corals (Lough et al., 2018) (Gong et al., 2019) and its bacterial consortia leading to coral bleaching and mortality (Bourne et al., 2016); (Peixoto et al., 2017); (Bernasconi et al., 2019); (Motone et al., 2020).

Coral reefs were found to be affected differentially during bleaching episodes and those species which survived had more stress tolerant symbionts and higher tolerance to thermal changes (Majumdar et al., 2018); (Thinesh et al., 2019) (van der Zande et al., 2020). Rare thermally tolerant algae and host species-specific algae may play important roles in coral bleaching (van der Zande et al., 2020). Along the Indian coast, coral reefs of Palk Bay (Bay of Bengal), varied bleaching and recovery pattern among coral genera was observed during the 2016 bleaching episode (Thinesh et al., 2019). Bleaching was high in Acropora (86.36%), followed by Porites (65.45%), while moderate to no bleaching was observed in Favites Symphyllia, Favia, Platygyra and Goniastrea.

Presence of stress-tolerant symbiont Durusdinium (Clade D) during the post bleach period indicated the high adaptive capacity of Acropora in tropical waters (Thinesh et al., 2019). Also Porites sp. were found to have higher thermal thresholds and showed good resilience to bleaching than species like Fungiid sp. (Majumdar et al., 2018). In Philippines, during the 2010 bleaching event, the size structure of the mushroom coral was found to be affected (Feliciano et al., 2018). In Indonesia , it was found that branching coral diversity may decrease relative to massive, more resilient corals (Hennige et al., 2010). This would have large-scale impacts upon reef bio-diversity and ecosystem services, and reef metabolism and net reef accretion rates, since massive species are typically slow growers (Hennige et al., 2010).

Macro-tidal coral reefs are particularly sensitive to medium to long-term changes in sea-level Andaman trenches (Simons et al., 2019). Data were compiled from 11 cities throughout East and Southeast Asia, with particular focus on Singapore, Jakarta, Hong Kong, and Naha (Okinawa) highlights several key characteristics of urban coral reefs, including “reef compression” (a decline in bathymetric range with increasing turbidity and decreasing water clarity over time and relative to shore), dominance by domed coral growth forms and low reef complexity, variable city-specific inshore-offshore gradients, early declines in coral cover with recent fluctuating periods of acute impacts and rapid recovery, and colonisation of urban infrastructure by hard corals (Heery et al., 2018).

In Taiwan, Province of China, calcification rate of the model reef coral *Pocillopora damicornis* was higher in coral reef mesocosms featuring seagrasses under ocean acidification conditions at 25 and 28°C. The presence of seagrass in the mesocosms helped to stabilise the metabolism of the system in response to simulated climate change (Liu et al., 2020a).

Increase in host susceptibility, pathogen abundance or virulence has led to higher prevalence and severity of coral diseases and lead to decline and changes in coral reef community composition (Maynard et al., 2015) . Relative risk has been found to be high in the province of Papua in Indonesia, Philippines, Japan, India, northern Maldives, the Persian Gulf and the Red Sea. For the combined disease risk metric, relative risk was considered lower for locations where anthropogenic stress was low or medium, condition found for some of these locations in Thailand (Maynard et al., 2015).

Degradation and loss of coral reefs can affect about 4.5 million people South East Asia and Indian Ocean (Lam et al., 2019). In the coral reef fisheries sector, there are about 3.35 million fishers in Southeast Asia and 1.5 million fishers in the Indian Ocean (Teh et al., 2013). The economic loss under different climate change scenarios and fishing effort were estimated to range from US$27.78 to US$31.72 million annually in Nha rang Bay, Vietnam. A survey conducted in Taiwan, Province of China, showed that the average annual personal willingness to pay was US$35.75 and total annual willingness to pay as US$0.43 billion. These high values indicate the need to preserve these coral reef ecosystems (Tseng et al., 2015). In Bangladesh the coral reef of St. Martin’s Island contributes 33.6 million USD/year to the local economy climate change along with other anthropogenic activities has been identified as a threat these habitats (Rani et al., 2020a).

Mitigation of global warming has been identified to be essential to maintain healthy coral reef ecosystems of Asia (Comte and Pendleton, 2018); (Heery et al., 2018); (Yan et al., 2019); (Lam et al., 2019). Restoration of reefs (Nanajkar et al., 2019) and building resilience through multiple mechanisms, such as innovative policy combinations, complemented by environmental technology innovations and sustained investment (Hilmi et al., 2019); (McLeod et al., 2019) are suggested.

An ecosystem-based approach to managing coral reefs in the Gulf of Thailand is needed to identify appropriate marine protected area networks and to strengthen marine and coastal resource policies in order to build coral reef resilience (Sutthacheep et al., 2013). Scope to develop novel mitigation approaches toward coral protection through the use of symbiotic bacteria and their metabolites (Motone et al., 2018); (Motone et al., 2020) has been suggested. Coral culture and transplantation within the Gulf are feasible for helping maintain coral species populations and preserving genomes and adaptive capacities of Gulf corals that are endangered by future thermal stress events (Coles and Riegl, 2013). Greater focus on understanding the flexibility and adaptability of people associated with coral reefs, especially in a time of rapid global change (Hoegh-Guldberg et al., 2019) and a well-designed research program for developing a more targeted policy agenda (Lam et al., 2019). is also recommended. Cutting carbon emissions (Bruno and Valdivia, 2016) and limiting warming to below 1.5˚C is essential to preserving coral reefs worldwide and protecting millions of people (Frieler et al., 2013) (Hoegh-Guldberg et al., 2017). Many visitors to coral reefs have high environmental awareness and reef visitation can both help to fund and to encourage coral reef conservation (Spalding et al., 2017).

The largest mangrove forests are in Asia contributing to about 42% of the world's mangroves and this includes Sundarbans the world’s largest remaining contiguous mangrove forest (Dasgupta et al., 2020.). Mangrove ecosystems are rich in biodiversity. The ecosystems are supported and maintained by both flora and a large array of living things, which include mammals, birds, fish, crustaceans, shrimps, insects and microbes (Tropical Coastal Ecosystems Portal. Available from http://www.nies.go.jp/TroCEP/index.html. Accessed 08-Oct. 2020). Contemporary rates of mangrove deforestation are lower than in the late twentieth century (Gandhi and Jones, 2019); (Friess et al., 2019). However, some areas in Asia continue the trend. Myanmar is the primary mangrove loss hotspot in Asia, exhibiting 35% loss from 1975–2005 and 28% between 2000–2014. Rates of loss in Myanmar were four times the global average from 2000–2012. The Philippines is additionally identified as a loss hotspot, with secondary hotspots including Malaysia, Cambodia and Indonesia (Gandhi and Jones, 2019).

Mangrove deforestation is expected to increase as many tropical nations utilise mangrove areas for economic security. Increased river damming would reduce fluvial sediment sources to the coast making mangroves more vulnerable SLR and uncertain climate with extreme oscillations can create unstable conditions for survival and propagation of mangrove (Friess et al., 2019).

Valuation of ecosystem services of mangroves indicated that they prevent more than 1.7 billion US$ in damages for extreme events (1-in-50-year) in Philippines (Menéndez et al., 2018). They reduce flooding to 613,500 people/year, 23% of whom live below the poverty line and avert damages to 1 billion US$/year in residential and industrial property. Mangroves have also become very popular as source of livelihood in Asia through tourism (Dehghani et al., 2010),(Kuenzer and Tuan, 2013), (Spalding and Parret, 2019) (Dasgupta et al., 2020.) and they support fisheries (Hutchison et al., 2014).

Mangroves, tidal marshes and seagrass meadows (collectively called coastal blue carbon ecosystems) sequester carbon dioxide from the atmosphere continuously over thousands of years, building stocks of carbon in biomass and organic rich soils. Carbon dynamics in mangrove-converted aquaculture in Indonesia indicated that the mean ecosystem carbon stocks in shrimp ponds were less than half of the relatively intact mangroves (Arifanti et al., 2019). Conversion of mangroves to shrimp ponds in the Mahakam Delta resulted in a carbon loss equivalent to 226 years of soil carbon accumulation in natural mangroves. In Philippines, abandoned fishpond reversion to former mangrove was found to be favourable for enhancing Climate Change Mitigation and Adaptation (Duncan et al., 2016). Integrated mangrove-shrimp farming, with deforested areas not exceeding 50% of the total farm area has been suggested to support both carbon sequestration as well as livelihood (Ahmed et al., 2018).

Globally the extent of blue carbon ecosystem has been estimated as 120380 km^{-2}, with highest spread by mangroves 114669 km^{-2}, (95.3%) followed by seagrass meadows 2201 km^{-2}, (1.8%) and salt marshes 3510 km^{-2}, (2.9%) (Himes-Cornell et al., 2018). In Asia, the total extent of these three ecosystems is 33224 km^{-2}, forming 27.6% of the global with highest spread of mangrove 32767 km^{-2}, which forms 28.6% of the global mangrove coverage. Area of seagrass meadows spread in Asia has been estimated as 236 km^{-2} and salt marsh 220 km^{-2},which forms 10.8% and 6.03% of the respective ecosystems globally (Himes-Cornell et al., 2018). Found at the interface between the land and the sea, seagrasses provide varied services apart from acting as ecosystem engineers providing shelter and habitat for several marine fauna which are fished in several Asian countries (Nordlund et al., 2018); (Jeyabaskaran et al., 2018); (Unsworth et al., 2019b) thereby providing livelihood to millions across the continent (UNEP, 2020).

The seagrass meadows are also good sinks of carbon (Fourqurean et al., 2012) capable of storing 19.9petagrams (Pg) organic carbon, but with very high regional and site and species variability (Ganguly et al., 2017);(Stankovic et al., 2018); (Gallagher et al., 2019); (Ricart et al., 2020). As highly efficient carbon sinks, these store up to 18 percent of the world's oceanic carbon and they also reduce the impacts of ocean acidification (UNEP, 2020).

The deterioration of this ecosystem is fast, 7% per year since 1990 (Waycott et al., 2009) which led to development of restoration protocols across Asia (Paling, 2009); (van Katwijk et al., 2016). In Vietnam, the loss of seagrass has been estimated as above 50% and in some regions complete loss has been observed (Van Luong et al., 2012). The seagrass meadows of Indonesia are fast deteriorating, and the need for increased local level autonomy for the management of marine resources and restoration have been highlighted (Unsworth et al., 2018). The need to develop science based policies for conservation including participatory methods (Fortes, 2018); (Ramesh et al., 2019) ;(Unsworth et al., 2019a), and large scale planting (van Katwijk et al., 2016) have been recommended to preserve the ecosystem services of these habitats.

Globally, the diversity of the plankton community has been predicted to be affected by warming and related changes (Ibarbalz et al., 2019) and these changes are expected in Asia also. Combined effects of high temperature, ocean acidification and high light exposure would affect important phytoplankton species in the SCS, *Thalassiosira pseudonana* (Yuan et al., 2018) and *Thalassiosira weissflogii.* (Gao et al., 2018b). Also in SCS the phytoplankton assemblage responses to rising temperature and CO2 levels were found to differ between coastal and offshore waters and the predicted increases in temperature and pCO2 may not boost surface phytoplankton primary productivity (Zhang et al., 2018).

Ocean warming and acidification can affect the functioning and ecological services of sedentary molluscs like the bivalves (Guo et al., 2016); (Zhao et al., 2017b); (Cao et al., 2018); (Zhang et al., 2019c); (Liu et al., 2020b) and gastropods(Leung et al., 2020) and also sea urchins (Zhan et al., 2020). The oyster *Crassostrea gigas* becomes more vulnerable to disease when exposed to acidification conditions and pathogen challenge indicating incapability for supporting long term viability of the population (Cao et al., 2018). More tolerance and benefits to rising pCO2 was observed in clam species like *Paphia undulate* which has been attributed to adaptation to its acidified sediment habitat (Guo et al., 2016). Warming boosted the energy budget of the marine calcifiers like the gastropod *Austrocochlea concamerata*, by faster shell growth and greater shell strength making them more mechanically resilient while acidification negatively affected the shell building thereby impacting the physiological adaptability (Leung et al., 2020). It is expected that there will be transgenerational acclimation to changes in ocean acidification in marine invertebrates (Lee et al., 2020b).

Assessment of the potential impacts and the vulnerability marine biodiversity in the Persian Gulf under climate change suggested a reduction of upto 35% of initial species richness and habitat loss for hawksbill turtles in south and southwestern parts of the Persian Gulf (Wabnitz et al., 2018).

Seaweeds are important biotic resource capable of capturing carbon and used widely as food, medicine and as raw material for industrial purposes. Warming and altered pH can affect seaweeds indifferent ways (Gao et al., 2016); (Gao et al., 2017); (Gao et al., 2018a), (Wu et al., 2019b). Outbreak of intense blooms of species like *Ulva rigida* (Gao et al., 2017) and *Ulva prolifera* (Zhang et al., 2019f) have increased due to varied factors including climate change. These have created huge economic losses in Yellow sea affecting local mariculture, tourism and the functioning of the coastal and marine ecosystems (Zhang et al., 2019f). Increased temperature was found to enhance the dark respiration (Rd) and light compensation point (EC) of *Ulva conglobate*, which thrives in the mid-intertidal to upper subtidal zones while the altered pH showed a limited effect (Li et al., 2020). Elevated temperature significantly enhanced growth, photosynthetic performances and carbon use efficiency of *Sargassum horneri* in both elevated and ambient CO2 levels suggesting that the present greenhouse effect would benefit the golden tide blooming macroalgae *Sargassum horneri*, which might enhance both the frequency and scale of golden tide (Wu et al., 2019b).

10.4.3.1 Key drivers to vulnerability

The vulnerabilities to disaster in coastal regions with high population densities are reported in several studies. (Sajjad et al., 2018) assessed the vulnerabilities of coastal community along the Chinese coast and showed that roughly 25% of the coastline and more than 5 million residents are in highly vulnerable coastal areas of mainland China, and these numbers are expected to double by 2100. Husnayaen et al. (2018) assessed along the Semarang coast in Indonesia and showed that 20% of the total coastline (48.7 km) is determined as a very high vulnerability. Mangroves continue to face threats due to pollution, conversion for aquaculture, agriculture, apart from Climate based threats like SLR and sea erosion (Richards and Friess, 2016; Romañach et al., 2018; Wang et al., 2018b) (Friess et al., 2019). Hypersalinity, storm effects sediment deposition, fishery development and land erosion are mainly responsible for most part of Sunderban mangrove degradations leading to loss of livelihood (Uddin, 2014); (Paul, 2017). In the Sunderbans of Asia, climate change is expected to increase river salinisation, which in turn could significantly negatively impact the valued timber species, *Heritiera fomes* (Dasgupta et al., 2017b). Augmented potential for honey production is also predicted which can increase man –wildlife conflict (Dasgupta et al., 2017b).

Destruction by natural hazards was found to remove the above ground C pool, but the sediment C pool was found to be maintained (Chen et al., 2018b). In Andaman & Nicobar islands the 2004 Indian Ocean Tsunami severely impacted the mangrove habitats at the Nicobar Islands (Nehru and Balasubramanian, 2018),while new inter-tidal habitats suitable for mangrove colonisation developed. Mangrove species with a wide distribution and larger propagules (showed high colonisation potential in the new habitats compared to other species (Nehru and Balasubramanian, 2018) Mangrove sites in Asia are predominantly minerogenic so continued sediment supply is essential for the long-term resilience of Asia's mangroves to SLR (Lovelock et al., 2015; Balke and Friess, 2016; Ward et al., 2016a; Ward et al., 2016b) .

10.4.3.2 Observed impacts

Primary production in Western Indian Ocean showed a reduction by 20% during the last six decades, attributed to rapid warming and ocean stratification which restricted nutrient mixing (Roxy et al., 2016) . Variation in secondary production- zooplankton densities and biomass in the East Asian Marginal Seas (EAMS) affected the recruitment of fishes due to mismatch in spawning period and larval feed availability during the last three Climate Regime Shifts (CRS) in the mid-1970s, late 1980s, and late 1990s, which were characterised by North Pacific Index (NPI) and Pacific Decadal Oscillation index (PDOI) (Kun Jung et al., 2017). In the western North Pacific Climate change has affected recruitment, and population dynamics of pelagic fishes like sardine and anchovy (Nakayama et al., 2018) and also shifts in the spawning ground and extension of spawning period in the chub mackerel *Scomber japonicas* (Kanamori et al., 2019).

Varied response to CRS Chinese Seas was observed for small pelagic (Ma et al., 2019) and Cephlalopods (Ichii et al., 2017). The winter and summer SSTs showed evidence of decadal variability with abrupt changes from cold to warm in substantial association with climate indices to which coastal cephalopods in China Seas responding differentially; some benefitting from warmer environment while others responded negatively (Pang et al., 2018). In the western and eastern North Pacific marine ecosystem it is indicated that groundfish may suffer more than pelagic fish (Yati et al., 2020) . Habitat Suitability Index models using SST, Chl-a, SSHA and SSS and fishing effort strongly indicated that Neon flying squid is affected by inter-annual environmental variations and it undertakes short term migrations to suitable habitat affecting the fisheries (Yu et al., 2015). The 2015-16 El Nino was found to impact coral reefs of shallower regions (depth of 5–15m) in South Andaman than those beyond 20 m (Majumdar et al., 2018). In the southeast coast of India, bleaching largely mediated by the SST anomaly and during the recovery period macro-algae outgrowth was observed (2.75%) indicating impacts on the benthic community (Ranith and Kripa, 2019). In South China Sea the increase in SST was found to be at a higher than the predicted in recent decade while the pH decreased at a rate of 0.012–0.014/year, more than the predicted due to high microbial respiratory processes releasing CO2 (Yuan et al., 2019). Simulation experiments showed differential adaption capacity of common species (Zheng, (2019).) (Yuan et al., 2019).

The Nations (2019) report on climate action and support trends have highlighted that the impacts of climate change on coastal ecosystems are mainly increased risks due to flooding, inundation due to extreme events, coastal erosions, ecosystem processes and on fisheries as variations in population or stock structures due to ocean circulation pattern, habitat loss degradation and ocean acidification. Analysis of data on occurrence of varied natural hazards from 1900 to 2019 (120 years) has shown that tropical cyclones, riverine floods and droughts have increased significantly and the impacts of these on coastal communities are also severe and destructive. The UNs average score for SDG Goal 14 (life under water) for Asia was estimated as 46 from scores of 40 nations and the Ocean Health Biodiversity index was comparatively high (average 87.9). However, the indices show that more region specific action plans are required to the achieve the UN 2030 goal for life under water.

Apart from the human community level impacts, the ecology and resource abundance of coastal waters have been found to be impacted by extreme events. During tropical cyclones ecological variations like lowering of SST, increase on chlorophyll a and decrease in oxygen (Chacko, 2019); (Girishkumar et al., 2019) have been observed. Global analysis on such events have indicated that these may have impact on the fishery directly by creating unfavourable ecological conditions and destruction of critical habitats indirectly by affecting the eggs and larvae and subsequent fishery recruitment (McKinnon et al., 2003); (Bailey and Secor, 2016). In South China Sea in July 2000, during a 3-day cyclone period, an estimated 30-fold increase in surface chlorophyll-a concentration was observed (Lin et al., 2003). The estimated carbon fixation resulting from this event alone is 0.8 Mt, or 2–4% of SCS's annual new production (Lin et al., 2003). Since an average of 14 cyclones pass over this region annually, the contribution of cyclones to annual new production has been estimated to be as high as 20-30% (Lin et al., 2003).

10.4.3.3 Projected impacts

Water pollution and climate stressors have been considered as major challenges to ecosystem sustainability and now it has been shown that the combined effect these two stressors would be more damaging (Buchanan et al., 2019). For seagrass beds the pollution stress was found to increase by 3.5% (from 39.7 % to 42.3%) when climate factors were added. Assuming the pollution levels to remain at 2014 levels different scenarios including RCP 2.6 and RCP 8.5 were worked out for Behoi Sea and the results indicated amplification of the impacts on ecosystem. Pollutants like Petroleum Hydrocarbons, Dissolved inorganic nitrogen and Soluble Reactive Phosphorus were the major pollution stressors (Lu et al., 2018) In the future, policies focused strictly on pollution control should be changed and should take into account the interactive effects of climate change for better forecast and management of potential ecological risks (Lu et al., 2018).

Projected changes in catch potential (%) by 2050 and 2100 relative to 2000 under RCP2.6 and RCP8.5 based on outputs from the dynamic bio-climate envelop model and the dynamic size-based food web models indicate that the marine and coastal resources of most Asian countries will be impacted with varying intensity (FAO, 2018b).

Better management of resources through projections of resource distribution, abundance and catch is required. However, lack of data (e.g., oceanographic surveys) and scientific knowledge is a constraint to this aim (Maung Saw Htoo et al., 2017). Effective forecasts of areas of resource abundance based on habitat preference have to be worked out for Asian region. Research Programs like EAF Nansen

Modelling and assessment of the vulnerability and habitat suitability of the Persian Gulf for 55 species to climate change indicated that there is a high rate of risk of local extinction in the southwestern part of the Persian Gulf, off the coast of Saudi Arabia, Qatar and the United Arab Emirates (UAE). Likelihood of reduced catch was observed and Bahrain and Iran were found to be more vulnerable to climate change(Wabnitz et al., 2018). Projected changes in fish catches can impact the supply of fish available for local consumption (i.e., food security) and exports (i.e., income generation) (Wabnitz et al., 2018). As per (UNESCAP, 2018a) Over 40 percent of coral reefs and 60 percent of coastal mangroves in the Asia-Pacific Region have already been lost, and approximately 80 percent of the region's coral reefs are currently at risk.

Regionally, the escalation in thermal stress estimated for the different global warming scenarios is greatest for Southeast Asia and least for the Pacific Ocean (Lough et al., 2018). For the 100 reef locations examined here and given current rates of warming, the 1.5 °C global warming target represents twice the thermal stress they experienced in 2016 (Lough et al., 2018).

In the southeast Asian region threats from both warming and acidification has indicated that by 2030, 99 percent of reefs will be affected and by 2050, 95 percent s are expected to be in the highest levels of threatened category (Burke et al., 2011), similar to global corals (Frieler et al., 2013), (Bruno and Valdivia, 2016) . Modelling results indicate that even under RCP scenarios the functional traits of coral reefs can be affected (van der Zande et al., 2020) and coral communities will mainly consist of small numbers of temperature-tolerant and fast-growing species (Kubicek et al., 2019). Increases in temperature (+3˚C) and pCO2 (+400 matm) projected for this century can reduce the sperm availability for fertilisation, which along with adult population decline either due to climate change or anthropogenic impacts (Hughes et al., 2017) can affect the coral reproductive success thereby reducing the recovery of populations and their adaption potential (Albright and Mason, 2013); (Hughes et al., 2018); (Jamodiong et al., 2018). In the southern Persian Gulf increased disturbance frequency and severity caused progressive reduction in coral size, cover, and population fecundity (Riegl et al., 2018), and this can lead to functional extinction. Connectivity required to avoid extinctions increased exponentially with disturbance frequency and correlation of disturbances across the metapopulation. In Philippines experiments have also proved that for Scleractinian corals like *A. tenuis, A. millepora* and *F. colemani* that spawn their gametes directly into the water column may experience limitations from sperm dilution and delays in initial sperm-egg encounters that can impact successful fertilisation (dela Cruz and Harrison, 2020).

Apart from these, threats, natural hazards have also been found to affect coral reefs of Asia. The extensive and diverse coral reefs of Muscat, Oman in the northeastern Arabian Peninsula were found to have long-term effects of Cyclone Gonu, which struck the Oman coast in June 2007 more than coastal development (Coles et al., 2015).

Sandy beaches are subject to highly dynamic hydrological and geomorphological processes, giving them more natural adaptive capacity to climate hazards (Bindoff et al., 2019). Progress is being made toward models that can reliably project beach erosion under future scenarios despite the presence of multiple confounding drivers in the coastal zone (AR6 WG2, Chap.3). Assuming minimal human intervention estimate impacts of SLR by 2100 under RCP8.5-like scenarios, 57–72% of Thai beaches (Ritphring, 2018), at least 50% loss of area on around a third of Japanese beaches (Mori, 2018) will disappear.

Marine heat waves (MHW) have been making changes in the structure and functioning of coastal and marine ecosystems (Kim and Han, 2017); (Oliver et al., 2017); (Oliver et al., 2019); (Frölicher and Laufkötter, 2018); (Smale et al., 2019) affecting resources like copepods (Doan et al., 2019) and coral reefs (Zhang et al., 2017c). in Asia. Coral reefs of Southeast Indian Ocean have been affected by marine MHW (Zhang et al., 2017c).

Simulation of RCP scenarios have shown that continued warming can drive a pole-ward shift in distribution of the seaweed Ecklonia cava of Japan and under the lowest emission scenario (RCP2.6), most population may not be impacted, but under highest emission scenario (RCP 8.5) the existing habitat may become unsuitable and it can also increase predation by herbivorous fishes (Takao et al., 2015).

10.4.3.4 Adaptation options

The Nations (2019) has identified establishment of protected areas, restoring ecosystems like mangroves / coral reefs, integrated coastal zone management practices, sand banks and structural technologies and implementing local monitoring networks for increasing adaptive capacity and protecting biodiversity of coastal ecosystem. In Asia, management of marine sites by earmarking protected areas (SDG 14) has been found to be low with only 27% area being protected. In India detailed climate change adaptation guideline coastal protection and management has been prepared considering various environmental and social aspects (Black et al., 2017). The Ocean Health Index for clean waters was also low, 54.6 and the threat to the ecosystem due to combined effect of pollution and climate change was high. Table 10.2 shows the ocean and Marine Protected Areas (MPA).

Table 10.2: Status of Ocean and MPA. Data Source: (Sachs et al., 2018)

	Ocean Health Index - Clean waters (0-100)	Fish stocks overexploited or collapsed (%)	Ocean Health Index - Fisheries (0-100)	Fish caught by trawling (%)	Ocean Health Index - Biodiversity (0-100)	Marine sites, mean protected area (%)
Eastern Asia	54.0	29.1	49.5	39.8	89.6	32.5
South-Eastern Asia	54.1	28.5	54.9	34.7	84.6	25.0
Western Asia	54.3	28.3	46.2	20.4	89.4	18.3
Southern Asia	50.3	17.4	51.0	15.1	88.3	41.2
Northern Asia	91.6	55.4	57.6	60.0	93.4	30.0
Asia	54.6	26.9	50.3	27.3	87.9	27.0

Conservation and Restoration of mangrove were found to be effective tools for enhancing ecosystem carbon storage and an important part of Reducing Emissions from Deforestation and forest Degradation plus (REDD+) schemes and climate change mitigation (Ahmed and Glaser, 2016). In East Asia restoration success has been attributed to right geomorphological locations (Van Cuong et al., 2015; Balke and Friess, 2016) and co-management models (Johnson and Iizuka, 2016; Veettil et al., 2019).

In South Asia, restoration programs have been largely successful (Jayanthi et al., 2018) but in some regions partly a failure due to inappropriate site selection, poor post planting care and other issues (Kodikara et al., 2017). Using remote sensing it was observed that there are high recovery rates of mangroves in a relatively short period of time (1.5 years) after a powerful typhoon indicating that natural recovery and regeneration would be a more economically and ecologically viable strategy. Better mangrove management through mapping is suggested (Castillo et al., 2018) (Gandhi and Jones, 2019). Statistical tools developed for modelling biomass and timber volume (Phan et al., 2019) and allometric models to estimate aboveground biomass and carbon stocks (Vinh et al., 2019) will be useful in estimating stocks in mangroves. Future mangrove loss may be offset by increasing national and international conservation initiatives that incorporate mangroves, such as the Sustainable Development Goals, Blue Carbon, and Payments for Ecosystem Services (Friess et al., 2019). Since seagrass meadows and marine macroalage are important habitats capable of combating impacts of climate change, the need for a global networking system with participation of stake holders has been suggested (Duffy et al., 2019).

10.4.4 Freshwater Resources

In Asia, freshwater resources, an important component of ecosystem services, are widely used for agriculture, domestic, irrigation, navigation, energy, industrial and ecosystem uses and services. Freshwater availability is changing at the global scale because of unsustainable use of surface and groundwater, pollution and other environmental changes. These changes in space and time, directly or indirectly, affect water use sectors and services (Wheater and Gober, 2015) (Rodell et al., 2018). About 82% of the global population served by freshwater provisions from upstream areas exposed to high threat (Green et al., 2015). Given that some of the fastest growing economies in the world today are in Asia, and the geographies of development are highly uneven, both climatic and non-climatic drivers such as socio-economic changes have contributed to water stress conditions in both water supply and demand in diverse sub-regions of Asia. In case of Asia therefore the entanglement between the non-climatic and climatic drivers makes it difficult to attribute environmental changes –both present and projected—neatly and exclusively to climatic drivers.

Immerzeel et al. (2020) has ranked all mountain-dependent water towers according to their water-supplying role and the downstream dependence of ecosystems, societies and economies. The resulting Global Water Tower Index (WTI) indicates that the upper Indus basin is both the most important and the most vulnerable Water Tower Unit (WTU) in the world. A WTU is defined as 'the intersection between major river basins and a topographic mountain classification based on elevation and surface roughness'. Whereas all important transboundary WTUs in Asia remain highly vulnerable, it is the Indus WTU (inhabited by approximately 235 million people in the basin in 2016, which is projected to increase by 50% by the middle of 21st century) where the average annual temperature is projected to increase by 1.9 °C between 2000 and 2050, with wide-ranging consequences and trans-sectoral spill overs. The Indus WTU faces a deep risk produced by a combination of factors including water stress, ineffective governance, hydro-political tensions, population growth and density, urbanisation and social transformations; with a significant bearing on SDG 6 on water, SDG 2 on food and SDG 7 on energy.

10.4.4.1 Key Drivers

Across Asia and its various sub-regions, the key drivers behind an increasingly inadequate supply of freshwater resources, affecting the livelihood security of millions, are varied, complex, and intersect with multiple social, cultural, economic and environmental stressors (Luo et al., 2017) (Tucker et al., 2015; Kongsager et al., 2016). Water stress' has been defined as the situation "when the demand for water exceeds its supply, during a certain period of time, or when poor quality restricts its use''(Felberg et al., 1999). See also Figure 4.32 in Lee et al. (2021a).

Freshwater resources in Asia, which include both surface water and groundwater, are considerably strained and changing climate is *likely* to act as a major stress multiplier (Fant et al., 2016) (Gao et al., 2018c) (Mack, 2018) (Dasgupta et al., 2015). In Southern and Eastern Asia (SEA) nearly 200 million people are at risk of serious water-stressed conditions. Effective mitigation might reduce the additional population-under-threat by 30% (60 million people), still there is a 1-in-2 chance that 100 million people across SEA might face a 50% increase in water stress and 1-in-10 chance that water stress would almost double in the absence of wide-ranging, multi-scalar adaptive measures (Gao et al., 2018c). In the absence of Millennium Development Goal 7c, that aimed to halve the population that had no sustainable access to water and basic sanitation before 2015, not been fully realised and sustainable development goals (SDG) 6 on water and sanitation not been effectively operationalised, the water-stress is *likely* to increase by the end of 2030 (Weststrate et al., 2019).

In Asia and elsewhere the interplay between the challenge of sustainability and climate change poses major policy challenges (von Stechow et al., 2016). The pursuit of SDG 6 —protection and restoration of water-related ecosystems, universal and equitable access to safe and affordable drinking water for all, improvement in water quality by reducing pollution, elimination of dumping and significant reduction in release of hazardous chemicals and materials, and treatment of wastewater through recycling and safe reuse globally—could be directly or indirectly challenged and undermined by climate change (Parkinson et al., 2019). Dissolved organic materials from sewage can enhance CO2 emission, especially in rapidly urbanising river systems which receives untreated wastewater/sewage across developing countries including Asia (Kim et al., 2019b). Conversely, policy interventions aimed at significant augmentation in water-use efficiency across all sectors, ensuring sustainable withdrawals and supply of freshwater to address water scarcity and a significant reduction in the number of victims of water scarcity, especially the poor and marginalised could mitigate vulnerabilities caused by climate change. More interdisciplinary research is needed on highly precarious future pathways and intersection between the climate and non-climate drivers in order to anticipate and mitigate diverging and uncertain outcomes.

10.4.4.2 Sub-regional Diversity

According to a quantitative scenario assessment for future water supply and demand in Asia to 2050, based on global climate change and socioeconomic scenarios (Satoh et al., 2017), water demand in sectors such as irrigation, industry, and households will increase by 30–40% around 2050 in comparison to 2010. Water stress is *likely* to be more pronounced in Pakistan, and northern parts of India and China. By mid-21st Century, the international transboundary river basins of Amu Darya, Indus, Ganges could face severe water scarcity challenges with climate change acting as a stress multiplier (*high confidence*). Within the country boundary as well, the water scarcity could be exacerbated, such as in India and China, due to various drivers like population and climate change. Research on the differentiated impact of climate change on freshwater sources across the Asian sub-regions remains inconclusive and requires assessment at sub-regional scale (IPCC, 2014b) (Wester et al., 2019).

10.4.4.3 Observed Impact

The climate change impact on different parts of freshwater ecosystems –as shown in section 10.4.2) of this chapter-- has affected water supply in various sub-regions of Asia. While headwater zones are susceptible to change in snow cover, permafrost and glaciers, the downstream plain areas of these river systems are vulnerable to increasing high demand of freshwater which will affect water availability in space and time. Observed impact of climate change has also been seen in direct physical losses such as precipitation (Mekong Delta), floods (Vietnam), salt-water intrusion leading to low agricultural productivity (Pervin et al., 2020) (Mora et al., 2018) (Almaden et al., 2019a).

The Hindu Kush-Himalaya (HKH) region extends 3500 km from Afghanistan in the west to Myanmar in the east is a source of major river systems originating in Asia, supports livelihoods, energy, agriculture and ecosystem for 240 million in the mountain and hills and 1.65 billion in the plains (Sharma et al., 2019). The HKH region stores about half of the ice mass in HMA, provisioning freshwater to almost 869 million population in the Indus, Tarim, Ganges and Brahmaputra river basins. While the warming climate increases the meltwater runoff enhancing water supply, it is indeed at the cost of glacier mass reduction that would eventually reduce meltwater and impact on the people's livelihood downstream in future (Nie et al., 2021). The melt runoff from the region play an important role in downstream agriculture such as in the case of Indus where two thirds of total irrigation withdrawal is from melt runoff in the pre-monsoon season (Biemans et al., 2019). Changes in cryosphere and other environmental changes have already impacted people living in high mountain areas and are *likely* to introduce new challenges for water, energy, and food security in the future (Rasul and Molden, 2019) (Borodavko et al., 2018; Adler et al., 2019; Bolch, 2019; Hoelzle et al., 2019; Shen et al., 2020).

With climate change impacts resulting in the shrinking and melting of snow, ice, glacier, and permafrost, and correspondingly causing increase in meltwater, the incidences of flash floods, debris flow, landslides, snow avalanches, livestock diseases, and other disasters in the HKH region have become more frequent and intense. Some of the key factors that come in the way of assigning confidence levels to climate change impacts include lack of sufficient observed data on factors such as river discharges, precipitation and glacier melt (You et al., 2017). Climate change impacts on cryospheric water sources in the Hindu Kush, Karakoram and Himalayan ranges which in turn carry consequences for the Indus, Ganges and Brahmaputra basins.

The combined impacts of climate change and non-climate drivers on hydrological processes and water resources in transboundary rivers in diverse regions of Asia were well noted in AR5. In Central Asia withdrawal is approximately equal to water availability, with Turkmenistan and Uzbekistan as most water stressed countries in the region (Karthe et al., 2017); (Russell, 2018). A study on water availability in mainland South Asia has pointed in the direction of decreasing precipitation trends in recent years, which have also contributed to the increasing incidence and severity of droughts (Liu et al., 2018b). There are reports of increase in occurrence and severity of different forms of droughts in the Koshi river basin (Central Himalaya) (Wu et al., 2019a; Hamal et al., 2020; Dahal et al., 2021; Nepal et al., 2021). Figure 10.5 shows the water stress in the HKH region. The water stress is relatively higher in western region compared to central and eastern region.

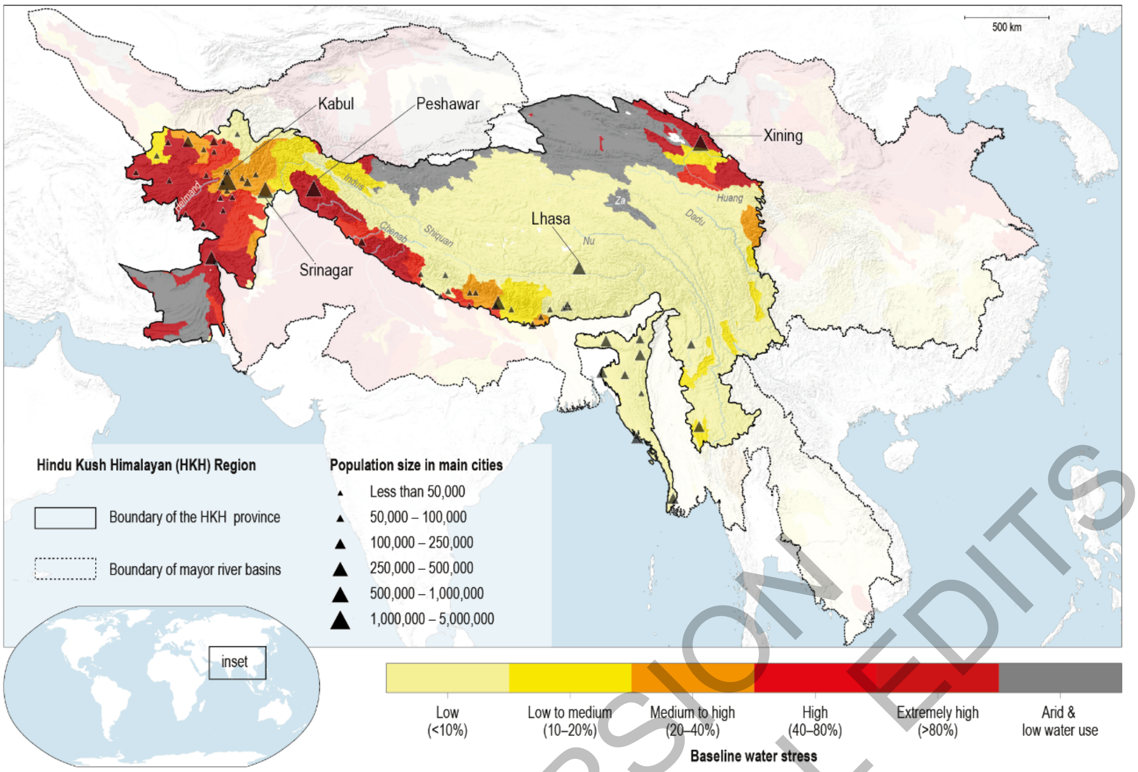


Figure 10.5: Water Stress in the Hindu Kush-Himalaya (HKH) region Source: (Wester et al., 2019). *The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people* (p. 627). Springer Nature; (Hu and Tan, 2018). No water, no growth – Does Asia have enough water to develop? China Water Risk. **Note:** The map is for illustrative purpose only. The boundaries and names shown and the designations used on this map are for river basins and do not imply official endorsement or acceptance by the United Nations.

Climate change is also having an impact on stream flows. A recent study (Chen et al., 2018f) has shown that with the average temperature after 1998 being 1.0°C higher than that during 1960–1998 in the Tienshan Mountains, the process of glacier shrinkage and decreases in snow cover and causing earlier runoff peak and aggravated extreme hydrological events, affecting regional water availability and adding to future water crisis in Central Asia. The magnitude and frequency of flooding have increased across Himalayan region in the past six decades such as Tarim basin in China (Zhang et al., 2016c) and higher Indus, Ganges and Brahmaputra (Elalem and Pal, 2015). The latter also reported the highest number of flood disaster and greater spatial coverage in the recent decades as compared to earlier decades. In the Middle Yellow River Basin, which has become much warmer and drier, climate variability accounts for 75.8% of streamflow decrease during 1980–2000. Whereas during 2001–2016, land use/cover change is the main factor in streamflow decrease, accounting for 75.5% of the decline (Bao et al., 2019). The changes in hydrological regime and extreme floods cause changes in the river morphology and river channel system which impact water availability.

In China, a quantitative assessment based on a multimodel dataset (6 global hydrological models driven by 3 observation-based global forcings) during the 1971-2010 period, suggested that climate variability dominated the changes in streamflow in more the 80% of river segment, while direct human impact dominated changes mostly in northern China (Liu et al., 2019b). In the Lancang-Mekong River basin, climate variability would have contributed 45% more flood occurrences in the middle of the basin while reservoir operation reduced it by 36% during 2008-2016 compared to the period 1985-2007 (Yun et al., 2020).

In western China, the total annual snow mass declines at a rate of 3.3 × 109 Pg per decade ($p < 0.05$), which accounts for approximately 0.46% of the mean of annual snow mass (7.2 × 1011 Pg). The loss could be valued in terms of replacement cost at CN¥0.1 billion (in the present value) every year ($1 = CN¥7) in the past 40 years. Compounded (Wu et al., 2021). In the Mekong River Delta in Vietnam, climate change impacts include a 30% annual increase in rainfall, shifting rainfall patterns, an average temperature increase of 0.5°C over the last 30 years, and an average sea level rise of 3mm per year over the last three decades, resulting in a greater flooding threat (Wang et al., 2021a).

A recent study (Wang et al., 2021b) has shown that during 1936–2019, due largely to intensified precipitation induced by a warming climate , the streamflow of Ob, Yenisei and Lena has increased by ~7.7%, 7.4% and 22.0%, respectively. Whilst rising temperature can reduce streamflow via evapotranspiration, it can enhance groundwater discharge to rivers due to permafrost thawing. In permafrost-developed basins, the thawing permafrost will continue to result in increased streamflow. However, with further permafrost degradation in future, the positive effect of permafrost thaw on streamflow would probably be offset by the negative effect of increase in basin evapotranspiration. This could result in a situation where runoff reaches threshold level and then declines. This is clearly marked in the Ob River basin, which is characterised by the highest precipitation. Whereas in case of Yenisei and Lena rivers, further research is needed.

The HKH region is susceptible to floods and related hazards caused by a cloud burst and other landscape-based processes such as glacial lake outburst floods which can seriously damage property, lives and infrastructure (Shrestha et al., 2010). Himalayan rivers are frequently hit by catastrophic floods caused by the failure of glacial lake (Cook et al., 2018) (Ahluwalia et al., 2016). In Kedarnath, India (western Himalaya), a flash flood was triggered by GLOF released from the Chorabari glacial lake in June 2013 which caused extensive flooding, erosion of riverbanks and damage to downstream villages and towns, as well as the loss of several thousand human lives in the state of Uttarakhand (Rafiq et al., 2019); (Das et al., 2015). Nepal has experienced 24 GLOF events which have caused considerable loss of life and damage to properties and infrastructure (Icimod, 2011). There is *high confidence* that current glacier shrinkages have caused more glacial lakes to form in most of the mountainous region including High mountain Asia but limited evidence that the frequency of GLOF has changed (Hock et al., 2019). (Veh et al., 2018) reported no clear trend of increasing GLOF events in the Himalayan region, although southern Himalaya was identified as a hotspot region compared to western Himalaya. Research has shown a decrease in glacier area of 24% in Nepal between 1980 and 2010 (Bajracharya et al., 2014).

Climate change impacts on both the quantity and quality of freshwater resources will hinder the attainment of SDG-6 (Water, 2020). Contamination of drinking water is caused by wildfires and drought that contribute to elevated levels of nutrients (nitrogen, phosphorus and sulphates), heavy metals (lead, mercury, cadmium and chromium), salts (chloride and fluorides), hydrocarbons, pesticides and even pharmaceuticals. Heavy rains and flooding also increase nutrients, heavy metals and pesticides as well as turbidity and fecal pathogens in water supplies - especially when sewage treatment plants are overwhelmed by runoff (Mora et al., 2018). Pharmaceuticals and personal care products (from source to disposal) are contributing to the vulnerability of urban waters. A study of vulnerability assessment of urban waters in highly populated cities in India and Sri Lanka, through analysing the concurrence of PPCPs, enteric viruses, antibiotic resistant bacteria, metals,

fecal contamination, and ARGs, also underlines the need for a resilience strategy and action plan (Rafiq et al., 2019).

Adequate water supply for various uses is crucial for millions of people living in the mountains of Asia. Particularly in the HKH region, mountain springs play an important role in generating stream flow for non-glaciated catchments and in maintaining dry-season flows across many watersheds (Scott et al., 2019) (Stott and Huq, 2014). There is a good deal of evidence that the springs are drying up or yielding less discharge (Tambe et al., 2012), (Tiwari and Joshi, 2014) (Sharma et al., 2016), threatening local communities who depend on spring water for their lives and livelihoods. Some of the main reasons for drying springs include anthropogenic impacts (deforestation, exploitative land use), infrastructure (road construction), socio-economic changes (increasing demand and modernisation of facilities) and climatic changes (changes in rainfall regime and higher temperature) (Stott and Huq, 2014; Tiwari and Joshi, 2014; Sharma et al., 2016).

The Ganges-Brahmaputra region also faces the threat increased frequency of flood events (Lutz et al., 2019). Floods and extreme events can impact river channel systems (Grainger and Conway, 2014). One of the challenges in South Asia is the shifting boundaries of river channels. For instance, the major floods on the

Indus in July 2010 altered the river's course in Pakistan, moving it closer to the Indian district of Kutch (Grainger and Conway, 2014). In the eastern tributary of Ganges system, the alluvial fan of the Koshi river basin has shifted to more than 113 km to the west in past two centuries (Chakraborty et al., 2010) which may be due to heavy sediment load from the Himalayan rivers in which about 50 million tons of sediment is deposited annually in the alluvial plains (Sinha et al., 2019) (Chakraborty et al., 2010).

Asia is no exception to the global trend of lake ecosystems providing drinking water to millions of people, being degraded (Jenny et al., 2020) and severely threatened at the same time by climate change (Mischke, 2020), with lake surface conditions, such as ice cover, surface temperature, evaporation and water level, responding dramatically to this threat, and carrying implications for water quantity and quality, food provisioning, recreational opportunities and transportation (Woolway et al., 2020). Due to substantial regional variability, the quantum of future changes in lake water storage remains uncertain. A recent study (Liu et al., 2019a) using Moderate Resolution Imaging Spectroradiometer (MODIS) 500m spatial resolution global water product data, and applying Least Squares Method (LSM) to analyse changes in the area of 14 lakes in Central Asia from 2001 to 2016, has shown that the shrinking of area changes for all plains lakes in the study region could be attributed to climate change and human activities.

10.4.4.4 Projections

Asian and global water demands for irrigation, despite geographical variation in terms of water availability, are *very likely* to be surpassing supply by 2050 (Chartres, 2014). A regional quantitative assessment (Lutz et al., 2019) of the impacts of a 1.5 versus a 2 °C global warming for a major global climate change hotspot: the Indus, Ganges, and Brahmaputra river basins (IGB) in South Asia, shows adverse impacts of climate change on agricultural production, hydropower production, and human health. A global temperature increase of 1.5 °C with respect to pre-industrial levels would imply a ≈ 2.1 °C temperature increase for IGB. Whereas under a 2.0 °C global temperature increase scenario, these river basins would warm up by ≈ 2.7 °C. Future warming is expected to further increase rain-on-snow (ROS) events that can cause the snowmelt flood during winter (Ohba and Kawase, 2020), affecting hydropower and resulting in river flooding, avalanches and landslides.

In the Mekong River Delta (in Vietnam) with an area of 40,500 km2 and the home to 17.8 million people in 2018, climate change is projected to increase the average temperature by 1.1-3.6 ◦C, and the maximum and minimum monthly flow are projected to increase and decrease, respectively, and *likely* to result in a high risk of food during the wet season and water shortages during the dry season (Wang et al., 2021a).

In High Mountain Asia, the glacier ice is projected to decrease by 49 ± 7 % and 64 ± 5% by the end of the century under RCP 4.5 and 8.5 scenarios (Kraaijenbrink et al., 2017). Local and regional-scale projections suggest that peak water will generally be reached around middle of the century, followed by steadily declining glacier runoff thereafter (Hock et al., 2019). A global-scale projection suggests that decline in glacier runoff by 2100 (RCP8.5) may reduce basin runoff by about 10% at least one month of the melt season in High Mountain Asia (Huss and Hock, 2018). Significantly, research on climate change and its impact across Asia remains inconclusive and requires an assessment at sub-regional scale (IPCC, 2014a); (Wester et al., 2019).

There is a projection of an increase in runoff until the 2050s mainly due to an increase in precipitation in the upper Ganges, Brahmaputra, Salween and Mekong basins, where it could be due to accelerated melting in the upper Indus basin. The runoff could increase in the range of 3-27% (7-12% in Indus, 10-27% in Ganges and 3-8% in Brahmaputra) by mid-century compared to the reference period (1998-2008) for Himalayan river basins depends on different RCP scenarios (Lutz et al., 2014a). Likewise, Khanal et al. (2021) suggested contrasting responses of climate change for HMAs rivers in which at the seasonal scale, the earlier onset of melting causes a shift in magnitude and peak of water availability whereas an annual scale, total water availability increases for the headwaters. The future flow would increase in the Central Himalaya region in Nepal (Ragettli et al., 2016); (Nepal, 2016); (Bajracharya et al., 2018). These changes in water availability in space and time will have serious consequences in downstream water availability for various sectoral uses and ecosystem functioning in Asia (Green et al., 2015) (Wijngaard et al., 2018); (Nepal et al., 2014); (Rasul and Molden, 2019) (Arfanuzzaman, 2018). However, future water availability has large uncertainty due to large variation in climate change projections among different global climate models (Nepal and Shrestha, 2015; Lutz et al., 2016; Li et al., 2019a).

A recent study (Didovets et al., 2021), covering eight river catchments having diverse natural conditions within Central Asia, where water availability/scarcity is also a major developmental concern, and using the eco-hydrological model SWIM (including scenarios from five bias-corrected GCMs under Representative Concentration Pathways 4.5 and 8.5) has show an increase of mean annual temperature in all catchments for both RCPs to the end of the 21st century. The projected changes in annual precipitation indicate a clear trend to increase in the Zhabay and to decrease in the Murghab catchments, and for other catchments, they were smaller. Both the projected trends for river discharge and precipitation show an increase in the northern and decrease in the southern parts of the study region. Whereas seasonal changes include a shift in the peak of river discharge up to one month, shortage of snow accumulation period, and reduction of discharge in summer months.

The intensity and frequency of extreme discharges are *very likely* to increase towards the end of the century. The future of the upper Indus basin water availability is highly uncertain in the long run due to uncertainty surrounding precipitation projections (Lutz et al., 2016). The future hydrological extremes of the Upper Indus, Ganges and Brahmaputra river basins suggest an increase in the magnitude of extremes towards the end of the 21st century by applying RCP4.5 and 8.5 scenarios, mainly due to increase in precipitation extremes (Wijngaard et al., 2017). In the Brahmaputra, Ganges and Meghna including the downstream component, the runoff is projected to increase by 16%, 33% and 40% respectively under the climate change scenarios by the end of the century in which the changes in runoff are larger in the wet seasons than the dry season (Masood et al., 2015). In the Mekong river basin also, extremely high flow events are *likely* to increase in both magnitude and frequency which can exacerbate flood risk in the basin (Hoang et al., 2016). However, the uncertainty is high in the future hydrological response due to large variation in precipitation projections, modelling approaches and bias corrections methods (Nepal and Shrestha, 2015; Lutz et al., 2016; Li et al., 2019a).

Current research on adverse relationship between climate change and river flows, research suggests that there is high possibility that some of the river basins affected by floods could be Brahmaputra, Congo, Ganges, Lena, Mekong, with a return period of 10 years (Best, 2018).

In most parts of the Upper Ganges and Brahmaputra rivers, the 50-year return level flood is *likely* to increase and to a lesser degree in Indus river. Similarly, the extreme precipitation events are also expected to increase to a higher degree in Indus than Ganges and Brahmaputra basins (Wijngaard et al., 2017). Increase in extreme precipitation events is *likely* to cause more flash flood events in the future (*medium confidence*). In case of Indus, increasing temperature trend in the future may lead to accelerated snow and ice melting which may increase the frequency and intensity of floods in the downstream areas (Hayat et al., 2019). The Ganges-Brahmaputra region also faces the threat of increased frequency of flood events (Lutz et al., 2019).Additionally, the Ganges basin also shows a higher sensitivity to changes in temperature and precipitation (Mishra and Lilhare, 2016).

Assessing the impact of climate change on water resources in nine alpine catchments in arid and semi-arid Xinjiang of China (Li et al., 2019a), it has been noted that even though the total discharge revealed an overall increasing trend in the near future, the impact of climate change on different hydrological components indicated significant spatiotemporal heterogeneity in terms of the area, elevation and slope of catchments, which could be usefully factored into climate adaptation strategies.

It was noted early on (Singh et al., 2011), that the main drivers that influence the provisioning of ecosystem services and human wellbeing in the HKH region are a mix of environmental change in general and climate change in particular, and much more data and knowledge a on the HKH region are needed in order to develop either a regional or global understanding of climate change processes.

Climate change impacts cryospheric water sources in the Hindu Kush, Karakoram and Himalayan ranges which in turn carry consequences for the Indus, Ganges and Brahmaputra basins. The impact of climate change on spring fed rivers in the Hindu Kush-Himalayas is under-researched and therefore make projections difficult. Further research is needed for understanding the impact of deforestation, urbanisation, development and introduction of water infrastructures such as tube-wells in the hill region (Aayog, 2017). This in turn call for greater investment in R&D for the Hindu Kush-Himalayas by both the national and regional organisations. There is *high confidence* that due to global warming Asian countries could experience increase of drought conditions (5-20%) by the end of this century (Prudhomme et al., 2014; Satoh et al., 2017).

Soil erosion in high mountains areas is particularly sensitive to climate change. A recent study (Wang et al., 2020) focused on the mid-Yarlung Tsangpo River, located in the southern part of the Tibetan Plateau, has revealed dramatic land surface environment changes due to climate change during the last decades. It has further shown that increasing precipitation and temperature would lead to increasing soil erosion risk in ~ 2050 based on the Coupled Model Intercomparison Project (CMIP5) and RUSLE models.

High-resolution climate change simulations suggest that due to deadly heat waves projected in some of the densely populated agricultural regions of South Asia (i.e. Ganges and Indus river basins), are *likely* to exceed the critical threshold of wet-bulb temperature of 35 °C under the business-as-usual scenario of future greenhouse gas emissions (Im et al., 2017).

[START BOX 10.4 HERE]

Box 10.4: Cryosphere

Asia's glaciers are in minor area shrinkage and mass loss among other world's glacierised regions during 2006-2016, resulting in near minimal contribution to sea level rise (1-7 Gt/a) (Zemp et al., 2019) (*high confidence*). However, Asia's glaciers are regarded as a reliable water source (Bolch, 2017). The melting water from Asia's glaciers protect ca. 220 million people in local and adjacent regions from drought, and the closer a region to river sources, the higher the fractions of melt water from glaciers (Pritchard, 2019). Researchers have found that the southern Tibetan Plateau has been consistently melting from 1998-2007 and is projected to continue melting until 2050 (Lutz et al., 2014b) (*high confidence*). The changes in snowmelt water can explain 19% of the variations in rivers of arid regions like Xinjiang, China (Bai et al., 2018) (*medium confidence*), and the 10.6% of the runoff of the upper Brahmaputra River was contributed by snow during 2003-2014 (Chen et al., 2017c) (*medium confidence*). The dominances of snow melt in spring were found in major river basins originating from southern Tibetan Plateau, compared to the glacier melt in summer (Lutz et al., 2014b).

On the other hand, the decreased stability of Asian glaciers, caused by warming climate (Ding et al., 2019) has posed a number of threats to regional security and water supplies (Gao et al., 2019). The *likely* increased frequency of hazards caused by abnormal glacier changes, such as the glacier collapses happened on two glaciers in western Tibet in 2016 (Kääb et al., 2018), and also surges which were frequently found in this vast region (e.g. Bhambri et al., 2017; Mukherjee et al., 2017; Ding et al., 2018), threatening the security of the local and down streaming societies (*high confidence*). However, the influence of climate change on natural hazards from glaciers needs further research.

The expansion of glacier lakes, following the shrinking glaciers, has also posed threat to social security downstream through glacier lake outburst flood (GLOF). The total amount and area of glacier lakes increased during last decade according to new studies (Zhang et al., 2015; Chen et al., 2017c) (*high confidence*). New GLOF events were continuously appearing all over Asia (e.g. Allen et al., 2016; Haeberli et al., 2016; Gurung et al., 2017). However, the frequency of GLOF has remained unchanged since later 1980s (Veh et al., 2019) (*high confidence*).

The impacts of permafrost changes on regional hydrology in Asia remains unclear. However, those changes may alter the soil carbon storage (e.g. Nie et al., 2019) and increase the riverine carbon exports (e.g. Song et al., 2019). But the fate of soil carbon within permafrost is more complicated and uncertain due to the influences of heterogeneous landforms, as pointed out in China's Second National Soil Survey (Jiang et al., 2019).

[END BOX 10.4 HERE]

10.4.4.5 Climate Vulnerability and Adaptation: Interfaces and Interventions

In Asia and its diverse sub-regions, the challenge of adaptation to climate change at diverse sectors, sites and scales of vulnerability in the domain of fresh water resources is compounded by the nexus between long-standing non-climatic vulnerabilities and climatic impacts, both observed and projected. Water insecurities in Asia are increasing due to excessive freshwater withdrawals (Satoh et al., 2017) economic and population growth (Gleick and Iceland, 2018), urbanisation and peri urbanisation (Roth et al., 2019) food insecurity (Demin, 2014) and lack of access to clean and safe drinking water (Cullet, 2016) which mostly affects the heath of most vulnerable sections of society.

Significantly, climate change will add to already existing vulnerabilities. In the case of Yellow River basin in China, underlining the interface between the future water scarcity and hydroclimatic and anthropogenic drivers, a recent study expects moderate to severe water scarcity over six Yellow River sub-catchments under the RCP4.5 scenario, and anticipates that human influences on water scarcity will be worse than that of climate change, with water availability in the downstream being impacted by concurrent changes in land-use and high temperature (Omer et al., 2020). Nearly 8% of internationally shared or transboundary aquifers (TBAs), ensuring livelihood security for millions of people through sustaining drinking water supply and food production, are currently overstressed due to human overexploitation (Wada and Heinrich, 2013). The Asia Pacific region has the highest annual water withdrawal due to its geographic size, growing population and irrigation practices, and water for agriculture continues to consume 80% of the region's resources (Taniguchi et al., 2017b; Visvanathan, 2018).

In South Asia, surface and groundwater resources are already under stress (both in terms of quality and quantity) due to population growth, economic development, poor governance/management and poor efficiency of use in economic production. In the last 40 years, there has been an increasing reliance on groundwater in South Asia for irrigation (Rodell et al., 2009; Surie and Prasai, 2015; Shah et al., 2018) (Tiwari et al., 2009) (Bhanja et al., 2016) (Shrestha et al., 2016; Mukherjee, 2018). It is significant to note that India, Bangladesh, Pakistan, and China together account for more than 50% of the world‘s groundwater withdrawals (Scott et al., 2019). A study conducted in Shahpur and Maner district of Bihar, India in which drinking water sourced from groundwater of 388 households was tested, shows that 70 to 90 percent of the sampled household's drinking water contained either arsenic or iron or both (Thakur and Gupta, 2019). Given the nexus between climatic and non-climatic drivers, an effective adaptation to the impacts of climate change would also demand sustainable development and management of shared aquifer resources, which in turn require reliable TBA inventories and improved knowledge production and knowledge sharing on the shared groundwater systems (Lee et al., 2018a).

In a study of peri-urban spaces, involving four South-Asian cities: Khulna (Bangladesh) (Pervin et al., 2020), Gurugram and Hyderabad (India), and Kathmandu (Nepal), shows nexus between intensifying use and deteriorating quality of water and the impact of climate change, resulting in peri-urban water insecurity and conflict (Roth et al., 2019). The challenge of ensuring access to water resources and their (re) allocation and prioritisation for marginalised communities remains on the agenda of policy-oriented interdisciplinary research and demands effective implementation of its findings at the grass root level by the administrative agencies. Taking water security as a key climate change adaptation goal at the urban-city-scale of Bangkok, a study (Babel et al., 2020) has shown the usefulness of a generic framework with 5 dimensions, 12 indicators, and a set of potential variables to support national level initiatives and plans in diverse climatic and socio-economic conditions across various sub-regions of Asia.

In the Kathmandu valley in Nepal, where groundwater resources are under immense pressure from multiple stresses, including over-extraction and climate change, mapping groundwater resilience to climate change has been demonstrated as a useful tool to understand the dynamics of groundwater systems, and thereby facilitating the development of strategies for sustainable groundwater management (Shrestha et al., 2020).

In Mekong Delta, the groundwater storage in Mekong Delta is projected to decline by more than 120 and 160 million cubic meter under RCP4.5 and RCP8.5 scenarios, respectively, by the end of the 21st century, in conjunction with land subsidence and sea level rise. This in turn calls for proactive planning and implementation of adaptation strategies that address multiple stresses in order to ensure sustainable utilisation of groundwater resources in the Mekong Delta in the context of future climatic conditions and associated uncertainties (Wang et al., 2021a). Proposed climate change adaptation strategies for the Mekong River Basin include a better understanding of the complex linkages between climate change, technological interventions, land use change, water use change, and socioeconomic developments both in the upstream and downstream riparian countries (Evers and Pathirana, 2018).

While South Asian countries have done well in attaining Goal 6 of Sustaining Development Goals, access to safe and clean drinking water remains a challenge. Taking Indian rivers as an example, it is suggested that participatory river protection and rehabilitation, based on comprehensive knowledge of the river-system dynamics, and local awareness at community level may act as a multiplier for river conservation measures (Nandi et al., 2016).

[START BOX 10.5 HERE]

Box 10.5: Case Study: Climate Vulnerability and Cross Boundary Adaptation in Central Asia

In Central Asia, water has been ranked in the top five global risks and water scarcity (Gleick, 1993; Zhupankhan et al., 2018). Cross boundary adaptation remains critically important in this region with abundant glaciers in Pamir Plateau of Tajikistan (Hu et al., 2017) and areas with severe glacier retreat in Tianshan Mountains (Liu and Liu, 2015). The spatial variations of glacier and other climate variables have added to uncertainty related to the dynamic of water cycle. The headwater regions, such as Pamir area, would be significantly affected by the climate parameters, such as the stronger rainfall intensity, more frequent rainfall and higher temperature (Luo et al., 2019). The water resources in Pamir plateau will range from-0.48% to 5.6% (Gulakhmadov et al., 2020), and the crop phenological period in Tajikistan and Kyrgyzstan will be about 1-2 weeks earlier. The threat of agricultural water stress is increasing as well. The oasis in downstream areas will face more complex water resource fluctuations, water crisis and desertification. In particular, rain fed agriculture in Northern Kazakhstan, Uzbekistan and Western Turkmenistan, is particularly dependent on water resources. Under RCP2.6 and RCP4.5 scenarios, considering CO_2 fertilisation effects and land use projections, the increase of CO_2 atmospheric concentration and accumulated temperature can contribute to 23% increase of cotton yield in Central Asia (Tian and Zhang, 2019), but extreme climate such as drought, heat waves and rainstorm will have 10% negative impact on agricultural production and ecological environment (Zhang and Ren, 2017). High efficiency water-saving technology will help the upstream and downstream water resources management in Central Asian countries to adapt to the variation in water resources quantity, frequency and spatial pattern.

[END BOX 10.5 HERE]

Hydro-climatic extreme in the HKH region could adversely impact the Ganga, Brahmaputra and Meghna Basins (Wijngaard et al., 2017; Acharya and Prakash, 2019). On adaptation, studies have recommended watershed or basin analysis to address the challenge of adaptation in urban spaces (Lele et al., 2018). A study of Northern Bangladesh, focused on encouraging traditional ways of cultivation, suggests that rural women have Indigenous Knowledge and their participation can play a useful role (Kanak Pervez et al., 2015). The knowledge pertains to agriculture, soil conservation, fish and animal production, irrigation and water conservation. There has also been a focus on gendered construction of local flood forecasting knowledge of rural communities in India living in the Gandak River basin (Acharya and Prakash, 2019). While designing the adaptation options, understanding Water-Energy-Food (WEF) nexus among different water use sectors are crucial (See **10.5.3.** for details). The understanding of WEF nexus could be beneficial for achieving water security in developing countries in Asia (Nepal et al., 2019).

AR5 had identified a number of adaptation challenges and options facing the stakeholders in the wake of climate change-induced vulnerabilities, uncertainties and risks in the freshwater sector, and underlined the importance of an integrated management approach, acknowledging diverse socio-economic contexts, differentiated capacities and uneven pace of impacts. Further validated by recent research in terms of their usefulness, these adaptation options include building and improving capital intensive physical water infrastructure such as irrigation channels, flood control dams and water storage (Nüsser and Schmidt, 2017). Drawing upon customary institutions and combining Indigenous Knowledge systems with scientific knowledge, innovative structures, including artificial glaciers, ice stupas and snow barrier bands, have been built by local communities in Ladakh and Zanskar and Himachal Pradesh in India (Hock et al., 2019). (Nüsser et al., 2019). Communities in Solukhumbu, Nepal, in response to depleting water flow in snow-fed rivers, have chosen adaptation through changing practices by collecting water from distance sources for domestic consumption (McDowell et al., 2013). Taking IPCC concept of climate risk as a basis for adaptation planning a pilot study of flood risk in Himachal Pradesh, India (Allen et al., 2018), integrating assessment of hazard, vulnerability and exposure in the complementary domains of climate change adaptation and disaster risk reduction, identifies stakeholder consultation, knowledge exchange and institutional capacity building as key steps in adaptation planning. Aquifer Storage and Recovery (ASR) has been proposed as an 'alternative climate-proof freshwater source' for deltaic regions in Asia, particularly those with a history of saline groundwater aquifers (Hoque et al., 2016). It is further argued (Hadwen et al., 2015) that water, sanitation and hygiene (WASH) objectives would need to be addressed as a component of a wider integrated water resource management (IWRM) framework.

Ensuring sustainability of the rivers and eco-systems requires coordinated and collaborative action on part of all countries with the long-term goal of synergising political, social, cultural and ecological facets associated with the riverine system. Daunting as this challenge is, evidence suggests that a long term view of transboundary basins, is not very optimistic as big rivers of Asia contribute heavily towards urban and agricultural activities, and are witnessing challenges of increasing sedimentation, large scale damming and pollution amongst others (Best, 2018). In case of China, Sun et al. (2016) show that the localised vulnerabilities within the Yangtze River Basin prompt an 'integrated basin-wide approach' that is able to account for the specific needs of each of its sub-basins.

In high mountain areas, factors that undermine effective adaptation to climate change include both the sudden-onset and slow-paced disasters and knowledge deficit about cryospheric change and its adverse impacts on water resources, agriculture, and hydropower sectors. Other key barriers include sectoral approach, overemphasis on structural approaches, the lack of context-sensitive, community-centric understanding of how these changes influence perceptions, options, and decisions about migration, relocation, and resettlement (Rasul et al., 2020) (Hock et al., 2019). More interdisciplinary research is needed on highly precarious future pathways and intersection between the climate and non-climate drivers in order to anticipate and mitigate diverging and uncertain outcomes.

10.4.5 Agriculture and Food

Asia accounts for 67% of the global agricultural production (Mendelsohn, 2014) and employs a large portion of the population in many developing member (Briones and Felipe, 2013; ADB, 2017b; ILO, 2017a). Since the release of IPCC AR5, more studies reinforce the earlier findings on the spatial and temporal diversity of climate change impacts on food production in Asia depending on the geographic location, agroecology, and crops grown (Hoegh-Guldberg et al., 2018; Ahmad et al., 2019), recognising that there are winners and losers associated with the changing climate across scales (Dasgupta et al., 2013a; Yong-Jian et al., 2013; Bobojonov and Aw-Hassan, 2014; Hijioka et al., 2014; Li et al., 2014a; Prabnakorn et al., 2018; Trisurat et al., 2018; Matsumoto, 2019). Despite the observed increase in total food production in terms of crops and food yields from 1990 to 2014 in Asia (FAO, 2015), there is *high confidence* that overall, at the regional level, the projected total negative impacts will far outweigh the expected benefits with India emerging as the most vulnerable nation in terms of crop production (Figure 10.6). Recent evidence also indicates that climate-related risks to agriculture and food security in Asia will progressively escalate as global warming reaches 1.5°C and higher above pre-industrial levels (IPCC, 2018b) with differentiated impacts across the Asian continent.

10.4.5.1 Observed Impacts

There remains a paucity of data for observed climate change impacts on Asian agriculture and food systems since the release of IPCC AR5. Most of these impacts have been associated with drought, monsoon rain, and oceanic oscillations, the frequency and severity of which have been linked with the changing climate (Heino et al., 2018; Heino et al., 2020). In general, major impacts to agricultural production such as those observed by the farmers in the Philippines and Indonesia include among others delays in crop harvesting, declining crop yields and quality of produce, increasing incidence of pests and diseases, stunted growth, livestock mortality, and low farm income (Stevenson et al., 2013). In South Asia, the series of monsoon floods from 2005 to 2015 contributed to high level of loss in agricultural production with peaks in 2008 and 2015 (FAO, 2018a). Similarly, in Pakistan, farmers are experiencing decline in crop yields and increasing incidence of crop diseases as a result of climate extremes particularly floods, droughts and heat waves (Fahad and Wang, 2018; Ahmad et al., 2019).

Limited studies have quantified the actual impacts of climate change on agricultural productivity and the economy. In a study in Mun River Basin, Northeast Thailand, yield losses of rice due to past climate trends covering the period of 1984–2013 was determined to be in the range of < 50kg/ha per decade or 3% of actual average yields with high possibility of more serious yield losses in the future (Prabnakorn et al., 2018). Likewise, in China, an economic loss of $595-858 million for the corn and soybean sectors was computed from 2000 to 2009 (Chen et al., 2016b). On the other hand, the intensive wheat-maize system in China seems to have benefited from climate change with the northward expansion of the northern limits of maize, and multi-cropping systems brought about by the rising temperature (Li and Li, 2014).

There is *high agreement* in more recent studies that linked the frequency and extent of El Niño phenomenon with global warming (Thirumalai et al., 2017; Wang et al., 2017a; Hoegh-Guldberg et al., 2018) that can trigger substantial loss in crop and fishery production. The 2004 El Niño caused the Philippines an 18% production loss during the dry season and 32% production loss during the wet season (Cruz et al., 2017). In the 2015 El Nino event, the Indian oil sardine fishery declined by more than 50% of the previous years (Kripa et al., 2018) severely impacting the coastal livelihood and economies (Shyam et al., 2017). The 2015-2016 El Niño also inflicted adverse impacts in agricultural productivity and food security, especially affecting the rural poor in middle- and lower-income countries in Southeast and South Asia (UNDP ESCAP OCHA RIMES APCC, 2017).

10.4.5.2 Projected Impacts

10.4.5.2.1 Fisheries and aquaculture

The fisheries and aquaculture production from Asia in 2019 was estimated at 159.67 mmt contributing to 74.7% of the global production (FAO, 2020). This sector provides employment to an estimated 50.46 million people where fishing and aquaculture are important socio-economic activities and fish products are a substantial source of animal protein (Bogard et al., 2015; Azad, 2017; FAO, 2018c). The economic contribution could be as high as 44 % of the coastal communities' GDP as in the case of Sri Lanka (Sarathchandra et al., 2018). Five Asian countries (i.e., China, Indonesia, India, Vietnam, Japan) are in the top 10 of the global fish producers, representing a cumulative share of 36% in 2018 (FAO, 2020). As a top producer with 15% global share, China also remains as a top exporter of fish and fish products with 14% global market share.

There is *high agreement* in the literature that Asian fisheries and aquaculture, including the local communities depending on them for livelihoods, are highly vulnerable to the impacts of climate change. Asia has been impacted by sea level rise (Panpeng and Ahmad, 2017), decrease in precipitation in some parts (Salik et al., 2015) and increase in temperature (Vivekanandan et al., 2016) which have drastic effects on fisheries and aquaculture (FAO, 2018c). Its coastal fishing communities is exposed to disasters, which are predicted to increase (Esham et al., 2018). Fisheries in most of South Asia and Southeast Asian countries involve small scale fishers who are more vulnerable to climate change impacts compared to commercial fishers (Sönke Kreft et al., 2016; Blasiak et al., 2017) though there is a general decreasing trend in number of small units (Fernandez-Llamazares et al., 2015; ILO, 2015). A regional study of South Asia forecast large decreases in potential catch of two key commercial fish species (hilsa shad and Bombay duck) in the Bay of Bengal (Fernandes et al., 2016) which forms a major fishery and food for coastal communities. About 69% of the commercially important species of the Indian marine fisheries were found to be impacted by climate change and other anthropogenic factors (Dineshbabu et al., 2020). Likewise, water salinisation brought about sea level rise is expected to impact on the availability of freshwater fish in Southwest coastal Bangladesh with adverse implications to poor communities (Dasgupta et al., 2017a). Analysis of fishery has indicated that there will be continued decrease in catch impacting the seafood sector in Philippines, Thailand, Malaysia and Indonesia (Nong, 2019). Climate change was predicted to decrease total productive fisheries potential in

South and Southeast Asia, driven by a temperature increase of approximately 2 °C by 2050 (Barange et al., 2014).

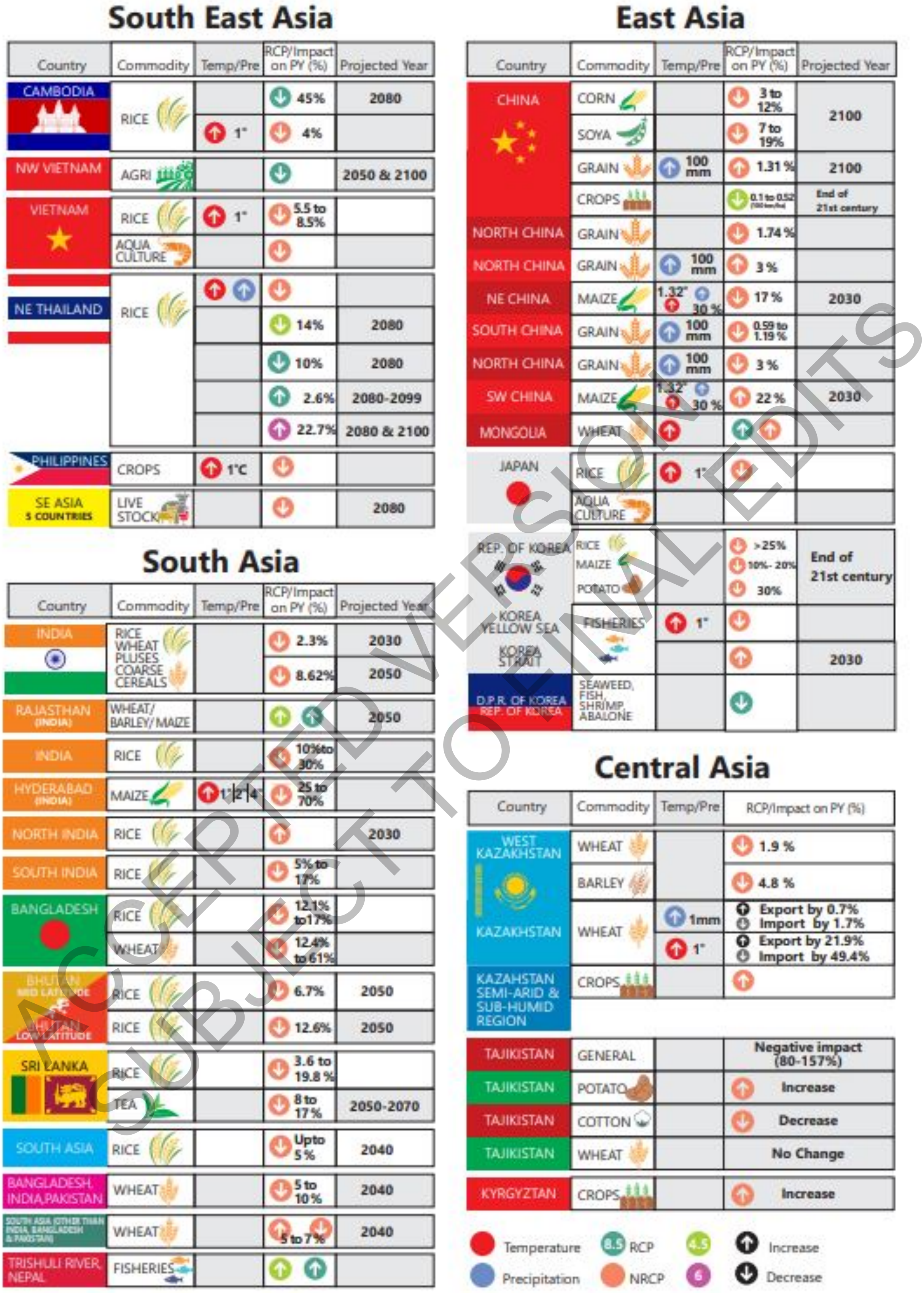
Like fisheries, Asian aquaculture is highly vulnerable to climate change. Shrimp farmers and fry catchers of Bangladesh are frequently affected by extreme climatic disruptions like cyclones and storm surges that severely damage the entire coastal aquaculture (Islam et al., 2016a; Kais and Islam, 2018). Majority of the shrimp farmers also observed that weather has changed abruptly during the last 5 years and that high temperature is most detrimental, lowers growth rate, increases susceptibility to diseases including deformation and affect production (Islam et al., 2016a). Low production in shrimp farming is also attributed to variation and intensity of rainfall perceived by majority of farmers as part of climate change impacts (Ahmed and Diana, 2015; Islam et al., 2016a; Henriksson et al., 2019). In Vietnam, small scale shrimp farmers are likewise vulnerable to climate change although those who practice extensive type of farming with low inputs are more vulnerable compared to those who practice more intensive type with more capital investment (Quach et al., 2015; Quach et al., 2017). Seaweed farming in Asia is very popular and the significance of seaweed aquaculture beds (SAB) in capturing carbon is recognised, but most of the farmed seaweeds are susceptible to climate change (Chung et al., 2017a; Duarte et al., 2017).

MHW are a new threat to fisheries and aquaculture (Froehlich et al., 2018; Frölicher and Laufkötter, 2018) including disease spread (Oliver et al., 2017), live feed culture (copepods) (Doan et al., 2018), and farming of finfishes like Cobia (Le et al., 2020). Predicting MHW is considered a pre-requisite for increasing the preparedness of farmers (Frölicher and Laufkötter, 2018). In Southeast Asian countries more than 30% of aquaculture areas are predicted to become unsuitable for production by 2050 - 2070 and aquaculture production is predicted to reduce 10% - 20% by 2050 - 2070 due to climate change (Froehlich et al., 2018).

10.4.5.2.2 Crop production

Since IPCC AR5, more studies have been done in different scales from local to global that focus on the differentiated projected impacts of climate change on the production and economics of various crops with rice, maize, and wheat among the major crops receiving more attention. New research findings affirm that climate change impacts on and will continue to significantly affect crop production in diverse ways in particular areas all over Asia (See Figure 10.6). Increasing number of sub-regional and regional studies using various modelling tools provide significant evidences on the overall projected impacts of climate change on crop production at the sub-regional and regional scales with clear indications of winners and losers among and within nations ((see for instance, (Mendelsohn, 2014; Cai et al., 2016; Chen et al., 2016b; Schleussner et al., 2016)).

Beyond the usual research interest on crop yields which has dominated current literature, recent studies such as those in Japan started to focus on the impacts of climate change on the quality of crops (see for instance, Sugiura et al. (2013) for apple, and Morita et al. (2016) and Masutomi et al. (2019) for rice). A large-scale evaluation by Ishigooka et al. (2017) shows that the increased risk in rice production brought about by temperature increase may be avoided by selecting an optimum transplanting date considering both yield and quality. More studies of this nature have to conducted for other crops in different locations to better understand and adapt to the negative impacts of the changing climate on the quality of crops (Ahmed and Stepp, 2016).



South East Asia

Country	Commodity	Temp/Pre	RCP/Impact on PY (%)	Projected Year
CAMBODIA	RICE		↓ 45%	2080
		↑ 1°	↓ 4%	
NW VIETNAM	AGRI		↓	2050 & 2100
VIETNAM	RICE	↑ 1°	↓ 5.5 to 8.5%	
	AQUA CULTURE		↓	
NE THAILAND	RICE	↑ ↑	↓	
			↓ 14%	2080
			↓ 10%	2080
			↑ 2.6%	2080-2099
			↑ 22.7%	2080 & 2100
PHILIPPINES	CROPS	↑ 1°C	↓	
SE ASIA 5 COUNTRIES	LIVE STOCK		↓	2080

East Asia

Country	Commodity	Temp/Pre	RCP/Impact on PY (%)	Projected Year
CHINA	CORN		↓ 3 to 12%	2100
	SOYA		↓ 7 to 19%	
	GRAIN	↑ 100 mm	↑ 1.31%	2100
	CROPS		↓ 0.1 to 0.52	End of 21st century
NORTH CHINA	GRAIN		↓ 1.74%	
NORTH CHINA	GRAIN	↑ 100 mm	↑ 3%	
NE CHINA	MAIZE	1.32° ↑ ↑ 30%	↓ 17%	2030
SOUTH CHINA	GRAIN	↑ 100 mm	↓ 0.59 to 1.19%	
NORTH CHINA	GRAIN	↑ 100 mm	↓ 3%	
SW CHINA	MAIZE	1.32° ↑ ↑ 30%	↑ 22%	2030
MONGOLIA	WHEAT	↑	↑ ↑	
JAPAN	RICE	↑ 1°	↓	
	AQUA CULTURE			
REP. OF KOREA	RICE MAIZE POTATO		↓ >25% ↓ 10%- 20% ↓ 30%	End of 21st century
KOREA YELLOW SEA	FISHERIES	↑ 1°	↓	
KOREA STRAIT			↑	2030
D.P.R. OF KOREA REP. OF KOREA	SEAWEED, FISH, SHRIMP, ABALONE		↓	

South Asia

Country	Commodity	Temp/Pre	RCP/Impact on PY (%)	Projected Year
INDIA	RICE WHEAT PLUSES COARSE CEREALS		↓ 2.3%	2030
			↓ 8.62%	2050
RAJASTHAN (INDIA)	WHEAT/ BARLEY/ MAIZE		↑ ↓	2050
INDIA	RICE		↓ 10% to 30%	
HYDERABAD (INDIA)	MAIZE	↑ 1° 2° 4°	↓ 25 to 70%	
NORTH INDIA	RICE		↓	2030
SOUTH INDIA	RICE		↓ 5% to 17%	
BANGLADESH	RICE		↓ 12.1% to 17%	
	WHEAT		↓ 12.4% to 61%	
BHUTAN MID LATITUDE	RICE		↑ 6.7%	2050
BHUTAN LOW LATITUDE	RICE		↓ 12.6%	2050
SRI LANKA	RICE		↓ 3.6 to 19.8%	
	TEA		↓ 8 to 17%	2050-2070
SOUTH ASIA	RICE		↓ Upto 5%	2040
BANGLADESH, INDIA,PAKISTAN	WHEAT		↓ 5 to 10%	2040
SOUTH ASIA OTHER THAN INDIA, BANGLADESH & PAKISTAN	WHEAT		↓ ↓ 5 to 7%	2040
TRISHULI RIVER, NEPAL	FISHERIES		↑ ↑	

Central Asia

Country	Commodity	Temp/Pre	RCP/Impact on PY (%)
WEST KAZAKHSTAN	WHEAT		↓ 1.9%
	BARLEY		↓ 4.8%
KAZAKHSTAN	WHEAT	↑ 1mm	↑ Export by 0.7% ↓ Import by 1.7%
		↑ 1°	↑ Export by 21.9% ↓ Import by 49.4%
KAZAKHSTAN SEMI-ARID & SUB-HUMID REGION	CROPS		↑
TAJIKISTAN	GENERAL		Negative impact (80-157%)
TAJIKISTAN	POTATO		↑ Increase
TAJIKISTAN	COTTON		↓ Decrease
TAJIKISTAN	WHEAT		No Change
KYRGYZTAN	CROPS		↑ Increase

Figure 10.6: Projected impacts of climate change to agriculture and food systems in sub-regions of Asia based on post IPCC-AR5 studies. The figure illustrates the spatial and temporal diversity of projected future impacts on food production highlighting that there are winners and losers associated with the changing climate at different scales. (Abbreviations AGRI-Agriculture; E-East; N-North; NRCP-No RCP analysis; Pre-Precipitation; PY-Production Yield;

RCP-Representative Concentration Pathway; S-South; Temp-Temperature; W-West). (Please refer to Table SM10.2 for details and supporting references).

New studies have projected the *likely* negative impact of pests in Asian agriculture. The golden apple snail (*Pomacea canaliculate*), which is among the world's 100 most notorious invasive alien species, threatens the top Asian rice-producing countries including China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines, and Japan with the predicted increase in climatically suitable habitats in 2080 (Lei et al., 2017). Similarly, a study by (Shabani et al., 2018) in Oman projected that pest of date palm trees, Dubas bug (*Ommatissus lybicus* Bergevin) could reduce the crop yield by 50% under future climate scenarios.

While there is general agreement that CO2 promotes growth and productivity of plants through enhanced photosynthesis, there remains uncertainty on the extent to which carbon fertilisation will influence agricultural production in Asia as it interacts with increasing temperatures, changing water availability, and the different adaptation measures employed (Ju et al., 2013; Jat et al., 2016; ADB, 2017b). As global warming compounds beyond 1.5 °C, however, the likelihood of adverse impacts to agricultural and food security in many parts of developing Asia increases (Mendelsohn, 2014; IPCC, 2018b). There is a growing trend towards more integrated studies and modelling that combines biophysical and socioeconomic variables (including management practices) in the context of changing climate to reduce uncertainty associated with future impacts of climate change to the agricultural sector ((see for instance (Mason-D'Croz et al., 2016; Smeets Kristkova et al., 2016; Gaydon et al., 2017)).

10.4.5.2.3 Livestock production

There is hardly any mention about the impacts of climate change on livestock production in the Asia chapter of AR5 due to limited studies on this area. This scarcity of information persists to the current assessment with very scanty information on the projected impacts and adaptation aspects of livestock production (Escarcha et al., 2018a). The use of scenarios/models to determine alternative futures with participatory engagement process has been recommended for informed policy and decision making with potential application in the livestock sector (Mason-D'Croz et al., 2016). Of the limited assessment available, a study on the smallholders' risk perceptions of climate change impacts on water buffalo production systems in Nueva Ecija, Philippines identified feed availability and animal health as the production aspects most severely affected by multiple weather extremes (Escarcha et al., 2018b). In the Mongolian Altai Mountains, early snowmelt and an extended growing season have resulted in reduced herder mobility and prolonged pasture use, which has in turn initiated grassland degradation (Lkhagvadorj et al., 2013a). Furthermore, reduced herder mobility has increased the pressure on forests resulting in increased logging for fuel and construction wood and reduced regeneration due to browsing damage by increasing goat populations (Khishigjargal et al., 2013; Dulamsuren et al., 2014).

In terms of direct impacts, climate change-induced heat stress and reduced water availability are *likely* to generally have negative effects on livestock (ADB, 2017b). In Hindu Kush-Himalaya (HKH) Region climate change has induced severe impacts on livestock through degradation of rangelands, pastures, and forests (Hussain et al., 2019). However, indirect effects maybe positive such as in Uzbekistan and South Asia where alfalfa and grassland productivity is expected to improve under warming conditions which have beneficial effects to livestock production (Sutton et al., 2013; Weindl et al., 2015).

At the global level, analysis involving 148 countries in terms of the potential vulnerability of their livestock sector to climate and population change shows that some Asian nations, particularly Mongolia, are *likely* to be the most vulnerable while South Asia is the most vulnerable region (Godber and Wall, 2014).

10.4.5.2.4 Farming systems and crop areas

There is new evidence since AR5 that farming systems and crop areas will change in many parts of Asia in response to climate change. In South Asia, a study in Nepal showed that farmers are inclined to change in cropland-use to reduce climate change risk (Chalise and Naranpanawa, 2016). In India, climate change is also predicted to lead to boundary changes in areas suitable for growing certain crops (Srinivasa Rao et al., 2016). A study in Bangladesh reveals a shift in crop choices among farmers implying changes in future rice cropping pattern. Specifically, temperature increase will compel farmers to choose irrigation based Boro, Aus and other crops in favor of rainfed Aman rice crop (Moniruzzaman, 2015).

In the coastal area of Odisha in India, adverse impact on the agriculture sector is anticipated considering the increasing temperature trends over the last 30 years for all the seasons (Mishra and Sahu, 2014). In a national study that groups Bangladesh into 16 sub-regions with similar farming areas, simulations of a 62 cm rise in mean sea level project damages to production because of area loss in excess of 31% in Sub-Region -15 and nearly 40% in Sub-Region -16 (Ruane et al., 2013). Also in Bangladesh, a study on predicting design water requirement of winter paddy rice under climate change condition shows that agricultural water resource management will help minimise drought risk and implement future agricultural water resources policies (Islam et al., 2018) that may have important implications to crop areas and production.

In East Asia, observed changes in agricultural flooding in different parts of China could influence farming systems and crop areas (Zhang et al., 2016b), as extreme events intensify in the context of changing climate. Agricultural management practice in China may also change to optimise soil organic carbon sequestration (Zhang et al., 2016a). A study on projected irrigation requirements under climate change using soil moisture model for 29 upland crops in Republic of Korea shows that water scarcity is a major limiting factor for sustainable agricultural production (Hong et al., 2016). In terms of drought, despite increasing future precipitation in most the scenario, crop-specific agricultural drought will be expected to risky significantly by rainfall variability (Lim et al., 2019a). On the other hand, a projected rise in water availability in the Korean Peninsula using multiple regional climate models and evapotranspiration methods indicates it will *likely* increase agricultural productivity for both rice and corn, but would decrease significantly in rainfed conditions (Lim et al., 2017b). Thus, irrigation and soil water management will be a major factor in determining future farming systems and crop areas in the country.

Global study on climate change-induced hot-spots of heat stress on agricultural crops shows that large suitable cropping areas in Central and Eastern Asia and the Northern part of the Indian subcontinent are under heat stress risk assuming the A1B emission scenario (Teixeira et al., 2013) and hence may reduce cropping areas in these regions. In Japan, the projected decline in rice yield in some areas, suggests that the current rice producing regions would be divided into suitable and unsuitable areas as temperatures increases (Ishigooka et al., 2017) with important implication on the possible shift in cropping area. Similarly, it has been shown that there will be change in the geographical distribution of the occurrence of poor skin color of table grape berries (Sugiura et al., 2019) and suitable areas for cultivation of subtropical citrus (Sugiura et al., 2014) in Japan by the middle of the 21st century.

There is emerging evidence from modelling and field experimentation that designing future farming systems and crop area that will promote sustainable development in Asia in the context of climate change would have to incorporate not only productivity and price considerations but also moderating temperature increase, enhancing water conservation, and optimising GHG mitigation potential (Sapkota et al., 2015; Zhang et al., 2016a; Ko et al., 2017; Lim et al., 2017b). Effects of agricultural landscape change on ecosystems services also need to be understood and taken into account in designing farming systems and allocating farm areas (Lee et al., 2015b; Zanzanaini et al., 2017).

10.4.5.3 Food Security

FAO (2001) defines food security as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. There is significant evidence that climate change significantly undermines both agricultural production and food security in Asia (ADB, 2017b). Increasing evidence from sub-regions and individual countries suggests that climate-related hazards such as increasing temperature, changing rainfall, sea level rise, drought, flooding, and the more frequent and intense occurrence of ENSO events, all impacts on agricultural production with significant effects on food security. All these hazards interact with non-climatic factors like competing demand for scarce water resources, rural-urban migration, food prices and increasing food demand in the long term, and poor governance, among others, that may worsen food insecurity in the region (Montesclaros and Teng, 2021).

In West Asia, particularly in Saudi Arabia and Yemen, increasing water scarcity brought about by temperature rise is anticipated to have severe impact on agriculture and food production that undermines food security (Al-Zahrani et al., 2019; Baig et al., 2019). Saudi Arabia, for instance, was forced to phase out its wheat production starting in 2016 and fully rely on import to conserve its drying fossil water resources (Al-Zahrani et al., 2019) which is also linked to water governance issue.

In Central Asia, a study using bioeconomic farm model shows very large differences in climate change impacts across farming systems at the sub-national level. Large-scale commercial farms in the northern regions of Kazakhstan will have positive income gains while small-scale farms in arid zones of Tajikistan will experience negative impact with *likely* effects to farm income security (Bobojonov and Aw-Hassan, 2014). Impacts on farmers' income in Western Uzbekistan will also significantly vary and could fall by as much as 25% depending on the extent of temperature increase and water use efficiency (Bobojonov et al., 2016).

In a regional study among South Asian countries using an integrated assessment modelling framework, changes in rice and wheat productions brought about by climate change are anticipated to engender wild price volatilities in the markets (Cai et al., 2016). Price spikes are projected for the period 2015 to 2040 in all South Asian regions with India, Pakistan and Sri Lanka predicted to witness increasingly much higher rice and wheat prices than under the baseline scenario creating major concerns over food affordability and food security. This will *likely* severely affect the overall economic growth of these countries since they are mainly agriculture driven economy.

A study on mapping global patterns of drought risk projected an increase of drought frequency and intensity in the populated areas of South to Central Asia extensively used for crop and livestock production with serious repercussion to food security and potential civil conflict in the medium- to long-term (Carrão et al., 2016). In Southeast Asia, a Philippine study on the relationship of seasonal rainfall, agricultural production, and civil conflict suggests that the projected change towards wetter rainy seasons and drier dry seasons in many parts of the country will lead to more civil conflict (Crost et al., 2018) with negative implications to food and human security. Similarly, floods and higher food prices are also associated with higher risks of social unrest in Asia that may undermine food security (Hendrix and Haggard, 2015; Ide et al., 2021).

Food insecurity will be localised across Asia where one part of the country or sub-region will be more food secured while the others, more insecure. This will require in-country or sub-regional trade and development cooperation to minimise the adverse impacts of food insecurity associated with the changing climate (Li et al., 2014a; Abid et al., 2016).

10.4.5.4 Key Drivers to vulnerability

There is *high confidence* that agriculture will continue to be among the most vulnerable sectors in Asia in the light of the changing climate (Mendelsohn, 2014; ADB, 2017b). Among the more vulnerable areas include mountain agriculture where fluctuation in crop production (Poudel and Shaw, 2016; Hussain et al., 2019) and food insufficiency is widespread than in lowland areas (Poudel and Shaw, 2015); (Kohler and Maselli, 2009). Also vulnerable are flood-prone areas like the Vietnam Mekong River Delta where 39% of the total rice area is exposed to sustained flood risks (Wassmann et al., 2019a). Increasing temperatures and changing precipitation levels will persist to be important vulnerability drivers that will shape agricultural productivity particularly in South Asia, Southeast Asia, and Central Asia as well as in selected areas of the region. With the increasing likelihood of extreme weather events like strong typhoons in the Philippines, the agricultural sector in the typhoon-prone areas of Southeast and East Asia as well as the Indus Delta, will be more vulnerable to crop destruction (Mallari and Ezra, 2016). Projections on increasing sea level rise and flooding such as those in Bangladesh and the Mekong Delta in Vietnam will submerge and decrease crop production areas and will severely affect agriculture and fishery sectors but will also trigger outmigration from these areas (ADB, 2017b).

Vulnerability of aquaculture-related livelihoods to climate change was assessed at the global scale using the MAGICC/SCENGEN climate modelling tools and Vietnam, Thailand were identified as most vulnerable in brackish water aquaculture production (Handisyde et al., 2017). Asian countries like China, Vietnam and the Philippines are also ranked highly vulnerable in marine production. Moreover, a recent vulnerability assessment of Korean aquaculture based on predicted changes in seawater temperature and salinity according to representative concentration pathways (RCP) scenario (RCP8.5) indicated that vulnerability was highest for seaweed, such as laver and sea mustard, while fish, shrimp, and abalone are relatively less vulnerable as they are less sensitive to high water temperature and their farming environments are controllable to a large extent (Kim et al., 2019a). In Indonesia, farming of white leg shrimp *Litopenaeus vannamei* has been found to be vulnerable to increased rainfall and temperature decrease (Puspa et al., 2018).

Climate change-induced vulnerability however is complicated by non-climatic drivers. In Thailand, for instance, a 38% reduction (from 21,486 to 13,328 million baht) in the export values of rice and products in the last quarter of 2011 has been attributed not only to impact of tropical cyclone Nock-Ten on Thai rice export but also with the economic slowdown in Thailand during 2011-2012 (Nara et al., 2014).

Considering the high vulnerability of Asia to climate change as a whole, there is a need to look at the drivers of vulnerability in an integrated and comprehensive manner. The increasing interest on nexus studies that links climate change impacts to agriculture with the other sectors like water, energy, land use change, urbanisation, poverty, economic liberalisation, and others ((see for example, (Takama et al., 2016; Aich et al., 2017; Eslamian et al., 2017; Duan et al., 2019b)) could contribute to a systemwide vulnerability reduction and an important initial step towards a more climate resilient future.

10.4.5.5 Adaptation Options

Since AR5, there is a surge in the volume of literature that documents and assesses the different adaptation practices already employed in Asian agriculture as well as those that provide future adaptation options. There is *robust evidence* that a variety of adaptation practices already employed in agriculture and fisheries are valuable in reducing negative effects of current climate anomalies but may not be sufficient to fully offset the adverse impacts of future climate scenarios. Recent literature, therefore focuses on how to build on current adaptation initiatives and processes to improve current and future outcomes (Iizumi, 2019).

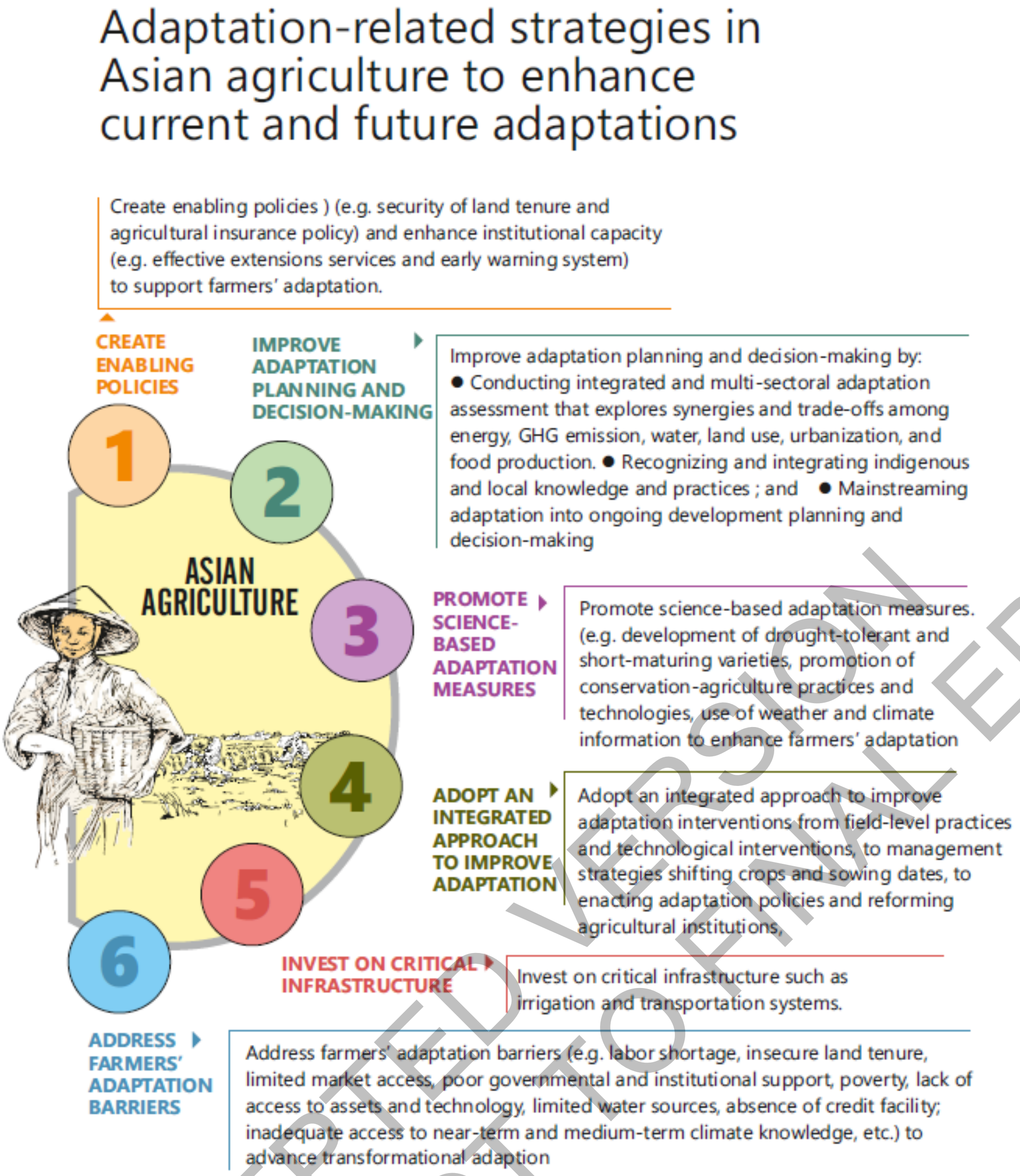
Asian farmers and fisherfolks already employ a variety of adaptation practices to minimise the adverse impacts of climate change. A recent systematic and comprehensive review of farmers' adaptation practices in Asia, Shaffril et al. (2018) categorised these practices into different forms such as crop management, irrigation and water management, farm management, financial management, physical infrastructure management, and social activities. "Climate-smart agriculture" - an integrated approach for developing agricultural strategies that address the intertwined challenges of food security and climate change – is increasingly being promoted in many parts of the region, especially in Southeast and South Asia with potentially promising outcomes (Chandra et al., 2017; Khatri-Chhetri et al., 2017; Shirsath et al., 2017; Westermann et al., 2018; Wassmann et al., 2019b). Site specific adaptations such as those in Pakistan include the farmers' utilisation of several adaptation techniques which include changing crop type and variety and improving seed quality; fertiliser application and use of pesticides and plant shade trees; and water storage and farm diversification (Fahad and Wang, 2018), as well as the implementation of a comprehensive climate information services to farming communities (World Meteorological Organization, 2017).

Adaptation measures are also beneficial to small scale fishers and fish farmers (Miller et al., 2018) and through fisheries management plans (FMP) and early warning systems, the Asian region is reducing climate impact (FAO, 2018c). The most common FMPs adopted in different Asian countries are limits to fishing gear, licensing schemes and seasonal closures (ILO, 2015) protection of nursery grounds, providing alternative livelihoods (Azad, 2017), limiting fish aggregating devices (FADs) and introduction of monitoring and control tool (Department of Fisheries (Thailand), 2015). Fishers' strong sense of belonging to their place of residence and the sense of responsibility to protect the vulnerable fish stock has been advantageously used for developing cooperatives and starting community-based fisheries management (FAO, 2012; ILO, 2015; Shaffril et al., 2017) and these have yielded positive results.

In aquaculture, most households in shrimp communities rely on process-oriented multiple coping mechanisms such as consumption smoothing, income smoothing, and migration that enhance the farmers' resilience to climate anomalies (Kais and Islam, 2018). Diversification and integration of varied resources and interventions in feed and husbandry are seen help the aqua farmers increase their profit and overcome impacts of climate change (Henriksson et al., 2019). Strategies like polyculture, integrated multitrophic aquaculture (IMTA) and recirculating aquaculture systems (RAS), have been suggested to increase aquaculture productivity, environmental sustainability, and climate change adaptability (Ahmed et al., 2019c; Tran et al., 2020). In Bangladesh, several adaptation measures like integrated (Akber et al., 2017) community-based adaptation strategies and integrated coastal zone management (Ahmed and Diana, 2015) have been recommended to increase climate resilience among shrimp farmers.

More recently, Nature-based Solutions (NbS) have gained attention globally to enhance climate adaptation. In the context of agriculture, NbS is seen as cost-effective interventions that can increase resilience in food production, while advancing climate mitigation and improving the environment (Iseman and Miralles-Wilhelm, 2021). Experiences in implementing NbS in agricultural landscapes have been documented both in agriculture and fisheries sectors that promotes production while providing co-benefits such as environmental protection and sustainability (Miralles-Wilhelm, 2021).

Despite the numerous adaptation measures already employed, there is sufficient evidence that farmers' current adaptation practices are inadequate to offset the worsening climate change impacts. A more comprehensive approach that integrates economic and social strategies with other measures is seen to reduce climate vulnerability. For instance, agriculture insurance is viewed as a promising adaptation approach to reduce risks and increase the financial resilience of farmers and herders in many Asian countries (Prabhakar et al., 2018; Matheswaran et al., 2019; Nguyen et al., 2019; Stringer et al., 2020). Similarly, participation of multiple stakeholders from all relevant sectors at different levels in adaptation planning and decision-making is seen as important factor in improving outcomes (Arunrat et al., 2017; Hochman et al., 2017; Chandra and McNamara, 2018). Moreover, while adaptation is local and context-specific, the following general adaptation-related strategies are distilled from current literature based on Asian experience to enhance current and future adaptations: 1) create enabling policies (Chen et al., 2018d) and enhance institutional capacity (Wang et al., 2014; Hirota and Kobayashi, 2019); 2) improve adaptation planning and decision-making (Xu and Grumbine, 2014; Asmiwyati et al., 2015; Dissanayake et al., 2017; Hochman et al., 2017; Qiu et al., 2018; Shuaib et al., 2018; Aryal et al., 2020b; Ruzol et al., 2021; Ruzol and Pulhin, 2021); 3) promote science-based adaptation measures (Alauddin and Sarker, 2014; Sapkota et al., 2015; Lim et al., 2017b); 4) adopt an integrated approach to improve adaptation (Teixeira et al., 2013; Yamane, 2014; Abid et al., 2016; Sakamoto et al., 2017; Sawamura et al., 2017; Trinh et al., 2018); 5) invest on critical infrastructure (Cai et al., 2016; Rezaei and Lashkari, 2018); and 6) address farmers' adaptation barriers (Alauddin and Sarker, 2014; Pulhin et al., 2016; Fahad and Wang, 2018; Gunathilaka et al., 2018; Almaden et al., 2019b) (See Figure 10.7 for details or examples of each strategy).



Create enabling policies) (e.g. security of land tenure and agricultural insurance policy) and enhance institutional capacity (e.g. effective extensions services and early warning system) to support farmers' adaptation.

Improve adaptation planning and decision-making by: ● Conducting integrated and multi-sectoral adaptation assessment that explores synergies and trade-offs among energy, GHG emission, water, land use, urbanization, and food production. ● Recognizing and integrating indigenous and local knowledge and practices ; and ● Mainstreaming adaptation into ongoing development planning and decision-making

Promote science-based adaptation measures. (e.g. development of drought-tolerant and short-maturing varieties, promotion of conservation-agriculture practices and technologies, use of weather and climate information to enhance farmers' adaptation

Adopt an integrated approach to improve adaptation interventions from field-level practices and technological interventions, to management strategies shifting crops and sowing dates, to enacting adaptation policies and reforming agricultural institutions,

Invest on critical infrastructure such as irrigation and transportation systems.

Address farmers' adaptation barriers (e.g. labor shortage, insecure land tenure, limited market access, poor governmental and institutional support, poverty, lack of access to assets and technology, limited water sources, absence of credit facility; inadequate access to near-term and medium-term climate knowledge, etc.) to advance transformational adaption

Figure 10.7: Adaptation related strategies in Asian agriculture to enhance current and future adaptations.

10.4.6 Cities, Settlements, and Key Infrastructures

Cities across Asia have large populations exposed to climatic risks but also present an opportunity for concerted climate action (Revi et al., 2014; Chu et al., 2017; Revi, 2017; Khosla and Bhardwaj, 2019) and report numerous examples of adaptation actions at various stages of planning and implementation (Dulal, 2019) (Singh et al., 2021b). However, challenges specific (though not exclusive) to Asian cities such as uneven economic development, rapid land use changes, increasing inequality, growing exposure to extreme events and environmental change such as land subsidence (with antecedent impacts on people and infrastructure), and large, socially differentiated vulnerable populations, remain key concerns as Asian cities simultaneously tackle challenges of sustainable development and equitable climate action.

10.4.6.1 Sub-regional diversity

By 2050, urban areas are expected to add 2.5 billion people, 90% of which will be in Asia and Africa (UNDESA, 2018). Critically, this urban population increase will be concentrated in India, China and Nigeria with India and China adding 416 million and 255 million urban dwellers respectively between 2018 and 2050 (UNDESA, 2018).

Asia is home to 54% of the world's urban population and by 2050, 64% of Asia's 3.3 billion people will be living in cities. Asia is also home to the world's largest urban agglomerations: Tokyo (37 million inhabitants), New Delhi (29 million), and Shanghai (26 million) are the top three with Cairo, Mumbai, Beijing and Dhaka home to nearly 20 million people each (UNDESA, 2018). By 2028, Delhi is projected to become the most populous city in the world. In certain parts of Asia (e.g. some cities in Japan and Republic of Korea), a steep decline in urban population is projected, mainly due to declining birth rates (Hori et al., 2020). Within Asia, rates of urbanisation differ sub-regionally. Eastern Asia has seen the most rapid urban growth with the percentage of urban population having more than tripled from 18 to 60 percent between 1950 and 2015, while rates of urbanisation have reduced in West Asia and remained steady in Central Asia (UNDESA, 2018).

Asian cities are seeing growing income inequality, with rural poverty being replaced by urban poverty (ADB, 2013). Regional studies show high and growing inequality within Indian and Chinese urban areas and reducing rural-urban income gaps in Thailand and Viet Nam (Baker and Gadgil, 2017; Imai and Malaeb, 2018). Critically, East Asia and the Pacific continues to house the world's largest population of slum dwellers at 250 million, with most numbers in China, Indonesia, and the Philippines and highest rates of urban poverty in Papua New Guinea, Vanuatu, Indonesia, and the Lao People's Democratic Republic (PDR) (McIlreavy, 2015; Baker and Gadgil, 2017). A lot of urbanisation, especially in South Asia, is also 'hidden' due to poor competing definitions of what is urban and limited data (Ellis and Roberts, 2016).

10.4.6.2 Key drivers of vulnerabilities

In Asian cities, exposure to climatic hazards such as changes in precipitation and in the Asian monsoon, sea level rise, cyclones, flooding, dust storms, heat waves, and permafrost thawing (Byers et al., 2018; Hoegh-Guldberg et al., 2018; Rogelj et al., 2018; Shiklomanov, 2019) and non-climatic vulnerabilities such as non-climatic hazards (e.g. seismic hazards), inadequate infrastructure and services, unplanned urbanisation, socio-economic inequalities, and existing adaptation deficits (Johnson et al., 2013; Araos et al., 2016; de Leon and Pittock, 2017; Meerow, 2017; Dulal, 2019) interact to shape overall urban risk (Shaw et al., 2016a; Rumbach and Shirgaokar, 2017; Dodman et al., 2019). Caught at the intersection of high exposure, socio-economic vulnerability, and low adaptive capacities, informal settlements in urban and peri-urban areas are particularly at risk (Meerow, 2017; Rumbach and Shirgaokar, 2017; Byers et al., 2018) (*robust evidence, high agreement*).

10.4.6.3 Observed and projected impacts

10.4.6.3.1 Multi-hazard risk

Of the multi-hazard global Average Annual Loss (AAL[3]) of US$293 billion, US$170 billion (58%) is in the Asia Pacific region (UNISDR, 2017). Of the top ten highest AALs associated with multi-hazards, six are in Asia (Japan, China, Korea, India, Philippines and Taiwan, Province of China) (UNISDR, 2017). As per Gu et al. (2015), 56% cities with population greater than 300,000 in 2014, are exposed to at least one of the six physical hazards (cyclones, floods, droughts, earthquakes, landslides, and volcanic eruptions). Cities in areas highly exposed and vulnerable to multiple hazards were also the ones that grew rapidly in population between 1950 and 2014, implying greater infrastructural investments in climate-sensitive areas. Among 27 cities highly exposed to multiple disasters, 13 cities had a population of 1 million or more in 2014. Among these were three megacities, Tokyo (Japan), Osaka (Japan) and Manila (Philippines), with more than 10 million inhabitants exposed to three or more hazards. Seven other cities with one million inhabitants or more in Asia were at high risk of three or more types of disaster. Manila is highly vulnerable to economic losses and disaster related mortality from all six types of disasters (Gu et al., 2015). Moscow (Russia) is the only megacity not exposed to the risk of any of the six types of physical hazards analysed (cyclones, floods, droughts, earthquakes, landslides, and volcano eruptions) (Gu et al., 2015). Of the eight megacities most vulnerable to disaster-related mortality, seven are in Asia, mainly Tokyo, Osaka, Karachi, Kolkata, Manila, Tianjin, and Jakarta, totalling 143 million people, and three of the four large cities with a population between

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[3] Average Annual Loss (AAL) is the average amount that a country could expect to lose each year over the long-term due to hazard incidence. It corresponds to the expected average loss per year considering all the events that could occur over a long time-frame, including very intensive events. It is a probabilistic indication of the direct economic losses expected due to total or partial damage of physical assets existing in the affected area. (UNISDR, 2017).

5 million to 10 million: are in Asia: Chennai (India, 9.6 million), Nagoya (Japan, 9.4 million), and Tehran (Iran, 8.4 million) (Gu et al., 2015).

10.4.6.3.2 Extreme temperatures and heat waves

Urbanisation and climate change interact to drive urban heat island (UHI) effect across Asian cities (Chapman et al., 2017) (Hauck et al., 2016) [also see Fig 6.4 in Ch 6]. Three regions expected to see higher maximum wet bulb temperature than global averages are southwest Asia around the Persian Gulf and Red Sea, South Asia in the Indus and Ganges river valleys, and eastern China (Im et al., 2017) (Perkins-Kirkpatrick et al., 2020).

Impacts of heat waves in cities at 1.5°C and 2°C are substantially larger than under the present climate (Hoegh-Guldberg et al., 2018). In South Asia particularly, more intense heat waves of longer durations and occurring at a higher frequency are projected with *medium confidence* over India (Murari et al., 2015) and Pakistan (Nasim et al., 2018; Ali et al., 2020) (Ali et al., 2018) (IPCC AR6, WGI, Table 11.5)(IPCC, 2021a). At the city-level, these projections could translate into significant impacts: at 1.5°C, on average, Kolkata will experience, heat equivalent to the 2015 record heat waves every year; Karachi about once every 3.6 years and under 2°C warming, both regions could expect such heat annually (Matthews et al., 2017). In Pakistan, Hyderabad is *likely* to be the hottest city by 2100 with the highest average temperature reaching upto 29.9°C (RCP4.5) to 32°C (RCP8.5) followed by Jacobabad, Bahawalnagar, and Bahawalpur cities (Ali et al., 2020). The frequency of heat wave days (HWF) will increase by 22.8, 22.3, and 26.5 days/year in northern, eastern, and western Japan, respectively with megacities such as Tokyo, Osaka, and Nagoya seeing large increases in HWF and related deaths (Nakano et al., 2013).

In China's urban agglomerations, an increase in the global warming from 1.5 to 2°C is *likely* to exacerbate the intensity of extreme maximum temperature 4.1 times (Yu et al., 2018d). From 1995–2014 China's urban agglomerations (Beijing-Tianjin-Hebei, Yangtze River Delta, Middle Yangtze River, Chongqing-Chengdu, and Pearl River Delta (PRD)) experienced no more than three heat danger days/year, which is projected to increase to 3–13 days by 2041–2060 and 8-67 days by 2081–2100 under high-emission shared socioeconomic pathways SSP3-7.0 and SSP5-8.5, resulting in approximately 260 million people (19% of total Chinese population) and 310 million people (39% of the total China population) respectively facing more than three heat danger days annually (Zhang et al., 2021). This projected risk exposure is reduced under low-emission pathways (SSP1-2.6 and SSP2-4.5), where annual heat danger days will remain similar to current levels or increase slightly (Zhang et al., 2021).

Critically, these projections of higher temperatures will have significant impact on heat-related morbidity and mortality, labour productivity, mental health impacts and health and well-being outcomes across all sub-regions of Asia (*medium evidence, high confidence*) (Im et al., 2017) (Pal and Eltahir, 2016; Arifwidodo et al., 2019; Arshad et al., 2020). In West Asia and North China Plain especially, extreme wet-bulb temperatures are expected to approach and possibly exceed the physiologic threshold for human adaptability (35°C) (Pal and Eltahir, 2016; Kang and Eltahir, 2018). By end century, under higher projections (RCP 8.5) daily maximum wet-bulb temperature is expected to exceed survivability threshold across most of South Asia (Im et al., 2017). City-specific studies articulate what these regional projections will mean for urban populations. For example, at 1.5 °C warming, without adaptation, annual heat-related mortality in 27 major cities across China is projected to increase from 32.1 per million inhabitants annually in 1986–2005 to 48.8–67.1 per million. This number increases to 59.2–81.3 per million for 2°C warming (Wang et al., 2019a). In Korea, deaths from heat disorders are expected to increase approximately fivefold under the RCP4.5 and 7.2-fold under RCP 8.5 by 2060 compared to the current baseline value of ~23 people/summer (Kim et al., 2016a). Importantly, heat exposure is differentiated within cities: it disproportionally affects the poorest populations (Lohrey et al., 2021) and those with lower access to green spaces (Arifwidodo and Chandrasiri, 2020).

10.4.6.3.3 Precipitation extremes: excess rainfall and drought and water scarcity

Warming from 1.5°C to 2°C will increase extreme precipitation events across Asia especially over East and South Asia (*medium evidence, high agreement*) (Zhang et al. 2018); (Zhang et al., 2020b) (Supari et al., 2020). In East and Central Asia, under 1.5°C warming, extreme 1-day and 5-day precipitation will increase by 28% and 15%, relative to 1971–2000 (Zhang et al., 2020b). In China's urban agglomerations, an increase in the global warming from 1.5 to 2°C is *likely* to increase the intensity of total precipitation of very wet days

1.8 times and double maximum 5-day precipitation (Yu et al., 2018d). Extreme rainfall has direct and increasing consequences on urban flooding risk (Dasgupta et al., 2013b), which is further exacerbated by urbanisation trends that reduce permeability, divert water flow, and disrupt watersheds (Chen et al., 2015b; Duan et al., 2016).

Urban extent in drylands in expected to increase from 2000-2030 with large expansions in West Asia, Central Asia, South Asia, and China with antecedent impacts on exposure to drought and water scarcity (Güneralp et al., 2015). Urban dryland extent in West Asia will increase from 19,400km^2 to 67,400km^2 (Güneralp et al., 2015). In the Haihe River Basin in China, the proportion of people exposed to droughts at 1.5ºC (without accounting for population growth) is projected to reduce by 30.4%, but increase by 74.8% at 2°C relative to people exposed in 1986–2005 (339.65 million) (Sun et al., 2017). 411 million people living in 330 cities above 300,000 population are exposed to drought risk, which include three Asian megacities Delhi (India), Karachi (Abbas et al.), and Kolkata (India). Drought-related economic losses are also high in Dhaka (Pervin et al., 2020), Istanbul (Turkey), Manila (Philippines), and Shenzhen (China), while Manila is also highly vulnerable to drought-related mortality (Gu et al., 2015).

Increasing urban drought risk will also have cascading impacts on regions from where water is imported, exacerbating drought exposure beyond urban settlements and limiting water availability in certain regions (Chuah et al., 2018; Garrick et al., 2019; Zhang et al., 2020c; Zhao et al., 2020). There is *medium evidence (high agreement)* that urban water insecurity is experienced differentially based on income, risk exposure, and assets, and that urban drought and water scarcity is causing material and on-material losses and damage (Singh et al., 2021a). Importantly, in several Asian cities, flood and drought risk is expected to occur concurrently, especially in South Asia which is projected to see the largest increase in urban land exposed to both floods and droughts (25% to 32% increase in flood and drought risk between 2000-2030).

10.4.6.3.4 Sea-level rise and coastal flooding

Global assessments identify Asia as the most exposed to SLR [see CCP 2.2.1], in terms of number of people living in low-elevation coastal zones and the number of people exposed to flooding from 1-in-100 year storm surge events (Jevrejeva et al., 2016; Abadie et al., 2020) (Neumann et al., 2015; Kulp and Strauss, 2019) (Haasnoot, 2021). Twelve of the top 20 countries exposed to SLR and associated flood events are in Asia and of these, China, India, Bangladesh, Indonesia and Viet Nam are estimated to have the highest total coastal population exposure (Neumann et al., 2015) (Edmonds et al., 2020). Critically, regardless of emissions scenario, 70% of the global population exposed to SLR and land subsidence are in eight Asian countries: China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines, and Japan (Kulp and Strauss, 2019). This is particularly concerning since in highly populated low-lying coastal cities across Asia, it is estimated that land subsidence could be as influential as climate-induced SLR over the twenty-first century (Cao et al., 2021; Nicholls et al., 2021). In East Asia & the Pacific (expected to see 0.2-0.5m SLR), without adaptation, 1 million people (range of 0.3-2.2 million) are projected to be affected by submergence under RCP8.5 by 2095. Limiting warming reduces this risk and under RCP 4.5, these numbers of people at risk are reached by 2140. However, continuing on RCP8.5 increases risk exposure to 7 million (estimated range of 2-24 million people) (Haasnoot, 2021). Notably, assuming present-day population and adaptation (in the form of existing protection standards), East and South Asia already have a large number of people at risk of a 100-year flooding event (63 million) because of relatively lower flood protection (except in China and Malaysia).

These global scenarios will have significant impacts on national and sub-national populations. For example, in Bangladesh, under 0.44m and 2m mean SLR, direct inundation is estimated to drive migration of 0.73- 2.1 million people by 2100 (Davis et al., 2018). Such migration will have direct development implications: for example, destination locations could see additional demands on jobs (594 000), housing (197000), and food (783×109 calories) by mid-century as a result of those displaced by SLR (Davis et al., 2018).

Among the 20 largest coastal cities with highest flood losses by 2050, 13 are in Asia[4], with a regional concentration in South, South East and East Asia (Hallegatte et al., 2013). Further, 9 of these cities (Guangzhou, Kolkata, Tianjin, Ho Chi Minh, Jakarta, Zhanjiang, Bangkok, Xiamen, Nagoya) also have an

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[4] Guangzhou, Mumbai, Kolkata, Shenzhen, Tianjin, Ho Chi Minh, Jakarta, Chennai, Surat, Zhanjiang, Bangkok, Xiamen and Nagoya

additional risk of subsidence due to sea-level rise and flooding (Hallegatte et al., 2013). Guangzhou, China is estimated to be the most economically vulnerable city in the world to SLR by 2050, with estimated losses of \$254 million per year under 0.2m SLR (Jevrejeva et al., 2016). With a 2°C warming, Guangzhou is expected to see SLR of 0.34m; under 5°C warming, this number rises to 1.93m. A more recent estimate calculates expected damage in Guangzhou due to SLR under RCP8.5 to reach US\$331 billion by 2050 and US\$420 billion under the high-end scenario with figures doubling by 2070. By 2100, expected damage could reach US\$1.4 trillion under RCP 8.5 and US\$1.8 trillion the high-end scenario. Similarly, in Mumbai (India) SLR damages amount to US\$49-50 billion by 2050 and could increase by a factor of 2.9 by 2070 (Abadie et al., 2020). In coastal cities such as Bangkok and Ho Chi Minh City, projected land subsidence rates, mainly due to excessive groundwater extraction, are comparable to, or exceed, expected rates of SLR, resulting in an additional 0.2 m sea level rise by 2025 (Jevrejeva et al., 2016). In Shanghai, current annual damage by coastal inundation is estimated at 0.03% of local GDP; under RCP4.5, this increases to 0.8% by 2100 (uncertainty range: 0.4%–1.4%), and further exacerbated by land subsidence and socioeconomic development (Du et al., 2020). It is important to note that these projections assume (1) no adaptation and (2) that damage repairs are undertaken and completed annually. Given these assumptions, while these estimates communicate the scale of projected impacts, they are indicators of possible damages in the absence of adaptation and not actual projections.

SLR affects economic growth, its drivers, and welfare outcomes (Hallegatte, 2012; Pycroft et al., 2016; Lee and Asuncion, 2020) through (1) permanent loss of land and natural capital, (2) loss of infrastructure and physical capital, (3) loss of social capital and migration, (4) temporary floods, food insecurity and loss of livelihoods, and (5) added expenditure for coastal protection. Without adaptation, direct damage to GDP by 2080 due to SLR would be highest in Asia (*robust evidence, medium agreement*), with China losing between \$64.2 billion (at A1B of 2.4∘C by the 2050s and 3.8∘C by the 2090s/ 0.47 m), \$95.8 billion (at RAHM scenario of 1.4 m SLR by 2100/1.12 m), and \$118.4 billion (at High SLR of 2m by 2100/1.75 m) in direct damages, and an additional \$5.7 billion, \$4.5 billion, and \$4.5 billion respectively due to migration (Pycroft et al., 2016). Closely after China, will be India, Korea, Japan, Indonesia, and Russia. Overall, Asia can experience direct losses of about \$167.6 billion (at 0.47 m), \$272.3 billion (at 1.12m), or \$338.1 billion (at 1.75m) and an additional \$8.5 billion, \$24 billion or \$ 15 billion at the respective SLR projections due to migration[5].

10.4.6.3.5 Tropical cyclones

Globally, there is *high confidence* that the proportion of intense tropical cyclones is expected to increase despite the total number of tropical cyclones expected to decrease or remain unchanged (Arias et al., 2021), especially in Southeast and East Asia (Knutson et al., 2015; Yamamoto et al., 2021). Historical trends from South Asia indicate that more lives are lost due to storm surge levels than the intensity of the cyclone (Niggol and Bakkensen, 2017). The number of people exposed to 1-in-100-year storm surge events, is highest in Asia. China, India, Bangladesh, Indonesia and Viet Nam have the highest numbers of coastal populations exposed (Neumann et al., 2015) with Guangzhou, Mumbai, Shenzen, Tianjin, Ho Chi Minh City, Kolkata, and Jakarta incurring losses of US\$1520 million due to coastal flooding in 2005 alone (Dulal, 2019), although Jakarta is exposed to monsoonal storm surge. It is projected that by 2050, without adaptation, the annual losses incurred in these cities will increase to approximately US\$32 billion (Dulal, 2019).

Globally, six of the top ten countries/places with the highest AAL associated with tropical cyclones are in Asia (Japan, Korea, Philippines, China, Taiwan, Province of China, and India) (Mori et al., 2021a). AAL associated with storm surge is primarily concentrated in Japan, China, Hong Kong SAR of China, and India. AAL associated with wind and storm surge relative to the existing capital stock in the country is highest in New Caledonia, Tonga, Vanuatu, Palau, Philippines, Fiji and Solomon Islands, indicating less resilience. For example, in Ise Bay, Japan, current storm surges are estimated to lead to property and business damage of approximately 100.04 billion JPY current adaptation (protective seawall) but this can more than double to 236.49 billion JPY under climate change-induced increases in storm surge intensity (Jiang et al., 2016).

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[5] Cumulative migration in high SLR scenarios is always higher, but since much of the migration has already occurred in earlier decades, the additional migration is lower in the high SLR scenarios than the A1B scenario.

10.4.6.3.6 Riverine floods

Over on-third Asian cities and about 932 million urban dwellers live in areas with high risk of flooding (Gu et al., 2015). Of 437 cities at low risk of flood exposure but highly vulnerable to flood-related economic losses, approximately half are in Asia (Gu et al., 2015).

Globally, China and India have the highest AALs associated with riverine floods, with a magnitude of USD 13 billion and USD 6 billion respectively. Other countries from Asia among the top ten of absolute AALs are Japan, Bangladesh and Thailand. There is an increased flood risk for habitations on the deltas influenced by both riverine and coastal drivers of flooding (Szabo et al., 2016a), globally exposing 9.3% more people annually to riverine flooding than otherwise estimated without the compounded influence (Eilander et al., 2020). Simultaneously, SLR and subsidence are also expected to increase the risk due to frequent flood events for these delta regions than the longer-return periods otherwise associated with SLR (Yin et al., 2020).

10.4.6.3.7 Permafrost thawing and associated risks

In Northern Eurasia, observed and projected climate change impacts are especially pronounced. On land, the presence of permafrost, which occupies substantial areas of eastern Russia, Mongolia and mountain regions of China, creates specific challenges for economic development and human activities. By 2050, it is *likely* that 69% of fundamental human infrastructure in the Pan Arctic will be at risk (RCP 4.5 scenario), including more than 1200 settlements (Hjort et al., 2018). Majority of population and absolute majority (85%) of large settlements on permafrost are located in Russia and 44% of those are expected to be profoundly affected by permafrost thaw by 2050 (Streletskiy et al., 2019; Ramage et al., 2021). Under RCP8.5, climate-induced decrease of bearing capacity and, in regions with ice-rich permafrost, thaw subsidence, is projected to affect 54% of all residential buildings on permafrost with combined worth of $20.7 billion USD; 20% of commercial and industrial structures and 19% in critical infrastructure with a total worth of $84.4 billion USD (Streletskiy, 2019). Transport infrastructure in Russia and China are impacted by thaw subsidence and to lesser degree from frost heave, which add significant operational costs and limit accessibility of remote settlements (Ni et al, 2021; Porfiriev et al., 2019).

Especially in Russia, significant populations and fixed infrastructure assets are located in urban centers on permafrost that is degrading significantly. Two major risks associated with permafrost degradation are loss of permafrost bearing capacity and ground subsidence (Streletskiy et al., 2015). The former determines the ability to support foundations of buildings and structures and is a vital characteristic of sustainability of the economic centers, while the latter impacts the ability of critical infrastructure (roads, railroads) to provide transportation and support accessibility of remote populations and economic centers on permafrost. Proximity of some settlements to the coasts or areas with uneven topography may further increase risks associated with permafrost degradation as ice-rich coasts characterised by high rates of coastal erosion, while settlements located on slopes may experience higher rates of mass wasting processes.

Observed changes in climate resulted in permafrost warming and increased thaw depth in undisturbed locations (Biskaborn et al., 2019), but in built up areas these transformations were exacerbated by human activities (Grebenets et al., 2012). Norilsk, the largest city built on permafrost above the Arctic Circle (Shiklomanov et al., 2017b) was found to have one of the highest trends of near-surface permafrost warming (Streletskiy et al., 2012). Anomaly high temperatures and earlier snowmelt in 2020 may have contributed to oil storage collapse and resulting spill of 20 thousand tons of diesel fuel in Norilsk area (Rajendan et al., 2021). The ability of foundations to support structures have decreased by 10 to 40% relative to the 1960s in the majority of settlements on permafrost in Russia (Streletskiy et al., 2012) and further expected to decrease by 20 to 33% by 2050-59 relative to 2006-15 (Streletskiy et al., 2019).

10.4.6.3.8 Risks and impacts on infrastructure

South Asia and Africa bear the highest losses from unreliable infrastructure and climate change will increase these losses due to hazards, and necessitate additional infrastructure investments to address new risks (Hallegatte et al., 2019; Lu, 2019)[6]. Specifically, power generation and transport infrastructure incur losses

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[6] While Hallegatte et al. (2019) estimate that in low- and middle-income countries, the cost of infrastructure disruptions range from $391-$647 billion, they highlight that "while these estimates are incomplete, they highlight the substantial costs that unreliable infrastructure impose on people in low- and middle- income countries".

of $30 billion a year on average from hazards (about $15 billion each), with low- and middle-income countries shouldering about $18 billion of the total amount (Koks et al., 2019; Nicholls et al., 2019).

Among the top 20 countries that are rapidly expanding their infrastructure stock while facing high disaster risk and low infrastructure quality, Laos, Philippines, Bangladesh, Cambodia, Kyrgyzstan, Bhutan, and Viet Nam are from Asia. (UNISDR, 2017; WEF, 2018). The losses are due to direct damage to infrastructure, disruption in services, and affected supply chains (Hallegatte et al., 2019). East Asia and the Pacific and South Asia have the highest adaptation deficits in coastal protection with USD 75 billion in the former and USD$49 billion in the latter (Nicholls et al., 2019). If overall damages are minimised, low- and middle-income countries may need to invest 0.1 to 0.5 percent of their GDP annually up to 2030 for protection against both coastal and river floods, varying based on level of acceptable risks, construction costs, urbanisation and climate uncertainties[7].

- **Power disruption:** Contrasting with high-income countries such as USA, where hazards, particularly storms, are responsible for 50% of power outages, this share is much lower in countries like Bangladesh or India, because system failures due to non-natural causes are very frequent. However, outages caused by hazards tend to be longer and geographically more widespread than other outages (Rentschler et al., 2019). Climate change induced sea-level is expected to impact power infrastructure even necessitating power plant relocation (Hallegatte et al., 2019). In Bangladesh, to avoid inundations caused by SLR (SSP2, RCP 8.5), approximately one-third of power plants may need to be relocated by 2030; an additional 30 percent power plants are *likely* to be affected by increased salinity of cooling water and increased frequency of flooding, while the northern region power plants will probably see a decrease in output because of droughts (Hallegatte et al., 2019). In 2013 in Chittagong (Pervin et al., 2020), users experienced about 16 power outages due to storms alone (Hallegatte et al., 2019). Further, low-carbon technology diffusion might make certain infrastructures redundant, leading to stranded assets.

  Across Asia, infrastructure impacts are mixed: net importers such as China and India will see GDP gains while extreme examples include Russia, a net exporter, which could see steep declines in fossil fuel production (Mercure et al., 2018). In low- and middle-income countries globally, disruption in power supply can impact firms directly (up to USD 120 billion per year), with coping costs (up to USD 65 billion a year), and other indirect impacts. Similarly, for households, the direct impact and cost of coping could be between USD 2.3 – 190 billion per year. Although all power outage is not due to natural hazards, there is a significant number that is attributed to disasters. Besides, outages caused by natural hazards tend to be longer and geographically larger than other causes (Hallegatte et al., 2019).

- **Transportation disruption:** Of the 20 countries in which the road and railway infrastructure is expected to be most affected in absolute terms due to multi-hazards, half are Asian (Koks et al., 2019). In low- and middle-income countries globally, the direct losses to firms on account of transportation disruption are about USD$107 billion per year, excluding the costs due to sales losses or delayed supplies and deliveries alone (Hallegatte et al., 2019). In the transport sector, floods and other hazards disrupt traffic and cause congestion, taking a toll on people and firms in rich and poor countries alike.

- **Water supply and disposal infrastructure disruption**: In low- and middle-income countries, disruption of water supply could lead to direct losses of about $6 billion per year to firms, and between $88 billion - $153 billion a year for households (willingness to pay to avoid disruption). Additionally, there are second order costs associated with finding alternate sources of water and health issues (of the order 6-9 billion USD per year accounting for medical bills and missed income) (Hallegatte et al., 2019). In China, climate models project that increasing number of wastewater treatment plant assets face climate-induced flood hazards in both the near and far future, potentially affecting as many as 208 million users by 2050 (Hu et al., 2019).

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[7] Estimates based on the DIVA model that uses SSP 2, 3 and 5 and RCP 2.6, 4.5 and 8.5 in Nicholls et al. (2019) and investments from Ward et al. (2017). According to this study, uncertainty regarding socioeconomic changes and climate change is small compared with the uncertainty around construction costs and tolerance to risk.

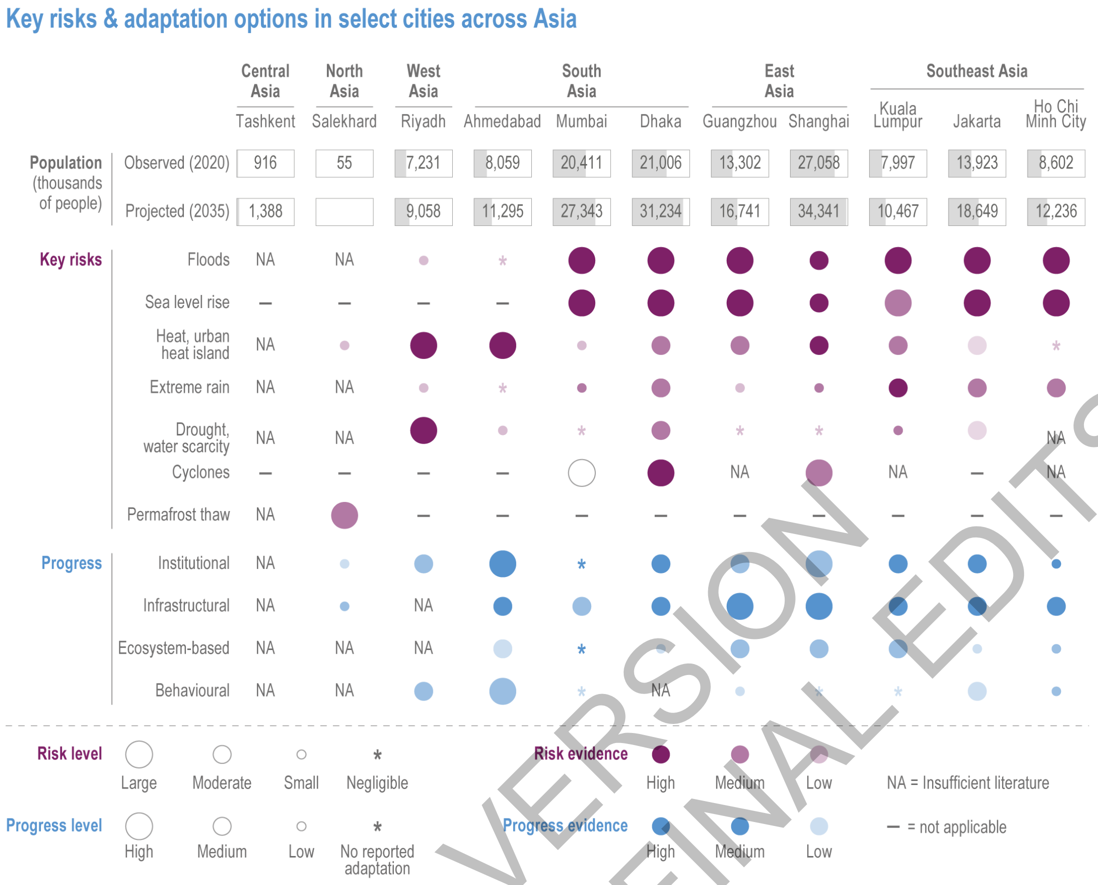

Figure 10.8: Risks and key adaptation options in select cities across Asia. Cities were chosen to ensure coverage of different sub-regions of Asia, represent different risk profiles, different city sizes (based on current population and projected growth) and reported progress on different adaptation strategies (infrastructural, institutional, ecosystem-based, and behavioural). Full line of sight in SM10.4.

10.4.6.4 Adaptation in cities across Asia

A review of urban adaptation in South, East and Central Asia found examples of 180 adaptation activities across 74 cities (Dulal, 2019). Most adaptation actions in Asia are in initial stages (Araos et al., 2016) with more (57%) focus on preparatory actions such as capacity building and vulnerability assessment and 43% implemented adaptation (see also SM10.4). Most adaptation actions were focused on disaster risk management (Dulal, 2019) though proportion of climate finance spent on disaster preparedness is not very high (as (Georgeson et al., 2016) show in megacities of Beijing, Mumbai, and Jakarta). Although key port cities across Asia are at high risk from climate impacts, it is estimated that adaptation interventions constitute only a small proportion of cities' climate efforts (Blok and Tschötschel, 2015).

Critically, most urban adaptation in South, East and Central Asia were reactive in nature (Dulal, 2019) (Singh et al., 2021b), raising questions on preparedness, proactive building of adaptive capacities, and whether present actions can lock certain cities/sectors into maladaptive pathways (Friend et al., 2014; Gajjar et al., 2018) (Salim et al., 2019) (Chi et al., 2020). China, India, Thailand, and Republic of Korea record the most number of urban adaptation initiatives, driven mainly by supportive government policies (Lee and Painter, 2015; Dulal, 2019). The number of actors working on urban adaptation is growing: in addition to national governments and local municipalities, civil society, private sector actors (Shaw, 2019), and transnational municipal networks (Fünfgeld, 2015) are emerging as important for knowledge brokering, capacity building, and financing urban adaptation (Karanth and Archer, 2014; Chu et al., 2017; Bazaz et al., 2018).

Adaptation options include (1) infrastructural measures such as building flood protection measures and sea walls, and climate-resilient highways and power infrastructure (Shaw et al., 2016b; Ho et al., 2017); (2) sustainable land use planning through zoning, developing building codes (Knowlton et al., 2014; Nahiduzzaman et al., 2015; Rahman et al., 2016; Ahmed et al., 2019b); (3) ecosystem-based adaptation measures such as protecting urban green spaces, improving permeability, mangrove restoration in coastal cities etc. (Brink et al., 2016; Fink, 2016; Yu et al., 2018d), (4) relocation and migration out of risk-prone areas (McLeman, 2019; Hauer et al., 2020; Maharjan et al., 2020); and (5) disaster management and contingency planning such as through early warning systems, improved awareness and preparedness measures (Shaw et al., 2016a). Asian cities are also focusing on institutional adaptation measures which cut across the five categories mentioned above such as through building capacity and local networks (Anguelovski et al., 2014; Friend et al., 2014; Knowlton et al., 2014), improving awareness (Knowlton et al., 2014), and putting local research and monitoring mechanisms in place (Lee and Painter, 2015) to enable adaptation.

10.4.6.4.1 Infrastructural adaptation options

The challenge of adapting infrastructure to climate change is two-fold: there are significant infrastructure deficiencies, especially in low income countries across Asia, and key infrastructures are at high risk due to climate change (Hallegatte et al., 2019; Lu, 2019). Infrastructural adaptation options in cities attempt to enable networked energy, water, waste, and transportation systems to prepare for and deal with climate risks better (Meerow, 2017) through interventions such as improved highways and power plants, climate-resilient housing, and improved water infrastructure, etc. (ADB, 2014).

- **Power infrastructure**: Adaptations in electricity systems include climate resilient power infrastructure, particularly essential for coastal megacities such as Manila, Mumbai, Bangkok, Ho Chi Minh City (Meerow, 2017; Duy et al., 2019), which double as regional economic hubs and are home to tens of millions of people within Asia. In the Philippines, solar panels at water pumping stations are installed to operate and maintain a minimal capacity to pump water if the electricity grid were to break down (Stip et al., 2019).

- **Water infrastructure:** Sustainable water supply and resource management are key to urban adaptation through improved water service delivery, wastewater recycling, and storm water diversion (Deng and Zhao, 2015; Xie et al., 2017; Yu et al., 2018d). Infrastructure-based adaptation options in urban water management include building water storage facilities, storm water management, and enhancing water quality improving permeability, managing runoff, and enabling groundwater recharge. One example is of Shanghai (China), where infrastructural and policy incentives come to together to enable adaptation: the city has been divided into 14 water conservancy zones, including 348 polder areas with 2517 km of dykes, 1499 pump stations, and 2203 sluices (Yu et al., 2018d). It also depends on a regional inundation control system, flood early warning system, and emergency plan to deal with flood risk and mitigate waterlogging (Chen et al., 2018e; Yu et al., 2018d). Another example is Ho Chi Minh City (Viet Nam), where, given significant increases in area at risk of flooding under climate change, the city has invested in storm sewer upgradation, dike works, improving drainage, and increasing height of road embankments and minor bridges (Storch and Downes, 2011; ADB, 2014; Ho et al., 2017). These infrastructural interventions were complemented by designing an early warning system to initiate flood mitigation procedures, such as isolating critical electrical and mechanical operating systems from water.

- **Built infrastructure**: Current built infrastructure adaptation interventions are mostly reactive (e.g., strengthening housing units, using sandbags during flooding, storing of food, evacuation) rather than preventive (e.g., relocation, building multi-storey and stronger housing units), mainly due to limited resources within most vulnerable households for investing in proactive measures (Francisco and Zakaria, 2019). For cities in North Asia seeing permafrost thawing, adequate land-use practices, permafrost monitoring, maintenance of infrastructure and engineering solutions (e.g. using thermosiphons) may temporarily offset negative effects of permafrost degradation in small, economically vital areas, but are *unlikely* to have an effect beyond the immediate areas (Shiklomanov et al., 2017b; Streletskiy, 2019). Importantly, thawing permafrost and GHG emissions create feedbacks where emissions amplify warming and drive additional thaw. Reducing these impacts through mitigation will reduce the need for adaptation significantly (Schaefer et al., 2014).

- **Infrastructure and technology:** Several infrastructural options employ technology such as smart meters to monitor water usage, technology-based service delivery but these are differentially adopted across Asian sub-regions with higher adoption across East Asia. Examples include the Yokohama smart city project in Japan, which has been smart eco-urbanism interventions since 2011 (e.g. energy saving and storage infrastructure, wastewater management, behavioural change towards renewable energy and low-carbon transportation) (IUC, 2019); the Tianjin Eco-city mega-project in China, which is testing a range of measures to meet urban sustainability goals in partnership with Singapore (ICLEI, 2014b; Blok and Tschötschel, 2015), development in New Songdo (Republic of Korea) which is experimenting with interventions such as embedded smart waste management (Anthopoulos, 2017), and national policy initiatives such as the Smart Cities Mission covering 100 cities in India (e.g. technology-enabled water, energy, and land management for urban agriculture in Nashik city) (ICLEI, 2014a). However, the efficacy of such measures, especially for larger sustainability and climate change goals remain to be seen (ICLEI, 2014b; ICLEI, 2014a; Caprotti et al., 2015; Anthopoulos, 2017).

Infrastructural measures alone are seldom effective in building urban resilience as seen in the examples of 2011 floods in Bangkok and 2005 typhoon in Manila (Duy et al., 2019) or projected estimates by Pervin et al. (2020) who find that structural interventions in existing drainage systems reduce flooding risk by 7-19% in Sylhet (Bangladesh) and Bharatpur (Nepal) but without proper solid waste management, area under flood risk could increase to 18.5% in Sylhet and 7.6% in Bharatpur in five years, rendering the infrastructural interventions ineffective over time. While in some cities, it is estimated that infrastructural adaptation through ‘hard’ flood protection strategies (e.g. storm-surge barriers and floodwalls) is more effective than institutional or ecosystem-based adaptation by 2100 (e.g.Du et al.in Shanghai), a hybrid approach where hard strategies protect from flood risk and soft strategies reduce residual risk from hard strategies is suggested (Du et al., 2020). In Japan, without adaptation, estimated damage costs of floods (caused by tropical cyclones, altered precipitation), by 2081-2100 under RCP2.6 will be 28% higher (compared to 1981-2000), rising to 57% higher under RCP8.5 (Yamamoto et al., 2021). With a combination of adaptation measures (such as land use control, piloti building, flood control measures), estimated damage costs can be reduced even below 1981-2000 levels and with a combination of mitigation and these adaptation measures, an estimated 69% reduction in flood damage costs are expected; demonstrating the importance of concerted and immediate climate action in reducing damage.

Infrastructural interventions can sometimes be maladaptive when assessed over longer time periods; e.g. the Mumbai Coastal Road (MCR) project aimed at reducing flood risk and protecting against SLR will potentially cause damages to intertidal fauna and flora and local fishing livelihoods (Senapati and Gupta, 2017); Jakarta’s Great Garuda project aimed at reducing flood risk is expected to *increase* flood risk for the poorest urban dwellers (Salim et al., 2019).

Figure 10.9: Effectiveness of select adaptation options in cities across Asia. Effectiveness is assessed based on the option's ability to reduce risk as reported in the literature.

10.4.6.4.2 Sustainable land use planning and regulation

Land use in cities impacts resource use (e.g. water, energy), risk (a function of population density, service provision, hazard exposure), and adaptive capacity, all of which influence efficacy of urban adaptation (de Coninck et al., 2018). Locally-suited land use planning and regulation (such as appropriate zoning or building codes, safeguarding land rights) can have adaptation co-benefits (Mitchell et al., 2015; Dhar and Khirfan, 2016), e.g. strict building regulations can protect urban wetlands and associated ecosystem services (Jiang et al., 2015); appropriate land zoning can safeguard green spaces, ensure improvements in permeability, and avoid new development in risk-prone locations (Duy et al., 2019); ensuring tenurial security or regularizing informal settlements can incentivise improvements to housing quality, thereby alleviating vulnerability of the most marginal (Mitchell et al., 2015).

Land tenure arrangements strongly shape urban dweller's vulnerability and their adaptive capacities (Roy et al., 2013; Michael et al., 2018). For example, in Khulna, Roy et al. (2013) find significant differences between the adaptive strategies of house owners and renters in low income settlements, a finding echoed in Bangalore (India) (Deshpande et al., 2018) and Phnom Penh (Cambodia) (Mitchell et al., 2015). In Riyadh (Saudi Arabia), land-based adaptation strategies include land zoning to control population and building density, demarcating environmental protection zones, and sub-urbanisation (Nahiduzzaman et al., 2015; Rahman et al., 2016). In many Asian cities, land subsidence control can serve as an adaptation strategy since it is estimated to significantly reduce relative sea-level rise (*high confidence*). This has an important implication in that subsidence control would be a good and a complementary measure to climate mitigation and climate adaptation in many coastal urban settings in Asia (Cao et al., 2021; Nicholls et al., 2021). Urban land use planning, if used proactively, can incentivise adaptation-mitigation synergies and avoid unintended negative consequences of urbanisation as Xu et al. (2019) show in Xiamen.

10.4.6.4.3 Ecosystem-based adaptation

The literature on urban Ecosystem-based Adaptation (EbA)[8], especially across Asia, has grown significantly since AR5 (Demuzere and al., 2014; Yao et al., 2015; Brink et al., 2016; Bazaz et al., 2018; de Coninck et

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[8] Ecosystem-based Adaptation (EbA) is defined by IPBES as the conservation, sustainable management and restoration of natural ecosystems to help people adapt to climate change (Glossary, 2019). In urban areas, EbA includes improving ecological structures (e.g. maintaining watersheds, forests, green roofs), ecological functions and processes (e.g. wetland functioning for flood protection), valuation measures (including monetary or non-monetary values to ecosystem service benefits), and investing in ecosystem management practices (i.e. enabling adaption co-benefits through the maintenance, preservation, restoration or creation of ecological structures) (Liu et al., 2014a; Brink et al., 2016). Thus, EbA adaptation actions include protecting urban green spaces, improving permeability, fostering urban

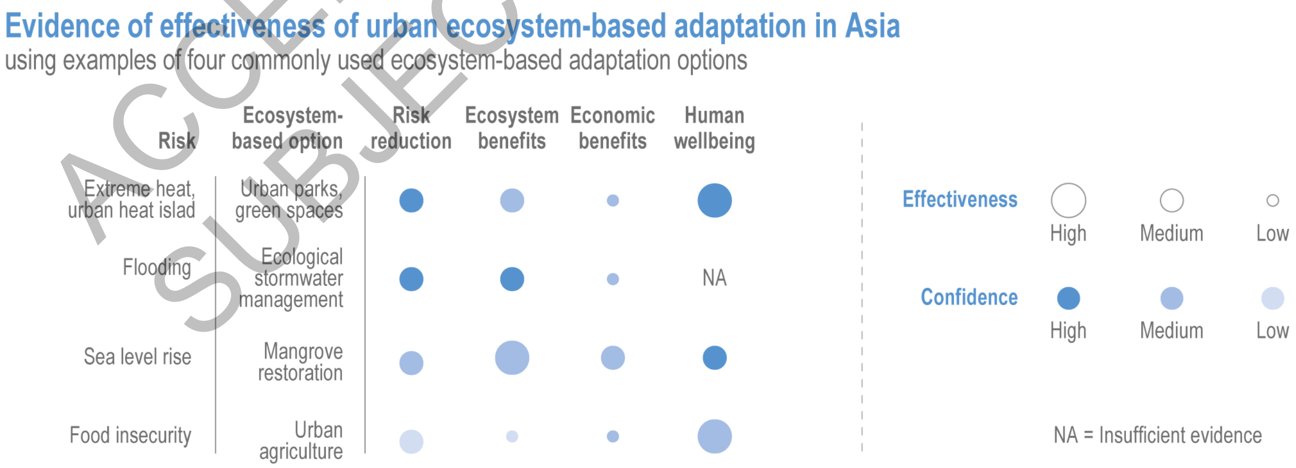
al., 2018; Ren, 2018). This growing literature reflects the wide recognition that infrastructural adaptation can often have ecological and social trade-offs (Palmer et al., 2015) and need to be complemented by ecosystem-based actions to manage risk more effectively (Du et al., 2020), build adaptive capacity, and in some cases, meet mitigation and sustainable development goals (Huang et al., 2020).

Illustrative examples of EbA in Asian cities include sponge cities in China for sustainable water management, flood mitigation, and minimising heat waves impact (Jiang et al., 2018; Yu et al., 2018d; Wang et al., 2019a; Zhanqiang et al., 2019), Singapore's Active, Beautiful, Clean Waters (ABC Waters) Programme, which uses bio-engineering approaches to protect river channels and prevent localised flooding, improve water quality, and create community spaces, and Dhaka's green roofs and urban agriculture (Zinia and McShane, 2018).

EbA approaches to manage floods, capture and store rainwater, restore urban lakes and rivers, and reduce surface run-off often blend infrastructural and ecosystem-based approaches. For example, in Tokyo (Japan), stormwater management is done by sophisticated underground infrastructure and an artificial infiltration stormwater system (Saraswat, 2016) (Mishra et al., 2019). China's Sponge City Program aims to reduce the impacts of flooding through low-impact development measures, urban greenery, and drainage infrastructure, such that 80 percent of urban areas reuse 70 percent of rainwater by 2020, which would help ensure the resilience of these cities to floods (Li et al., 2016b; Stip et al., 2019).

Case studies on urban EbA also raise equity concerns (*medium evidence, medium agreement*) such as interventions biased towards suburban areas in Guangzhou (China) (Zhanqiang et al., 2019); inadequate consideration of low-income, vulnerable populations (Blok and Tschötschel, 2015; Meerow, 2017) (Mabon and Shih, 2021); and low familiarity with interventions such as artificial wetlands, water retention ponds, green façade/walls can restrict inclusiveness (Zinia and McShane, 2018). Further, urban EbA is constrained by a range of factors such as inadequate institutional structures and processes for connecting different remits and knowledge systems and tradeoffs in landuse for different purposes (Mabon and Shih, 2021; Singh et al., 2021b).

EbA interventions are not uniform across Asian cities: in a global study on urban EbA, Brink et al. (2016) find Eastern Asia, India and Israel report most EbA interventions and there is variable and *limited evidence* on effectiveness and scalability (SM10.5). Using a risk framing (i.e. the extent to which an option reduces risk), urban EbA options in Asian cities score as being 'low to medium' effective (See SM10.5). However, when the assessment is expanded to assess the ecosystem benefits, economic impacts, and human wellbeing co-benefits of EbA, effectiveness increases. Figure 10.10 shows the evidence of effectiveness of EbA.


Evidence of effectiveness of urban ecosystem-based adaptation in Asia
using examples of four commonly used ecosystem-based adaptation options

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agriculture, mangrove restoration in coastal cities, improved wetland management, etc. (Doswald et al., 2014; Brink et al., 2016; de Coninck et al., 2018).

Figure 10.10: Evidence on effectiveness of ecosystem-based adaptation using examples of four commonly used EbA options[9]. Effectiveness is assessed qualitatively based on the evidence (for full line of sight see SM10.5) and is examined through four framings: potential to reduce risk (e.g. reduced exposure to hazard; reduced risk); benefits to ecosystems (through improved ecosystem health, high biodiversity); economic benefits (e.g. improved incomes, fewer man-days lost, better livelihoods); and human wellbeing outcomes (e.g. health, quality of living etc.). Darker shading signifies high effectiveness while lightest shade signifies low effectiveness of an EbA option (i.e. the option scores low on the indicator).

For example, urban agriculture is identified as offering multiple benefits such as mitigating emissions associated with food transportation from rural to urban areas, improving food and nutritional security, strengthening local livelihoods and economic development, improved microclimate, soil conservation, improved water and nutrient recycling, efficient water management (Padgham and Dietrich, 2015; Patil et al., 2019) but can potentially undermine ecosystem services through land use changes, water over-extraction or applying chemical fertilisers (Ackerman et al., 2014), expose smallholders to volatile markets and crops that are not consumed by farming households themselves, thus undermining food security, or increasing work burdens on women, and health externalities – e.g. through use of untreated wastewater, or rearing poultry and livestock in unsanitary conditions. There remain gaps on understanding the differential impacts of urban agriculture at different scales as well as its effectiveness in improving adaptive capacity at scale.

10.4.6.4.4 Migration and planned relocation

There is *medium evidence* with *high agreement* that climatic risks are exacerbating internal and international migration across Asia (IDMC, 2019) (Maharjan et al., 2020) **[Box 10.2].** In coastal cities, formal 'retreat' measures such as forced displacement and planned relocation (Oppenheimer et al., 2019) are commonly considered 'last resort' adaptation strategies once other infrastructural and ecosystem-based protect and accommodate strategies are exhausted (Haasnoot et al., 2019) (CCP 2.3). In contrast, migration (which can take various forms from seasonal, temporary mobility to circular or permanent movement), is a regular feature across Asian urban settlements (Maharjan et al., 2020)[Also see Box 10.2; MIGRATION CCB].

There is *robust evidence* (*medium agreement*) that across Asia, migration (and increasingly planned relocation) will continue to be a key risk management strategy, especially in low lying flood-prone cities (e.g. in SE and South Asia) and across drylands (e.g. in South and Central Asia) (Davis et al., 2018) (Ajibade, 2019) (Lincke and Hinkel, 2021). While there is insufficient evidence to project migration numbers under different warming levels, it is well established that migration as an adaptation strategy is not equally available to all (Ayeb-Karlsson, 2020) and climatic risks might reduce vulnerable populations' ability to move due to losses of assets, thus reinforcing existing inequalities and differential adaptive capacities (Singh and Basu, 2020);(Zickgraf, 2019) (Blondin, 2019; Cundill et al., 2021; Gavonel et al., 2021).

There is *medium evidence* (*low agreement*) about the effectiveness of migration and planned relocation in reducing risk exposure. Evidence on climate-driven internal migration shows that moving has mixed outcomes on risk reduction and adaptive capacity. On one hand, migration can improve adaptive capacity by increasing incomes and remittances as well as diversifying livelihoods (Maharjan et al., 2020). On the other, migration can expose migrants to new risks. For example, in Bangalore (India), migrants often face high exposure to localised flooding, insecure and unsafe livelihoods, and social exclusion, which collectively shape their vulnerability (Byers et al., 2018);(Singh and Basu, 2020). In Metro Manila (Philippines) and Chennai (India), planned relocations to reduce disaster risk have often exacerbated vulnerability, due to relocation sites being in environmentally sensitive areas, inadequate livelihood opportunities, and exposure to new risks (Ajibade, 2019; Jain et al., 2021) (Meerow, 2017).

10.4.6.4.5 Disaster management and contingency planning

There is rich case-based evidence across Asia on urban adaptation to extreme events with relatively more evidence on rapid-onset events such as cyclones and flooding than slow-onset disasters such as drought (Ray and Shaw, 2019; UNESCAP, 2019); (Singh et al., 2021a) see Box 10.7 on Loss and Damage). Overall, there

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[9] Assessing effectiveness of adaptation actions is challenging because of the lack of a clear goal that signifies effective adaptation, varied conceptual framings and metrics used to assess effectiveness, and low empirical evidence on effectiveness of implemented adaptation actions, (Singh et al., 2021a);(Owen, 2020).

has been a growing emphasis on 'build back better' interventions (Mannakkara and Wilkinson, 2013); (Hallegatte et al., 2018) that approach disaster management holistically through infrastructural solutions such as climate-resilient housing or sea walls and soft approaches such as strengthening livelihoods, developing early warning systems (EWS)[10], increasing awareness about disaster risks and impacts, and building local capacities to deal with them (Bhowmik et al., 2021). Notably, urban disaster management is effective when land use planning processes including greenfield development, zoning and building codes, and urban redevelopment are leveraged to reduce and/or avoid risk, thereby averting potential maladaptation (Kuhl et al., 2021).

There is relatively lower empirical evidence on how microenterprises and businesses are adapting to increased risk but recent examples in Mumbai, India (Schaer and Pantakar, 2018) and Kratie, Cambodia (Ngin et al., 2020) suggest that businesses primarily adopt temporary and reactive responses rather than long-term, anticipatory adaptation measures.

A review of innovative disaster risk reduction (DRR) approaches notes the use of GIS and drone-based technologies for mapping risk exposure and impacts, mobile-based payments for post-disaster compensation, to transnational initiatives and learning networks on urban resilience (Izumi et al., 2019). Further, technology-based innovations such as using big data (Yu et al., 2018b), improved warnings through mobile phones, or mobilising relief through social media (Carley et al., 2016) are proving effective for disaster preparedness, relief and recovery. Community-based DRR is consistently ranked as most effective for its role in transforming DRR towards being more context-relevant and inclusive. Ecosystem-based disaster risk reduction (EbDRR) is also gaining prominence and includes strategies such as mangrove plantation and rejuvenation in vulnerable coastal areas. Nature-based solutions for flood protection and reducing drought incidence have emerged as an alternative to costlier 'hard' infrastructure (Rozenberg and Fay, 2019); (UN-Water, 2018); (Zevenbergen et al., 2018). Some cities are also reporting adaptation to heat risk. For example, Ahmedabad (India) has pioneered preparedness for extreme temperatures and heat waves by developing annual Heat Action Plans, building regulations to minimise trapping heat, advisories about managing heat stress, and instituting cool roofs policy (Ahmedabad Municipal, 2018).

Financing, regulations, and institutional processes have a significant role to play in incentivising disaster risk reduction and resilience in large-scale city-level built infrastructure by the private sector and other actors. Currently there are gaps in these mechanisms, leading to infrastructure development in disaster-prone areas, increasing exposure to people, property, economy and systems (Jain, 2013). Both firms and governments need to take disaster risks into consideration in supply-chain management to avoid disruptions and subsequent negative effects (Abe and Ye, 2013). There are several institutional challenges faced during DRR and CCA implementation including overlapping efforts and inefficient use of scarce resources due to inappropriate funding mechanisms, a lack of coordination and collaboration, a lack of implementation and mainstreaming, scale mismatches, poor governance, the socio-political-cultural structure, competing actors and institutions, lack of information, communication, knowledge sharing, and community involvement, and policy gaps (Seidler et al., 2018; Islam et al., 2020).

10.4.6.5 Enabling urban adaptation across Asia

There is growing empirical evidence of conditions enabling and constraining urban adaptation (Table 10.3) with relatively more literature from South, South East, and East Asia. Governance and capacity-related deficits are repeatedly identified as significant barriers to urban adaptation (*robust evidence, high agreement*) and interact with financial and informational constraints to mediate adaptation action.

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[10] The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or Indigenous knowledge. EWS are also considered for ecological applications e.g., conservation, where the organisation itself is not threatened by hazard but the ecosystem under conservation is (an example is coral bleaching alerts), in agriculture (for example, warnings of ground frost, hailstorms) and in fisheries (storm and tsunami warnings). (IPCC, 2018a)

Table 10.3: Barriers and enablers to adaptation across Asian cities.

Indicator	As an enabler	As a barrier
Governance and planning	**National policy directives** to adapt. e.g. strong national climate commitments in China, India, and Thailand (Dulal, 2019); and dedicated public-private councils on climate change in Seoul, Republic of Korea (Lee and Painter, 2015). Participatory planning, **co-producing solutions**, and engaging multiple stakeholders. E.g. Surat (Anguelovski et al., 2014; Karanth and Archer, 2014; Chu et al., 2017), Guwahati (Archer et al., 2014) in India; Bandar Lampung and Semarang in Indonesia (Archer et al., 2014); Seoul in Republic of Korea (Lee and Painter, 2015) **Devolving decision-making** to city governments (ADB, 2013) and strong **political leadership** helps institutionalising adaptation programs (Anguelovski et al., 2014; Friend et al., 2014; Lee and Painter, 2015), e.g. in Moscow (Russia) where the city mayor has spearheaded climate action (van der Heijden et al., 2019) **Mainstreaming climate adaptation** in city plans (UN-HABITAT and UNESCAP, 2018)	**Low accountability and transparency** in planning processes with inadequate spaces for public dialogue (Friend et al., 2014) and limited accountability to the most economically and politically marginalised people within cities (Garschagen and Marks, 2019). 65% of 180 urban adaptation interventions across Asia are **reactive** in nature (Dulal, 2019) thus missing opportunities for risk prevention and preparedness (Francisco and Zakaria, 2019). **Lack of forward-looking, learning-oriented processes** constrain adaptation with short-term development priorities often overshadowing long-term climate action needs (Friend et al., 2014; de Leon and Pittock, 2017; Gajjar et al., 2018; Khaling et al., 2018) (Garschagen and Marks, 2019; Jain et al., 2021). **Fragmented governance, lack of mainstreaming** between CCA and DRR (Fuhr et al., 2018; Khaling et al., 2018) E.g. in Vietnam, Thailand, Indonesia (Friend et al., 2014) and Metro Manila (Philippines) (Meerow, 2017)
Information	Knowledge sharing through **transnational municipal networks** such as C40, ACCRN, A-PLAT (Fünfgeld, 2015) City-level knowledge creation and knowledge transfer institutions (Lee and Painter, 2015)	**Data gaps** on projected climate risks and impacts in certain sub-regions and small settlements (Revi et al., 2014) **Numerous tools** for assessing vulnerability, adaptation planning (Nordgren et al., 2016)
Technology, infrastructure	Early warning systems, climate information, modelling studies inform adaptation decision-making (Reed et al., 2015; Singh et al., 2018a)	Inadequate **regional downscaled data** at city-scale (ADB, 2013; Khaling et al., 2018) Inadequate **cost benefit analyses** of different adaptation strategies (Khaling et al. 2018)
Capacity and awareness	A focus on **learning, experimentation, awareness and capacity building**, leads to more sustained, legitimate, and inclusive adaptation (ADB, 2013; Anguelovski et al., 2014); Reed et al. (2015)	Limited access and capacity to use risk assessment tools (ADB, 2013; Shaw et al., 2016b)
Finance	**Dedicated adaptation financing**. E.g. in Beijing, adaptation spending is 0.33% of city's GDP (Georgeson et al., 2016); steering international and local funding to leverage adaptation benefits in urban development programs such as in Surat (India) (Cook and Chu, 2019); mainstreaming climate adaptation into development programming to leverage developmental finance for adaptation action (Cuevas et al., 2016; Narender and Sethi, 2018).	Inadequate **adaptation funding**, lack of **financial devolution** to city governments (Fuhr et al., 2018) (Garschagen and Marks, 2019).

10.4.7 Health and Wellbeing

Climate change is increasing risks to human health in Asia by increasing exposure and vulnerability to extreme weather events such as heat waves, flooding and drought, air pollutants, increasing vector-borne and water-borne diseases, undernutrition, mental disorders and allergic diseases (*high confidence*). Sub-regional diversity in socio-economic and demographic context (e.g., aging, urban vs agrarian society, increasing population vs reduced birth rate, high income vs low to middle income) and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia (*high confidence*).

10.4.7.1 Observed Impacts

High temperatures affect mortality and morbidity in Asia (*high confidence*). In addition to all-cause mortality (Dang et al., 2016; Chen et al., 2018e), deaths related to circulatory, respiratory, diabetic (Li et al., 2014b) and infectious disease (Ingole et al., 2015), as well as infant mortality (Son et al., 2017) are increased with high temperature (*high confidence*). Increased hospital admissions (Giang et al., 2014; Lin et al., 2019) and ambulance transport (Onozuka and Hagihara, 2015) coincide with increased ambient temperature (*high confidence*). Heat waves are particularly detrimental to all-cause and cause-specific mortality (Chen et al., 2015a; Lee et al., 2016; Guo et al., 2017b; Yin et al., 2018). Both rural and urban populations are vulnerable to heat-related mortality (Ma et al., 2015; Chen et al., 2016a; Wang et al., 2018a). Individuals with lower degrees of education and socio-economic status, older individuals and individuals living in communities with less green space are more susceptible to heat-related mortality (*high confidence*) (Yang et al., 2012a; Huang et al., 2015b; Seposo et al., 2015; Son et al., 2016; Kim and Kim, 2017). These heat effects have been attenuating over recent decades in East Asian countries, although the driving force behind this remains unknown (*high confidence*) (Chung et al., 2017c; Chung et al., 2018).

Rising ambient temperatures accelerates pollutant formation reactions and may modify air-pollution related health effects (*medium confidence*). Higher temperatures are associated with increased effects of ozone on mortality (Shi et al., 2020). Climate change causes intensified droughts and greater wind erosion resulting in increased intensity and frequency of sand and dust storms (Akhtar et al., 2018). Mortality and hospital admissions for circulatory and respiratory diseases are increased after exposures to Asian dust events (*high confidence*) (Hashizume et al., 2020). El Niño has a major influence on weather patterns in various regions. For example, it causes dry conditions that sometimes result in forest fires and trans-boundary haze that increased all-cause mortality in children by 41% in Malaysia (Sahani et al., 2014).

Ambient temperature is associated with the risk of an outbreak of mosquito-borne disease in South and Southeast Asia (*high confidence*) (Servadio et al., 2018). Warmer climates are associated with a higher incidence of malaria (Xiang et al., 2018). Moderate rainfall also promotes malaria infection, while excessive rainfall decreases the risk of malaria (Wu et al., 2017b). El Niño intensity is positively associated with malaria incidence in a single year in India (Dhiman and Sarkar, 2017). The duration and survival rate of dengue mosquito development, mosquito density, mosquito biting activity, mosquito spatiotemporal range and distribution, and mosquito flying distance are all affected by temperature (*high confidence*) (Li et al., 2018b). Temperature, precipitation, humidity and air pressure are major weather factors associated with dengue fever transmission (*high confidence*) (Sang et al., 2014; Choi et al., 2016; Xu et al., 2017).

Climate change alters the hydrologic cycle by increasing the frequency of extreme weather events such as excess precipitation, storm surges, floods and droughts (*high confidence*). Water-borne diseases such as diarrhea, leptospirosis and typhoid fever can increase in incidence following heavy rainfall, tropical cyclones and flooding events (*high confidence*) (Deng et al., 2015; Levy et al., 2016; Li et al., 2018b; Matsushita et al., 2018; Zhang et al., 2019b). Droughts can cause increased concentrations of pathogens, which overwhelm water treatment plants and contaminate surface water. A positive association between ambient temperature and bacterial diarrhea has been reported, compared with a negative association with viral diarrhea (Carlton et al., 2016; Wang et al., 2018c).

Asia has the highest prevalence of undenourishment in the world, which was 11.4% in 2017, representing more than 515 million people. Southeast Asia has been affected by adverse climate conditions such as floods and cyclones, with impacts on food availability and prices (FAO, 2018d). Crop destruction due to tropical cyclones can include salt damage from tides blowing inland (*medium confidence*) (Iizumi and Ramankutty, 2015). Sea level rises result in intrusion of saline water into the coastal area of Bangladesh and people living in these areas face an increased risk of hypertension resulting from high salt consumption (Scheelbeek et al., 2016).

Weather conditions have been linked to mental health. High temperatures increase the risk of mental problems including mental disorders, depression, distress and anxiety in Vietnam (Trang et al., 2016), Hong Kong, China (Chan et al., 2018) and Republic of Korea (Lee et al., 2018d). In addition, high temperatures are reported to increase the risk of mortality from suicide in Japan, Republic of Korea, Taiwan, Province of China (Kim et al., 2016c), India (Carleton, 2017) and China (Luan et al., 2019). Extreme weather events such as storms, floods, hurricanes and cyclones increase injuries and mental disorders (post-traumatic stress disorder (PTSD) and depressive disorders) (Rataj et al., 2016), thereby negatively affecting well-being (*high confidence*).

Higher temperatures and increased CO2 elevate the level of allergens such as pollen, which can result in increased allergic diseases, such as asthma and allergic rhinosinusitis. The association between variations in ambient temperature and the occurrence of asthma has been reported in several Asian countries/regions such as Japan (Yamazaki et al., 2015), Republic of Korea (Kwon et al., 2016), China (Li et al., 2016a) and Hong Kong, China (*medium confidence*) (Lam et al., 2016).

10.4.7.2 Projected Impacts

Climate change is associated with significantly increased mortality (*high confidence*). Figure 10.11 shows projected health impacts due to climate change in Asia. The global estimates of excess deaths due to malnutrition, malaria, diarrhea and heat stress are approximately 250,000 deaths per year in 2030-2050 under the medium-high emissions scenario, assuming no adaptation (World Health Organization, 2014). The impacts are expected to be greatest in South, East and Southeast Asia. Another projection showed that the change in heat-related deaths is largest in Southeast Asia, which was 12.7% increase in the end of the century under a high-emission scenario (Gasparrini et al., 2017). As the proportion of older individuals in the population rises, the number of years lost due to disability increases more steeply (Chung et al., 2017b). In the 2080s, the number of annual temperature-related deaths is estimated to reach twice that in the 1980s in China (Li et al., 2018c). Over a 20-year period in the mid-21st century (2041–2060), the incidence of excess heat-related mortality in 51 cities in China was estimated to reach 37,800 (95% CI: 31,300–43,500) deaths per year under RCP8.5 (Bazaz et al., 2018).

Increased concentrations of fine particulate matter and ozone influenced by extreme events such as atmospheric stagnations and heat waves are projected to result in additional 12,100 and 8,900 deaths per year due to fine particulate matter and ozone exposure, respectively in China in the mid-century under RCP4.5 (Hong et al., 2019a). Excess ozone-related future premature deaths is noticeable in 2030 in East Asia and India for RCP8.5 (over 95% of global excess mortality) (Silva et al., 2016).

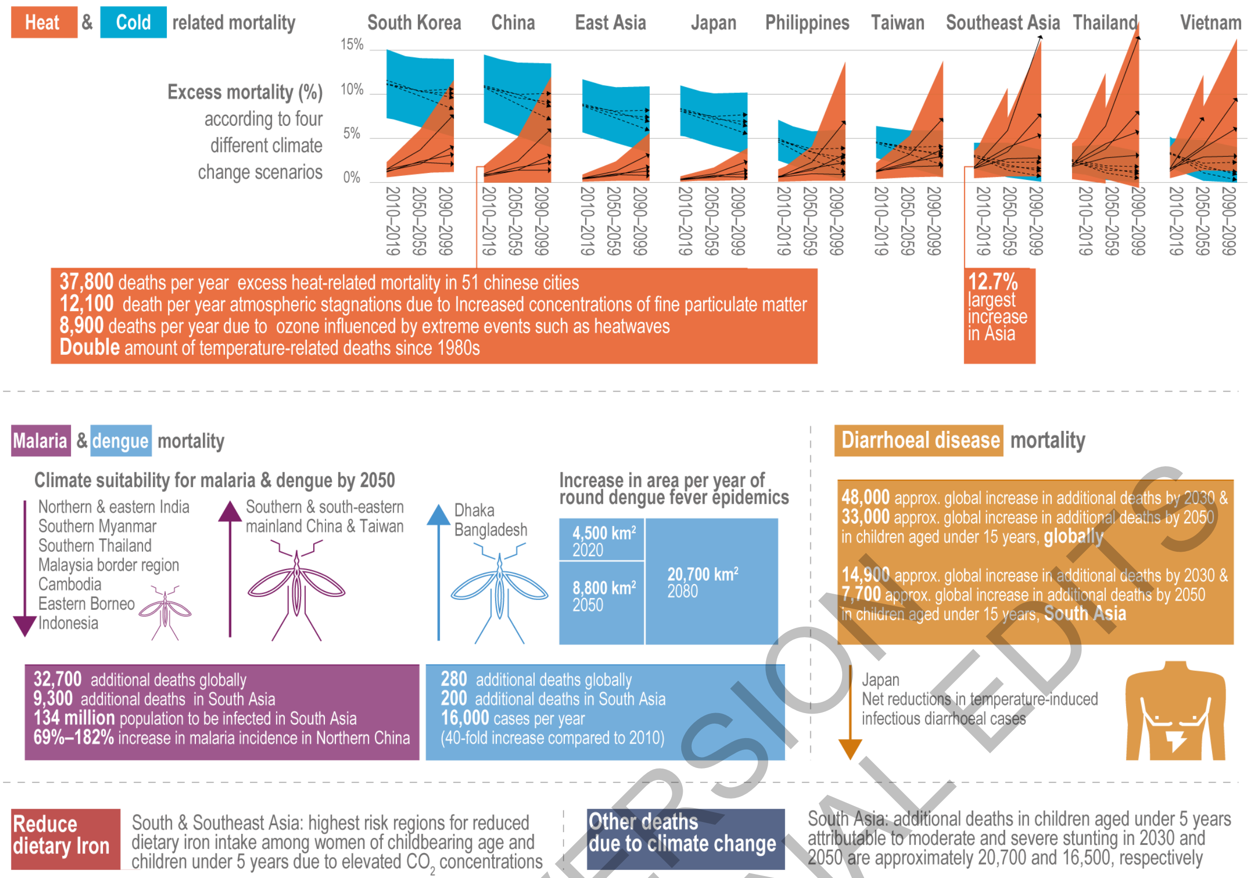

Figure 10.11: Projected health impacts due to climate change in Asia

The global estimates for increases in malaria and dengue deaths (annual estimates) are approximately 32,700 and 280 additional deaths, respectively, in 2050 under the medium-high emissions scenario (World Health Organization, 2014). Among these additional deaths, 9,300 and 200 deaths, respectively, are projected to occur in South Asia. The population at risk of malaria infection is estimated to increase by 134 million by 2030 in South Asia under the medium-high emissions scenario, considering socio-economic development. If no actions are taken, malaria incidence in northern China is projected to increase by 69%–182% by 2050 (Song et al., 2016). Another study suggested a decrease in climate suitability for malaria in northern and eastern India, southern Myanmar, southern Thailand, the Malaysia border region, Cambodia, eastern Borneo and Indonesia by 2050 (Khormi and Kumar, 2016). By contrast, climate suitability for malaria is projected to increase in the southern and south-eastern mainland of China and Taiwan, Province of China (Khormi and Kumar, 2016).

Dengue incidence is projected to increase to 16,000 cases per year by 2100 in Dhaka, Bangladesh, if ambient temperatures increase by 3.3°C without any adaptation measures or changes in socio-economic conditions (Banu et al., 2014). This would represent an increase in incidence of over 40-fold compared with 2010. Higher numbers of dengue fever cases are projected to occur under RCP 8.5 than RCP2.6 in China (Song et al., 2017). Compared with the average numbers in 1997–2012, the annual number of days suitable for dengue fever transmission in the 2020s, 2050s and 2080s will increase by 15, 25 and 40 days, respectively, in south China under RCP8.5. In addition, areas in which year-round dengue fever epidemics occur will *likely* increase by 4500, 8800 and 20,700 km^2 in the 2020s, 2050s and 2080s, respectively, under RCP8.5 (Nahiduzzaman et al., 2015).

The global estimates for increases in deaths due to diarrheal disease (annual estimates) in children aged under 15 years in 2030 and 2050 are approximately 48,000 and 33,000 additional deaths, respectively, under the medium-high emissions scenario (World Health Organization, 2014). Among these additional deaths, 14,900 and 7,700 deaths, respectively, are projected to occur in South Asia. An updated projection with pathogen-specific approach estimated 25,000 additional annual diarrheal deaths in Asia in 2080-2095 under the high emission scenario (Chua et al., 2021), while in some countries such as Japan, net reductions in temperature-induced infectious diarrheal cases were estimated, because viral infections are dominant in these countries during the cold season (Onozuka et al., 2019).

South and Southeast Asia are projected to be among the highest risk regions for reduced dietary iron intake among women of childbearing age and children under 5 years due to elevated CO2 concentrations (*medium confidence*) (Smith and Myers, 2018). The estimated number of additional deaths due to climate change in children aged under 5 years attributable to moderate and severe stunting in 2030 and 2050 are approximately 20,700 and 16,500, respectively, in South Asia, under the medium-high emissions scenario (World Health Organization, 2014). In Bangladesh, due to climate change, river salinity is projected to be increased in coastal and freshwater fishery communities leading to significant shortages of drinking water in the coastal urban areas (Dasgupta et al., 2014c).

10.4.7.3 Adaptation Options/Co-benefits

The health co-benefits of greenhouse gas mitigation measures in energy generation have been reported to reduce disease burden. In China, the implementation of greenhouse gas policies would reduce the air pollution associated disease burden by 44% in 2020 under the Integrate Carbon Reduction scenario compared with the business as usual scenario (Liu et al., 2017b). Transition to a half-decarbonised power supply for the residential and transport sectors would avoid 55,000-69,000 deaths in 2030 compared with the business as usual scenario (Peng et al., 2018). A shift in travel modes from private motor vehicles to the use of mass rapid transit lines is estimated to reduce CO2 equivalent emissions by 6% in Greater Kuala Lumpur and bring important health co-benefits to the population (Kwan et al., 2017). The 25 measures developed for reducing air pollution levels in Asia and the Pacific would reduce carbon dioxide emissions in 2030 by almost 20% relative to baseline projections and decrease warming by 0.3°C by 2050 which could eventually reduce heat-related excess deaths in the region (UNEP, 2019). The 25 measures include conventional emission controls focusing on emissions that lead to the formation of fine particulate matter (PM2.5), next-stage air-quality measures for reducing emissions that lead to the formation of PM2.5 and are not yet major components of clean air policies in many parts of the region, and measures contributing to development priority goals with benefits for air quality. Health co-benefits outweigh mitigation costs in Republic of Korea up to 2050 (Kim et al., 2020). Low-carbon pathways consistent with the 2 ◦C and 1.5 ◦C long-term climate targets defined in the Paris Agreement are associated with the largest health co-benefits when coordinated with stringent air pollution controls in Asia followed by Africa and Middle East (Rafaj et al., 2021).

Strategies to increase energy efficiency in urban built environment by compact urban design and circular economy policies can reduce greenhouse gas emissions and reap ancillary health benefits; compared to conventional single-sector strategies, national CO2 emissions can be reduced by 15%–36%, and the annual deaths from 25,500 to 57,500 are avoidable from air pollution reduction in 637 Chinese cities (Ramaswami et al., 2017). In a city in China, the existing mitigation policies (e.g., promotion of tertiary and high-tech industry) and the one adaption policy (increasing resilience) increased co-benefits for wellbeing (Liu et al., 2016a).

Changing dietary patterns, particularly reducing red meat consumption and increasing fruit and vegetable consumption, contributes to the reduced greenhouse gas emissions, as well as premature deaths. The adoption of global dietary guidelines was estimated to avoid 5.1 million deaths per year relative to the reference scenario, in which the largest number of avoidable deaths occurred in East Asia and South Asia, and greenhouse gas emissions would be reduced most in East Asia (Springmann et al., 2016). In China, dietary shifts to meet the national dietary reference intakes reduced the daily carbon footprint by 5-28% depending on scenario (Song et al., 2017). In India, the optimised healthy diets (e.g., lower amounts of wheat, and increased amounts of legumes) could help reduce up to 30% water use per person for irrigation and reduce diet-related greenhouse gas emissions. This would result in 6,800 life-years gained per 100,000 population in 2050 (Milner et al., 2017).

10.5 Adaptation Implementation

10.5.1 Governance

10.5.1.1 Points of departure

Climate change governance is characterised by a scalar/stakeholder turn which includes (i) acknowledgement of the importance of both sub-national and transnational-regional scales along with the global scale; (ii) involvement of diverse stakeholders in decision-making systems; (iii) reliance on bottom-up architectures of governance that are supported by the framework given by the SDGs; (iv) emphasis on developmental and environmental co-benefits; (v) recognition of diverse experiences of marginalisation and social stratification, and their impacts on participation in governance-related activities; and (vi) greater decentralisation and strengthening of local institutions.

10.5.1.2 Findings

In order to facilitate local adaption, especially in a context characterised by regional diversity and spatial-temporal variation, climate adaptive governance invites greater policy attention to institution building (formal and informal) at multiple scales and across sectors, (Mubaya and Mafongoya, 2017). Ecosystem-based incremental adaptation (EbA) approach underlines the advantage of drawing upon ecosystem services for reducing vulnerabilities, increasing resilience of communities to adapt to climate change, and minimising threats to social systems and human security, provided climate change remains below 2°C or, better yet, below the 1.5°C of global warming (Barkdull and Harris, 2018).

Focus on multi-level governance, both below and beyond the state level, is steadily growing (Jogesh and Dubash, 2015; Jörgensen et al., 2015; Beermann et al., 2016). Discernible diversity across political systems and sectors in Asia notwithstanding, issues relevant to multilevel climate governance includes interplay between top-down national initiatives, which stem from supra-national, regional and sub-regional levels. In case of India, national climate governance has proliferated beyond the National Action Plan on Climate Change (NAPCC) to include State Action Plans on Climate Change (SAPCC) of over 28 states and union territories, demonstrating graphically the shared ‘co-benefit’ in terms of creating greater space for innovation and experimentation (Jörgensen et al., 2015).

In Japan’s “Climate Change Adaptation Act”, enacted by the Japanese Diet in June 2018, the national government shall formulate a National Action Plan (NAP) to promote adaptation in all sectors. Climate change adaptation act of Japan recommends prefectures and municipalities to designate “local climate change adaptation center (LCCAC)” as local climate change data collection and provision center, to provide more locally specific information and support for adaptation planning at the level of local municipalities. The Japanese government, in partnership with the private sector, has formulated a new comprehensive strategy, named Society 5.0, which aims at devising a number of technological innovative solutions (Mavrodieva and Shaw, 2020).

Significantly, the co-benefit concept for international city partnerships, comparative analysis of the challenges, capabilities and limitations of urban areas in Asia with regard to climate change adaptation governance remains under researched (Beermann et al., 2016).

In case of Vietnam, especially at district and commune levels, where the policy capacities in hierarchical governance systems to deal with climate change impacts are generally constrained, the value of clear legal institutions, provision of financing for implementing policies, and the training opportunities for governmental staff has been well demonstrated (Phuong et al., 2018b). A key finding is that any effort to support local actors (i.e. smallholder farmers) should ensure augmentation of policy capacity through necessary investments.

In case of China, a combination of market-based policies, emissions trading systems, growing number of environmental NGOs and international network appears to be serving as an important tool for climate governance, (Ramaswami et al., 2017; Wang et al., 2017b). Public private partnership (PPP) too is receiving increasing focus, especially with regard to climate related cost–effective and innovative infrastructure projects. In the absence of major investments in resilience, climate change may force up to 77 million people into poverty trap by 2030 (WorldBank, 2016). As seen in the case of Japan, most of the countries in Asia face the challenge of contractual allocation of risks associated with natural hazards and climate change between the public and private sectors and its long-term management in the face of uncertainty. Risk sharing, therefore could be addressed by clear definition and allocation (WorldBank, 2017). Given that in Asia, especially Singapore, China, Japan and Korea, water sector is a target of industrial and technology policy, PPPs could prove to be mutually beneficial. As a middle ground, key findings of a study on Indonesia (Yoseph-Paulus and Hindmarsh, 2016), underline the importance of building, sustaining and augmenting local capacity by addressing inadequacies with regard to resource endowment and capacity building, public awareness about climate change, government–community partnerships, vulnerability assessment, and providing inclusive decision making space to Indigenous Knowledge systems and communities.

In agriculture sector, farmers in Asia are adapting to climate change at the grass root level (Tripathi and Mishra, 2017). A recent, comprehensive and systematic review (Shaffril et al., 2018) shows how farmers in diverse sub-regions of Asia have adopted diverse adaptation strategies through management of crop, irrigation and water, farms, finances, physical infrastructure and social activities. Much more qualitative research on farmers' perceptions and decision-making about adaptation practices is needed in order to capture their location-specific priorities and diverse understanding of risks and threats. A study of Vietnamese smallholder farmer's perception of their current and future capacity to adapt to climate change (Phuong et al., 2018a) found considerable difference between farmers in crop production and livestock production in terms of their motives behind adopting particular planned adaptation options.

A study on farmers' awareness of and adaptation to climate change in the dry zones of Myanmar, critically dependent on agriculture, indicates how those in the frontline of the adverse effects of climate change are steadily abandoning the common sesame/groundnut cropping pattern, and trying to adapt to risks and uncertainties with the aid of conventional agricultural practices such as rainwater-collection, water-harvesting techniques, and resorting to the traditional weather forecasting techniques for weather prediction. Similarly, a case study of the Gandak Basin in Nepal shows that incorporation of local knowledge into agricultural practices and weather warning systems works best when coupled with multiple sources of information based on a method of triangulation. This also intersects with gender outcomes, where women frequently receive information from the men of their households, rather than directly from state institutional sources (Acharya and Prakash, 2019). Climate change adaptive governance is facilitated by improved cross-scalar and cross-sectoral cooperation, exchange of information and experiences and best practices (Smith et al., 2014; Watts et al., 2015; Gamble et al., 2016; Gilfillan et al., 2017).

An integrated approach informed by science, which examines multiple stressors along with Indigenous Knowledge, appears to be of immense value (Elum et al., 2017). A study on Pakistan concludes that poor agricultural communities are among the worst victims of climate change (Ali and Erenstein, 2017) and that farmers who are younger, better educated, belonging to joint families and possessing more landholdings are *likely* to adapt sooner and better. Correspondingly, this category achieved higher levels of income and food security. The climate-development nexus suggests that climate change adaptation practices at farm level can have significant development outcomes, besides reducing risk posed by changing weather patterns. Central to climate change adaptation (CCA) process is the growing recognition of the role that institutions play in both hierarchical setting and across different scales to influence implementation of CCA in diverse areas of governance across social and political domains. Cuevas (2018) highlights the usefulness of mainstreaming CCA into local land use planning in Albay, Philippines, by involving networks of interacting institutions and institutional arrangements for overcoming obstacles that are potentially counterproductive and conflictual.

As noted by AR5 (IPCC, 2014a), research on issues related to both climate change impacts on livestock production --demand for which is expected to double by 2050 in a world of 10 billion-- and policy choices with regard to adaptation, especially at the local scale, is still limited but in progress (Rojas-Downing et al., 2017). The promise of diversification of livestock animals (within species), crop diversification, and transition to mixed crop-livestock systems needs to be further explored. A study of livestock farmers in Pakistan shows that risk coping mechanisms such as purchasing livestock insurance and increasing land areas for fodder are far more rewarding policy options in comparison to selling livestock and migration. Relatedly, the association of migration with adaptation measure is context specific and involves a number of factors pertaining to the socio-economic circumstances of vulnerable agricultural groups in countries like India and Bangladesh (Ojha et al., 2014). In the 2010 United Nations Framework Convention on Climate Change's Cancun Adaptation Framework, migration was recognised as a form of adaptation that should be included in a country's long-term adaptation planning where appropriate (Paragraph 14f).

Also, agricultural climate adaptation policy targeting livestock farmers in rural areas is *very likely* to benefit from better education and awareness and increased access to extension services among livestock farmers on climate risk-coping choices and strategies (Rahut and Ali, 2018). In Myanmar, the lack of adequate agricultural extension strategies has had a negative impact on adaptation outcomes in what is labelled the central dry zone. Farmers' perceptions of climate change contribute to a comprehensive understanding of the context where they identify deforestation and related activities as the main culprits. Their adaptive methods include agricultural land preparation and crop rotation practices in addition to rainwater harvesting techniques (Swe et al., 2015). A study of vulnerable areas in Bangladesh (Alam et al., 2017), has shown that with policy support livestock rearing can prove to be a viable and substitute for crop production in areas prone to riverbank erosion. Carefully worked out partnerships between government organisations and NGOs can come to the rescue of poor farmers and their precarious households by providing information about best practices of local adaption strategies, including credit options with various institutions and creating an enabling environment for the promotion of agro-based industries. A study in community forestry in the Indian Himalayas (Gupta and Koontz, 2019) has shown how the synergies and successful partnerships could evolve between government and NGOs in local forest governance, with the former providing technical and financial support, and the latter directing the communities to those resources and in the making up for each other's limitations and thus enabling and augmenting community efforts in forest governance.

A study of Pakistan (Ali and Erenstein, 2017) shows that factors such as enhanced awareness about various climate risk coping strategies, better education and agricultural extension services, augmenting farm-household assets, lowering the cost of adaptation, improving access to services and alternative livelihoods, and providing support to poorer households appear to have paid rich dividends. Countries such as Bhutan and Sri Lanka have included provisions for 'climate-smart agriculture' in their NDCs (Amjath-Babu et al., 2019).

In the domain of forest adaptive governance, ever since the introduction of Reducing Emissions from Deforestation and forest Degradation plus (REDD+) at (COP 13) 2007 in Bali, the Indonesian experience suggests that some of the major challenges include curbing emissions, changes in cross-sectoral land-use as well as practice within forestry. and lack of effective, efficient and equitable implementation of diverse forest governance practices. The issue of how forest governance institutions are conceived and managed, both at national and sub-national levels, involving state, private sector and civil society, also needs serious attention (Agung et al., 2014).

In an example from Nepal, Clement (2018) shows that deliberative governance mechanisms can create the space for alternative framings of climate change to take a hold in ways that are cognisant of both the local and global contexts; this moves beyond a dependence on techno-managerialism in the construction of solutions, where local governance solutions can support institutional changes. The possibilities more incorporating deliberative methods into wider governance architecture are also expanded through an acknowledgment of the role of social learning; this is observable in the multi-stakeholder involvement that this approach fosters in regions of South Asia such as the Brahmaputra River Basin (Varma and Hazarika, 2018). Additionally, recent studies have reconfirmed the importance of linking Indigenous Knowledge with the scientific knowledge of climate change in diverse regions of the globe, including Asia and Africa (Hiwasaki et al., 2014; Etchart, 2017) (Taremwa et al., 2017) (Vadigi, 2017; Apraku et al., 2018; Inaotombi and Mahanta, 2018; Makondo and Thomas, 2018) for building farmers' resilience, enhancing climate change adaptation, ensuring cross cultural communication, promoting local skills, drawing upon Indigenous Peoples' intuitive thinking processes and geographical knowledge of remote areas.

A study of Sylhet Division in Bangladesh, deploying knowledge quality assessment' (KQA) tool found significant co-relation between a narrow technocratic problem framing, divorced from traditional knowledge strongly rooted in local socio-cultural histories and relatively low project success due to skewed risk-based calculation disconnected to the ground realities (Wani and Ariana, 2018) (Haque et al., 2017) while highlighting the vulnerability of the Bajo tribal communities, inhabiting the coastal areas of Indonesia, to climate change, share several examples of their Indigenous Knowledge and traditions of marine resource conservation, and show how this wisdom, a valuable asset for climate adaptation governance, has been passed from generation to generation through oral tradition.

10.5.1.3 Knowledge Gaps and Future directions

One of the major knowledge gaps in the domain of climate adaptation governance relates to implementation by various stakeholder at multiple scales and sharing of information and experiences in this regard. There is a need to assuage the perceptions of distrust in global information, through governance methods that engage multiple stakeholders in open and lucid channels of communication (Stott and Huq, 2014). This is observable in the structure of the New Urban Agenda which formed a part of the Sustainable Development Goal pertaining to cities and has been shaped by a bottom-up process marked by diverse participation including communities, experts and activists, rather than the top-down variant that is observable in the MDGs (Barnett and Parnell, 2016). This approach could also be evidenced in the Paris Agreement, which placed the onus of a successful global governance regime on the development of efficient systems of regional governance. However, these emerging systems of regional governance could equally pose a challenge to the global in way that can be witnessed through the development of such financial groups such as the BRICS and Asian Infrastructure Investment Bank (AIIB), which resulted from a perception of inadequate institutional transformation at the global level. From another perspective, a comprehensive approach would require simultaneous implementation of both Bottom-Up and Top-Down models of governance, retaining flexibility of scale.

Given the concerns surrounding food security, especially in the light of the principles of common but differentiated responsibility, under the Nationally Determined Contributions (NDCs) submitted by South Asian nations under the Paris agreement, emission reduction commitments are *less likely* to include agriculture sector. Prospects for enhancing both adaptive capacity and food security could be improved by strengthening resilience and profitability through the introduction of a basket of policy choices and actions including structural reforms, agriculture value chain interventions, and landscape-level efforts for climate resilience. Correspondingly, the substantial adaptation finance gap could be closed with the help of both private finance (autonomous adaptation) and international financial transfers (Amjath-Babu et al., 2019).

For nearly five decades, integrated coastal management (ICM), advocated by several international organisations (e.g., IMO, UNEP, WHO, FAO) and adopted by over 100 countries, has been acknowledged as a holistic coastal governance approach, aimed at achieving coastal sustainability and reducing the vulnerability of coastal communities in the face of multiple environmental impacts (*high confidence*). In view of threats posed to coastal ecological integrity by climate change induced tropical storm activity, accelerated sea level rise, and littoral erosion and socio-ecological impacts on the livelihood security of vulnerable coastal communities, the pressing need for approaches that innovatively combine coastal zone management and climate change adaptation measures, is widely acknowledged (Rosendo et al., 2018) yet under researched. A study focusing three coastal cities of Xiamen, Quanzhou and Dongying in China, a country with nearly 12% of national coastline already covered under the ICM governance framework, suggests that whereas ICM approach has been found to be effective in promoting the overall sustainability of China's coastal cities (Ye et al., 2015) using accurate and reliable data, as well as the developing unified standards could usefully reveal changing conditions and parameters related to ICM performance.

Steadily the regional scale of climate adaptive governance is acquiring salience in diverse sub-regions of Asia and more policy oriented empirical research is needed on how various regional forums, agencies and multilateral organisations could further contribute by way of in-house expertise and other resources, including financial. A study of climate adaptation in the health sector in South East Asia (Gilfillan, 2018) highlights the growing role of Asian Development Bank and the Asia-Pacific Regional Forum on Health and Environment, and shows that their mandates and goals could mutually benefit from the institutionalisation of coordination mechanism. An example from the Maldives shows that 2014 Tsunami, climate change and the risk of extreme weather events have led to the legitimisation of state-led population resettlement programmes; in China, this has occurred through the re-naming of previously existing resettlement initiative as climate adaption initiatives. However, the efficacy of resettlement as a CCA measure requires further scrutiny (Arnall, 2019). In India, the National Adaptation Fund on Climate Change (NAFCC) has been instituted in order to enable states to implement adaptation programmes. However, this does not address the question of mainstreaming CCA into designs for development (Prasad and Sud, 2019). This is closely related to the development of National Adaptation Programmes of Action (NAPAs) where the mainstreaming of adaptation within countries has been an important concern. Insights from developing countries indicate that there is still much ground to cover. The NAPA of the Maldives prioritises food security, coastal resources and public health, while Nepal has prioritised ecosystem management and public health, and food security, among other concerns (Saito, 2013). Importantly, Bangladesh's NAPA has shown that there is potential for 'reflexivity' in the integration of adaptation objectives with sectoral objectives (Vij et al., 2018). Conspicuous by its absence is the transboundary scale adaptation policies in South Asia (Vij et al., 2017).

A distinguishing feature of the case of Japanese apple growers is the co-existence of both top-down and bottom-up adaptation practices. The former pertains to farmers who rely on the support of the cooperative for agricultural support and follow institutional mechanisms. The latter pertains to non-co-op farmers who have been responsible for innovative practices of cultivation such as the shift to peaches and the sale in the market of apples without leaf-picking. Importantly, the non-co-op group also have access to sales channels that may not be accessible to the former owing to their direct interactions with customers, among other factors (Fujisawa and Kobayashi, 2011; Fujisawa et al., 2015) The significance of this combination of top-down and bottom-up approaches to agricultural adaptation practices may be further sharpened by formulating approaches for Asia and the Pacific region in ways that contribute to the fortification of food security objectives and the idea of co-benefits. This may be carried out by enhancing the ability of farmers to better manage cultivation practices in the context of climatic variability (FAO, 2018d).

There exist numerous barriers to the mainstreaming of climate change adaptation (CCA) measures across Asia. The integration of CCA into the dissemination of localised climatic information and its uptake and implementation through institutional policy arrangements remain areas of concern (Cuevas, 2018). Institutional incentives to agricultural production, for instance, are frequently compounded by the negative impacts these have on existing bases of natural resources. The disconnected operations of local governmental agencies coupled with inadequacies of cross-sectoral coordination further highlights the prevalent food-water-energy nexus (Rasul, 2016). One possible way of addressing these intersecting sources complexity is by locating emerging CCA measures in educational development. The introduction of CCA thinking into land use planning in the Philippines is an example of the successful role of enhancing public education and awareness through the dissemination of information by institutional channels. The linkages between the strength of local leadership and the inclusion of CCA in localised planning activities are also well illustrated by this case study (Cuevas, 2018).

As shown in the case of Pakistan, level of education shares a positive relationship with the implementation of adaptation measures (Ali and Erenstein, 2017). However, a closer examination of the educational imperatives that drive CCA in ways that improve the representational architecture of adaptation actions through a focus on gender is needed. Mainstreaming of gender into CCA would involve addressing a host of barriers to education and involvement that are often rooted in the differential structures of households, social norms and roles, and the domestic division of labour (Rao et al., 2019). A study from the Indian state of Bihar shows that gender plays a major role in determining intra-household decision making and also inhibits the ability of female-headed households to establish access to agricultural extension services (Mehar et al., 2016). Even within wider female farmer-operated federations such as the Bangladesh Kishani Sabha (BKS), the barriers to participation stem from social factors that include the limitation of female mobility through the gendered division of labour and a lack of recognition of female agency (Routledge, 2015). Gendered inequalities in educational attainment and outcomes viewed through the lens of social vulnerability thus intersect with environmental vulnerabilities in ways that affect the ability of women to participate in CCA, owing also to a lack of access to health and sanitation facilities. These factors have a direct impact on the ability of adaptation to be effective in the global South, and are especially important in the context of the commitments of CEDAW (UN Convention on the Elimination of All Forms of Discrimination Against Women) countries to the objective of gender equality (Roy, 2018).

[START BOX 10.6 HERE]

Box 10.6: Bangladesh Delta Plan 2100

"*The Bangladesh Delta Plan (BDP) 2100 is the plan moving Bangladesh forward for the next 100 years. We have formulated BDP 2100 in the way we want to build Bangladesh."* (Commission, 2018).

Vision of BDP is revealed by this statement of Sheikh Hasina, the honourable Prime Minister of Bangladesh. Government approved BDP 2100 in 2018. Achievement of safe, climate resilient and prosperous delta is the aspiration of delta plan. Ensuring water and food security with economic growth, environmental sustainability, climate resilience, vulnerability reduction to natural hazards and minimising different challenges of delta through robust, adaptive and integrated strategies, and equitable water governance are the mission of this mega plan. Under this mission, three higher-level goals and six specific goals have been determined. Three higher-level goals include elimination of extreme poverty by 2030; achieve upper middle-income status by 2030 and being a prosperous country beyond 2041. Six specific goals of BDP 2100 are fully linked with SDG Goal 2, 6, 13 and 14 and partially linked with Goal 1, 5, 8, 9, 11 and 15. These specific goals comprise wide ranges of issues, including land and water resources, climate change, disaster, wetlands and ecosystems, river system and estuaries. Vision, mission and goals of BDP 2100 reveal that this mega plan is a holistic and integrated approach considering diversified themes and sectors for the whole country. The implementation of the BDP 2100 requires total spending of an amount of about 2.5% of GDP per annum. Series of strategies have been formulated for better implementation of the mega pan.

Water is the key and complicated resource of Bangladesh and therefore, BDP 2100 has kept water at the center of the plan. It aims to promote wise and integrated use of water and other resources through development of effective institutions and equitable governance for in-country and trans-boundary water resources management.

Along with water, for the first time in any development planning, BDP 2100 has taken the climate change issue as an exogenous variable in developing the macroeconomic framework of the plan. In a brief, it is said that the principle of BDP 2100 is "Living with Nature".

[END BOX 10.6 HERE]

10.5.2 Technology and Innovation

10.5.2.1 Point of Departure

Much like any other field, climate change adaptation is greatly facilitated by science, technology and continuous innovation. These ranges from the application of existing science, to the development of new scientific tools and methods, to the utilisation of Indigenous Knowledge and citizen sciences. Many of the pressing problems in Asia, including water scarcity, rapid urbanisation, loss of natural habitats, biodiversity, rising coastal and river basin hazards, and agricultural loss can be effectively minimised through the adoption of suitable science and technological methods. Despite the current challenges in the region, many significant advances in science and technology have been made, and the future prospects look bright. The following sections outline the present status and future prospects of science and technology in scaling up adaptation actions in four key sectors, namely disaster risk reduction, water and agriculture, urbanisation and forests and biodiversity.

10.5.2.2 Findings

10.5.2.2.1 Disaster Risk Reduction

Technological advances have enhanced the capabilities of Asian countries to monitor and prepare for climate-related hazards. Remote sensing technologies and GIS are widely used for disaster risk reduction (Kato et al., 2017), e.g., to assess and mitigate risks of an area to potential climate-related disasters (Wu et al., 2018b). The potential impacts of different types of hazards can be visualised using interactive maps (Lee, 2017), which helps local communities to understand risks and find appropriate evacuation areas (Cadiz, 2018). These provide situational overview and instant risk assessment (Yang et al., 2012b). As emerging technologies, artificial intelligence (AI) can identify conditioning factors of a landslide disaster (Hong et al., 2019b). Mobile virtual reality is used for disaster mitigation training, through a three-dimensional visualisation of a past disaster (Ghosh et al., 2018).

A community-based disaster risk reduction system provides risk investigation, training, and information analysis (Liu et al., 2016b). Sharing information enhances to establish such a system and contribute to disaster-prevention (Nakamura et al., 2017). One example is an online mapping tool, which has been developed by volunteers (Sakurai and Thapa, 2017). Social media enables population to reach real time information on a disaster (Ghosh et al., 2018), raises situation awareness (Yin et al., 2012), and empower communities towards appropriate emergency actions (Leong et al., 2015). Among various forms of social media, Twitter is widely used as social sensors to detect what is happening in a disaster event (Sakaki et al., 2013). Accuracy of information on Twitter has been proved in collecting local details about floods (Shi et al., 2019b), however it is noticed that Twitter generates rumors as well (Ogasahara et al., 2019). AI is expected to reduce human error when they operate a decision making system (Lin et al., 2018). Since technologies supporting disaster risk reduction completely depend on electricity, the loss of power supply and communication constrains the recovery work in disaster affected areas (Sakurai et al., 2014).

10.5.2.2.2 Urban sector

In the urban sector, a wide variety of sensor technologies are being used to monitor urban land-use and climate changes over time, and to better understand the potential impacts of future changes. These sensors range from large optical/thermal/radar satellite instruments with (near) global coverage (e.g., Landsat (US Geological Service), Sentinel (European Space Agency), ALOS (Japan Aerospace Exploration Agency), MethaneSAT to portable sensors embedded in mobile phones (e.g., phone cameras or temperature sensors) whose data are collected into centralised databases through crowdsourcing (Fenner et al., 2017; Meier et al., 2017). To combine and extract useful information from these heterogeneous sensor data – e.g., for conducting climate risk assessments (Perera and Emmanuel, 2018; Bechtel et al., 2019) and/or simulations of future land-use/climate changes in urban areas (Bateman et al., 2016), (Iizuka et al., 2017) (Liu et al., 2017c) – artificial intelligence technologies (e.g., machine-learning algorithms) are now being widely adopted (Johnson and Iizuka, 2016), (Joshi et al., 2016) (Mao et al., 2017). Thanks to advances in cloud computing technology, which allows for online processing of massive volumes of remote sensing data, high resolution (~30 meters) global urban area maps from the late 1990s to 2018 are now available from several different sources (Gong et al., 2020). Using these historical maps, researchers have been able to generate maps of future urban land-use changes at the global level to 2100 (Chen et al., 2020a), which can help to elucidate the potential impacts of this future urban expansion and identify adaptation needs. Technology also plays a major role in urban planning and design in the context of adaptation. To mitigate rising urban temperatures and reduce the impacts of climate-related hazards, many new “gray” infrastructure and “green” infrastructure technologies are being adopted in urban areas in Asia, e.g., cool (i.e. high solar reflectance) rooftops and pavements as well as green (i.e. vegetated) rooftops to mitigate high temperatures; and porous pavements to mitigate flooding (Akbari and Kolokotsa, 2016).

10.5.2.2.3 Water and agriculture

Majority of the Asian region is witnessing water stress in terms of both quantity and quality, due to poor management system and governance. This has dire consequences for national GDP as majority of the population belongs to agrarian community and their water dependent agriculture system. Despite a substantial investment and progress in research and development and capacity building in recent past, majority of the developing countries in Asian region are struggling to manage both water resources and agriculture sector heavily reliable on water resources, in lieu of rapid global changes. Considering the frequent extreme weather conditions, progress in management task become even more mammoth and hence need for advance science and technology viz. smart agriculture, robust early warning system using downscaled meteorological information, participatory approach, IWRM etc. for better climate change adaptation is critically important for these countries.

Having scientific knowledge relevant at local scale through placed knowledge is important to identify climate change risk and vulnerability. And once integrated with socio-economic attributes, it can be useful for natural resource management, agriculture etc. (Leith and Vanclay, 2017). Role of big data and data mining is undeniably very huge to get reliable climatic information and hence for designing appropriate adaptation measures for natural resource measurement. For example, use of big data in terms of early warning system and real time observation data provides more accurate information on hydro-meteorological extreme weather conditions or hazards like drought, flood, will help farmers and local government units to improve their perception and hence preparedness for better adaptation (Hou et al., 2017) (Ong and G.L.B.L., 2017). Using big data, different adaptation measures like new cultivar breeding, cropping region adjustment, irrigation pattern change, crop rotation and cropping practice optimisation are being designed in agriculture sector, which have greatly increased crop yield, leading to higher resource use efficiency as well as greatly increased soil organic carbon content with reduced greenhouse gas emissions. It results in win-win situation in terms of enhancing food security and mitigating climatic warming (Deng et al., 2017). However, usability and application of this technology are still not common especially in the data scarce regions. Integrated numerical simulations are efficient tools for estimating current status and predicting risk and efficiency of adaptive capabilities of different countermeasures for sustainable natural resource management like water (Kumar, 2019). Similarly, agent based model is commonly used to estimate risk of food borne diseases due to climate change, using tunable parameters such as hygiene level, microorganism's growth rate and number of consumers and hence has the potential to be a useful tool for optimising decision-making and urban planning strategies related to health and climate change (Gay Garcia et al., 2017). Integrated Assessment Model (IAM) under the Shared-Socioeconomic Pathway (SSP) framework is effectively used to estimate future energy development and possible mitigation strategies to reduce GHGs emission related to energy sector (Bauer et al., 2017). Sound understanding of different drivers, pressures and stress factors such as abnormal temperature, rainfall, insect pest/pathogen and their interaction pattern with genetic makeup of crops; is the key to produce high-yielding varieties of wheat with better nutritional quality and resistance to major diseases (Goel et al., 2017). Another critical point to address this water security is inclusive, polycentric and adaptive governance. Polycentric governance is a means that water management plans and policies should be framed and agreed by all relevant stakeholders. For adaptive governance, more emphasis will be on finding the best pathways to make robust water management plans amid rapid global changes. The benefit of such plans should reach the end users in terms of providing clean water, protection from hydrological hazards and maintaining the health of the ecosystem. In addition, there is urgent need for co-management, which includes the cycle of co-design, co-implementation and co-delivery throughout the whole water cycle. The best suitable example is using the Circulating and Ecological Sphere (CES) approach. CES is a concept that complements and supports regional resources by building broader networks, which is composed of natural connections (connections among forests; city and countryside; groundwater, rivers and the sea) and, economic connections (composed of human resources, funds, and others), thus complementing each other and generating synergy (Mavrodieva and Shaw, 2020). Another suitable example for managing water resources is Participatory Watershed Land-use Management (PWLM) approach. PWLM is another very innovative and successful approach for more robust water resource management explained by (Kumar et al., 2020). It helps to make land-use and climate change adaptation policies more effective at a local scale. This is an integrative method using both participating tactics and computer simulation modelling for water resource management at a regional scale.

10.5.2.2.4 Forests and Biodiversity

Technologies and its applications to identify habitat degradation, ecosystem functions and biodiversity conservation are increasing in Asia, with many countries looking up to new and improved means for forest and biodiversity monitoring and conservation. In particular, there has been an impressive use of temporal satellite data, particularly from the Landsat and the MODIS series for widespread monitoring of forests and ecological resources. These provided reliable information on forests and ecosystem services at country level, in difficult terrains, such as the mountains, cross-boundaries and otherwise inaccessible areas. For instance, Yin et al. (2017) estimated cross-boundary forest resources in Central Asia using remote sensing techniques, a region which traditionally suffered from lack of reliable forest data. In a separate study, Reddy et al. (2020) used long-term MODIS forest fire data from 2003–2017 to characterise fire frequency, density, and hotspots in South Asia. Archival of scientific data, particularly helped the provisioning of scientific research, backed by the state-of-the art modelling techniques, advance-computing methods and innovations in big data analysis. A number of studies simulated forest futures from local to continent scale under different socio-economic and climate scenarios. As for instance, at local scale, DasGupta et al. (2018) projected future extent of mangroves in the Sundarban delta under four local scenarios, while Estoque et al. (2019) modelled and developed spatial maps of regional forest futures in Southeast Asia using the five SSP scenarios. Science and technology also helped the monitoring of species diversity and abundance, pivotal for sustaining ecosystem and ecosystem based adaptation. Digital camera traps, radio-collaring methods have largely replaced old film cameras and labour-intensive methods of photo-screening to count target species (Pimm et al., 2015). This enhanced scientific capacities to monitor biodiversity and facilitate better conservation in difficult terrains, control poachers and maintain steady ecological balance. Umapathy et al. (2016), for example used VHF radio-collars and satellite-based tracking tools to monitor the movement of Bengal tigers in hostile island terrain. Photo recognition and other non-invasive techniques for individual identification have been rising in Asia. For example, a study by Gray et al. (2014) used fecal-DNA samples to estimate the population density of Asian elephant in Cambodia. The advancement of citizen science programs has greatly facilitated better monitoring of forest resources, including invasive floral and faunal species (Chandler et al., 2017; Johnson et al., 2020). In Asia, citizen science has been used effectively in India (Chandler et al., 2017), also in Malaysia for the monitoring the urban bird abundance (Puan et al., 2019).

10.5.2.3 Knowledge Gaps and Future Directions

With rapid advances of technologies, the use of appropriate technologies generates some degree of management problems. To resolve such problems, the enhancement of information science is essential to understanding design, implementation and adoption of digital tools under crisis (Xie et al., 2020). For example, social media research reveals a way of controlling malicious information (Tanaka et al., 2014) and its characteristics under Covid-19, showing a plain text message can be more powerful in the context of citizen engagement than media richness communications (Chen et al., 2020b). Information behaviour needs more investigation to understand how people survive and connect in the era of information overflow (Pan et al., 2020). Moreover, a new set of data e.g., travel history record and personal health data etc. becomes an important base of disaster risk reduction (Xie et al., 2020). Analysis of these personal data requires careful consideration, as it generates ethical issues (Sakurai and Chughtai, 2020). Indicators or measurements of technology enabled crisis response needs to be developed for further risk reduction (Wong et al., 2020). (Akbari and Kolokotsa, 2016). On the other hand, adopting infrastructure technologies requires investment, and due to the inherent uncertainties of climate projections, the future payoffs of these investments are also somewhat uncertain (Ginbo et al., 2020). In water and infrastructure sector for example, various options exist for conducting cost-benefit analysis considering future uncertainty, i.e. so-called robust approaches, which are able to identify adaptation projects/infrastructure that can achieve their intended purpose(s) across a wide range of climate scenarios (Dittrich et al., 2016). Despite a substantial investment and progress in research, development and capacity building in recent past, majority of the developing countries in Asian region are struggling to manage both water resources and agriculture sector. Considering the frequent extreme weather conditions, progress in management task has become even more mammoth and hence we need a holistic solution, which is currently missing in field implementation. These should be based on advance science and technology in association other attributes like social, economic, political dynamics, which play a pivotal role in sustainable management of water resources/agriculture, as a way forward.

10.5.3 Lifestyle Changes and Behavioural Factors

Point of departure: Understanding the motivations and processes underpinning decisions to adapt or not is key to enabling adaptation (Clayton et al., 2015; de Coninck et al., 2018; Taylor, 2019; van Valkengoed and Steg, 2019a; van Valkengoed and Steg, 2019b) (cross reference to Sec 17.2.2.1 in Chapter 17) because how and why certain people adapt is shaped by socio-cultural factors, ways of making sense of risks and uncertainty, and personal motivations to undertake action (Nguyen et al., 2016; Mortreux and Barnett, 2017; Singh et al., 2018b; van Valkengoed and Steg, 2019b). The IPCC's Assessment Report 5 was critiqued for silences on how perceptions shape climate action and the behavioural drivers of adaptation responses (Lorenzoni and Whitmarsh, 2014). Addressing this gap and assessing the growing literature from social sciences, notably psychology, behavioural economics, and risk perception studies, the IPCC Special Report on 1.5C (de Coninck et al., 2018) comprehensively assessed behavioural dimensions of climate change adaptation for the first time. However, compared to studies on mitigation behaviour, the literature on what motivates adaptation remains a gap (Lorenzoni and Whitmarsh, 2014; Clayton et al., 2015).

Findings: There are three key aspects of adaptation that psychology and behavioural science contribute to: understanding perceptions of climate risk, identifying the behavioural drivers of adaptation actions, and analysing the impacts of climate change on human well-being (Clayton et al., 2015). Overall, there is growing acknowledgement that individual adaptation is significantly shaped by perceptions of risk; perceived self-efficacy, i.e. beliefs about which options are effective and one's ability to implement specific adaptation interventions; socio-cultural norms and beliefs within which adaptation decisions are taken; past experiences of risk management; and the nature of the intervention itself (Grothmann and Patt, 2005; Werg et al., 2013; Clayton et al., 2015; Truelove et al., 2015; Pyhälä et al., 2016; Deng et al., 2017; Sullivan-Wiley and Short Gianotti, 2017; Taylor, 2019; van Valkengoed and Steg, 2019a). This is in addition to more commonly understood factors shaping adaptation behaviour such as technical know-how and cost and benefits associated with an option.

Across Asia, behavioural aspects of adaptation have been studied to a lesser extent: a global meta-analysis of 106 studies found most research focussed on North America and Europe with only 12% papers from Asia (van Valkengoed and Steg, 2019a). Within Asia, behavioural drivers of adaptation decision-making have been studied primarily in agriculture (in South, East, and SE Asia) and disaster risk management (from SE and East Asia) (Table 10.4) and tend to focus on technical adaptation interventions rather than how and why people adapt (Sun and Han, 2018).

Table 10.4: Table of sectors and sub-regions where behavioural aspects of adaptation have been assessed. NE= No Evidence

Sub-region	Sector	Adaptation interventions	Behavioural aspects affecting adaptation	Supporting references
West Asia	Agriculture	Soil and water conservation activities to mitigate drought impacts	Response efficacy and perceived severity shape water conservation	Iran (Keshavarz and Karami, 2016)
Central Asia	NE	NE	NE	NE
South Asia	Agriculture	Conservation agriculture, adjusting agricultural practices	Risk perceptions shape adoption of adaptation strategy (e.g. perceptions of decreasing rainfall motivate building water storage tanks)	Nepal (Piya et al., 2013; Halbrendt et al., 2014)
		Sustainable water management practices, adjusting agricultural practices	Risk perception is shaped by socio-cultural context, memories, experiences and expectations (of future change)	India (Singh et al., 2016)
		Alternate wetting and drying irrigation, alternative crop selection, using drought-resistant seeds	A combination of attitudes, self-efficacy, outcome efficacy, and community efficacy predict intent to adapt strongly	Sri Lanka (Truelove et al., 2015)
		Adjustment in farm management including growing short duration or drought-tolerant varieties, pest resistant varieties, changing planting distance, increasing weeding, soil conservation techniques, cultivation of direct seeded rice, switching to non-rice crops	Farmers' education, access to credit and extension services, experience with climate change impacts such as drought and flood, information on climate change issues, belief in climate change and the need to adapt all variously determine their decision-making	Nepal (Khanal et al., 2018)
	Disaster management	Flood and cyclone preparedness measures such as using durable building materials, raise plinth levels, storing food and water	Disaster management behaviour is intuitive: low evidence to suggest outcome-expectancy, self-efficacy, and preparedness intention follow linear patterns	India (Samaddar et al., 2014); Bangladesh (Dasgupta et al., 2014b)
		Use of emergency toolkits and evacuation plans	Risk perception and knowledge of adaptation options shape uptake and perceived benefits	Pakistan, Bangladesh (Alvi and Khayyam, 2020)
		Insurance to deal mitigate financial losses from floods, droughts	Frequency, severity of previous extreme events, socio-economic settings, ability to pay shape decisions to take crop insurance. Acceptability of flood insurance depends on perceived efficacy of the insurance (among other factors such as age of household head, landownership, off-farm income sources)	Pakistan (Arshad et al. 2016) (Abbas et al., 2015)

		Embankments/dikes for flood risk mitigation	Willingness to contribute manual labour to flood protection measures is positively influenced by the number of adult family members, livestock damage, compensation received and expected effectiveness of the intervention, but is negatively influenced by age and education of the household head, farm income and the distance of the farm from the river.	Pakistan (Abbas et al., 2019)
Southeast Asia	Agriculture	Changing agricultural practices, diversifying livelihoods	Values, personal and social beliefs of risk shape adaptation	Vietnam (Le Dang et al., 2014; Cullen and Anderson, 2016; Nguyen et al., 2016; Arunrat et al., 2017)
	Disaster management	Raising floor height to avoid flooding, retrofitting houses	Perceived probabilities and perceived consequences of flood shape preparedness	Vietnam (Reynaud et al., 2013; Ling et al., 2015)
		Flood insurance	Likelihood of purchasing flood insurance increased with higher physical exposure and subjective perceptions of vulnerability	Malaysia (Aliagha, 2013; Aliagha et al., 2014)
		Evacuation	Individual risk perceptions lead to learning, but only where previous disaster experiences are traumatic	Philippines, India (Walch, 2018)
		Disaster preparedness measures such as having kits, undertaking precautionary measures	Perceived self-efficacy was the most significant measure affecting reactive adaptation; education had the highest effect size on anticipatory adaptation.	Cambodia (Ung et al., 2015)
East Asia	Agriculture	Changing agricultural practices, diversifying incomes, adopting water saving technology, purchasing weather insurance	Perceived self-efficacy strongly predicts adaptive intent	China (Jianjun et al., 2015; Zhang et al., 2016a; Burnham and Ma, 2017; Feng et al., 2017)
	Disaster management	General	Higher education, being in environments where climate is discussed leads to stronger risk perceptions	Taiwan, Province of China (Sun and Han, 2018)
		Drought management through early warnings, prevention information	Policies can positively shape adaptation decision-making depending on how information is given, what support is provided	China (Wang et al., 2015).

In agriculture, studies demonstrate how perceptions of risk (e.g. climate variability) (Singh et al., 2016; Zheng and Dallimer, 2016; Burnham and Ma, 2017; Feng et al., 2017), socio-cultural norms and personal experiences (Masud, 2016; Nguyen et al., 2016; Singh et al., 2016), and perceived efficacy of adaptation interventions in having a positive/desirable impact (Halbrendt et al., 2014; Truelove et al., 2015; Feng et al., 2017) affect adaptation decisions. Policies on providing early warnings of drought or information on prevention techniques shape farmer decisions to undertake adaptation interventions (Wang et al., 2015).

In disaster risk management, risk appraisal (Samaddar et al., 2014; Rauf et al., 2017; Hung et al., 2018), previous experience and losses (Said et al., 2015; Hung et al., 2018; Walch, 2018)[11], perceived probabilities and consequences (Reynaud et al., 2013), perceived self-efficacy (Ung et al., 2015; Hung et al., 2018), and awareness (Hung et al., 2018; Wu et al., 2018a; Alvi and Khayyam, 2020) shape preparedness. Individual risk management is nested within public policies such as those on flood management which shape individual flood risk perception and protective behaviours (Reynaud et al., 2013) as well as personal factors such as religious beliefs (Alshehri et al., 2013). For example, communities often perceive disasters as 'acts of God' (Birkmann et al., 2019) or punishment for wrongdoings (Alshehri et al., 2013; Iqbal et al., 2018), which might constrain adaptive action. However, religious faith can also motivate people to prepare for extreme events, as Alshehri et al. (2013) show in Saudi Arabia demonstrating how "Islam urges that it is most important to prepare the people to escape from disaster" (p.1825).

Trust in public action as a mediator of risk management had conflicting evidence: some studies discussed trust being critical to effective preparedness (Kittipongvises and Mino, 2015; Walch, 2018) while others found that trust in public actions such as structural interventions to mitigate flood impacts can lower individual motivations to act since they feel protected (Hung et al., 2018).

Belief in climate variability and change significantly shapes adaptation decision-making (Le Dang et al., 2014; Singh et al., 2016; Khanal et al., 2018; Liu et al., 2018a) with those believing in climate change and associated impacts tending to engage in adaptation. Crucially, those who do not believe in climate change, can be influenced by social norms (Arunrat et al., 2017) thereby incentivising adaptation behaviour. While risk perception is a critical step in adaptation decision-making, higher risk perception does not necessarily signal better capacity to cope: in Taiwan, Province of China, Sun and Han (2018) highlight how perceptions of climate risk as a global problem tends reduce its urgency as an individual issue. Providing information on climate risks, impacts, and possible adaptation options enables adaptation behaviour (Piya et al., 2013; Zheng and Dallimer, 2016; Rauf et al., 2017) but information alone is not sufficient to motivate adaptive behaviour. Specifically, awareness building on concrete measures and outcomes such as amount of water saved or number of deaths averted rather than abstract notions of climate change motivate adaptation (Deng et al., 2017; Rauf et al., 2017).
Lifestyle changes: Changes in current lifestyles and consumption patterns are acknowledged as critical to climate action (de Coninck et al., 2018; IGES, 2019). With rapidly changing diets and increasing purchasing power, lifestyle changes in countries across Asia, especially those with large populations such as China and India will be critical to contributing to global climate solutions (IGES, 2019). Lifestyle shifts that can contribute towards adaptation include:

- Engaging in urban agriculture through rooftop gardening, community gardens in urban and peri-urban areas etc. (with implications for food associated footprints but also nutritional, livelihood, and wellbeing benefits) (Mohanty et al., 2012; Ackerman et al., 2014; Padgham and Dietrich, 2015)
- Shifts towards organic farming and creating demand for organically sourced food and other materials
- Shifts towards water-saving behaviour such as rainwater harvesting, water conservation, reducing water usage etc.

Knowledge gaps: Overall, understanding behavioural factors shaping adaptation implementation and uptake is important (*medium evidence, high agreement*). While there is a growing literature on behavioural drivers of adaptation at individual and household levels, gaps remain in understanding how socio-cognitive factors affect adaptation behaviour at higher scales (e.g. at local or sub-national government, in the private sector etc.)[12]. More empirical evidence is needed in sectors beyond agriculture and disaster risk management (e.g.

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[11] Two exceptions to this were found. One is a survey in Saudi Arabia which tested public perceptions of disaster risk and found that direct experience with such disasters does not directly influence risk perception (Alshehri et al., 2013). Second, a study on flood experience and ensuing adaptation behaviour in Pakistan found that those with prior flood experience do not make significantly different choices than those who have no experience of flooding; what is more significant is repeated exposure to flooding events (Said et al., 2015)

[12] Some studies compare nationally representative surveys on climate perceptions and their impacts on climate action to demonstrate that higher risk perception leads to higher motivations to undertake climate action (Corner, Markowitz, and Pidgeon 2014; Smith and Mayer 2018). Others, however, highlight that higher risk perception can lead to a normalization

factors motivating urban adaptation) and better coverage across Asia's sub-regions. Importantly, there are no studies on behavioural aspects of adaptation from Central Asia.

10.5.4 Costs and Finance

10.5.4.1 Point of departure

Estimates of adaptation costs and financial needs have evolved significantly from the previous IPCC assessments. These developments are based on the improvements in the understanding on how the hazard interacts with the physical and socio-economic elements and how to capture these interactions in systematic modelling frameworks. The developments are also clearly reported especially in the area of addressing the underestimates in adaptation costs that the previous studies suffered from as the previous studies tend to rely on data from wealthy economies (Carleton et al., 2020);(Hochrainer-Stigler et al., 2014). The adaptation cost estimates also improved from the previous IPCC reports due to constant improvements in capturing the loss and damages of disaster events (Hochrainer-Stigler et al., 2014). The reliance of earlier studies on correlations to derive adaptation costs was addressed to some extent by addressing the endogeneity of disaster measures (Kousky, 2014), especially by relying upon the physical measures of disaster such as wind speed, though more work is needed in this area.

10.5.4.2 Findings

Climate change can cause significant impacts and as a result can impose considerable adaptation costs to countries and people. Despite the importance, the research on adaptation costs is limited in Asia, especially on the economy wide costs, while fragmented literature is available on sector level adaptation costs. Most of the available literature on adaptation costs at the regional level originate from the work carried out by the development finance institutions such as ADB.

Estimates suggest that climate change impacts could result in a loss of 2% of GDP of South Asian countries by 2050 and 9% by 2100 (Ahmed and Suphachalasai, 2014). These impacts will be felt in major vulnerable sectors, including agriculture, water, coastal, marine, health and energy, and will have significant impact on the economic growth and poverty reduction in the region. Countries could differ widely in terms of economic costs they face. In South Asia, the economic costs were projected to be 12.6% of GDP for the Maldives, which is the highest among the South Asian countries, and 6.6% for Sri Lanka, the least among the South Asian countries. The resultant adaptation costs for countries were projected to range from 0.36% (Copenhagen Cancun Scenario for 2050) to 1.32% (BAU scenario) of GDP in various scenarios during 2010-2050 (ibid) (*Medium agreement*, *limited evidence*).

Arto et al. (2019) have reported the adaptation costs of Mahanadi delta in India for agriculture, fisheries and infrastructure sectors (Arto et al., 2019). The cumulative adaptation costs for 2015-2016 were reported to be 276 million USD for agriculture and 0.163 million USD for fisheries. In comparison, the modelled cumulative agricultural GDP loss due to climate change impacts was reported to be 5% up to 2050, and 8% for infrastructure. Adaptation interventions such as embankments were found to provide an avoided losses (adaptation benefits) to the tune of 2.2% of the delta GDP by 2050. Similarly, input subsidies in seeds, fertilisers and biofertilisers were found to buffer the shocks in agriculture by 10%, and buffers the GDP per capita by 3% (ibid).

Markandya and González-Eguino (2019) have estimated the adaptation cots and residual adaptation costs accrued due to insufficient adaptation using integrated assessment models. Using the residual damages as a measure of loss and damage, the authors have estimated adaptation costs and residual costs under high damages-low discount rate and low damages-high discount rate scenarios. The estimates suggested adaptation costs of 182, 193 billion USD by 2050, 737, and 783 by 2100 for South Asia and East Asia respectively under high damages-low discount rate scenario. The residual costs for the same scenario were 289% and 76% for 2050 and 238% and 62% for 2100 for South Asia and East Asia respectively. Estimates

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of risks, leading to lower climate action (Luís, Vauclair, and Lima 2018). In all of these papers, there is a recognition that the literature on perceptual drivers of climate action is US-centric and is negligible in Asia (Capstick et al. 2015).

for low damages-high discount rate were significantly lower adaptation costs and residual costs for both the sub-regions of Asia.

Climate change adaptation efforts can be characterised as fragmented, incoherent, and lacking a perspective (Ahmed et al., 2019a), and the picture on adaptation financing can be stated as similarly fragmented with very limited literature published in peer reviewed journals. Adaptation financing is crucial for supporting vulnerable countries enhance adaptation as it is evident that the enhanced adaptation finance support has positively affected the pace of adaptation in low-income countries (Ford et al., 2015). At the organisational level, adaptation financing provided multiple functions that include risk assessment functions, valuation functions, and risk disclosure functions (Linnenluecke et al., 2016).

Of the total global public adaptation finance of 28 billion USD, East Asia and Pacific attracted 46% of the total funding, while south Asian countries attracted only 9% of the total funding (UNEP, 2016). These differences reflect the capacity of countries to attract adaptation finance. Some of the important adaptation-targeted climate funds are Pilot Program for Climate Resilience, Green Climate Fund, and Least-Developed Countries Fund, and South Asian countries have significantly benefited from these dedicated climate funds. Due to disaster implications of climate change, there is a need to allocate adaptation finances for disaster risk reduction (DRR). Estimates suggest that East Asia and Pacific allocated 27% of the total adaptation funds to DRR while South Asia allocated 25% (Caravani, 2016). Low-income economies tend to allocate more adaptation funds to DRR (46%) while lower-middle income economies allocated 22%.

Least developed countries lack the capacity to adapt to climate change and the Least Developed Country Fund (LDCF) has been found to make significant contribution to adaptation in these countries (*High agreement, limited evidence*). Based on the interview-based field research in four least developed countries, Sovacool et al. (2017) opined that the LDCF projects are contributing to the adaptive capacity of these countries (Sovacool et al., 2017). They also found that these projects are taking a marginal approach to adaptation rather than radical or transformational one.

Kissinger et al. (2019) have estimated the climate financing needs in the land sector under Paris Agreement. The estimates suggested adaptation needs of 2.5 billion USD for Bangladesh, 40.5 million USD for Lao PDR, 31 million USD for Mongolia, for the forest sector alone (*Low agreement, limited evidence*).

Financing green growth and low-carbon development can provide resilience benefits (*High agreement, limited evidence*). Kameyama et al. (2016) have estimated the cost of low carbon investments that can provide resilience benefits in Asia and reported that such low-carbon development will cost in the range of USD125-149 billion annually. A combination of public, private, bilateral and multilateral funding sources, and carbon market offsets, were suggested to achieve this level of funding. In terms of the total resources available, a combination of public, private and bi-, and multilateral funding could help the region to raise as much as 222.3-412.5 billion USD annually, with a possibility to reach higher amounts depending on the future economic growth of countries in the region. Soil carbon sequestration in agricultural soils was found to be a win-win solution for both mitigation and adaptation as it can help improve soils while increasing farm yields and income of smallholders (Aryal et al., 2020a).

New adaptation financing sources have been emerging which could provide country-specific adaptation financing suiting local level adaptation needs in Asia. The newly established Asia Infrastructure Investment Bank (AIDB), and newly emerging developing country development finance institutions are known to provide an additional adaptation finance (Neufeldt et al., 2018). However, despite these emerging financial sources, the region will fall short of the adaptation target in the Paris Agreement (ibid).

10.5.4.3 Knowledge Gaps

Adaptation cost estimates can vary between various studies due to the differences in methodologies they adopt. Some studies have conducted cost assessments using a combination of stakeholder consultations and quantitative modelling of climate change impacts and adaptation (Ahmed and Suphachalasai, 2014), while others depended solely on the quantitative modelling. Studies also differ in the coverage of sectors too, they either focused on the multiple vulnerable sectors (Ahmed and Suphachalasai, 2014) or on a single sector (Hossain et al., 2019). Studies differed in their estimates depending on their ability to take into consideration the transition costs of sudden adaptation (Hossain et al., 2019), nature of social cost/damage functions employed (Arto et al., 2019), discount rates applied (Markandya and González-Eguino, 2019), and consideration for the effects of GHG mitigation on adaptation needs (Duan et al., 2019a). In addition, the assumptions made on the pace of adaptation in estimating adaptation costs can make a difference in adaptation cost estimates. Adaptation at a slow or normal pace could require more adaptation finance, as large amount of damage remain not eliminated, than when adaptation is implemented at a faster rate (Markandya and González-Eguino, 2019). Though there have been improvements in adaption cost estimates, there is a need to address the issue of endogeneity ((Kousky, 2014); (Samuel et al., 2019)). The vast majority of studies that rely on databases such as EM-DAT tend to suffer from such endogeneity problems due to their inability to control the causality between GDP and damages (Kousky, 2014). Costs attributable to non-economic loss and damages are the least reported and least quantified in the adaptation costs literature due to lack of sufficient, robust and accessible methodologies (Chiba et al., 2017); (Chiba et al., 2019); (Serdeczny, 2019)). This is a major limitation in assessing adaptation costs and financial needs and it can lead to gross underestimation of adaptation costs. A detailed description of issues related to non-economic loss and damages and its importance in strengthening adaptation is provided in Box 10.7 (Loss and damage across Asia: mapping the evidence and knowledge gaps), and Table 10.5.

[START BOX 10.7 HERE]

Box 10.7: Loss and Damage Across Asia: Mapping the Evidence and Knowledge Gaps

Losses and damages are climate impacts after implementing adaptation and mitigation actions, signifying the presence of residual risks (Kugler and Sariego, 2016; Mechler et al., 2019) (Chapter 1). These residual risks indicate that despite adaptation, there are soft and hard adaptation limits (Mechler et al., 2019). This box reviews the adaptation literature across 51 countries in Asia on L&D, and adaptation barriers and limits and identifies knowledge/regional gaps. The key messages are (1) climate-induced L&D is already occurring across Asia (*medium evidence, high agreement*), (2) these L&Ds are *very likely* to increase at higher warming levels (*medium evidence, high agreement*), and (3) measuring and attributing non-economic/intangible L&D remains a challenge (*low evidence, high agreement*).

Findings on losses and damages in Asia: Evidence on climate-related L&D highlights tangible or material losses and damages such as loss to life, property, infrastructure and livelihoods (*medium evidence, high agreement*); and intangible or non-material losses and damages such as increasing conflict and civil unrest, erosion of sociocultural practices, and decreased wellbeing (*low evidence, high agreement*). The main constraint in assessing past and future L&D is that this terminology is not used prominently or consistently in the disaster management and climate risk literature in Asia, which potentially leads to underreporting. In contrast, there is *robust evidence (high agreement*) on adaptation constraints, notably on governance, informational, and physical constraints to adapting but regional evidence is very uneven with gaps in Central, North and West Asia. Table 10.5 presents a summary of L&D but draws on national/sub-national studies.

Knowledge gaps

- Attribution studies linking anthropogenic climate change and L&D remain focused on rapid-onset extreme events and evidence on L&D from slow-onset events such as drought and water scarcity is low (Singh et al., 2021a) (Pereira et al., 2019).
- Regional evidence gaps in Central, North and West Asia. Further, *low evidence* of national-level projected loss and damages (Uchiyama et al., 2020; Singh et al., 2021a).
- Disproportionate emphasis on economic L&D while intangible, non-economic L&D are relatively less measured and reported (Chiba et al., 2017); (Bahinipati, 2020). Economic loss estimates are largely approximations and therefore suffer from various methodological, assumption, and data-related uncertainties.
- Insufficient literature differentiating L&D under future adaptation scenarios, which makes assessment of residual damages and future L&D difficult. L&D projections are constrained by limited understanding on how vulnerabilities will evolve with economic and demographic changes. Most projected L&D are based on the population and GDP projections. More future projections are based

on the RCP scenarios and least number of studies were conducted on the combination of RCP and shared socio-economic pathways.

- Mitigation will have L&D and adaptation co-benefits (Kugler and Sariego, 2016; Toussaint, 2020), especially at the lower temperature stabilisation 1.5ºC (Nishiura et al., 2020), but the literature is currently insufficient to assess these L&D co-benefits of mitigation efforts.
- Negligible regional evidence on limits to adaptation.

Way forward: Developing robust metrics and institutions for measuring and reporting L&D at national and regional scales, especially non-economic damages and L&D due to slow-onset events is critical. In addition to vulnerability assessments, assessing L&D and limits to adaptation can inform adaptation prioritisation and enhance adaptation effectiveness (e.g.(Craft and Fisher, 2016) (Leiter et al., 2019)). Lessons are available from biodiversity and ecosystem services monitoring frameworks that have well-developed metrics and processes (e.g., (Díaz et al., 2020)).

[END BOX 10.7 HERE]

Table 10.5: Tangible and intangible losses and damages across Asia. For definitions on losses and damages and limits, see Cross-Chapter Box LOSS in Chapter 1.

Magnitude of losses and damages	
■	High (>50% sector/population affected relative to reported baseline)
▦	Medium (25-50% sector/population affected)
□	Low (<25% sector/population affected)
▒	Not assessed due to inadequate evidence

Evidence	
***	High (≥ 10 papers)
**	Medium (5-9 papers)
*	Low (≤ 4 papers)
NE	No evidence

Adaptation constraints	
E	Economic
S	Socio-cultural
H	Human capacity
G	Governance
F	Financial
I	Informational/Technology
P	Physical
B	Biological

Sub-region (no. of papers)	Key risks reported in L&D papers	**Losses and damages**					**Adaptation constraints** (bold ticks denote strong barrier)								**Adaptation limits**	
		Tangible				Intangible	E	S	H	G	F	I	P	B	Soft	Hard
		Past	RCP 2.5	RCP 4.5	RCP 8.5											
East Asia (32)	Coastal flooding, Heat waves, SLR	▦ ***	▦ *	▦ **	■ **	□ *	✓			✓	✓	**✓**	✓		NE	NE
South East Asia (4)	Coastal flooding, SLR	▦ *	▒	▒	▒	□ *			✓	✓		✓			NE	NE
South Asia (18)	Coastal flooding, Drought, SLR, Heat waves	▦ ***	▦ *	▦ **	■ **	□ **	✓			**✓**	✓	✓			*	**
Central Asia (3)	Snowmelt, Heat waves, Drought	▦ *	▒	▒	▦ *	□ *						✓	✓		NE	NE
North Asia (2)	Permafrost thaw	▒	▒	■ *	■ *	□ *							✓		NE	NE
West Asia (9)	Heat waves, Drought	□ **	▒	▦ *	■ *	□ *							✓		*	**

Table Notes:

East Asia: (Yu et al., 2018c); (Tezuka et al., 2014); (Udo and Takeda, 2018); (Udo and Takeda, 2018); (Chen et al., 2017b); (Li et al., 2015a); (Lee et al., 2017); (Abadie et al., 2017); (Liu et al., 2019d); (Liu, 2020); (Liu and Chen, 2020); (Chung et al., 2017b); (Lee et al., 2018c); (Lee et al., 2019); (Kim and Lee, 2020); (Lee and Kim, 2016); (Lee et al., 2018b); (Kim et al., 2016a); (Yu, 2016); (Lei et al., 2015); (Wang et al., 2019b); (Liu et al., 2019c); (Elliott et al., 2015); (Wu et al., 2019d); (Yu et al., 2018a); (Feng et al., 2018a); (Yu et al., 2020); (Li et al., 2015b; Chen et al., 2017a); (Zhao et al., 2016b); **South East Asia:** (Dau et al., 2017); (Giuliani et al., 2016); (Mehvar et al., 2018); (Vu and Ranzi, 2017); **South Asia:** (Abadie et al., 2017); (Ahmed et al., 2016b); (Aslam et al., 2017); (Bahinipati, 2020); (Bahinipati and Patnaik, 2020); (Bhowmik et al., 2021); (Chhogyel and Kumar, 2018); (Chiba et al., 2017); (van der Geest, 2017); (Jevrejeva et al., 2016; Jevrejeva et al., 2018; Khan et al., 2020); (Leng and Hall, 2019); (Mehvar et al., 2019); (Mishra et al., 2017); (Patankar and Patwardhan, 2016); (Jevrejeva et al., 2016); (Wijetunge, 2014); **Central Asia:** (Babagaliyeva et al., 2017); (Groll et al., 2015); (Otto et al., 2017); **North Asia:** (Hjort et al., 2018); (Tschakert et al., 2019); **West Asia:** (Ashrafzadeh et al., 2019b); (Bierkens and Wada, 2019); (Gleick, 2014); (Gohari et al., 2017); (Houmsi et al., 2019); (Mantyka-Pringle et al., 2015); (Mosavi et al., 2020); (Pal and Eltahir, 2016); (Ghomian and Yousefian, 2017).

10.5.5 Risk Insurance

10.5.4.1 Point of departure:

Risk insurance approaches and tools have significantly evolved during recent years. The emphasis has been mainly on mitigating the adverse selection and moral hazard that has been the limitations of traditional area-based crop insurance approaches (He et al., 2019). This has been achieved by shifting the indemnity calculations on to the specific weather parameters and developing a weather index (Greatrex et al., 2015); (Fischer, 2019). Technological applications in the development of insurance products have seen a significant progress, including that of the blockchain and smart contracts (Gatteschi et al., 2018). There are technological developments in loss estimation, which has been a major limitation in the traditional insurance approaches in the past that either delayed the indemnity payment or have misjudged the losses. Application of multi-model and multi-stage decision support systems has begun to make crop loss assessments for insurance more efficient (Aggarwal et al., 2020). Technological applications also include remote sensing (Di et al., 2017) and mobile phone app technologies (Meena et al., 2018) to provide accurate and quick damage assessments, and application of internet-based indemnity approvals have enabled quick payment of indemnities (OECD, 2017b).

10.5.4.2 Findings

As against financing post-disaster relief and reconstruction, which has been the norm of disaster management for decades in Asia, the evolution of ex-ante risk financing in the form of risk insurance has seen a steady rise globally and in Asia. The rise in popularity for risk financing in general and insurance in specific stem from the observation that governments have recognised the burden of mainly financing the post-disaster relief and reconstruction only (Juswanto and Nugroho, 2017; UNESCAP, 2018c; ADB, 2019), and from the realisation of cost savings and efficiency that risk financing for risk mitigation brings to the overall risk reduction (*High agreement*, *medium evidence*). As a result, a gamut of risk financing instruments have been introduced to finance disaster risk reduction and climate change adaptation initiatives in Asia among which risk insurance has gained prominence for it provides a low cost and easy option for individuals, provides an opportunity for the governments to effectively engage the private sector in implementation, and has ability to inculcate risk-aware decision making at various levels (Hazell and Hess, 2017; UNESCAP, 2018c) (*High agreement*, *medium evidence*).

Several Asian countries including India, The Philippines, China have a significant experience of offering agricultural insurance against typhoons, droughts and floods (Yang, 2018). For the most part, these insurance systems followed a traditional indemnity based insurance which faced several challenges in implementation including moral hazard and adverse selection, disagreements and delays in crop damage assessments that relied upon crop cutting experiments, often leading to delay in processing indemnity payments, costly insurance premiums, and poor insurance expansion (Patnaik and Swain, 2017; Ghosh et al., 2019) (*High agreement*, *robust evidence*). Other factors contributing to poor penetration of insurance include limited awareness on the importance of insurance, and poor access.

To tackle the problem of costly insurance premiums, governments have subsidised the premiums (Ghosh et al., 2019). Premium subsidies have been reported to undermine the ability to convey the real cost of risks by the insured (price distortion), and encouraged adverse selection and moral hazard (Nguyen and Jolly, 2019). On the contrary, subsidies have been suggested to address the issue of adverse selection associated with the insurance (Zhao et al., 2017c).

Despite the fact that the insurance programs are able to obtain high participation rates due to subsidised premiums, their impact on farmers' income seems to be insignificant especially under the conditions of low indemnities, low guarantee, and wide coverage (Zhao et al., 2016a). The subsidy burden of insurance on national governments is found to be significant with an estimated 6 billion dollars spent by China alone on insurance (Hazell et al., 2017). In addition, the insurance programs in the Asian countries are reporting higher producer claim ratios, and often governments have to spend more than the money being transferred to the insured through the insurance programs (ibid).

To address the issues associated with the traditional indemnity insurance, efforts have been made to develop weather index insurance in Asia that bases the payouts on the rainfall or temperature index rather than on the direct damage measurements. The parametric insurance products help avoid the delays in insurance payouts as they are based on modelled risks rather than actual damage measurements, and control the adverse selection and moral hazard though basis risks could be increased due to improper matching of payouts with the index (De Leeuw et al., 2014). Index insurance is known to promote public-private partnerships that in turn will enhance the efficiency of overall program delivery (Hazell and Hess, 2017). Several countries including India, Bangladesh, Thailand, Indonesia, Myanmar, and The Philippines either are currently piloting or are expanding the weather index insurance (Surminski and Oramas-Dorta, 2014; Tyagi and Joshi, 2019). Index insurance is constantly expanding with an estimated 194 million farmers already enrolled in China and India, which is much lower than the potential number of farmers it can reach (Hazell et al., 2017).

Few significant bottlenecks that are limiting the scaling up of weather index insurance include lack of reliable weather data, low density of weather stations leading to high basis risk, and limited data on damage and hazard for parametric modelling of the insurance (Shirsath et al., 2019). Several innovations are being tried and tested to overcome the limitations associated with the index insurance which include developing multiscale index insurance, application of remote sensing, smartphone based near-surface remote sensing, and building insurance based on vegetation indices instead of relying on weather data alone (Hufkens et al., 2019). Alternative indices such as using Normalised Difference Vegetation Index (NDVI) are being tested for their applications in designing index-based insurance in India (IFAD, 2017). Agro-meteorology-based statistical analysis and crop growth modelling have been suggested to calibrate and to rectify faulty weather indices (Shirsath et al., 2019; Zhu et al., 2019). Establishing automatic weather stations can improve the data accuracy while avoiding the delay in acquiring the weather data (Sinha and Tripathi, 2016). These technological applications have already started finding space within insurance programs designed by national governments in Asia. For example, the government of India has released new operational guidelines for the application of new technologies such as drones, remote sensing, and mobile phone apps in implementation of the national agricultural insurance which is the third largest insurance in the world (Department of Agriculture, 2019).

10.5.4.3 Knowledge Gaps

Despite these developments, several issues still seem to hinder the penetration of insurance in Asia. Issues such as lack of sufficient choices, lack of clear model, lack of legal support, limited or absence of proper monitoring and evaluation, and limited data for underwriters to properly evaluate claims have been suggested (Nguyen and Jolly, 2019). Low interest among the potential buyers due to unaffordable insurance premiums, lack of provision for partial loss claim settlement, high hassles in claim settlement process, and lack of timely settlement of claims are reported (Parappurathu et al., 2017). In addition, insurance has been reported to have expanded the coverage of cash crops at the expense of drought resistant subsistence crops with effects on natural capital and potential increase in farmer’s vulnerability to market price fluctuations (Müller et al., 2017).

Regional catastrophic insurance pools have also received attention in Asia. With the formation of Southeast Asia Disaster Risk Insurance Facility (SEADRIF) (Haraguchi and Lall, 2019), the regional insurance pool has been introduced in the Southeast Asia region initially being piloted in Lao PDR and Myanmar and to be expanded to the rest of the ASEAN region. Regional catastrophic insurance provides vulnerable countries to buffer climatic shocks by diversifying the risks beyond country boundaries.

10.5.6 Social protection

10.5.6.1 Point of departure

Social protection (SP) encompasses of initiatives that involve transfer income or assets to the poor, protect the vulnerable against risks to their livelihood, and enhance the social status and rights of the marginalised (Béné et al., 2014; Kothari, 2014). Social protection offers a wide range of instruments (e.g., cash transfers, insurance products, pension schemes and employment guarantee schemes) that can be used to support households that are exposed to climate changes (Bank, 2015). It also presents an opportunity to develop inclusive comprehensive risk management strategies to address loss and damage from climate change as well as means to climate change adaptation (CCA) (Aleksandrova, 2019).

Social protection programmes assist individuals and families, especially the poor and vulnerable, cope with crises and shocks, finds jobs, improve productivity, invest in the health and education of their children, and protect the aging population (Bank, 2018b). Social protection that is well-designed and implemented in a more long-term approach can enhance human capital and productivity, reduce inequalities, build resilience, empowerment and end inter-generational cycle of poverty (*medium evidence, medium agreement*) as indicated from various experiences in the region such as cash transfer programmes in Indonesia (Kwon and Kim, 2015); Benazir Income Support Programme in Pakistan (Watson et al., 2017); Chars Livelihoods Programme in Bangladesh (Pritchard et al., 2015); Minsei-in designated volunteer social workers in Japan (Boeckmann, 2016). Key consideration in strengthening resilience through social protection programmes is to design with climate and disaster risk considerations in mind and implemented in close synergy with existing programs, such as on sustainable livelihoods, early warning systems, and financial inclusion (Bank, 2018a) (Coirolo et al., 2013).

10.5.6.2 Findings

The Asia region is already the most disaster prone in the world, with over 200,000 lives lost and almost a billion-people affected by storms and floods alone between 2005 and 2014, while a heat wave in North and Central Asia in 2010 killed 56,000 people (United Nations, 2015). Climate change is increasing the frequency and intensity of these sudden and slow-onset disasters, amongst them, hydrological changes in major river basins where 1.5 billion people live (such as the Indus, Ganges, Brahmaputra, Mekong, Yellow, Yangtze, Tarim, Amu and Syr Darya rivers) (Bank, 2017a). According to the latest estimates of the International Labour Organisation (ILO), 55% of the global population (around four billion people) remains without any SP benefits, whereas the SP coverage gap is the highest in Africa (82.2%) and Asia and the Pacific (61%) (ILO, 2017b).

Risks are generally amplified for people without social protection or essential infrastructure and services, and for people with limited access to land and quality housing, especially those in exposed areas and informal settlements without secure tenure (ESCAP, 2017). Stateless people are disproportionately affected by climate change and disasters as they tend to reside in hazard-prone areas and their statues as non-citizens often limits access to assistance (Connell, 2015). The three main types of social protection, namely (i) social safety nets (also known as social assistance), which include conditional and unconditional cash transfers, public work programs, subsidies, and food stamps; (ii) social insurance, which consists of contributory pensions and contributory health insurance; and (iii) labour market measures, which include instruments such as unemployment compensation (Bank, 2018b). The potential for an integrated adaptive social protection is not yet harnessed by policymakers in tackling the structural causes of vulnerability to climate change (Tenzing, 2019). Public works program, i.e. India's MGNREGA should take into account climate risk in planning and support development of community assets to increase collective resilience.

Aligning social protection with climate change interventions are attempts to develop more durable pathways out of poverty and climate vulnerability, examples from the Mahatma Gandhi National Rural Employment Guarantee Act in Andhra Pradesh (MGNREGA) depicts the attempt to align through mainstreaming approach has helped women and their households (Steinbach et al., 2016) (Adam, 2015). On another note, Catastrophe Insurance Framework, first model introduced in Shenzen, China, provides timely relief for citizens and operates as a safety net particularly for the poorest residents who do not have disposable income to cover the costs associated with bodily injuries arising from disasters (Telesetsky and He, 2016). The DOLE (Department of Labour and Employment) Integrated Livelihood and Emergency Employment Program (DILEEP) in Philippines, is part of the recovery efforts after Typhoon Haiyan, provide short-term wage employment and facilitates entrepreneurship for people affected by natural calamities and economic shocks (Bank, 2018b).

In each of these instances, governments are using social protection to protect populations suffering from climate change or adversely affected by structural, pro-climate economic reforms (Hallegatte et al., 2015) However, additional research is still needed and new tools developed to inform policy design and support the implementation of "green" social protection, as well as to measure the net welfare impacts of such policies

(Canonge, 2016). In order to enhance social protection programmes, one of the cross-cutting issues is to discuss the linkages between gender roles and responsibilities, food security, agricultural productivity and the mediating role that social protection programmes can have (Jones et al., 2017). Social protection has a potentially important role to play in contributing to food security and agricultural productivity in a gender-responsive way (Holmes and Jones, 2013). As such experience from Challenging the Frontiers of Poverty Reduction: Targeting the Ultra Poor (CFPR/TUP) programme in Bangladesh, promoted social innovation by creating social and economic values, fostering microenterprises, food security, fostering inclusive growth and whilst empowering ultra-poor women (Emran et al., 2014; Mahmuda et al., 2014). Although there is increasing evidence that social protection programmes are having positive impacts to reduce vulnerability in women's everyday lives (Jones et al., 2017). However, transformative impact of these programmes is rare due to limitation in recognising women's access to productive inputs and resources (Tanjeela and Rutherford, 2018; Cameron, 2019).

On the other hand, poor governance practices affect delivery of social protection programmes, and the ability of beneficiary households to reap benefits from such support (Sijapati, 2017). In Nepal, closer look at public expenditure, about 60% of social protection budget is used by social insurance programmes that predominantly consists of public sector pensions (Babken Babajanian, 2014; Koehler, 2014). Towards this end, more efforts needed to improve its existing programmes so that there is an equality of opportunities, along with secured human rights, citing example from Nepal's Child Grant is indicative of an incremental approach to social policy (Garde et al., 2017). Meanwhile, in Philippines despite the existence of flagship national interventions that cover a significant number of people in need and have clear and robust implementation rules, there are still many programs with overlapping mandates and target population, and several gaps in their monitoring systems (Bank, 2018b).

Thus, having an integrated social protection information system would allow policymakers to better monitor inputs, outputs and outcomes (e.g., who are beneficiaries, what are they receiving, at what frequency, what are the existing gaps) (OECD, 2017a; Samad and Shahid, 2018). Evidence-based from three countries' assessment (Mongolia, Nepal and Vietnam), the political and institutional arrangements (the software) is as important as the technical fixes (the hardware) in the success of using ICT for delivering social protection programs (ADB, 2016). By 2050, climate-induced migration will *likely* be a major policy aspect of the rural-urban nexus as slow onset impacts of climate change in Sub-Saharan Africa, South Asia, and Latin America will *likely* force over 143 million people to migrate within their national borders (Kumari Rigaud, 2018). This will have major implications for SP systems and therefore national SP strategies should be designed to anticipate and address climate-induced internal mobility (Schwan and Yu, 2017). For instance, it does not offer a solution for maintaining Indigenous culture often strongly affected or even disrupted by climate change (Olsson, 2014). Hence, an effective approach needs to combine different policy instruments to support protection, adaptation and migration (O'Brien et al., 2018).

Evidently, social protection has been typically financed through the combination of government tax revenues and Official Development Assistance (ODA) challenges of the increasing frequency and intensity of natural and economic crises, are putting strains on these traditional financial sources (Durán-Valverde, 2020).In this context, innovative financing schemes are seen as critical to achieve the sustainable financing of social protection (Asher, 2015; UNICEF, 2019) via social and solidarity economy, as seen in women's autonomous adaptation measures in precautionary savings and flood preparedness in Nepal (Banerjee et al., 2019), and self-help groups as development intermediaries (Anderson, 2019). Still, there are constraints of SP to reach those who are most vulnerable to climate change and other hazards due to their legal status, such as attention to forcibly displaced populations within the social protection field has been limited (Sabates-Wheeler, 2019).

10.5.6.3 Knowledge gaps

Government social protection can attenuate negative impacts in facing disasters, depending on difference in political systems and focus on socio-political measures (*medium evidence, medium agreement*) not only in restoring livelihoods but also easing mental burdens faced by rural households in developing countries (Kosec and Mo, 2017) (Dalton et al., 2016) (Liebenehm, 2018). However, limited government capacities and fiscal feasibility may impede the expansion and effective implementation of social protection as developing countries need further support to design, adjust and implement social protection schemes effectively

(Klonner, 2014; Schwan and Yu, 2017). Most countries have comprehensive strategies for both SP and CC, few have attempted to align them, as in practice, they remain in separate institutional homes, governed by their own intra-sector coordination groups and funding channels (Bank, 2018b) (Steinbach et al., 2016). Thus, significant knowledge gaps remain in terms of understanding the potential of SP to build long-term resilience to climate change (Ulrichs et al., 2019). Future efforts should be geared to develop climate-responsive social protection policies that consider a broad range of issues including urbanisation and migration, impact of green policies on the poor, access to essential health care and risks to socially marginalised groups (Aleksandrova, 2019). Along with strengthening links to climate information and early warning systems, finance for enabling social protection systems to address climate-related shocks and stresses dynamically needs to be scaled up (Ulrichs et al., 2019) (Kuriakose et al., 2013).

10.5.7 Education and Capacity Development

10.5.7.1 Point of departure

Countries with the least capacity are hit first and hardest by impacts, such as the Himalayan region and densely-populated deltas in Asia (De Souza et al., 2015); (Khan, 2017). Acknowledging the limitation in terms of capacity and coping mechanisms towards climate change, education, training and awareness-building is central to sustaining long-term capacity-building (Clemens et al., 2016). Education has lot more to offer and room for improvements in addressing climate change, particularly in the climate hotspots of the Asia region where mostly poor, disadvantaged and vulnerable communities to CC are residing (Mani et al., 2018). In particular, dissemination of climate change awareness and information need more explanation (Wi and Chang, 2018); (Steg et al., 2014),(Cho, 2020) international and national support through institutions and financing is critical for successful capacity-building (Hemachandra, 2019); capacity building must be designed for long-term and self-sustaining (Gustafson et al., 2018); national ownership by recipient countries and members of communities of capacity building efforts is key to ensuring their success (Mikulewicz, 2017); (Roberts and Pelling, 2016).

10.5.7.2 Findings

The need to develop tailored climate communication and education strategies for individual nations as public awareness and risk perceptions towards climate change vary greatly (Lee et al., 2015a) (*medium evidence, high agreement*). Improving and investing on basic education, climate literacy and place-based strategies of climate change are vital to enhance public engagement, societies adaptive capacity and support for climate action (Lutz et al., 2014c); (Hu and Chen, 2016). As stated in IPCC Special Report 1.5C sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (Roy et al., 2018). Hence, various concepts are introduced to foster awareness, understanding, knowledge, participation as well as commitment towards managing climate change in a sustainable manner, such as Education for Sustainable Development (ESD) aimed at integrating principles and practices of sustainable development in all aspects of education and learning to foster individuals who will contribute to the realisation of a more sustainable society (Kitamura, 2017).

Climate Change Education (CCE) is also now addressed in the context of Education for Sustainable Development (ESD) that allows for learners to understand the causes and consequences of climate change and their readiness to take actions (Mochizuki and Bryan, 2015). ESD and CCE are gaining broader attention, for instance in China (Han, 2015) and Korea (Sung, 2015), however development of policies and implementation of initiatives regarding ESD and CCE still face a handful of challenges, in which requires a strong political will and consensus of key stakeholders (Læssøe and Mochizuki, 2015). Effective communication on climate change education particularly for younger generation engagement is also essential as they are our future leaders as climate change is an inter-generational equity issue (Corner et al., 2015). Action for Climate Empowerment (ACE) of Article 6 UNFCCC, target youth as a major group for effective engagement in the formulation and implementation of decisions on climate change (UNFCCC, 2015). Increasing attention from countries in Asia, such as Thailand, India, to encourage innovative ways to provide adequately in educating and engaging youth in climate change issues (Dür and Keller, 2018); (Narksompong and Limjirakan, 2015).

Integrated approach of knowledge about climate change, embraces both the importance in bridging knowledge of climate science and respecting Local Knowledge and Indigenous Knowledge, should be at the heart of any effort to educate citizens to have a deeper understanding of the causes and consequence of climate change in a holistic manner (Aswani et al., 2018). Indigenous Peoples—comprising about six percent of the global population—play a crucial role in the fight against CC for two interlinked reasons, first, they have a particular physical and spiritual relationship with land, water and associated ecosystems and tend to be among the most vulnerable to CC (Magni, 2017). Second, they have a specialised ecological and traditional knowledge relevant to finding the best solutions to CC (Rautela and Karki, 2015). Indigenous knowledge systems and resource management practices are important tools for both mitigating and adapting to CC (Fernandez-Llamazares et al., 2015). Indigenous knowledge is increasingly recognised as a powerful tool for compiling evidence of CC over time (Ahmed et al., 2016a). Knowledge of Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR) provide a range of complementary approaches in building resilience and reducing the vulnerability of natural and human systems to the impacts of CC and environmental hazards (Mall et al., 2019). The adaptation dimension involves developing knowledge and utilising existing Local Knowledge and Indigenous Knowledge, skills and dispositions to better cope with already evident and looming climate impacts (Aghaei et al., 2018). It is also important to ensure inclusive efforts in DRR across different nations and communities as well as increasing skills and capacities of women towards DRR efforts (Hemachandra et al., 2018); (Reyes and Lu, 2016); (Drolet et al., 2015); (Alam and Rahman, 2014); (Islam et al., 2016b). More effective and efficient teaching and learning strategies as well as collaborative networks are needed to increase preparedness and DRR activities across various levels of community (Gampell et al., 2017); (Shiwaku et al., 2016); (Takahashi et al., 2015); (Oktari et al., 2015); (Tuladhar et al., 2015b).

As shown in Table 10.6, education and capacity-building aspects affecting adaptation by sub-regions examples.

Table 10.6: Education and capacity-building aspects affecting adaptation by sub-regions examples.

Sub-region		Adaptation interventions	Education and Capacity-building aspects affecting adaptation	Supporting references
North Asia	Human well-being	PEEX (Pan-Eurasian Experiment) originated from a bottom-up approach by the science communities aiming at resolving major uncertainties in Earth system science and global sustainability issues concerning the Arctic and boreal pan-Eurasian regions, as well as China	Educating next generation of multidisciplinary experts and scientists capable of finding tools in solving future environmental, socioeconomic and demographic development of the Arctic and boreal regions as well as China	Pan Eurasian regions, as well as China (Kulmala et al., 2015)
West Asia	Agriculture	Smallholders farmers' vulnerability assessment	Level of education high more human capacity, adaptive capacity, less vulnerability	Iran (Jamshidi et al., 2019)
Central Asia	Agriculture, Water Resources, and Energy	Carrying out the selection and cultivation of drought-tolerant salt tolerant crops, preservation of the upper watershed of the rivers, improve climate resilience of hydro-facilities	Focal point for the preparation and implementation of programs for CC at the regional level, increased capacity of professionals in targeted areas and networking between them, and strengthen institutional, technical and human resources to promote adaptation and research in fields of climate and hydrological investigations, geographical information systems (GIS), environmental impact assessment, and protection and re-cultivation of lands,	Kazakhstan, Tajikistan, and Kyrzigstan Mountain societies in Central Asia (Schmidt-Vogt et al., 2016) (Xenarios et al., 2019)

South Asia	Agriculture	Productivity, net crop income, improvement in livelihoods and food security	Farmers' education, easy access to farm advisory services, weather forecasting and marketing information affect adaptation decisions.	Pakistan (Abid et al., 2016)
		Passive adaptation in agricultural and farming practices implicitly to cope with climate change	Increasing knowledge on climate change crucial to take concrete steps dealing with perceived climatic changes	India (Tripathi and Mishra, 2017)
		Farmers' perceptions shape knowledge vice versa on climate change	Age, education, occupation, farming experience, knowledge about coping strategies, significantly related with farmers' perception about climate change.	India (Aslam Ansari, 2018)
	Disaster Risk Reduction	Local institutions preparedness and capacity managing disaster at local scale	Capacity-building, technical support and financial capacity as well as adopt proactive approach to achieve higher level of disaster preparedness.	Pakistan (Shah et al., 2019)
Southeast Asia	Agriculture	Farm cultural practices adopt to minimise production losses due to extreme weather	Small scale farmers' attendance in climate change training enhance adaptive capacity.	Vietnam (Trinh et al., 2018)
		Farmers' barriers to adopt adaptation measures lack of fund and timely information	Knowledge of crop variety, increase educational outreach and communicating CC related information likelihood employ adaptive strategies.	China (Zhai et al., 2018)
		In Lower Mekong Basin, farmers in rural, under-resourced communities are unaware of how climate change will affect them.	Scientific findings can be merged with local knowledge at a community level to help raise awareness; knowledge gaps on both can be filled for better understanding and adaptation planning.	Cambodia, Laos, Vietnam, Thailand (USAID, 2015); (Gustafson et al., 2018)
	Coastal areas	Households' vulnerability due to variation in socio-economic and livelihoods assets.	Increase resilience by establishing effective communication system, improve knowledge on climate.	Vietnam; Indonesia ((Huynh and Stringer, 2018); (Nanlohy et al., 2015)
	Disaster Risk Reduction	Capacity-building through learning lab on disaster risk management for sustainable development (DRM-SD).	Transfer learning initiative to provide approach guidelines and innovative mechanisms for DRM practitioners who will have the know-how and potential for leadership in DRM-SD.	Four ASEAN countries; Malaysia, Vietnam, Lao PDR, Cambodia (Ahmad Shabudin et al., 2017)
East Asia	Disaster Risk Reduction	Community participation and disaster education need to be conducted so that people can take actions in disaster management.	Educational resilience system tested and revised through experiences from past disasters. Also recognising gender perspectives into mainstream disaster management. 'School-based recovery concept' facilitates short-term recovery and the longer-term community building needs. It can also help communities in building new networks and solving chronic social problems.	Japan (Matsuura and Shaw, 2014; Saito, 2014; Shiwaku et al., 2016)
	Bridging Indigenous Knowledge and scientific knowledge	Effort to solve real-world problems should first engage with those local communities that are most affected, beginning	Paying attention to the Indigenous perception of a hazard and risk can increase the effectiveness of projects implemented by practitioners who might need to communicate risks in the future.	(Mistry and Berardi, 2016; Roder et al., 2016)

		from the perspective of Indigenous Knowledge and then seeking relevant scientific knowledge	Empowering younger generation to ensure continuity of Indigenous cultures and theirlinked ecosystems.	

Knowledge gaps: Capacity-building at national and local levels still need to address gaps in research and practice, such as impacts and results of different preparedness measures (Alcayna et al., 2016). Ad-hoc and localised documentations and monitoring of efforts to build adaptive capacities has rendered it difficult to assess success (Cinner et al., 2018). Recommendations for strengthened capacity building are sometimes made or understood in isolation from the underlying structural issues shaping vulnerability, or without adequately recognising the political relationships that mediate the ways in which particular technical interventions result in differentiated outcomes for different groups (Archer and Dodman, 2015). Thus, design and decision-based tools such as rapid assessment for community resilience to climate change as well as rapid approach to monitor the effectiveness of aid projects support community- based adaptation to climate change is analysed using multidimensional approach, procedural, distributional, rights and responsibilities (Nkoana et al., 2018); (Jacobson et al., 2019). As a model of communication and engagement, citizen science has the potential to promote individual and collective climate change action (Groulx et al., 2017). More than information provision is needed to mobilise public action on climate change (Kyburz-Graber, 2013). Citizen science links communication and engagement in a manner that hold important lessons on ways to promote collective responses to climate (Bonney et al., 2016); (Wals et al., 2014). The power of science-based citizen engagement lies in citizen group contribution in drawing upon their local knowledge to enrich the knowledge base required for management decisions (Sayer et al., 2015). Scientific evidence may be less attuned to the complexity of local realities in managing climate change, thus citizen science has the potential in bridging this gap and has many advantages for climate mitigation and adaptation practice and policy (Ford et al., 2016). While citizen science uses citizens as policy passive objects for research in conducting measurements for big data sets, citizen social science (CSS) is gaining its momentum where it repositions citizens as central co-learners that can widen the climate science evidence-base to a more holistic understanding for the benefit of all (Kythreotis et al., 2019).

10.6 Climate Resilient Development Pathways

10.6.1 Climate-resilient Development Pathways in Asia

Climate-resilient development pathways (CRDPs) are ‘trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate’ (Roy et al., 2018). Moving beyond a business-as-usual scenario, CRDPs involve not only adaptation and mitigation choices but also sustainable development implications and societal transformation (Roy et al., 2018). This basic understanding of CRDPs explicitly reflects that climate action (mitigation and adaptation) and sustainable development are fundamentally integrated and interdependent.

There is *high confidence* that currently implemented climate action in Asia (such as climate smart agriculture, ecosystem-based disaster risk reduction, investing in urban blue-green infrastructure) can meet adaptation, mitigation, and sustainable development goals simultaneously, presenting opportunities for climate-resilient development (CRD). However, there also exist significant barriers to CRD such as fragmented, reactive governance; inadequate evidence on which actions to prioritise and how to sequence them; and finance deficits. Some Asia countries and regions offer solutions to overcome these barriers: Through use of advanced technologies (in-situ observation and remote sensing, a variety of new sensor technologies, citizen science, artificial intelligence, and machine learning tools); regional partnerships and learning; improved forecasting capabilities; and better risk awareness (*high confidence*).

Asian countries are repeatedly identified as the most vulnerable to climatic risks with key sectors such as agriculture, cities and infrastructure, and terrestrial ecosystems expected to see high exposure to multiple hazards (Section 10.3). Owing to rapid development and large populations, Asian countries have large and growing GHG emissions: in 2018, five of the top 10 emitters in the world were Asian : China (1), India (3), Japan (5) Republic of Korea (8), and Indonesia (10) (Friedlingstein et al., 2019) although it is critical to note that per capita emissions and cumulative emissions are relatively lower than developed economies (Raupach et al., 2014). However, in the 2020 Sustainability Index and Dashboard, only two Asian countries made it to the top 30 countries in the world: Japan (17) and Republic of Korea (20) (Sachs et al., 2020). Finally, Asia has varied capacities to adapt with high heterogeneity in adaptation progress across the region.

Given this context of high risks, growing emissions, and varied adaptive capacities in Asia, CRDPs can enable (1) reducing existing vulnerability and inequality, (2) sustainable development and meeting the SDGs, and (3) managing multiple and often concurrent risks, including climate change and disaster risks Potentially, combinations of adaptation and mitigation options will be required to lead to climate-resilient development (see Fig on CRDPs in Ch 18) and some of these are outlined in Table 10.7. For example, climate-smart agriculture strengthens food security (SDG 2, Zero Hunger) (Aggarwal et al., 2019); urban disaster management such as Jakarta Disaster Risk Reduction Education Initiative contributes to SDG 11 (Sustainable Cities) (Ajibade et al., 2019).

Table 10.7: Adaptation options that can have mitigation and SDG synergies and trade-offs, providing opportunities for triple wins necessary for CRDPs.

Adaptation option	**Mitigation impacts (H/M/L/NA)**[a]	**Implications on SDGs**		**References**
		Positive	**Negative**	
Wetland protection, restoration	*Medium synergy* Carbon sequestration through mangroves	SDGs 8, 14, 15		(Griscom et al., 2020) in SE Asia
Solar drip irrigation	*High synergy* Shift to cleaner energy	SDGs 2, 7, 12	SDG 10	(Alam et al., 2020) in South Asia
Climate-smart agriculture	*High synergy*[b] No till practices and improved residue management can reduce soil carbon emissions	SDGs 2, 12		(Aggarwal et al., 2019), (Aryal et al., 2020b), (Aryal et al., 2020a), and (Tankha et al., 2020) in South Asia; (Chandra and McNamara, 2018) in SE Asia
Integrated smart water grids	*High synergy* Reduced energy needs for supplying water	SDGs 6, 9, 11, 13		(Kim, 2017) in Asia
Disaster risk management (including early warning systems)[c]	Not applicable	SDGs 9, 11	SDGs 5, 10	(Ajibade et al., 2019), (Herbeck and Flitner, 2019), (Aryal et al., 2020b) and (Mishra, 2020) in South and SE Asia; (Iturrizaga, 2019) in Asia; (Sovacool et al., 2012) in Bhutan; Grefalda et al. (2020) in Philippines
Carefully planned resettlement and migration (including decongestion of urban areas)	Inadequate evidence to make an assessment	SDGs 8, 10, 11	SDGs 6, 10, 11	(Arnall, 2019) in Asia; (Maharjan et al., 2020) in South Asia; (Estoque et al., 2020) in the Philippines; Banerjee et al. (2019) in Nepal
Aquifer storage and recovery	*Low synergy*	SDGs 6, 12		(Lopez et al., 2014) in Saudi Arabia; (Hoque et al., 2016) in South and SE Asia
Nature-based solutions in urban areas: green infrastructure (including urban green space, blue-green infrastructure)	*High synergy* Blue-green infrastructure act as carbon sinks	SDGs 3, 9, 11		(Mabon et al., 2019) in Japan; (Estoque et al., 2020) in the Philippines; (Byrne et al., 2015) and (Zhang et al., 2020a) in China; (Mabon and Shih, 2018) in Taiwan, Province of China; (Liao, 2019) and (Radhakrishnan et al., 2019) in Singapore
Coastal green infrastructure	*High synergy*	SDGs 9, 11, 13, 14, 15		(Sovacool et al., 2012), (Chow, 2018) and (Zinia and McShane, 2018) in Bangladesh; (Koh and

				Teh, 2019) and (Herbeck and Flitner, 2019) in SE Asia; (Giffin et al., 2020) in Asia

Table Notes:
[a] Expert judgement
[b] Climate change adaptation options in the agricultural sector include soil management, crop diversification, cropping system optimisation, and management, water management, sustainable land management, crop pest and disease management, and direct seeding of rice (Aryal et al., 2020b). Other specific agricultural practices that have adaptation and mitigation synergies include between tillage and residue management, alternate wetting and drying, site-specific nutrient management, crop diversification to less water-intensive crops such as maize, and improved livestock management (Aryal et al., 2020a).
[c] Risk management strategies in agriculture include crop insurance, index insurance, social networking and community-based adaptation, collective international action, and integrated agro-meteorological advisory services (Aryal et al., 2020b).

The following sub-sections examine CRDPs through three approaches that are particularly important in Asia and have a large body of evidence to assess implications for adaptation, mitigation, and sustainable development. The three illustrative approaches are: (1) Disaster risk management and adaptation synergies; (2) Food Water Energy Nexus; (3) Poverty alleviation and meeting equity goals.

10.6.2 Disaster Risk Reduction and Climate Change Adaptation Linkages

10.6.2.1 Point of Departure

There is growing evidence on the interconnectedness of extreme weather, climate change and disaster impacts (Asia, 2017; Reyer, 2017). In the Asian region, climate-related disasters have become more recurrent and destructive in terms of both economic and social impacts (Bhatt et al., 2015); (Aich et al., 2017); (Vij et al., 2017). Projections of increasing frequency, intensity, and severity of climate-related disasters call for better integration of climate change adaptation and disaster risk reduction (Sapountzaki, 2018) in policy development to address risks efficiently (Rahman et al., 2018) and to promote sustainable development pathways for reduced vulnerability and increased resilience(Seidler et al., 2018). Connecting climate change adaptation and disaster risk reduction efforts in both policy and practice continue to be a challenge, however, because the convergence of national policy and planning processes on CCA and DRR within Asia is in its early stages (Cousins, 2014) and structural barriers persist (Mall et al., 2019). CCA and DRR have developed as separate policy domains because of the different temporal and spatial scales considered, the diversity of actors involved, the policies and institutional frameworks adopted, and differences in tools and methodological approaches used. This has resulted to the CCA and DRR communities, and the knowledge and research they produce to support planning and decision making not always being well connected (Street et al., 2019).

10.6.2.2 Findings

Climate risk management in Asia is approached by focusing on hazards that are associated with extremes, i.e., extreme weather events with increased frequency and severity, and climate-and weather-related events. For example, farming has been affected by climatic variability and change in a wide variety of ways that include an increase in drought periods and intensity, a shortage of irrigation water availability, an increase in flooding and landslides, pest infestation of crops, a rising number of crop diseases, the introduction of invasive species and crop weeds, land degradation and an overall reduction in crop yields (Khanal et al., 2019). Estimation of the number of daily patients of heat-related illness based on the weather data and newly introduced metrics shows that the effects of age, successive days, and heat adaptation are key variables (Kodera et al., 2019).

Because most developing countries in Asia are highly vulnerable to the impacts of climate change due to a number of factors, many studies have focused on understanding vulnerability, for instance, gendered vulnerability at micro scale, which limits capacity to respond to both climatic and socioeconomic stressors (Ferdous and Mallick, 2019); vulnerability of urban poor communities due to the interaction of environmental and social factors (e.g., low incomes, gender, migrant status) and heightens the impacts of climate change on the poor (Porio, 2014); socio-ecological vulnerability where a degraded environment influences hazard patterns and vulnerability of people (Depietri, 2020); and livelihood vulnerability due to perceived climate risks and adaptation constraints (Fahad and Wang, 2018); (Hossain et al., 2020).

Risk assessments have been undertaken for different hazards such as floods (Al Saud, 2015; Al-Amin et al., 2019; Jha and Gundimeda, 2019; Mahmood et al., 2019; Zhang et al., 2019e); drought (Guo et al., 2019; Mainali et al., 2019); rainfall-induced landslide (Li et al., 2019b), sea level rise (Imaduddina and Subagyo, 2014; Suroso and Firman, 2018) and heat stress (Onosuka et al., 2019), among others, as well as environmental assessment, for example, in coastal zones (Islam and Zhang, 2019). Different types of strategies for climate risk management have also been studied including in-situ adaptation through ecosystem-based and community-based adaptation (Jamero et al., 2017); managed retreat or relocation (Buchori et al., 2018; Doberstein et al., 2020); planned sheltering in flood zones (Wu et al., 2019c); sustainable livelihoods that consider long term CCA measures of farmers and fishermen (Nizami et al., 2019; Shaffril et al., 2019); coastal afforestation through mangrove plantation (Rahman et al., 2018); management of ecosystem services to mitigate the effects of droughts (Tran and Brown, 2019); pre-investments, including holistic assessment of the basin (Inaoka et al., 2019); institutionalisation, where entry points are identified in efforts to build resilience (Lassa, 2019) and adaptive governance (Walch, 2019); and linking science and local knowledge (Mehta et al., 2019; van Gevelt et al., 2019).

The sectors that CCA and DRR have been linked are varied: (Filho et al., 2019) assessed adaptive capacity and resilience to climate change based on urban poverty, infrastructure and community facilities; (Mabon et al., 2019) looked at adaptation via the built environment, green roofs, and citizen and private sector involvement in smaller-scale greening actions; (Lama and Becker, 2019) focused on adaptation to reduce risk in conflicts; (Banwell et al., 2018) studied the link between health, CCA and DRR; and (Izumi et al., 2019) surveyed science, technology and innovation for DRR, {Banwell, 2018, Towards Improved Linkage of Disaster Risk Reduction and Climate Change Adaptation in Health: A Review} to name a few. Vulnerable groups have been given much attention such as farmers (Afroz, 2017; Gupta et al., 2019; Jawid and Khadjavi, 2019; Khanal et al., 2019; Shi et al., 2019a), women (Goodrich et al., 2019; Udas et al., 2019); (Hossain et al., 2019); and children, elderly and refugees (Asia, 2017). Finally, issues identified include water resources management (Bhatta et al., 2019; Sen et al., 2019; Zhang et al., 2019a); food security (Aleksandrova et al., 2016; Le, 2016); disaster governance (Blanco, 2015); climate boundary shifting wherein impacts of climate change are significant for crop production, soil management, and DRR (Talchabhadel and Karki, 2019); and institutional dimensions of CCA (Cuevas, 2018); (Islam et al., 2020).

Case studies on climate risk management and integrated CCA and DRR actions highlight some key lessons including an integrated and transformative approach to CCA, which focuses on long term changes in addressing climate impacts (Filho et al., 2019); adoption of an adaptive flood risk management framework incorporating both risk observation and public perceptions (Al-Amin et al., 2019); holistic approach and non-structural and technological measures in flood control management (Chan, 2014); monitoring of changes in urban surface water in relation to changes in seasons, land covers, anthropogenic activities, and topographical characteristics for managing watersheds and urban planning (Faridatul et al., 2019); removing ‘gender blindness’ in agrobiodiversity conservation and adaptation policies (Ravera et al., 2019); understanding uncertainties in CCA and DRR at the local level (van der Keur et al., 2016; Djalante and Lassa, 2019); promoting the use of Local Knowledge and Indigenous Knowledge alongside scientific knowledge (Hiwasaki et al., 2014); and increasing information, education and communication activities, and capacity development on DRR at the local level (Tuladhar et al., 2015a).

Several studies also identify enabling conditions to effectively implement CCA and DRR actions. In the Arab region in Asia (ARA), the following are critical: capacity building to develop knowledge and awareness, mainstreaming CCA and DRR in the national strategies and policies (e.g., water and environmental strategies), empowering the role of CCA and DRR actors notably women and rural societies, adopting lessons learned from regions with similar physical characteristics to ARA, establishing forecasting and prediction platforms that is supported by advanced monitoring technologies (e.g., remote sensing), and encouraging universities and research centers to develop studies on CCA and DRR. In Southeast Asia, laws and policies, institutional and financial arrangements, risk assessment, capacity building, and planning and implementation are entry points in integrating CCA and DRR (Lassa and Sembiring, 2017; Agency, 2018). According to (Cutter et al., 2015), holistic solutions and integrated approaches, rigorous risk research that shows coherent science-based assessment and knowledge transfer from research to practice, and aligned targets on disaster risk management, climate change and sustainable development targets are critical. Social capital and social protection measures could promote pro-poor and gender responsive adaptation and socially inclusive policy (Dilshad et al., 2019; Yari et al., 2019). Community-based approaches could allow local perceptions of climate change and experience of place to be included in planning (Dujardin et al., 2018; Dwirahmadi et al., 2019; Widiati and Irianto, 2019) and multi-stakeholder participation could engage various actors like the private sector in CCA and DRR. Further, multi-level climate governance could benefit from vertical and horizontal interactions at different levels and layers in the city (Zen et al., 2019). To mainstream and secure funding commitment, CCA and DRR could be integrated into national development plans and sectoral long-term plans (Ishiwatari and Surjan, 2020; Rahayu et al., 2020; Rani et al., 2020b).

10.6.2.3 Knowledge Gaps

Adaptation follows knowledge on risks, and literature exists that systematically identifies and characterises exposure and vulnerability, but gaps still exist. Decision making under uncertainty is challenged by the lack of data for adapting to current and uncertain future climate, the different perceptions of risk, and the potential solutions across different cultures and languages (van der Keur et al., 2016). Lack of downscaled climatic data, diverse institutional structures, and missing links in policies, are among the challenges in South Asia (Mall et al., 2019). In agriculture, there are gaps in the use of advanced farming techniques such as drought-resistant crops, and information on climate change to support farming households in making adaptation decisions (Akhtar et al., 2019; Khanal et al., 2019; Ullah et al., 2019). Better understanding of effective water management is crucial due to conflicts for shared water in ARA (Shaban and Hamze, 2017; UNDP, 2018). For delta regions, gaps identified are methodologies and approaches appropriate for understanding social vulnerability at various scales, pathways required for adaptation policy and response in the deltas that transcend development, and the lessons from implemented policy and how practice can build on these lessons in the deltas, among others (Lwasa, 2015). Approaches in tackling the challenges of climate change and disasters in the cities of developing countries could be better understood, and shared between cities so they can learn from one another (Filho et al., 2019).

10.6.3 Food Water Energy Nexus

Point of Departure: Food, energy, water, and land are vital elements for sustainable development as well as enhancing resilience to both climatic and non-climatic shocks. All these resources are highly vulnerable to climate change (10.3.1; 10.3.4; 10.3.4). Poor people are most affected due to changes in resources availability and accessibility. Food, water, and energy security are interconnected (Bizikova et al., 2013; Ringler et al., 2013; Rasul, 2014; Chang et al., 2016; Ringler et al., 2016). Although adapting to the climate change is one of the core component of global, regional, national and sub-national agenda, the focus of adaptation action has remained sectoral. Undermining the interlinkages of food energy and water security may increase trade-offs between sectors or places, which may lead to maladaptation (Barnett and O'Neill, 2010; Howells et al., 2013; Lele et al., 2013). Therefore, focusing on the nature of trade-offs and synergies across food water and energy nexus for integrated management of resources is a potential strategy for adaption to both climatic and non-climatic challenges (Bhaduri et al., 2015; Zaman et al., 2017). Due to its importance to the Paris Agreement and Sustainable Development Goals (SDGs), food water energy nexus approach got increasing attentions to capture synergies and minimise trade-offs in this interconnected system, which is also critical for enhancing adaptation together (Bazilian et al., 2011; Lawford et al., 2013; UNESCAP, 2013; FAO, 2014; Rasul and Sharma, 2014; Taniguchi et al., 2017a; Sukhwani et al., 2019; Sukhwani et al., 2020).

Findings: The FEW nexus can be evaluated in the two-way interactions between water-food, water-energy and food energy (Taniguchi et al., 2017a). The water energy nexus includes water for energy and energy for water (Rothausen and Conway, 2011; Hussey and Pittock, 2012; Byers et al., 2014), water food nexus, which includes water for food and impact of food production on water (Hoekstra and Mekonnen, 2012) and energy consumption for food production and food crops for biofuel production (Tilman et al., 2009). Food water energy land nexus has diversified implications at the sub-regional level in Asia. The increase in water supply-gap raises questions about sustainability of main mode of electricity generation in South Asia-thermal power generation and hydropower generation- are both threatened by water shortage in South Asia (Luo, 2018b; Mitra et al., 2021). Furthermore, policy mismatch driven anthropogenic cause lead unsustainable water use for food production in India. For example, subsidised electricity supply for watering agriculture plays key role in losing groundwater's buffer capacity against the various changes including climate variabilities (Badiani et al., 2012; Mitra, 2017). In the Mekong River basin of Southeast Asia, massive and rapid export oriented hydropower development will have direct implication on regional food security and livelihoods through major negative effect on the aquatic ecosystem (Baran and Myschowoda, 2009; Dugan et al., 2010; Arias et al., 2014). Similarly, in Central Asia, shifting of water storage for irrigation to power development has increased risks on reliable quality and quality of water (Granit et al., 2012). Deforestation lead agro-environmental changes led to decrease forest water supply, increase irrigation water demand and negatively effect on cropland stability and productivity (Lim et al., 2017a; Lim et al., 2019b).

Knowledge gaps: Despite getting attention at the global, regional, national and sub-national agenda, there are many challenges remain in both scientific research and policy actions. The scientific challenges include data, information and knowledge gaps in understanding food energy water and land interlinkages, and lack of systematic tools to address trade-offs (Liu et al., 2017a). Until very recently, implementation of food energy water nexus focused primarily on technical solutions, whereas governance, i.e. the institutions and processes governing the WEF nexus, has not received much consideration (Scheyvens and Shivakoti, 2019). At the policy end, the common challenges for implementation of water energy food land nexus are absence of sectoral coordination (Pahl-Wostl, 2019); the influence of political priorities on decisions and lack of processes for scientific knowledge to shape decisions; lack of capacity to understand interlinkages between sectors; lack of multistakeholder engagement in planning and decision-making processes; and lack of incentive mechanisms and adequate finance to support the approach (Bao et al., 2018; Scheyvens and Shivakoti, 2019).

10.6.4 Social Justice and Equity

Social justice focuses on justice-related implications of social and economic institutions, examined in different ways such as distributional justice (distribution of benefits and burdens across different societal groups; procedural justice (the design of just institutions and processes for decision-making); inter-generational justice (duties of justice to future generations); and recognitional justice (recognition of historical inequality) (Thaler et al., 2017). Climate change is affecting every aspect of our society and economy, thus it is pertinent to understand the interactions between social justice and climate change impacts (Tol, 2018). In particular focusing on how vulnerability to various impacts is created, maintained and distributed across geographical, social, demographic and economic dimensions (Bulkeley et al., 2014; Schlosberg and Collins, 2014; Van de Vliert, 2014; Burke et al., 2016). For instance, environmental and health consequences of climate change, which disproportionately affect low-income countries and poor people in high-income countries, profoundly affect human rights and social justice (Levy and Patz, 2015). Furthermore, great concern is expressed about the plight of the poor, disadvantaged and vulnerable populations when it comes to climate but not in other policy domains (Winters, 2014).

Evidence is increasing on the importance of focusing on environmental sustainability and relieving poverty and social injustice are not conflicting aims, in fact there is a further need for mainstreaming such approaches in order to respond to the climate change challenge in a socially just manner (Mayrhofer and Gupta, 2016). These not conflicting aims are described as co-benefits as reiterated in the IPCC reports as a central concept that refers to 'the positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare' (IPCC, 2014b). Better understanding of how social justice affects and is affected by efforts to build adaptive capacity will be crucial to avoiding unintended and even perverse outcomes. For example, in Andaman coast of Thailand, responses to climate change trends and events tended to be reactive rather than proactive, making already vulnerable people even more vulnerable and undermining their capacity to adapt in the future (Bennett et al., 2014). Different forms of inequality, moreover, render some groups of people more vulnerable than others to damage from climate hazards. In Mumbai, India, for example, the houses of poorer families required repeated repairs to secure them against flood damage, and the cumulative cost of those repairs consumed a greater proportion of their income than for richer populations (UN, 2016). Building the resilience of vulnerable groups requires strong community and government institutions that can support efforts to cope with devastating events, offering social protection and social development initiatives to support at-risk or vulnerable groups (Drolet et al., 2015). In addition, agencies need to consider how they can best work in ways which potentially support longer-term positive change to gender roles and relations, such as post-disaster activities must build and resource women's resilience and adaptive capacity in practice and challenge the constraints that impinge on their lives (Alam and Rahman, 2019) (Hadiyanto et al., 2018) (Yumarni and Amaratunga, 2018) (Sohrabizadeh et al., 2016) (Sadia et al., 2016).

Insights from the environmental justice literature show that an over-emphasis on emission reductions at national levels obscures negative impacts on disadvantaged communities, including low-income communities (Burch and Harris, 2014). The issue of social justice and adaptation is particularly relevant because of the politics that drive how adaptation and recovery efforts and investments are targeted towards specific populations, places, and capacities (Klinsky et al., 2017). Hence, climate justice and equity need to be highlighted more explicitly in integrative approaches to mitigation and adaptation (Moellendorf, 2015; Henrique KP, 2020) (*medium evidence, high agreement*).

The term climate justice is used to problematise global warming in ethical and political contexts. It does so by employing the concepts of environmental justice and social justice to examine inequalities and violation of human/collective rights in relation to climate change impacts (Ghimire, 2016)

At the heart of climate justice concerns lies the asymmetry that those who have contributed least to the problem of climate change i.e. greenhouse gas (GHG) emissions are the ones who will be affected by its adverse impacts the most. It is about sharing the burden and benefits equitably – i) among developed and developing countries in the context of historical responsibility, and ii) within nations to uplift the marginalised and affected populations who have contributed the least to the problem in the contexts of per-capita equity and local vulnerability (Joshi, 2014; Chaudhuri, 2020; Shawoo, 2020).

An ethical analysis of the climate regime reveals an abiding strong interconnection between economic circumstances, geopolitical power and the justice claims that nations can assert in negotiations (Okereke, 2016). Events within the climate regime highlight the importance of questioning the extent to which claims of justice can ever be truly realised in the context of international regimes of environmental governance as well as how much concerns for justice are motivated by other con- cerns such as relative economic gains or geopolitical objectives (Sikor T, 2014) .

The global land rush and mainstream climate change narratives have broadened the ranks of state and social actors concerned about land issues, while strengthening those opposed to social justice-oriented land policies (Borras, 2018).The five deep social reforms (redistribution, recognition, restitution, regeneration and resistance) of socially just land policy are necessarily intertwined. But the global land rush amidst deepening climate change calls attention to the linkages, especially between the pursuit of agrarian justice on the one hand and climate justice on the other. Here, the relationship is not without contradictions, and warrants increased attention as both unit of analysis and object of political action. Understanding and deepening agrarian justice imperatives in climate politics, and understanding and deepening climate justice imperatives in agrarian politics, is needed more than ever in the ongoing pursuit of alternatives. For example, the intersection between land grabs and climate change mitigation politics in Myanmar has created new political opportunities for scaling up, expanding and deepening struggles toward ‘agrarian climate justice’(Sekine, 2021).

[START FAQ10.1 HERE]

FAQ 10.1: What are the current and projected key risks related to climate change in each sub-region of Asia?

Climate change related risks are projected to increase progressively at 1.5°C, 2°C and 3°C of global warming in many parts of Asia. Heat stress and water deficit are affecting human health and food security. Risks due to extreme rainfall and sea level rise are exacerbating in vulnerable Asia.

Climatologically, the summertime surface air temperature in South, Southeast and Southwest Asia is high, and its coastal area is very humid. In these regions, heat stress is already a medium risk for humans. Large cities are warmer more than 2°C compared to the surroundings due to heat island effects, exacerbating heat stress conditions. Future warmings will cause more frequent temperature extremes and heat waves especially in densely populated South Asian cities, where working conditions will be exacerbated and day-time outdoor work becomes danger. For example, incidence of excess heat-related mortality in 51 cities in China is estimated to reach 37,800 deaths per year over a 20-year period in the mid-21st century (2041–2060) under the RCP 8.5 scenario.

Asian glaciers are the water resources for local and adjacent regions. Glaciers are decreasing in Central, Southwest, Southeast and North Asia, but are stable or increased in some parts of Hindu Kush-Himalaya. The glacier melt water in southern Tibetan Plateau has increased during 1998-2007, and the total amount and area of glacier lakes increased during last decades. In the future, maximum glacial runoff is projected in High Mountain Asia. Glacier collapses and surges, together with glacier lake outburst flood (GLOF) due to the expansion of glacier lakes, will threaten the securities of the local and down streaming societies. The glacier is *likely* to disappear by nearly 50% in High Mountain Asia and about 70% in Central and Western Asia by the end of the 21st century under the RCP4.5 scenario, and more under the RCP8.5 scenario.

As a large number of populations is living in the drought-prone areas, water scarcity is a prevailing risk across Asia through water and food shortage leading to malnutrition. Population vulnerable to impacts related to water is going to increase progressively at 1.5°C, 2°C and 3°C of global warming. Aggravating drought condition is projected in Central Asia. Water quality degradation also has profound impact on human health.

Extreme rainfall causes floods in vulnerable rivers. Observed changes in extreme rainfall vary considerably region by region in Asia. Extreme rainfall events (such as heavy rainfall > 100 mm day^{-1}) have been increasing in South and East Asia. In the future, most of East and Southeast Asia are projected to experience more intense rainfall events as soon as by the middle of the 21st century. In those regions, the flood risk will become more frequent and severe. It is estimated that over 1/3rd Asian cities and about 932 million urban dwellers are living in areas with high risk of flooding.

Sea level rise is continuing. Higher than the global mean sea level rise is projected in Asian coasts. Storm surge and high wave by tropical cyclones of higher intensity are high risk for a large number of Asian mega-cities facing the ocean; China, India, Bangladesh, Indonesia and Viet Nam have the highest numbers of coastal populations exposed, thus most vulnerable disaster-related mortality.

Changes in terrestrial biome are observed that are consistent with warming, such as an upward move of treeline position in mountains. Climate change, human activity, lightning and quality of forest governance and management determine increase of wildfire severity and area burned in North Asia last decades. Changes in marine primary production are also observed. Up to 20% decrease over the past six decades in the Western Indian Ocean due to ocean warming and stratification restricts nutrient mixing. The risk of irreversible loss of many ecosystems will increase with global warming.

The likelihood of adverse impacts to agricultural and food security in many parts of developing Asia will progressively escalate with the changing climate. Potential of total fisheries production in South and Southeast Asia is also projected to decrease.

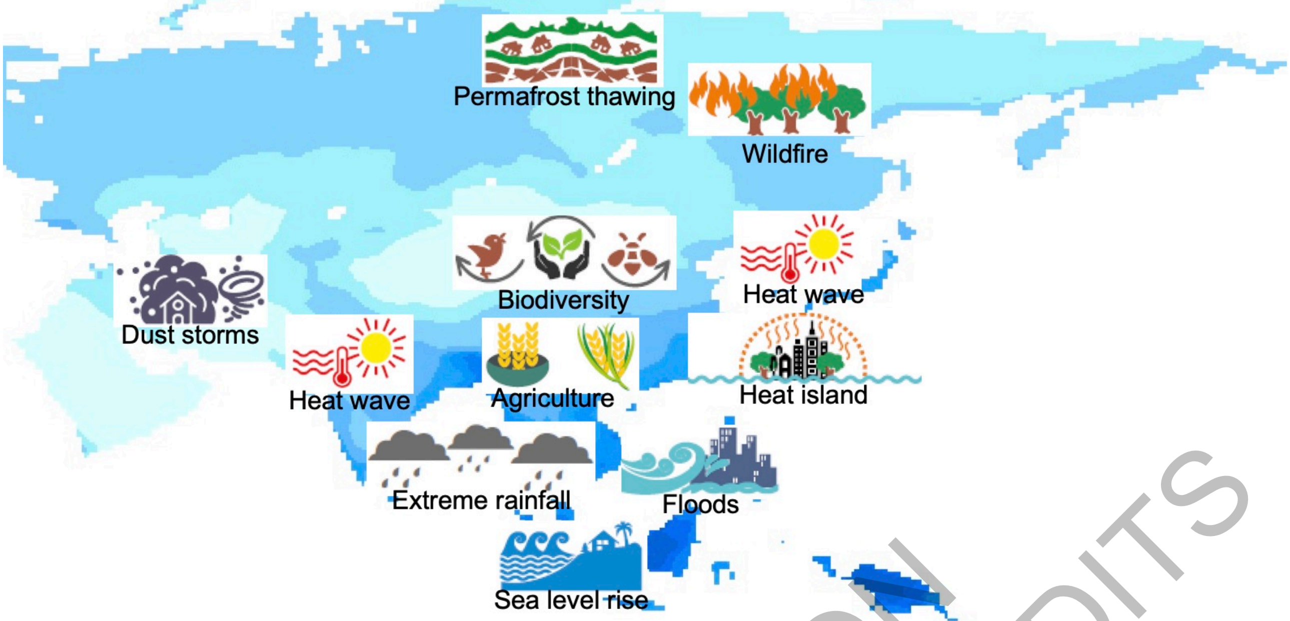


Figure FAQ10.1 Key risks related climate change in Asia.

[END FAQ10.1 HERE]

[START FAQ10.2 HERE]

FAQ 10.2: What are current and emerging adaptation options across Asia?

Mirroring the heterogeneity across Asia, different countries and communities are undertaking a range of reactive and proactive strategies to manage risk in various sectors. Several of these adaptation actions show promise; reducing vulnerability and improving societal wellbeing. However, challenges remain around scaling up adaptation actions in a manner that is effective and inclusive while simultaneously meeting national development goals.

Asia exhibits tremendous variation in terms of ecosystems, economic development, cultures, and climate risk exposure. Mirroring this variation, households, communities, and governments have a wide range of coping and adaptation strategies to deal with changing climatic conditions, with co-benefits for various non-climatic issues such as poverty, conflict, and livelihood dynamics.

Currently, Asian countries have rich evidence on managing risk, drawing on long histories of dealing with change. For example, to deal with erratic rainfall and shifting monsoons, farmers make incremental shifts such as changing what and when they grow or adjusting their irrigation practices. Communities living in coastal settlements are using early warning systems to prepare for cyclones or raising the height of their houses to minimize flood impacts. These types of strategies, seen across all Asian sub-regions, based on local social and ecological contexts, are termed *autonomous adaptations* that occur incrementally and help people manage current impacts.

Currently and in the future, Asia is identified as one of regions most vulnerable to climate change, especially on extreme heat, flooding, sea level rise, and erratic rainfall. All these climatic risks, when overlaid on existing development deficits show us that incremental adaptation will not be enough, transformational change is required. Recognizing this, at sub-national and national levels, government and non-governmental actors are also prioritizing *planned adaptation strategies* which include interventions like 'climate-smart agriculture' as seen in South and South East Asian countries or changing labour laws to reduce exposure to heat as seen in West Asia. These are often sectoral priorities governments lay out through national or subnational policies and projects, drawing on various sources of funding: domestic, bilateral, and international. Apart from these planned adaptation strategies in social systems, Asian countries also report and invest in adaptation measures in natural systems such as expanding nature reserves to enable species conservation; or setting up habitat corridors to facilitate landscape connectivity and species movements across climatic gradients.

Overall, the fundamental challenges that Asia will see exacerbate under climate change are around water and food insecurity, poverty and inequality, and increased frequency and severity of extreme events. In some places and for some people, climate change, even at 1.5°C and more so at 2°C, will significantly constrain the functioning and wellbeing of human and ecological systems. Asian cities, villages, and countries are rising to this current and projected challenge, albeit somewhat unevenly.

Some examples of innovative adaptation actions are China's Sponge Cities which are trying to protect ecosystems while reduce risk for people, now and in the future. Another example is India's Heat Action Plans that are using 'cool roofs' technologies and awareness building campaigns to reduce impacts of extreme heat. Across South and Southeast Asia, climate-smart agriculture programmes are reducing greenhouse gas emissions associated with farming while helping farmers adapt to changing risks. Each country is experimenting with infrastructural, nature-based, technological, institutional, and behavioral strategies to adapt to current and future climate change with local contexts shaping both the possibility of undertaking such actions as well as the effectiveness of these actions to reduce risk. What works for aging cities in Japan exposed to heatwaves and floods may not work for pastoral communities in the highlands of Central Asia but there is progress on understanding what actions work and for whom. The challenge is to scale current adaptation action, especially in most exposed areas and for most vulnerable populations, as well as move beyond adapting to single risks alone (i.e. adapt to multiple coinciding risks such as flooding and water scarcity in coastal cities across South Asia or extreme heat and flash floods in West Asia). In this context, funding and implementing adaptation is essential and while Asian countries are experimenting with a range of autonomous and planned adaptation actions to deal with these multiple and often concurrent challenges, making current development pathways climate-resilient is necessary and, some might argue, unavoidable.

Table FAQ10.2.1: System transitions, sectors, and illustrative adaptation options.

System transitions	**Sectors**	**Illustrative adaptation options**
Energy and industrial systems	Energy and industries	• Diversifying energy sources • Improving energy access, especially in rural areas • Improving resilience of power infrastructure • Rehabilitation and upgrading of old buildings
Land and ecosystems	Terrestrial and freshwater ecosystems	• Expanding nature reserves • Assisted species migration • Introducing species to new regions to protect from climate-induced extinction risk • Sustainable forest management including afforestation, forest fuel management, fire management
	Ocean and coastal ecosystems	• Marine protected areas • Mangrove and coral reef restoration • Integrated coastal zone management • Sand banks and structural technologies
	Freshwater	• Integrated watershed management • Transboundary water management • Changing water access and use practices to reduce/manage water demand • High efficiency water-saving technology • Aquifer storage and recovery
	Agriculture, fisheries, and food	• Changing crop type and variety, improving seed quality • Water storage, irrigation and water management • Climate-smart agriculture • Early warning systems and use of climate information services • Fisheries management plans (e.g., seasonal closures, limited fishing licenses, livelihood diversification)

Urban systems	Cities, settlements and	• Flood protection measures and sea walls • sustainable land use planning and regulation • Protecting urban green spaces, improving permeability, mangrove restoration in coastal cities • Planned relocation and migration • Disaster management and contingency planning
	Key infrastructures	• climate-resilient highways and power infrastructure • relocating key infrastructure
Health systems		• Reducing air pollution • Changing dietary patterns

[END FAQ10.2 HERE]

[START FAQ10.3 HERE]

FAQ 10.3: How is Local Knowledge and Indigenous Knowledge being incorporated in the design and implementation of adaptation projects and policies in Asia?

Indigenous People, comprising about six percent of the global population, play a crucial role in managing climate change for two important reasons, first, they have a physical and spiritual connection with land, water and associated ecosystems, thus making them most vulnerable to any environmental and climatic changes. Second, their ecological and local knowledge are relevant to finding solutions to climate changes.

Local Knowledge and Indigenous Knowledge (LIK) play an important role in the formulation of adaptation governance and related strategies (IPCC 2007), and best quality, locality specific knowledge can help address serious lack of education on climate change and uncertainties surrounding quality, salience, credibility and legitimacy of available knowledge base.

Key findings across Asia, underline the importance of building, sustaining and augmenting local capacity through addressing inadequacies in terms of resource base, climate change awareness, government-community partnerships, and vulnerability assessment. Furthermore, inclusion of Local Knowledge and Indigenous Knowledge as well as practices will improve adaptation planning and decision-making process to climate change.

In climate sensitive livelihoods, integrated approach informed by science that examines multiple stressors along with LIK appears to be of immense value. For instance in building farmers' resilience, enhancing climate change adaptation, ensuring cross cultural communication, and promoting local skills are drawing upon Indigenous People's intuitive thinking processes and geographical knowledge of remote areas.

There is also a widespread recognition that Local Knowledge and Indigenous Knowledge are important in ensuring successful ecosystem-based adaptation (EbA). However, this recognition requires more practical and translation into LIK driven EbA projects. For instance, in the Coral Triangle region, creating historical timelines and mapping seasonal calendars can help to capture LIK while also feeding this information into climate science and climate adaptation planning. Identifying indigenous crop species for agriculture by using LIK is already identified as an important way to localise climate adaptation, an example observed from Bali's vital contribution of moral economies to food systems have long build resilience among groups of communities in terms of food security and sovereignty even with challenges faced due to modernizing of local food systems.

Many of the pressing problems of Asia, including water scarcity, rapid urbanisation, deforestation, loss of species, rising coastal hazards, agricultural loss can be effectively negated, or at least minimised through proper adoption of suitable science and technological method. Climate change adaptation is greatly facilitated by science, technology and innovation. This ranges from application of existing science, new development on scientific tools and methods, application of LIK and citizen sciences. Deploying Knowledge Quality Assessment Tool found significant co-relation between science-based and LIK framing would help to address, acknowledge, and utilise integrated approach in showing how the respect to this wisdom of LIK, a valuable asset for climate adaptation governance. LIK based environmental indicators need to be seen as part of a separate system of knowledge that coexists with, but is not submerged into, another conventional knowledge system.

In the context of education and capacity development of climate change, integrated approach of embracing both the importance of climate science and LIK is acknowledged. The LIK is increasingly recognised as a powerful tool for compiling evidence of climate change over time. Such as knowledge of climate change adaptation (CCA) and disaster risk reduction (DRR) provide a range of complementary approaches in building resilience and reducing vulnerability of natural and human systems. Developing knowledge and utilising existing Local Knowledge and Indigenous Knowledge, skills, and dispositions to better cope with already evident and looming climate impacts. Engaging communities in the process of documenting and understanding long-term trends and practices will enable both Local Knowledge and Indigenous Knowledge as well as Western scientific assessments of change in designing appropriate climate adaptation measures.

[END FAQ10.3 HERE]

[START FAQ10.4 HERE]

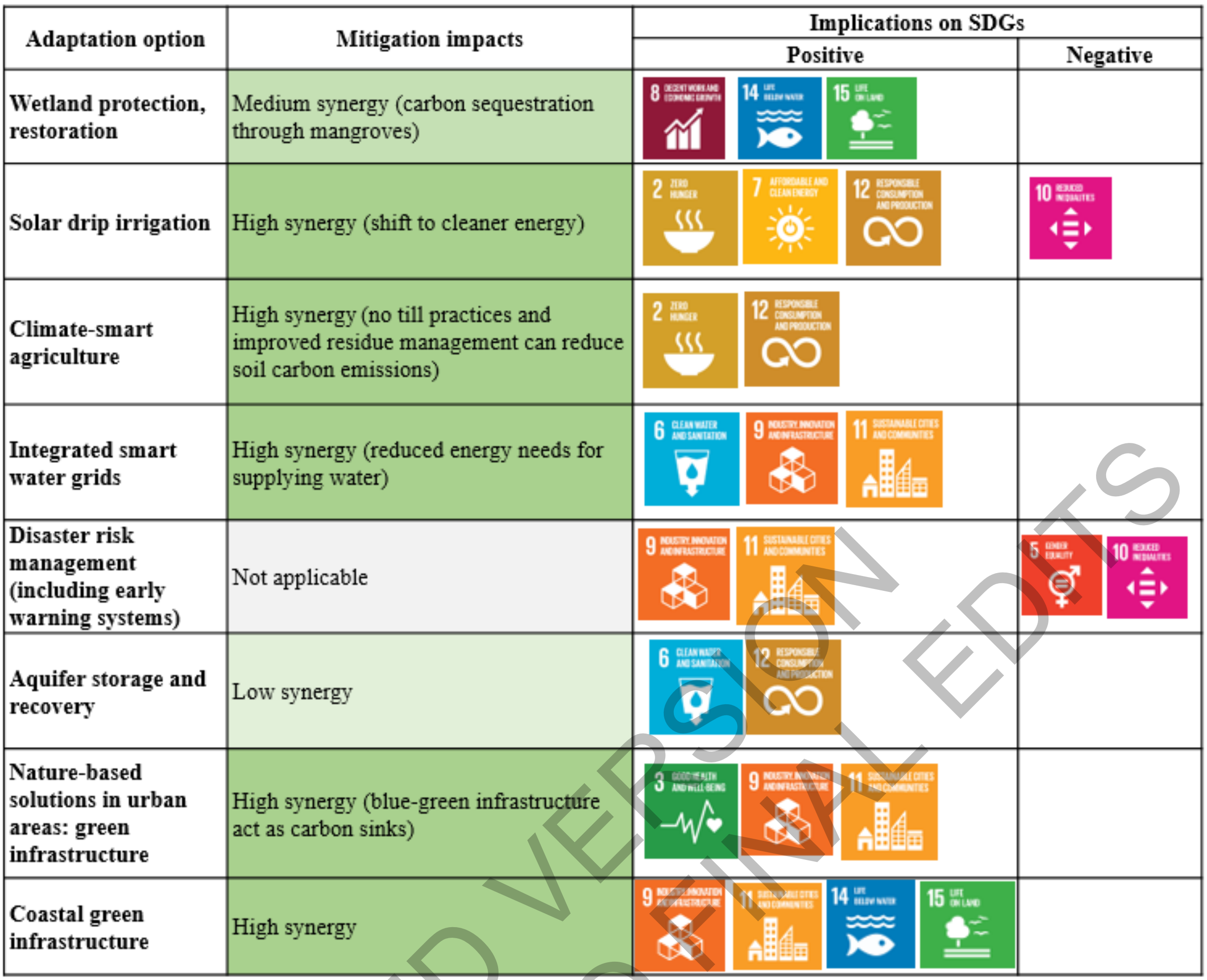
FAQ 10.4: How can Asia meet multiple goals of climate change adaptation and sustainable development within the coming decades?

Asian countries are testing ways to develop in a climate resilient manner to meet goals of climate change and sustainable development simultaneously. Some promising examples exist but the window of opportunity to put some of these plans in place is small and reducing, highlighting the need for urgent action across and within countries.

In order to achieve multiple goals of climate change adaptation, mitigation, and sustainable development; rapid, system transitions across energy systems; land and ecosystems; urban and infrastructural systems; are critical. This is especially important across Asia, which has the largest population exposed to current climate risks, high sub-regional diversity, and where risks are expected to rise significantly and unevenly under higher levels of global warming. However, such transformational change is deeply challenging because of variable national development imperatives; differing capacities and requirements of large, highly unequal, and vulnerable populations; and socio-economic and ecological diversity that requires very contextual solutions. Further, issues such as growing transboundary risks, inadequate data for long-term adaptation planning, finance barriers, uneven institutional capacity, and non-climatic issues such as increasing conflict, political instability, and polarization, constrain rapid, transformational action across systems.

Despite these challenges, there are increasing examples of action across Asia that are meeting climate adaptation and sustainable development goals simultaneously such as through climate smart agriculture, disaster risk management, and nature-based solutions. To enable these system transitions, vertical and horizontal policy linkages; active communication and cooperation between multiple stakeholders; and attention to the root causes of vulnerability are essential Further, rapid systemic transformation can be enabled by policies and finances to incentivize capacity building, new technological innovation and diffusion. The effectiveness of such technology-centric approaches can be maximized by combining with attention to behavioral shifts such as by improving education and awareness, building local capacities and institutions, and leveraging Indigenous and local knowledge.

The window of opportunity to act is small and reducing; if system transitions are delayed, there is high confidence that climatic risks will increase human and natural system vulnerability as well as increase inequality and erode achievement of multiple SDGs. Thus, urgent, systemic change that is suited to national and sub-national socio-ecological contexts across Asia is imperative.



Adaptation option	Mitigation impacts	Implications on SDGs	
		Positive	Negative
Wetland protection, restoration	Medium synergy (carbon sequestration through mangroves)	8 DECENT WORK AND ECONOMIC GROWTH 14 LIFE BELOW WATER 15 LIFE ON LAND	
Solar drip irrigation	High synergy (shift to cleaner energy)	2 ZERO HUNGER 7 AFFORDABLE AND CLEAN ENERGY 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	10 REDUCED INEQUALITIES
Climate-smart agriculture	High synergy (no till practices and improved residue management can reduce soil carbon emissions)	2 ZERO HUNGER 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	
Integrated smart water grids	High synergy (reduced energy needs for supplying water)	6 CLEAN WATER AND SANITATION 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES	
Disaster risk management (including early warning systems)	Not applicable	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES	5 GENDER EQUALITY 10 REDUCED INEQUALITIES
Aquifer storage and recovery	Low synergy	6 CLEAN WATER AND SANITATION 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	
Nature-based solutions in urban areas: green infrastructure	High synergy (blue-green infrastructure act as carbon sinks)	3 GOOD HEALTH AND WELL-BEING 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES	
Coastal green infrastructure	High synergy	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 14 LIFE BELOW WATER 15 LIFE ON LAND	

Figure FAQ10.4.1: Adaptation options, mitigations impacts and implications on SDGs.

[END FAQ10.4 HERE]

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