Geophysics from Kolmogorov to Climate

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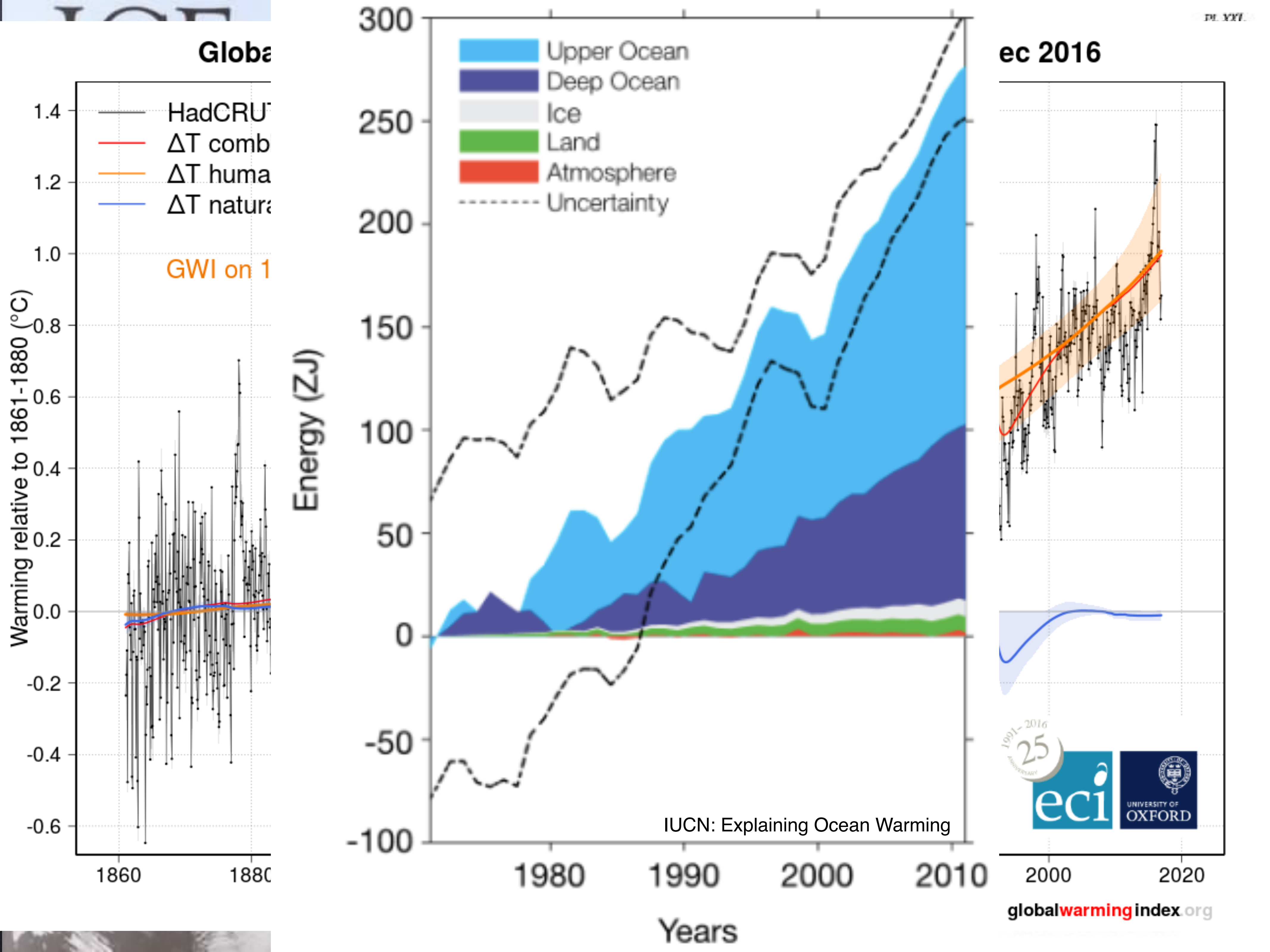
Climate Fluctuations and Non-equilibrium Statistical Mechanics: an interdisciplinary dialogue
Dresden 7/17/17, 11-11:50

Sponsors: NSF 1245944, 1258907, 1350795, Gulf of Mexico Research Initiative, and the Office of Naval Research



Globa
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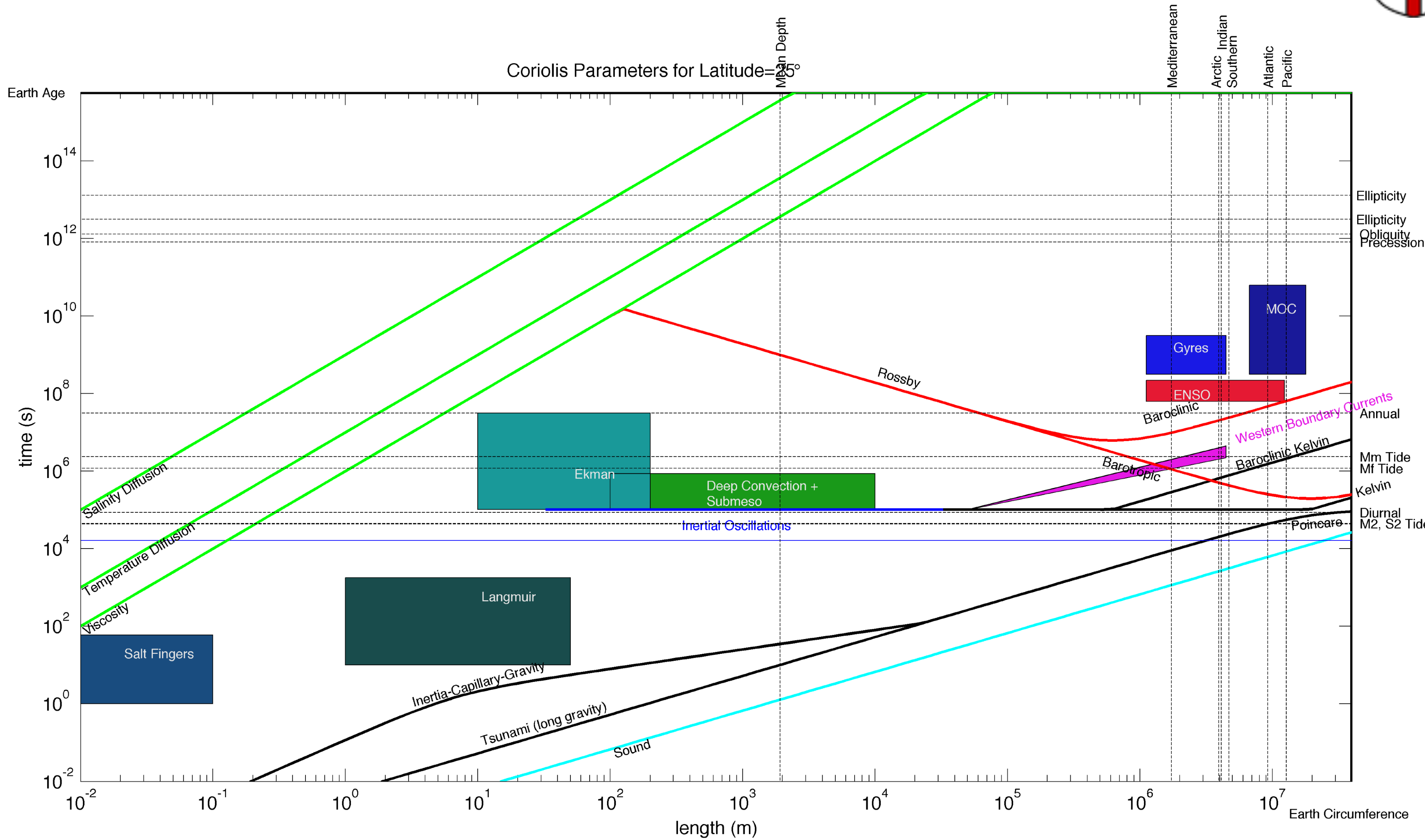
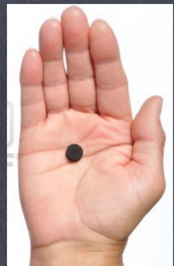
Warming relative to 1861-1880 (°C)
Upper Ocean
Deep Ocean
Ice
Land
Atmosphere
Uncertainty
Energy (ZJ)
Years
IUCN: Explaining Ocean Warming
1991–2016
25
eci
UNIVERSITY OF OXFORD
globalwarmingindex.org

The Ocean is Vast & Diverse

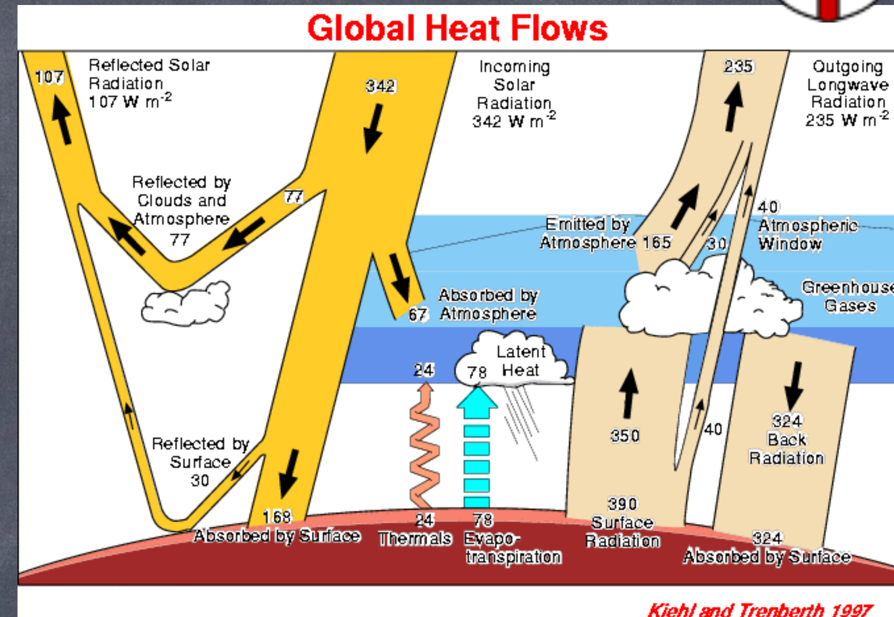


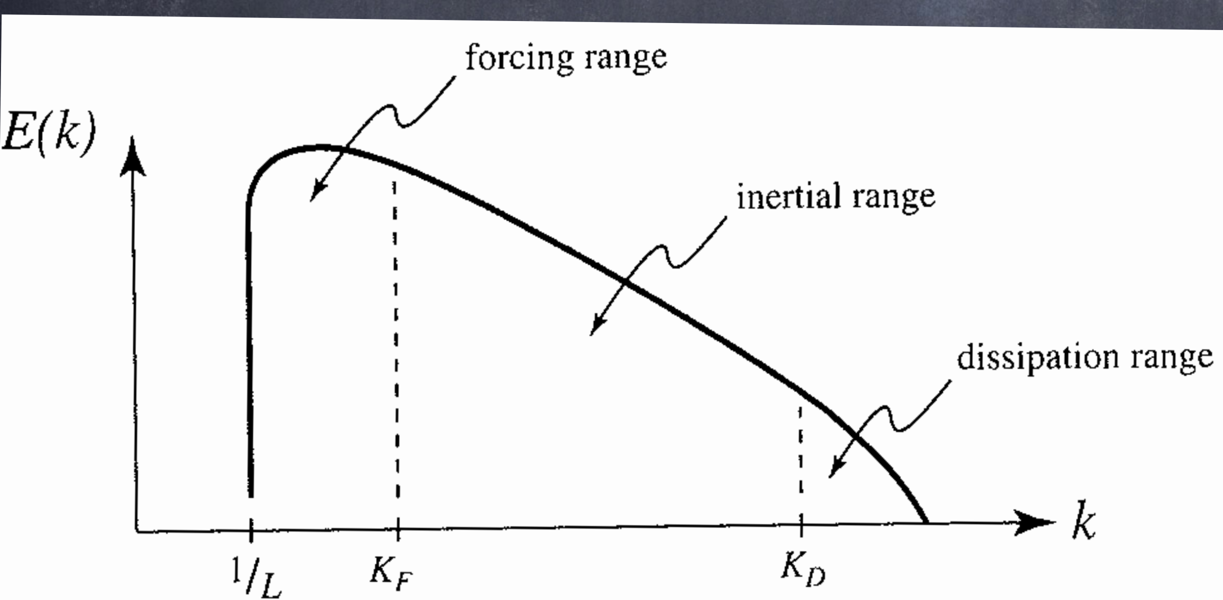
The climate also depends on atmosphere, cryosphere, biosphere, pedosphere, lithosphere & coupled modes!

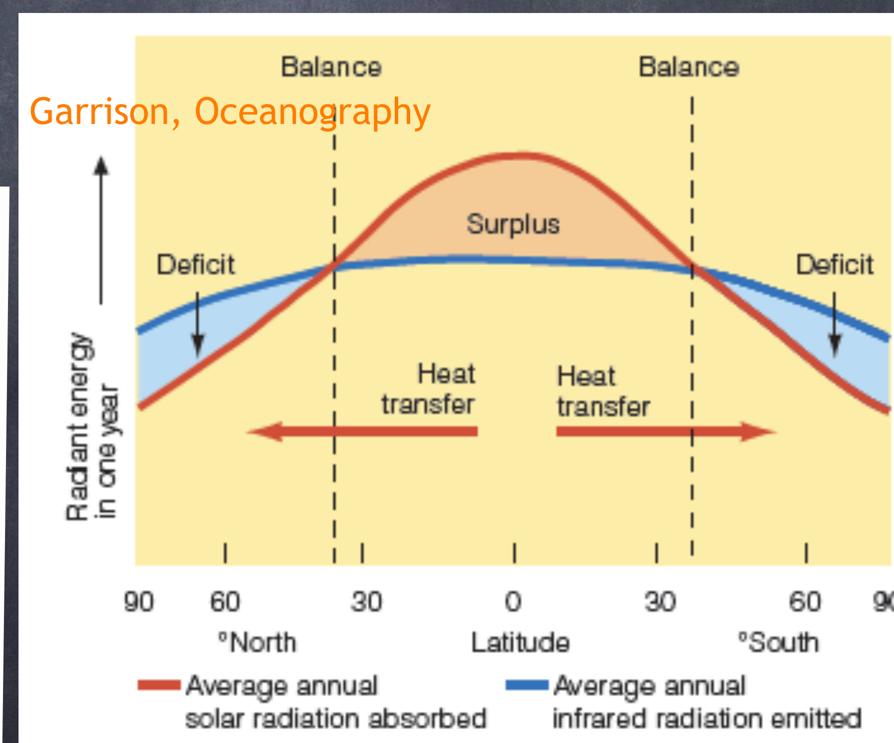


The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale

KE dissipation concludes turbulence cascades to scales about a billion times smaller







CLIMATE

Thermal Energy Budget

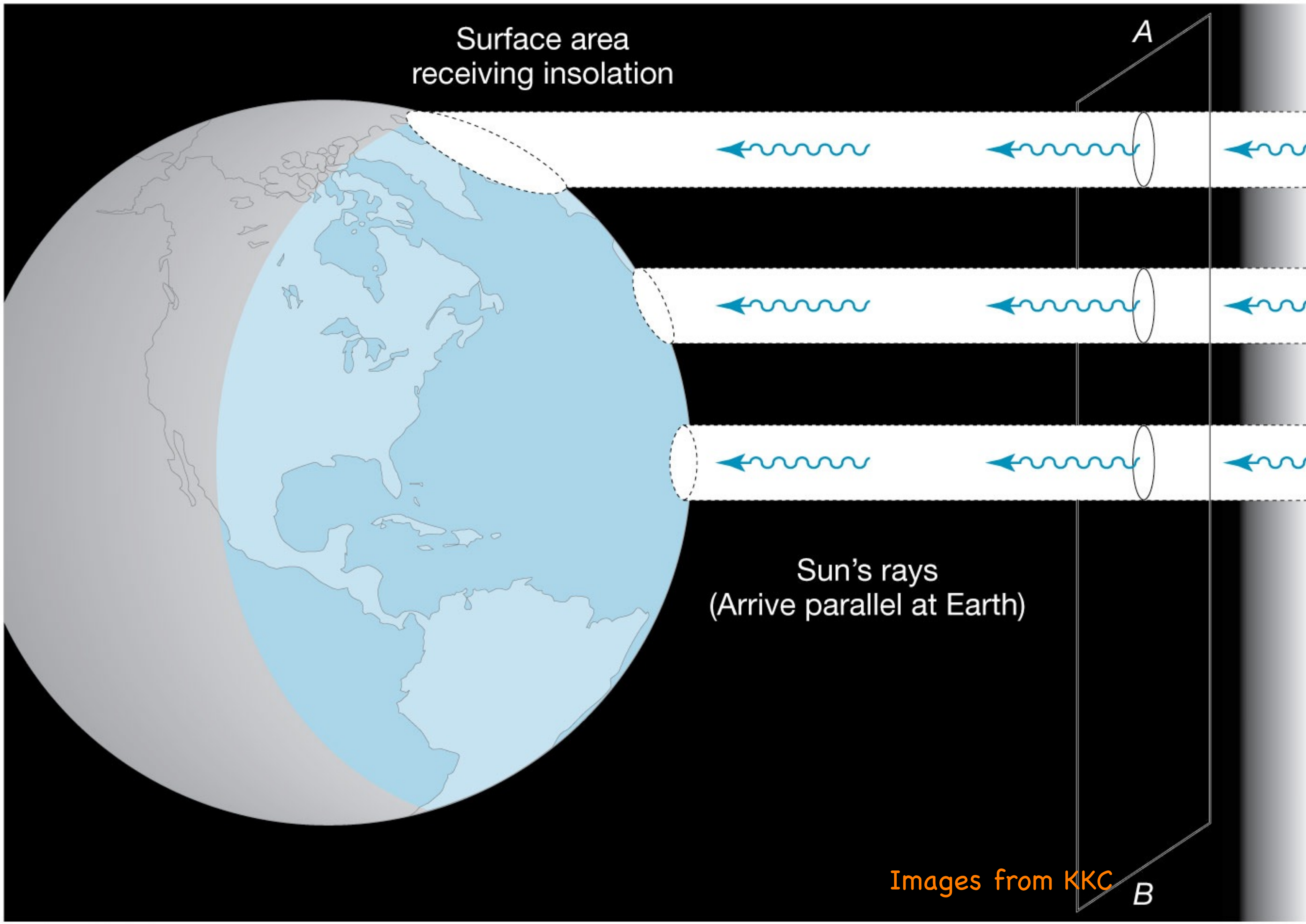
Insolation: The amount of energy per unit time in arriving electromagnetic radiation that through a unit surface area.

Dimensions (Energy/T/L^2 = Power/L^2)=S_0/4=1370 W/m^2/4=342 W/m^2

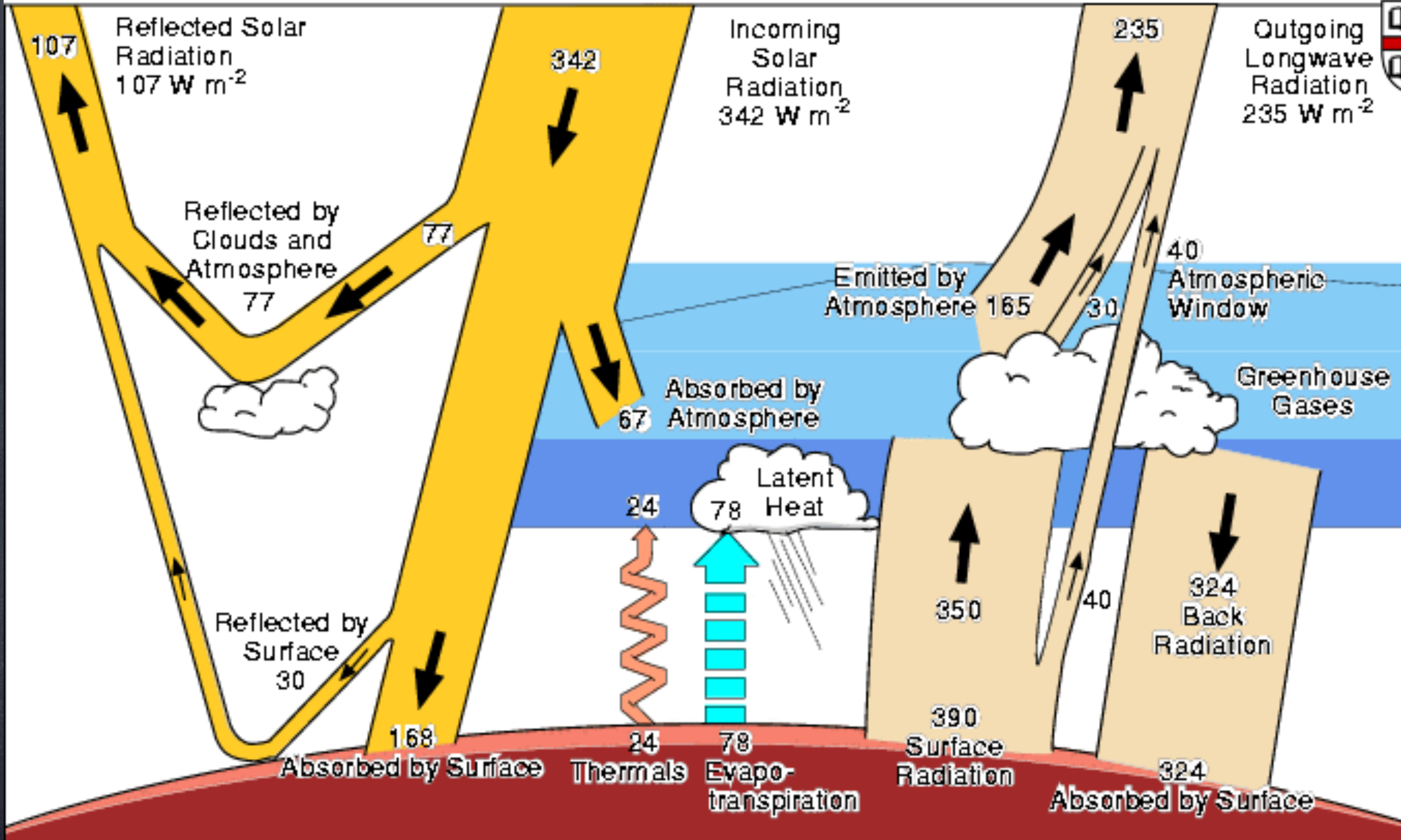
Away from tropics, the Sun's light does not arrive perp. to the Earth's surface (sun not directly overhead)

So poles have shorter days, increased albedo, decreased perp. component

Reduced Polar Power!



Global Heat Flows



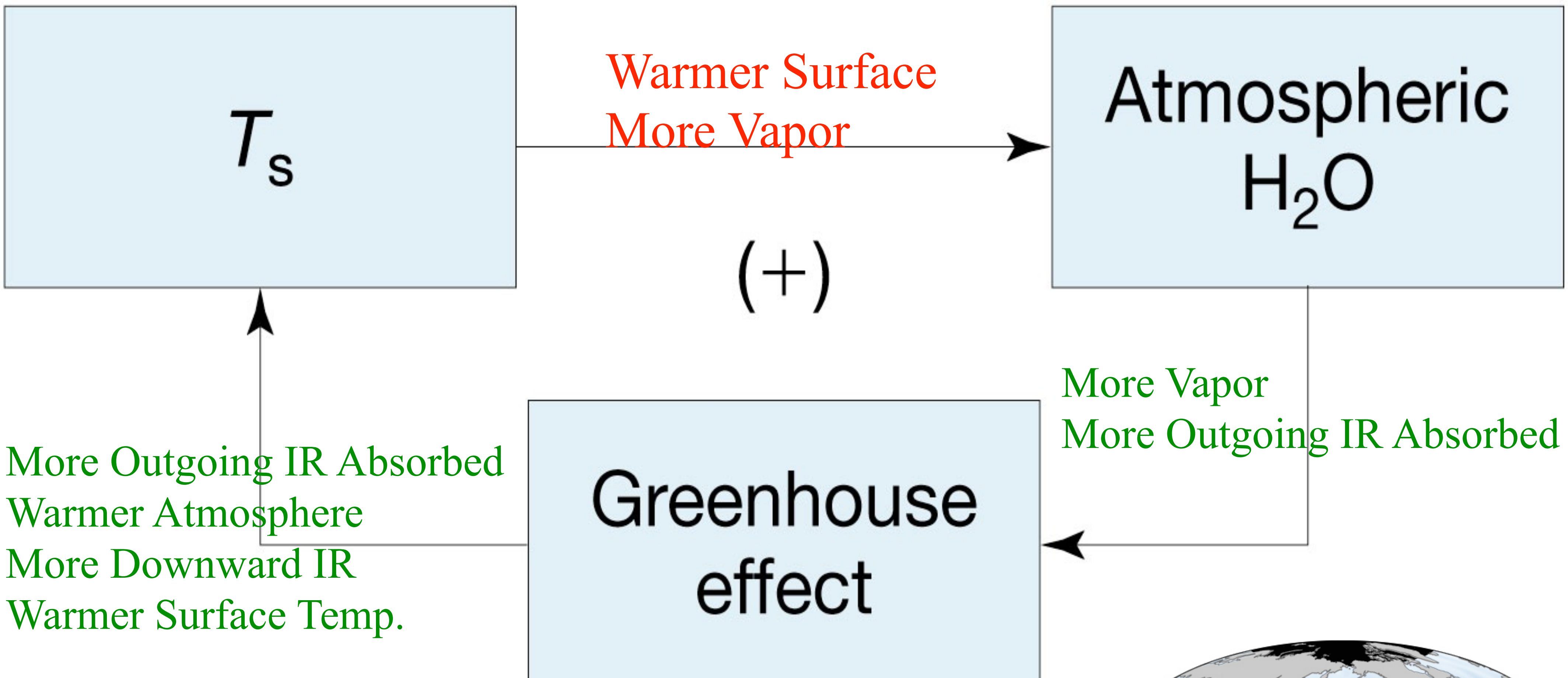
Kiehl and Trenberth 1997

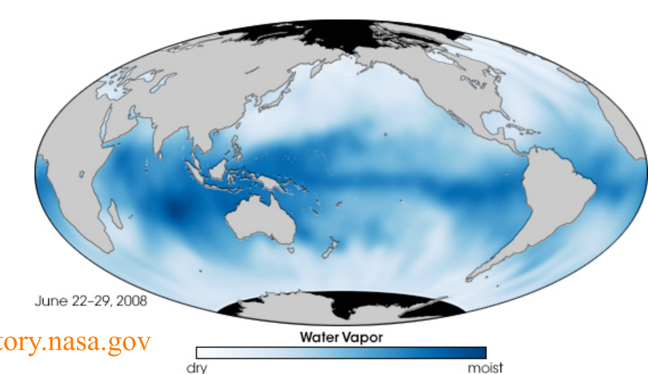
Simple: Planetary Energy Balance

$$c\frac{dT}{dt} = R_{\text{incoming}}(T) - R_{\text{outgoing}}(T)$$

E.g., Water Vapor Feedback & $R_{outgoing}(T)$:

Water Vapor is the most important GHG on Earth, not only because it absorbs most of the outgoing IR, but also because it responds to surface temperature changes

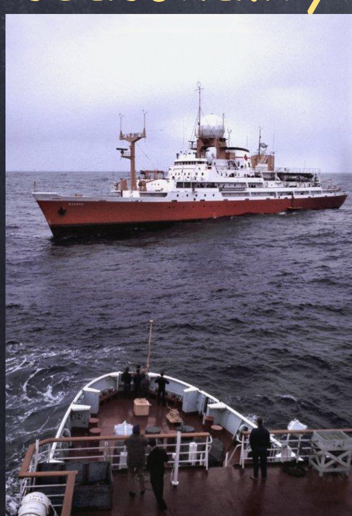


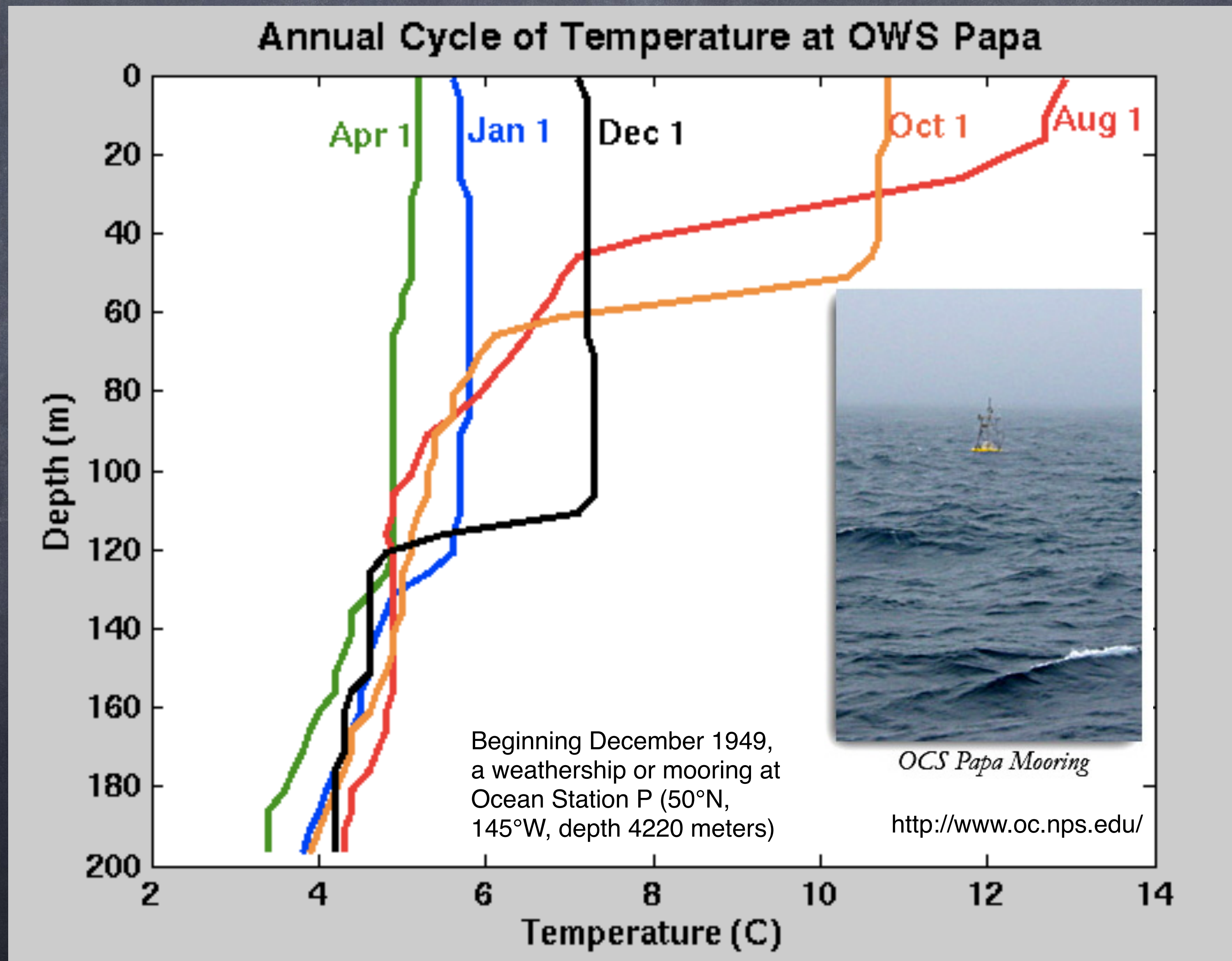


earthobservatory.nasa.gov

Surface, Mixed Layer, Seasons?

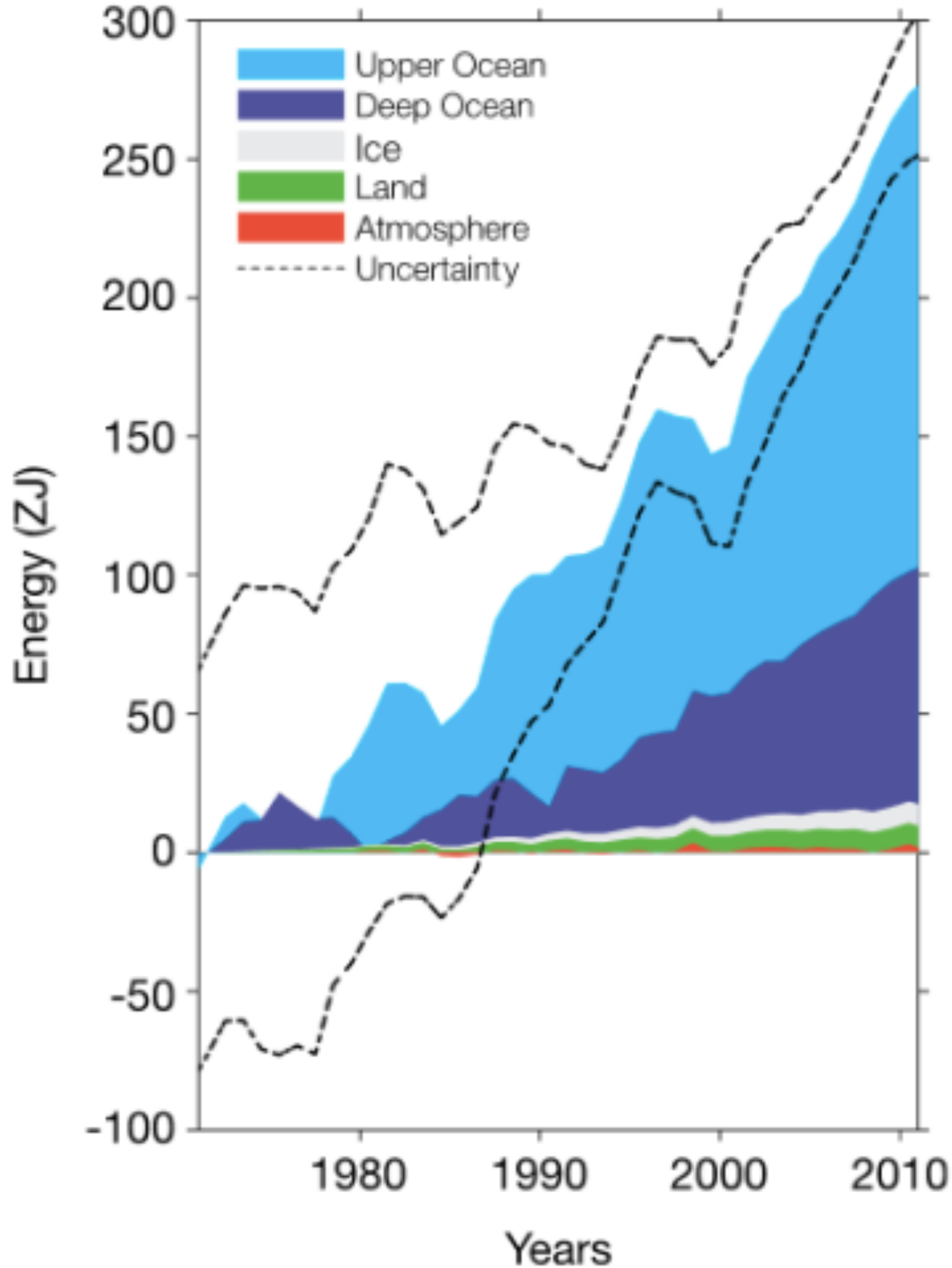
0.7 W/m^2
=
Atmosphere:
1.5K/yr
=
3.4m Ocean:
1.5K/yr
=
34m Ocean:
0.15K/yr
=1% of
mixed layer
seasonality



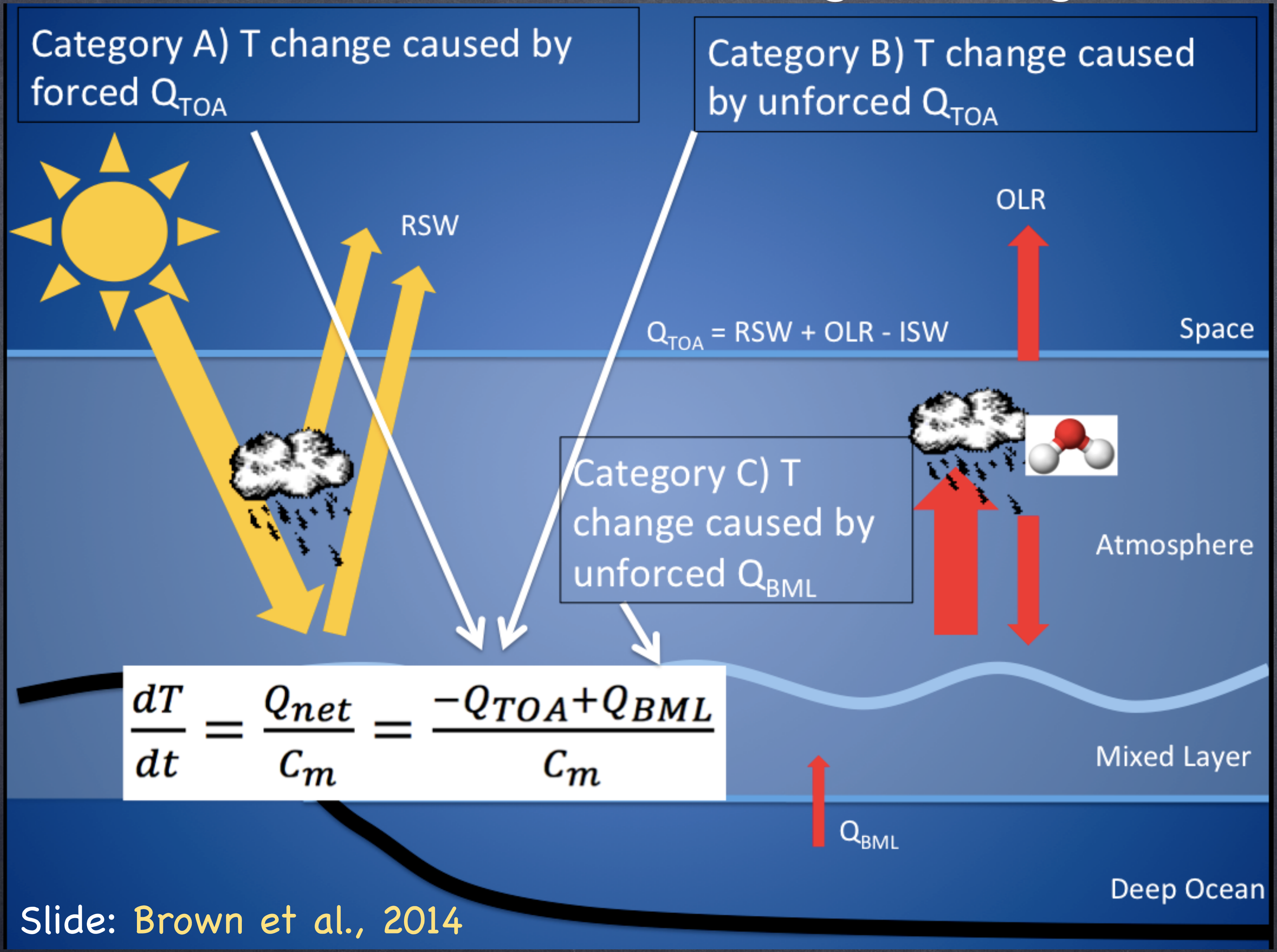


Air-Sea Exchanges

- Ocean heat capacity, even just mixed layer, is vastly larger than the atmosphere
- Air-sea heat fluxes are sensitive to air-sea temperature differences (and wind—i.e. momentum differences)
- Thus heat anomalies end up in the ocean

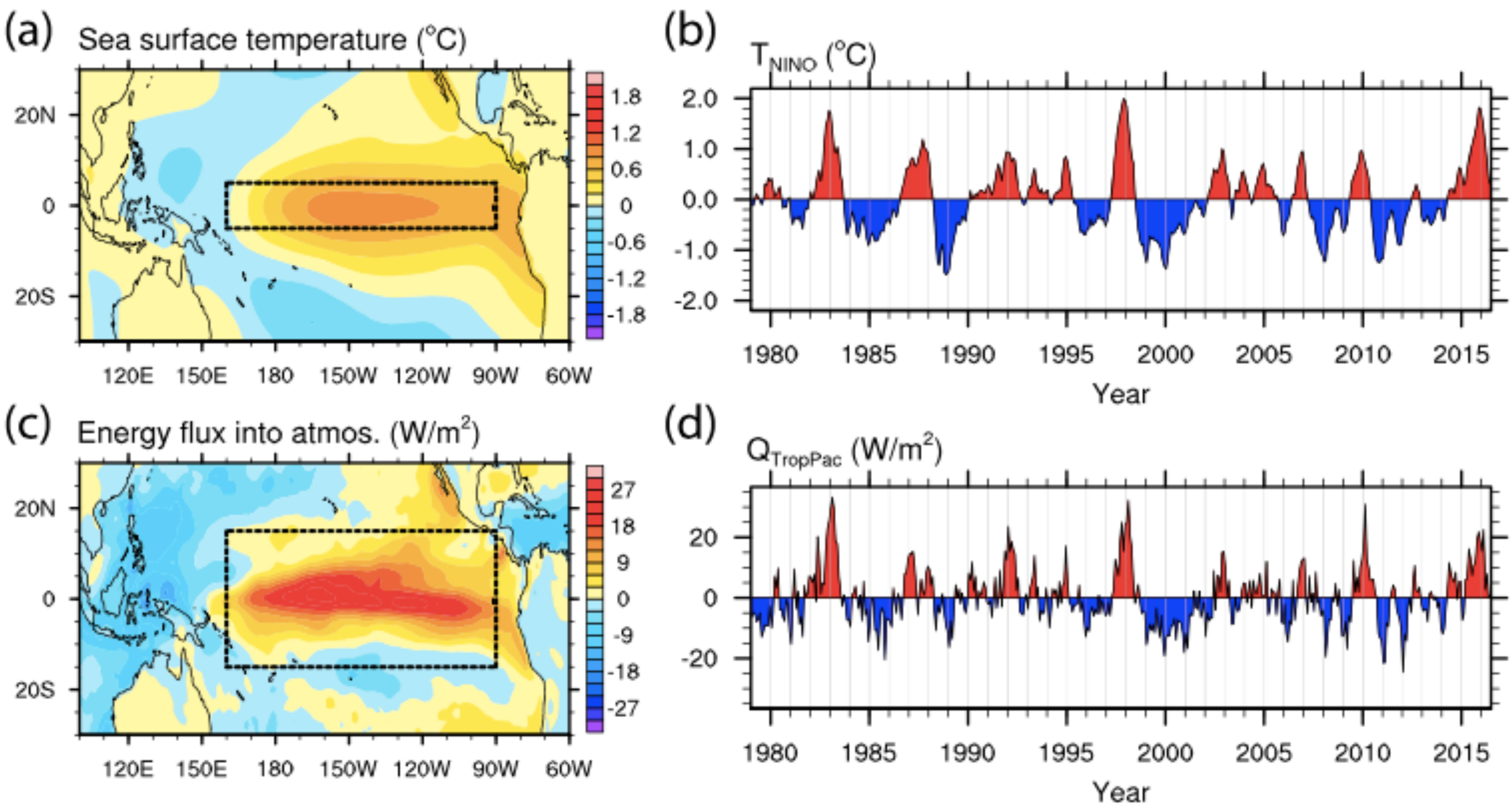


GMST: Surface Energy Budget



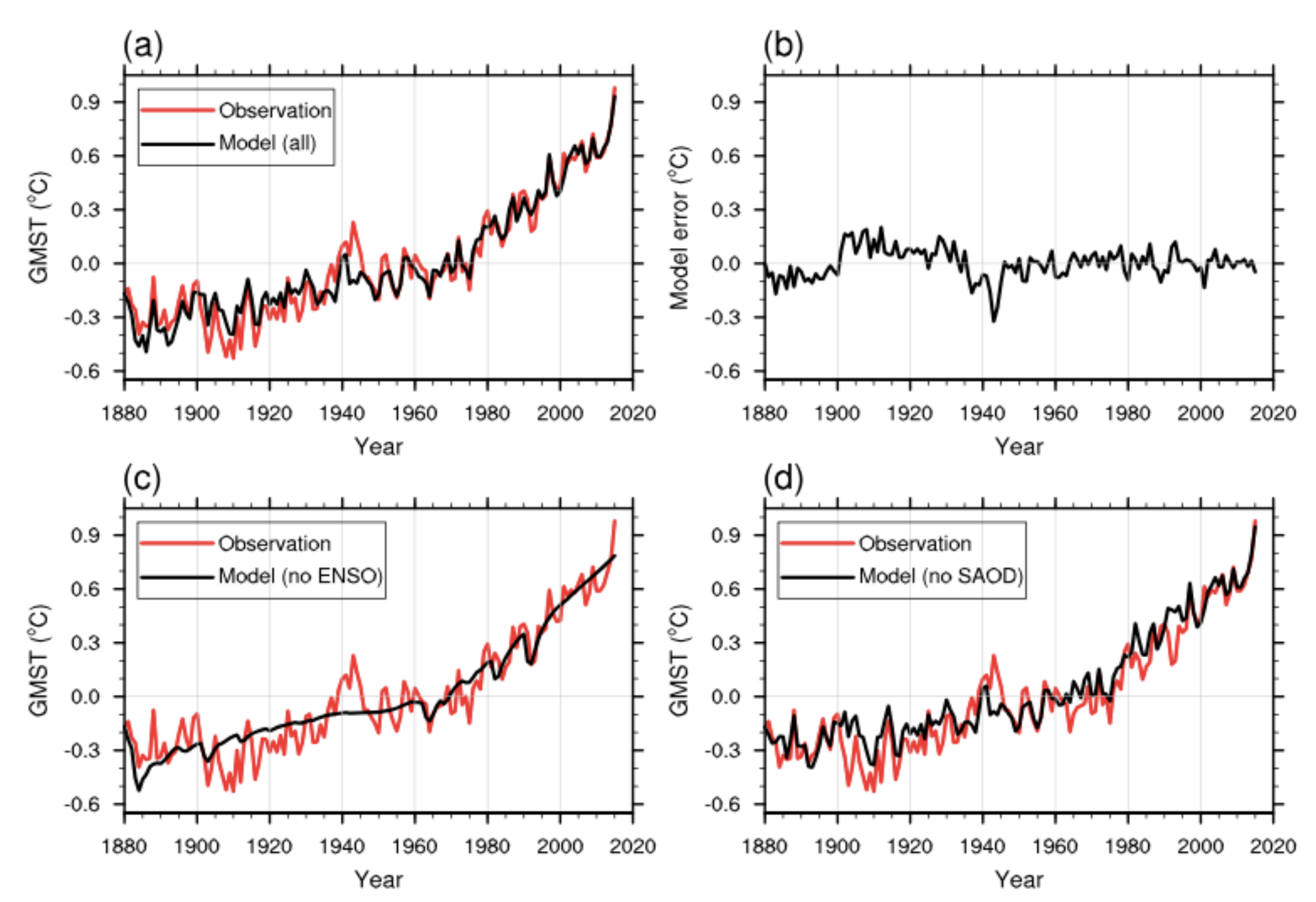
- 3.4m of ocean has heat capacity of whole atmosphere
- Ocean Mixed Layer is about 100m deep.

Effect of Climate Modes, e.g., Hu & Fedorov (2017)

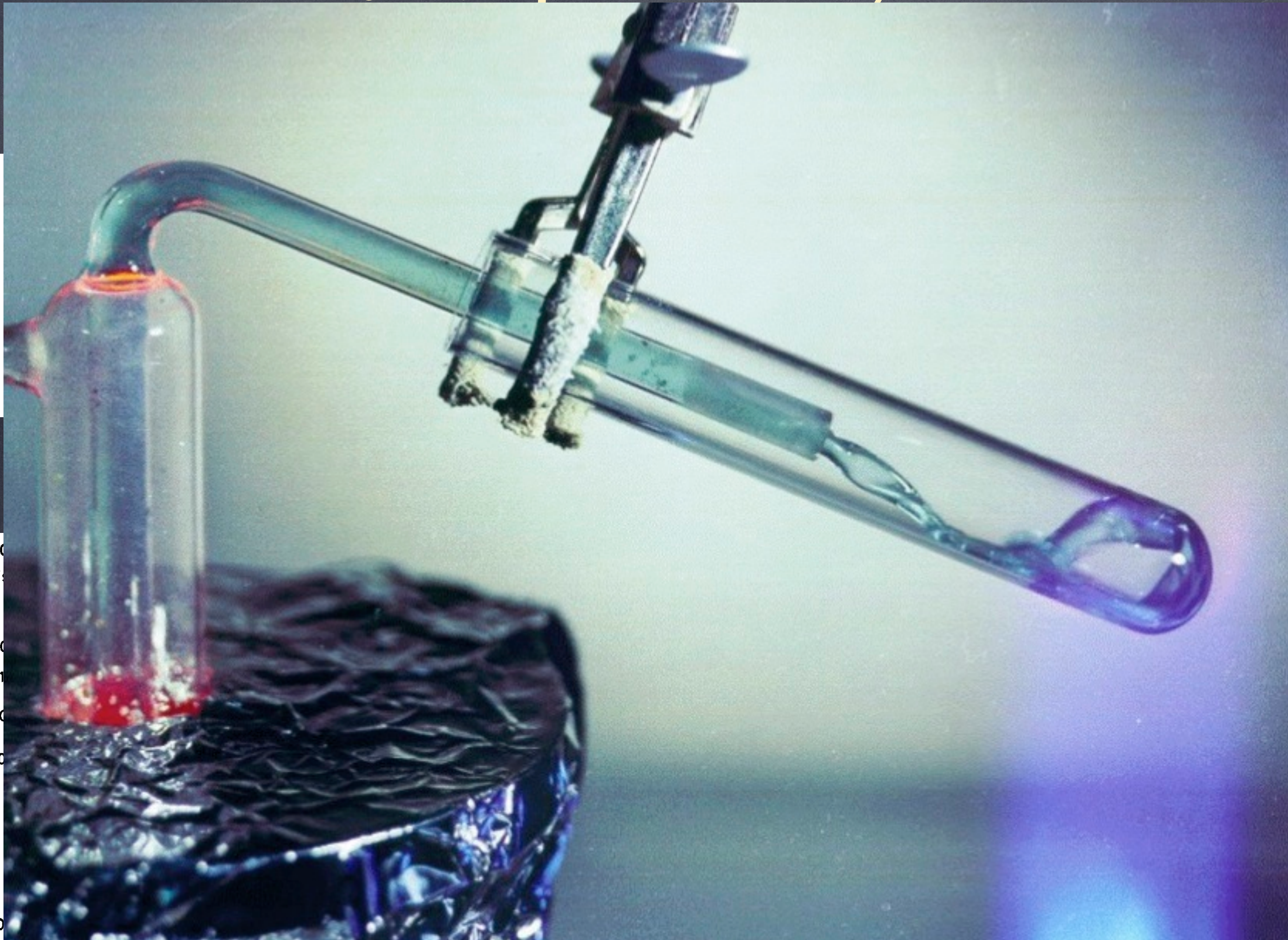


$$\frac{dT_g}{dt} = -\frac{T_g}{\tau} + a \cdot \log(CO_2/CO_{2,ref}) + b \cdot T_{NINO} + c \cdot SAOD + d,$$

Effect of Climate Modes, e.g., Hu & Fedorov (2017)



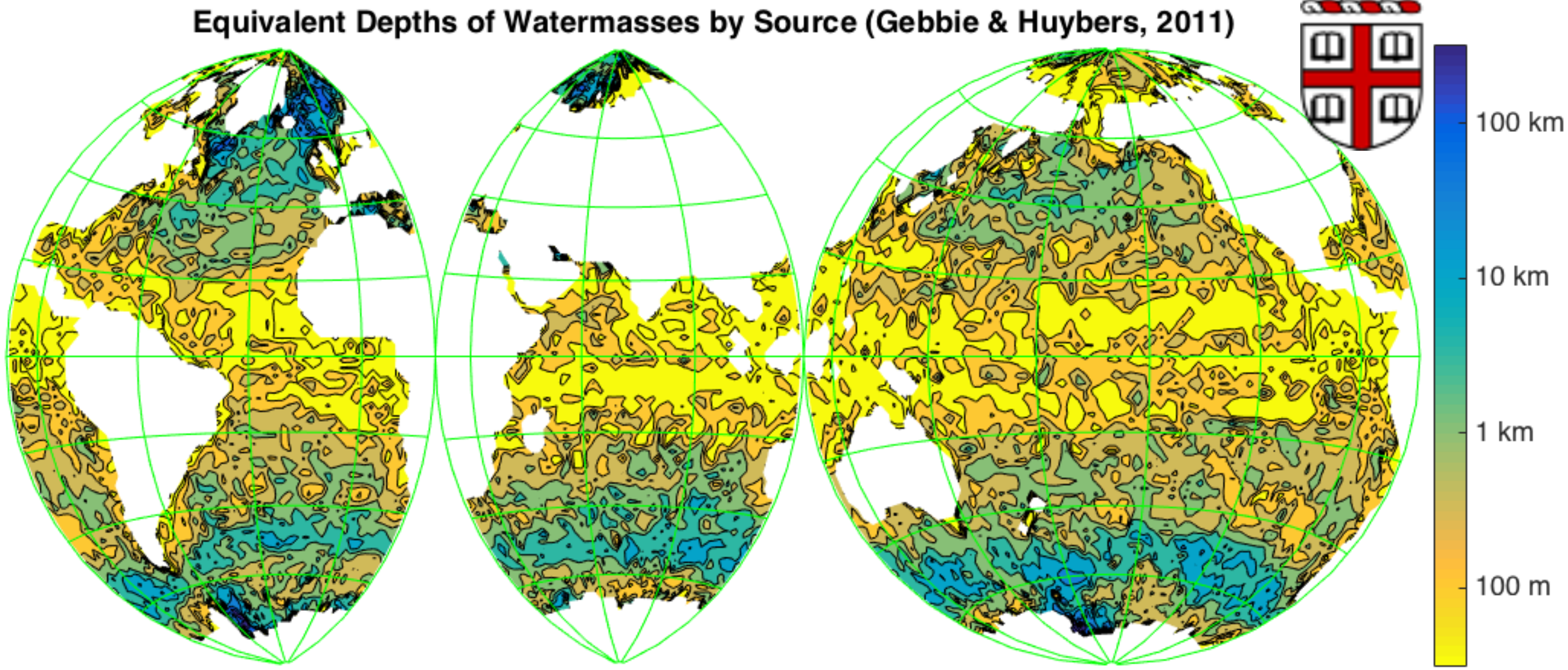
Modeling of variability



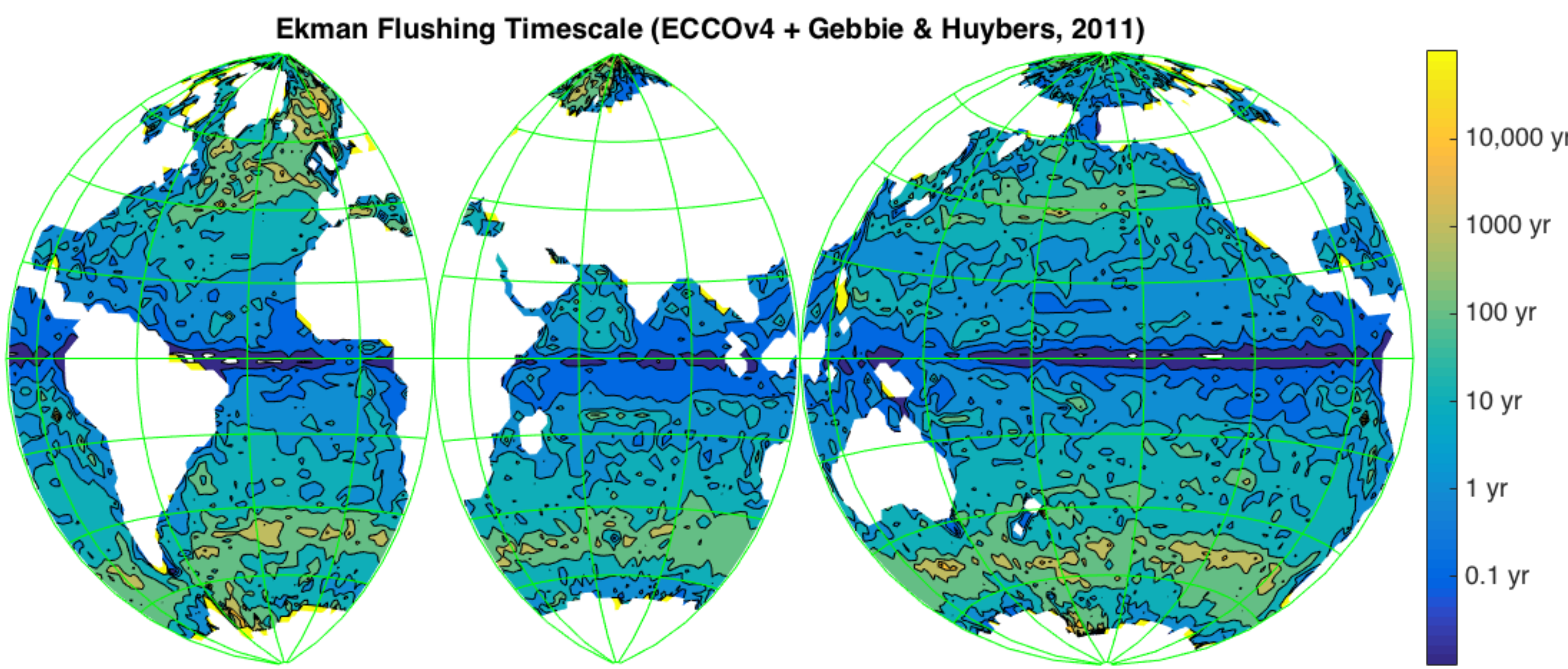
Still, these are systems in thermodynamic equilbrium

- These toy models are interesting and useful, but they have only one temperature.
- The real system is inherently unable to achieve a (thermodynamic) equilibrium state.
- However, we do normally assume that "infinitesimal parcels" of air or water can be described with a single temperature, entropy, etc., and thus yield to standard thermodynamics.

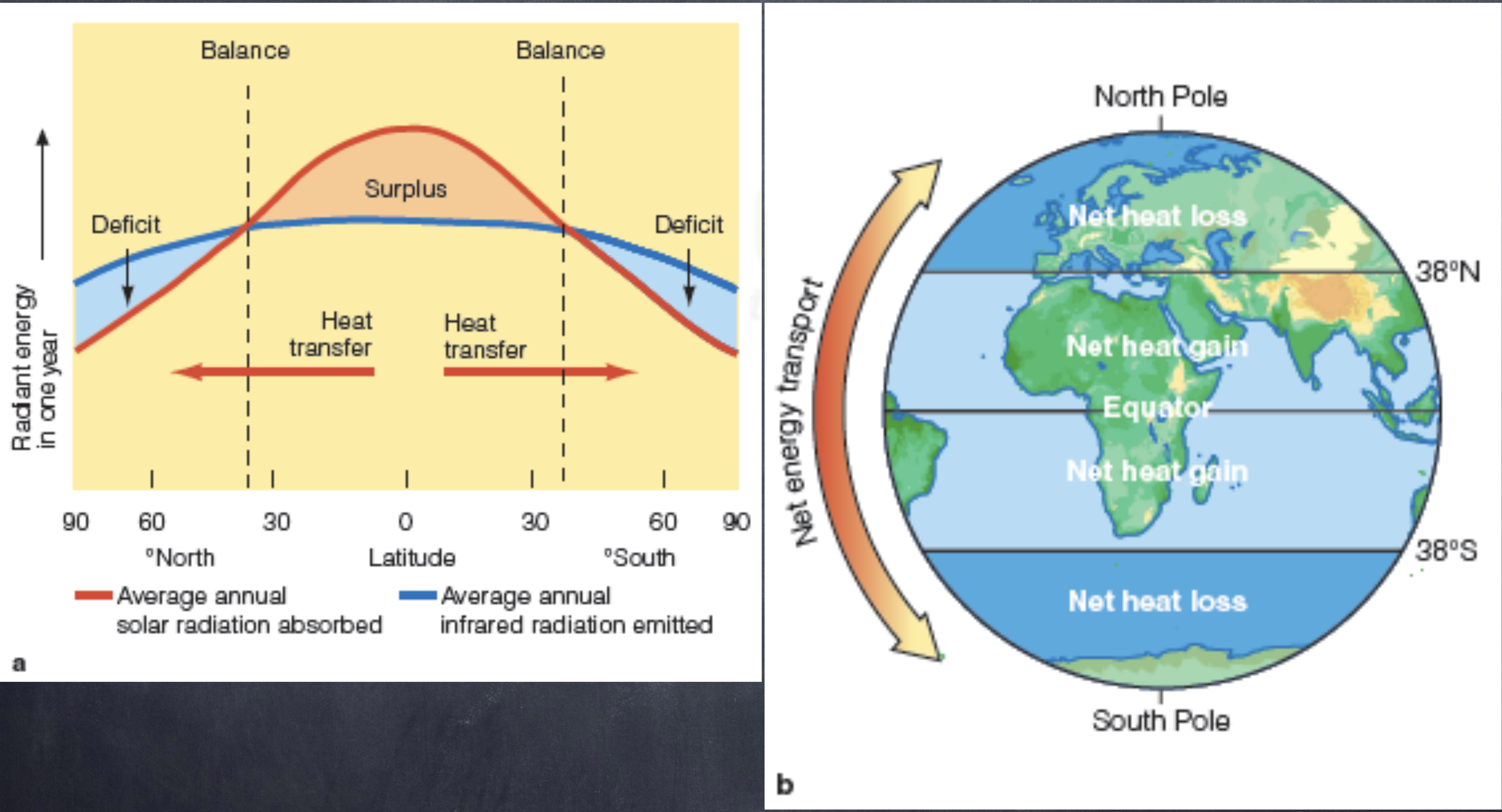
Consider lots of 1D Oceans: one per watermass



Wind (Ekman) flushing gives upper limit to λ^{-1} timescale



But what if heating is uneven (but steady state)?



Incomplete Redistribution!—A Nonequilibrium Steady-State

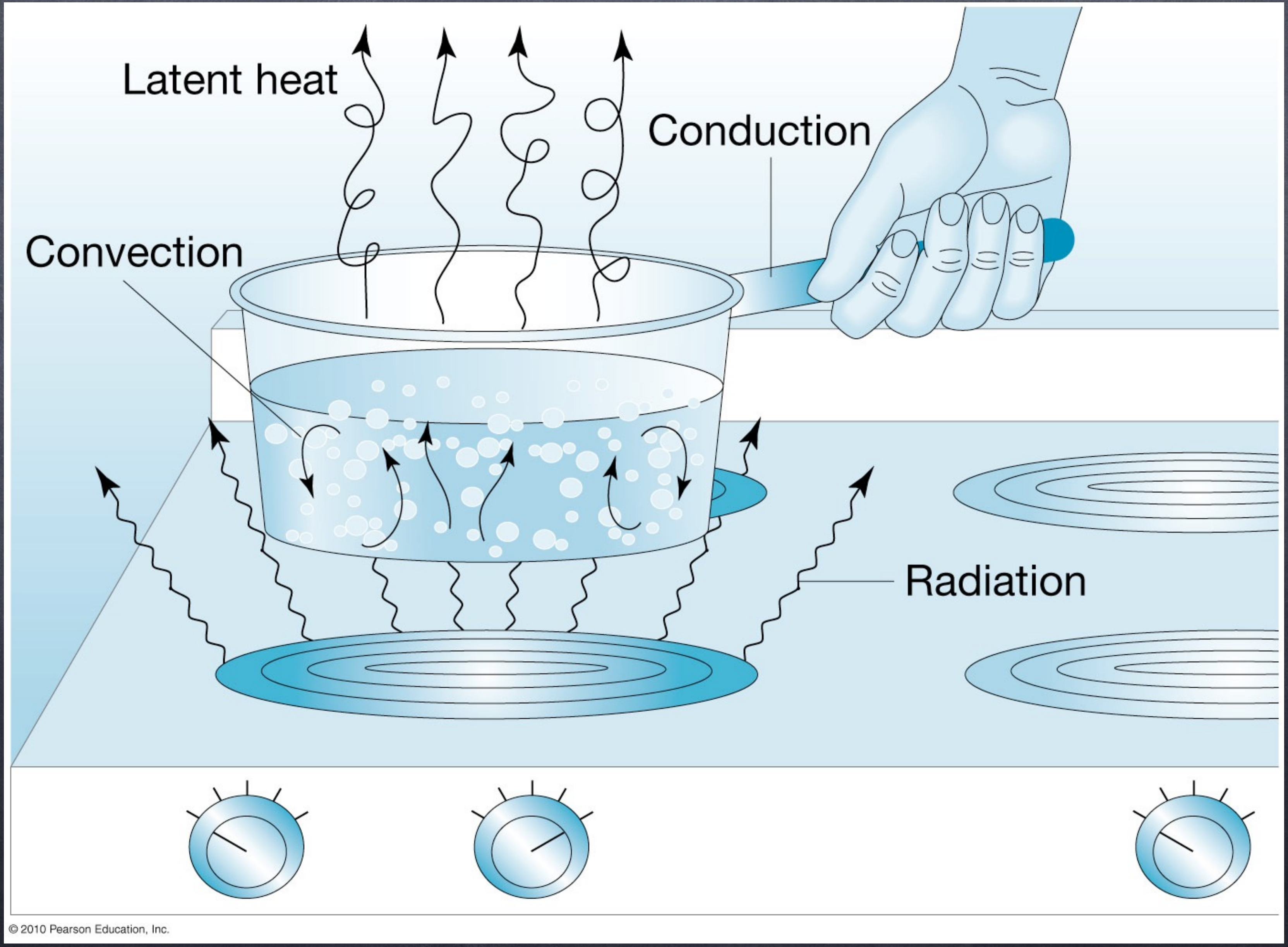
How does Energy Flow?:

Energy may flow by Conduction, Radiation, and Convection of Sensible and Latent Heat (vapor & ice transport).

Convection: transfer of energy by fluid motion when heated from below

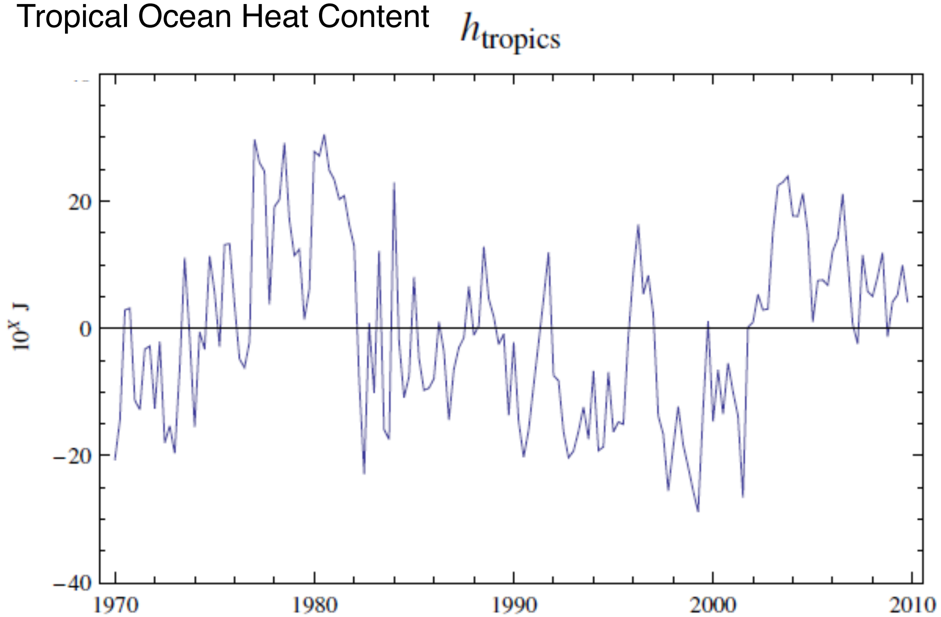
Conduction: transfer of energy by direct contact between molecules (not fluid motion)

Radiation: transfer of energy by electromagnetic waves, or by transfer through other force fields

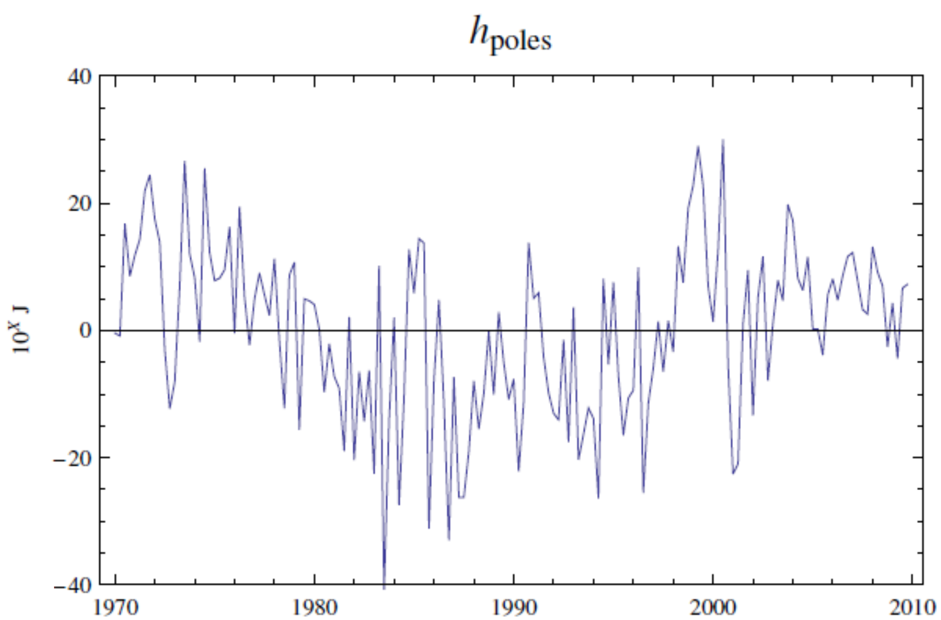


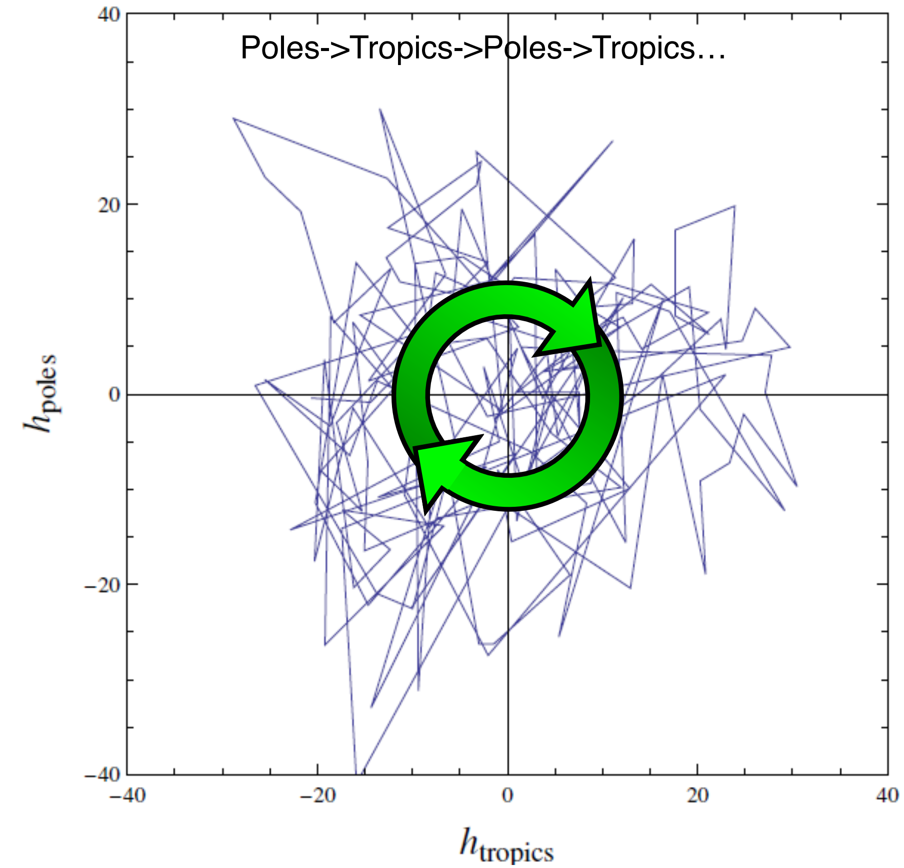
If Connections Occur Between Regions— Probability Currents Can Arise.

Tropical Ocean Heat Content



Polar Ocean Heat Content





This is the root of most stochastic model predictability beyond persistence

R. Zia, J. B. Weiss, D. Mandal, and BFK, 2016: Manifest and subtle cyclic behavior in nonequilibrium steady states. In Journal of Physics: Conference Series, volume 750, page 012003. IOP Publishing.

KOLMOGOROV

Mechanical Energy Budget

and

Nonequilbrium Mechanisms

Atmospheric Redistribution/Heat Engine might be like this:

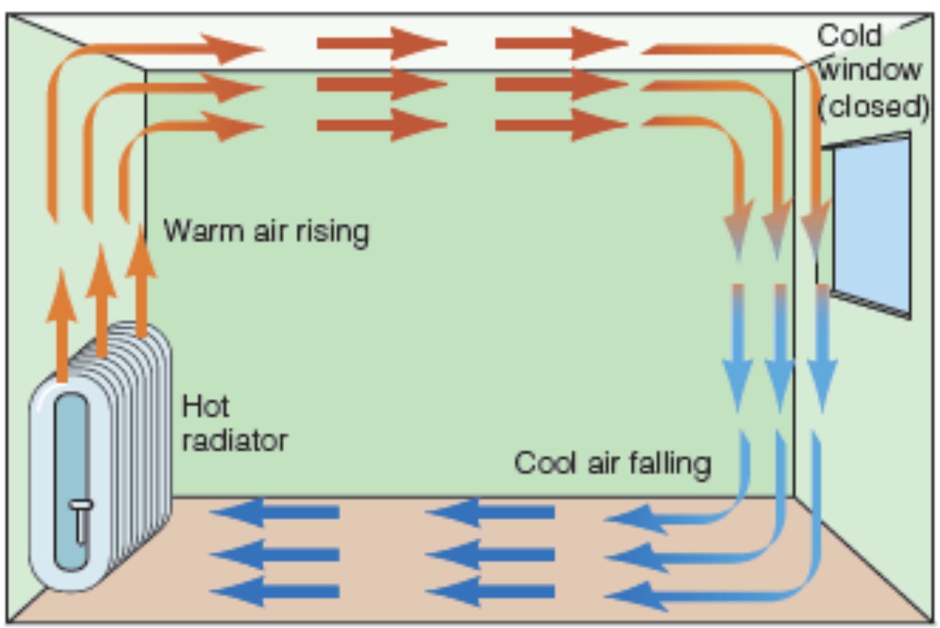


Figure 8.7 A convection current forms in a room when air flows from a hot radiator to a cold closed window and back. (For a practical oceanic application of this principle, look ahead to Figure 8.17.)

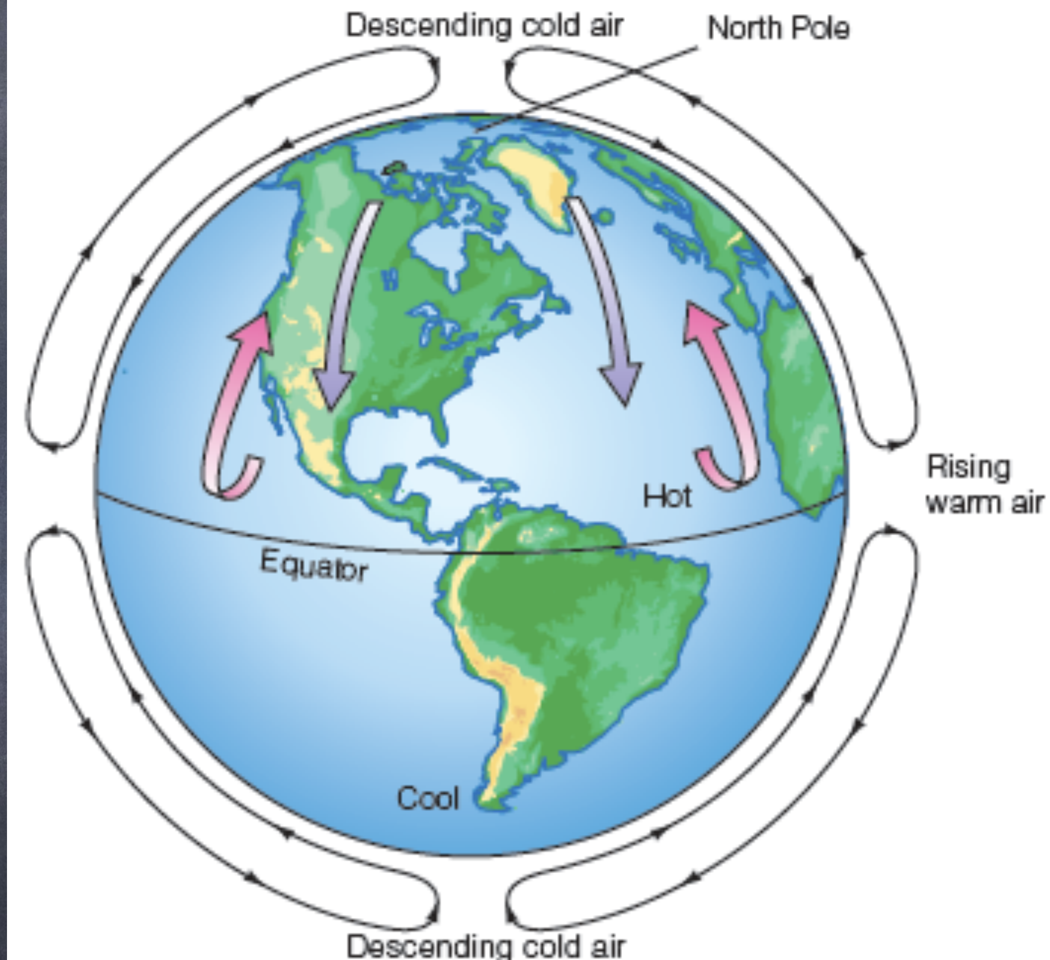
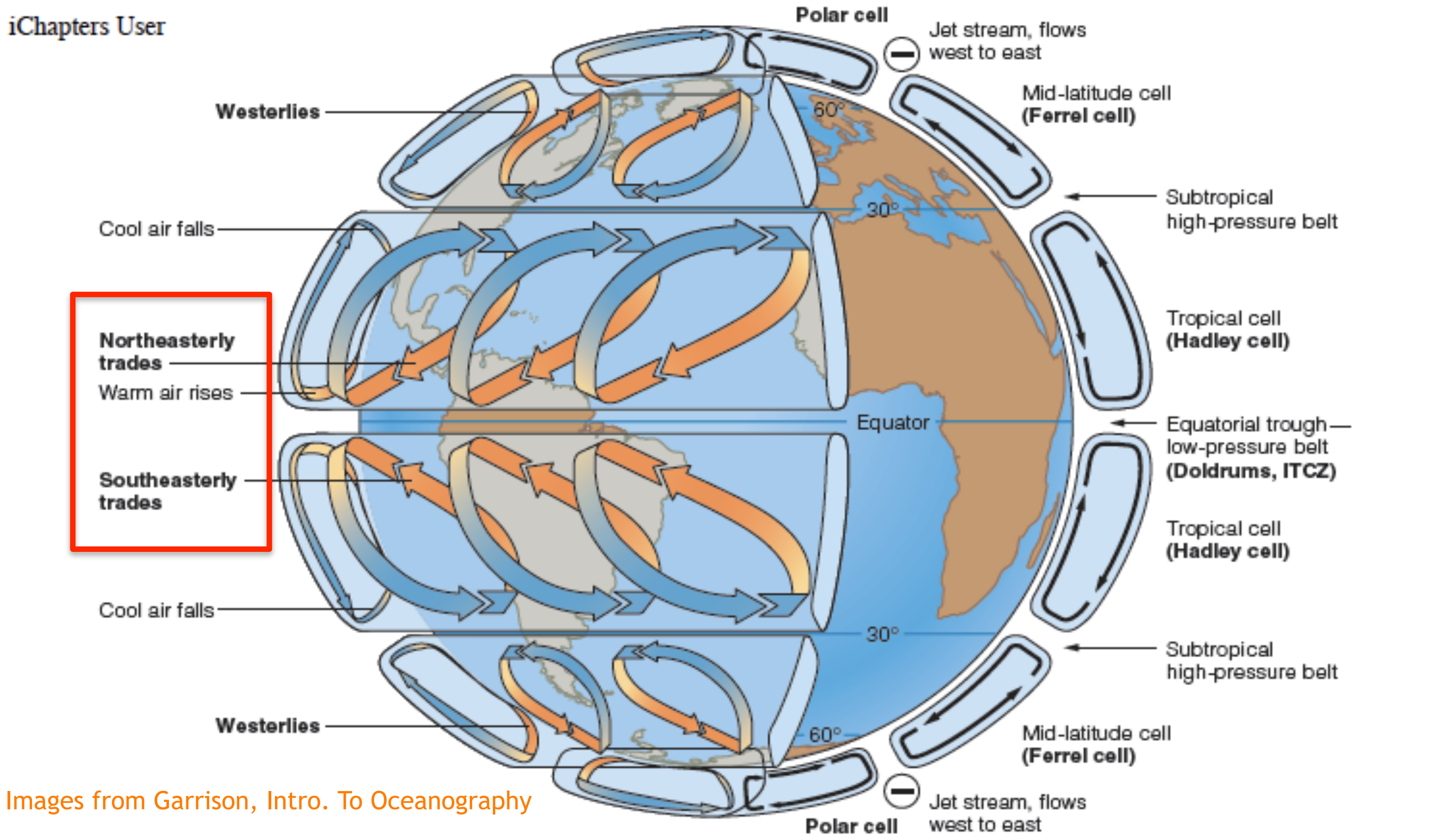


Figure 8.8 A hypothetical model of Earth's air circulation if uneven solar heating were the only factor to be considered. (The thickness of the atmosphere is greatly exaggerated.)

Halley's Idea, essentially
Except, the planet is rotating! (Hadley's idea)

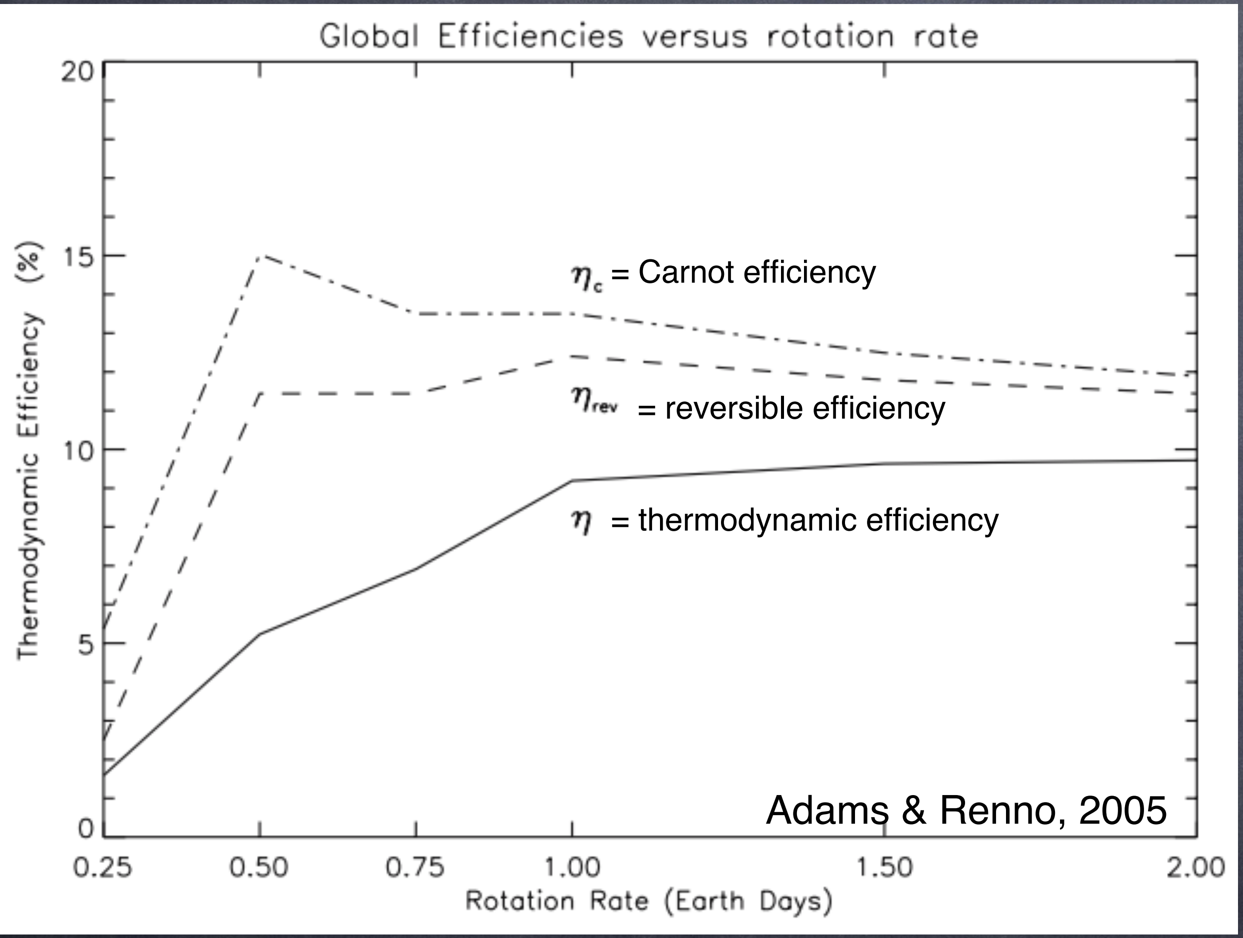
With the Coriolis Force, the winds are more zonal… and considerably less efficient.

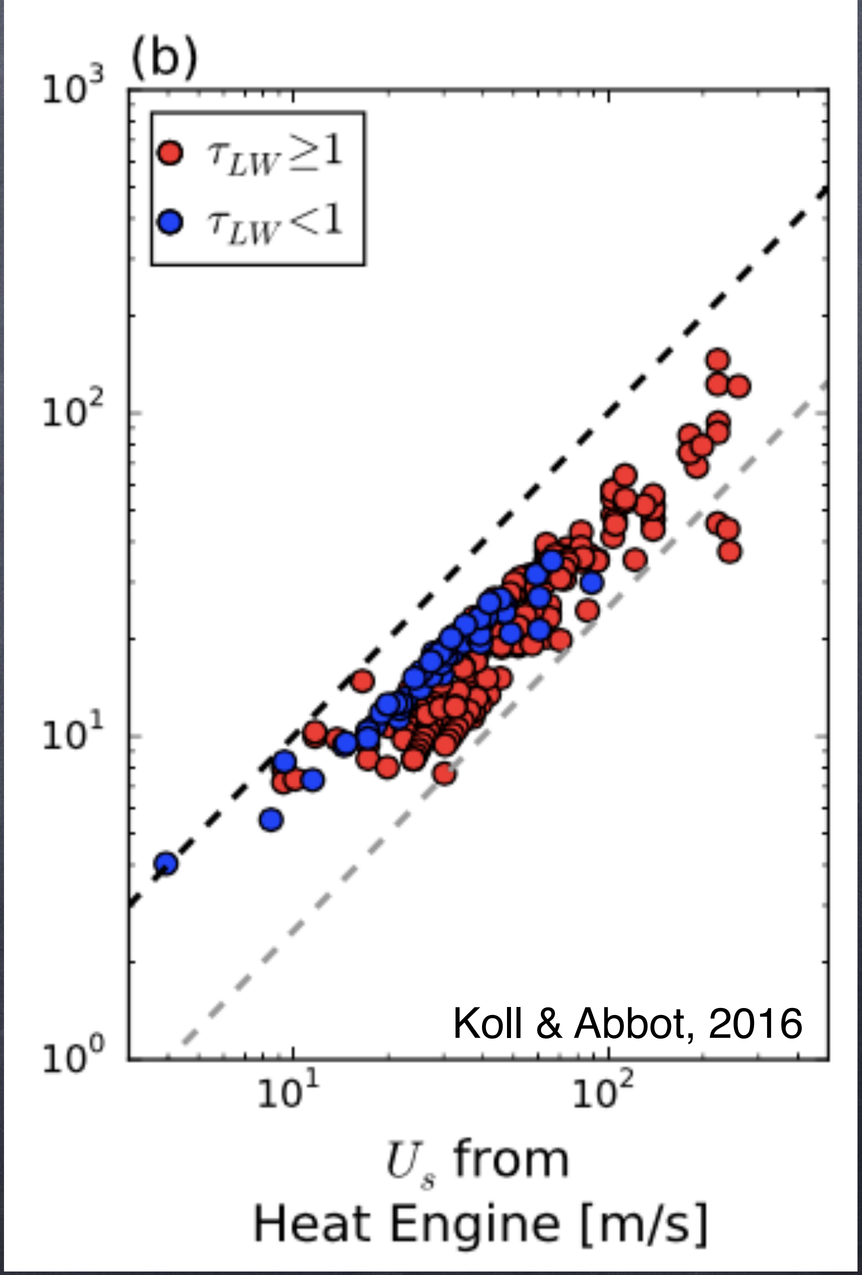


Images from Garrison, Intro. To Oceanography

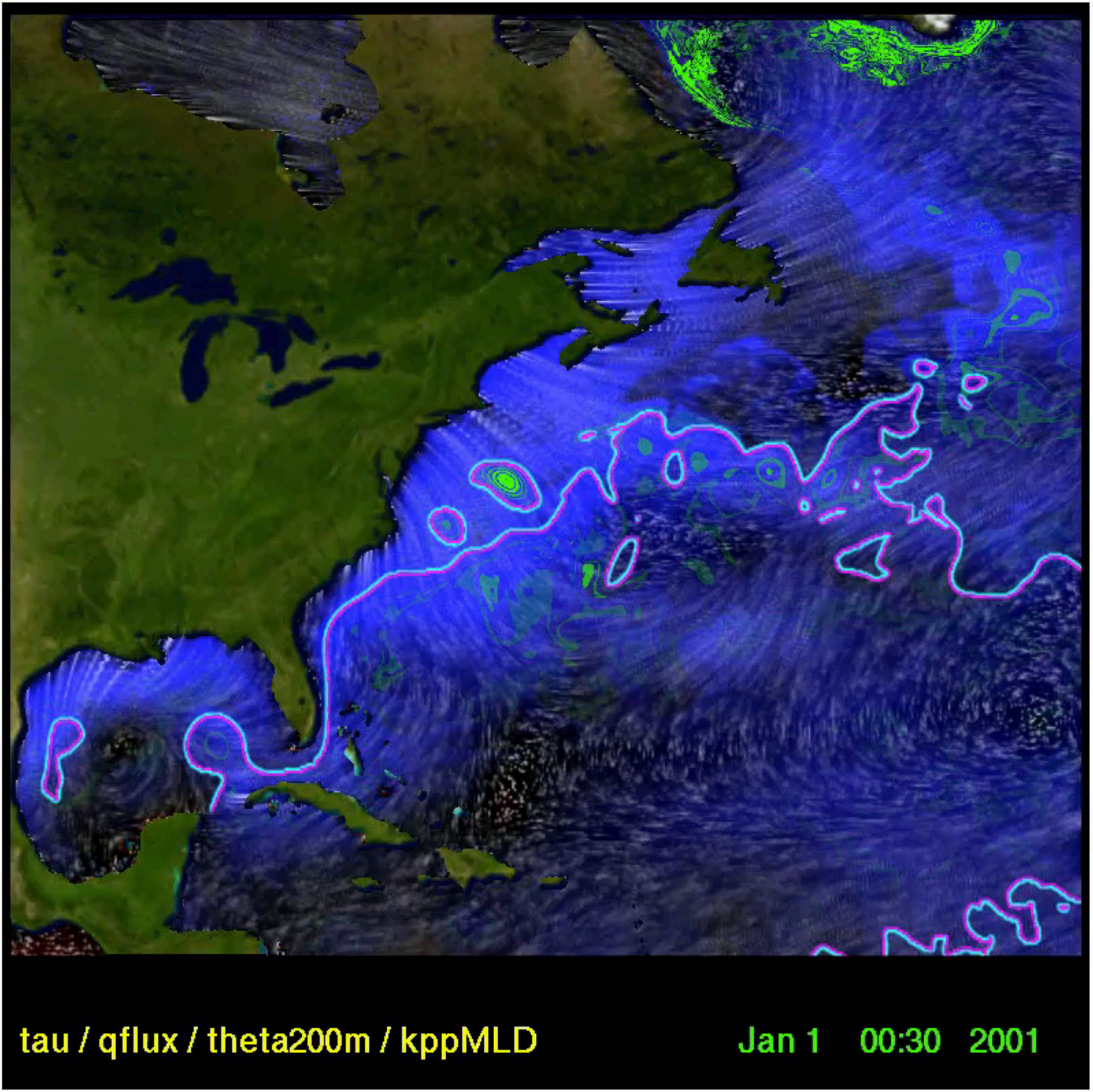
How is Mechanical Energy created?

Carnot Cycle with 342 W/m²? No, but simplified (dry, no continents) atmospheres are proportionally so.





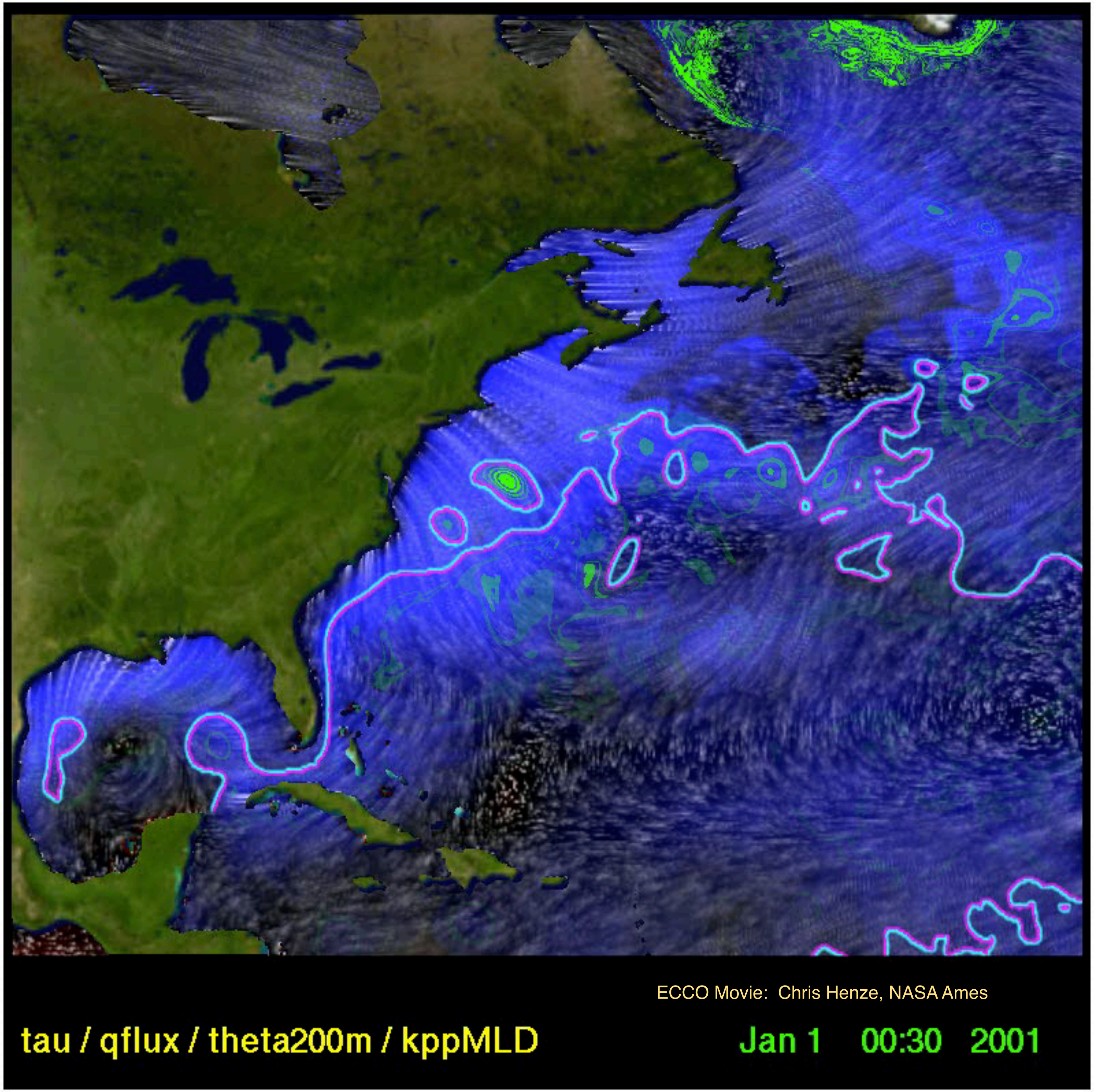
To a lesser degree, there is also energy from tides and radioactive decay, and residual energy from planetary accretion



Weather, Atmosphere Fast

Ocean, Climate Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere



Weather,
Atmosphere
Fast

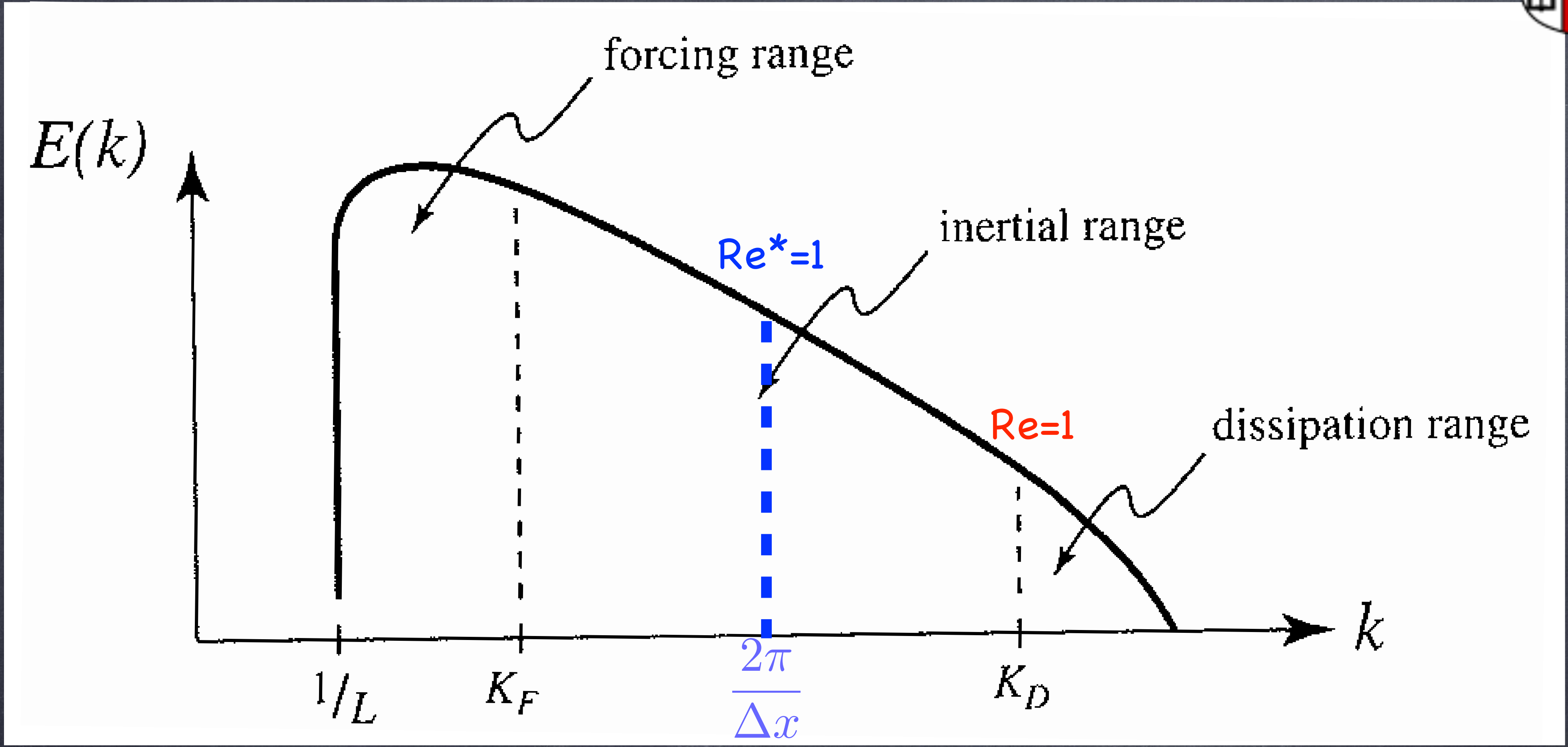
Ocean, Climate
Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere

So, if both ocean & atmosphere are turbulent…

- The classic statistical physics prob. is fully-developed, homogenous, isotropic turbulence.
- Richardson, Kolmogorov, Oboukhov, Monin, Yaglom, Kraichnan, Charney, Mandelbrot, Frisch, etc.
- The key idealization involves flows that are much larger than the damping scale and much smaller than the forcing scale—an inertial range.
- The challenge in applying this approach in the earth system is that new parameters (f, N) introduce other significant scales along the way.

Truncation of Cascades in models



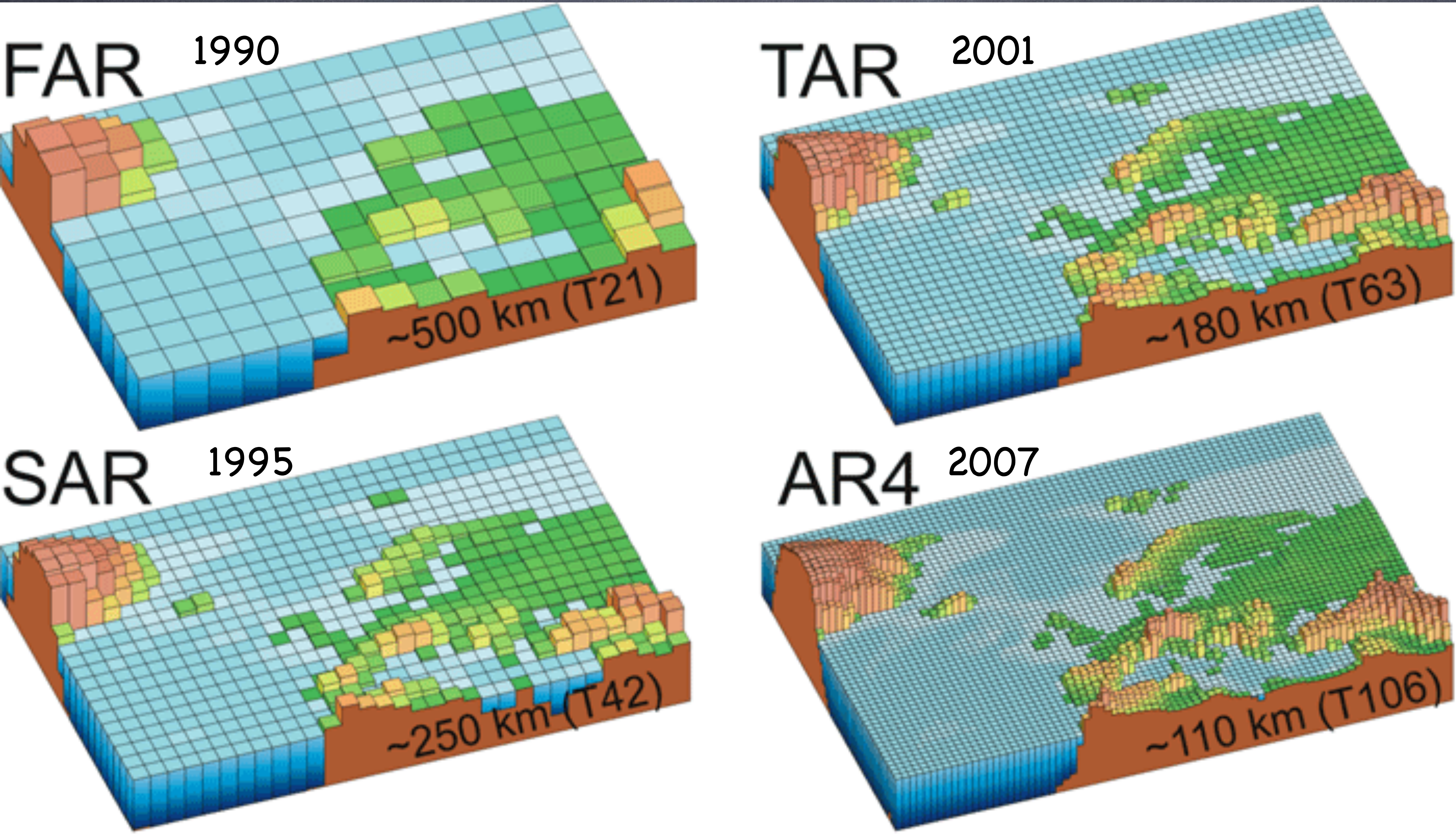
1963: Smagorinsky Devises Viscosity Scaling,
Energy Flow is Preserved,
but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

$$\nu_{*h} = \left(\frac{\Upsilon_h \Delta x}{\pi}\right)^2 \sqrt{\left(\frac{\partial u_*}{\partial x} - \frac{\partial v_*}{\partial y}\right)^2 + \left(\frac{\partial u_*}{\partial y} + \frac{\partial v_*}{\partial x}\right)^2}.$$

Gridscale-dependent

Climate model resolution introduces a scale...

Image: ipcc.ch



Can Atmospheric "turbulent mixing" do the meridional transport?

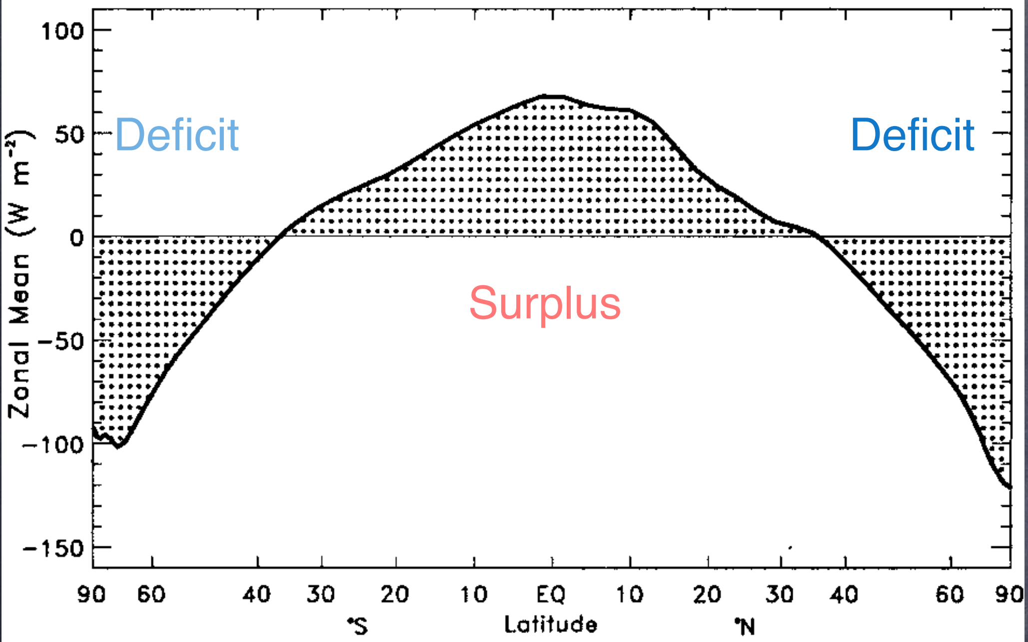


FIG. 1. TOA annualized ERBE zonal mean net radiation (W m^{-2}) for Feb 1985–Apr 1989.

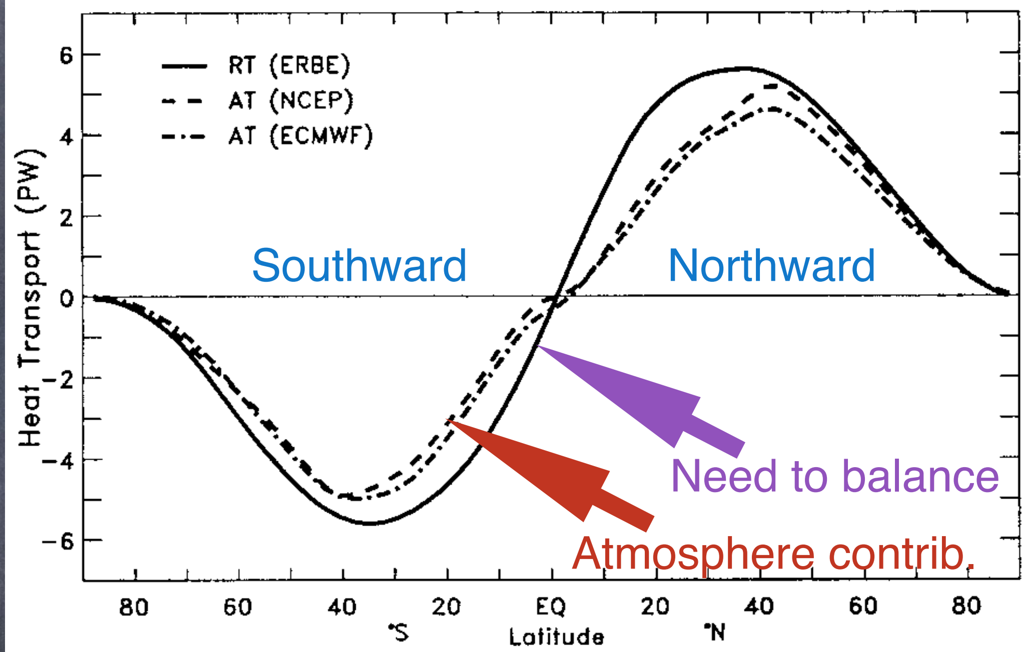


FIG. 2. The required total heat transport from the TOA radiation RT is given along with the estimates of the total atmospheric transport AT from NCEP and ECMWF reanalyses (PW).

Trenberth & Caron 01

What's Left is Ocean Transport

Not just mixing: different basins differ in direction and magnitude!

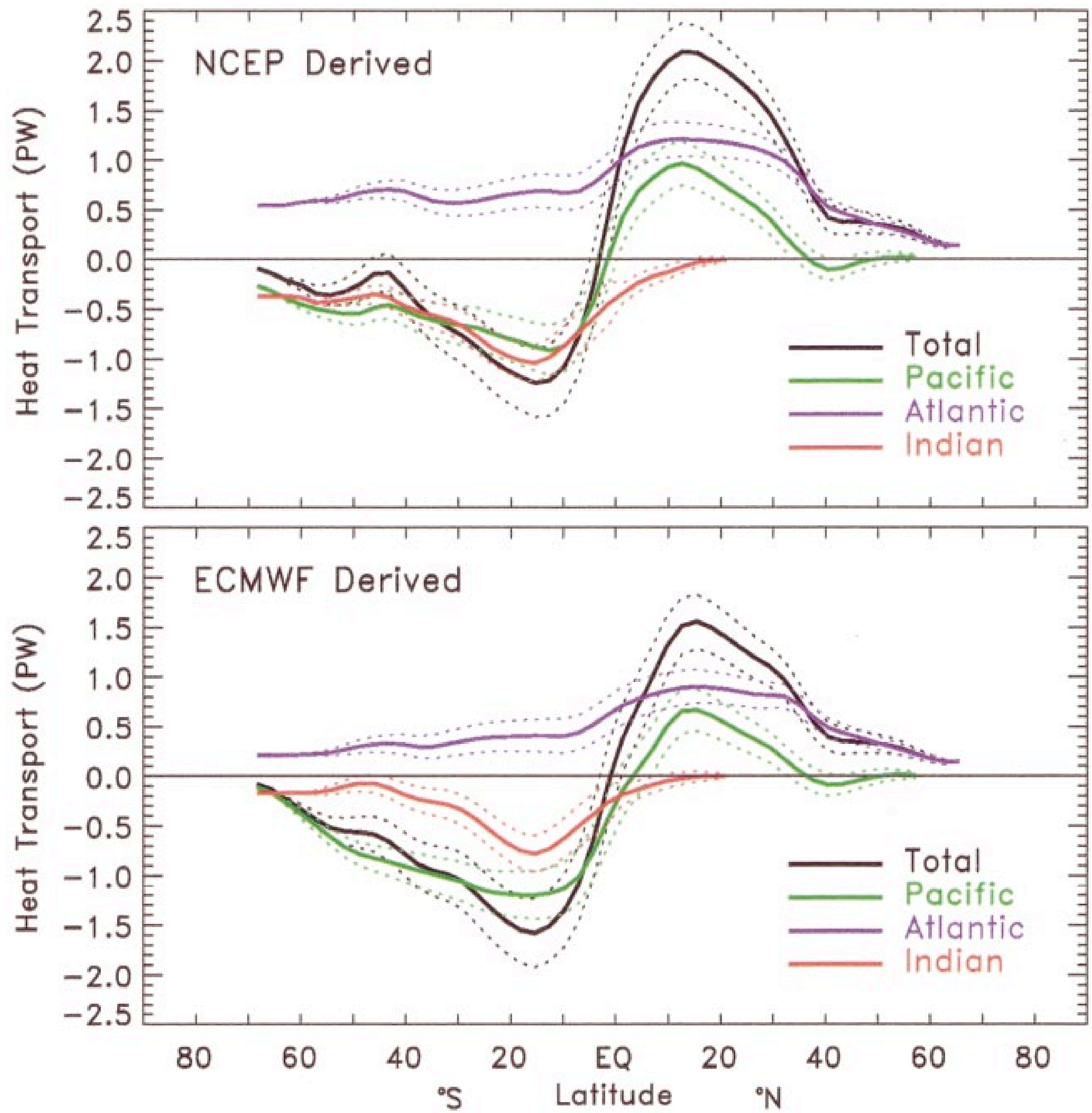


FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

Pot'l Temperature & Salinity of the Ocean

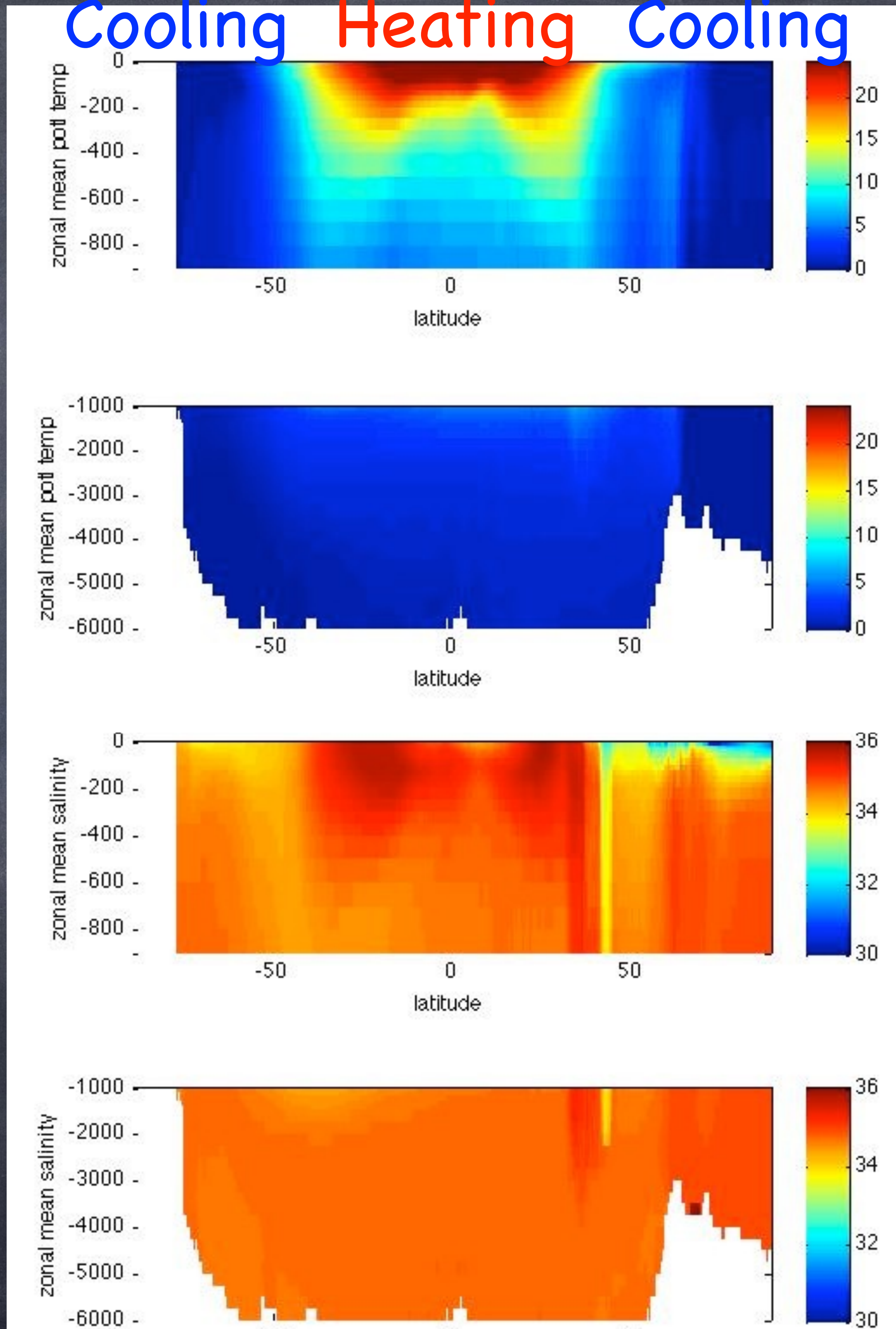
Thermocline-->

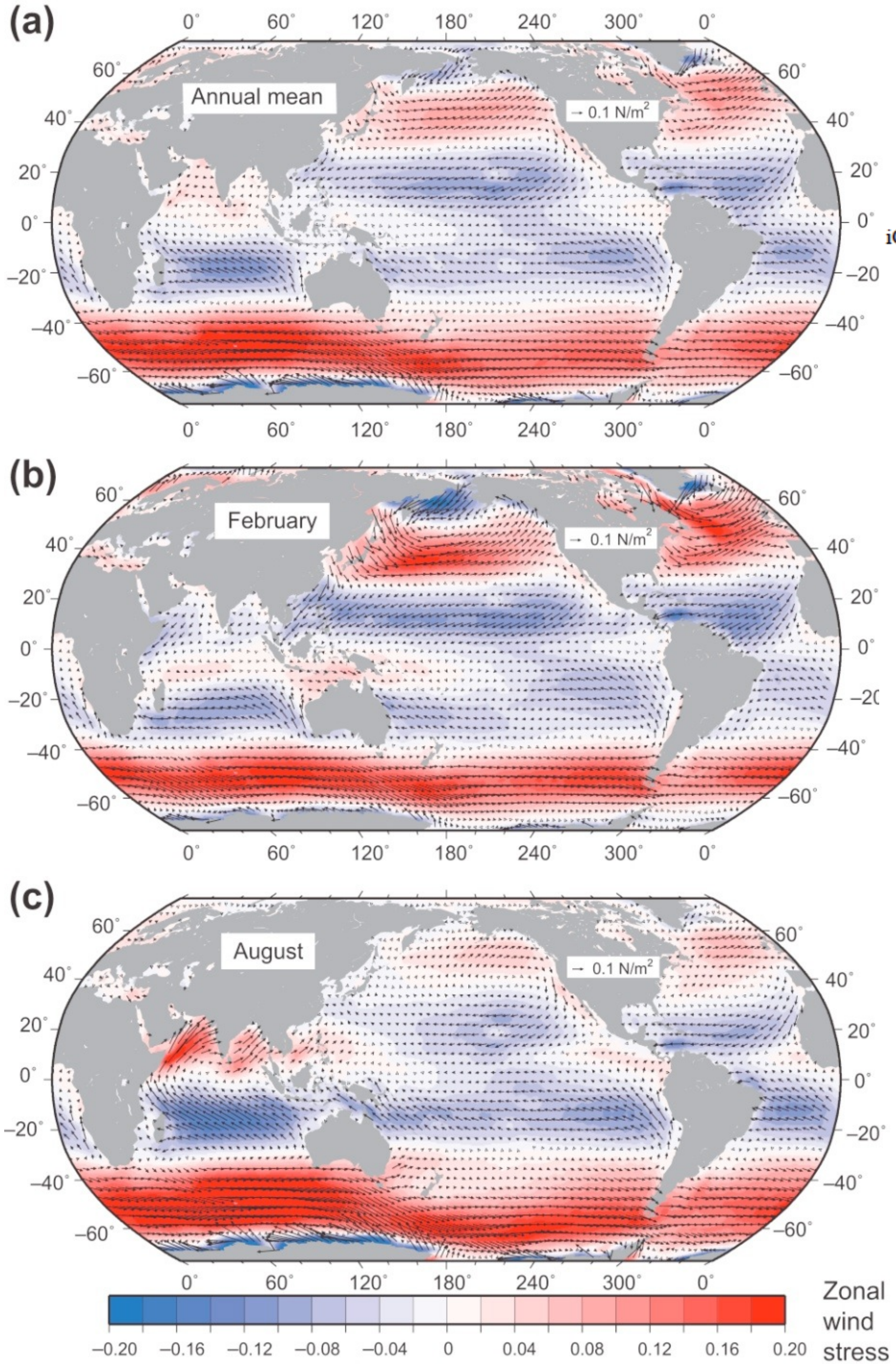
Seawater is fairly incompressible, pressure increases linearly w/ depth, and conversion from internal to mechanical is negligible

Halocline-->

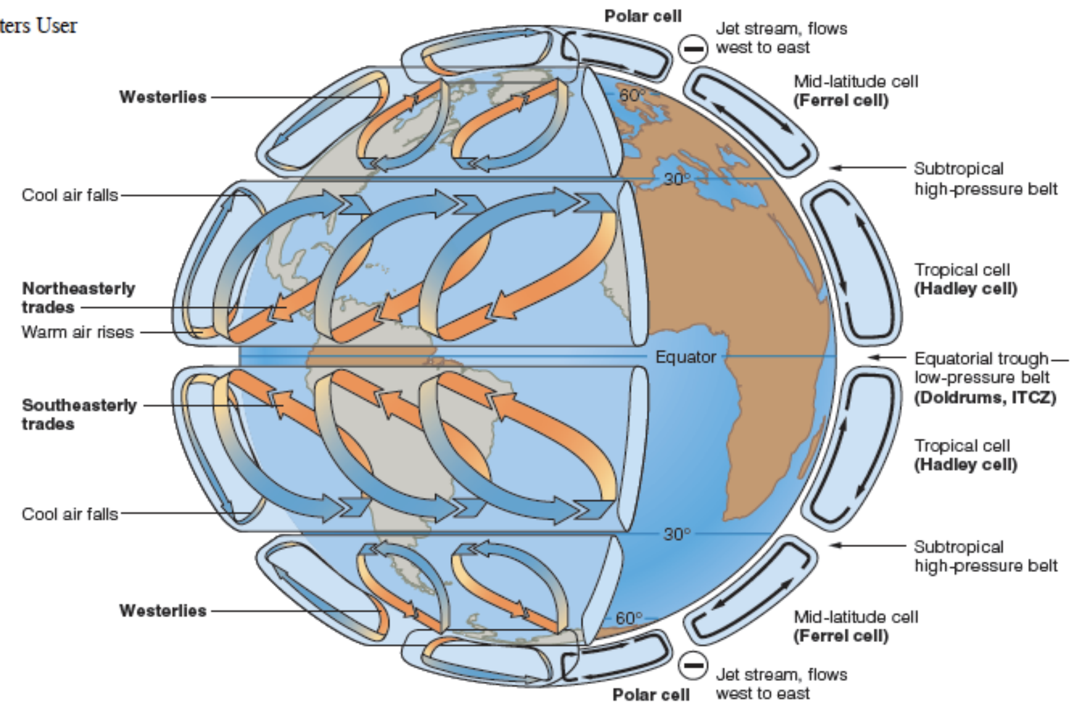
Cooling & Heating at same pressure: Ocean is NOT a heat engine

Data from Gouretski & Kolterman 04





Mean wind stress (arrows) and zonal wind stress (color shading) (N/m²): (a) annual mean, (b) February, and (c) August, from the NCEP reanalysis 1968–1996 (Kalnay et al., 1996).



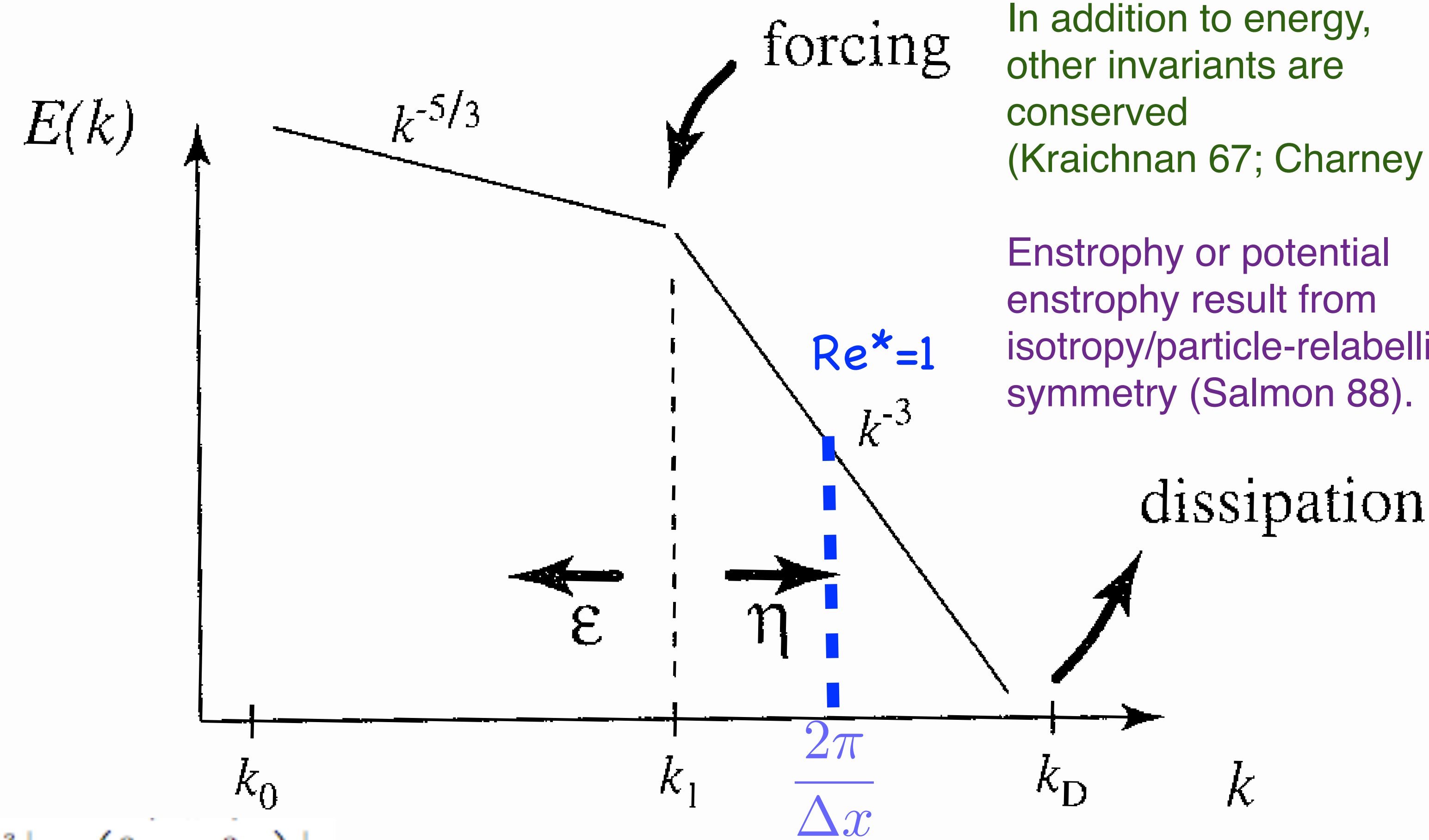
So, the ocean receives much of its mechanical energy from other more direct sources: winds and tides.

TALLEY

Another problem... Turbulence isn't 3d Turbulence at the 10-100km scale

- The ocean is wide (10,000km)
- But not deep (4km)
  - Motions in upper 1km
- The layer of blue paint on a globe has roughly the right aspect ratio!
- Atmosphere is a little taller (30km), but eddies are bigger (1000km)
- Motions are largely 2d

2d & QG Turbulence Differ



In addition to energy, other invariants are conserved (Kraichnan 67; Charney 71).

Enstrophy or potential enstrophy result from isotropy/particle-relabelling symmetry (Salmon 88).

$$\nu_* = \left(\frac{\Lambda \Delta x}{\pi}\right)^3 \left|\nabla_h \left(\frac{\partial u_*}{\partial y} - \frac{\partial v_*}{\partial x}\right)\right|.$$

1996: Leith Devises Viscosity Scaling, 2D Enstrophy Flow is Preserved

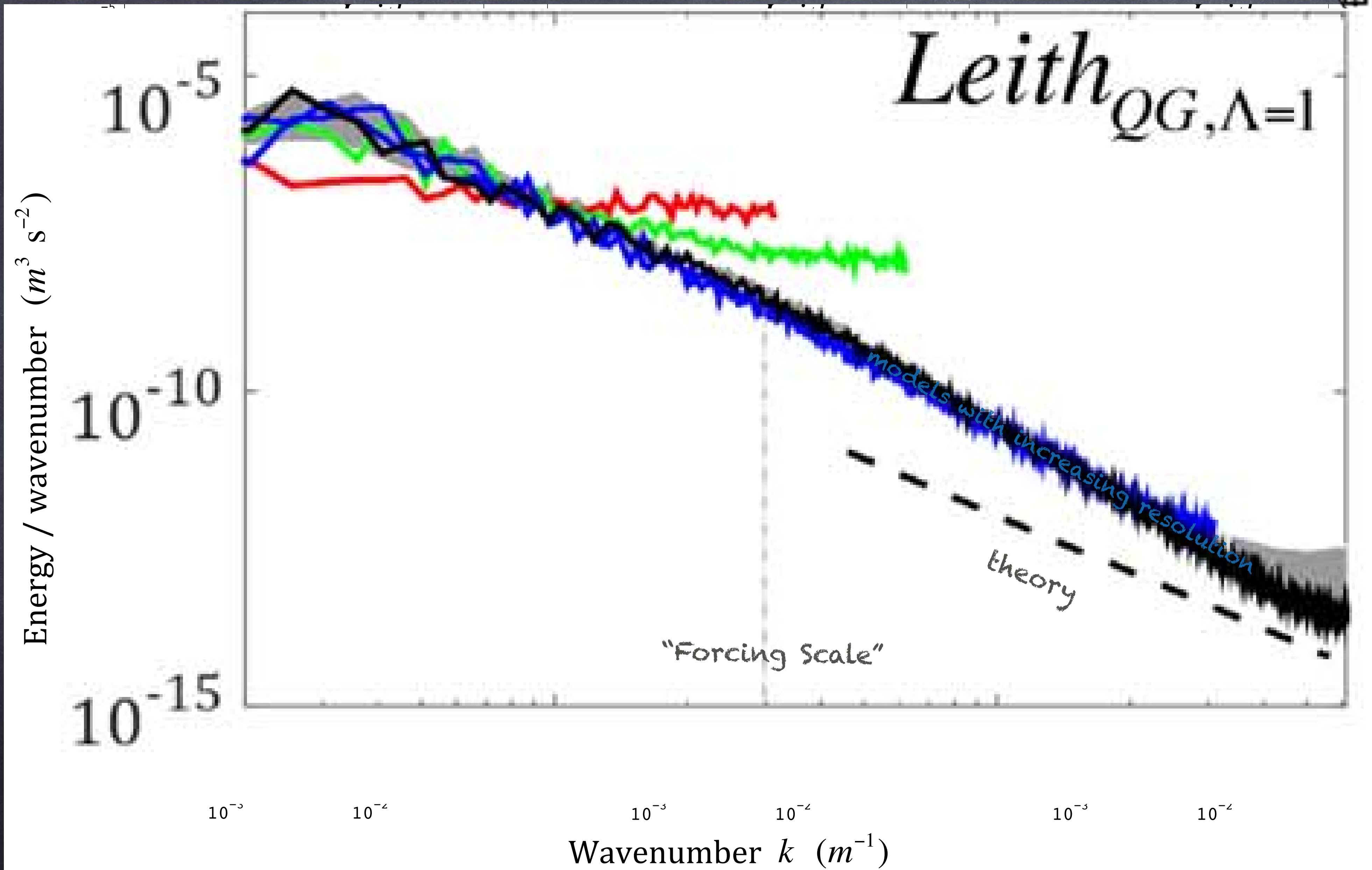
BFK and D. Menemenlis, 2008: Can large eddy simulation techniques improve mesoscale- rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319–338. AGU Geophysical Monograph Series.

S. D. Bachman, BFK, and B. Pearson, 2017: A scale-aware subgrid model for quasigeostrophic turbulence. Journal of Geophysical Research–Oceans, 122:1529–1554. URL http: //dx.doi.org/10.1002/2016JC012265.

B. Pearson, BFK, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58. URL http://dx. doi.org/10.1016/j.ocemod.2017.05.007.

Where does ocean energy go?

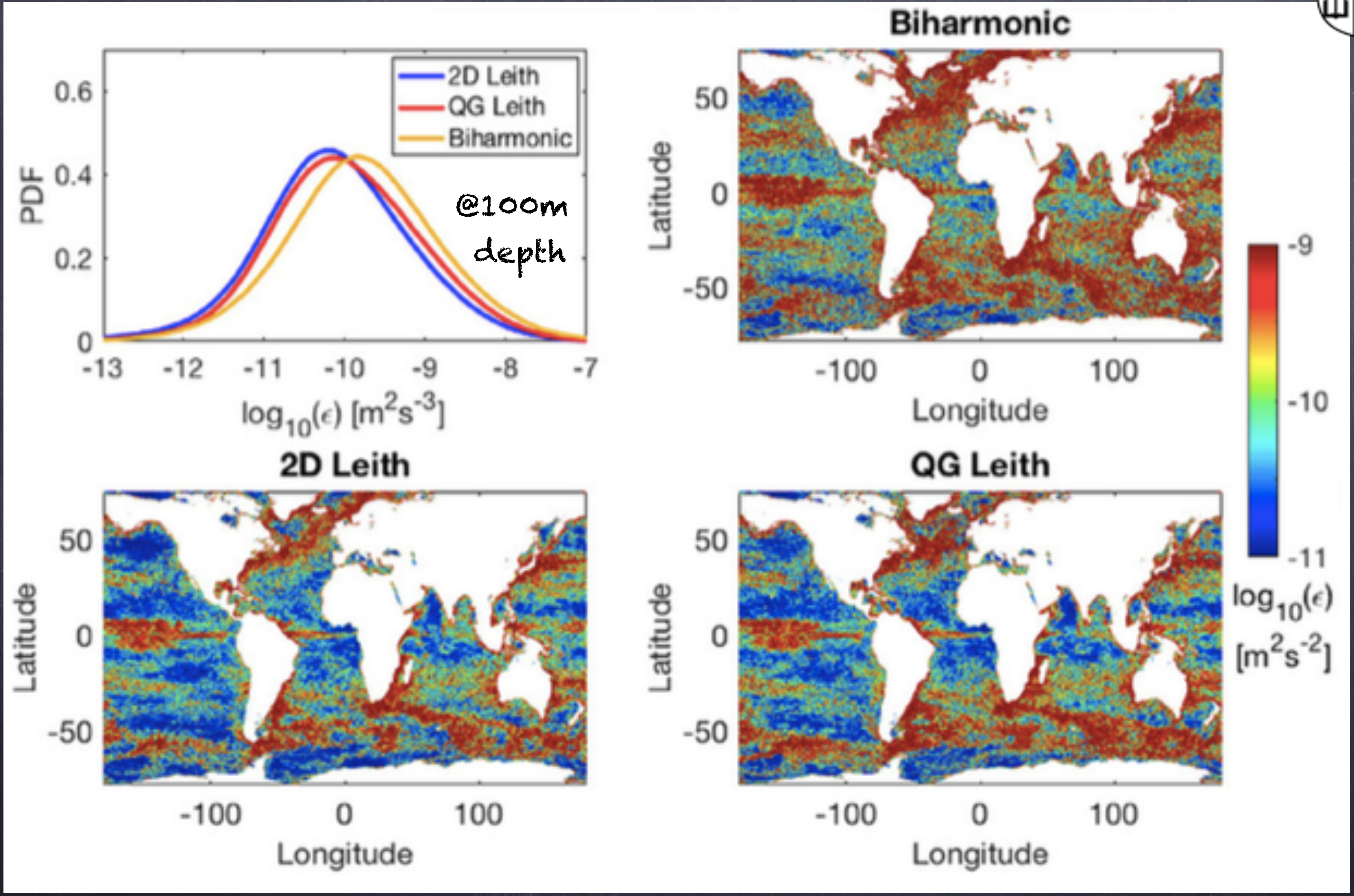
Spectrally speaking



S. D. Bachman, B. Fox-Kemper, and B. Pearson, 2017: A scale-aware subgrid model for quasi- geostrophic turbulence. Journal of Geophysical Research–Oceans, 122:1529–1554. URL http: //dx.doi.org/10.1002/2016JC012265.

Where does ocean energy go?

Statistically & geographically speaking



B. Pearson, B. Fox-Kemper, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58. URL http://dx. doi.org/10.1016/j.ocemod.2017.05.007.

Where does ocean energy go?

Phenomenologically speaking

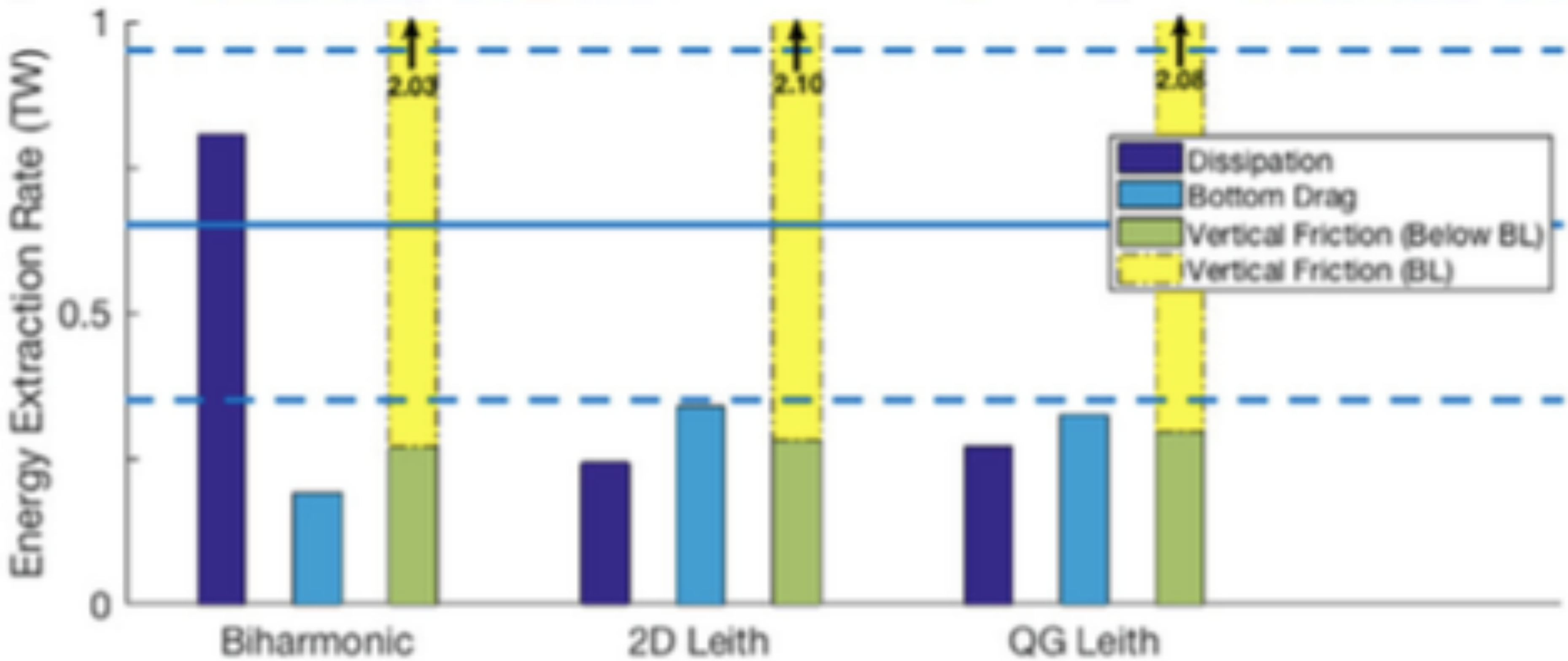


Fig. 9. Global energy extraction rates by dissipation, bottom drag, vertical friction in the boundary layer, and vertical friction below the boundary layer for each simulation. The solid line shows the observed global bottom drag energy extraction calculated by Wright et al. (2013), along with error bars (dotted lines). This figure uses a snapshot of the flow field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

B. Pearson, B. Fox-Kemper, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58. URL http://dx. doi.org/10.1016/j.ocemod.2017.05.007.

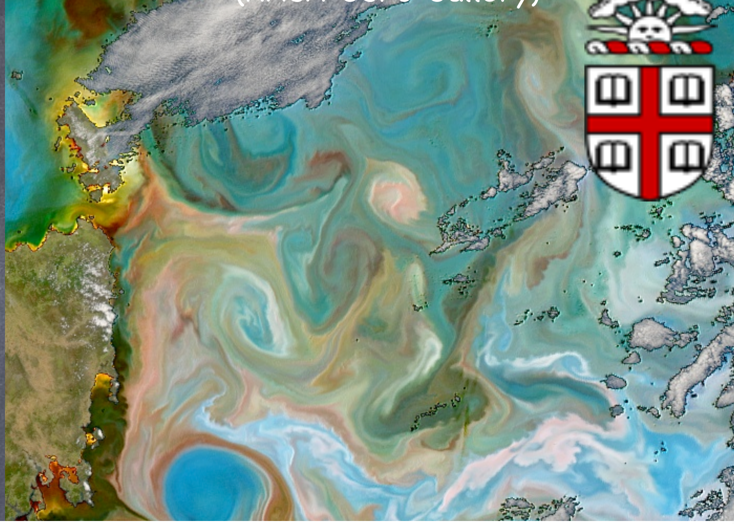
The Mesoscale

100
km

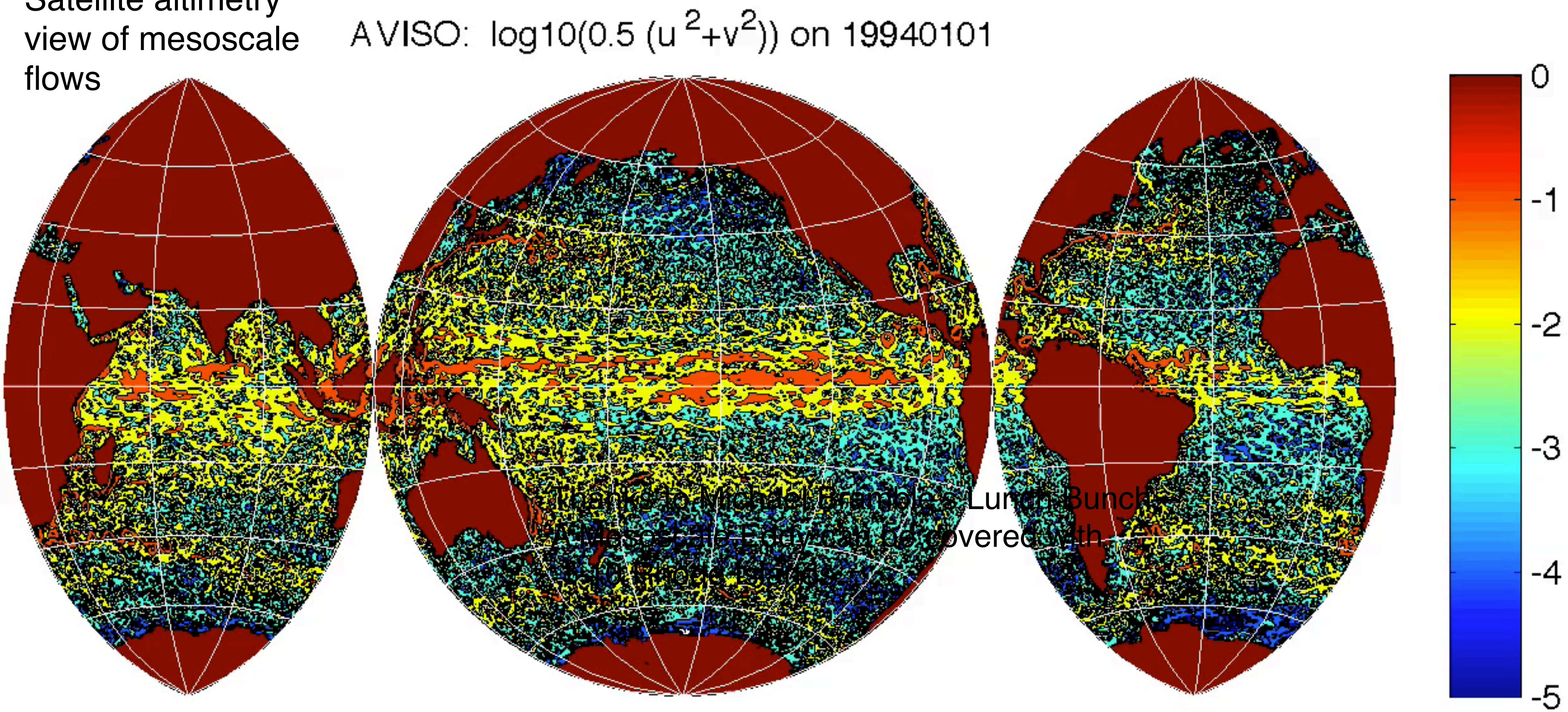
- Boundary Currents
- Eddies
- 100km, months

(Capet et al., 2008)

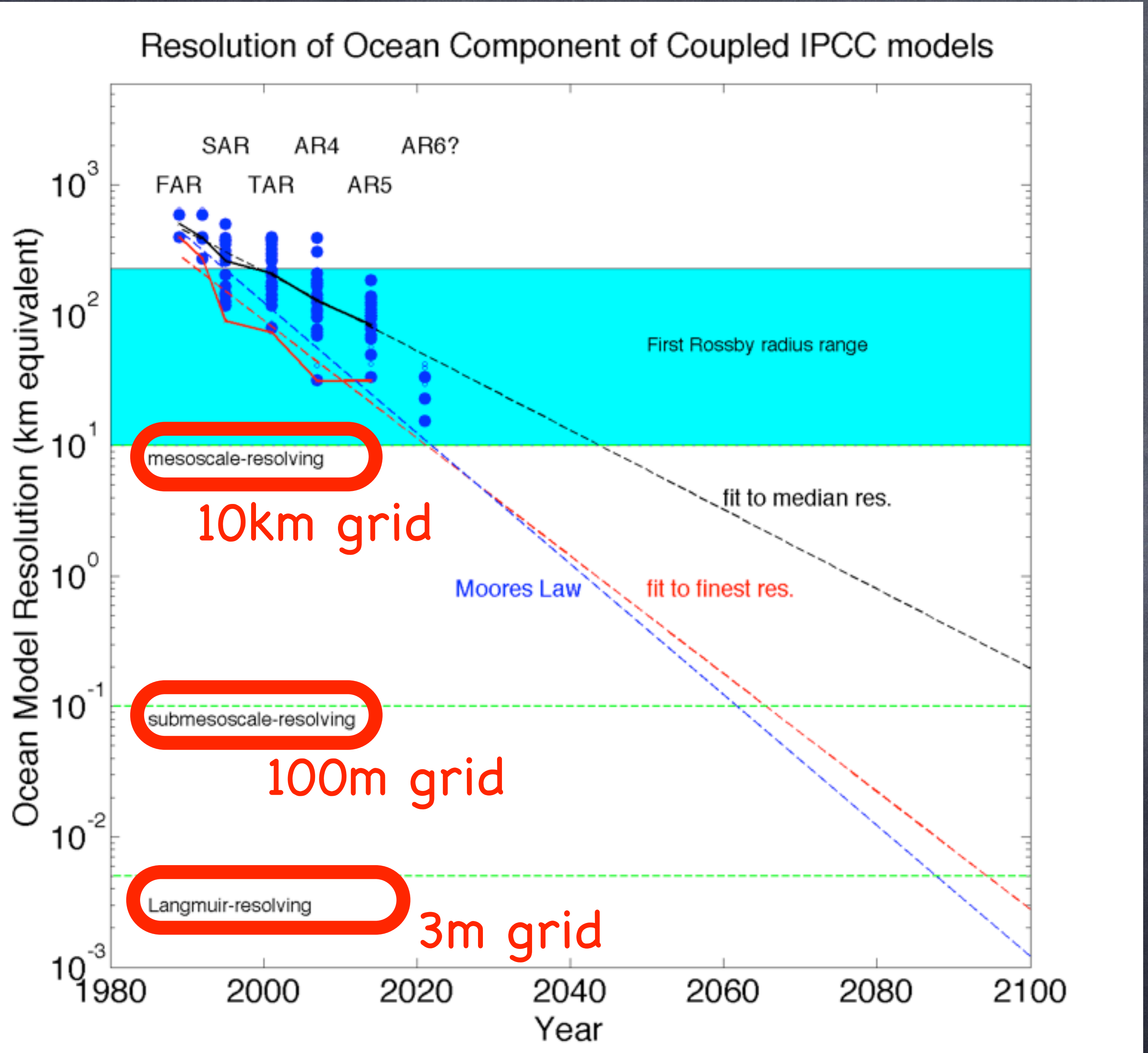
(NASA GSFC Gallery)



Satellite altimetry view of mesoscale flows



Too Simple: What about directly modeling processes in climate models?
Don't we have big enough computers? or won't we soon?



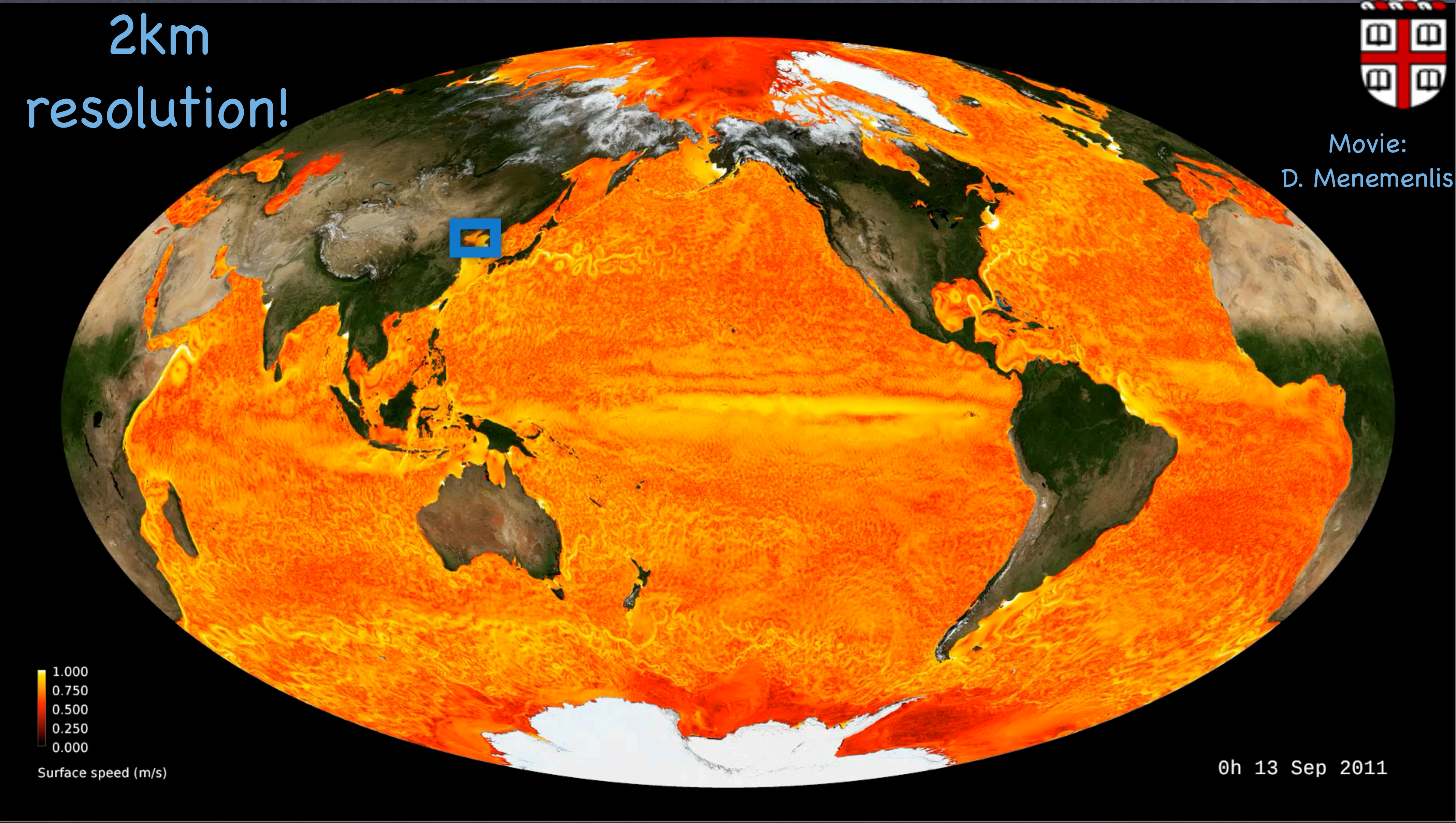
Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

ECCO2 Model

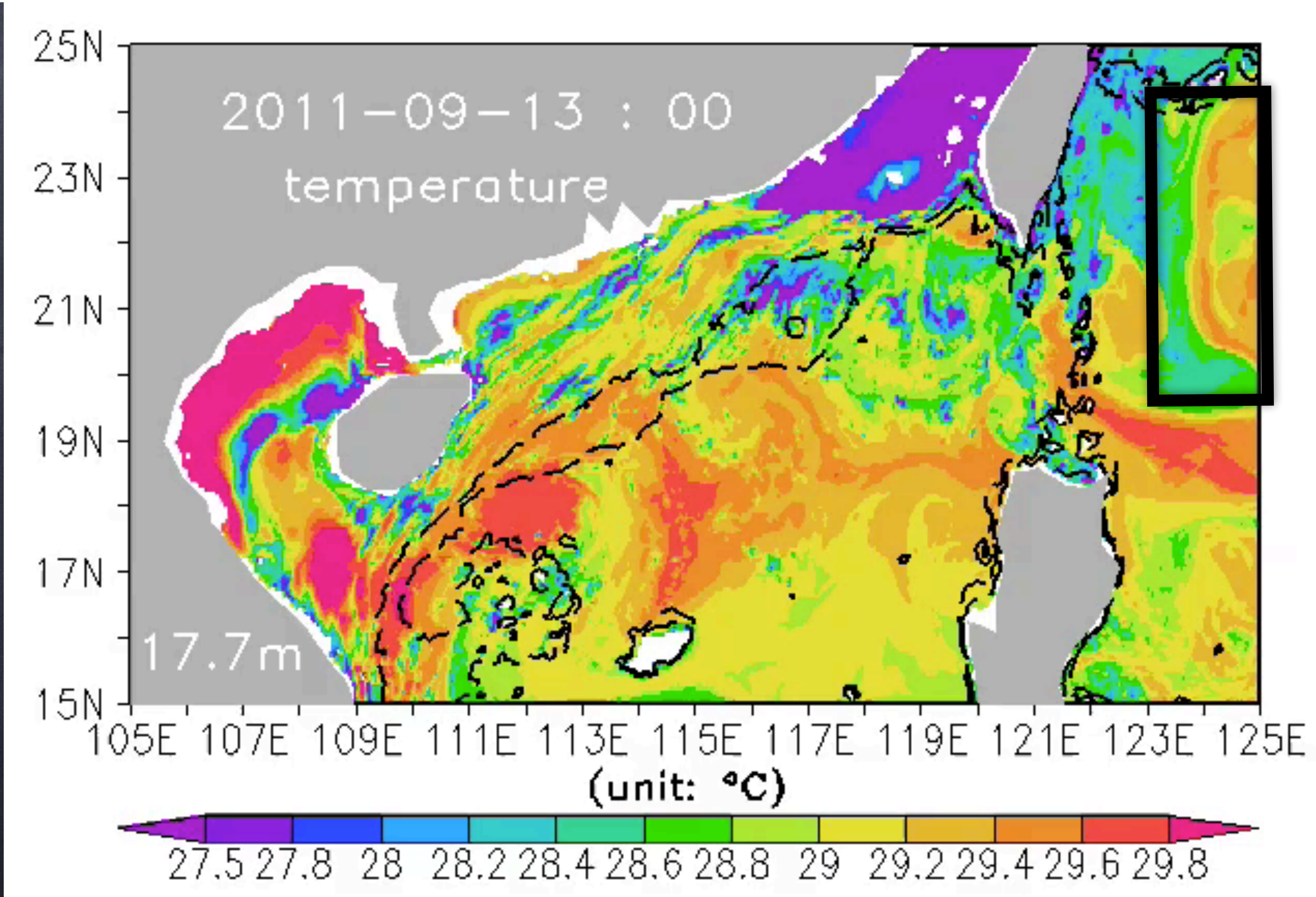
Viscosity Scheme: BFK and D. Menemenlis. Can large eddy simulation techniques improve mesoscale-rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319-338. AGU Geophysical Monograph Series, 2008.

LLC4320 Model



B. Fox-Kemper, S. Bachman, B. Pearson, and S. Reckinger. Principles and advances in subgrid modeling for eddy-rich simulations. CLIVAR Exchanges, 19(2):42-46, July 2014.

LLC4320 Model



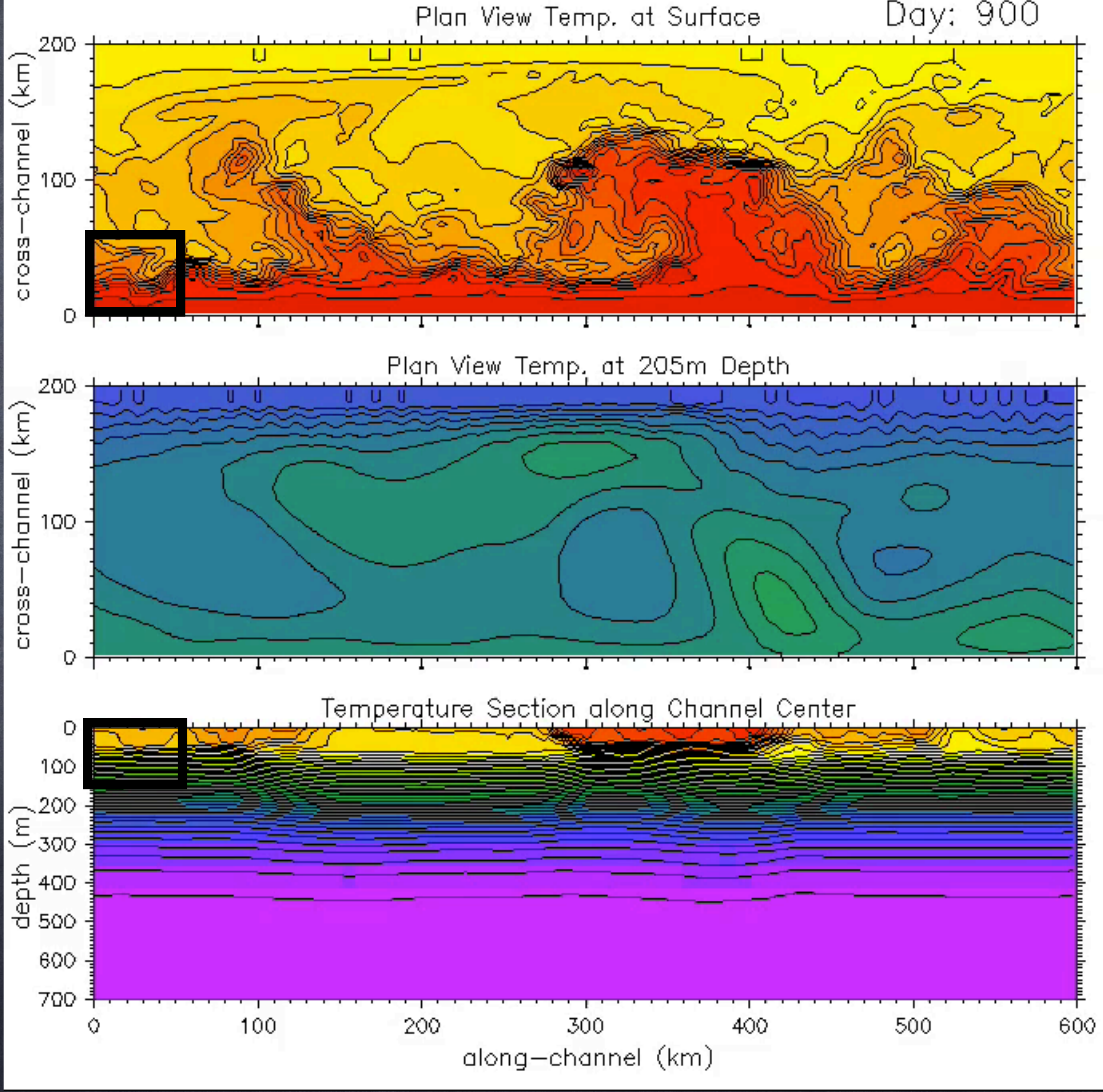
Movie:
Z. Jing

Brown Visitor from S. China Sea Institute of Ocean.

Z. Jing, Y. Qi, BFK, Y. Du, and S. Lian. Seasonal thermal fronts and their associations with monsoon forcing on the continental shelf of northern South China Sea: Satellite measurements and three repeated field surveys in winter, spring and summer. Journal of Geophysical Research-Oceans, August 2015. Submitted.

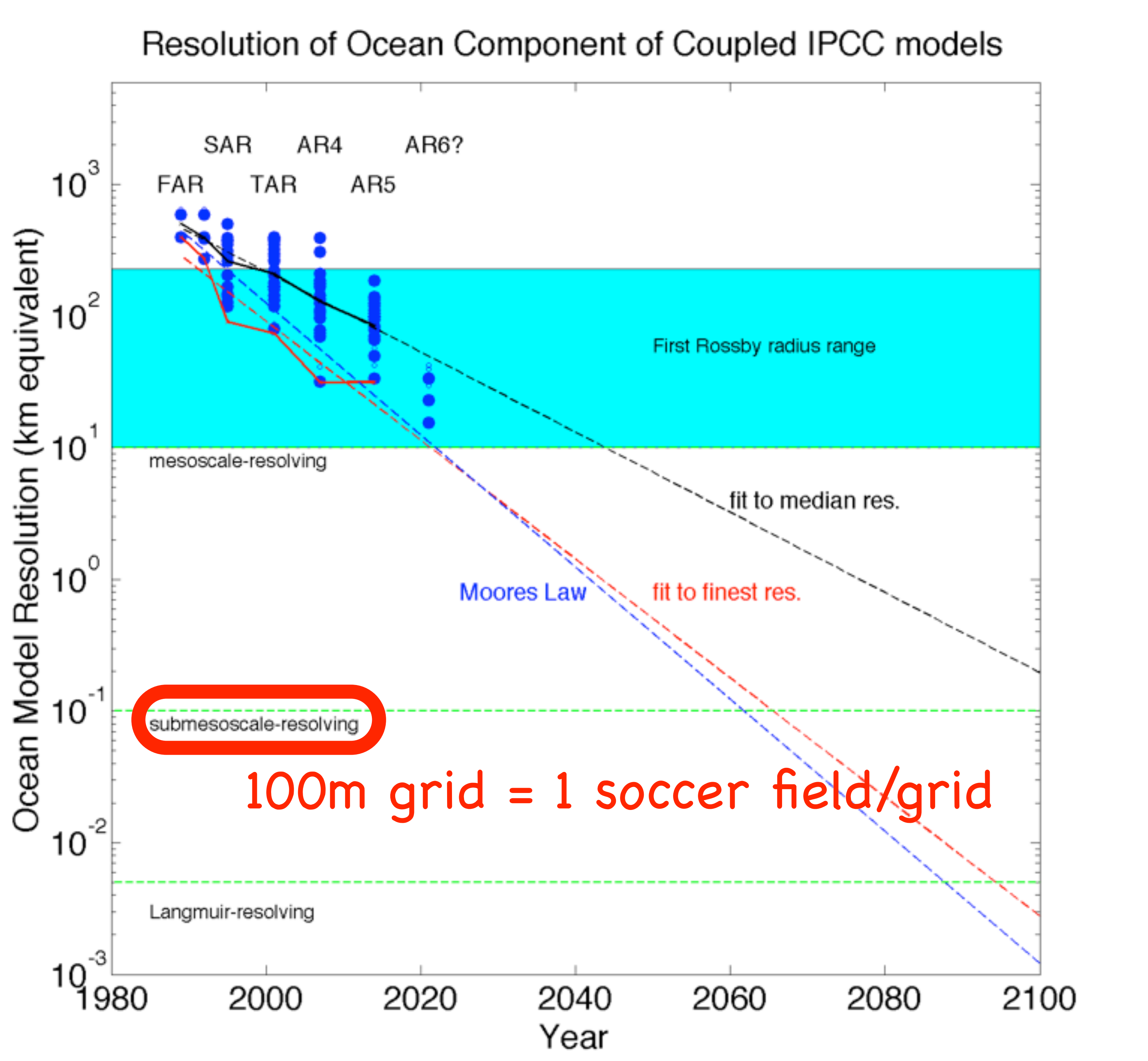
200km x 600km x 700m domain

1000 Day Simulation



G. Boccaletti, R. Ferrari, and BFK. Mixed layer instabilities and restratification. Journal of Physical Oceanography, 37(9): 2228-2250, 2007.

What about modeling important processes in climate models?
Don't we have big enough computers? or won't we soon?



Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

The Character of the Submesoscale

← 10 km

(Capet et al., 2008)

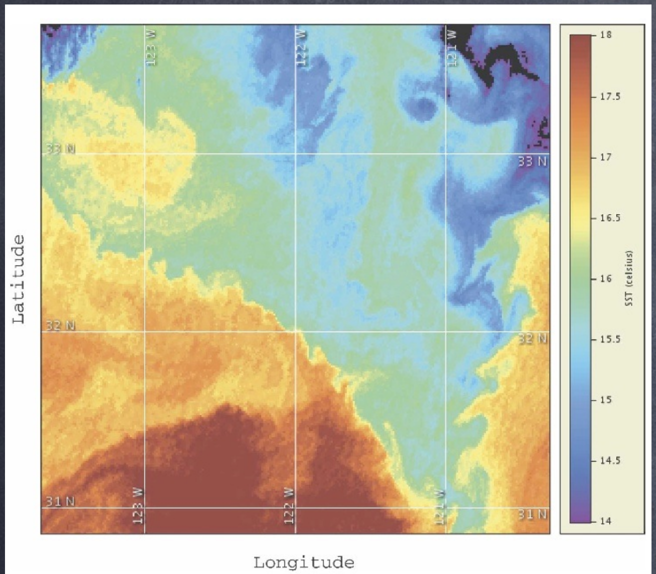
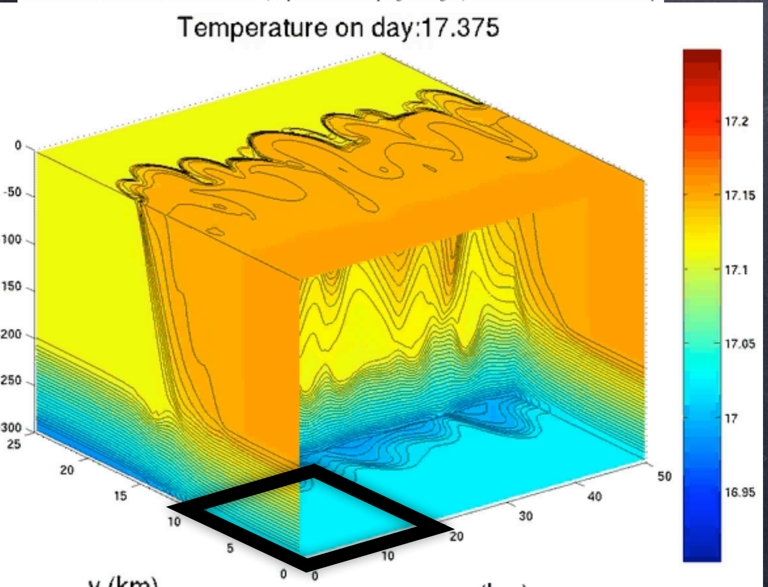


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently

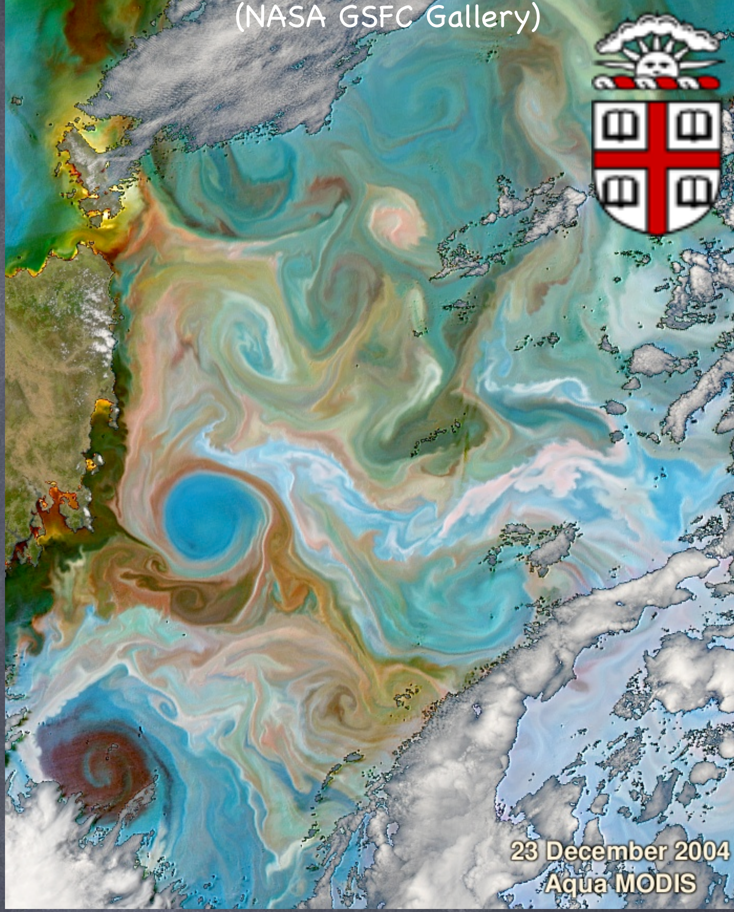


- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08-11).

(NASA GSFC Gallery)



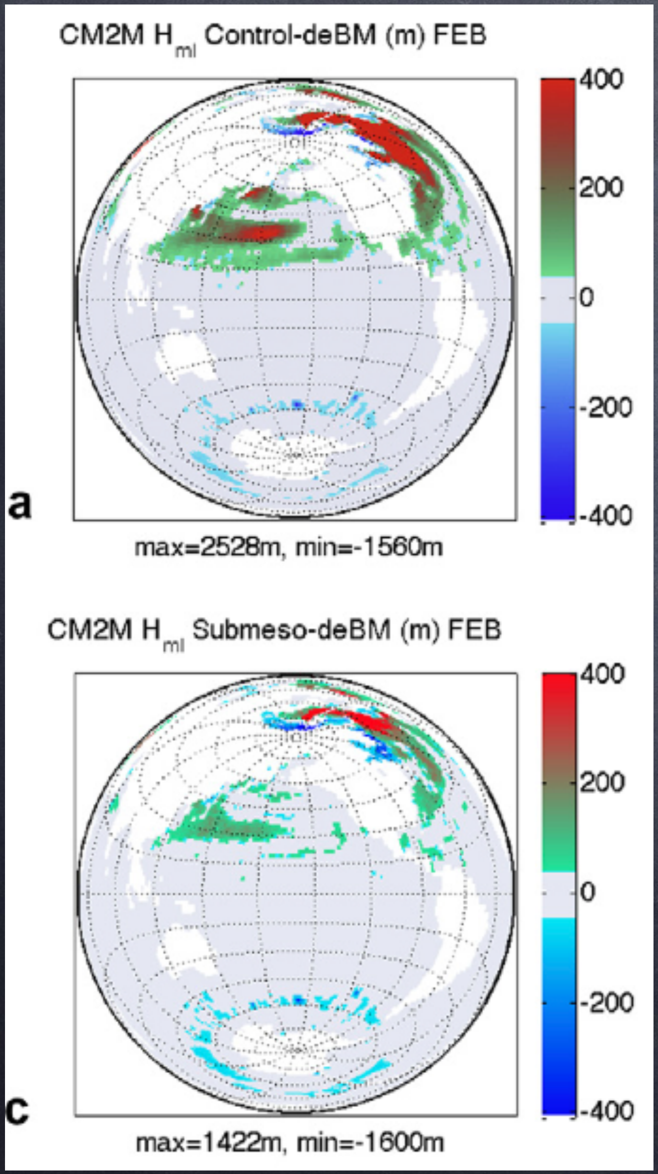
BFK, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography, 38(6):1145-1165, 2008

BFK, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Global Ocean Climate is SENSITIVE to these Submesoscale Eddies! At least in parameterized form

Implemented in IPCC AR5 & 6: NCAR, GFDL, Hadley, NEMO,...

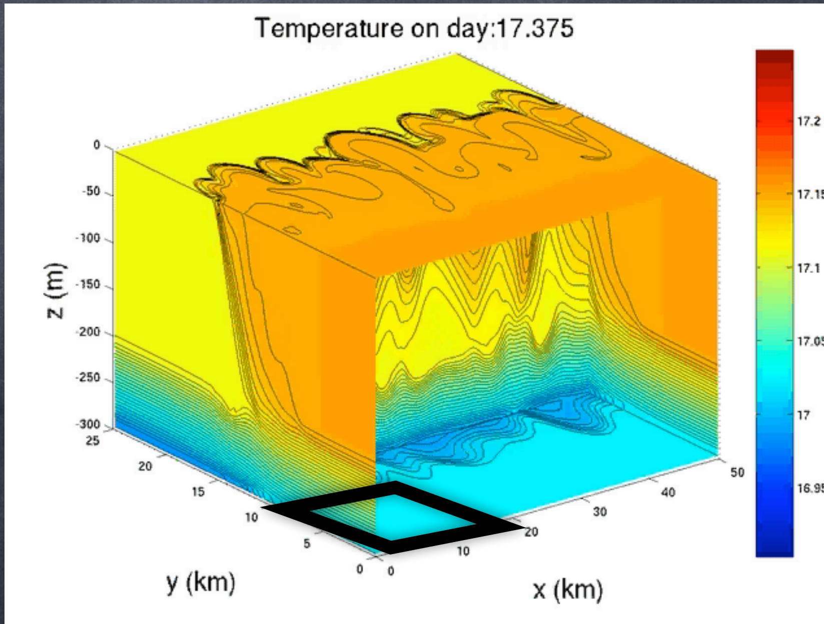


February Mixed layer depth Bias w/o MLE

O(0.1 W/m^2) change to global mean net fluxes, Regional: 5 to 50 W/m^2

Deep Mixed Layer Bias reduced

February MLD Bias With MLE Parameterization

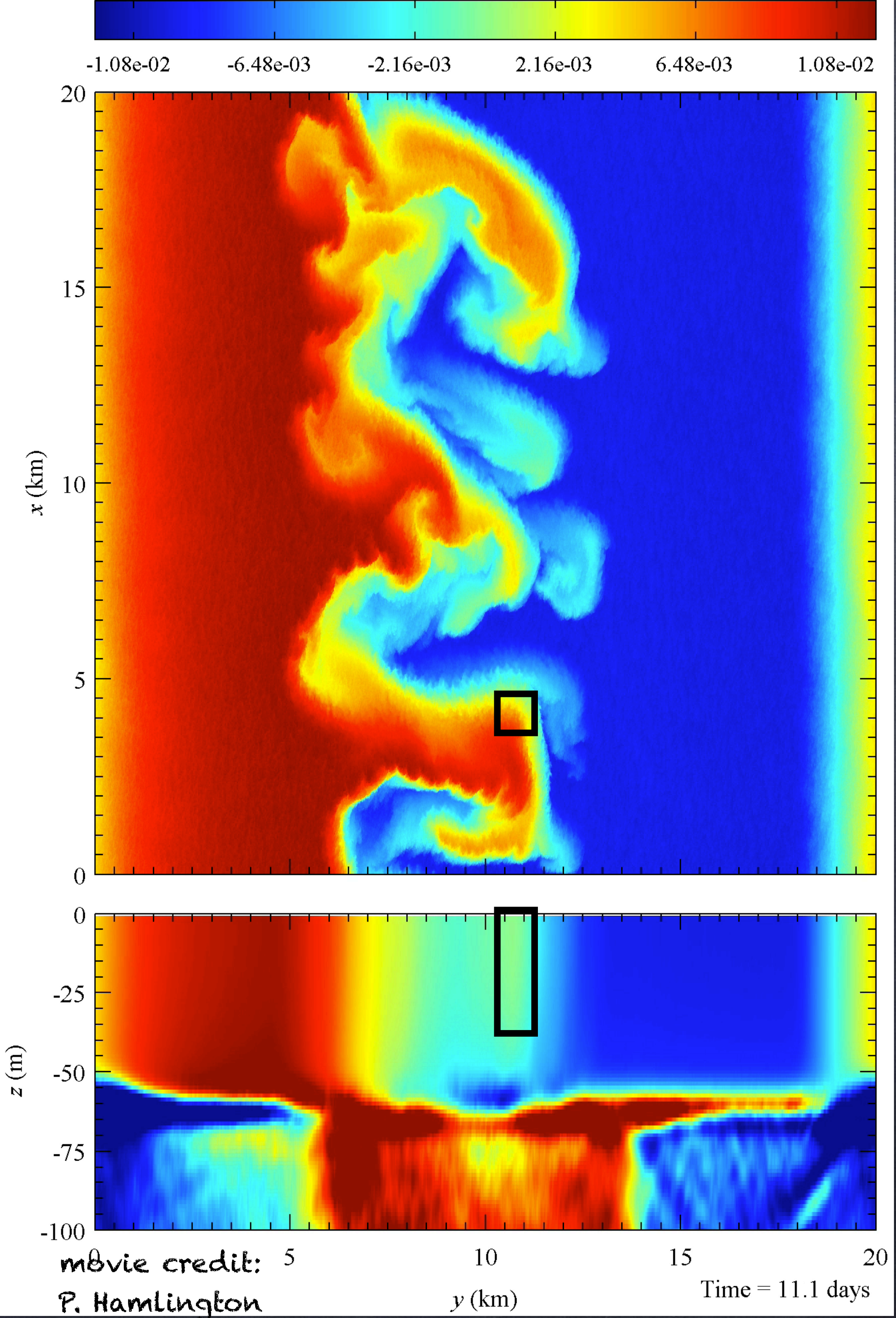


BFK, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mix layer eddies. III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

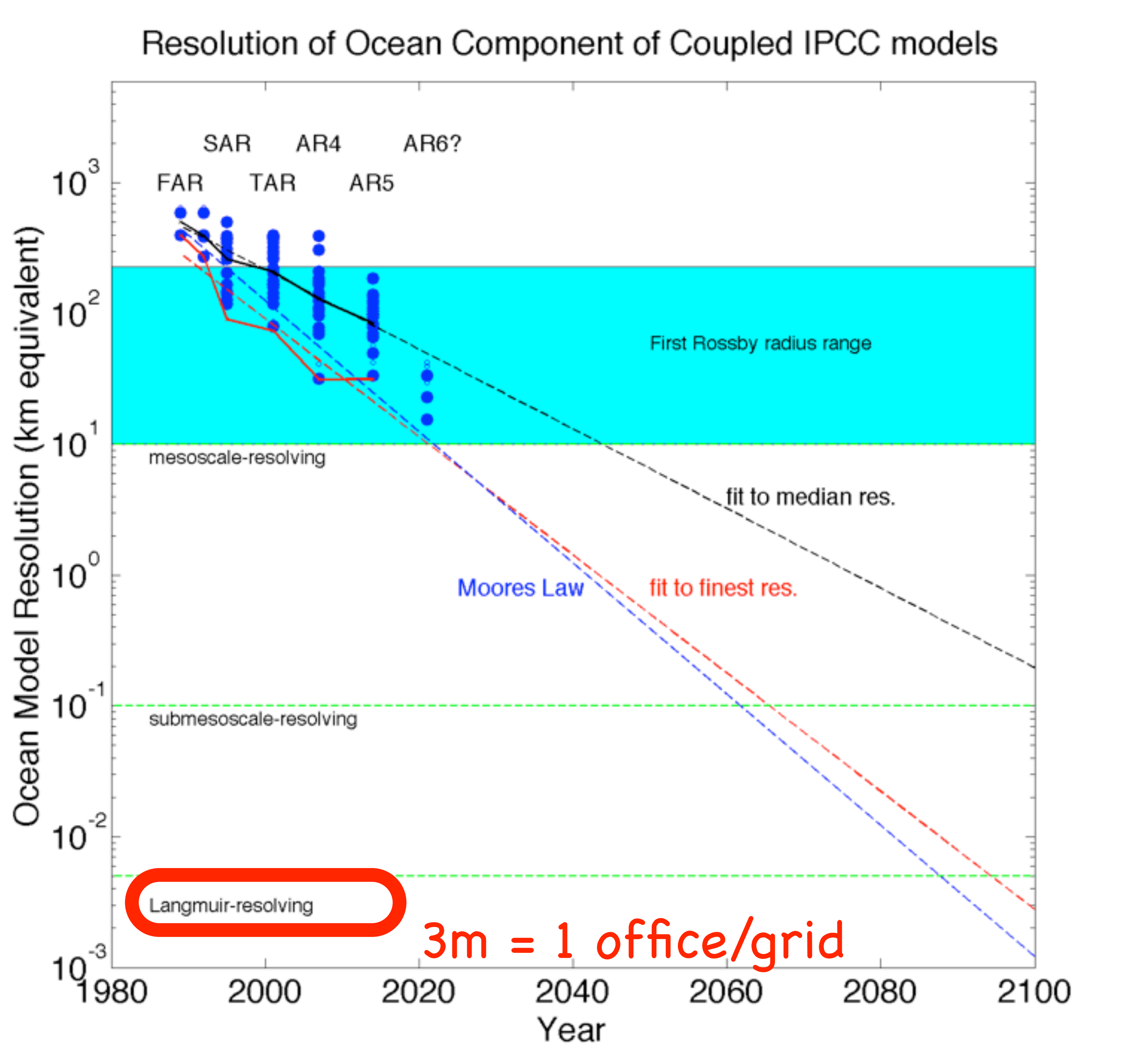
20km x 20km x 150m domain

10 Day Simulation

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9): 2249-2272, September 2014.



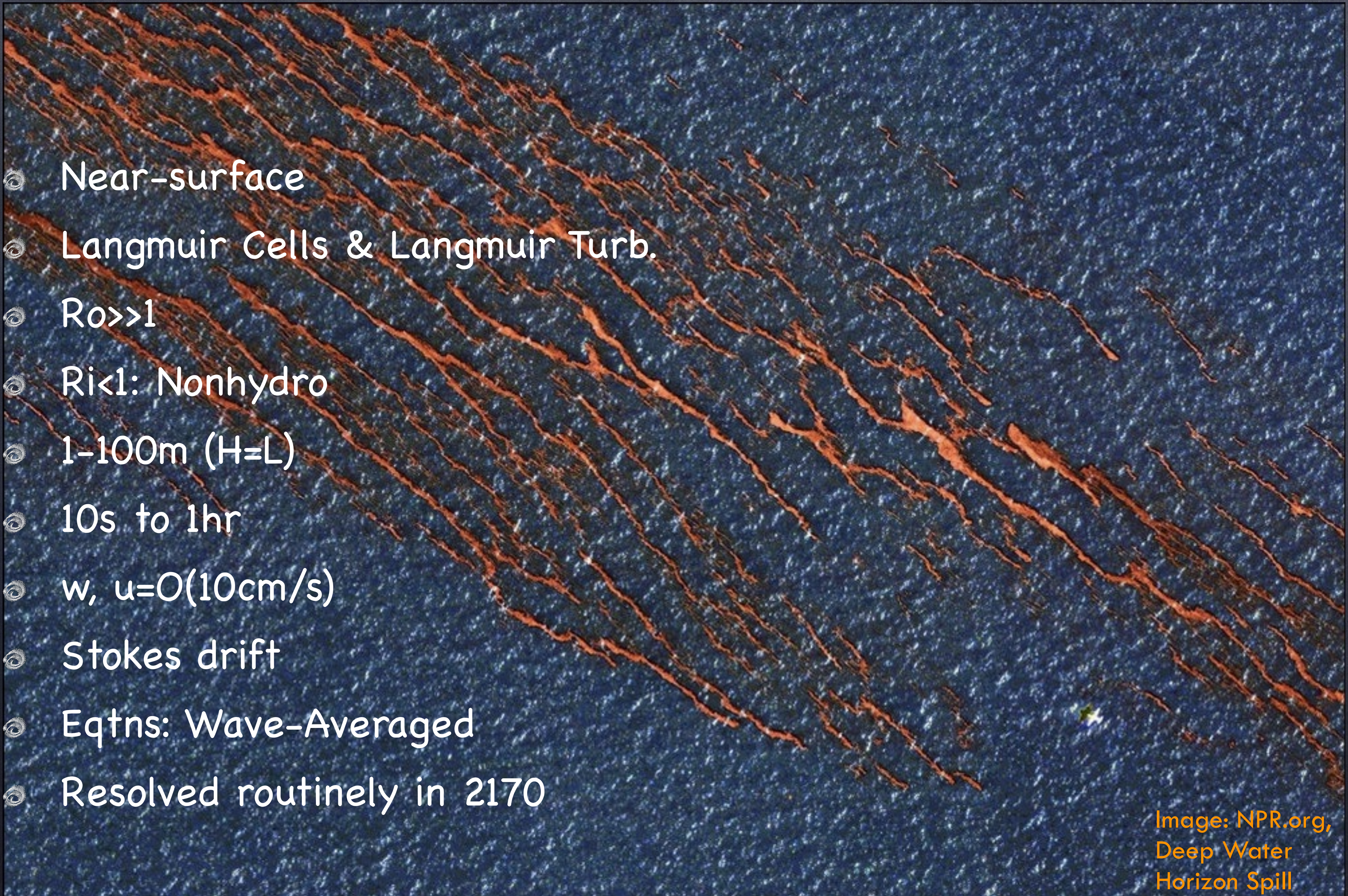
Climate Model Resolution: an issue for centuries to come!



Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

The Character of Langmuir Turbulence



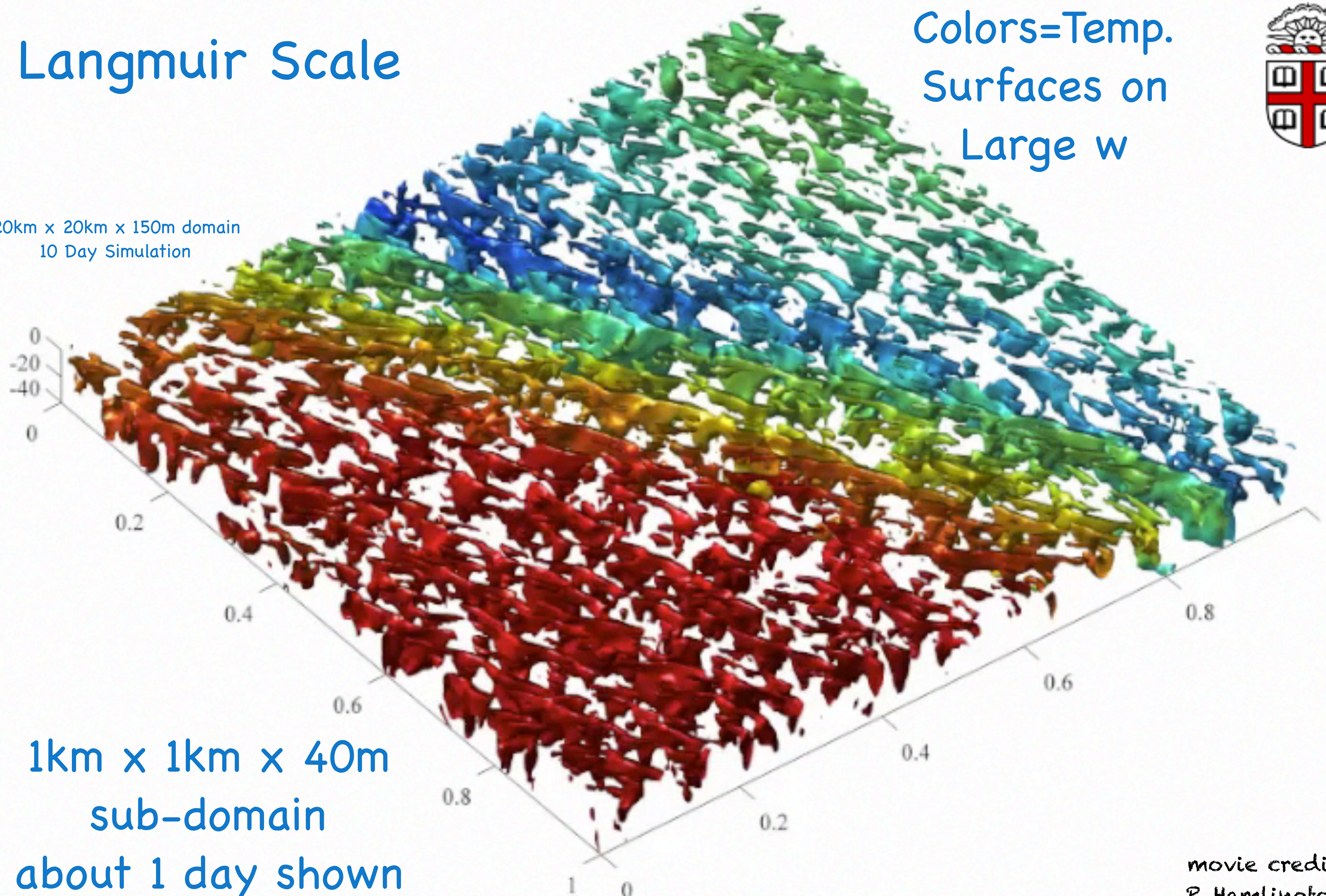
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns: Wave-Averaged
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

Langmuir Scale

Colors=Temp.
Surfaces on
Large w

20km x 20km x 150m domain
10 Day Simulation



1km x 1km x 40m
sub-domain
about 1 day shown

movie credit:
P. Hamlington

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Q. Li, A. Webb, BFK, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein, 2016: Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, 103:145– 160.

Turbulence: what to do?

- Climate modelling requires that we truncate the model grid at coarse resolution (albeit improving slowly)
- Whatever resolution we can afford will leave some physics unresolved or partially-resolved, so we need subgrid closures!
- The vast & diverse scales of motion in the ocean suggest that we cannot use a one-size-fits-all approach, e.g., a turbulent cascade of 3d turbulence
- So, we have to invent new subgrid closures repeatedly, parameterizing processes important at each gridscale

Between Climate & Kolmogorov

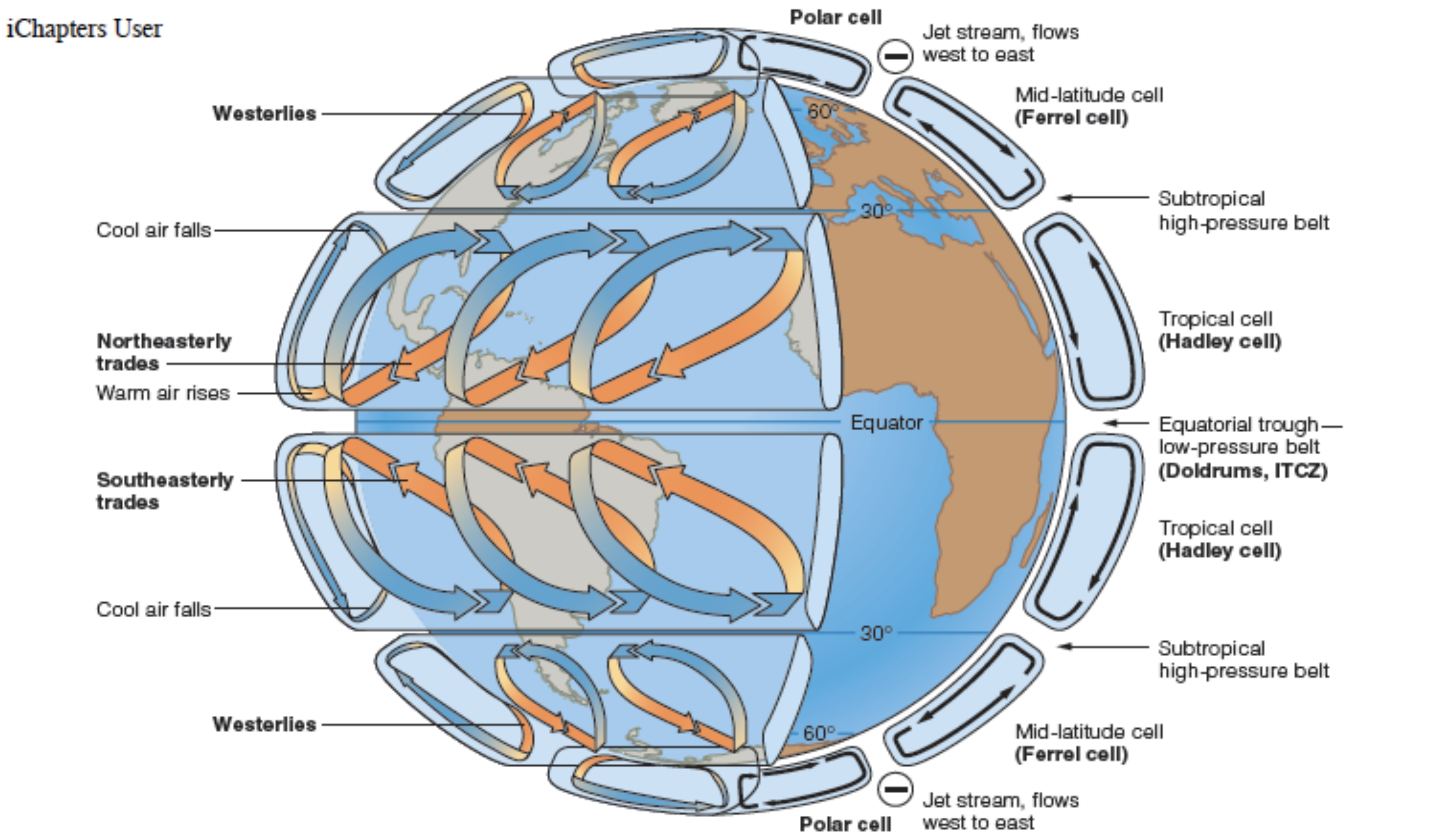
Climate "Cells", "Gyres" and "Modes"

"Modes"?=?"Fluctuations"?

Atmospheric Cells

Thermally direct, e.g., Hadley Cells, are heat engines.

Thermally indirect are rectification of turbulence (storms)



Oceanic Gyres

Flow along pressure contours (due to Coriolis)

These wind-driven features dominate thermal transport

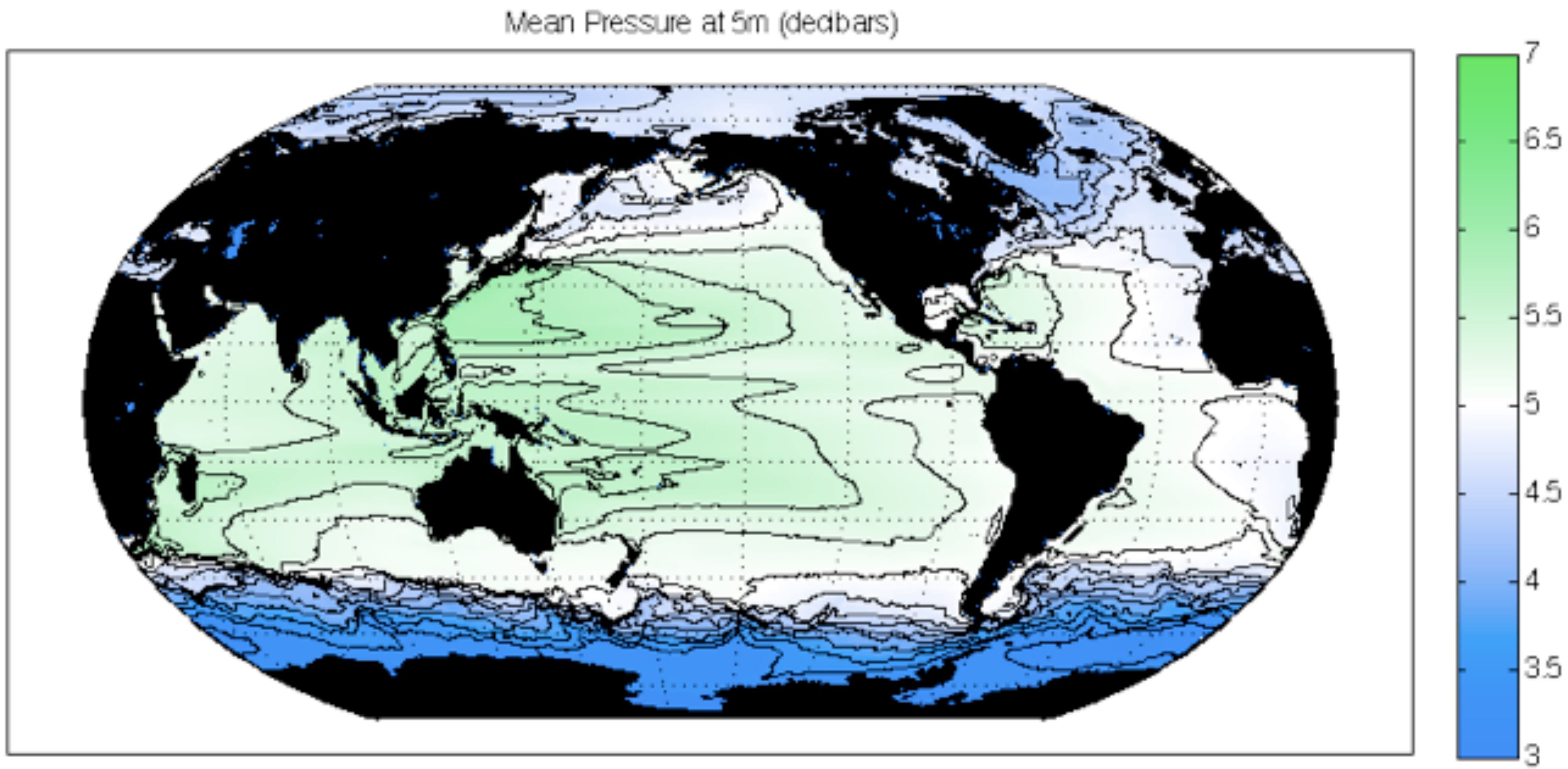
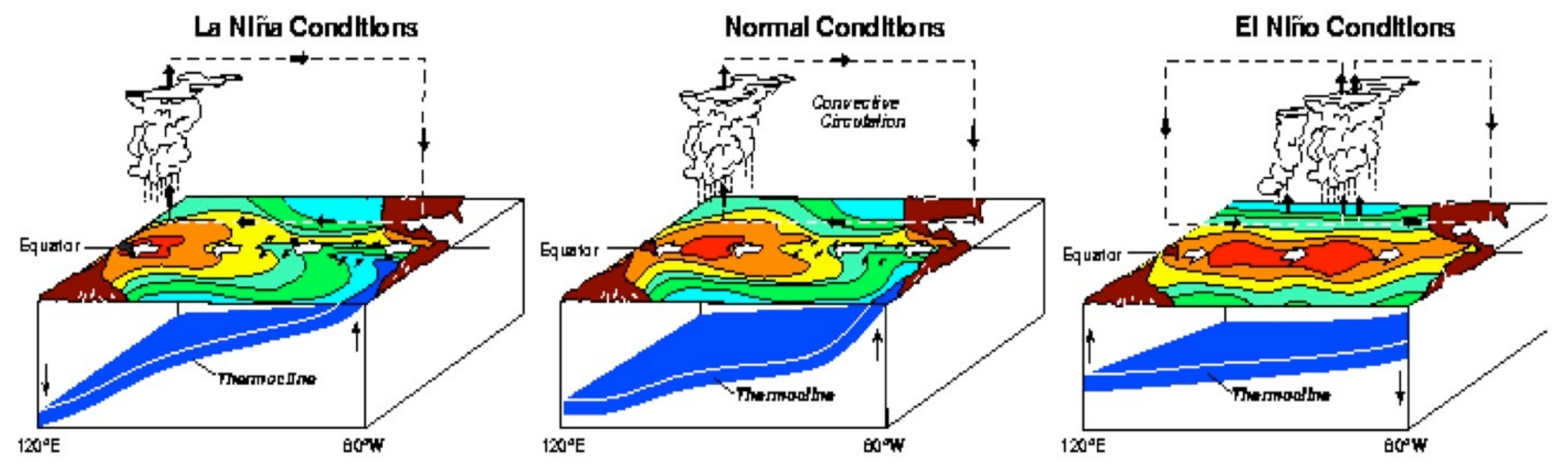


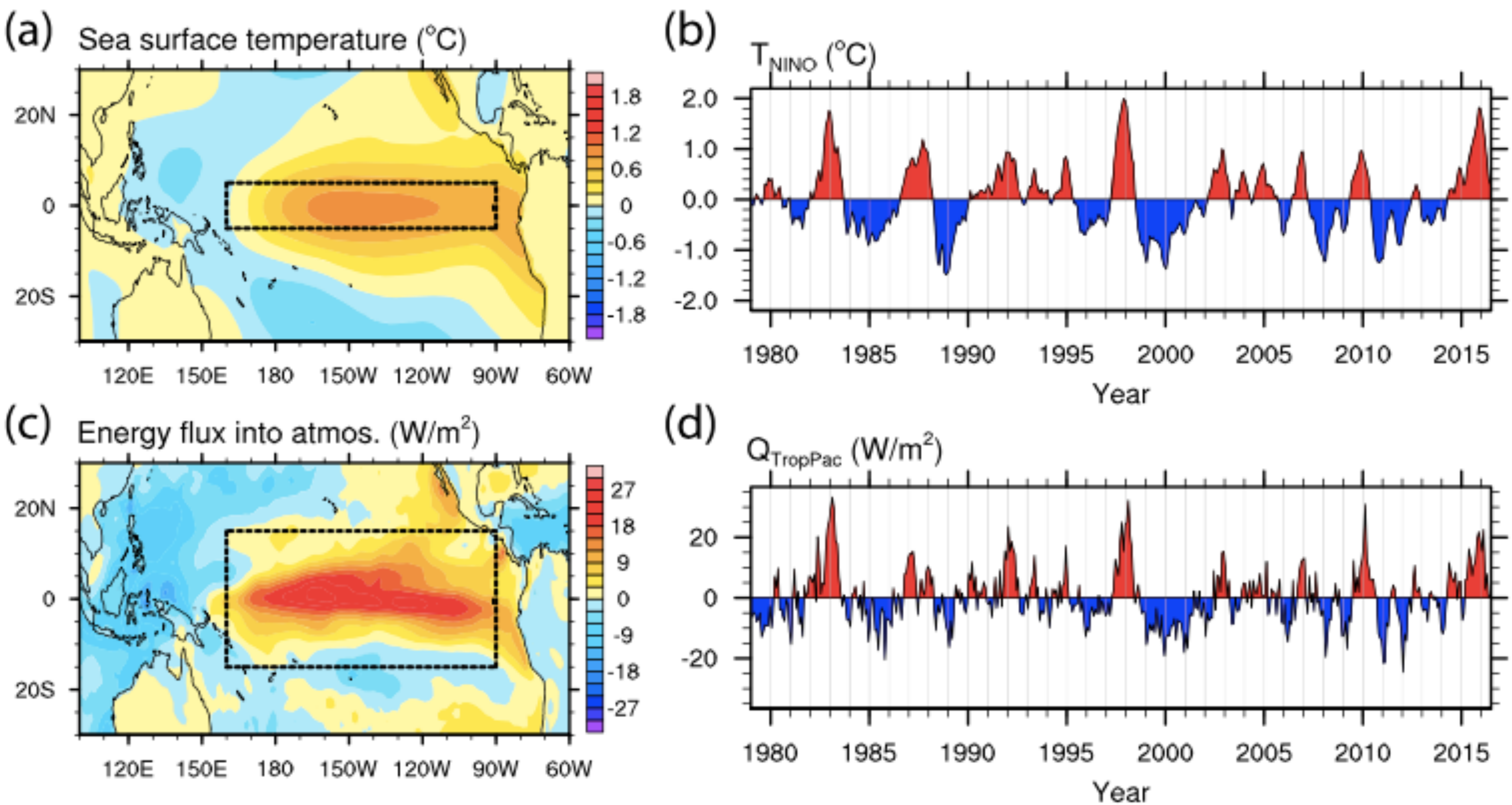
Figure 6: Pressure relative to atmospheric pressure just below the sea surface (5 meters depth) from the ECCO2 ocean data assimilating ocean model (Menemenlis et al. 2008, ecco2.org). Contour interval is 0.2 decibars.

Climate Variability "Modes"

The most famous is El Nino/Southern Oscillation:
By most metrics, it is the largest mode of variability on the Earth after seasonal & diurnal cycles.

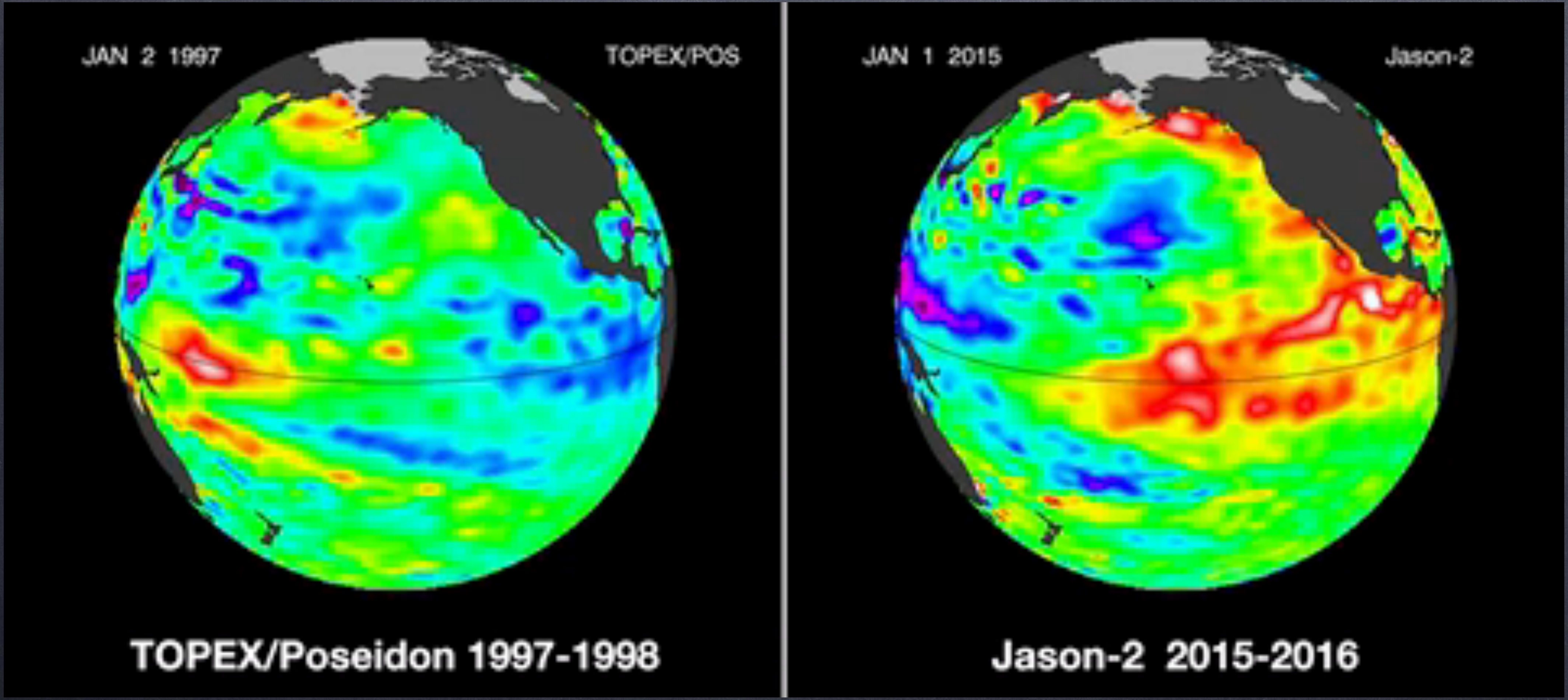


Effect of Climate Modes, e.g., Hu & Fedorov (2017)



$$\frac{dT_g}{dt} = -\frac{T_g}{\tau} + a \cdot \log(CO_2/CO_{2,\mathrm{ref}}) + b \cdot T_{\mathrm{NINO}} + c \cdot \mathrm{SAOD} + d,$$

El Nino: 1998 vs 2015



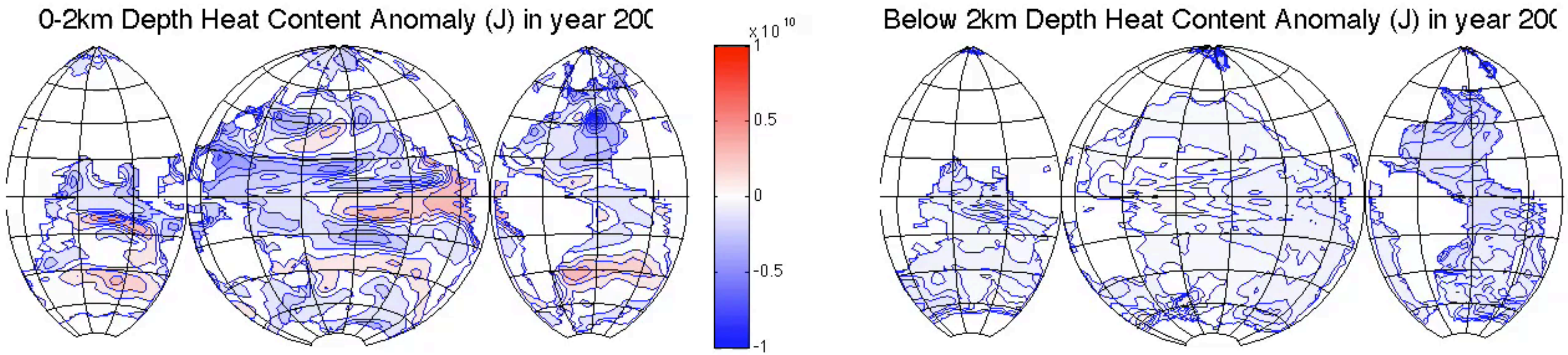
- SSH Movie Credit: NASA JPL

Observing & Prediction Challenges

“Cells”, “Gyres”, “Modes”, & “Weather”

What does a climate model—WITHOUT WARMING—look like in Ocean Heat Content Variability?

Doesn't even include mesoscale eddies

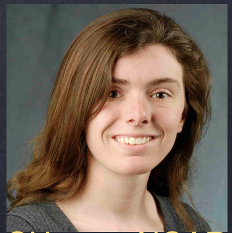


Contours = 4 units

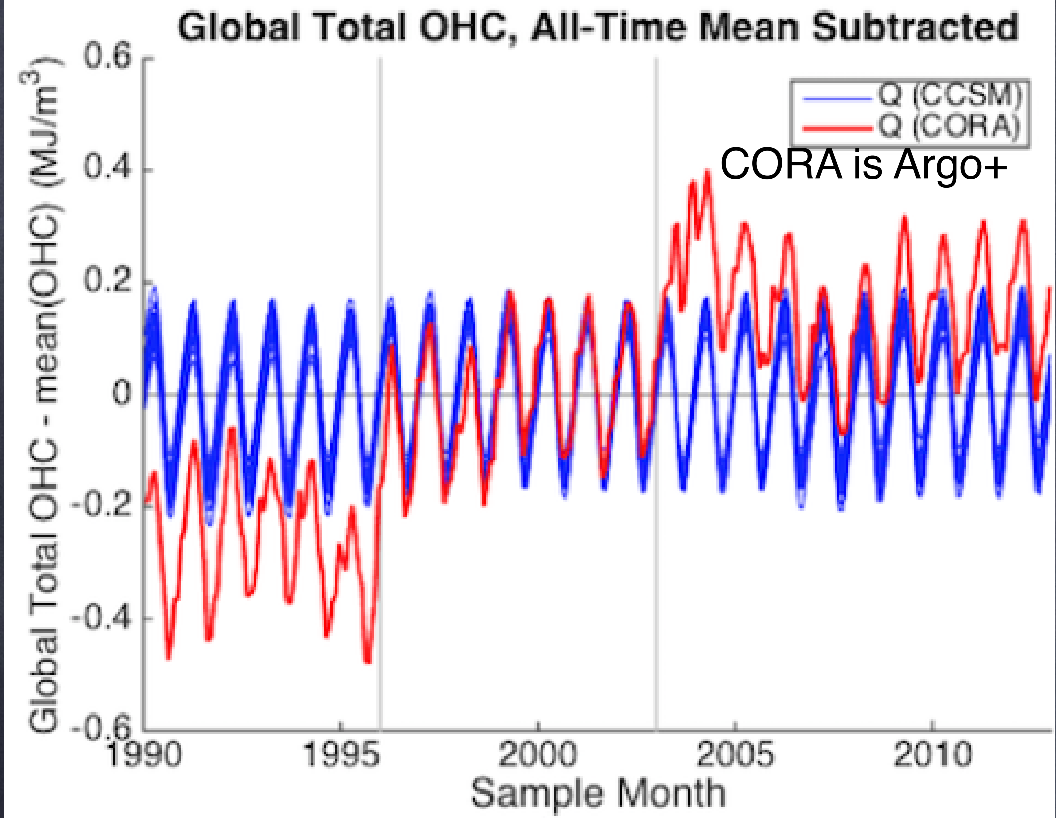
Contours = 1 unit

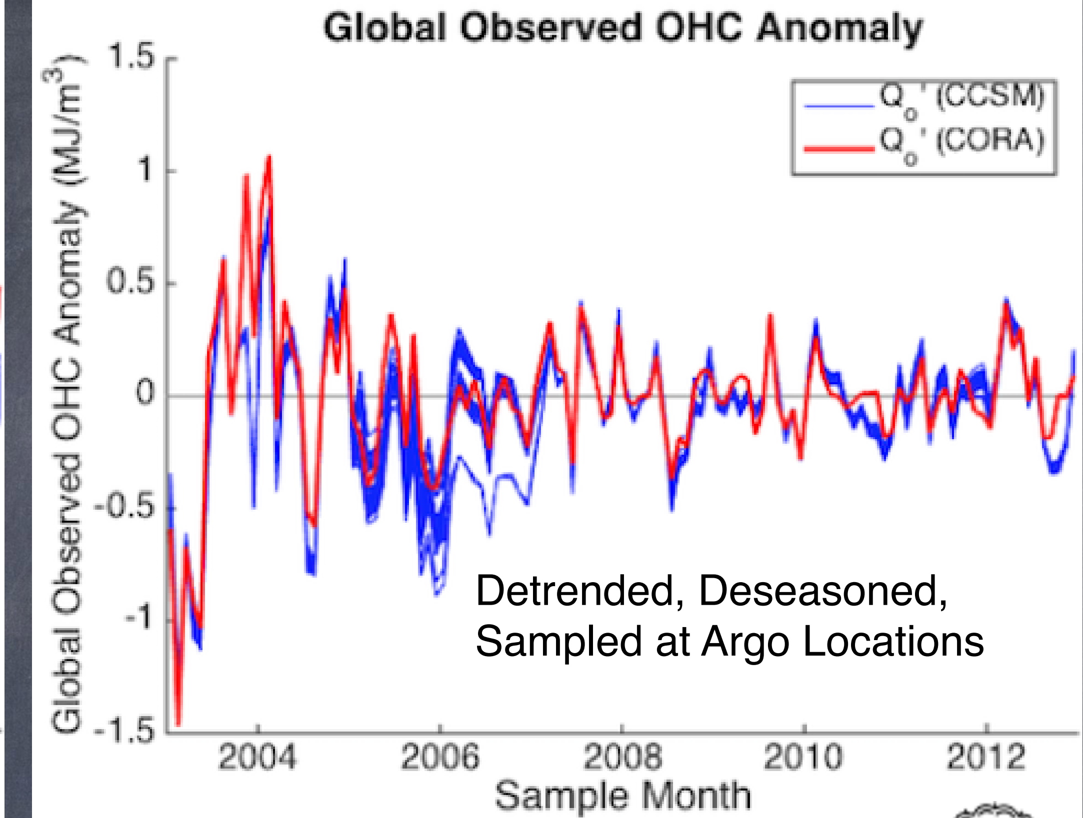
From the >1000yr steady forcing CCSM3.5 runs of Stevenson et al. 2012

S. Stevenson, BFK, and M. Jochum, 2012: Understanding the ENSO-CO2 link using stabilized climate simulations. Journal of Climate, 25(22):7917–7936.



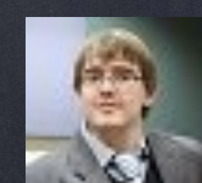
CU, now NCAR





Sophisticated analysis to overcome Ship & Argo sampling problems—inherent uncertainty, O(0.2W/m²), on interannual to decadal timescales in global average.

O(10W/m²) without analysis.



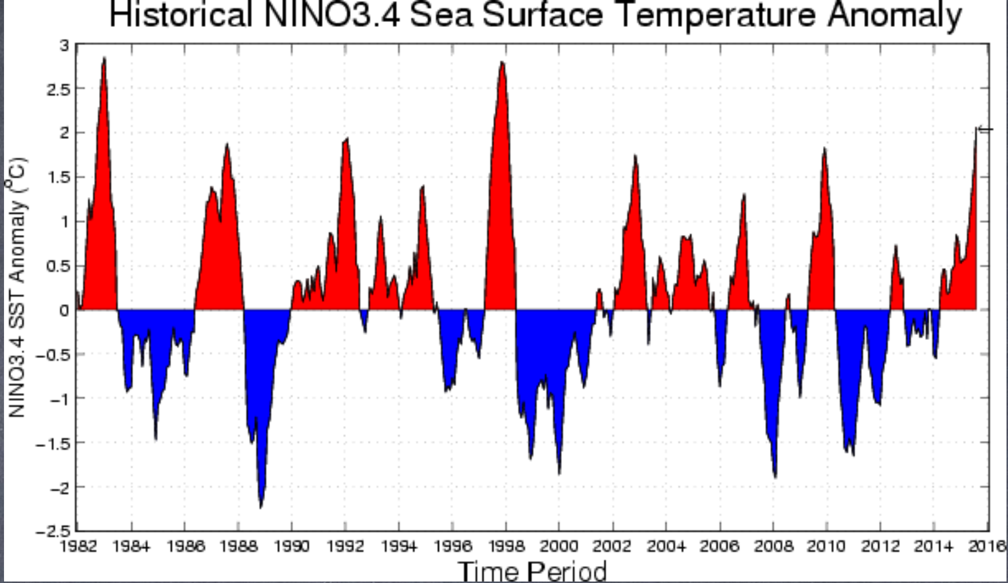
CU, soon Brown

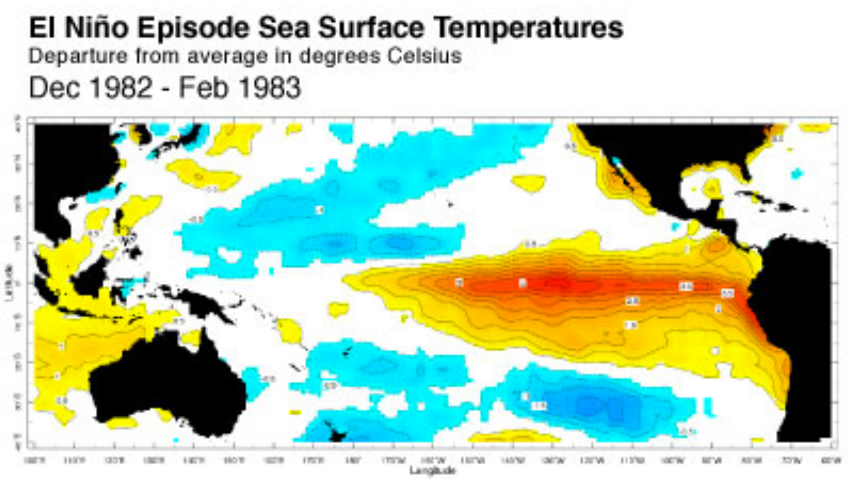
A. D. Nelson, J. B. Weiss, B. Fox-Kemper, 2015: Reconciling observations and models of ocean heat content variability. Submitted.

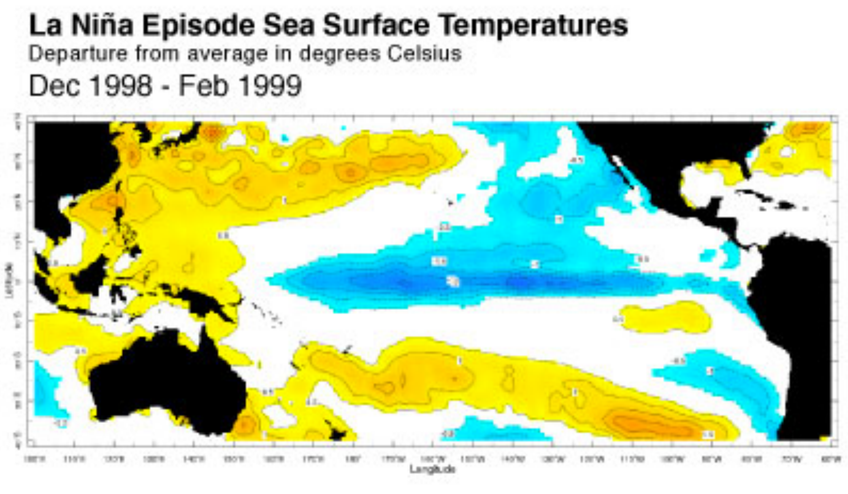
Prediction of variability

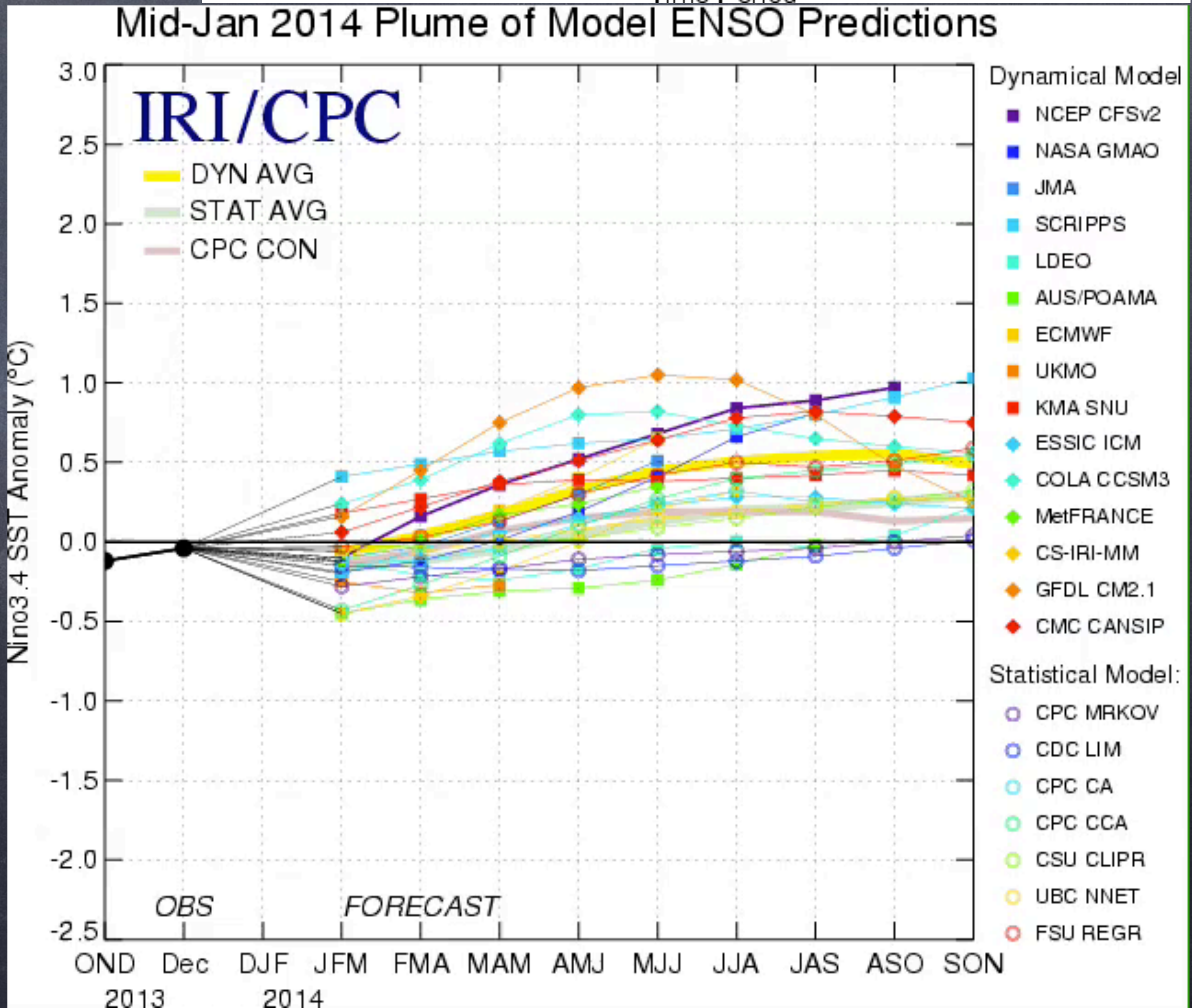
Predictability of ENSO events limited to < 1yr

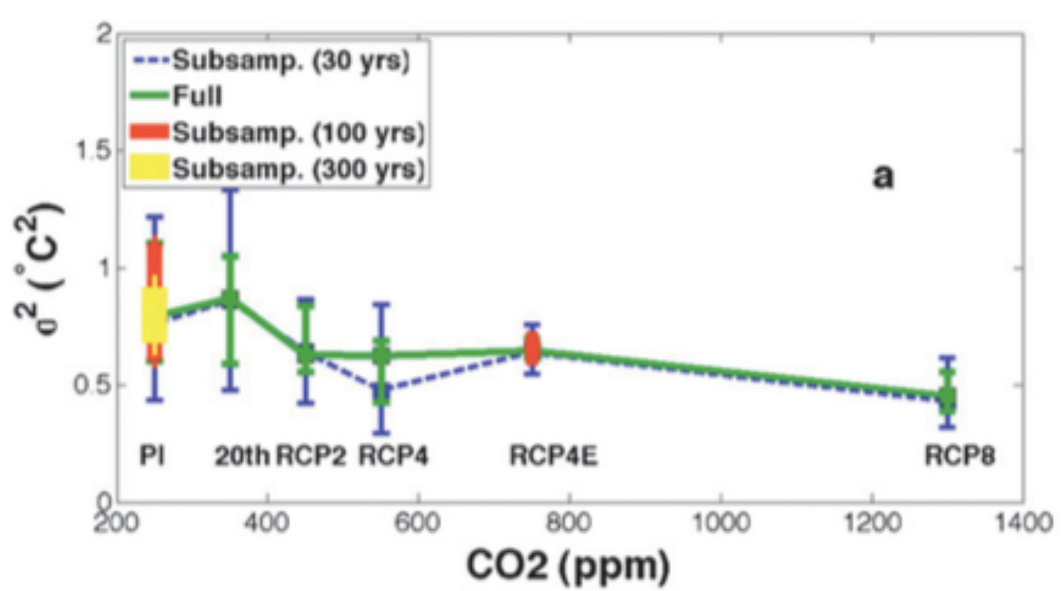
ENSO statistics more predictable?











Does ENSO variability change with climate?...

(>200 yr to detect)

CU, now UCSB

Big GHG Change to ENSO impacts!

INDIRECT Proxy Reconstructions won't work!!!

S. Stevenson, BFK, M. Jochum, R. Neale, C. Deser, and G. Meehl. Will there be a significant change to El Nino in the 21st century? Journal of Climate, 25(6): 2129-2145, March 2012.

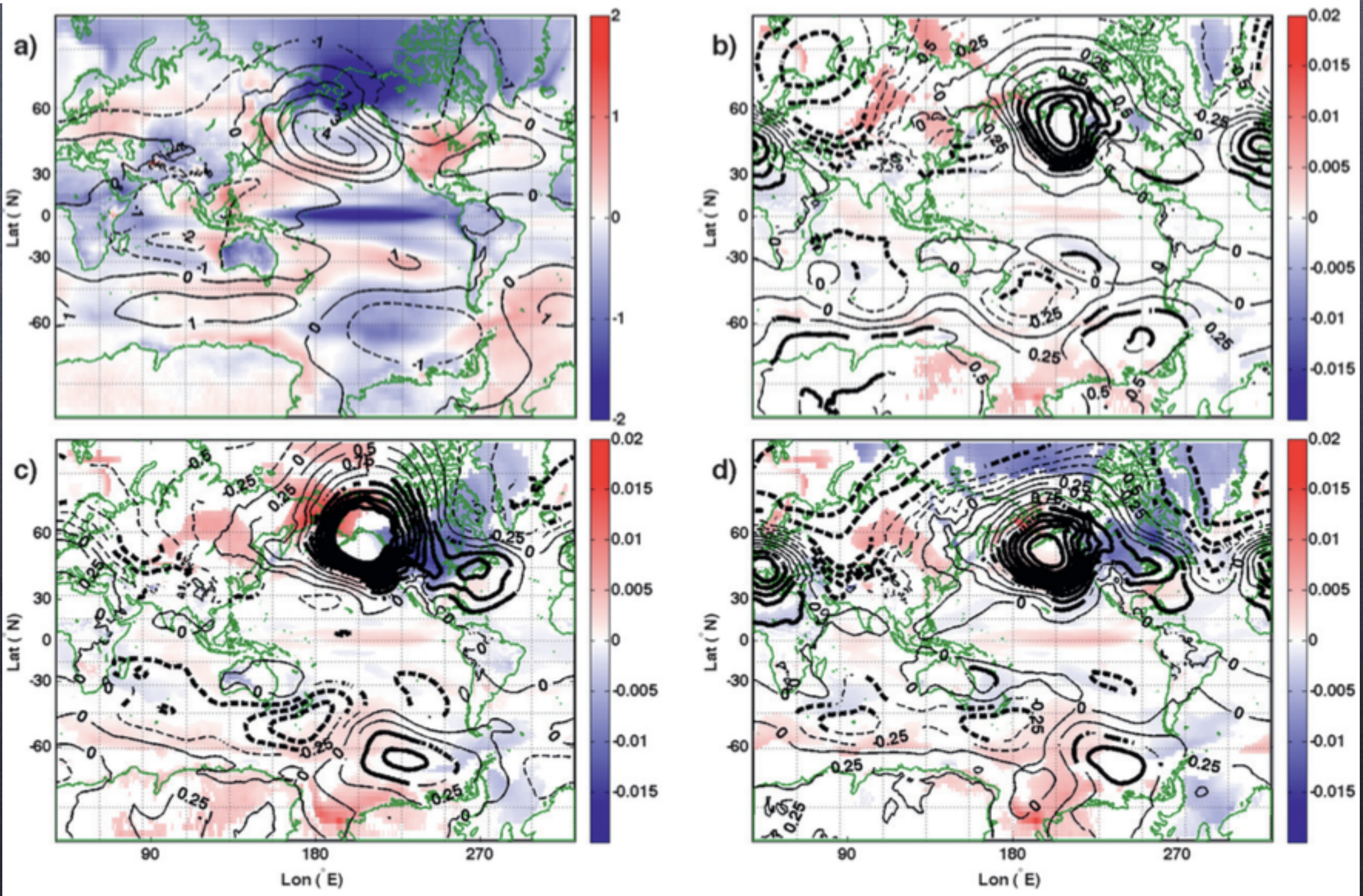
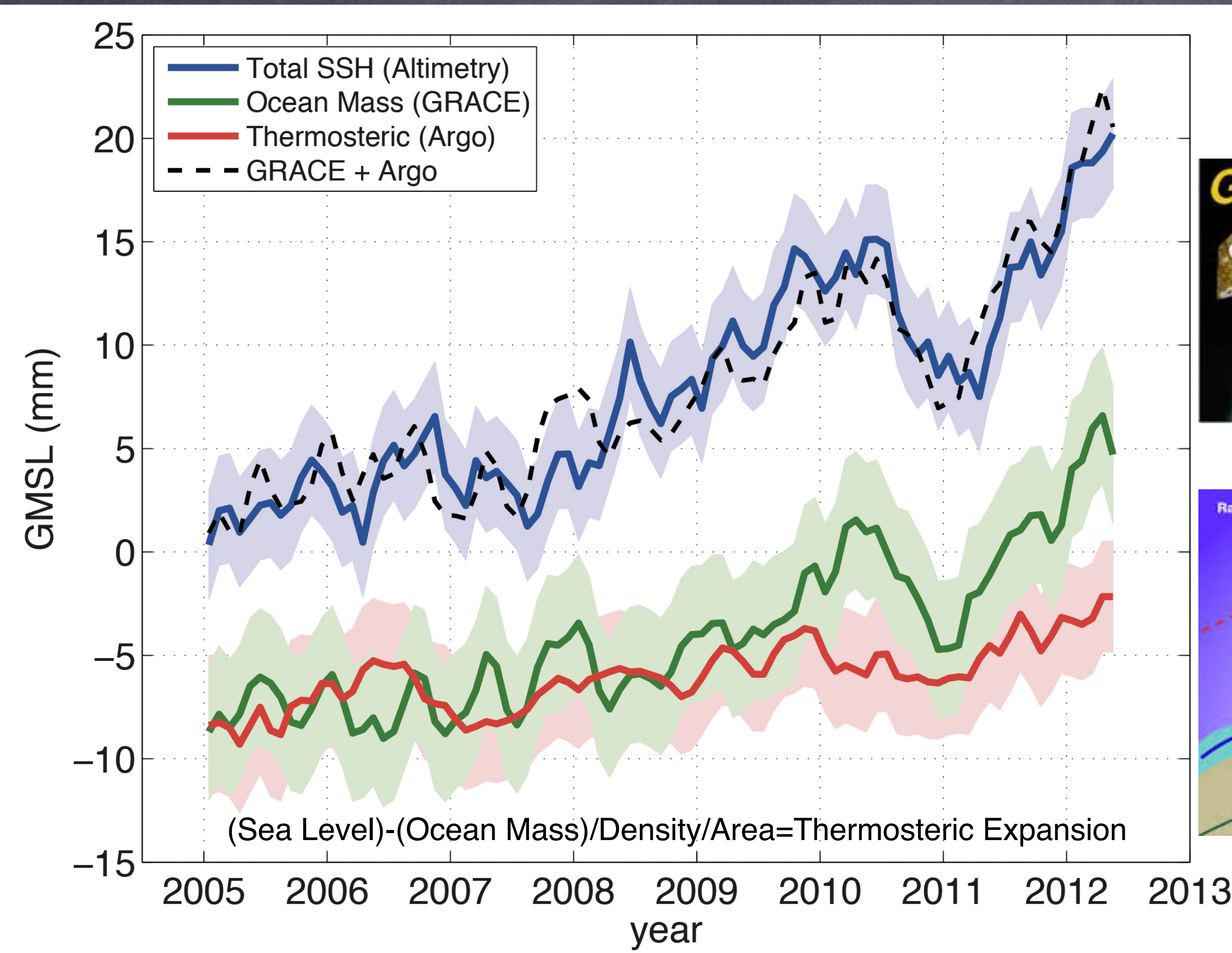


FIG. 6. As in Fig. 5, but for La Niña DJF.

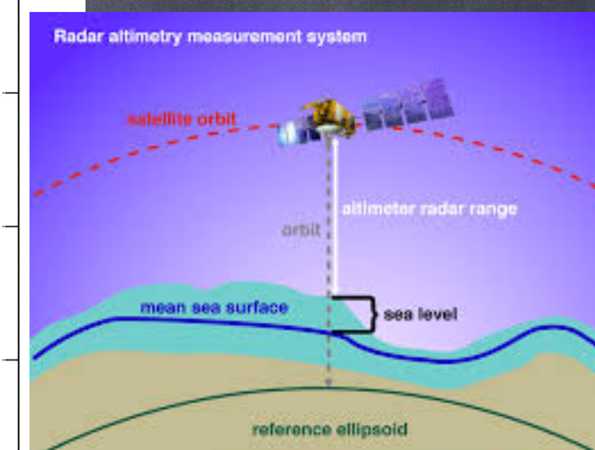
Climate: What is important?

- To approximate absorption, reemission, and redistribution of the Sun's energy across the globe
- Need atmospheric, biological, & geological chemistry (greenhouse gasses) & clouds for absorption & reemission
- Need atmospheric & oceanic motions to redistribute
- Important motions are structured (cells, gyres, modes) and turbulent (weather, eddies, storms)
- Oceans are the relevant energy reservoir
- On longer timescales, changes to the lithosphere affect the cells, gyres, & modes.

Another reason to care about ocean warming—and to observe it (by subtraction): Sea Level Rise



podaac.jpl.nasa.gov



nesdis.noaa.gov

IPCC AR5, 2013