Thermohaline Circulation

ES 383

Colby at Bigelow, September 2019

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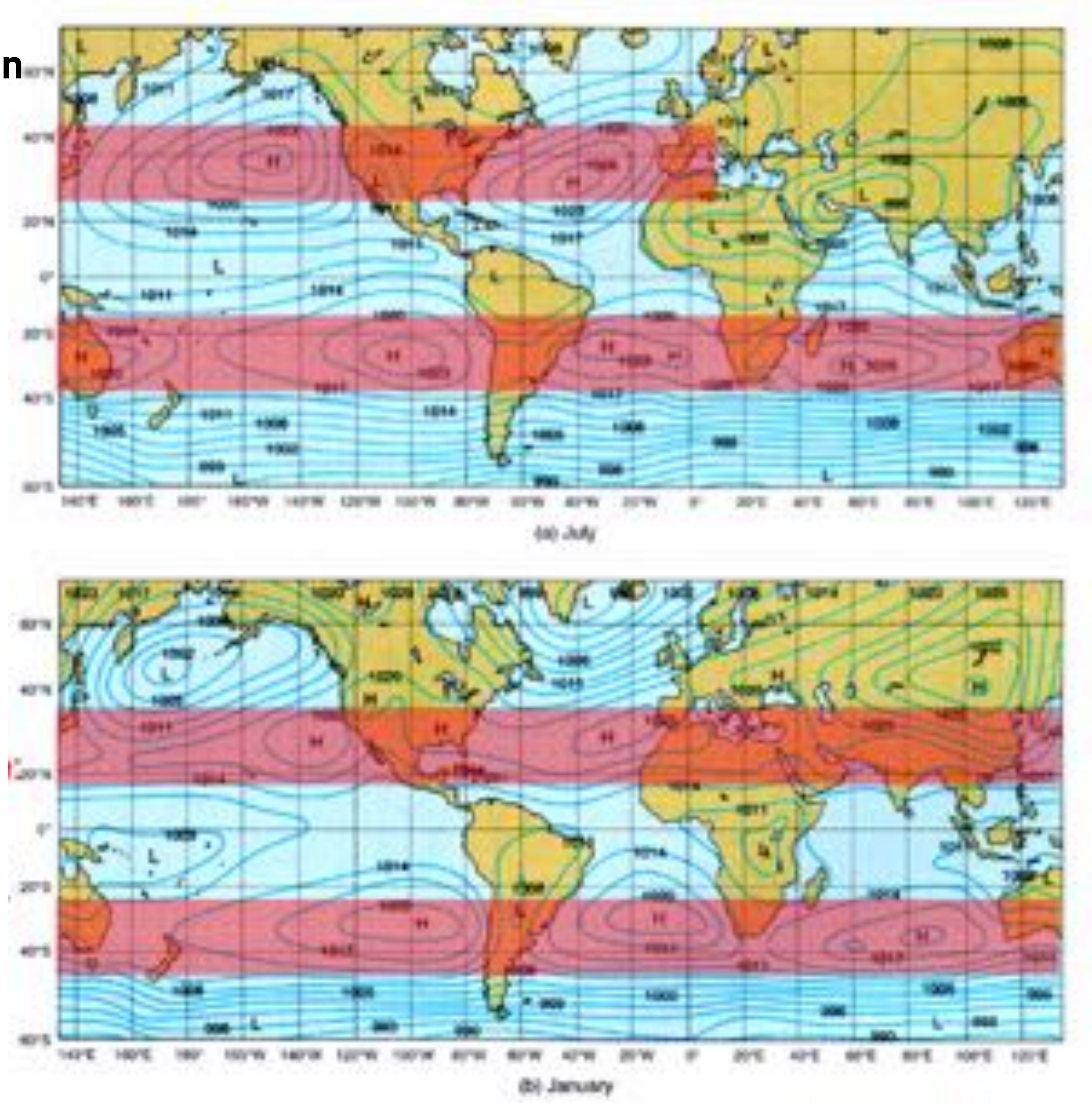
To understand ocean circulation, use fluid dynamics:

Navier-Stokes equations

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

Global Thermo-Haline Circulation

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



(a) July

(b) January

Image: David Townsend

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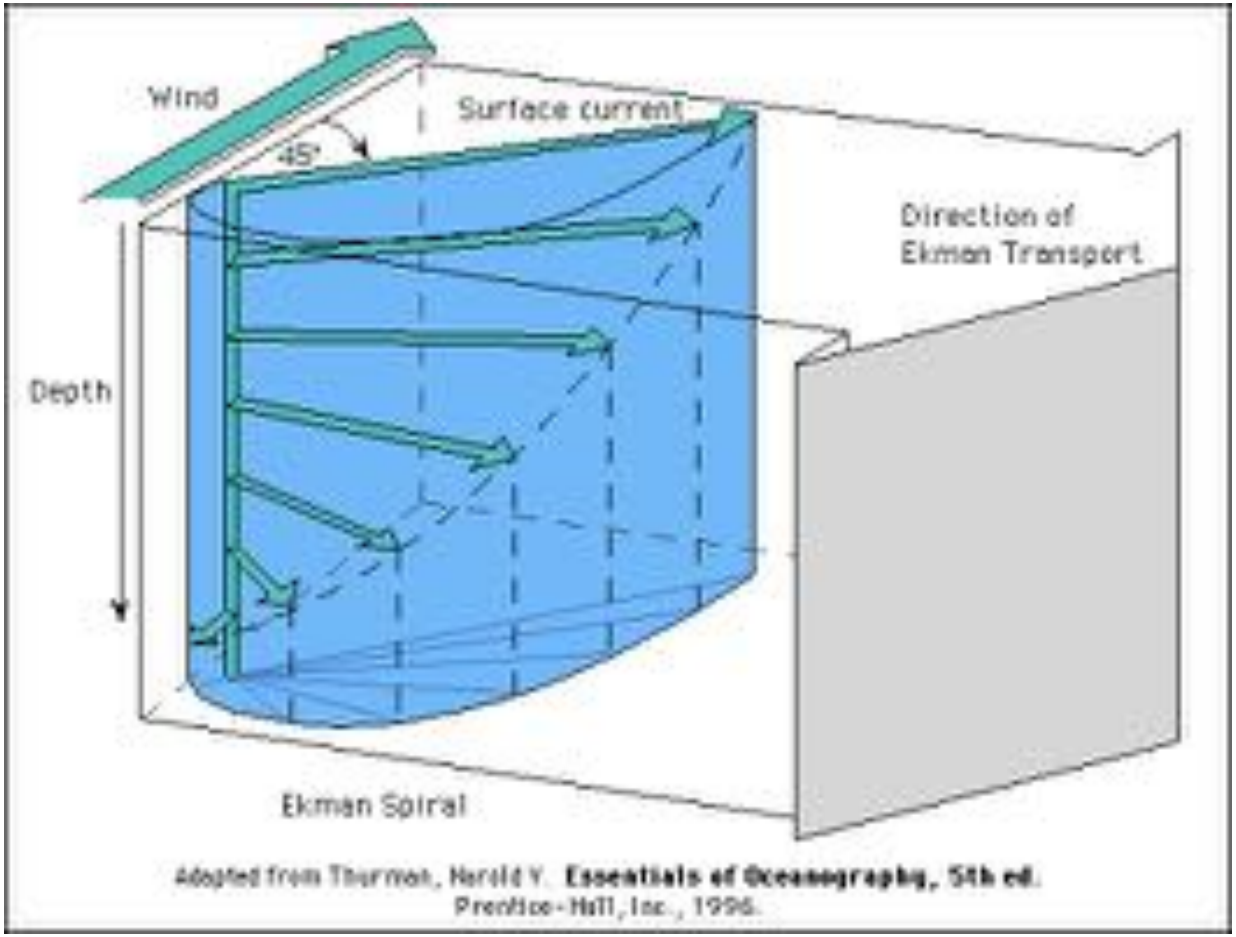
Connection with ocean currents

Fridtjof Nansen – Attempted to reach the North Pole in 1893. While the ship was frozen in ice, Nansen observed that the ice drifted 20-40º 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 90º from wind -
Up to 100 m layer

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When the wind blows on the ocean surface:

Near-surface Ekman Currents

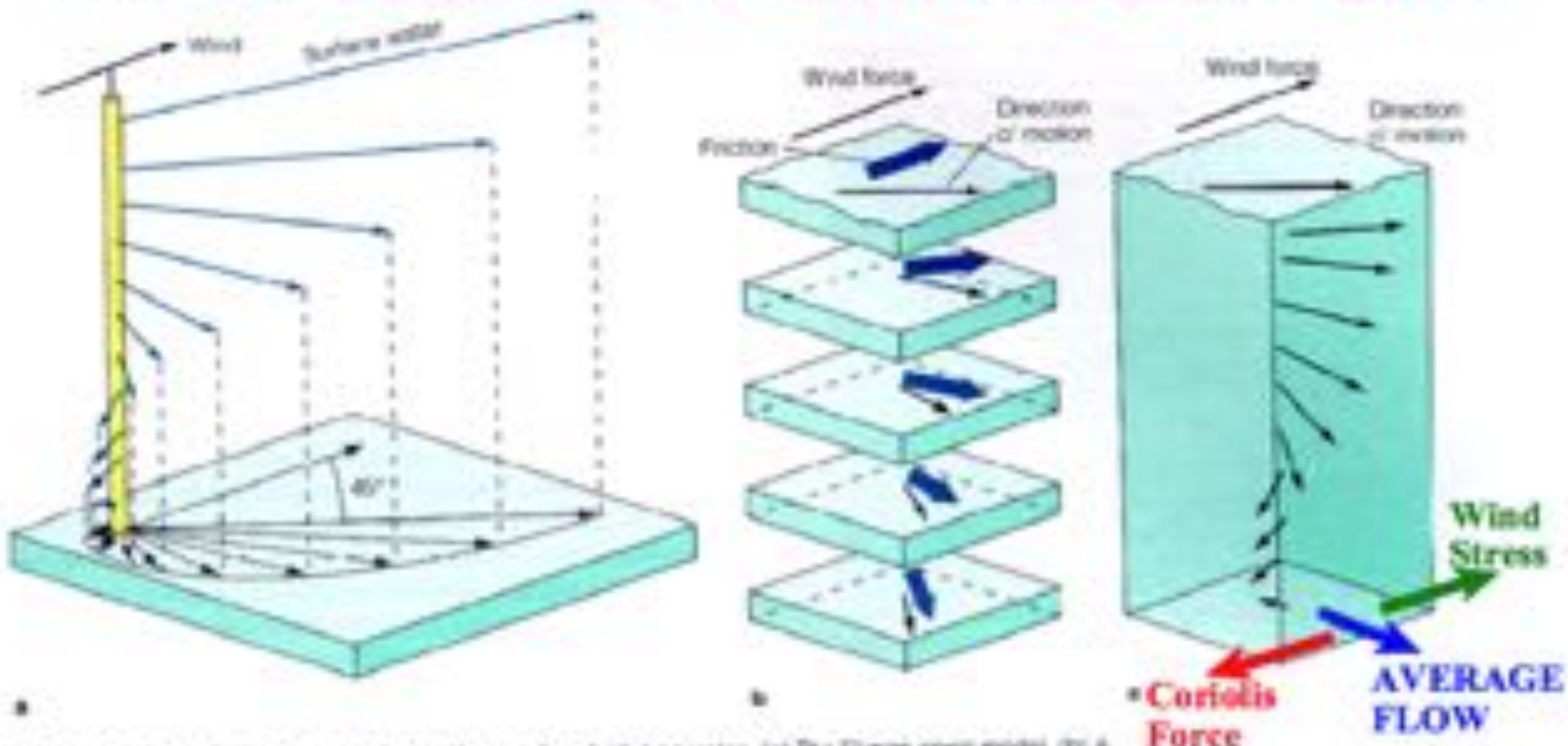
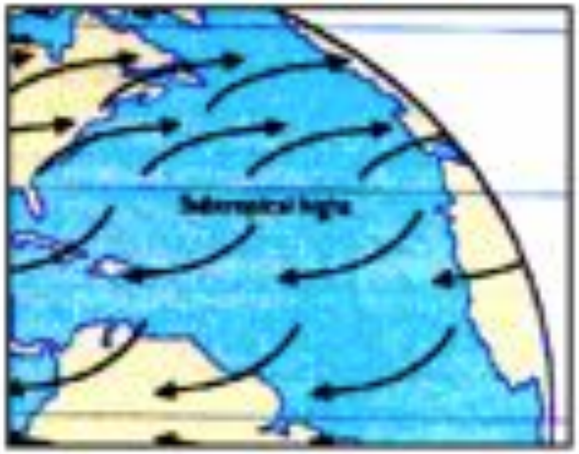


Image: David Townsend

The North Atlantic Ocean



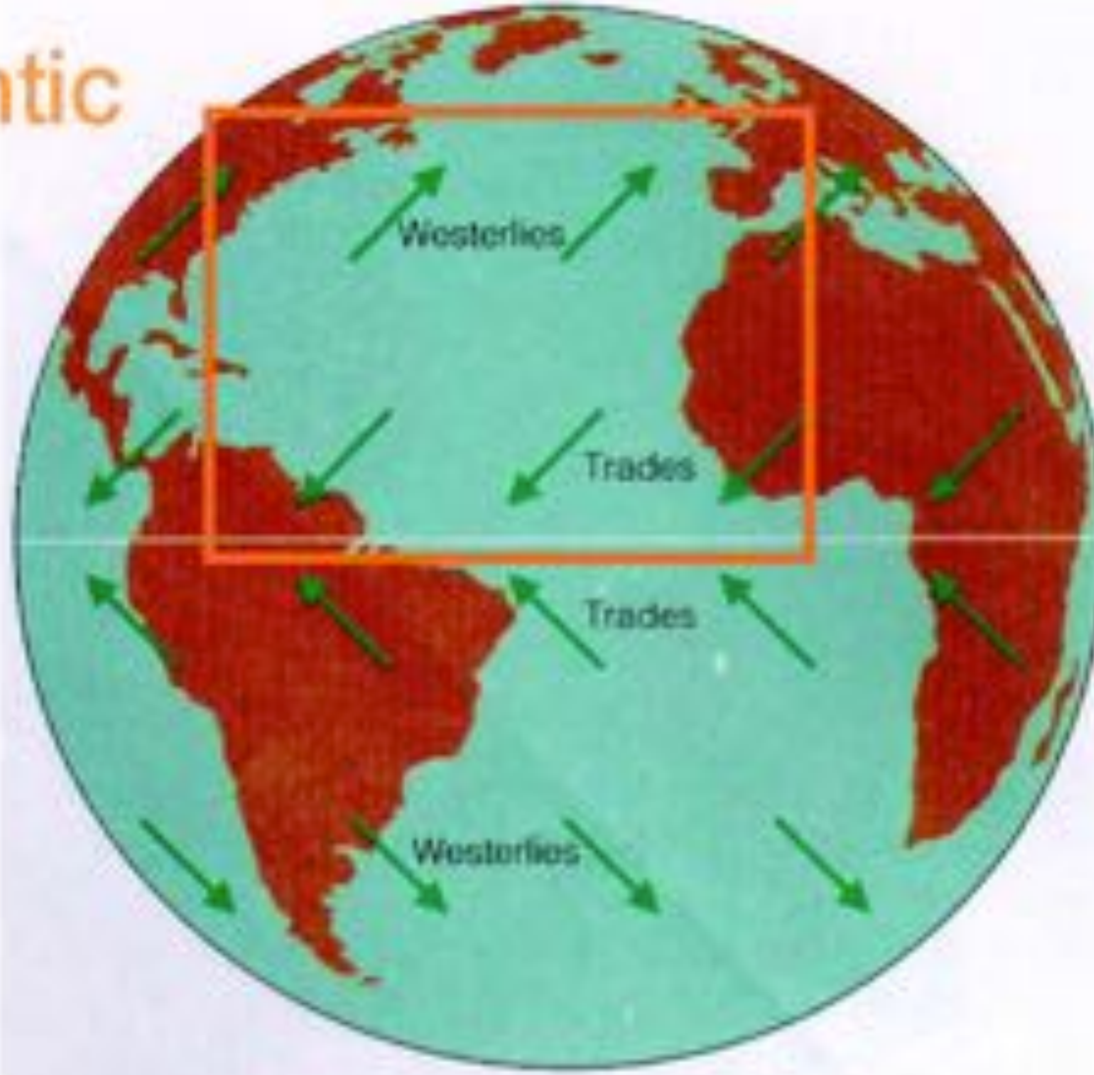
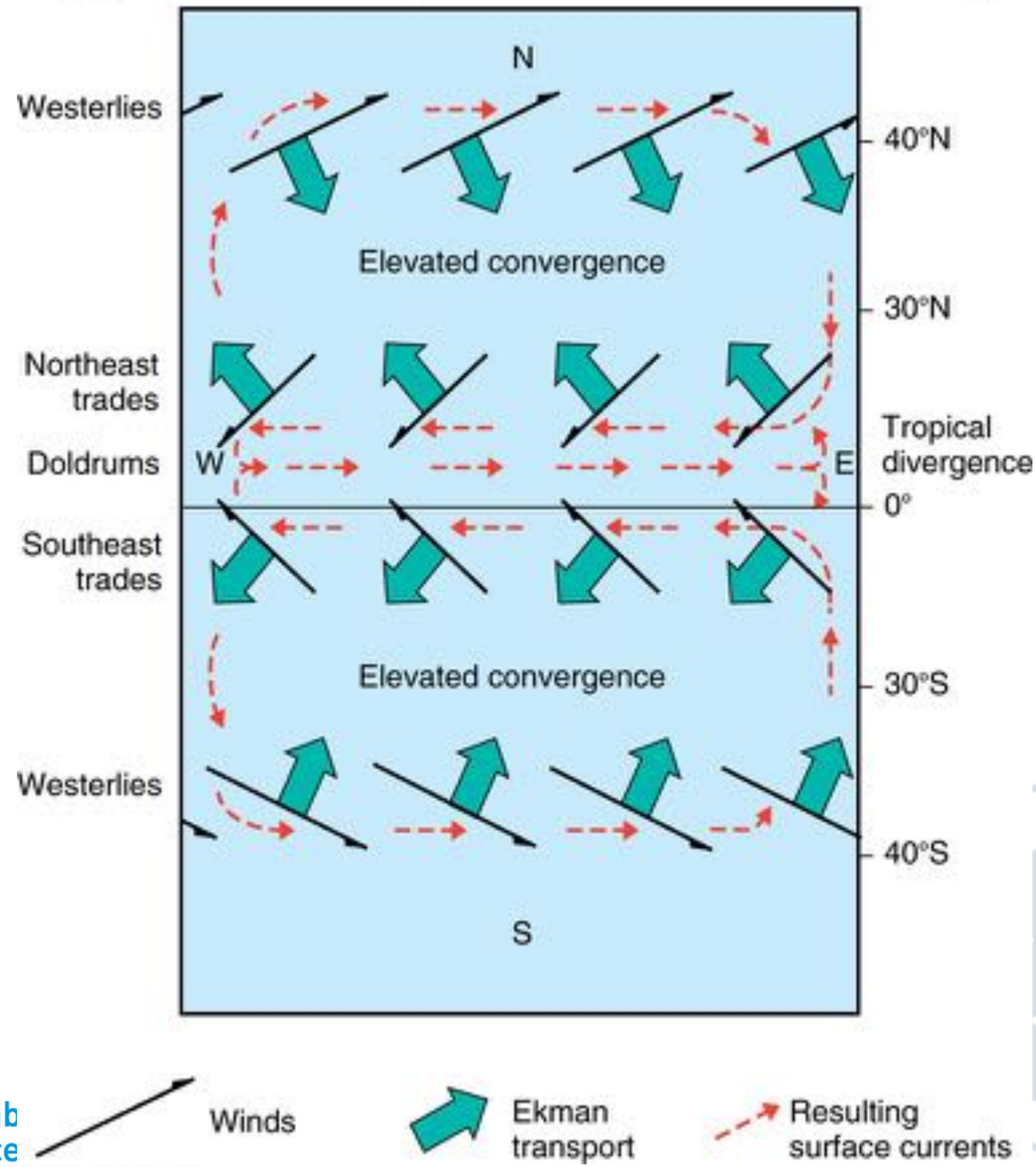


Image: David Townsend



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What happens is this:

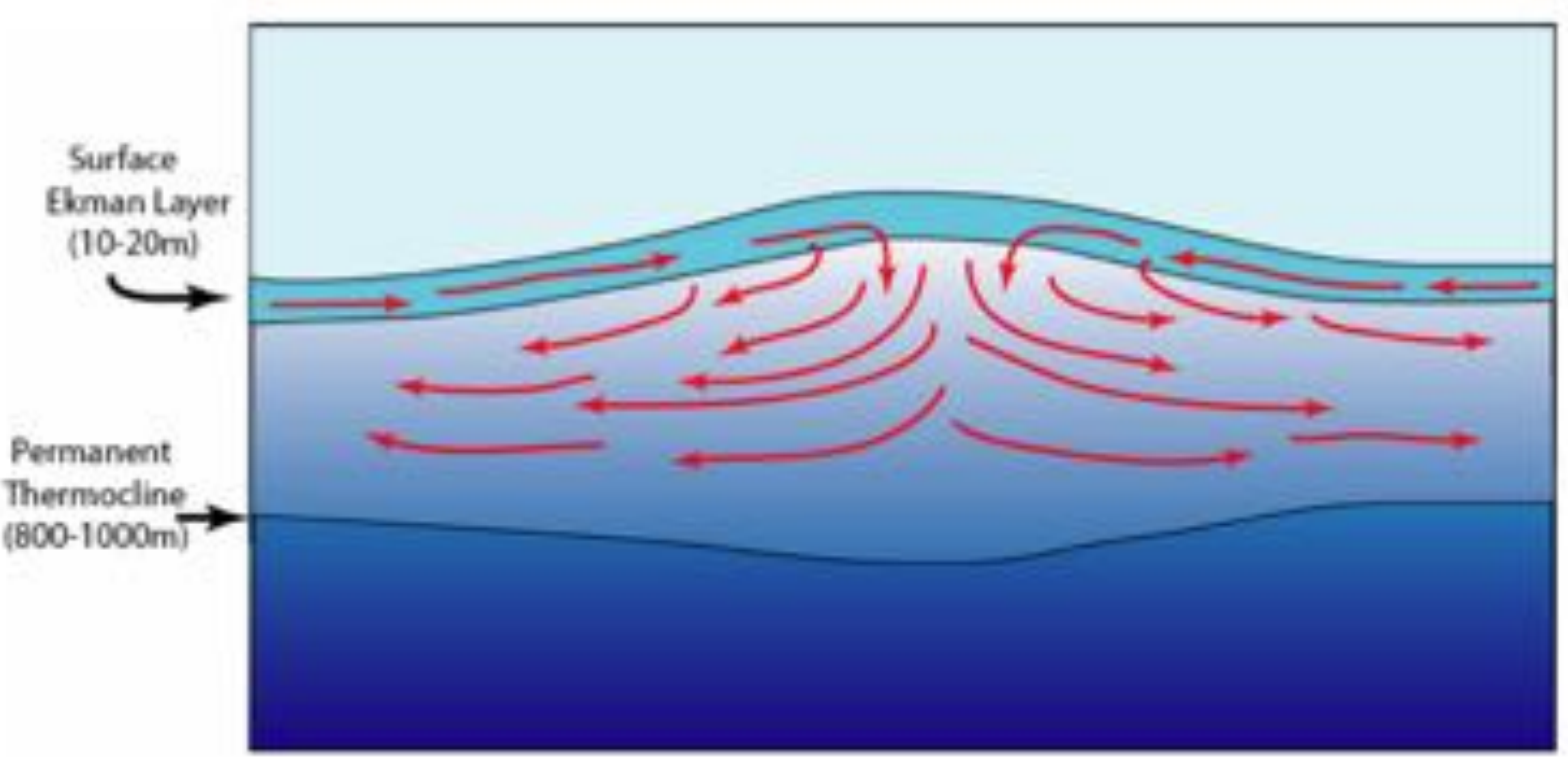

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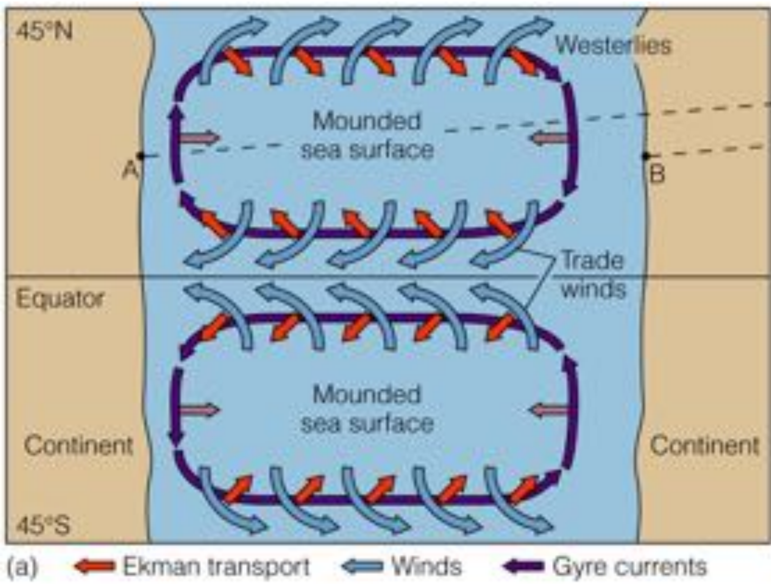
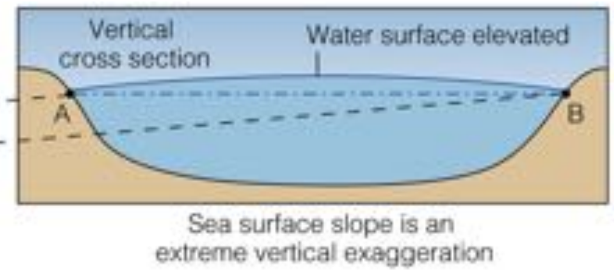
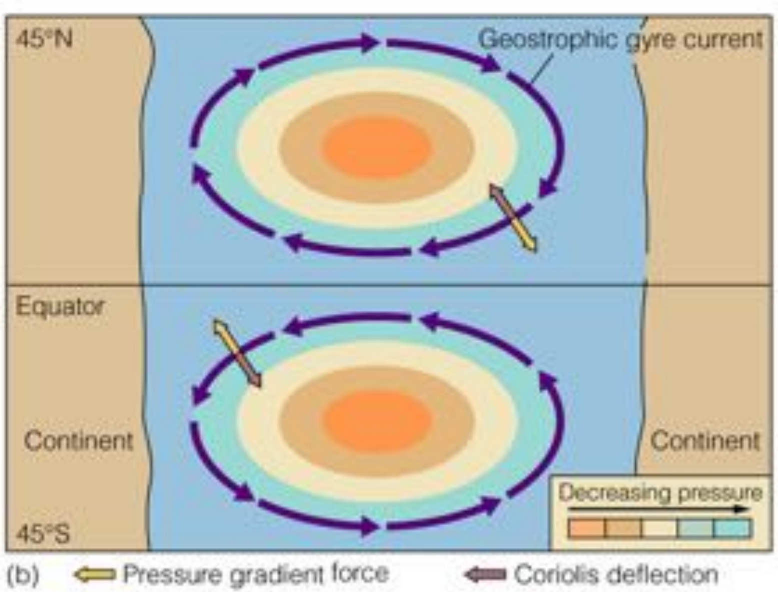
Image: David Townsend

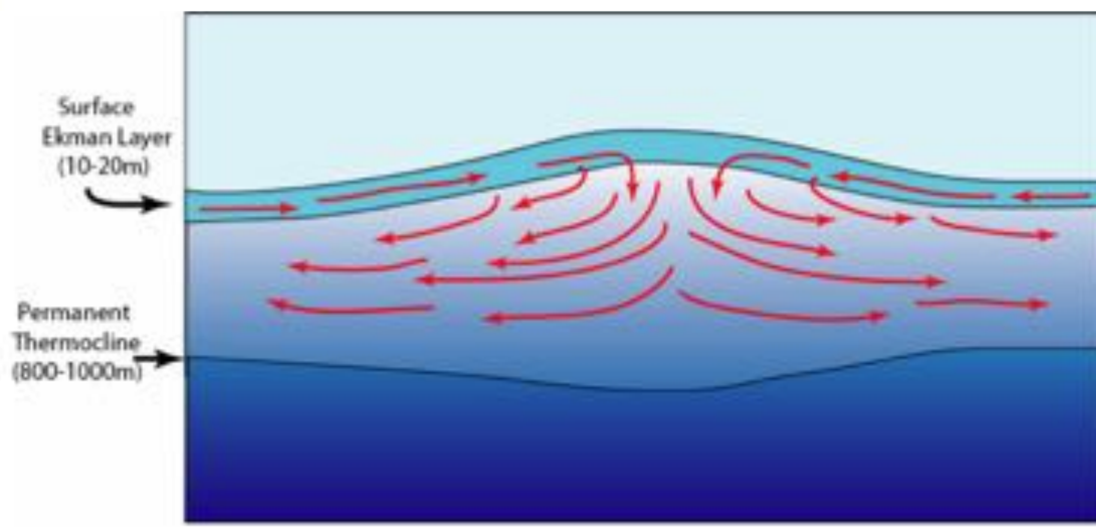




Ekman spiral can extend 100-200 m
Ekman drift, typically 10-20 m
- based on wind & turbulence
- difficult to measure

Pychnocline: 100s of meters





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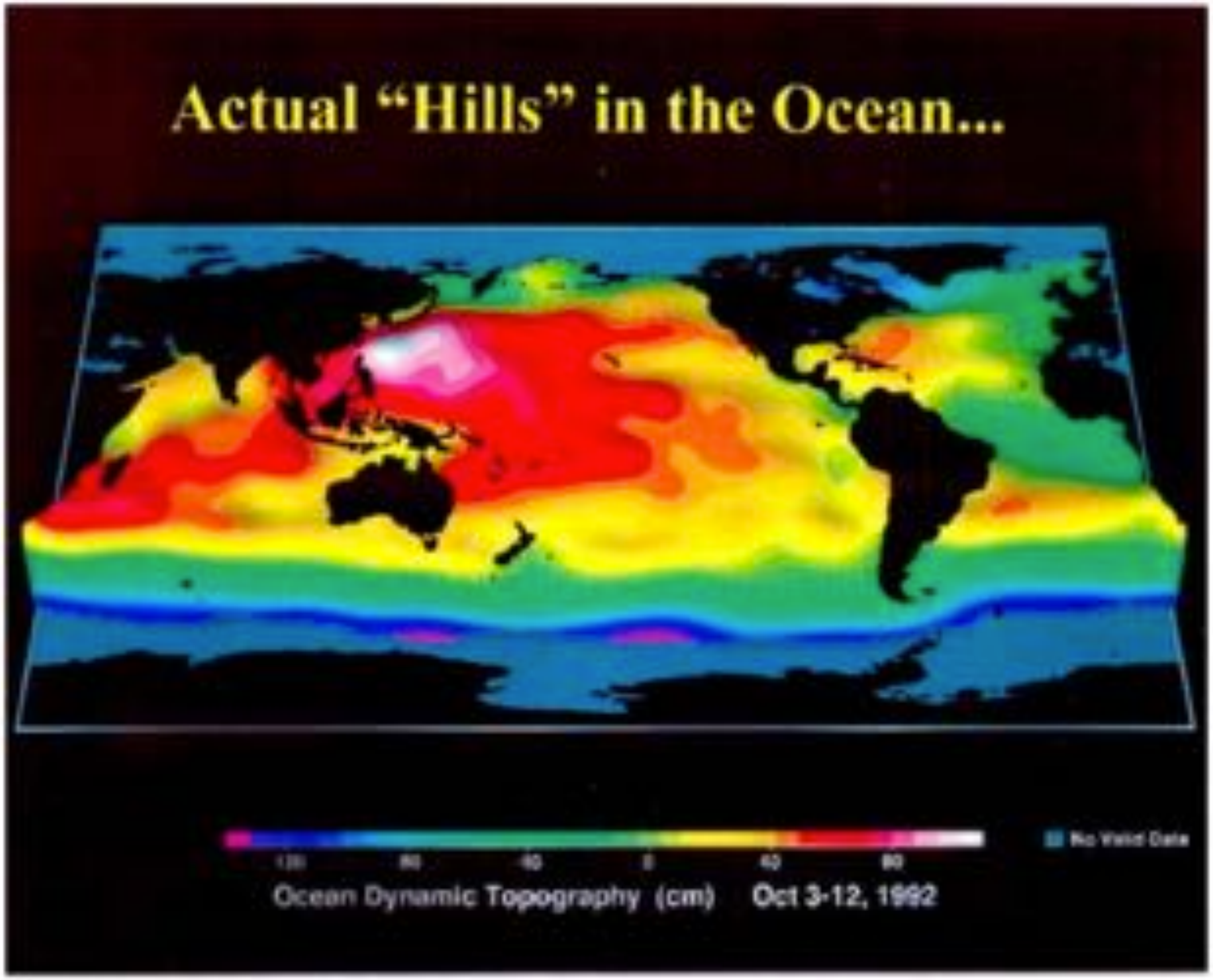


From the Topex-Poseidon Satellite
using *“Radar Altimetry”*...

Geostrophy – pressure gradient balanced by Coriolis effect.

Image: David Townsend

Resulting Global Ocean Circulation Patterns

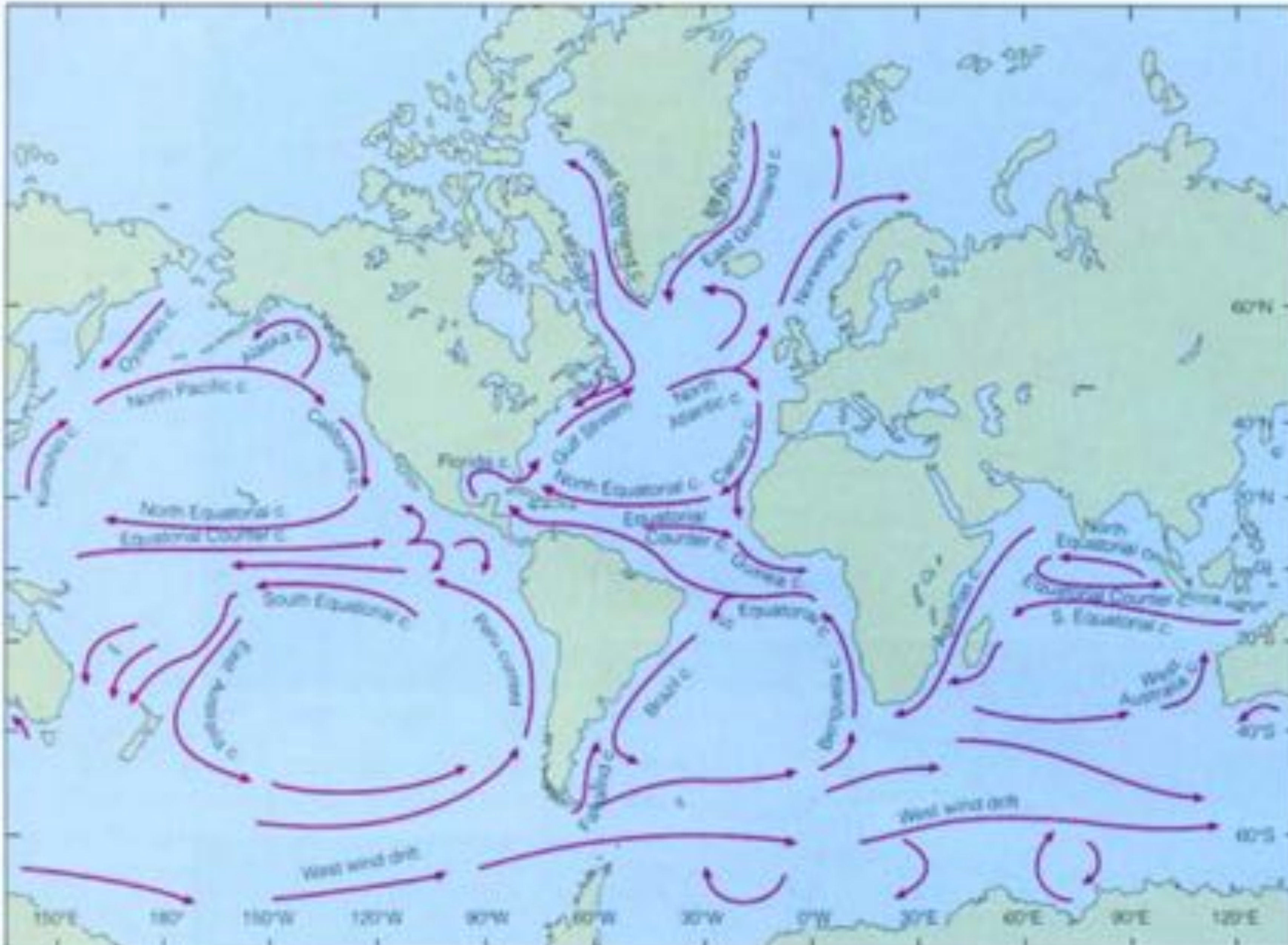
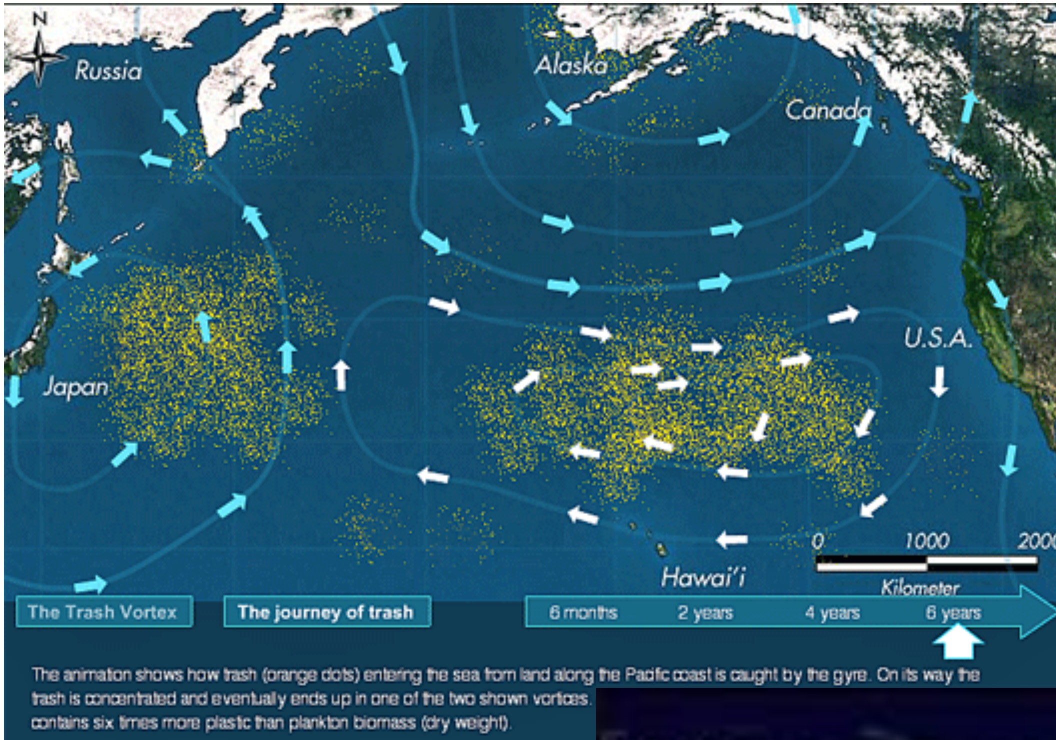
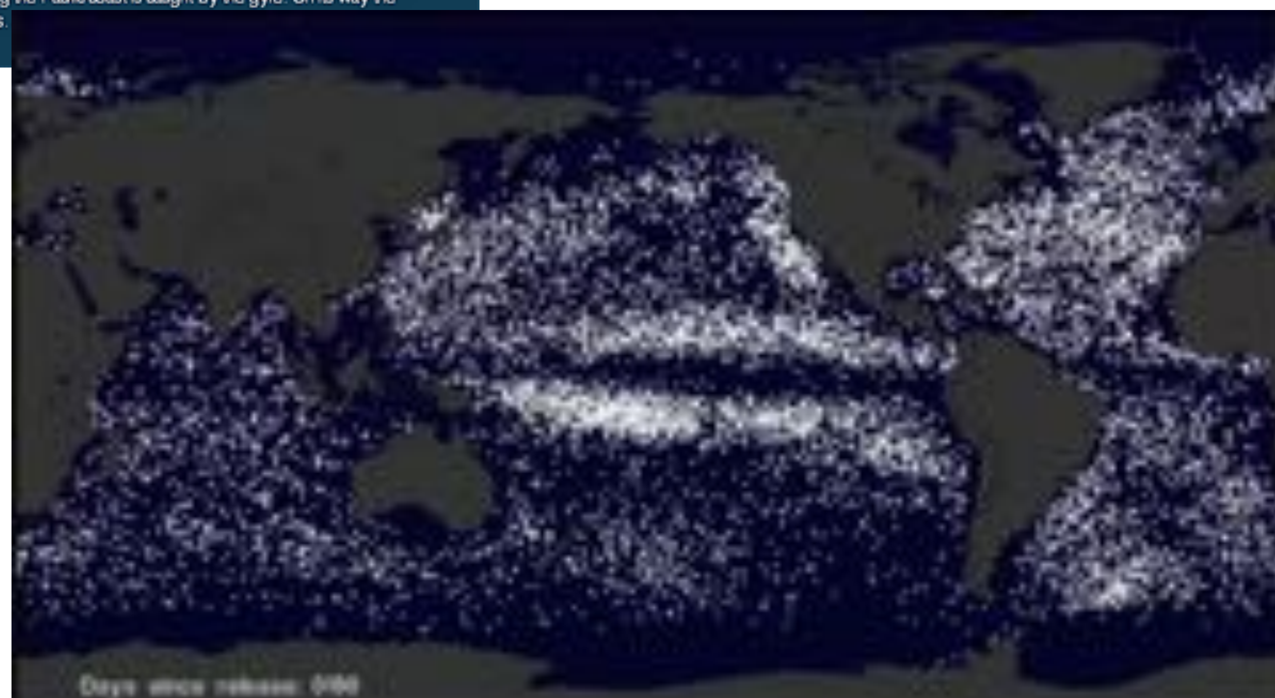


Image: David Townsend



The animation shows how trash (orange dots) entering the sea from land along the Pacific coast is caught by the gyre. On its way the trash is concentrated and eventually ends up in one of the two shown vortices.
contains six times more plastic than plankton biomass (dry weight).



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Global Thermo-Haline Circulation

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

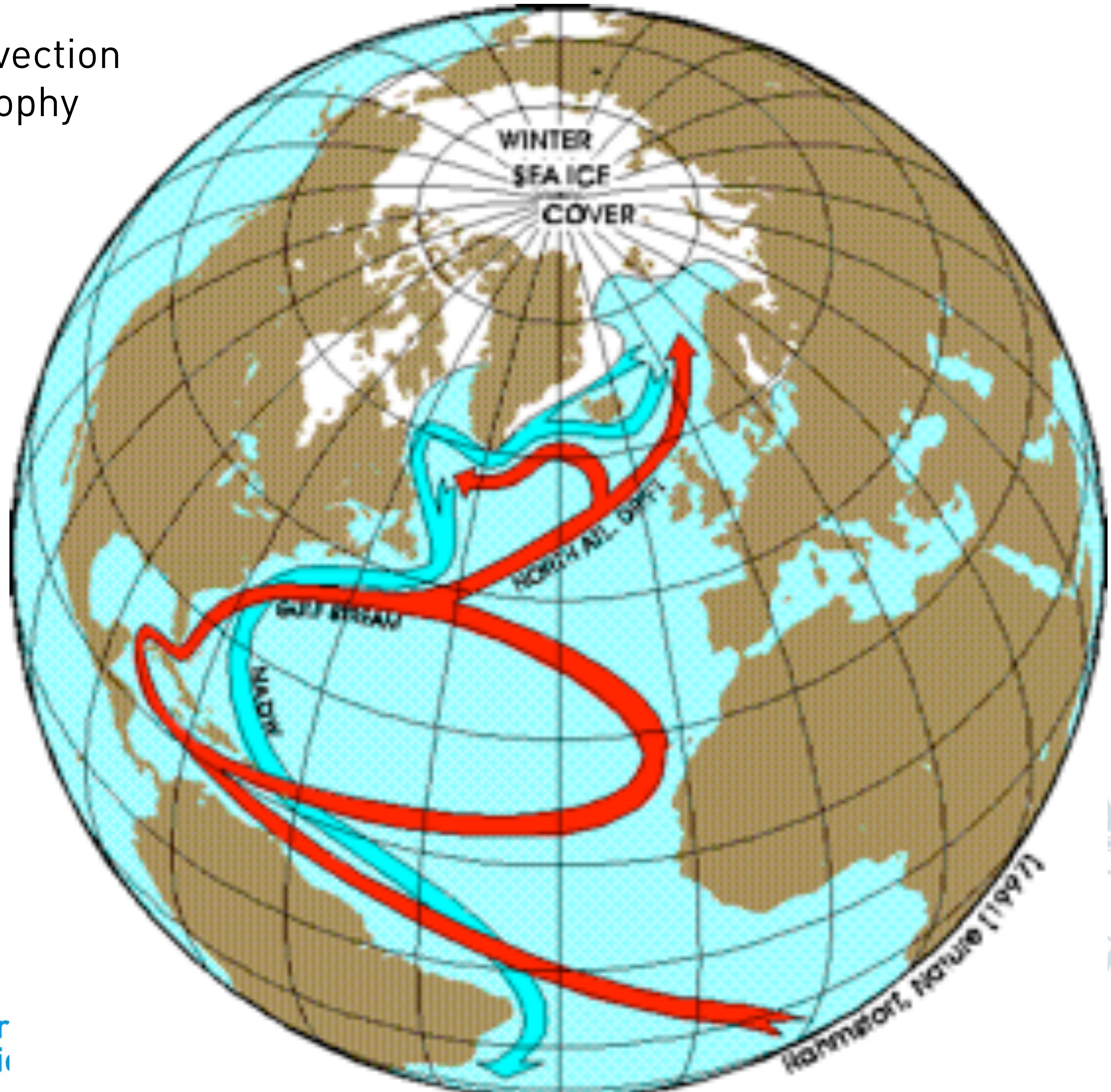
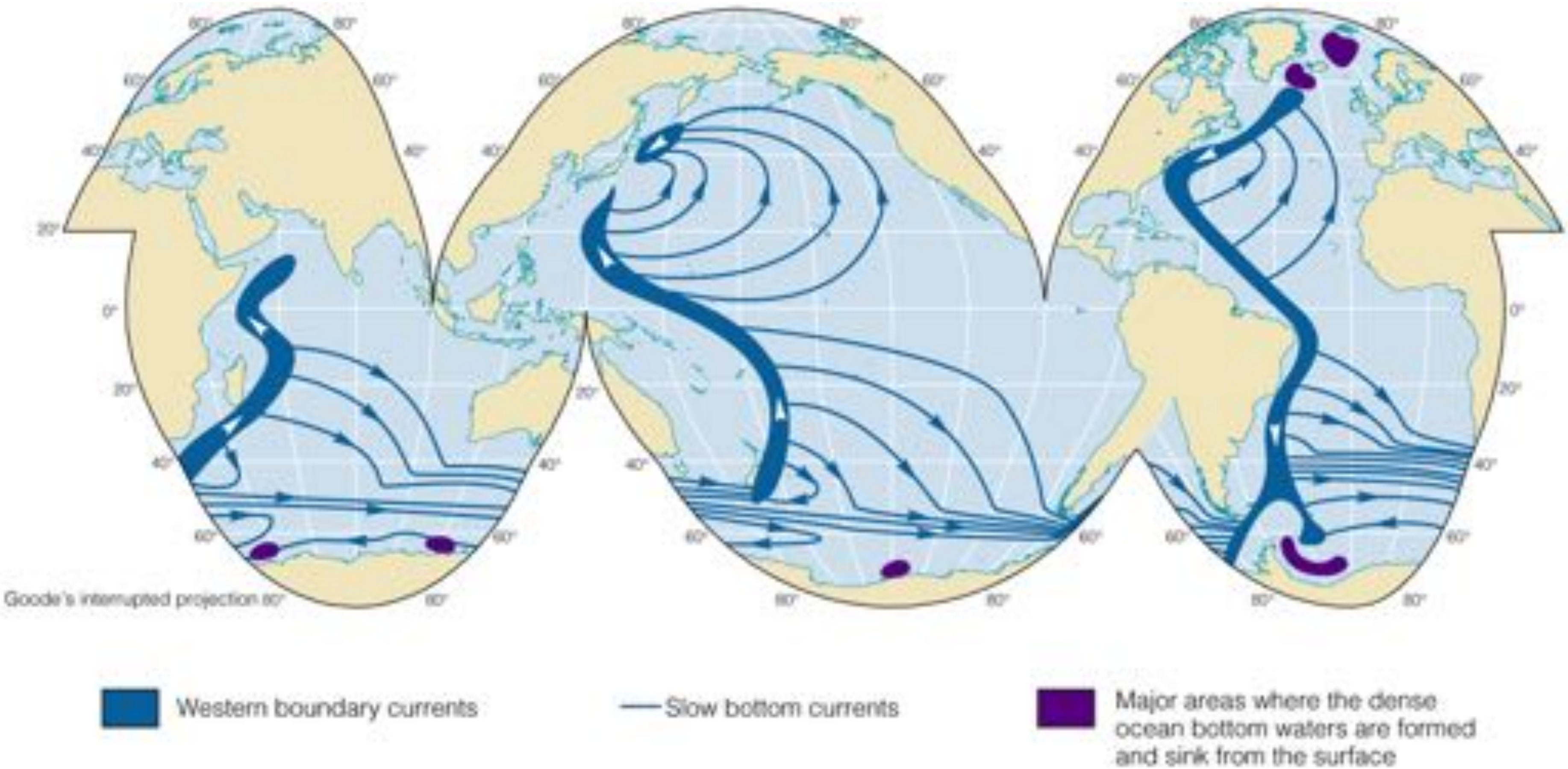
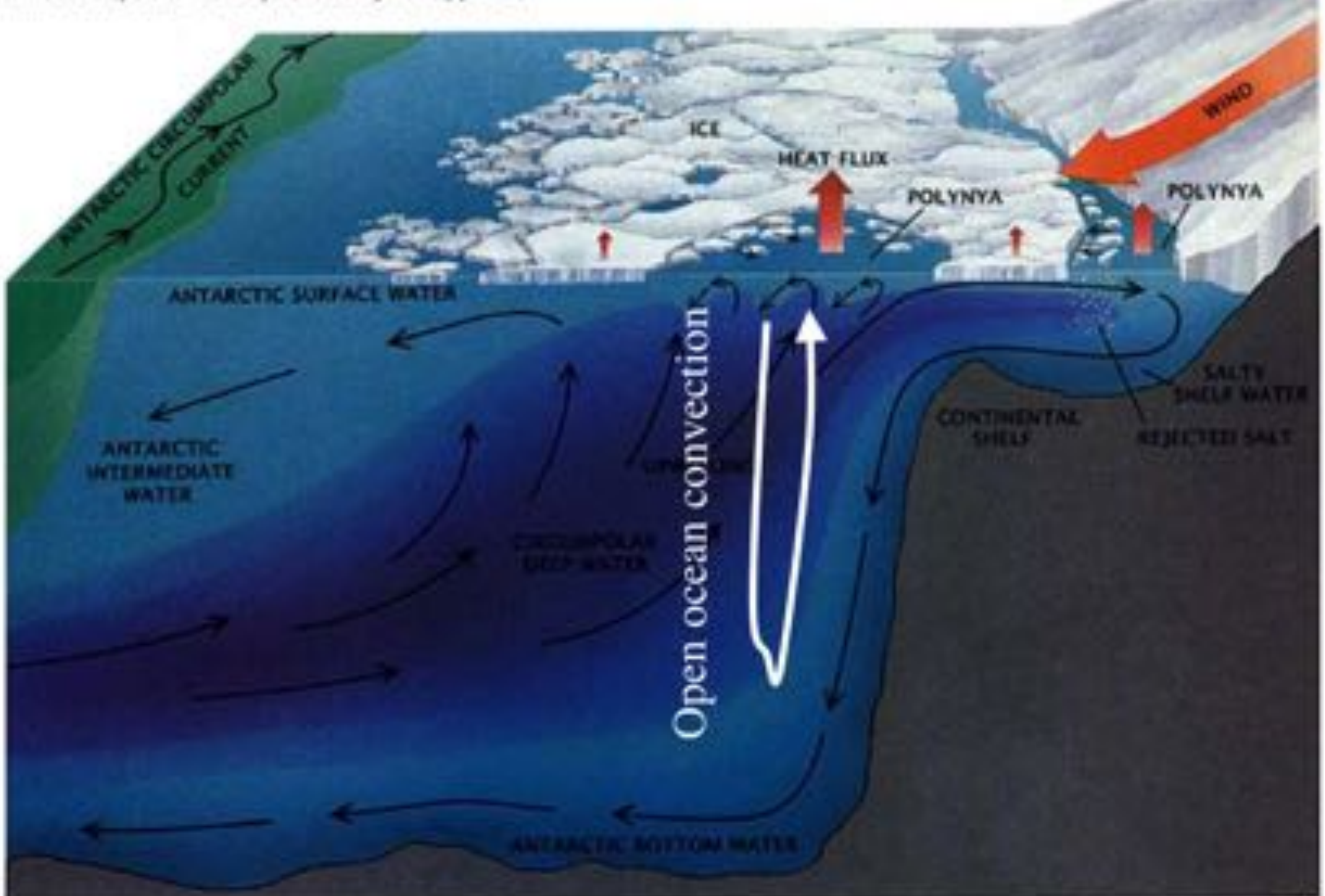


Image: Stefan Rahmstorf

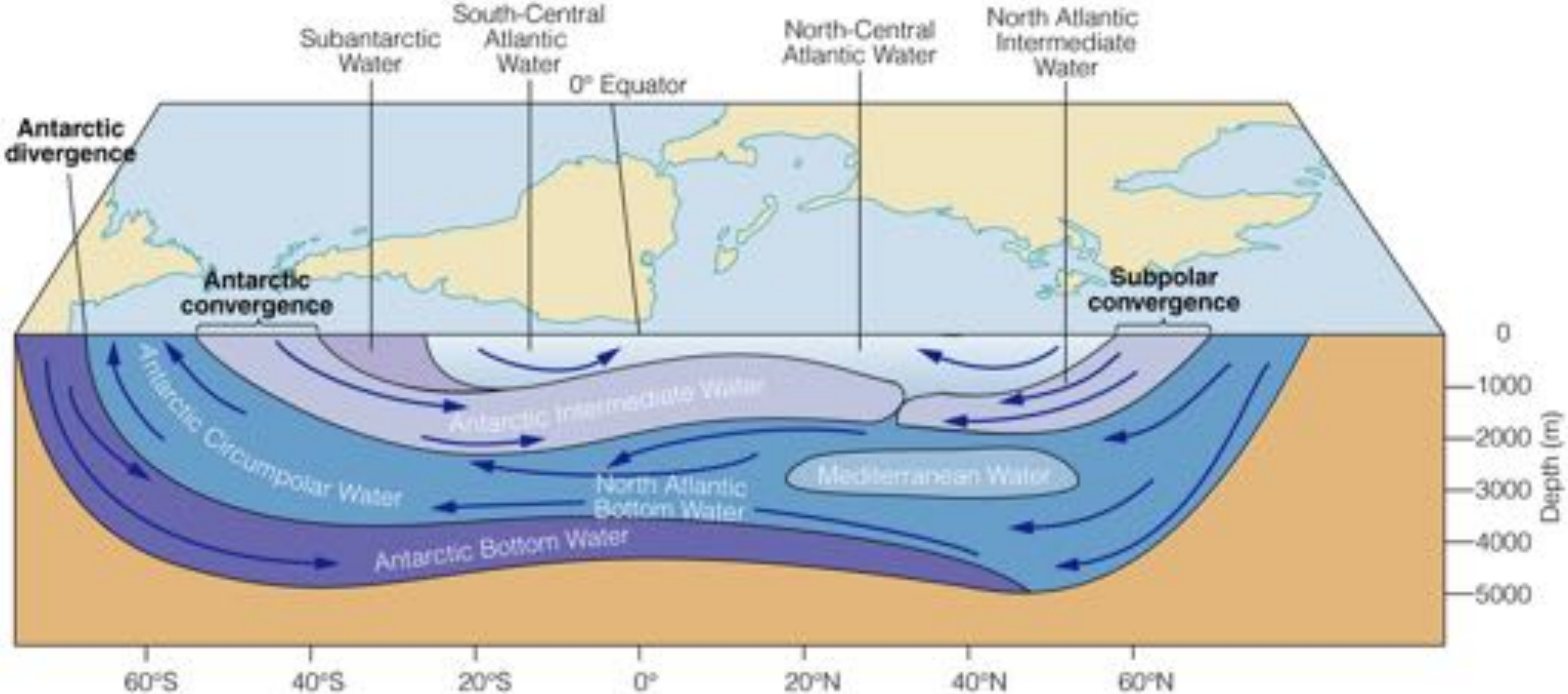
<u>Sites of deep convection</u>

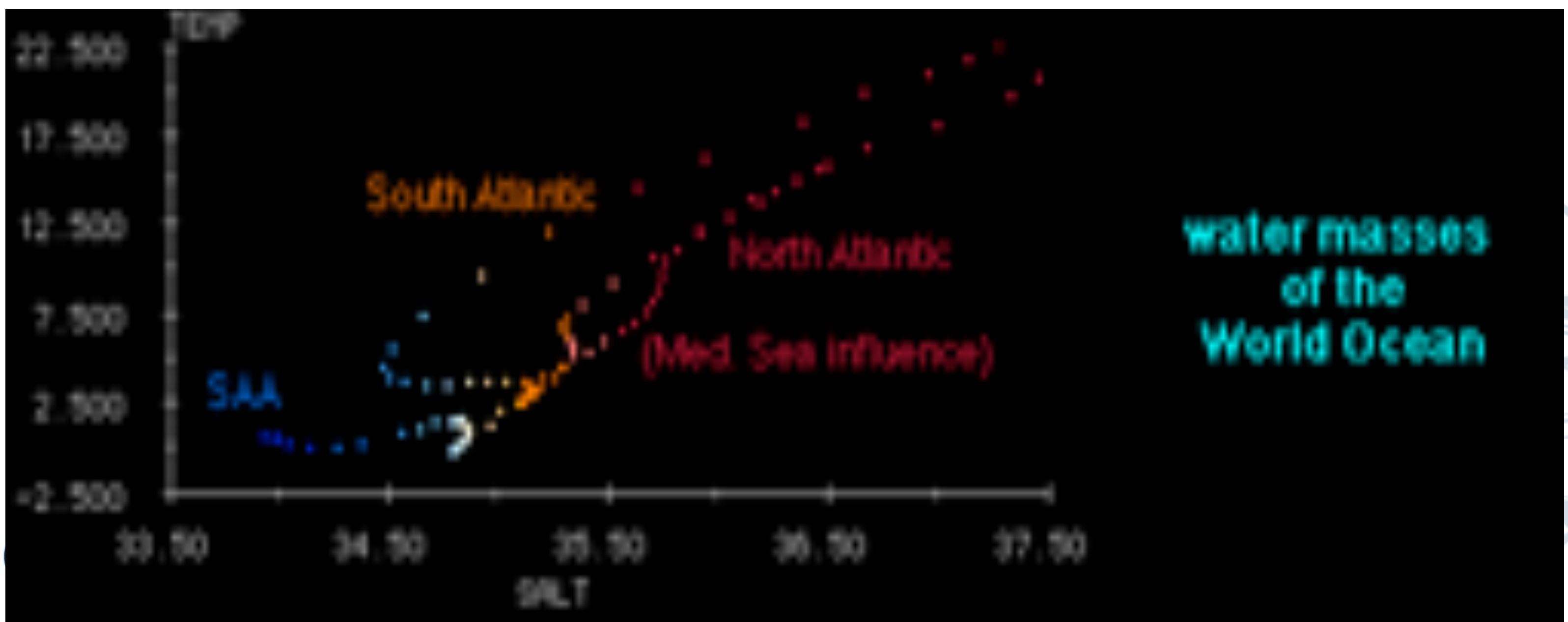


Source: Gordon, Arnold L. and Josefino, C. Comiso (1988) "Polynyas in the Southern Ocean." *Scientific American*, June 1988, Vol. 256, No. 6, p. 92.

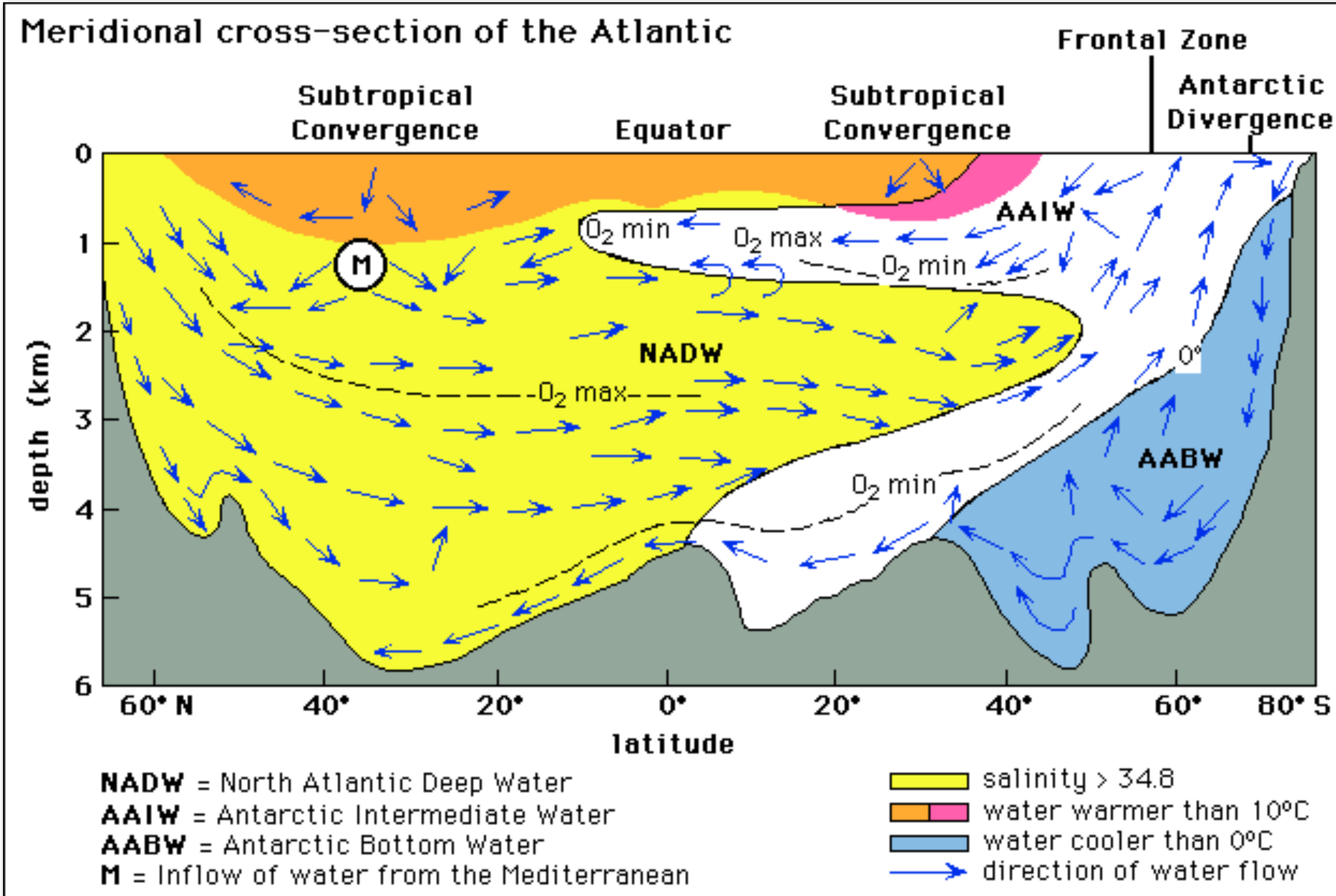


Meridional circulation pattern of the Southern Ocean (the ocean surrounding Antarctica) is dominated by the upwelling of a warm, salty water mass called the Circumpolar Deep Water and its transformation into Antarctic Surface Water, which ultimately sinks to become Antarctic Intermediate Water and Antarctic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


Subantarctic Water
South-Central Atlantic Water
0° Equator
North-Central Atlantic Water
North Atlantic Intermediate Water
Antarctic divergence
Antarctic convergence
Subpolar convergence
Antarctic Circumpolar Water
Antarctic Intermediate Water
North Atlantic Bottom Water
Mediterranean Water
Antarctic Bottom Water
0
1000
2000
3000
4000
5000
Depth (m)
60°S
40°S
20°S
0°
20°N
40°N
60°N


TEMP
22.500
17.500
12.500
7.500
2.500
-2.500
33.50
34.50
35.50
36.50
37.50
SALT
South Atlantic
North Atlantic
(Med. Sea influence)
SAA
water masses of the World Ocean

Big



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

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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

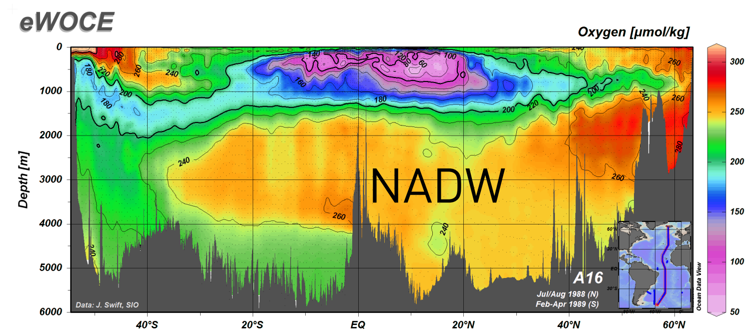
Antarctic Intermediate W

Antarctic Bottom W

Mediterranean

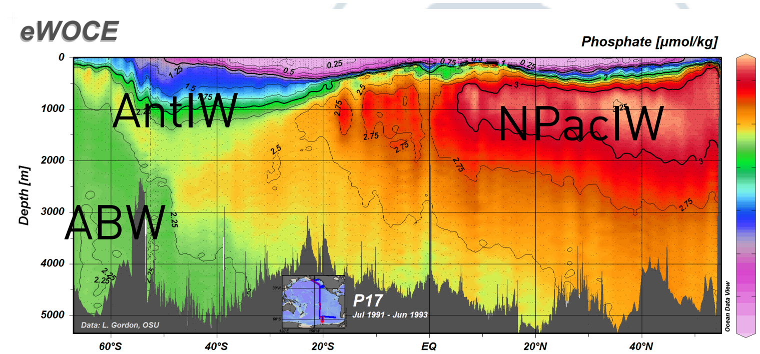
N Atlantic Deep W

S



S Oxygen N

S Phosphate N



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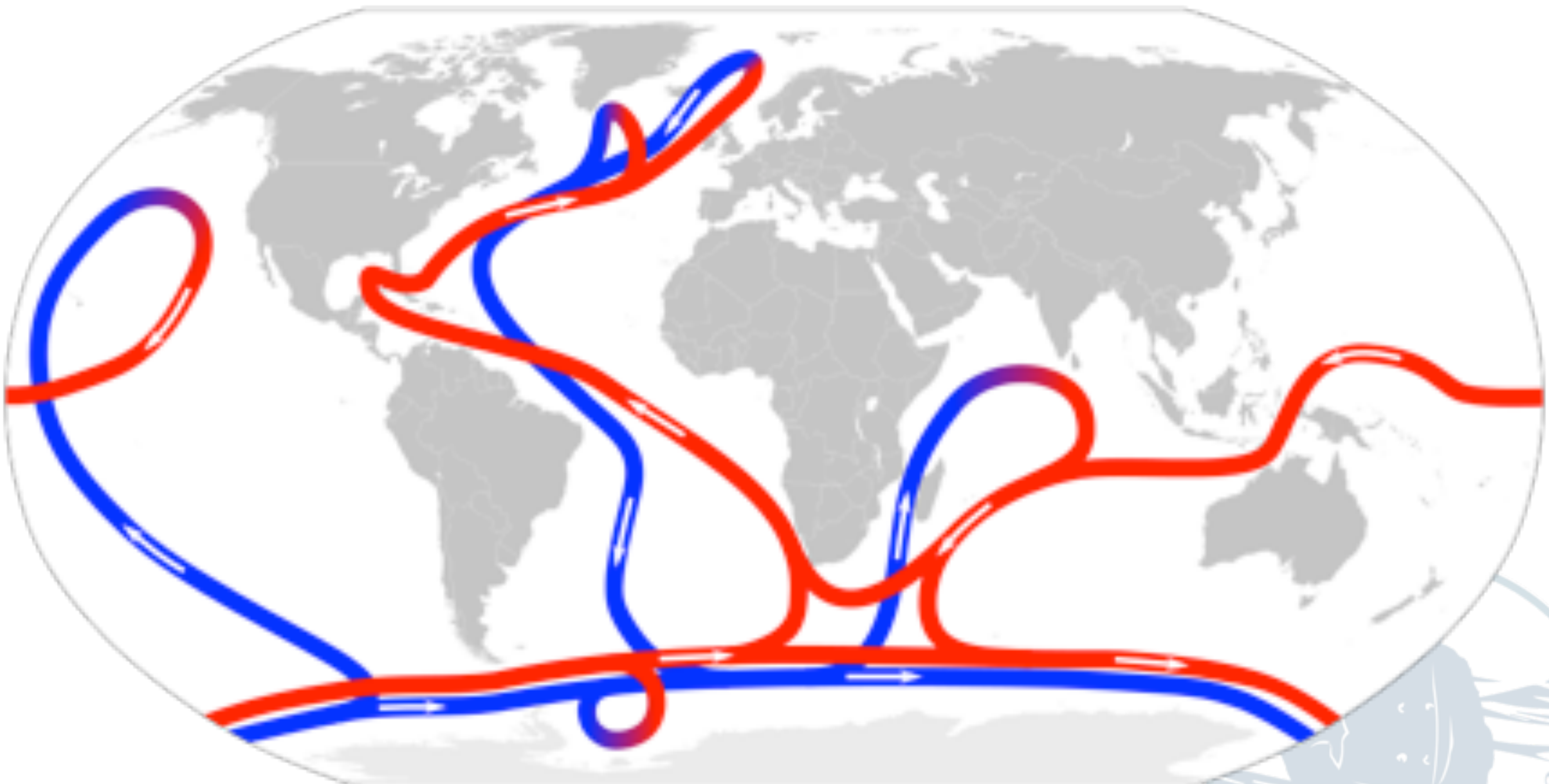
Global Thermohaline Circulation

(Simpler Picture)



[Perpetual Ocean: http://www.youtube.com/watch?v=xusdWPuWAoU](http://www.youtube.com/watch?v=xusdWPuWAoU)
[Circulation: http://www.youtube.com/watch?v=3niR_-Kv4SM](http://www.youtube.com/watch?v=3niR_-Kv4SM)

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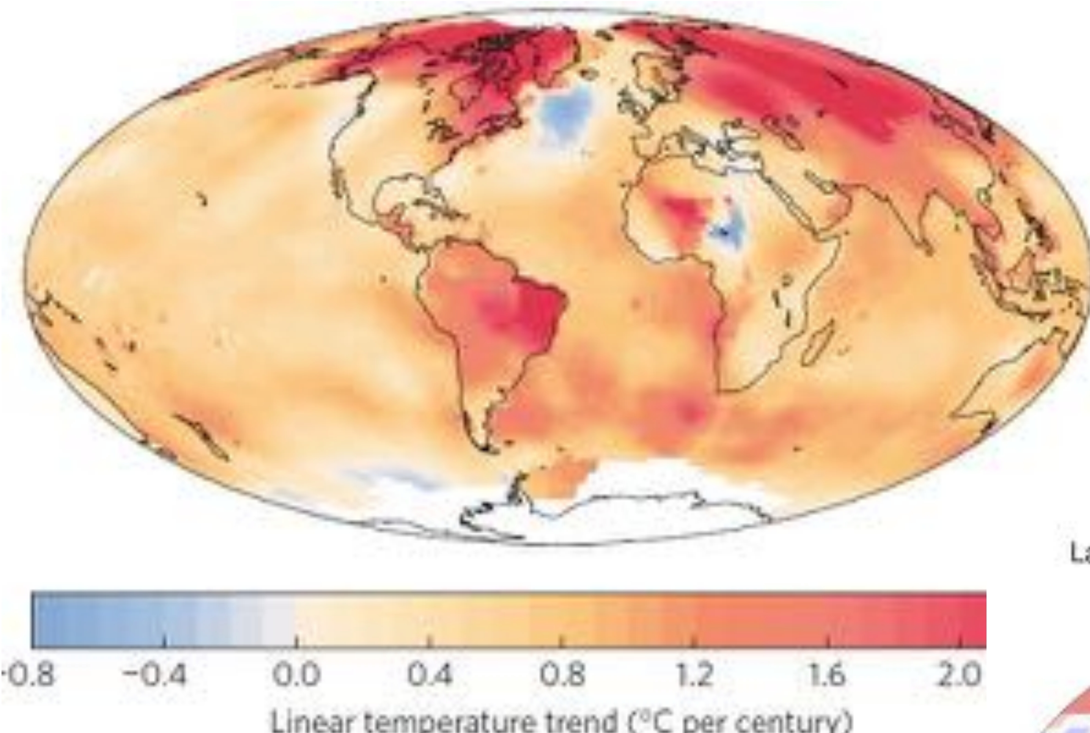
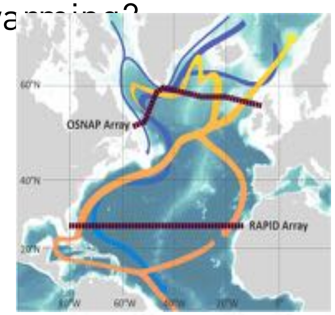
What's changing? The Atlantic Meridional Overturning Circulation = AMOC

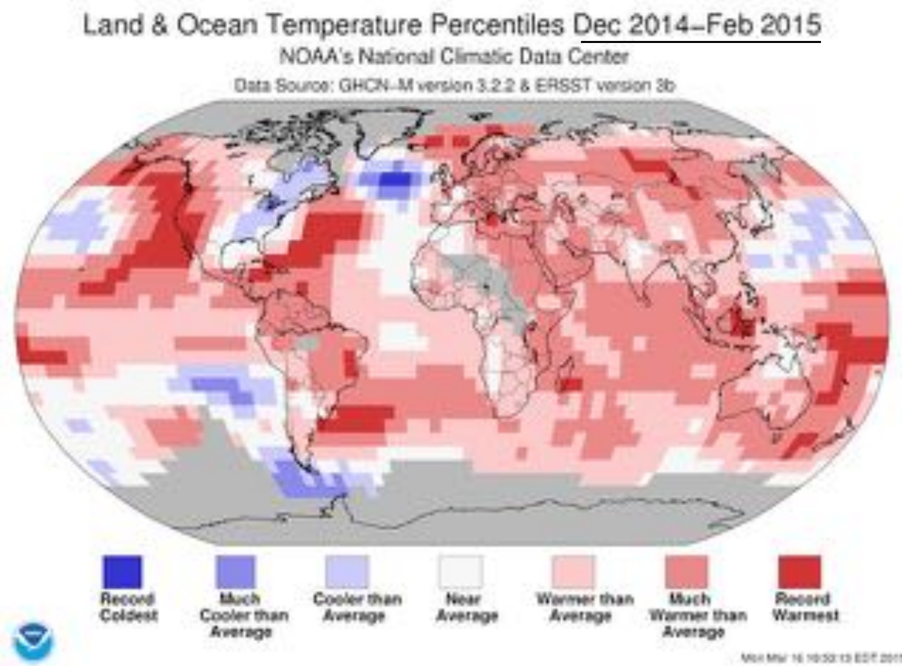


Linear temperature trend from 1900 to 2013. The cooling in the subpolar North Atlantic is remarkable and well documented by numerous measurements – unlike the cold spot in central Africa, which on closer inspection apparently is an artifact of incomplete and inhomogeneous weather station data (Rahmstorf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



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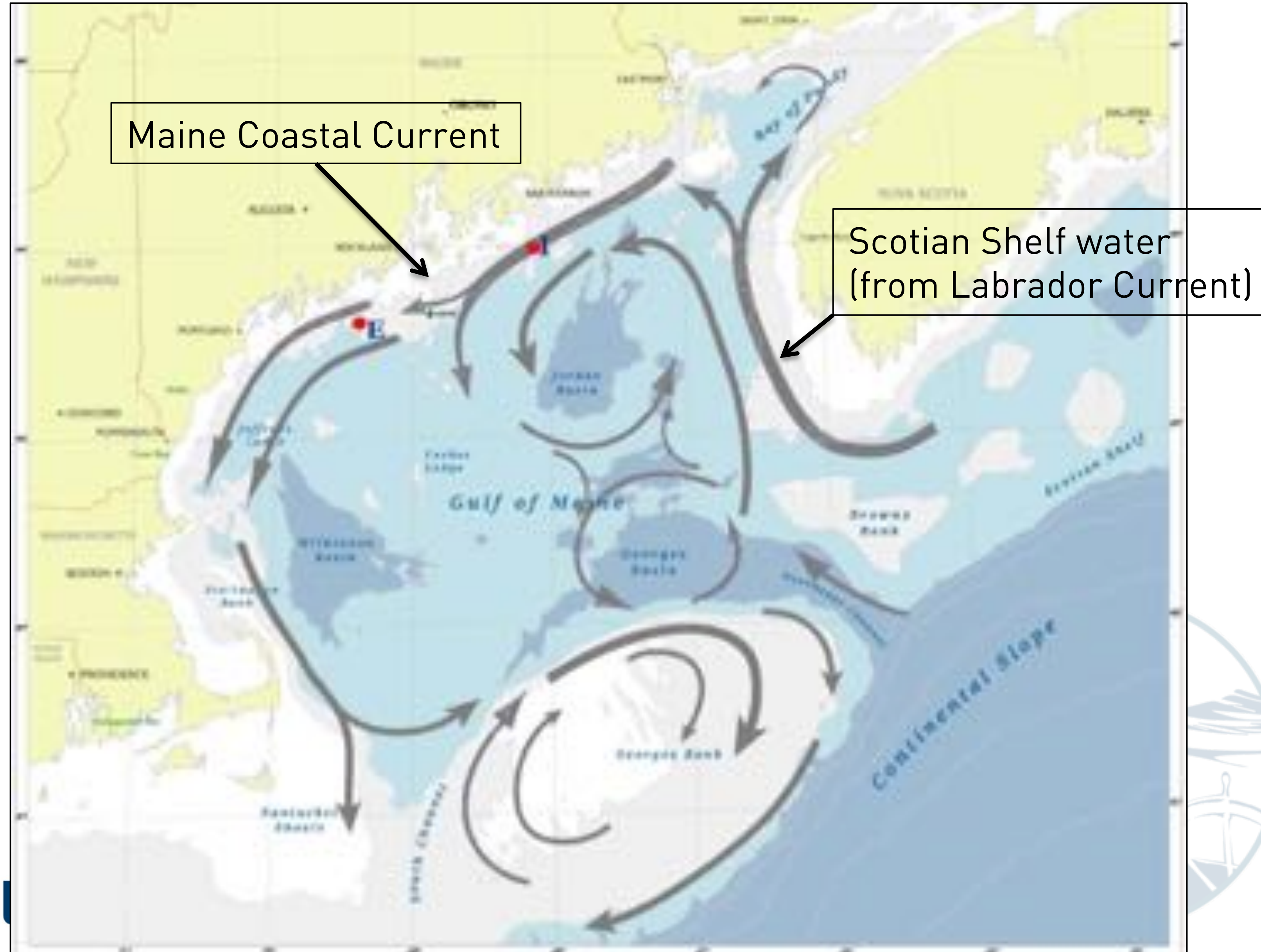
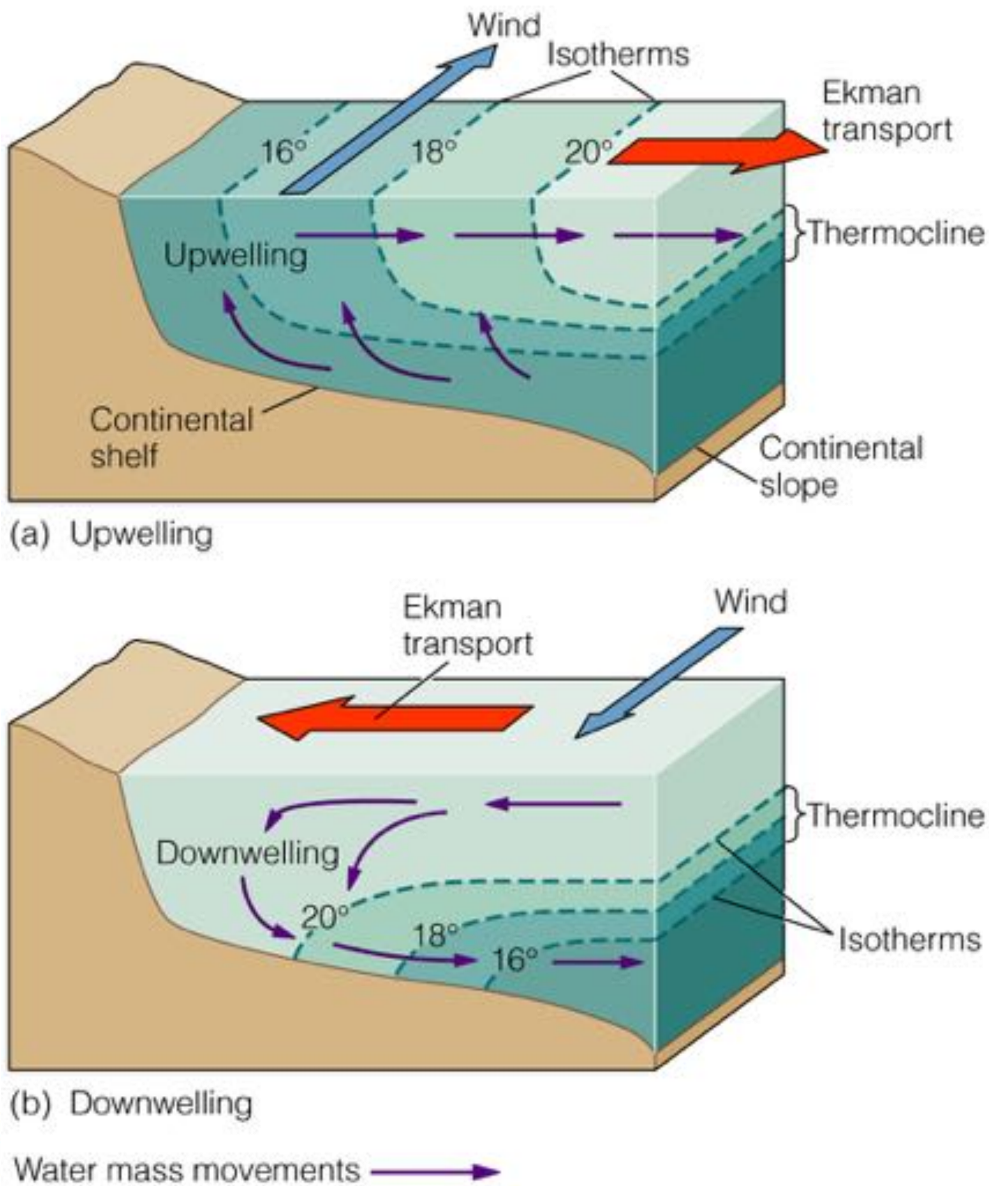
http://www.realclimate.org/index.php/archives/2015/03/whats-going-on-in-the-north-atlantic/

Gulf of Maine



Pettigrew 2005

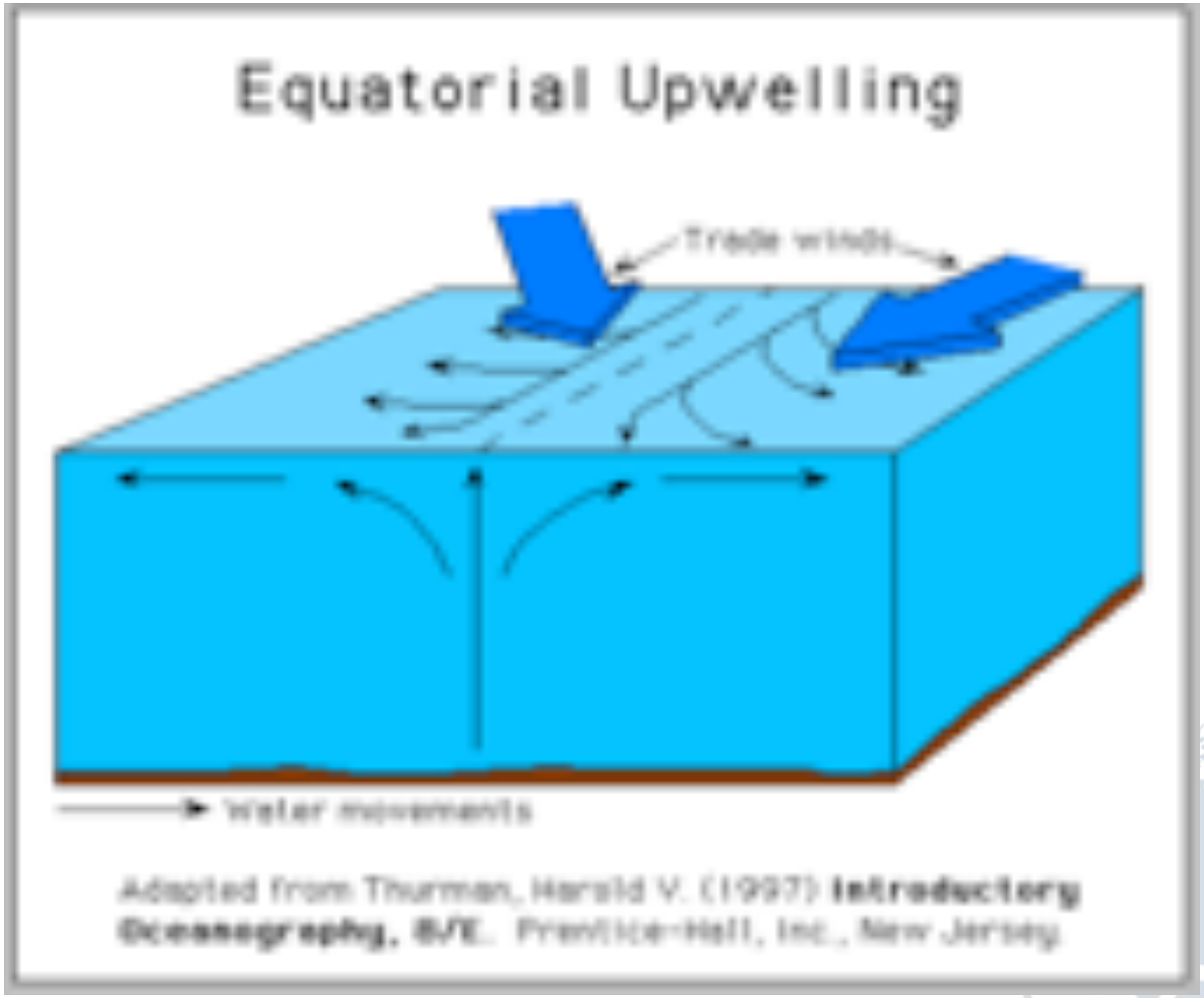
Other currents



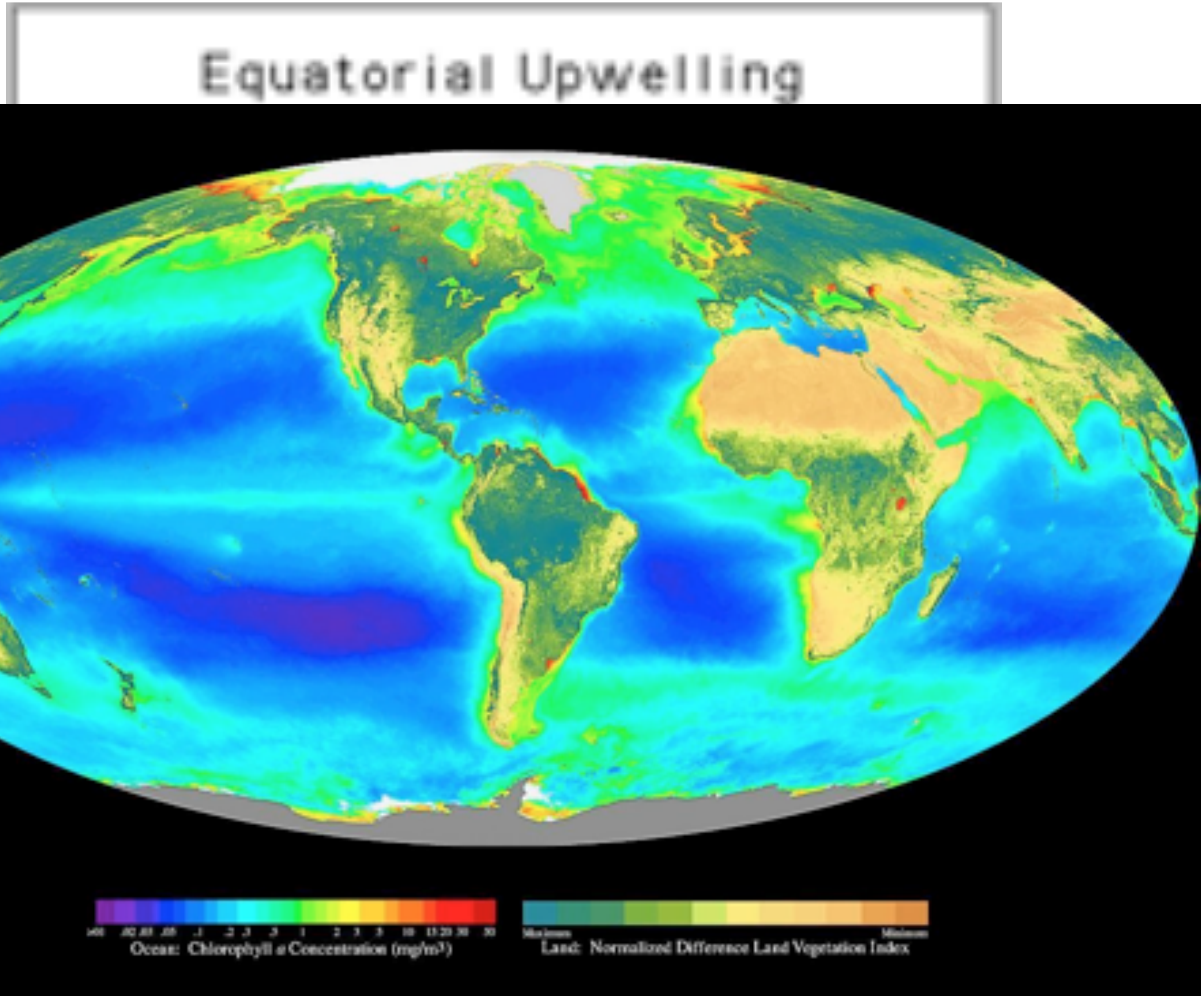
Upwelling & Downwelling

- Coastal up/down welling more common on US west coast

Other currents

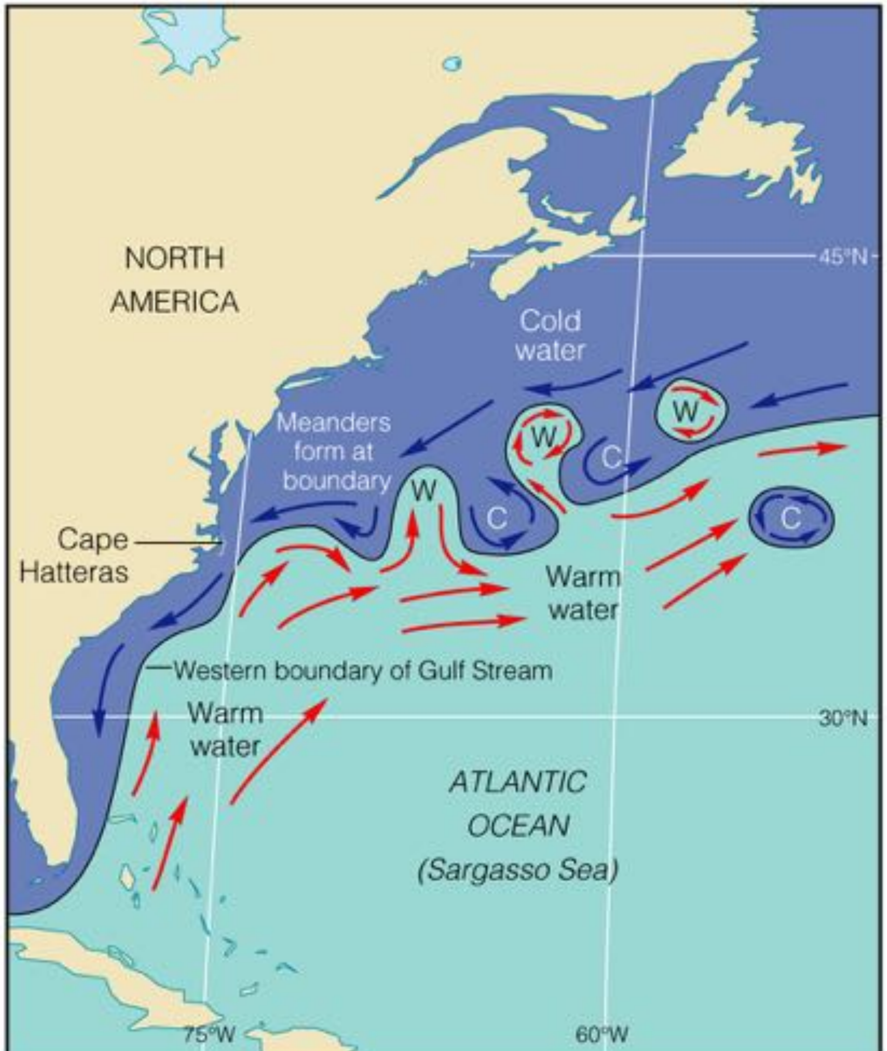


Other currents

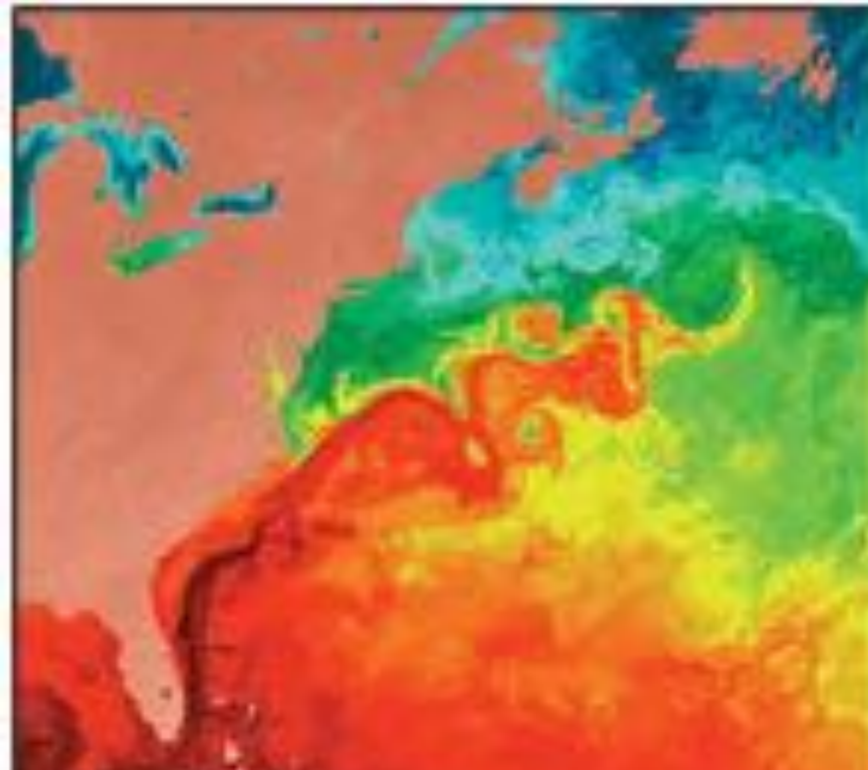


Other currents

Eddies

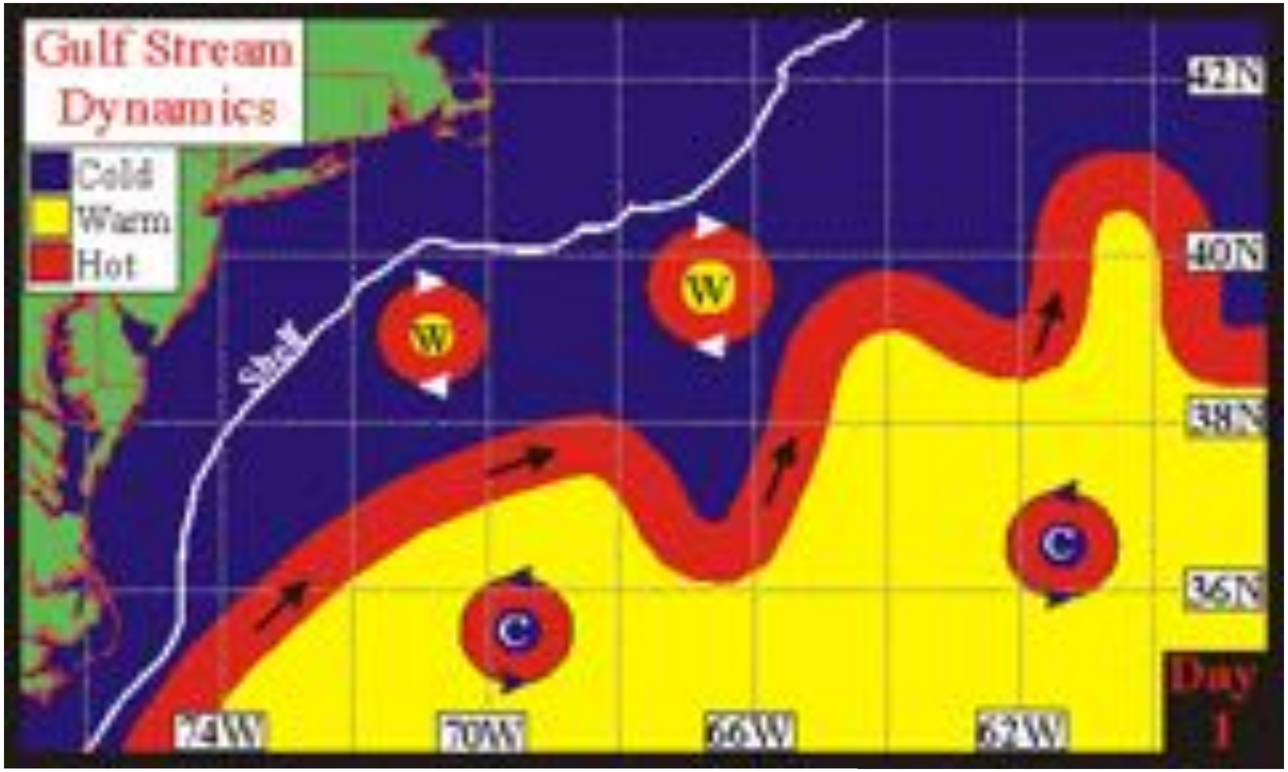


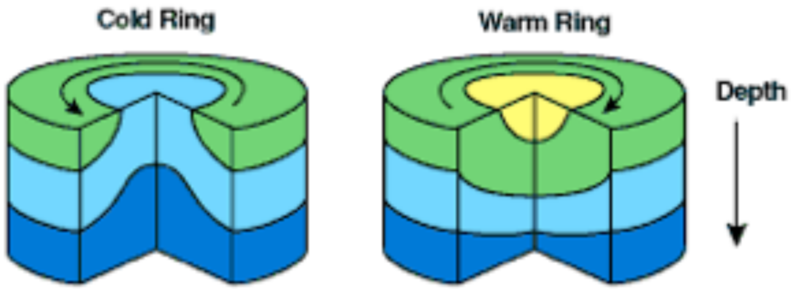
Robinson projection



Other currents

Eddies





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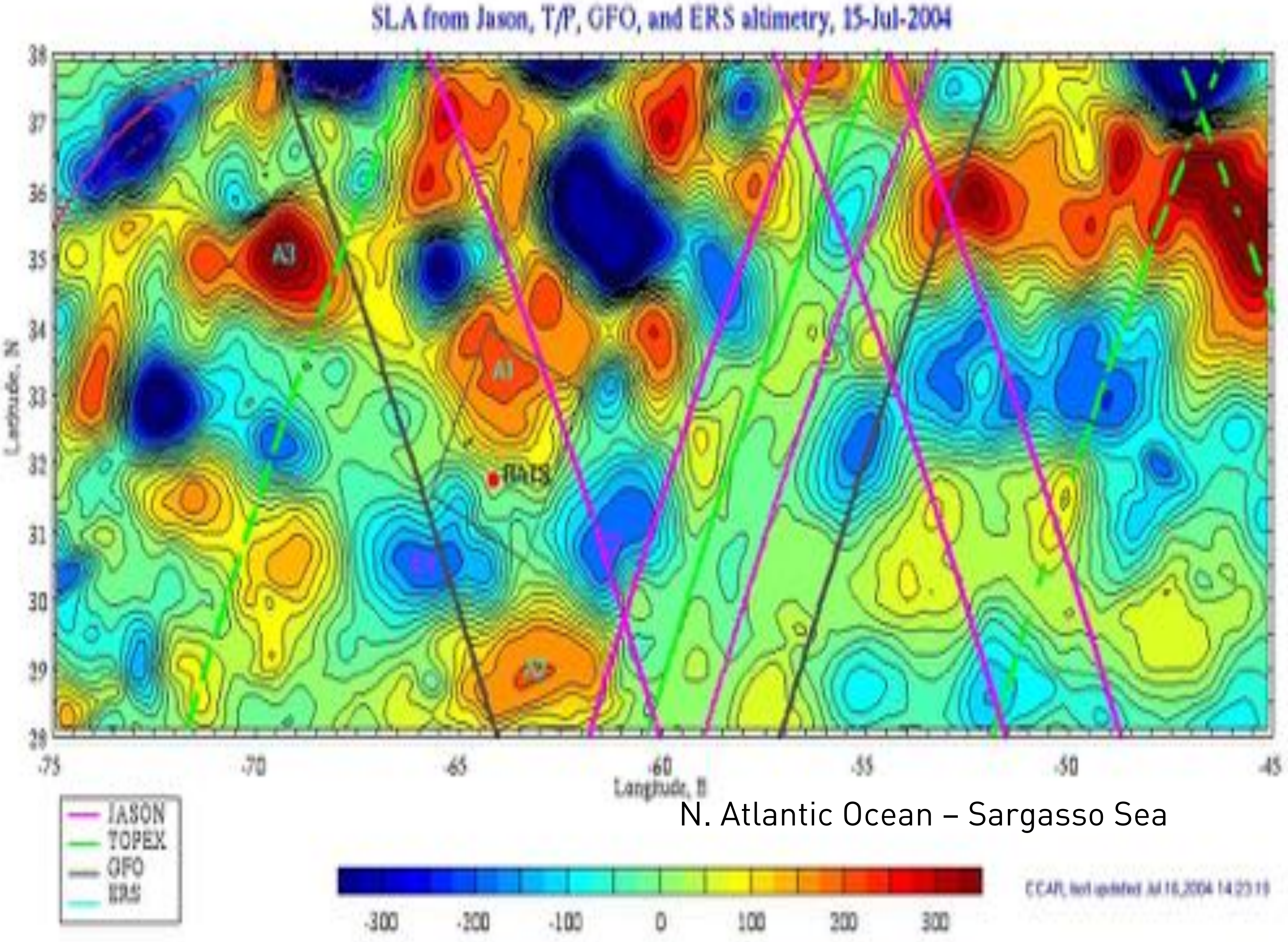
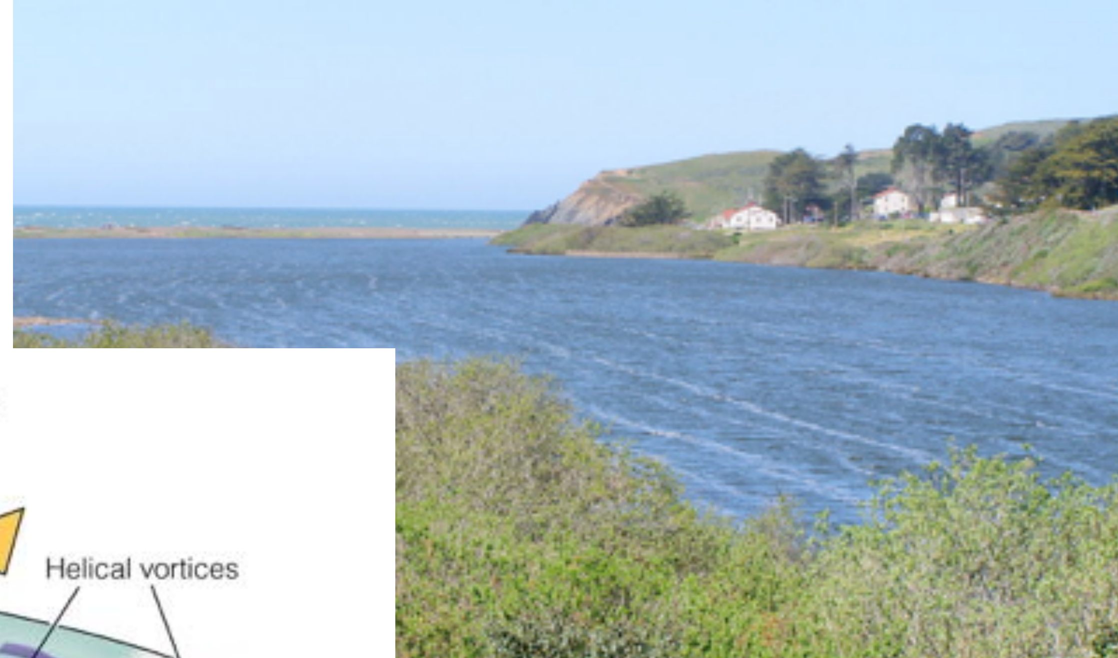
Sea surface height maps: eddies everywhere!

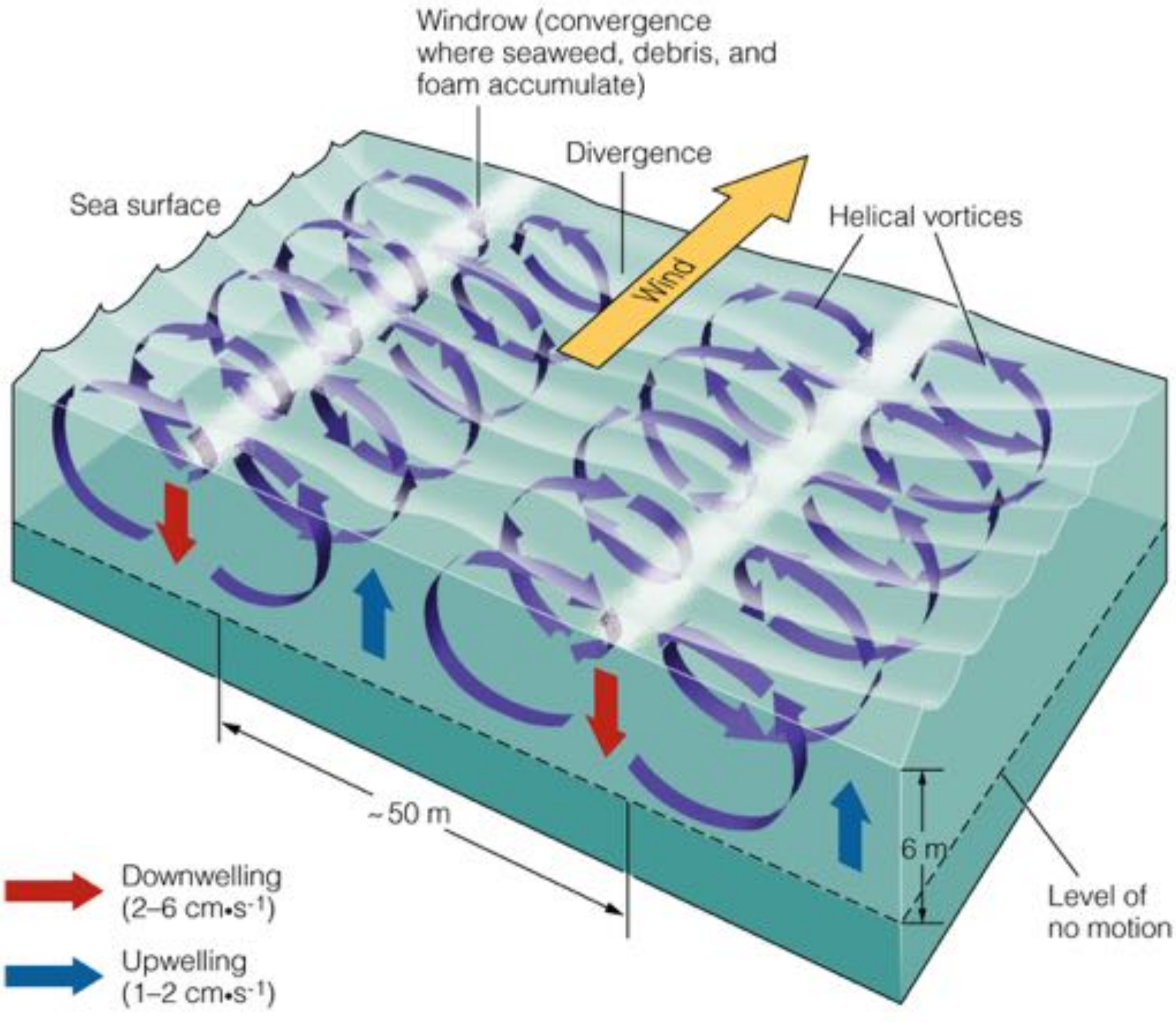


N. Atlantic Ocean – Sargasso Sea

Other currents

Langmuir Circulation





(a)

Ocean Modeling

Physical processes:

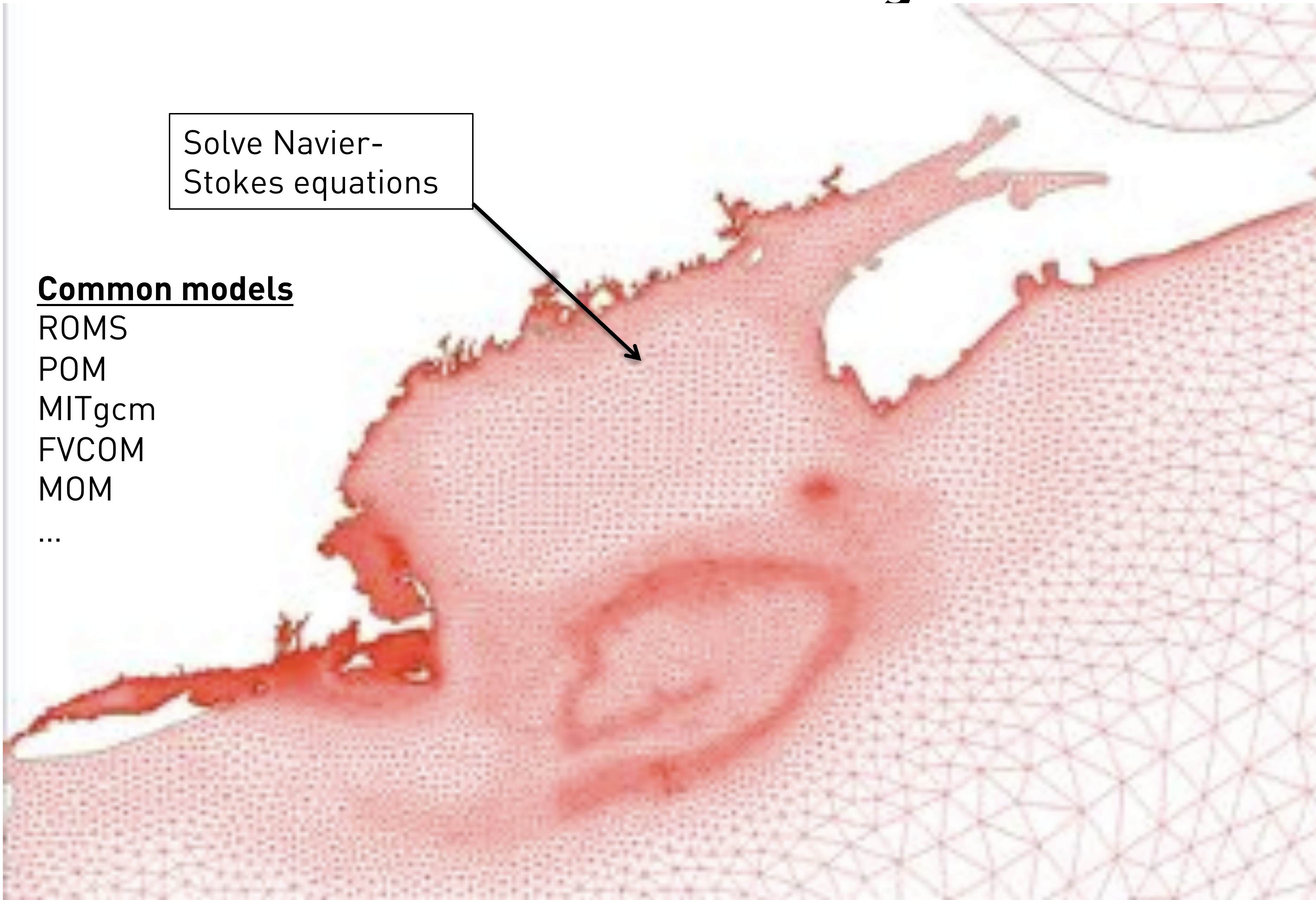
- Ocean movement/dynamics, including horizontal and vertical advection
- Exchange of energy between the ocean and external sources (radiation, precipitation, evaporation, river-runoff, wind, etc)
- 3D mixing and dissipation processes

Advantages

- Comparatively less expensive
- Higher spatial/temporal resolution compared to other methods
- Ability to forecast

→ ***Add to understanding of processes***
→ ***Not done in silo***

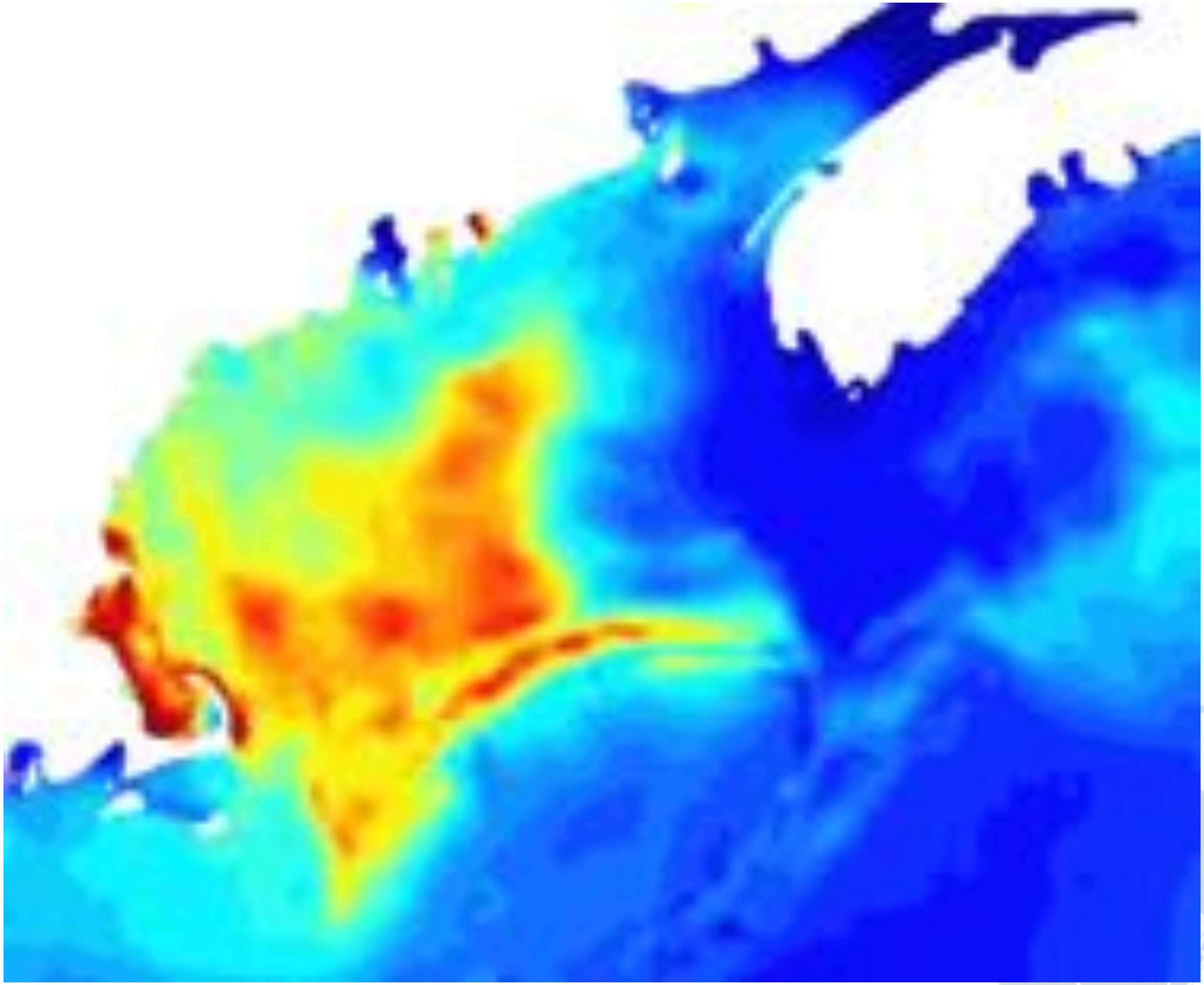
Ocean Modeling



Solve Navier-Stokes equations

Common models
ROMS
POM
MITgcm
FVCOM
MOM
...

Ocean Modeling



Climate

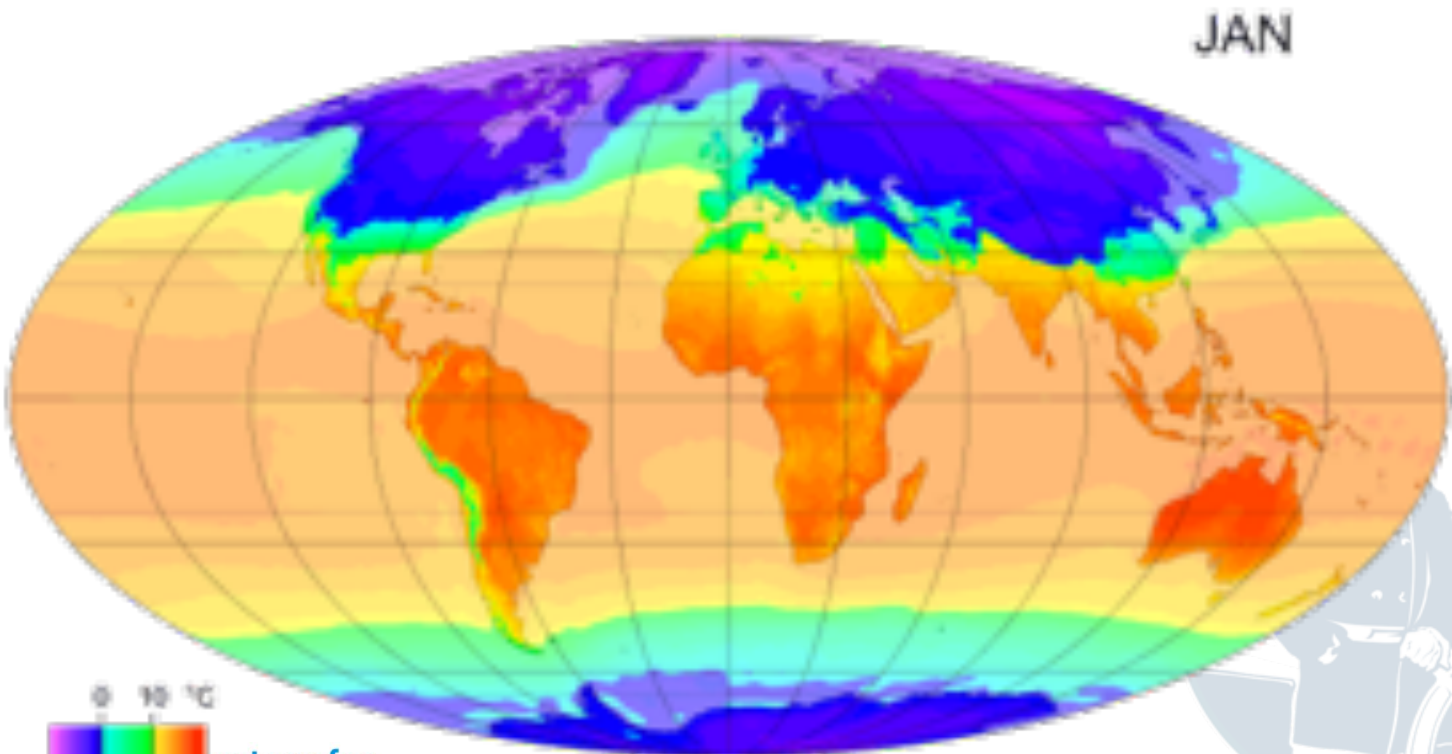
Long term statistical properties at a location
- temperature, precipitation, etc.
- is an average (or other statistical property) over long period of time
- can be large or small spatial scale

According to IPCC, includes:
- atmosphere, hydrosphere, cryosphere, land surface, and biosphere

Note: IPCC = Intergovernmental Panel on Climate Change

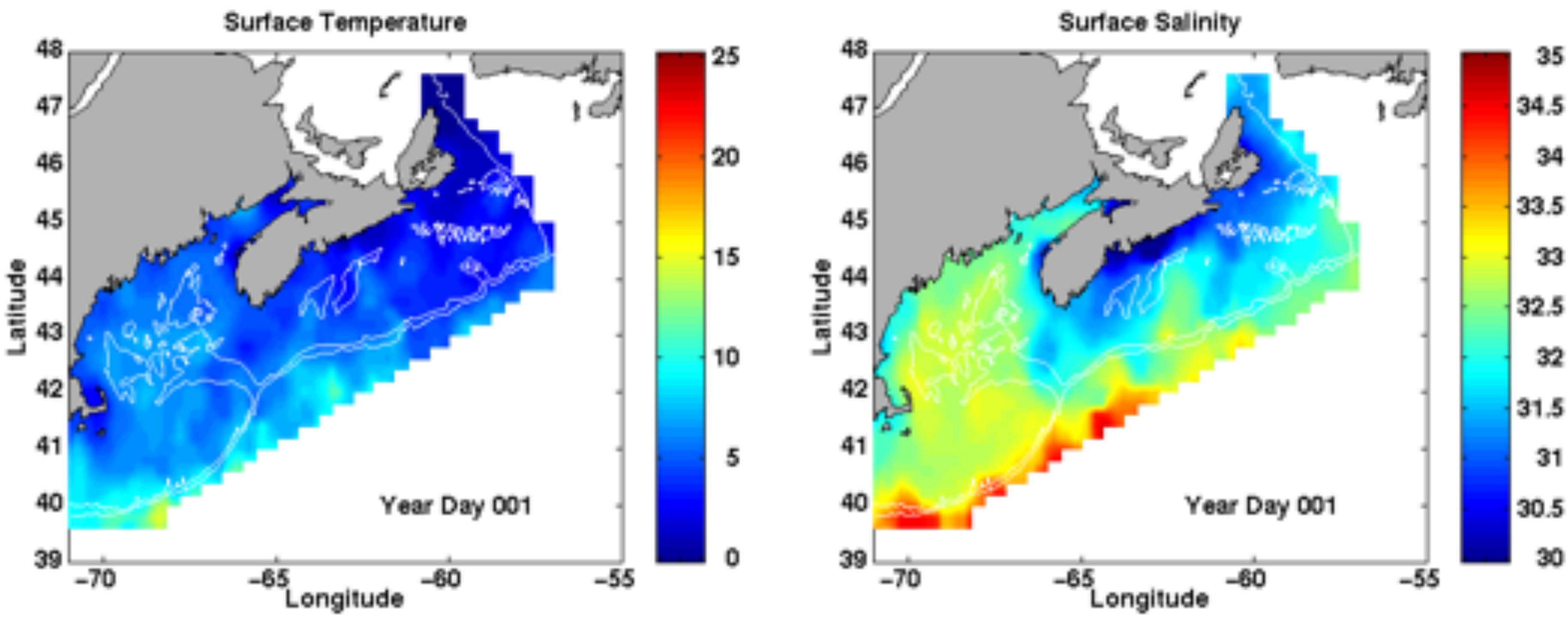
Climatology

- Representation of average conditions, typically a seasonal cycle



Climatology

Gulf of Maine surface conditions through a climatological year DFO Canada



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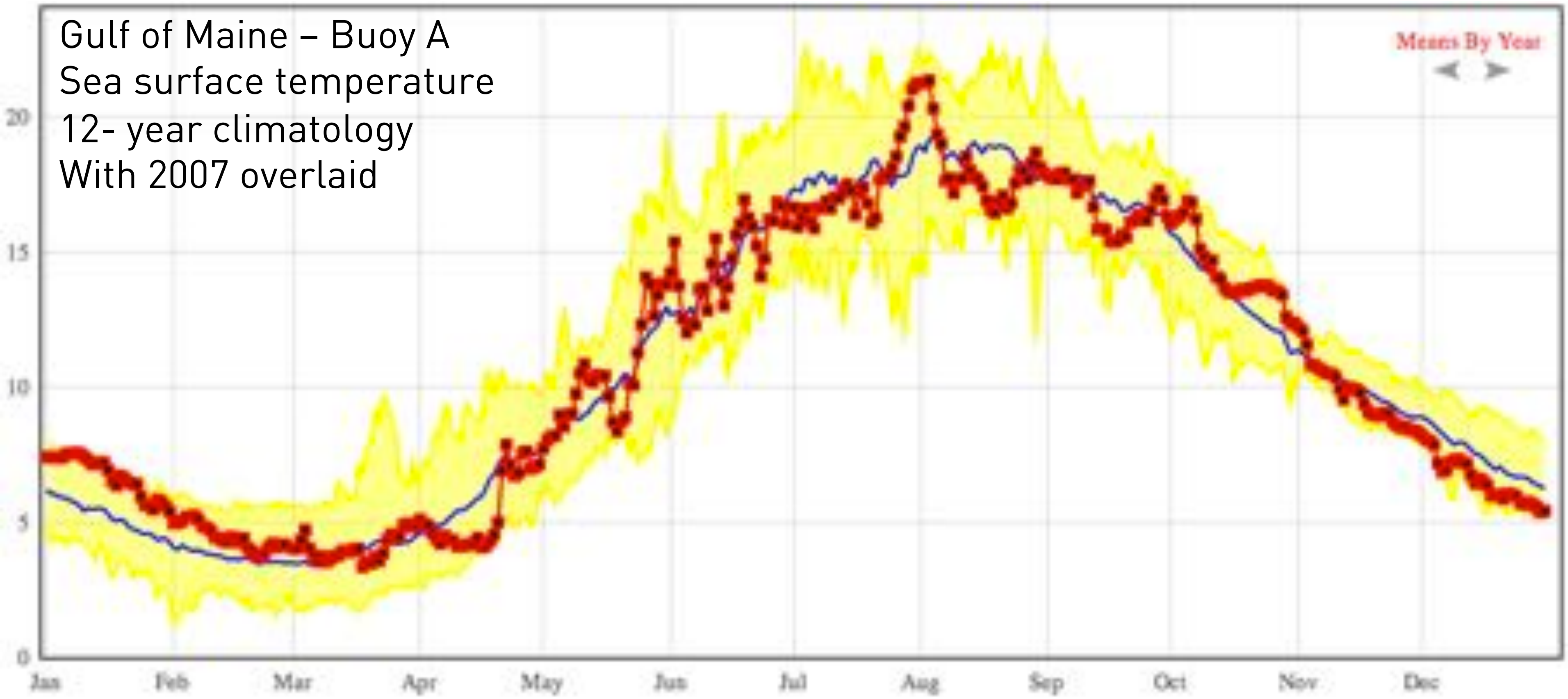
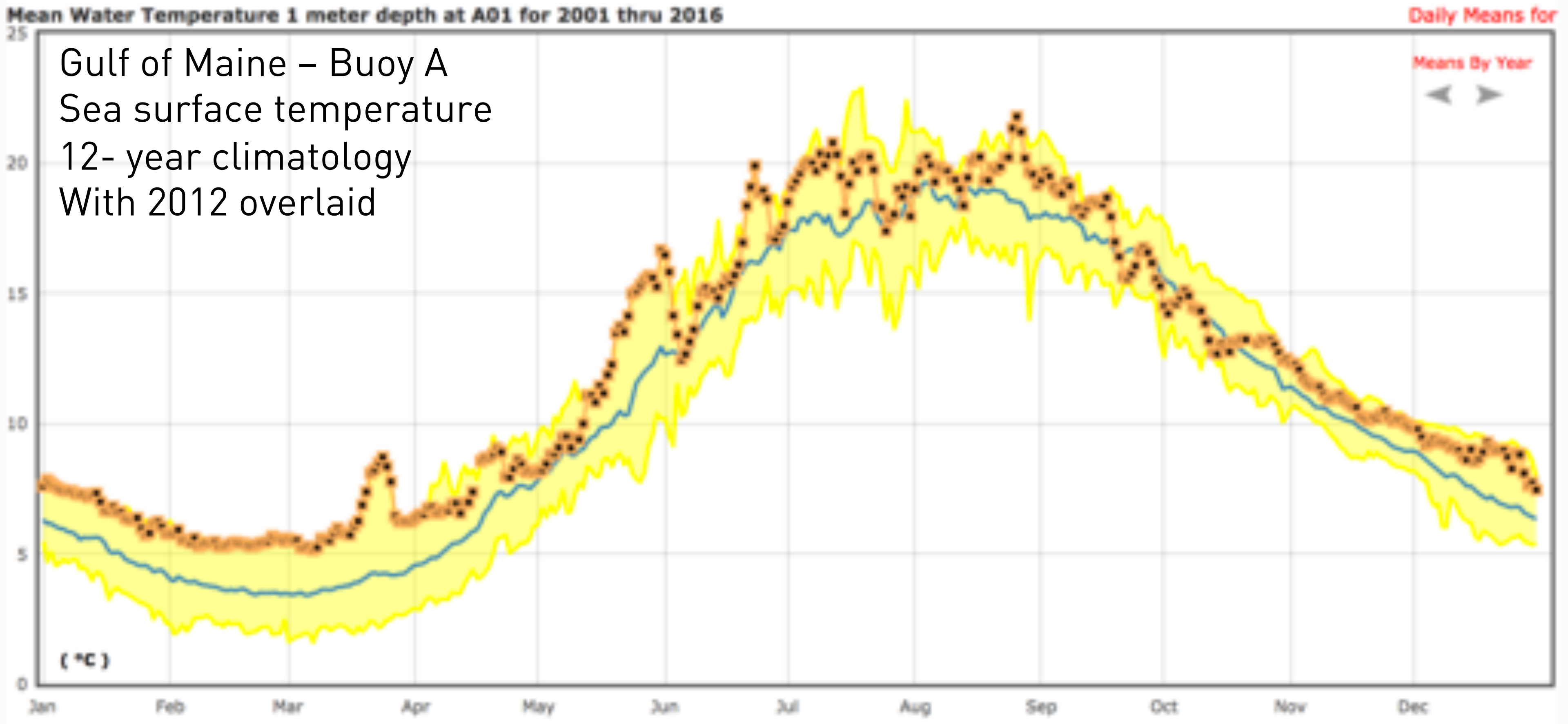
Climatology

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



Climatology

- … but some years deviate more than others



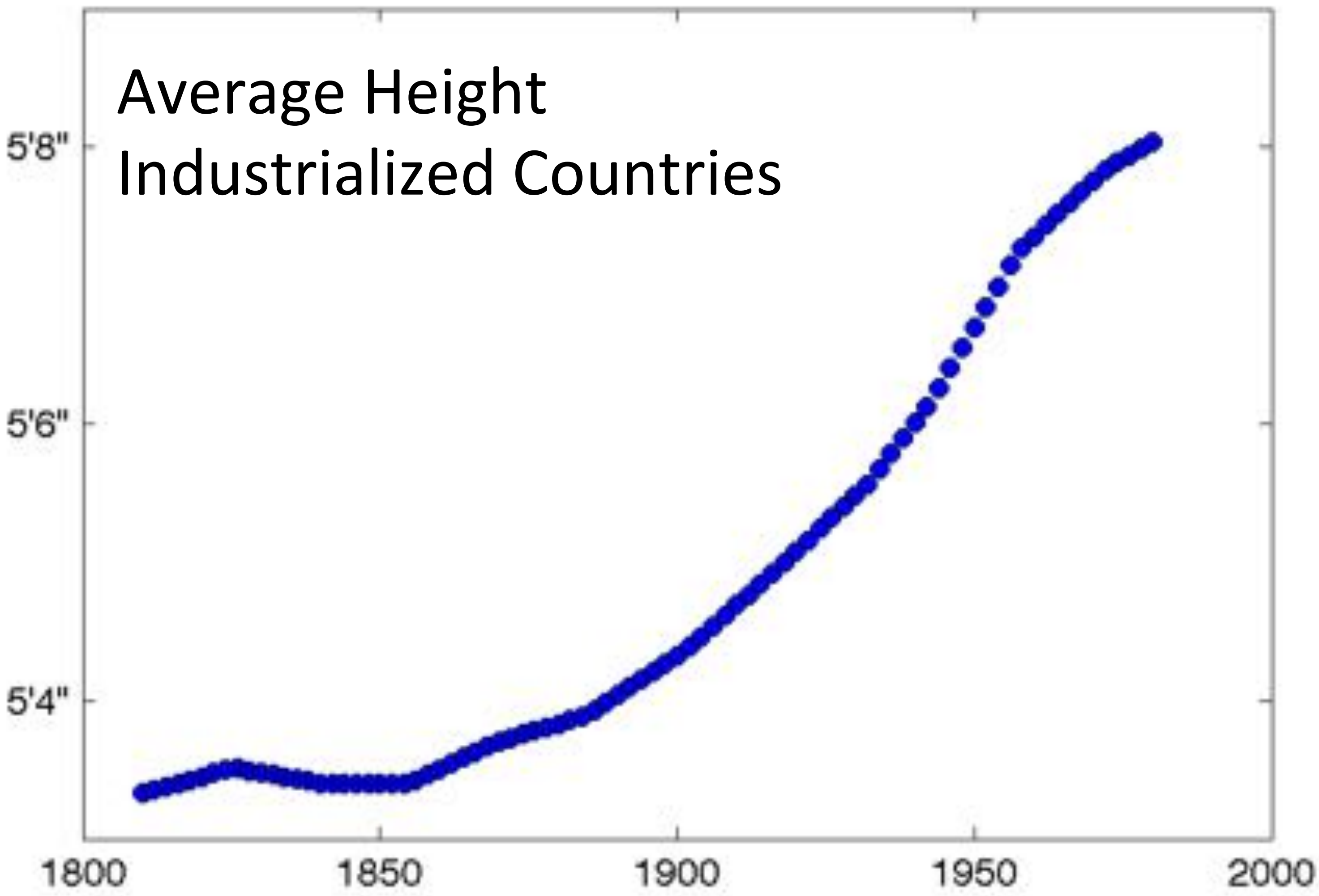
Climate versus Weather

- 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

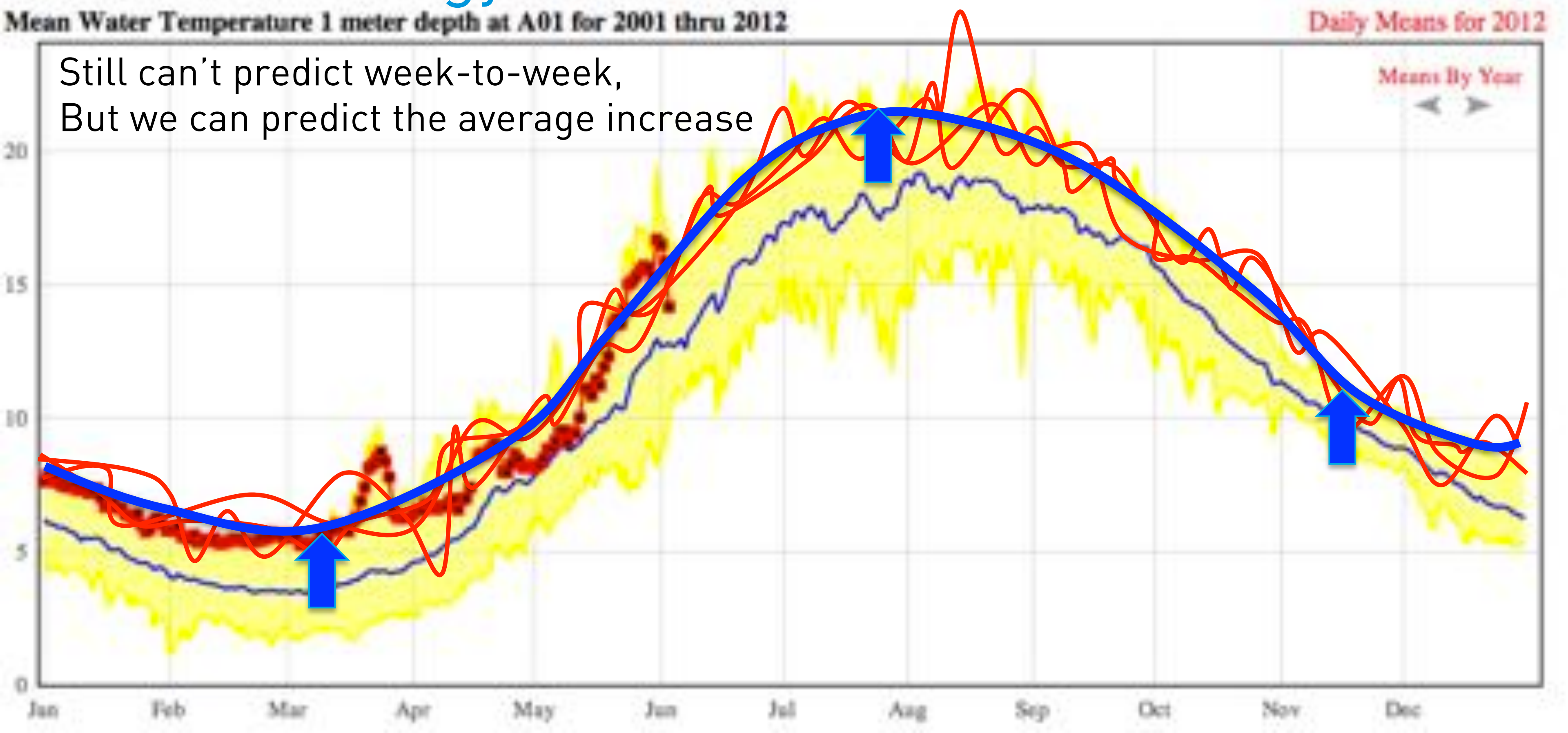
Climate versus Weather



Slide credit: A. Pershing

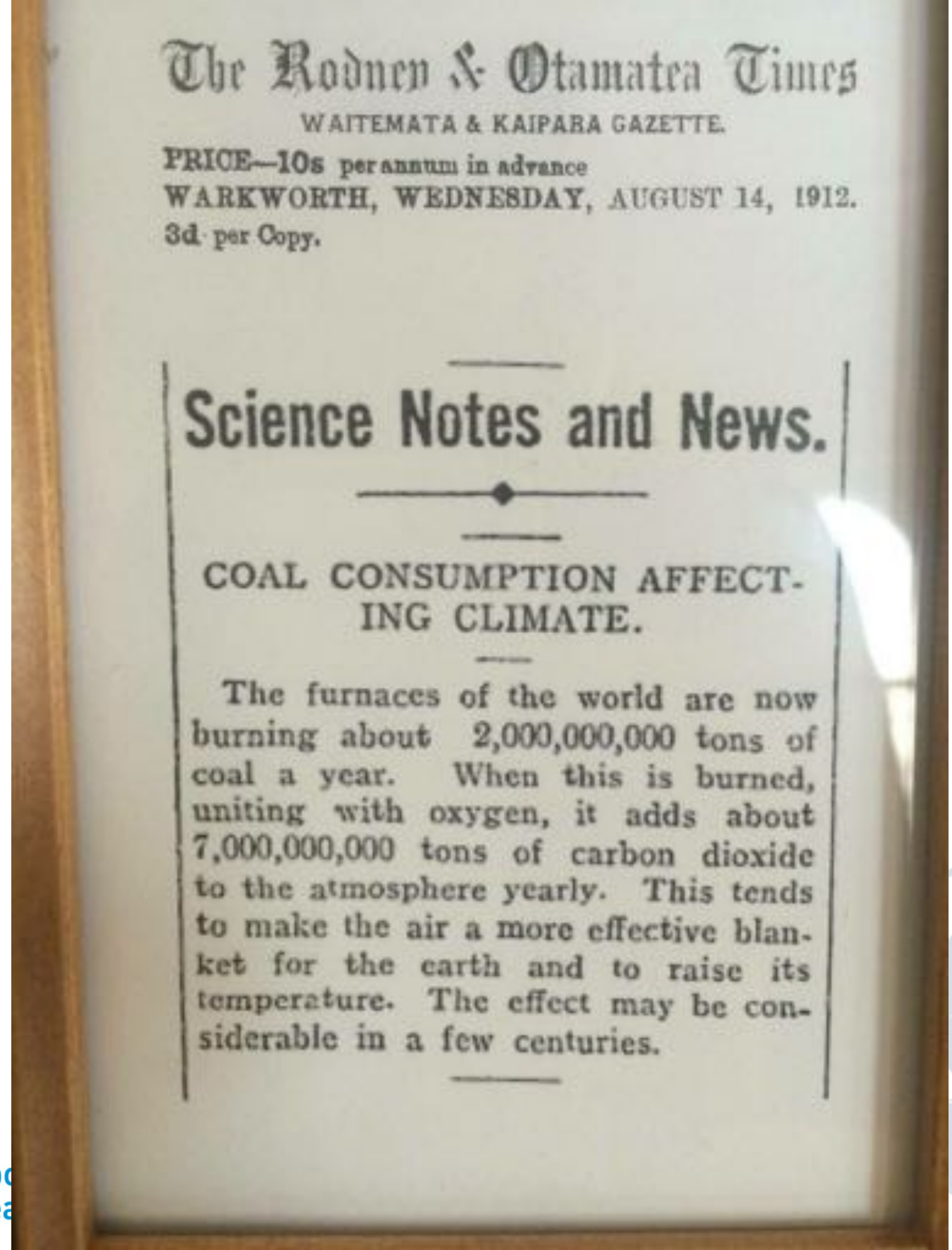
Climatology

- With enough persistent deviation, the climatology can shift



Greenhouse effect

1912



The Rodney & Otamatea Times

WAITEMATA & KAIPARA GAZETTE.

PRICE—10s per annum in advance

WARKWORTH, WEDNESDAY, AUGUST 14, 1912.

3d per Copy.

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.

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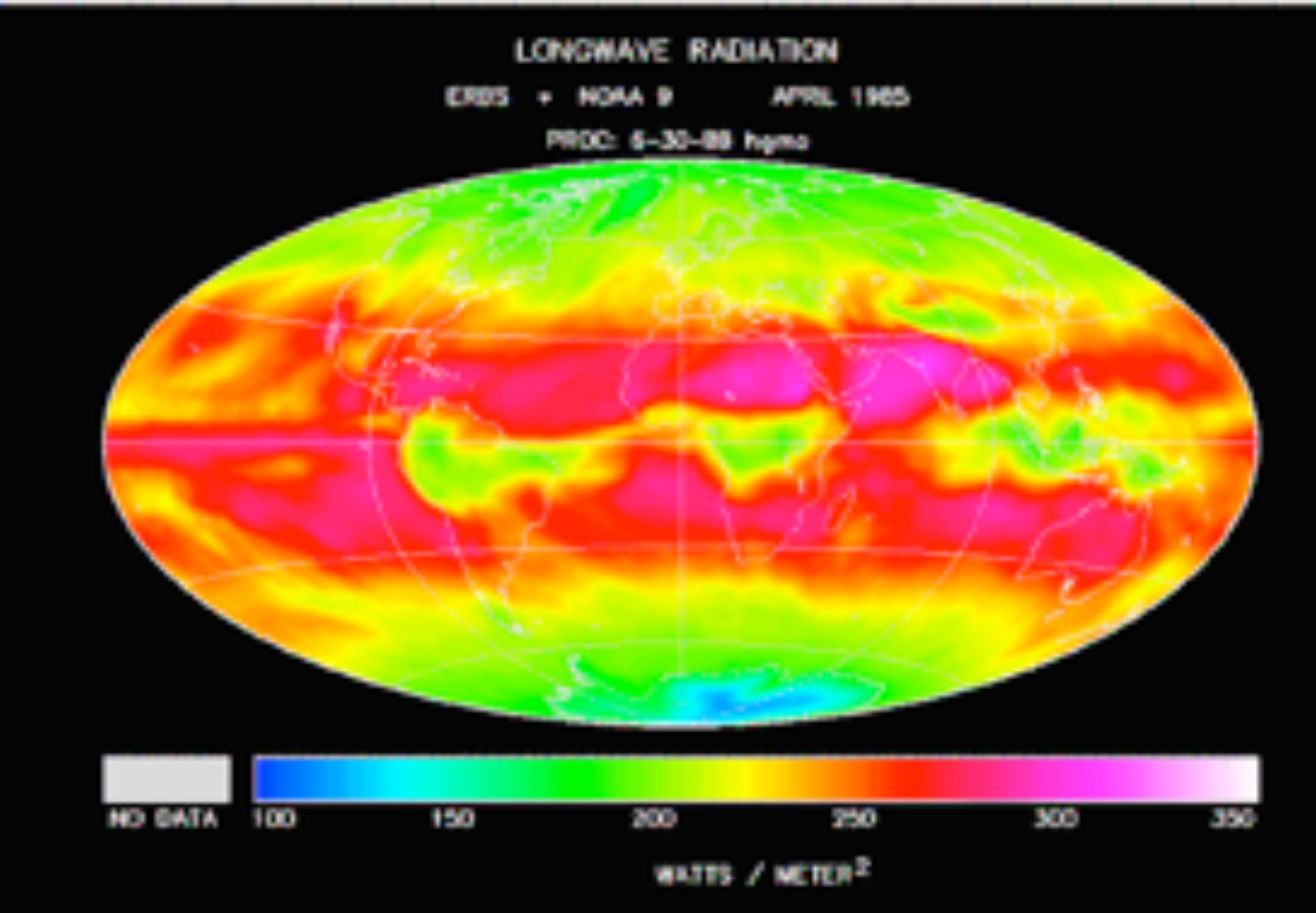
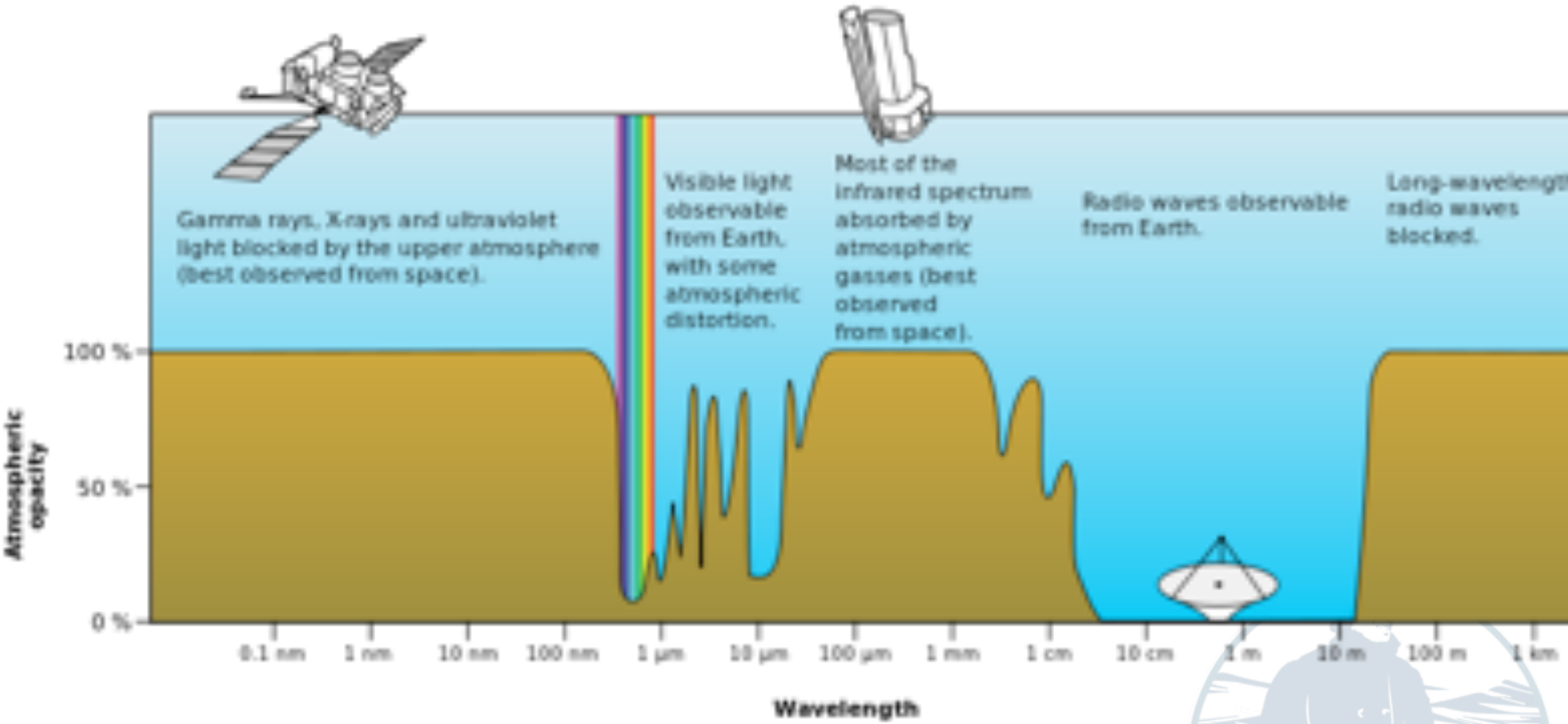
Ocea

Greenhouse effect





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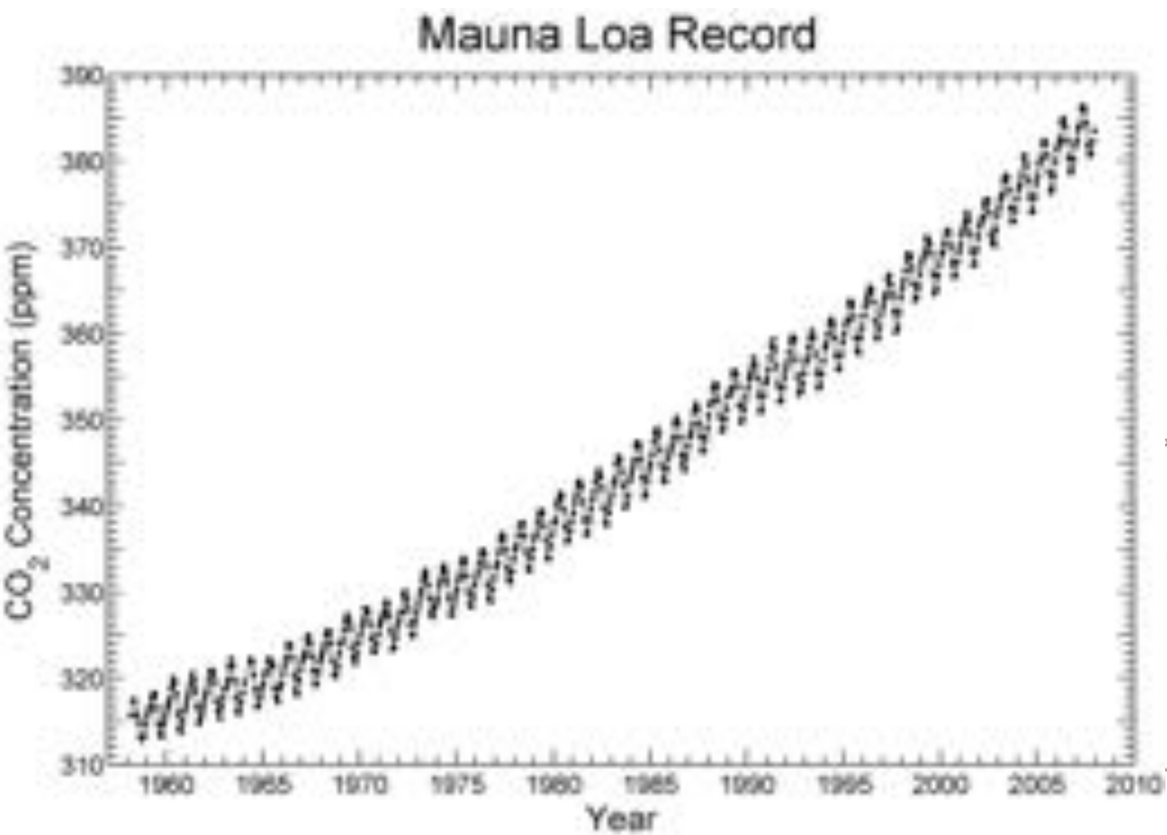
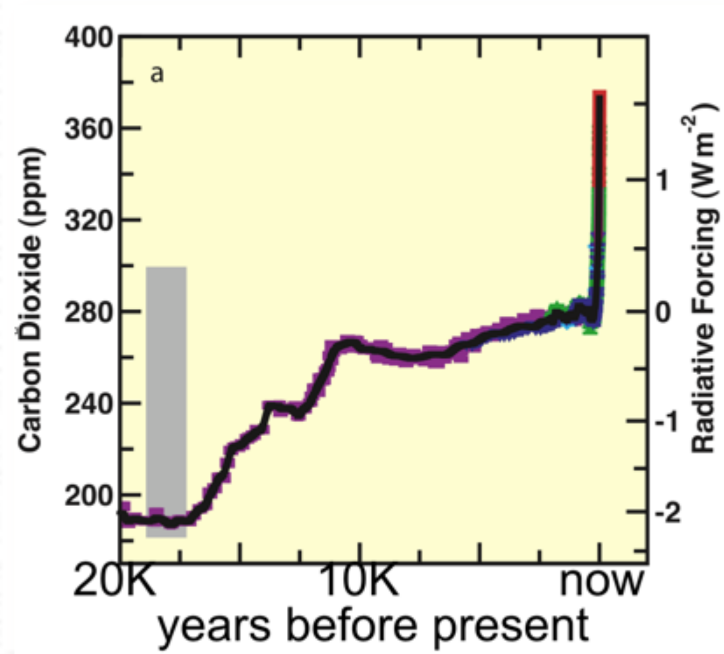
Greenhouse gasses: absorb IR

Most important greenhouse gases:

- H_2O (water vapor)
- CO_2 (carbon dioxide)
- CH_4 (methane)





Feedback

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

Important climate feedbacks

albedo
water vapor
clouds
lapse rate
CO_2 dissolution

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

↑

Warming

Negative feedback: desertification

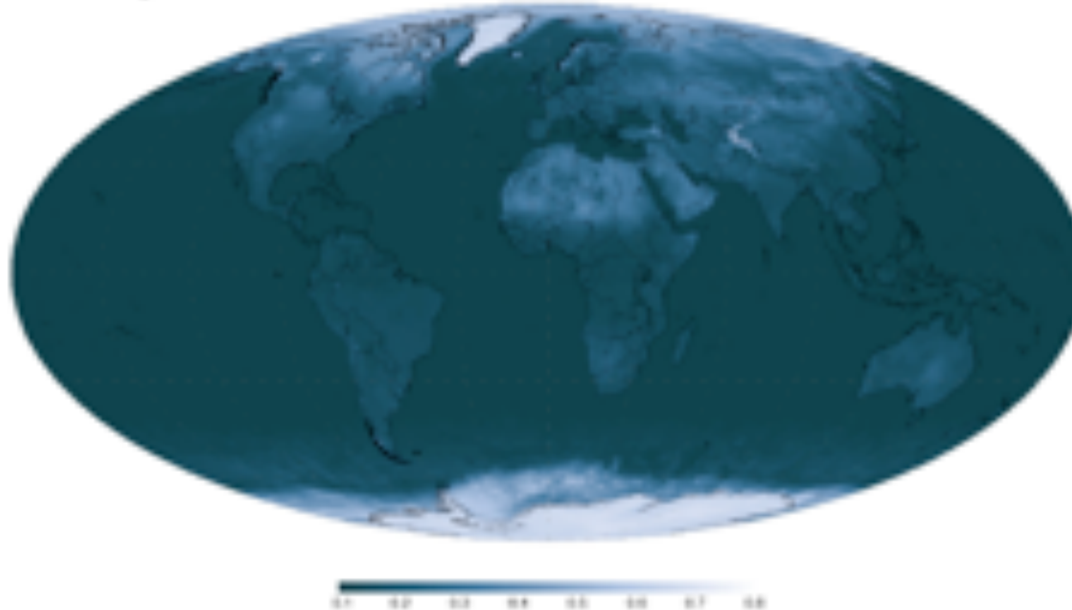
Warming → Deserts → higher albedo

↑

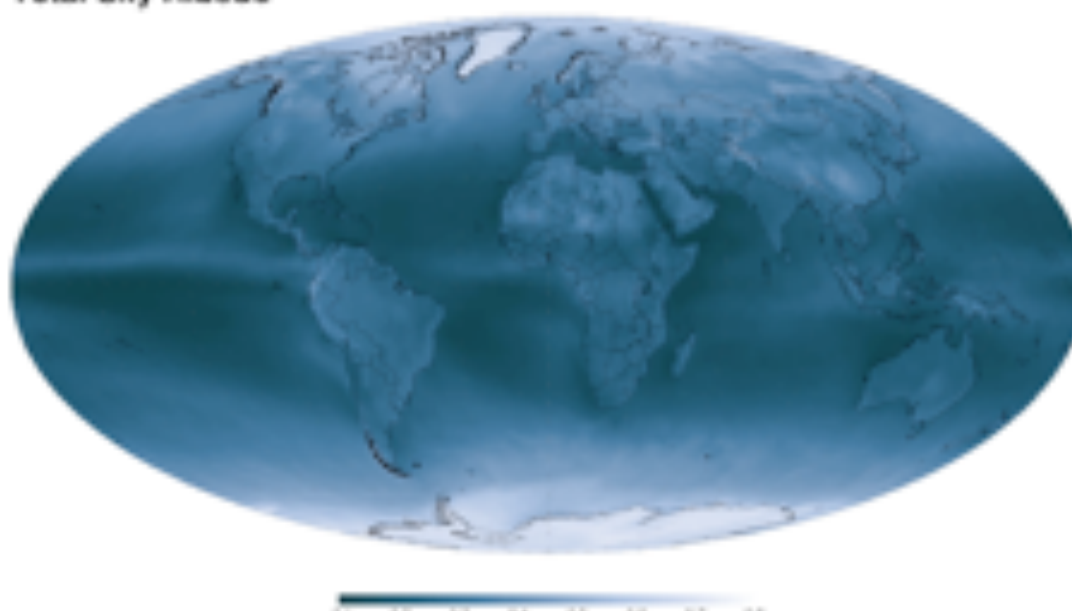
Cooling

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

Clear Sky Albedo



Total Sky Albedo



Albedo – reflecting power of a surface

- higher albedo → more energy reflected

-lower albedo → more energy absorbed

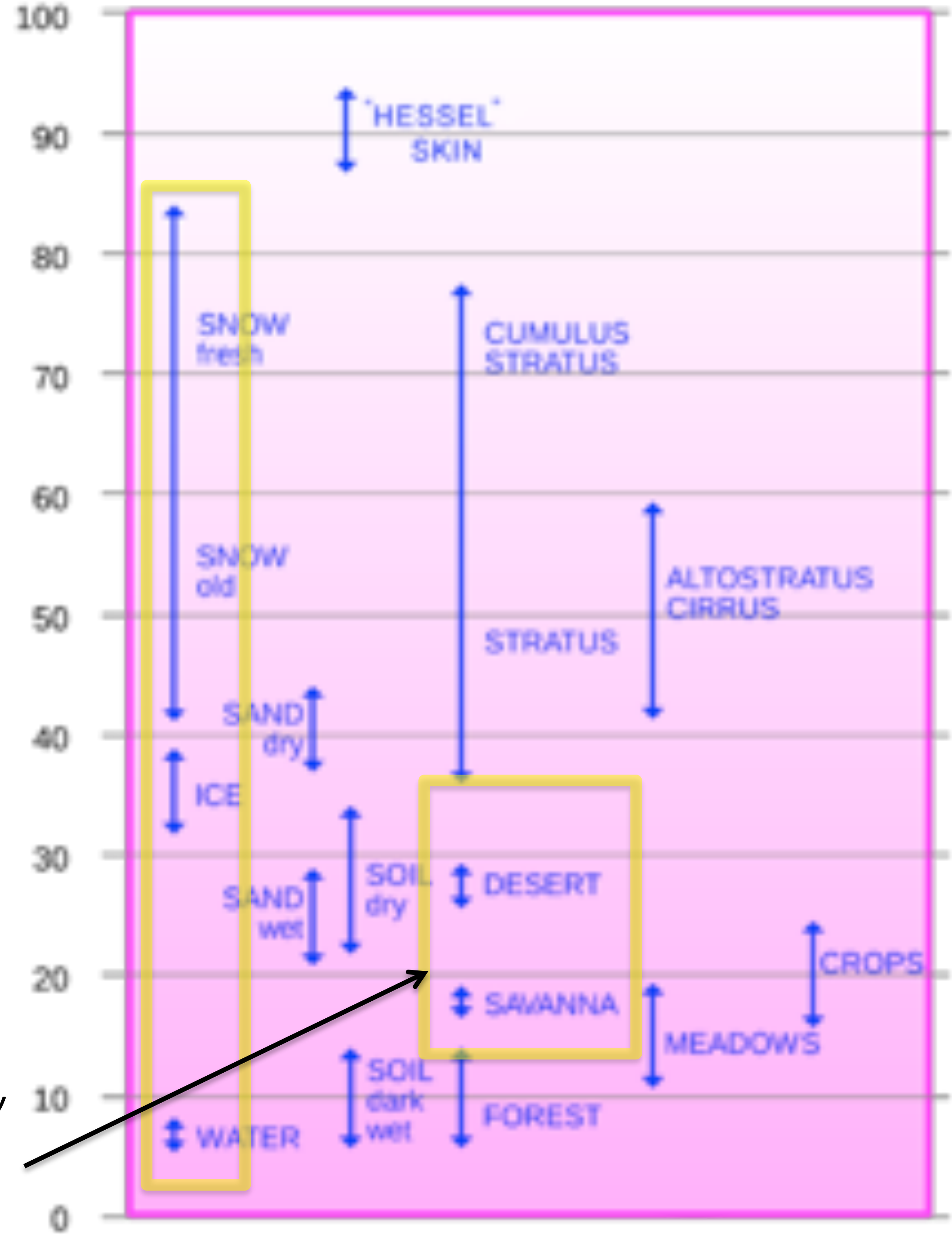
Positive feedback: Ice albedo

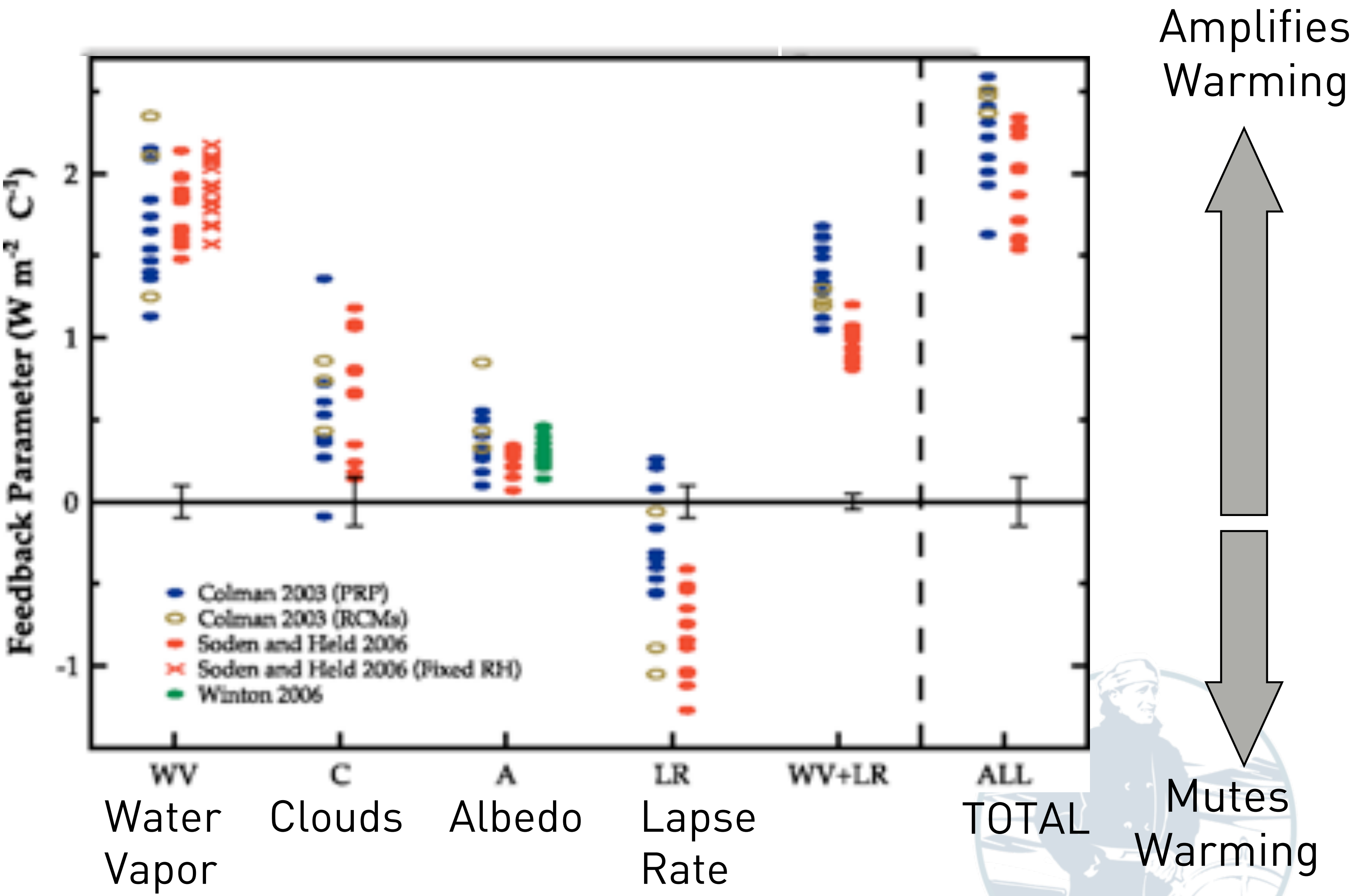
Warming → Less Ice → lower albedo
↑
Warming

Negative feedback: desertification

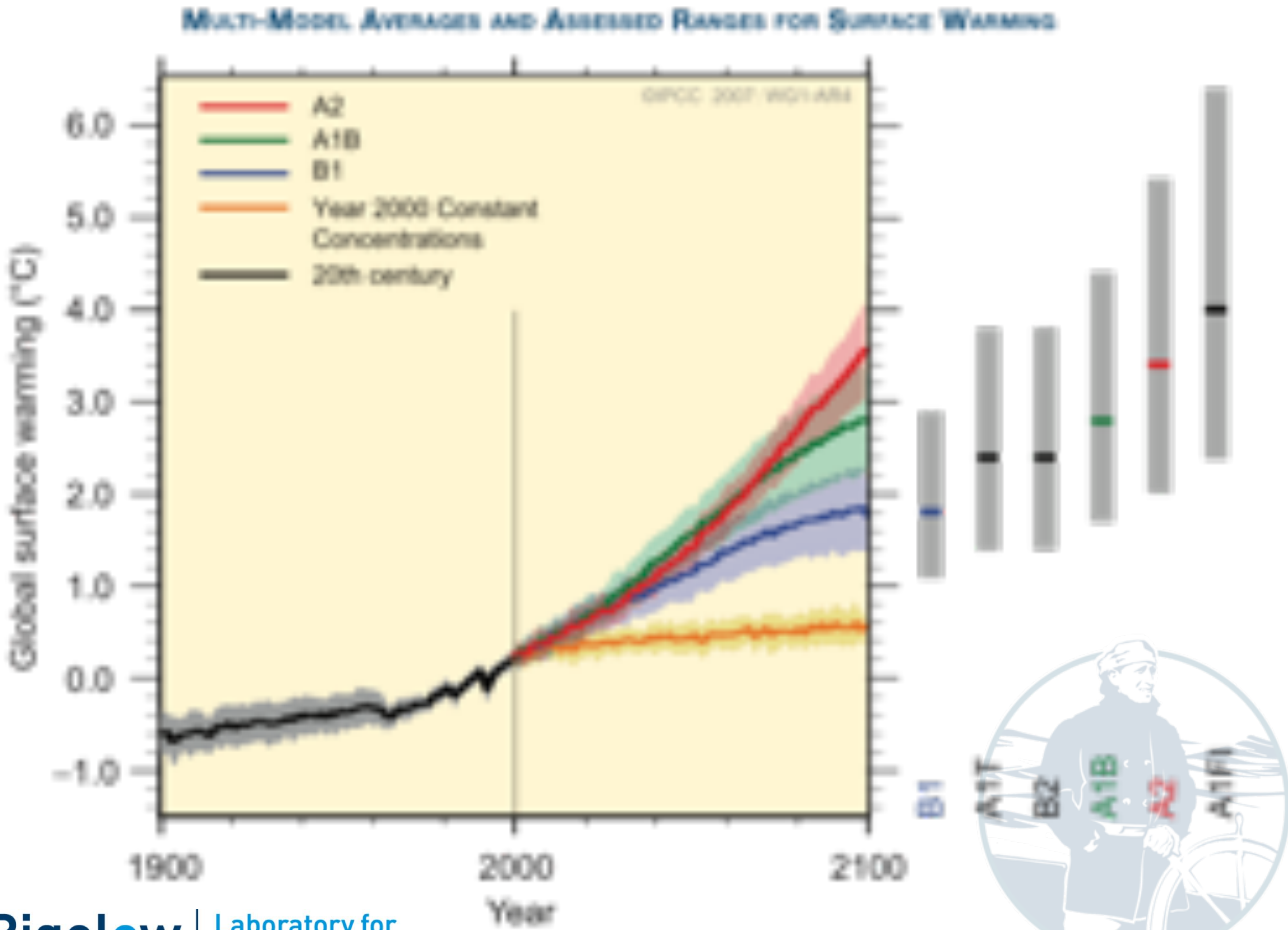
Warming → Deserts → higher albedo
↑
Cooling

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




Feedback Parameter (W m^{-2} C^{-1})
2
1
0
-1
Colman 2003 (PRP)
Colman 2003 (RCMs)
Soden and Held 2006
Soden and Held 2006 (Fixed RH)
Winton 2006
WV
C
A
LR
WV+LR
ALL
Water Vapor
Clouds
Albedo
Lapse Rate
TOTAL
Amplifies Warming
Mutes Warming

IPCC



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IPCC

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

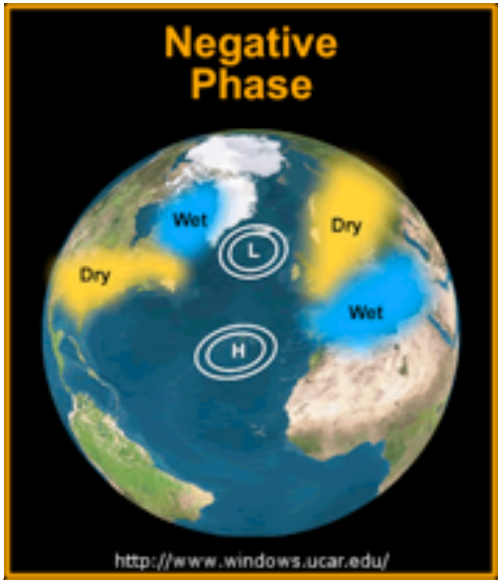
- Climate doesn't change the same everywhere.
- Also, rapid ups and downs can be more important than gradual increase (e.g. sea level and storm surges)

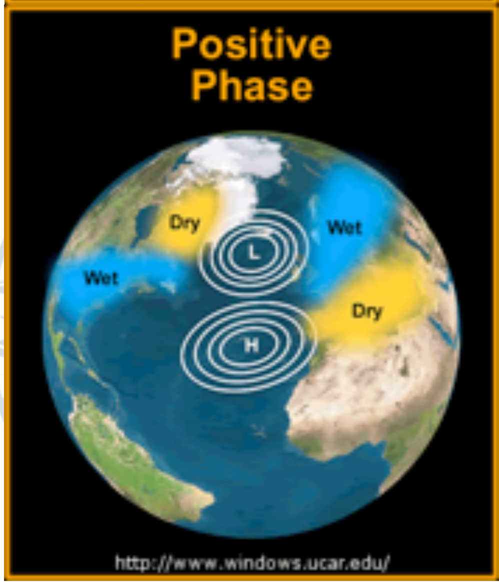
Climate Oscillations & Tele-connections

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





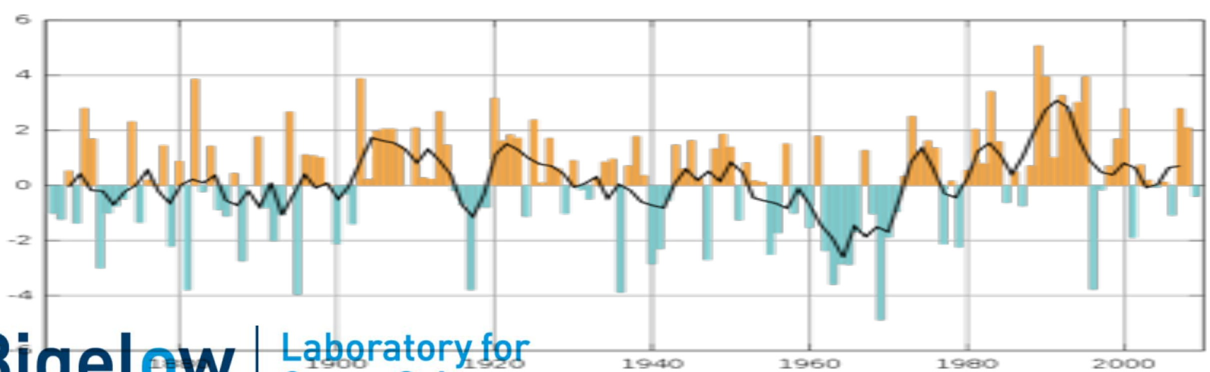


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Image: NOAA

Climate Oscillations

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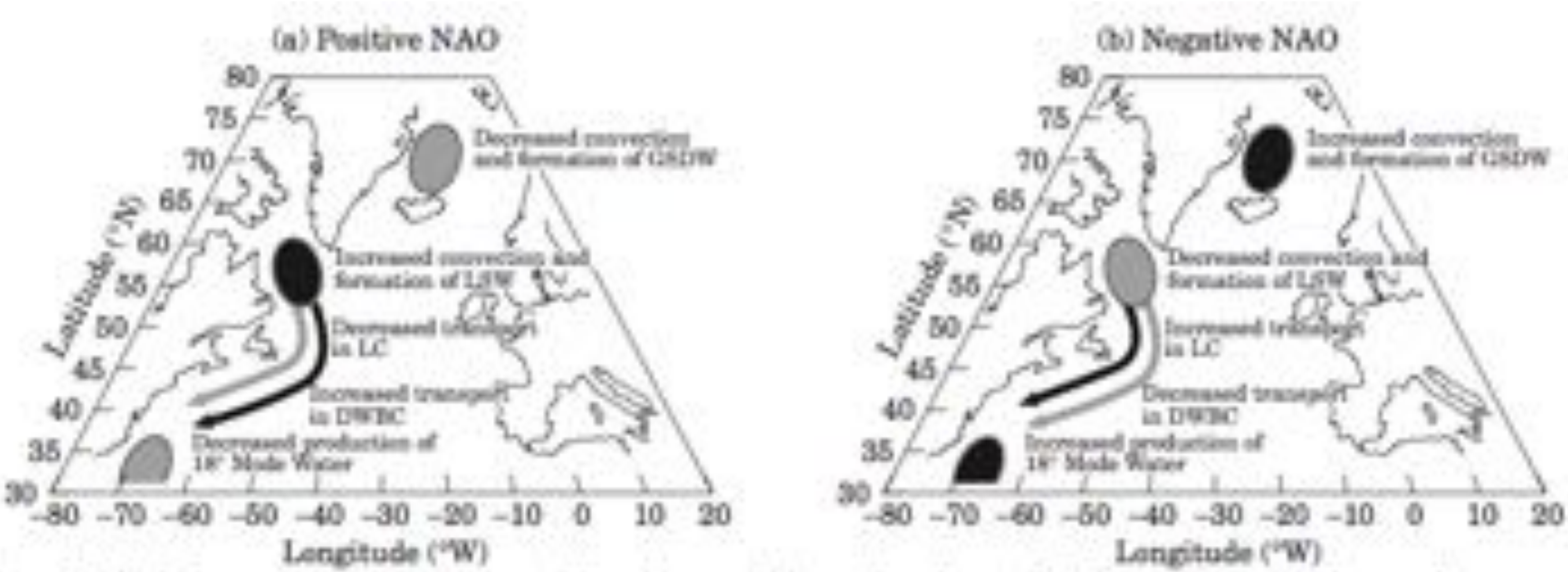
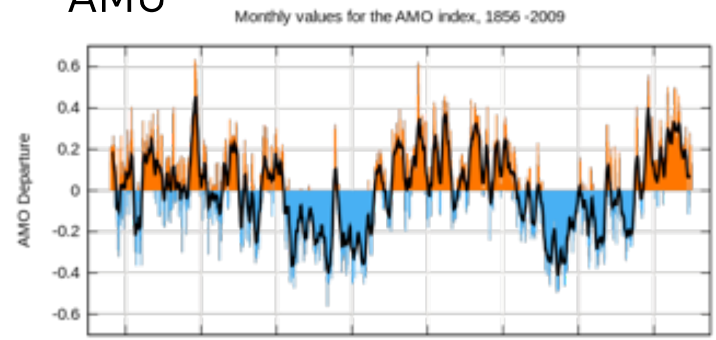


DWBC=Deep Western Boundary Current; GSDW=Greenland Sea Deep Water; LC=Labrador Current; LSW=Labrador Sea Water (Greene & Pershing 2000)

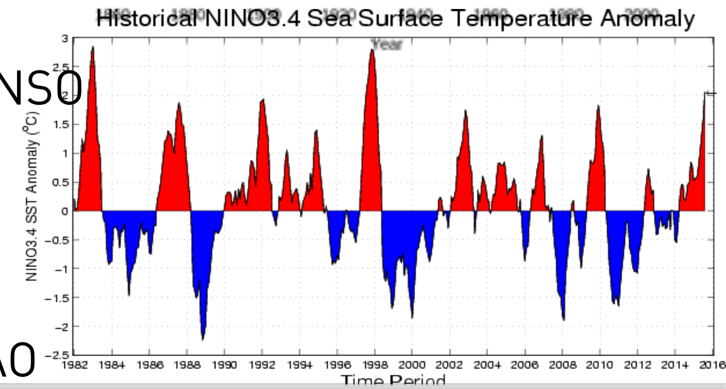
Other important climate oscillation indices

- 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)

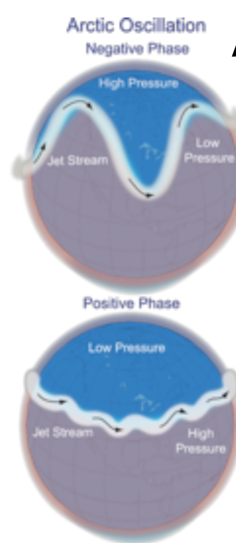
AMO

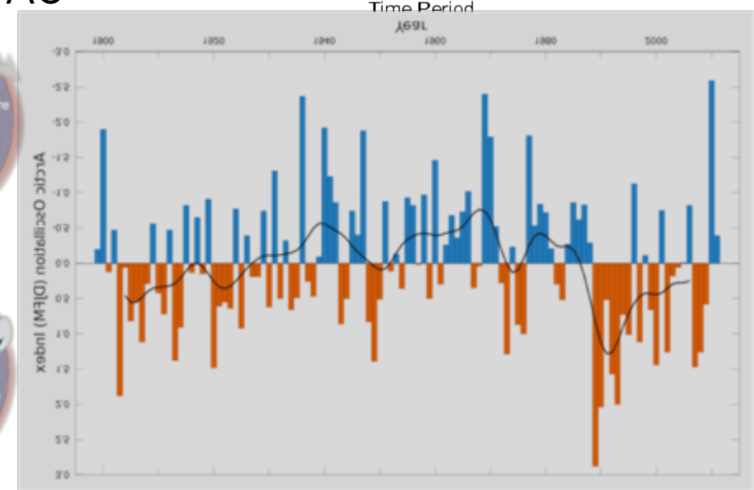


ENSO



AO





Data source, if you want to download:

http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml

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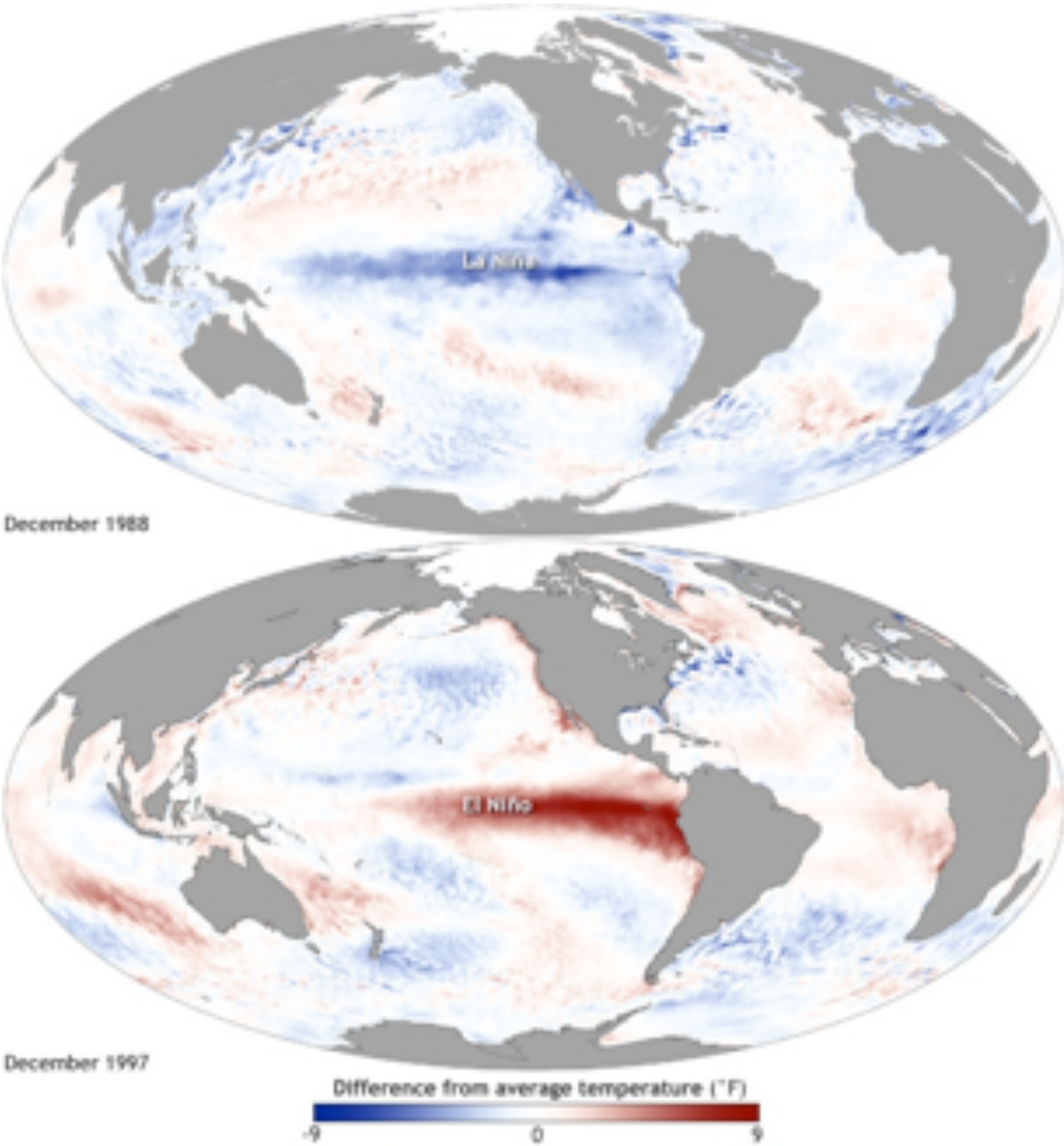
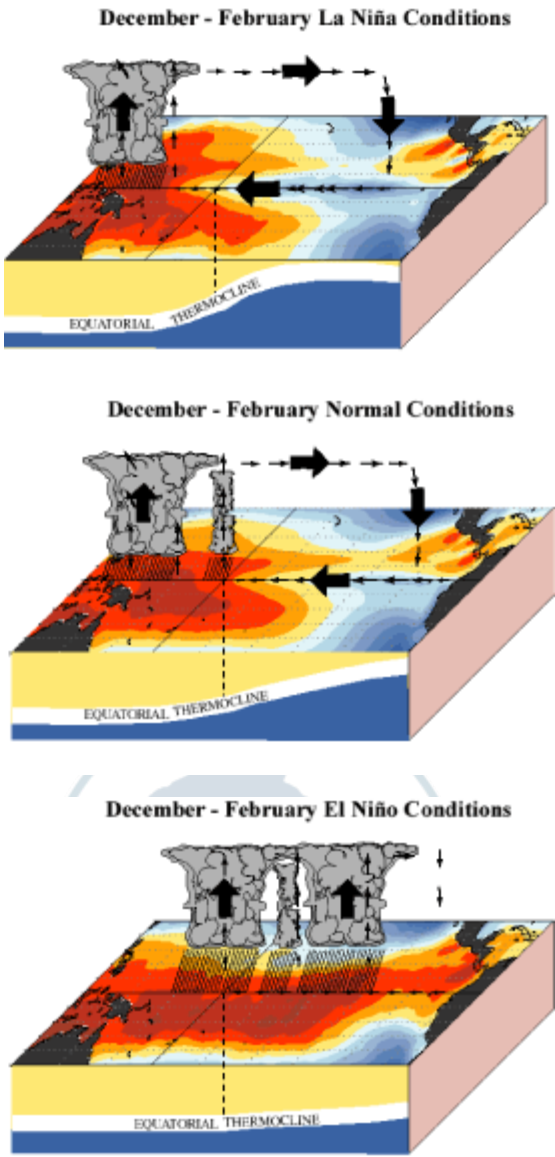
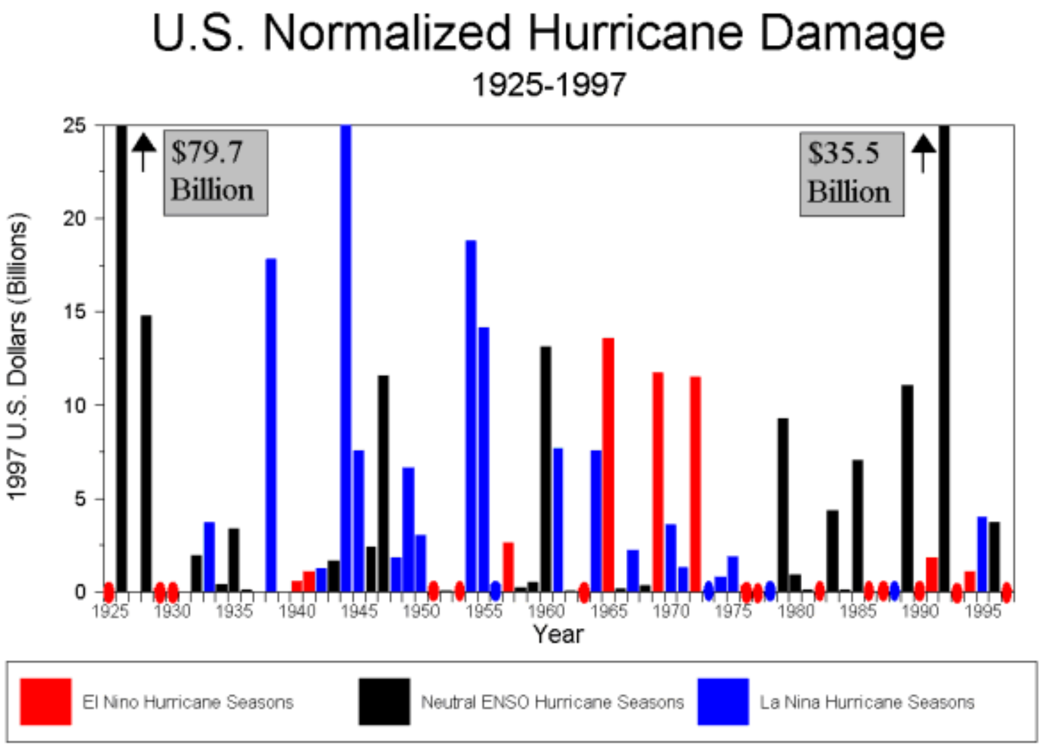
ENSO oscillations





Risk Predictions



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

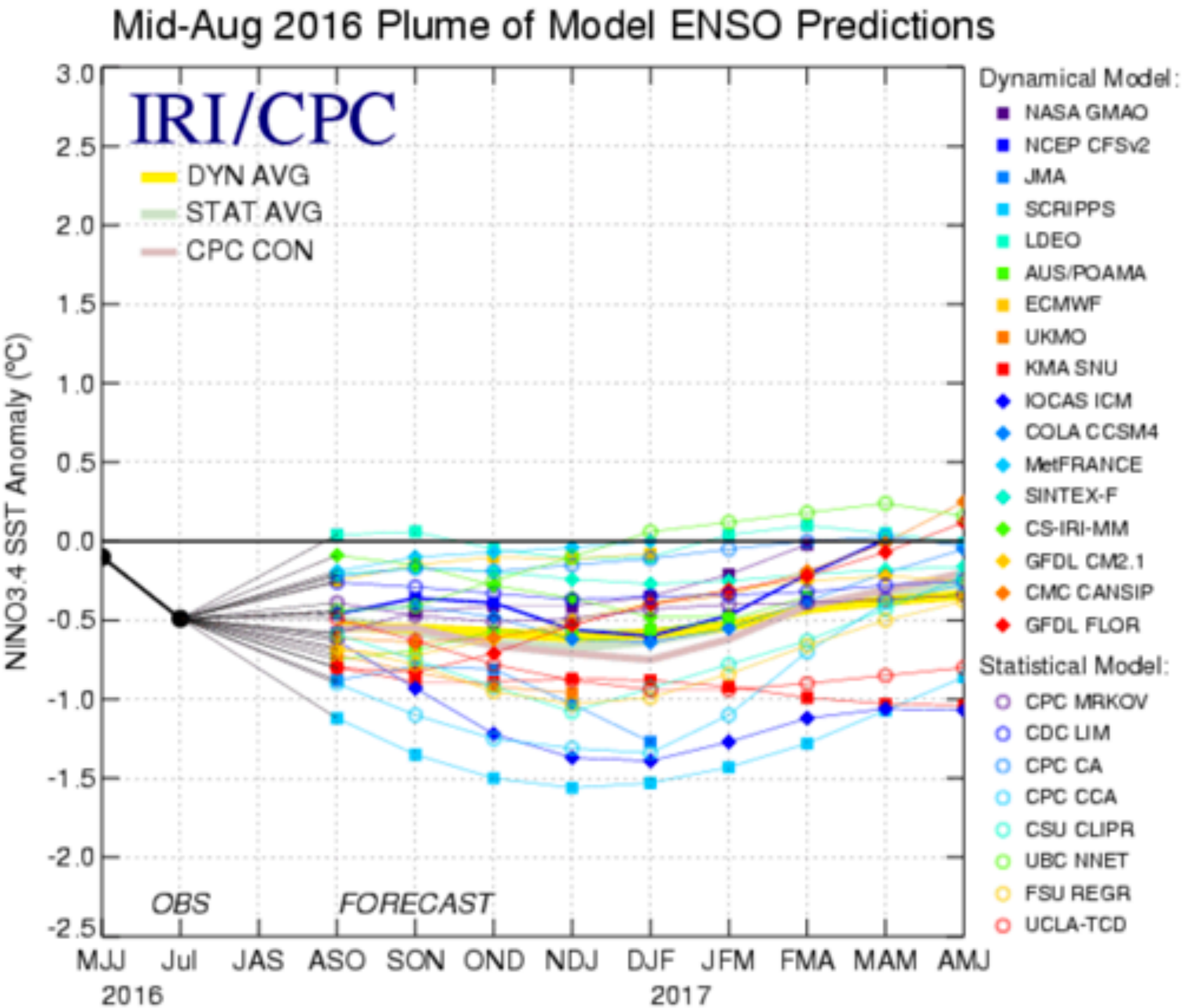


Figure 6. Forecasts of sea surface temperature (SST) anomalies for the Niño 3.4 region (5°N-5°S, 120°W-170°W). Figure updated 16 August 2016.

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/