

Thermohaline Circulation

ES 383

Colby at Bigelow, September 2018



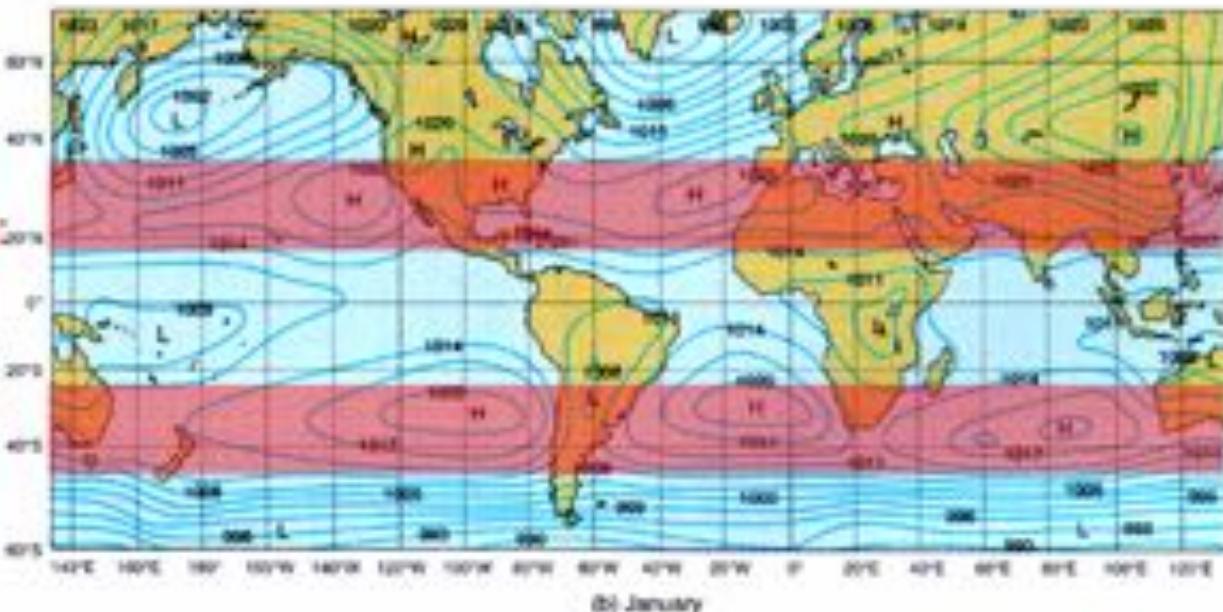
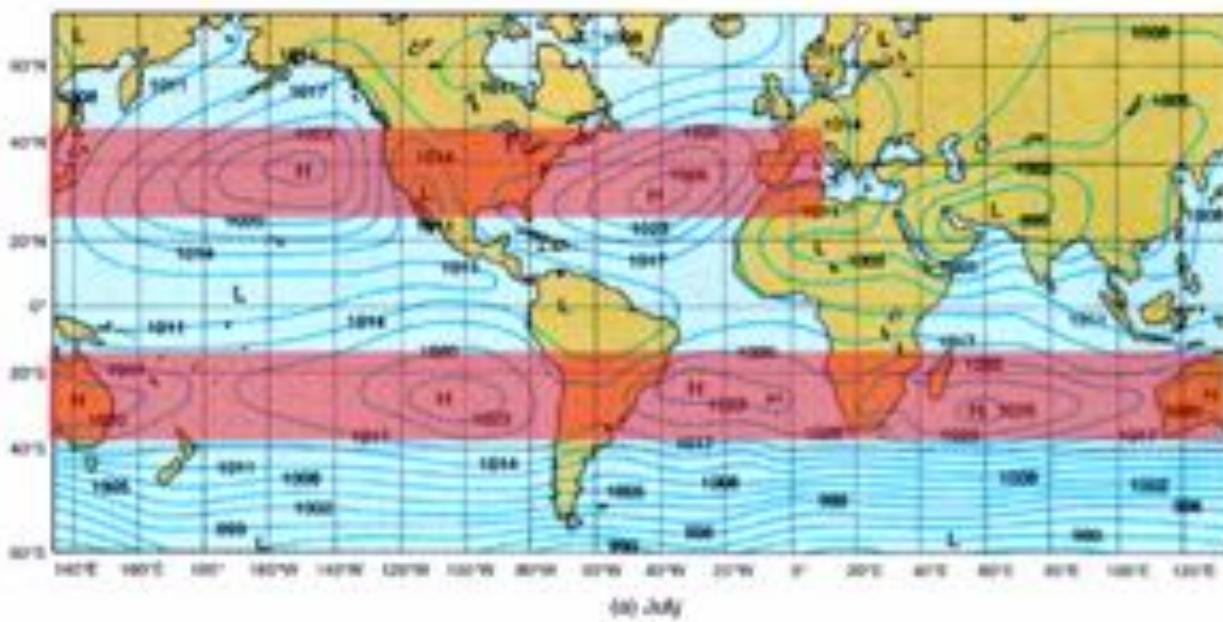
To understand ocean circulation, use fluid dynamics:

Navier-Stokes equations

$$\begin{aligned}\partial_t \rho \vec{v} + \nabla \cdot \rho \vec{v} \vec{v} + 2\vec{\Omega} \wedge \rho \vec{v} + g\rho \hat{k} + \nabla p &= \nabla \cdot \vec{\tau} \\ \partial_t \rho + \nabla \cdot \rho \vec{v} &= 0 \\ \partial_t \rho S + \nabla \cdot \rho S \vec{v} &= 0 \\ \partial_t \rho \theta + \nabla \cdot \rho \theta \vec{v} &= \frac{1}{c_{pS}} \nabla \cdot \mathcal{F}_\theta \\ \rho &= \rho(\theta, S, p)\end{aligned}$$



Start with atmospheric circulation



Connection with ocean currents

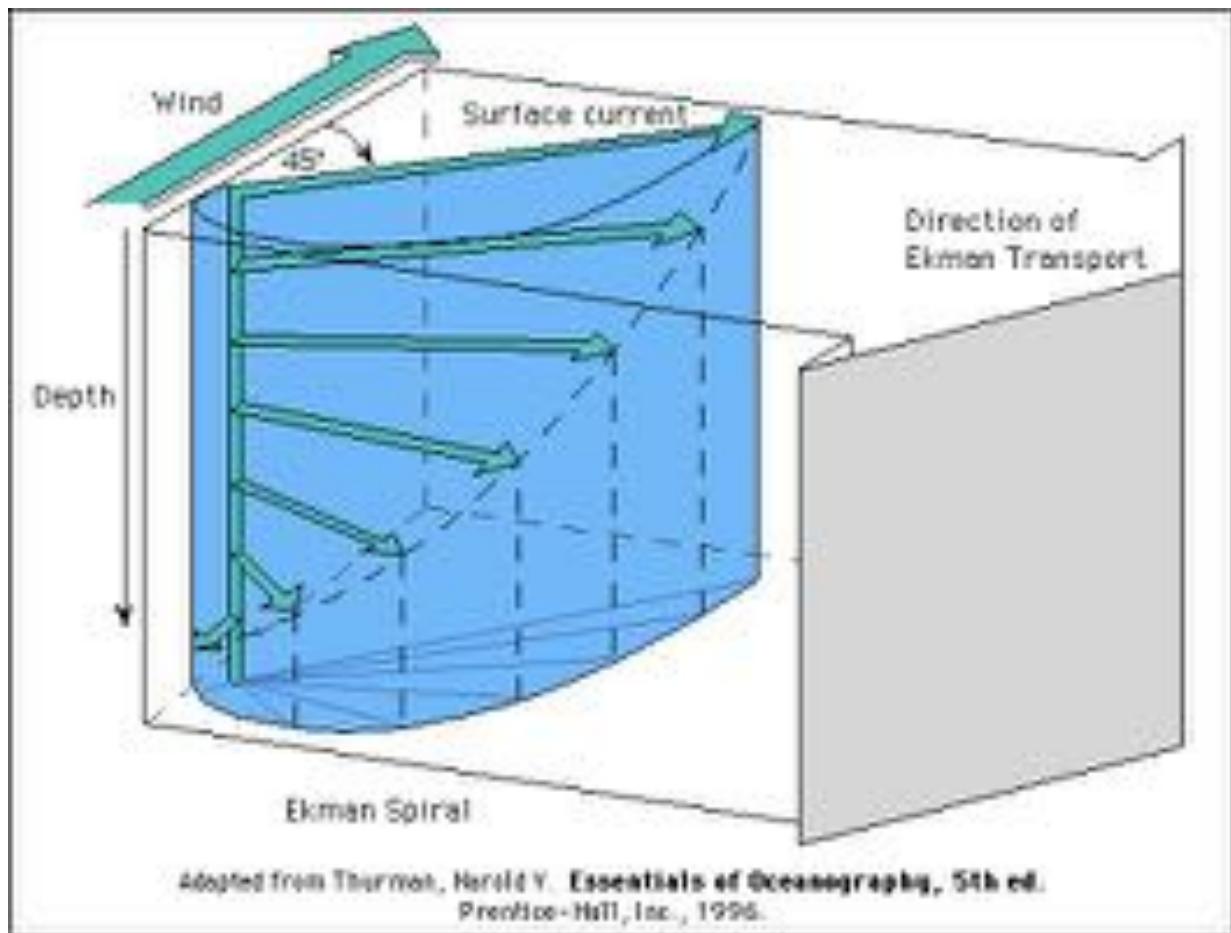


Fridtjof Nansen –
Attempted to reach the North Pole in 1893. While the ship was frozen in ice, Nansen observed that the ice drifted 20-40° to right of wind.

Competitor of Robert Peary

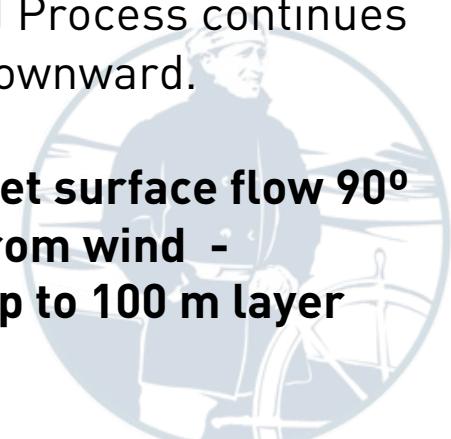


Ekman spiral



Vagn Walfrid Ekman -
Formalized the effect
of Coriolis on flow.

- 1) Wind friction produces drag on water.
 - 2) Apparent deflection to the right (Northern hemisphere) due to the rotation of the earth.
 - 3) Process continues downward.
- Net surface flow 90° from wind - Up to 100 m layer**



When the wind blows on the ocean surface:

Near-surface Ekman Currents

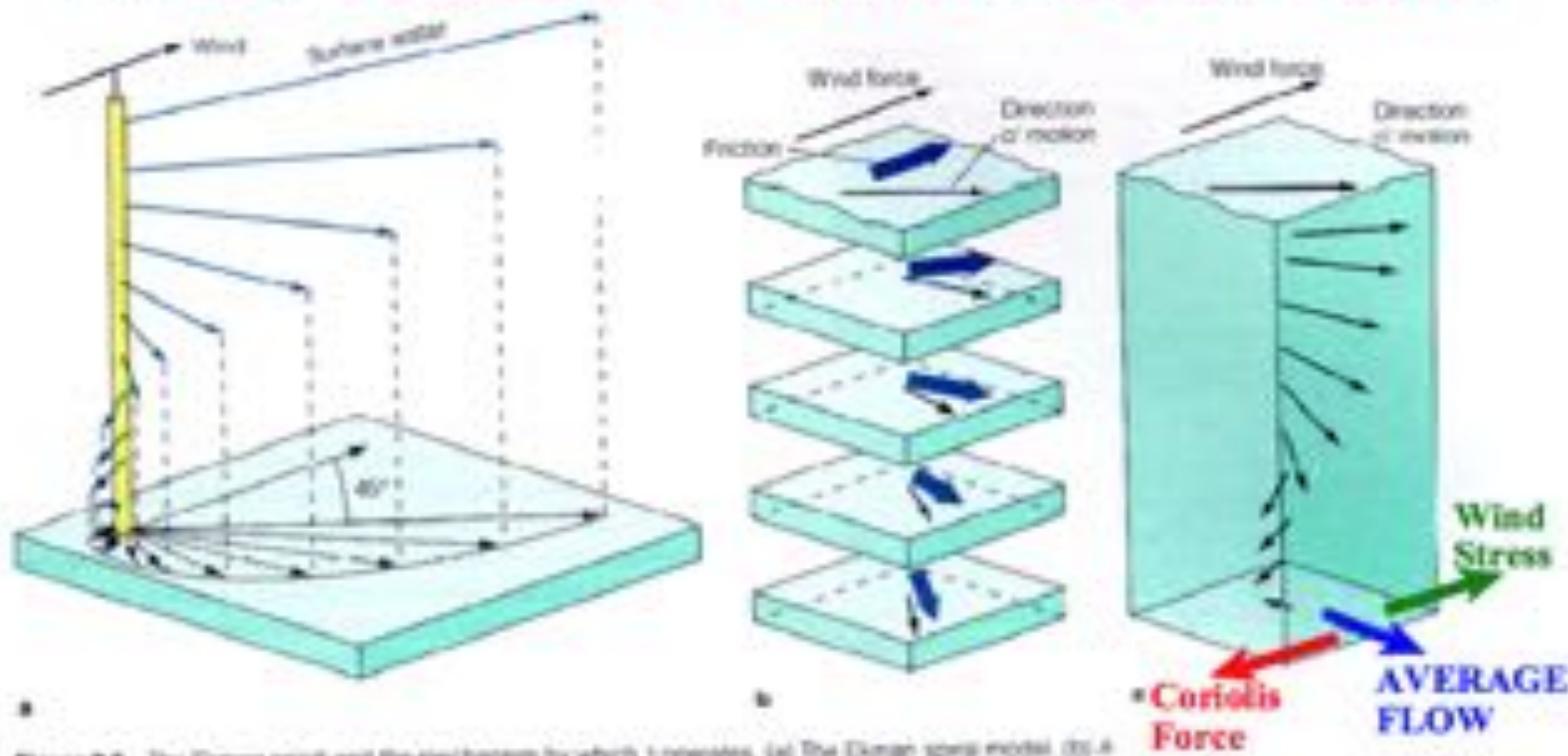
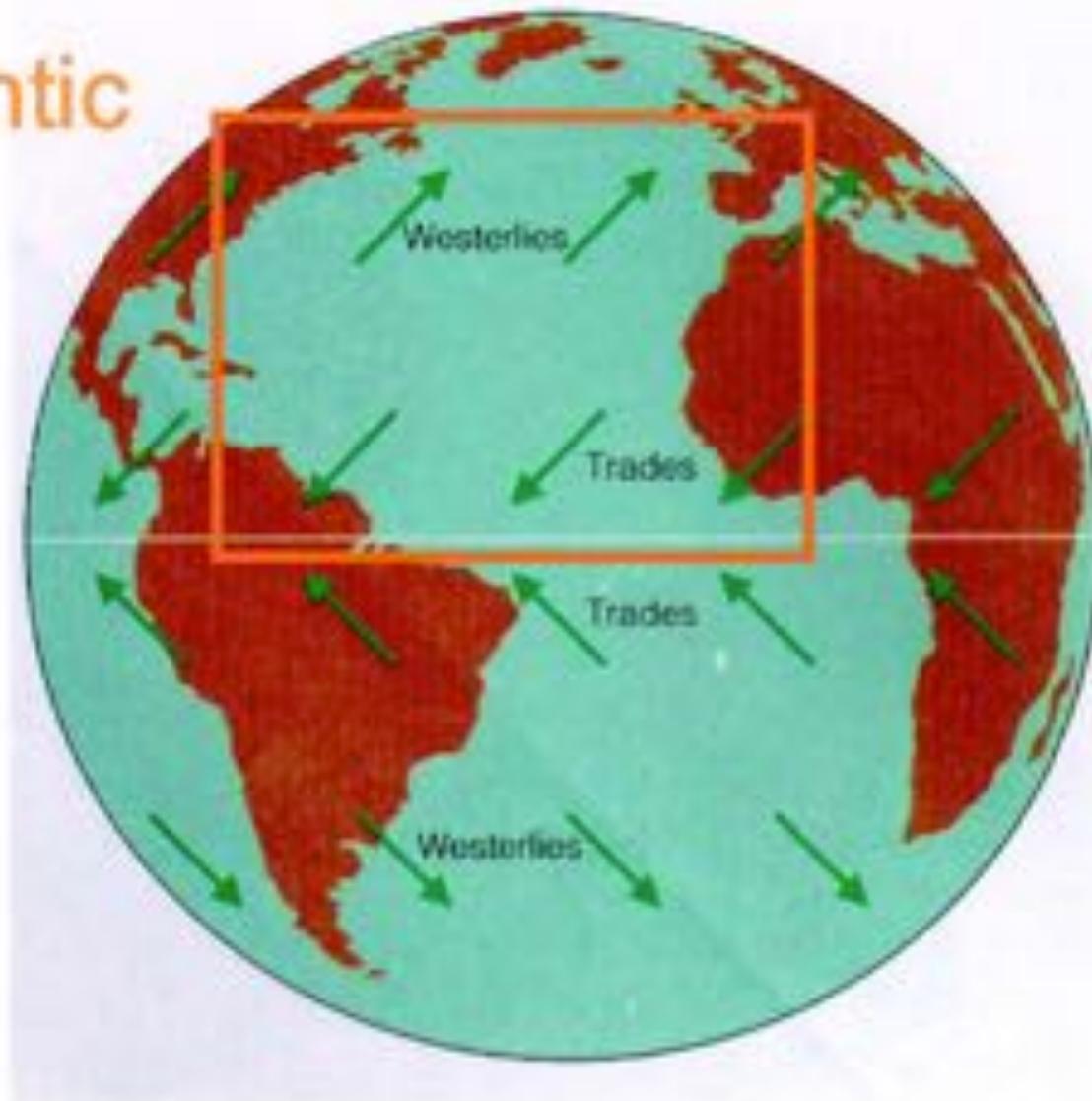
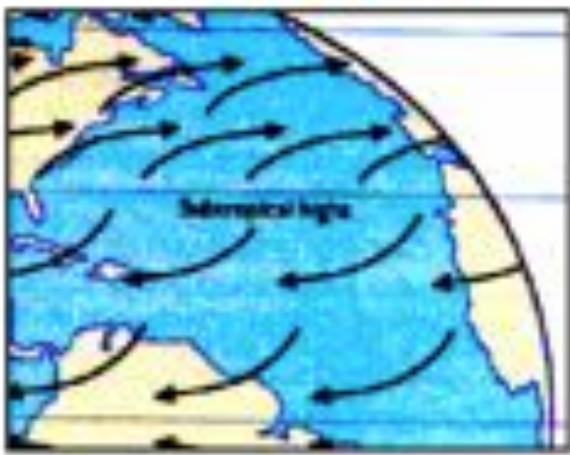
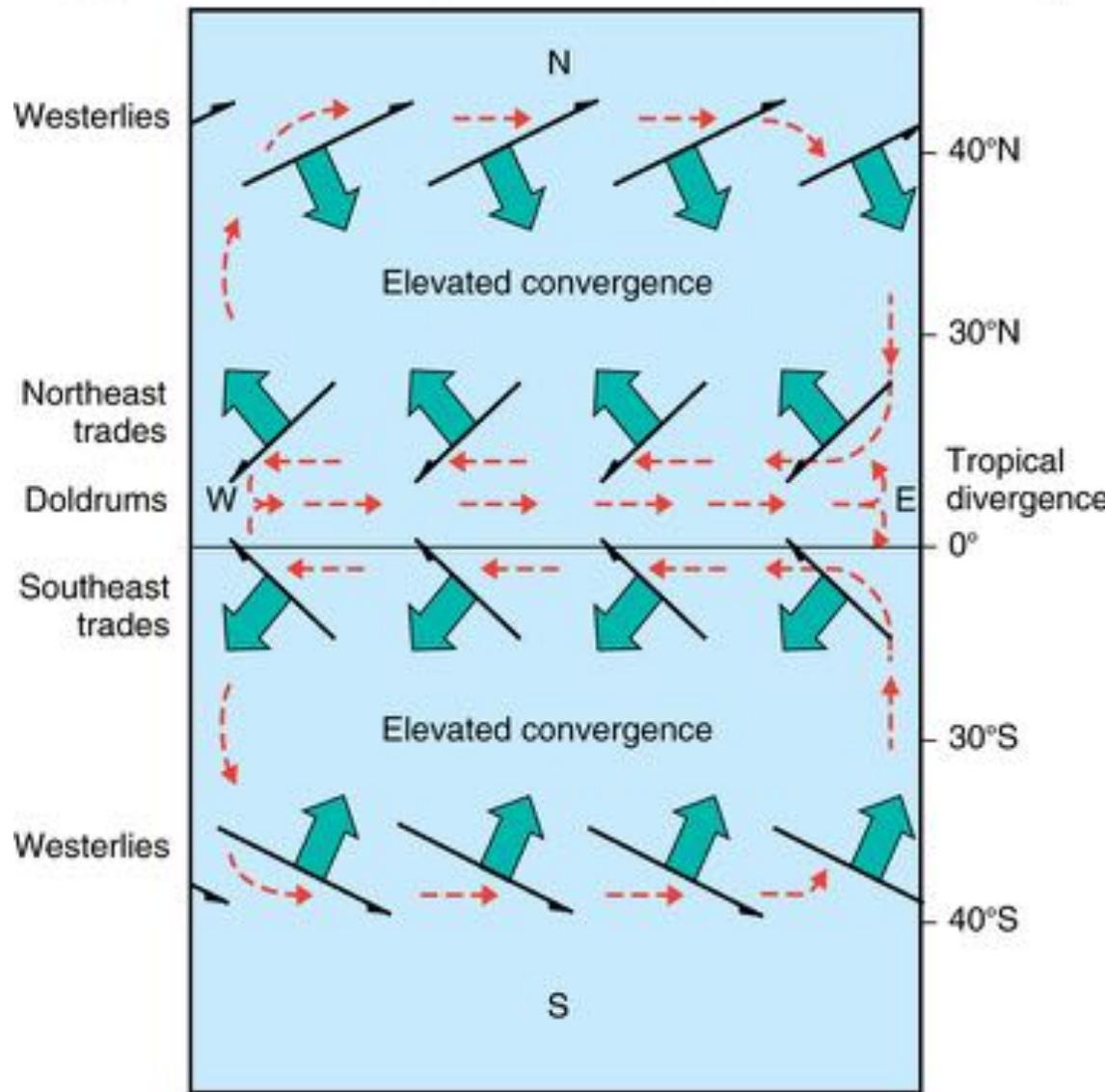


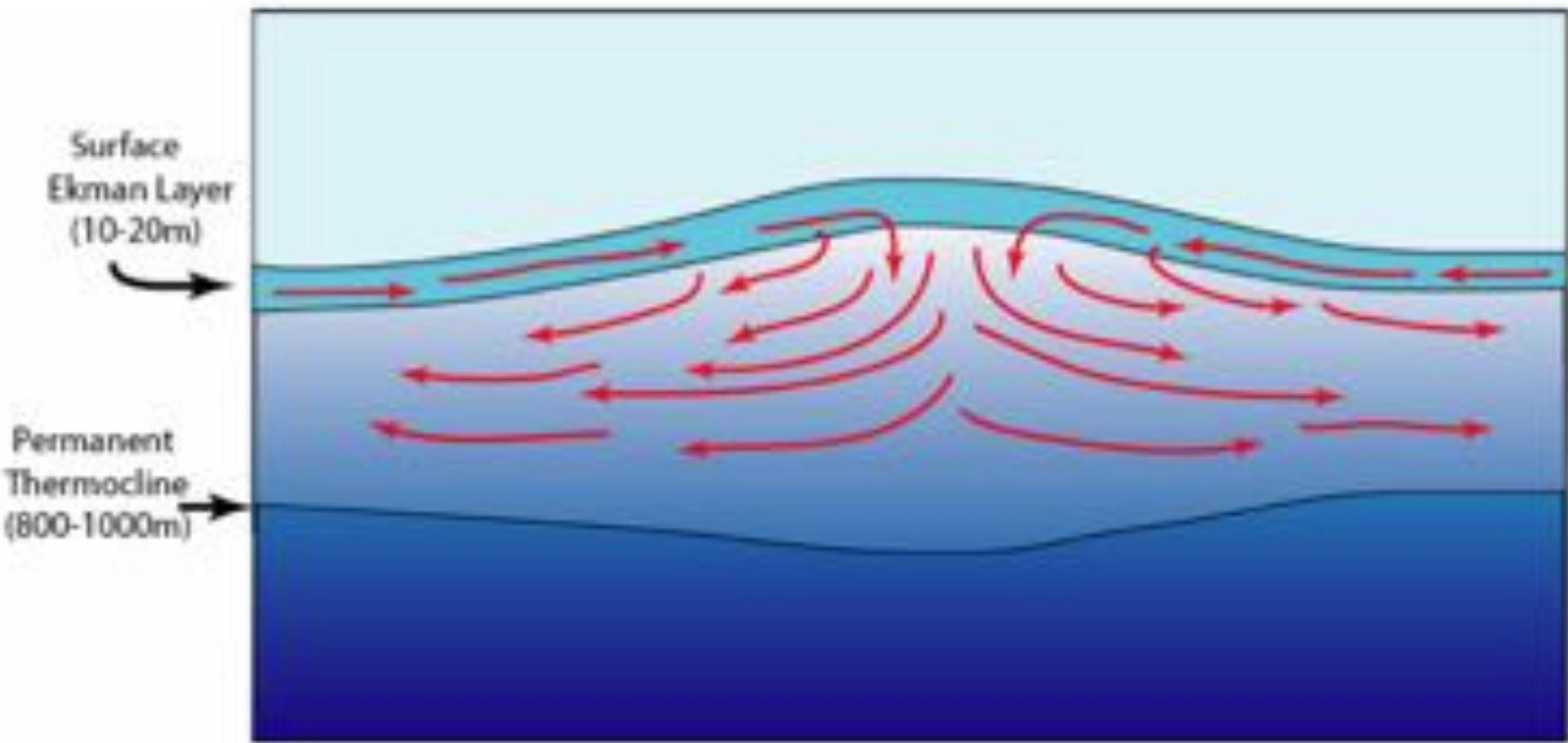
Figure 8.8 The Ekman spiral and the mechanism by which it operates. (a) The Ekman spiral model. (b) A body of water can be thought of as a set of layers. The top layer is driven forward by the wind, and each one below is moved by friction. Each succeeding layer moves with a slower speed and at an angle to the layer immediately above it—to the right in the Northern Hemisphere, to the left in the Southern Hemisphere—until friction becomes negligible. (c) Though the direction of movement is different for each layer in the stack, the theoretical average flow of water in the Northern Hemisphere is 90° to the right of the prevailing surface wind.

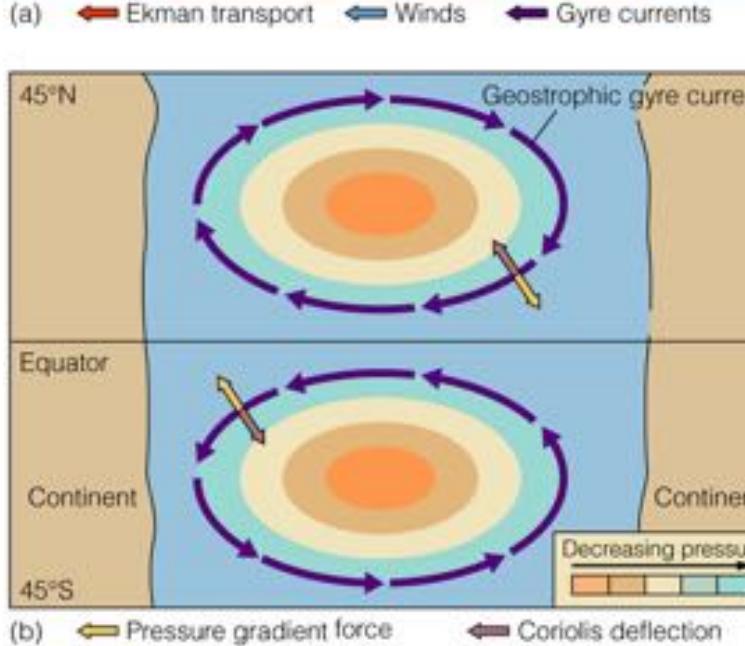
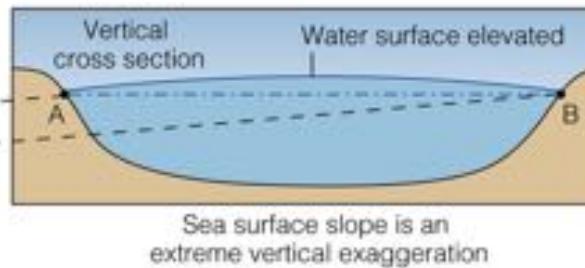
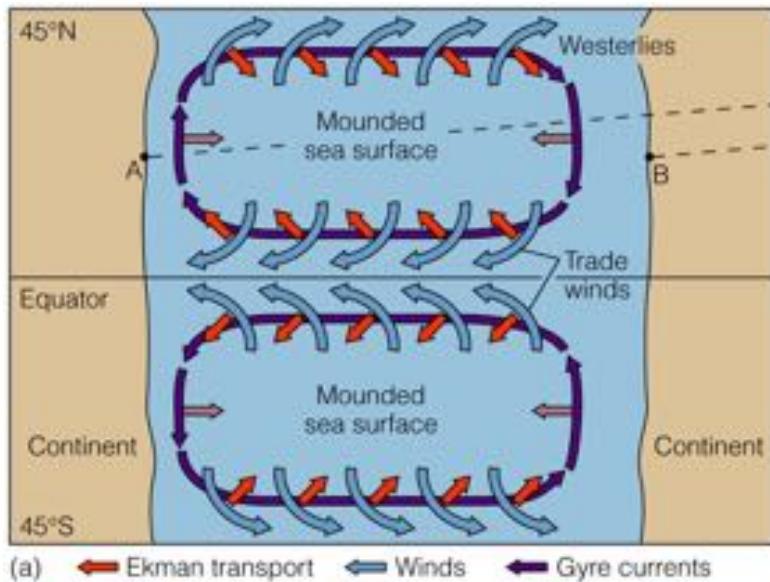
The North Atlantic Ocean





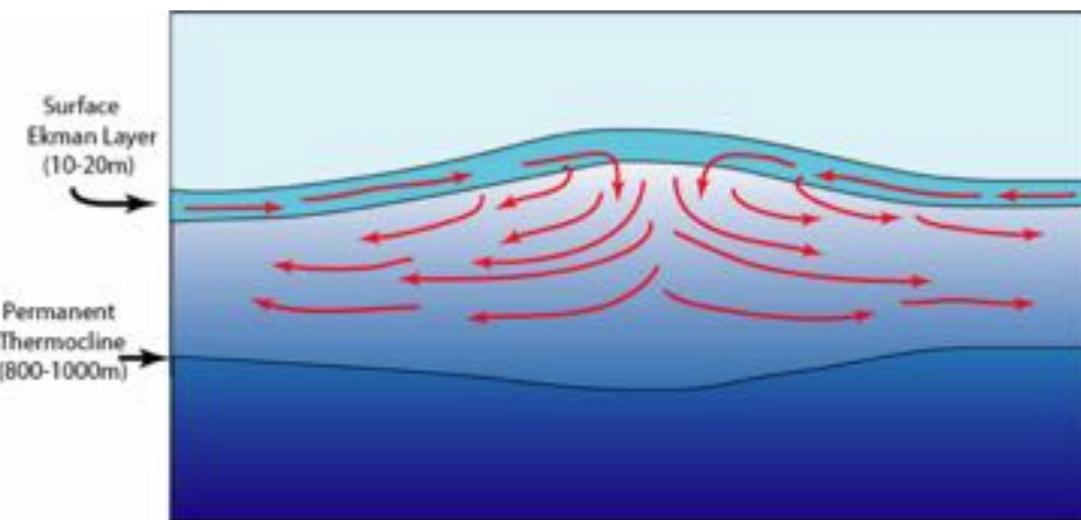
What happens is this:



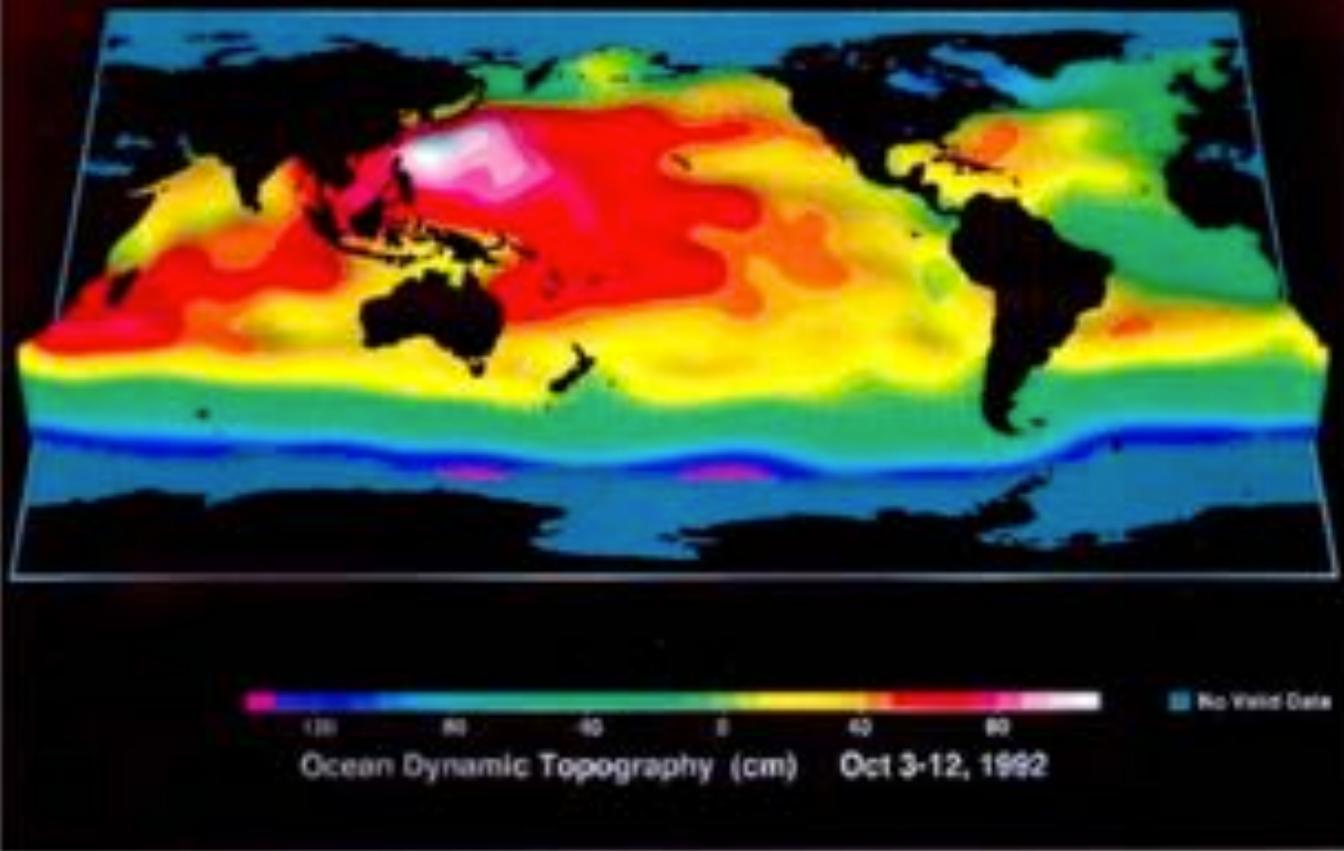


Ekman spiral can extend 100-200 m
 Ekman drift, typically 10-20 m
 - based on wind & turbulence
 - difficult to measure

Pycnocline: 100s of meters



Actual “Hills” in the Ocean...



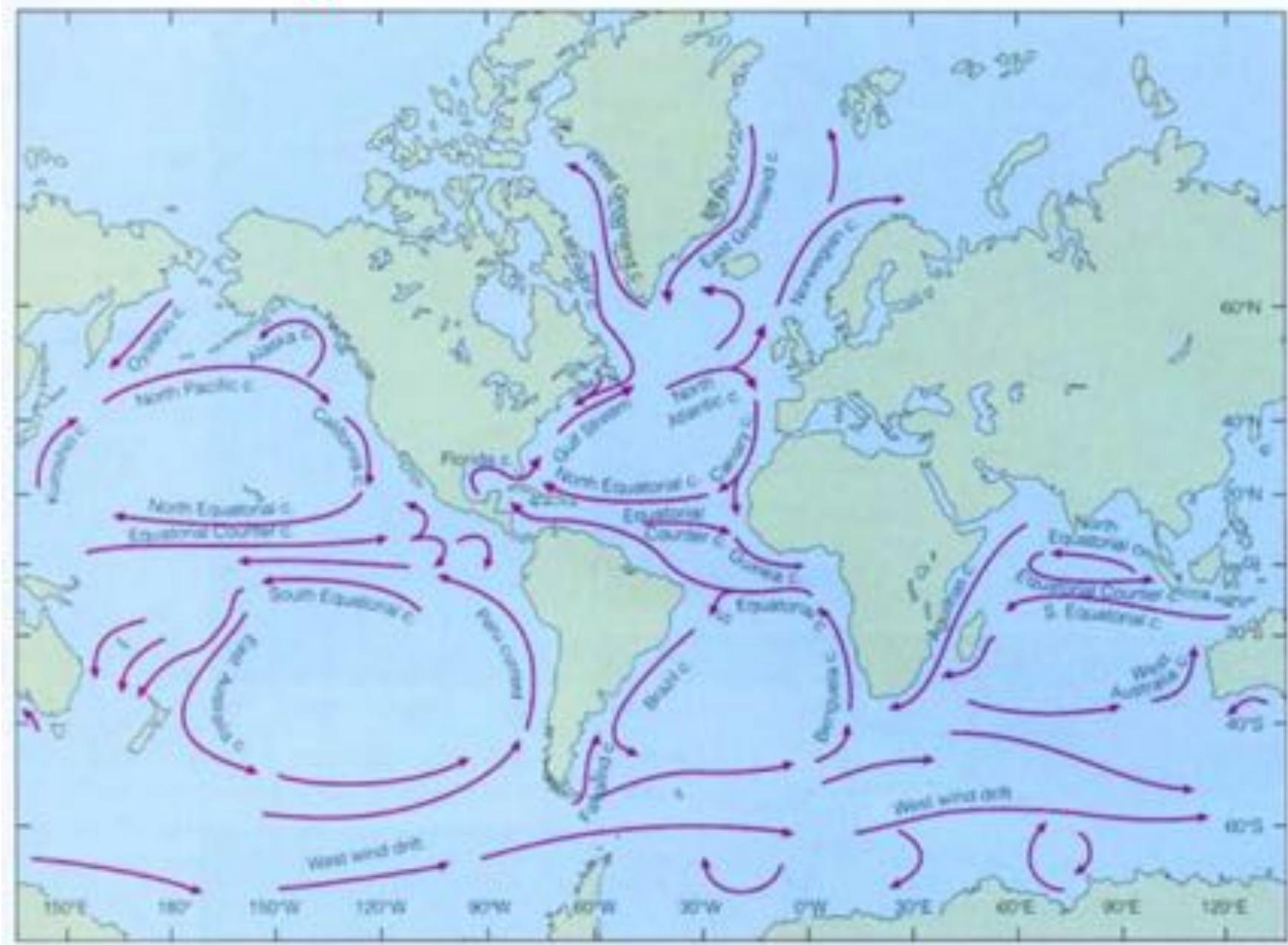
From the Topex-Poseidon Satellite
using “Radar Altimetry”...

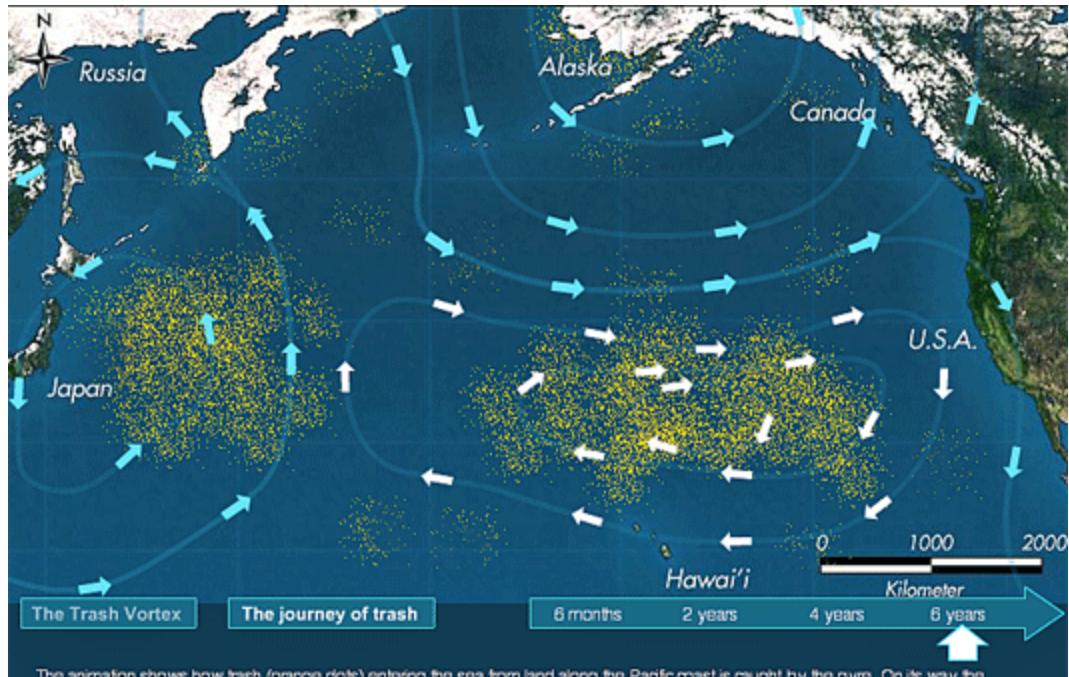
Geostrophy – pressure gradient balanced by Coriolis effect.



Image: David Townsend

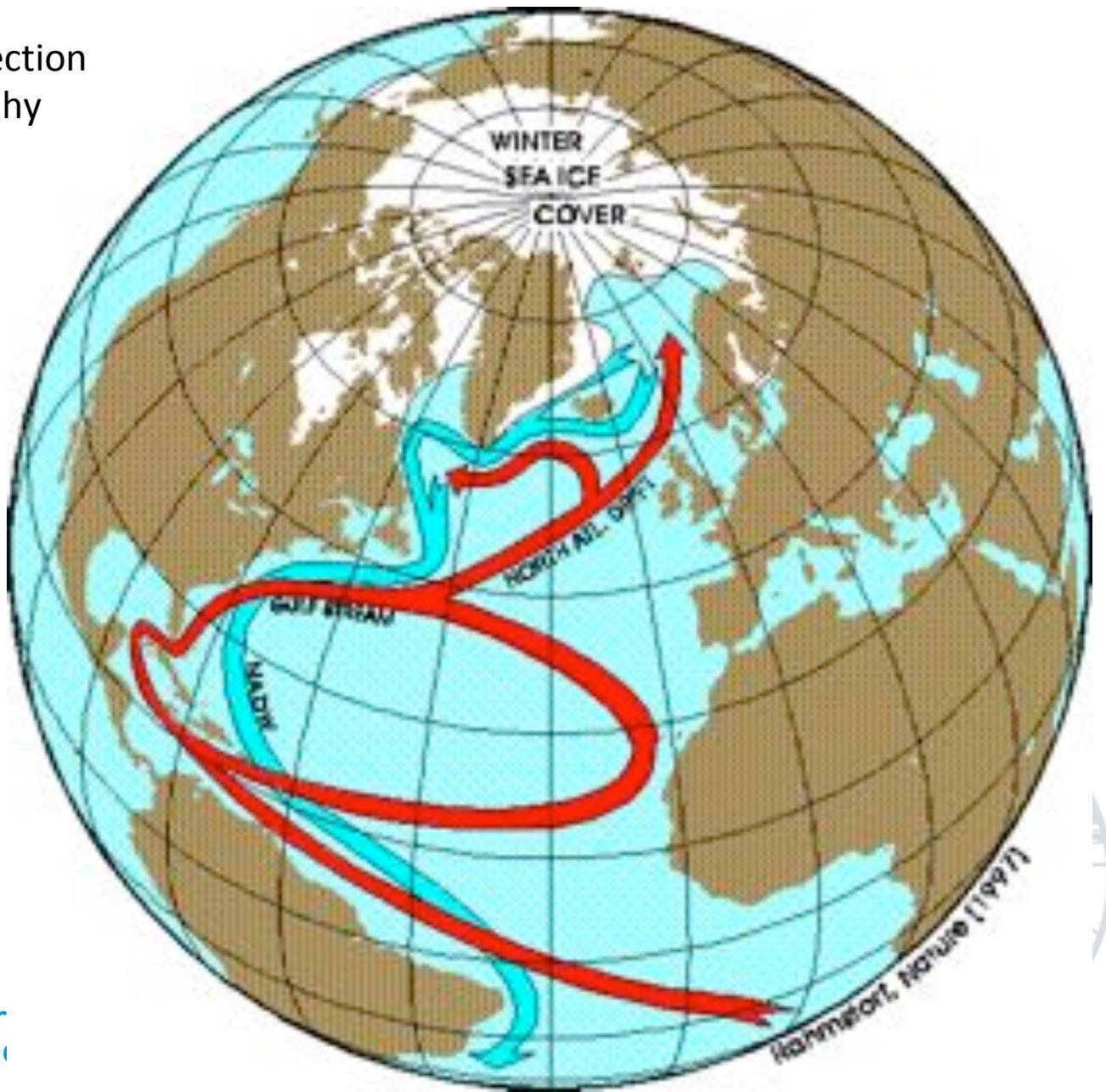
Resulting Global Ocean Circulation Patterns



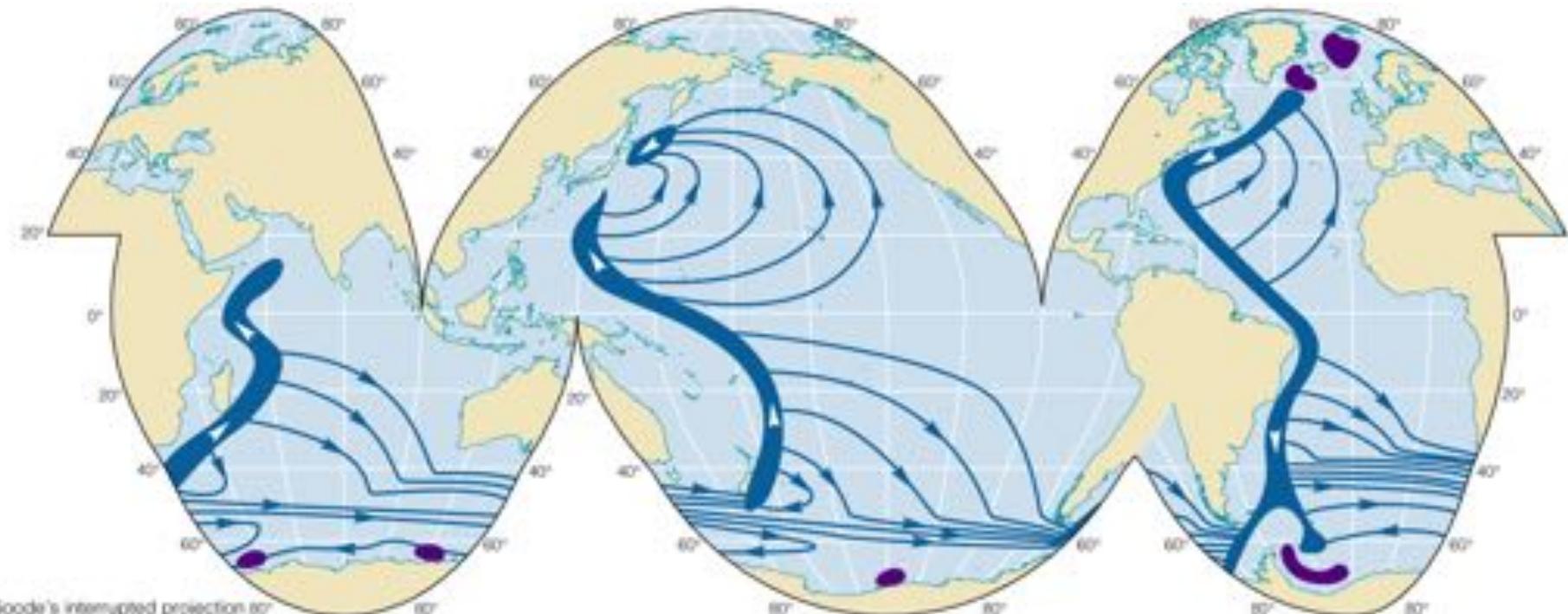


Global Thermo-Haline Circulation

1. Atmospheric convection
2. Coriolis & geostrophy
3. Deep convection



Sites of deep convection



Western boundary currents

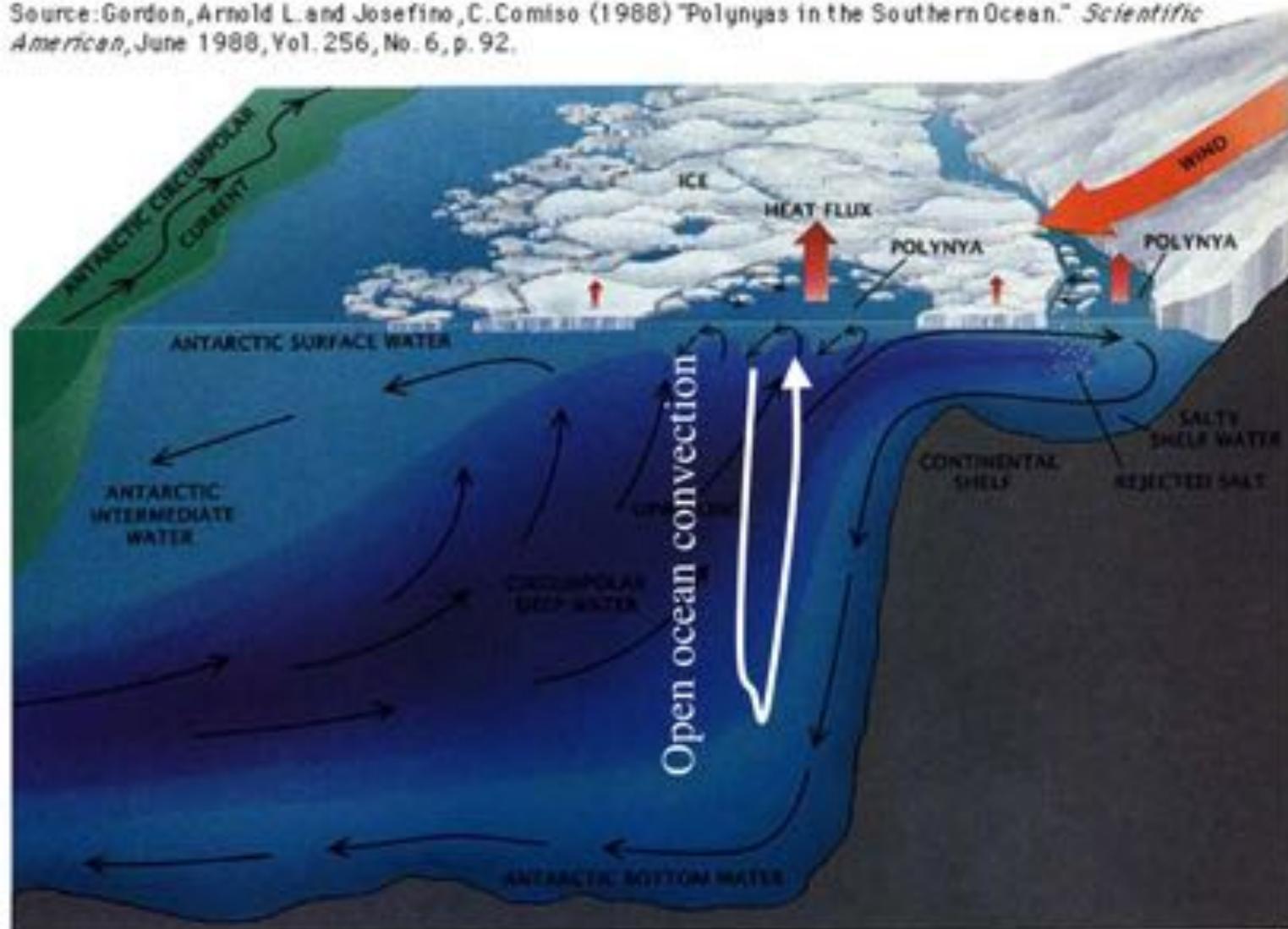
— Slow bottom currents



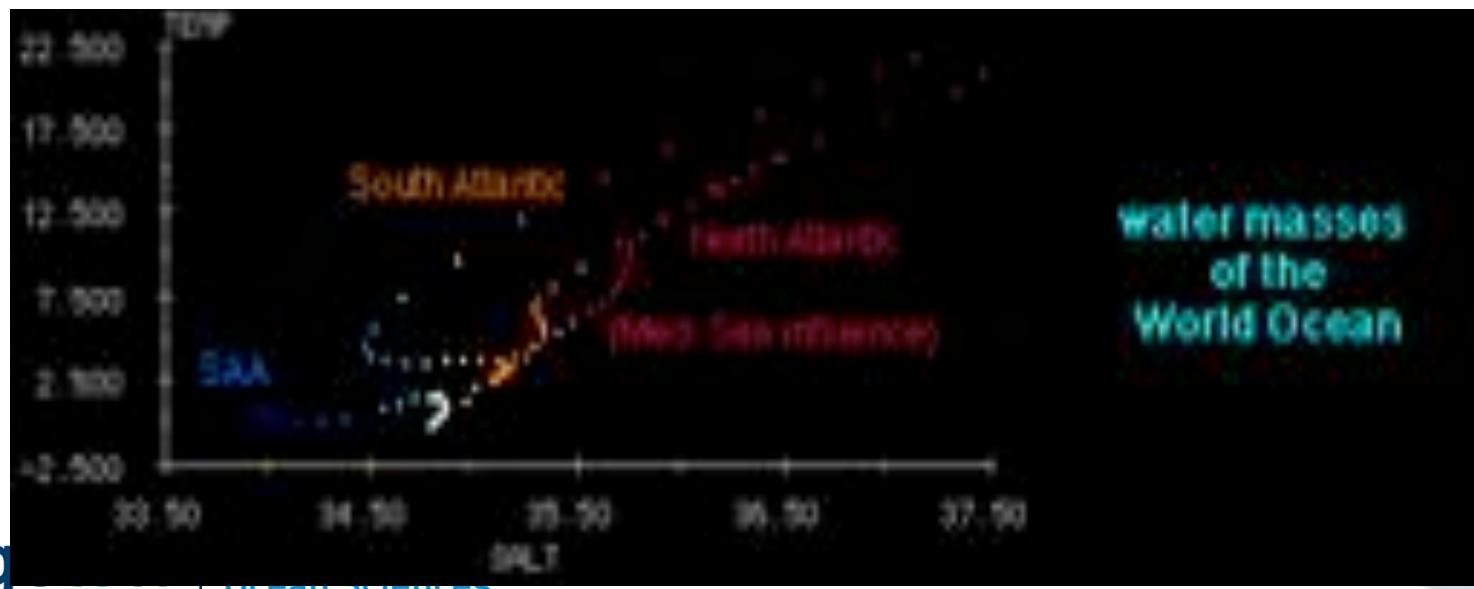
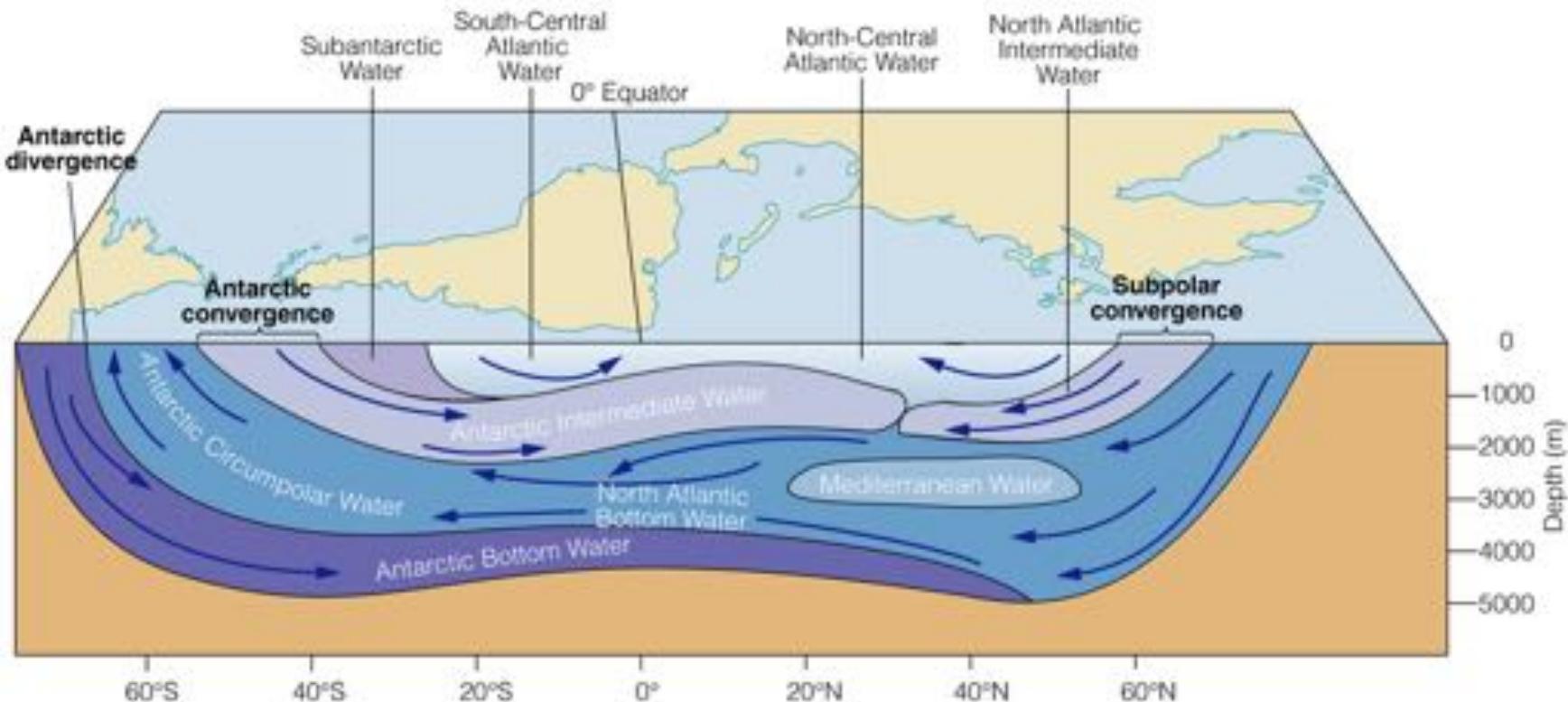
Major areas where the dense ocean bottom waters are formed and sink from the surface



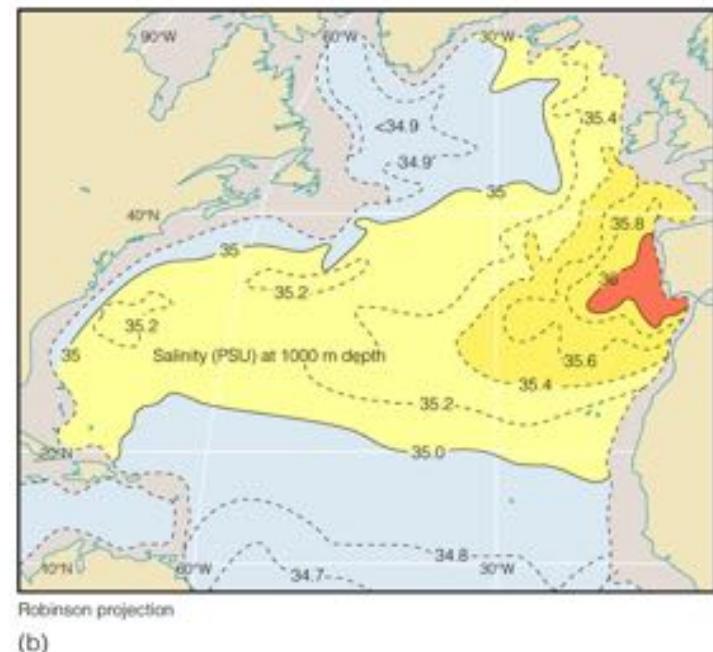
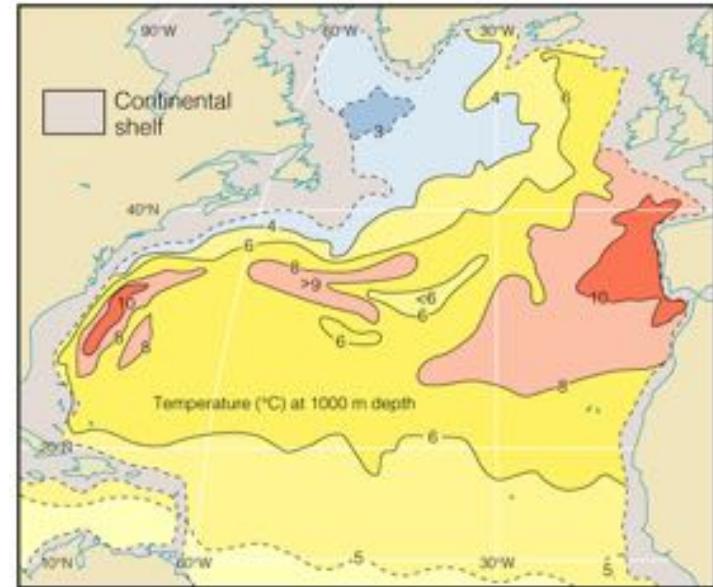
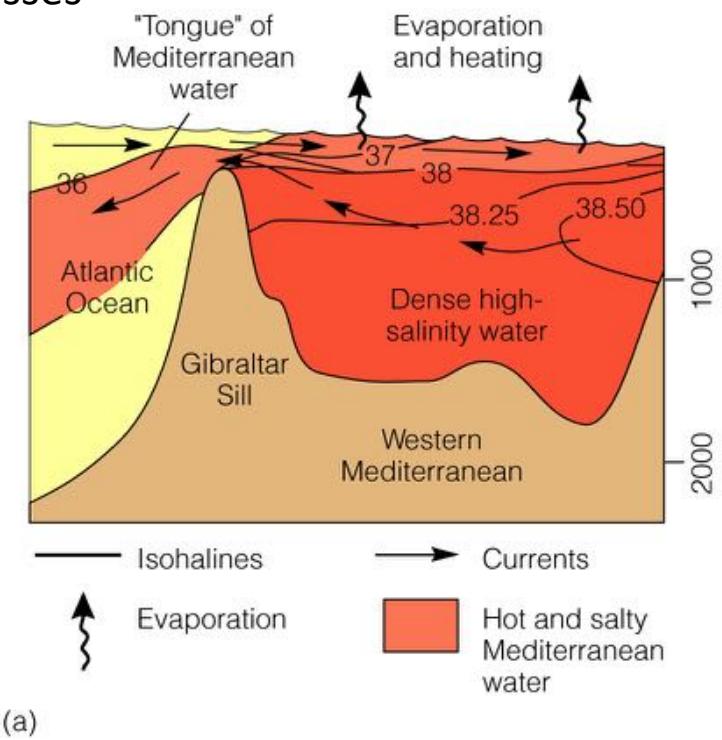
Source: Gordon, Arnold L. and Josefino, C. Comiso (1988) "Polynyas in the Southern Ocean." *Scientific American*, June 1988, Vol. 256, No. 6, p. 92.



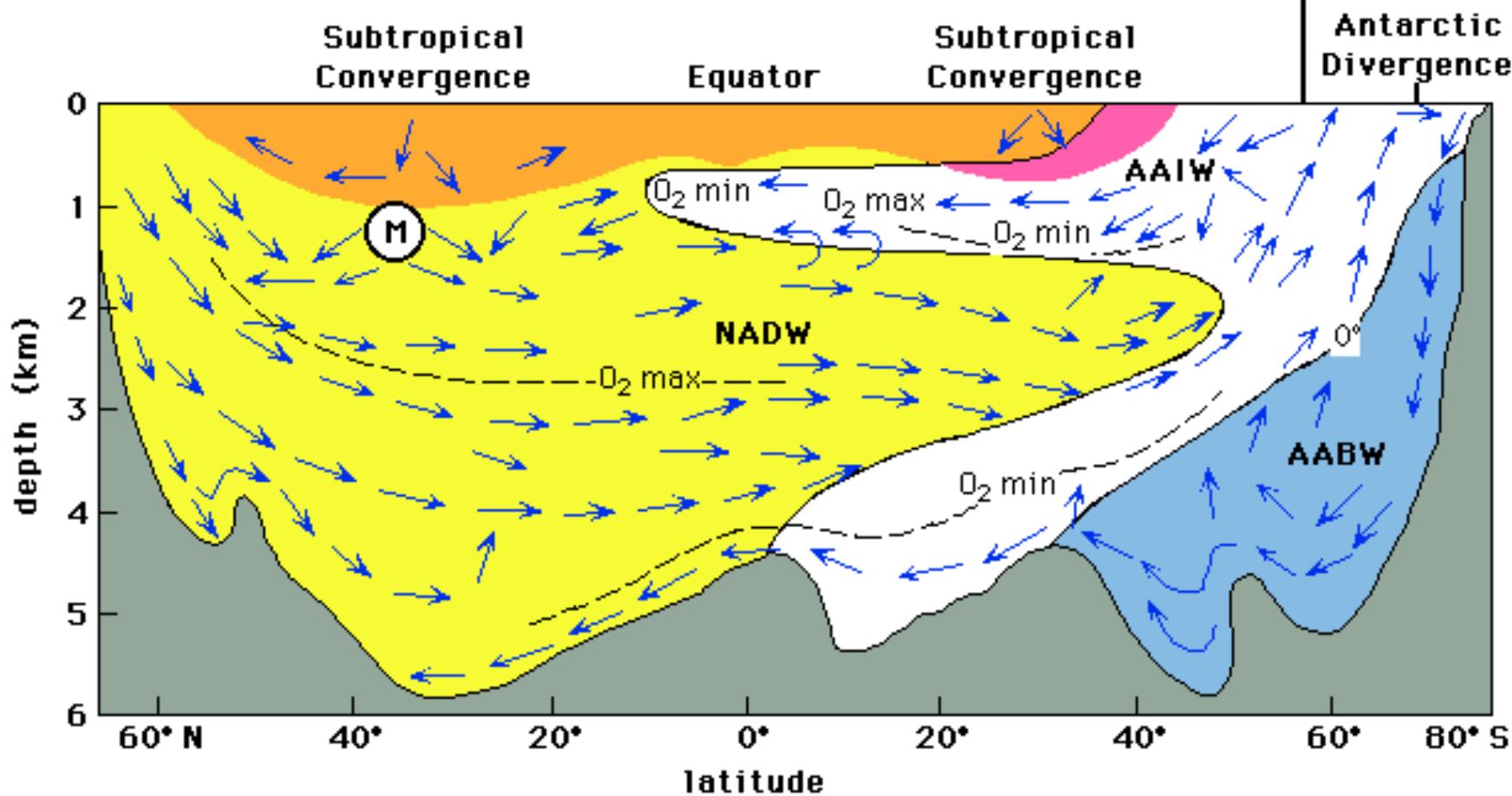
Meridional circulation pattern of the Southern Ocean (the ocean surrounding Antarctica) is dominated by the upwelling of a warm, salty water mass called the Circumpolar Deep Water and its transformation into Antarctic Surface Water, which ultimately sinks to become Antarctic Intermediate Water and Antarctic Bottom Water. The circulation is driven by wind and the exchange of heat and fresh water between the ocean and the atmosphere.



Water masses



Meridional cross-section of the Atlantic



NADW = North Atlantic Deep Water

AAIW = Antarctic Intermediate Water

AABW = Antarctic Bottom Water

M = Inflow of water from the Mediterranean

salinity > 34.8

water warmer than 10°C

water cooler than 0°C

direction of water flow

Adapted from Open University (1989) *Ocean Circulation*, Pergamon Press.

Other tracers for identification of water masses:

1) Natural:

- 1) Nutrients (PO_4 , SiO_4 , O_2 , Ba, other trace metals...)
- 2) Isotopes (He, Ra/Rn, ^{18}O , ^{14}C , ...)

2) Anthropogenic:

- 1) Isotopes (tritium ^3H , strontium, ^{14}C , freons, ...)
- 2) Arctic: pesticides

Antarctic Intermediate W

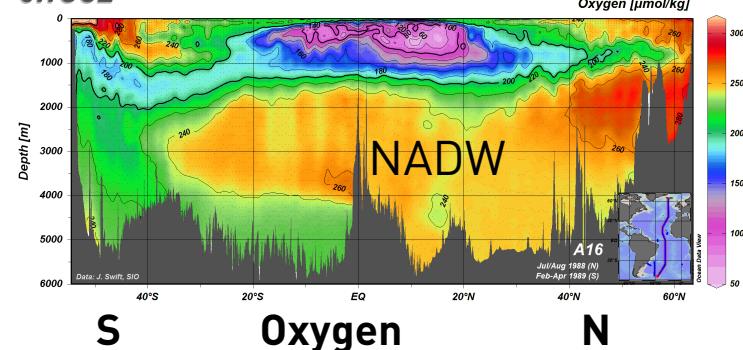
Antarctic Bottom W

Mediterranean

N Atlantic Deep W

S

eWOCE



S

Oxygen

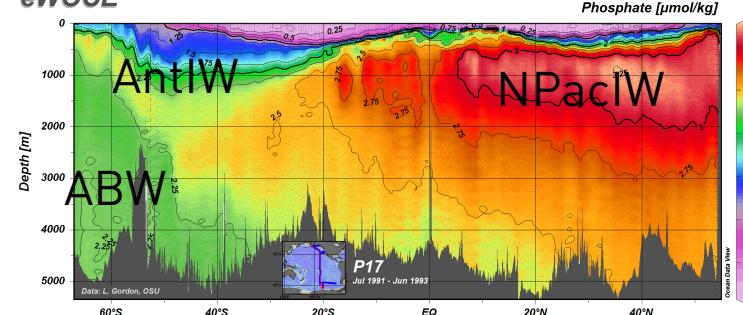
N

S

Phosphate

N

eWOCE



60°S

40°S

20°S

EQ

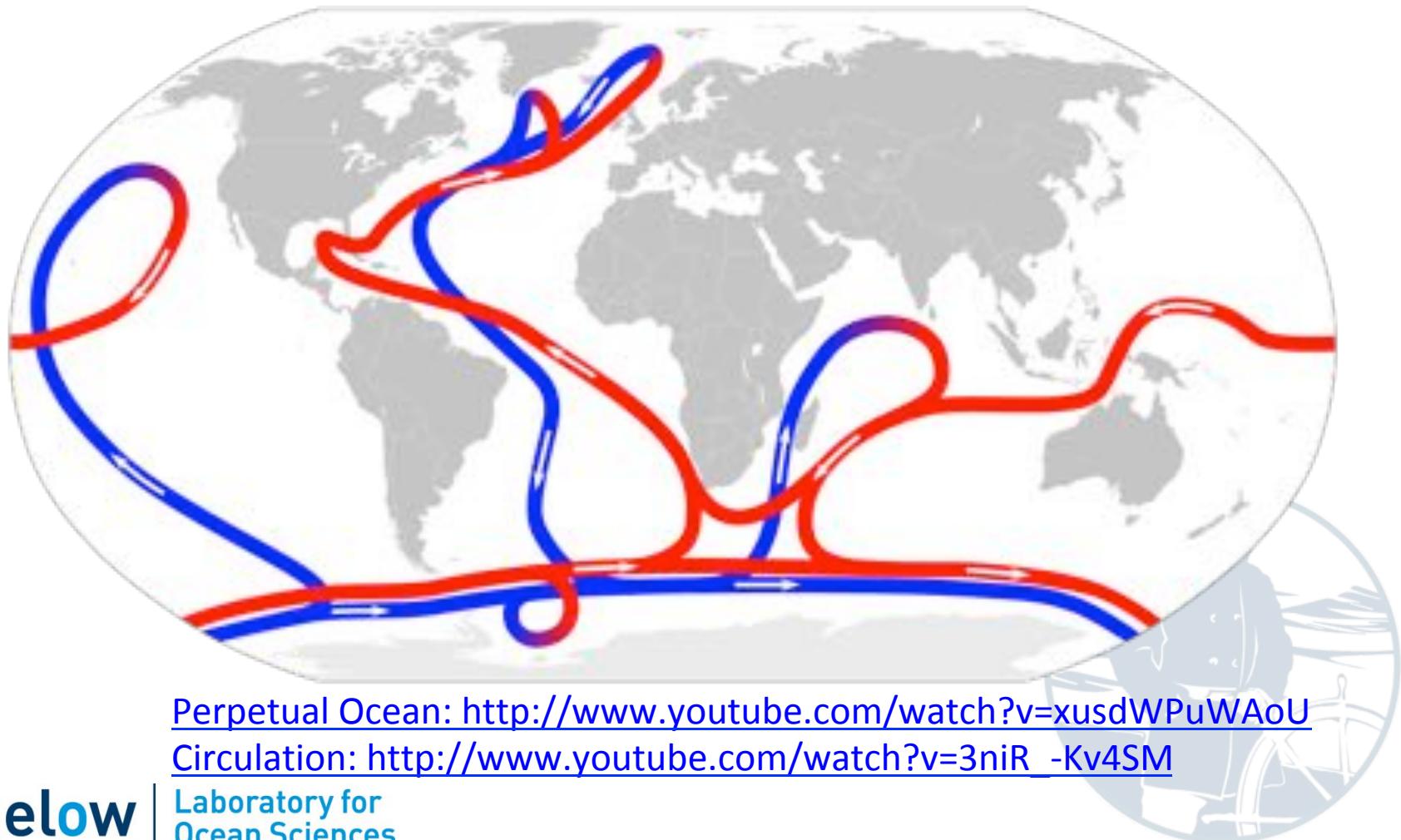
20°N

40°N

60°N

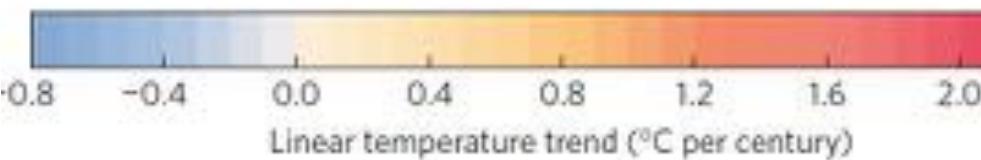
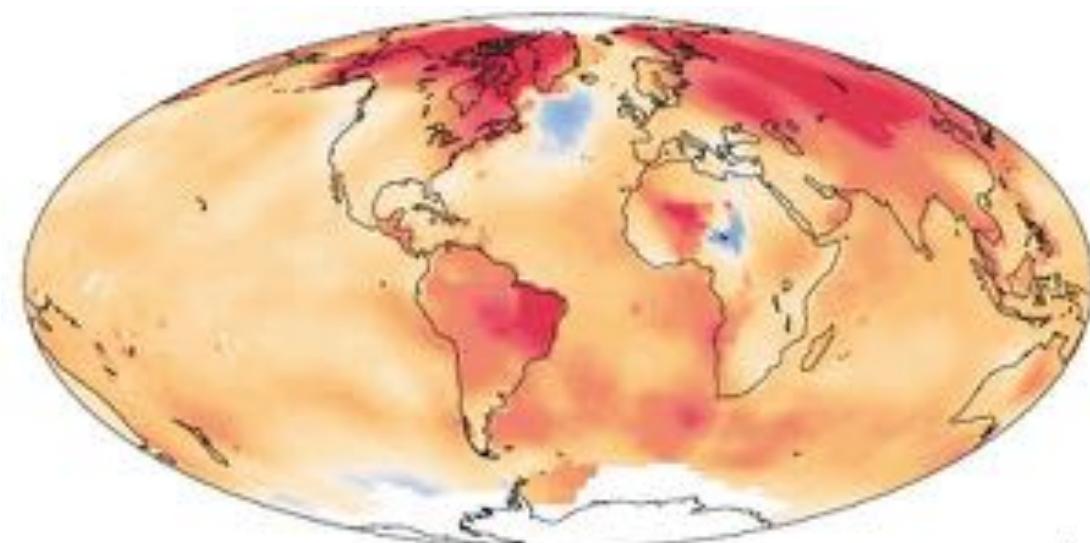
Global Thermohaline Circulation

(Simpler Picture)



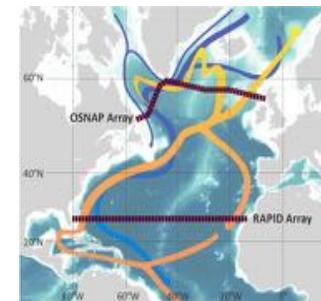
Perpetual Ocean: <http://www.youtube.com/watch?v=xusdWPuWAoU>
Circulation: http://www.youtube.com/watch?v=3niR_-Kv4SM

What's changing? The Atlantic Meridional Overturning Circulation = AMOC



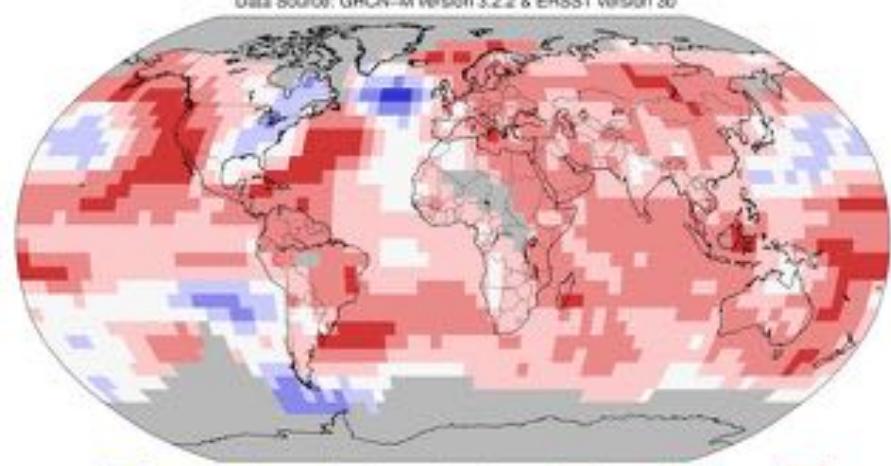
Linear temperature trend from 1900 to 2013. The cooling in the subpolar North Atlantic is remarkable and well documented by numerous measurements – unlike the cold spot in central Africa, which on closer inspection apparently is an artifact of incomplete and inhomogeneous weather station data (Rahmstorf et al. 2015).

- Natural variability?
- Wind-driven or buoyancy (density)-driven?
- Teleconnection? Atlantic Multidecadal Oscillation (SST) and/or Atlantic Oscillation (winds)?
- Global warming?



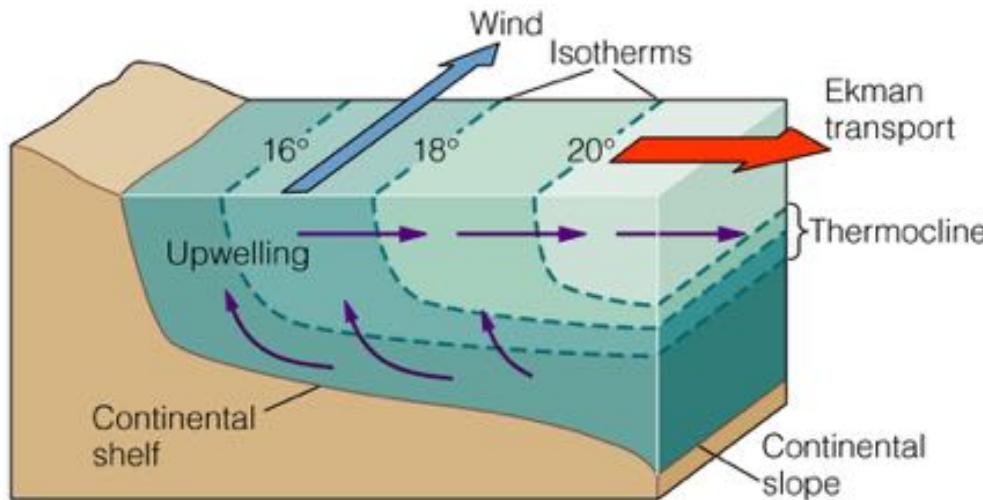
=> RAPID
(26°N) and
OSNAP
(50–60°N)
arrays

Land & Ocean Temperature Percentiles Dec 2014–Feb 2015
NOAA's National Climatic Data Center
Data Source: GHCN-M version 3.2.2 & ERSST version 3b

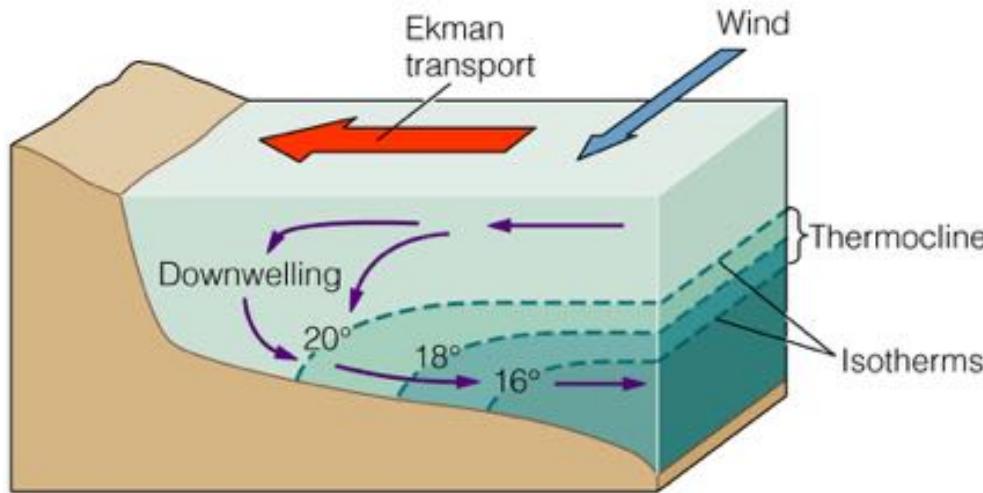


Other currents

Upwelling & Downwelling



(a) Upwelling



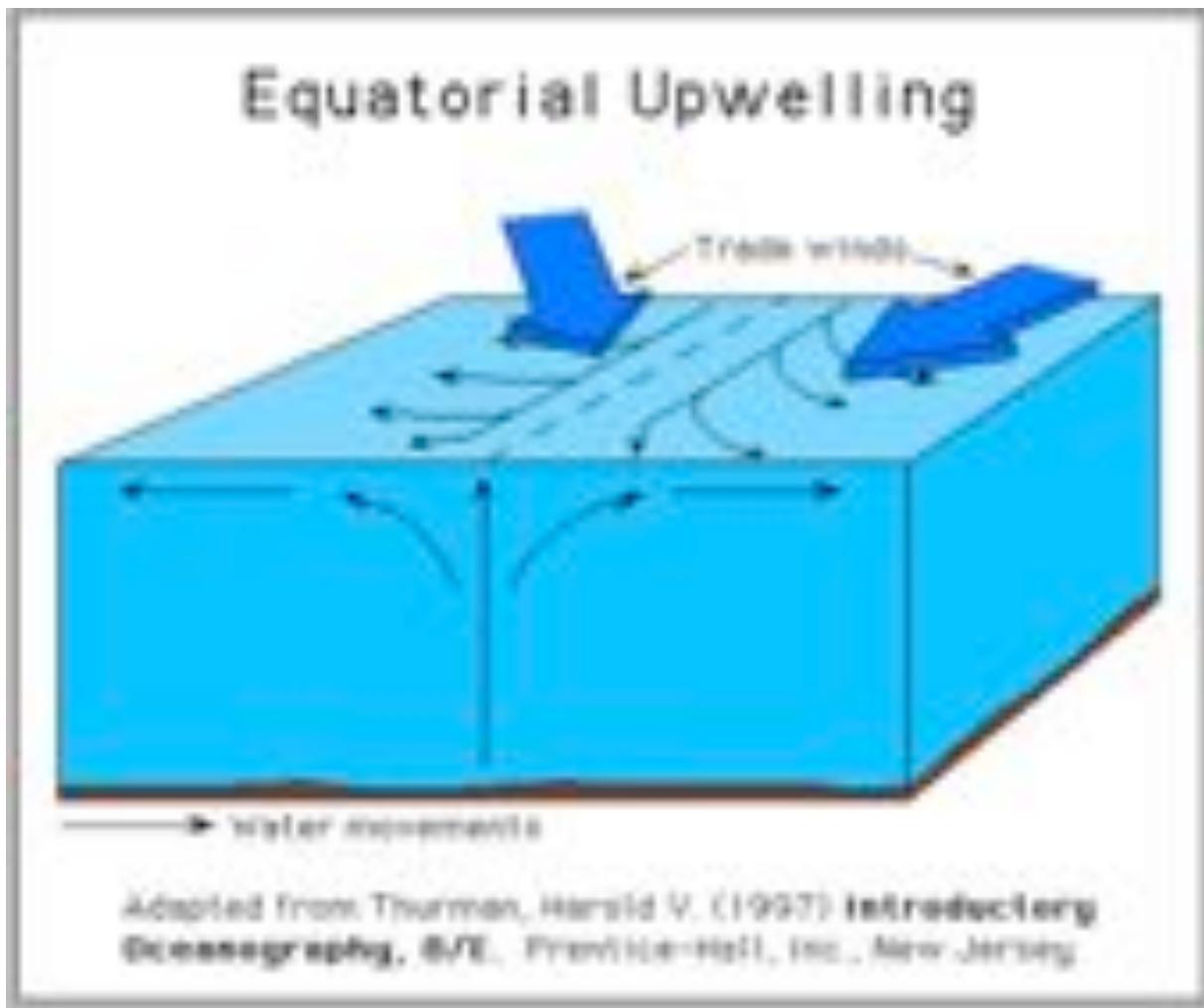
(b) Downwelling

B

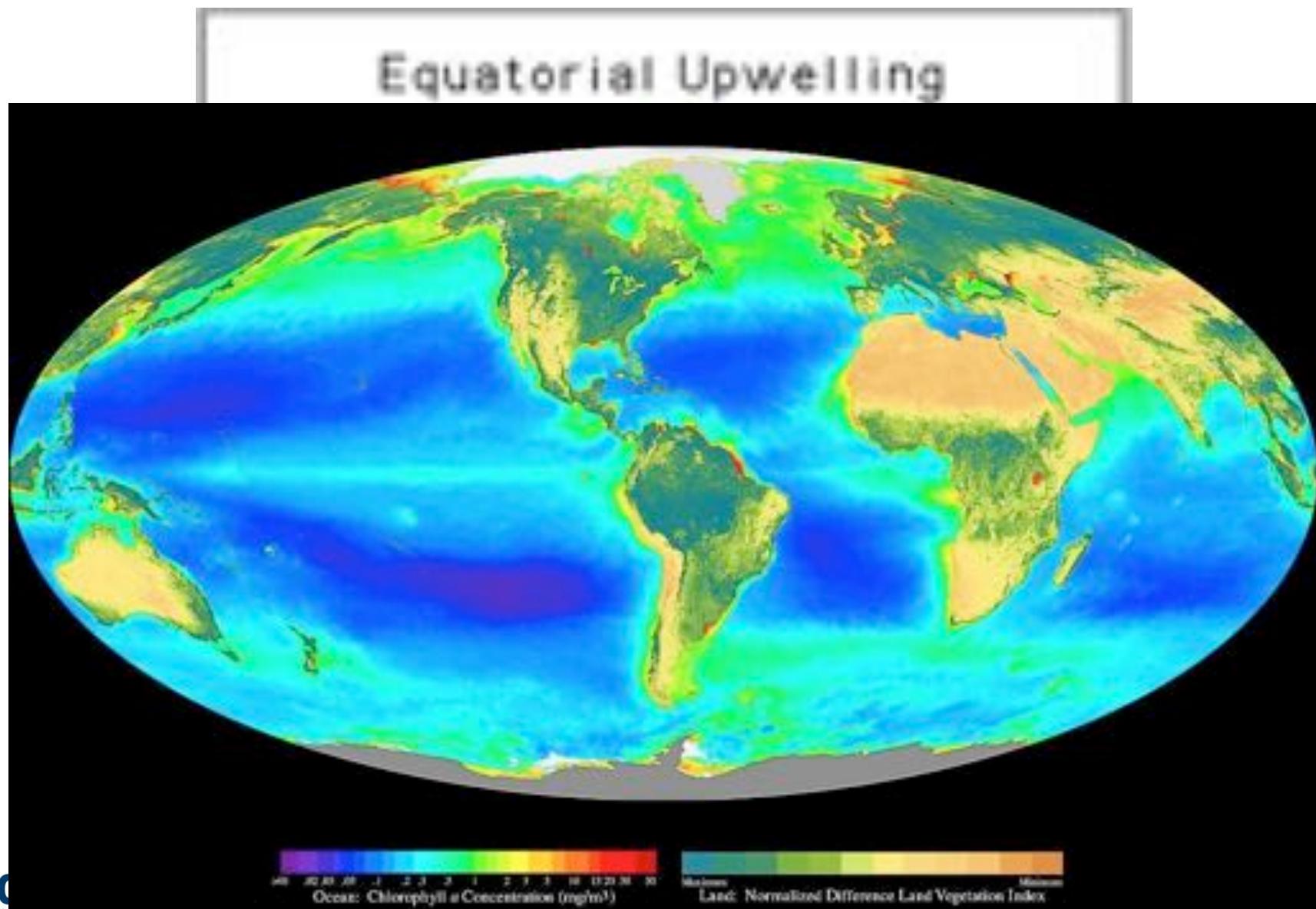
Water mass movements →



Other currents



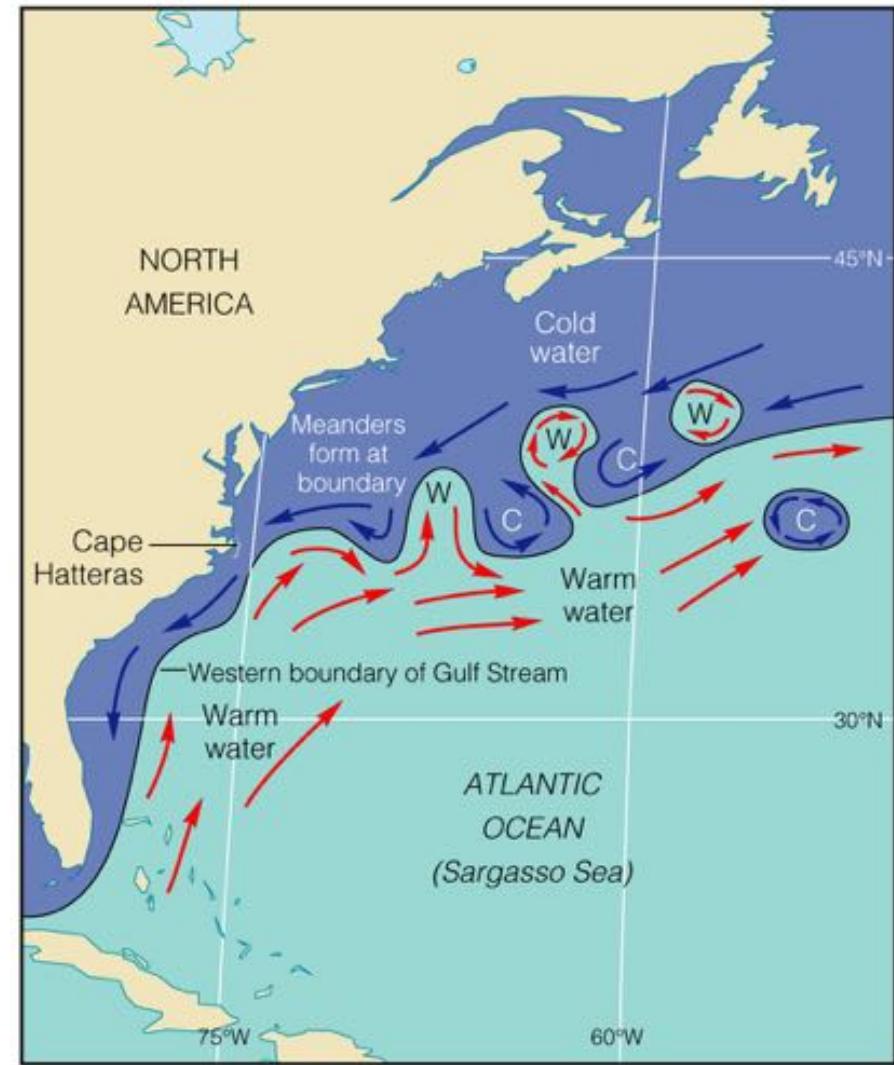
Other currents



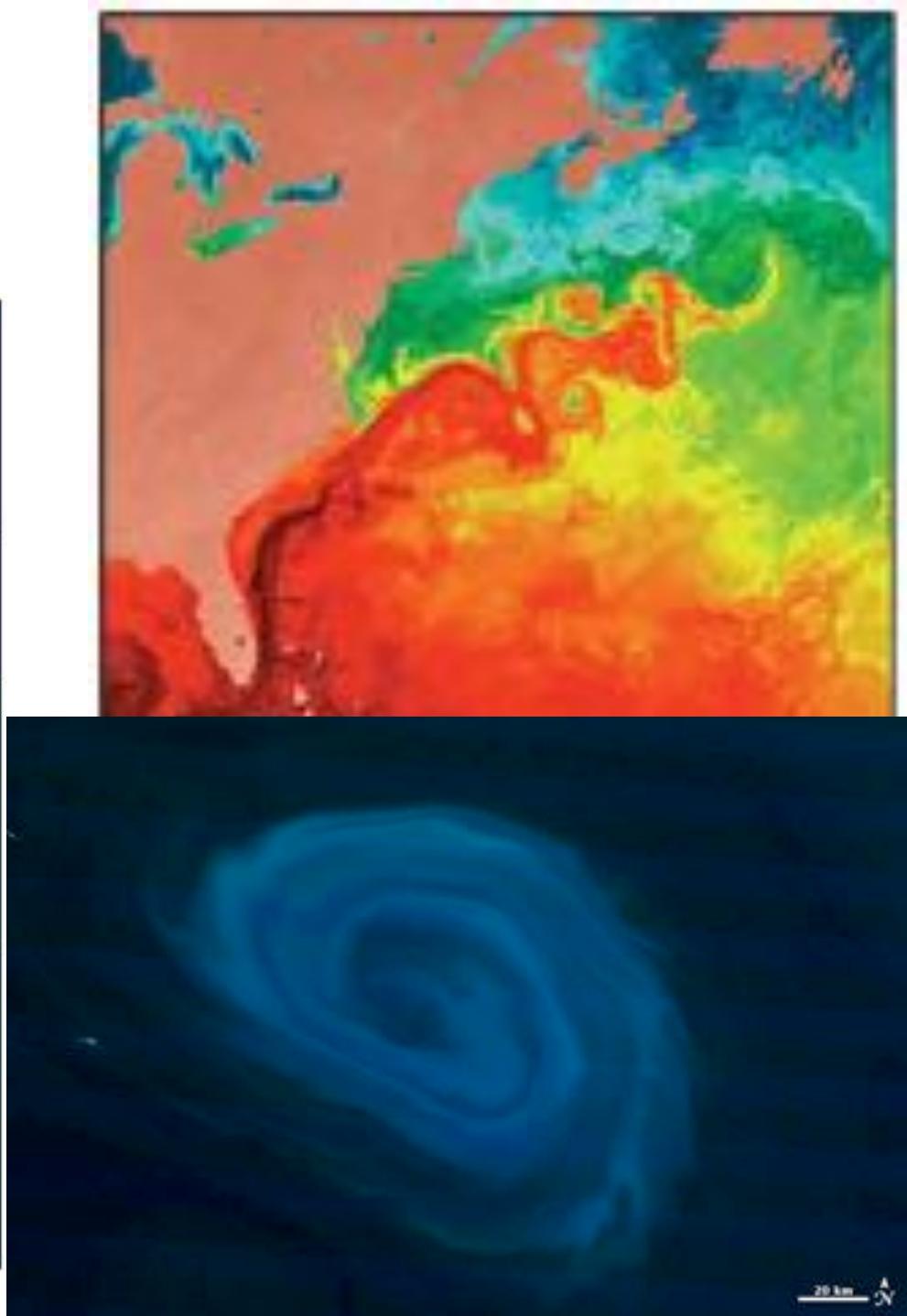
Big

Other currents

Eddies

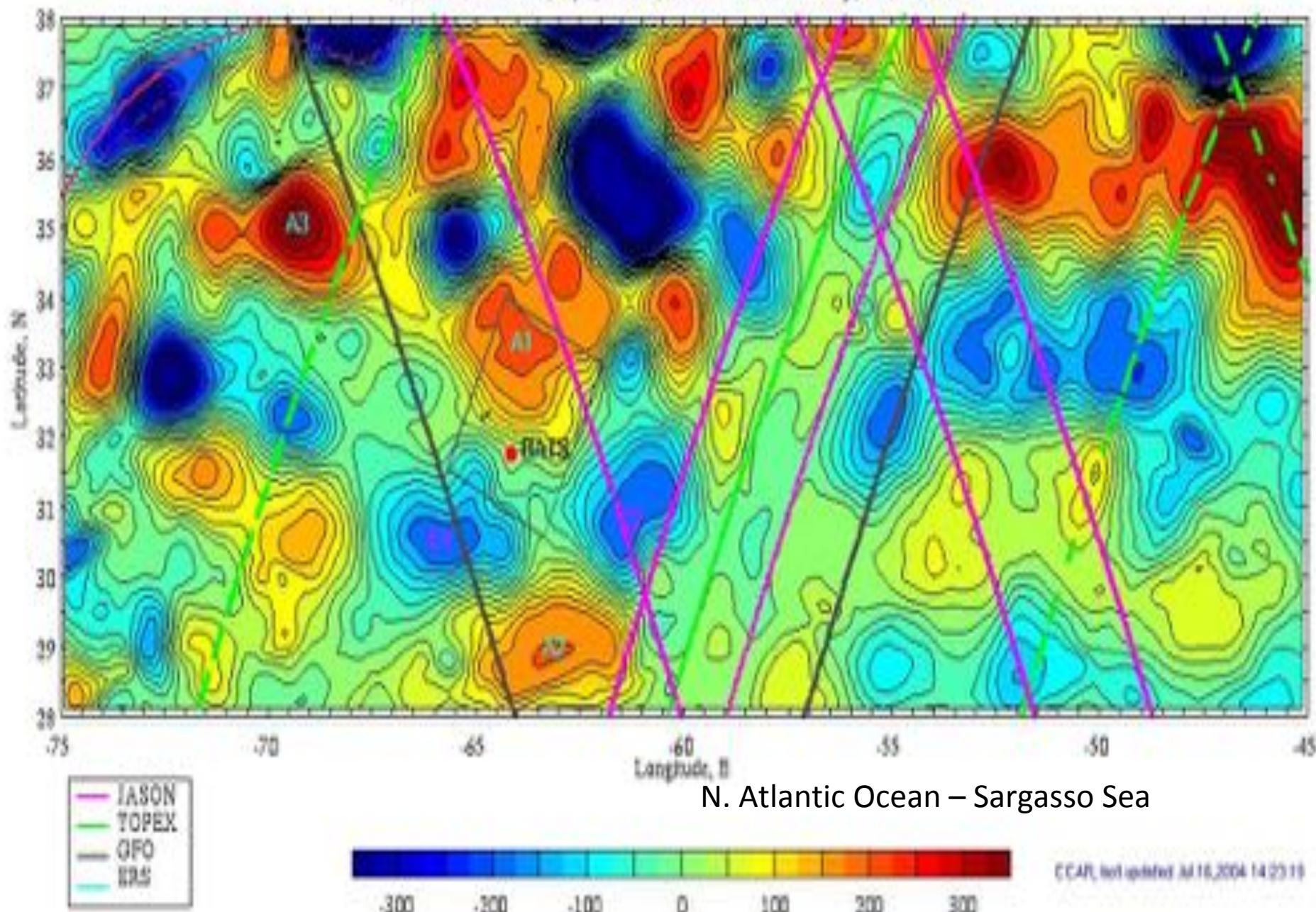


Robinson projection



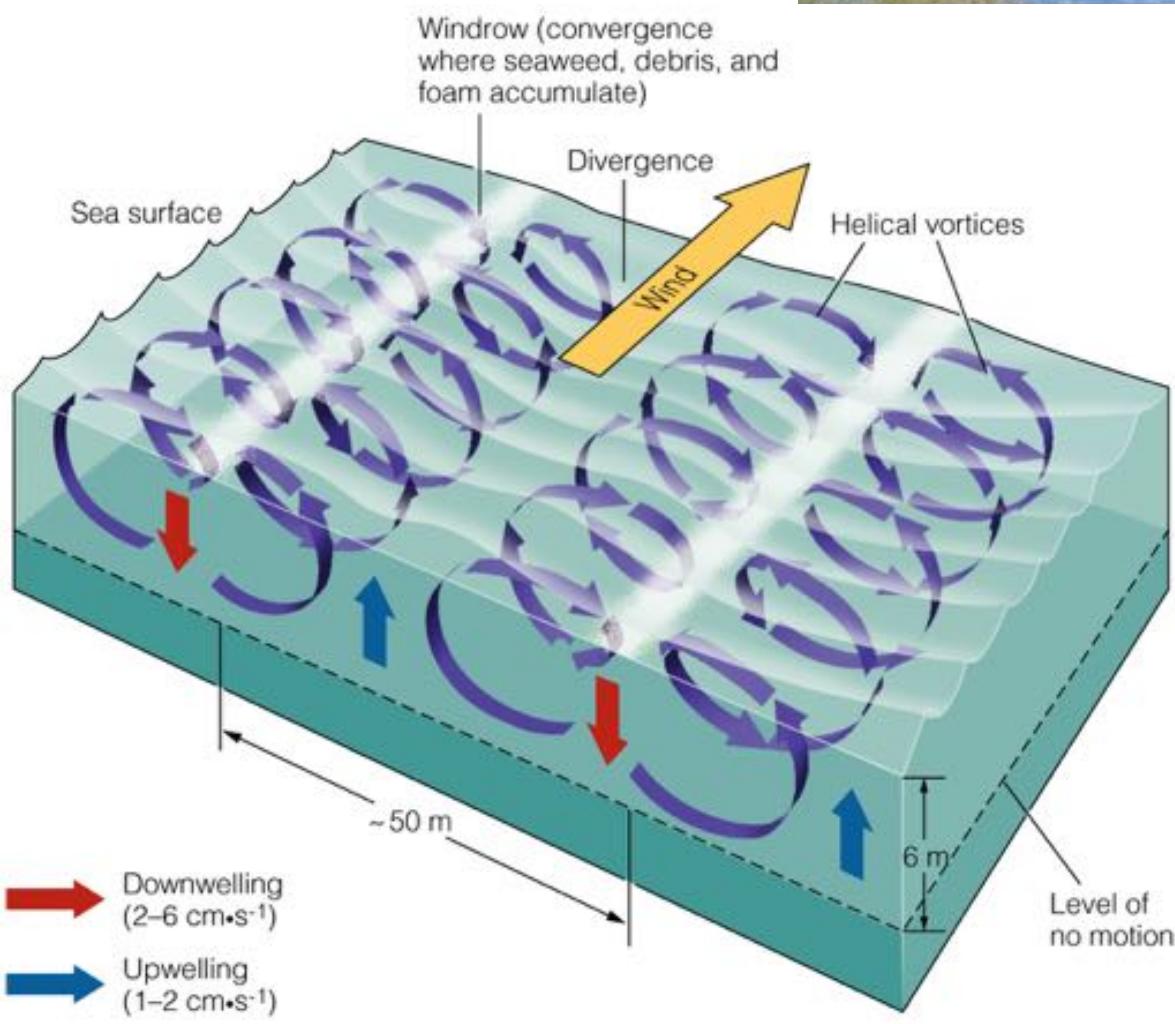
Sea surface height maps: eddies everywhere!

SLA from Jason, T/P, GFO, and ERS altimetry, 15-Jul-2004



Other currents

Langmuir Circulation



(a)

Other currents

Langmuir Circulation



Climate

Long term statistical properties at a location

- temperature, precipitation, etc.
- is an average (or other statistical property) over long period of time
- can be large or small spatial scale

According to IPCC, includes:

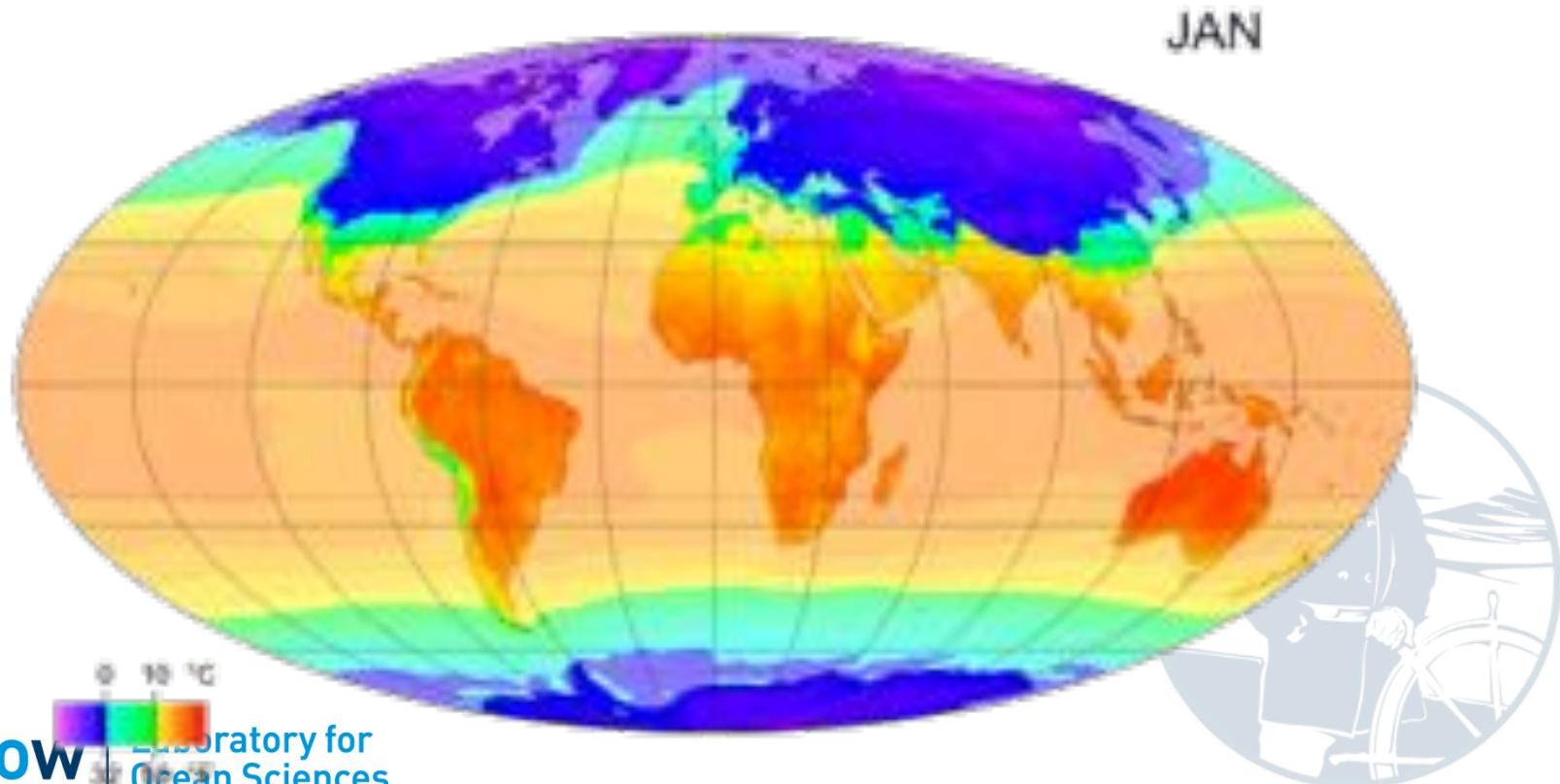
- atmosphere, hydrosphere, cryosphere, land surface, and biosphere

Note: IPCC = Intergovernmental Panel on Climate Change



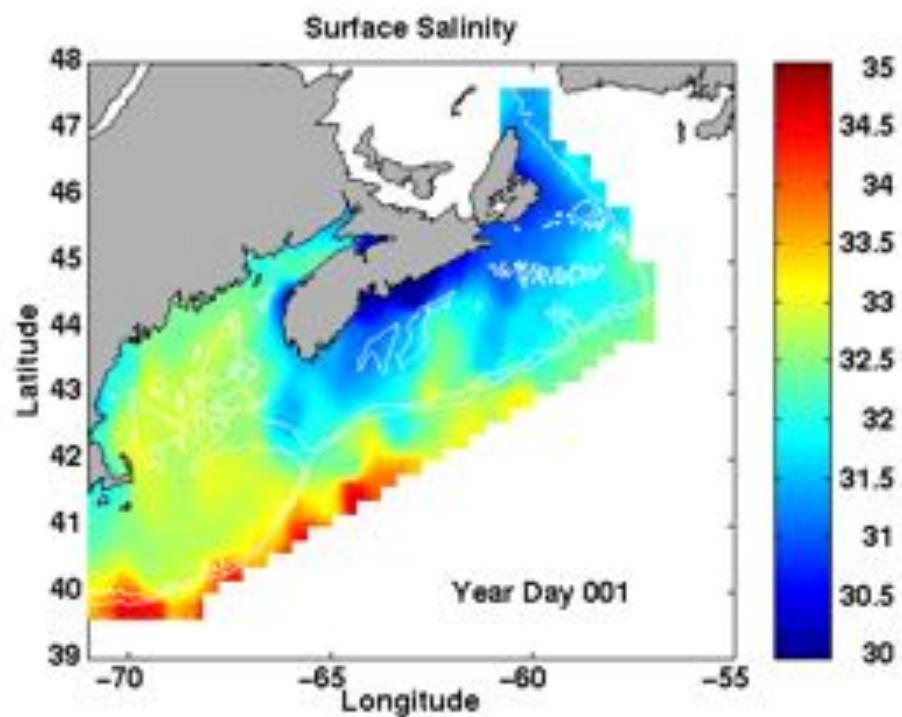
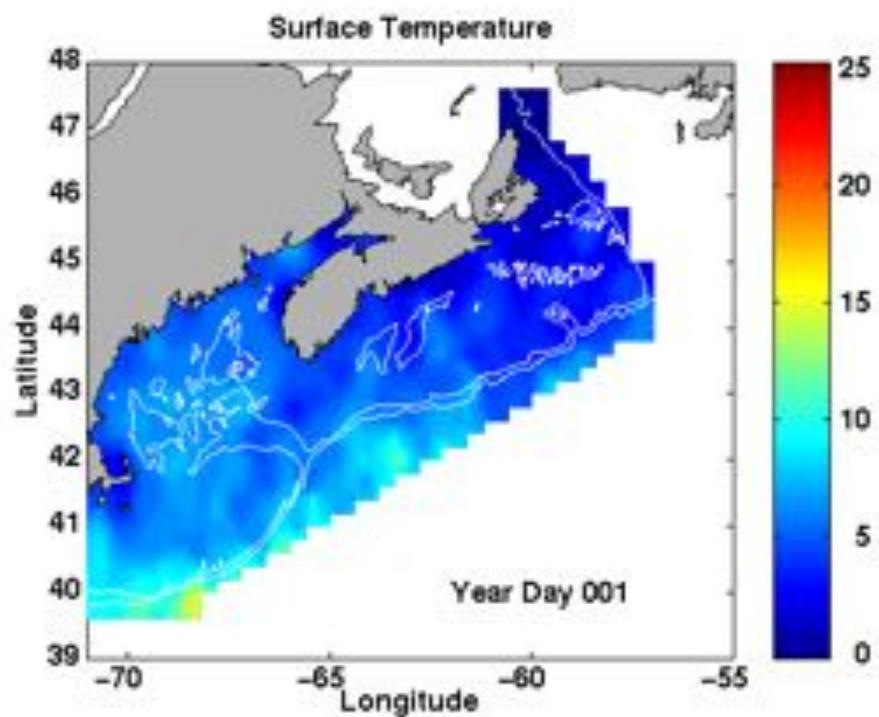
Climatology

- Representation of average conditions, typically a seasonal cycle



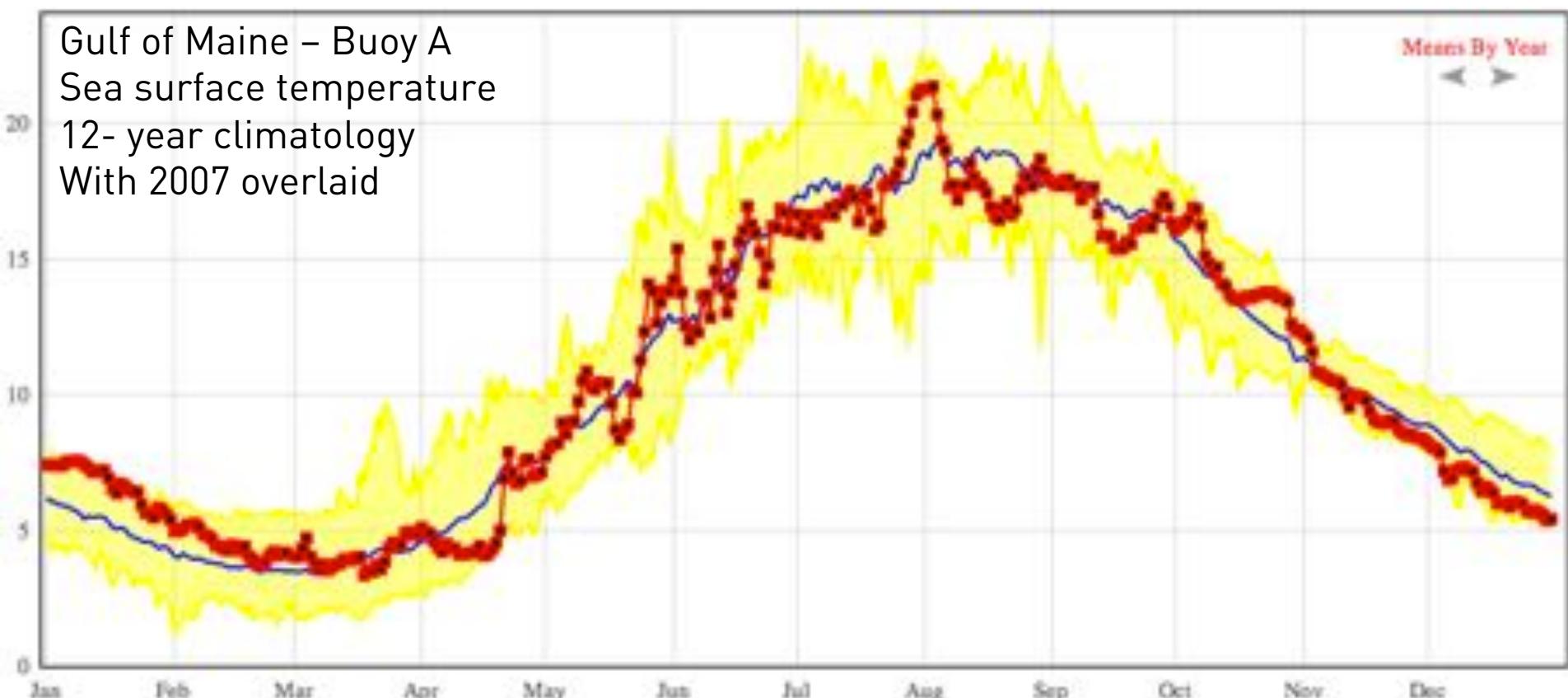
Climatology

Gulf of Maine surface conditions through a climatological year DFO Canada



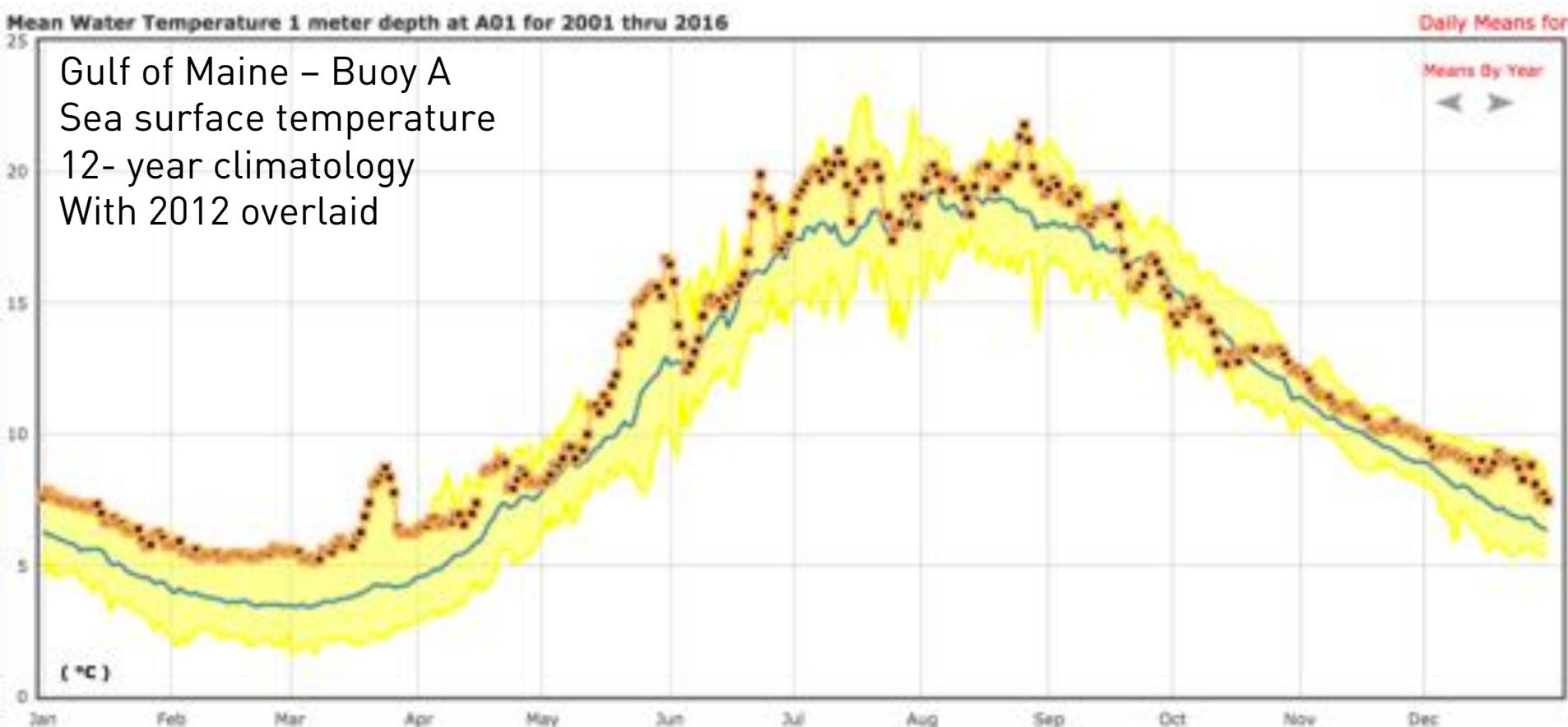
Climatology

- A climatological year never quite occurs
- Data: <http://neracoos.org/datatools/>



Climatology

- ... but some years deviate more than others



Climate versus Weather

- We can't predict the weather 2 weeks from now.
- How can we predict the climate in 2050?

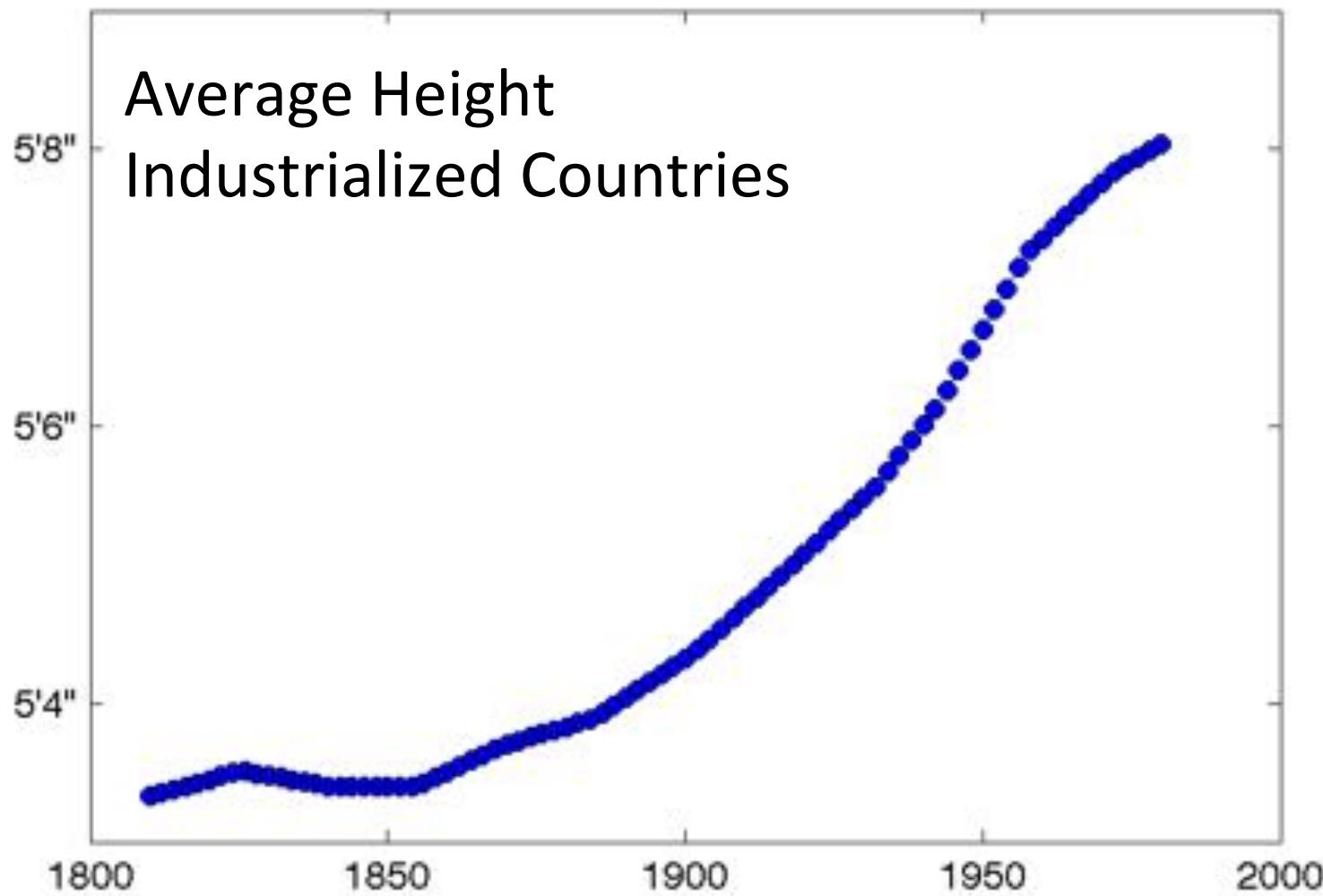


Climate versus Weather

- Weather = conditions right now
 - Hour-to-hour, day-to-day
 - City-specific
- Climate = broadly averaged conditions
 - Temporal scale: multi-decadal
 - Spatial scale: usually regional to global

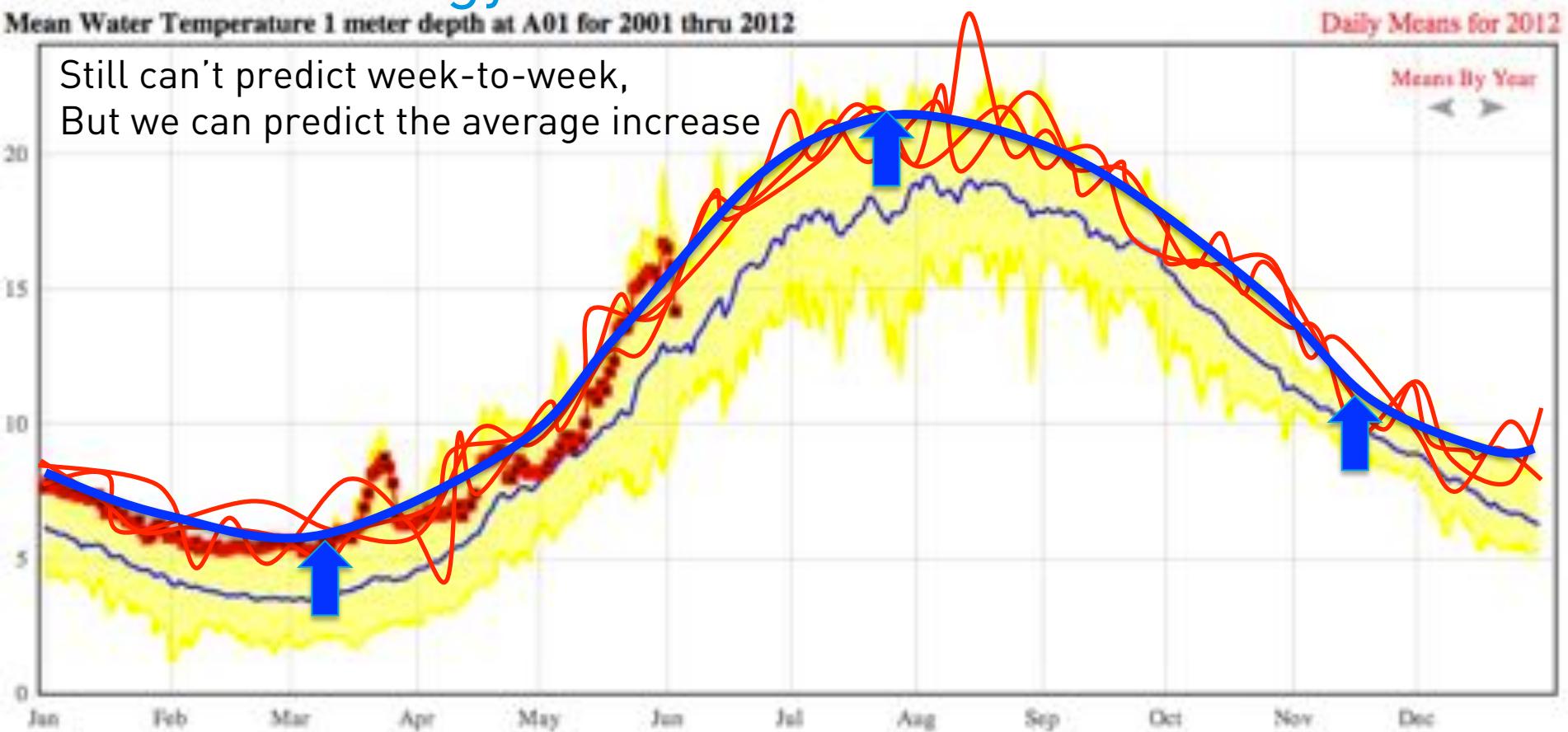


Climate versus Weather



Climatology

- With enough persistent deviation, the climatology can shift



Greenhouse effect

The Rodney & Otamatea Times

WAITEMATA & KAIPARA GAZETTE.

PRICE—10s per annum in advance

WARKWORTH, WEDNESDAY, AUGUST 14, 1912.

3d. per Copy.

1912

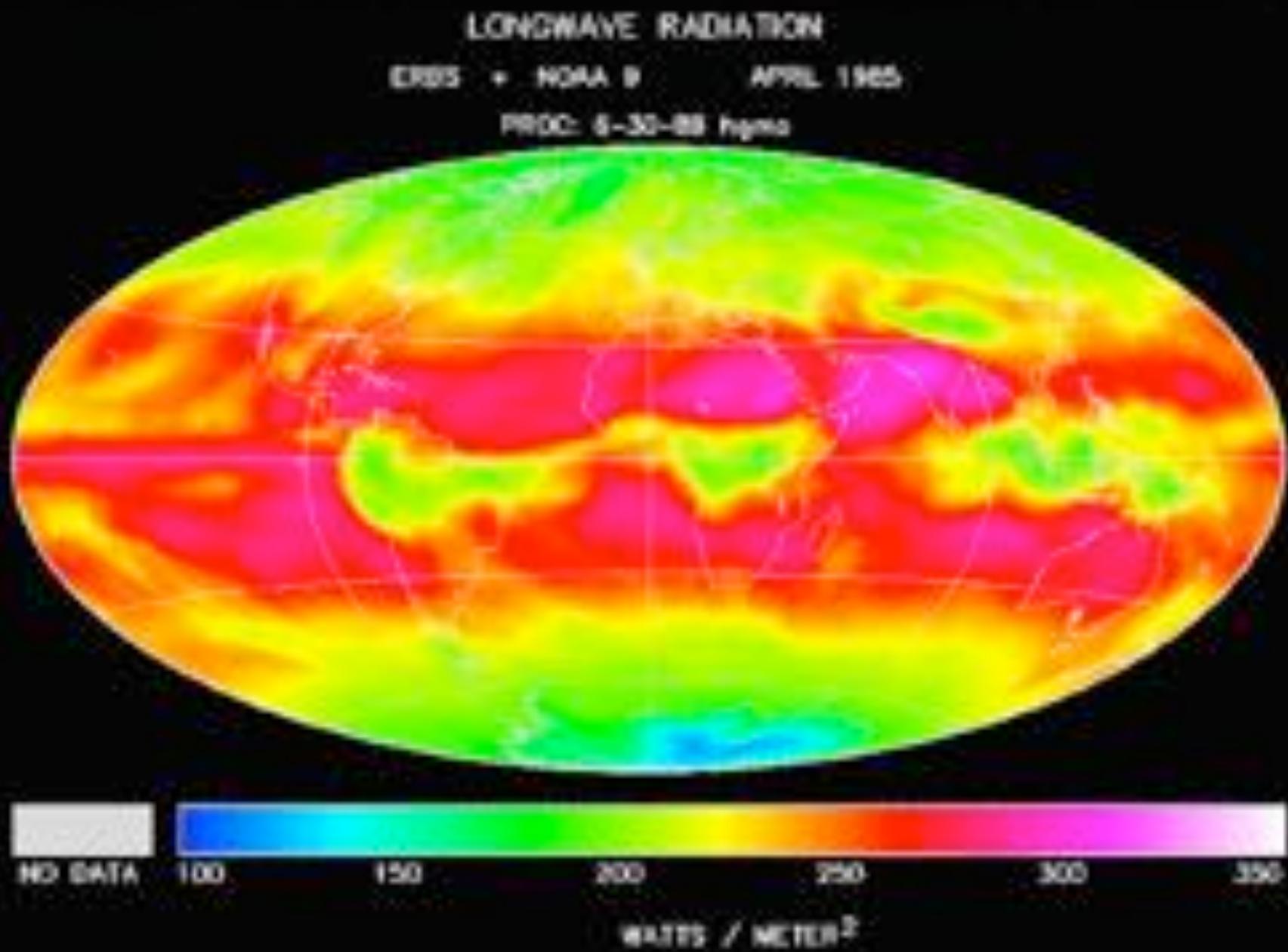
Science Notes and News.

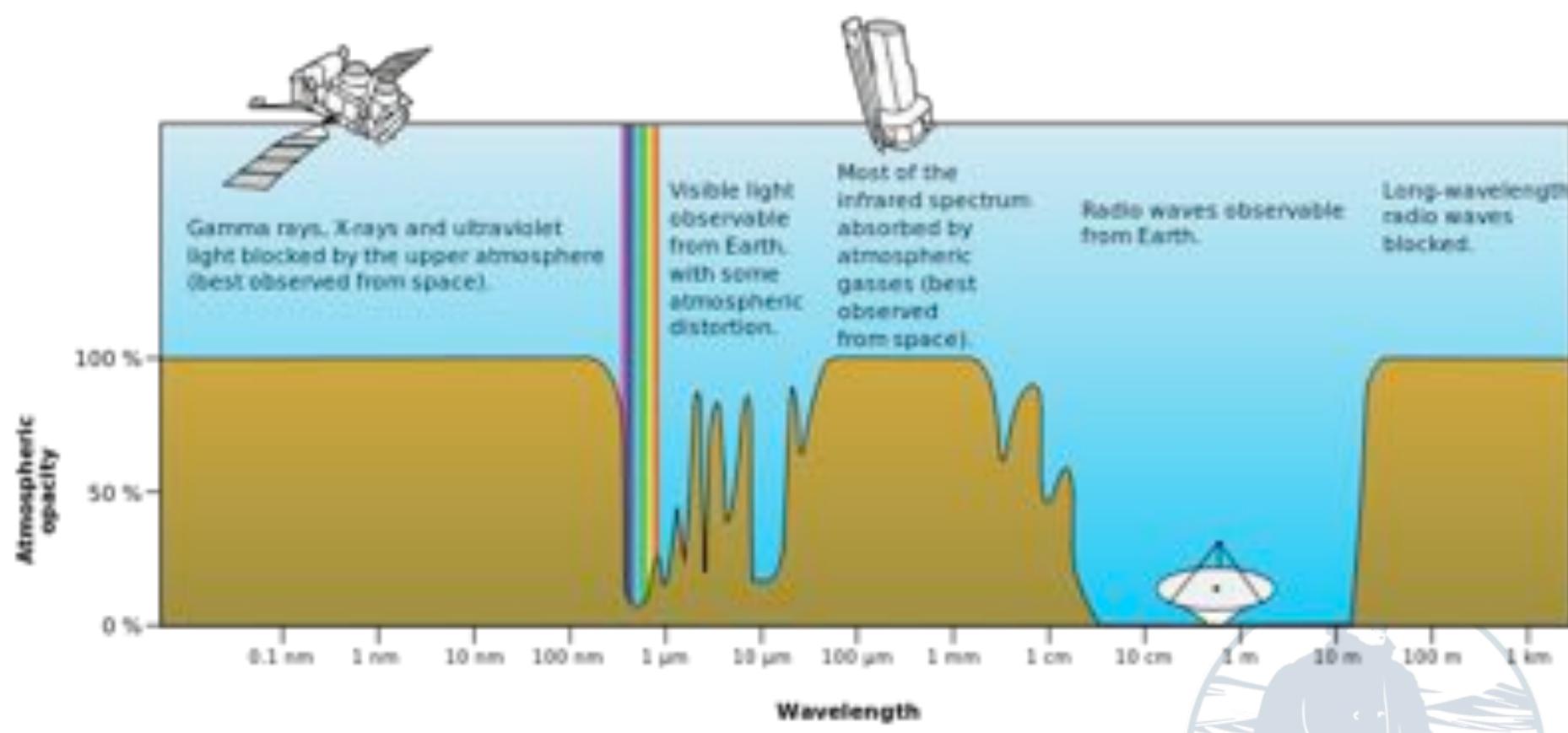
COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.



Greenhouse effect





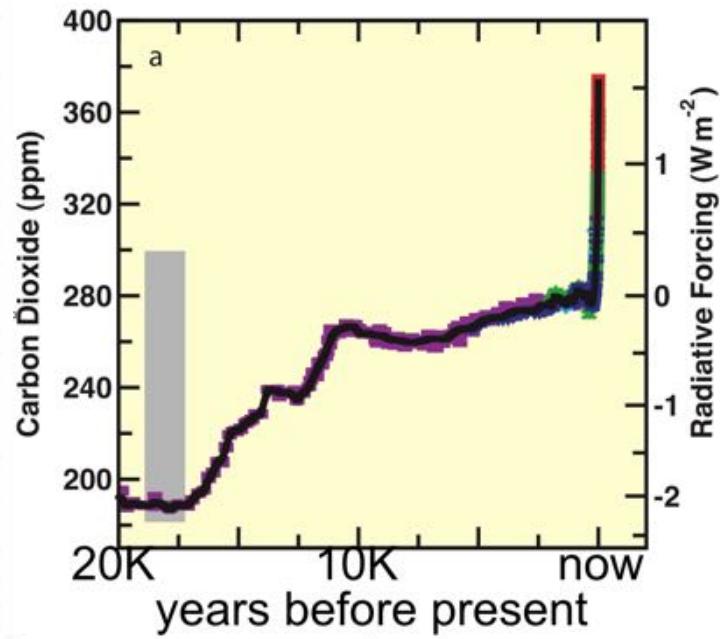
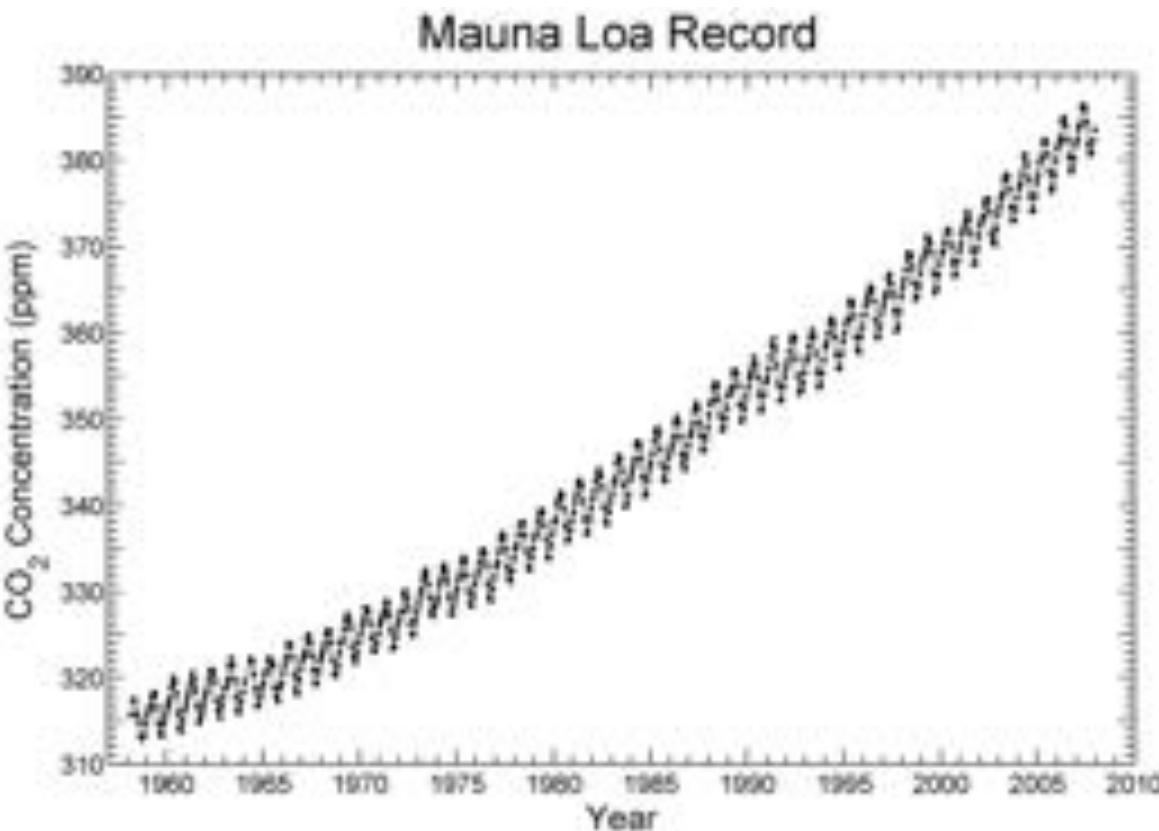
Greenhouse gasses: absorb IR

Most important greenhouse gases:

H₂O (water vapor)

CO₂ (carbon dioxide)

CH₄ (methane)



Feedback

- **positive feedback:** amplifies warming
- **negative feedback:** counteracts warming

Important climate feedbacks

albedo

water vapor

clouds

lapse rate

CO₂ dissolution



Clear Sky Albedo



Albedo – reflecting power of a surface

- higher albedo → more energy reflected
- lower albedo → more energy absorbed

Positive feedback: Ice albedo

Warming → Less Ice → lower albedo



Total Sky Albedo



Negative feedback: desertification

Warming → Deserts → higher albedo



Note: This desertification feedback is very small and doesn't consider effects to the hydrological cycle

Albedo – reflecting power of a surface

- higher albedo → more energy reflected
- lower albedo → more energy absorbed

Positive feedback: Ice albedo

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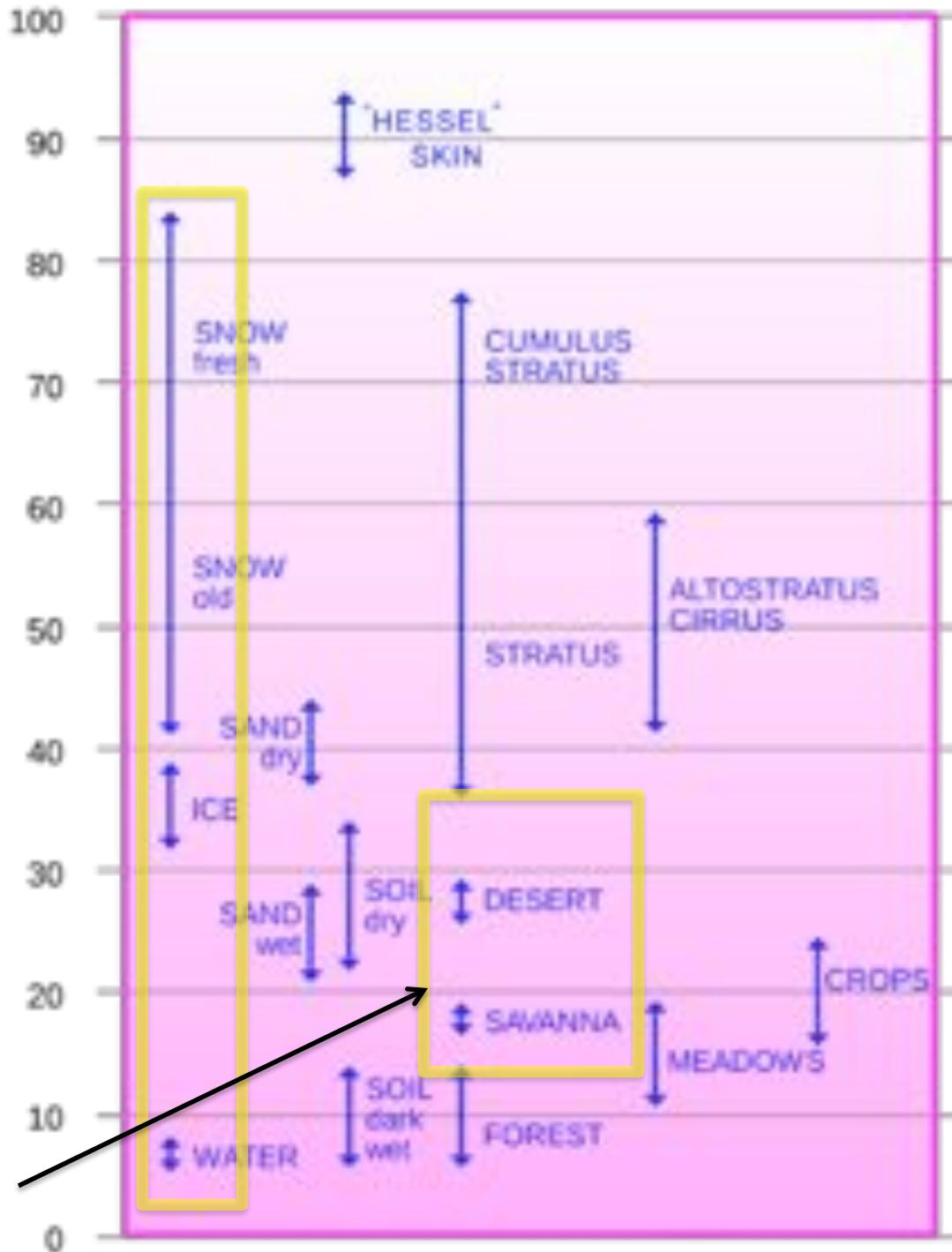


Negative feedback: desertification

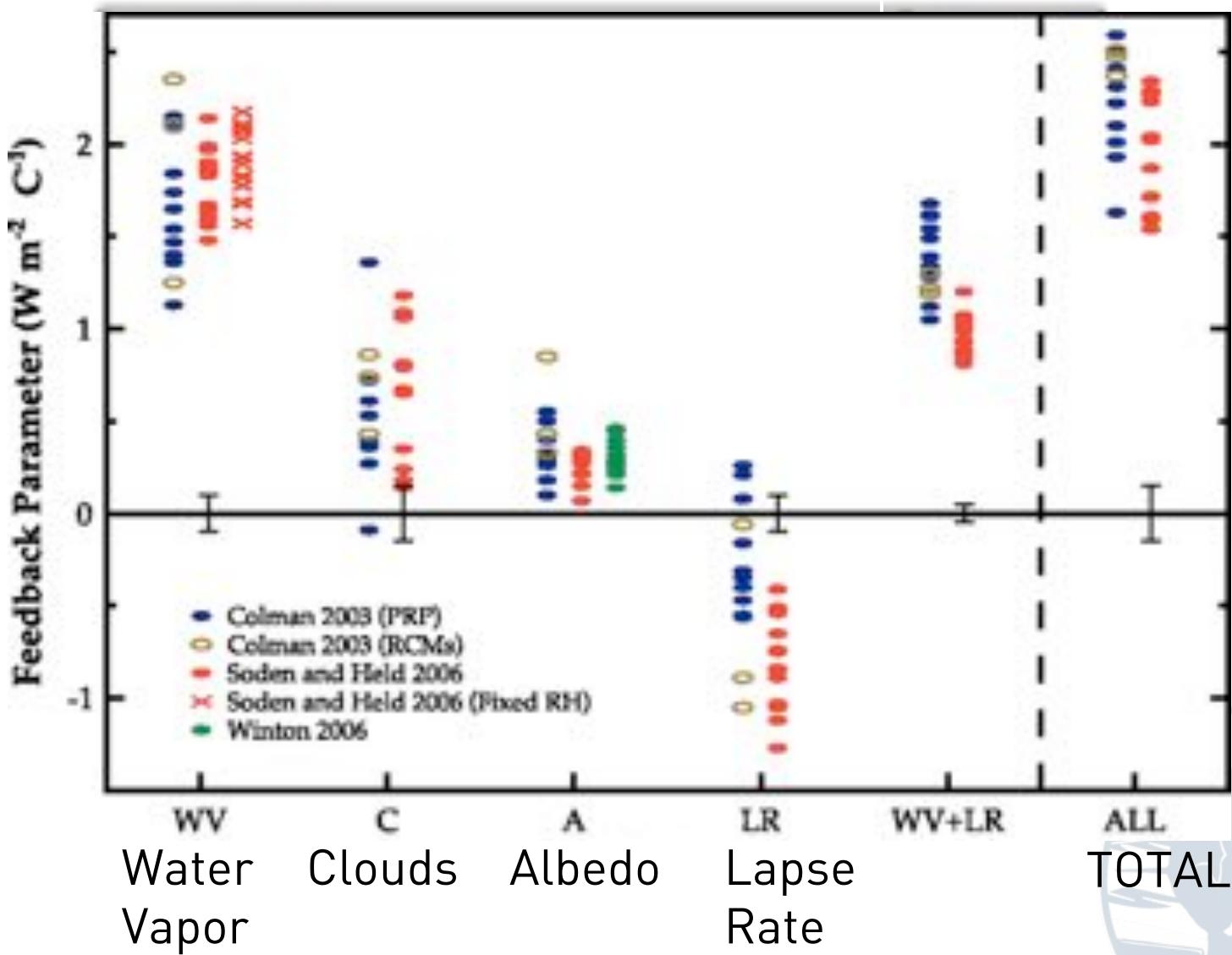
Warming → Deserts → higher albedo



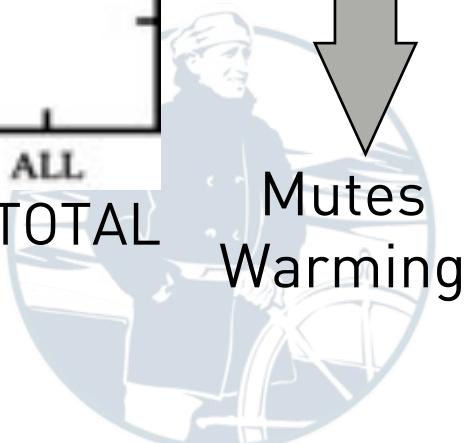
Note: This desertification feedback is very small and doesn't consider effects to the hydrological cycle



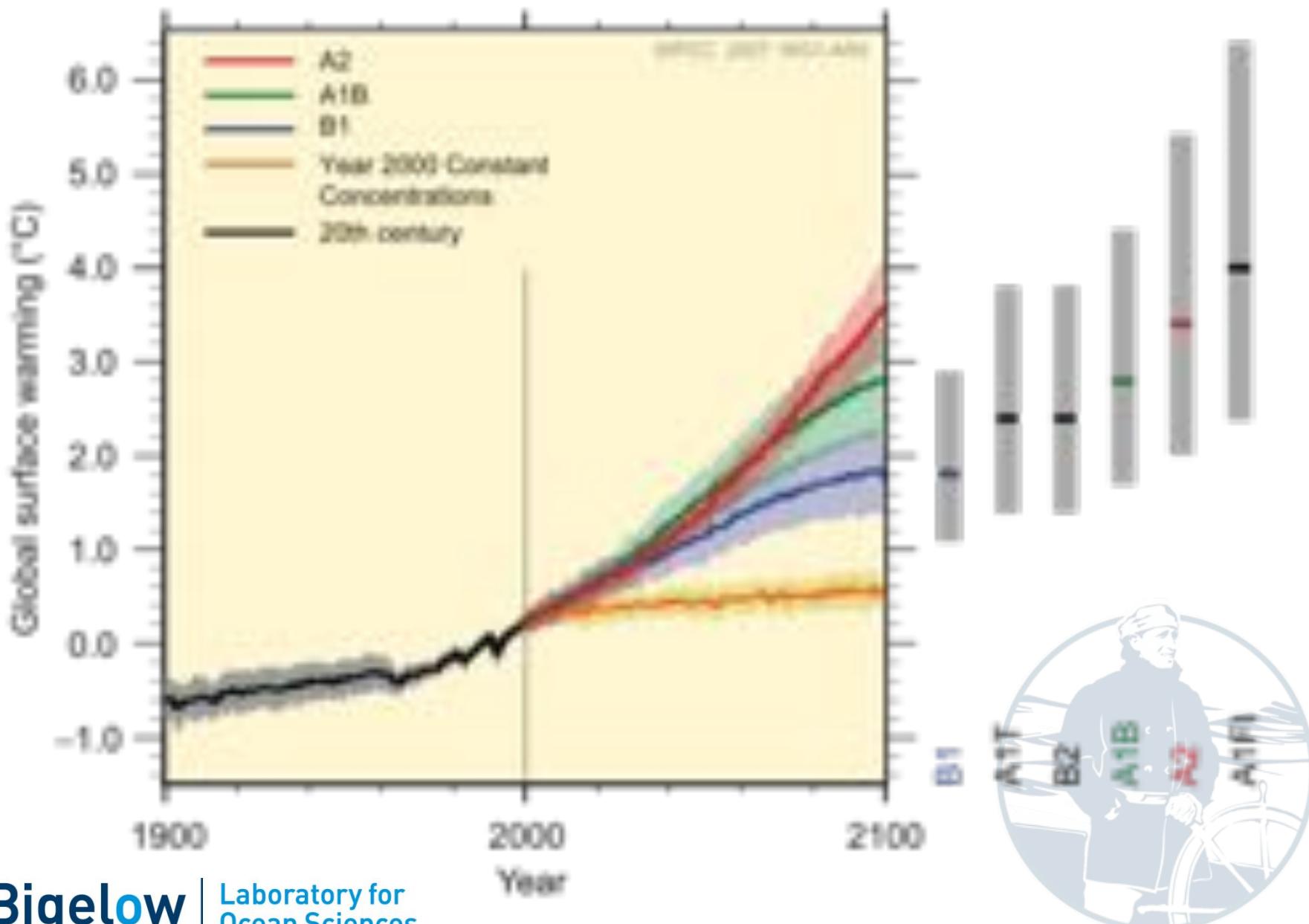
Amplifies
Warming

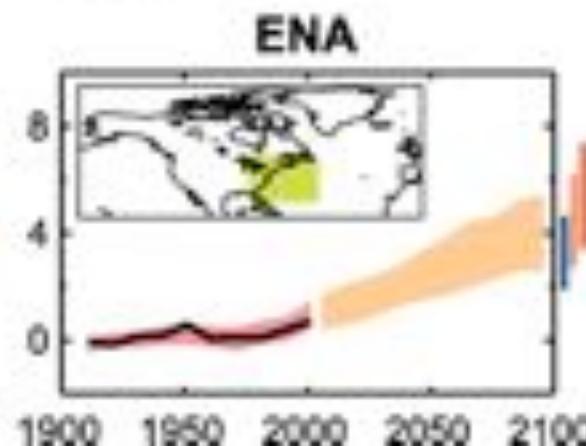
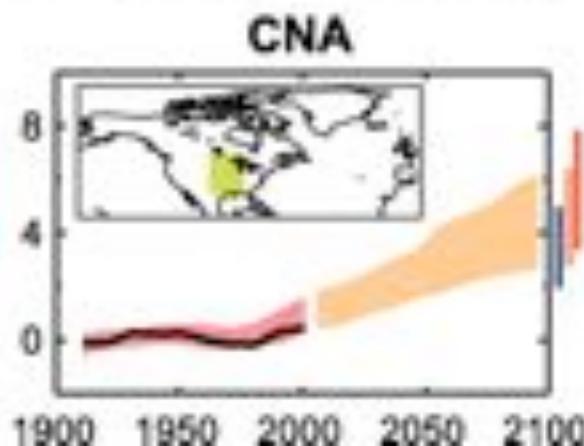
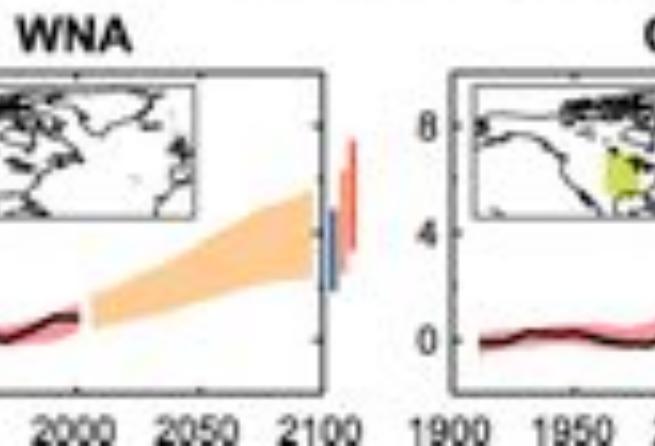
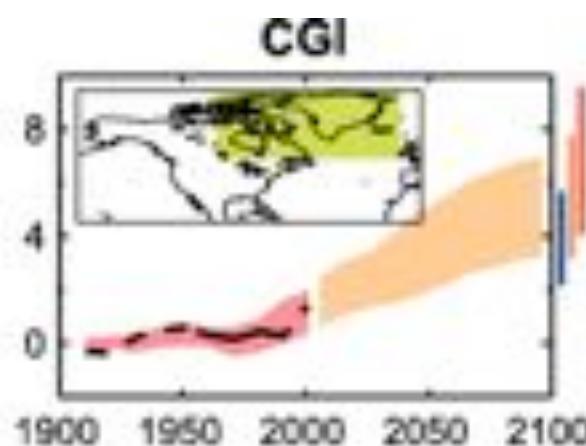
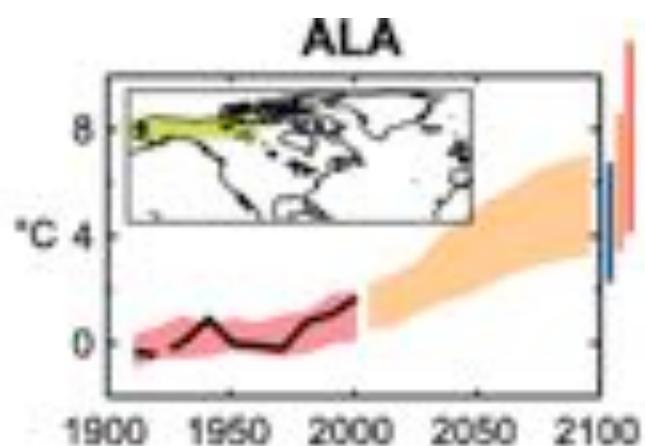


Mutes
Warming



MULTI-MODEL AVERAGES AND AMBIENTED RANGES FOR SURFACE WARMING





Notes

- Gradual changes don't tell everything
- E.g. total precipitation can change little, but *variance* can change
 - i.e. more precipitation concentrated into intense events
- Also, rapid ups and downs can be more important than gradual increase (e.g. sea level and storm surges)



Climate Oscillations & Tele-connections

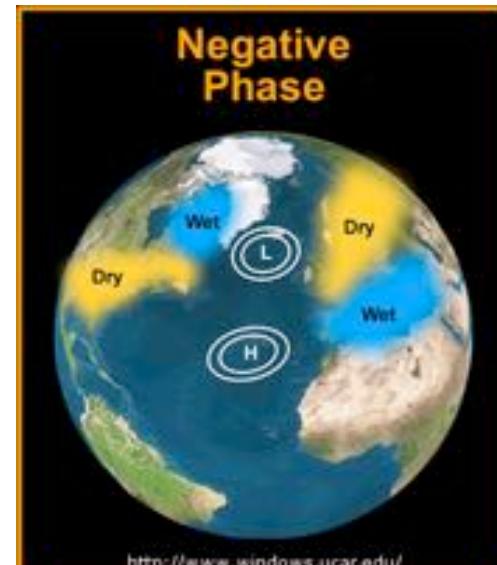


Climate Oscillations

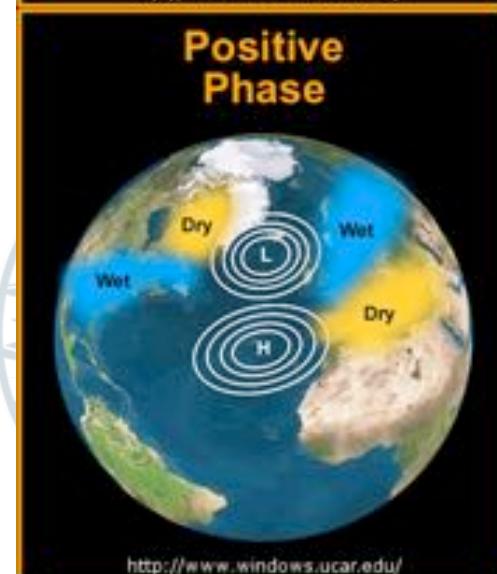
- quasi-periodic fluctuations in global-scale conditions

1) North Atlantic Oscillation

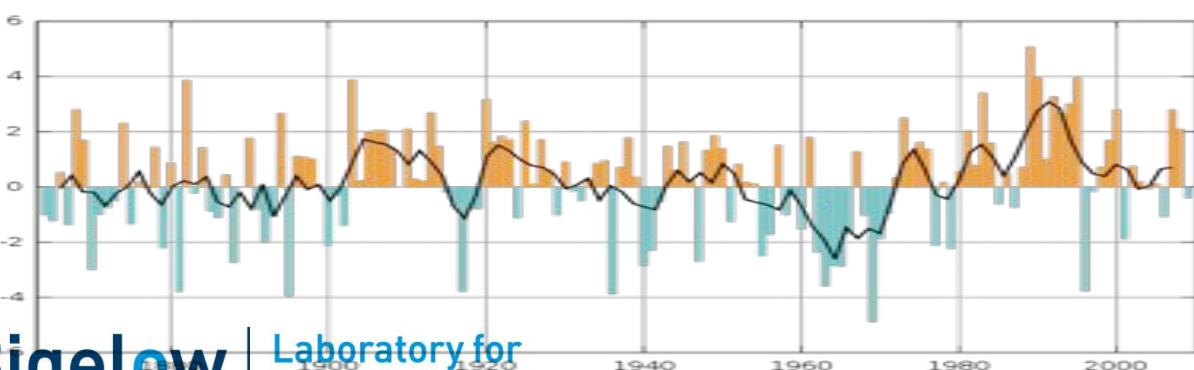
- High pressure over the Azores
- Low pressure over Iceland
- Strength of this difference → NAO index



<http://www.windows.ucar.edu/>



<http://www.windows.ucar.edu/>

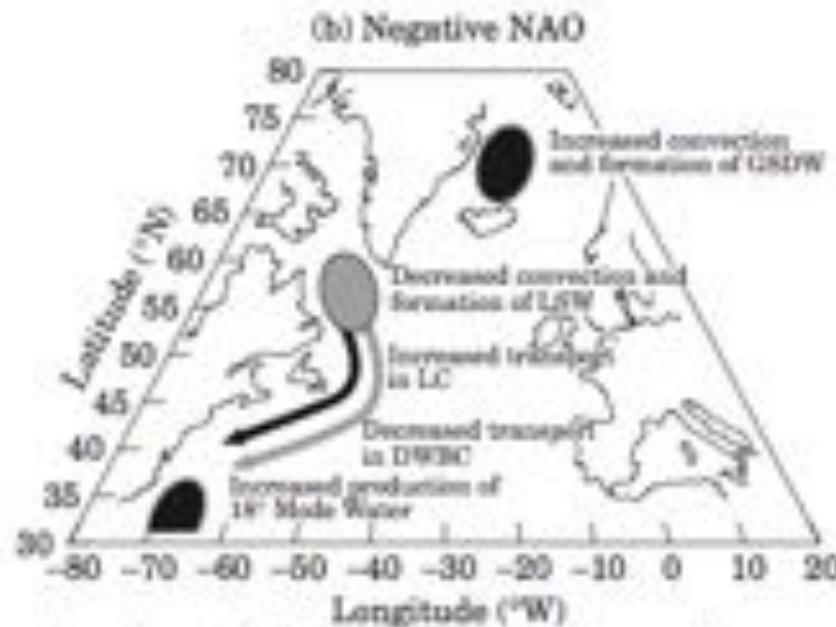
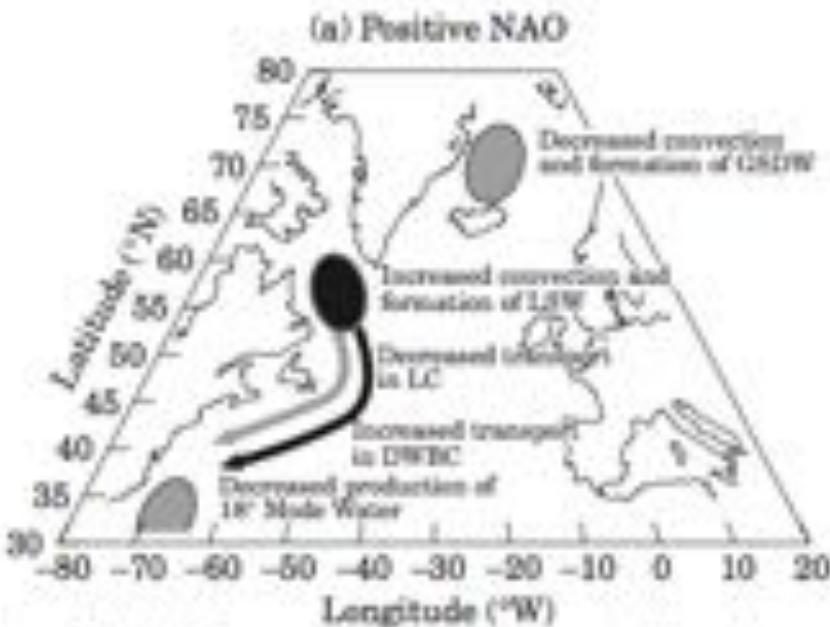


Climate Oscillations

- quasi-periodic fluctuations in global-scale conditions

1) North Atlantic Oscillation

- High pressure over the Azores
- Low pressure over Iceland
- Strength of this difference → NAO index

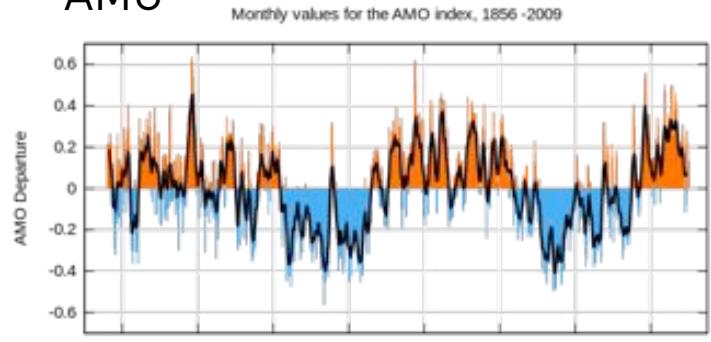


DWBC=Deep Western Boundary Current; GSDW=Greenland Sea Deep Water; LC=Labrador Current; LSW=Labrador Sea Water (Greene & Pershing 2000)

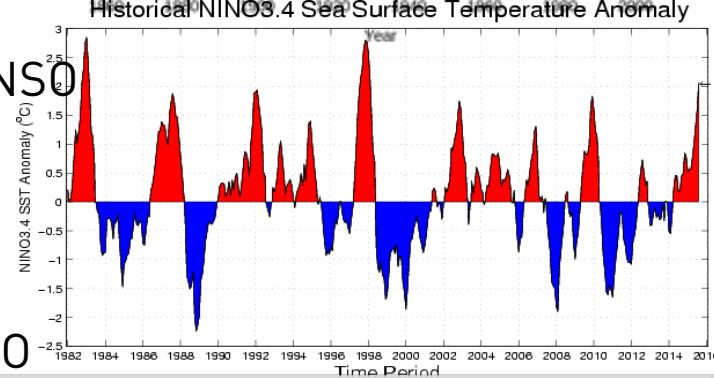
Other important climate oscillation indices

- North Atlantic Oscillation (NAO) ✓
- Southern Annular Mode (SAM)
- Tropical Northern Atlantic Index
- Tropical Southern Atlantic Index
- El Niño Southern Oscillation (ENSO)
- Atlantic Multidecadal Oscillation (AMO)
- Pacific Decadal Oscillation (PDO)
- Arctic Oscillation (AO)
- Arctic Ocean Oscillation (AOO)

AMO



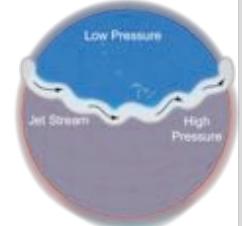
ENSO



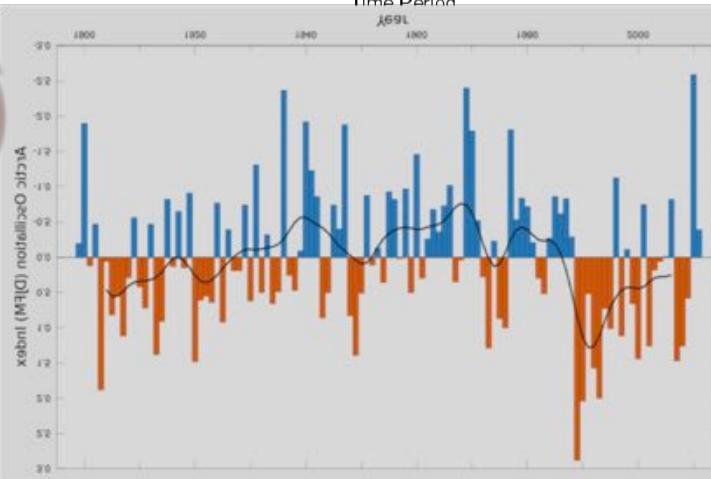
Arctic Oscillation
Negative Phase



Positive Phase



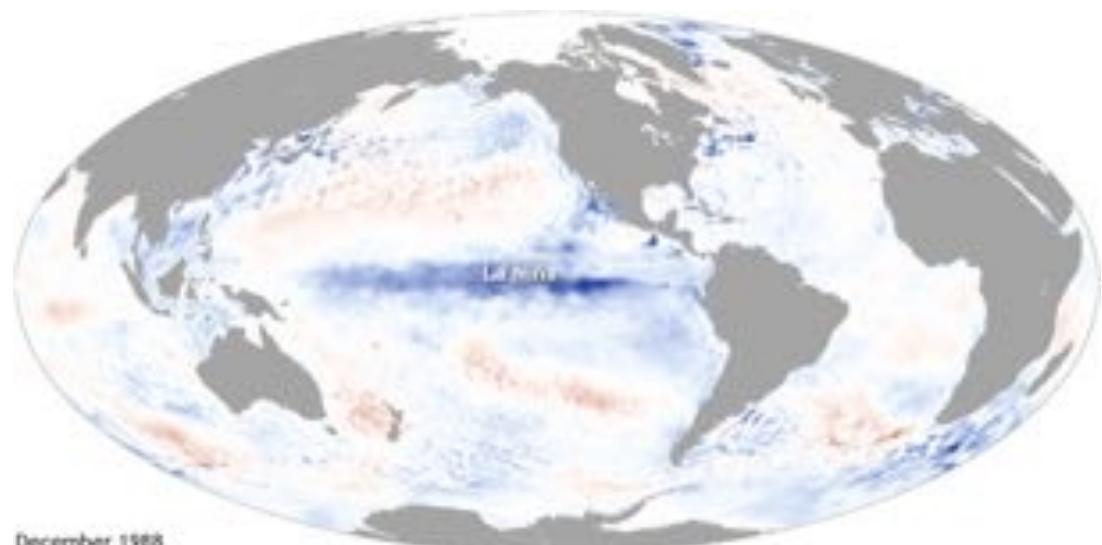
AO



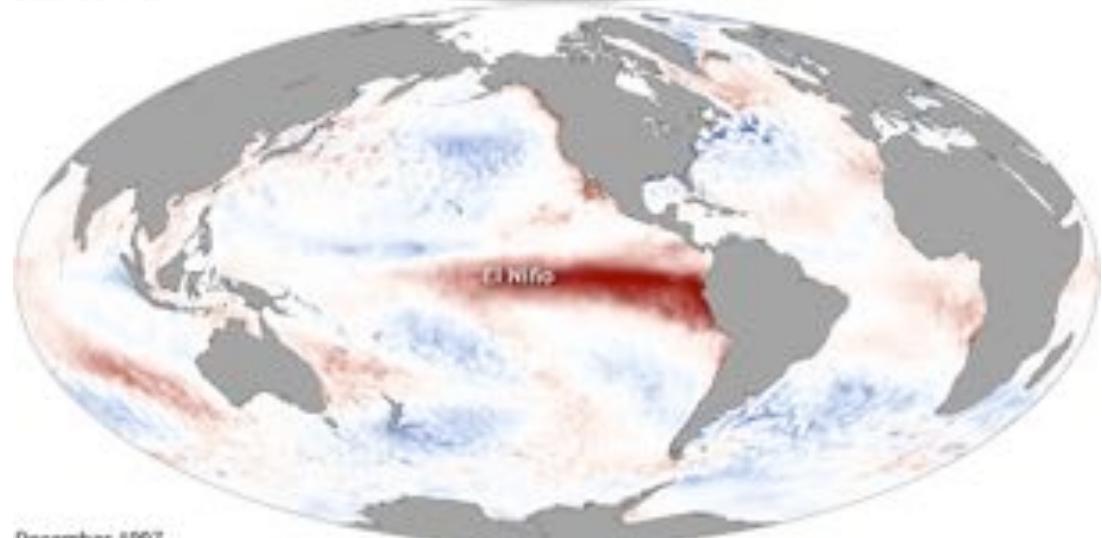
Data source, if you want to download:

[http://www.cpc.ncep.noaa.gov/products/precip/
CWlink/daily_ao_index/teleconnections.shtml](http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml)

ENSO oscillations



December 1988

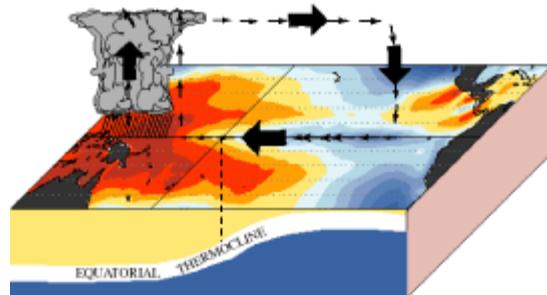


December 1997

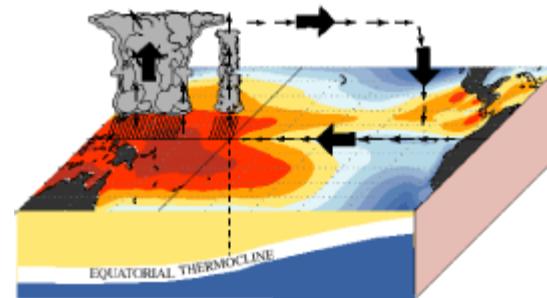
Difference from average temperature (°F)

-9 0 9

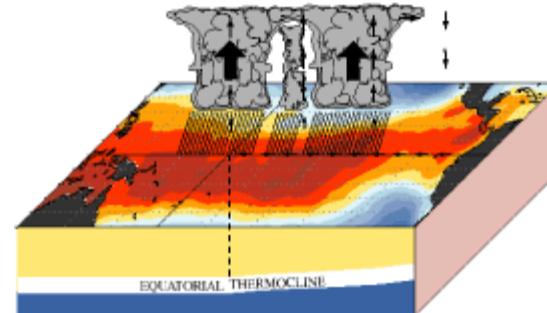
December - February La Niña Conditions



December - February Normal Conditions

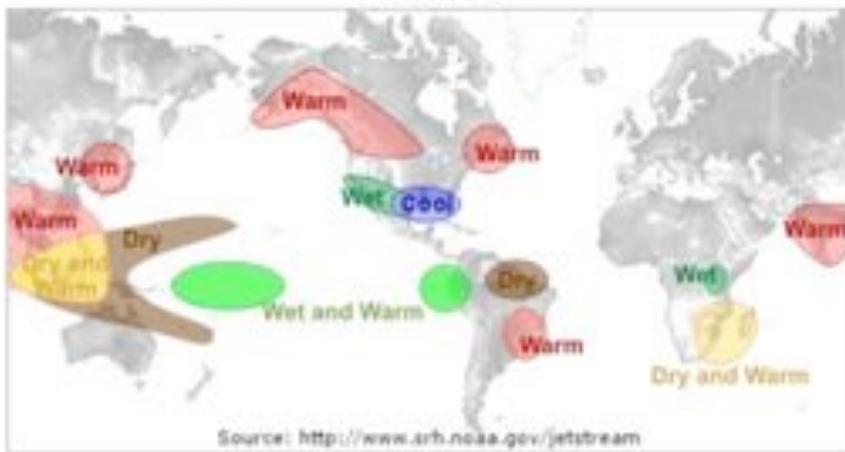


December - February El Niño Conditions

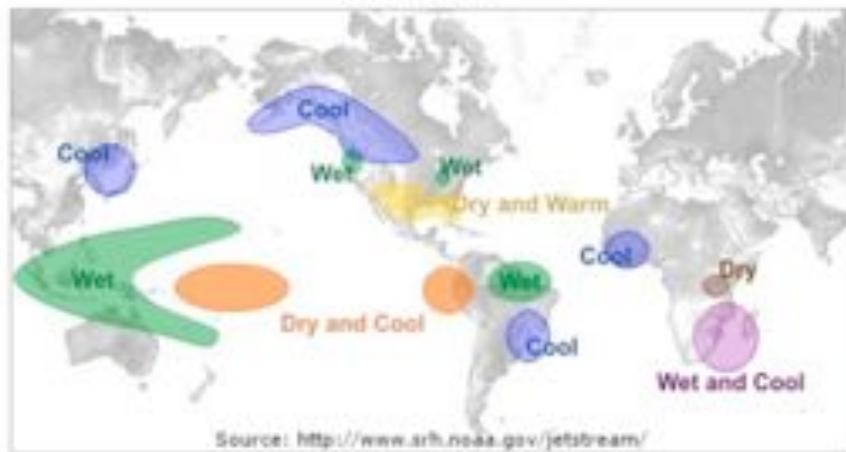


ENSO oscillations

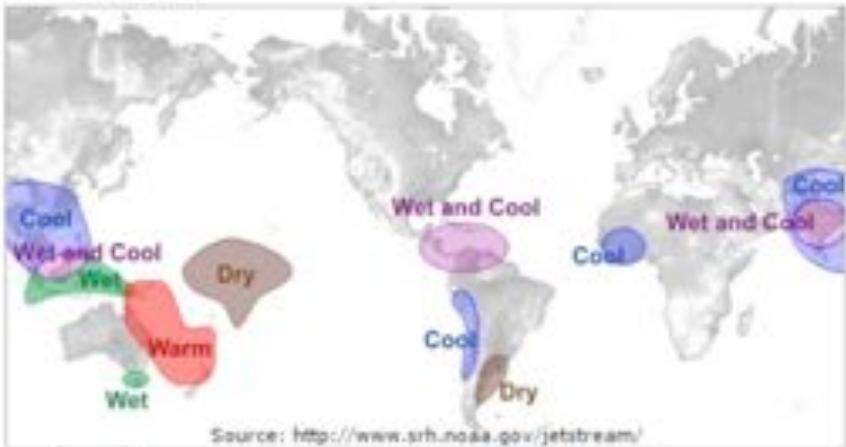
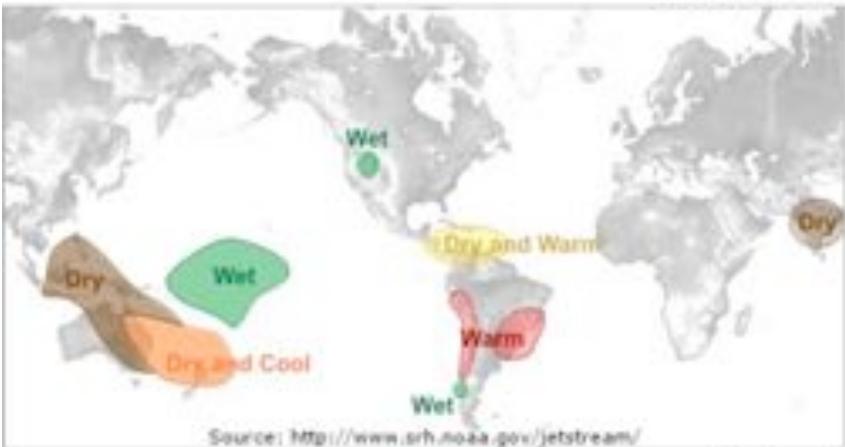
El Niño



La Niña



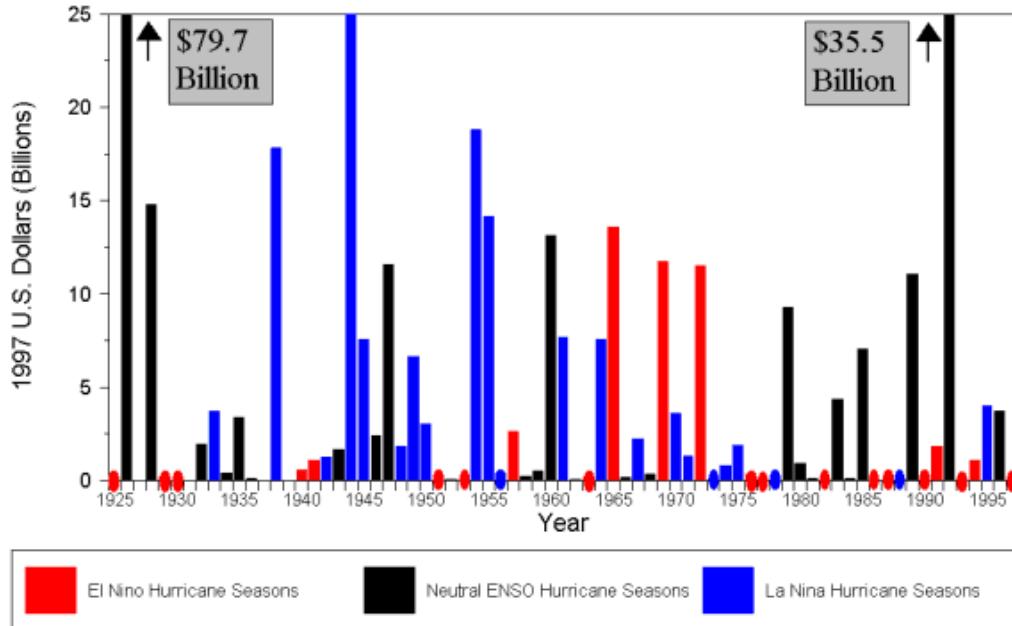
Effects: December - February



Effects: June - August

Risk Predictions

U.S. Normalized Hurricane Damage 1925-1997



Normalized U.S. hurricane damage record for 1925-1997. Years designated as La Niña events are shown in blue, El Niño events in red, and neutral years in black. Values less than \$500 million are shown as an ellipse on the X-axis. From Pilke & Landsea (1999)

Innovations in Rural and Agriculture Finance
FOR FOOD, AGRICULTURE,

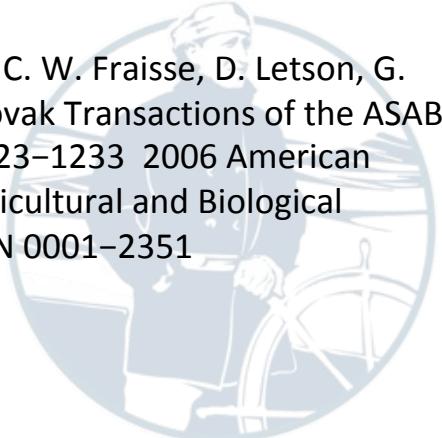
AND THE ENVIRONMENT New Approaches
for Index Insurance: ENSO Insurance in Peru

Jerry R. Skees and Benjamin Collier

Focus 18 • Brief 11 • July 2010

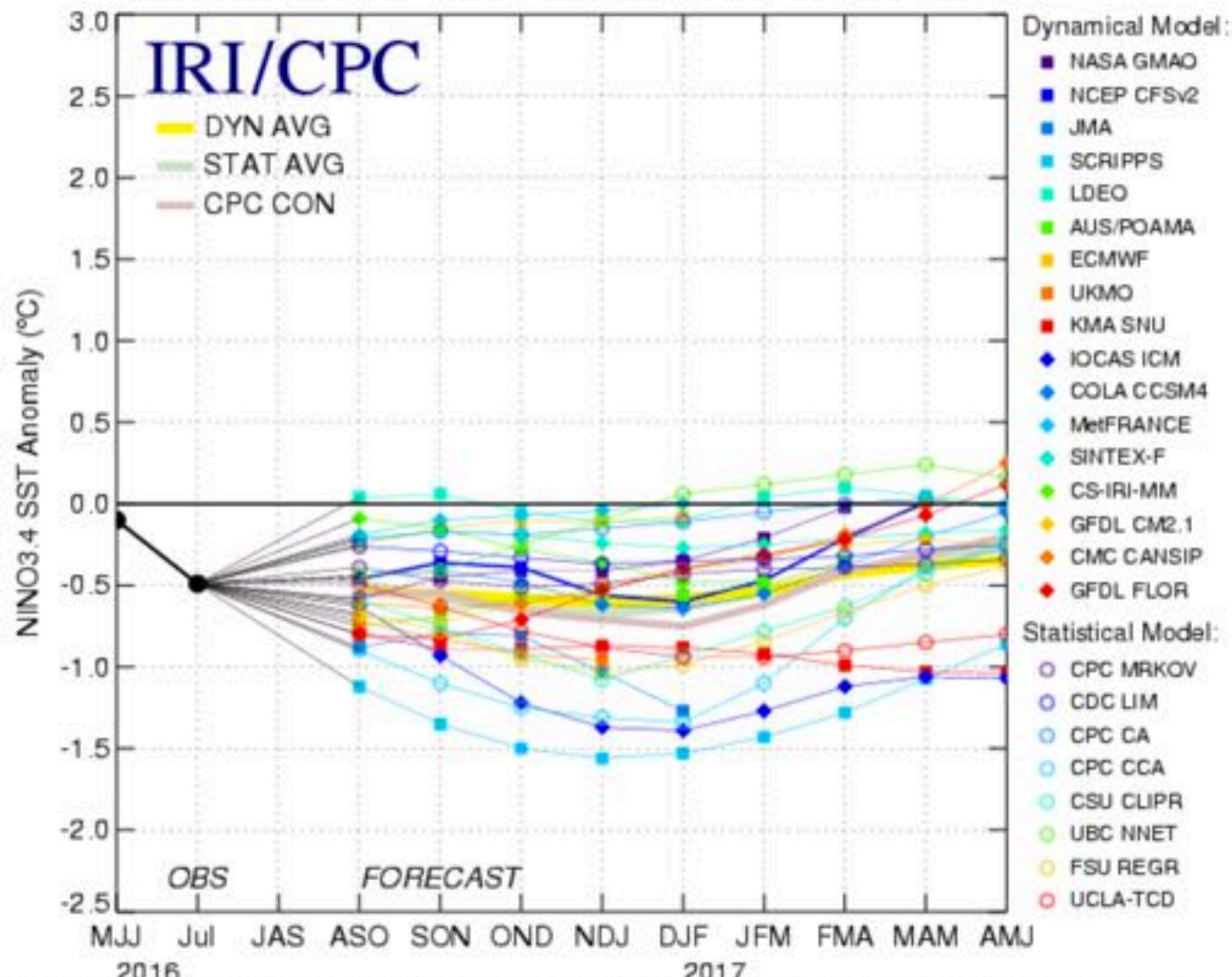
IMPACT OF CLIMATE INFORMATION ON
REDUCING FARM
RISK BY OPTIMIZING CROP INSURANCE
STRATEGY

V. E. Cabrera, C. W. Fraisse, D. Letson, G.
Podestá, J. Novak Transactions of the ASABE
Vol. 49(4): 1223-1233 2006 American
Society of Agricultural and Biological
Engineers ISSN 0001-2351



ENSO Forecasts

Mid-Aug 2016 Plume of Model ENSO Predictions



Range of current ENSO forecasts. The start for each set of curves is the forecast for that month made the previous month. An interactive web page showing forecasts of one model at a time highlighted against a background of more lightly colored lines for all other models is provided by the [International Research Institute for Climate and Society](#).

<http://iri.columbia.edu/our-expertise/climate/enso/>

Figure 6. Forecasts of sea surface temperature (SST) anomalies for the Niño 3.4 region (5°N - 5°S , 120°W - 170°W). Figure updated 16 August 2016.