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Climate Change Impacts and Vulnerabilities in Canada's Pacific Marine Ecosystems

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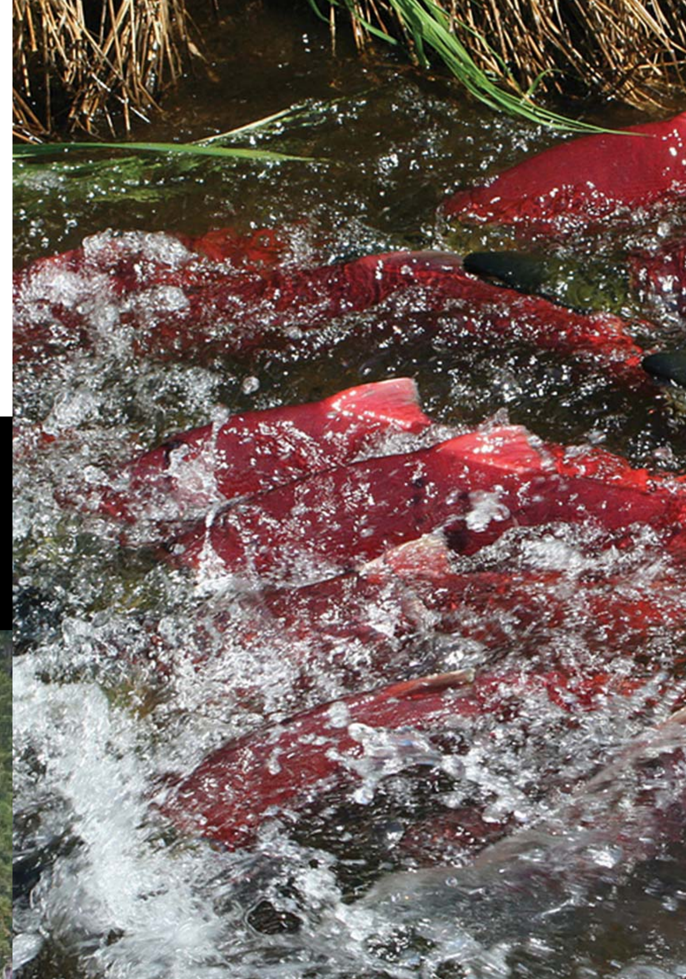


Executive Summary

Canada's Pacific marine ecosystems, which lie adjacent to the coast of British Columbia, are rich, extraordinarily productive, and highly textured with conditions that vary considerably on different scales of time and space. This marine and coastal environment is unique and of cultural, socio-economic, and ecological significance to the people of British Columbia and the rest of Canada. Global environmental changes caused by greenhouse gas emissions are an increasing concern for the health of the whole region's biologically rich ecosystems, and these must be examined in the context of the existing local and regional impacts, which are more manageable than global changes. The Canadian Parks and Wilderness Society and WWF-Canada commissioned the present report to synthesize current and projected impacts of these global changes, herein called "climate changes," on Canada's Pacific marine ecosystems. This report, and its companion report on adaptation approaches, was prepared to inform measures that can be employed to reduce the vulnerability of Canadian Pacific social-ecological systems to climate change, which can be considered in ocean and coastal resource planning.

The synthesis in this report is based on two components: (1) a review of the literature relating to marine climate changes and impacts in British Columbia and the northeast Pacific Ocean, including projections from the Canadian Regional Climate Model and global climate models; and (2) a preliminary screening level vulnerability assessment, including components of exposure, sensitivity, and adaptive capacity.

The climate and coastal oceanography of British Columbia, and Canada's Pacific, is particularly complex. Its coastal ocean is situated within a highly heterogeneous and dynamic transition zone between the California Current upwelling system and the Alaska Coastal Current downwelling system. Less is known about British Columbia's north coast marine region than about the southern region of the province, and while projections

of future changes are still somewhat uncertain, this synthesis uses the best available evidence to characterize future trends in British Columbia's physical and chemical characteristics related to climate changes. Expected physical trends include, but are not limited to:

- Increases in sea surface temperatures
- Generally increased precipitation and extreme precipitation events, and decrease in snowpack
- Changes in the temperature, seasonal patterns, and other characteristics of runoff
- Increased turbidity of runoff and deposition of sediment / decreased transparency
- Generally decreased salinity and changes in seasonal salinity patterns
- Increased stratification of ocean waters
- Deoxygenation of ocean waters
- Decreases in ocean pH
- Rise in sea level, which will vary in magnitude and location
- Changes in oceanographic currents
- Changes in upwelling patterns causing changes in the variability of oceanography
- Changes in the character of the El Niño Southern Oscillation, such as increased oscillation frequency
- Increased maximum wave heights and possibly storminess in general

We also highlight evidence of a variety of observed and expected changes in the distributions and occurrences of species in the area, largely associated with poleward or onshore movements (Section 4). Some proportion of these biological changes is undoubtedly the result of oceanographic and climate variability, while some is likely the result of underlying longer-term global change. It is presently difficult to apportion causality to these two timescales of environmental change, but all of these changes are informative nevertheless. A number of commercially and culturally important species may undergo major changes in distribution and abundance, phenology (timing of migration or other seasonal patterns), and physiological condition or resilience, thus affecting the provision of ecosystem services and current human patterns of resource exploitation, in addition to inherent ecosystem values.

Types of general observed and anticipated biological changes include:

- Poleward shifts of species ranges, such as those for Pacific salmon species, southern pink shrimp, Pacific cod, hake and Humboldt squid
- Mismatches and reassembly of communities and food webs, such as the change in the composition of the zooplankton community, which will affect the species that prey on them
- Changes in phenology, or timing of life stages and migration, including changes in the timing of the spring plankton bloom
- Physiological stress, such as the stress on Pacific salmon species stemming from changes in ocean temperatures, and the stress on shell-forming species stemming from acidification
- Reduction of suitable habitat and favourable conditions such as that caused by the shoaling of deoxygenated and acidic waters
- Increased species introduction pathways and facilitation of invasive species establishment, and increased incidences of diseases and parasitism; such invasive species include the European green crab and non-native tunicate species
- Nutrient enrichment and increased occurrences of algal blooms
- Increased vulnerability of ecosystems to other anthropogenic stressors, such as overfishing and pollution

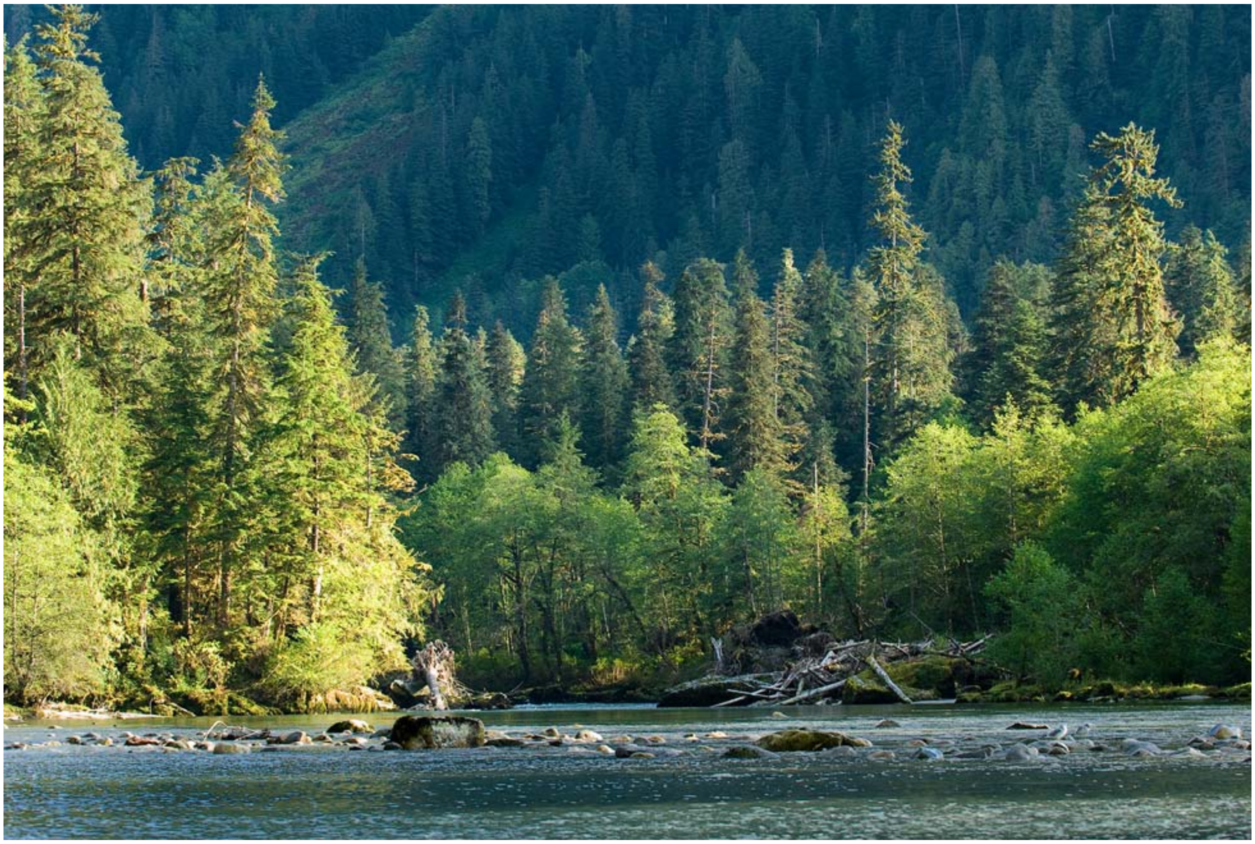
Climate change will affect marine biota differentially, thus leading to potentially widespread mismatches of co-evolved species (e.g., predators and prey at key life stages) and reassembly of species with unknown but potentially large effects on the structure and function of biological communities, including increased rates of species replacement, extirpation, and extinction. It is reasonable to assume that such changes could push marine ecosystems toward or beyond tipping points and into degraded or otherwise altered states from which recovery or return would be unlikely. Indeed, any ostensible recovery to previous states should be considered temporary, and an artefact of variability, as British Columbia marine ecosystems will be increasingly non-stationary, in a structural and functional sense, as global oceanographic changes manifest regionally and locally.

Executive Summary

Beyond providing a broad summary of estimable or conspicuous physical and biological changes that are increasingly affecting Canada's Pacific, we further identify what we consider to be sensitive and vulnerable components to climate changes, including areas at the scale of B.C. ecosections and habitats (sections 5.2 and 5.3). These estimated sensitivities, along with information on other human stressors in the region that affect adaptive capacity, help us to further identify at-risk or vulnerable areas to further inform planning, management, and policy responses to climate changes. Important components including habitat features emerging from our assessment that are considered sensitive to climate change and likely to be vulnerable include:

- Oceanographic processes in areas critical for larval retention and transport that are sensitive to intensification of estuarine conditions (Dixon Entrance, Queen Charlotte Sound ecosections, Juan de Fuca Strait);
- Sediment shorelines and other nearshore habitats that serve as important spawning habitats for forage fishes and are sensitive to erosion and sea-level rise (Hecate Strait, Strait of Georgia, other ecosections);
- Biogenic coral habitats in canyons and channels between slope and shelf areas, which are prime points for exposure to acidic water (Queen Charlotte Sound, Continental Slope ecosections);
- Areas where topographically induced upwelling of deeper water supports productivity and diversity; for example, the shelf break and seamounts where species and habitats would be sensitive to increases of oxygen-depleted and acidic water (Continental Slope ecosection);
- Commercially harvested groundfish species, other non-commercial species and their habitats between 250-400m depth, where increasing levels of oxygen-depleted water are already reducing suitable habitat for these species and will continue to do so;
- Areas considered important as nursery and juvenile rearing habitats (estuaries, seagrass, and other nearshore habitats) that would be sensitive to changing physical conditions, particularly temperature, salinity, turbidity, and stratification;
- Areas through which migrating species transit in large numbers for part of their life cycle, which will be sensitive to changing physical conditions and/or new predators that arrive as a result of climate changes (Queen Charlotte Strait, Johnstone Strait, some fjords); and
- Harvested species that are longer-lived and more resistant to short-term climate variability because they can afford to have long periods of low or no recruitment, but that are more sensitive to longer-term directional change in a given location because they cannot adapt as fast as shorter-lived species (e.g., Pacific Ocean perch, rockfishes, sablefish).

The potential impacts of climate changes on these species and ecosystems must be assessed in the context of the other local and regional human stressors in the system, since these influence the system's capacity to adapt to climate change impacts. From our assessments, ecosections with compromised adaptive capacity (i.e., those that have high levels of human stressors) and therefore higher vulnerability are Strait of Georgia, Queen Charlotte Strait, Johnstone Strait, and Juan de Fuca Strait. The habitats that are considered most vulnerable by virtue of a combination of high exposure and sensitivity to climate changes and compromised adaptive capacity due to human stressors are shallow rocky reefs, seagrasses, kelp beds, and undifferentiated (either hard or soft) shelf habitats.

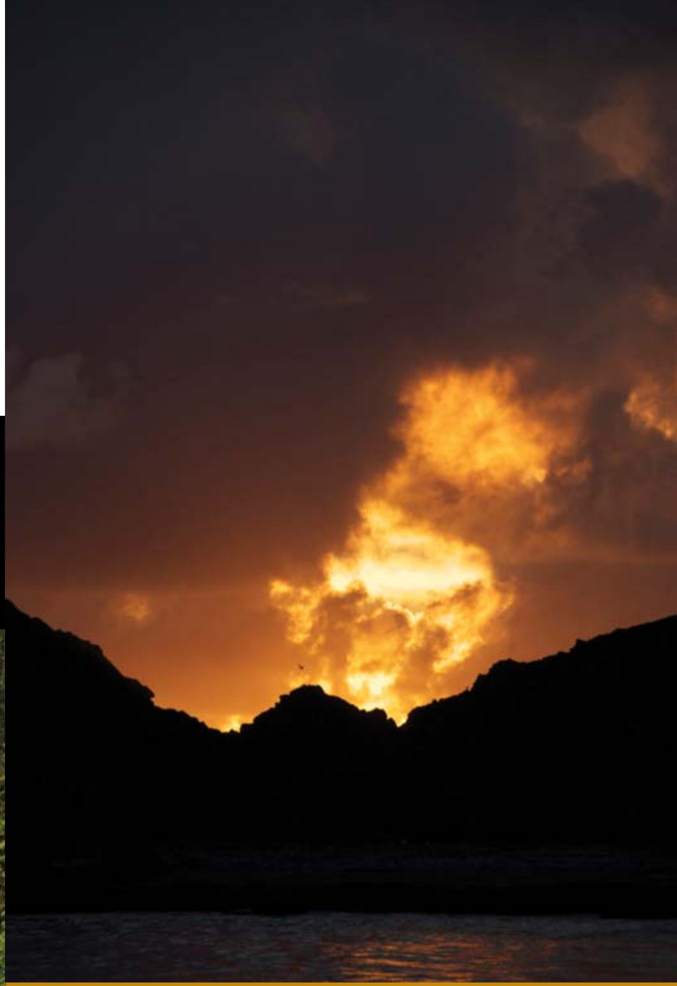


However, it may be that the position of Canada's Pacific marine ecosystem in an oceanographic transition zone, and its otherwise high degree of spatial and temporal heterogeneity make the flora and fauna of this area naturally adaptable and resilient to ecological change, giving the system short-term resistance and resilience to climate change impacts. Alternatively, its position in a transition zone exposes the system to sudden non-linear changes or flips of the ecosystem that may endure in persistently altered states. An important point reinforced by this report is that while we may reasonably anticipate particular types of climate changes to manifest in the region, and the trends and direction of those changes, the specific outcomes or broad-system responses to such changes cannot currently be estimated with a high degree of confidence.

An important implication of this report is that regional planning should include the modification of human activities from three standpoints: (1) that human activities and the management of those activities must be made responsive, dynamic, and flexible; (2) that dependence on ecologically important ecosystem components that are vulnerable and dwindling should be minimized; and (3) regional and local stressors should be proactively managed and adjusted to minimize the cumulative stress on the ecosystem, thereby optimizing the resilience and functional integrity of this non-stationary ecosystem to protect both short-term and long-term values.

This report sets the stage for a discourse on what measures may be relevant to reducing ecosystem vulnerability to the effects of climate change documented here. A discussion of climate adaptation approaches is provided in a companion report, *Adaptation to Climate Change Impacts in Canada's Pacific Marine Ecosystems: Moving from vulnerability to action* (Bryan et al. in prep).

Introduction



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1.1 Purpose and approach

This report, the first of two, describes a preliminary assessment of the past and future physical, chemical, and biological changes in Canada's Pacific marine ecosystems related to climate change. For convenience, the term "climate change" is used here to refer broadly to the global environmental changes resulting from the emissions of greenhouse gases, including oceanographic changes that are not strictly "climate changes," such as acidification, deoxygenation, and salinity changes.

The intent of this report is to provide an overview of key climate change impacts and a preliminary assessment of vulnerabilities of the marine ecosystems of Pacific Canada. Such work is a necessary foundation for efforts to reduce the vulnerability of these marine ecosystems to the impacts of climate change; namely, climate adaptation planning. Our work here is directed primarily to ocean and coastal resource planning efforts in this region, including First Nations Marine Use Planning on the coast, planning within the Pacific North Coast Integrated Management Area (PNCIMA), and other sub-regional planning efforts. Marine resource managers, and communities and users who depend on these resources will also find this report useful for understanding climate change impacts as they move toward planning for them within their management mandates.

We used two interlinked approaches in this effort to understand and synthesize the impacts of climate changes, on the local and regional marine ecosystems of Canada's Pacific. These were (1) a literary review of climate changes and projections, and the generally understood impacts on marine life, and (2) a screening-level vulnerability assessment of the region's marine systems, habitats, and major taxonomic groups to climate change.

1.2 Review of climate changes and impacts

Our survey of the literature included information about past changes, as well as model projections of physical and chemical changes from the broader region within which Canada's Pacific coast is situated. We chose to examine ecological changes and impacts on different types and hierarchical levels of ecosystem components, including measured and projected changes in physical and chemical variables, expected changes to B.C. ecosections and habitat types, and measured and expected changes in taxonomic groupings and key species of interest. The selection of these components was based partially on the availability of information.

This synthesis included information and guidance from a peer review that included a series of workshops and interviews with resource persons on the marine and coastal ecosystem of British Columbia. We expect more explicit forecasting of ecological impacts of climate change in the near future through the use of whole-system ecosystem models, or end-to-end models, but these tools are just now emerging globally, and we did not use such whole-ecosystem forecasting in the present synthesis.

Opposite page: left, sea grass in a mid-coast estuary; right, sunset on Haida Gwaii.

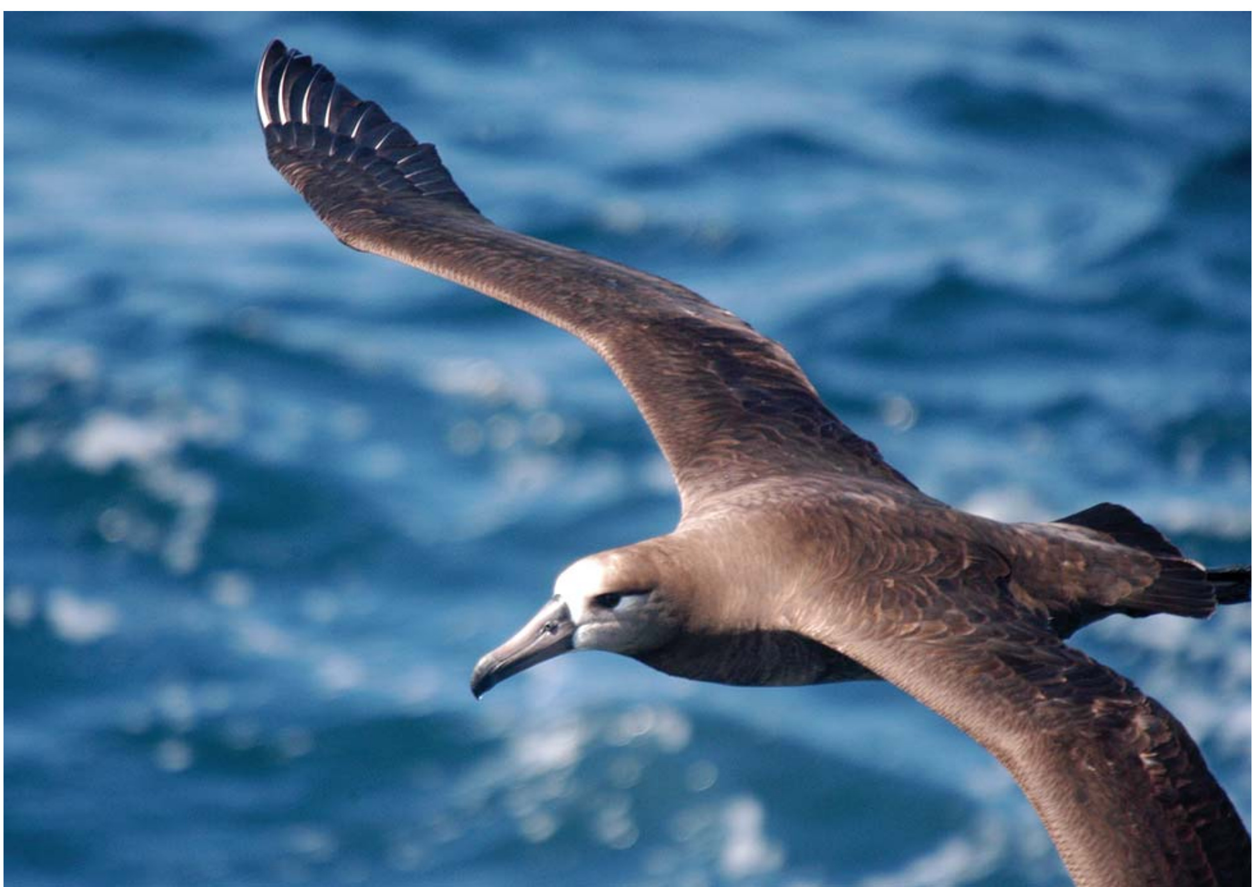
Above: Sea gull hunting puffins on the Scott islands.

1.3 Preliminary vulnerability assessment

In our preliminary approach to vulnerability assessment, we identified and compiled some components of the climate-sensitive elements of biogeographic units, ecosections, habitats, and taxonomic groups. Such a vulnerability assessment depends on the science of understanding (measuring and forecasting) the physical and chemical changes, and the responses of the habitats, species, and biological communities to them. But it also depends on the understanding of other human impacts that influence this biota, and the resistance and resilience of this system to climate change. The potential impacts of climate change on these species and ecosystems, therefore, must be assessed in the context of the other local and regional human stressors in the system, since these influence the system's capacity to adapt to climate change impacts.

Plans for assessing the status, vulnerabilities, or impacts on various components of the area and the ecosystem in general, and ultimately managing human impacts in an integrated manner, must focus on the important elements of healthy ecosystems. They must also account for the known sensitivities, exposure, and adaptive capacity of those elements, or components of those elements, to both the global climate change stressors and the more local and regional stressors not related to climate change.

The preliminary vulnerability assessment presented here is a first step toward achieving such plans for British Columbia. This assessment is undertaken by examining the vulnerability of habitats to climate change, as habitats are one proxy for the elements of a healthy ecosystem. The habitat vulnerabilities can then be summarized on the scale of the 12 ecosections identified as part of British Columbia's biogeographic characterization (Section 5). In doing so, we have illustrated one way in which such vulnerability assessments could be further developed to provide spatially explicit estimates of exposure, susceptibility, and adaptive capacity that can be useful for understanding and prioritizing responses to climate impacts at a particular spatial scale.



Even with our efforts, our present understanding of this complex ecosystem and the broader social-ecological system is relatively coarse given the limitations in the information available for this assessment, and the methods we were able to use at this juncture. The information about climate change impacts is even more sparse. This report is thus presented as a first step toward a more comprehensive, integrated, scientific approach that is necessary to support planning and adaptation to climate change impacts, including refined vulnerability assessment and refined forecasting of impacts at all levels of organization and at finer spatial scales.

Given the existing uncertainty, management or adaptation approaches can and should proceed in a proactive and precautionary manner, but obviously in a cost-efficient manner. This requires work to identify and prioritize adaptation approaches and management strategies, and this is addressed in the companion report, *Adaptation to Climate Change Impacts in Canada's Pacific Marine Ecosystems: Moving from vulnerability to action* (Bryan et al. in prep).

The ocean-based economy is a significant component of the B.C. economy, creating $11.6 billion in revenues in 2005 (GS Gislason & Associates, 2007). Climate change impacts to the Pacific coast affect the socio-economic well-being of B.C. communities in a multitude of ways and, conversely, that human dimension affects ecosystem health in terms of functional integrity, the production of ecosystem services, and the resistance and resilience to local and regional manifestations of climate change. Thus, there are important "positive" feedbacks in the system that can reinforce a healthy system or, conversely, reinforce the degrading of a system. Although socio-economic considerations are outside the scope of the present report, they are critically important and necessary for planning for climate change impacts.

1.4 Organization of this report

The nature of Canada's Pacific marine environment is presented in Section 2 and sets the context for understanding the broad system impacted by climate change. Section 3 is a review of physical and oceanographic changes that are currently being observed and are predicted to result from climate change in Canada's Pacific.

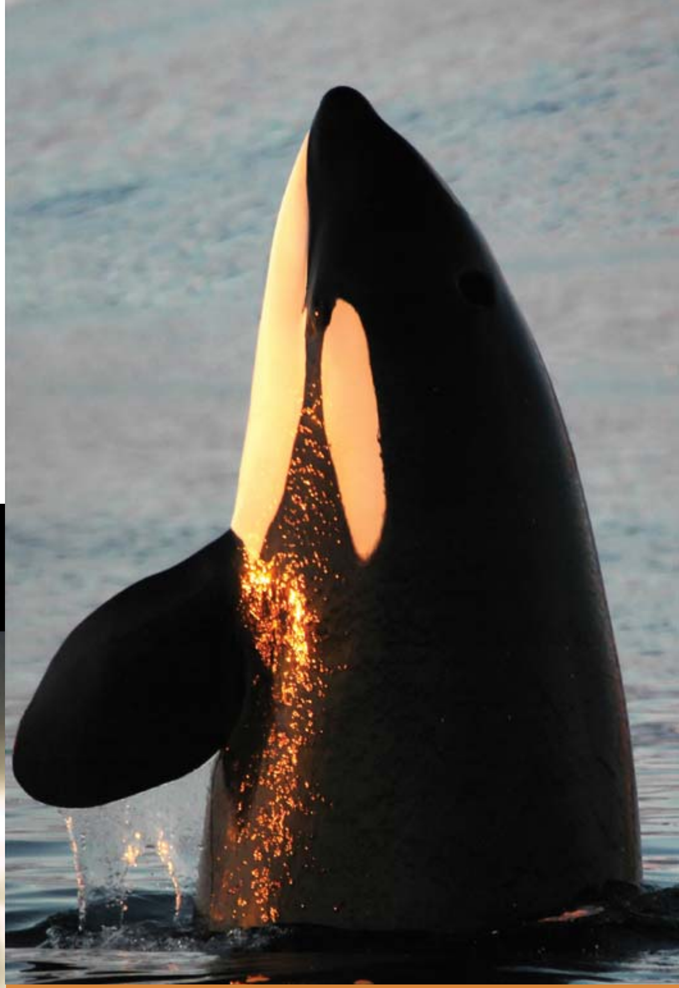
An overview of the impacts of these changes on marine life and the ecosystems in the region is presented in Section 4. Section 5 builds toward a vulnerability assessment and presents both a qualitative and quantitative approach to understanding sensitivity and vulnerability of ecosystem components to climate change. Section 6 provides a more specific review of the sensitivity and responses of economically important taxa, as well as other taxa, to climate changes.

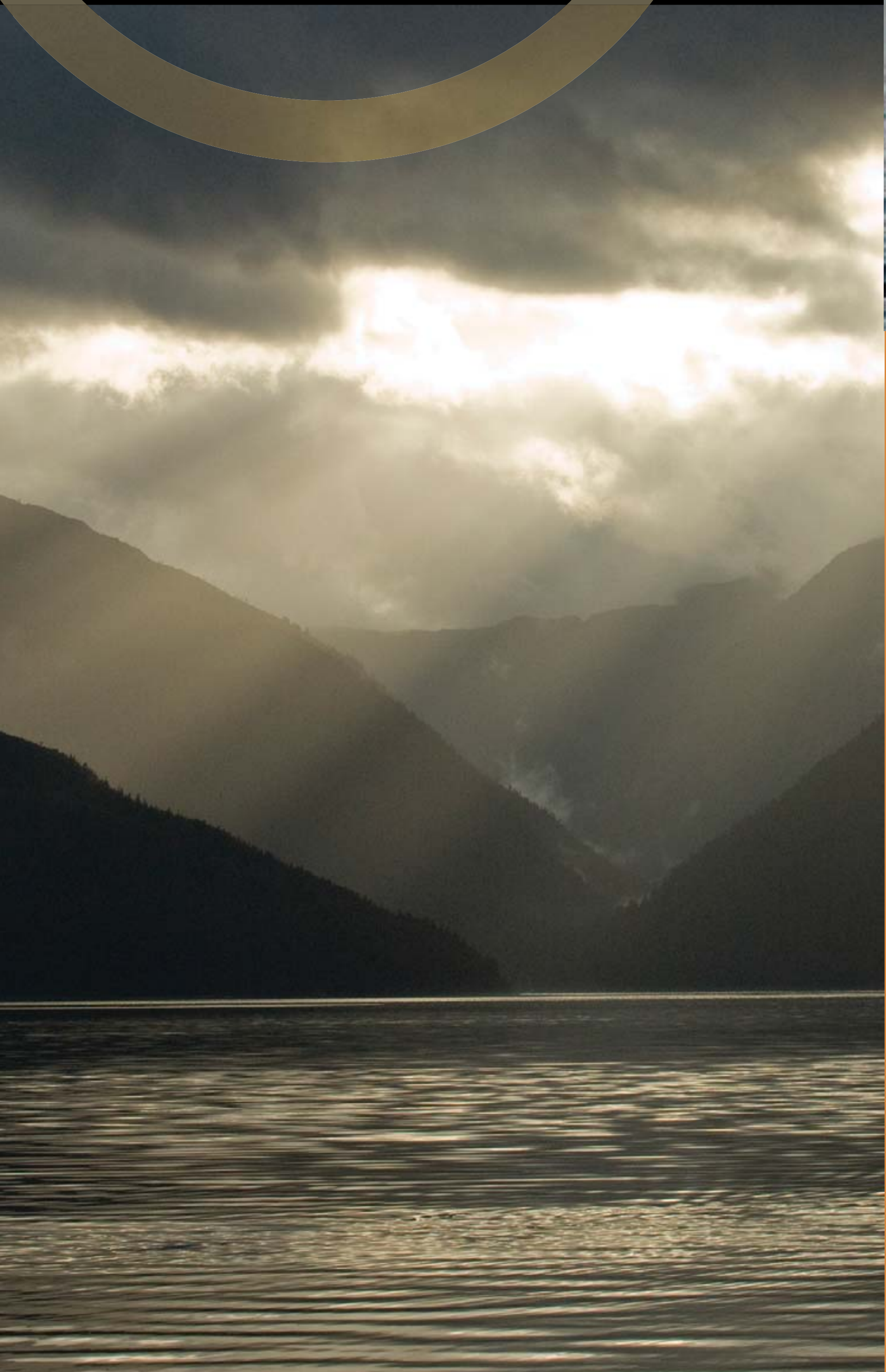
Section 7 synthesizes the main conclusions emanating from the report and relates these to the forthcoming companion report, *Adaptation to Climate Change Impacts in Canada's Pacific Marine Ecosystems: Moving from vulnerability to action*.

Opposite: Blackfoot albatross.

Above: Harbour seal.

The context of Canada's Pacific Ecosystems





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The context of Canada's Pacific ecosystems

To understand how British Columbia's marine and coastal ecosystems will be affected by climate change, it is useful to begin by providing some context of the natural system of the region. This context includes both present and past physical, biological, and ecological characteristics, as well as the natural variability of those characteristics, and the influence of other anthropogenic stressors that we know affect this system. This context has an important bearing on the regional ecosystems and their adaptive capacity and resilience to climate change impacts.

The marine area off the coast of British Columbia and its four biogeographic units are illustrated in Figure 2.1. These biogeographic units are used as the starting point of discussions in Section 5 about the sensitivities and vulnerability of British Columbia ecosystems on the scales of biogeographic units, ecosections, and habitats. The remainder of this section will discuss the various scales and contexts of natural variability and human stressors.

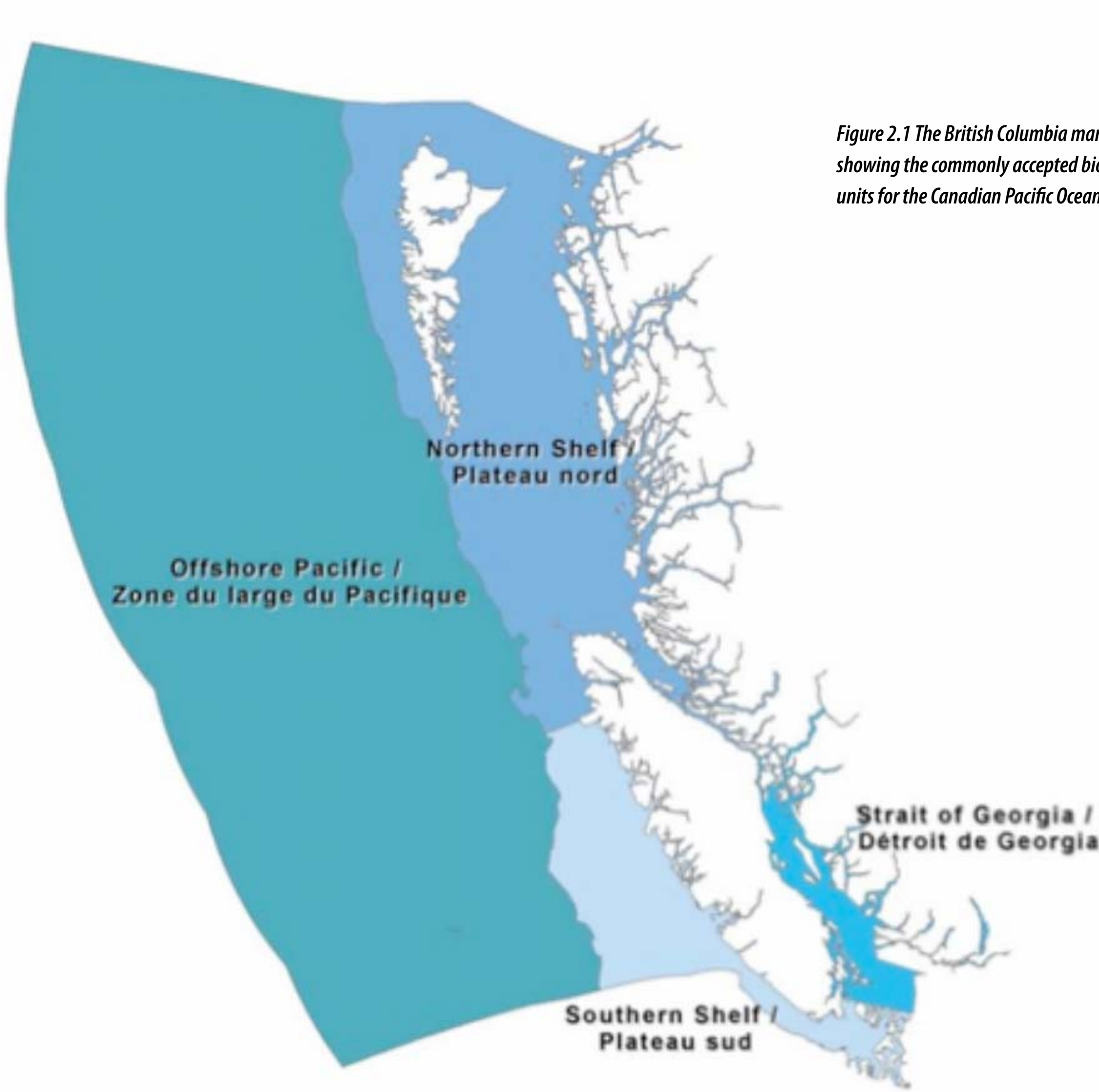


Figure 2.1 The British Columbia marine region showing the commonly accepted biogeographic units for the Canadian Pacific Ocean (DFO 2009a).

The context of Canada's Pacific ecosystems

2.1 A highly dynamic coastal transition zone

The British Columbia marine region encompasses a coastal transition zone between the northward-flowing Alaska Current and the southward-flowing California Current. These are fed by the North Pacific Current (or West Wind Drift), which flows toward the B.C. coast from the west, and diverges at this transition zone (Figure 2.2). The relative dominance of the Alaska and California currents determines the location of this coastal transition zone (Perry et al. 2007). The location of this transition zone fluctuates with the natural fluctuations of these currents.

Figure 2.2 Main current systems in the area of interest. (Source: GLOBEC (http://www.cop.noaa.gov/stressors/climatechange/current/fact-globecpne.aspx)

Along the California Current, upwelling (the lifting of bottom water toward the surface) predominates, while in the Alaska Current, downwelling (the sinking of surface water) is common. The strength of both up- and downwelling varies seasonally and inter-annually with El Niño Southern Oscillation (ENSO) events being an important contributor to the variability in the longer time scales (Royer 1998). Fluctuations of the latitude at which the North Pacific Current intersects the shelf have important implications for the ocean dynamics of the B.C. coastal ecosystems. A northward shift in the intersection results in an increased influence of the Californian Current and associated upwelling, particularly in southern British Columbia. A southern shift brings the entire B.C. coast under the influence of the northward-flowing, downwelling regime of the Alaska Current.

These changes occur at varying scales of time and space, and are known to strongly influence the biology of this overall region in terms of changes, and overlapping of populations and assemblages, which vary in their responsiveness to these oceanographic changes, and their inertia. The influence of these North Pacific currents is part of the broadest oceanographic context that makes B.C. marine ecosystems unique and highly variable.

The transition zone resulting from this interplay of oceanography and geography coincides generally well with British Columbia's Northern Shelf biogeographic unit (Figure 2.1 and Figure 2.2). The natural variations of this coastal transition zone imply that all of British Columbia is variably exposed to this transition zone.

The spatial and temporal complexity of this ecosystem is fractal, as closer examination of this area reveals both the high complexity and the considerable dynamics of oceanographic and geophysical features at all spatial and temporal scales, indicating complex habitat characteristics at the scale of species and biological communities. For instance, sea surface temperature, as depicted in Figure 2.3 for the area indicated as the transition zone, is just one of many examples of this high spatial and temporal complexity.

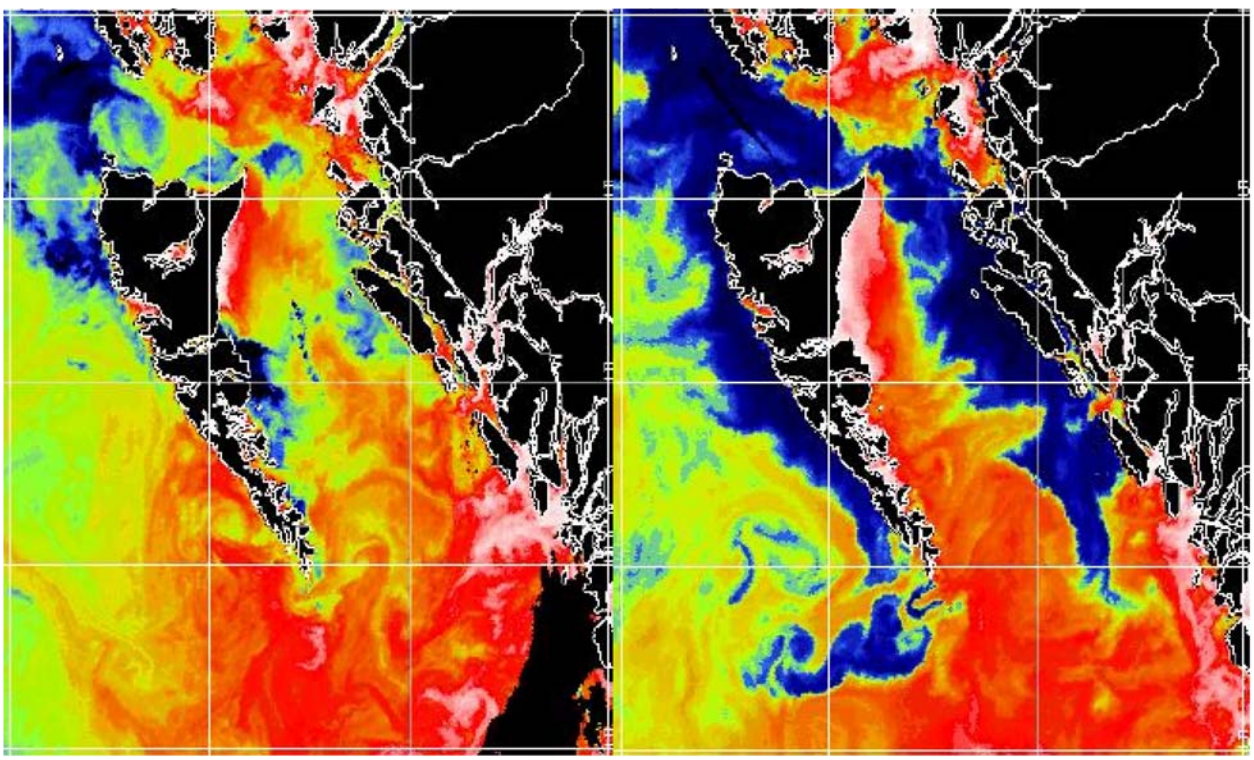


Figure 2.3 Sea surface temperature (SST) images of observations by AVHRR sensor on NOAA satellites from the northern section of the Northern Shelf area on 26 May 1993 (left panel) and 23 July 1994 (right panel). White denotes warmest SST, followed toward cooler waters by red, orange, yellow, green, blue, dark blue (from Perry et al. 2007).

2.2 High primary productivity and habitat diversity

High primary productivity and diversity of habitats set the stage for the abundant and diverse spectrum of life in the marine areas of British Columbia. The ecosystem services provided by this diversity of marine life and habitats enabled the flourishing of First Nations civilizations and communities. It also enabled the survival of those communities, as well as nurtured new communities and economies.

The diversity of habitats results from the interaction of oceanography, geomorphology, and climate at multiple spatial and temporal scales. Understanding the impacts of climate change—that is, the effects of expected physical and chemical changes on the biology—requires describing and dealing with this spectrum of unique and interacting features, as well as the local human impacts to the system.

These impacts and interacting features vary spatially and "fractally," and thus require examination of a hierarchy of meaningful scales. In addition to summarizing broad generalities, in Section 5 we summarize the characteristics of biogeographic units, ecosections, and habitats, which provides a basis for further understanding climate change impacts at finer scales.

2.3 Biodiversity and migratory and transient species

Given that marine biodiversity declines with latitude, Canada's Pacific should exhibit a moderate to low biodiversity. However, the high productivity and habitat diversity of this region has led to the development of a relatively rich fauna and flora (Lo et al. 2011) with certain taxa, such as sea stars (Asteriodea) exhibiting a very high species diversity (Lamb and Hanby 2005), while other taxa have relatively low species diversity.

Another effect of high productivity and habitat diversity is the prominence of migratory and transient species in Canada's Pacific marine ecosystems. For example, B.C. marine areas are home to many migratory species, including stopover migrants such as seabirds migrating to Alaska in the summer; destination migrants, such as whales and Steller sea lions and salmon; and environmental migrants, such as zooplankton and pelagic fish species that migrate northward during warm conditions (Perry et al. 2007). Salmon provide an important transfer of nutrients from the open ocean to British Columbia's terrestrial and freshwater ecosystems when they migrate back to their natal streams as adults, which is important, as high precipitation tends to make the region nutrient-poor (Perry et al. 2007). Migrations of marine mammals have evolved to changing environmental conditions, but it is unknown if they will be able to adapt at the rate of climate change predicted for the future (Stern 2002). Most marine mammal populations are thought to be increasing in abundance, including several baleen whale species, sea lion species, harbour seals, and sea otters. Although this is generally thought to have resulted from reduced harvest of these species, these increases could also have resulted from increased food production in the area (Perry et al. 2007).

2.4 General ecosystem structure and function

Although the Pacific marine areas of Canada are highly dynamic and textured, and although each major biogeographic unit and other finer scale units such as ecosections have unique collections and mixtures of features and habitats, there are also general features that characterize Canada's coastal Pacific.

Virtually all of Pacific Canada has common geological features that affect the physical functioning of its marine ecosystems. These features include steep mountains, valleys, and fjords, glacially scoured and tectonically formed; shelves and shallow basins; and the influence of very large islands—namely, Haida Gwaii and Vancouver Island, and abundant smaller islands (e.g., Conway and Johannessen 2007). Glacially derived sediment is likely a strong shaper of benthic habitats (e.g., Perry et al. 2007), in addition to sediment otherwise weathered and transported by alluvial processes (Johannessen and Macdonald 2009).

The region is influenced by a multitude of watersheds dominated by spring and summer meltwater runoff, which is critical to phytoplankton blooms, and thus the marine food web (Conway and Johannessen 2007). Phytoplankton production is ultimately the driver of the high biological productivity in British Columbia's Pacific coastal marine areas. It is influenced by the extent of upwelling winds (Perry et al. 2007) that vary seasonally and on longer time scales, and by considerable nutrient input from the Fraser River and the other coastal watersheds. Compared with other regions from southern California to Alaska, British Columbia has moderate annual phytoplankton biomass but high long-term fishery yields of resident fish populations (Ware and Thomson 2005). This implies high productivity rates.

The marine food webs of British Columbia are based on phytoplankton, nearshore macrophytes, and detritus (Perry et al. 2007). Macrophytes serve as important food sources for most B.C. nearshore food webs. Kelp and eelgrass are the dominant macrophytes in this system, and serve as important habitat for fishes and invertebrates, and also as moderators of currents.

The marine food webs of British Columbia can be represented generally by the simplified food web in Figure 2.4, originally presented by Perry et al. (2007) to represent the food web of the Northern Shelf area. On the broadest level, this figure shows how aspects of global change can influence different parts of the system differentially, thereby modifying the assemblages, structures, and presumably functions of biological communities. For example, the phytoplankton "sub-web" may be more sensitive to acidification than the macrophyte sub-web, thus potentially shifting the flows in the overall food web accordingly.

Perry et al. (2007) also suggested that this trophic structure appears robust to the reduction or elimination of single food-web components, provided there are other species in the same functional group. However, it is not well understood how much functional redundancy exists and which species will be critically affected by direct stressors and cascading indirect effects.

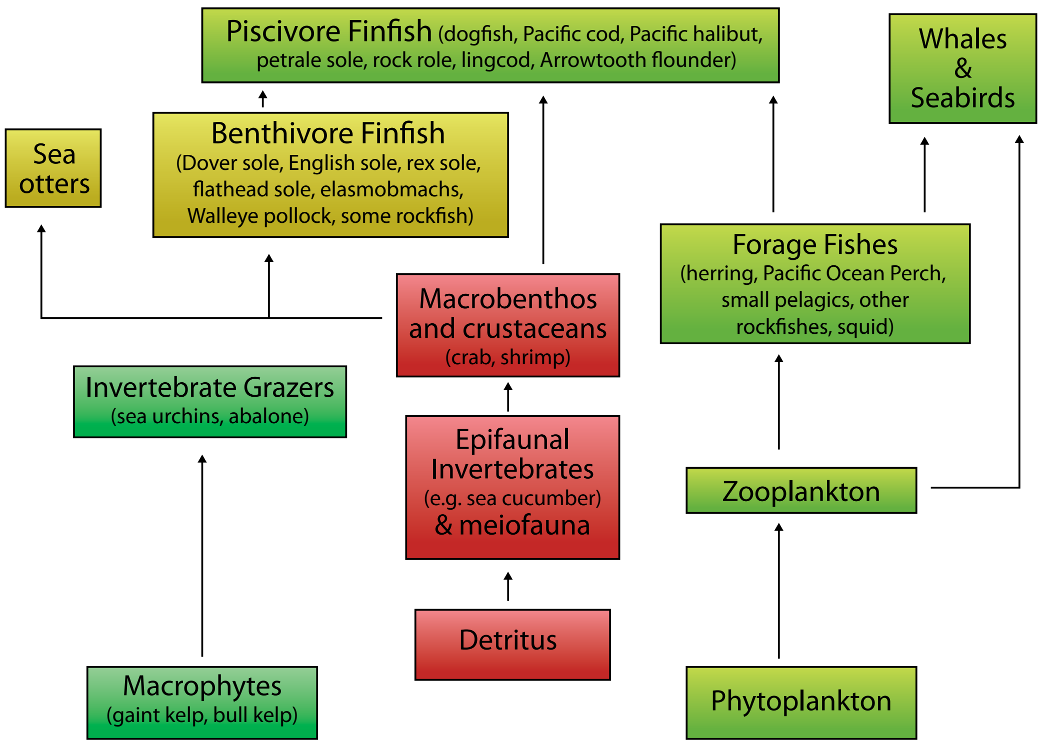


Figure 2.4 Simplified schematic food webs for the Northern Shelf Area also corresponding to the PNCIMA region (Perry et al. 2007).

Because Figure 2.4 is an (intentionally) highly aggregated characterization of marine food webs in British Columbia, there is as much or more uncertainty in relative structural and functional effects, redundancy, resistance, resilience, etc. within the boxes of the diagram as among them. For example, some phytoplankton and zooplankton groups and species are much more vulnerable to acidification than others, so we would expect a shift in the assemblages of phytoplankton and zooplankton, and probably to some extent of their associated predator, competitor, prey, and microbial communities. A simple illustrative example of this unpredictability from the intertidal zone is barnacles, which should do poorly as pH drops, but they do better because their normally dominant competitors, mussels, tolerate acidification less well than barnacles. Such effects on the overall function of the sub-web are largely unpredictable, and almost entirely unknowable without quantitative accounting and modelling.

Our current understanding of the ecological processes driving B.C. marine ecosystems is guided by decades of research on individual components with high societal value, but it is also increasingly shaped by these ecosystem modelling exercises, which provide valuable quantitative insights into the structure and dynamics of the biological communities, their linkages to human activities (e.g., fishing), and environmental (e.g., climate) variability and change. The present exercise is an attempt to synthesize what is currently known about key components of the system as an initial scoping step in understanding changes and vulnerabilities related to climate change, rather than an exploration of system dynamics based on explorations with these existing models.

2.5 Non-climate anthropogenic stressors

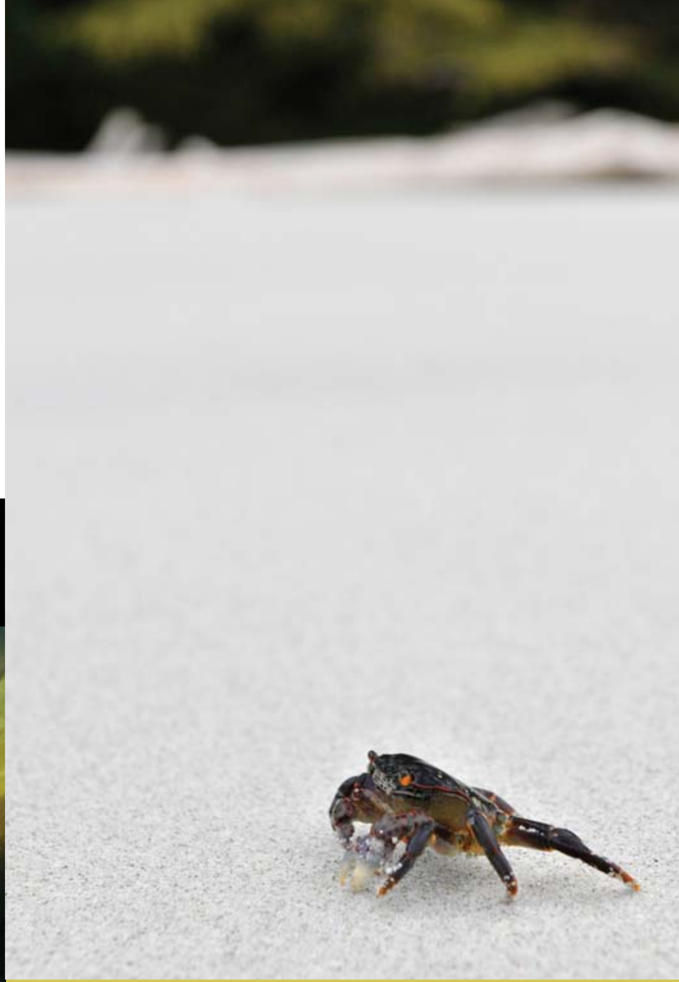
It is necessary to understand local and regional anthropogenic stressors when estimating climate change impacts because organisms and biological communities experience the combined impacts of these stressors, which in turn determine the resistance and resilience of biota. In coastal British Columbia, local and regional stressors include a broad and unique spectrum of stressors that arise from human activity, including habitat destruction and degradation, direct extraction and biomass removal, pollution, and introduced species. These stressors and the activities that give rise to them are driven by economic, governance, and social factors (e.g., Rogers et al. 2008, Okey and Loucks 2011).

A more comprehensive list of major human-driven stressors on the biodiversity of this area was compiled by Kimmel (2009), marine-specific stressors in the area are listed in Ban and Alder (2008) and Okey and Loucks (2011), and approaches to analyzing cumulative human impacts of these stressors are available in Ban et al. (2010). Identifying these stressors is key to developing strategies for responding to the impacts of climate change (i.e., climate adaptation strategies) because they occur at scales and jurisdictions that are manageable (regionally and locally). In comparison, large-scale impacts related to global change are manageable only at the global scale.

An expert-based approach is being developed for the West Coast of Vancouver Island (WCVI) to estimate the impacts of climate change relative to all these stressors in a spatially explicit context (Okey and Loucks 2011). This approach includes the assessment of the vulnerability of a set of indicators and habitat classes to these stressors by subject-expert panels. This initiative has produced estimates of the relative degree of stress that each stressor exerts on the overall system and larger subsystems, as well as other expert-based rankings that enable the general identification and prioritization of state and pressure indicators and management strategies. Habitat-specific and other spatially explicit estimates of impact/vulnerability from this WCVI initiative are still emerging. Other spatially explicit, habitat-based estimates of cumulative impacts, as well as relative impacts for British Columbia, are available from Ban et al. (2010). The information underlying those estimates of cumulative impacts includes estimates of the relative impacts of stressors on different ecosystem/habitat types.

Ultimately, estimates of stress specific to the marine ecosystems of British Columbia, such as those from the WCVI initiative, should be used in future analyses of impacts on British Columbia's marine ecosystems, such as climate vulnerability assessments, as well as in end-to-end ecosystem models that will be available in the future (for examples, see Appendix A). This will allow the local and regional manifestation of climate change impacts to be understood in the context of the various other local and regional human impacts on this ecosystem. But because these are not yet practically available, and because screening-level vulnerability and risk prioritization are necessary at least on broad scales, the present analysis will utilize estimates of relative and cumulative impacts from the work of Ban et al. (2010) in Section 5 of this report.

Changes in climate and oceanography



3

Increased atmospheric concentrations of greenhouse gases will affect nearshore marine and oceanographic conditions in British Columbia in a variety of ways (e.g., winds, currents, water temperature and salinity, oxygen content, pH). Some impacts will result from local temperature and precipitation changes; others will come about because of rearrangement of regional and large-scale atmospheric and ocean circulation patterns. The predicted impact of climate change on a number of physical and chemical parameters has been summarized by Johannessen and Macdonald (2009) for the Strait of Georgia in Figure 3.1.

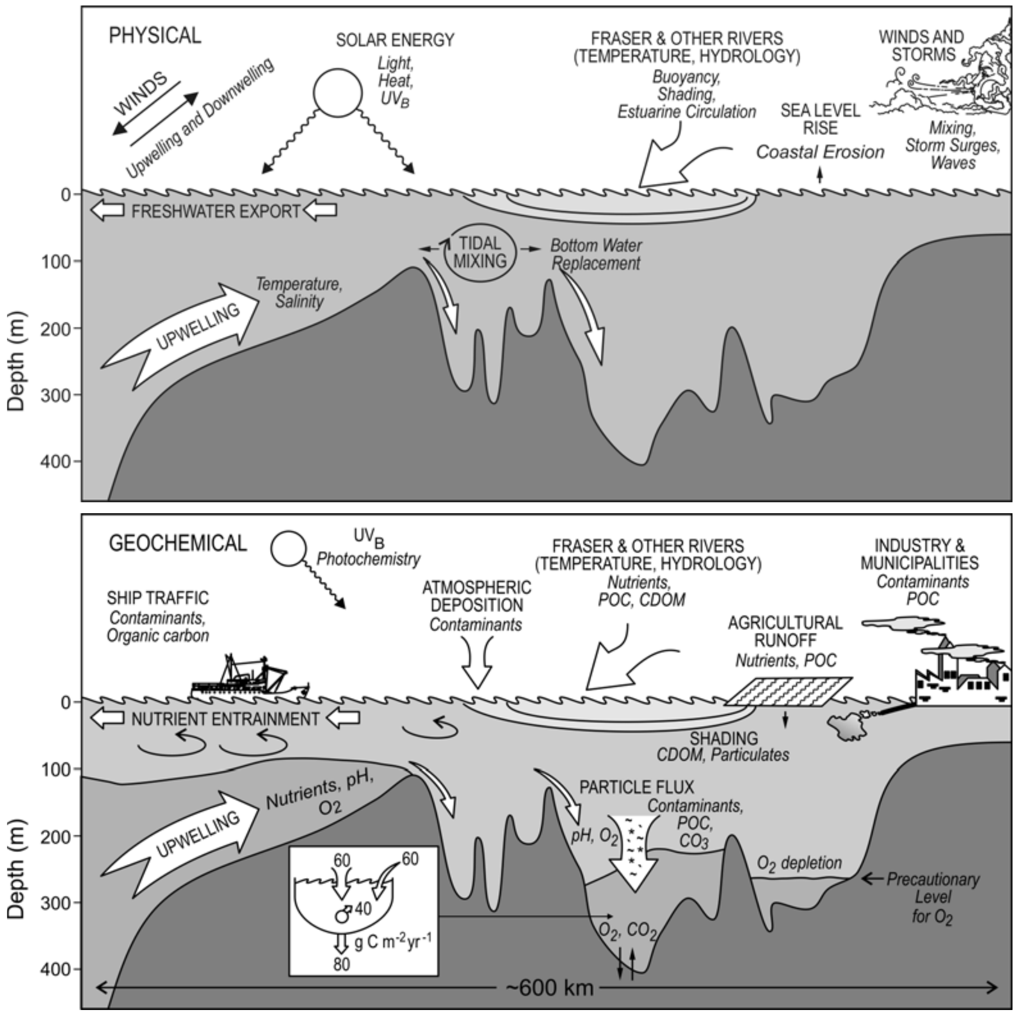


Figure 3.1 Schematic diagram of physical and chemical changes in the Strait of Georgia as a result of global environmental change combined with other local and regional stressors (from Johannessen and Macdonald 2009).

Such figures are intended only to highlight broad categories of change for discussion, and cannot fully depict all the local and regional stressors, or the cumulative or combined effects of these stressors and changes. Ocean acidification, for example, is an emerging problem in the upper ocean (upper 100 m) and at depth. It results from the direct diffusion of CO_2 from the atmosphere to the intermediate ocean, and its effects are exacerbated by hypoxia. The increased stratification of the upper water column, due to surface water freshening and temperature rise, reduces the ventilation of the ocean, thereby increasing hypoxia. However, increases in stratification also decrease the rate of anthropogenic CO_2 being taken up by the intermediate ocean.

Changes in climate and oceanography

An important caveat regarding any general projections of physical and chemical changes related to global-scale climate change impacts, especially in relation to Canada's Pacific marine systems, is that changes related to the natural variability and complex oceanography of the region can be erroneously construed as broader-scale or global changes in climate and oceanography. Ecological changes in the oceans are thought to be occurring, and being driven by changes across this spectrum from natural variability to long-term climate change. Distinguishing this natural variability from these directional changes is a great challenge, and is crucially important for understanding climate change and its impacts. In the North Pacific, the climate change signal is projected to become stronger than the climate variability signal by approximately 2035 (Overland and Wang 2007). The climate change signal is already the dominant signal in terms of hypoxia and northward shifts of some biota (F. Whitney, Fisheries and Oceans Canada, pers. comm., 2 March 2009).

Although long-term trends in physical and chemical conditions in Canada's Pacific waters are expected be consistent with global trends (i.e., warmer, more acidic, more stratified, rising sea level), this area is quite heterogeneous in terms of both oceanography and coastal habitats. For instance, sea surface temperature will sometimes be anomalously low when temperatures in most other seas are anomalously high, as occurred in 2007 and 2008, and the frequency and character of such fluctuations might change. Also, northeastern Pacific surface waters are among the most acidic on earth (and are continuing to acidify), a consequence of the shoaling (shallowing) of the aragonite and calcite saturation horizons (DFO 2008b).

3.1 Temperature

According to the IPCC Fourth Assessment Report (IPCC 2007, Solomon et al. 2007), the temperature of open ocean waters adjacent to the B.C. coast will increase between 0 and 1°C from 2015 to 2025, and between 1 and 2°C from 2045 to 2055. These are rapid and large changes for B.C. marine ecosystems, as water temperature strongly influences the distributions of organisms. During the last century, sea surface temperatures in the Strait of Georgia in British Columbia have increased by about 1.0°C, a slower rate than that projected for the future (Figure 3.2).

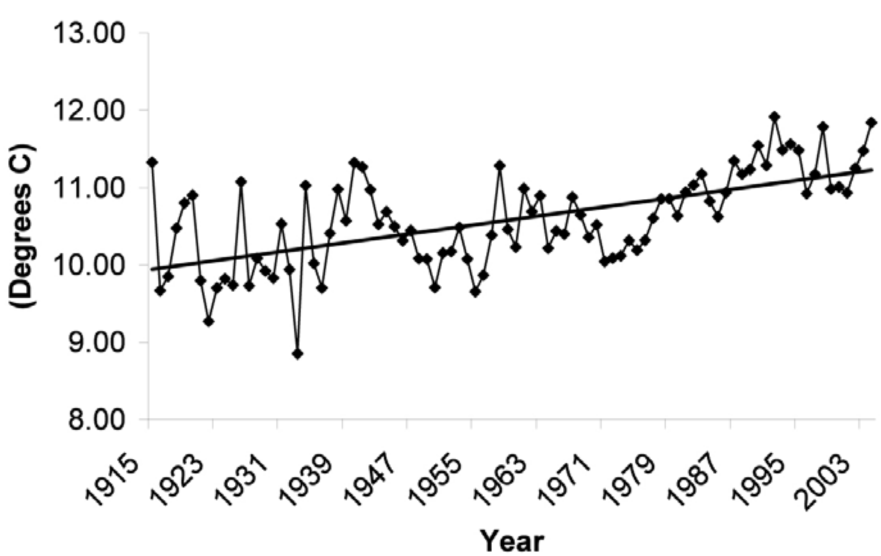


Figure 3.2 Mean annual sea surface temperature measured at lighthouses around the Strait of Georgia from 1915 to 2004. A linear trend indicates an increase of 1.0°C over 90 years (figure and caption from Beamish et al. 2009).

The rate of temperature increase in the Strait of Georgia is generally consistent with lighthouse records from throughout southern British Columbia. The rate of increase is consistently higher at stations on the mainland coast that are exposed to freshwater runoff that is warming at a faster rate (Figure 3.3).

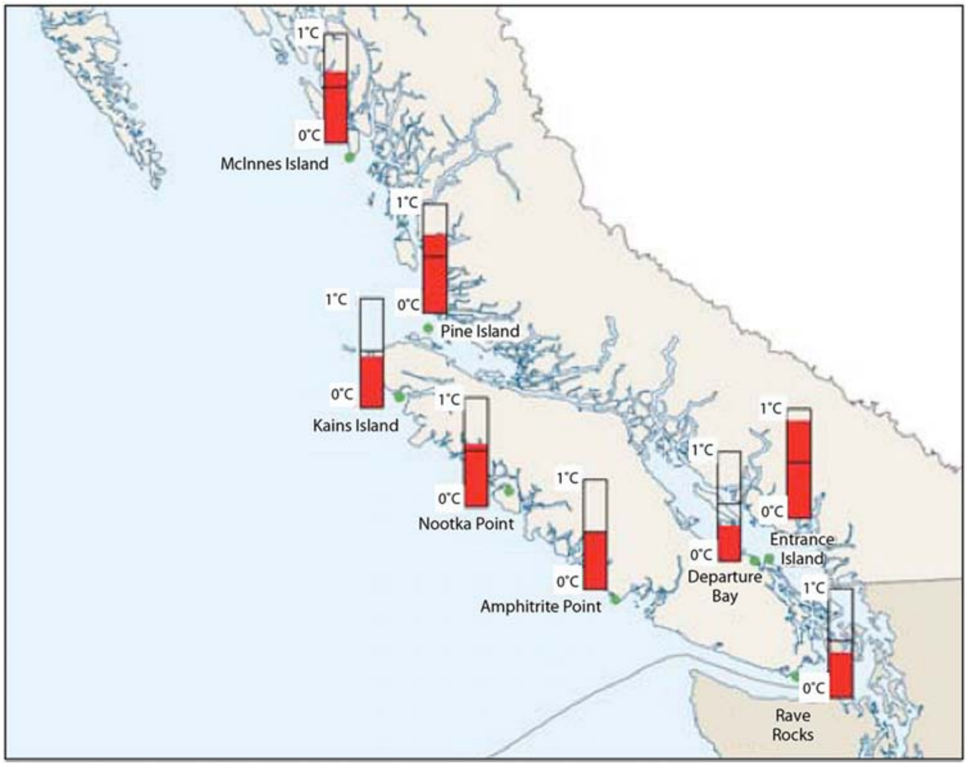


Figure 3.3 Rate of change in sea surface temperature (°C/50 years) at nine lighthouse stations on the B.C. coast, Fisheries and Oceans Canada, www.pac.dfo-mpo.gc.ca/sci/osap/data. Each full bar is 1°C. (Figure from B.C. Ministry of Environment 2007.)

This recorded rate of change in surface waters is consistent with measurements of changes in deeper ocean waters adjacent to the B.C. coastline (Figure 3.4).

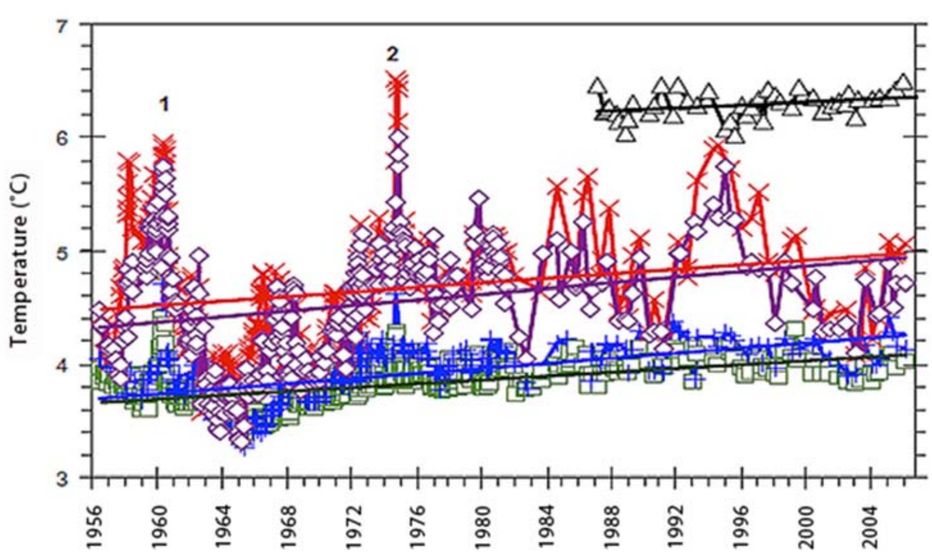


Figure 3.4 Increases in temperature at different isopycnal surfaces (between 100 m and 400 m) and stations along Line P off the west coast of Vancouver Island (Whitney et al. 2007).

Changes in climate and oceanography

Assuming this historically observed rate of sea surface temperature increase, in less than 100 years the waters around Langara Island, at the extreme northwest point of the B.C. coast, would experience sea surface temperatures similar to those currently observed off Amphitrite Point, which is located at the southwest coast of Vancouver Island. But the projected rate of ocean temperature increase in the region is higher than this historically observed increase (IPCC 2007). Increases in ocean temperature are speeding up in the region and around the world.

While conditions in waters close to the coast will be influenced by the open ocean temperature increase, they will also be influenced by various other factors, such as increases in land temperature, potential changes in wind patterns, cloud cover, local hydrography, precipitation, upwelling, and currents (discussed in the following sections).

Examination of recent shorter-term temperature variations can provide insights into some of the factors and mechanisms driving temperature changes. These include annual and multi-year weather and oceanographic patterns and cycles such as the El Niño Southern Oscillation (ENSO). For example, despite various anomalies and pockets of warm water along and adjacent to the B.C. coastline, and despite warmer sea conditions globally, the northeastern Pacific Ocean and much of the B.C. coast experienced several years of anomalously cold water associated with La Niña oceanographic and atmospheric conditions, such as winds and currents that lead to cooler waters (DFO 2009b, DFO 2010a, McKinnell 2008). Waters adjacent to British Columbia began to warm again in 2009 (DFO 2010a), but then became anomalously warm again in 2010 (DFO 2011). The ocean temperature reporting in the Department of Fisheries and Oceans' State of the Pacific series is characterized by anomalies and ENSO-related explanations.

Temperature changes over land, other than the direct impact on coastal conditions, are also linked to the marine ecosystem due to their influence on anadromous species that spend part of their life cycle in the ocean and part of it in freshwater or estuarine environments, such as salmon and steelhead trout. These species are vulnerable to increases in stream and river temperatures and changes in the amount and timing of snowmelt (see Section 5.3 for time series and discussion). Air temperatures over the land area of British Columbia and around the world may increase faster than ocean temperatures, and river and other watershed runoff appears to be warming at least twice the rate as that of the nearshore ocean (Figure 3.5; also see Walker and Sydneysmith 2007, Rodenhuis et al. 2007).

To estimate the potential impact of climate change on marine life and biodiversity, it is important to know not only the magnitude of physical and chemical changes, but also how the character and variability of these properties change in different regions of British Columbia (Murdock et al. 2007, Rodenhuis et al. 2007). For example, analyses based on the period 1971–2000 indicate that, when compared with natural variability, maximum surface air temperature increased over the coastal region much more than in other areas of the province (Murdock et al. 2007). Equally important are how marine life and biota are sensitive or vulnerable to changing conditions.

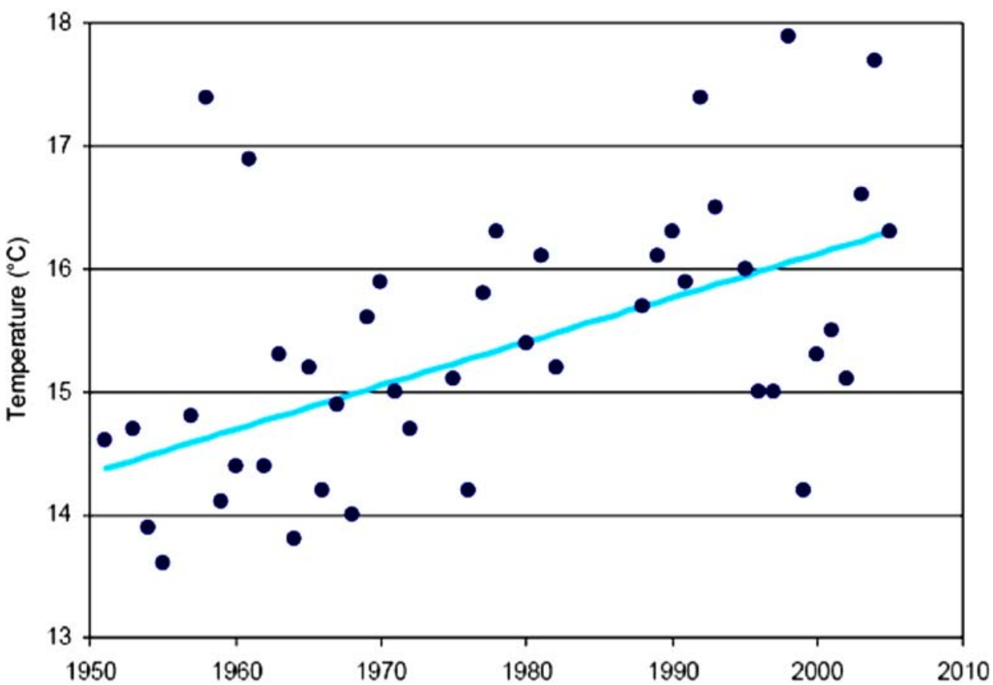


Figure 3.5 Increase in average summer (June, July, August) temperature of the lower Fraser River at Hell's Gate at the rate of 0.3 ± 0.1ºC per decade since 1950. Data from the Pacific Salmon Commission and Institute of Ocean Sciences, Fisheries and Oceans Canada.

3.2 Precipitation and hydrology

Extreme precipitation events are expected to increase during the coming century in most regions of the world (Kharin et al. 2007), as well as in British Columbia during some seasons and in some areas (Pike et al. 2008). Precipitation has generally increased over the province during the 20th century, with positive trends in all seasons (Rodenhuis et al. 2007). The observed trends from the last 50 years indicate that summer precipitation has increased over much of the province, while winter precipitation has decreased (Figure 3.6; B.C. Ministry of Environment 2007; also see Walker and Sydneysmith 2007). Confidence in predictions of precipitation increases is highest in the Northern Shelf area.

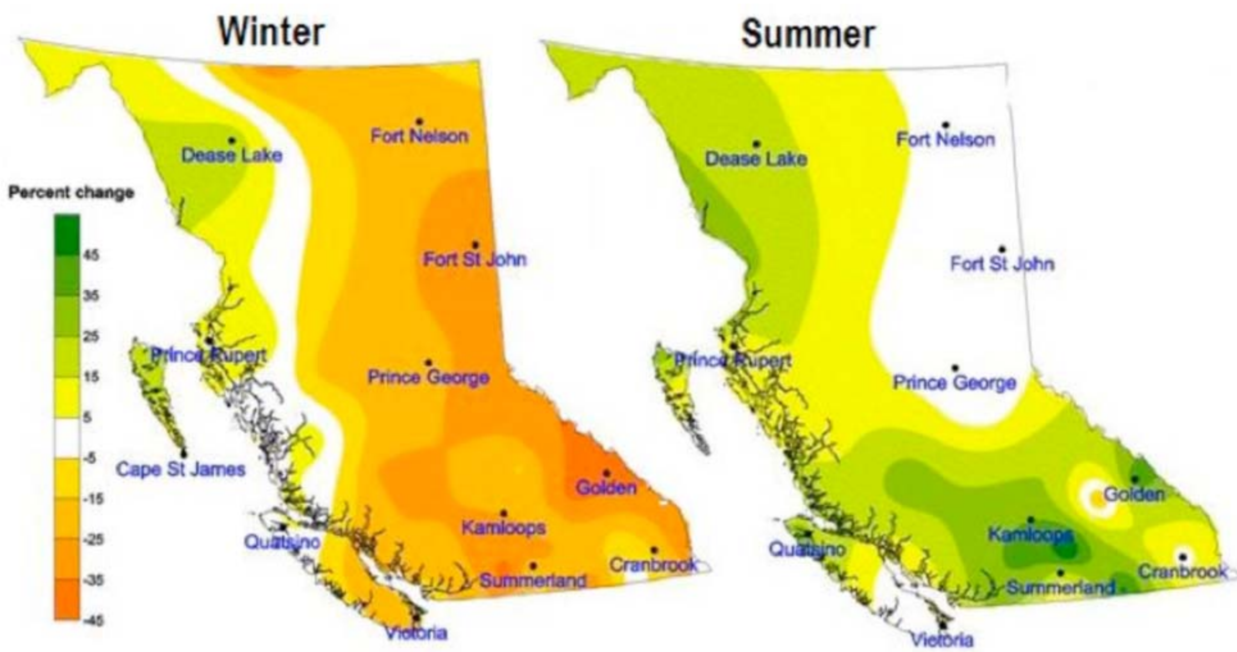


Figure 3.6 Fifty-year trends in winter and summer precipitation, shown as percentage change, 1950–2001. Data from Environment Canada (modified from B.C. Ministry of Environment 2007).

According to global climate projections, annual precipitation in British Columbia will generally increase by 0–6% by the 2020s, and by 3–11% by the 2050s. Seasonal allocation of these changes is more uncertain and follows a pattern that is opposite to the trend over the last 50 years: the increase in precipitation is mainly due to wetter winters, while summer precipitation will generally decrease. As part of a global trend, the frequency of extreme precipitation events is expected to increase (IPCC 2007, Solomon et al. 2007).

Predictions for the 2050s based on global models point to a 6% increase in annual precipitation due mainly to wetter winters (+7%), while summers become drier (-3%). Projections from this same ensemble for British Columbia's north coast indicate a 6% increase in winter precipitation and an 8% decrease in summer precipitation, resulting in a local annual increase of 6% (Rodenhuis et al. 2007).

Results from the Canadian Regional Climate Model correspond well with the global models regarding the wetter annual conditions in British Columbia (Rodenhuis et al. 2007), but they indicate increased precipitation in both winter (+14%) and summer (+10%) for the 2050s. The same model projects an increase in precipitation of up to 25% for both summer and winter over the north coast region. The regional model was forced by the A2 emissions scenario. The regional climate model results have the advantage of providing projections on a much finer spatial resolution than do the global models (45 km versus 350 km), but, because they are based on a single simulation, they lack the statistical robustness of the ensemble values (Rodenhuis et al. 2007).

Among the hydrological responses to the predicted increase in temperature and changes in precipitation is a general decrease in snowpack. According to a regional climate model, this decrease is particularly large in the coastal mountain ranges where, in spite of an increase in precipitation, higher temperatures cause a reduction of about 55% in the spring snowpack by the 2050s (Rodenhuis et al. 2007). This shift from snowpack runoff to rain runoff is causing a subsequent shift in the timing of the annual flow of rivers to earlier in the season (Figure 3.7).

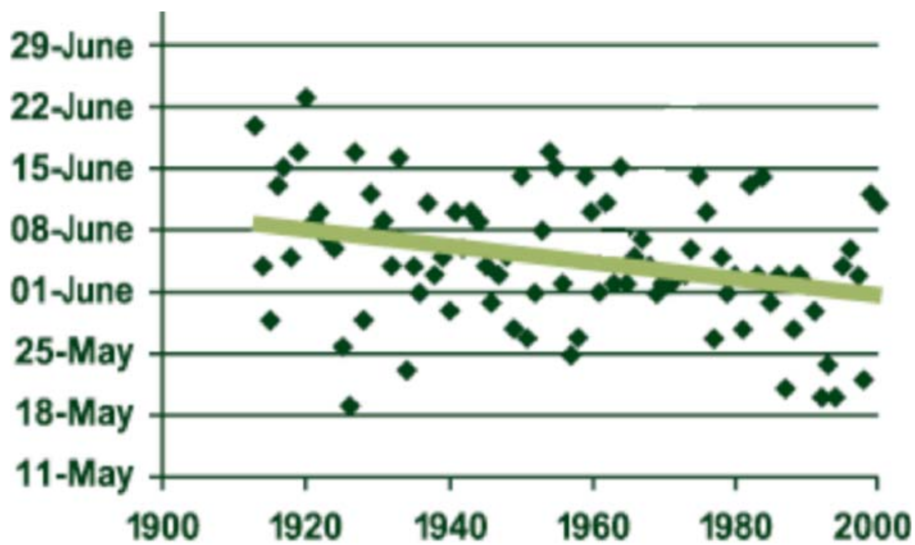


Figure 3.7 Timing of one-third of Fraser River Annual Flow (1913–1998). Data from the Canadian Historical Homogenized Temperature Datasets. Analysis by Canadian Institute for Climate Studies, 2001, for Ministry of Water, Land and Air Protection (taken from http://www.env.gov.bc.ca/soe/et02/09_climate/riverflow.html).

The initial response of glaciers to warming is an increase in runoff. This is then followed by a decrease in runoff as glacier mass and area decrease. Analyses of B.C. glaciers over the last decades indicate that even under present-day climate conditions, most the province's glaciers have already passed the first phase and that runoff is generally decreasing (Stahl et al. 2006). Projections for the Bridge Glacier (south Coast Mountain region) are of a 20% decrease in runoff for the period between 2050 and 2100 under present climate conditions. The same study estimates that summer runoff in the 2050s will be reduced by 25% under a global warming projection, where the annual temperature at the glacier will be 0.9˚C warmer at that time (Stahl 2007). Glaciers are an important source of fresh water and can act as buffers to river-flow decrease during periods of drought. Glacier runoff also regulates stream temperature and can be important to the well-being of cold-water species such as salmonids. The decrease in glacier runoff will further add to the stress on stream ecosystems already impacted by drier, warmer, and less-oxygenated summer conditions.

In general terms, the predicted changes in streamflow follow precipitation and temperature, with decreases in summer and fall flow, increases in winter flow, and an anticipation of the spring peak in basins affected by snow and glaciers due to earlier melting. Still, other factors such as evaporation, soil moisture, and groundwater flow are important in defining changes to runoff in more detail. There is uncertainty associated with some of these projections. For example, streamflow in the Illecillewaet watershed (a tributary of the Columbia River in British Columbia) at the end of the 21st century is projected to remain mostly unchanged despite a 26% decrease in future glacial runoff, due to a similar increase in groundwater flow (Loukas 2004). Low salinity stress in estuarine environments may be better described by changes in peak flow, as opposed to changes in annual flow (Morrison et al. 2002).

While predictions are lacking for many of the important rivers in British Columbia, especially in the Northern Shelf area (such as the Skeena), we can expect increased overall runoff, mainly due to wetter winters accompanied by a decrease in runoff during the drier, summer and spring months. Perhaps more importantly for the region's unique biology and biodiversity, it will be the changes in the timing and character of this runoff related to the interaction of these projected effects with changes in snowpack.

Furthermore, it is also the influence of these factors on groundwater that drives the water availability and quality in many systems, and is essential for the survival of many species, particularly salmon. The snowpack drives groundwater in many important fish-producing areas, and changes (e.g., declines) in snowpack due to climate are likely a very significant consideration. Some believe that there is a crisis coming in water management in British Columbia, and because this has generally not been an issue in the past in the province, especially in the coastal rainforest, many jurisdictions lack planning and knowledge related to the status of groundwater and are tending toward overexploitation as water use increases (e.g., the wine-growing areas of the Okanagan). Net decreases in precipitation will tend to occur in the southern part of British Columbia, but planning for the entire Pacific region should include consideration of water management issues.

3.3 Terrigenous runoff

The increase in intense precipitation events can generate increased turbidity in rivers, lakes, and near-coastal waters. A higher concentration of suspended material in the water column can be deleterious to filter feeders and result in larger sedimentation rates, which can have a negative impact on bottom communities by decreasing bottom oxygen concentrations and impacting the efficiency of filter feeders. Extra runoff would likely deliver more organic matter to the nearshore areas, further impacting the biota and increasing the likelihood of deep anoxic conditions. The fjords of this region can be particularly affected by this increased runoff, siltation, and organic enrichment because of their tendency to feature deep hypoxic or anoxic basins with delicate chemistries with chemical interfaces that are at or near tipping points for habitability of their biological communities (e.g., Johannessen and Macdonald 2009), including relict assemblages of sessile invertebrates on fjord walls (T.A. Okey, personal observations).

3.4 Salinity

The salinity of the surface waters of the North Pacific Ocean has decreased, as indicated by a freshening of the waters at Ocean Station P, west of Vancouver Island, at an average rate of 0.0036 y^{-1} during the last 50 years (Whitney and Robert 2007, Figure 3.8). This indicates a change that is modifying the physics (e.g., stratification and ventilation) of north Pacific surface waters. This change may also be biologically significant, or at least indicative of a trend that will have direct effects on biota.

These and other similar measurements in the North Pacific are consistent with the general prediction of an intensification of the hydrological cycle, in the sense that rainy areas such as the Pacific Rim will become more rainy, as discussed in Section 3.2. They are also consistent with trends from the Alaskan coast and Bering Sea, indicating a general freshening of surface waters due to enhanced precipitation in northern areas. Measurements of increased vertical stratification in the northeast Pacific Ocean (Section 3.5) and decreased oxygen concentrations (Section 3.6) are also consistent with these patterns of decreased salinity. The mechanism is that increased rain decreases surface salinity, and the density of surface water also decreases with warmer temperatures. Both of these changes decrease vertical stratification and ventilation, which decreases oxygen and exacerbates acidification effects.

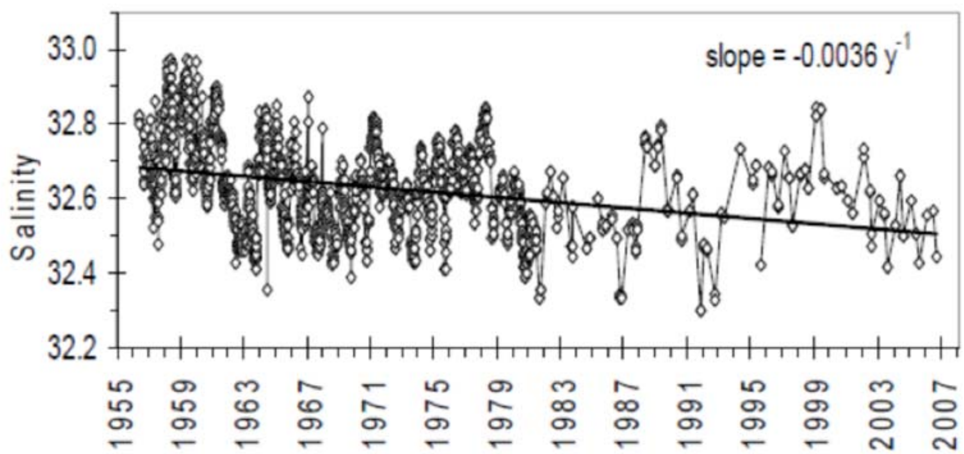


Figure 3.8 Decline in surface salinity at Ocean Station P from 1956 to present (Whitney and Robert 2007).

Perhaps as important as this basin scale change in surface salinity and oceanography are the accentuation of salinity patterns and the modification of seasonal salinity fluctuation regimes in nearshore settings inhabited by vulnerable shallow-water and coastal communities. The salinity in most B.C. coastal areas, especially throughout the north, will decrease (during winter), but the nearshore surface salinity in the southern portion of Vancouver Island may actually increase in some areas and during some seasons because of potential decreases in rainfall and runoff in particular areas such as the southern portion of Vancouver Island (Figure 3.6). At least the frequency of extremely low salinity events may decrease.

3.5 Vertical stratification

Ocean density tends to increase from the surface down, such that lighter water sits on top of denser water in a configuration known as stable stratification. The top-heavy configuration, with denser water on top of light water, occurs very rarely and over short periods of time because of its inherent instability. While the water column is essentially always stably stratified, the degree of stratification (the density differences between shallow and deep layers) varies. The density of water decreases with rising temperatures. As our atmosphere warms, surface waters warm and stratification will be reinforced (Whitney et al. 2007). Stratification will also increase with the expected reduction in surface water salinity since density decreases with decreasing salinity (fresh water is "lighter" than salt water).

The impacts of temperature and salinity on stratification will tend to be larger on semi-enclosed water bodies than on the open ocean. The relative isolation of the first allows large anomalies to be maintained over time, while in the open ocean, anomalies tend to be weakened by transport and mixing with adjacent waters. Also, while rainfall reduces the salinity of open ocean surface waters, these changes are relatively small, and much larger changes in surface salinity can occur as a result of continental runoff into fjords, bays, or inlets. The subarctic Pacific is strongly stratified because of the freshness of the surface layer (Freeland et al. 1997).

The stronger the stratification, the larger the amount of energy required to bring light water parcels down or heavy water parcels up. That is, stratification inhibits vertical motion, and hence mixing, within the water column. An increase in stratification can reduce the transport of nutrients from the deep ocean into the euphotic layer, impacting primary production. It can also reduce the penetration of oxygen-rich surface waters into lower portions of the water column. Taking into account that warming will already reduce the oxygen levels of the surface waters, the increase in stratification could lead to anoxic conditions, with consequences for species that occupy deep ocean waters (Whitney et al. 2007), or any waters below surface layers.

3.6 Oxygen

Dissolved oxygen is expected to decrease in the global ocean by 1-7% this century (Sarmiento et al. 1998, Keeling et al. 2010, Rabalais et al. 2010), but these changes are occurring much more rapidly in the North Pacific Ocean where oxygen has already decreased by 22% during the last 50 years at depths of between 100 and 400 m (Whitney et al. 2007, Figure 3.9). This is a rate of 0.39–0.70 μM y^{-1} or an integrated rate of 123 mmol m^{-2} y^{-1}. Similar trends have been measured west of Haida Gwaii (Crawford et al. 2007), and oxygen loss has now been examined in a variety of locations throughout BC coastal waters with loss rates of 0.5 to 1 μM per year common below the surface mixed layer (F. Whitney, Pers. Comm. 8 March 2012).

This oxygen decline in waters between 250 and 400 m depth along the British Columbia's continental shelf likely affects commercial fish populations by decreasing or compressing available fish habitat (F. Whitney, Pers. Comm. 8 March 2012). Examination of 11 years of fisheries data and ~25 years of oceanographic data shows that both the range of groundfish and oxygen rich waters are shrinking by about 3 m per year (F. Whitney, Pers. Comm. 8 March 2012). These findings are consistent with published declines of oxygen and deep water fish in California (McClatchie et al 2010, Koslow et al 2011). Furthermore, survey data show that oxygen declines are occurring in all areas of the subarctic Pacific (Keeling et al., 2010).

Oxygen saturation decreases with water temperature, so that warming surface waters will reduce the dissolved oxygen concentration. Higher rates of oxygen loss occur at depth because of weakening ventilation and continued consumption of oxygen via remineralization processes (Whitney et al. 2007). Increased rainfall in the region, which freshens the surface waters, is stratifying the upper water column thereby reducing the ventilation of seawater with the atmosphere. This stratification would normally be expected to decrease nutrient supply to the photic zone, thus reducing the photosynthesis and productivity. However this does not seem to be occurring across the subarctic Pacific because of nutrient accumulations immediately below the ocean mixed layer (Whitney 2011). Over time, as the whole volume of the oceans generally warm, the reduction in oxygen concentration will be felt at all depths. In the eastern subarctic Pacific, mixing occurs during winter storms in the top 100 to 125 m (Watanabe et al. 2001), in which oxygen levels are near 100% saturation. Oxygen rapidly declines below this layer, with less than 10% saturation below 500 m (Aydin et al. 2004).

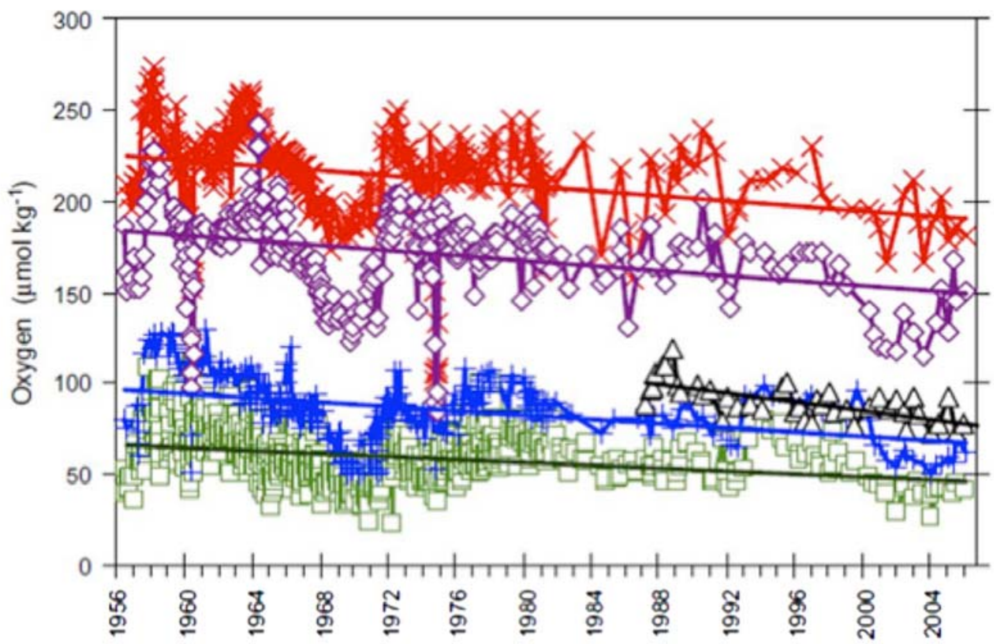


Figure 3.9 Declines in dissolved oxygen at different isopycnal surfaces (between 100 and 400 m) and stations along Line P off the west coast of Vancouver Island (Whitney et al. 2007).

Oxygen minimum zones (OMZs) are expanding all over the world, and these low oxygen conditions can impinge on coastlines such as along the West Coast of North America where it has affected marine life considerably in recent years (Grantham et al. 2004, Dybas 2005, Chan et al. 2008), often being referred to as anoxic or "dead" zones. Such anoxic zones strongly affect marine life; they are expected to become more widespread, and may co-occur with acidification hot-spots. A similar scenario could apply to British Columbia in the future.

In Saanich Inlet, a coastal fjord example, the depth of hypoxic waters in spring and summer is now 25 meters shallower than it was 50 years ago, shrinking habitat for many marine organisms (F. Whitney, pers. comm., 2 March 2009). Dissolved oxygen can be low or absent in the deeper water within coastal fjords (inlets) because (1) the glaciers that carved the fjords usually leave shallow sills of glacial moraine at their mouths, thereby preventing mixing of waters in the deep basins of these fjords with more oxygenated offshore waters; (2) the high input of nutrients and organic material, and the high primary productivity of these inlets lead to high rates of microbial decomposition in these deeper layers, which uses up oxygen (Dallimore et al. 2005, Hay et al. 2009, Dallimore and Jmieff 2010). Though strong tidal mixing can keep the deep water in many British Columbia fjords well oxygenated, these coastal features can have unique sensitivities to deoxygenation and other climate change related impacts (Johannessen and Macdonald 2009).

On a broader scale, and notwithstanding variability in sensitivities, deoxygenation is likely to have profound effects on marine ecosystems throughout Canada's Pacific and the entire North Pacific.

Changes in climate and oceanography

3.7 Ocean pH

Oceans play a critical role in the global carbon cycle, and the carbon cycle strongly influences earth's climate and chemical balances. Over the past 250 years, oceans have absorbed about 130 billion metric tons of CO_2, or more than a third of all human-produced CO_2 emissions (Feely et al. 2008). The consequences are a reduction in ocean pH and carbonate ion concentrations, and subsequent decrease in calcium carbonate saturation in the oceans (Orr et al. 2005). This absorption of modern CO_2 emissions has decreased ocean pH to the lowest levels in 20 million years (Caldeira and Wickett 2003, Feely et al. 2004, Sabine et al. 2004, Caldeira and Wickett 2005, Orr et al. 2005, Hauri et al. 2009). This is causing considerable changes to marine life because pH influences a variety of physiological processes. This in turn impacts the ability of many organisms to produce and maintain their calcium carbonate structure (Feely et al. 2004, Feely et al. 2008).

Calcifying organisms include bottom-dwelling groups such as corals, molluscs (e.g., clams, oysters, mussels, gastropods), sea urchins and sea stars, and components of the plankton, such as coccolithophores and pteropods. Different groups produce different forms of calcium carbonate. Corals tend to produce calcite, pteropods produce aragonite, while urchins and stars mostly produce magnesium-rich calcite. Each of these

forms has a different solubility, with aragonite being more soluble than calcite. The solubility of magnesium-rich calcite increases with the amount of magnesium present and can be the highest of the three forms.

As the pH scale is logarithmic, each whole unit decrease in pH is equal to a 10-fold increase in acidity (Guinotte and Fabry 2008). The IPCC AR4 model mean indicates a decrease in global surface ocean pH ranging from 0.1 to 0.2 units in 2050. Other models suggest that the pH of surface oceans will decrease by 0.3 to 0.4 units by the end of the century (Feely et al. 2008). This radical change in pH will have serious impacts on many marine organisms, as they may be unable to adapt to lower ocean pH at the present rate of change (Feely et al. 2008). These impacts are due to changes in calcite and aragonite saturation levels, which is the concentration of carbonate below which calcite or aragonite begins to dissolve (see Figure 3.10 for modelled global trends) (Guinotte and Fabry 2008). At higher latitudes, there is a decrease in the depth of the aragonite saturation horizon (the depth at which water becomes under-saturated in aragonite), as colder waters hold more CO_2 and are therefore more acidic than warmer waters. Thus, corrosive waters are occurring first at higher latitudes, such as the northeast Pacific, due to temperature effects on CO_2 absorption (Orr et al. 2005, Byrne et al. 2010), thereby causing major shifts in distributions and community assemblages by both latitude and depth.

The aragonite saturation depth along the B.C. coast is presently located between 200 and 400 m, and some predictions indicate these depths will decrease to between 100 and 400 m in the 2040s (Guinotte and Fabry 2008), meaning that aragonite-dependent organisms will need to move to shallower waters for access to aragonite. As the deep ocean becomes more acidic and less saturated in aragonite, the upwelling of unsaturated water into the continental shelf of western North America, which already happens on a seasonal basis (Feely et al. 2008), could become more frequent and occur over larger areas. A rapid drop in pH has been recorded on the Washington side of the entrance to the Juan de Fuca Strait (Wootten et al. 2008). There is little data for the carbonate system for the Canadian West Coast, but a few observations show that the Juan de Fuca Strait and Vancouver Island Coastal Current have high CO2 concentrations due to tidal mixing in the strait (Ianson et al. 2003).

The northeastern Pacific Ocean naturally has some of the lowest pH waters in the world, because it is at the end of the ocean conveyer belt, and CO_2 has built up from respiration in these old waters that upwell along this coastline (Feely et al. 2008, Hauri et al. 2009). Marine organisms of the area have thus adapted to these marginal pH conditions, but the pH of these waters is declining further due to acidification, and this may lead to severe ecological impacts and considerable change. There are some examples of rapid ecological change in nearby marine intertidal habitats associated with these decreasing trends in pH (e.g., Wootton et al. 2008).

Another environmental impact of ocean acidification is the potential change in trace (heavy) metal bioavailability. A fraction of the trace metals present in aquatic environments is found adhered (or "adsorbed") to the surface of clay particles and other materials in the sediments. These adsorbed metals are not usually assimilated by organisms. Adsorption declines as acidification increases (Elder 1988). This means the previously adsorbed metals can be released into the water column in a chemical form that can be assimilated by the biota and incorporated into the food web. Adsorption is not the only mechanism controlling trace metal bioavailability, which depends on a host of other site-specific processes, some of them also influenced by pH.

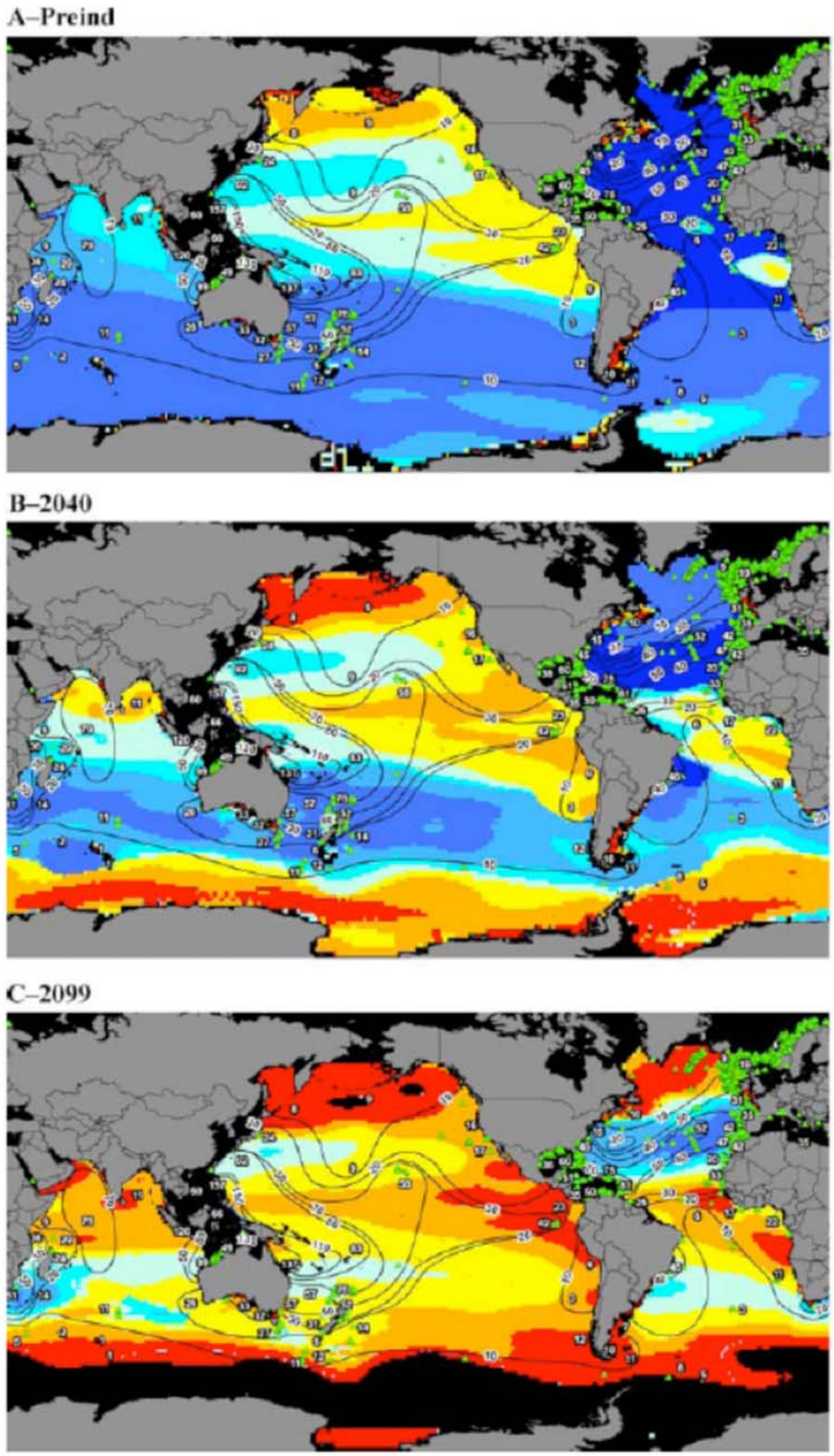
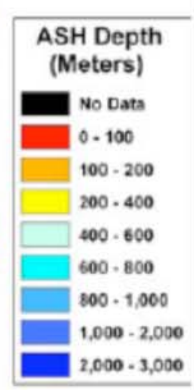


Figure 3.10 Depth of aragonite saturation horizon (ASH) projected under different scenarios: (A) 1756 (pre-industrial), pCO_2 = 278 ppmv (parts per million per volume); (B) 2040, pCO_2 = 513 ppmv; and (C) 2099, pCO_2 = 788 ppmv. Green triangles are locations of deep-sea scleractinian bioherm-forming coral species, and contours show diversity for 706 species of azooxanthellate corals. Black areas in the Southern Ocean and North Pacific indicate areas where the ASH depth has reached the surface. (Source: Guinotte and Fabry 2008.)



3.8 Sea level

Global sea level is expected to rise by 10 to 22 cm by 2050, and by 21 to 44 cm by 2100 (IPCC 2007) (Figure 3.11); it is expected to continue rising for millennia as a result of anthropogenic sea-level rise. The two global causes of sea-level rise are (1) changes in volume to thermal expansion and salinity effects, and (2) changes in volume due to melting of glaciers, ice caps, and other ice and snow (IPCC 2007, Thomson et al. 2008).

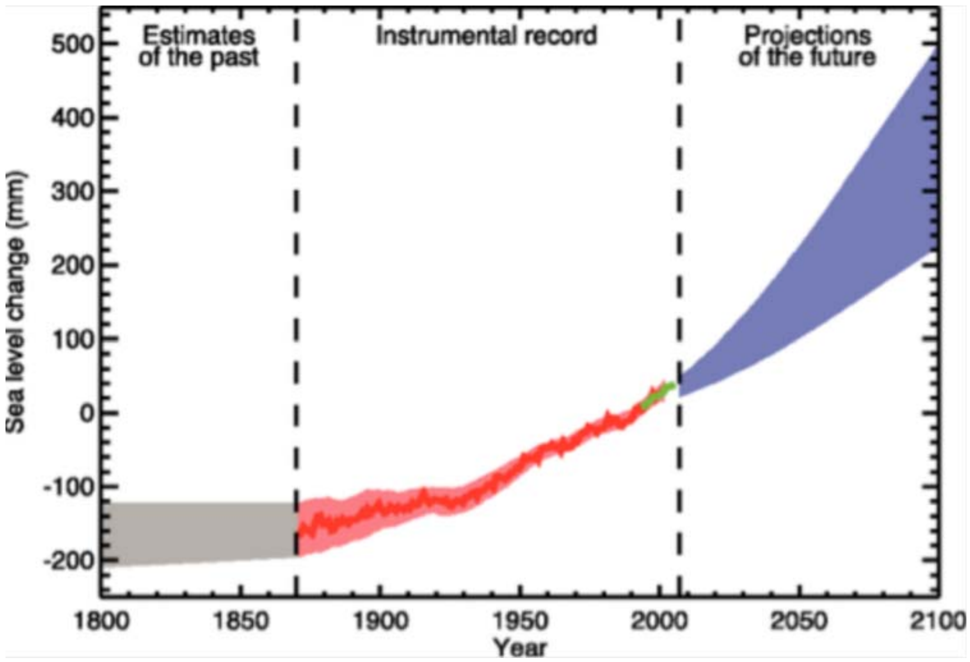


Figure 3.11 Measurements and projections of global mean sea level (deviation from the 1980–1999 mean) (IPCC 2007).

However, sea-level rise is far from uniform along shorelines because it is strongly influenced by local processes such as the speed at which the land is rising and falling, and this varies considerably on small scales due to particular geological and geomorphological histories (e.g., uplift and subsidence) (Thomson and Crawford 1997, Walker and Sydneysmith 2007). For example, Mazzotti et al (2009) estimated that the subsidence of the Fraser River Delta will augment global sea-level rise by as much as 1 to 2 m there. Other regional factors that influence the variability of sea-level rise include variations in ocean temperature, salinity, winds, tidal characteristics, wave exposure, and ocean circulation (IPCC 2007, Thomson et al. 2008).

In their report on sea-level rise in British Columbia, Thomson et al. (2008) categorized these types of changes into four principal driving mechanisms of relative sea-level variability: (1) Eustatic—changes in ocean volume due to the melting of glaciers, ice caps, and ice sheets; (2) Steric—changes in ocean volume due to density changes from thermal expansion and salinity effects; (3) Regional—changes due to dynamic atmospheric and ocean processes; and (4) Local—changes in sea level due to vertical land motions associated with isostatic and tectonic processes.

El Niño events can increase regional sea level by 10 to 40 cm for months at a time. The 1997-1998 El Niño-related increase of 10 cm caused coastal inundation (shoreline retreat), or as much as 12 m horizontally on segments of the Haida Gwaii shore (Barrie and Conway 2002, Cherniawsky et al. 2004). Global sea-level rise by 2100 could add 4 times as much change to that amount, such that a comparable El Niño event during 2100 could cause (horizontal) shoreline inundation by as much as 60 m from (some) present shorelines. Presently, however, El Niño events characterize B.C. sea-level rise (Thomson et al. 2008).

Although projections do not indicate more intense El Niño events under warmer conditions, there is some indication that these events might become more frequent and/or intense (Merryfield 2006). El Niño events would be occurring more often, and every stage of the oscillation would become faster so that anomalies would be of shorter duration. Under such conditions, impacts on more sensitive ecosystem components might increase, but impacts on more resistant components might diminish.

The rates of sea-level rise along the inner and outer coastal waters in British Columbia will vary also because of spatial differences in glacio-isostatic rebound (Thomson and Crawford 1997). It is expected that tectonic uplift and crustal rebound from the weight of ice sheets that covered the B.C. coast 12,000 years ago will offset sea-level rise to some degree (Thomson and Crawford 1997), but sea-level rise is also governed by other factors, such as erosion and deposition rates, which vary over the extent of this coastline.

Ocean warming (a component of steric sea-level rise) is predicted to account for nearly 50% of the observed rate of global sea-level rise (IPPC 2007). However, in British Columbia, regional thermal expansion and salinity effects will exacerbate this (Thomson et al. 2008). In the Strait of Georgia, thermal expansion and salinity account for 37% and 63%, respectively, of total steric sea-level rise (Thomson et al. 2008). The mean observed absolute sea-level rise (not accounting for steric sea-level rise) in the province is in agreement with estimates of global eustatic sea-level rise (1.5–2.0 mm/year) observed from tide gauge data, in addition to the global IPPC estimates (1.85±0.5 mm/year between 1961 and 2003) (Thomson et al. 2008).

The longest available records for sea-level rise are from Prince Rupert (Abeysirigunawardena and Walker 2008). Here, sea level has been rising at a rate of 11–12 cm per century over the past 95 years (B.C. MOE 2007) due to global sea-level rise and vertical movement of the coast (Thomson and Crawford 1997). Recent estimates indicate an average mean sea level increased by 1.4 ± 0.6 mm per year between 1939 and 2003 (Abeysirigunawardena and Walker 2008).

On any particular segment of the coast, flooding, erosion, beach migration, and coastal dune destabilization are not determined exclusively by the degree of sea-level rise. Impacts also depend on a host of other factors that define the vulnerability of these habitats to sea-level rise. These include local relief, geology, sea-level tendency, shoreline displacement, tidal range, and wave height. Based on these and other parameters, an analysis of coastal sensitivity to sea-level rise has been developed for all of Canada (Shaw et al. 1998, BCME 2007). According to these estimates, most of the mainland fjordal systems of Pacific Canada have low sensitivity to sea-level rise, but the sensitivity is moderate around most of Vancouver Island and in some northern areas, including the areas around Prince Rupert and Bella Bella. Sensitivities are rated as high at the northeast corner of Haida Gwaii and at the Fraser River Delta (Figure 3.12; see also Mazzotti et al. 2009).

The science of global, regional, and local sea-level projections and shoreline sensitivity is progressing rapidly. The estimates for all of Pacific Canada discussed above (Figure 3.12) are relatively rough and on a relatively broad scale, and thus have limited use for planning and management. Currently, sea-level-rise sensitivity of specific coastal estuaries in British Columbia is being estimated using the shore-zone dataset (http://www.coastalandoceans.com/shorezone.html), and the ratings are being expressed at a much finer scale on

Google Earth compatible files (D. Biffard, B.C. Ministry of Environment, pers. comm., 10 November 2010). This approach focuses on examining the relative sensitivity of habitats at a much finer scale, but it does not improve the accuracy, precision, and spatial resolution of sea-level-rise prediction.

Recent work has been conducted to better understand storm surge and sea-level rise partly to set the stage for higher-resolution prediction (Abeysirigunawardena and Walker 2008, Abeysirigunawardena 2010). Such work can be used as a foundation to develop rigorous quantitative modelling estimations of shoreline sensitivity at a resolution and precision that would be more useful on a local level. However, this is possible only with higher-resolution data of shoreline elevations, geomorphology, and features.

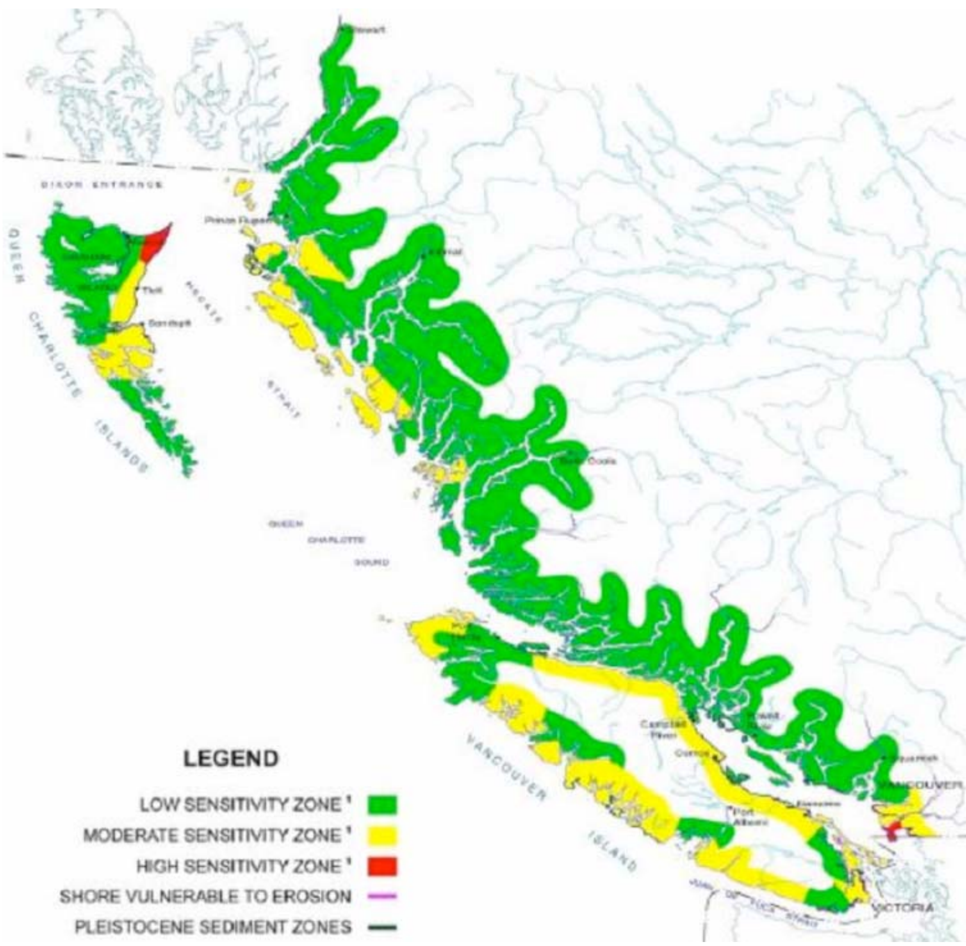


Figure 3.12 Sensitivity of Canada's Pacific coast to sea-level rise and erosion. (Figure from Hay & Company Consultants cited in BCME 2007. Earlier work by Shaw et al. 1998, Atlas of Canada, http://atlas.nrcan.gc.ca)

LIDAR (light detection and ranging) overflights are one potential data source for such modelling. Some topographic LIDAR data have been collected around the city of Ucluelet, on the west coast of Vancouver Island for the purpose of tsunami modelling. The team that conducted this work includes individuals from the Geological Survey of Canada, Pacific Geoscience Centre/Canada Hydrographic Service and Environment Canada, and the Spatial Vision Group in Vancouver. The only other topographic LIDAR data in coastal British Columbia were collected at Roberts Point. One attempt at collecting bathymetric LIDAR data off Price Island was not deemed useful due to interference by kelp and bubbles (M. Foreman, R. Hare, and J. Cherniawsky, Fisheries and Oceans Canada, pers. comm., 17 November 2010).

Fisheries and Oceans Canada is developing a Regional Ocean Modelling System (ROMS) for the B.C. shelf that will use global climate model downscaling techniques (M. Foreman, Fisheries and Oceans Canada, pers. comm., 17 November 2010). This model could potentially be expanded or transferred for ROMS modelling for other areas of Pacific Canada for the estimation of sea-level rise, storm surge, and tsunami projections using high-resolution LIDAR data. Other modelling approaches could potentially be used as well if such data were available.

On a broader geographic scale, the Canadian Hydrographic Service is working with the U.S. National Geophysical Data Center to build a bathymetric DEM (Digital Elevation Model) of the B.C. coast for the purpose of tsunami run-up modelling to be integrated with parallel modelling and estimates for Alaska and Washington State. The U.S. National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory will conduct the tsunami modelling for the region based on these Digital bathymetric Elevation Models in coordination with the Fisheries and Oceans Canada (R. Hare, Fisheries and Oceans Canada, pers. comm., 17 November 2010).

3.9 Oceanic currents

Two major currents in the region may intensify with global climate change: the North Pacific Current, which brings warm waters from the central Pacific, and the California Current, which flows southward from British Columbia to Mexico (IPCC 2007). The latitude at which the Pacific Current impinges on the coast is regulated by the wind. Predicted changes in wind patterns off the coast of British Columbia are subject to some uncertainty (IPCC 2007), but there are indications that point to a potential intensification of the North Pacific Current, which would bring warmer waters from the mid-Pacific into the region. Also, changes in differential heating between land and ocean associated with warming could result in the northward shift and intensification of the subtropical anticyclone (IPCC 2007) that, in turn, would lead to strengthening of the California Current and northward shift, and increase in the upwelling regime off the Pacific coast. This could bring cold water from depth during upwelling seasons, thus partially counteracting the heating. An increase in upwelling has been observed in the California coast region over the last 30 years, and regional climate model simulations indicate that upwelling intensification will occur under future warming (Snyder et al. 2003). These deep waters are richer in nutrients, poorer in oxygen, and more acidic than the waters usually occupying the shelf, and could generate significant ecosystem impacts. For example, deep upwelled water has been associated with shelf hypoxic events observed off the Oregon coast. In several cases these events resulted in near-total mortality of fish and shellfish species, and the generation of sulphide-oxidizing bacterial mats (Chan et al. 2008).

3.10 The El Niño Southern Oscillation (ENSO)

The ENSO cycle is an important component of the interannual variability in the PNCIMA region. The area is exposed to warmer than average conditions during El Niño and colder than average conditions during La Niña (Figure 3.13). The oceanographic impacts related to changes in ocean temperature discussed above, including the changes to stratification, all apply to the alterations brought about by the warm and cold phases of the ENSO. The predicted changes to ENSO due to global warming are described in Section 3.8 (Sea level) above.

3.11 The Pacific Decadal Oscillation (PDO)

The PDO represents a pattern of sea surface temperature variability similar to ENSO, but with much lower frequency (Figure 3.13). There is no clear consensus on what causes the PDO, and consequently, its response to a warmer climate is not known. There is some evidence that a good portion of the oscillation known as PDO is in fact the sum of three (maybe independent) processes: lower frequency modulation of ENSO, variability of high latitude winds, and variability of ocean currents in the west Pacific (Schneider and Cornuelle 2005).

At the moment, there are no indications that the behaviour of either the ENSO or the PDO will be drastically altered under climate change, but one must keep in mind that in the future, the anomalies related to these phenomena will be overlaid on a different mean state.

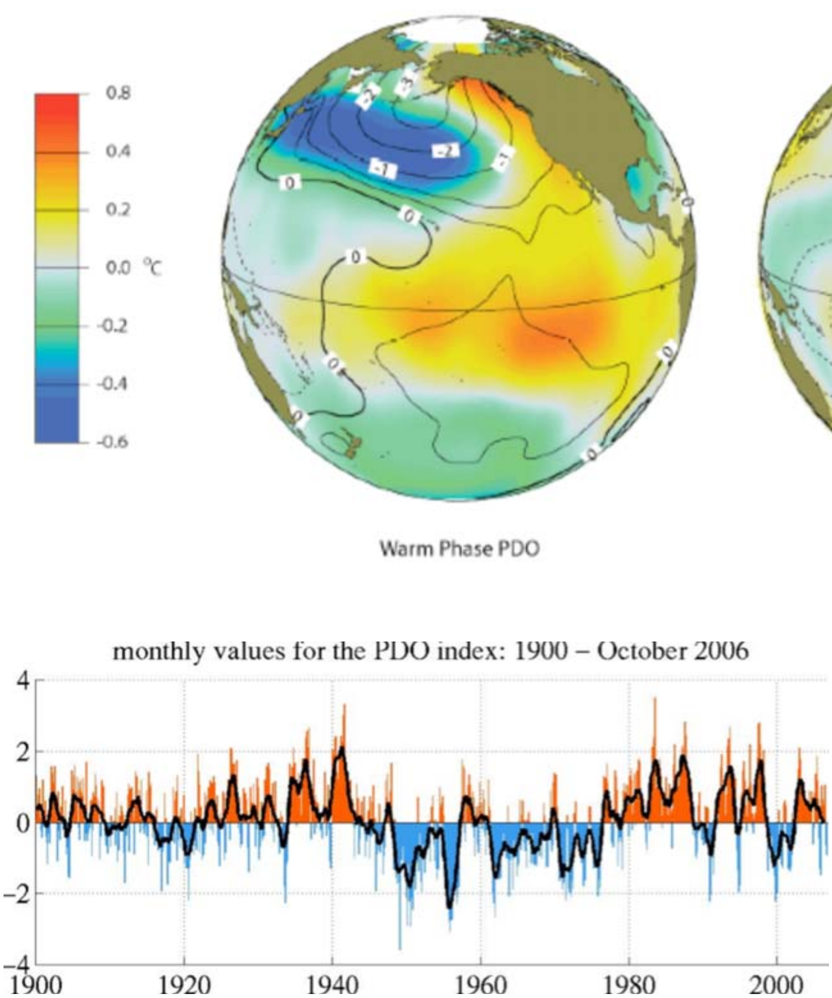


Figure 3.13 Comparison of typical warm phase of the PDO (top left) and warm phase of the ENSO (top right) sea surface temperature anomalies. The PDO index at the bottom provides the temporal variability of the temperature spatial pattern. Positive index values are associated to warm sea surface temperatures in the eastern (and northeastern) Pacific Ocean. Source: Climate Impact Group, University of Washington (http://www.cses.washington.edu/cig/pnwc/aboutpdo.shtml).

Changes in climate and oceanography

3.12 Storminess and wave heights

There is relatively good consensus that storm activity is generally shifting poleward globally; namely, increases in high latitudes and decreases at low latitudes. However, there is considerable uncertainty about mid-latitude storms (Easterling et al. 2000). The Eastern Pacific is highlighted as a unique area with a possible strengthening and equatorward shift of storms, but not increases in frequency (Bengtsson et al. 2006). A recent ensemble analysis of IPCC global climate models (Ulbrich et al. 2008) also indicated a poleward shift in storm activity globally, including a 7% increase in storms near the Aleutian Islands by 2100. But this analysis indicated no change or less than a 1% increase off the coast of British Columbia.

In contrast to these uncertain projections for storms in the vicinity Canada's Pacific marine region, new research (Ruggiero et al. 2010) reveals that SWHT (Significant Wave Height), measured as the average wave height of the one-third largest waves, has increased by more than half a metre since the mid-1970s at buoys offshore of Oregon. This research indicates that the very largest waves have increased by about 2.5 m during that period. These observed increases in large ocean waves off Oregon are consistent with general predictions of the U.S. Climate Change Science Program that increased ocean temperatures will lead to increased intensities of hurricanes and extra-tropical storms, which will increase wave activity, including the sizes of the largest waves (Karl et al. 2008).

This rate of increase in the height of the largest waves is particularly concerning because these strongly affect the rates of coastal erosion and the frequency of coastal flooding, which are also known to have increased in the region. It is likely that these trends in wave heights are the result of changes in storm tracks, higher winds, and more intense winter storms related to global climate change, but they could also be the result of changes in ocean cycles such as the PDO and ENSO, which are not necessarily independent of global climate changes.

The character of El Niño events, and other aspects of ENSO, may change with global warming (Trenberth et al. 2002, Merryfield 2006). Extreme weather events associated with potential increases in El Niño amplitude, frequency, or duration will likely cause considerable coastal inundation and erosion, especially when combined with future sea-level rise (Abeysirigunawardena and Walker 2008, Abeysirigunawardena et al. 2009) and high tides (Thomson et al. 2008, Section 3.8).

Changes in the character of storms, the heights of the largest waves, and other factors that combine to affect shorelines may have severe effects on low-lying coastal communities of the region and their infrastructure, as well as the coastal ecologies of the area, and this is summarized by Walker and Sydneysmith (2007) for B.C. coastal areas. One example is the necessity to relocate entire towns and communities, which some coastal Arctic communities are now facing. Other examples are the implications for proposed oceanic wind farms in the area, and other related developments. Such changes may cause serious engineering challenges for such planned infrastructure and developments, in addition to changing the morphologies of whole coastlines, habitats, and ecosystems. With a rising global sea level, storm surges will have an increasing impact on the coast of British Columbia, particularly on low-lying regions. Given the uncertainty in the projections surrounding these variables, any planning should assume that storms and wave heights would increase considerably during the coming century.

Overview of changes on marine life

4

Overview of impacts on marine life

Canada's Pacific marine areas harbour a unique and broad diversity of marine life. Various types of fishes, invertebrates, and algae benefit human communities and economies through direct utilization. A much broader array of species is not directly utilized, but most or all species collectively contribute to the provision of ecosystem services from which humans benefit. Many species, for example, support, control, or otherwise influence other biological components of the ecosystem through predation, competition, habitat modification, and other ways that reinforce or shape the structure and functions of these ecosystems.

Climate change will have *differential* effects on these species, modifying species relationships and reassembling biological communities. This, in turn, will affect ecosystem structure and function, and thus ecosystem services. The alterations to the physical environment brought about by climate change will affect individual physiology and behaviour, as well as species distributions and phenologies (timing of migrations and life stages). These direct effects will, in turn, affect relative abundances and inter- and intraspecific interactions (e.g., competition, parasitism, and predation), thus resulting in changes to community composition and biodiversity.

Harley (2011) provided a clear example from intertidal ecosystems of Pacific Canada's Southern Shelf region of how climate change can, in such a way, alter these interspecific relationships with important implications for the structure, functions, and biodiversity of these marine ecosystems. That example indicates that warming conditions favour the predatory sea star, *Pisaster ochraceus*, which thereby reduces the cover and vertical extent of mussel beds, with cascading effects on associated species.

Planning responses to climate changes cannot be effective, however, without more specific information about what specific changes are occurring and will occur. Effectively forecasting the effects of climate change on species and communities, even in one ecosystem, is a challenging task that requires, among other things, national and international commitment to the development of stock and whole ecosystem models linked to, or integrated with, global climate models (Okey et al., unpublished manuscript). Such forecasting approaches are being developed, and some examples have appeared in special issues of marine science journals (e.g., Hollowed et al. 2011).

In the meantime, observed ecological changes—such as increased abundances of southern species, declines of more northern species, and other unusual sightings and changes—provide insights into past, current, and future changes, even if these changes are related to El Niño events and other cycles of climate and ocean variability. Indeed, examination of the biological responses to this variability is a useful analogue for understanding directional climate change, with the caveat that the character of these shorter-term events might be quite different from the physical and chemical changes that might be expected with longer-term climate change.

The following points are summarized generalizations about how climate change might affect Canada's Pacific marine ecosystems and biological communities based on observations of changes, knowledge of these settings, ecological theory, and some modelling. These points are intended as examples and not as a comprehensive summary of impacts.

Overview of impacts on marine life

4.1 Shifts in species distributions, community composition, and structure

- We should expect differential effects of climate change on marine species. Some, such as Pacific salmon species, sardines, anchovies, and Pacific hake, are extremely responsive to changes in oceanographic conditions (e.g., Robinson and Ware 1994, Ware and Thomson 2000, Wright et al. 2005), while others are much less responsive. There will be shifts in communities and their composition in any given location, especially those prone to large or sudden physical changes, such as in transition zones like those found on Canada's Pacific coast. Such shifts occur as natural variability in transition zones, but the frequency, magnitude, and character of such changes are likely to change and be more directional in the future.

- Changes in phenology (timing of migration or life stages) will also cause species mismatches where interactions are co-evolved to overlap in space and time. For example, changes to the timing of the peak phytoplankton bloom may mean other species that directly or indirectly depend on them may be affected. This will not only impact individual populations and species, but will also lead to reassembly of organisms in different seasons or places and changes or loss of ecosystem function.

- In addition to scenarios of changes to timing in arrival and departure of species discussed above, considerable reassembly of communities can occur simply through the differential effects on existing native species, thereby shifting the balance of interspecific interactions, as in the example from Canada's Southern Shelf region provided by Harley (2011) and as discussed above.

4.2 Increased occurrence and establishment of new species

- Poleward shifts in the ranges of some species along northeast Pacific coastlines are expected based on theory, but are also evident in monitoring across the whole region (Brodeur et al. 2003, 2005; Orsi et al. 2007, Harding et al. 2011), in comparative climate envelope modelling (e.g., Cheung et al. 2009, Cheung et al., in review), and in a variety of other observations from sub-regions (e.g., Zachrel et al., 2003, Brodeur et al. 2006, Trudel et al. 2006, Wing 2006, Rogers-Bennett 2007). An early example includes a number of observations of unusual species occurrences made during the 1982–1983 El Niño event. These observations were documented by Fulton (1985), and a number of these are summarized in Appendix B. Recent anomalous occurrences (Brodeur et al. 2006, Trudel et al. 2006, Wing 2006) are discussed in Section 5.4. Some of these changes are anomalies related to oceanographic variability, but they can inform us about changes expected with climate change.

- The biological responses will thus be more complex than a simple general northward migration with all species moving at the same pace (Schiel et al. 2004). For example, range shifts will be vertical (Harley et al. 2006) and shoreward (Brodeur et al. 2006). The success of any species in reaching and colonizing a new area will be determined by a host of factors, including obstacles to transport, frequency of introductions, and interactions with the existing community (Lima et al. 2007, Sanford and Swezey 2008, Lockwood et al. 2005) rather than just the common proxy of temperature.

4.3 Loss of biodiversity and changes in favourable conditions

- Ocean acidification will result in shoaling (becoming shallow) of the aragonite and calcite saturation horizons, which, in the northeast Pacific, are already relatively shallow. This means that the effects of acidification will likely result in serious physiological impacts on the calcifying biota, and other pH-sensitive biota, throughout Canada's Pacific (e.g., DFO 2008b).

- Changes in ocean conditions and nutrient availability will influence patterns of primary production, toxic algal bloom frequency, timing, location, and their impacts on biota and human communities.

- Deoxygenation will constrain the movements and force the range shifts and generally decrease habitable space for marine organisms. Such range shifts may be vertical, forcing deep-water-adapted species to shallower waters, where they may be more vulnerable.

- Climate changes are likely to alter the range, status, and vulnerability of endangered species, potentially causing range extensions or contractions, loss of critical habitat, and other survival challenges, in addition to wholesale community changes as mentioned above.

- The occurrence and impacts of disease are likely to increase. Higher temperatures increase the rate of development of pathogens and number of generations per year. Hosts already stressed because of climate change will be more susceptible to infection (Harvell et al. 2002). Climate change may also result in pathogen range expansion; for example, warmer waters have been associated with the range expansion of an oyster parasite in the northeastern United States (Ford 1996), and withering syndrome in abalone species on the Pacific coast (albeit presently south of British Columbia) (van Blaricom et al. 1993, Moore et al. 2000).

- Oceanographic changes related to climate change may make British Columbia more vulnerable to the introduction of the pathogens and parasites listed above, as well as invasive species in ballast water and on ship hulls, drilling muds, and other vectors. The European green crab (*Carcinus maenas*) has travelled north from San Francisco Bay to the west coast of Vancouver Island, and may expand its range to northern British Columbia and Alaska (Gillespie et al. 2007). The golden star tunicate (*Botryllus schlosseri*) and violet tunicate (*Botrylloides violaceus*) are currently established on the east and west coasts of Vancouver Island, and data on their temperature and salinity tolerances indicate that both species are able to inhabit most areas of the B.C. coast (Epelbaum et al. 2009).

- Changes in the exposure of organisms to toxic substances will occur with changes in the physical and chemical characteristics of the environment, on the land and in the sea, and at the coastal interface. Changes will also affect the regimes of local pollution, the long-range transport of persistent chemicals, and other pollution dynamics.

- A changing storm regime, including increased maximum wave heights, and increased likelihood of marine disasters may affect B.C. ecosystems and add to, or have synergistic effects with, other climate change stressors. Related problems could include increased risk of massive oil or chemical spills from increased tanker traffic and energy installations; shoreline flooding and destruction of infrastructure; and increased risk due to more frequent storm events.

- There are indications that the physiological effects of increased CO_2 levels are more pronounced for invertebrates than for fish (Harley et al. 2006), though the mechanistic understanding of the physiological effects of CO_2 on ocean biota is incomplete (Pörtner et al 2005). Large marine fish are likely to be more sensitive to high temperature stress than are smaller fish (Perry et al. 2007).

- Ainsworth et al. (2011) have made initial attempts at simulating the combined effects of acidification, deoxygenation, primary production, zooplankton community structure, and species range shifts on whole northeastern Pacific marine biological communities using fishery-ecosystem trophodynamic models. One key finding was that the combined effects of all factors indicated to be greater than the sum of the effects of each factor, suggesting that effects may be synergistic.

4.4 Changes due to interactions with other stressors

Some even broader generalizations of climate impacts are useful to recognize for this region as well:

- Marine and coastal biological communities with stable, genetically diverse populations and higher biodiversity are more resistant to environmental changes and hence should be more resilient to the impacts of global warming (Hughes et al. 2003, Steneck 2002, Ehlers et al. 2008, Duffy and Stachowicz 2006).

- Biological communities and taxa under the pressure of forestry, fisheries, pollution, and other human activities will be less resilient to climate change impacts as a result of direct stresses on marine ecosystems through destruction and degradation of habitat, direct stress, or effects on organisms.

- Coastal marine and aquatic ecosystems will be more vulnerable to the effects of logging, and foreshore and nearshore development. Changes in stream debris, boulders, and dams due to logging changes the flow hydrology, erosion, sediment, nutrient dynamics, modification of creek groundwater characteristics, and flooding prevalence. These activities and the loss of riparian habitat structure and function affect water quality, estuarine rearing conditions, cover and habitat removal, food availability, predator avoidance areas (refugia), and a variety of other natural supports of biodiversity. Climate change will have greater impacts on the ecology of these already-stressed areas than on those less stressed by local and regional human activities.

- Economically exploited species tend to be top predators in their communities. Removal of top predators reduces the local species richness, simplifies the structure and trophic relations of the community, and leads to an increase in shorter-lived prey populations. Exploitation of forage fishes (e.g., herring) also reduces top predators by removing available production. Both types of fisheries tend to make the community more vulnerable to environmental variability, including climate change (Perry et al. 2007).

- Community response will be largely determined by the impact on key species (Sanford 1999, Schiel et al. 2004). These species must be identified and closely monitored. Examples of key species in the B.C. marine areas include subtidal kelps, eelgrass meadows, and coral and sponge reefs (biogenic habitat forming components), the purple sea star and other predators from salmon to seabirds, orcas, pinnipeds (predation pressure), forage fishes, benthic invertebrates, and plankton such as copepods and krill (prey availability). New approaches are available to rank species importance in whole ecosystems (Okey 2004, Jordan et al. 2008), and this could allow conservation prioritization.

Toward a vulnerability assessment

5

Toward a vulnerability assessment

The bulk of the present report consists of summarized information about the physical, chemical, and biological changes in British Columbia's marine region associated with climate change. With it, we convey a picture of a variety of changes and potential changes that should be expected in the province's marine ecosystems. However, a strategic approach is needed in order for this summarized information to be useful for the formation of management responses.

In this section, we present an approach to developing a climate vulnerability assessment that will allow prioritization of efforts to address climate change impacts in British Columbia. Our approach for this preliminary vulnerability assessment is to characterize and summarize the vulnerability of marine life to climate change on the scale of the 12 ecosections that have been delineated for British Columbia's marine region (Section 5.2). The relative vulnerability of each ecosection is characterized through assessment of the general sensitivity of key marine habitats to climate change and non-climate stressors, and the relative intensity of those stressors in each ecosection.

In sections 5.1, 5.2 and 5.3 we begin describing the sensitivity of British Columbia's marine ecosystems to climate changes on the scales of coastal biogeographic units, ecosections, and habitats to provide a foundation for future refinement of more quantitative vulnerability assessment approaches. In Section 5.4 we present a preliminary spatially explicit vulnerability assessment at the scale of ecosections and habitats. This is done in this preliminary analysis using ratings of habitat sensitivities to climate changes from Teck et al. (2010) using regional habitat distributions and regional extractions of climate variables that depict climate changes for three climate variables for British Columbia's marine region. This preliminary analysis is presented as an example for the purposes of demonstrating one approach to estimating climate vulnerability, which can and should be enhanced with more region-specific information when it becomes available.

5.1 British Columbia's three coastal biogeographic units

At the first level of refinement in understanding the sensitivity and vulnerability of Canada's Pacific marine ecosystems to climate change we provide overviews of British Columbia's three coastal biogeographic units: the Northern Shelf, the Southern Shelf, and the Strait of Georgia. Examination of features at this scale provides a good context in which to conceptualize the effects of the physical and chemical changes discussed in Section 2. It is also the scale at which regional assessment and planning initiatives are developed, whether these are primarily government-driven, broadly participatory and collaborative, or some combination thereof. In these sections, we discuss geography, habitats, and unique features.

5.1.1 Northern Shelf

The Northern Shelf area extends from the Alaska border south to the Brooks Peninsula on northwest Vancouver Island, and Quadra and Bute Inlets to the southeast, and from the shorelines and estuaries to the bottom of the continental slope (Figure 2.1). It includes seven of the 10 marine ecosections designated for British Columbia: Dixon Entrance, Hecate Strait, the North Coast fjords, Queen Charlotte Sound, Queen Charlotte Strait, Johnstone Strait, and the majority of the continental slope ecosection. While this area is less monitored and studied by scientists than the southern region of British Columbia, research in the Northern Shelf area continues to increase. The *Ecosystem Status and Trends* report was recently produced for the North Coast and Hecate Strait ecozone (Cummins and Haigh 2010). That report discusses physical and chemical

changes, including increased temperature and decreased salinity of upper ocean waters, decreasing dissolved oxygen, increasing dissolved CO_2, and potential biological changes, such as shifting species distributions.

This area also coincides with the Pacific North Coast Integrated Management Area (PNCIMA), which is one of Canada's five featured Large Ocean Management Areas (LOMAs) that has been designated as a focal area for implementing aspects of Canada's Oceans Act, including integrated marine resource planning. Important compendiums of information and syntheses have been developed for describing the different components of the Northern Shelf (PNCIMA) area for the purposes of understanding the system (Lucas and Jamieson 2007, Lucas et al. 2007, Perry et al. 2007). These include overviews of considerable amounts of information by a wide variety of experts. We point out that the information and generalizations found in this particular overview literature, which refers to the PNCIMA, is fully interchangeable with the Northern Shelf area regarding ecological descriptions, and somewhat interchangeable with other B.C. marine settings.

The Northern Shelf area consists of a mainland and island geography with important river systems, a mountainous and mostly rocky coastline, snowpack and flow regimes, complex oceanography, a glacially flattened continental shelf, and important connectivity between ecosystem components (e.g., Lucas et al. 2007). It surrounds Haida Gwaii (formerly the Queen Charlotte Islands) and a variety of important nearshore and subtidal habitats. It extends inland through extensive estuarine fjord systems, and is bordered by and connected to most of British Columbia's coastal watersheds, including lake, river, and tributary systems, and it covers a large area of continental shelf, and includes submarine canyons (Figure 5.1).

Productivity around the boundaries of the Northern Shelf area is driven by seasonal and episodic switches in upwelling and downwelling, variable seasonal patterns of freshwater runoff from watersheds, and enhancement by strong tidal mixing in narrow passes and channels and at other ecological interfaces. The banks on the continental shelf in the region are separated by large and deep troughs connecting to the deeper continental slope.

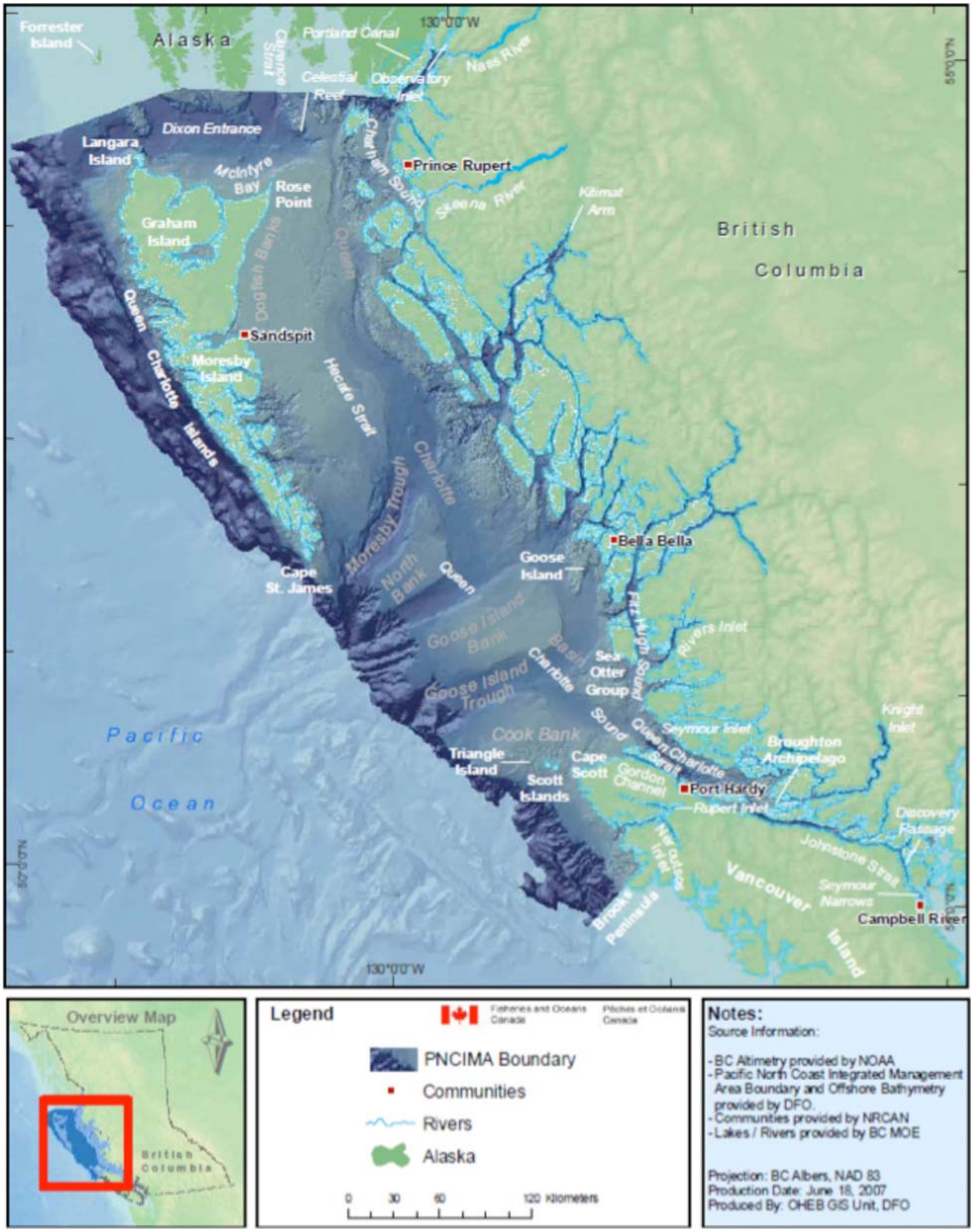


Figure 5.1 Northern Shelf biogeographic unit showing bathymetric features and characteristics of the area. This area corresponds with the Pacific North Coast Integrated Management Area (PNCIMA), which this map was made to describe (Fisheries and Oceans Canada).

Toward a vulnerability assessment

The food web of this large Northern Shelf ecosystem is depicted in Figure 5.2 based on trophodynamic ecosystem modelling using Ecopath with Ecosim (e.g., Ainsworth et al. 2002, Ainsworth and Pitcher 2005c, 2005b, 2005a, 2006, Ainsworth et al. 2008; also see Appendix A). Differences in this depiction of the food web and that of Figure 2.4, which was also intended by Perry et al. (2007) to summarize the Northern Shelf ecosystem food web, reflect differences in approaches, conceptual models, questions of interest, and available information. These approaches can inform each other, and considerable additional information has become available in the few years since Ainsworth's models were initially constructed. Although the modelling approach used was initially designed for examining fishery-ecosystem interactions and exploring fisheries policy, progress is being made in understanding climate change impacts with this approach, as exemplified by Ainsworth et al. (2011), and this is expected to continue at a rapid pace (e.g., see Hollowed et al. 2011).

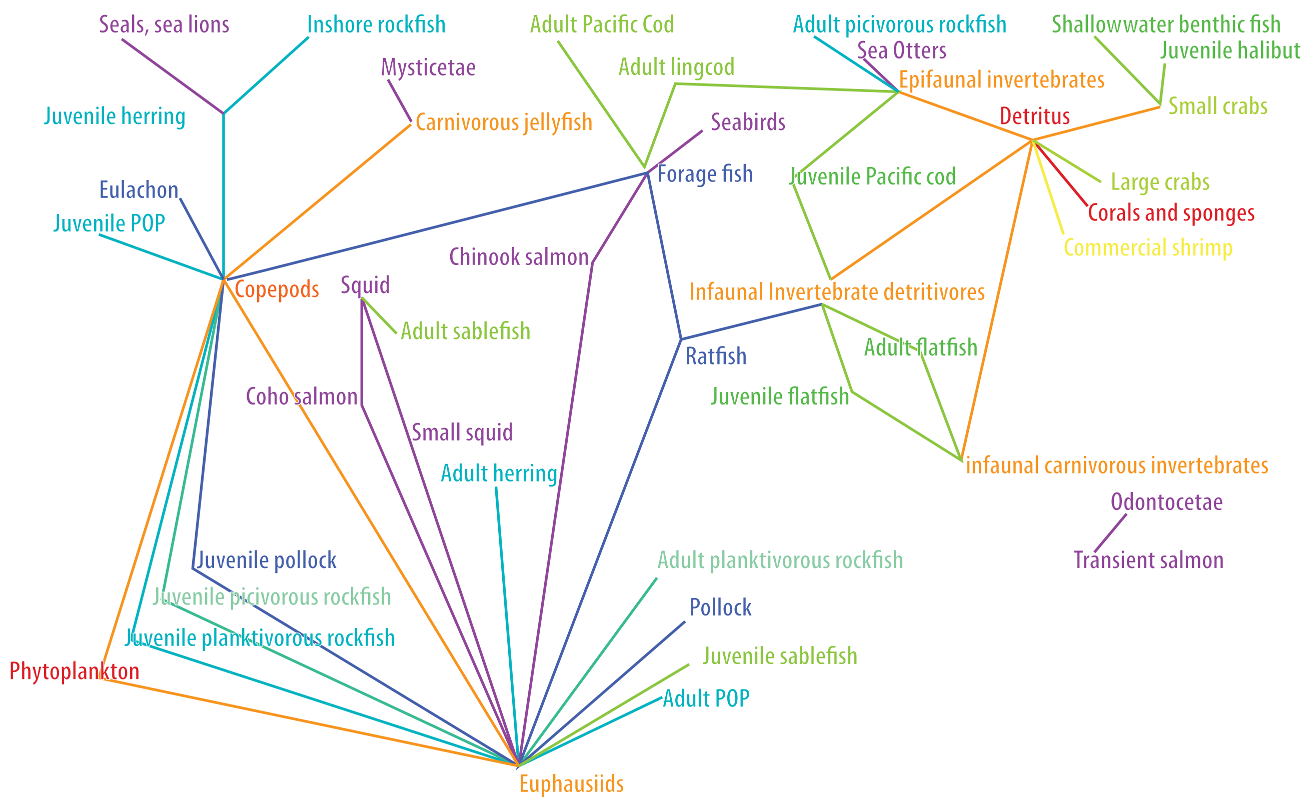


Figure 5.2 Food web diagram of the Northern Shelf marine ecosystem based on trophodynamic modelling using Ecopath with Ecosim (unpublished figure by C. Ainsworth).

There is presently much interest in sustainable, ecosystem-based, and integrated management of the Northern Shelf area. The capacity and interest for understanding the effects of climate change in the context of other human activities, and for climate adaptation planning continue to grow in the region.

Overall, the expression of climate change impacts will be variable across the Northern Shelf area owing to the wide range of ecosections and habitats in the area, and understanding of this variability will be key to successful planning for social-ecological sustainability.

5.1.2 Southern Shelf

The Southern Shelf biogeographic unit extends from the Brooks Peninsula on the west coast of Vancouver Island south through the Strait of Juan de Fuca to the northern edge of Washington State's San Juan Islands, at the beginning of the Strait of Georgia, and is delineated from an ecological perspective by DFO (2009a) to include the San Juan Islands and United States waters extending to the shoreline of Washington State (Figure 2.1). This unit extends from the high water mark to the toe of the continental slope adjacent to the west coast of Vancouver Island.

The marine resources management of much of the Southern Shelf is the focus of an ongoing planning process coordinated by West Coast Aquatic—a participatory advisory board for the management of marine and aquatic resources of the west coast of Vancouver Island (WCVI). This project continues to be implemented as the "Tsawalk Partnership," named after the integrated and ecosystem-based Nuu-chah-nulth guiding principle *Hishuk ish tsawalk,* or "Everything is one." The geographic scope for that project is the area of Ha-houlthee (territorial wealth) of 15 First Nations of the Nuu-chah-nulth people. The implied marine area of this Ha-houlthee in Canadian waters is shown in Figure 5.3.

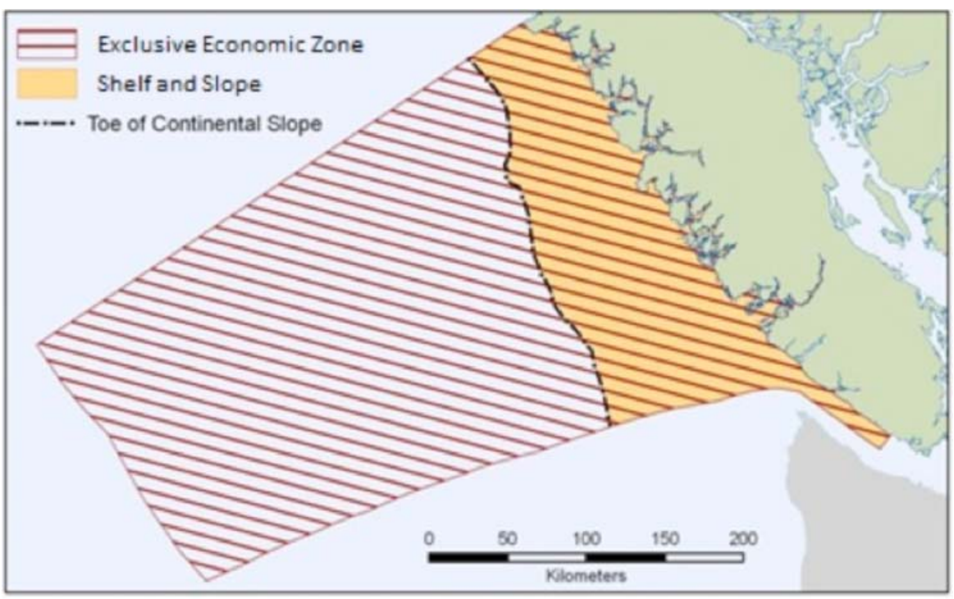


Figure 5.3 Area of the Exclusive Economic Zone (red hatching) associated with the Ha-houlthee (traditional area) of the Nuu-Chah-Nulth First Nations on the west coast of Vancouver Island, limited by the standard 200 nautical mile limit of the EEZ. The orange area demarcates the continental shelf and slope (From Alidina et al. 2010).

As in most of British Columbia, the coastline of the Southern Shelf is highly articulated by estuarine fjords, but the watersheds on the WCVI are smaller and different geomorphologically than those on the mainland, and the runoff is thus of smaller magnitude and different seasonal character. The Juan de Fuca Strait, in contrast, is a glacially influenced trough from which a major buoyancy current influences outer coastal waters, and through which many species migrate. The WCVI and the Juan de Fuca Strait contain, and are exposed to, spatially and seasonally complex interfaces of estuarine outflow, upwelling patterns, and local and regional currents and eddies, including the Juan de Fuca Eddy, nicknamed "The Big Eddy" ecosystem. These processes are all strongly influenced by oceanographic cycles such as ENSO (Dallimore et al. 2005, Okey and Dallimore 2011) and exhibit complex interactions with migratory fauna. The spatial and temporal complexity that the dynamic Southern Shelf ecosystem is exposed to is partially recorded in anoxic fjords, which contain archives of paleontological records of change (Wright et al. 2005, Dallimore and Jmieff 2010). The productivity, fisheries, and other biological implications of climate variability and change in the Southern Shelf area are also being addressed by an emerging literature (e.g., Robinson and Ware 1994, Ware and Thomson 2000, Ware and Thomson 2005, Mackas et al. 2007, Beamish et al. 2009)

The intertidal and subtidal setting of this area was described by Okey et al. (2011), based partly on descriptions in Thomson (1981): The rocky seashore and shallow rocky subtidal features such as pinnacles and small islands are interspersed with soft sediment on the relatively narrow (20- to 80-km-wide) Vancouver Island Shelf, which slopes gently from the coastline to the shelf break at about 180-m depth, though it can be much narrower and shallower where submarine canyons and valleys impinge on shoreline. The rugged terrain of "bumps, knobs, and deep canyons" of the continental slope is similar to that of the adjacent land topography (Thomson 1981), and on the shelf. Strong across-slope and downslope turbidity currents, and other mass wasting processes occur on the continental slope, carrying sediment and other material toward the Cascadia Basin, which is more than 3,000 m deep in places. A thick layer of sediment from these turbidity currents forms the continental rise, which begins at the 1,800-m contour (Thomson 1981).

Thanks to their greater accessibility, the ecosystems of the Southern Shelf area are more studied and understood than those of the Northern Shelf area. Patterns of human activities likewise reflect some historical differences among these broad geographic units, but activities such as fisheries and forestry impose stress throughout all of the coastal areas of British Columbia. Fisheries and Oceans Canada (DFO) recently completed its *Ecosystem Status and Trends* report for the WCVI (Ianson and Flostrand 2010), which is a useful compilation of the status and recent trends of components of the ecosystem for which data were available to DFO, based largely on the components of the ecosystem for which DFO takes responsibility for tracking. West Coast Aquatic, through the Tsawalk Partnership, mentioned above, is conducting a long-term project to identify the region's stressors, understand the state of the ecosystem through the selection and monitoring of a broad set of social-ecological indicators, and develop management strategies and evaluation approaches with the engagement of local communities, for the purpose of social-ecological sustainability planning (Okey and Loucks 2011).

In addition to this long-term approach, ecosystem modelling of various types is being developed for the Southern Shelf region that can be used to begin to understand how climate change will affect these marine ecosystems in the future. Ainsworth et al. (2011) included an early WCVI model in their examination of climate impacts on northeast Pacific ecosystems, and that preliminary work indicated potentially major impacts, and effects of combinations of impacts that are more than additive. Additional ecosystem models are also being developed in this region. Espinosa-Romero et al. (2011) developed an Ecopath model of WCVI kelp forest ecosystems to address questions about the effects of expanding sea otter populations along this coastline (Figure 5.4). Cisneros-Montemayor (2010) developed a model of the WCVI pelagic ecosystem to address questions about sardines and other forage fishes (Figure 5.5). As in the Northern Shelf area, dramatic differences in these models reflect differences in approaches, conceptual models, questions of interest, available information, and in this case ecosystem and setting.

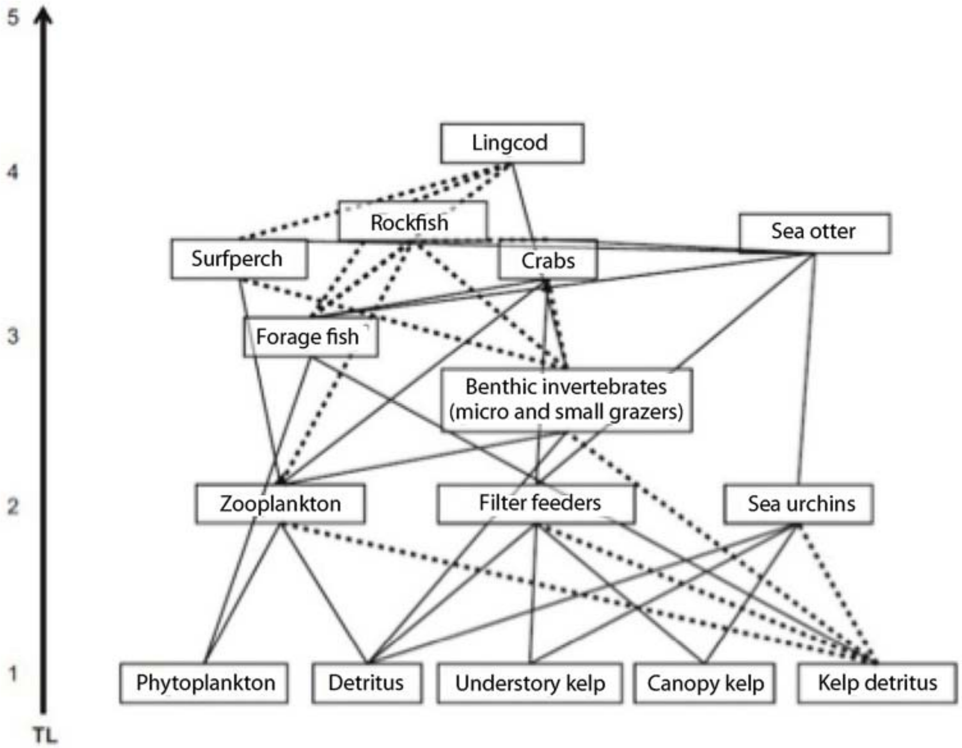


Figure 5.4 Food web diagram of the kelp forest ecosystems on the west coast of Vancouver Island by Espinosa-Romero et al. (2011).

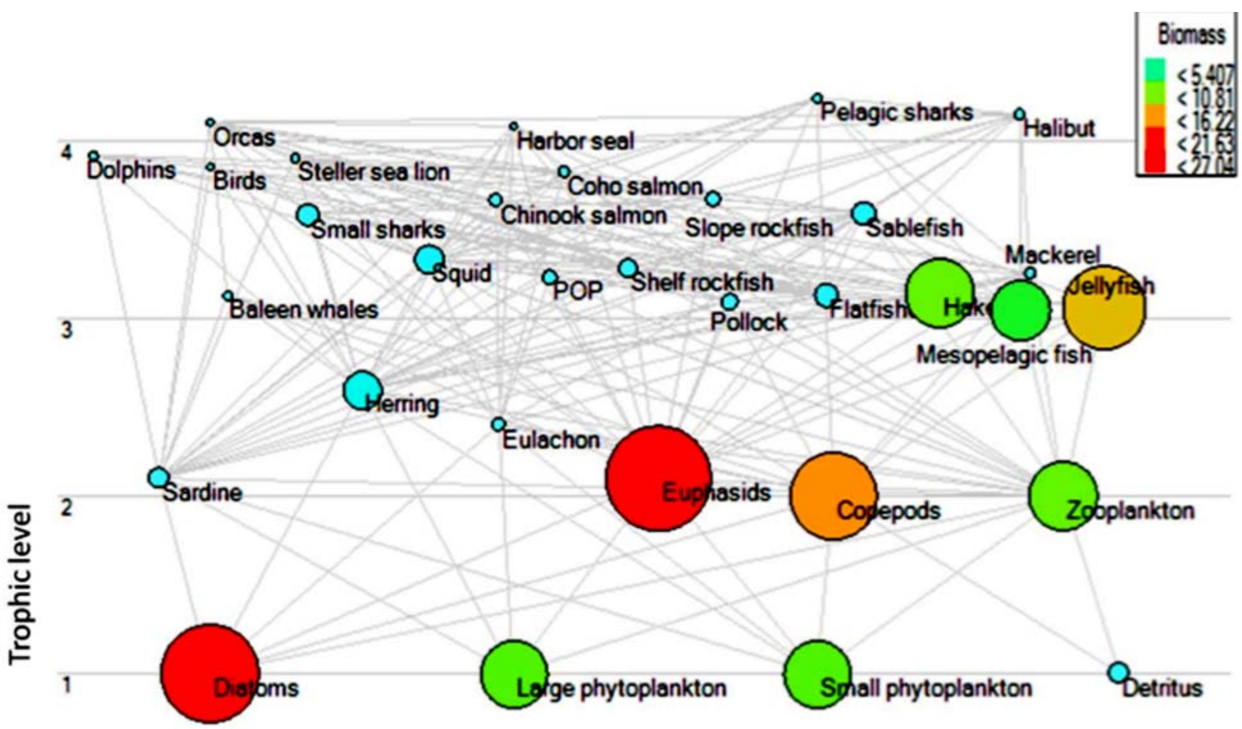


Figure 5.5 The pelagic food web off the west coast of Vancouver Island (from Cisneros-Montemayor 2010).

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These trophodynamic fishery ecosystem models can be used directly in exploring the impacts of climate change, or they can be linked to, or integrated with, physical and biogeochemical models, such as the Regional Ocean Modelling System (ROMS) for the B.C. shelf (M. Foreman, Fisheries and Oceans Canada, pers. comm., 17 November 2010), which was discussed previously. Such linking would bring ecological climate forecasting approaches closer to a true end-to-end modelling approach that is explicitly mechanistic with physical, chemical, and biological realms. Such regional-scale modelling can be connected to global ocean-atmosphere models as part of whole earth-system modelling efforts to obtain an even better understanding of the potential impacts of climate change as each component of the system continues to be refined.

Still, such modelling and forecasting need evaluation and ground-truthing, in this case using ongoing empirical programs for monitoring indicators of ecosystem and social-ecological system status and health, as well as pressure indicators so that management strategies can be developed and evaluated. Such monitoring approaches and underlying approaches indicator development are being developed by West Coast Aquatic, but will need continued collaboration and attention by all interested and responsible agencies and parties.

5.1.3 Strait of Georgia

The Strait of Georgia is considered an inland sea, as it lies between Vancouver Island and the mainland of British Columbia, and is connected with the Pacific Ocean through the Johnstone Strait to the north and the Haro and Juan de Fuca straits to the south (Figure 5.6). It was formed by a crustal downfolding due to the crustal upfolding of Vancouver Island just to the west. This crustal upfolding had resulted from the collision of the Juan de Fuca Plate with the North American Plate, and the subduction of the former under the latter (Thomson 1981). It was further sculpted by the Cordilleran Ice Sheet of the Fraser Glaciation between 29,000 and 15,000 years ago.

Shallow sills restrict water movement between the Strait of Georgia and the Pacific Ocean, so waters deeper than 100 m in the Strait of Georgia have a long residence time and are replaced only during deep-water renewal events that occur seasonally, much like a large fjord (Johannessen and Macdonald 2009). It is mostly influenced, therefore, by estuarine circulation driven by the Fraser River and smaller rivers and streams, and to a lesser degree by tidally driven interchange with offshore waters through the Juan de Fuca and Johnstone straits (Johannessen and Macdonald 2009). These characteristics and dependencies all signify high sensitivity to climate change.

Furthermore, the Strait of Georgia is surrounded by the most densely populated and urban parts of British Columbia, and this marine biogeographic unit has been exposed to the most concentrated of human stressors, has had the longest history of contemporary human activities, and has thus been modified more than others in Canada's Pacific (e.g., Pauly et al. 1998, Pitcher 2005, Johannessen and Macdonald 2009, Ban et al. 2010).

In examining the Strait of Georgia as a case study of climate change impacts in the context of local human impacts, Johannessen and Macdonald (2009) concluded that a number of its components are vulnerable, or sensitive, to climate change. For example, they reviewed how benthic and pelagic habitats in the Strait of Georgia would be impacted and reduced by decreases in pH and dissolved O_2, how sea-level rise and storms will affect intertidal and estuarine habitats, how seasonal shifts in biological production patterns will affect the whole food web, how a number of coastal and ocean changes will affect Pacific salmon species, and how endangered species such as killer whales will be increasingly stressed and at much greater risk. These authors emphasized that management of local stressors that are not related to climate change would increase the resilience of this system to the increasing impacts of climate change. Fisheries and Oceans Canada has produced a broader technical document on the status and trends of the Strait of Georgia ecosystem (Johannessen and McCarter 2010).

Figure 5.6 The Strait of Georgia situated between the southern half of Vancouver Island and the southern mainland of British Columbia. (Figure from Johannessen and Macdonald 2009.)

Because of its close proximity to human population centres, the Strait of Georgia is the most thoroughly researched and best understood of Pacific Canada's three coastal bioregions. A variety of research is conducted in this area by universities, public agencies, and others. Fisheries and Oceans Canada is coordinating a broad ecosystem-level research program for the Strait of Georgia called "The Strait of Georgia Ecosystem Research Initiative," which is intended as the foundation for an ecosystem-based approach for the

Strait of Georgia (see http://www.pac.dfo-mpo.gc.ca/science/oceans/detroit-Georgia-strait/index-eng.htm). A central emphasis of this initiative is the impacts and vulnerabilities of climate change on the Strait of Georgia marine ecosystem in the context of other human stressors.

This program consists of three interdependent components: (1) analysis of existing historical data, (2) empirical field measurements and investigation, and (3) analysis using numerical models and ecosystem indicators. An end-to-end model representing all ecosystem components and trophic interactions, linked with physical conditions including circulation, will help lead to a better understanding of the effects of climate change and other stressors on the Strait of Georgia ecosystem. A whole-ecosystem trophodynamic model (Ecopath) is also being constructed for the Strait of Georgia as a complement and parallel approach to the aforementioned more explicit end-to-end modelling approach (Li et al. 2010). A food web diagram from this ecosystem model provides some insight into the structure of the biological community at the level of species aggregation chosen for this model (Figure 5.7).

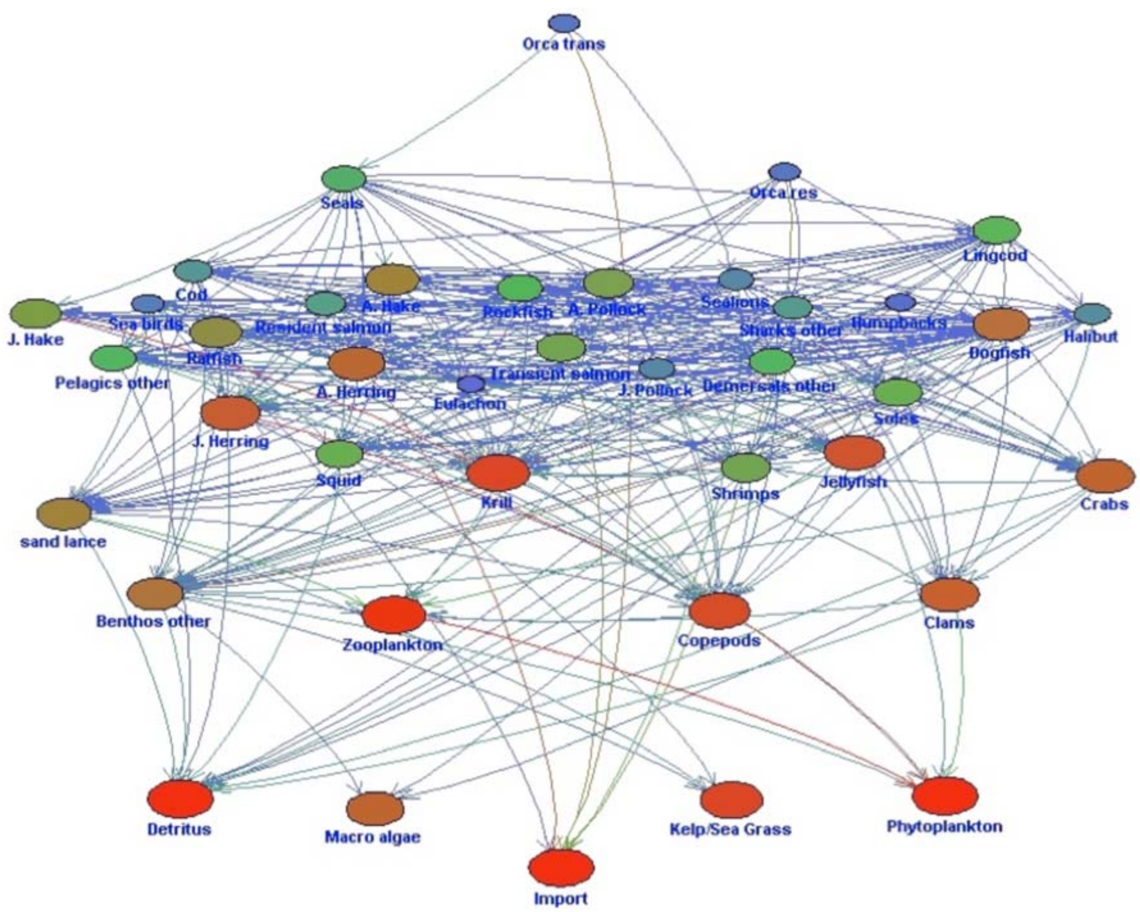


Figure 5.7 The food web of the Strait of Georgia from the Ecopath with Ecosim trophodynamic model described in Li et al. (2010).

As described previously, these models can be used to begin forecasting the impacts of climate change on Canada's Pacific marine ecosystems. The preliminary models are available for commencing this work, which will lead to continued refinement of these approaches (Appendix A).

5.2 Sensitive characteristics of B.C. ecosections

The marine ecosections of British Columbia were classified based on the *British Columbia Marine Ecological Classification* (BCMEC) developed by the Provincial Land Use Coordination Office in 1997 and updated in 2002 (Government of British Columbia 2002). The BCMEC is a hierarchical ecological mapping system based on physical, oceanographic, and biological characteristics, and is intended as a planning tool for marine and coastal resource management, conservation, and protection. The BCMEC was developed from previous federal and provincial marine ecological classification efforts; in particular, the *Classification of the Marine Regions of Canada*. This classification system used physical criteria important to regional ecological processes to designate ecozones (ice regimes and ocean basins), ecoprovinces (ocean regimes and continental margins), ecoregions (marginal seas), and ecosections (mixing and stratification). In British Columbia, 12 marine ecosections were identified, ranging in size from 1,500 to 171,000 km^2.

Fisheries and Oceans Canada recently refined its biogeographic classification of Canadian marine areas (DFO 2009a) on the scale of ecoregions, but used the term "biogeographic unit" (Figure 2.1) instead of "ecoregions." The *2010 Canadian Marine Status and Trends Report* series (DFO 2010b) used the term "ecozone" for what was originally called "ecoregion" in the 2002 classification. These do not match, exactly, with the biogeographic units specified in the 2009 classification of biogeographic units, which is used herein. The smaller ecosections, useful for the present exercise, are shown in Figure 5.8, along with a variety of hydrologic and oceanographic features that characterize each of them.

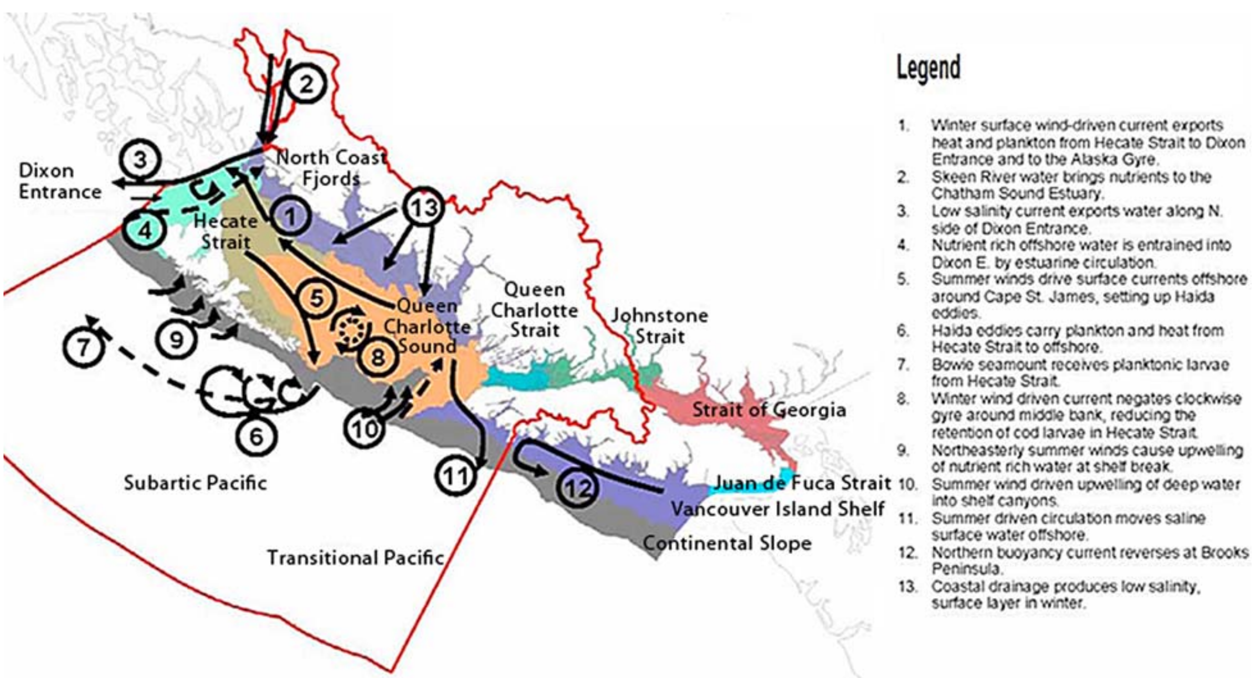


Figure 5.8 B.C. marine ecosections (shaded) and ecosystem features (black circles and lines) in the PNCIMA. From J. Mathias, DFO Oceans Directorate, unpublished report "Rationale for the LOMA Boundary" 2003.

Toward a vulnerability assessment

The sensitivities of Canada's Pacific ecosections to climate change impacts are summarized in Table 5.1, with brief descriptions of each ecosection presented along with potential major global change effects. This is followed by narrative sections on unique characteristics of B.C. ecosections. However, this cursory treatment of ecosection features and their sensitivities inevitably misses many subtle, conspicuous, and other potential effects of climate change. Our goal in this section is to provide a general picture of the types of sensitivities of these ecosections. An examination of sensitive characteristics of B.C. marine habitats and the coast-wide proportion of each habitat in each ecosection is provided here as a further foundation upon which region-specific vulnerability assessments can be built and refined. The habitat proportions should be considered coarse estimates and are from a compilation of best available spatial data, which are known to have gaps (Appendix C).

Table 5.1 Summary of B.C. marine ecosections (adapted from Government of British Columbia (2002)), organized by biogeographic unit (DFO 2009a), and some expected effects of climate change.

Marine Ecosection	Physiographic Features	Oceanographic Features	Biological Features	Boundary Rationale	Potential Major Climate Change Effects
Northern Shelf					
Dixon Entrance	Across-shelf trough with depths mostly < 300 m; surrounded by low-lying coastal plains (Hecate Depression)	Strong freshwater influence from mainland river runoff drives north-westward flowing coastal buoyancy current and estuarine-like circulation	Mixture of neritic and subpolar plankton species; migratory corridor for Pacific salmon; some productive and protected area for juvenile fishes and invertebrate development	Distinguished from area to south by strong freshwater discharge influence	Increase in runoff and stratification. Reduction in salinity and associated changes to the buoyancy driven flow. Ocean warming. Sea-level rise.
Hecate Strait	Very shallow strait dominated by coarse bottom sediments; surrounding coastal lowlands	Semi-protected waters with strong tidal currents that promote mixing; dominantly "marine" waters	Neritic plankton communities w/ oceanic intrusion; nursery area for salmon and herring; abundant benthic invertebrates; forage for marine mammals and birds	Marine in nature but much shallower, with associated greater mixing than areas to the south	Ocean warming. Sea-level rise. Changes in runoff and salinity.
North Coast Fjords	Deep, narrow fjords cutting into high coastal relief	Very protected waters with restricted circulation; often strongly stratified	Low species diversity and productivity due to poor water exchange and nutrient depletion; unique species assemblages in benthic and plankton communities	Unique physiography and stratification compared with bordering regions	Ocean and continental warming. Increase in runoff. Decrease in salinity. Increased stratification and likely intensification of anoxia.
Queen Charlotte Sound	Wide shelf characterized by several large banks and inter-bank channels	Ocean wave exposures with depths mostly >200 m and dominated by oceanic water intrusions	Mixture of neritic and oceanic plankton communities; northern limit for many temperate fish species	More oceanic (deep) and marine than Vancouver Island Shelf and Hecate Strait	Oceanic warming. Intrusion of low anoxic and acidic waters into canyons.

Marine Ecosection	Physiographic Features	Oceanographic Features	Biological Features	Boundary Rationale	Potential Major Climate Change Effects
Queen Charlotte Strait	Predominantly shallow (< 200 m); high relief area with deeper fjord areas	High current and high relief area; very well mixed; moderate to high salinities with some freshwater inputs in the inlets and fjords	Very important for marine mammals; migratory corridor for anadromous fishes; moderate shellfish habitat	More marine than Johnstone Strait; much more shallow with high relief and high currents than Queen Charlotte Sound	Ocean and continental warming. Increase in runoff. Decrease in salinity.
Johnstone Strait	Narrow, constricted channels	Protected coastal waters with strong currents; well mixed; poorly stratified	Migratory corridor for anadromous fishes; rich sessile, hard substrate invertebrate community; diverse species assemblage of benthic fishes	Johnstone Strait has greater mixing and more channels than areas to south; Queen Charlotte Strait more marine	Changes in currents, temperature, salinity, and productivity
Continental Slope	Steep sloping shelf	Strong across slope and downslope; turbidity; currents	Upwelling zone; productive coastal plankton communities and unique assemblages of benthic species	Transitional area between continental slope and abyssal plane	Acidification and anoxia in the deep layers. Ocean warming. Changes to ocean currents.
Southern Shelf					
Vancouver Island Shelf	Narrow, gently sloping shelf	Open coast with oceanic wave exposures; northward, coast-hugging buoyancy current due to freshwater influence; seasonal upwelling at outer margin	Highly productive with neritic plankton community; northern limit for hake, sardine, northern anchovy, and Pacific mackerel; productive benthic community; rich fishing grounds for benthic fish and invertebrates	More open shelf than Juan de Fuca Strait; more freshwater influence (coastal buoyancy current) than Queen Charlotte Sound	Oceanic warming. Changes to nearshore buoyancy-driven flow and offshore ocean circulation.
Juan de Fuca Strait	Deep trough; major structural feature accentuated by glacial scour	Semi-protected coastal waters with strong "estuarine-like" outflow current (coast-hugging buoyancy current to north); major water exchange conduit with "inland sea"	Migratory corridor for anadromous fish; moderately productive; mixture of neritic and oceanic plankton species	Much more marine than Strait of Georgia; less "open shelf" than Vancouver Island Shelf	Changes in currents, temperature, productivity, salinity, oxygen, and acidity.
Continental Slope	Steep sloping shelf	Strong across slope and downslope; turbidity; currents	Upwelling zone; productive coastal plankton communities and unique assemblages of benthic species	Transitional area between continental slope and abyssal plane	Acidification and anoxia in deep layers. Ocean warming. Changes to ocean currents.

Marine Ecosection	Physiographic Features	Oceanographic Features	Biological Features	Boundary Rationale	Potential Major Climate Change Effects
Strait of Georgia					
Strait of Georgia	Broad shallow basin surrounded by coastal lowlands (Georgia Depression)	Protected coastal waters with significant freshwater input; high turbidity and seasonally stratified; very warm in summer	Nursery area for salmon, herring; abundant shellfish habitat; neritic plankton community	Stronger Fraser River signature than areas to north or west	Increased temperature. Changes in runoff and currents. Acidification and dissolved oxygen.
Offshore Pacific					
Subarctic Pacific	Includes abyssal plain and continental rise; major fault occurs along west margin; seamount chain trends NW/SE	Eastward-flowing subarctic current bifurcates at coast with northerly flowing Alaska Current; current flow generally northward throughout year	Summer feeding ground for Pacific salmon stocks; abundance of pomfret, Pacific saury, albacore tuna, and jack mackerel in summer; boreal plankton community	Northern and western boundaries undefined; eastern boundary coincident with shelf break; southern boundary indistinct	Freshening of surface waters, increased stratification, decreased oxygen concentrations, change in productivity
Transitional Pacific	Includes abyssal plain, and continental rise; also includes spreading ridges, transform faults, triple junction, and plate subduction zone	Area of variable currents; southerly areas may be affected by southward-flowing California Current in summer, but remainder of area characterized by weak and variable currents; Davidson Current along shelf edge flows north in winter, south in summer	Transition zone between southerly, temperate, and northerly boreal plankton communities; mixing of oceanic and coastal plankton communities adjacent to coastal shelf	Northern boundary indistinct and approximately coincident with southern limit of Alaskan Current (winter); eastern boundary at shelf break. southern and western boundaries undefined	Freshening of surface waters. Increased stratification. Decreased oxygen concentrations. Change in productivity.

5.2.1 Dixon Entrance

Located on the northwestern edge of the Northern Shelf, Dixon Entrance is a rich and highly productive ecosection due to a combination of hydrological and oceanographic factors: heat (warm water) and plankton are exported from Hecate Strait to Dixon Entrance during winter by surface-wind-driven currents, nutrients arrive from the Skeena River to the east; it contains fronts of low- and high-salinity water; and nutrient-rich offshore waters are entrained because of estuarine circulation (Figure 5.8). This ecosection contains important biological features, such as a larval gyre for Dungeness crab. Based on existing spatial datasets, this ecosection is thought to contain 57% of Pacific Canada's known hard-slope areas, 24% of the kelp areas, 13% of the rocky intertidal, and 11% of the deep rocky reef areas (Table 5.2).

Because the ecology of Dixon Entrance is strongly influenced by freshwater runoff, hydrological intensification related to climate change will likely affect this system by intensifying its estuarine features, but the effects of these physical changes on the ecology of Dixon Entrance has not been projected in detail. The temperature of the water from Hecate Strait will increase and winter runoff will increase, but summer flows will likely decrease, thus changing the patterns of entrainment of nutrient-rich oceanic water. There will likely be a general reduction in salinity and associated changes to the buoyancy-driven flow, and sea-level rise may have some effects here.

5.2.2 Hecate Strait

Hecate Strait is a very important rearing area for the larvae of fishes and invertebrates. It features floating egg masses, complex gyres and ocean circulation, and a unique flora and fauna associated with a mostly soft-sediment environment. The water in Hecate Strait heats up considerably as it moves across this relatively shallow shelf region. It moves south and then offshore across the continental slope during summer and north to Dixon Entrance during winter. It features rich, soft, bottom communities, including sea pens and sea whips, clams, gastropods, sea cucumbers, crabs (e.g., Dungeness crab), forage fishes; important spawning and rearing areas for fishes such as Pacific cod, sole, and flounder; and even grey whale resting and feeding areas (Lucas and Jamieson 2007). Based on existing spatial datasets, Hecate Strait includes 57% of Pacific Canada's soft, shallow habitats; 44% of harder, deep, rocky reef habitat; 27% of hard, shallow habitat; 17% of the rocky intertidal; 13% of the shallow rocky reef; 14% of the beach; and 10% of the soft shelf (Table 5.2).

Relatively higher temperatures in Hecate Strait would suggest that features in this ecosection might be more thermally exposed. However, the effects of increases in temperatures and changes in salinity, nutrients, turbidity, sedimentation, and currents related to climate change have not been projected. Climate impacts on productivity of this very important and unique spawning ground are therefore a major concern. The Hecate Strait ecosection is also one of the few areas with extensive sedimented shorelines, and thus is a concern for forage fishes such as sand lance and smelt, nesting shorebirds, and nesting sea turtles, all of which use sedimented shorelines. Sea-level rise may reduce these habitats, so management strategies should protect the ecological processes that maintain sedimented shorelines. We suggest that Hecate Strait may also be protected from deeper acidic and anoxic waters owing to its location, thus limiting its exposure to deeper waters (in contrast to areas that would be immediately adjacent to the continental slope). If this were to be confirmed, then we would expect parts of this ecosection to serve as a refugium for species that may be forced out from areas more exposed to acidic waters.

A present-day and historical Ecopath modelling exercise has been conducted for the Hecate Strait (Beattie 1999), and this could be used in future studies to estimate the broad system effects of climate change in this ecosection.

5.2.3 North Coast Fjords

Although the fjords of British Columbia have relatively low species diversity and productivity due to poor water exchange and nutrient depletion, they contain unique species and assemblages of benthos and plankton. They therefore contribute to the overall ecological and species diversity. Indeed, British Columbia's fjords are the refuges of certain taxa from the distant past, such as brachiopods, which were very common throughout the Paleozoic era prior to the Permian-Triassic extinction, which occurred 250 million years ago (and perhaps even from the Neoproterozoic era, more than 500 million years ago). Much of this invertebrate fauna inhabits a rich "fouling" community on the vertical walls of these fjords, but other fauna inhabit the upper water column and the soft-sediment sea floor. Many of these inlets also used to have huge runs of sockeye salmon, and there is currently active research in the Rivers Inlet area (B. Hunt, UBC Earth and Ocean Sciences, pers. comm., 12 March 2009). Based on existing spatial datasets, this ecosection contains 38 and 35% of Pacific Canada's beach and mud flat areas, respectively, and 16, 15, 10, and 10% of the region's shallow rocky reef, rocky intertidal, soft shelf, and soft-slope habitats, respectively (Table 5.2).

The fjords of this region can be particularly affected by the increased hydrological cycle causing increased runoff, siltation, and organic enrichment, and changes in the character of this runoff due to varying degrees of changes in proportion of rain to snowmelt (and glacial) runoff. The fjords are also particularly vulnerable to changes that would reduce their oxygen levels, as are the inlets, which feature deep hypoxic or anoxic basins with delicate chemistries with chemical interfaces near tipping points for habitability of the organisms living there. The basic dynamics of silled fjord ecosystems are shown in (Figure 5.9). Anoxia will probably increase on these scales with global warming trends at rates from 0.7°C to 3°C per century by increasing remineralization rates of organic detritus (Crawford et al. 2007).

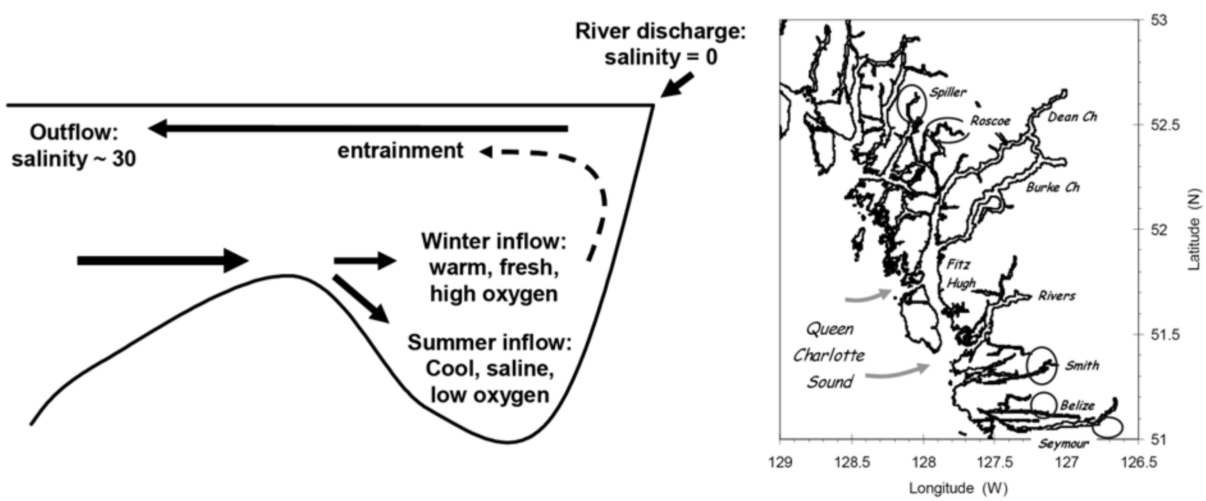
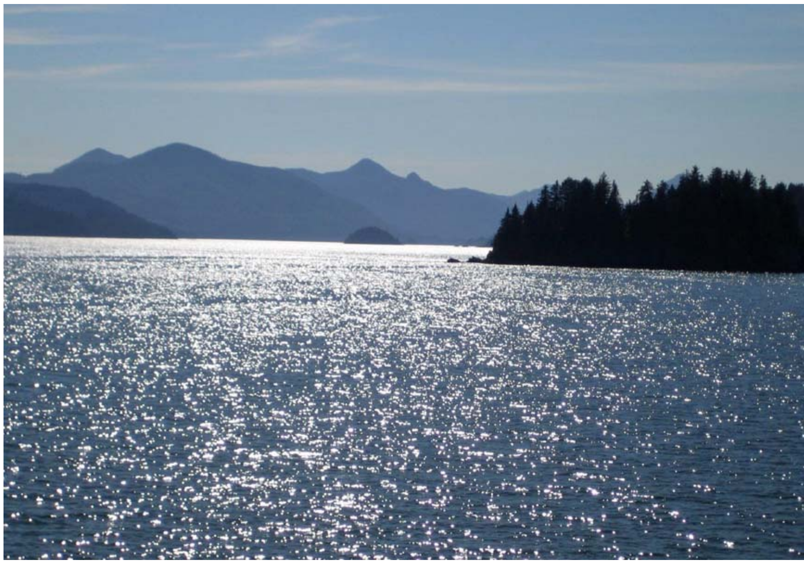


Figure 5.9 Circulation in an inlet with a sill near its entrance, showing the potential for anoxia behind sills and hypoxia throughout the system (left panel), and the central B.C. coast, showing coastal inlets in which anoxic conditions (circles) have been found (Crawford et al. 2007).

5.2.4 Queen Charlotte Sound

Queen Charlotte Sound is a continental shelf in the central basin of the Northern Shelf generally shallower than 200 m and intersected by cross-shelf channels (troughs) that lead to the heads of submarine canyons and banks in between. It is an interface of nearshore and oceanic plankton and nekton (e.g., fish), and an important fishing ground in British Columbia thanks to these habitat features and their implications for productivity. Hydrological and oceanographic dynamics drive low saline water from the North Coast fjords to the northeast, upwelling from submarine canyons from the southwest, and other cross-shelf currents and dynamics that make this ecological setting unique. This ecosection contains high percentages of Pacific Canada's hard and soft shelf, and slope areas, its hard shallow habitat, and its kelp habitat (Table 5.2).



This area contains important glass sponge reefs and cold-water coral concentrations (biogenic habitat), which are vulnerable to bottom contact fishing, and to projected changes in temperature, oxygen, and acidification. Pacific hake migration, important commercial fish spawning and rearing, and forage fish concentrations are important features of this area. A number of whale species enter and inhabit areas of Queen Charlotte Sound, as do foraging fur seals (Lucas and Jamieson 2007). Aggregation of shark species and other species are also conspicuous (R. Williams, unpublished data).

Climate change effects include ocean warming and changes in salinity, flows, and currents, but as a productive shelf adjacent to the continental slope, this setting might be most vulnerable to the occasional impingement of corrosive and anoxic waters onto the shelf as the northeast Pacific continues to become more acidic and anoxic. Anoxic events such as those observed off Oregon may become common in places such as Queen Charlotte Sound as the transition zone shifts northward.

5.2.5 Queen Charlotte and Johnston straits

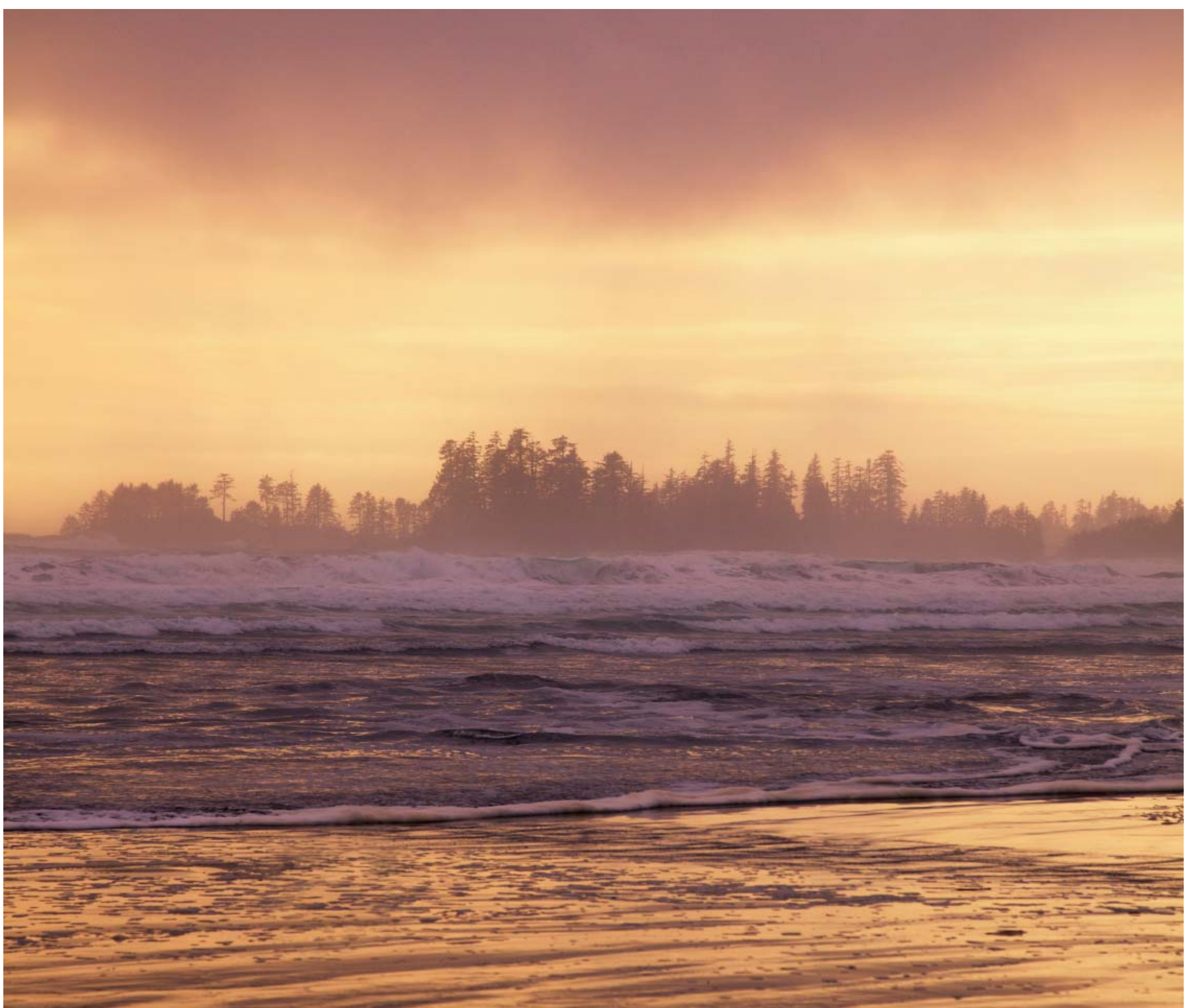
Queen Charlotte and Johnston straits are extremely important migratory corridors and zones of mixing. These straits harbour unique and rich assemblages of marine life, and present extraordinary opportunities for feeding for migratory species. This is an area where sea life and active food chains and food webs concentrate. Fishing activities have focused on this area for similar reasons. Aggregations of herring and top predators such as marine mammals are a good indicator of this (e.g., Lucas and Jamieson 2007). Projected changes in currents, temperature, salinity, pH, turbidity, and productivity would undoubtedly have considerable impacts here, but specific impacts have not been estimated.

5.2.6 Continental Slope

With no continental shelf on the west coast of Haida Gwaii, the continental slope has a higher ecological significance than in typical coastal settings. The intertidal areas of the rugged west coast of Haida Gwaii has 8% of Pacific Canada's beaches, 4% of the rocky intertidal, and some other nearshore habitats (Table 5.2). The continental slope is the location of summer upwelling, a conduit for enhanced productivity that is exploited by coastal and pelagic species, as demonstrated by the concentration of whales and turtles over the continental slope. This ecosection, in its own right, harbours a wide array of continental slope fauna oriented to the bottom topography, including important commercially targeted fish species such as tanner crab, hake, and sablefish, and biogenic habitat-forming species such as sponge reefs and deep-water corals. This ecosection includes 89% of Pacific Canada's submarine canyon areas, 45% of the soft slope, and 19% of the hard shelf and hard slope (Table 5.2). The major concerns related to climate change for these areas are acidification and anoxia in the deep layers that impinge upon the continental slope. Ocean warming and changes to ocean currents are also a concern. More specific estimations of the ecological impacts of global change on this environment have not been made.

5.2.7 Vancouver Island Shelf

Vancouver Island Shelf features large proportions of both hard and soft shelf, shallow, and intertidal habitats, as well as 21% and 18% of Pacific Canada's kelp and seagrass habitats, respectively (Table 5.2). The



outer coast of this shoreline is exposed to the largest storm waves, but this ecosection also features a great deal of protected coastline and some soft intertidal and subtidal communities and mud flats. It undergoes considerable seasonal fluctuations of productivity owing to seasonal changes in upwelling, ocean current systems such as the Davidson Current and the Juan de Fuca eddy, and the buoyancy current from the Fraser River through the Juan de Fuca Strait. Its high productivity is reflected in both benthic and neritic communities. This part of British Columbia is also expected to undergo changes in precipitation and runoff, potentially including drying in some seasons. This area will likely be sensitive to climate change impacts because of these exposures. A broad spectrum of human stressors and/or pressures on the coastal and marine ecosystems of this ecosection is discussed in Okey and Loucks (2011).

5.2.8 Juan de Fuca Strait

The Juan de Fuca Strait is a deep trough carved by glaciers through which a major buoyancy current of fresh water flows from the Fraser River and other rivers to the Pacific Ocean, and through which tidal currents flow, and through which marine life and commerce connect the Salish Sea (e.g., the Strait of Georgia and Puget Sound) with the Pacific Ocean. It is moderately productive and an important migratory corridor for fishes and other marine life. The variety of physical and chemical changes that affect the Salish Sea and the adjacent Pacific Ocean will affect the Juan de Fuca Strait.

5.2.9 Strait of Georgia

This ecosection is also one of British Columbia's three coastal biogeographic units, and was thus discussed in the previous section. The ecological uniqueness of this inland sea is illustrated by the very high proportion of sheltered habitats, including seagrass (59%) and soft intertidal (58%). It also includes 21% of Pacific Canada's shallow rocky reefs, 12% of the region's rocky intertidal, 11% of the soft slope, and 10% of the soft shallow environments (Table 5.2). Its ecological sensitivity to climate change is increased by its significant (warming) freshwater input, very warm summer temperatures, its seasonal stratification and turbidity, exposure to acidification and dissolved oxygen, its role as a nursery area for a variety of species, including herring, salmon, and various shellfish, and its concentration of human population and activities, which act as stressors that decrease the system's resilience to climate change impacts.

5.2.10 Subarctic and transitional Pacific

The offshore subarctic and transitional Pacific areas extend seaward beyond the continental shelf to the edge of Canada's Exclusive Economic Zone, and so include all of Pacific Canada's deep habitats and seamount habitats. These ecozones are exposed to freshening of surface waters, increased stratification, decreased oxygen concentrations, acidification, changes in currents, upwelling and buoyancy current effects, and changes in productivity and biological communities. This report does not address these ecosections or the biogeograpic unit they are found in.

5.3 Sensitive characteristics of B.C. marine habitats

The goal of this section is to examine the characteristics of B.C. marine habitats sensitive to climate changes. We also report the proportion of each habitat in each B.C. ecosection to provide a foundation upon which region-specific vulnerability assessments can be developed and refined. Habitats are distributed unevenly across the ecosections, and Table 5.2 shows the percentage of each habitat in each ecosection. This representative view of habitats of ecosections allows for a vulnerability assessment approach that recognizes habitat types that cover a relatively small area, but that would have high social-ecological importance related to their coastal and nearshore distributions.

Table 5.2 The proportion of habitats in each ecosection of Canada's Pacific marine region. Numbers represent the coast-wide proportion of a habitat found in each ecosection. See Appendix C for data sources.

	Dixon Entrance	Hecate Strait	North Coast Fjords	Queen Charlotte Sound	Queen Charlotte Strait	Johnstone Strait	Vancouver Island Shelf	Juan de Fuca Strait	Continental Slope	Strait of Georgia	Subarctic Pacific	Transitional Pacific
Kelp	24	13	8	18	11	0	21	3	1	2	0	0
Seagrass	4	3	7	2	2	4	18	0	1	59	0	0
Beach	1	14	38	0	10	11	14	0	8	5	0	0
Mud flats	0	1	35	0	13	38	9	0	1	2	0	0
Soft Intertidal	5	7	5	0	4	6	12	1	1	58	0	0
Rocky Intertidal	13	17	15	6	5	5	21	2	4	12	0	0
Soft Shallow	7	57	6	3	2	3	9	2	1	10	0	0
Hard Shallow	7	27	6	31	1	1	19	2	1	5	0	0
Shallow Rocky Reef	4	13	16	9	0	4	30	1	2	21	0	0
Deep Rocky Reef	11	44	5	32	0	3	0	2	3	0	0	0
Soft Shelf	4	10	10	34	2	2	25	2	4	7	0	0
Hard Shelf	10	9	4	40	2	1	13	1	19	2	0	0
Canyon	0	0	0	0	0	0	1	0	89	0	2	8
Soft Slope	4	0	10	25	1	3	1	1	45	11	0	0
Hard Slope	57	0	0	23	0	0	0	0	19	0	0	0
Undefined Slope	0	0	0	0	0	0	0	0	76	0	2	21
Deep	0	0	0	0	0	0	0	0	1	0	56	44
Seamount	0	0	0	0	0	0	0	0	0	0	39	61
Total area	2.4	2.8	2.0	8.0	0.5	0.5	3.7	0.3	7.4	1.8	37.7	32.8

5.3.1 Rocky intertidal

While species that inhabit the intertidal zone tend to exhibit high temperature tolerance, many live close to their physiological temperature limits and will not have the ability to make large physiological adjustments to warmer conditions (Tomanek and Somero 1999). Many species in these communities, particularly the heat-tolerant mid- to high-intertidal species, might be more vulnerable to warming than the less-heat-tolerant species (Harley et al. 2006). Intertidal organisms will shift poleward along shorelines with increasing temperatures, as has been documented in various settings, including the west coast of North America (e.g., Barry et al. 1995, Sagarin et al. 1999, Rivadeneira and Fernandez 2005, Mieszkowska et al. 2007).

Climatic impacts on the survival or behaviour of one or a few key species may drive community-level change in a variety of nearshore assemblages. For example, the strength with which the purple sea star (*Pisaster ochraceus*), a keystone predator and the most common intertidal sea star in British Columbia, interacts with its principal prey (habitat-forming mussels) varies with water temperature (Sanford 1999). Exposure to warmer waters increases both the sea star's mid-intertidal abundance and per capita consumption rate, which could lead to the substitution of large sections of mussel beds (and the hundreds of species that inhabit them) by an assemblage of algae and other invertebrates (Sanford 1999, Harley et al. 2006).

The recruitment of barnacle and mussels exerts an important control on the abundance of these populations. Mussel beds harbour a large number of species and constitute an important habitat of the northeastern Pacific coast (Smith et al. 2006). Studies point to an increase in the percentage of intertidal area covered by

barnacles and mussels as latitude increases over the Northeast Pacific shores. This is partly due to changes in upwelling strength along the coast (Connely et al. 1998). Under the more intense upwelling conditions of the south a larger fraction of the planktonic larvae of these sessile species are advected offshore, reducing recruitment and adult populations (Connely et al. 2001). The projected intensification and northward shift of the upwelling regime could result in a decrease in the number of barnacles and mussels on the intertidal areas of the northern B.C. shores. Temperature increases might also cause loss of diversity in the province's mussel beds. Along the California coast, recent large declines in diversity within mussel beds (an average loss of 58%) have been attributed in part to warmer conditions (Smith et al. 2006), though mussel growth increases with temperature (Menge et al. 2008).

In addition to higher water temperatures, organisms of the high intertidal shorelines will be exposed to higher air temperatures, and changes in moisture and precipitation. With expected changes in precipitation patterns, exposure of these organisms to fresh water may increase during winter, and decrease during summer. Such changes make higher intertidal zones less habitable, thus decreasing the vertical extent of intertidal zones, especially when predators are less affected than their foundation species prey (e.g., Harley 2011).

Increases in maximum wave heights and associated increases in the range of wave intensity (Ruggiero et al. 2010) to which organisms are exposed will shift the optimal habitat niches of intertidal organisms in space and time, thereby shifting biological assemblies. Moreover, increased maximum wave heights can catastrophically remove large areas of intertidal and subtidal organisms. Sea-level rise (e.g., Thompson et al. 2002) will also shift intertidal communities to higher levels except where bulkheading will constrain the inland migration of particular habitats.

5.3.2 Subtidal rocky reef and hard slopes

Subtidal rocky reef and hard slopes are less studied than intertidal areas in this region, but like these intertidal zones, they would also be subject to differential effects of species, resulting in changes in interspecific interactions. These habitats will be affected by all the climate change variables listed in Section 2. For example, both fishes and invertebrates may be greatly affected by changes in oxygen, pH, temperature, salinity, and productivity. One illustrative example is that urchins are common on the shallow sea floor of some areas of the west coast of Vancouver Island, but acidification could severely affect their populations, thus having a large impact on urchin fisheries. Furthermore, a decline of urchins or other shellfish prey may lead to declines in sea otters, which strongly structure and engineer kelp forest communities.

5.3.3 Kelp forests

Many fishes and invertebrates, such as herring, salmon, surf smelt, sand lance, abalone, and sea urchins, depend on kelp beds for spawning and nursery areas (Shaffer 2000). Kelp beds are also important for contributing a significant amount of fixed carbon to the nearshore ecosystem (Duggins et al. 1989). As sea surface temperatures increase, an increase in the kelp species of the genus *Macrocystis* relative to *Nereocystis* has been observed, but it is unknown how this will affect ecosystems (Lucas et al. 2007).

The increases in temperature and stratification, and the reduced upwelling experienced during El Niño conditions have very negative impacts on kelp forests of the northeastern Pacific (Steneck et al. 2002). Along the B.C. coast, temperatures and stratification are projected to increase, but so is upwelling. An increase in storm-related disturbance is a potential risk, but it is possible that storminess will not increase appreciably in Canada's Pacific. The former impacts mentioned may seriously affect the variety of species that depend on kelp forests for habitat and spawning substrate (Lucas et al. 2007).

Grazers, such as sea urchins, play an important role in controlling kelp forest structure, and a reduction in urchin population would be favourable to kelp forests. Urchins are among the calcifying organisms that will be directly impacted by ocean acidification. A 0.4 reduction in pH has caused a 24% decrease in fertilization success of the purple sea urchin (*Heliocidaris erythrogramma*) under laboratory conditions (Havenhand et al. 2008). Adverse effects of acidification, including decreases in growth, on both gastropods and urchins have also been demonstrated by Shirayama and Thornton (2005).

In Australia, the observed impacts of climate change to kelp communities include contraction of kelp ranges and declines in abundance due to increased temperatures, local extinctions of cold-water species as a result of current alterations, increased mortality in early life stages due to increased UV levels, shifts in community abundance, and increased mortality associated with storms and flood events (Okey et al. 2006, Poloczanska et al. 2007).

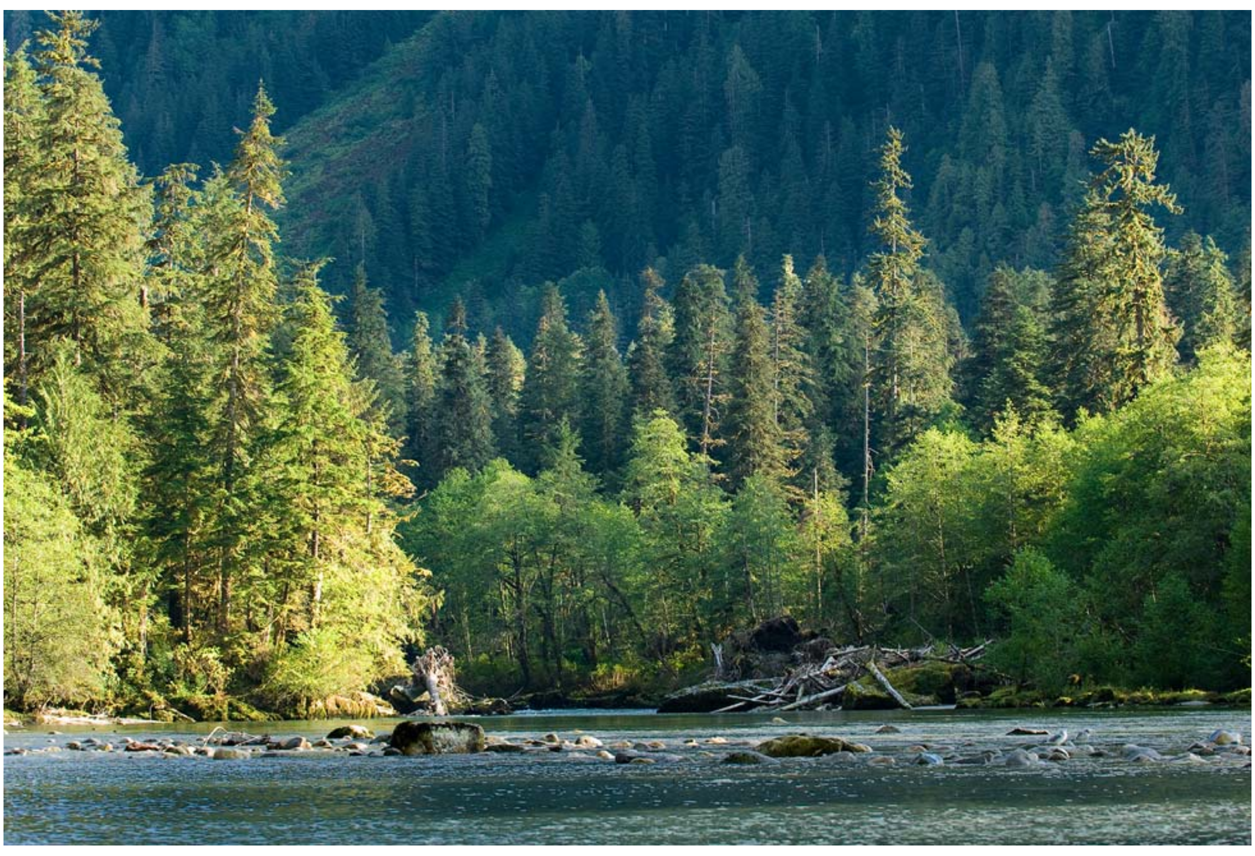
5.3.4 Seagrasses

A discussion of seagrasses and their habitats is found in Section 6.1. It is possible that, in some cases, seagrasses may benefit from the effects that are expected with climate change, such as increased seawater CO_2 concentrations, given that they are vascular plants. However, such potential net effects are highly uncertain since a variety of changes will occur, some of which will negatively impact seagrasses. Furthermore, there are a variety of fish and invertebrate species associated with seagrasses in seagrass habitats, and it is more likely that any negative effects on this habitat will also be felt on these species (Poloczanska 2006).

5.3.5 Estuaries

B.C. inlets are fjord systems with rivers at their head and an estuarine circulation pattern with fresh water flowing out at the surface and saltwater entrained below, setting up stratification in fjords. If rain generally increases in northern coastal British Columbia, more fresh water will enter fjords on the surface and a larger plume of fresh water will enter the ocean from these fjords and coastlines. Climate change may, however, reduce estuarine circulation during drought periods and accelerate it during freshet periods, thereby changing estuarine regimes on seasonal, annual, and other scales.

Ocean acidification can increase the bioavailability of trace metals. This potential impact would be more serious around areas receiving urban runoff and sewage, as well as in areas with salmon aquaculture, an activity that can increase the levels of trace metals in the environment (Chou et al. 2002).



5.3.6 Salt marshes and tidal/mud flats

Accelerated sea-level rise can impact salt marshes through inundation, erosion, and saltwater intrusion (Scavia et al. 2002). The impacts of erosion might be balanced or buffered by an increase in vertical accretion rates (Thomson et al. 2008). Two processes related to climate change can increase accretion rates: CO_2 fertilization effects could increase primary production and deposition of organic matter; the predicted increase in rainfall may result in larger deposition of inorganic matter.

Still, on a global average, vertical accretion values would have to be two to seven times higher than the ones observed over the last 100 years in order to keep up with the predicted globally averaged sea-level rise (Day et al. 2008). This global average might not be all that important in British Columbia's tectonic regions given isostatic rebound and other factors that are decreasing the effects of sea-level rise in some parts of the province.

By lowering salinity and providing nutrients, freshwater input reduces the level of a number of wetland stressors and could help these environments cope with sea-level rise (Day et al. 2008). Although most B.C. rivers do not have large nutrient loads, biological communities are likely adapted to exploit the small amounts of nutrients provided. While the increase in precipitation might ameliorate conditions during winter, the predicted decrease in summer rainfall might result in increased salinity, and other stressors for the marshes in the North Coast region.

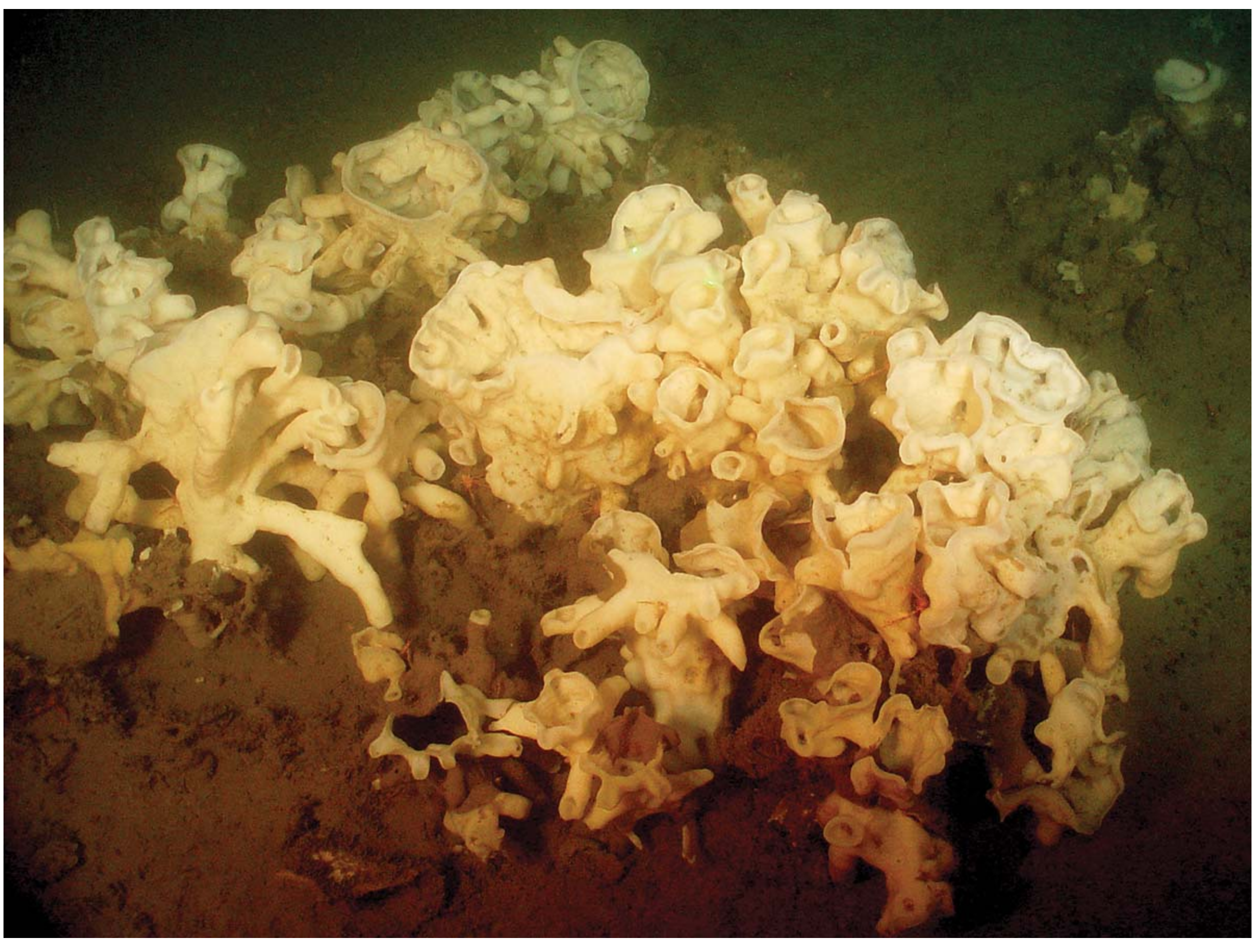
Toward a vulnerability assessment

As with salt marshes, the balance between sediment deposition and erosion will determine the impacts of sea-level rise on tidal/mud flats. There are indications that the predicted rates of sea-level rise might cause significant and rapid loss of intertidal flats, an important source of food for many groups, including seabirds (Galbraith 2002). These environments are also threatened by the projected rise in intense precipitation events that can lead to increased erosion of channel areas and excessive deposition of sediment in other areas (UK Biodiversity Group 1999), though the North Coast has relatively low sediment deposition rates. Both erosion and extra deposition can have negative impacts on bottom-dwelling organisms, as these are washed away by the intense flows or smothered in sediments.

5.3.7 Cold-water corals and sponge habitat

Ocean acidification will impact cold-water corals, which provide habitat for numerous fish and invertebrate species. In the Northeast Pacific, these corals are found at depths of about 180 m. Projections indicate that in the North Coast region, the depths between 100 and 200 m will be exposed to waters that will be undersaturated in aragonite by 2060 (Guinotte et al. 2006). Hypoxia related to upwelling of deeper waters onto the shelf and warming could also present a threat to cold-water corals.

Increases in stratification and sediment transport into the nearshore area can negatively impact glass sponge communities and reefs, as these organisms are sensitive to low oxygen and high turbidity levels (Leys et al.



2004). The sponge reefs residing in the shelf canyons farther offshore in the Queen Charlotte Sound area might benefit from an increase in nutrient input as the upwelling regime moves farther north (Whitney et al. 2005). These gains might be offset if the increase in upwelled water results in a significant reduction in oxygen concentrations near the bottom.

5.3.8 Seamounts

Seamount ecosystems are exposed to pelagic and oceanic currents and influences. The fauna on seamounts are highly dependent on, and sensitive to, changes in the advection of secondary production via ocean currents, so any changes to primary and secondary productivity would have a strong effect on seamount ecosystems, and this is expected with climate change. Seamounts are also exposed to changes in dissolved oxygen, pH, stratification, mixed-layer depth, and sometimes water transparency and light. For these reasons, seamounts should be expected to be sensitive to climate change, and thus should be good barometers of change in pelagic and oceanic environments.

5.3.9 Soft shelves and slope

Soft-sediment habitats and fauna will be affected by decreases in ocean pH, changes in primary production, hydrology, storminess, and extreme weather events. Acidification will erode the shells of molluscs, echinoderms, and other groups with carbonate shells. Changes in water column primary production will alter abundances, community interactions, and benthic pelagic coupling. Changes in prevailing current dynamics will affect considerable soft-sediment systems. Changes in freshwater input will modify the benthic community over vast areas. Okey (2006) provides additional information on the effects of climate change on soft bottoms.

5.3.10 Submarine canyons

Submarine canyon ecosystems may be affected by climate change in a variety of ways. Submarine canyons are collectors and conduits of organic detritus, which plays important roles as both habitat and food (Okey 1997, 2003), and they themselves are habitats and features on the sea floor that affect local currents and production. Changes in productivity, currents, storms, upwelling, acidification, and dissolved oxygen, as well as other factors related to climate change, may have strong effects on submarine canyons and the bathyal and abyssal ecosystems and biological communities that they may feed.

5.4 A preliminary climate vulnerability assessment for Canada's Pacific marine areas

The vulnerability of Canada's Pacific marine ecosections to climate change was estimated in this preliminary assessment as the sum of the vulnerability of habitats to climate change. Habitat is here considered in a broad sense including physical forms and features such as substrate, relief, and depth, as well as biogenic features such as eelgrass and kelp beds. The vulnerabilities of each of these habitats were summarized for each of the 12 ecosections identified as part of British Columbia's biogeographic characterization (see Section 5.1). Although both habitat types and sensitivity estimates for this preliminary analysis are borrowed from recent analyses of the California Current (Halpern et al. 2009, Teck et al. 2010), we supplement this information with more regionally specific information on broad-scale habitats noted above.

Estimating the vulnerability of ecosystems, habitats, areas, and other entities to climate change requires quantification of exposure, sensitivity, and adaptive capacity (Figure 5.10). Multiple indicators of each of these three components of vulnerability can be identified and quantified to derive an overall estimate of vulnerability, as by Hobday et al. (2006).

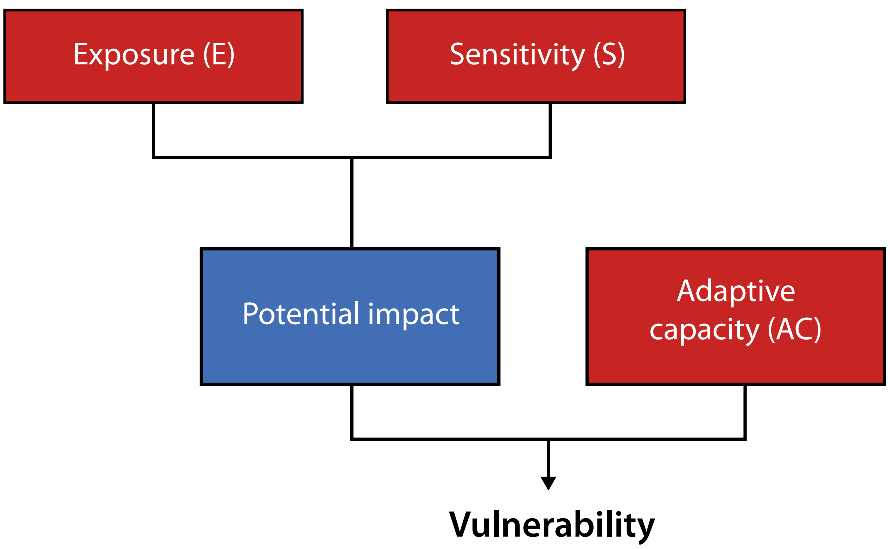


Figure 5.10 Components of vulnerability from the Allen report (2005).

Our example vulnerability assessment for B.C. marine ecosystems is intended to illustrate a framework to which emerging information can be applied to produce improved estimates of vulnerability. Additionally, to be useful for regional planners and managers, such climate impact and vulnerability assessments need to be at a spatial scale and resolution that is relatable to the scale at which management and adaptation measures for addressing climate change vulnerabilities may be undertaken. In this section, the potential impacts of climate change are estimated on the basis of exposure and sensitivity indicators for habitat types within B.C. marine ecosections using spatial data that encompass the entire region of interest. Indicators of exposure to three climate stressors—temperature change, acidification, and UV exposure—are extracted from climate data used in Halpern et al. (2008). Indicators of sensitivity of habitats to these climate stressors are taken from Teck et al. (2010). Adaptive capacity is here estimated as the inverse of the product of exposure and sensitivity of non-climate stressors, based on estimates of both in Ban et al. (2010). This assumes that adaptive capacity of habitats to climate stressors is inversely proportional to the level of local anthropogenic stressors acting on them.

5.4.1 Calculating potential climate impacts of temperature, acidification, and UV

We derived maps of potential climate change impacts for our region by combining coarse-scale habitat and benthic class characterization (taken from Ban et al. 2010 and updated during the present effort to better represent shallow habitats), inferred sensitivities to climate change stressors (taken from Teck et al. 2010), and regional extractions of climate change data for SST, acidification, and UV change (synthesized by Halpern et al. 2008). All three climate datasets depicted change in actual or modelled conditions from a previous time period to a more recent time period (from 1990–95 to 2000–05 for SST, from pre-industrial (1870) to 2000–09 (projected) for aragonite saturation state, and from 1996 to 2004 for UV change in the UVB spectrum). All three were expressed on a standardized scale from 0 to 1 (0 no change, 1 most change). Supplementary documentation associated with Halpern et al. (2008) provides more detail on the processing of these datasets for their global analyses.

The native resolution for climate data varied, but they were available as down-sampled datasets at a 1-km^2 resolution for our region. We used these data to relate climate exposure to regional habitat data at an approximate scale of 1:50,000. Expert-derived vulnerability values of the habitat types to climate stressors from the California Current region (Teck et al. 2010) were used as sensitivity scores in our analysis for the 18 habitat types and bottom types mapped from a compilation of sources. What Teck et al. (2010) called vulnerability, we consider to be sensitivity based on the framework from the Allen report (2005). The sensitivity scores that we borrowed from Teck et al. (2010) are from a broader study that examined many multiple stressors and used expert opinion to score and rank the "vulnerability" (i.e., sensitivity) of habitats and ecosystems of the California Current region. These habitat and bottom types and their sensitivity scores are illustrated in Table 5.3; the scores ranged in value from 0 to 3.4.

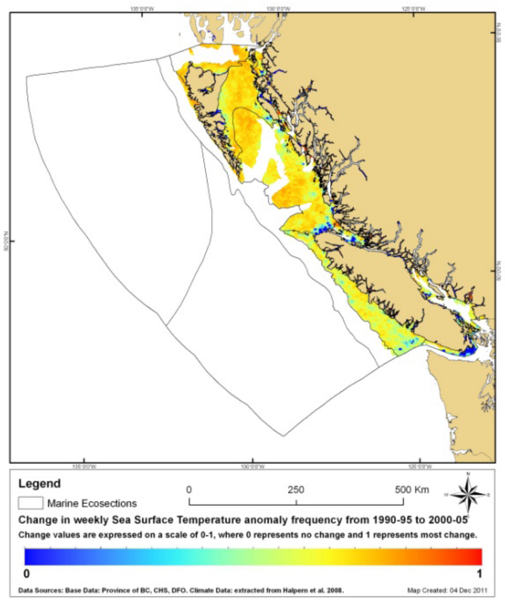
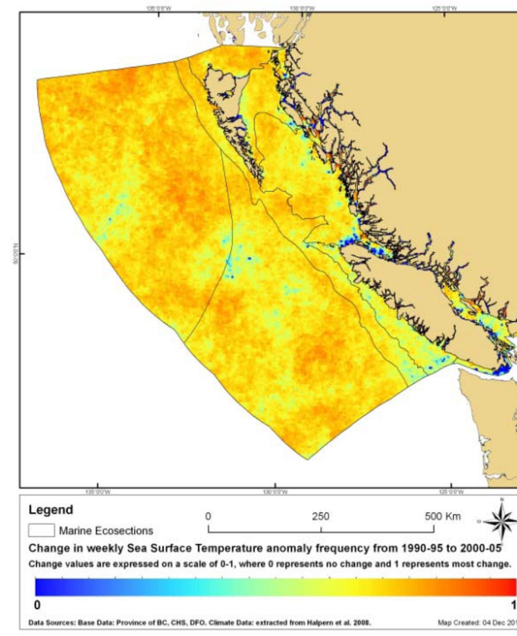
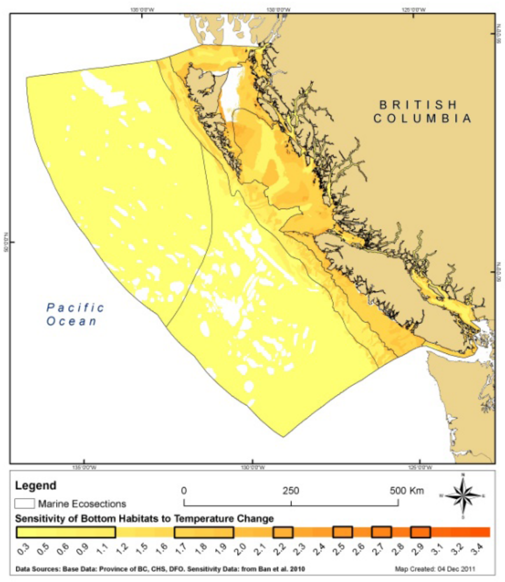
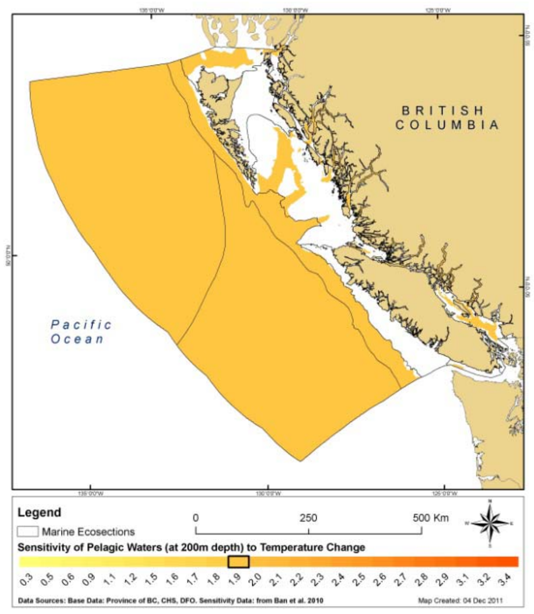
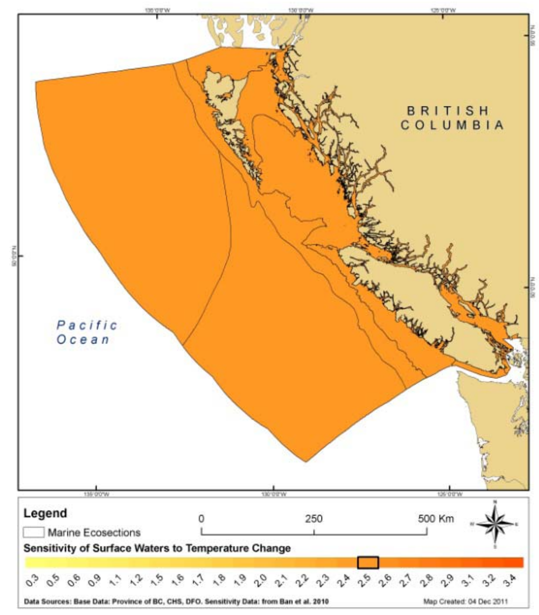
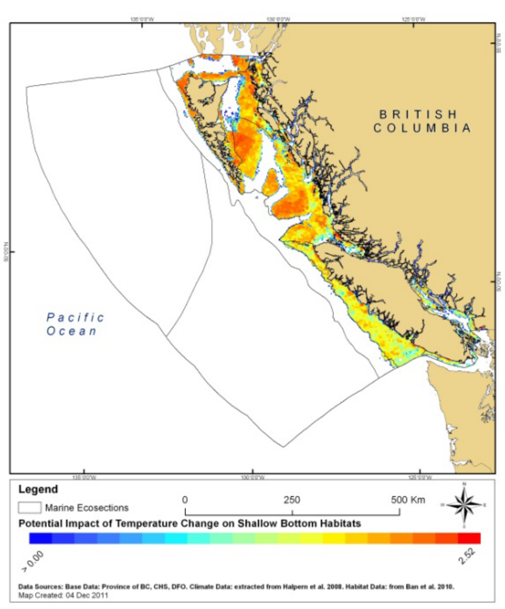
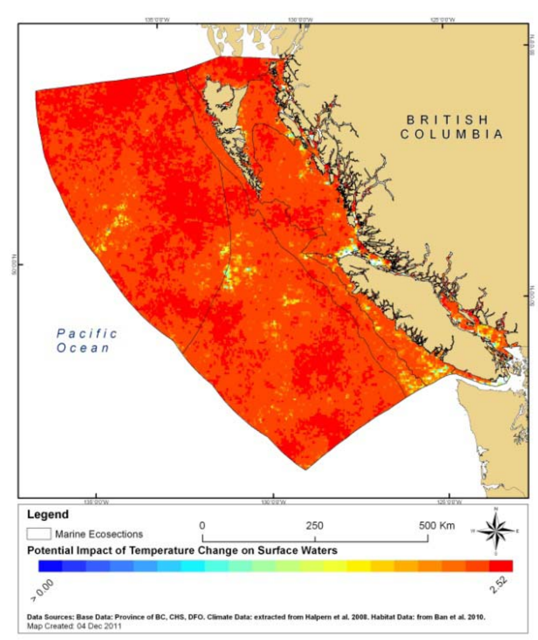
For ease of calculations, habitat data were organized into tabular summaries containing habitat type and their areas within spatial units or planning units of 2 km by 2 km (BCMCA 2011). Each planning unit was assigned a climate exposure value for each of the three climate variables using the climate datasets noted above. We calculated potential climate impacts in tables for all habitats where there were climate stressor data from the above-noted sources. Potential impact from temperature change was limited to surface water habitats and shallow bottom habitats, as SST data do not reliably represent temperature changes at deeper depths. Potential impact from acidification was calculated for all bottom, surface, and pelagic habitats (waters at 200-m depth), and we assumed that change in aragonite saturation represented changes across all habitats. Potential impact from UV change was calculated only for surface water habitats and shallow bottom habitats. The potential impact scores were mapped (Figure 5.11, Figure 5.12, and Figure 5.13) and summarized by ecosection, and are presented here as potential impact scores per unit of area (sq. km) in three broad groupings: bottom habitats, surface waters, and pelagic waters. We also report mean potential impact scores by habitat type for the entire region (Table 5.4).

Table 5.3 Expert-derived sensitivity scores for different habitat/bottom types, taken from Teck et al. (2010).

CLIMATE STRESSOR	HABITAT TYPE | BOTTOM TYPE																	
	SALT MARSH	MUD FLATS	BEACH	ROCKY INTERTIDAL	KELP	SEAGRASS	ROCKY REEF	SUSPENSION REEF	SOFT SHELF	SOFT SLOPE	SOFT DEEP	HARD SHELF	HARD SLOPE	HARD DEEP	CANYON	SEAMOUNT	SURFACE WATERS	DEEP PELAGIC WATERS
Temperature change	1.8	1.8	1.7	3.1	2.9	1.9	2.2	2.2	1.7	0.6	0.5	1.9	1.2	0	1.7	0	2.5	1.9
Acidification	2.4	2.4	1.8	2.7	2.0	2.1	2.2	2.5	2.6	3.4	2.5	2.7	3.4	3.4	2.6	2.6	3.2	2.7
UV change	1.9	1.7	1.8	2.3	1.6	1.5	1.7	1.8	0	0	0	0	0	0	0	0	2.5	0.8

Potential Climate Impact from a climate stressor (c) on a unit area of a habitat type (a), $I_{(ac)}$, was calculated as follows:

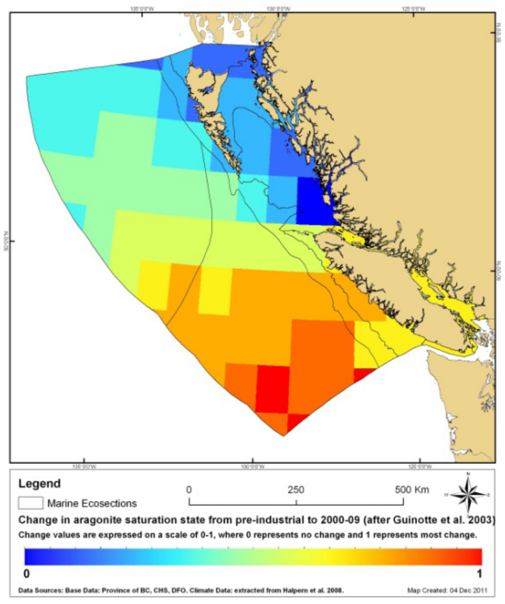
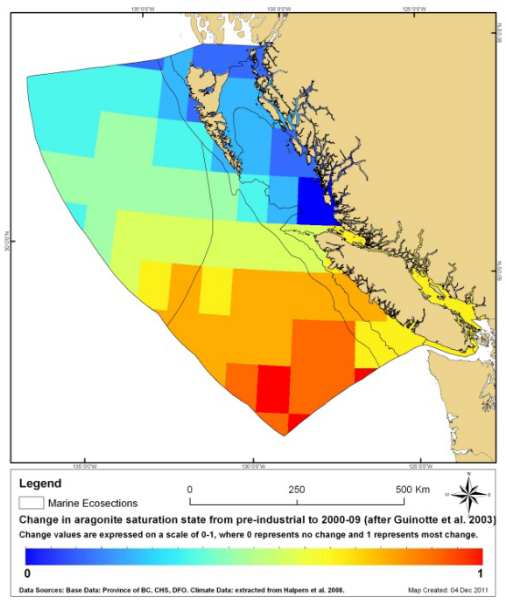
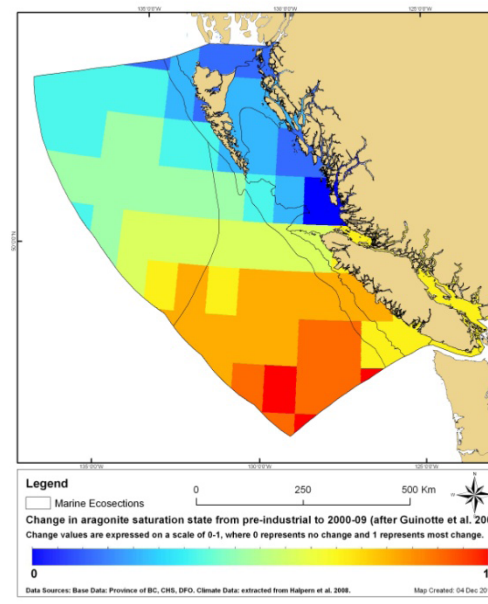
$$I_{(ac)} = E_{(ac)} \times S_{(ac)}$$	*Where:* *$E_{(ac)}$ is the exposure value of climate stressor c acting on the unit area of habitat type a* *$S_{(ac)}$ is the sensitivity of habitat a to climate stressor c*

<table>
<tr><th></th><th>BOTTOM HABITATS</th><th>DEEP PELAGIC WATERS</th><th>SURFACE WATERS</th></tr>
<tr><td rowspan="2">EXPOSURE</td><td>
</td><td>No suitable dataset available; it was deemed that SST data would not be indicative for deeper waters off the shelf</td><td>
</td></tr>
<tr><td colspan="3">Exposure Dataset: Change in SST anomaly frequency between 1990–95 and 2000–05 (extracted from Halpern et al. 2008). This dataset was thought to be indicative only for surface water habitats and benthic habitats on the shelf (< 200 m deep).</td></tr>
<tr><td rowspan="2">HABITAT SENSITIVITY</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">Sensitivity Dataset: Habitat sensitivities to temperature change assigned values from Teck et al. (2010).</td></tr>
<tr><td rowspan="2">POTENTIAL IMPACT</td><td>
</td><td>Not Calculated</td><td>
</td></tr>
<tr><td colspan="3">Potential Impact maps of temperature change showing potential impact values summarized for each 2-km by 2-km planning unit.</td></tr>
<tr><td>ECOSECTION SUMMARY</td><td colspan="3">

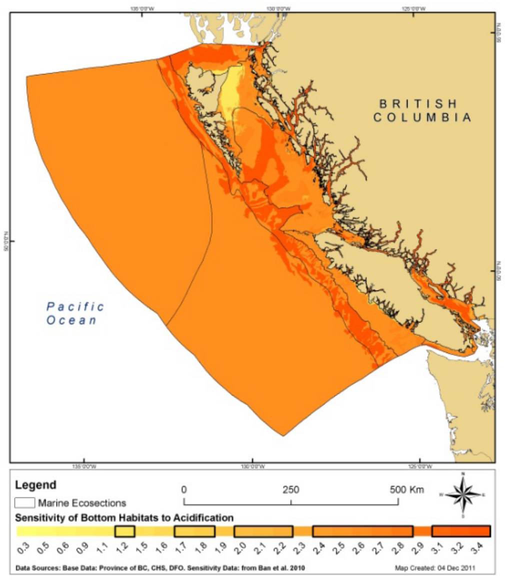
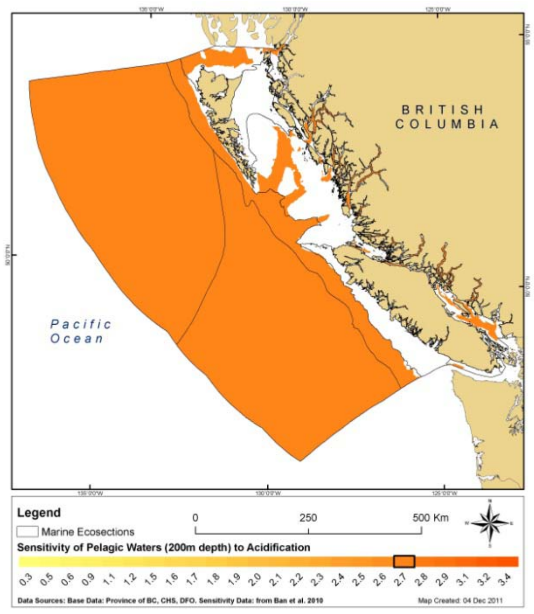
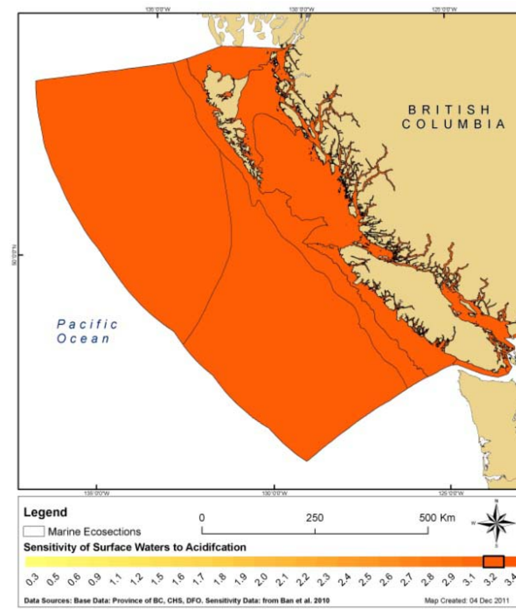
Mean Potential Impact of Temperature Change/km² on Bottom Habitats				Mean Potential Impact of Temperature Change/km² on Surface Water Habitats	
Ecosection	Impact/km²			Ecosection	Impact/km²
Continental Slope	N/A			Continental Slope	0.39
Queen Charlotte Sound	0.25			Queen Charlotte Sound	0.37
Subarctic Pacific	N/A			Subarctic Pacific	0.39
Transitional Pacific	N/A			Transitional Pacific	0.38
Vancouver Island Shelf	0.22			Vancouver Island Shelf	0.33
Dixon Entrance	0.25			Dixon Entrance	0.39
Hecate Strait	0.17			Hecate Strait	0.36
Johnstone Strait	0.13			Johnstone Strait	0.21
Juan de Fuca Strait	0.15			Juan de Fuca Strait	0.23
North Coast Fjords	0.16			North Coast Fjords	0.25
Queen Charlotte Strait	0.16			Queen Charlotte Strait	0.24
Strait of Georgia	0.16			Strait of Georgia	0.27

</td></tr>
</table>

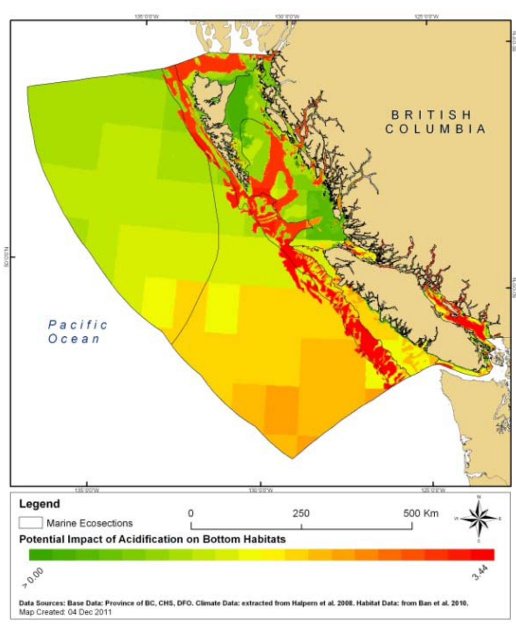
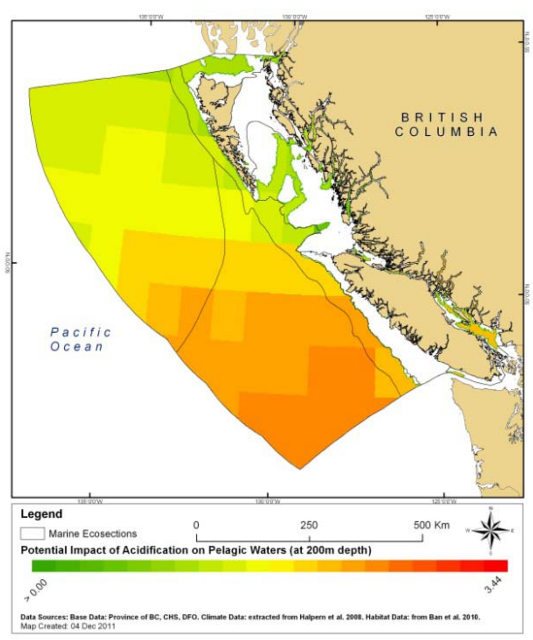
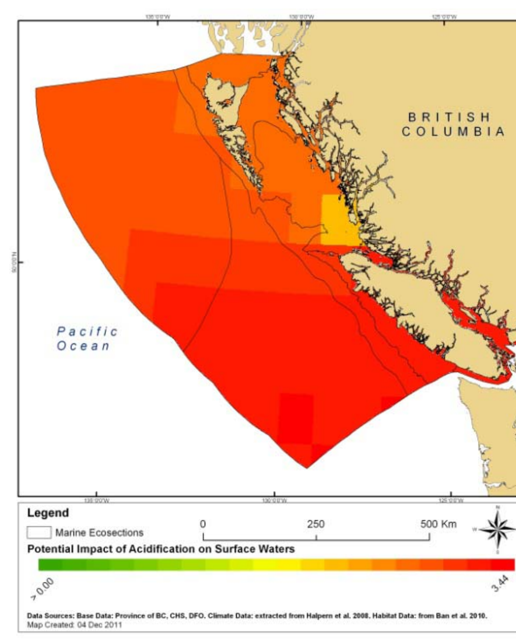
Figure 5.11 Estimated Potential Impact of Temperature Change calculated for the region from exposure and sensitivity maps and summarized by ecosection.

	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
EXPOSURE			

Exposure Dataset: Change in aragonite saturation state, 1870 to 2000–09 (projected). Source data from Guinotte et al. (2003), regional extraction from Halpern et al. (2007).

	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
HABITAT SENSITIVITY			

Sensitivity Dataset: Habitat sensitivities to acidification assigned values from Teck et al. (2010)

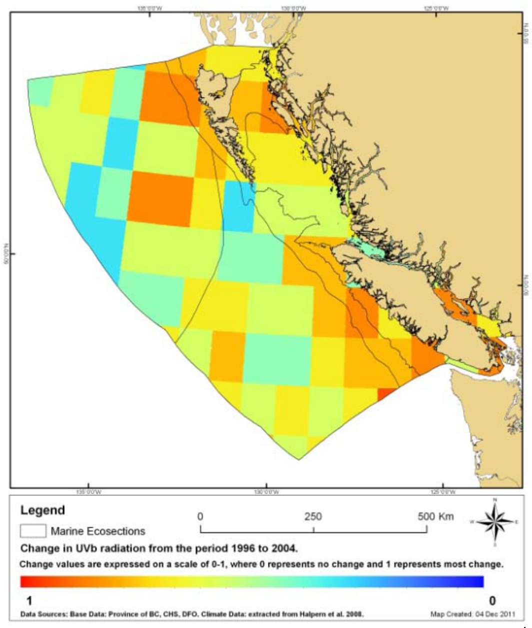
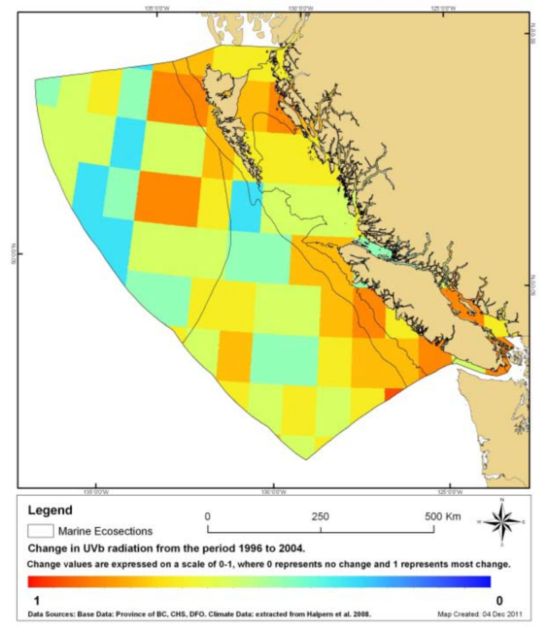
	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
POTENTIAL IMPACT			

Potential Impact maps of acidification showing potential impacts values summarized for each 2-km by 2-km planning unit.

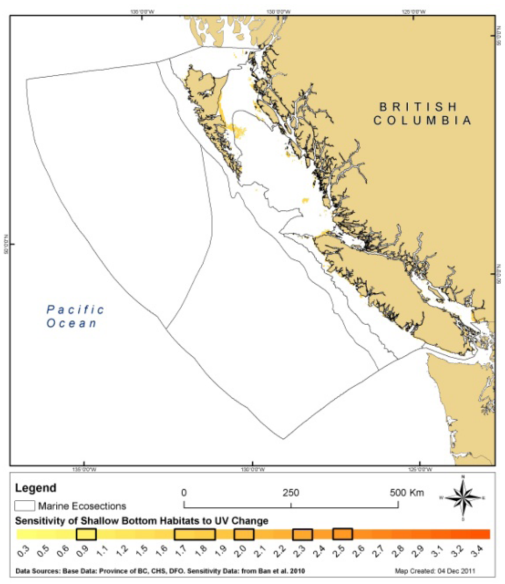
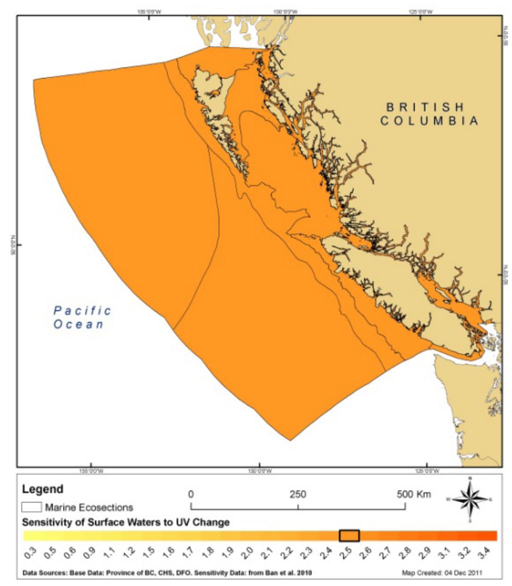
ECOSECTION SUMMARY

Mean Potential Impact of Acidification/km² on Bottom Habitats		Mean Potential Impact of Acidification/km² on Pelagic Waters (> 200 m)		Mean Potential Impact of Acidification/km² on Surface Waters	
Ecosection	Impact/km²			Ecosection	Impact/km²
Continental Slope	0.56	Continental Slope	0.46	Continental Slope	0.58
Queen Charlotte Sound	0.46	Queen Charlotte Sound	0.44	Queen Charlotte Sound	0.52
Subarctic Pacific	0.44	Subarctic Pacific	0.46	Subarctic Pacific	0.54
Transitional Pacific	0.47	Transitional Pacific	0.48	Transitional Pacific	0.57
Vancouver Island Shelf	0.50	Vancouver Island Shelf	0.45	Vancouver Island Shelf	0.57
Dixon Entrance	0.49	Dixon Entrance	0.43	Dixon Entrance	0.52
Hecate Strait	0.38	Hecate Strait	0.44	Hecate Strait	0.53
Johnstone Strait	0.54	Johnstone Strait	0.37	Johnstone Strait	0.44
Juan de Fuca Strait	0.53	Juan de Fuca Strait	0.47	Juan de Fuca Strait	0.59
North Coast Fjords	0.49	North Coast Fjords	0.31	North Coast Fjords	0.43
Queen Charlotte Strait	0.51	Queen Charlotte Strait	0.37	Queen Charlotte Strait	0.49
Strait of Georgia	0.49	Strait of Georgia	0.45	Strait of Georgia	0.50

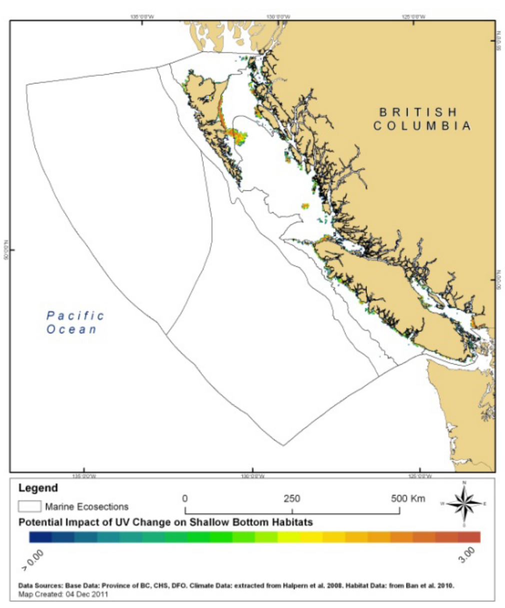
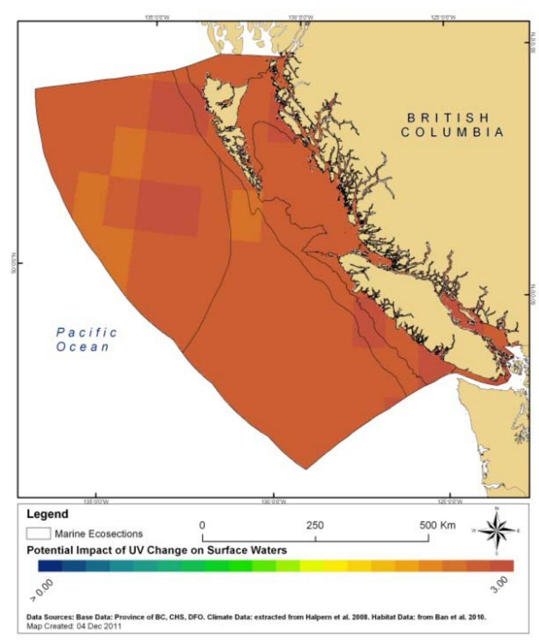
Figure 5.12 Estimated Potential Impact of Acidification calculated for the region from exposure and sensitivity maps and summarized by ecosection.

	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
EXPOSURE		N/A – no UV exposure only applicable to shallow waters	

Exposure Dataset: Change in UVB spectrum between 1996 and 2004. Source data are from NASA; regional extraction of these data from Halpern et al. (2008). Exposure to UV for bottom habitats was limited to only shallow bottom habitats (<= 30 m deep).

	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
HABITAT SENSITIVITY		N/A	

Sensitivity Dataset: Habitat sensitivities to UV change assigned values from Teck et al. (2010).

	BOTTOM HABITATS	DEEP PELAGIC WATERS	SURFACE WATERS
POTENTIAL IMPACT		N/A	

Potential Impact maps of UV change showing potential impacts values summarized for each 2-km by 2-km planning unit.

ECOSECTION SUMMARY

Mean potential impact of UV change/km² on Bottom Habitats (<= 30 m deep)				Mean Potential Impact of UV change/km² on Surface Waters	
Ecosection	Impact/Km²			Ecosection	Impact/Km²
Continental Slope	0.24			Continental Slope	0.50
Queen Charlotte Sound	0.27			Queen Charlotte Sound	0.46
Subarctic Pacific	N/A			Subarctic Pacific	0.44
Transitional Pacific	N/A			Transitional Pacific	0.45
Vancouver Island Shelf	0.28			Vancouver Island Shelf	0.49
Dixon Entrance	0.13			Dixon Entrance	0.47
Hecate Strait	0.09			Hecate Strait	0.49
Johnstone Strait	0.15			Johnstone Strait	0.34
Juan de Fuca Strait	0.31			Juan de Fuca Strait	0.48
North Coast Fjords	0.27			North Coast Fjords	0.40
Queen Charlotte Strait	0.16			Queen Charlotte Strait	0.36
Strait of Georgia	0.20			Strait of Georgia	0.43

Figure 5.13 Estimate Potential Impact of UV Change calculated for the region from exposure and sensitivity maps and summarized by ecosection.

Toward a vulnerability assessment

Table 5.4 Mean Potential Impact/km² of three climate stressors on the habitat/bottom types in Canada's Pacific waters. N/C = Not Calculated (where climate stressor data were absent), N/A = Not Applicable (where climate stressors are not felt).

DEPTH RANGE	HABITAT/BOTTOM TYPE	TEMPERATURE CHANGE	ACIDIFICATION	UV CHANGE	SUM
	Surface Waters	0.37	0.55	0.45	1.37
↑ Intertidal	Beach (Intertidal)	0.26	0.55	0.52	1.33
	Mud flats (Intertidal)	0.11	0.51	0.32	0.94
	Rocky Intertidal	0.32	0.92	0.60	1.84
	Soft Intertidal	0.19	0.70	0.46	1.35
	Undefined Intertidal	0.28	1.02	0.65	1.95
0-30 m ↓	Kelp	0.36	0.33	0.30	0.99
	Seagrass	0.23	0.38	0.30	0.91
	Hard Shallow	0.23	0.45	0.35	1.03
	Soft Shallow	0.00	0.22	0.00	0.22
	Undefined Shallow	0.14	0.50	0.24	0.88
	Rocky Reef (Shallow)	0.27	0.38	0.33	0.98
↑ 30-200 m ↓	Rocky Reef (Non-Shallow)	0.29	0.37	N/A	0.66
	Hard Shelf	0.26	0.47	N/A	0.73
	Soft Shelf	0.22	0.46	N/A	0.68
	Undefined Shelf	0.24	0.56	N/A	0.8
	Pelagic Water (at 200 m deep)	N/C	0.46	N/A	0.46
↑ 200-2,000 m ↓	Soft Slope	N/C	0.56	N/A	0.56
	Hard Slope	N/C	0.58	N/A	0.58
	Undefined Slope	N/C	0.61	N/A	0.61
↑ >2,000 m	Seamount	N/C	0.45	N/A	0.45
	Canyon	N/C	0.47	N/A	0.47
	Undefined Deep	N/C	0.45	N/A	0.45
	Hard Deep	N/C	0.45	N/A	0.45

The estimated potential impact of changes in temperature on bottom habitats appears to be most prominent in shallow regions (< 200 m) of Queen Charlotte Sound, Dixon Entrance, and Vancouver Island Shelf. Surface waters appear to be impacted in all regions to more or less the same extent (Figure 5.11). Kelp habitats demonstrated the highest potential impact scores from temperature change, followed by rocky reef habitats (Table 5.4), suggesting that these habitats will likely see impacts of temperature changes first.

Our analysis indicates that impacts of acidification on benthic habitats will be most prominent in the continental slope, Johnstone Strait, and Juan de Fuca Strait ecosections. Other ecosections will also be affected and show relatively more or less comparable potential impact scores for acidification (Figure 5.12). The exception to this is the Hecate Strait ecosection, which appears to have low exposure and comparatively lower sensitivity to acidification. This would corroborate the earlier suggestion that Hecate Strait may be more sheltered from the effects of acidification because of its geographic characteristics. On average, slope habitats (200–2000 m) also exhibit the highest mean potential impact scores for acidification, followed by shelf habitats (30-200 m) (Table 5.4).

The potential impact scores from UV change indicate that generally surface waters in all ecosections will be affected at more or less the same level, except for Johnstone Strait and Queen Charlotte Strait, both of which seem to have somewhat lower scores (Figure 5.13). Shallow benthic habitats (< 30 m) that are susceptible to impacts from UV change show the most potential impact scores in the Juan de Fuca Strait ecosection. Intertidal habitats generally show the most potential impacts from UV change.

We note again here that the illustrative analyses provided above to calculate potential climate impacts do not include other important variables, such as deoxygenation and salinity changes. Such variables and changes "downscaled" to the region should be included in any future analyses to provide more realistic and reliable estimates.

5.4.2 Inference of ecosection and habitat vulnerability to climate change

We used the calculated potential climate impact scores (from above) with a measure of adaptive capacity to derive a mean vulnerability value for each ecosection and habitat type. To estimate adaptive capacity, we used the mean cumulative impact scores (non-climate impacts) from locally occurring anthropogenic activities in each habitat and ecosection reported in Ban et al. (2010) for our region. The reported cumulative impact scores were on a smaller per unit area (200-m pixel), whereas our calculated potential climate impact scores were reported per square kilometre. To make our values comparable, we standardized both the cumulative impact scores and the potential climate impacts to a scale of 0–1.

We took the standardized cumulative impact (CI) scores to be an indicator of adaptive capacity, such that adaptive capacity would be inversely proportional to cumulative impacts of non-climate stressors (1/CI). High cumulative impact scores for an ecosection or habitat would thus imply it had a low adaptive capacity to climate change. To derive the vulnerability, we took the sum of standardized potential climate impact scores for the climate stressors for each ecosection or habitat (S) and divided it by the adaptive capacity (1/CI). The results are illustrated below in Table 5.5 and Table 5.6.

Table 5.5 Tabular illustration of how potential climate impact scores with anthropogenic impact scores (cumulative impact scores) are used to derive values for ecosection vulnerability to climate change.

		Standardized scores for mean potential climate impact/km² by ecosection			Sum of standardized potential climate score (S)	Standardized anthropogenic impact score (CI)	Ecosection vulnerability to climate S ÷ (1/CI)
		Acidification	Temperature change*	UV change			
SURFACE WATERS	Continental Slope	0.98	0.66	0.85	2.50	0.04	0.11
	Queen Charlotte Sound	0.89	0.62	0.79	2.30	0.13	0.30
	Subarctic Pacific	0.93	0.66	0.74	2.33	0.01	0.02
	Transitional Pacific	0.98	0.64	0.76	2.39	0.00	0.01
	Vancouver Island Shelf	0.98	0.56	0.84	2.37	0.21	0.50
	Dixon Entrance	0.88	0.66	0.80	2.35	0.18	0.42
	Hecate Strait	0.91	0.61	0.83	2.35	0.17	0.40
	Johnstone Strait	0.74	0.35	0.58	1.67	0.25	0.42
	Juan de Fuca Strait	1.00	0.40	0.82	2.22	0.04	0.08
	North Coast Fjords	0.74	0.43	0.68	1.85	0.22	0.41
	Queen Charlotte Strait	0.84	0.42	0.62	1.88	0.29	0.55
	Strait of Georgia	0.85	0.46	0.73	2.05	0.46	0.94
PELAGIC WATERS	Continental Slope	0.78	n/a	n/a	0.78	0.14	0.11
	Queen Charlotte Sound	0.75	n/a	n/a	0.75	0.17	0.12
	Subarctic Pacific	0.78	n/a	n/a	0.78	0.01	0.01
	Transitional Pacific	0.82	n/a	n/a	0.82	0.02	0.02
	Vancouver Island Shelf	0.77	n/a	n/a	0.77	0.28	0.22
	Dixon Entrance	0.74	n/a	n/a	0.74	0.28	0.21
	Hecate Strait	0.75	n/a	n/a	0.75	0.28	0.21
	Johnstone Strait	0.63	n/a	n/a	0.63	0.81	0.51
	Juan de Fuca Strait	0.80	n/a	n/a	0.80	0.65	0.52
	North Coast Fjords	0.53	n/a	n/a	0.53	0.49	0.26
	Queen Charlotte Strait	0.63	n/a	n/a	0.63	0.78	0.49
	Strait of Georgia	0.77	n/a	n/a	0.77	1.00	0.77
BENTHIC HABITATS*	Continental Slope	0.95	0.49	0.41	1.85	0.24	0.44
	Queen Charlotte Sound	0.78	0.43	0.46	1.67	0.14	0.24
	Subarctic Pacific	0.76	n/a	n/a	0.76	0.00	0.00
	Transitional Pacific	0.81	n/a	n/a	0.81	0.00	0.00
	Vancouver Island Shelf	0.85	0.37	0.48	1.69	0.30	0.51
	Dixon Entrance	0.84	0.43	0.22	1.49	0.18	0.27
	Hecate Strait	0.64	0.29	0.16	1.08	0.27	0.29
	Johnstone Strait	0.93	0.22	0.25	1.40	0.53	0.75
	Juan de Fuca Strait	0.91	0.26	0.54	1.70	0.47	0.80
	North Coast Fjords	0.84	0.28	0.46	1.58	0.45	0.71
	Queen Charlotte Strait	0.87	0.28	0.27	1.42	0.55	0.78
	Strait of Georgia	0.83	0.27	0.33	1.43	0.91	1.31

*Benthic habitats standadized impact score for temperature change is only indicative for shallow habitats < 200 m deep and does not include habitats deeper than 200 m.

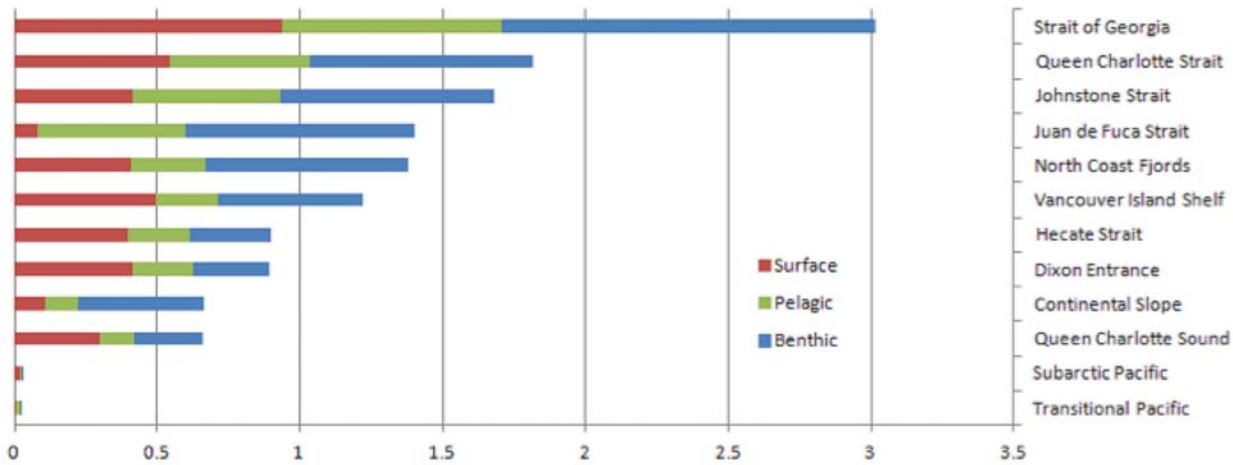


Figure 5.14 Summed climate change vulnerability scores for surface, pelagic, and benthic components by ecosection.

Table 5.6 Tabular illustration of how potential climate impact scores with anthropogenic impact scores (cumulative impact scores) are used to derive values for habitat vulnerability to climate change.

	Standardized scores for mean potential climate impact/ km^2 by habitat/bottom type			Sum of standardized potential climate score (S)	Standardized anthropogenic impact score (CI)	Habitat vulnerability to climate S ÷ (1/CI)
	Acidifica-tion	Temperature change	UV change			
Kelp	0.32	0.35	0.29	0.96	0.86	0.82
Seagrass	0.37	0.23	0.29	0.89	1.00	0.88
Rocky Reef (Shallow)	0.38	0.27	0.33	0.97	1.00	0.97
Rocky Reef (Non-Shallow)	0.36	0.28	n/a	0.65	1.00	0.65
Hard Shelf	0.46	0.25	n/a	0.71	0.33	0.23
Soft Shelf	0.45	0.22	n/a	0.67	0.54	0.36
Undefined Shelf	0.55	0.23	n/a	0.78	0.64	0.50
Soft Slope	0.55	n/c	n/a	0.55	0.49	0.27
Hard Slope	0.56	n/c	n/a	0.56	0.47	0.27
Undefined Slope	0.60	n/c	n/a	0.60	0.35	0.21
Undefined Deep	0.44	n/c	n/a	0.44	0.00	0.00
Hard Deep	0.44	n/c	n/a	0.44	0.00	0.00
Seamount	0.44	n/c	n/a	0.44	0.01	0.01
Canyon	0.46	n/c	n/a	0.46	0.39	0.18

With regard to vulnerability, our metric for adaptive capacity is based only on cumulative impact scores for local human activities (Ban et al. 2010) and inherently assumes that high cumulative impacts from local human activities reduce adaptive capacity. Not surprisingly, our analysis indicates that the most stressed ecosections and habitats are also the most vulnerable to the climate change stressors noted in this preliminary assessment. Ecosections with the compromised adaptive capacity and therefore higher vulnerability are Strait of Georgia, Queen Charlotte Strait, Johnstone Strait, and Juan de Fuca Strait (Figure 5.14). The habitats that are considered most vulnerable are shallow rocky reef, seagrasse, kelp bed, and undifferentiated shelf habitats.

5.4.3 Depicting shoreline sensitivity to sea-level rise

A recently completed coast-wide shoreline sensitivity assessment from B.C. Parks by Robyn Hooper, Doug Biffard, and Tory Stevens rates the sensitivity of B.C. shoreline segments on the basis of foreshore (marine) and backshore (terrestrial) features making use of shore-zone classification,[1, 2] and the Broad Ecosystem Inventory.[3] This assessment rates the sensitivity of the province's shorelines, and hence their potential for change or modification by sea-level rise. It is presented here as another illustration of how scores or ratings may be used to discern and prioritize areas for management response based on sensitivity, impacts, or vulnerability.

The shoreline sensitivity model is a relative sensitivity model that assumes a uniform change in sea level, storm surge, storm intensity, and wind/wave patterns; that is, a constant exposure level of sea-level change. However, determining the impact of sea-level rise requires an understanding of how relative sea level will change across the B.C. coast, then relating that to the shoreline sensitivity model presented here. It is known that a number of factors affect relative sea level in the province and that sea-level-rise projections are not uniform throughout the region. In particular, post-glacial rebound together with tectonic plate movement in the region has manifested in uplift of land and a recently decreasing sea level in some in parts of the coast (Thomson et al. 2008, Bornhold 2008). These sources establish that the level of uplift decreases west to east; namely, from the outer shore (west coast of Vancouver Island and Haida Gwaii) to the inner shore (the mainland). Additionally, wind and oceanographic factors also play a role in determining sea level in given locations and times. Without a comprehensive spatial depiction that integrates the various determinants to sea-level rise, we are currently unable to derive a map of the potential impact of sea-level rise along Canada's Pacific shorelines. Nonetheless, we consider it instructive to present a summary of shoreline sensitivity in various classes from the work of B.C. Parks within this assessment (Table 5.7).

This summary of sensitivities indicates that for some ecosections, more than 60% of their shorelines have high or very high sensitivity to sea-level rise. These ecosections are Dixon Entrance, Hecate Strait, and Juan de Fuca Strait. Ecologically valuable shoreline habitats in these sensitivity classes may be considered at particular risk of loss to sea-level rise.

1 Physical Shore-Zone Mapping System, http://www.ilmb.gov.bc.ca/risc/pubs/coastal/pysshore/index.htm
2 Biological Shore-Zone Mapping System, http://www.ilmb.gov.bc.ca/risc/pubs/coastal/bioshore/index.htm
3 "Broad Ecosystem Inventory," http://www.env.gov.bc.ca/ecology/bei/

Table 5.7 Percentage of shoreline in each sensitivity class for B.C. ecosections.

		Dixon Entrance	Hecate Strait	North Coast Fjords	Queen Charlotte Sound	Queen Charlotte Strait	Johnstone Strait	Vancouver Island Shelf	Juan de Fuca Strait	Strait of Georgia	Continental Slope	BC coast-wide
SHORELINE SENSITIVITY	Very Low	1.6	2.6	7.7	2.9	10.6	15.2	4.1	1.3	6.5	10.0	7.3
	Low	8.5	13.5	19.6	22.4	21.3	20.4	15.9	13.5	19.5	33.4	19.2
	Moderate	19.4	23.2	30.2	21.6	22.5	28.0	24.8	16.5	18.6	20.3	25.7
	High	40.4	45.3	21.3	35.2	31.0	25.5	28.5	39.9	40.4	27.2	28.5
	Very High	30.1	15.4	21.2	17.9	14.7	10.9	26.6	28.8	15.0	9.1	19.3
	Length km	1,299	2,033	14,623	1,176	1,581	3,677	5,330	445	4,416	1,927	36,506

Sensitivity and responses of key taxonomic groups and species

6

6.1 Primary producers

6.1.1 Phytoplankton

In general terms, the phytoplankton community of cold, well-mixed, nutrient-rich waters is dominated by large diatoms, and the ratio of new production to total community production is high. Under these conditions, zooplankton are dominated by crustaceans, such as large copepods. The food web is short (there are few trophic levels between primary producer and top predator) and efficient, capable of sustaining many large predators such as fishes, seabirds, and marine mammals. Warmer, more-stratified, and nutrient-poor waters tend to be dominated by smaller phytoplankton species, and the zooplankton is mostly composed of small crustaceans and gelatinous species. The switching between cold and warm regimes can thus lead to considerable changes in the more conspicuous marine life at higher trophic levels.

Ware and Thomson (2005) suggested that the trophic dynamics in the Northeast Pacific are strongly bottom-up controlled, meaning that changes in primary production (essentially phytoplankton) exert control over the higher trophic levels. But exploration of B.C. marine ecosystem dynamics with whole-system trophodynamic models indicates mixed (bottom-up and top-down) control (e.g., Ainsworth and Pitcher 2005a, 2006, Ainsworth et al. 2008). The transport of nutrients into the photic layers of the shelf and coastal waters is of fundamental importance to the regulation of primary production in this area. Nutrients for phytoplankton growth are mainly supplied by processes that bring deeper, nutrient-rich water closer to the surface (coastal upwelling and vertical mixing) and by river discharge (Whitney et al. 2005). If these processes are highly variable and subject to multiple overlapping cycles, then stronger bottom-up control is likely, but if the organisms in the food web are adapted to rapidly exploiting predictable resources, then the system may have stronger top-down control (mixed control).

As climate changes, a series of physical parameters with distinct (and sometimes opposing) environmental effects are modified simultaneously. The projected intensification of coastal upwelling and river discharge will tend to increase nutrient input. The predicted increase in stratification will decrease nutrient supply by inhibiting mixing. Note that larger river runoff generally promotes two opposing trends on supply: a positive direct impact and a negative indirect one through an increase in stratification.

The following are indications that primary production is reduced under warmer, more stratified conditions on the Canada's Pacific and surrounding areas:

- The increase in stratification caused by the warm waters that occupy the coast and shelf areas of the Northeast Pacific during El Niño conditions reduces nutrient input and primary production in the region (Wong et al. 1998, Whitney et al. 1998, Goes et al. 2001). This is also observed for shorter-lived El Niño like anomalies (Kudela et al. 2006, Mackas et al. 2006).

Sensitivity and responses of key taxonomic groups

- Observations show that the decrease in California fishery yields associated with a shift toward a positive (warm phase) PDO in the mid- to late seventies could have been partially caused by a decrease in primary production brought about by the increase in ocean temperature (Ware and Thomson 2005).

- The surface cooling and stronger winds (and hence more intense mixing) occurring in open ocean waters of the eastern Pacific during positive PDO periods tend to increase primary production offshore (Beamish et al 2009).

- More than half the variability in primary production observed in the region off Vancouver Island between 2000 and 2004 can be explained by variations in temperature, with warmer periods being characterized by lower production and colder periods characterized by higher production (Mackas et al. 2007).

There are also indications that the composition of the phytoplankton in Canada's Pacific will be impacted by climate change. Laboratory experiments indicate that warming of the Bering Sea might shift the system's phytoplankton populations from diatom to nanophytoplankton-dominated (Hare et al. 2007).

6.1.2 Seagrasses and macroalgae

Data on marine plants on the B.C. coast are dominated by the kelp species *Nereocystis luetkeana* and *Macrocystis integrifolia,* and eelgrass species, particularly *Zostera marina*, as these form essential and conspicuous habitat for numerous bird, invertebrate, and fish species (Lucas et al. 2007), as described in Section 4.2. A variety of effects on both seagrasses and macroalgae can be expected with climate change (Okey et al. 2006, Poloczanska 2006, Poloczanska et al. 2007). In general, macroalgal communities may be degraded, and in some cases seagrasses may benefit, but non-climate-related stressors may confound such general predictions.

Under current oceanic concentrations, carbon is a limiting nutrient for seagrasses but not for macroalgae. The future increase in oceanic carbon concentration will favour seagrass development and might lead to the replacement of macroalgae by seagrasses and a consequent shift toward a more detritus-based food web when other conditions allow such shifts to take place (Harley et al. 2006). Currently, there is a lack of information on the productivity of kelp and eelgrass beds, and no comprehensive lists of marine plant species in British Columbia. The long-term impacts of global warming on seagrasses and macroalgae are still relatively unknown (Lucas et al. 2007).

6.2 Invertebrates

6.2.1 Zooplankton

The fluctuations in zooplankton populations are closely related to changes in primary production. For example, the impacts on phytoplankton populations caused by the shift toward a positive PDO in the mid- to late seventies resulted in a decrease in zooplankton biomass off the coast of California and an increase in zooplankton biomass in the open waters of the eastern Pacific (Ware and Thomson 2005, Beamish et al 2009). The cool-high production cycles versus warm-low production cycles observed between 2000 and 2005 were also evident in zooplankton biomass (Mackas et al. 2007).

Warmer ocean conditions have been associated with a decrease in the population of large calanoid copepods (*Neocalanus* spp. and *Calanus marshallae*) in the shelf areas of the Bering Sea (Springer et al. 2008) and have also been related to changes in zooplankton phenology. Warmer than usual conditions along the B.C. coast are thought to have caused the populations of two copepods (*Neocalanus cristatus* and *N. plumchrus*) to peak earlier in the year (Bertram 2001, Mackas et al. 1998). These changes in phenology might result in mismatch between zooplankton development and their food supply, as well as a mismatch between zooplankton availability and the species that prey of them, such as forage fishes and seabirds (Mackas et al. 2007). As with phytoplankton, discussed previously, the composition of the zooplankton communities in the region will most likely be altered and a poleward shift in many of the species found in the Northeast Pacific is expected (Ji et al. 2010, Mackas et al. 2007). Richardson (2008) also explains some of the ecological implications of these phenological shifts in the zooplankton of Canada's Pacific. Warmer conditions were also among the main drivers behind the large increase in gelatinous zooplankton in the Bering Sea during the 1990s (Brodeur et al. 2008)

6.2.2 Krill

Krill (family: Euphausiidae) are zooplankton that are forage for many fishes and marine organisms, and have been the subject of a commercial krill fishery in previous years. As members of the zooplankton, the potential impacts to zooplantkon discussed in Section 6.2.1 Zooplankton apply to krill as well. Warmer, more stratified waters resulted in a decrease in the krill population in the southeastern Bering Sea in 1997 (Napp and Hunt 2001). Warmer conditions related to El Niño caused a decrease in the abundance of the krill *Euphasia pacific* off the coast of central California. On the B.C. coast, warm ocean conditions are associated with low krill abundance (DFO 2006a).

6.2.3 Shrimp and prawns

The warm water conditions off coastal British Columbia from 2003 to 2005 appear to have caused smooth pink shrimp (*Pandalus jordani*; family: Pandalidae), a southern species, to expand its range into British Columbia sometime between 2004 and at least the 2007 survey (DFO 2008b), relative to annual spring surveys since 1973. This species is apparently now occupying parts of the B.C. range of its northern cold-water counterpart, *P. borealis* (J. Boutillier, Fisheries and Oceans Canada, pers. comm., 7 April 2009). Changes in climate and oceanography are expected to affect the recruitment, growth, and survival of shrimp and prawns, as well as many other taxa.

6.2.4 Clams, scallops, and other bivalves

Commercially important clams and scallops are distributed throughout the subtidal and intertidal areas of the North Coast. The habitat used by these clams is discussed in Lucas and Jamieson (2007). As sediment-dwelling filter feeders, most bivalve populations are affected by changes in primary production, detritus production, enrichment and runoff, and sedimentation and disturbance. Climate-related changes that cause changes in watershed function, oceanography, disturbance regimes, and overall community structure, such as changes in temperature, participation, current regimes, and pH, will affect these organisms. As organisms that rely heavily on sequestering calcium carbonate from seawater, bivalves are one of the groups considered particularly vulnerable to acidification, the effects of which are expected to be strong in this region (DFO 2008b, Wootton et al. 2008).

6.2.5 Northern abalone

Northern abalone (*Haliotis kamtschatkana*) is another species of mollusc that relies on sequestering calcium carbonate from seawater, and is thus vulnerable to expected changes in this region, especially given the worrisome outlook for acidification and its ecological effects in the region (DFO 2008b, Wootton et al. 2008). Additionally, emerging disease (van Blaricom et al. 1993, Moore et al. 2000), and historical overfishing and ongoing poaching of this species render it vulnerable. Abalone consumes marine macroalgae and is preyed on by sea otters (*Enhydra lutris*), all of which inhabit shallow rocky habitats. In addition to the direct impacts of global oceanographic changes, exploitation, and disease, northern abalone is thus vulnerable to changes in their prey and predators, which in turn are vulnerable to a variety of impacts and changes themselves.

6.2.6 Squid and octopus

Commercially important squid and octopus in British Columbia include the opal squid (*Loligo opalescens*), the neon flying squid (*Ommastrephes bartrami*), and the giant Pacific octopus (*Octopus dofleini*). The B.C. habitats these species occupy are discussed in Lucas and Jamieson (2007). Squid populations are responsive to oceanographic changes, and their populations are known to fluctuate and quickly shift ranges. Landings of *L. opalescens* increased in northern British Columbia during the late 1990s, but the reasons for this increase are unclear (DFO 2006b, Pellegrin et al. 2007). The recent appearance of Humboldt squid (*Dosidicus gigas*) in the province is covered in the anomalous nekton section (6.4).

6.2.7 Crabs

Commercial crab species in the North Coast area include Dungeness crab (*Cancer magister*), two species of tanner crab, *Chionoecetes tanneri*, and *C. bairdi*. Dungeness crab are abundant in the western Hecate Strait, around Prince Rupert, and in McIntyre Bay in southeast Dixon Entrance (Lucas and Jamieson 2007). These distributions are likely due to the presence of broad shallow banks and an active regime of sedimentation and river influence, providing optimal conditions for food provision and habitats for different life stages and seasons, such as seagrass and other habitats. Changes in climate and oceanography that influence this regime and habitat characteristics (e.g., currents, wave regimes, precipitation, temperature) will also likely influence the abundance and distribution of this important species. In addition to fishing pressure, Dungeness crabs in the region are vulnerable to other human impacts, such as pollution from pulp mills (Yunker and Cretney 1995) and other sources, and watershed, coastal, and estuarine modification. Juvenile Dungeness crabs are also known to be vulnerable to predation by the invasive European green crab (*Carcinus maenas*) (Pellegrin et al. 2007), and warming ocean conditions throughout British Columbia could aid in the northward spread of this exotic species.

Tanner crabs are distributed along Pacific Canada's continental slope (Lucas and Jamieson 2007). Early life stages of tanner crabs are considered to be very important species ecologically on the continental slope portions of Pacific Canada, in part due to the predominance of their early life stages as prey of important fish species (Pellegrin et al. 2007). There is some evidence that the recruitment of tanner crabs, and other crab species, is sensitive to climate fluctuations (Zheng and Kruise 2006), though it also may relate to the abundance of their groundfish predators. Furthermore, increased shoaling of acidic waters may further impact such continental slope populations.

6.2.8 Sea cucumbers and sea urchins

Commercially exploited echinoderms such as sea cucumbers (holothurians) and sea urchins (echinoids) also sequester calcium carbonate from seawater for their skeletal structures, and thus may be particularly vulnerable to acidification. Their life stages are triggered by seasonal changes in environmental conditions, so longer-term changes would likely affect the timing and characteristics of these life stages.

6.3 Commercial fishes

The warming along the coast and intensification of the Aleutian Low associated with the warm (positive) phase of the PDO tend to reduce the fisheries landings in the south of British Columbia and the U.S. northwest, and increase landings of stocks exploited in northern British Columbia and Alaska. In British Columbia, periods of positive PDO have been related to higher pink, coho, and sockeye salmon catches, and to lower chinook salmon landings (Hare and Mantua 2000), but a longer-term climate change signal may adversely affect all Pacific salmon stocks in the province. A review of climate change impacts on British Columbia's commercial fish stocks was recently conducted by Beamish et al. (2009). Table 6.1 summarizes some of their conclusions.

Longer-lived species are more resistant to short-term climate variability because they can afford to have long periods of low or no recruitment. But in general, these species are likely more vulnerable (less resilient) to longer-term directional change in a given location because they cannot adapt as fast as shorter-lived species. The initial detectability of climate impacts may, however, be opposite. Climate change impacts will likely be first noted on shorter-lived species, as the whole population will respond to changed conditions within the short generation time. For longer-lived species, such as sablefish (~100 years), there may be a much greater lag time for the impacts of climate change to be noticed in the whole population (Beamish et al. 2009), even though they will be less capable, ultimately, of coping with changed conditions. This makes such longer-lived species particularly vulnerable.

In the area west of Vancouver Island, there are indications that warming would result in a shift in the makeup of fishery resources, with a decline in the availability of salmon, herring, and resident hake and an increase in the importance of migratory hake, mackerel, and tuna (Robinson and Ware 1994, Ware and Thomson 2000, Wright et al. 2005, Walker and Sydneysmith 2007). Similar changes are likely to occur elsewhere in Pacific Canada.

Fishing frequently results in the selective removal of older and larger individuals from the population. This alteration of the demographic structure tends to generate a shortening of the spawning season, a decrease of age-at-maturity, and shorter generation replacement times. All these factors tend to make the exploited population less resilient and more sensitive to disturbances and changes in climate (Perry et al. 2007).

Global bioclimatic envelope modelling was recently conducted for commercial fish species (Cheung et al. 2009), and this approach has now been downscaled to the Northeast Pacific Ocean (Cheung et al., in review), focusing on 28 pelagic nekton species that are captured in pelagic trawl monitoring across the whole region (Brodeur et al. 2003, 2005; Orsi et al. 2007; Harding et al. 2011). This downscaled modelling of the region indicates an approximate 250-km poleward shift in the latitudinal centroid of these species from 2005 to 2055 under the reasonable SRES A1B scenario of atmospheric CO_2 concentrations (720 ppm by 2100). These modelled estimates by Cheung et al. (in review) were incorporated into simulations by Ainsworth et al. (2011) to estimate the combined ecological impacts of different climate variables on Northeast Pacific biological communities, as a step toward integrated ecological modelling of climate impacts on Northeast Pacific marine ecosystems.

Table 6.1 Summary by Beamish et al. (2009) of potential impacts of greenhouse gas-induced climate change on key species in the B.C. fishery during the next 50 years.

Species	Potential impact
Sablefish	Stocks in the south may be reduced, but the northern stock may benefit from stronger year classes. A key factor will be the protection of the spawning stock from overfishing. If overfishing does not occur, the adult population should be able to survive prolonged periods of poor recruitment over the next 50 years.
Pacific herring	Stocks in the Strait of Georgia should remain at high levels, but offshore stocks would be reduced by increased predation.
Pacific hake	The Strait of Georgia stock should continue at high abundance. The offshore stock should also remain at higher abundance levels provided it is not overfished. If abundance increases, more fishes will move farther north, perhaps off the Queen Charlotte Islands and into Queen Charlotte Sound.
Pacific halibut	The abundance within the population should remain at high levels as a consequence of a stormier North Pacific in the winter. The abundance off Canada may be reduced slightly as fewer juveniles migrate farther south.
Pacific Ocean perch	The major impact will be increases in the frequency of strong year classes, which will improve abundance.
Pacific sardine	In the Northeast Pacific, Pacific sardine abundances follow trends that are associated with the spawning and rearing environment off California and Mexico. The mechanisms remain unknown. If the Aleutian Low intensifies, it is possible that the trends in sardine production may continue, perhaps with increased production during favourable periods. Off British Columbia, Pacific sardine will increase in abundance and may establish resident populations in increasing productivity regimes, but the natural fluctuations will still occur. This means that one of the future regime shifts will result in conditions unfavourable for sardine reproduction and a natural collapse will occur. However, there may be residual stocks of sardine that reside longer, or all year, in the Canadian zone as more sardines move north into it in the summer.
Pacific cod	Pacific cod will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.
Pacific salmon	Pacific salmon from the Fraser River stocks will suffer major impacts in fresh water and in the ocean. Sockeye, pink, and chum from the Fraser River will be reduced in abundance as a consequence of reduced freshwater survival as juveniles and spawning adults. The production of wild coho and chinook will also be reduced, but the reduction will be less than for the other species. Pacific salmon stocks from the Skeena and Nass rivers and to the north will increase in abundance as a result of improved ocean productivity. Pacific salmon will begin to reproduce in Arctic rivers. Pink salmon will be excellent indicators of climate-related change. Basin-scale changes in growth, survival, and straying rates will all indicate when large-scale changes occur.

Sensitivity and responses of key taxonomic groups

6.3.1 Pacific salmon

The Pacific salmon (*Oncorhynchus* spp.; family: Salmonidae) of British Columbia will be particularly vulnerable to projected changes in climate and oceanography, given the proximity to southern range limits and expected adverse effects to both marine and freshwater habitats and production. The survival of pink, chum, and sockeye salmon increases with ocean temperature for Alaskan stocks (northern part of range), but decreases with increasing temperatures for B.C. and Washington stocks (southern part of range), suggesting that climate change may impact these various ends of stock distributional ranges differently (Mueter et al. 2002). Pacific salmon are cold-water species, and southern British Columbia is generally near their southern distribution limit. As sea temperatures increase, their southern range limits will move north, thereby potentially extirpating some salmon species from parts of the province. This overall concept is illustrated for sockeye salmon, *O. nerka*, in Figure 6.1.

Salmon populations will also suffer a series of negative impacts caused by climate change during the freshwater stages of their life cycle. Higher temperatures and lower oxygen concentrations in streams and lakes can be harmful to larvae and juvenile individuals, and can also adversely influence spawning and incubation. Temperature impacts are already being observed in the salmon population of the lower Fraser River, where the water has been warming (Figure 6.2), and this is causing significant pre-spawning mortality (B.C. Ministry of Environment 2007).

Figure 6.1 Southern limit for sockeye salmon distribution (Burgner 1991).

At higher temperatures, a larger fraction of precipitation will occur in the form of rain, which can lead to an increase in winter streamflow and damage to eggs. Earlier snowmelt and a decrease in the snowpack can result in lower summer and fall streamflows, decreasing available habitat area and further intensifying the impacts of higher temperature and reduced oxygen concentrations (Battin et al. 2007). Warming is changing the timing of snowmelt, which determines the date and duration of the spring freshet (Figure 6.3), which is in turn related to patterns of salinity in estuaries and nearshore marine environments.

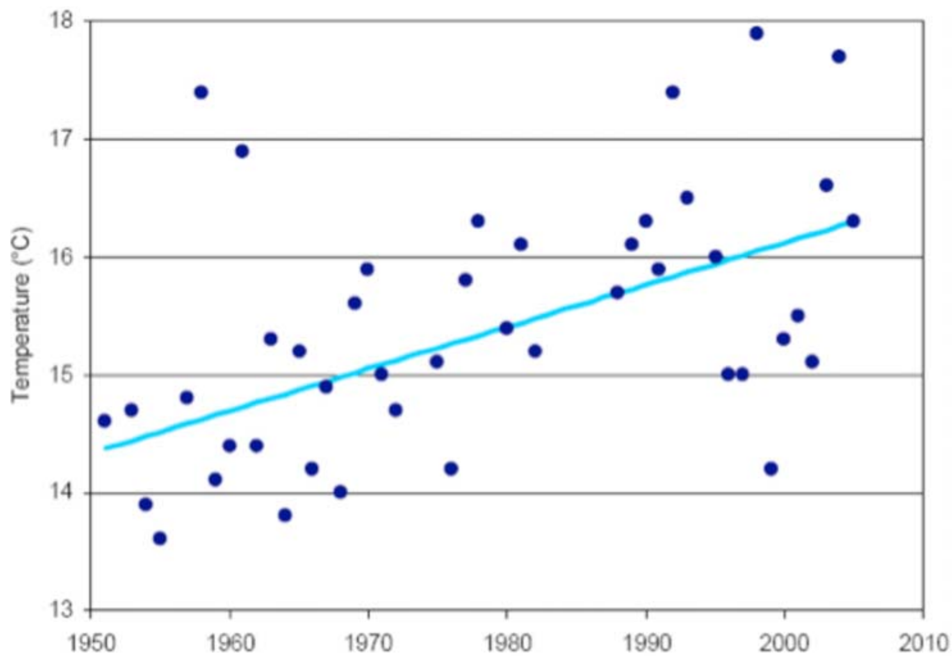


Figure 6.2 Increase in average summer (June, July, August) temperature of the lower Fraser River at Hell's Gate at the rate of 0.3 ± 0.1ºC per decade since 1950. Data from the Pacific Salmon Commission and Institute of Ocean Sciences, Fisheries and Oceans Canada (B.C. Ministry of Environment 2007).

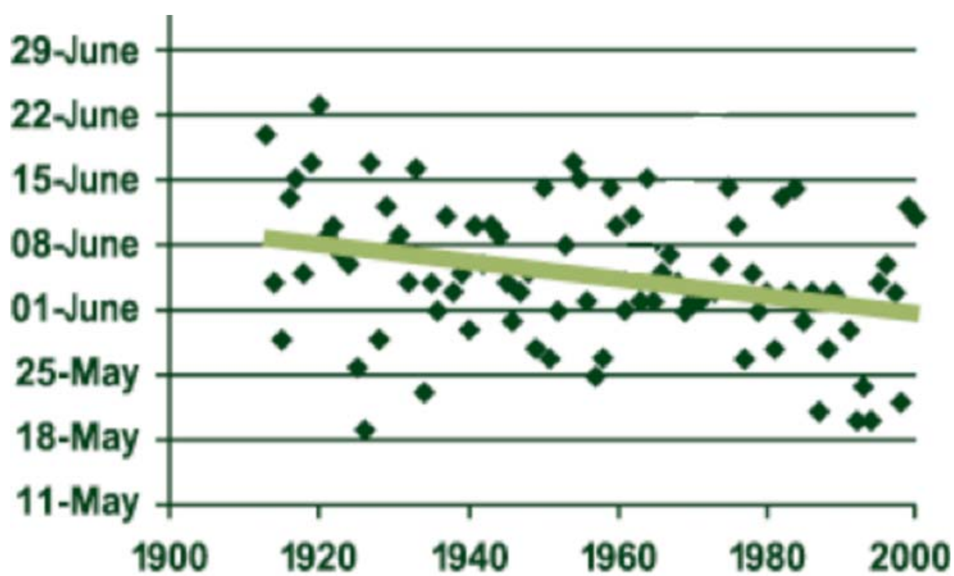


Figure 6.3 Timing of one-third of Fraser River Annual Flow (1913–1998). Data from the Canadian Historical Homogenized Temperature Datasets. Analysis by Canadian Institute for Climate Studies, 2001, for Ministry of Water, Land and Air Protection (Government of British Columbia).

Sensitivity and responses of key taxonomic groups

Increase in summer melt and consequent riverflow, together with higher water temperatures, might reduce the survival of salmon migrating up the Fraser River (Beamish et al. 2009; see also Figure 6.4). Model estimates indicate that changes to the freshwater environment can result in declines of 10–20% in 2025 and of 20–40% in 2050 in the spawning population of chinook salmon of the Snohomish basin in Washington State (Battin et al. 2007).

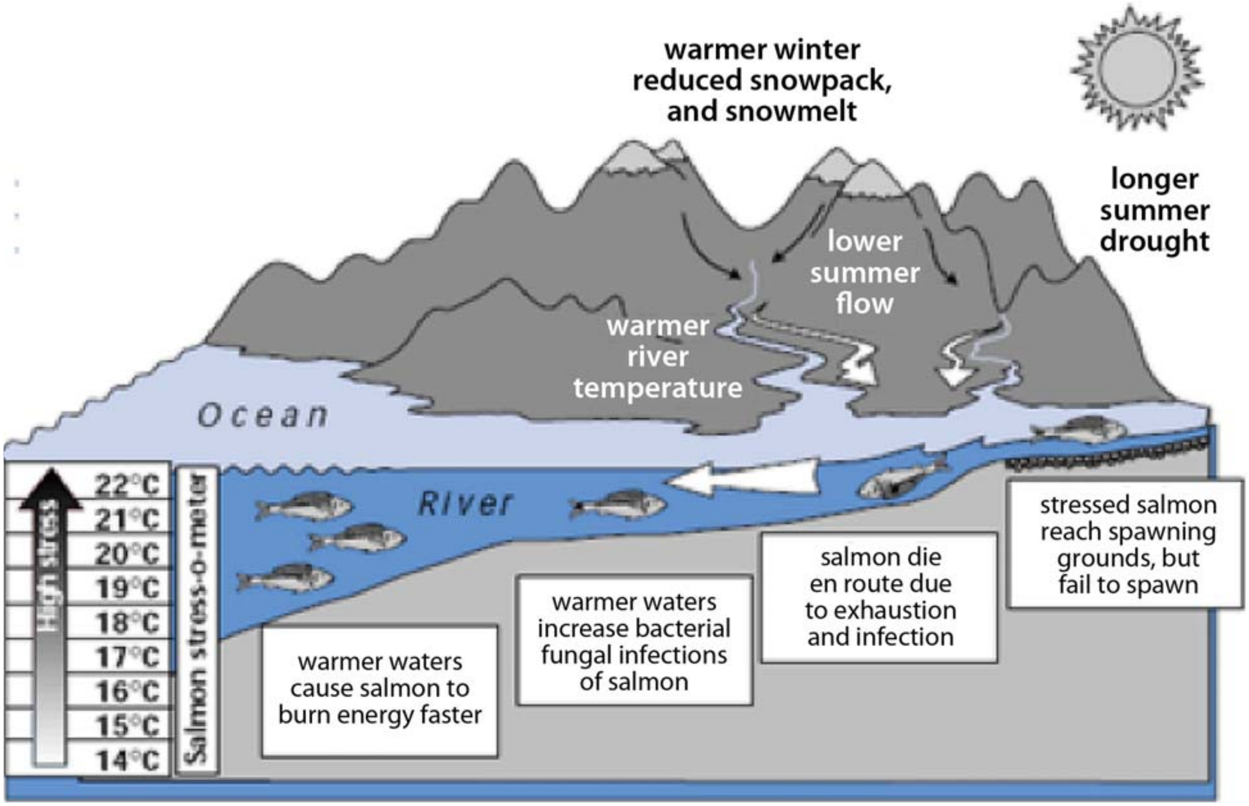


Figure 6.4 Effects of warmer temperature and lower flow on salmon. Based on Burgner (1991). Graphic from the poster, Temperature Rising: Climate Change in Southwestern British Columbia (Natural Resources Canada).

Warming over land, lakes, and rivers is expected to be more intense and occur at a faster pace compared with the ocean (IPCC 2007). This implies that watershed modifications to salmon habitat may occur faster than changes affecting ocean habitat, but understanding the relative importance of these changes to salmon populations requires further study.

Salmon landings in the whole North Pacific tend to increase during periods of positive PDO. This is partly related to the intensification of the Aleutian Low pressure system and subsequent increase in oceanic mixing and upwelling, which improve salmon survival at sea (Beamish and Bouillon 1993). However, the productivity of Fraser River sockeye stocks is largely controlled by survival during the freshwater stages, and the impacts of Aleutian Low variability on these stocks are relatively small (McKinnell 2008).

Fisheries and Oceans Canada and the Pacific Salmon Commission have been dealing with pre-spawning mortality related to the freshwater challenges facing migrating salmon for a number of years. To understand potential climate impacts on salmon, the following issues with the en-route river mortality of migrating salmon need to be considered:

- Timing and entry into the river due to flow and temperature conditions will likely change with climate
- Parasitism and disease will likely increase, affecting the viability of migrants
- Flow and freshet changes will make it difficult for migrating fish to transit rapids, pools, and falls, and make it to the spawning grounds
- Warm water, fungi, lack of water in tributaries, and dewatering of spawning areas
- Near-lethal or lethal temperatures in the headwaters of river systems and lakes, and projections of what impact climate changes will impose on the temperature regime of major salmon-producing systems in British Columbia
- Added stressors will cause exhaustion of the energy reserves of migrating fishes before reaching spawning grounds

At-sea mortality of Pacific salmon may also be very important (e.g., Okey et al. 2007, Williams et al. 2010), and should be considered as well.

Finally, there are major differences between the various species of salmon in their biology and life cycles. For example, sockeye swim about three-quarters of the way across the Pacific, while other species stick closer to the coast. The length of life cycles differ; the use of portions of rivers and lakes varies by species; some species "stray" into adjacent systems, whereas others do not; and so on. To adequately understand climate impacts on Pacific salmon in this region, the different sensitivities and vulnerabilities for each species need to be assessed.

Sensitivity and responses of key taxonomic groups

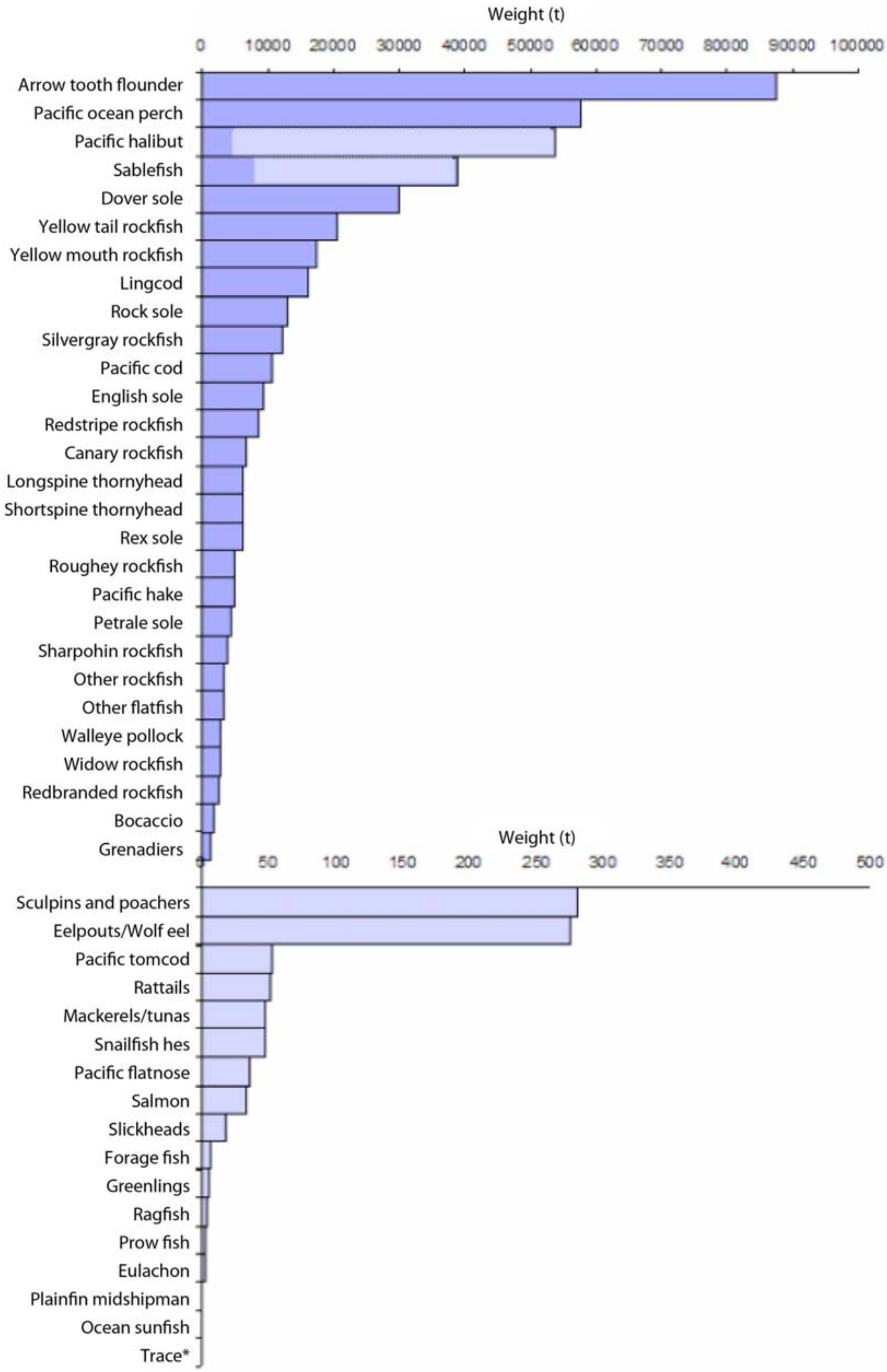


Figure 6.5 Species catch by weight in the B.C. groundfish trawl fishery from 1996 to 2005. Sablefish and halibut catch combined trawl (dark blue), and sablefish or halibut fishery (light blue) catches, respectively. Species included in the lower chart account for less than 1% of the cumulative catch by weight. Trace category includes catches of nearly 50 species (from Fargo et al. 2007). Note that these data do not include midwater trawl, where hake are captured, or finer mesh shrimp trawls. Hake is the largest harvest in British Columbia.

6.3.2 Arrowtooth flounder

Arrowtooth flounder (*Atheresthes stomias*) occupy the shelf until the age of four years, when they migrate to deeper waters along the continental slope (Lucas and Jamieson 2007). They make up the largest catch of the B.C. groundfish trawl fishery (Figure 6.5 and Figure 6.6).

This is a voracious predator that, along with other large fish predators such as walleye pollock and Pacific cod, has increased its biomass considerably since the mid-1970s in the Gulf of Alaska while important pelagic forage fishes have declined. This shift is thought to be the result of a shift to a warmer water regime (Anderson and Piatt 1999, Hunt et al. 2002, Wilderbuer et al. 2002, Spencer 2008), thus potentially representing a future climate change (warming) scenario.

6.3.3 Sablefish

Sablefish (*Anoplopoma fimbria*; family: Anoplopomatidae) is a very long-lived species in British Columbia (113 years), making populations vulnerable to overfishing. The catch per unit effort of this species in the province decreased steadily and considerably from 1991 until at least 2001 (Beamish et al. 2009), indicating that this species is overfished. The resilience of overfished populations to additional stressors such as climate change is generally reduced. However, the longevity of this species enables sablefish populations to withstand long periods of poor recruitment, such as during the 1990s, assuming that overfishing is not occurring.

There are general indications that "There are trends in sablefish production that are related to climate and ocean conditions on a decadal scale" (Beamish et al. 2009). For instance, recruitment of the B.C. stocks of this bathydemersal species is apparently favoured by positive PDO conditions with colder open-ocean, warmer waters off the coast of British Columbia and an intensified Aleutian Low (King et al. 2000). Recruitment in the population off California, however, seems to respond in an opposite manner, being lower during positive PDO conditions. Schirippa (2008) found that high recruitment in the California sablefish population was significantly associated with low sea level and low values of the North Pacific Index (and zooplankton indices); these conditions are associated with cold water along the coast, more upwelling, stronger southward currents, and lower salinity.

These two stocks are delineated at about 50°N latitude—at the northern Vancouver Island boundary of the Northern Shelf area—but this still indicates context-dependent differences in effects in different parts of the overall range of this species. In general, conditions favourable to recruitment may decline with climate change in southern British Columbia, whereas recruitment may improve in the Northern Shelf area (Beamish et al. 2009), but these general predictions are uncertain. Additionally, hypoxia may limit the habitat range of sablefish. Over the past 25 years, habitat at a depth range of 100–800 m has been lost to groundfish at a rate of 7–11% (F. Whitney, personal communication). The distributions and boundaries of these stocks may shift northward, such that California stocks and their contrary dynamics might displace the B.C. stocks in the Northern Shelf area, though it is unclear which relationship with the PDO would hold where, and how this would relate to longer-term oceanographic changes related to a global climate change signal. Fishing pressure appears to be a key factor influencing resilience of sablefish to climate impacts.

6.3.4 Pacific hake

The Canadian Pacific hake (*Merluccius productus*; family: Merlucciidae) fishery is often Western Canada's largest in terms of landed biomass, when Pacific herring is not the largest. The tip of Vancouver Island and Queen Charlotte Sound was considered the northern range limit of the migratory stock of Pacific hake, but since the mid-1990s, this stock has expanded its range northward to southeast Alaska, and the northern extent of their spawning ground moved from Cape Mendocino to Vancouver Island. The spawning area of Pacific hake shifted northward from southern California to the Oregon-B.C. coastline (by ~1600 Km) during the warm summers of 2004 and 2005 (Brodeur et al. 2006). Previously, only a small percentage of the overall biomass of this migrating stock occupied Canadian waters, but now more than 40% of this stock migrates to Canadian waters, compared with 25% in previous years (Beamish et al. 2009). Production of the Strait of Georgia population (a different stock) has also increased with rising local temperatures during recent decades, and this trend should continue with a warming climate. These observations imply increases in the Northern Shelf area. Despite this range expansion and increased productivity, the biomass index of this stock has declined steadily since 1987, possibly due to overfishing by both the United States and Canada. However, there is speculation that an observed dispersion or decrease of hake in southern B.C. waters might relate to the recent appearance of the more southern Humboldt squid (*Dosidicus gigas*) in B.C. waters, or declines in a main prey species of Pacific hake, the euphausiid (krill) *Thysanoessa spinifera* (DFO 2008b).

6.3.5 Walleye pollock

Walleye pollock (*Theragra chalcogramma*) are said to be the most abundant fish species in the North Pacific (e.g., Lucas and Jamieson 2007). In the Northern Shelf area, they are distributed along the continental slope as adults, and in a variety of shallow habitats as juveniles (Shaw and McFarlane 1986, Lucas and Jamieson 2007). This species is likely a very important part of the structure and functioning of this ecosystem. It is thought to be sensitive to climate fluctuations (Stabeno et al. 1995, Criddle et al. 1998, Anderson and Piatt 1999, Wespestad et al. 2000, Ciannelli et al. 2005), due largely to the effect of different ocean climate regimes on the interactions of recruitment dynamics, predation, and cannibalism. Changes in climate in the Northern Shelf area is expected to affect walleye pollock populations and, in turn, the rest of the Northern Shelf ecosystem.

6.3.6 Pacific cod

British Columbia is at the southern limit of the Pacific cod (*Gadus macrocephalus*; family: Gadidae) range. Warming will shift this range to the north, and it is likely that in the future there will be no populations in the Strait of Georgia or off the west coast of Vancouver Island. The new southern limit might be in Alaska, meaning this resource would be absent from B.C. waters (Fu and Beamish 2008). The recruitment of Pacific cod in the province is sensitive to climate and oceanographic changes, including temperature and current speeds. Because of this sensitivity, the proximity of British Columbia to the southern range extent of this species, and the ease of making (fishery-dependent) estimates of abundance, Pacific cod and pink salmon are considered good indicators of climate change effects in the Canadian zone (Beamish et al. 2009).

However, overfishing can potentially confound the effects of climate change in addition to reducing the resiliency of populations to climate change impacts. British Columbia Pacific cod populations are currently considered to be at extremely low levels as a result of low recruitment due to poor oceanographic conditions (Beamish et al. 2009) and overfishing. Fishery landings and landed values have been extremely low for a number of years.

6.3.7 Pacific Ocean perch

Pacific Ocean perch (*Sebastes alutus*; family: Sebastidae) has been overfished in the North Pacific. It is highly vulnerable to overfishing owing to its longevity (100 years) and associated slow reproduction, and because it is a schooling species. In Canada, Pacific Ocean perch is the main species of the rockfish (*Sebastes* spp.) and thornyhead (*Sebastolobus* spp.) fishery, but its proportion of the overall catch has declined since the 1970s. As with sablefish, Pacific Ocean perch is another long-lived species with highly variable recruitment that is strongly affected by ocean conditions. Pacific Ocean perch recruitment is thought to reflect oceanographic regime shifts—the last good recruitment years being the 1977–1988 regime (Schnute et al. 2001). As with other B.C. stocks, recruitment of Pacific Ocean perch is favoured during positive PDO conditions and should improve if these become more frequent under a warming climate, but there is a danger that more frequent shifts in these oceanographic regimes and conditions will be more likely to lead to overfishing due to the challenges in advance prediction of year-class strength in this species and other rockfishes (Beamish et al. 2009).

Sensitivity and responses of key taxonomic groups

6.3.8 Other rockfish species

The rockfishes (family: Sebastidae) are made up of a highly diversified genus (*Sebastes*) and two species of thornyheads (*Sebastolobus*). They include nearshore and slope demersal species with partitioning of food and habitat resources. The rockfish species captured in the hook and line fishery include canary, yelloweye, redstripe, sharpchin, bocaccio, widow, silvergrey, redbanded, rougheye, quillback, shortraker, copper, china, black, tiger, vermilion, yellowtail, redstripe, rosethorn, greenstriped, blue, dusky and yellowmouth rockfishes; Pacific ocean perch (treated separately); and shortspine thornyhead. Species captured in the B.C. hook and line fishery are shown in Figure 6.6. The catches of commercially important rockfish species and other inshore rockfish species are provided in Lucas and Jamieson (2007). Bocaccio and canary rockfish are currently being considered for protection under the Species at Risk Act (see http://www.pac.dfo-mpo.gc.ca/consultation/sara-lep/index-eng.htm).

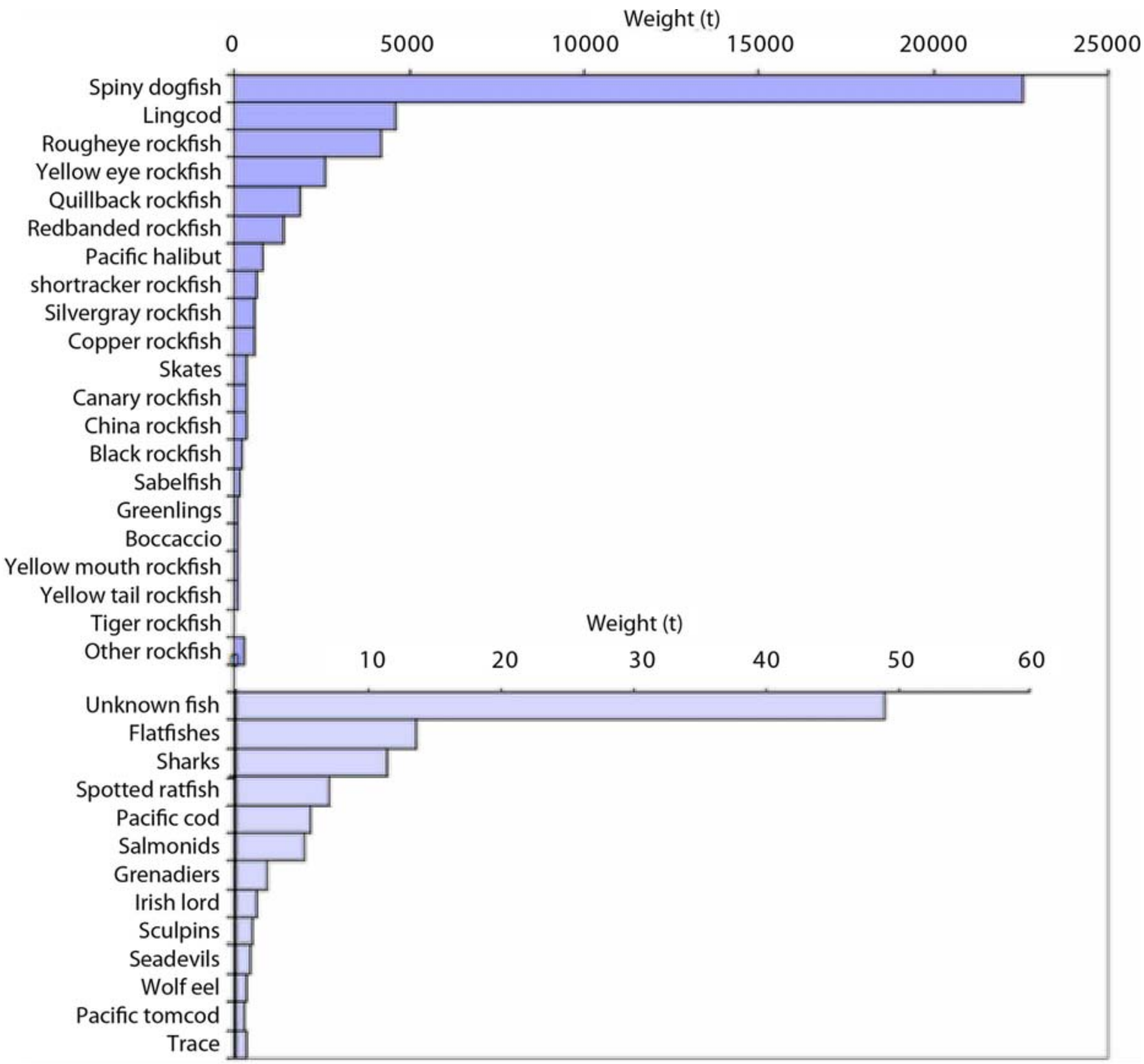
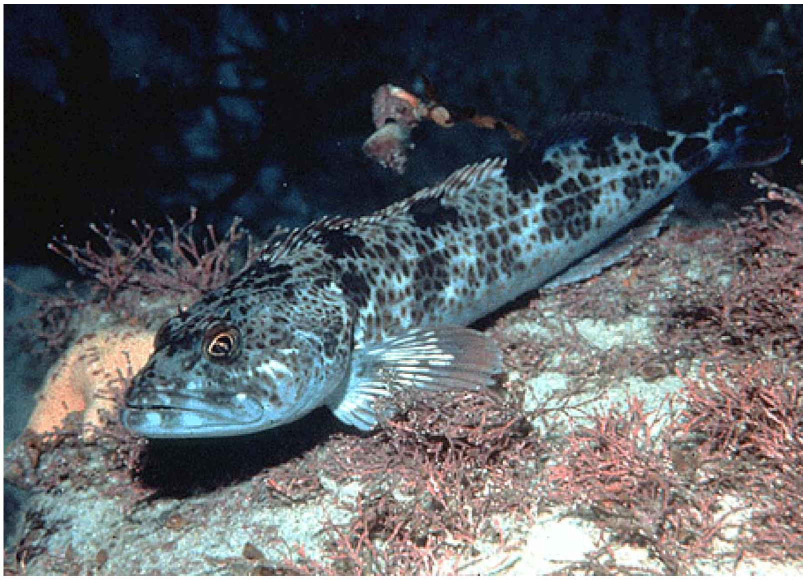


Figure 6.6 Species catch by weight in the B.C. hook and line fishery, 1996 to 2005. Species included in the lower chart account for less than 1% of the cumulative catch by weight. Trace category includes small catches of 15 species (from Fargo et al. 2007).

6.3.9 Lingcod

Although British Columbia is the centre of the distribution of lingcod (*Ophiodon elongates*; family: Hexagrammidae) in the Northeast Pacific, their distribution apparently does not extend north of the northern part of Vancouver Island (southern Queen Charlotte Sound and the Vancouver Island Shelf) (e.g., Lucas and Jamieson 2007). They also occur in the Strait of Georgia, being more abundant in the northern than the southern part of the strait (Haggarty et al. 2004). No studies have been published explicitly on the effects of climate change on lingcod, but their recruitment is also thought to be influenced by ocean climate variability (Haggarty et al. 2004). They are reliant on nearshore production of fish and invertebrate prey, and other aspects of nearshore habitat that might be affected by climate change.



6.3.10 Pacific halibut

Pacific halibut (*Hippoglossus stenolepis*; family: Pleuronectidae) is considered to be at an all-time high biomass. As with the northern population of sablefish, halibut recruitment is favoured by positive PDO conditions, and if climate change brings about an intensification of the Aleutian Low, halibut stocks could be positively impacted overall. On the other hand, this might not mean an increase in halibut populations off British Columbia, as most of the individuals found off Canadian waters hatch to the north and migrate south into the region. Ocean warming might inhibit this southward movement so that, even though overall stocks increase, they become more restricted to Alaskan waters and B.C. populations may remain the same or decrease (Beamish et al. 2009).

6.3.11 Sole

Among the flatfish caught in the B.C. groundfish trawl fishery are various types of sole, including English, rock, butter, and sand; rock sole is also caught in the hook and line fishery. Sole species in the province are generally considered to be in a healthy state (Fargo et al. 2007). Like other flatfish, including halibut and flounder, sole are more robust to fishing than other groundfish, as they have a relatively high intrinsic rate of increase and high reproductive output compared with most species (Fargo et al. 2007). Climate change impacts to sole populations in Pacific Canada are not well understood, but negative effects are predicted in other locations. In Portugal, lower recruitment success is predicted for sole species since a strong decrease in rainfall over the Portuguese river basins, as well as a concentrated period of heavy rain in winter, will decrease river drainage (Vinagre et al. 2007). Positive effects of climate change on sole have been recorded in the North Sea and include increased growing periods due to increasing winter temperatures, and higher growth rates associated with higher summer temperatures (Teal et al. 2008). Further increases, however, are predicted to impact nursery quality if benthic food production cannot meet increasing energy requirements (Teal et al. 2008).

Sensitivity and responses of key taxonomic groups

6.3.12 Pacific herring

Pacific herring (Clupea pallasii; family: Clupeidae) is heavily fished in British Columbia and stocks were overfished in the past during a period of climate-related poor recruitment (Hourston and Haegele 1980). Some say B.C. herring stocks are in generally good condition (Beamish et al. 2009) based on the relatively high biomass of Strait of Georgia stocks, but the west coast of Vancouver Island stocks are at historically low levels (DFO 2008b), and other B.C. stocks are at low levels, such as those in the Northern Shelf (Figure 6.7). Pacific herring is an important forage fish that supports a wide suite of predators. Herring fisheries thus reduce the forage available to this suite of marine species. Like other migratory pelagic species, Pacific herring is known to be strongly influenced by climate-ocean fluctuations and oscillations (Ware 1991). In addition to fishery effects and primary production, populations of Pacific herring are strongly controlled by predation, particularly from Pacific hake. This means herring populations might be impacted by the increase and northward displacement of the outer coast Pacific hake stock. Pacific herring biomass has declined in British Columbia during the past few years (Figure 6.7). They prefer cool water; warm ocean water appears to be associated with poor recruitment (Schweigert 2007) and higher hake predation, so as water temperatures in the province increase over the long term, it is likely that Pacific herring will be replaced by southern forage fish species such as sardines. Beamish et al. (2009) are optimistic, however, about Strait of Georgia stocks, suggesting that their abundance might remain high due to lower predation there by Pacific hake.

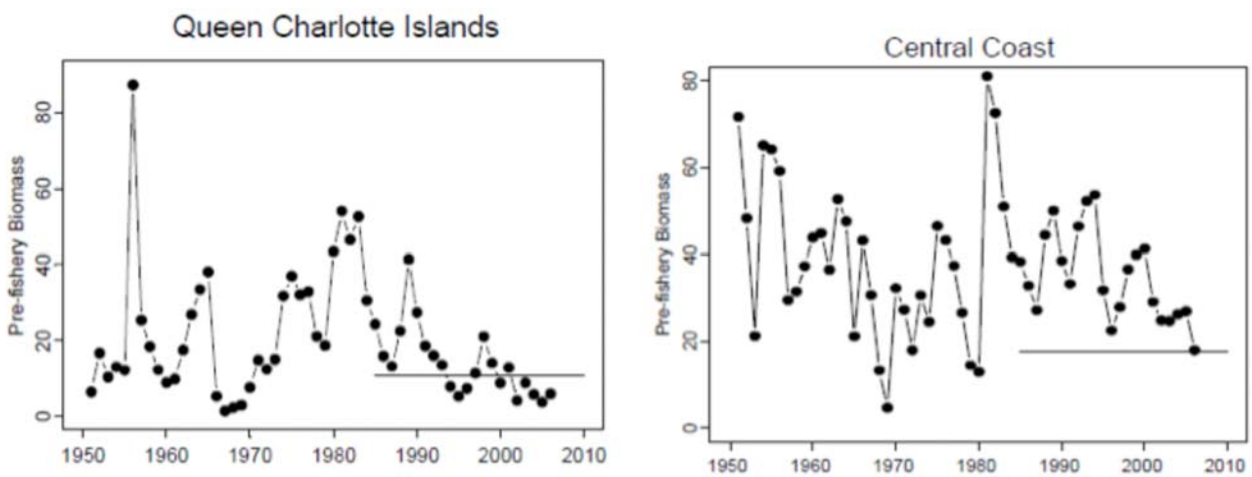


Figure 6.7 Changes in pre-fishery herring biomass (1,000 tonnes) in Haida Gwaii (formerly the Queen Charlotte Islands) and the central coast of British Columbia (Schweigert 2007).

6.3.13 Pacific sardine

Pacific sardine (Sardinops sagax; family: Clupeidae) is a plankton-eating forage fish that supported the world's largest fishery (in both Canada and the United States) early last century; its subsequent collapse is thought to have been due to the combined effects of climate-ocean variability and "boom and bust" overfishing (MacCall 1979, Ware and Thomson 1991). Pacific sardine spawns mainly in southern California during winter, and the adults migrate northward to Canada in midsummer (ranging from northern Mexico to southeastern Alaska). The Canadian and U.S. stocks at both ends of this migration vanished in 1947 and 1951, respectively. This species was absent from Canadian waters for almost 50 years until it began arriving

in 1992 (Hargreaves et al. 1994). Notwithstanding fisheries impacts, large-scale changes in ocean-climate conditions strongly influence Pacific sardine distributions and abundances by affecting their food (Kawasaki and Omori 1986). The recent small recovery signal in British Columbia is thought to reflect a change in the physical dynamics of the ocean. Pacific sardine production tends to increase under positive PDO climate. Fluctuations between favourable and unfavourable conditions for sardines may become more frequent if the PDO increases in frequency, but more positive PDO states and warmer coastal waters might result in a general increase in sardine populations off British Columbia and might induce the establishment of a resident population in the area (Beamish et al. 2009). Sardines were widespread throughout the southern Hecate Strait and Queen Charlotte Sound in 2006 and 2007, thanks to recent warm conditions and a very strong 2003 year-class (DFO 2008b). Such resident populations could replace populations of Pacific herring as they move farther north. Unusually large numbers of sardines and anchovies were captured in southeastern Alaska during the anomalously warm years 2004 and 2005 (Wing 2006).

6.3.14 Eulachon

Eulachon (*Thaleichthys pacificus*; family: Osmeridae) are small, anadromous fish that spawn in more than 30 rivers along the west coast of British Columbia (Schweigert 2007). Their overall distribution is along the west coast of North America between northern California and the eastern Bering Sea. The eulachon is an important fish species, both socially and culturally, to First Nations peoples in British Columbia (Beacham et al. 2005). The oil content in these unique fish is so high that, once dried, they can be used as candles. In rivers, the spawning period for eulachon can be several weeks. In British Columbia, the spawning period varies temporally, with the Fraser River population spawning in April, while northern populations such as those in the Skeena River spawn in March (Beacham et al. 2005). Eulachon populations have declined over the past 20 years, possibly due to bycatch during shrimp fishing (Hay and McCarter 2000). However, large-scale climate change may also be a factor. Current research suggests that eulachon spawning runs may be impaired by spring freshet events gradually changing to summer and fall freshets (Schweigert 2007). The decline in abundance is not observed across the entire distribution of eulachon; abundance has increased in some B.C. rivers, but abundance in the central coastal region of British Columbia is low (Beacham et al. 2005).

Sensitivity and responses of key taxonomic groups

6.3.15 Other species

The following species caught incidentally in the B.C. groundfish trawl fishery and hook and line fishery (Fargo et al. 2007) provide a broader (albeit incomplete) sampling of the fish biodiversity in British Columbia, at least the species directly affected by these fisheries.

Each one of these species inhabits a unique functional niche and is affected by the various dimensions of climate change. Community-wide gradients of mismatches of co-evolved species would likely occur with the biodiversity of Pacific Canada's marine ecosystems.

Table 6.2 List of some additional species caught in the groundfish trawl, and hook and line fisheries.

B.C. groundfish trawl fishery:	
Oreos Dragonfish and viperfish Bristlemouth and fangjaw Lumpsuckers and skilfish Slipskins Pacific sandfish Hairtails Medusafish Pricklebacks Pacific barracuda White croaker Quillfish Gunnels Gobies Giant wrymouth Manefishes	Pomfrets Northern ronquil Tubeshoulders Barreleye Javelin spookfish Myctophids Dreamers Opah Clingfishes Pipefish and tubesnouts Cuskpout Crested ridgehead Toadfishes King-of-the-salmon Billfishes
B.C. hook and line fisheries:	
Drums Bigfin lanternfish Pacific hake Skilfish Surfperches Striped marlin Prickleback Tubenoses	Walleye pollock Barracudinas Snailfishes Rockweed gunnel Wrymouths Sturgeons Hagfishes

6.4 Anomalous nekton occurrences

Because nekton (fishes and squid) are highly mobile (especially pelagic nekton), they can respond very quickly to changes in oceanographic conditions, and many species do so during years when oceanographic conditions are anomalous. Examination of the patterns of nekton responses to oceanographic fluctuations can thus provide valuable insights, albeit probably conservative, into how these species and communities might respond to longer-term climate change.

During the 1982–1983 El Niño event, a number of unusual sightings of marine species off British Columbia were compiled by Fulton (1985), and these are listed in Appendix B. During the anomalously warm years of 2004 and 2005, a number of warm-water fish species were observed in the marine waters of British Columbia and Alaska (Brodeur et al. 2006, Trudel et al. 2006, Wing 2006). A sampling of these is shown in Figure 6.8.

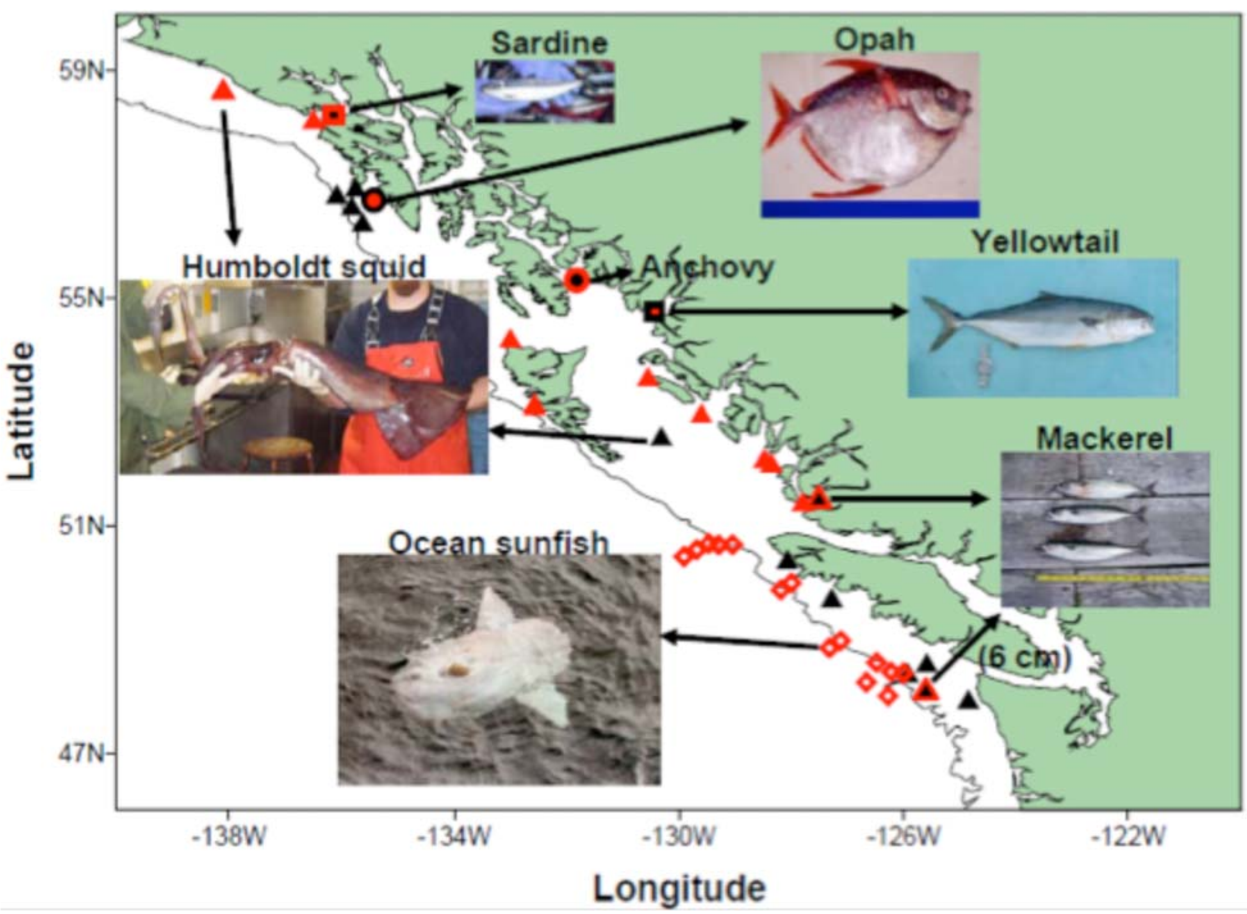


Figure 6.8 Some documented occurrences of warm-water species of fishes and squid in British Columbia and southeast Alaska in 2004 and 2005. Black triangles: Humboldt squid (2004); red triangles: Humboldt squid (2005); open red diamonds: Ocean sunfish (reproduced from Trudel et al. 2006).

Humboldt squid, mackerel, and Ocean sunfish are discussed here. Sardines and anchovies are discussed in 6.3.13 Pacific sardine.

Sensitivity and responses of key taxonomic groups

6.4.1 Humboldt squid

Humboldt squid (*Dosidicus gigas*), a predatory species that is typically abundant from Mexico to Chile, has recently arrived in the California Current and Canada's Pacific waters (Cosgrove 2005, Trudel et al. 2006, DFO 2008b). Dozens were stranded on Tofino beaches in the summer of 2009, and hundreds had washed up on Washington's coast in previous years. This species may have increased in abundance as a result of declines in its predators from overfishing, or as the result of competitive advantages in a lower oxygenated Northeast Pacific due to surface freshening and increased stratification, or for other reasons related to warming conditions. Humboldt squid consume a variety of commercially important fishes, such as Pacific hake (*Merluccius productus*) (Brodeur et al. 2006), and some suggest that they may consume herring, sardines, and salmon as well (Trudel et al. 2006). The presence of these squid might change the distributions and migratory behaviours, and success of these important fish species due to fear-based interactions (Frid et al. 2007), in addition to changing their populations through direct consumption.

6.4.2 Pacific mackerel

The discovery of juvenile Pacific mackerel (*Scomber japonicas*; family: Scombridae) in B.C. waters in 2005 (Trudel et al. 2006) indicates local reproduction of this species for the first time. Adults were observed to invade British Columbia in the early 1990s and may have contributed to the very poor year-classes of Pacific salmon species and stocks throughout the province, as Pacific mackerel are voracious predators of out-migrating salmon (Ware and Hargreaves 1993, Hargreaves and Hungar 1995). The very low salmon returns in 2007 and 2008 may again be associated with the occurrence of Pacific mackerel in the anomalous 2005 year. As the climate change signal emerges from the variability associated with this dynamic region within the coming half-century, Pacific mackerel may become much more common in British Columbia, thus having a more permanent negative effect on salmon and potentially many other species throughout the whole region.

Brodeur et al. (2006) found that the spawning area of a different species, Pacific jack mackerel (*Trachurus symmetricus*; family: Carangidae), shifted northward from southern California to the Oregon-B.C. coastline (by ~ 1600 Km) during the warm summers of 2004 and 2005. Off Oregon, they observed many young-of-the-year, as well as eggs and larvae in plankton samples. See also Orsi et al. (2007) for more information on distributions and changes.

6.4.3 Ocean sunfish

Ocean sunfish (*Mola mola*) are open-ocean species not normally observed in coastal areas, but they were particularly abundant from at least Oregon through British Columbia in 2004 and 2005 (Brodeur et al. 2006, Trudel et al. 2006), with a concentration in northern Queen Charlotte Sound and the adjacent continental slope (R. Williams, unpublished data). Ocean sunfish prey on plankton such as jellies and crustaceans; benthos such as sea stars, brittle stars, and benthic algae; and nekton such as cephalopods and some bony fish.

6.4.4 Other southern and oceanic species

The southern species Pacific butterfish (*Peprilus simillimus*) was very abundant off Oregon in September 2005 (Brodeur et al. 2006), while other offshore species such as Pacific pomfret (*Brama japonicus*), yellowtail (*Seriola lalandi*), and opah (*Lampris guttatus*) were observed in these inshore northern areas (Brodeur et al. 2006, Trudel et al. 2006, Wing 2006). Both Pacific hake and spiny dogfish (*Squalus acanthias*) declined in this area during these anomalously warm years (Brodeur et al. 2006).

6.5 Selected higher vertebrates

In addition to the inherent and iconic value of higher vertebrates, many are considered useful indicators of ecosystem health, and certain keystone species such as the sea otter have the capacity to bolster ecosystem resilience and resistance to climate change impacts. Only a few categories and taxa are listed here.

6.5.1 Marine birds

Global shifts in plankton communities, such as those toward smaller phytoplankton, and smaller and more gelatinous-dominated zooplankton, will affect higher trophic levels, including seabirds (Frederiksen et al. 2006), as will shifting forage fish communities. Warmer than average surface waters in the Bering Sea caused a decrease in the populations of copepods preyed on by least auklets (*Aethia pusilla*) and has been related to nutritional stress in these birds (Springer et al. 2008). Warmer than average temperatures and weak upwelling conditions have been linked to pervasive die-offs of Brandt's cormorant (*Phalacrocorax penicillatus*) and the common murre (*Uria aalge*) on the California coast during 2005 (Parrish et al. 2007). El Niño conditions in central California were related to a decrease in prey availability and reproductive success of the marbled murrelet (*Brachyramphus marmoratus*) in central California (Becker et al. 2007). Warmer and more stratified waters in the southeast Bering Sea were related to a decrease in prey (krill) availability and large mortality (~11%) of short-tailed shearwaters (*Puffinus tenuirostris*) in the region (Napp and Hunt 2001).

Impacts may be attributed to modifications in the average production, but also to changes in the timing of primary production cycles. The growth rate of three seabird populations nesting on Triangle Island, the largest seabird colony in British Columbia, decreased with the observed increase in ocean water temperature during the 1990s (Figure 6.9). For two of these birds, Cassin's auklet and rhinoceros auklet, the increase in ocean temperature caused a mismatch between the time of seabird breeding and the availability of their main prey, the copepod Neocalanus cristatus. The copepod population peak occurs earlier in the year under warmer conditions (Bertram 2001). Prey timing, rather than prey abundance, was the key factor determining seasonal prevalence of the copepod in Cassin's auklet nestling diets (Hipfner 2008). Earlier population peaks under warmer conditions have also been observed for another important seabird prey, the copepod N. plumchrus (Mackas et al. 1998). The lost of tidal flats to sea-level change will decrease feeding grounds and may also negatively impact marine birds (Galbraith et al. 2002).

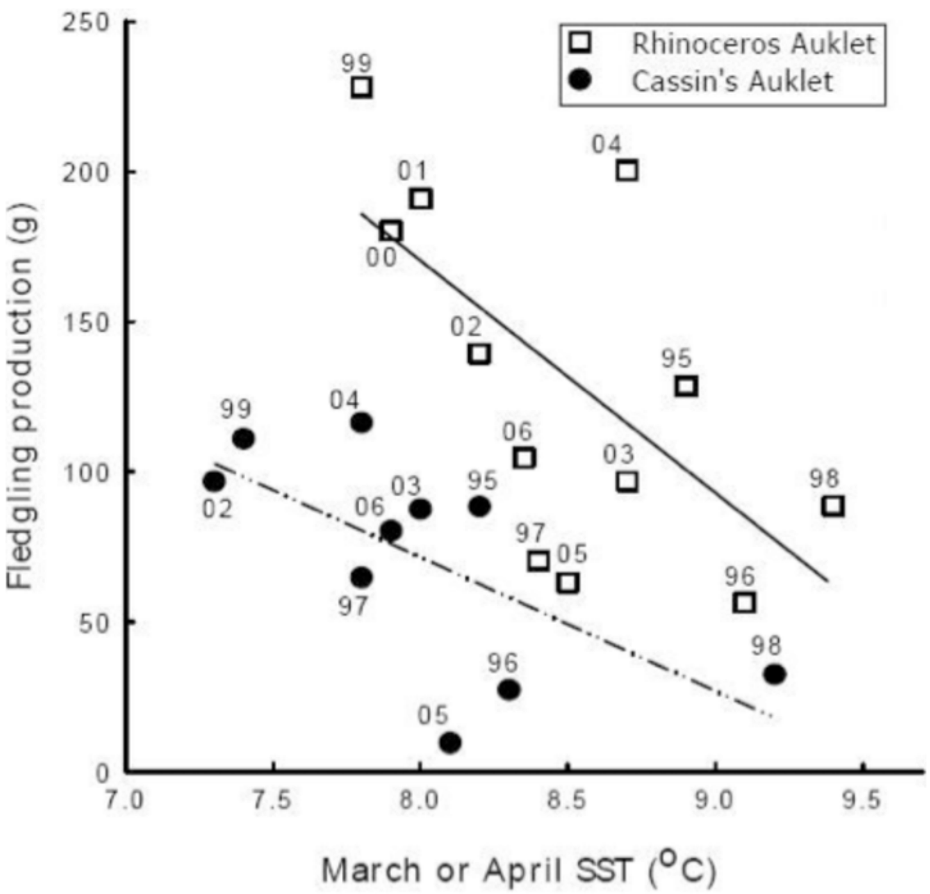


Figure 6.9 Fledgling production of Cassin's and rhinoceros auklets breeding on Triangle Island, British Columbia (northern tip of Vancouver Island), and March or April sea surface temperature, showing a strong relationship between poor production and warm sea temperatures (figure modified from Hipfner 2008).

Seabird populations will also likely be adversely affected by changes in nesting habitat due to sea-level rise and other habitat degradation. Some species nest on offshore rocks that may be inundated by sea-level rise, and others nest on the intertidal fringe of sandy beaches and rocky substrate alike, both in exposed and protected estuarine settings.

6.5.2 Marine mammals

It is expected that the main impacts of climate change to marine mammals will be indirect, mainly through changes in prey availability and the structure of prey communities at specific locations (Simmonds and Isaac 2007, Learmonth et al. 2006). In general, marine mammals would be negatively impacted by a shift toward warm-water primary production conditions in the region. Past declines in marine mammal populations in the northeastern Pacific have been linked to decreases in primary production (Schell 2000, Francis et al. 1998). Other indirect effects include susceptibility to disease and contaminants, changes to reproductive success, and increased competition with other marine mammals (Learmonth et al. 2007). The increased occurrences of toxic algal blooms as a result of nutrient enrichment and increased temperature have fatally poisoned cetaceans, pinnipeds, and manatees (Gilmartin and Forcada 2002). Morbillivirus infections have caused the deaths of striped dolphins in the Mediterranean Sea and of seals in Europe; these infections have been linked to changes in the range and migratory patterns of marine mammals, leading to the spread of viruses and novel pathogens (Learmonth et al. 2006).

Cetaceans

Canada's Pacific is home to many cetacean species, including baleen and toothed whale species, Pacific white-sided dolphins, and Dall's and harbour porpoises. Baleen whale adults will likely not be directly affected by temperature changes (compared with other marine mammals), although their calves will still be susceptible to changes (Learmonth et al. 2006). Most baleen whale species must migrate large distances, and so experience great temperature variations (Learmonth et al. 2006). Toothed whales, however, will likely be more directly affected by temperature changes, as they are smaller and have a limited range of water temperatures that they can inhabit (Learmonth et al. 2006). Shifts in community structure are also likely effects of climate change—in northwest Scotland, changes to the cetacean community have been related to ocean warming (Learmonth et al. 2006).

Survey results by Williams and Thomas (2007) have provided abundance estimates for many cetacean species inhabiting all the coastal waters of Canada's Pacific coast. Based on line-transect surveys covering a total of 4,400 km of trackline during the summers of 2004 and 2005, and abundances of a number of marine mammal species were estimated (Table 6.3), providing useful reference points with which future survey data can be compared.

Table 6.3 Estimated abundances (with 95% confidence intervals) of seven species of marine mammals in B.C. coastal waters (Williams and Thomas 2007).

Species	Abundance estimate[a]	Confidence interval
Harbour porpoise	9,120	4,210-19,760
Dall's porpoise	4,910	2,700-8,940
Pacific white-sided dolphin	25,900	12,900-52,100
Humpback whale	1,310	755-2,280
Fin whale	496	201-1,220
Common minke whale	388	222-680
Northern resident killer whale	161	45-574

Grey whales

Grey whales (*Eschrichtius robustus*) tend to exploit benthic prey in the northern Bering Sea and the Chukchi Sea, and rely on prey from the water column in addition to benthic prey when feeding in the Vancouver Island and north and central coast region. The predicted increases in river runoff and associated decreases in salinity and rise in turbidity of shallow areas can result in a decline in the biomass of the benthic species exploited by the grey whale in the northern feeding areas (Bluhm and Gradinger 2008). At the same time, the potential changes to primary production off the B.C. coast could reduce food availability for this species in the area.

Killer whales

Lusseau et al. (2004) found that the group size of resident orcas in the Johnstone Strait varied in relation to large-scale ocean climate variation, as did their salmonid prey. These killer whales tended to live in smaller groups when there was less salmon available, indicating that changes in climate, oceanography, and prey availability would alter their behaviour, distribution, and abundance in the future.

Salmon, particularly adult chinook, are the predominant prey species taken by both northern and southern resident killer whales (*Orcinus orca*) in British Columbia (Ford et al. 1998, Ford and Ellis 2005, Ford and Ellis 2006, Williams et al. 2011). Reductions in quantity and quality of salmonids will thus adversely affect B.C. resident killer whale populations (Ford et al. 2005). Killer whale "critical habitat" in British Columbia, as defined by the federal Species at Risk Act, is strongly influenced by salmon abundance, which is considered a limiting factor in killer whale recovery (Ford 2006, DFO 2008a). In addition to reductions in preferred prey, the resilience of killer whale populations to climate impacts is reduced by other human disturbances, such as noise and chemical pollution (Williams et al. 2006).

Sensitivity and responses of key taxonomic groups

Pinnipeds

In Canada's Pacific marine areas, there are five species of pinniped: Steller and California sea lions, northern fur seals, northern elephant seals, and Pacific harbour seals. The decrease in production brought about by El Niño conditions disperses prey and diminishes the foraging success of the northern elephant seal (*Mirounga angustirostris*), resulting in a decrease in the rate of mass gain by females (Crocker et al. 2006) and a reduction in the weaning weight of pups (Le Boeuf and Crocker 2005). Changes in production and prey assemblages likewise can affect the other species of pinniped in the region.

Direct effects of climate change on pinnipeds include the loss of haul-out and breeding sites due to rising sea levels. Addtionally, habitats with water temperatures at which pinnipeds can physically survive will be reduced (Learmonth et al. 2006).

Sea Otters

The population and distribution of sea otters (*Enhydra lutris*) in British Columbia is small (Heise et al. 2007), and they are designated as threatened under the Species at Risk Act. The current ranges are expanding from Tofino to Cape Scott on the outer coast of Vancouver Island, and from a small population on British Columbia's central coast. The population is expanding into its historical range prior to the fur trade of the late 19th century. Sea otters promote the development of kelp forest ecosystems by preying on the dominant subtidal herbivores such as sea urchins and abalone. They also prey on crabs and excavate soft sediments for clams. They depend on kelp beds for resting and foraging areas. It is possible that projected physical and chemical changes in the coastal oceans will negatively affect sea otters and their continuing recovery and expanding distributions through, for example, adverse effects on kelp or their prey resources, but direct evidence for this is scanty. The more salient point to be made about sea otters in relation to climate change, however, is the potential of "ecosystem engineer" species to increase ecosystem resistance and resilience to projected changes in climate and oceanography. The re-establishment of sea otter-dominated ecosystems may increase the robustness of this system as well as its realized productivity.

Decades of observation and experimentation have consistently shown that in the northern parts of their range, urchin barrens shift back to rich and productive kelp forest ecosystems with considerably larger biodiversity and biomasses when sea otters re-establish themselves. This will presumably slow and lessen the impacts of climate change-induced effects. One conspicuous physical example of this is the well-known function of kelp forests in the reduction of wave energy along the shoreline.

There are First Nations oral histories of a very large fringing kelp bed from Barkley Sound to Port Renfrew. The area behind the fringe was referred to as the highway, as they could travel this stretch of coast in canoes, even in heavy weather. This highway would have been a good source of food as well, given the plethora of ecological studies that show high biodiversity in sea otter-dominated ecosystems with stable biomasses of invertebrates and increased biomasses of fish species.

6.5.3 Elasmobranches

Salmon shark

There is some evidence for recent increases in populations of salmon sharks (*Lamna ditropis*; family: Lamnidae), or coastal concentrations of this species, in the North Pacific, and some of the explanations for these increases relate to climate change (Okey et al. 2007). Williams et al. (2010) describe an apparently newly developed summertime concentration of salmon sharks in the northern Queen Charlotte Sound, and one of their explanations is that warming conditions have led returning Pacific salmon to more consistently use their northern return route through Queen Charlotte Sound, rather than their southern route through the Juan de Fuca Strait (e.g., Thomson et al. 1994, Healey 1998), and this has enabled the salmon sharks to set up an effective feeding gauntlet there. If this speculation is true, this would represent an indirect behaviour-mediated and cascading adverse effect of climate change on Pacific salmon.

6.5.4 Reptiles

Turtles

Climate change impacts to turtles in Canada's Pacific are not currently well understood, but it is predicted that they will lose habitat as a result of rising sea levels. Additionally, the observations of species such as green sea turtles (*Chelonia mydas*) increase during anomalously warm years, and so this might be a good indicator of long-term climate change if any effect of diminishing beaches can be separated. In Australia, the predicted impacts of increased temperatures on turtles include a poleward shift in species foraging ranges, earlier breeding, and the skewing of turtle sex ratios toward females (Poloczanska et al. 2007). Similar observations have also been made elsewhere in the world—a northward shift of cetaceans and turtles was observed in the Northeast Atlantic (McMahon and Hays 2000, MacLeod et al. 2005, Robinson et al. 2009), earlier nesting was observed in the United States (Weishampel et al. 2004), and modelling evidence shows that warmer temperatures produce more females (Yntema and Mrosovsky 1982, Godfrey et al. 1999, Booth and Astill 2001, Glen and Mrosovsky 2004). Rising sea levels is another climate change impact that will adversely affect turtles by the loss of breeding and nesting sites through increased flooding and erosion (Poloczanska et al. 2007).

7 Conclusions

Conclusions 7

This report is a review of what is known about the impacts of climate change on Canada's Pacific coastal marine ecosystems (B.C. waters) and a preliminary assessment of the sensitivity and vulnerability of this region's marine ecosystems to climate change. This synthesis should complement other initial assessments of the impacts of climate change on Canada's Pacific fisheries resources (e.g., Beamish et al. 2009) and the ongoing assessment of the state of Canada's Pacific Ocean by Fisheries and Oceans Canada (e.g., DFO 2008b). The recent synthesis of climate impacts in Australia (Hobday et al. 2006) began with extensive literature reviews of selected ecosystem components and habitats, including surveys of the global literature related to the component being examined. This approach provided insights into potential climate impacts within the relatively data-poor systems of Australia. We have similarly attempted to highlight some of the key topical issues and ecosystem components that might be vulnerable to climate change in Canada's Pacific coastal marine ecosystems with implications for biodiversity, the sustainability of human systems, and approaches to management and adaptation.

This project, and the resulting report, was initially steered and guided by a network of resource experts on the subject in British Columbia, and benefited from this input considerably. Given our survey of the literature and input from local and regional experts, we conclude that notable changes in marine ecosystems related to climate change are occurring and will continue in the coastal and marine areas of British Columbia during this century, with potentially major changes in weather patterns, oceanography, extreme events, coastal interfaces productivity, and the structure and function of biological communities. These ecological changes will disrupt human systems on a variety of social, economic, and cultural levels.

Types of impacts that are being observed and also anticipated include shifts in species distributions, community composition and structure, increased occurrence and establishment of new species, loss of biodiversity, decreases in favourable conditions and habitat (for instance, from intrusion of anoxic and acidified waters), and increased stress on (and decreased resilience of) exploited species and habitats that are also impacted by local and regional human activities. An important point reinforced by this work is that while we may reasonably anticipate particular types of climate changes to manifest in the region, as well as the trends and direction of those changes, the specific outcomes or broad-system responses to such changes cannot currently be estimated with a high degree of confidence. This can change in the near future with investments in end-to-end, or whole-ecosystem, modelling approaches that include linkages to downscaled outputs from atmosphere-ocean global climate models.

In addition to improving our understanding of how these changes will manifest in Canada's Pacific marine ecosystems, we developed the preliminary vulnerability assessment to provide a framework for examining the spatial patterns of vulnerability to climate impacts on the levels of habitat and B.C. ecosections. Results from this framework can be used to help prioritize resources for approaches to research, management, and adaptation, and can thus be thought of as a screening-level analysis for proactive decision-making. Although this preliminary vulnerability assessment was incomplete in that not all conspicuous climate change variables could be included at this juncture, it exemplifies how existing knowledge and information borrowed from broader-scale analyses and from neighbouring systems can be used to provide an initial assessment of climate change vulnerability in this region. The results indicated variable climate impacts across the habitats and ecosections of Canada's Pacific marine ecosystems, highlighting particular areas of greater vulnerability. The Strait of Georgia, Queen Charlotte Strait, Johnstone Strait and Juan de Fuca Strait have higher vulnerabilities to climate change, due in part to the existing level of local stressors that compromise their adaptive capacity to climate change. On a coast-wide basis, the habitats that are considered most vulnerable are shallow rocky reefs, seagrasses, kelp beds, and undifferentiated shelf habitats.

7.1 Uncertainty in climate changes, impacts, and vulnerabilities

Limited knowledge about ecosystem functioning and the natural complexity of ecological systems make it challenging to predict the impacts of climate change. Analytical climate and oceanographic prediction and forecasting alone is difficult given the complexity of ocean-atmosphere systems and their interactions, in addition to the lack of monitoring data and capacity, as also concluded by Lucas et al. (2007). Knowledge gaps include the temporal scope on which climate change impacts will occur, such as monthly, seasonal, decadal, centennial, and millennial changes, as well as the spatial distributions of vulnerability and impacts.

Even on geological scales, the effect of tectonic activity on sea-level rise, and the degree to which isostatic rebound will negate coastal inundation is understood with a relatively low degree of precision (Thomson et al. 2008). In terms of biological information, examples of data paucity include food web linkages, zooplankton feeding patterns, and the distributions of juvenile and larval fish (also noted by Lucas et al. 2007), but this just scratches the surface of our state of knowledge relative to the complexity of these ecological systems. Uncertainty in model projections will always exist, as will knowledge gaps, but the skill and usefulness of some analytical approaches are nevertheless improving rapidly as we learn which parts of the system can be understood at general levels.

Although long-term trends in physical and chemical conditions in Canada's Pacific waters are expected be consistent with global trends (e.g., warmer, more acidic, more stratified, rising sea level), Canada's Pacific marine ecosystems are quite heterogeneous in terms of both oceanography and coastal habitats, and this makes the identification of trends even more challenging. For instance, sea surface temperature in B.C. waters will sometimes be anomalously low when temperatures in other regions and seas are anomalously high, as occurred in 2007 and 2008. Furthermore, the frequency and character of such fluctuations might change in unpredictable ways.

Another conspicuous example of uncertainty related to variability is that northeastern Pacific surface waters are among the most acidic on earth (and are continuing to acidify)—a consequence of the shoaling (shallowing) of the aragonite and calcite saturation horizons (DFO 2008b). The effects of ocean acidification on biota may be felt first and more intensely in areas such as the northeastern Pacific (Wootton et al. 2008), where the water is already less saturated in terms of calcite and aragonite (the forms of calcium carbonate produced by many organisms, such as corals and certain phytoplankton functional groups). This could result in far-ranging ecological and socio-economic impacts much sooner than has been anticipated. The biota of this region may, however, be somewhat pre-adapted to acidification because of the naturally lower pH along these coastlines, and thus more resistant or resilient to coming changes.

The lack of readily available downscaled projections of temperature, acidification, and other climate changes for which we mapped and summarized potential impacts at an ecosection scale introduce another level of uncertainly at finer scales, though they still provide an indication of change at a regional level.

7.2 Improving climate impact and vulnerability assessments

Examples presented in this report of how climate change can alter interspecific relationships, such as how climate changes differentially impact barnacles, mussels, and predatory sea stars in Pacific Canada's intertidal ecosystems (e.g., Harley 2011), make a strong argument for investment in research into (1) direct biological effects of the projected climate change stressors (physical and chemical changes) and non-climate-related changes, including physiological, phenological (timing of life history stages), and behavioural/distribution effects; and (2) broader-system ecological effects; for example, through the use of ecosystem models to understand the indirect effects of climate change in the whole food web and biological community, and in the context of other human stressors.

Without the continued improvement of such effects, information, and the ecosystem models they inform, an understanding of whole-system dynamics and climate effects remains speculative, inferential, and retrospective. A number of constructed ecosystem models already exist for B.C. marine ecosystems in the form of whole food web trophodynamic models (see Appendix A), and this type of analytical approach work needs to be connected with the global climate models and other physical and biogeochemical models that estimate the local and regional manifestation of climate change. These must also be connected to the development of management strategies and the formal (modelling) evaluation of management strategies.

These analytical approaches must also be complemented with data collection, such as monitoring of carefully selected indicators of the ecological and social-ecological integrity and health of these systems, in addition to pressure indicators to track the effectiveness of chosen management strategies. This can inform the reduction and mitigation of local and regional non-target stressors and the adaptive and flexible shifting of human activities in the contexts of broader adaptation plans (see Bryan et al. in prep).

In the short term, the preliminary vulnerability assessment presented here should be improved and refined with the incorporation of additional climate variables and changes downscaled to the regional analyses to provide more useful and reliable vulnerability estimates and prioritization.

The establishment of science programs designed specifically to understand the impacts resulting from climate change will aid in informing management actions. Such programs bring us closer to understanding the effects of regional and local anthropogenic stressors on marine and coastal ecosystems, as well as the effects of natural cycles and fluctuations. These programs should include the identification of indicators, the establishment of long-term monitoring, and modelling to forecast climate change impacts not just on the physical variables, but also in terms of the ecological effects. These programs would benefit from the incorporation of decision tools, and the evaluation of adaptive management, and adaptation strategies.

7.3 Moving from impacts to adaptation

Climate impacts on species and ecosystems are now observed throughout the world's oceans. Assessing the impacts of climate change is particularly challenging for marine ecosystems, owing to climate and oceanographic variability in relation to long-term climate trends; however, the climate change signal is predicted to emerge from the climate variability signal within a few decades. Moreover, the ways in which coastal and marine organisms are sensitive, exposed, or vulnerable to climate impacts is not yet fully understood—and we should not expect to gain full understanding of these impacts before management and policy actions should be taken.

It may be that the position of Canada's Pacific marine ecosystems in an oceanographic transition zone, and its otherwise high degree of spatial and temporal heterogeneity make the flora and fauna of this area naturally adaptable and resilient to ecological change, giving the system short-term resistance and resilience to climate change impacts. Alternatively, its position in a transition zone exposes the system to sudden non-linear changes or flips of the ecosystem that may persist in permanently altered states.

The most sensible strategy given the lasting uncertainty of climate impacts is to use the best available science in a tiered analytical approach that begins with screening-level vulnerability assessment; investment in smart and efficient design of mechanistic modelling approaches, monitoring and other data collection; and an adaptive approach to management and policy that can be slowly integrated into analyses and evaluated ever more formally. Regardless of the uncertainties of how climate change impacts will manifest in Pacific Canada, there is now global consensus that planning and management of coastal marine ecosystems will need to involve proactive consideration of climate change impacts, both over short and long time frames, in the context of existing local and regional stressors.

Fisheries, forestry, and other sources of watershed modification, and a variety of other human activities also affect biological communities. We conclude that understanding and managing these activities directly and indirectly affect the resistance, resilience, and vulnerabilities of these ecosystems to climate change impacts. Focusing on what we know with regard to the sensitivity and key vulnerabilities to climate change, and the adaptive capacity of the system as influenced by local human activities will allow adaptive management to be more effective.

An increased understanding and awareness of climate change impacts in Canada's Pacific marine ecosystems will enable better-informed adaptation strategies for marine ecosystems—the subject of the companion volume to this report (Bryan et al. in prep). In that report, we further discuss and detail potential approaches and strategies to reduce vulnerability and increase adaptive capacity of Canada's Pacific marine ecosystems to climate changes.

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APPENDIX A Ecosystem models in British Columbia

Forecasting the impacts of climate change on marine ecosystems will require different types of ecosystem models, and some of these are being applied to various marine areas of British Columbia. A number of trophodynamic fisheries-ecosystem models have been developed using the Ecopath with Ecosim approach, for example, and these have been applied to several areas around the province (Figure A1). These types of models are being used to explore climate change impacts (e.g., Ainsworth et al. 2011), and such work will continue to expand (e.g., Cheung et al., in revision).

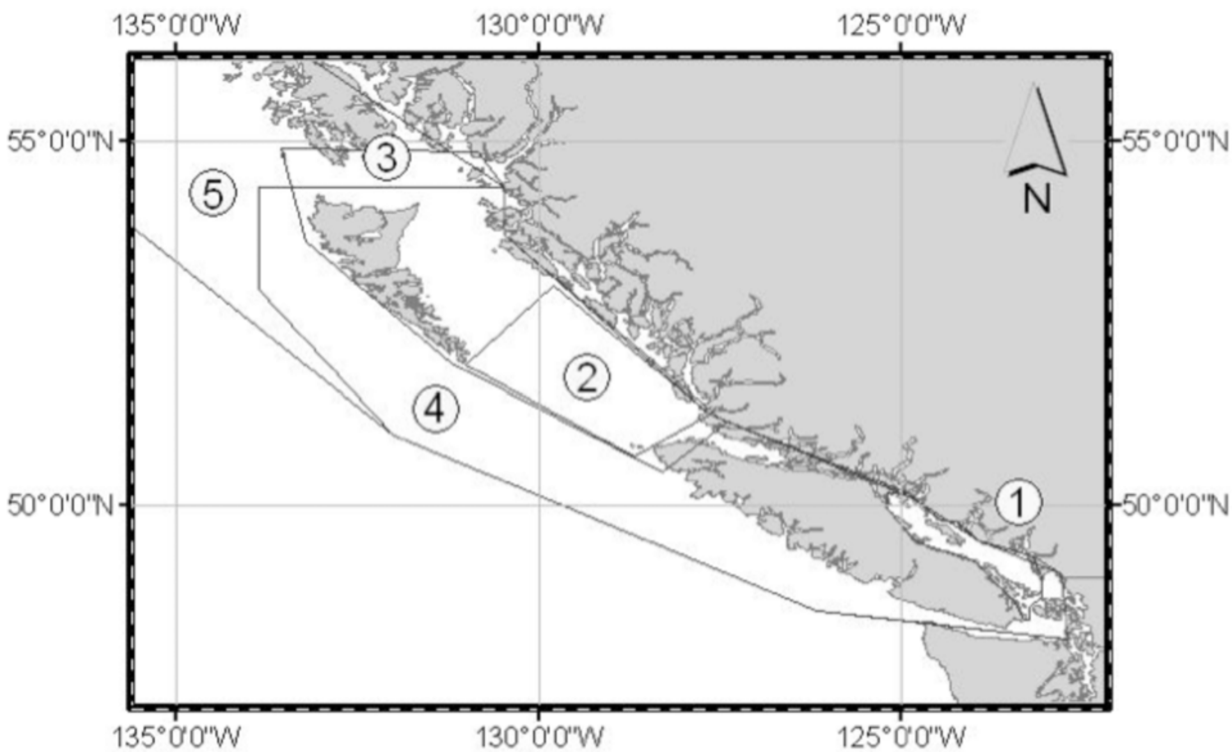

Figure A1. Areas in which trophodynamic fisheries-ecosystem models have been developed using the Ecopath with Ecosim approach.

Number	Area	Authors
1	Strait of Georgia	Daalsgard et al. 1998 Venier 1996 Beamish et al. 2001 Wallace and Dalsgaard 1998 Preikshot 2006 Li et al. 2010 Beamish et al. (in prep.)
2	Hecate Strait	Pauly and Christensen 1996 Beattie 1999
3	Northern B.C. (incl. Dixon Entrance, Hecate Strait and Queen Charlotte Sound)	Beattie 2001 Vasconcellos and Pitcher 2002 Ainsworth et al. 2002 Ainsworth and Pitcher 2005 a, b, c Ainsworth and Pitcher 2005a, 2006, 2009 Ainsworth 2006 Ainsworth et al. 2008 Ainsworth et al. 2011
4	B.C. Shelf	Preikshot 2006 Espinosa-Romero et al. 2011
5	NE Pacific Ocean	Preikshot 2006

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Appendix A

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APPENDIX B. Summary of unusual sightings of marine species off British Columbia during the 1982–83 El Niño

The following table is reproduced from Fulton (1985)

1. Extensions of Northern Range				
Fish				
	Synodus lucioceps (California lizard fish)	Cape Beal (Brady's Beach)	Aug 15, '83	Bamfield Marine Station (Bergey)
	Xiphias gladius (Swordfish)	47°01.1'N, 130°24'W	Sept 20, '83	PBS, caught in gill net (Sloan)
		46°01.1'N, 128°39.4'W	June 30, '82	University of Victoria
	Remora remora	46°42'8N, 131.25.0'W	Aug 4, '83	PBS (Robinson)
Plankton				
Copepod				
	Acartia danae	48°49.0'N, 128°37.4'W	Sept 20, '83	IOS plankton haul (Ashton)
		46°32'N, 125°57'W	Sept '35	Davis (1949)
2. Isolated sightings				
Fish				
	Genyonemus lineatus (White croaker)	Swanson Channel	March '83	B.C. Provincial Museum (Teden)
	Seriola lalandi dorsalis (Yellowtail)	47°57.0'N, 130°50.0'W	Aug 5, '83	B.C. Provincial Museum (Teden)
	Trachurus symmetricus (Jack mackerel)	Barkley Sound	"	"
		47°33.0'N, 131°12.4'W	July 12, '83	(Bauer)
	Engraulis mordax (Anchovy)	Quatsino Sound	Nov 18, '83	B.C. Provincial Museum, young, small specimens indicate spawning? (Teden)
	Sardinops sagax (Pacific sardine)	Calyoquot Sound	Aug '83	Schooling with anchovy (Dawson)
Invertebrates				
	Emerita analoga (California sand crab)	Kyuquot Sound	Aug '83	Juveniles on Sand Beach (Austin)

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Appendix B

Birds				
	Puffinus occidentalis (Brown pelican)	Victoria	July 24, '83	(Hill)
		Denman Island	July 27, '83	(Sparrowhawk)
		Cape Beal	Aug & Nov '83	Bamfield Marine Station (Bergey)
	P. bullgeri (New Zealand shearwater)	"	"	"
	P. creatopus (Pink-footed shearwater)	"	"	"
	Thalasseus elegans (Elegant tern)	Queen Charlotte Islands	Summer '83	(Phillips)
	Sterna caspia (Caspian tern)	"	"	"
	Steganopus tricolor (Wilsons phalarope)	"	"	"
Reptiles				
	Dermochelys schlegelii (Leatherback turtle)	Off Nootka Sound	Summer '83	(Cary)
Plankton				
Copepods				
	Scottocalanus persecans	Queen Charlotte Sound	May '83	(Ashton)
	Pleuromamma xiphias	50°43.0'N, 131°08.3'W	Aug '83	"
	Heterostylites longicornis	"	"	"
	Arietellus plumifera	"	"	"
	Aegisthus macronatas	"	"	"
3. Widespread Sightings				
Invertebrates				
	Velella velella (By-the-Wind-Sailor)	B.C. Coast	Mar-Sept '83	Many sightings all summer on outer coast
Fish				
	Mola mola (Ocean sunfish)	B.C. Coast & Juan de Fuca Strait & Johnstone Strait	Mar-Nov '83	Numerous sightings
	Scomber japonicus (Chub/Pacific Mackerel)	B.C. Coast & Strait of Georgia	June-Dec '83	Particularly abundant in Barkley Sound (486 fish in one seine set)
	Sarda chiliensis (Pacific bonito)	B.C. Coast	July & Sept '83	Several sightings
	Brama japonica (Pomfret)	Edge of Continental Shelf, Dixon Entrance	Aug '83	Catches on set lines

Continued on next page

Plankton				
1. Copepods				
	Mesocalanus tenuicornis	B.C. Coast	Spring & Summer '83	(Ashton)
	Lucicutia flavicornis	"	"	"
	Ctenocalanus vanus	"	"	"
	Euchirella curticaudata	"	"	"
	Euchirella rostrata	"	"	"
2. Molluscs				
	Euclio pyramidata	"	"	"
3. Salps				
	Salpa fusiformis	"	"	"

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APPENDIX C. Description of benthic characterization data used for reporting proportion of habitats within ecosections

The benthic characterization dataset is a generalized characterization of the offshore and inshore environments of Canada's Pacific Ocean. It was compiled by Selina Agbayani (WWF-Canada) from various sources to depict the general bottom types (offshore and inshore) and biogenic habitats (inshore) by depth strata. The full list of bottom types and habitats that this characterization captures is depicted in the summary table below.

The three main bathymetry datasets used to obtain depth information for the benthic classes were the West Coast bathymetry dataset from the Canadian Hydrographic Service (CHS) at pixel resolution of 75 m, the Living Oceans Society (LOS) bathymetry dataset at a pixel resolution of 100 m (derived from contour data from Nautical Data International [NDI] and the Province of B.C.) and a bathymetry dataset created from digitizing nearshore polygons from hard-copy nautical charts by Ian Murfitt (undated). The LOS and Murfitt bathymetries provided more resolution in the nearshore areas than was available from the 75-m CHS bathymetry raster. The Murfitt data in particular helped to identify and refine intertidal areas and some of the large, deep inlets along the B.C. coast. The matching Murfitt land dataset was used as the coastline. Four depth classes were used: Shallow < 30 m), Shelf (30–200 m), Slope (200–2,000 m) and Deep (> 2,000 m). To further refine the delineation of shallow areas, kelp (bull and giant) and eelgrass layers from BCMCA Atlas (2011) were used to refine the delineation of shallow areas (< 30-m depths). There are known gaps in the coverage of kelp and eelgrass data, and no data areas does not necessarily indicate an absence of these habitats.

The depth classes were combined with substrate information to create the habitat classes. Substrate information for intertidal areas (Beach, Mud, Sand/Mud and Rocky) were obtained from the Murfitt intertidal dataset. The BCMCA benthic classes was sourced from Natural Resources Canada, and the B.C. marine ecological classification from the Province of British Columbia; Howes et al. (1997) was used for offshore areas and areas those where substrate is not identified in the Murfitt dataset. The BCMCA substrate classes were Hard (bedrock, boulders, cobble, some sand/gravel areas), Sand (sand, gravel/sand, some muddy areas), Mud (mud, sandy mud) and Unknown (not sampled). The WWF soft benthic classes are a combination of the BCMCA Sand and Mud classes, while the Hard and Unknown classes translate to Hard and Undefined, respectively.

Also included in the habitat layer are rocky reefs, canyons, and seamounts. The rocky reef layer was taken from a Bathymetric Position Index (BPI) analysis by Ban et al. (2010), a second-order derivative of bathymetry identifying the location of a point relative to its surrounding area (Wright et al. 2005). While the rocky reefs were coastal in nature, the modelled reefs were found in a variety of depths, from shallow to deep. Therefore, the rocky reef layer from Ban et al. (2010) was split into two categories: shallow rocky reefs (< 30 m) and non-shallow rocky reefs (> 30 m). Canyons and seamounts were added from the DFO undersea features dataset (Manson 2009). These features are not associated with a specific depth or substrate, but have unique characteristics in terms of habitat value and sensitivity.

Kelp and eelgrass are also included within this dataset as separate biogenic habitats that overlap in area with the benthic habitat layer. The kelp layer is a combination of the BCMCA bull kelp and giant kelp layers, while the eelgrass layer is largely unchanged from the original BCMCA features. Both kelp and eelgrass habitats were clipped to the Murfitt coastline to match the benthic classes.

TABLE: Summary of benthic class types, depth, and substrate sources

HABITAT CLASS	CODE	DEPTH	SUBSTRATE (SOURCE)
Beach (Intertidal)	BITDL	Intertidal (< 30 m)	Beach (Murfitt)
Mud Flats (Intertidal)	MFITDL	"	Mud (Murfitt)
Rocky Intertidal	RITDL	"	Rocky (Murfitt)
Soft Intertidal	SITDL	"	Soft (BCMCA)
Hard Intertidal	HITDL	"	Hard (BCMCA)
Undefined Intertidal	UITDL	"	Substrate Undefined
Kelp	KELP	"	Substrate Undefined (BCMCA 2011)
Eelgrass	SEAG	"	Substrate Undefined (BCMCA 2011)
Rocky Reefs (shallow)	RRSHLW	Shallow (< 30 m)	Hard (Ban et al. 2010)
Soft Shallow	SSHLW	"	Soft (BCMCA 2011)
Hard Shallow	HSHLW	"	Hard (BCMCA 2011)
Undefined Shallow	USHLW	"	Substrate Undefined
Rocky Reefs (not shallow)	RRNSHLW	Non-shallow (< 30 m)	Hard (Ban et al. 2010)
Soft Shelf	SSHLF	Shelf (30–200 m)	Soft (BCMCA)
Hard Shelf	HSHLF	"	Hard (BCMCA)
Undefined Shelf	USHLF	"	Substrate Undefined
Soft Slope	SSLOPE	Slope (200–2,000 m)	Soft (BCMCA 2011)
Hard Slope	HSLOPE	"	Hard (BCMCA 2011)
Undefined Slope	USLOPE	"	Substrate Undefined
Canyon	CANYON	Depths undefined	Substrate Undefined (Manson 2009)
Soft Deep	SDEEP	Deep ((> 2,000 m)	Soft (BCMCA)
Hard Deep	HDEEP	"	Hard (BCMCA)
Undefined Deep	UDEEP	"	Substrate Undefined
Seamounts	SEAMT	Variable depth	Substrate Undefined (Manson 2009)

Appendix C

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GLOSSARY

Accretion	Process of growth or build up through natural processes or by gradual accumulation of particles. Natural shorelines and beaches build up gradually by deposit of sand.
Adaptive Capacity	The ability of an entity (species, system etc) to cope or adjust to climate changes. This may be by moderating effects of negative changes and/or taking advantage of opportunities, or coping with the consequences. [1]
Anadromous Species	Species born in fresh water that spend part of their life in the ocean and return to spawn in freshwater. Salmon, steelhead trout, sturgeon and lamprey are pacific species that are anadromous.
Aragonite	One of the forms of naturally occurring, crystal forms of calcium carbonate ($CaCO_3$), the other being Calcite. It is formed by biological and physical processes. Marine organisms use this form of $CaCO_3$ to build protective structures and shells.
Aragonite Shoaling Zone	The depth of water at which the saturation state of Calcium Carbonate (Ω) is < 1. Saturation state is a measure of the amount of available Carbonate (CO_3^{2-}) in seawater. Waters with Ω > 1 are favourable to formation of $CaCO_3$ shells by organisms where as waters with Ω < 1 are corrosive and enable the dissolution $CaCO_3$ of shells. An decrease in the depth of the shoaling zone indicates under saturated water (Ω < 1) occurs at a shallower depth than previously, as is currently observed in the North Pacific.
Benthic	Relating to the bottom of the sea and of the organisms, both plant and animal, that live in or on the substrate.
Biogenic Habitat	Certain plants and animals grow in such a manner that they provide a unique environment and physical structure for other organisms. Habitats created by plants or animals are called biogenic. Biogenic habitats may offer space for attachment, hiding places from predators, and shelter from harsh environmental conditions. Examples of biogenic habitats include salt marshes, seagrass beds, kelp beds, shellfish beds, and cold-water corals.[2]
Biogeographic Unit	The first division Canada's Biogeographic Classification of Marine Areas are been termed biogeogpahic units. There are 12 such units nationally, 4 of which are in the Pacific waters of Canada. These major biogeographic units are defined on a combination of bathymetry and/or water masses, along with food web functionality and when available coherence in variation in recruitment across groups of similar taxa.[3]
Buoyancy Current	The estuarine-like current that floats on top of the higher salinity marine water and it forms a current of freshwater outflow, for example water from the Fraser River form a water mass
Cascades / Cascading Effects	A sequence of events in which each produces the circumstances necessary for a shift or change in a system or its constituent parts. In ecology the effects or predator removal can have cascading effects, enabling prey species to proliferate and further modify their environment or species they depend on. Such changes are much greater then changes to inter species relationships, since they change the structure and components of the system such that it is characterized much differently than they may have been in the past.

Glossary

Climate change	It is used here to refer broadly to the global environmental changes resulting from the emissions of greenhouse gases, including oceanographic changes that are not strictly "climate changes," such as acidification, deoxygenation, and salinity changes. This usage is similar to that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.
Climate Variability	Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)[4].
Downwelling	It is movement or sinking of surface waters downwards to deeper depths. Downwelling generally occurs when surface waters converge (come together) and in the process pushing surface water downwards. Areas of down welling are nutrient poor and have low productivity because nutrients are not continuously supplied by deeper waters rising from below the surface (a process called upwelling and the opposite of downwelling).
Ecosection	Ecosections are areas with minor physiographic and macroclimatic or oceanographic variations. There are 114 ecosections in British Columbia varying from pure marine units to pure terrestrial units. Ecosections are meant to be mapped at small scales (1:250,000) for resource emphasis and area planning.[5]
Ecosystem Services	The benefits that society obtains from ecosystems, and that ecosystems generate. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth.
End-to-end Model	A single modeling framework that combines sub-models of physiochemical and oceanographic processes, with lower and higher trophic level ecosystem models. Such models are particularly useful for studying the effects of climate and physical changes on tropic groups.
ENSO (El Niño Southern Oscillation)	El Niño, in its original sense, is a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the inter-tropical surface pressure pattern and circulation in the Indian and Pacific Oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño event is called La Niña.[6]
Eustatic	As it relates to sea level change from changes in ocean volume due to the melting of glaciers, ice caps, and ice sheets.

Exposure	As it relates to climate change is the nature and degree to which a system is exposed to significant climatic variations[7]
Hypoxia	Hypoxia means "low oxygen." In aquatic ecosystems, low oxygen usually means a concentration of less than 2-3 milligrams of oxygen per liter of water (mg/l). A complete lack of oxygen (0 mg/L) is called anoxia. Since organisms that can live without oxygen (such as some microbes) are the only residents in these areas, they are sometimes called "dead zones". Hypoxia is primarily a problem in estuaries and coastal waters, although it can also be a problem in freshwater lakes.[8]
Intertidal	The zone or area covered by water at high tide and exposed to the air at low tide.
Isostatic	As related to sea level changes, isostatic changes are regional or local changes due to vertical land motions, associated with recovery from the weight of glaciers during the last Ice Age (rebounding) and or uplift or sinking from tectonic processes in the earth's crustal plates.
Phenology	Natural phenomena (and the study of those phenomena) that recur periodically (e.g. development stages, migration) and their relation to climate and seasonal changes.[9]
Photic zone	The surface layer of the ocean that receives sufficient sunlight light to allow photosynthesis by plankton and marine plants.
Resilience	The amount of change or disturbance that can be absorbed by a system (e.g., an organism, population, community, or ecosystem) before the system is redefined by a different set of processes and structures; the ability of a system to recover from change or disturbance without a major phase.[10]
Resistance	The ability of a system (e.g. an organism, population, community, or ecosystem) to withstand a change or disturbance without significant loss of structure or function. [11]
Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. [12]
Social-ecological System	System with interacting and interdependent physical, biological and social components, emphasizing the 'humans-in-nature' perspective.[13]
Steric	As it relates to sea level, are the changes in ocean volume of the ocean due to density changes from thermal expansion and salinity effects. This is a contributing factor to sea level rise.
Stratification	The formation of layers of different densities within the water column. The density differences are a result of differences in salinity and temperature between the layers.
Subtidal	The zone below the low tide zone.
Taxa/Taxonomic Group	the systematically classified group of organisms, living or once living classified on the basis of their presumed evolutionary relationships.
Upwelling	It is upward movement of waters from deeper areas toward the surface and to shallower waters. Upwelling generally occurs when deeper waters encounter topographic features (like seamounts or the edge of continents) and are caused to flow upward. or when water masses diverge (move apart) and in the process pushing deeper water upwards. Areas of upwelling are nutrient rich and generally have high productivity because nutrients are continuously supplied by deeper waters. This is the opposite of downwelling.

Glossary

Vulnerability	The vulnerability of an entity to climate change is the extent to which an entity (a species, habitat, or ecosystem) is susceptible to harm from climate changes. It is a function of the character, magnitude, and rate of climate variation to which the entity is exposed to, the sensitivity of the entity to those climate changes, and its adaptive capacity.[14]

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