SIO 210: Dynamics V Ekman & Atmosphere

Ekman layers
Ekman layer convergence: upwelling and downwelling
Wind patterns (atmosphere)
Ocean's Ekman transport and upwelling/downwelling

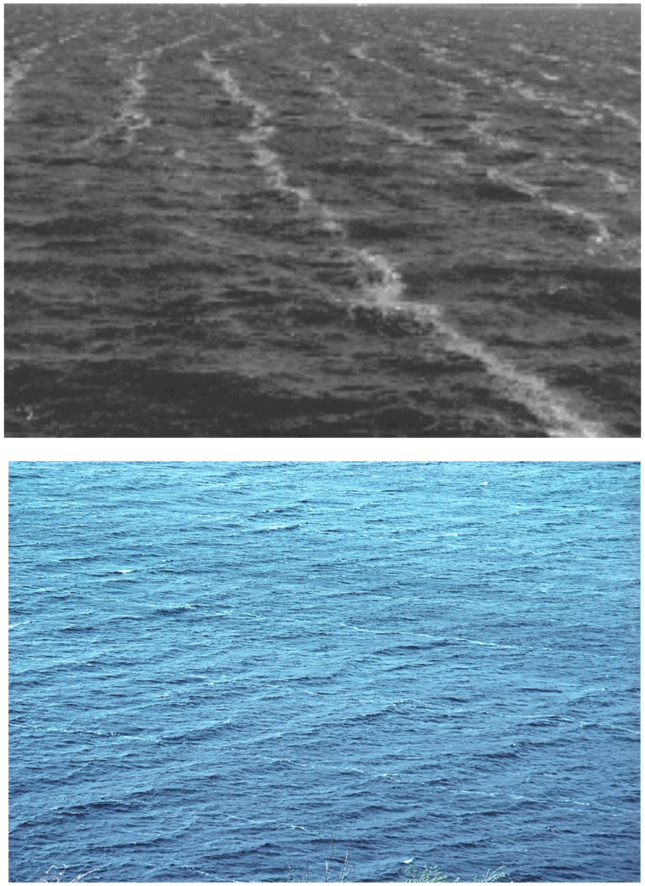
READING:
DPO: Chapter 7.5

Wind forcing: initial response

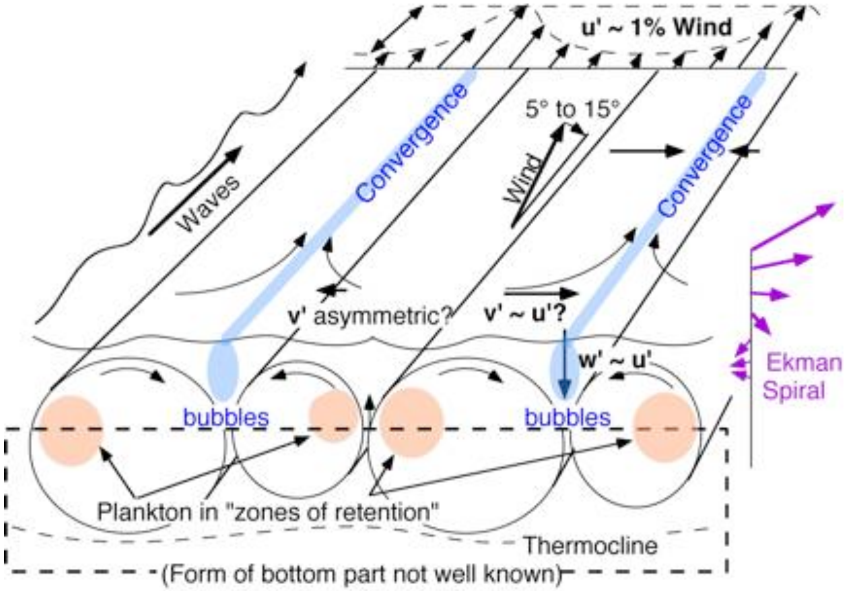
- First effect is to create wind waves, short period up through longer period swell

- These transmit the wind stress to the ocean

Wind forcing: small scale response: Langmuir circulation



Wind rows at sea surface (DPO Fig. S7.9)

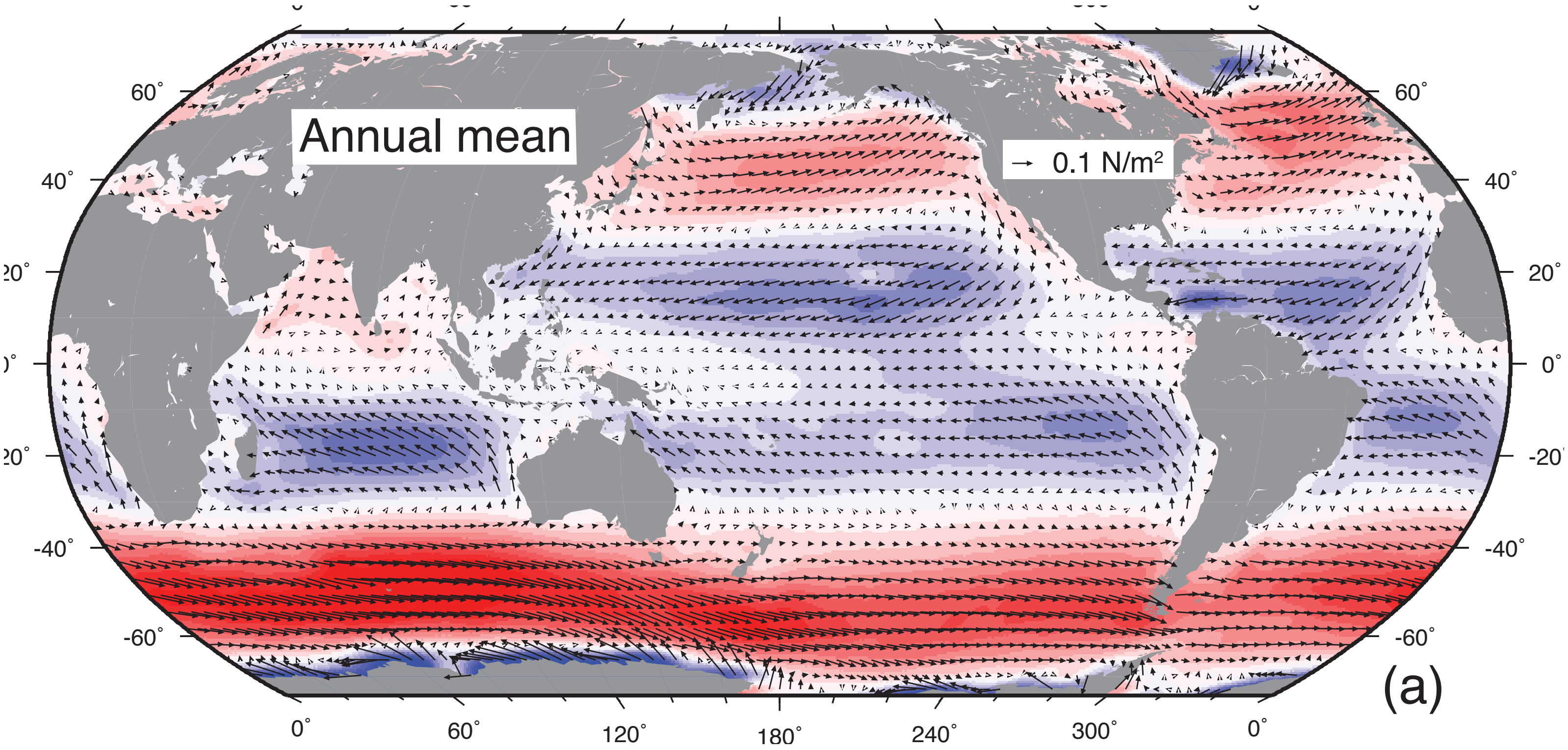


Horizontal scale: 10-50 m

Vertical scale: 4-6 m

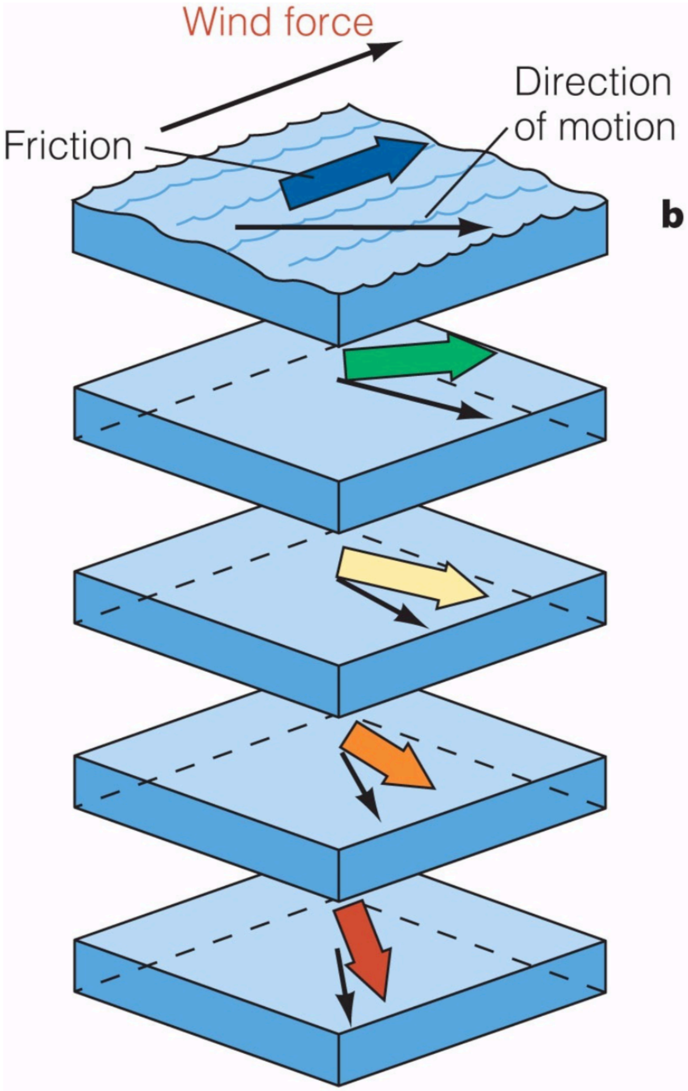
Cartoon from Smith and Pinkel (2003) (DPO Fig. S7.10)

Wind forcing: How does the ocean respond to wind stress at time scales longer than hours?



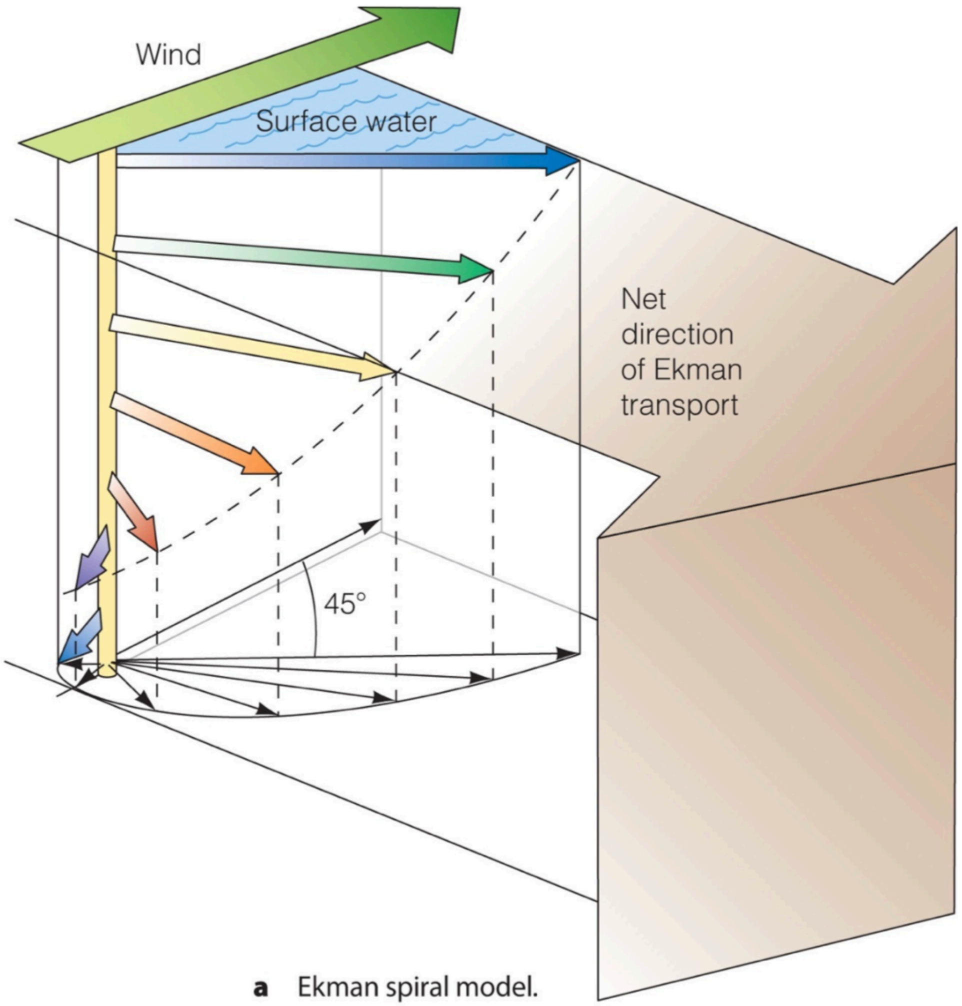
DPO Fig. 5.16a

Wind forcing with Coriolis: Ekman layer



b A body of water can be thought of as a set of layers. The top layer is driven forward by the wind, and each layer below is moved by friction. Each succeeding layer moves with a slower speed and at an angle to the layer immediately above it—to the right in the Northern Hemisphere, to the left in the Southern Hemisphere—until water motion becomes negligible.

Wind forcing with Coriolis: Ekman layer



a Ekman spiral model.

Source: From Pipkin, Gorslin, Casey, and Hammond, *Laboratory Exercises in Oceanography.*
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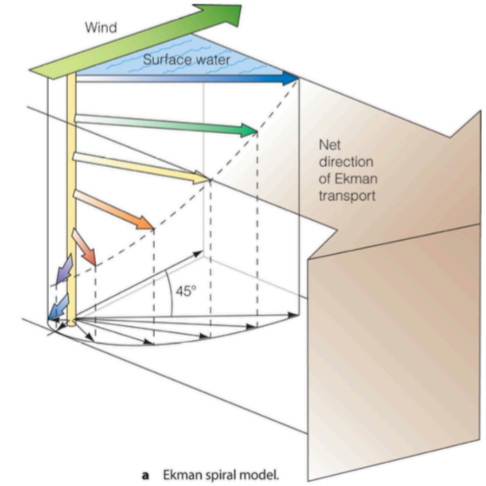
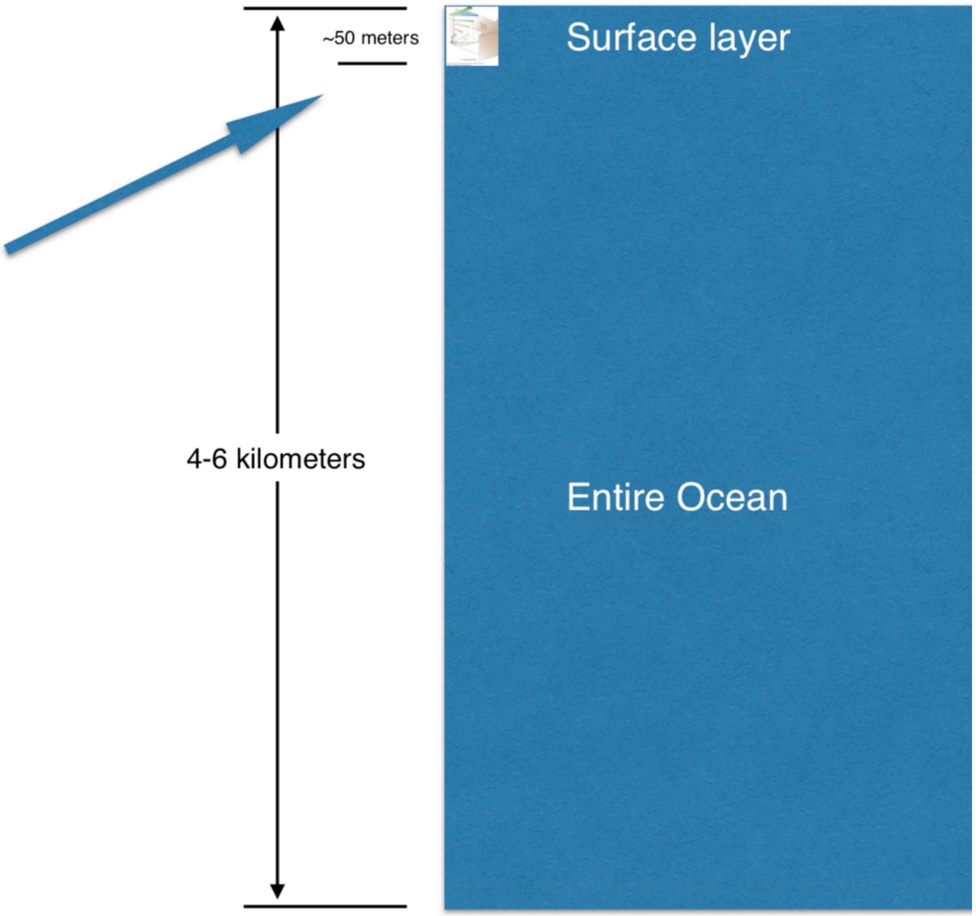
Figure 9-5a p266

Wind forcing with Coriolis: Ekman layer



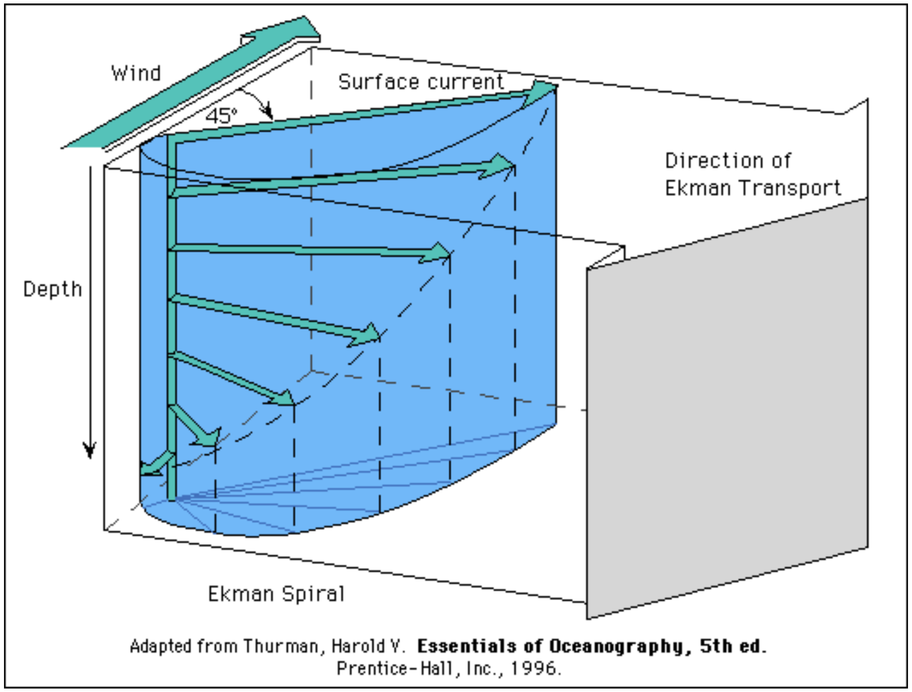
a Ekman spiral model.

Source: From Pipkin, Gorslin, Casey, and Hammond, *Laboratory Exercises in Oceanography.* © 1987 by W. H. Freeman and Co. Reprinted by permission.



Ekman velocity spiral

- Surface velocity to the right of the wind (northern hemisphere, due to Coriolis)
- Surface layer pushes next layer down slightly the right, and slightly weaker current
- Next layer pushes next layer, slightly to right and slightly weaker current
- Producing a “spiral” of the current vectors, to right in northern hemisphere, decreasing speed with increasing depth
- Details of the spiral depend on the vertical viscosity (how frictional the flow is, and also whether “friction” depends on depth)



Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

Vertical scale: about 50 meters

Complete force balance with rotation

Ekman balance

Three equations in local Cartesian coordinates:

Horizontal (x) (west->east)

acceleration + advection + Coriolis = pressure gradient force + viscous term

Horizontal (y) (south->north)

acceleration + advection + Coriolis = pressure gradient force + viscous term

Vertical (z) (down->up)

acceleration +advection (+ neglected very small Coriolis) = pressure gradient force + effective gravity (including centrifugal force) + viscous term

Complete force balance with rotation

Ekman balance

x: $\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + w\,\partial u/\partial z \boxed{- fv =}$
$- (1/\rho)\partial p/\partial x + \partial/\partial x(A_H\partial u/\partial x) +$
$\partial/\partial y(A_H\partial u/\partial y) \boxed{+\partial/\partial z(A_V\partial u/\partial z)}$ (7.11a)

y: $\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + w\,\partial v/\partial z \boxed{+ fu =}$
$- (1/\rho)\partial p/\partial y + \partial/\partial x(A_H\partial v/\partial x) +$
$\partial/\partial y(A_H\partial v/\partial y) \boxed{+\partial/\partial z(A_V\partial v/\partial z)}$ (7.11b)

z: $\partial w/\partial t + u\,\partial w/\partial x + v\,\partial w/\partial y + w\,\partial w/\partial z$ (+ neglected small Coriolis) =
$\boxed{- (1/\rho)\partial p/\partial z} - \boxed{g} + \partial/\partial x(A_H\partial w/\partial x) +$
$\partial/\partial y(A_H\partial w/\partial y) +\partial/\partial z(A_V\partial w/\partial z)$ (7.11c)

Hydrostatic
(doesn't
figure in)

Equations of motion and frictional balance in an Ekman layer

Three APPROXIMATE equations:

Horizontal (x) (west-east):	Coriolis = vertical viscosity
Horizontal (y) (south-north):	Coriolis = vertical viscosity
Vertical (z) (down-up) (hydrostatic balance):	0 = pressure gradient force + effective gravity

NOTE: NO HORIZONTAL PRESSURE GRADIENT FORCE OR ACCELERATION in an Ekman layer

That is:

$$x: \quad -fv = \partial/\partial z(A_V \partial u/\partial z)$$

$$y: \quad fu = \partial/\partial z(A_V \partial v/\partial z)$$

Ekman transport

The wind stress on the ocean surface is the vector

$$\boldsymbol{\tau} = (\tau^{(x)} , \tau^{(y)})$$

Integrate the Coriolis/friction balances in the vertical

x: $-fv = \partial/\partial z(A_V \partial u/\partial z) \rightarrow -fV_{EK} = A_V \partial u/\partial z = \tau^{(x)} /\rho$

y: $fu = \partial/\partial z(A_V \partial v/\partial z) \rightarrow fU_{EK} = A_V \partial v/\partial z = \tau^{(y)} /\rho$

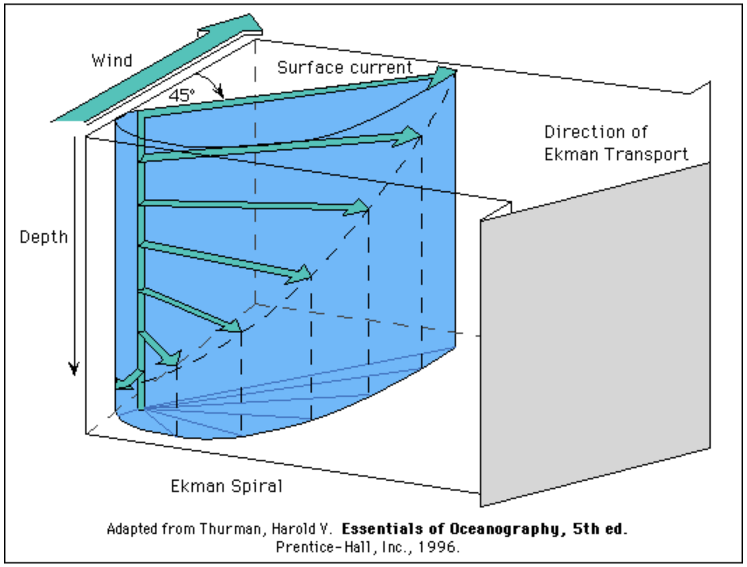
- U_{EK} and V_{EK} are the "Ekman transport" $\int u dz$, $\int v dz$

- Ekman "transport" is exactly to the right of the wind stress (northern hemisphere) (to left of wind stress in southern hemisphere since f has the opposite sign).

- Ekman transport does not depend on the size or structure of A_V (but the detailed structure of the spiral DOES depend on it)

Ekman layer “transport”

- “Transport”: 90° to wind, to right in NH and left in SH
- $U_{Ek} = \tau/\rho f$ (units are m^2/s, not m^3/s so technically this is not a transport; need to sum horizontally along a section to get a transport).

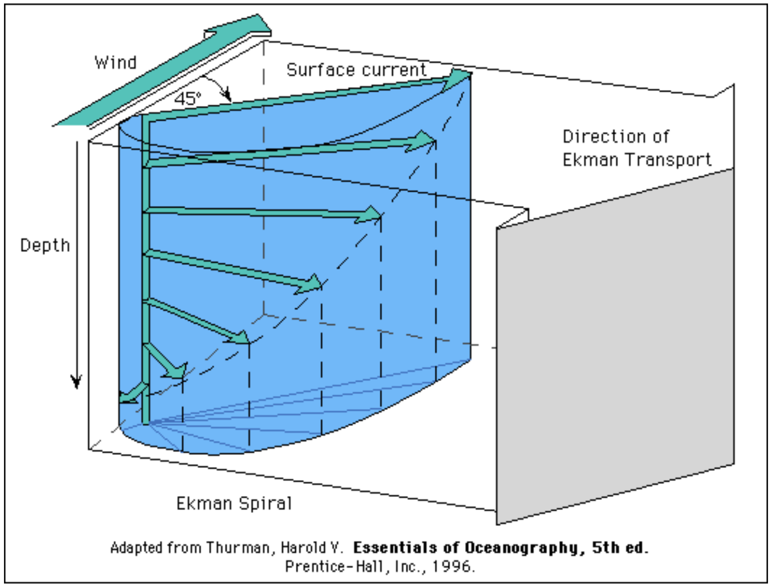


Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

- Typical size: for wind stress 0.1 N/m^2, $U_{Ek} = 1\ m^2/s$. Integrate over width of ocean, say 5000 km, get total transport of $5 \times 10^6\ m^3/sec$ = 5 Sv.

Ekman layer depth

- Depth: depends on eddy viscosity A_V (why?) $D_{ek} = (2A_V/f)^{1/2}$

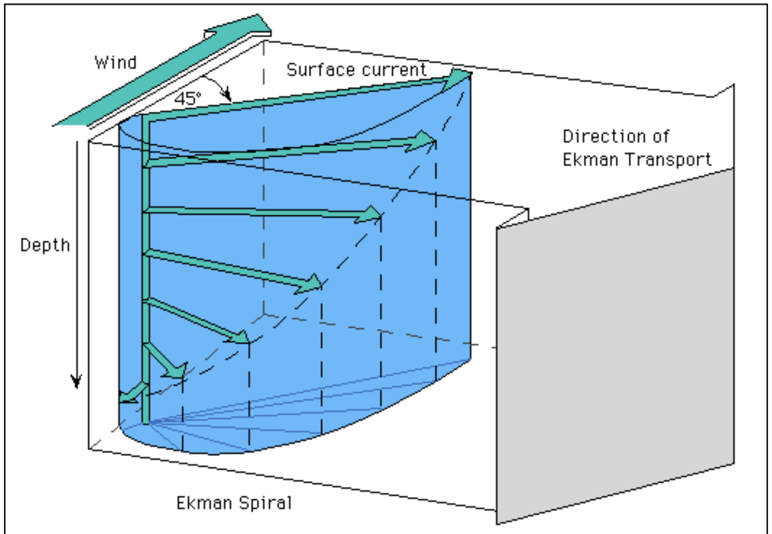


Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

- Eddy viscosity A_V is about 0.05 m^2/sec in turbulent surface layer, so Ekman layer depth is 20 to 60 m for latitudes 80° to 10°.

Ekman layer velocity

- Velocity: spirals with depths and magnitude depends on eddy viscosity (why?) If A_V is constant, surface velocity is 45° to wind



Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

- For eddy viscosity 0.05 m^2/sec, and wind stress of 1 dyne/cm^2 (.1 N/m^2), surface velocity is 3 cm/sec at 45°N.

Observations of Ekman layer

CHERESKIN: EKMAN BALAN

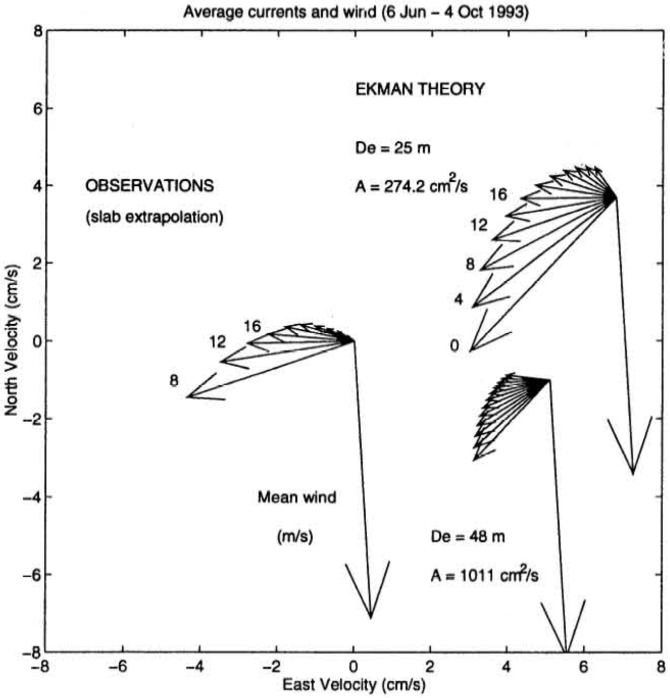


Figure 9. Mean ageostrophic spiral calculated from observations using a slab extrapolation from 8 m to the surface and the corresponding Ekman spirals calculated by fitting *e*-folding depth scale from amplitude decay and from rate of turning of the velocity vector. Theoretical spirals are offset from the origin for clarity. Mean wind vector is also shown. Scales are centimeters

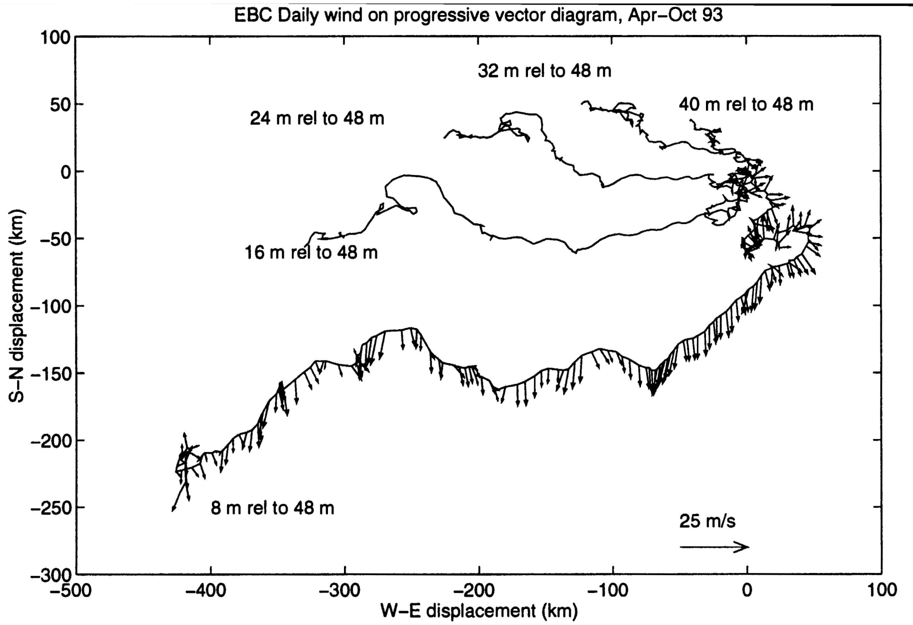
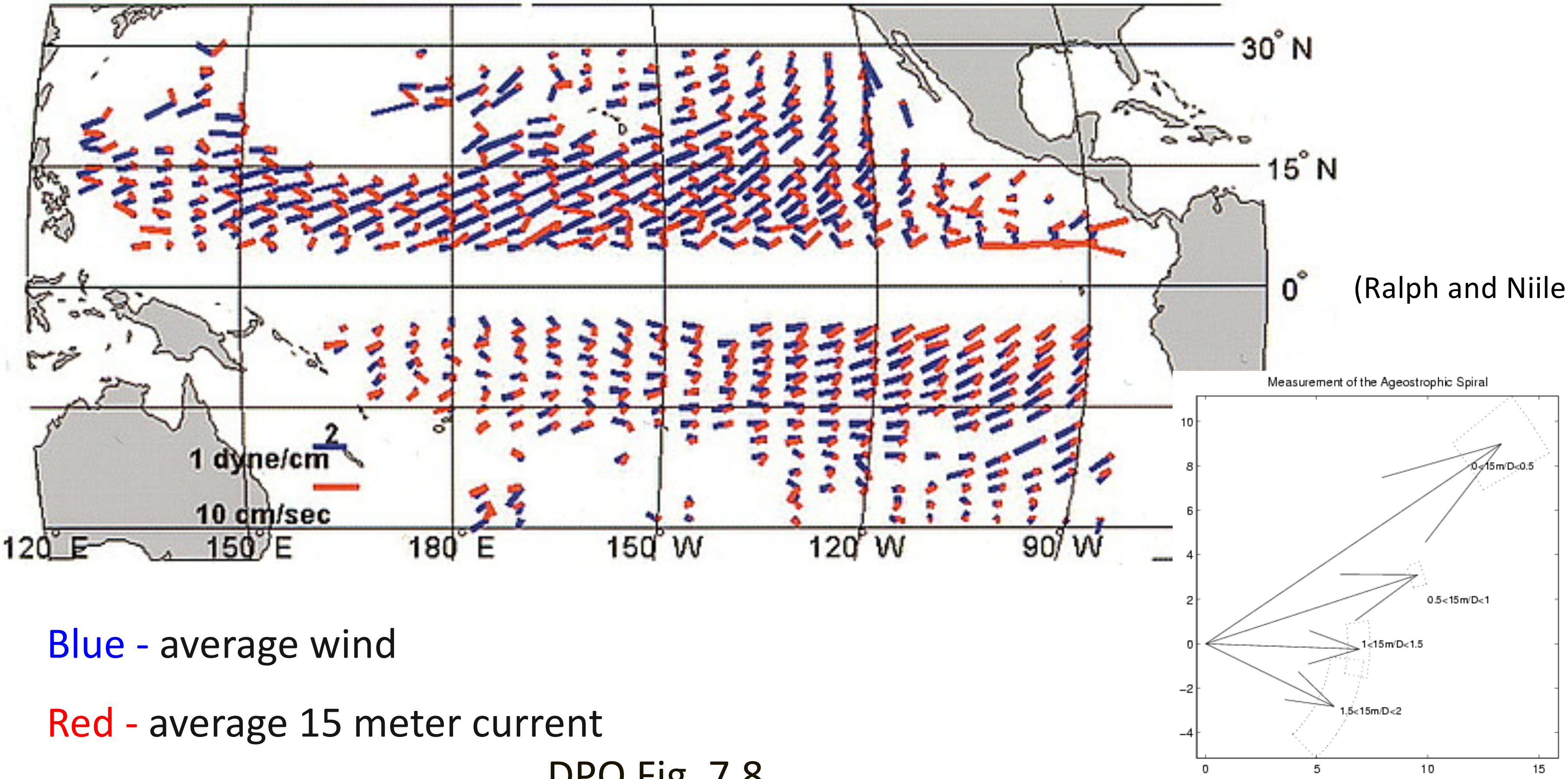


Figure 5. Progressive vector diagram, using daily averaged currents relative to the flow at 48 n, at a subset of depths from the ADCP. Daily averaged wind velocity vectors are plotted at nidnight UT along the 8-m relative to 48-m displacement curve. Wind velocity scale is shown at bottom right.

Direct current measurements in California Current region revealed excellent Ekman-type spiral (Chereskin, JGR, 1995)

DPO Fig. 7.7

Basinwide demonstration of Ekman balance using surface drifters



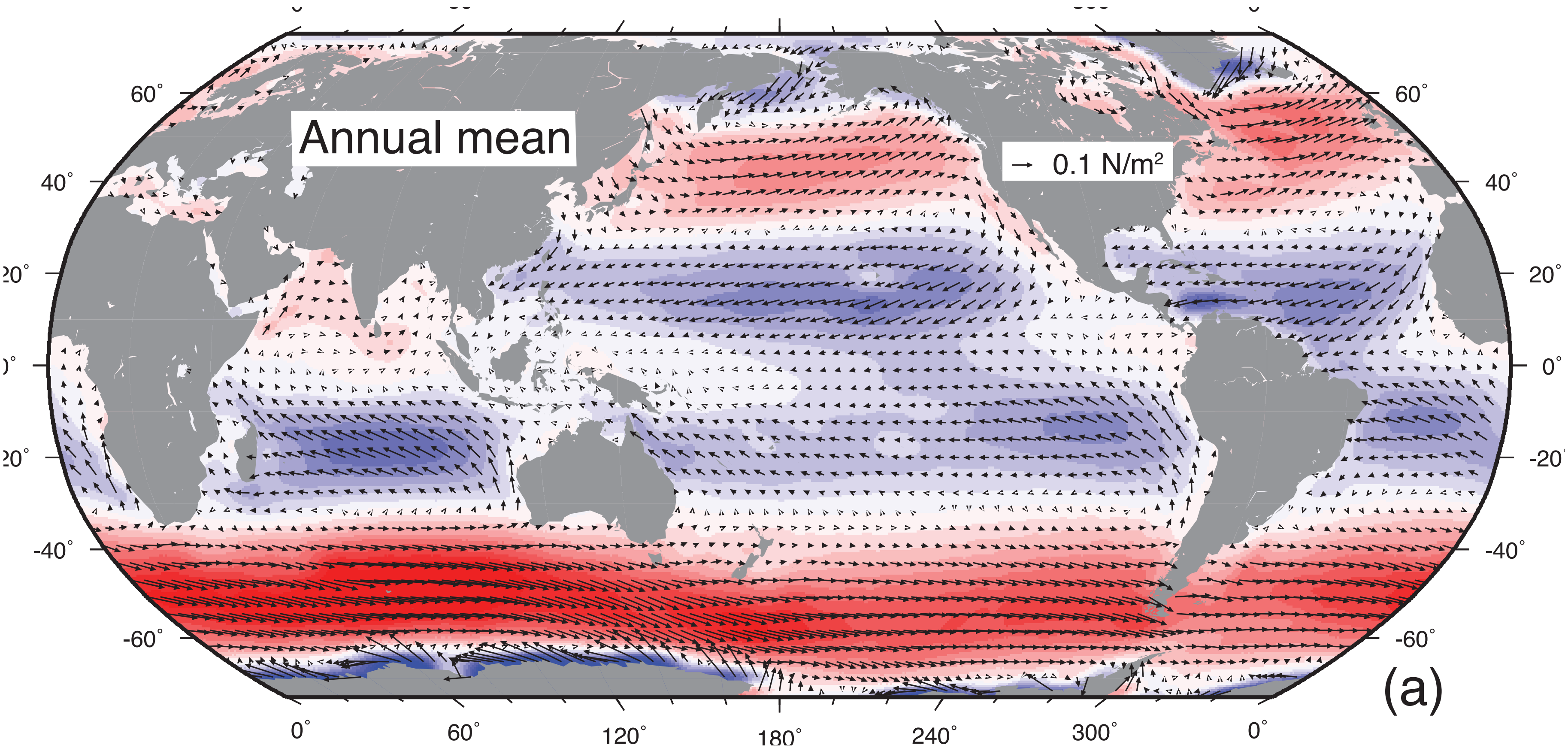
(Ralph and Niiler, 1999)

Blue - average wind

Red - average 15 meter current

DPO Fig. 7.8

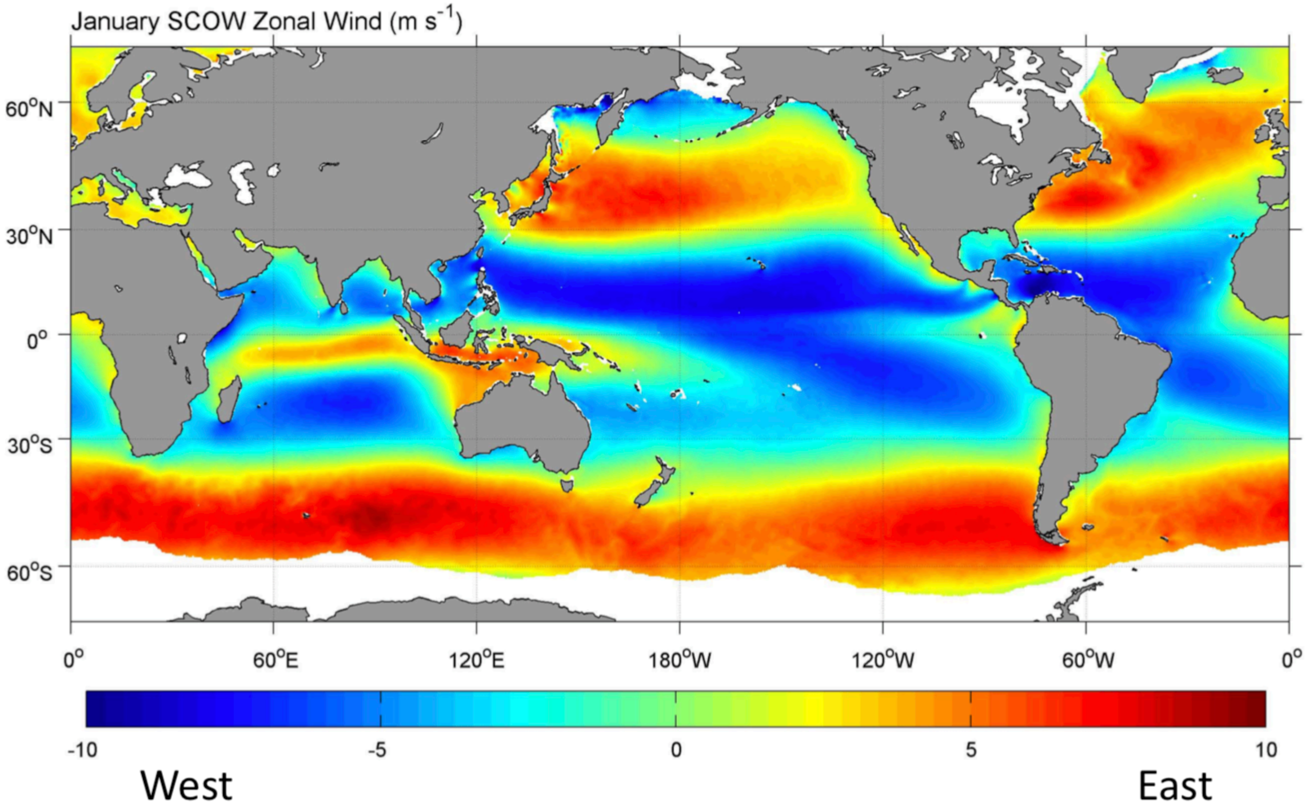
Surface wind stress



DPO Fig. 5.16a

Zonal winds

Wind velocity

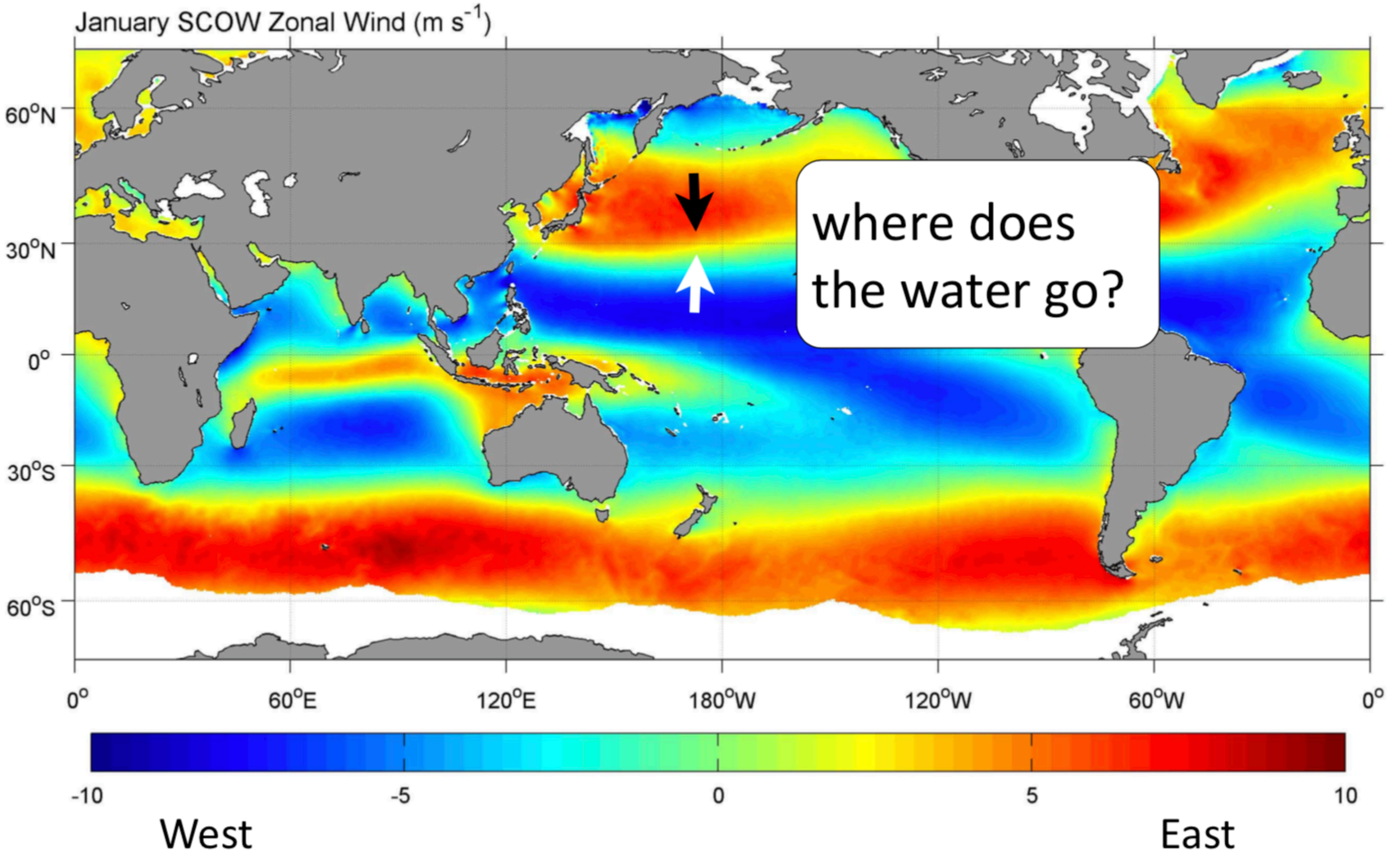


Risien and Chelton, OSU (http://numbat.coas.oregonstate.edu/scow/index.htr

Ekman transport convergence and divergence:

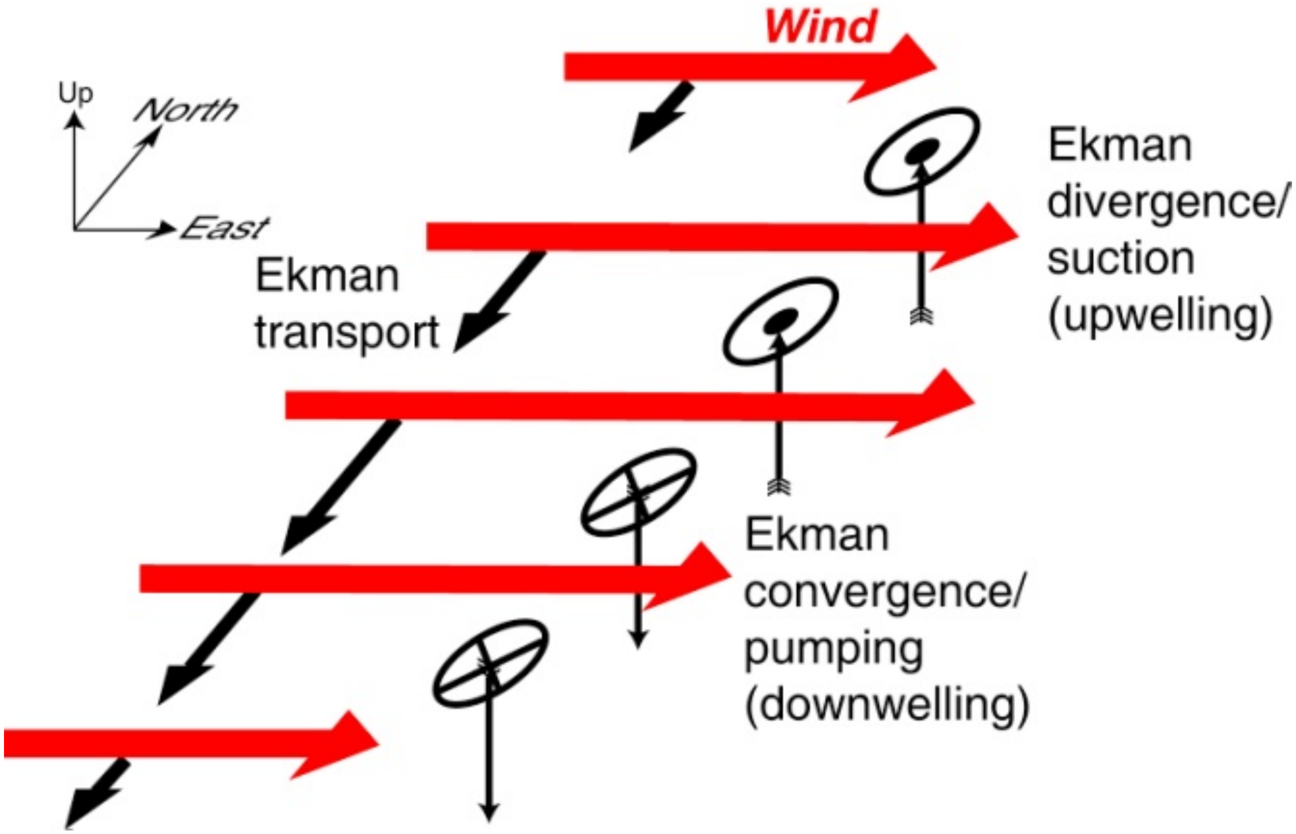
downwelling and upwelling

What direction is the Ekman Transport?



where does the water go?

Ekman transport convergence and divergence



Northern Hemisphere

DPO Fig. S7.12

Wind stress curl and Ekman pumping

Ekman transport convergence: causes vertical velocity out of the bottom of the Ekman layer.

1. Wind stress creates Ekman transport to the right (NH).

x: $-fV_{EK} = \tau^{(x)} / \rho$
y: $fU_{EK} = \tau^{(y)} / \rho$

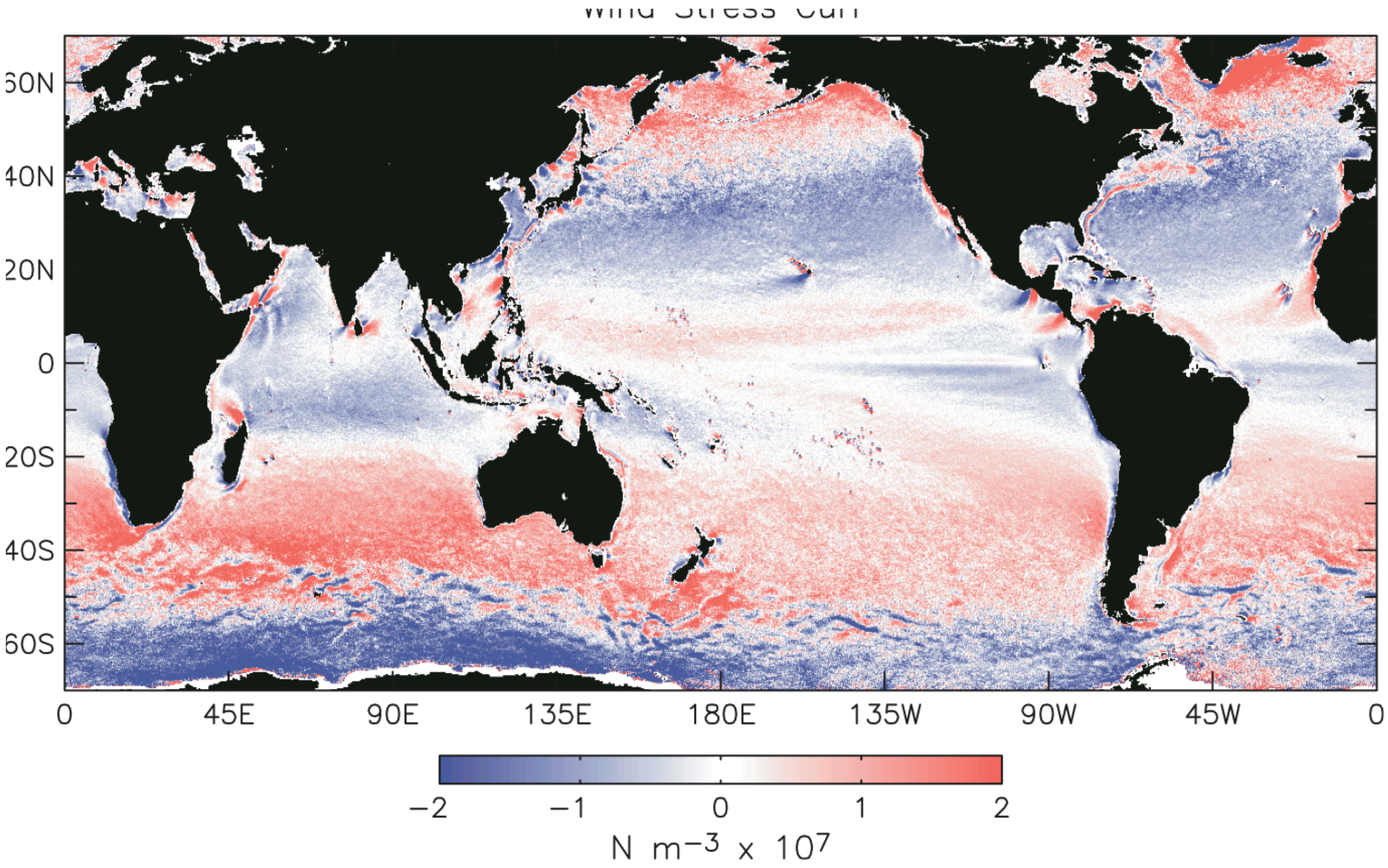
2. Ekman transport convergence causes downwelling

$(\partial U_{EK}/\partial x + \partial V_{EK}/\partial y) + (0 - w_{EK}) = 0$ so

$w_{EK} = \partial/\partial x(\tau^{(y)} / f\rho) - \partial/\partial y(\tau^{(x)} / f\rho) = \hat{k} \bullet \nabla \times (\vec{\tau} / f\rho)$

If wind stress curl is positive (NH), Ekman upwelling. "Ekman suction"
If wind stress curl is negative (NH), Ekman downwelling "Ekman pumping"

Global surface wind stress curl



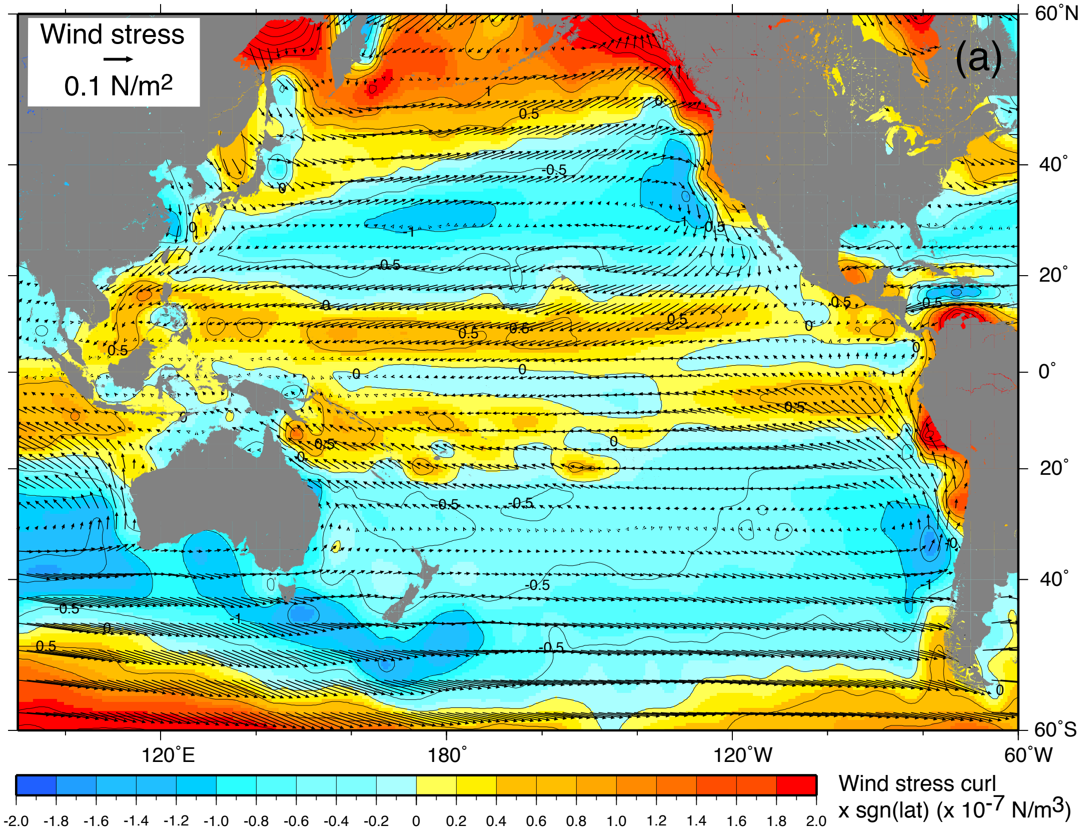
Northern Hem:
Red = upwelling
Blue = downwelling

Southern Hem:
Red = downwelling
Blue = upwelling

Chelton et al., 2004)

DPO Fig. 5.16d

Ekman pumping for the Pacific



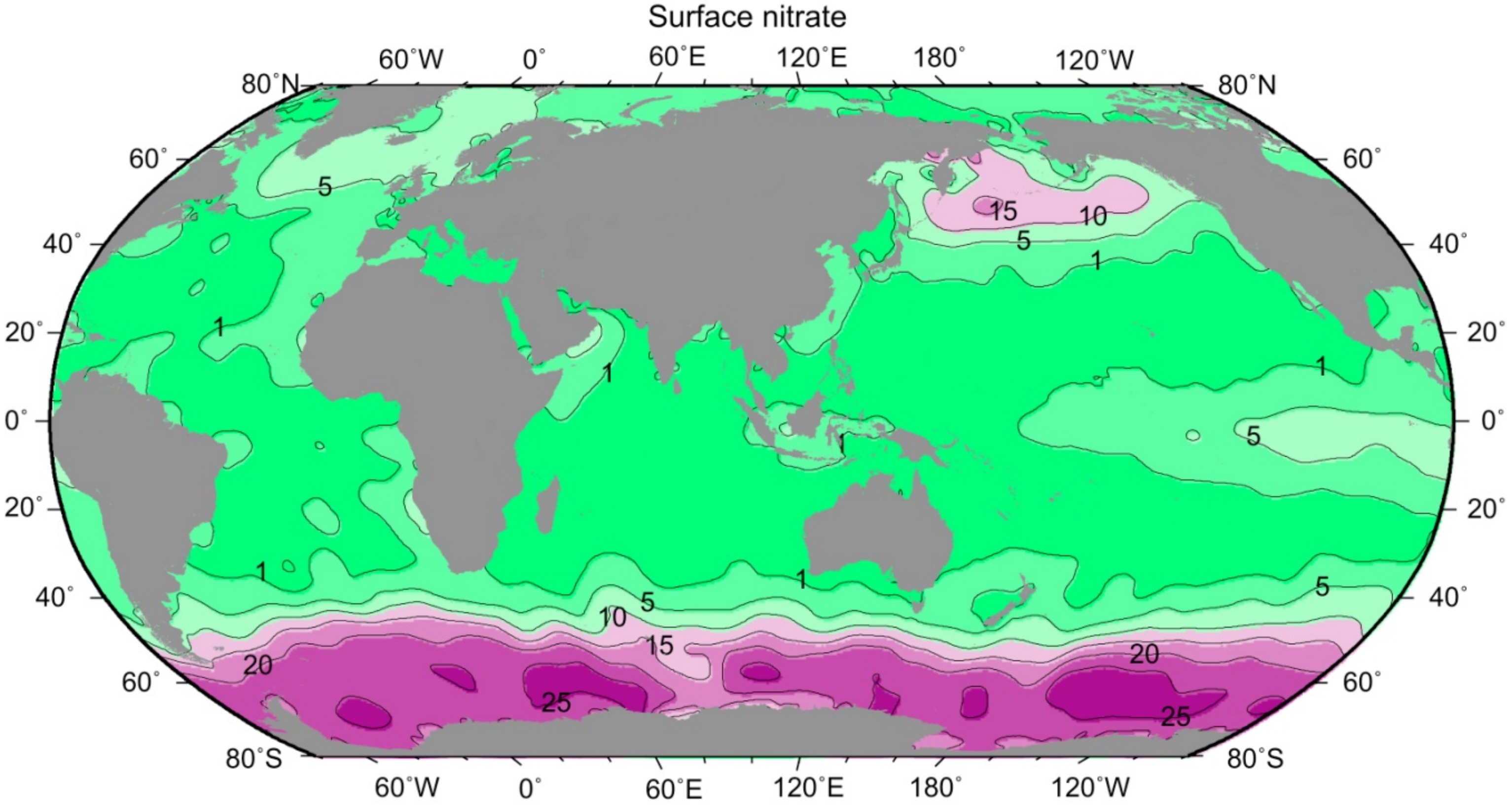
Blue regions:
Ekman pumping (wind curl is negative in northern hemisphere and positive in southern hemisphere)

Yellow-red regions:
Ekman suction (opposite wind curl from blue)

- Ekman transport convergence = downwelling = "Ekman pumping"
- Ekman transport divergence = upwelling = "Ekman suction"

DPO Fig. S5.10

Evidence of Ekman vertical velocity: surface nitrate concentration

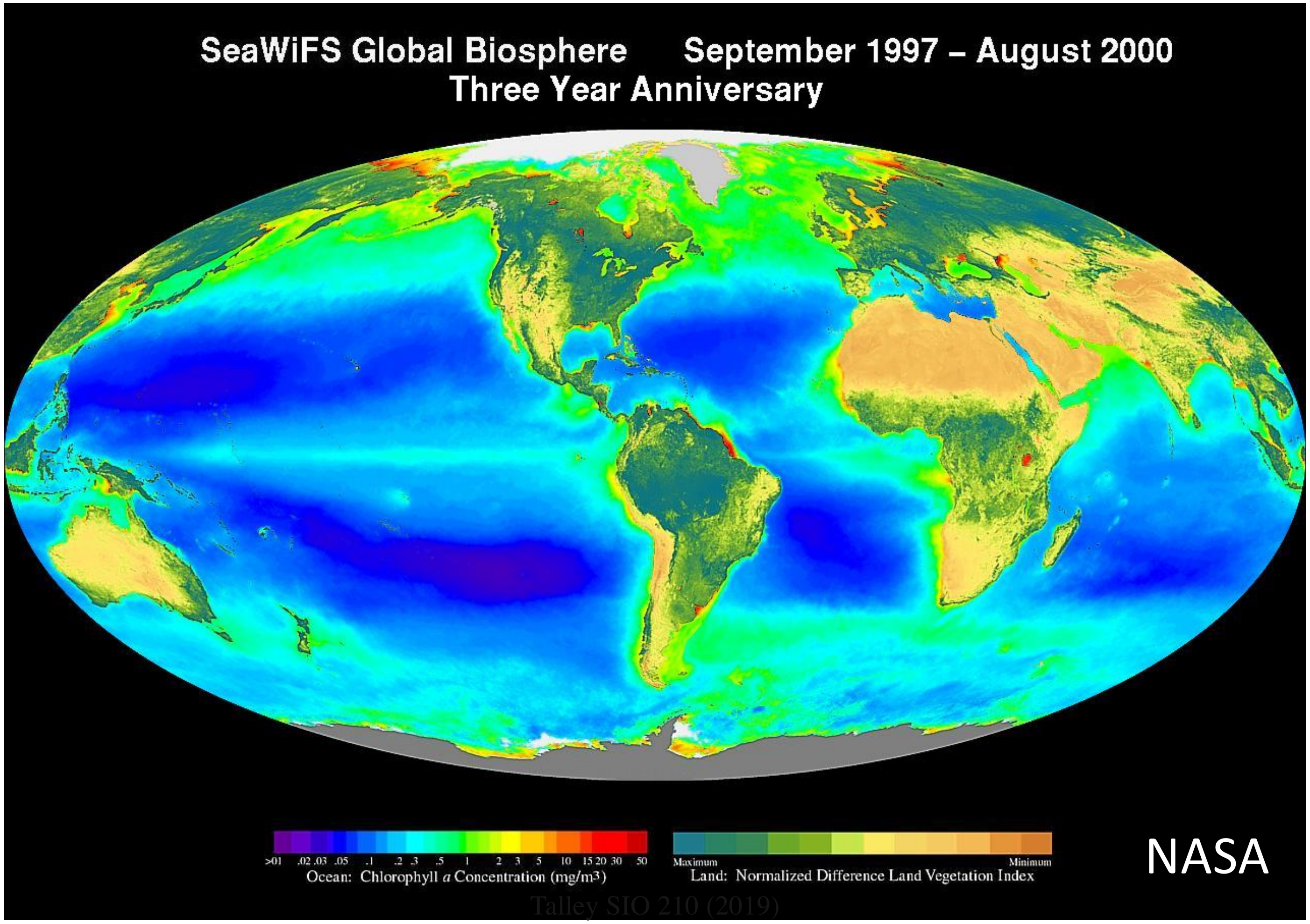


Data from gridded climatology, NODC (Levitus and Boyer, 1994)

High nitrate indicates upwelling of nutrients from below the surface layer

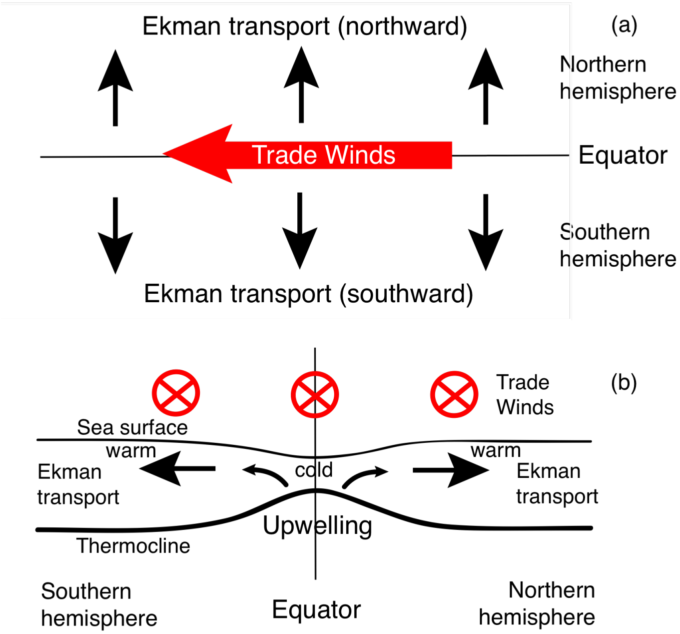
DPO Fig. 4.23

Evidence of Ekman vertical velocity: Chlorophyll concentration



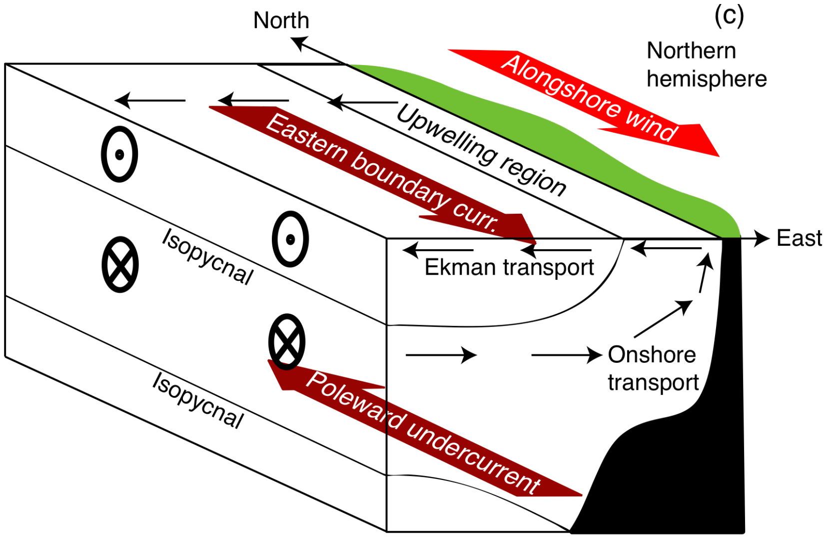
Ekman divergence (Ekman upwelling) at equator and at land boundaries

Equatorial



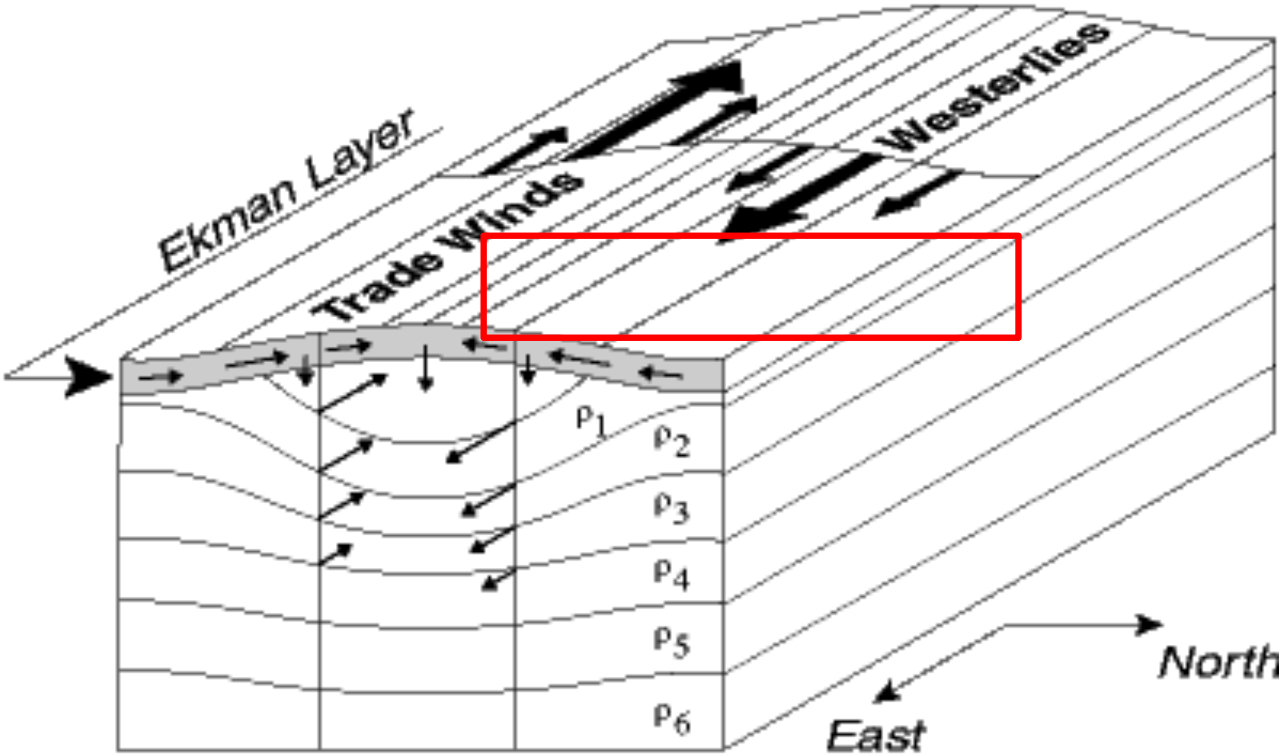
Land boundary

(northern hemisphere, like California)



DPO Fig. 7.6

Ekman transport convergence and divergence: mid-ocean



Vertical velocity at base of Ekman layer: order (10^{-4}cm/sec)

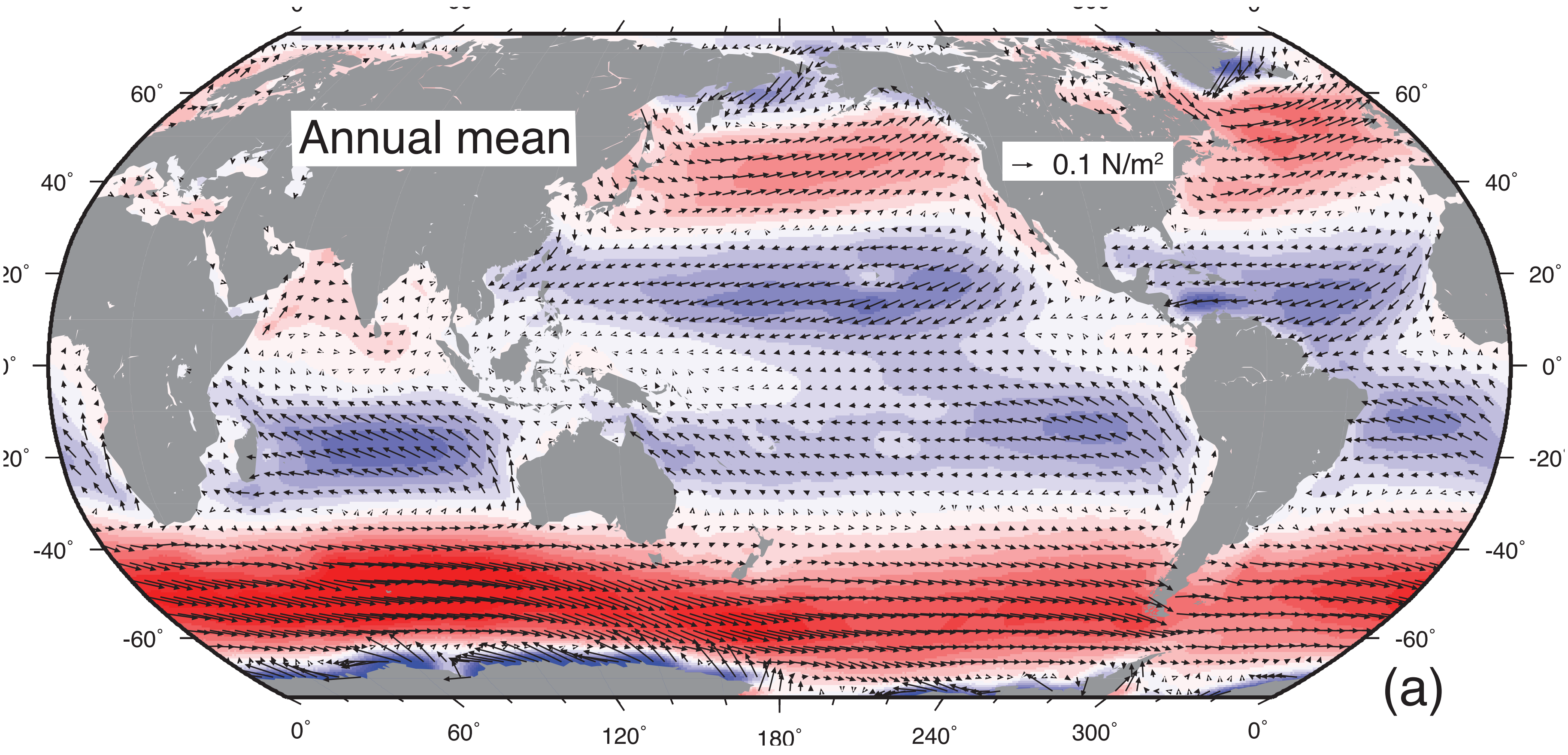
(Compare with typical horizontal velocities of 1-10 cm/sec)

Atmospheric circulation

- Vertical structure: troposphere, stratosphere, mesosphere, thermosphere
- Forcing: unequal distribution of solar radiation
- Direct circulation
  - Land and sea breeze
  - Monsoon
  - Equatorial: Walker circulation
- Mean large-scale wind and pressure structure
  - Hadley circulation
  - Jet Stream
  - Surface pressure
  - Surface wind stress

- DPO Chapter 5.8 (for wind patterns)

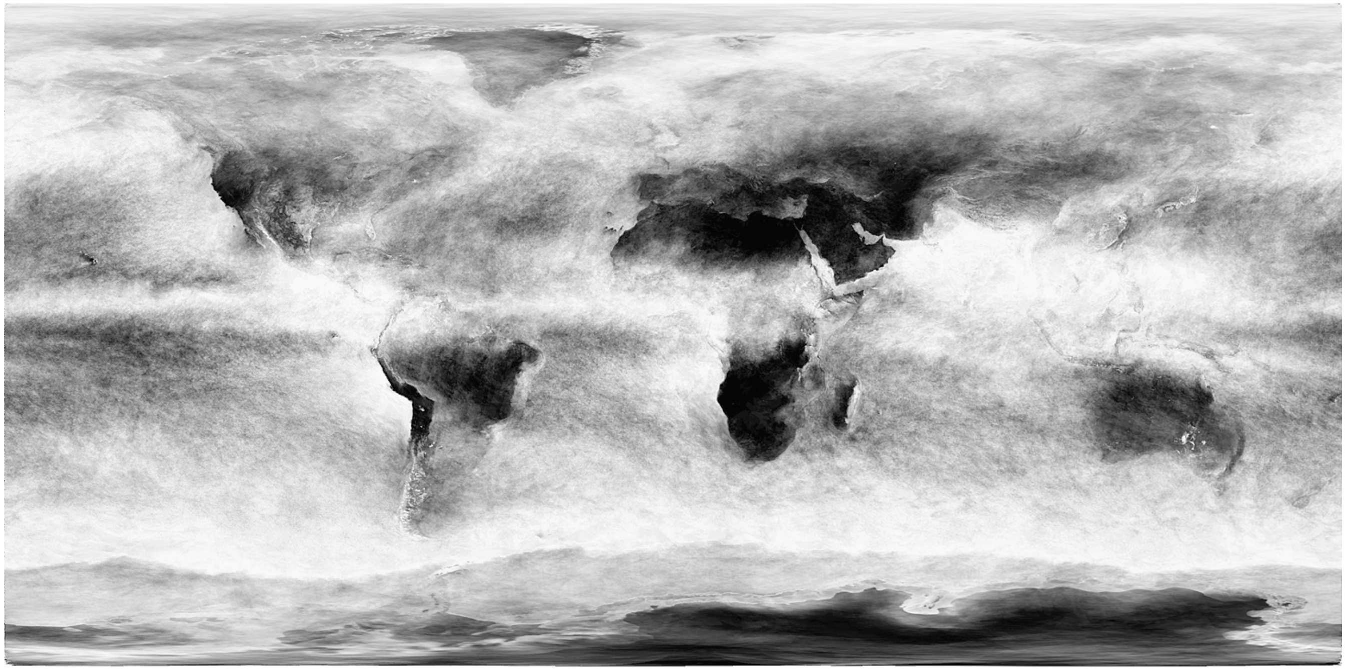
Surface wind stress



DPO Fig. 5.16a

Cloud cover

associated with sea level pressure
(low pressure = rising air - moist;
high pressure = sinking air – dry)

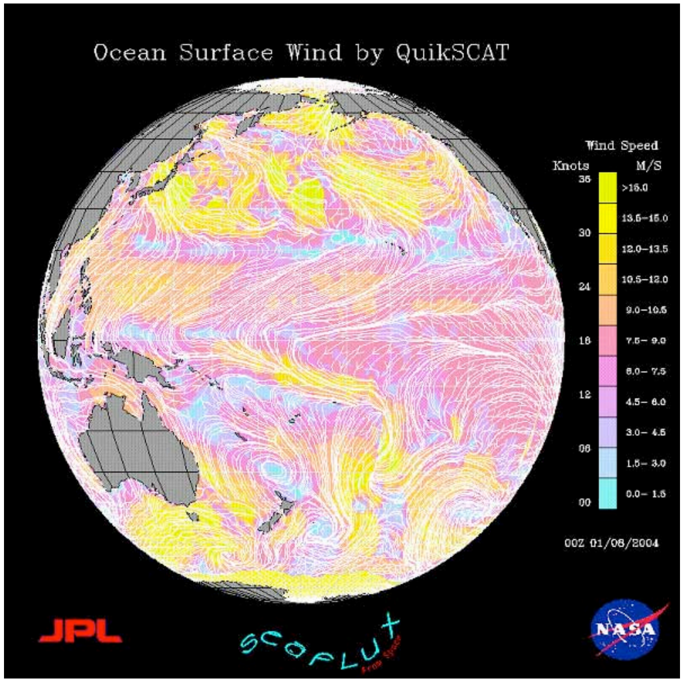


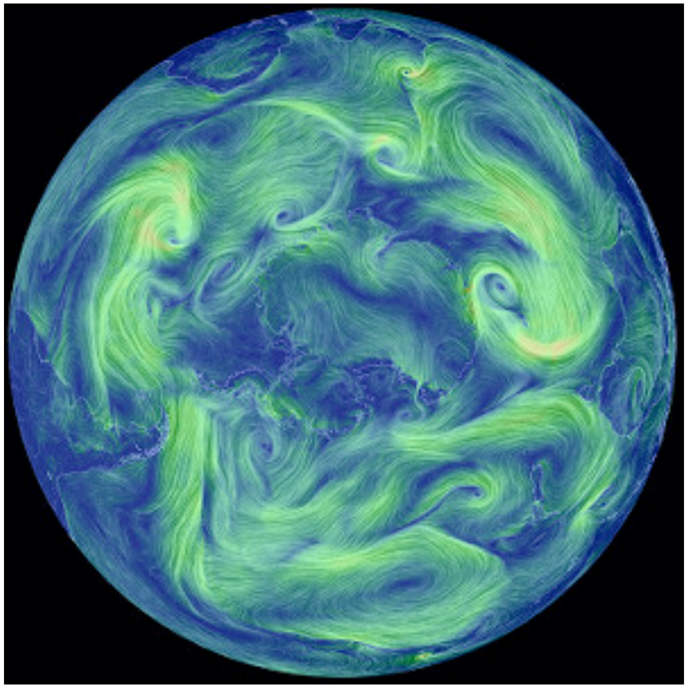
Cloud fraction (monthly average for August, 2010) from MODIS on NASA's Terra satellite. Gray scale ranges from black (no clouds) to white (totally cloudy). ***Source: From NASA Earth Observatory (2010).***

TALLEY

DPO Figure 5.8

NASA and computer wind products

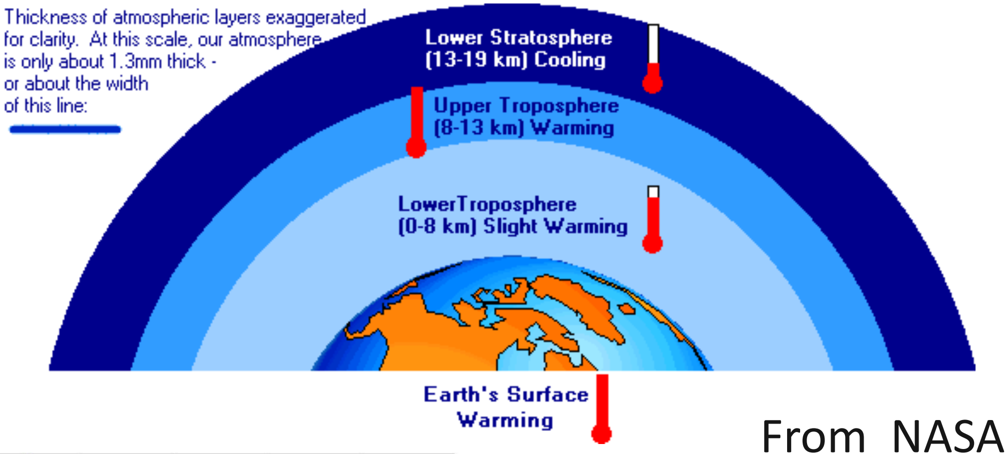




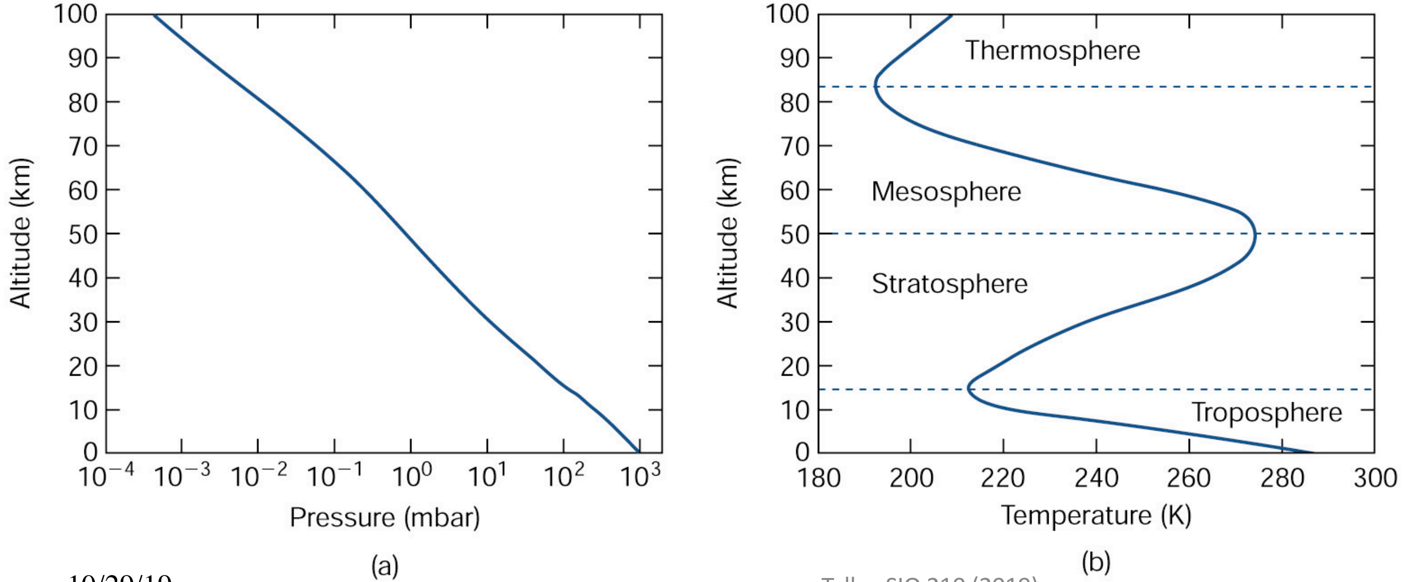
https://winds.jpl.nasa.gov/

https://earth.nullschool.net/about.html

Atmosphere structure



From NASA Science site

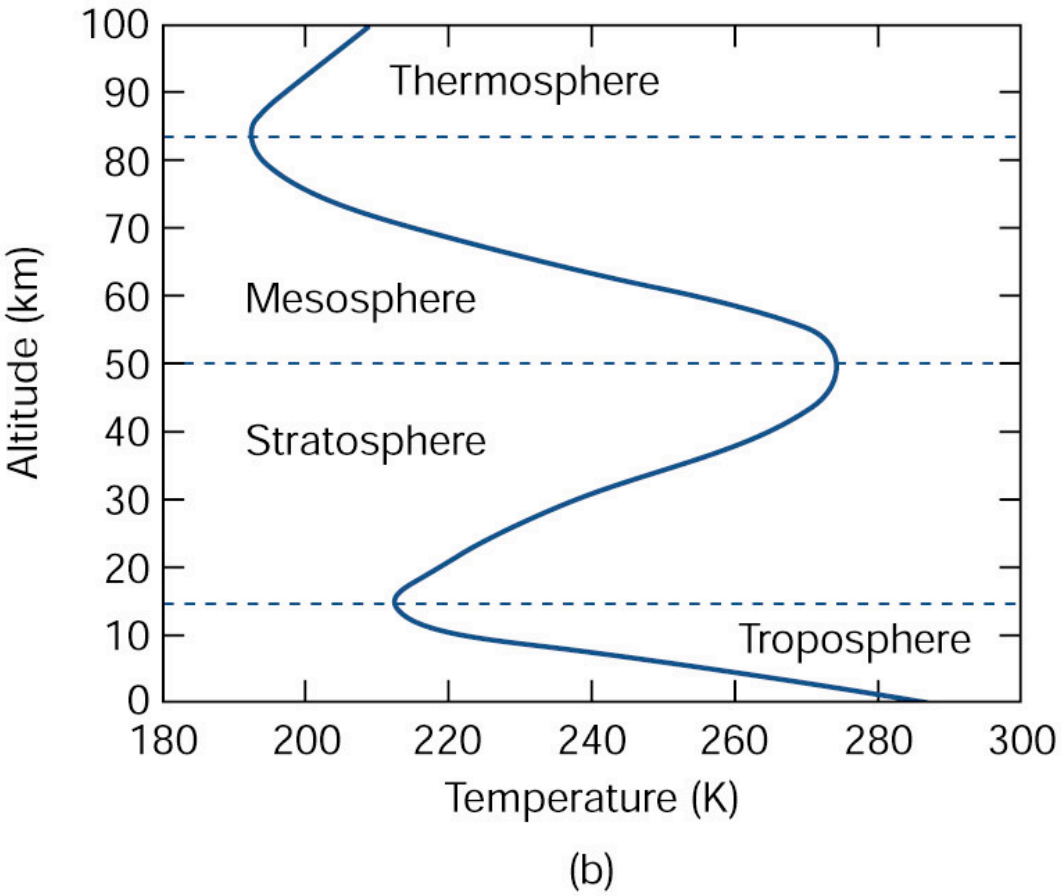


Kump, Kasting, Crane (2004) textbook

Atmospheric temperature structure

Stratosphere is warmest at top: due to absorption of the sun's UV radiation. (The ozone maximum is in the middle of the stratosphere.)

Troposphere: nearly uniform potential temperature so temperature drop with height is nearly adiabatic



Kump, Kasting, Crane (2004) textbook

Adiabatic lapse rate and potential temperature

Air is compressible (much more so than water). Thus the effects of compressibility on temperature are much the same as we've already learned for the ocean.

Adiabatic lapse rate Γ:

$$\Gamma_d = -(dT/dz)_{\text{dry parcel}} = g/c_p$$

where subscript d = dry, using the 1st law of thermodynamics to relate temperature and pressure change, and then using hydrostatic balance.

In dry atmosphere, adiabatic lapse rate is 9.8 ° /km

In moist atmosphere, adiabatic lapse rate is 6 to 7 ° /km

Potential temperature: reference level is the ground, taken as 1000 mbar.

Winds

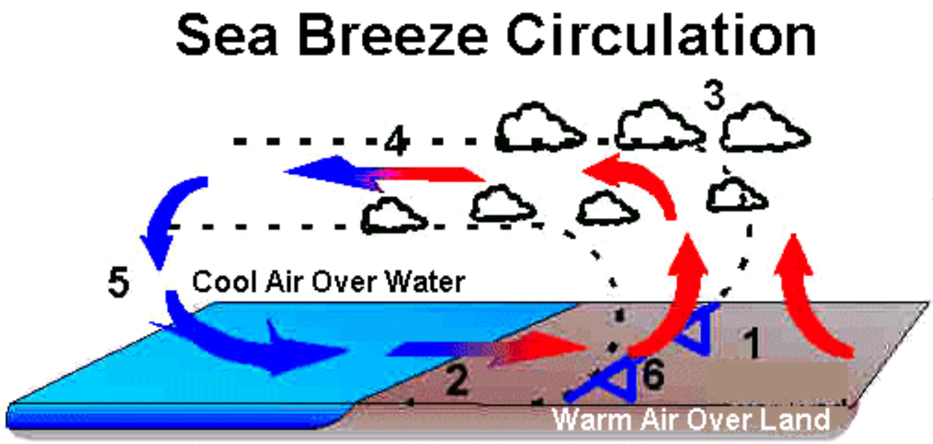
- Winds are forced mainly by heating from the earth's surface below.
- Air rises in warmer locations.
- (As it rises, if over the ocean, it tends to carry moisture and cause precipitation.)
- Because it has much higher specific heat, water temperature varies much more weakly with given surface heat flux than does land (since dirt includes both water and lower-specific-heat air).
- With diurnal or seasonal forcing of adjacent land and sea, the sea temperature varies a little and the land temperature varies a lot. This creates diurnal or seasonal reversals of locations of rising air in the atmosphere ("seabreeze" and "monsoon")
- "Direct circulation": wind (or current) blowing from high to low pressure

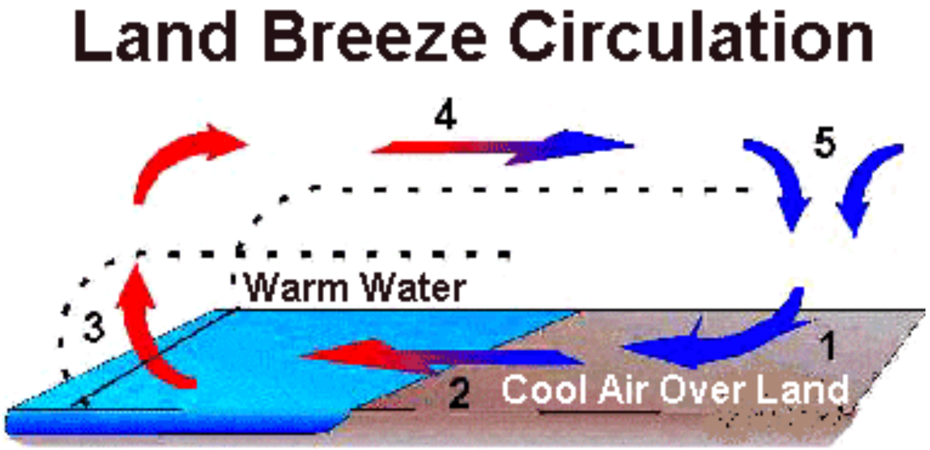
Direct circulation

- "Direct circulation": wind (or current) blowing from high to low pressure. Rotation effects are either negligible or relatively unimportant

- Examples presented here:
    1. Diurnal winds (sea and land breeze, driven by land-sea temperature contrast)
    2. Monsoonal winds (seasonal, driven by land-sea temperature contrast in the tropics where rotation is a minor factor)
    3. Walker circulation (permanent, equatorial atmospheric circulation driven by zonal SST contrast)

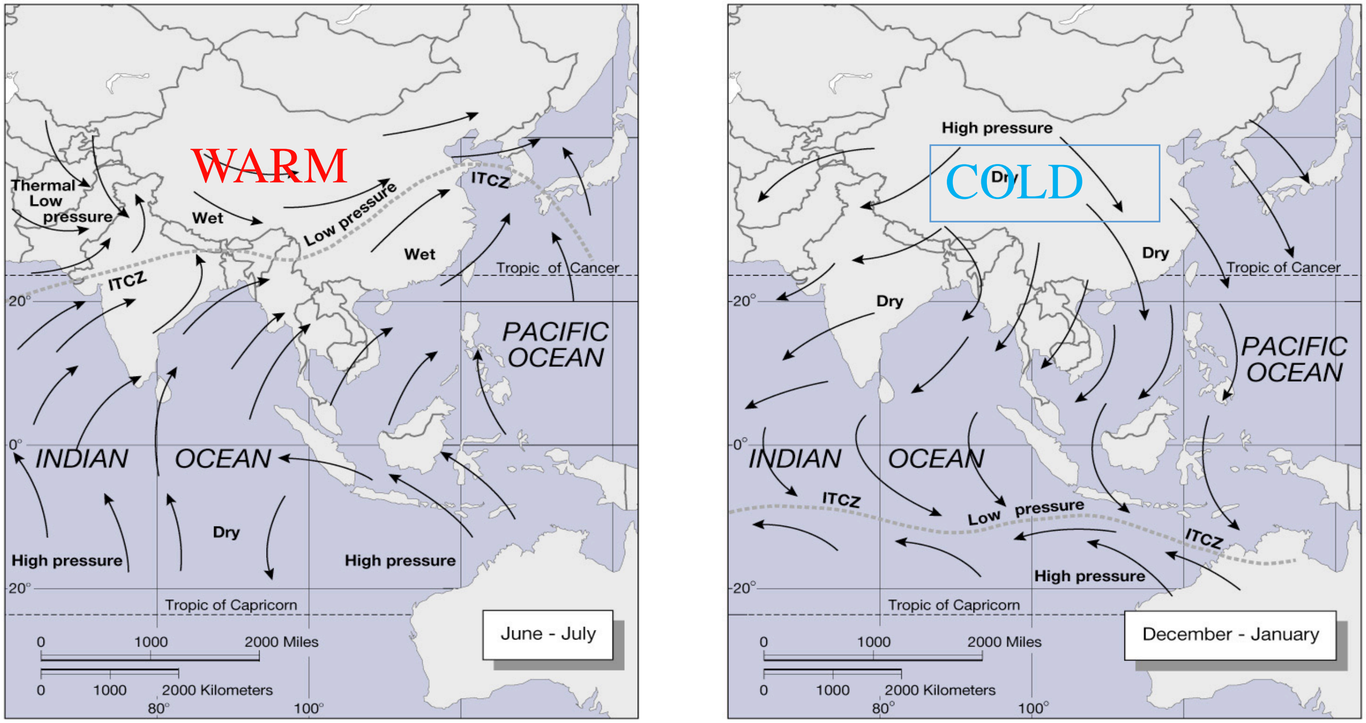
Wind response to differential heating: Diurnal - Land and sea breeze





- Diurnal cycle of heating and cooling
- Land temperature extremes are much larger than ocean temperature extremes through the daily cycle (because the specific heat of water is so high compared with air and dirt)
- Hot-cold contrast creates upward convection in the air above the warm area (land in the day, ocean in the night), and sinking over the cooler area

Wind response to differential heating: Seasonal - Monsoons



(a) (b)

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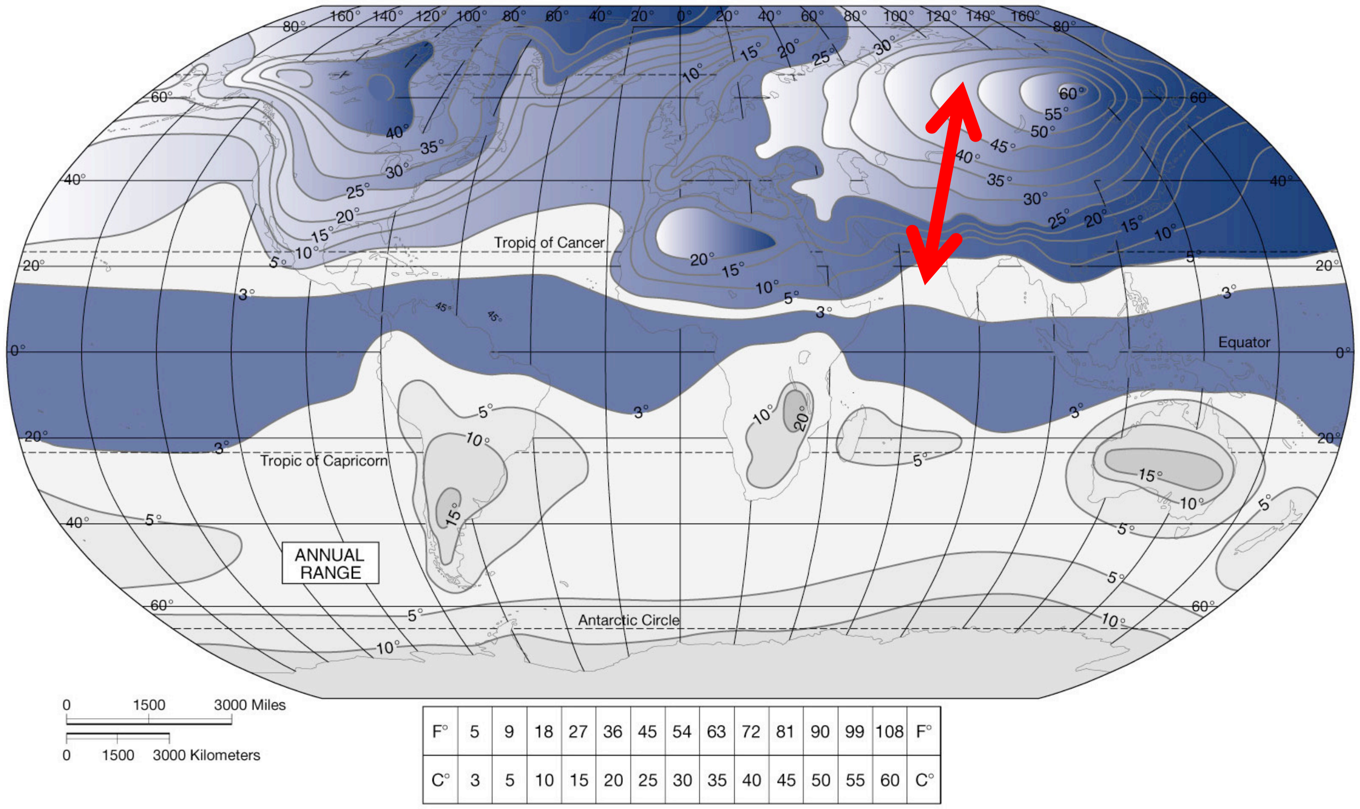
Northern hemisphere summer

Northern hemisphere winter

- Same idea as diurnal sea breeze: ocean seasonal temperature range is much smaller than land seasonal temperature range. Rising air over warmer area and sinking over cooler, modified by Coriolis deflection
- “Direct circulation” driven by differences in heating and cooling

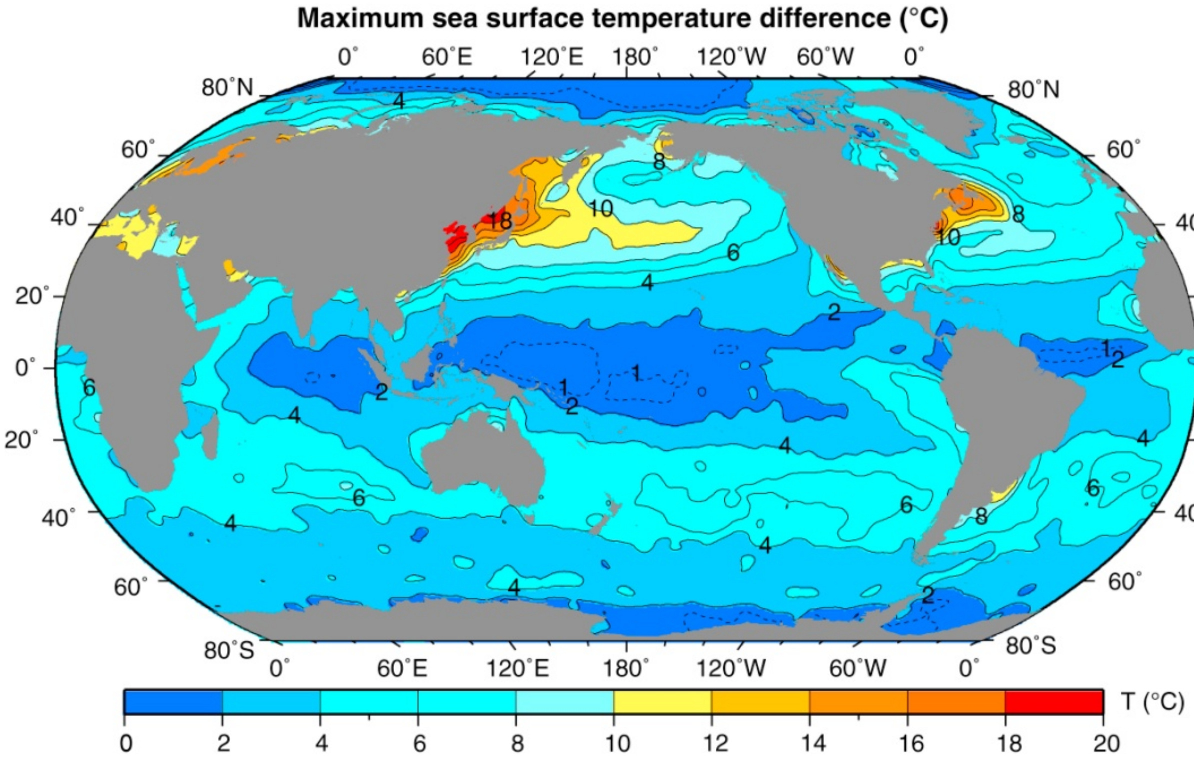
Kump, Kasting, Crane (2004) textbook

Annual range of surface temperature (°F)



F°	5	9	18	27	36	45	54	63	72	81	90	99	108	F°
C°	3	5	10	15	20	25	30	35	40	45	50	55	60	C°

Kump, Kasting, Crane (2004) textbook

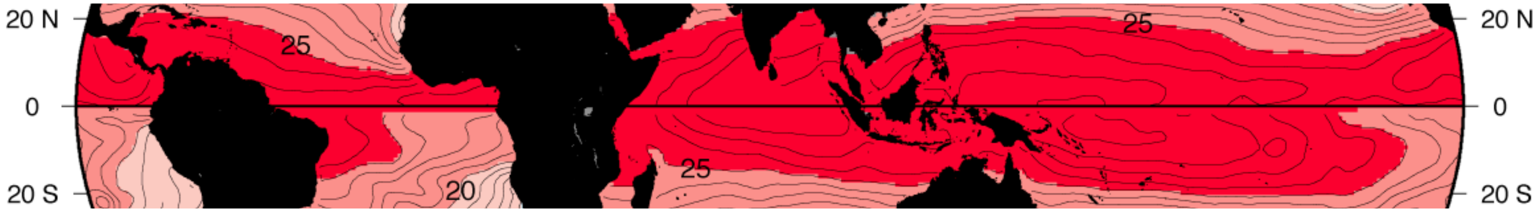


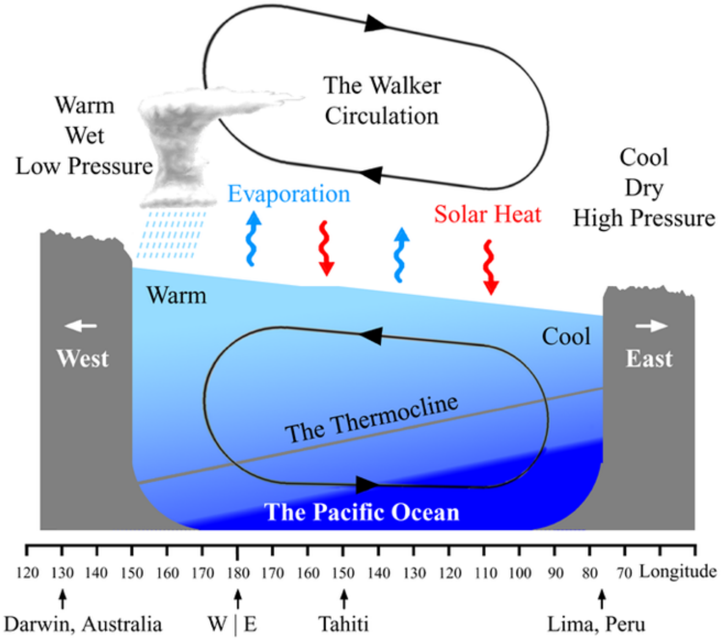
Can see that monsoon is not driven by the SST annual range in the Arabian Sea– has to be the land annual range. Monsoon: SST remains relatively constant while land temperature goes through large annual cycle.

Annual range of sea surface temperature (° C), based on monthly climatological temperatures from the World Ocean Atlas (WOA05) (NODC, 2005a, 2009).

DPO Fig. 4.9

Equatorial winds: Direct atmospheric circulation
Walker circulation: (Coriolis not important as f ~ 0)



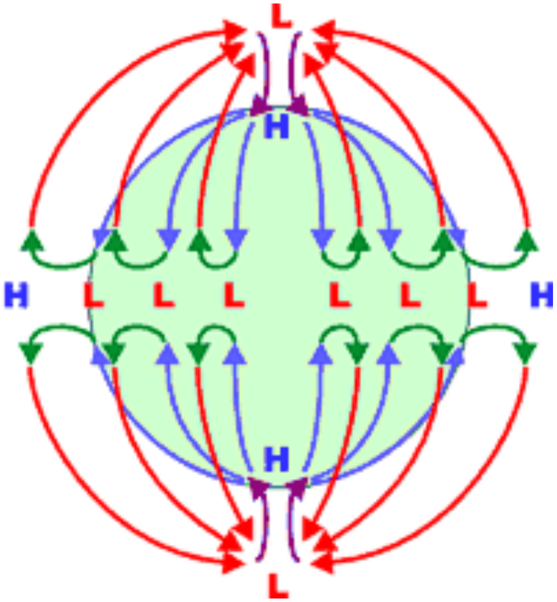


“Bjerknes feedback” between the ocean and atmosphere. Warm water causes air to rise, creates wind, that sets up currents, that causes SST contrast.

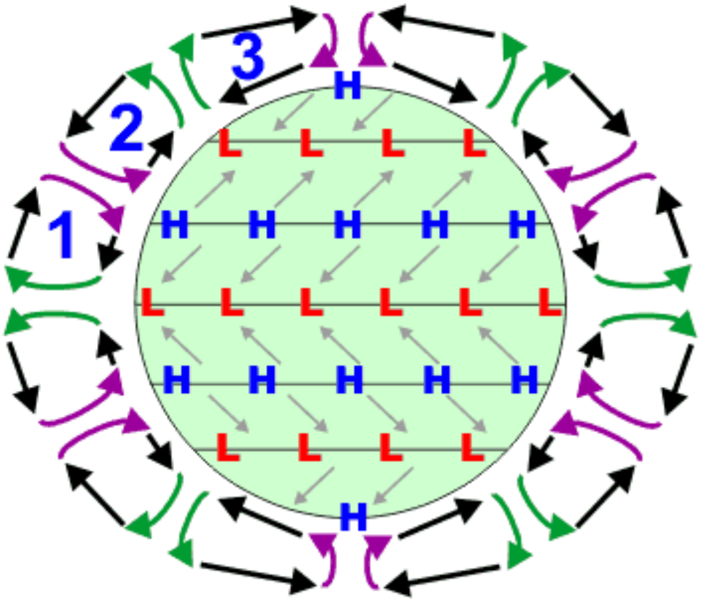
Mean large-scale wind and pressure structure

Convection and subsidence, in response to global heating and cooling

What we might expect from global heating and cooling

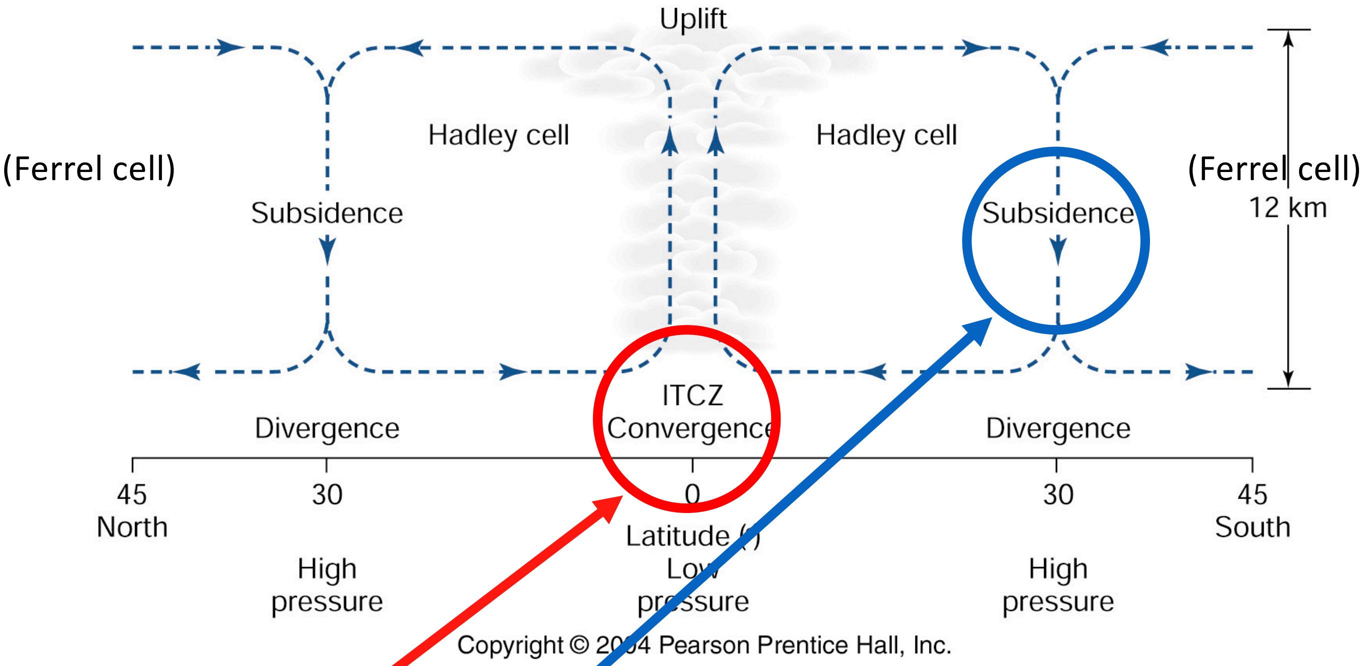


What we actually have - 3 cells - due to rotation



1. Hadley 2. Ferrel 3. Polar

Hadley cell



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ITCZ = Intertropical Convergence Zone

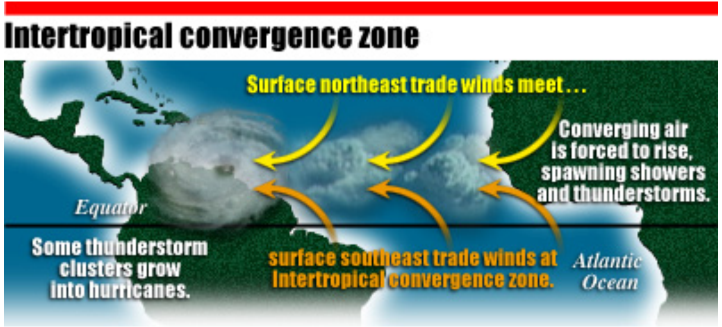
Actually not exactly on equator: seasonal variations in insolation, so ITCZ sits at maximum heating location.

ITCZ is well developed north of equator (because of land distribution).

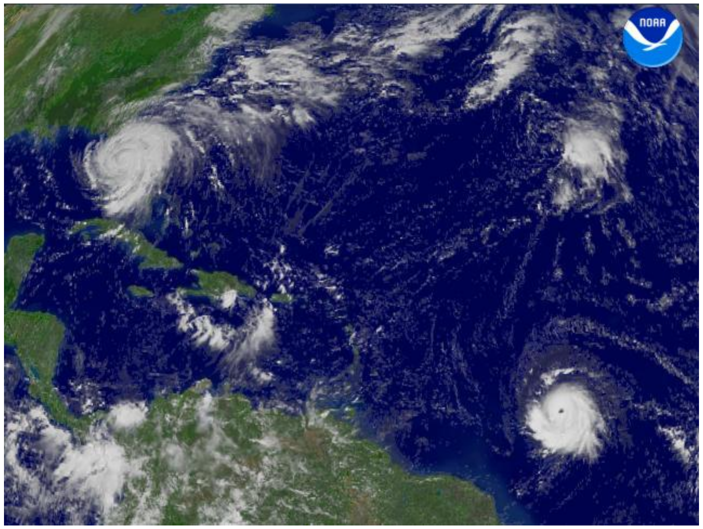
Subsidence at about 30 ° N, S

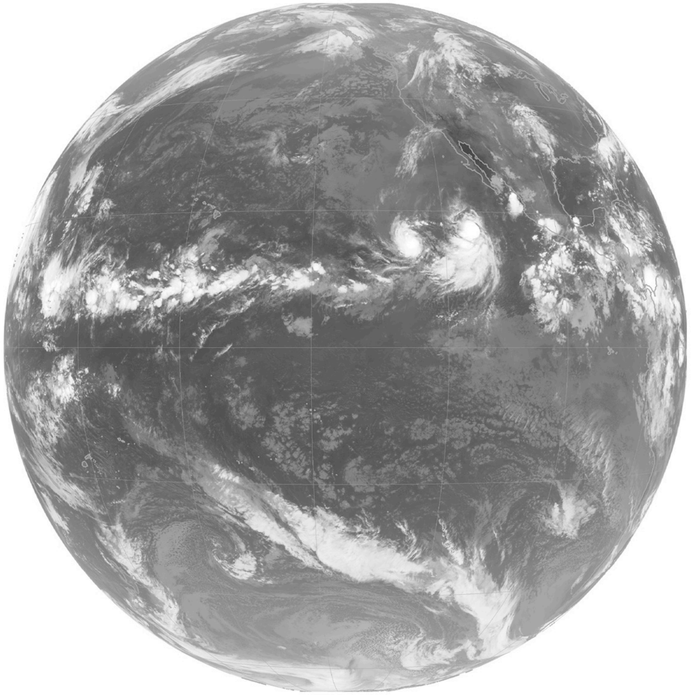
Kump, Kasting, Crane (2004) textbook

Intertropical Convergence Zone



Atlantic Ocean 9/04

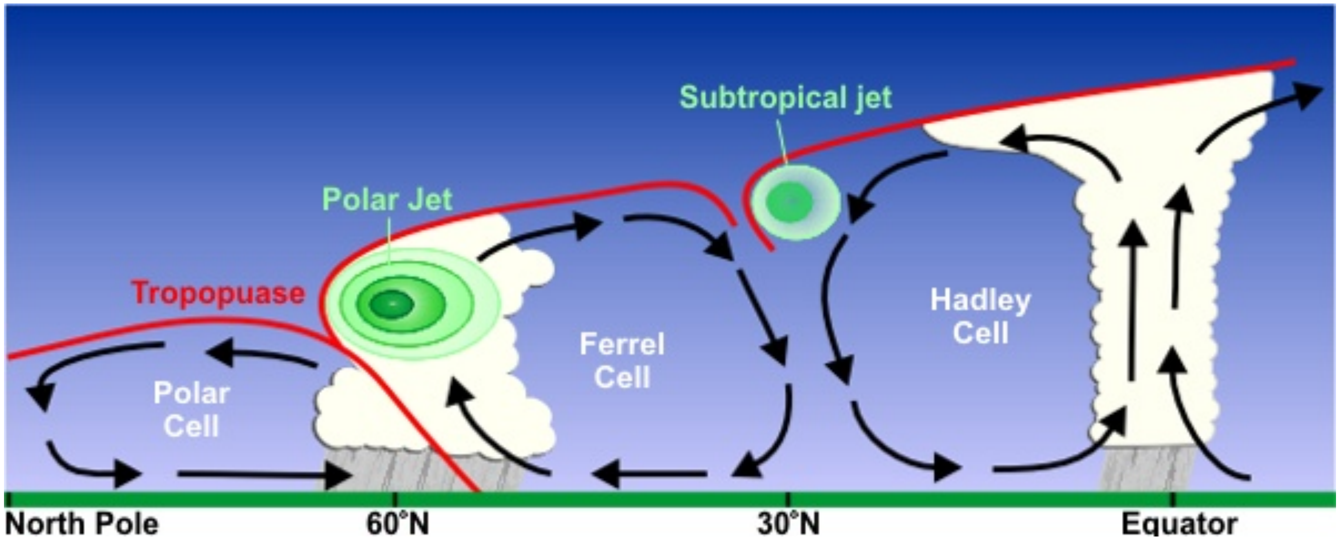




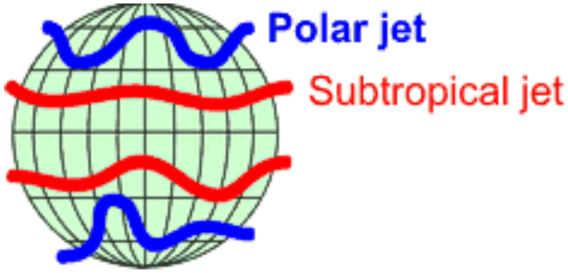
Pacific Ocean

ITCZ spawns hurricanes

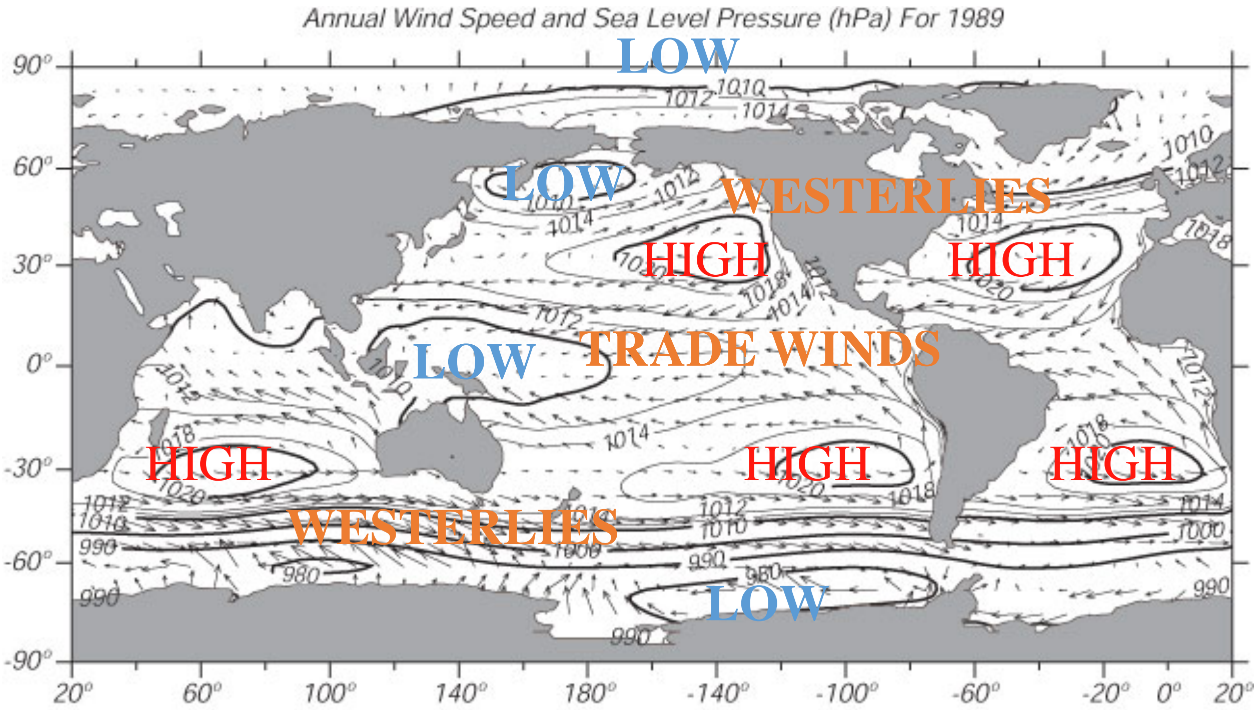
The three cells and the jet streams: Polar and Subtropical Jets



Polar easterlies **Westerlies** **Trades (easterlies)**



Annual mean surface winds and surface pressure



Wind stress

- Wind stress drives the ocean (waves, currents).
- Transfer of momentum from wind to ocean.
- Wind speed is measured above the sea surface. In practice measurements are at different heights. For consistency, adjust all measurements to a 10 meter height.

- Actual stress on the ocean:

$$\tau = c_D \rho u^2$$

where u is the wind speed at 10 meters, ρ is the air density 1.3 kg/m^3, and c_D is the (dimensionless) drag coefficient, which is determined empirically.

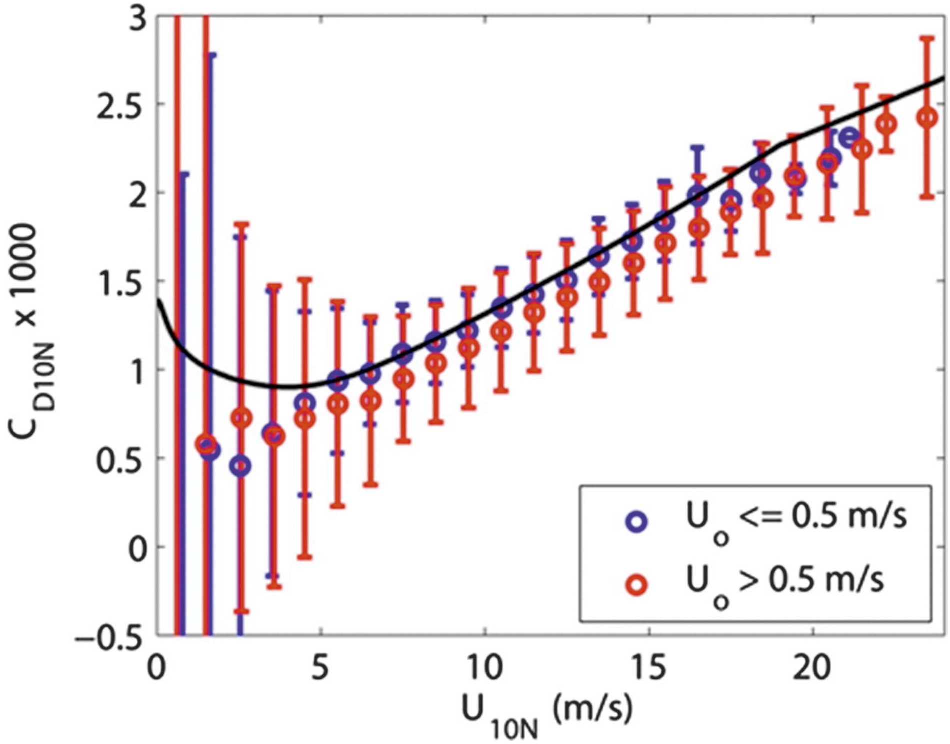
Units of wind stress: Newton/m^2

(check this using density times velocity squared)

Wind stress continued

Drag coefficients “COARE 3.5” determined from direct measurements, including high wind speeds

[At low wind speed $c_D \sim 1.1 \times 10^{-3}$]



Edson et al. (JPO, 2013)