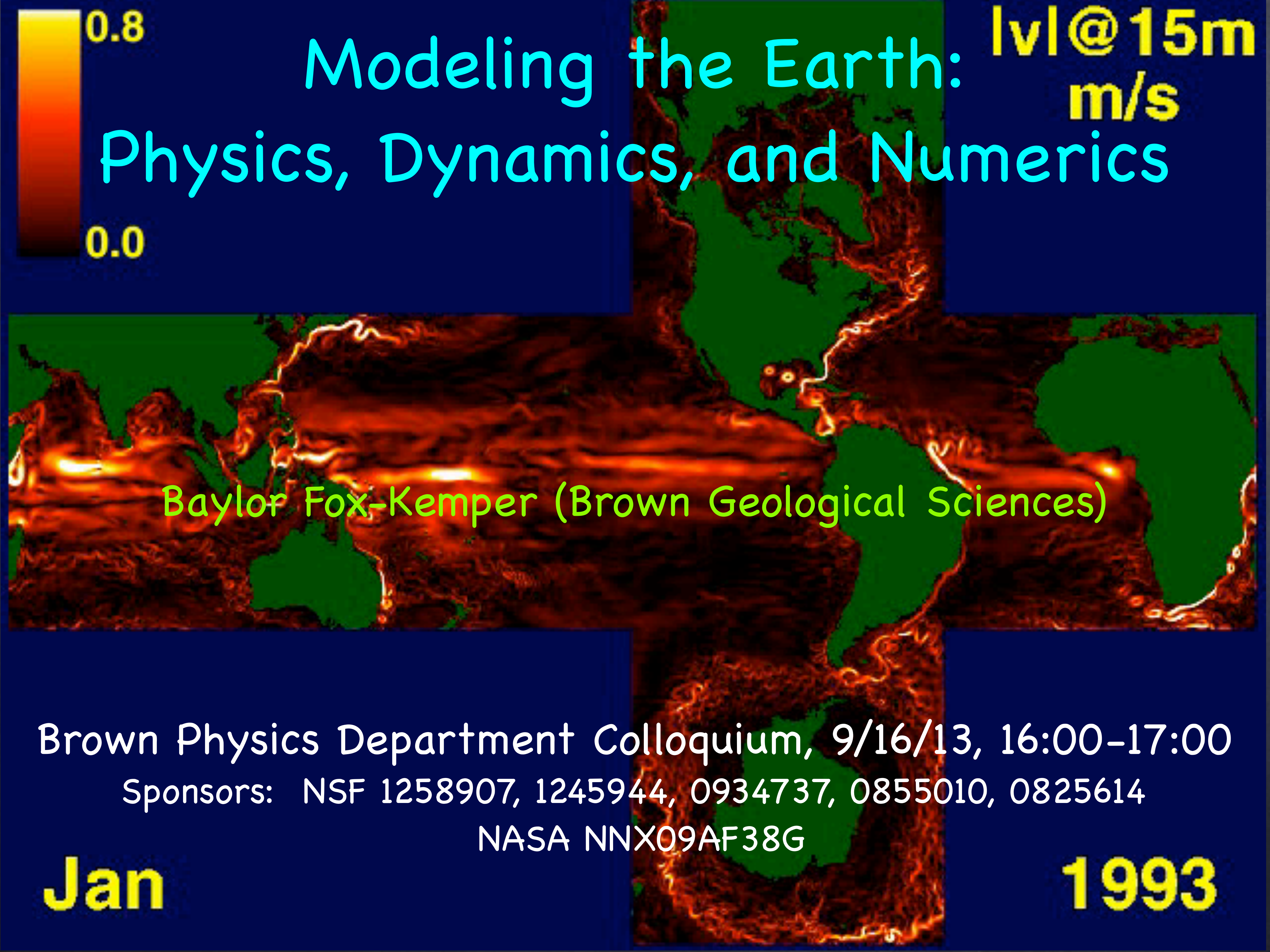
Modeling the Earth: Physics, Dynamics, and Numerics



Baylor Fox-Kemper (Brown Geological Sciences)

Brown Physics Department Colloquium, 9/16/13, 16:00-17:00

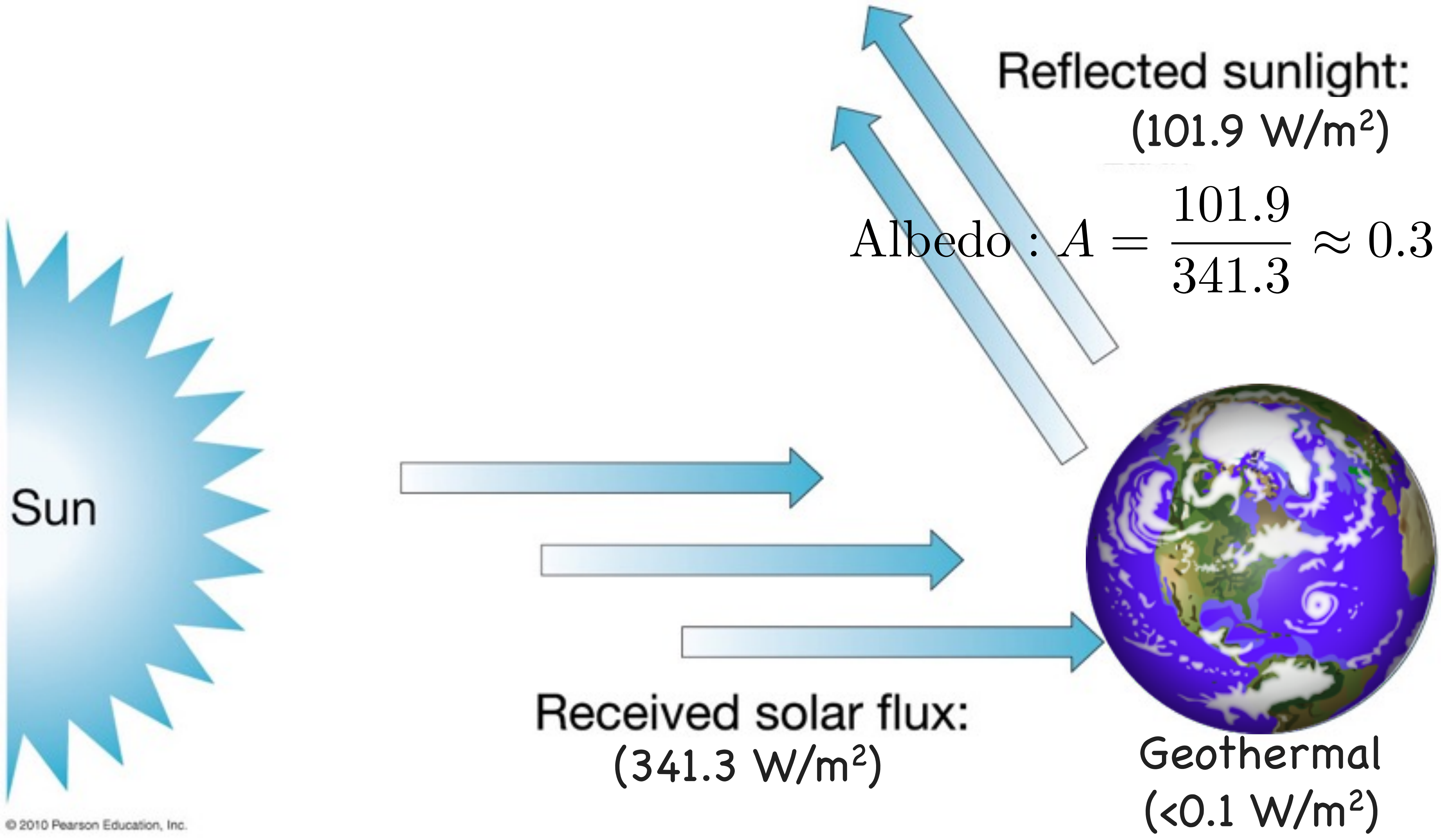
Sponsors: NSF 1258907, 1245944, 0934737, 0855010, 0825614
NASA NNX09AF38G

What to Expect

- Part I
  - How does the Earth balance its energy? (Physics)
  - How does this energy flow? (Dynamics)
  - Why predicting the flow & storage difficult? (Numerics)
- Part II
  - Processes in Climate Models
  - Processes I work on
  - A case study--Truncating the Mesoscale

Striking a balance:

Earth's Equilibrium Energy Balance



Reflected sunlight:
(101.9 W/m²)

$$\text{Albedo} : A = \frac{101.9}{341.3} \approx 0.3$$

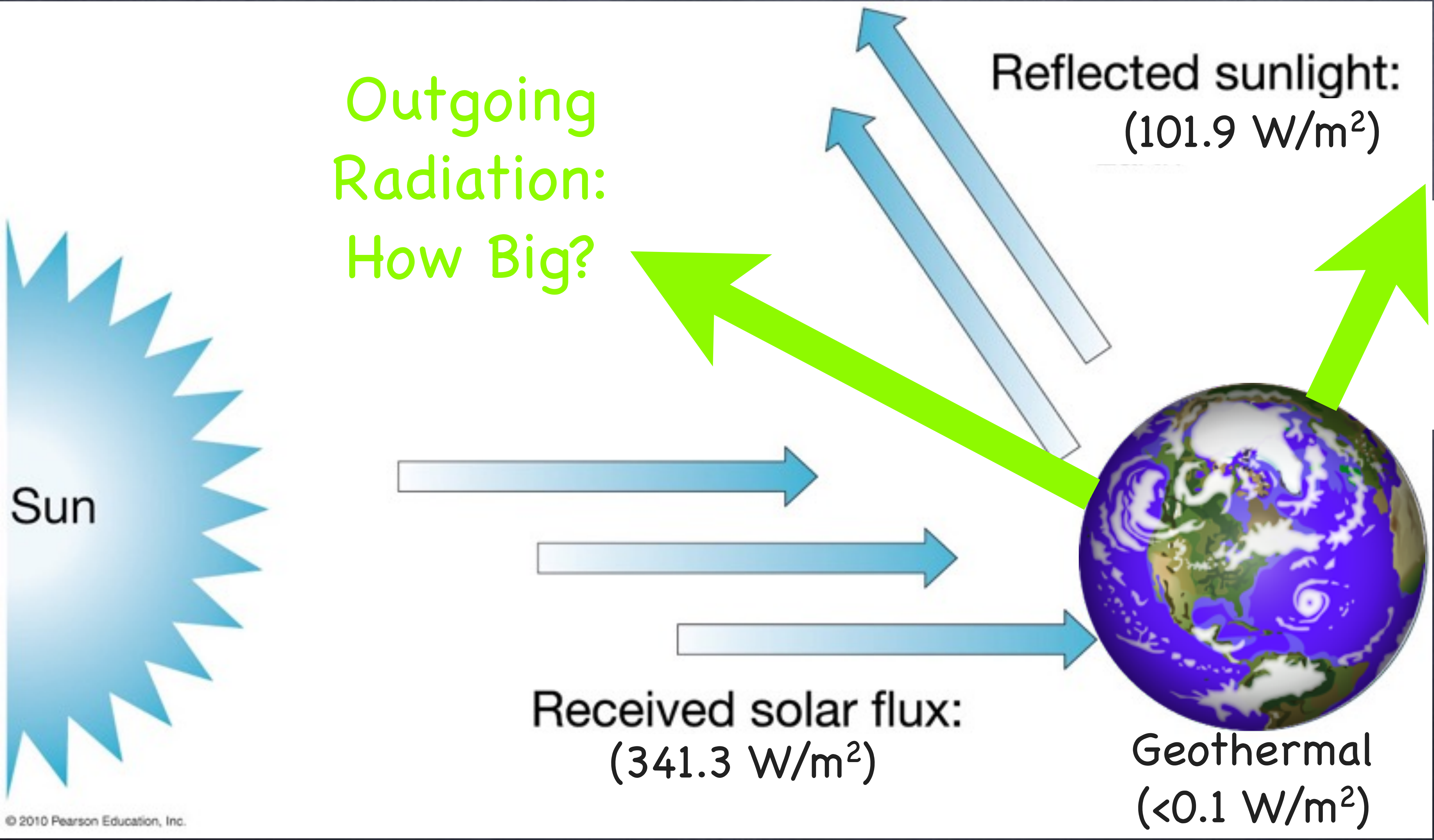
Received solar flux:
(341.3 W/m²)

Geothermal
(<0.1 W/m²)

Images from KKC

Striking a balance:

Earth's Equilibrium Energy Balance



Outgoing Radiation: How Big?

Reflected sunlight: (101.9 W/m²)

Sun

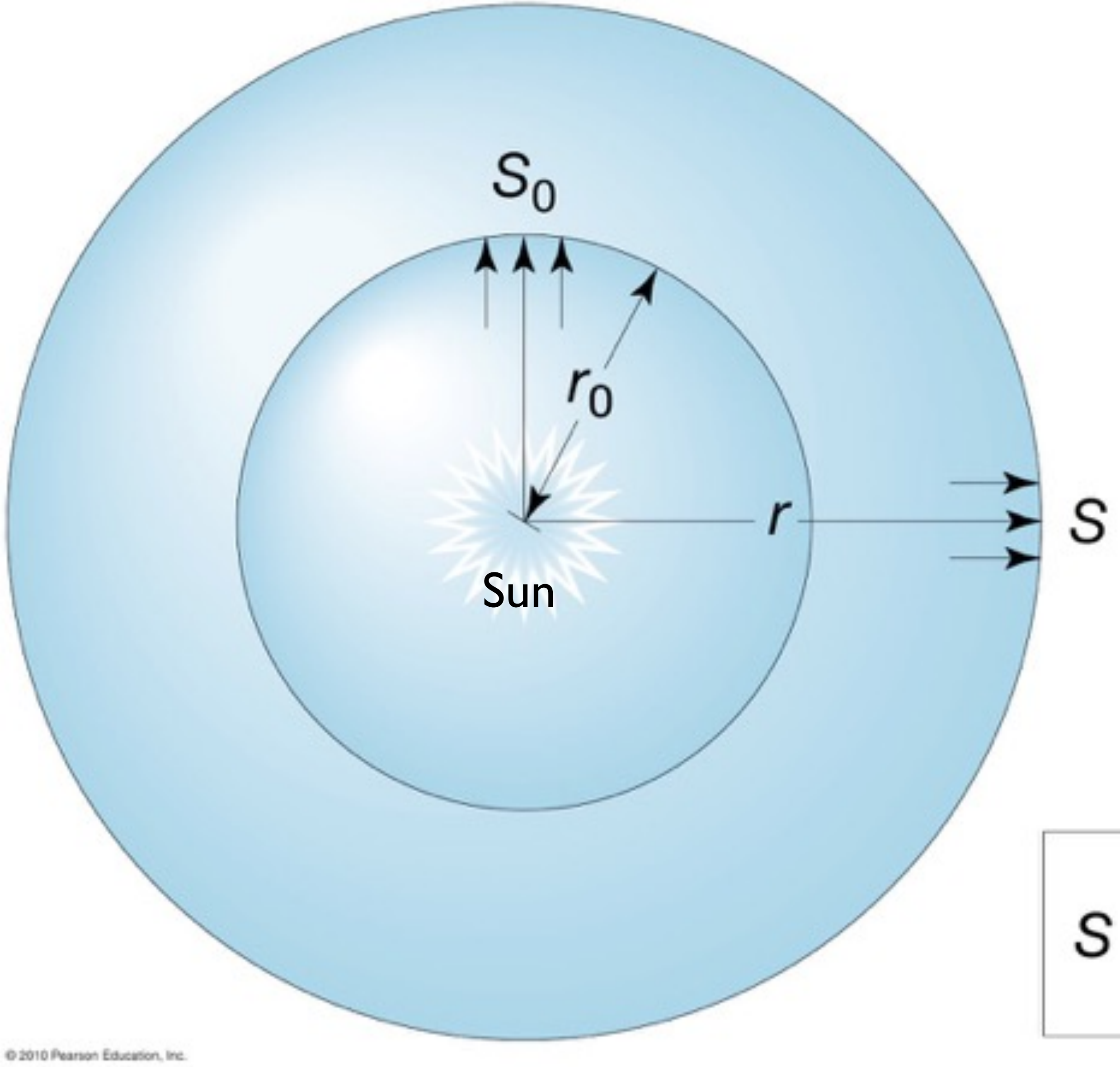
Received solar flux: (341.3 W/m²)

Geothermal (<0.1 W/m²)

Images from KKC

Inverse square law:

Each spherical shell receives same power, different area



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$$\text{Area} = 4\pi r^2$$

$$\frac{\text{Power}}{\text{Area}} \propto \frac{1}{r^2}$$

$$\boxed{S = S_0\left(\frac{r_0}{r}\right)^2}$$

S_0 = 1366 W/m^2

(solar constant)

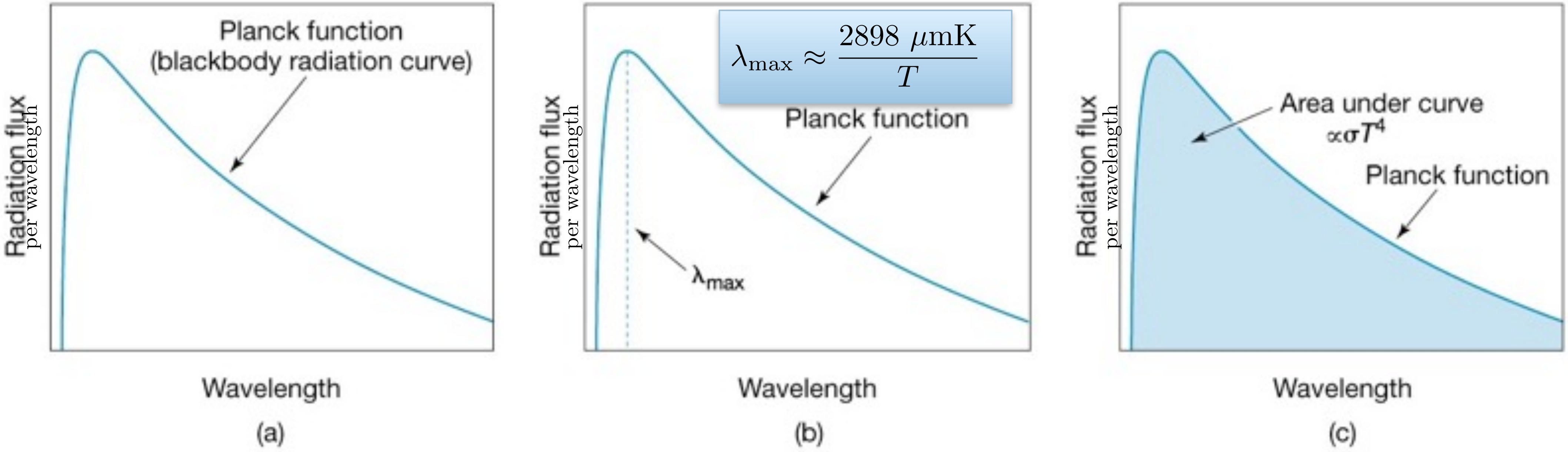
r_0 = 1AU

$$1\text{AU} = 1.496 \cdot 10^{11}\text{m}$$

Images from KKC

Blackbody: a body that emits electromagnetic radiation equally well at all wavelengths

Blackbody Radiation: the electromagnetic radiation given off by a blackbody. This radiation is characterized by the body's absolute temperature



$$\lambda_{\max} \approx \frac{2898\ \mu\mathrm{mK}}{T}$$

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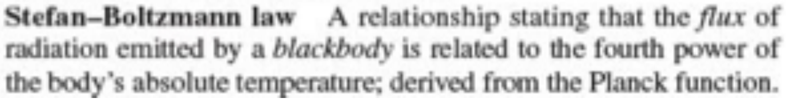
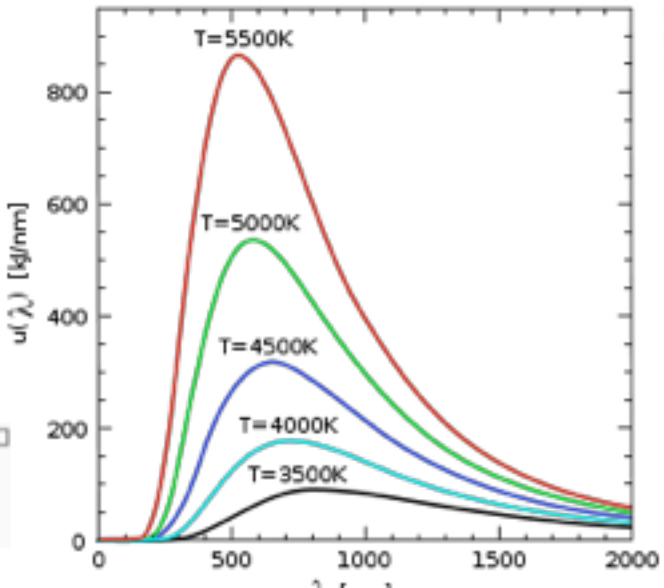
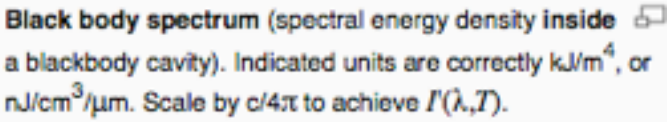


Stefan–Boltzmann law A relationship stating that the *flux* of radiation emitted by a *blackbody* is related to the fourth power of the body's absolute temperature; derived from the Planck function.





Black body spectrum (spectral energy density **inside** a blackbody cavity). Indicated units are correctly kJ/m^4, or nJ/cm^3/µm. Scale by c/4π to achieve $I'(\lambda,T)$.

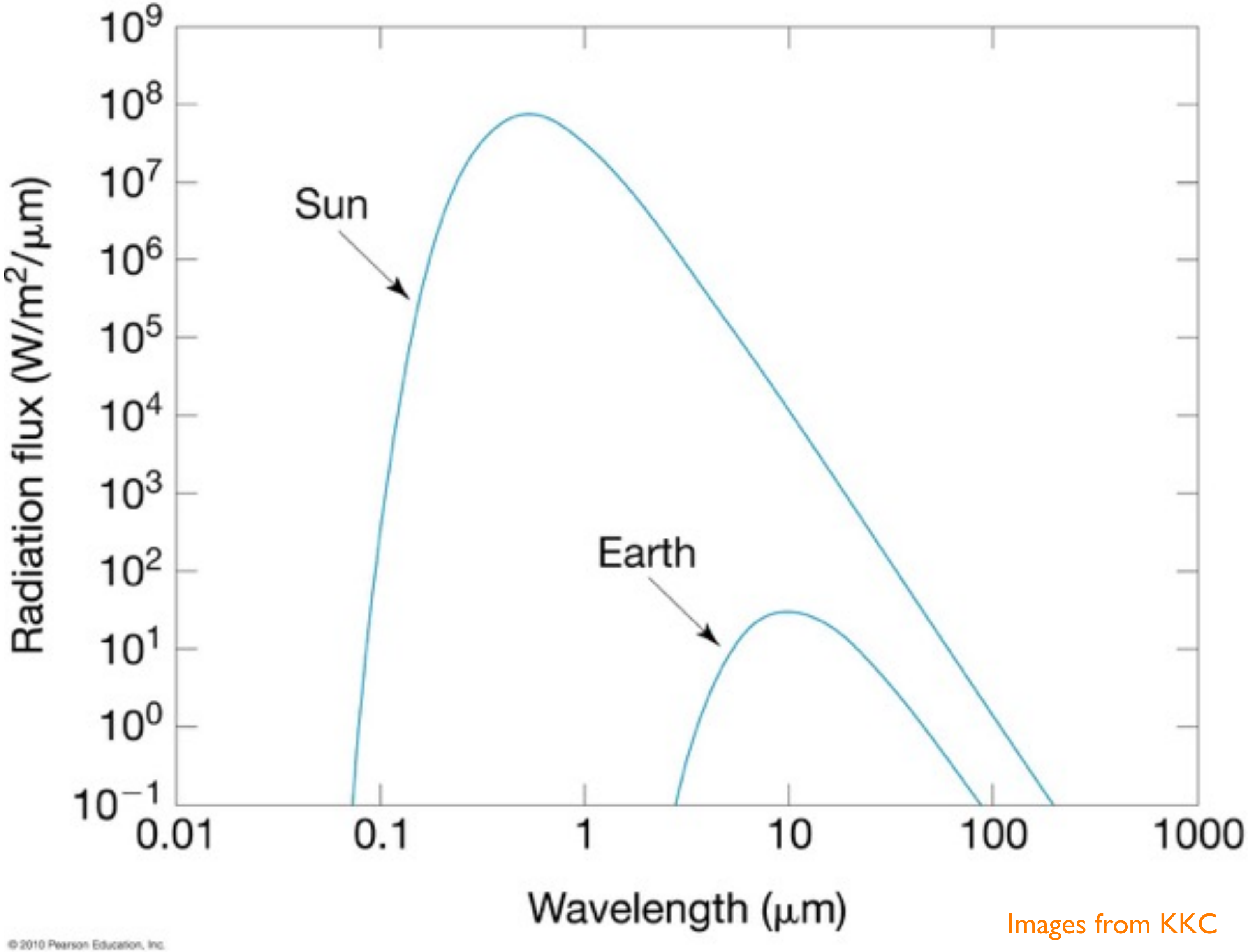
Images from KKC, Wikipedia

The Sun & Earth both emit radiation, but:

Sun is dominantly in visible wavelengths,
Earth is primarily infrared wavelengths, not visible
Much greater solar Flux

Note Scale:

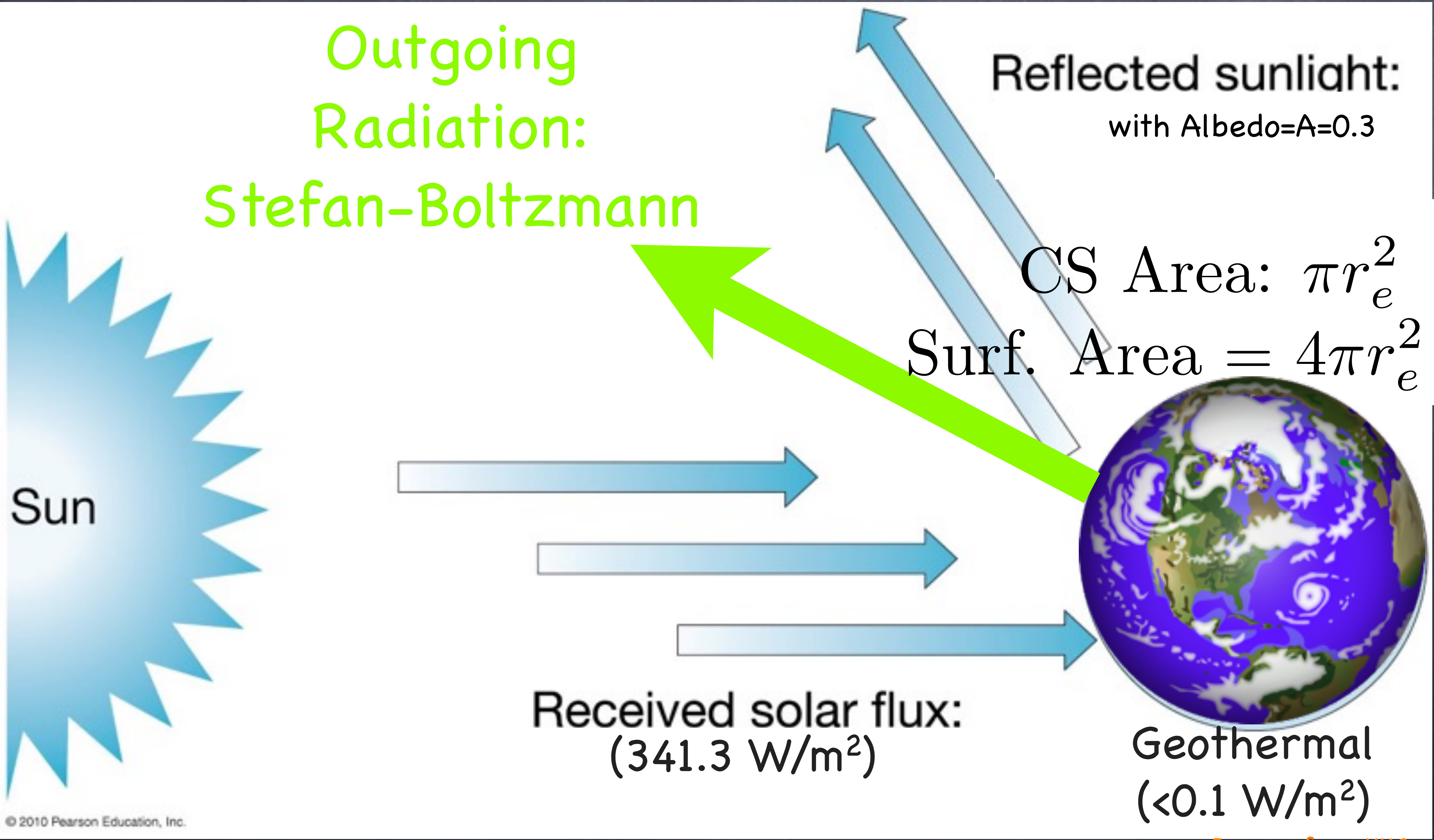
Logarithmic!



Images from KKC

Striking a balance:

Earth's Equilibrium Energy Balance



Outgoing Radiation: Stefan-Boltzmann

with Albedo=A=0.3

$$\text{CS Area: } \pi r_e^2$$

$$\text{Surf. Area} = 4\pi r_e^2$$

(341.3 W/m^2)

Geothermal (<0.1 W/m^2)

Images from KKC

Striking a balance:

Effective Radiating Temperature

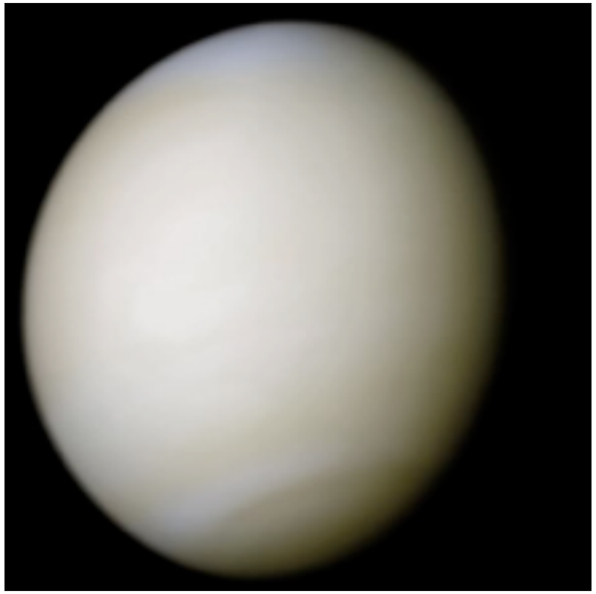
$$\text{S-B Out} = 4\pi r_e^2 \sigma T_e^4 = \pi r_e^2 S_0 \frac{r_0^2}{r^2}(1 - A) = \text{Solar In}$$

Solving for the Temp:

$$T_e = \sqrt[4]{\frac{S_0 r_0^2}{4\sigma r^2}(1 - A)}$$

$$\text{known} : S_0 = 1366 \frac{W}{m^2}, r_0 = 1AU, \sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$

Different Planets, Different Climates

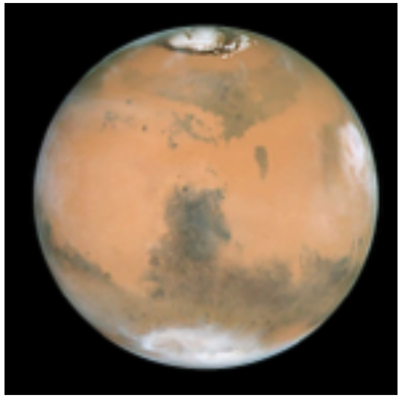


Venus

Planetary Albedo: 0.8
Distance to Sun: 0.72AU
Surf. Temp: 730K

Earth

Planetary Albedo: 0.3
Distance to Sun: 1.0AU
Surf. Temp: 288K



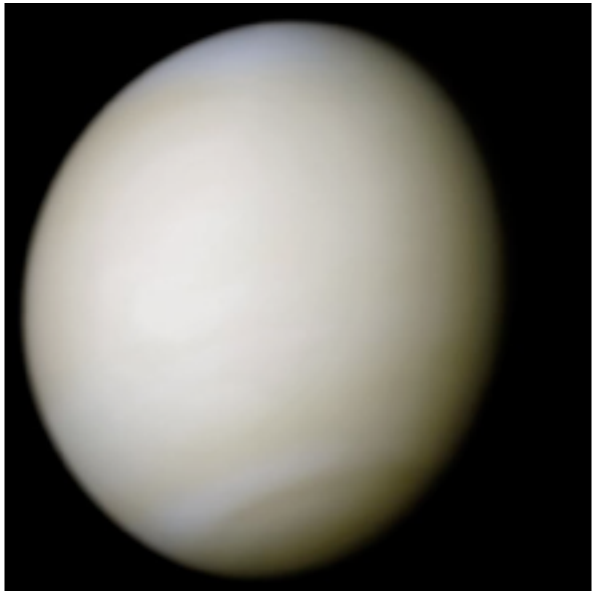
Mars

Planetary Albedo: 0.22
Distance to Sun: 1.52AU
Surf. Temp: 218K

Images from Wikipedia

$$T_e = \sqrt[4]{\frac{S_0 r_0^2}{4\sigma r^2}(1-A)}$$

$$\text{known}: S_0 = 1366\frac{W}{m^2}, r_0 = 1AU, \sigma = 5.67\cdot 10^{-8}\frac{W}{m^2K^4}$$

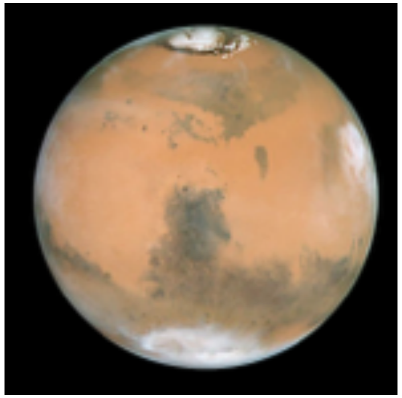


Venus

Planetary Albedo: 0.8
Distance to Sun: 0.72AU
Surf. Temp: 730K
Eff. Rad. Temp: 219K

Earth

Planetary Albedo: 0.3
Distance to Sun: 1.0AU
Surf. Temp: 288K
Eff. Rad. Temp: 255K



Mars

Planetary Albedo: 0.22
Distance to Sun: 1.52AU
Surf. Temp: 218K
Eff. Rad. Temp: 212K

Images from Wikipedia

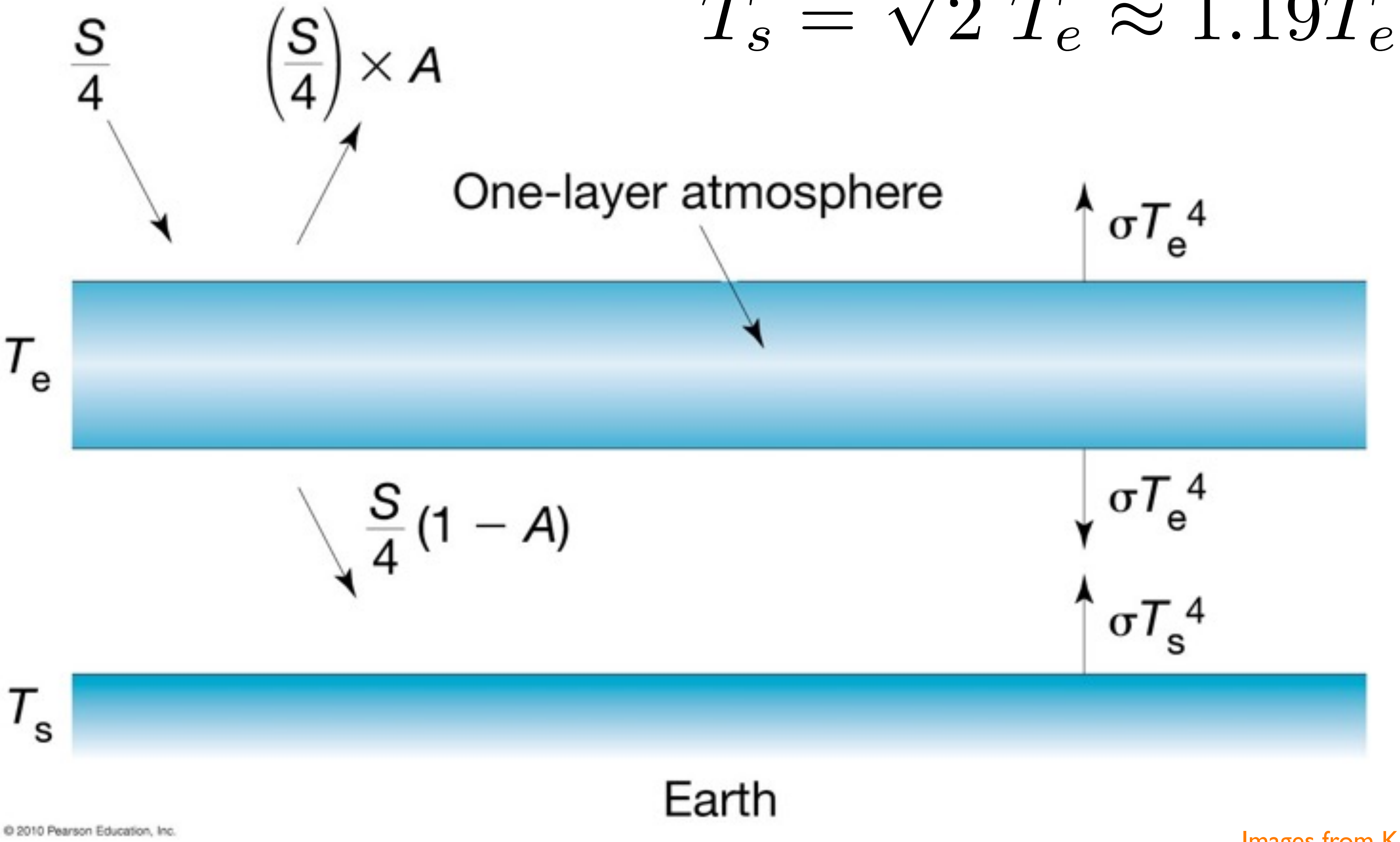
So, we're in the ballpark. How do we do better?

- The Effective Radiating Temperature is not the same as the Surface Temperature!
- Exchanges of energy among the reservoirs in the system sets the temperatures
- At equilibrium when outgoing=incoming, but the details determine the temperatures of various reservoirs of energy
- CRUCIAL: What components are likely to vary?

Striking a More Complex Balance:

1-Layer Atmosphere Model, The Simplest Greenhouse

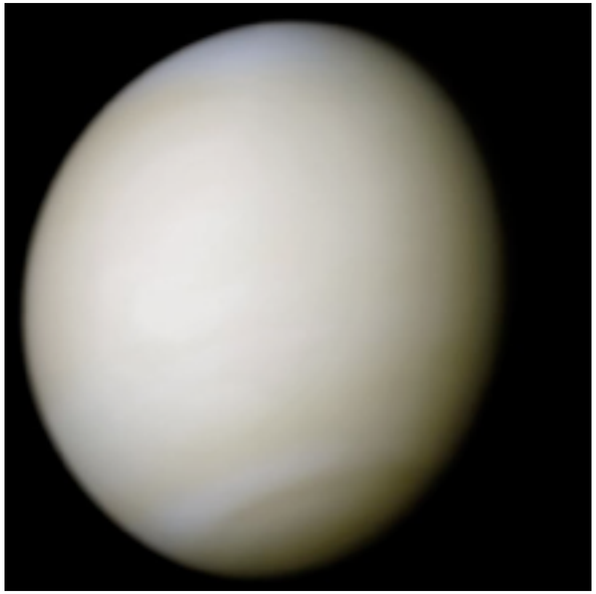
$$T_s = \sqrt[4]{2}\,T_e \approx 1.19 T_e$$

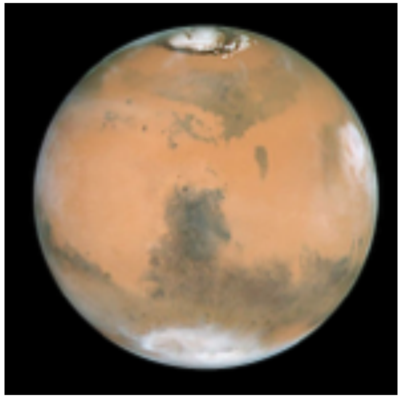


Images from KKC

$$T_e = \sqrt[4]{\frac{S_0 r_0^2}{4\sigma r^2}(1-A)} \quad T_s = \sqrt[4]{2}\, T_e \approx 1.19 T_e$$

$$\text{known} : S_0 = 1366 \frac{W}{m^2}, r_0 = 1AU, \sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$$





Venus

Planetary Albedo: 0.8
Distance to Sun: 0.72AU
Surf. Temp: 730K
Eff. Rad. Temp: 219K
1-Layer Surf. T: 261K
UNDERESTIMATE

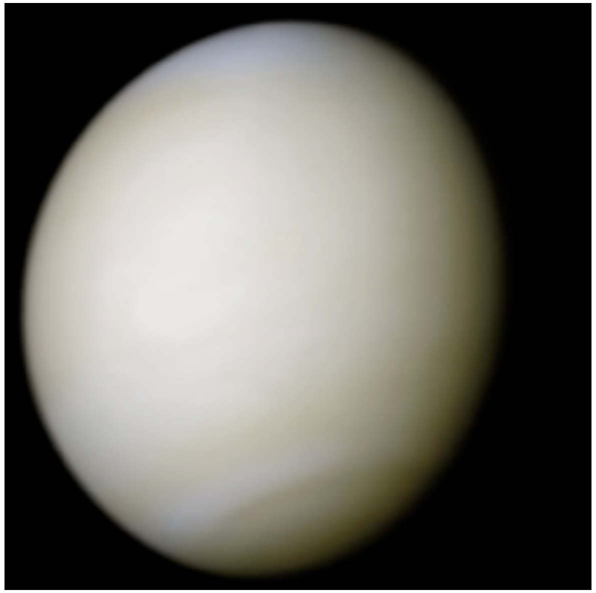
Earth

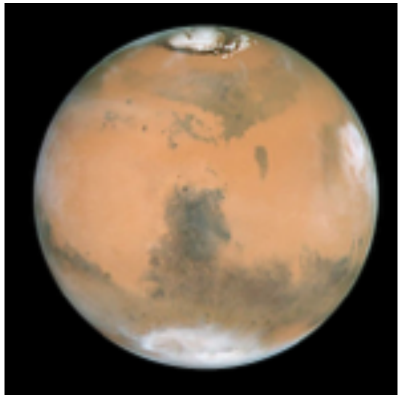
Planetary Albedo: 0.3
Distance to Sun: 1.0AU
Surf. Temp: 288K
Eff. Rad. Temp: 255K
1-Layer Surf. T: 303K
SLIGHT OVERESTIMATE

Mars

Planetary Albedo: 0.22
Distance to Sun: 1.52AU
Surf. Temp: 218K
Eff. Rad. Temp: 212K
1-Layer Surf. T: 259K
OVERESTIMATE

Different Atmospheres...





Venus atmosphere by volume:
96.5% carbon dioxide (CO_2)
3.5% nitrogen (N_2)
150ppm sulfur dioxide (SO_2)
70ppm argon (Ar)
20ppm water vapor (H_2O)

Mean Surf. Pressure (93 atm)

Earth atmosphere by volume:
78% nitrogen (N_2)
21% oxygen (O_2)
0-4% water vapor (H_2O)
0.04% carbon dioxide (CO_2)
1.7ppm methane (CH_4)
0.3ppm nitrous oxide (N_20)
0.1ppm ozone (O_3)
Mean Surf. Pressure (1 atm)

Mars atmosphere by volume:
95.3% carbon dioxide (CO_2)
2.7% nitrogen (N_2)
0.13% oxygen (O_2)
1.6% argon (Ar)
0.03% water vapor (H_2O)

Mean Surf. Press. (0.006 atm)

Data from KKC, Wikipedia

Solar “Constant” on longer timescales, varies T_e & T_s by about 0.01%=0.02K

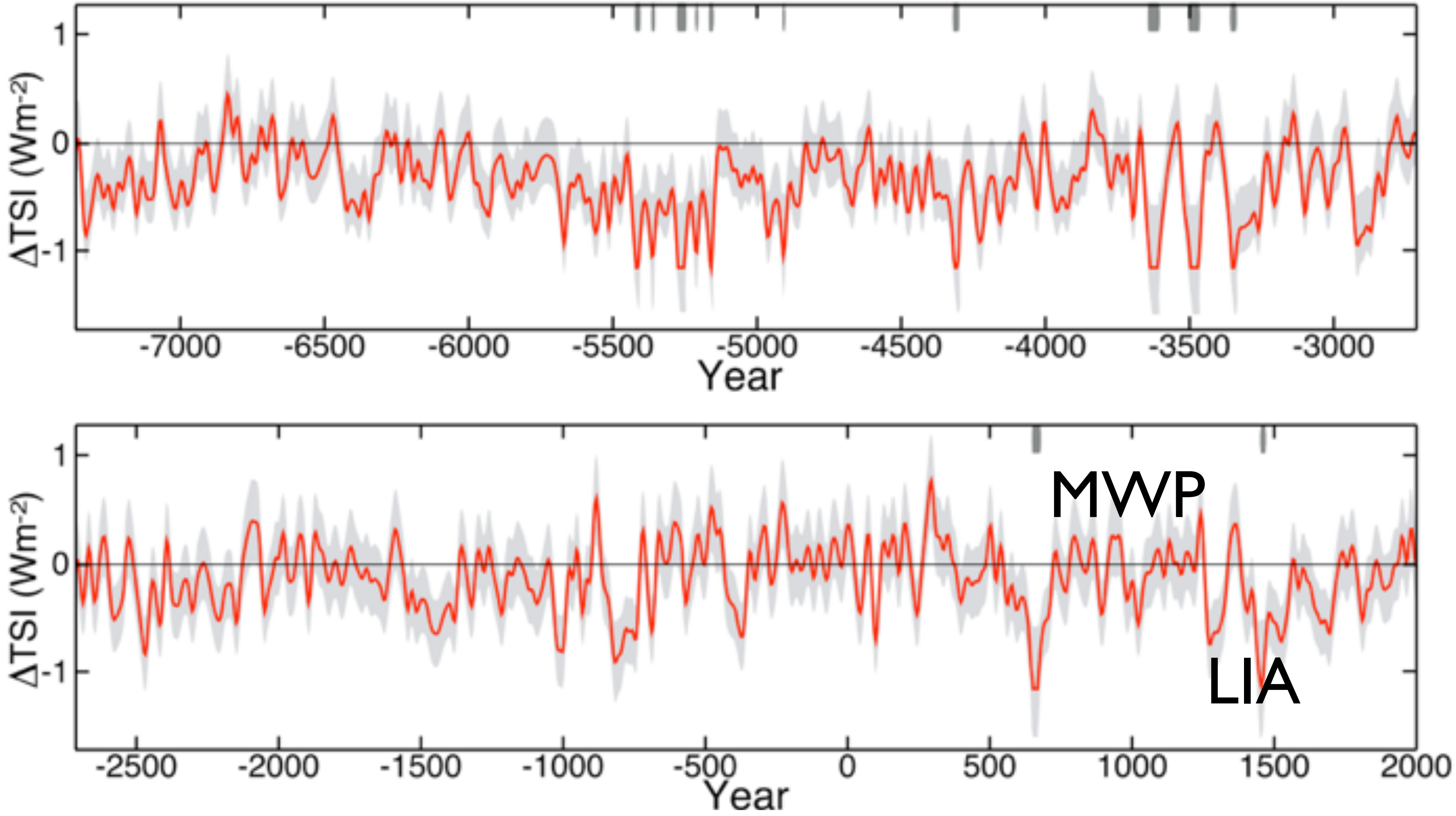
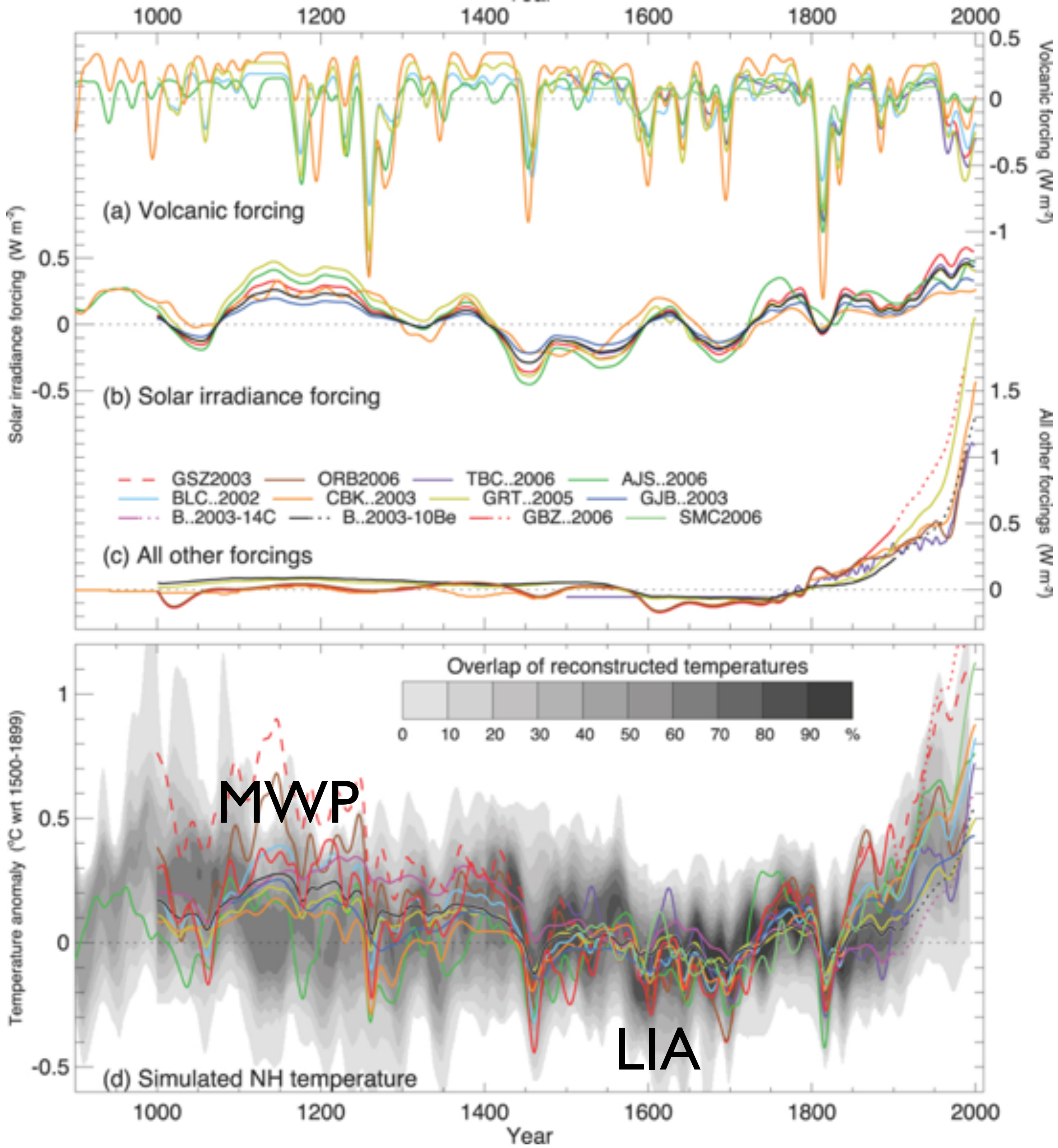


Figure 2. 40-year (cycle) averaged TSI for the past 9300 years based on its relationship with B_r relative to the value of the PMOD composite during the solar cycle minimum of the year 1986 (1365.57 Wm^{-2}). The shaded band is the 1σ uncertainty considering the uncertainties of the TSI-B_r calibration and of the reconstruction of B_r. The bars in the top of each plot mark periods when TSI reaches the minimum value of 1364.64 Wm^{-2} corresponding to ϕ = 0 MV and B_r = 0 nT. During these periods the uncertainty is not defined and was set to 0.5 Wm^{-2}.

Steinhilber et al. 2009

Climate Variations?

- The geological record shows much greater variability than the solar constant suggests
  - Ice Ages, Medieval Warm Period, volcanic winters, Dinosaurs, etc.
- Thus, the exchanges of energy among the reservoirs in the system probably varies, as well as the sun!
- CRUCIAL: Positive feedbacks exist in the system that elevate variation in T_e & T_s
- Human perturbations (Land Use, CO_2) might affect these! QUANTITATIVE, NOT QUALITATIVE DETERMINATION



Until about 1900, Volcanic and Solar "constant" variability dominated.

Not so any more.

Figures: IPCC AR4

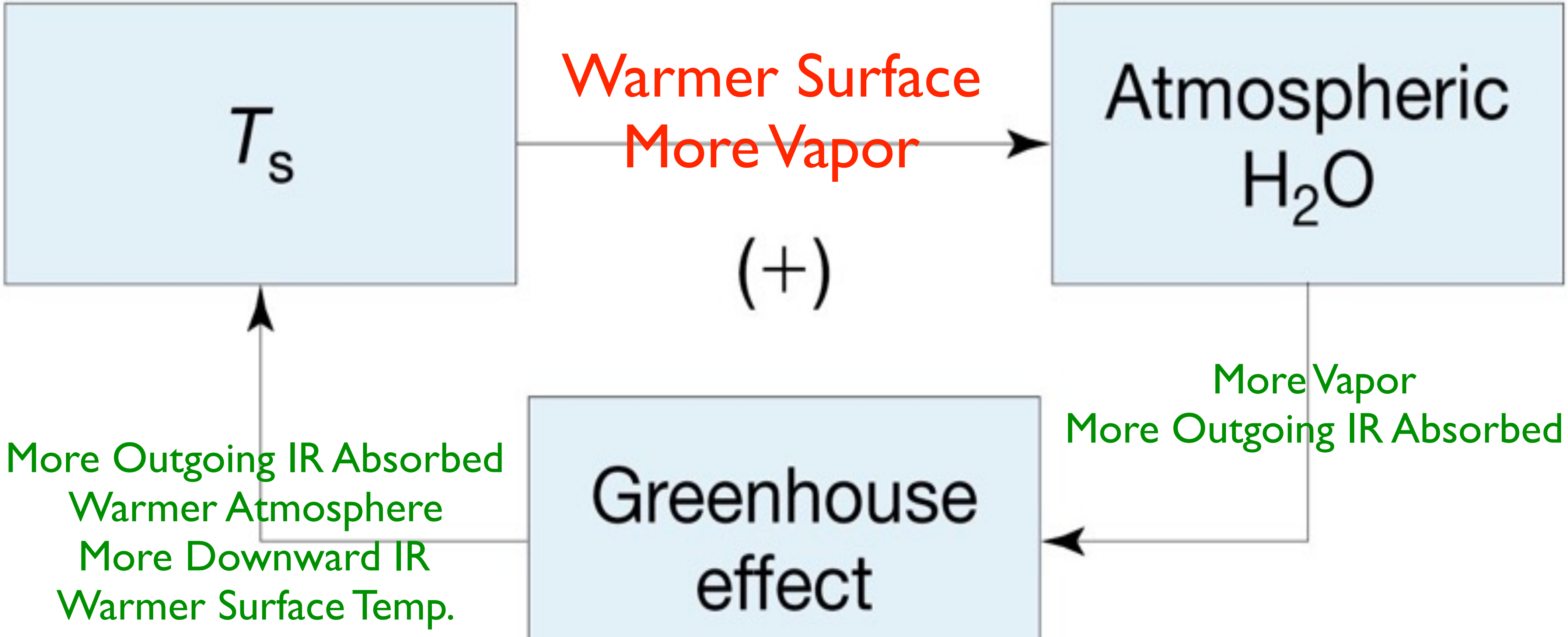
Doubling of CO_2: with and without feedbacks

- More atmosphere, more greenhouse effect (Venus vs. Mars)
- More greenhouse gasses, more greenhouse
- What would happen if we add greenhouse gasses to Earth's atmosphere?
  - If we take account only of extra absorption by CO_2, a 1.2K increase
  - In 1906, Arrhenius estimated that doubling CO_2 would raise temps by 5-6K
  - Why so different? Positive feedbacks!

Arrhenius from Wikipedia

Water Vapor Feedback:

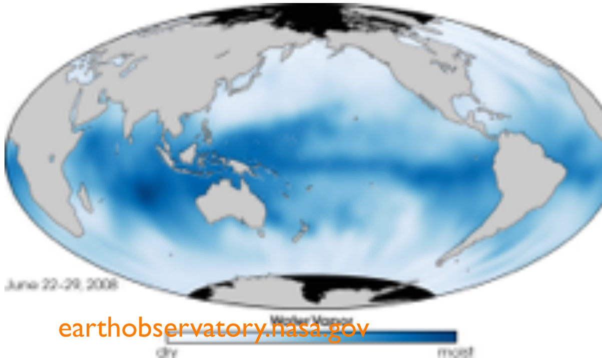
Water Vapor is the most important GHG on Earth, not only because it absorbs most of the outgoing IR, but also because it responds to surface temperature changes



Warmer Surface
More Vapor

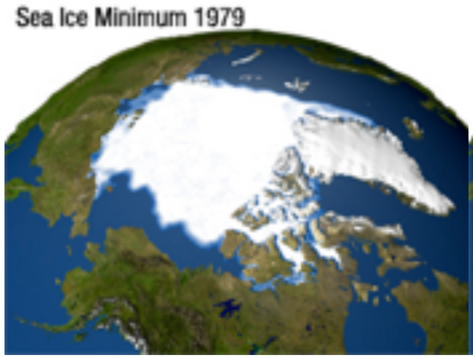
More Vapor
More Outgoing IR Absorbed

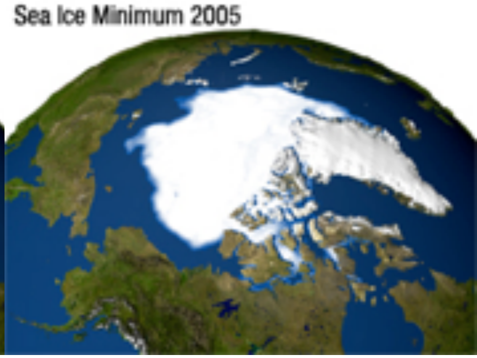
More Outgoing IR Absorbed
Warmer Atmosphere
More Downward IR
Warmer Surface Temp.

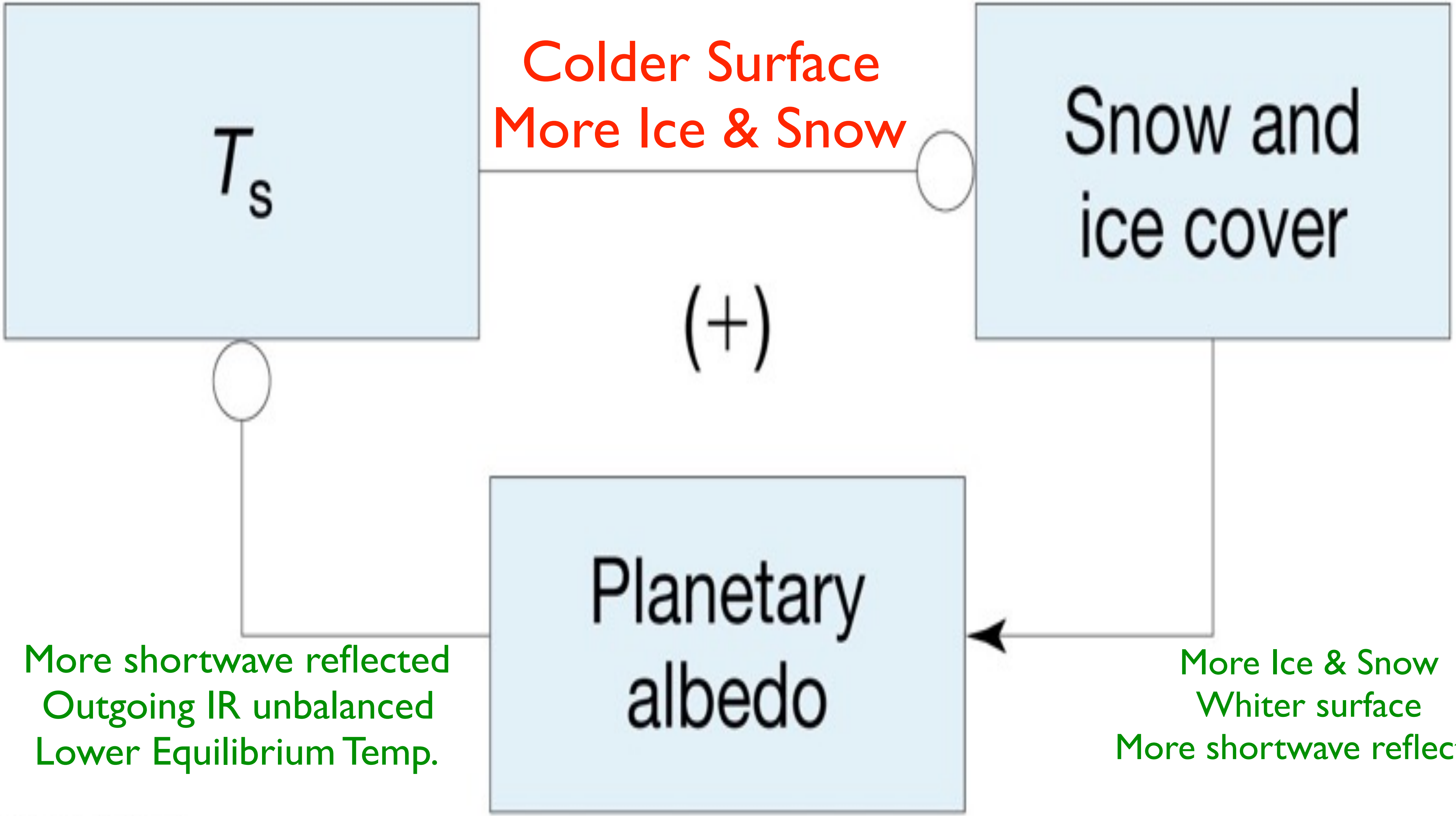


earthobservatory.nasa.gov

Ice Albedo Feedback







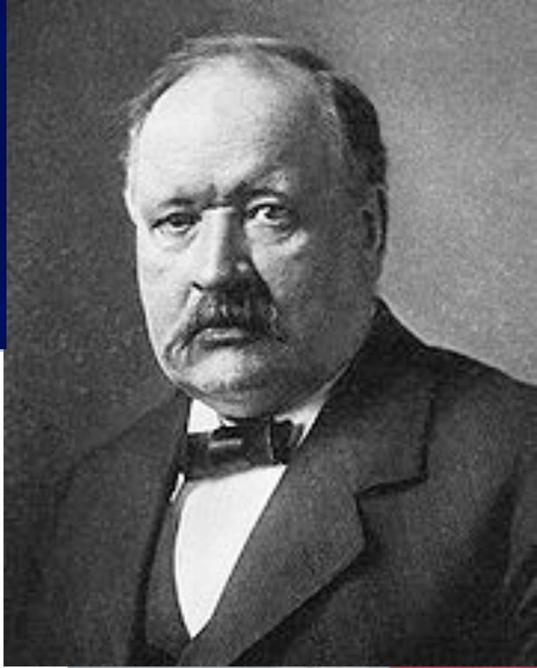
Colder Surface
More Ice & Snow

More Ice & Snow
Whiter surface
More shortwave reflec

More shortwave reflected
Outgoing IR unbalanced
Lower Equilibrium Temp.

Images: www.nas

Rise of the IPCC



- In 1906, Svante Arrhenius estimated that doubling CO_2 would raise temps by 5-6K, and halving would decrease by 4-5K
- The Charney et al. 1979 National Academy Assessment warned of a 1.5K to 4.5K warming with doubled CO_2
    - Charney worked on the first numerical weather models (1952)
- This range came from two climate model efforts
    - Jim Hansen's group at NASA Goddard
    - Suki Manabe's group at Princeton
- The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988.
- The IPCC has completed four assessment reports, developed methodology guidelines for national greenhouse gas inventories, special reports and technical papers. They collect the results of many!

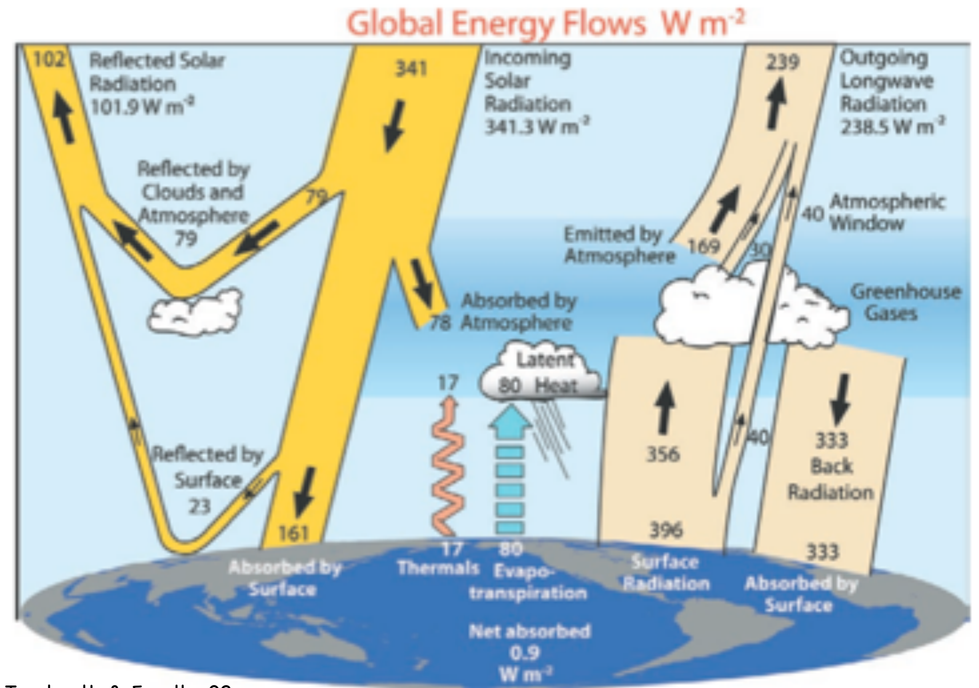
Images from Wikipedia, unescso.org,

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

The energy then flows through the system (mostly by winds & ocean currents) affecting storage in reservoirs, e.g. different latitudes, until it finds it way out

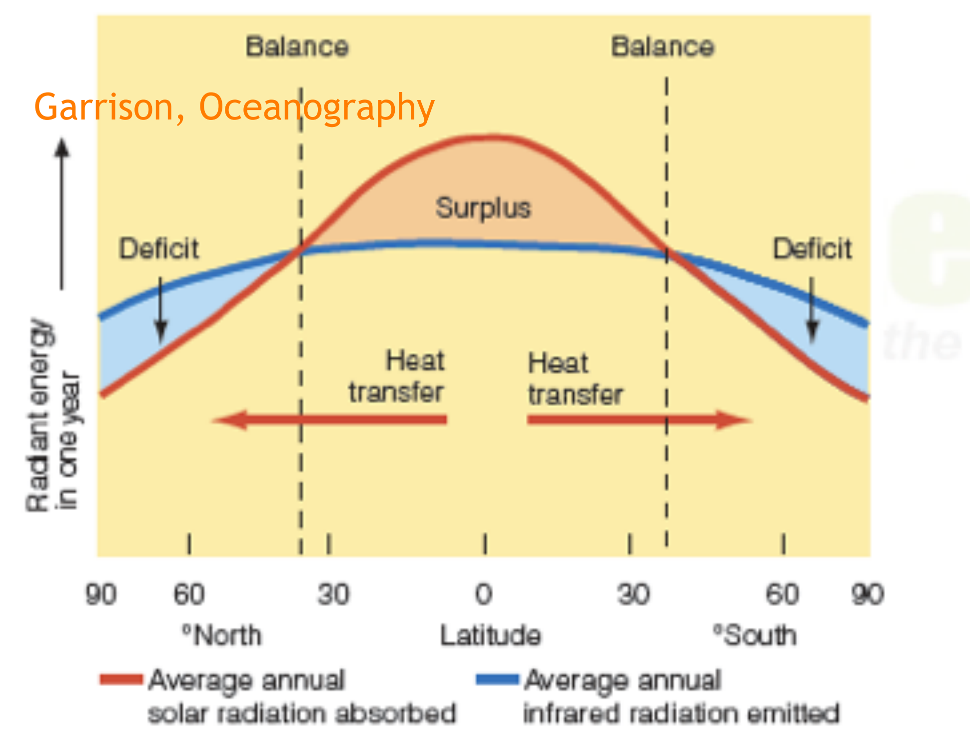
Many Positive Feedbacks Involved

(Thermodynamically, this is a nonequilibrium steady state...)



Trenberth & Fasullo, 09

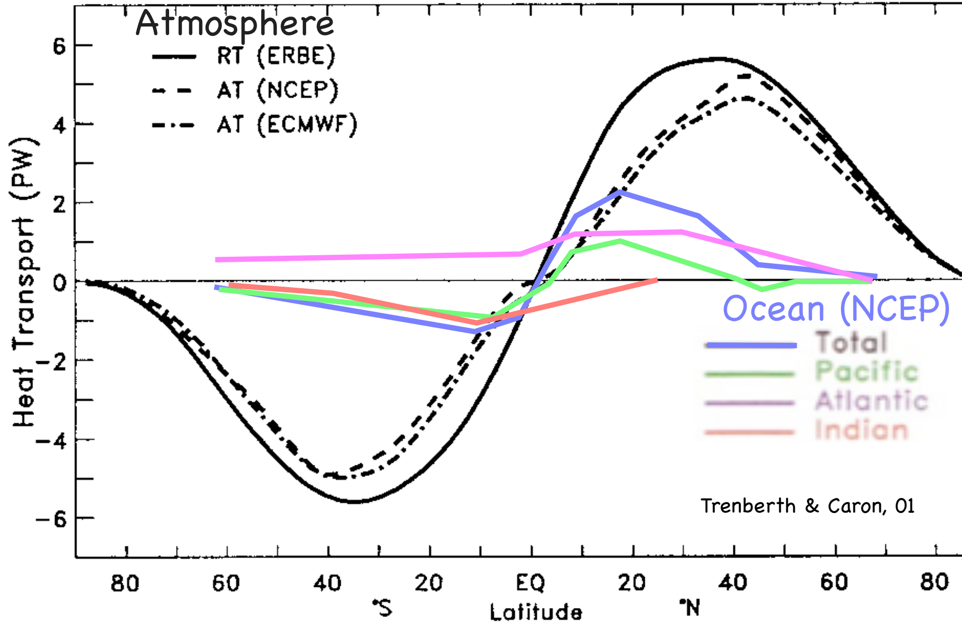
Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.


Garrison, Oceanography

Air-Sea Flux Errors vs. Data

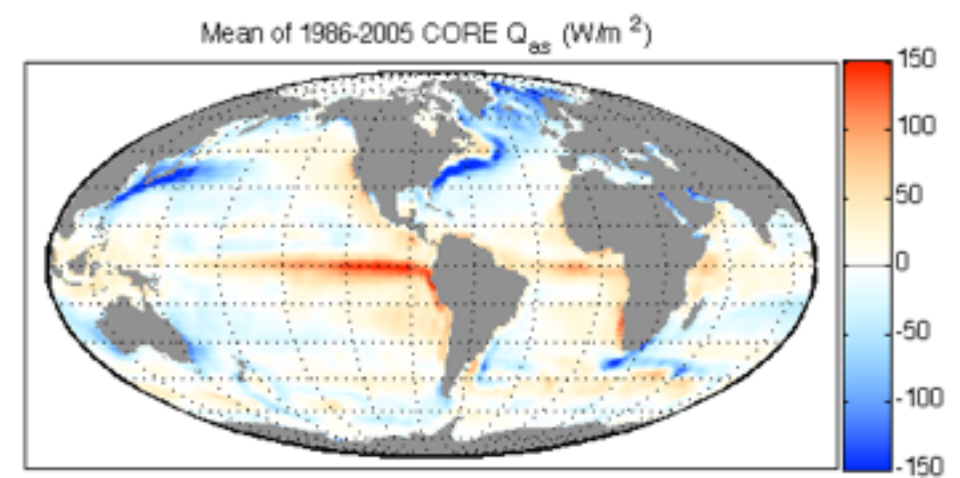
Heat capacity & mode of transport is different in A vs. O

S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.

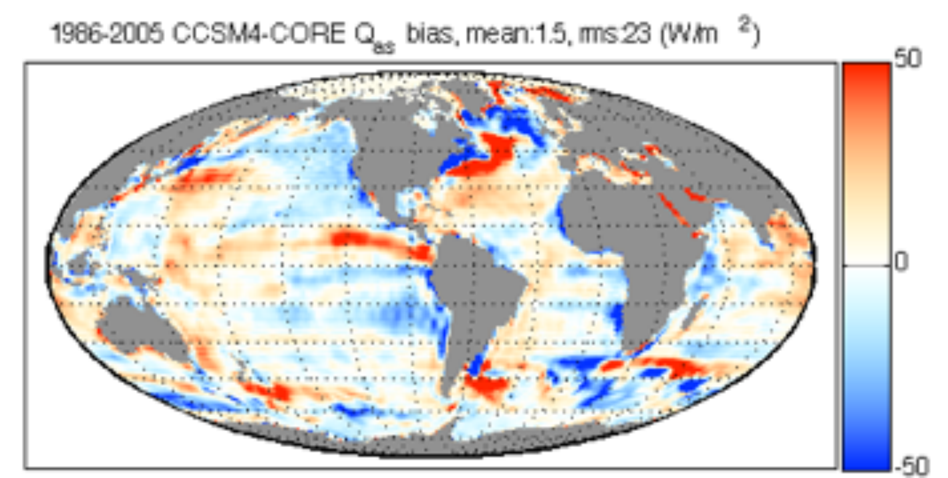


Trenberth & Caron, 01

Mean

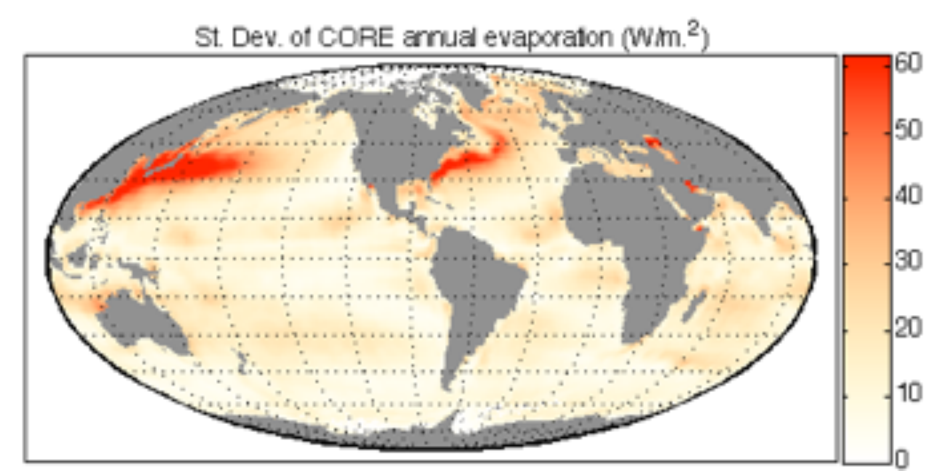


Mean of 1986-2005 CORE Q_{as} (W/m ^{2})

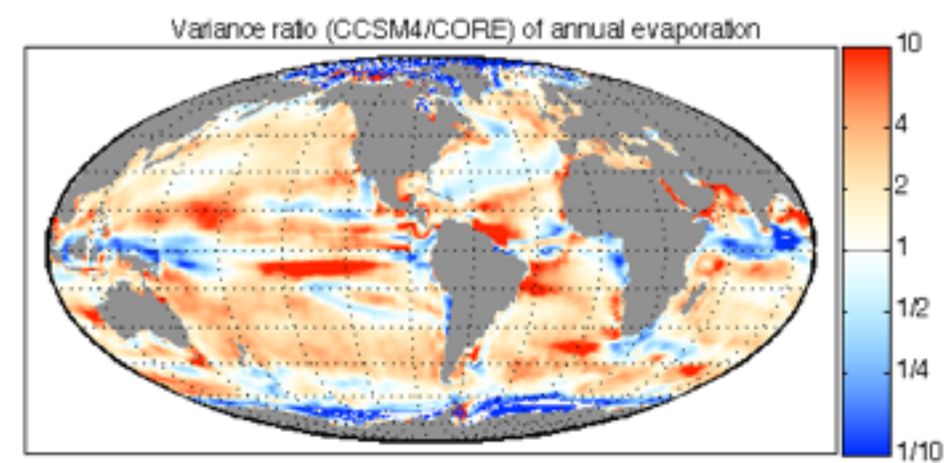


1986-2005 CCSM4-CORE Q_{as} bias, mean:1.5, rms:23 (W/m ^{2})

Annual 9-15mo

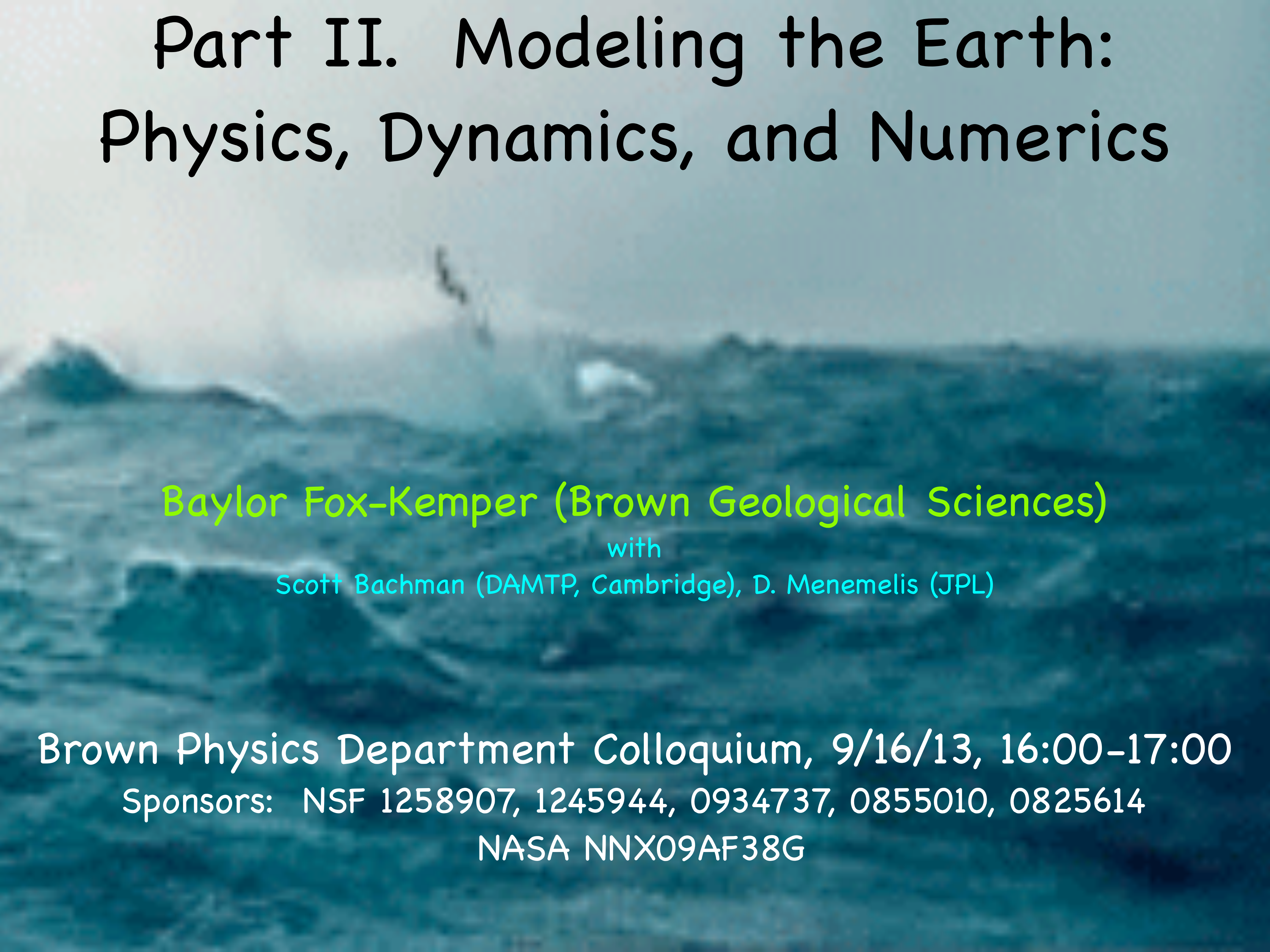


St. Dev. of CORE annual evaporation (W/m.^{2})



Variance ratio (CCSM4/CORE) of annual evaporation

Part II. Modeling the Earth: Physics, Dynamics, and Numerics

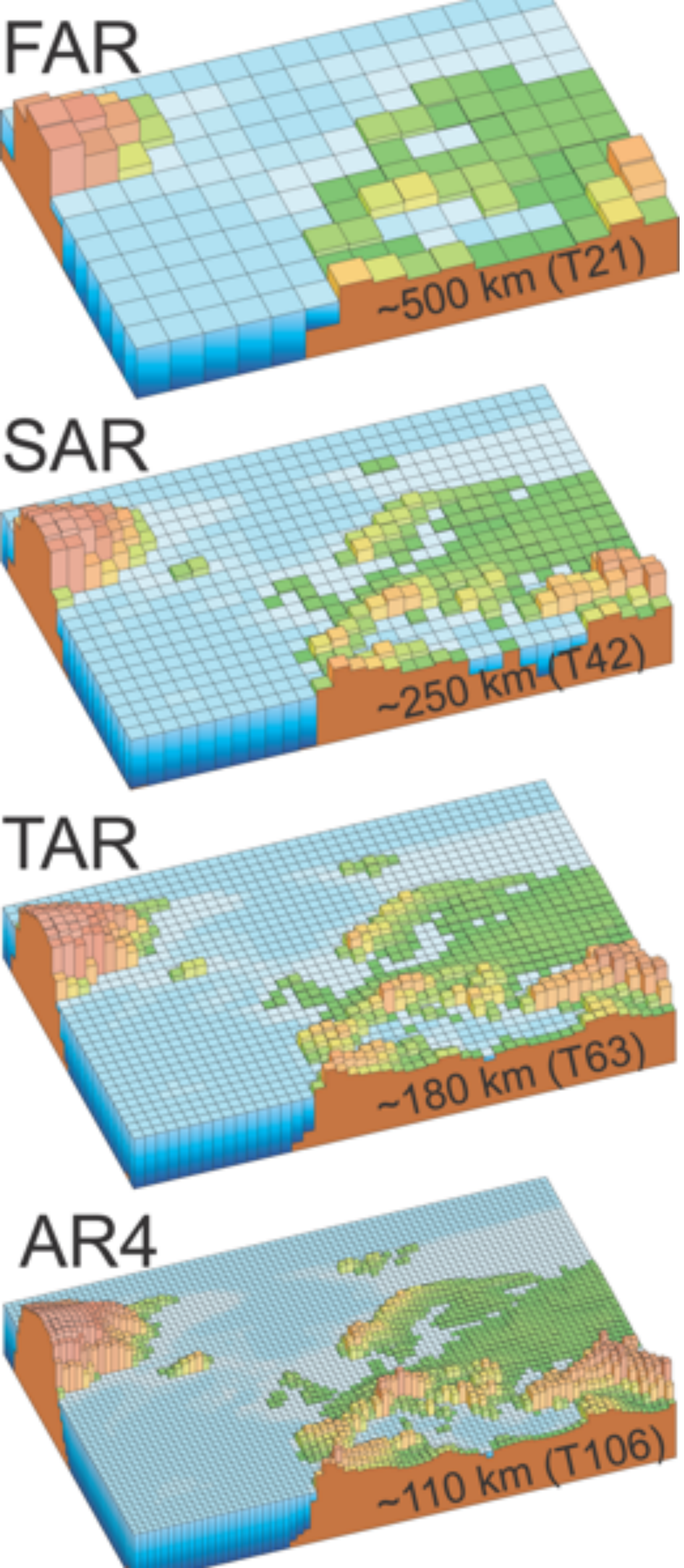


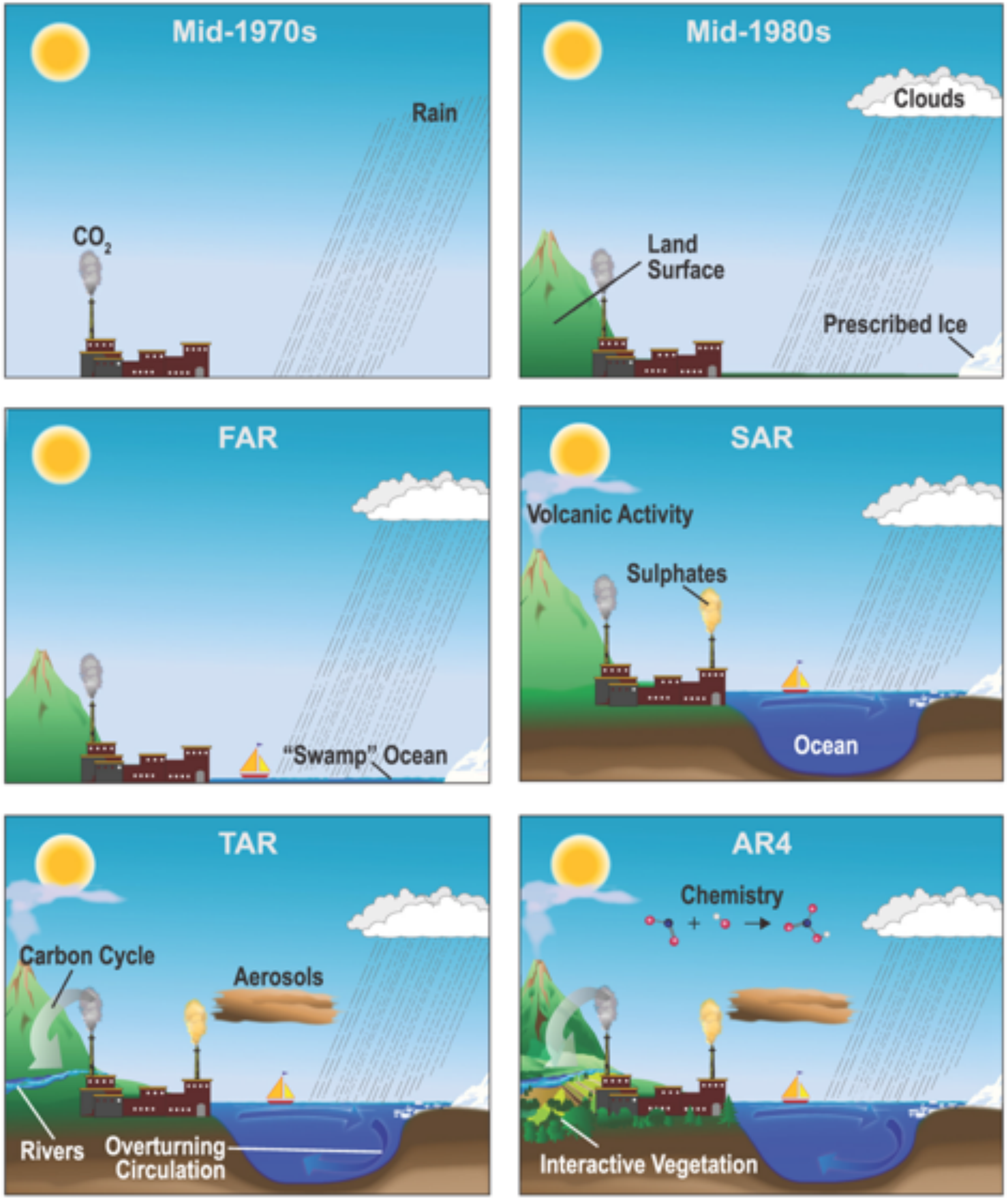
Baylor Fox-Kemper (Brown Geological Sciences)
with
Scott Bachman (DAMTP, Cambridge), D. Menemelis (JPL)

Brown Physics Department Colloquium, 9/16/13, 16:00-17:00

Sponsors: NSF 1258907, 1245944, 0934737, 0855010, 0825614
NASA NNX09AF38G

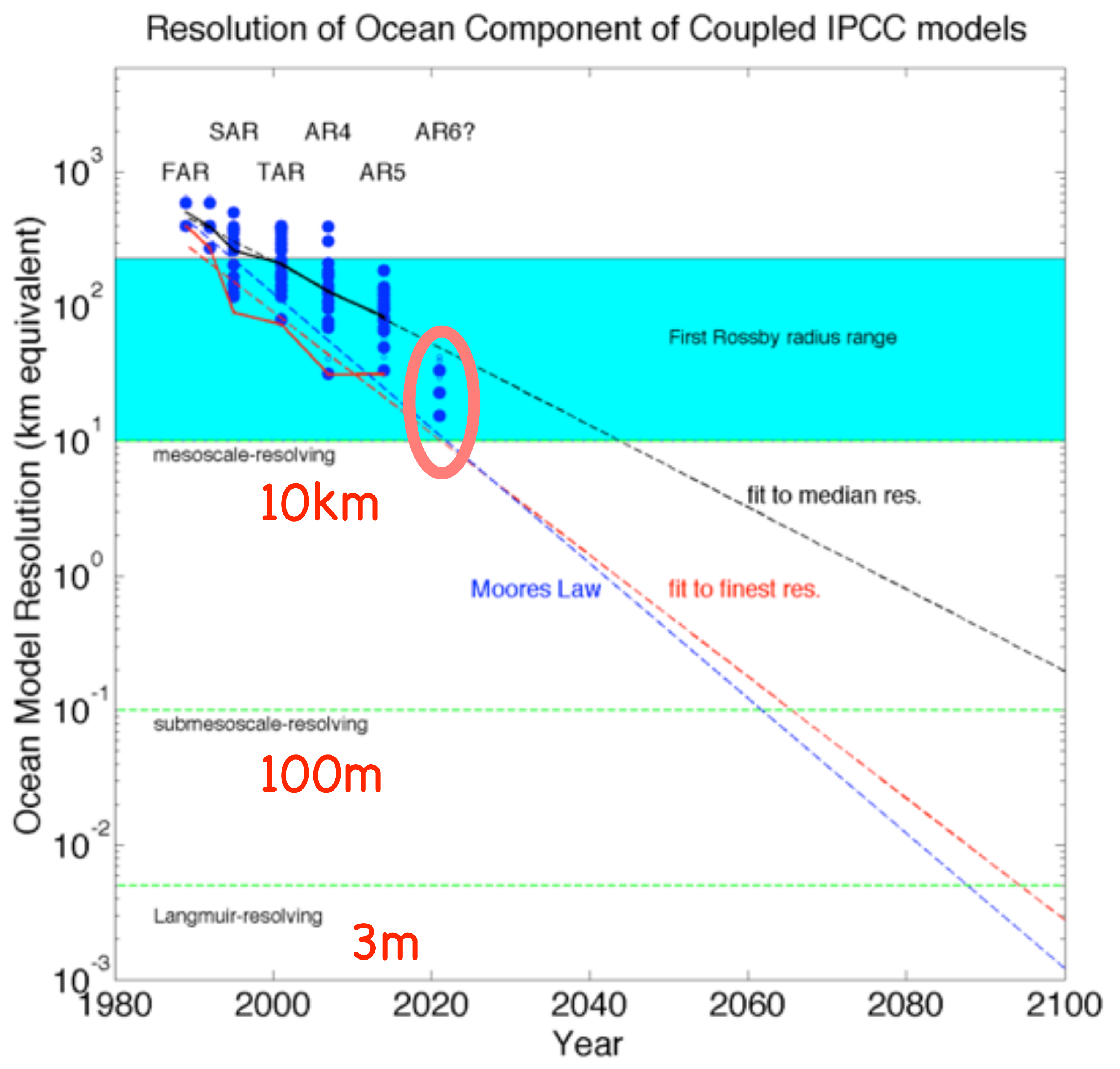
The World in Global Climate Models



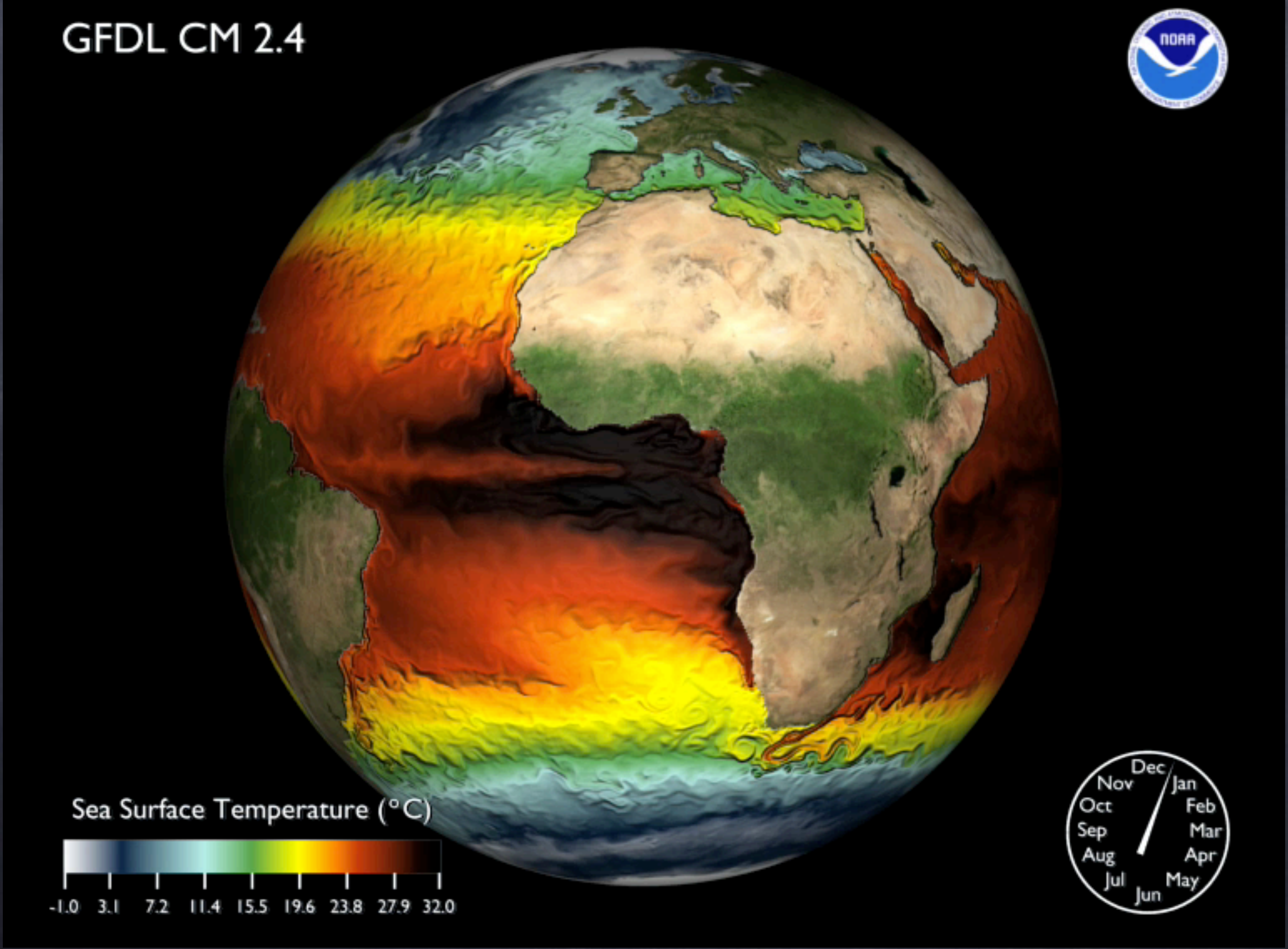


Better resolution, more processes!, Figures: IPCC.ch

Resolution will be an issue for centuries to come!

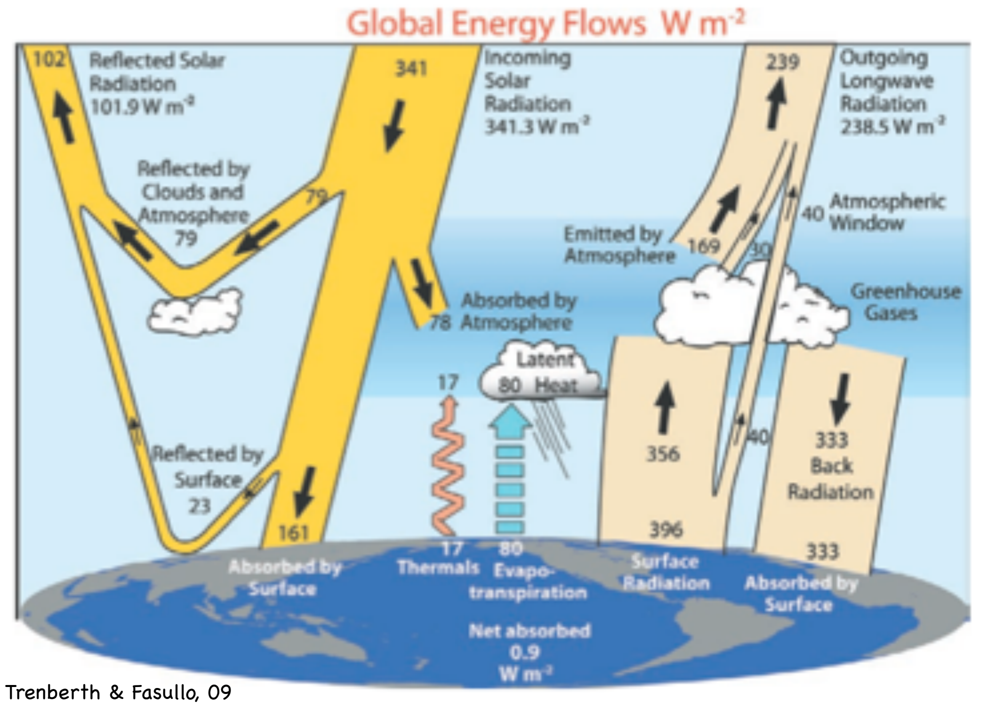


If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect



A prototype mesoscale-eddy-rich climate model

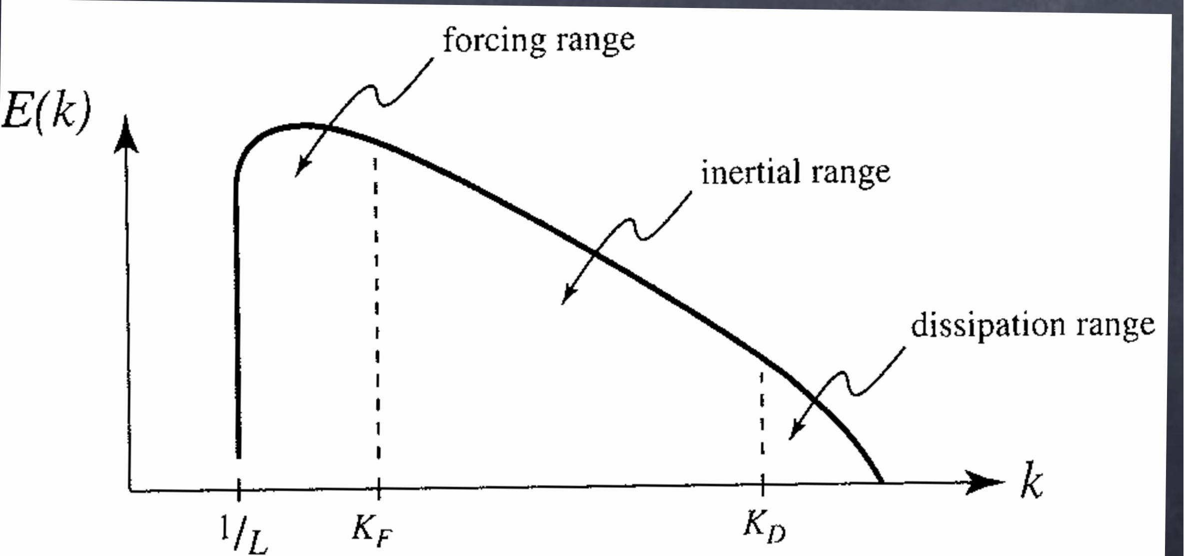
The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale

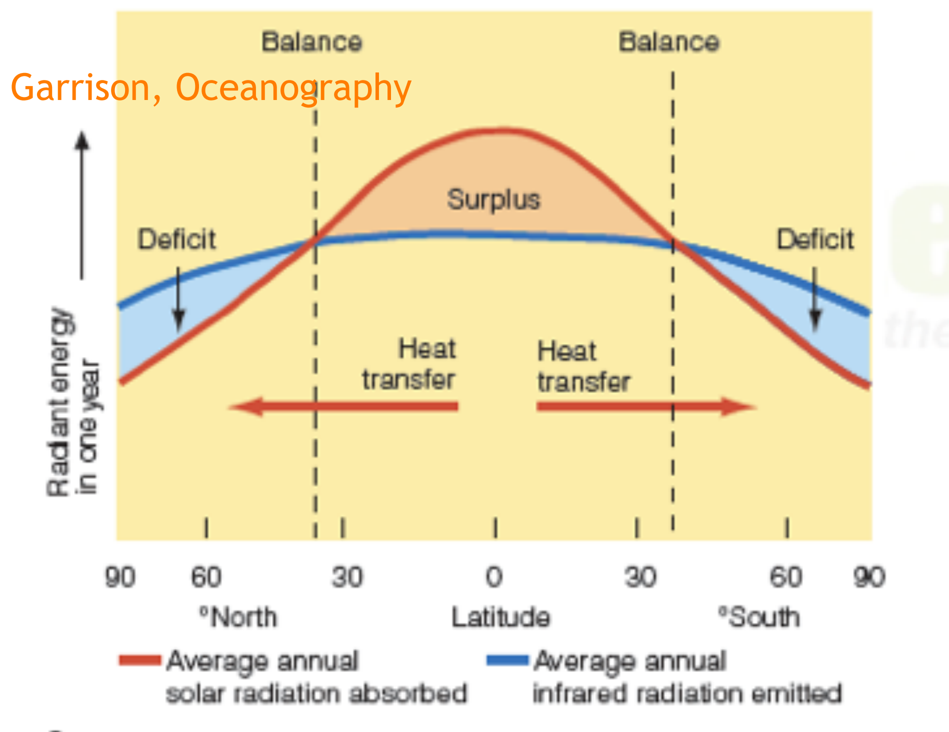


Trenberth & Fasullo, 09

FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

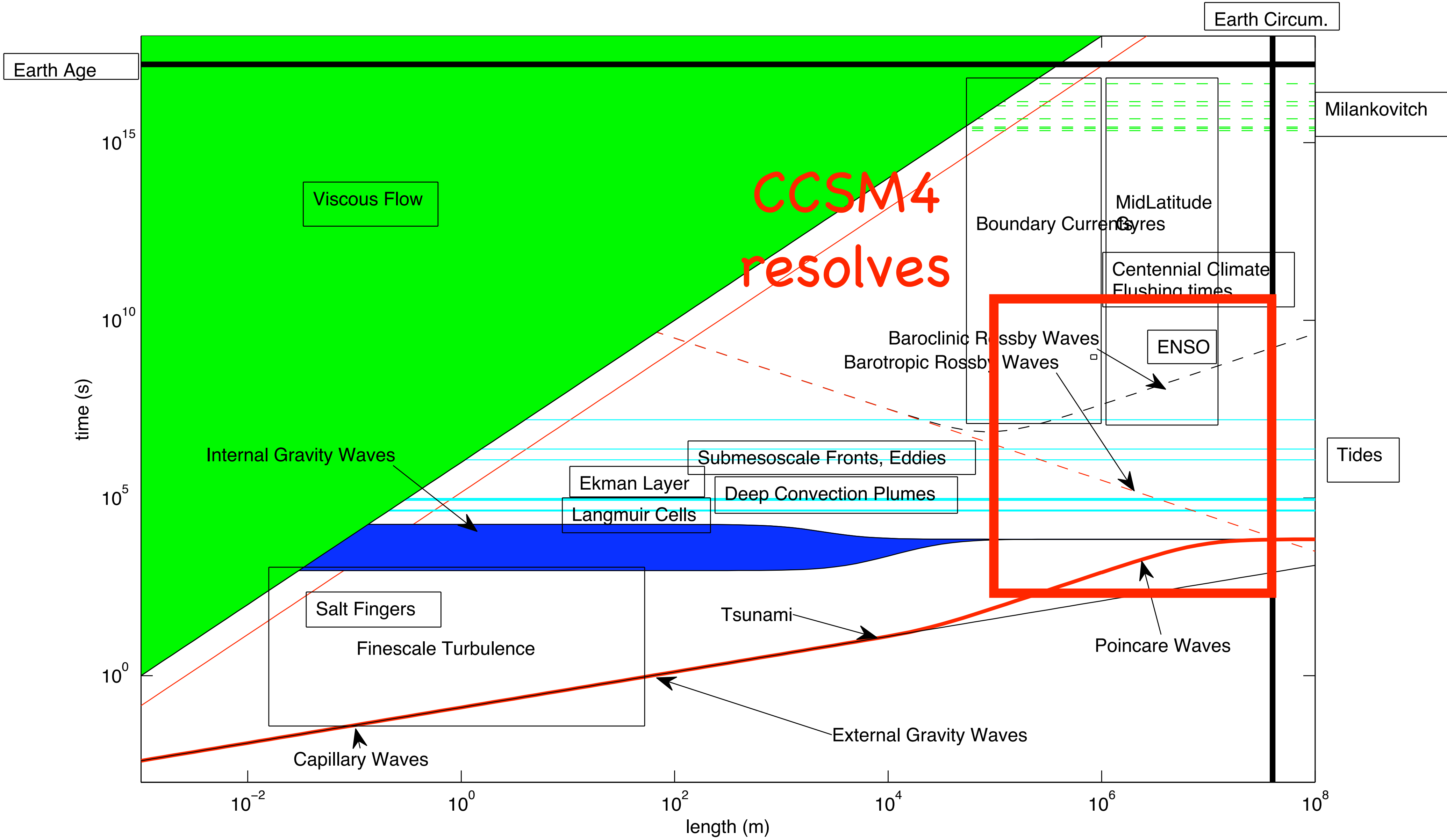
Dissipation concludes turbulent cascades on scales about a trillion times smaller



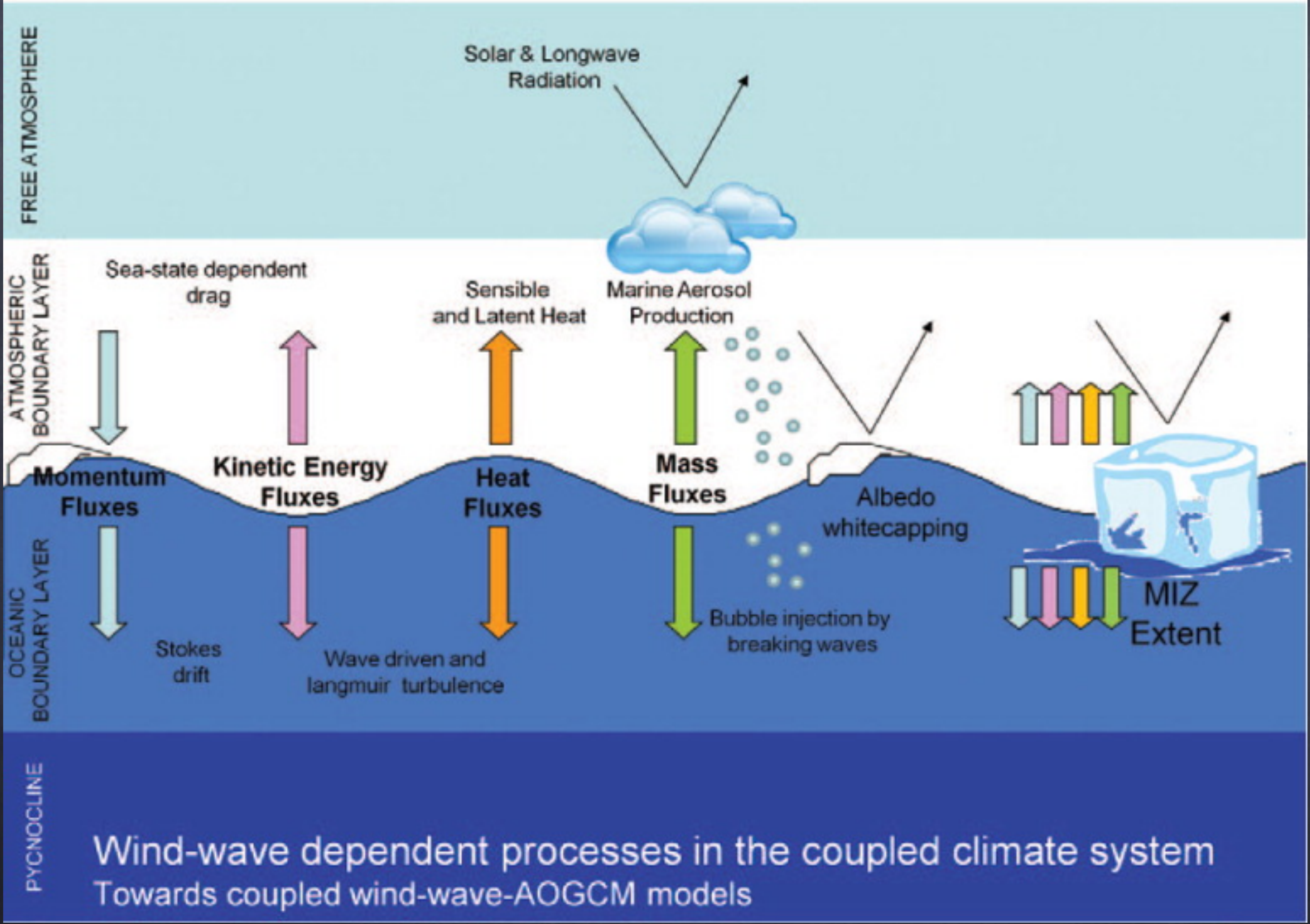


Garrison, Oceanography

The Ocean is Vast & Diverse:
Q: What processes to parameterize?
Today's A: Unresolved Upper Ocean with Air-Sea Impact



Needed Process: Surface Waves



L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. Bulletin of the American Meteorological Society, 93(11):1651-1661, 2012.

Needed Process: Submesoscale

(Capet et al., 2008)

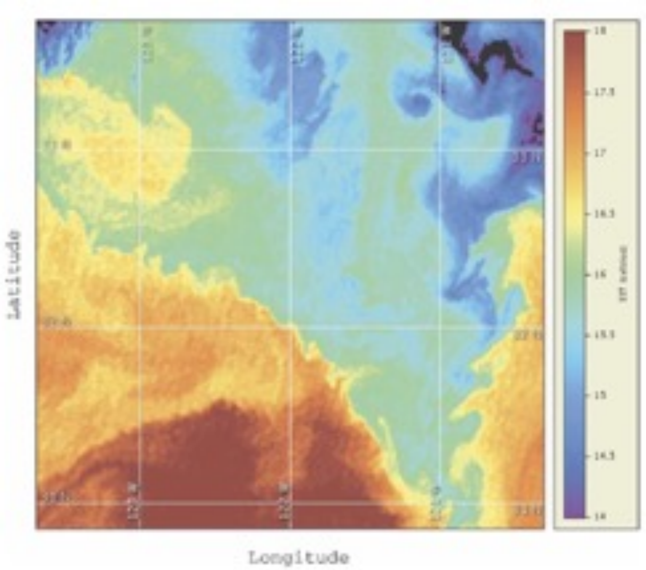
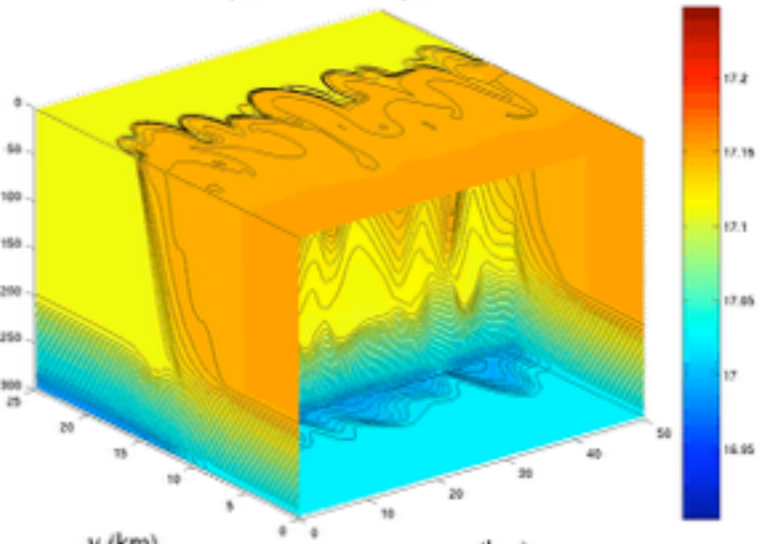


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently

Temperature on day:17.375



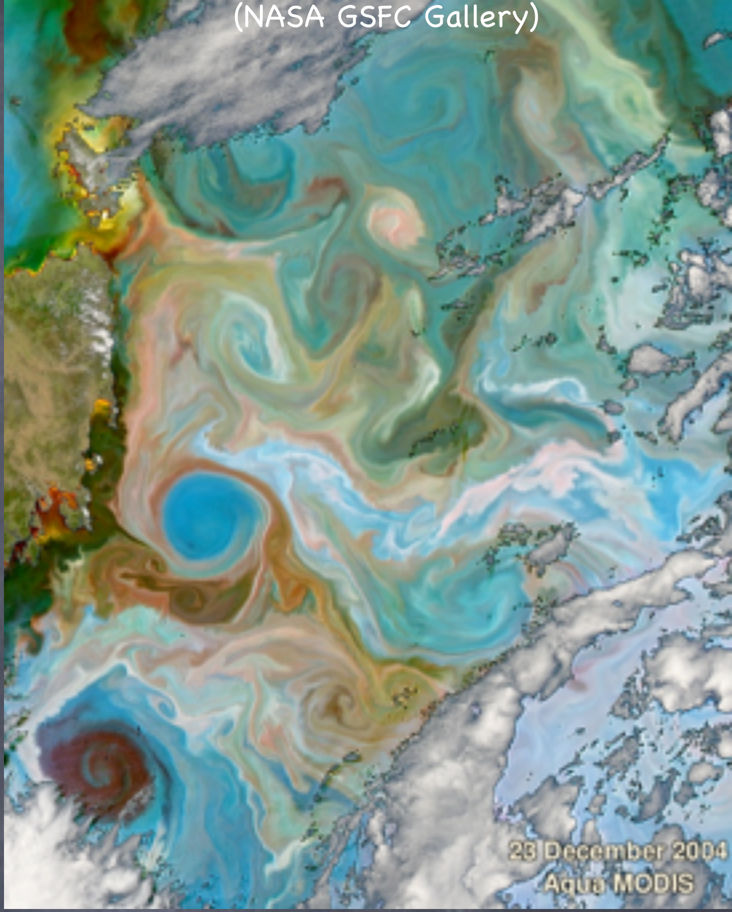
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations of submesoscale baroclinic instability?

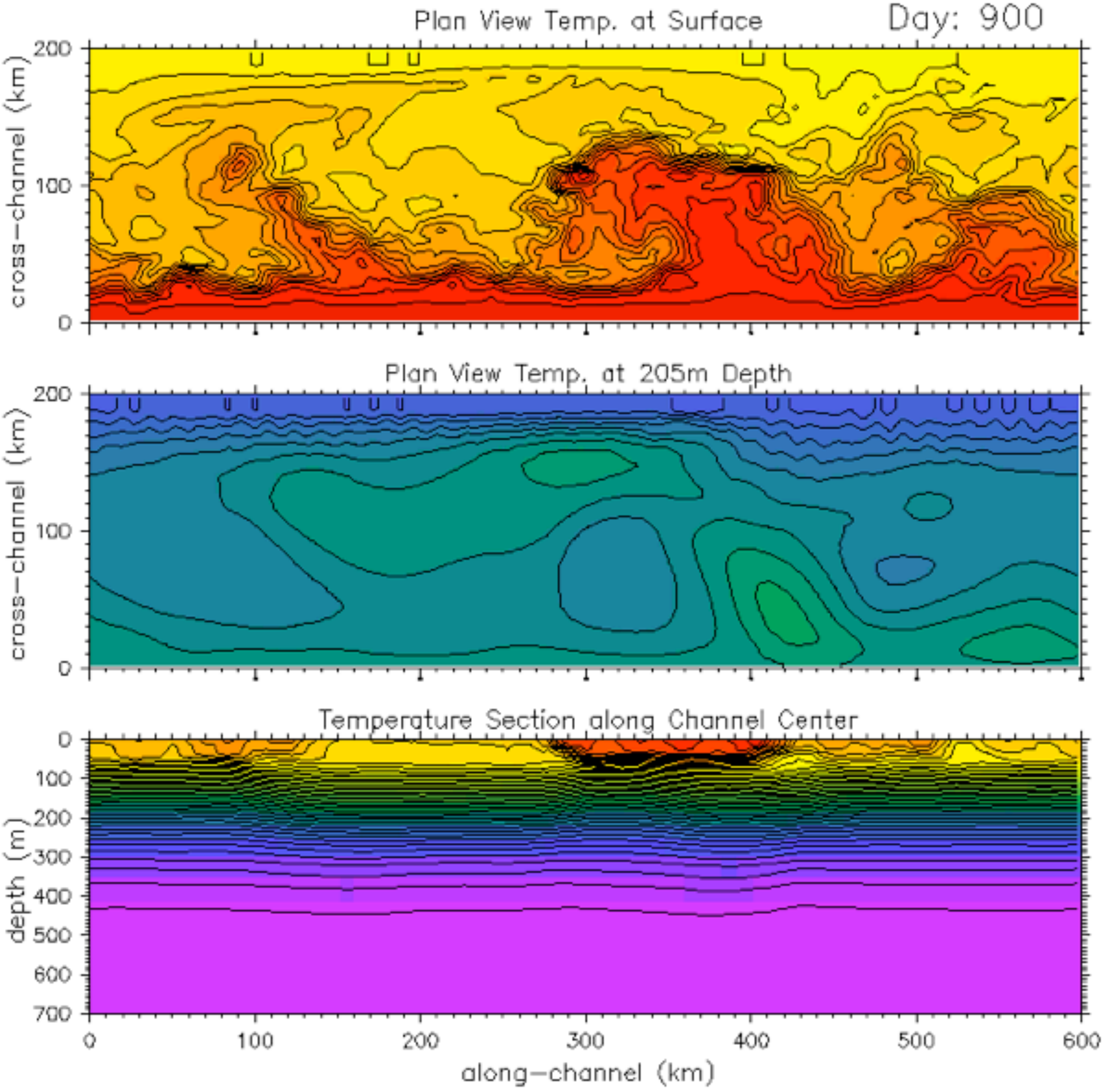
(NASA GSFC Gallery)

← 10 km



B. Fox-Kemper, 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

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



Big, Deep (mesoscale eddies)

interact with

Little, Shallow (submeso eddies)

B. Fox-Kemper, 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.

Needed Process: Mesoscale Eddies

(Capet et al., 2008)

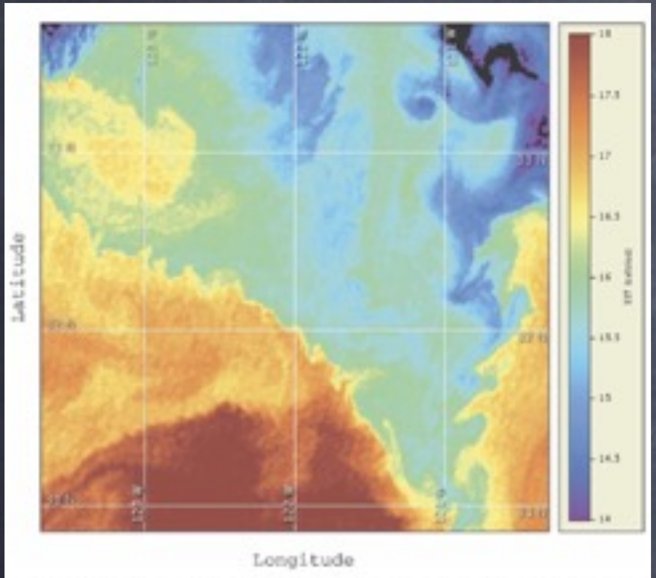
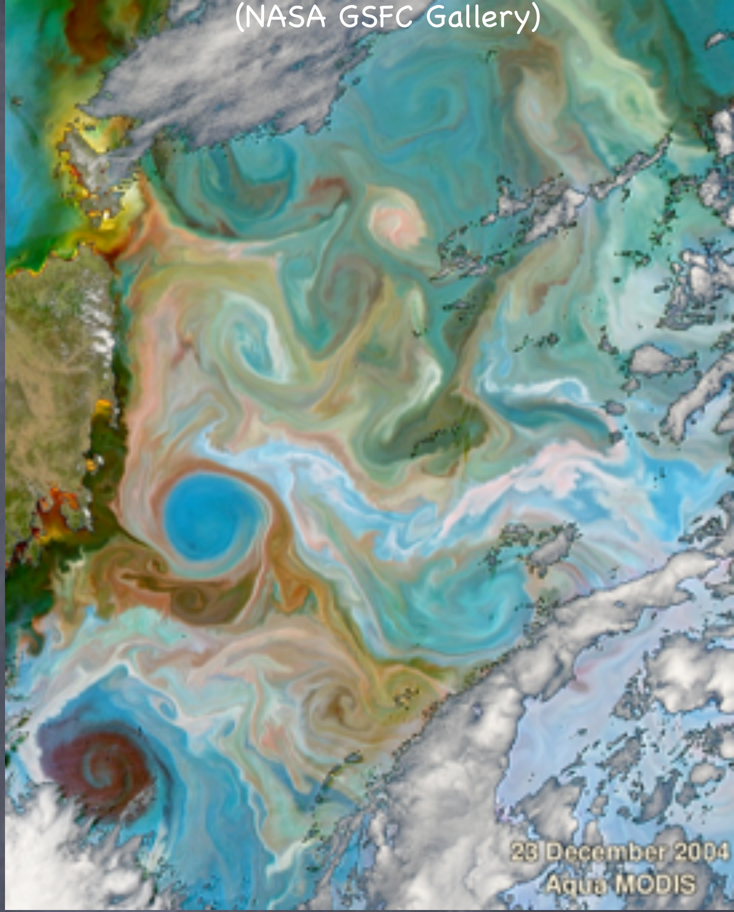


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (>17°C) show submesoscale instabilities with wavelengths around 30 km (right front) or 15 km (left front). Images for 1 day earlier and 4 days later show persistence of the instability events.

- Boundary Currents
- Eddies
- Ro=O(0.1)
- Ri=O(1000)
- Full Depth
- Quasi-2d
- Eddies strain to produce Fronts
- 100km, months

← 100 km

(NASA GSFC Gallery)



Eddy processes mainly baroclinic & barotropic instability. Quasigeostrophy is likely to be very accurate.

What is a parameterization/subgrid model?

Fluid equations for A&O are PDEs (Rotating, Stratified Navier-Stokes), but we cannot resolve to dissipation, so we use statistical or bulk subgrid models to capture multiscale interactions:

- Express the coarse-grain averages of quantities (including the subgrid effects), e.g.:

$$\overline{\frac{\partial \tau}{\partial t}} \qquad \overline{\frac{\partial u}{\partial x}} \qquad \overline{\frac{\partial u\tau}{\partial x}}$$

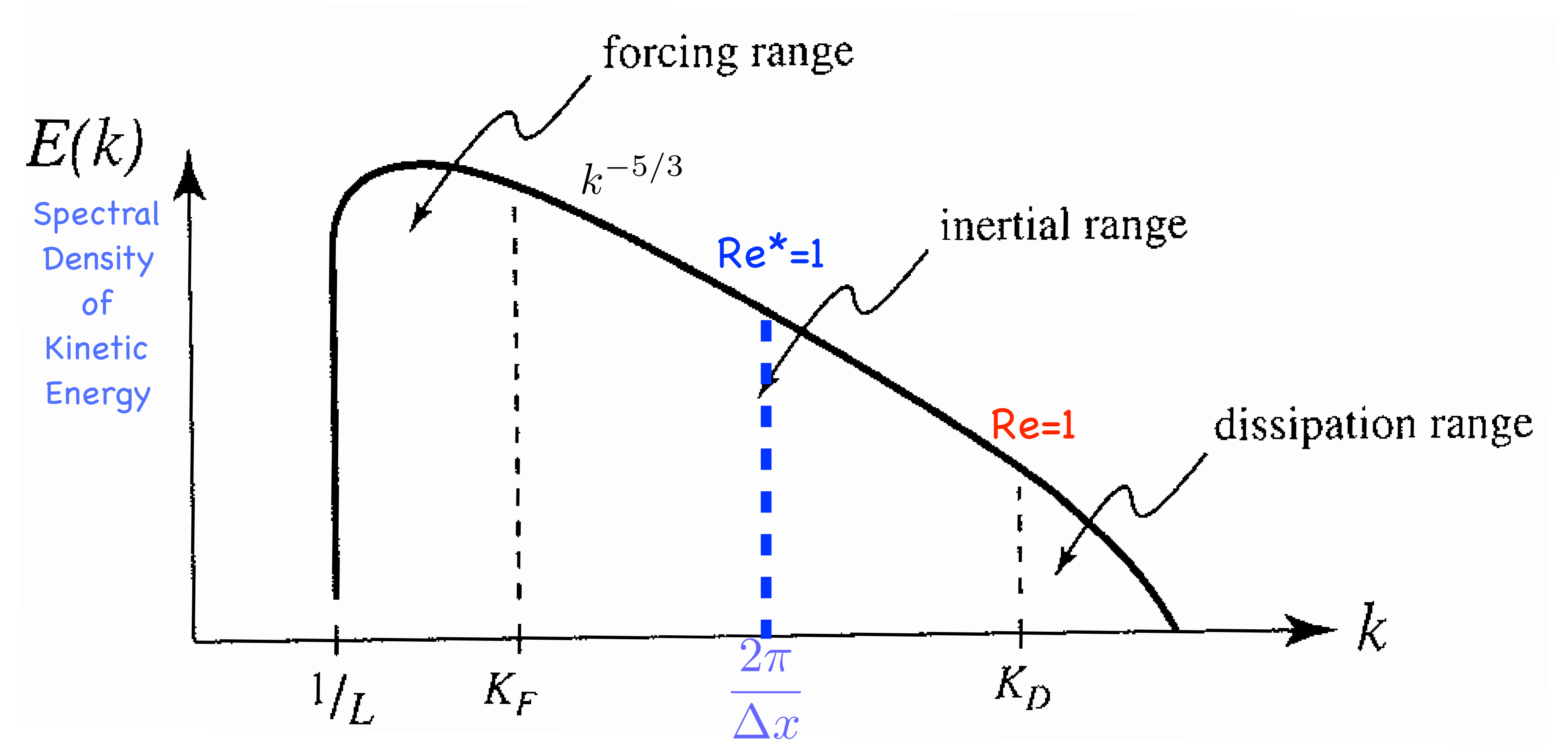
- As a function of the resolved coarse-grain fields

$$\overline{\frac{\partial \tau}{\partial t}} = \frac{\partial \overline{\tau}}{\partial t} \qquad \overline{\frac{\partial u}{\partial x}} = \frac{\partial \overline{u}}{\partial x} \qquad \overline{\frac{\partial u\tau}{\partial x}} = \frac{\partial \overline{u}\;\overline{\tau}}{\partial x} + \frac{\partial \overline{u'\tau'}}{\partial x}$$

- Note that nonlinear terms require special treatment
- These couple different scales, small talks to large

Kolmogorov ’41

3D Turbulence Cascade



1963: Smagorinsky Scale & Flow Aware Viscosity Scaling,

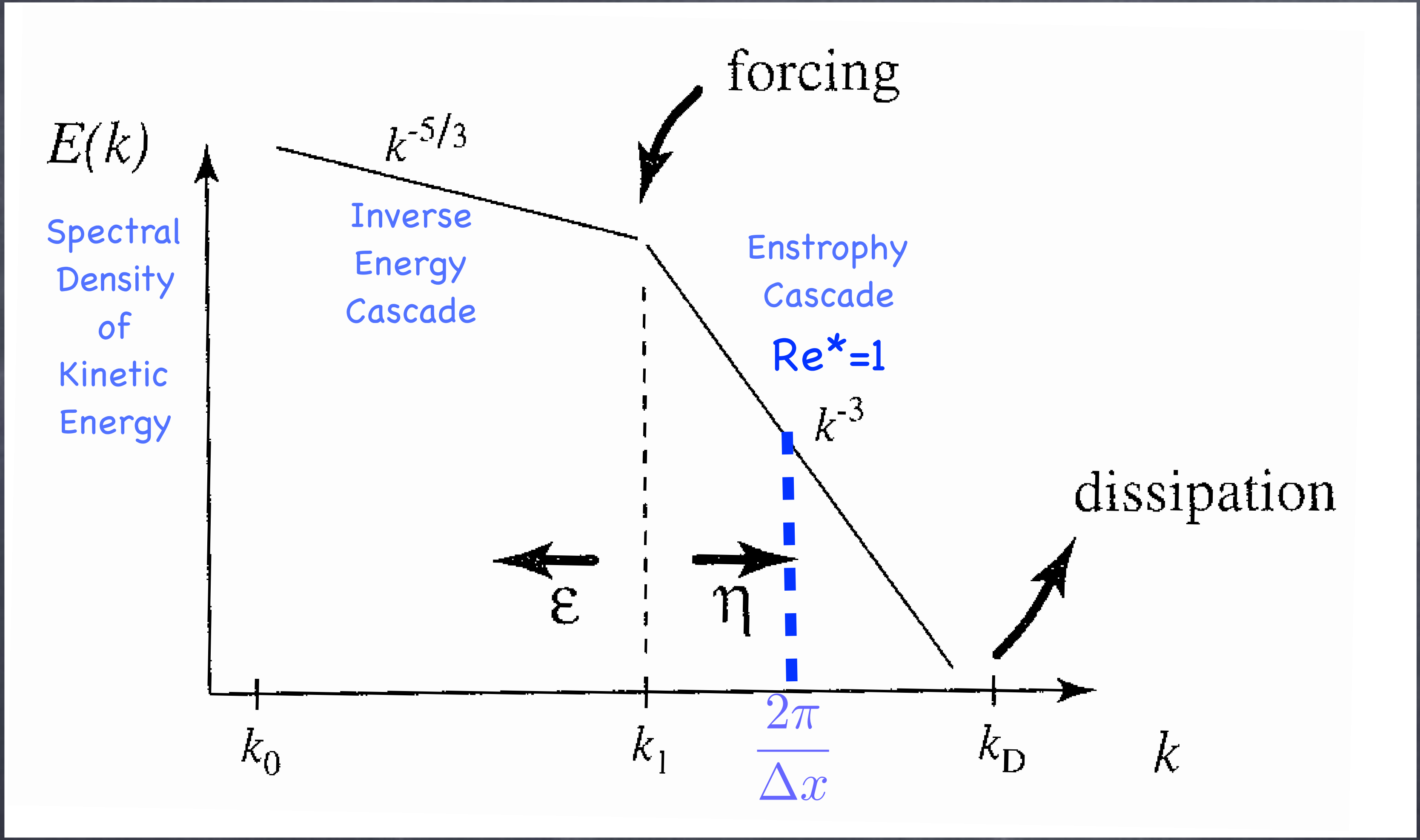
So the Energy Cascade is Preserved,

but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

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

2D Turbulence Differs

R. Kraichnan, 1967 JFM

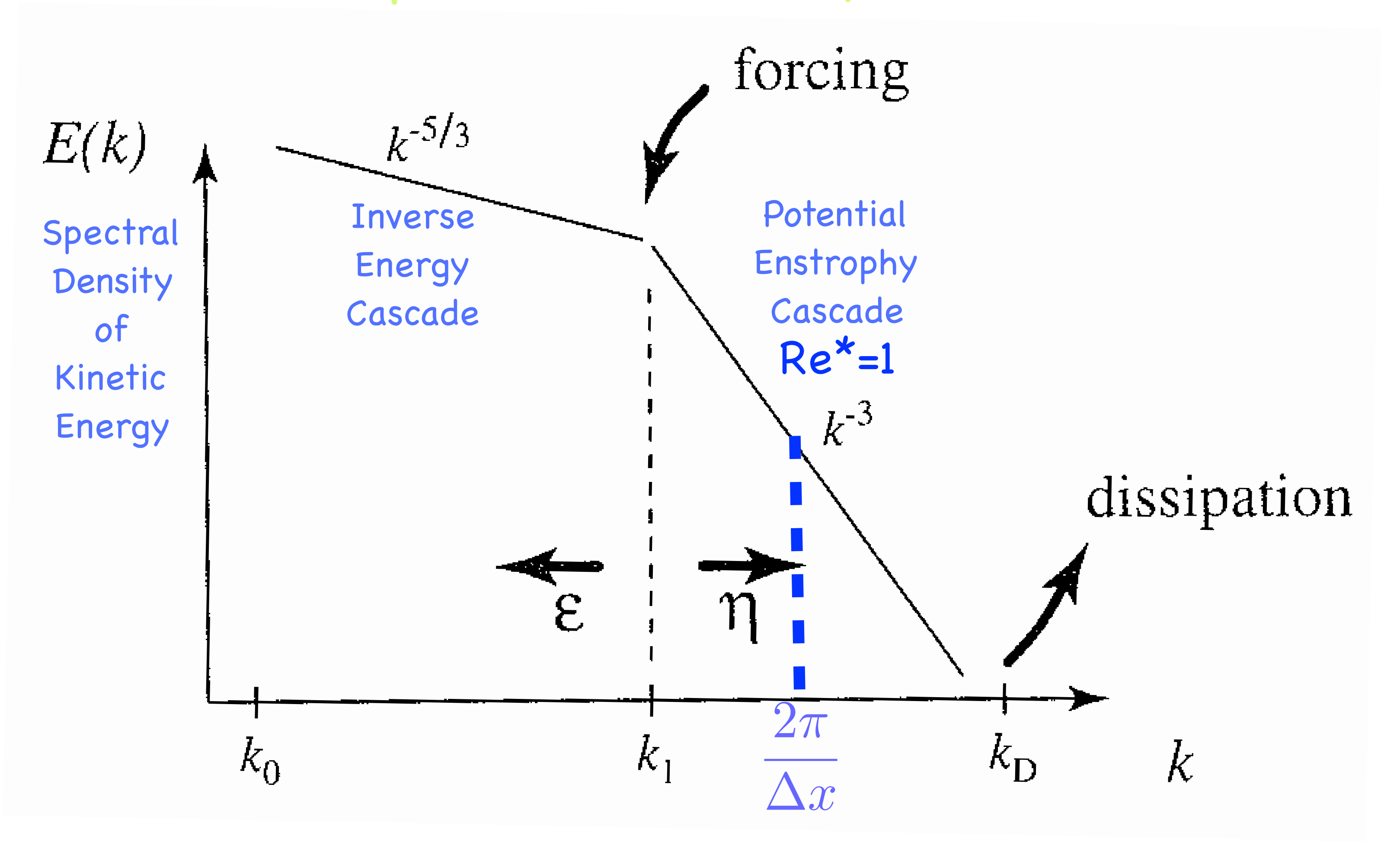


1996: **Leith** Devises Viscosity Scaling,
So that the Enstrophy (vorticity^2) Cascade is Preserved

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

Mesoscale (QG) Turbulence: Pot'l Enstrophy cascade (potential vorticity^2)

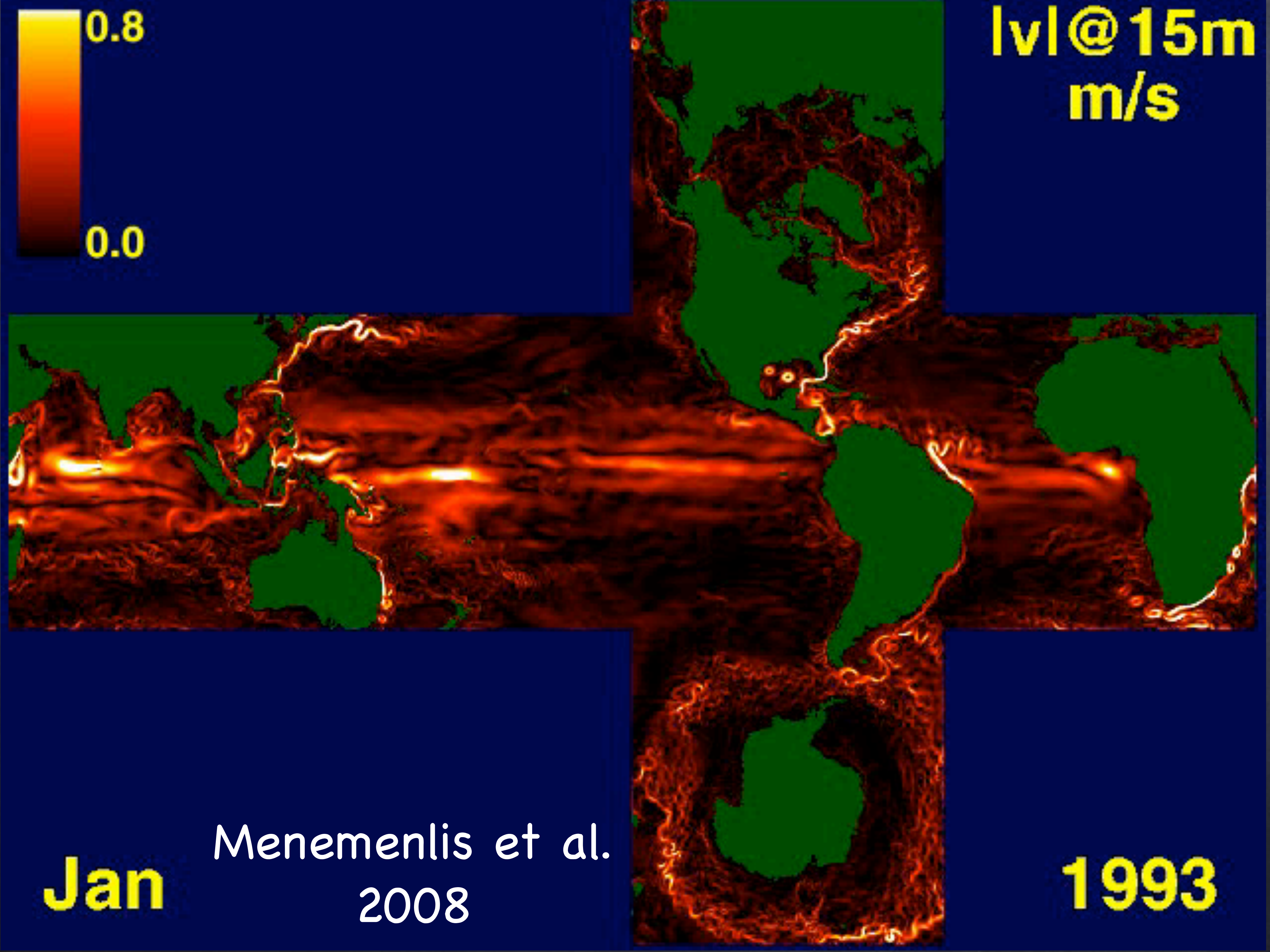
J. Charney, 1971 JAS



F-K & Menemenlis '08: Revise Leith Viscosity Scaling, So that diverging, vorticity-free, modes are also damped

$$\nu_* = \left(\frac{\Delta x}{\pi}\right)^3 \sqrt{\Lambda^6|\nabla_h q_{2d}|^2 + \Lambda_d^6|\nabla_h(\nabla_h \cdot \mathbf{u}_*)|^2}$$

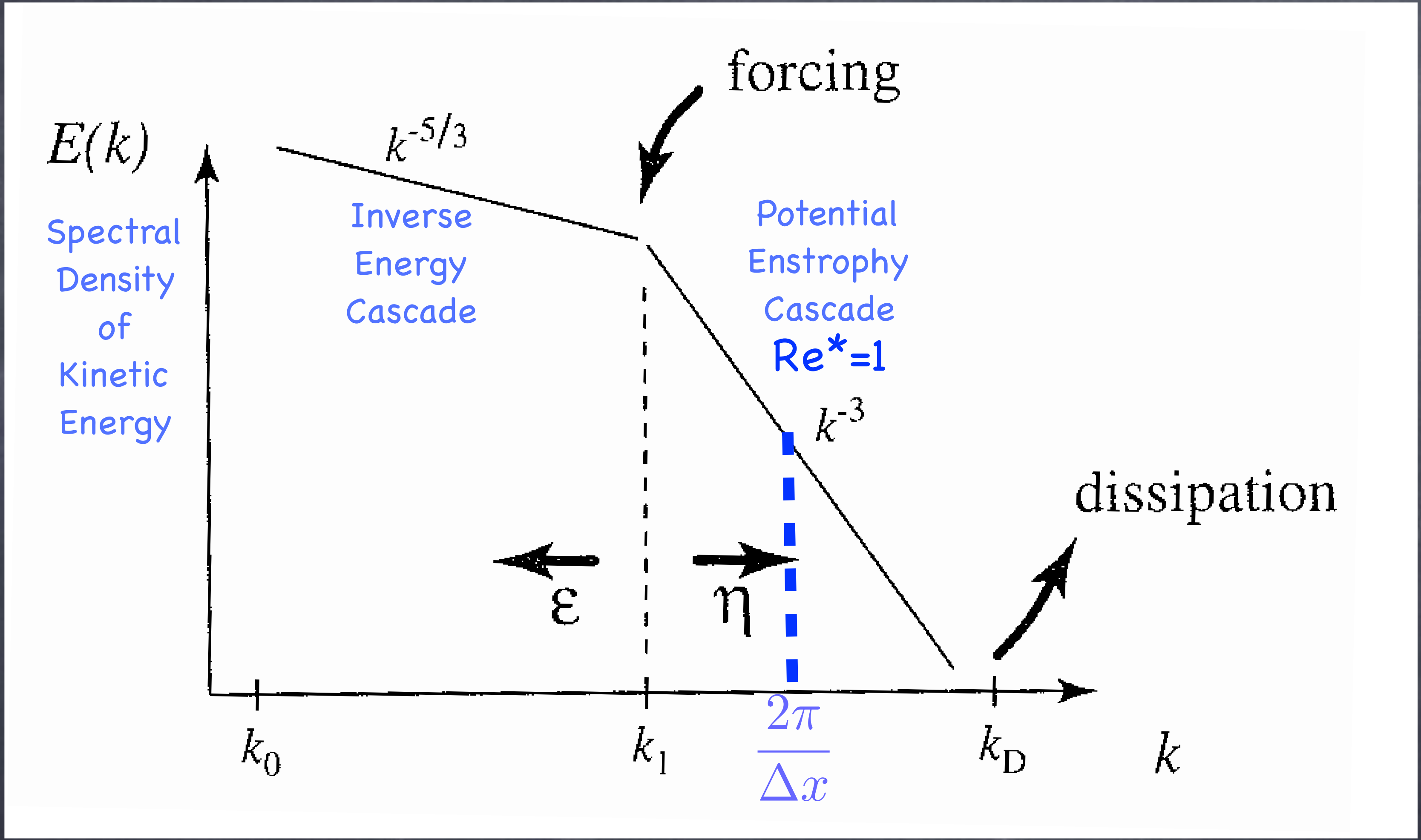
B. Fox-Kemper and D. Menemenlis. Can large eddy simulation techniques improve mesoscale-rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319-338. AGU Geophysical Monograph Series, 2008.



Menemenlis et al.
2008

Mesoscale (QG) Turbulence: Pot'l Enstrophy cascade (potential vorticity²)

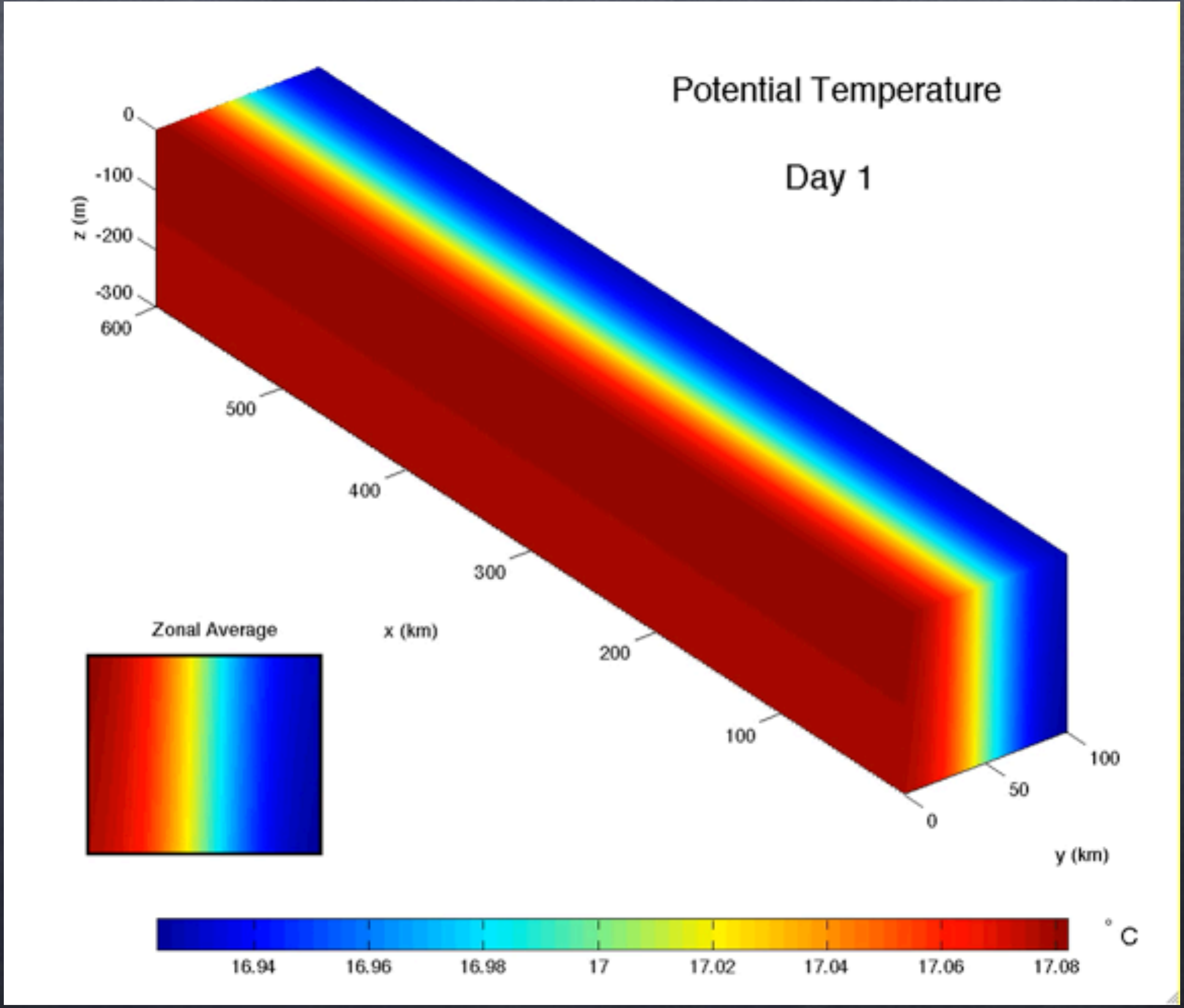
J. Charney, 1971 JAS



F-K & Menemenlis '08 Conjecture: a more ambitious course would combine the best aspects of coarse resolution ocean models (mesoscale eddy dynamics) with the adaptive methods (numerics and scaling laws instead of fixed coefficients) typical of higher-resolution large eddy simulations.

Trying out the Conjecture (with S. Bachman, former PhD)

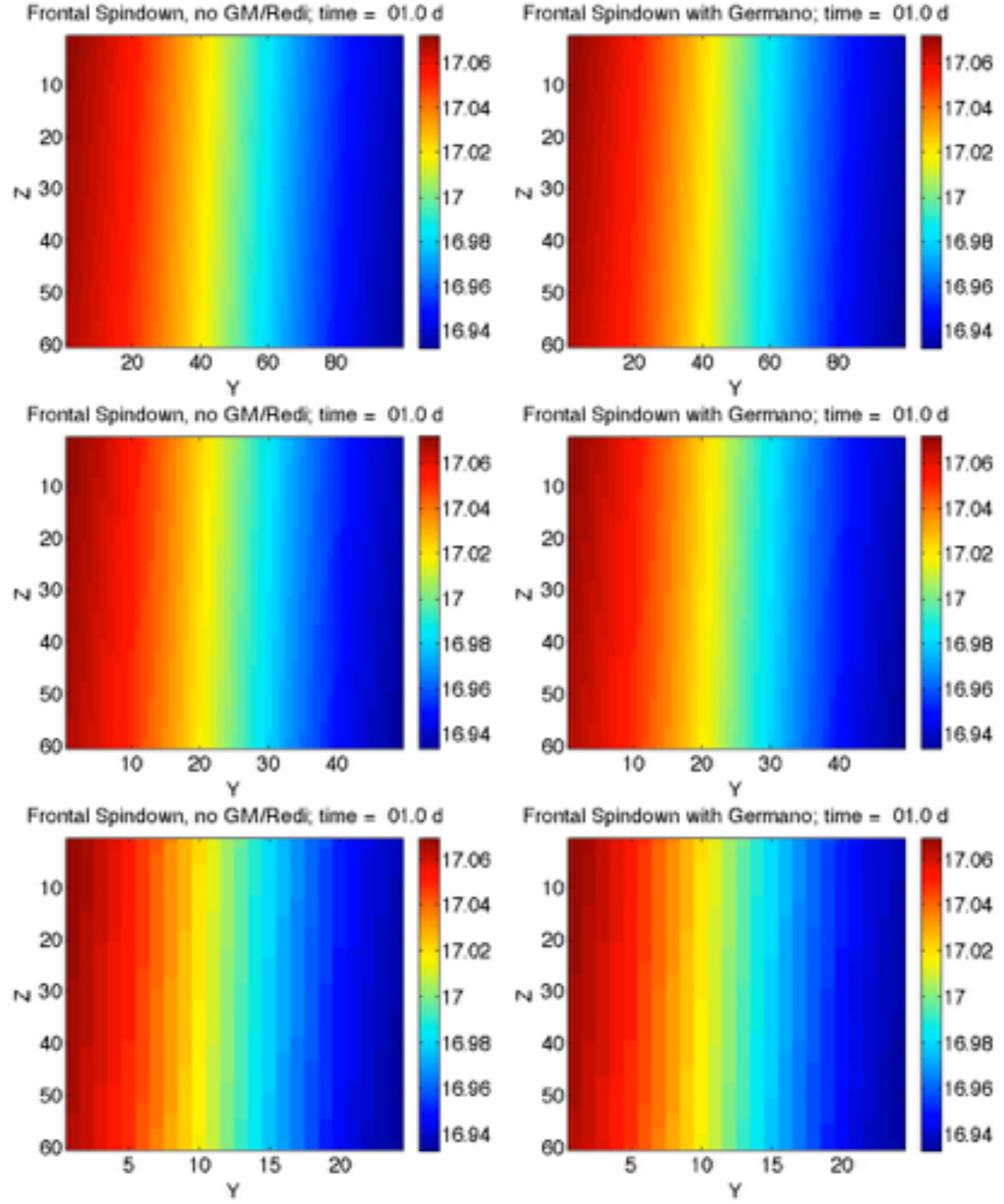
Evolution of a Temperature Front



A Recent Step Forward
(with S. Bachman, former PhD)

Old

New

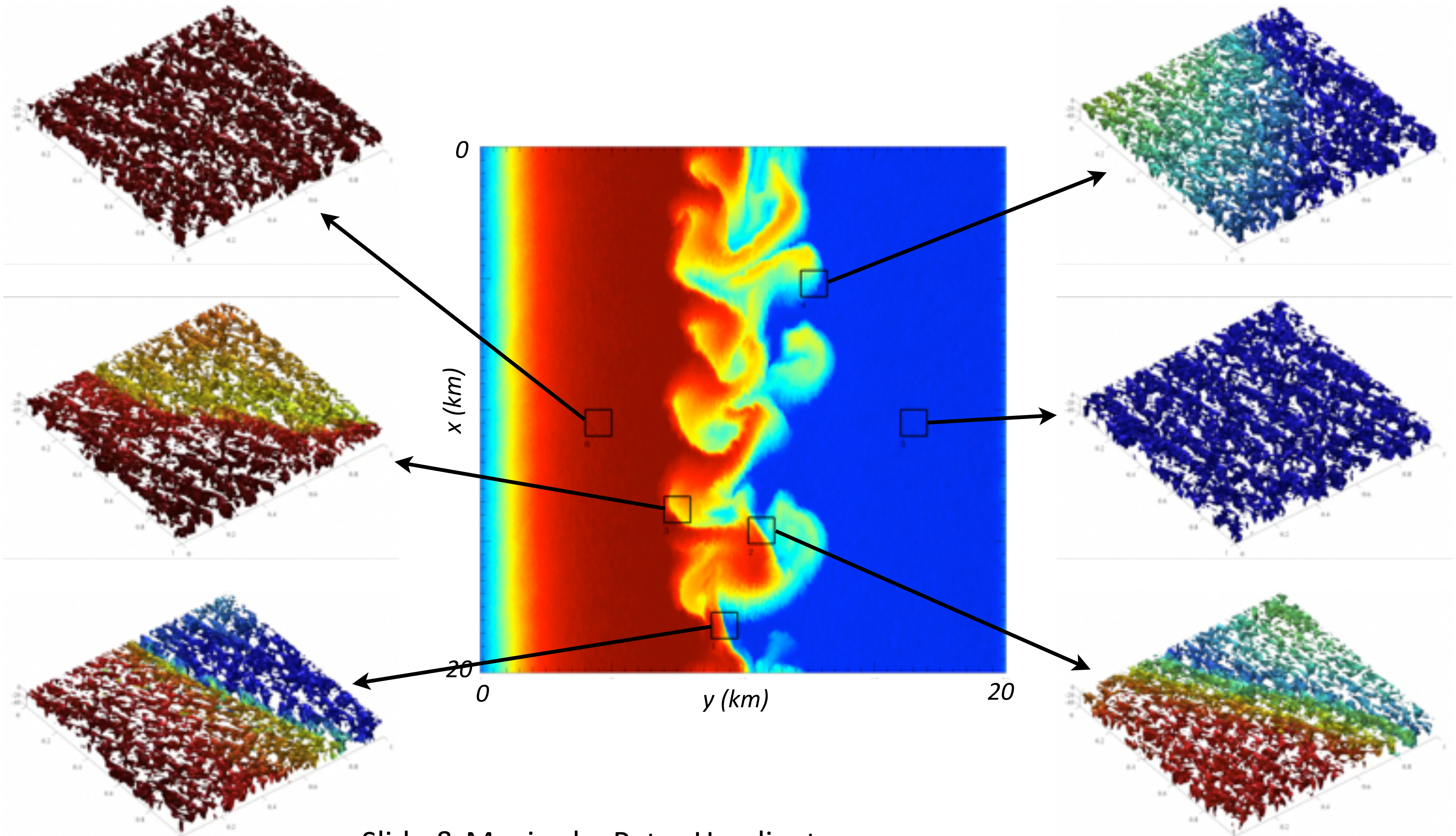


Instead of using the least viscosity and diffusivity numerically possible

We estimate the rate of pot'l enstrophy transfer to small scale

Matching this rate provides a dynamically accurate scaling of all mesoscale eddy parameters-- still numerically OK!!

Diverse types of interaction--Can a simple spectral transfer suffice?

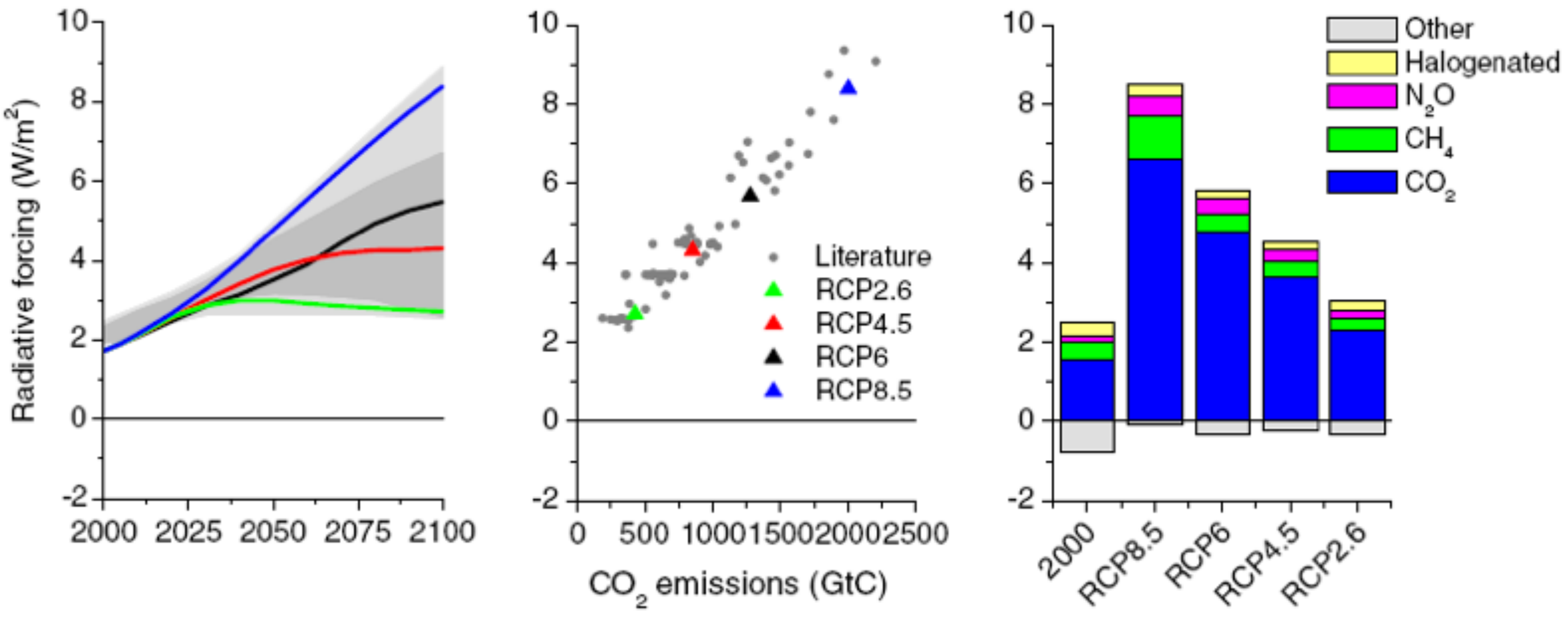


Slide & Movies by Peter Hamlington

P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale simulations. Submitted, 2013.

The Future?

- The IPCC AR5 scenarios envision a range of planetary energy imbalances: (5x to 40x variations in S_0)
- These Representative Concentration Pathways estimate a range of our possible policy choices



van Vuuren 2011

The Future?

2007 Report 2013 Report

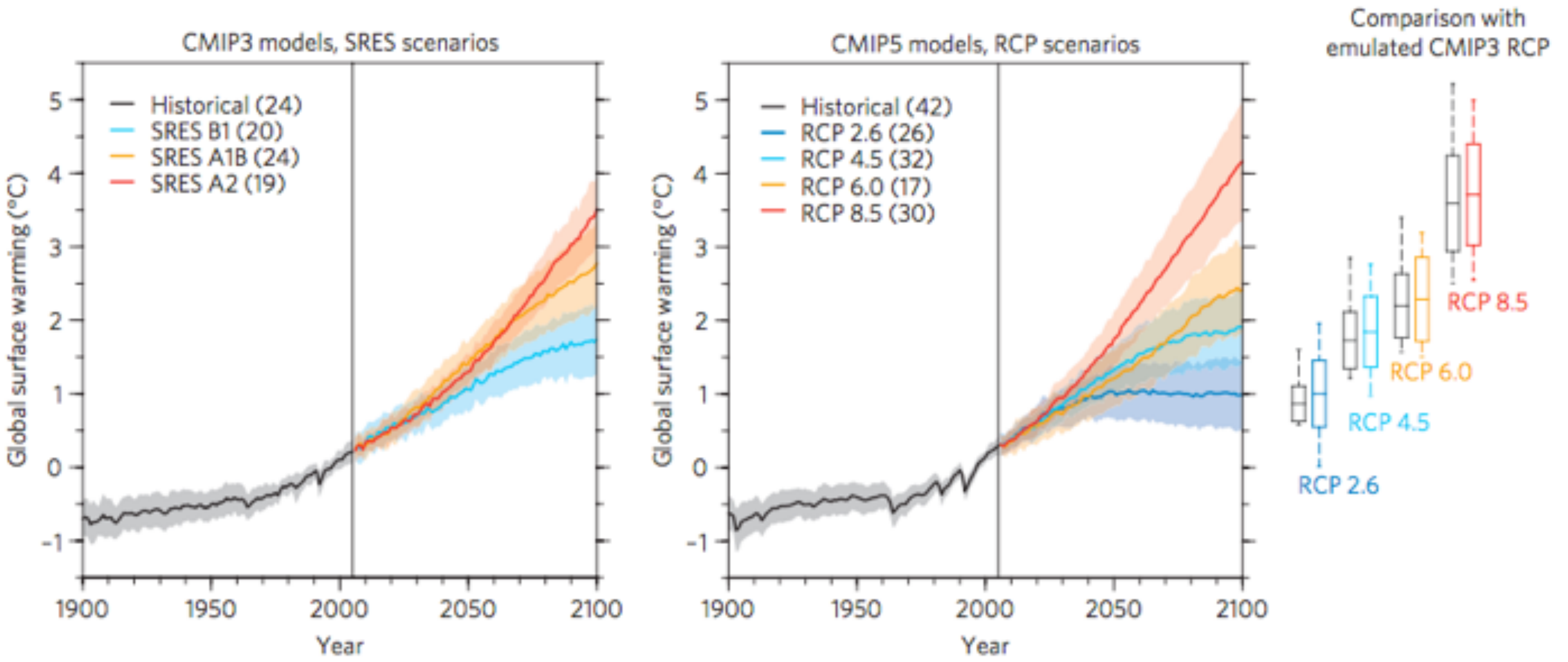
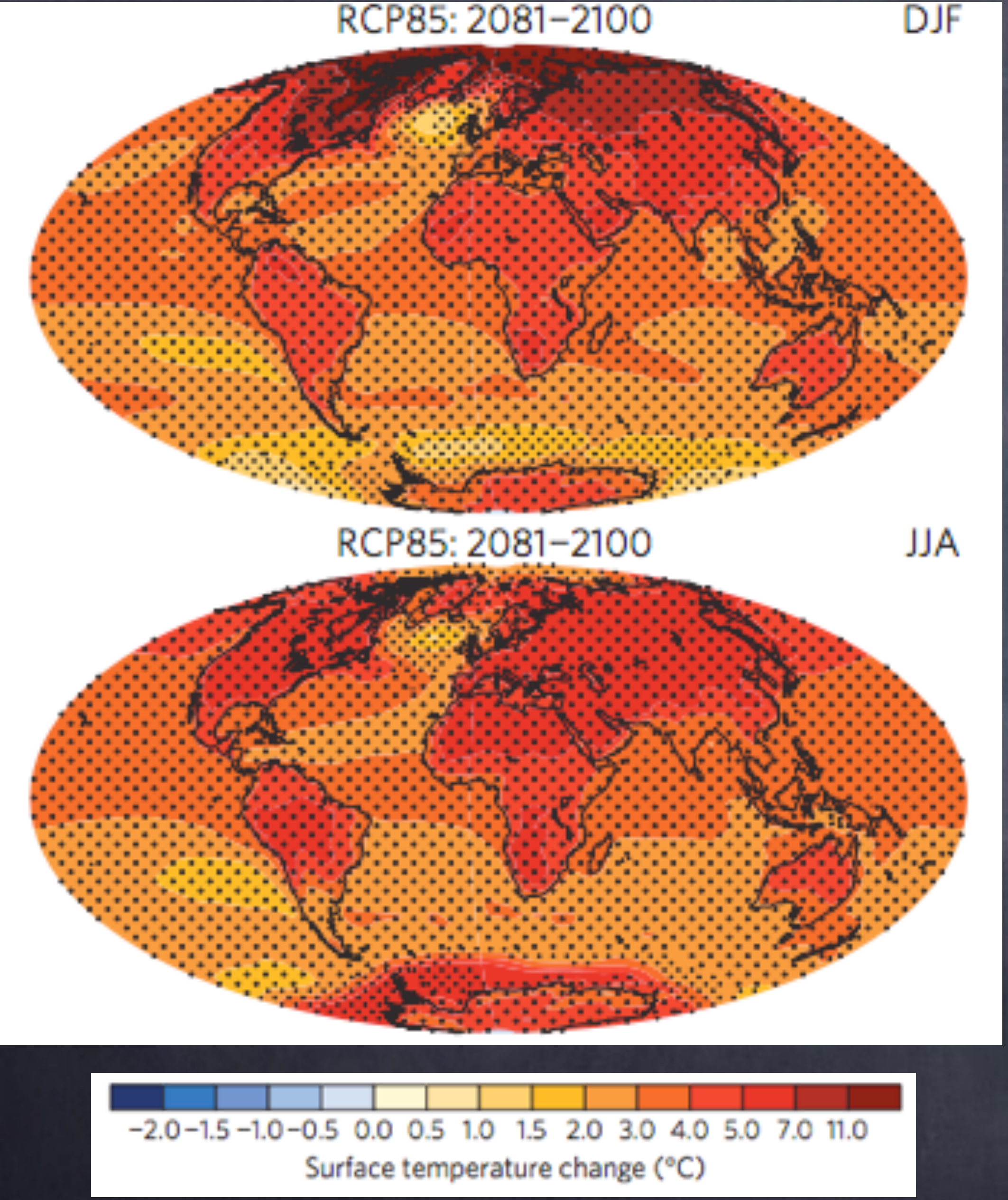
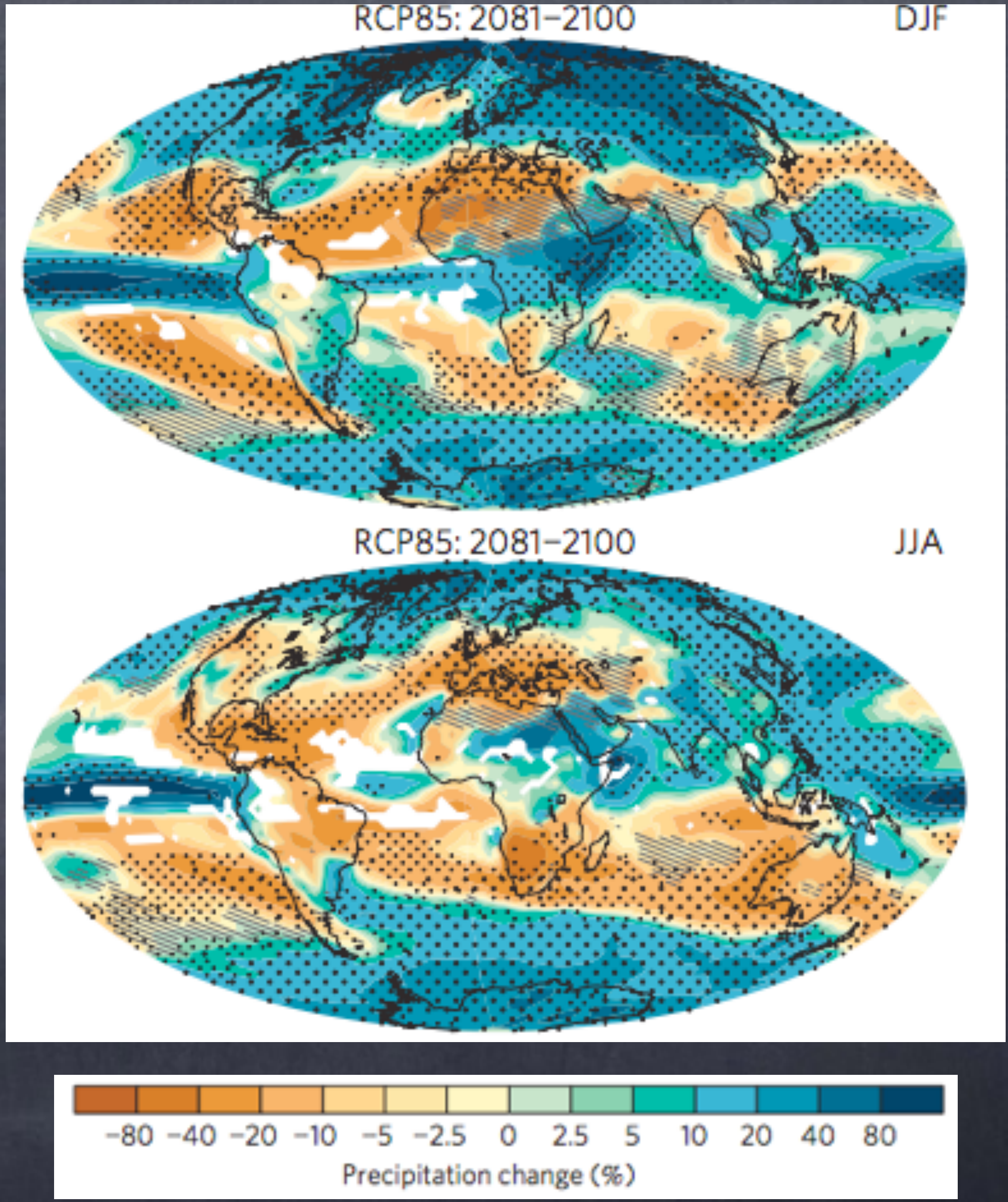


Figure 1 | Global temperature change and uncertainty. Global temperature change (mean and one standard deviation as shading) relative to 1986-2005 for the SRES scenarios run by CMIP3 and the RCP scenarios run by CMIP5. The number of models is given in brackets. The box plots (mean, one standard deviation, and minimum to maximum range) are given for 2080-2099 for CMIP5 (colours) and for the MAGICC model calibrated to 19 CMIP3 models (black), both running the RCP scenarios.

Will the next round be different due to mesoscale eddies? Probably not in global mean, but in regions:

The Future?





Stippling Indicates High Robustness (Knutti & Sedlácek, 2013)

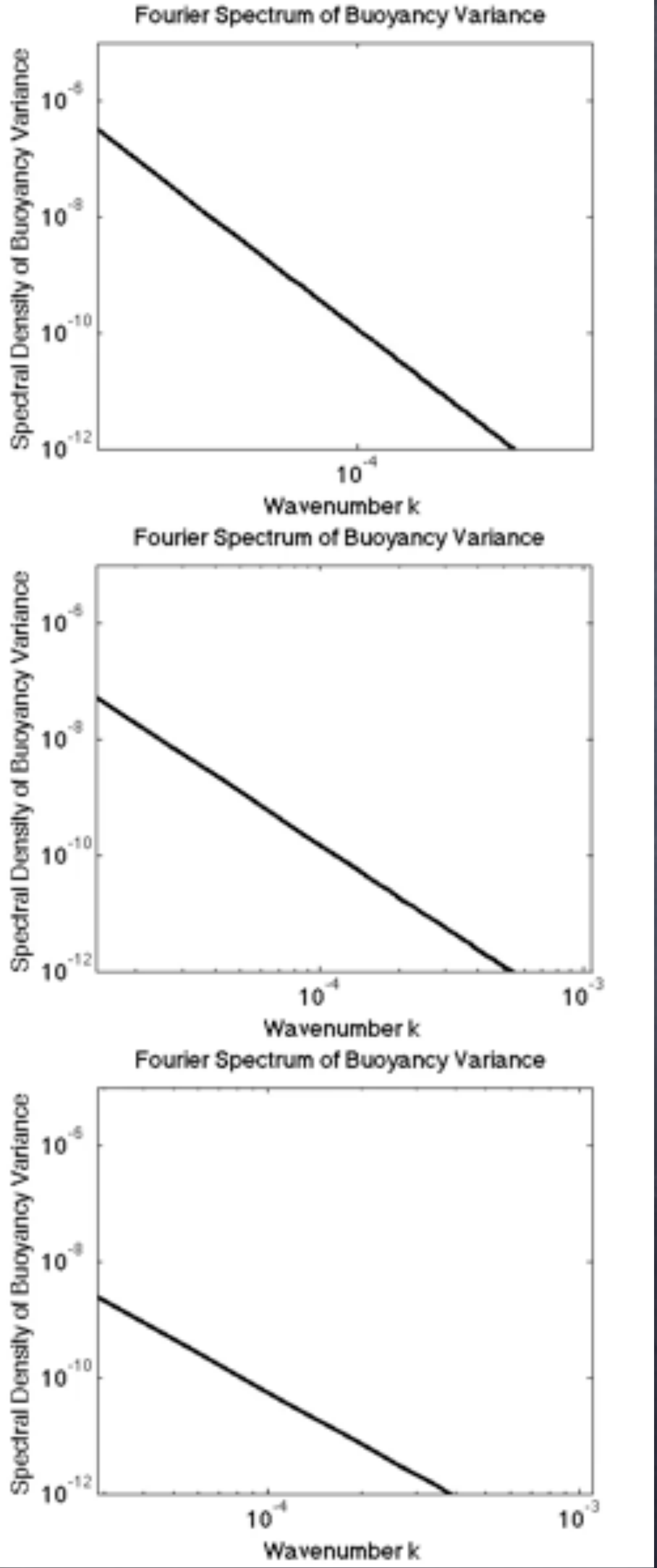
Conclusions

- Climate modeling is challenging partly due to the vast and diverse scales of fluid motions
- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute non-negligibly to the air-sea exchange
- Process models, especially those spanning a whole or multiple scales, are needed to study these connections and improve subgrid models.
- Even with increasing computational capability, process and scale-specific adaptations are necessary to represent what remains unresolved.

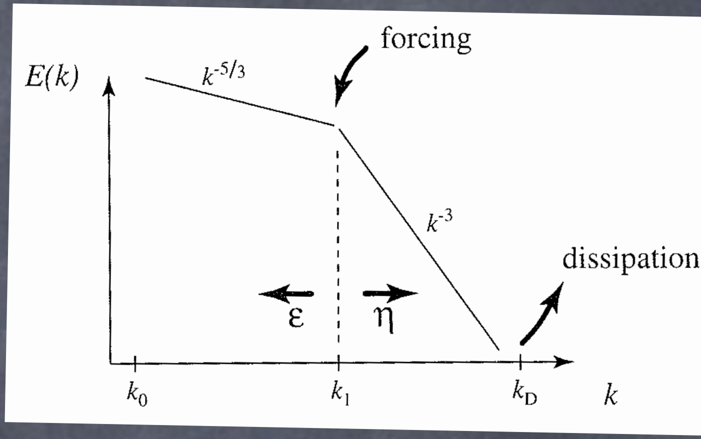
ALL PAPERS AT fox-kemper.com/pubs

EXTRA SLIDES FOLLOW

A Recent Step Forward
(with S. Bachman, former PhD)



Instead of using the least viscosity and diffusivity numerically possible



We estimate the rate of pot'l enstrophy transfer to small scale

Matching this rate provides a dynamically accurate scaling of all mesoscale eddy parameters--still numerically OK!!

Mixed Layer Eddy Restratification

Estimating eddy buoyancy/density fluxes:

$$\overline{\mathbf{u}'b'} \equiv \mathbf{\Psi} \times \nabla \bar{b}$$

A submes

$$\mathbf{\Psi} = \frac{C}{-}$$

$\mu(z)$

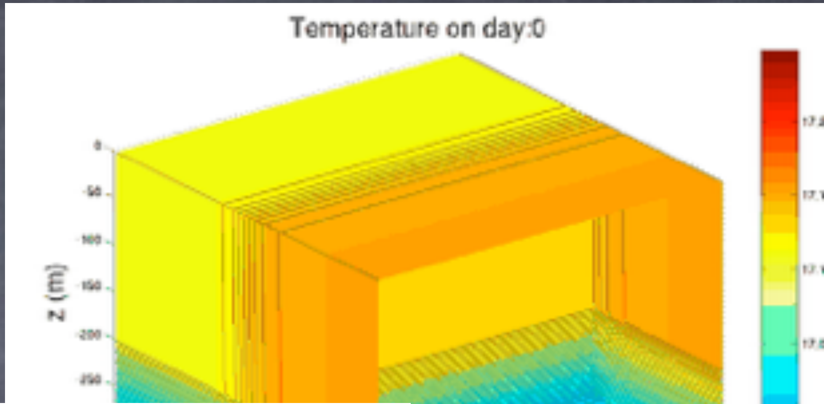
For a con

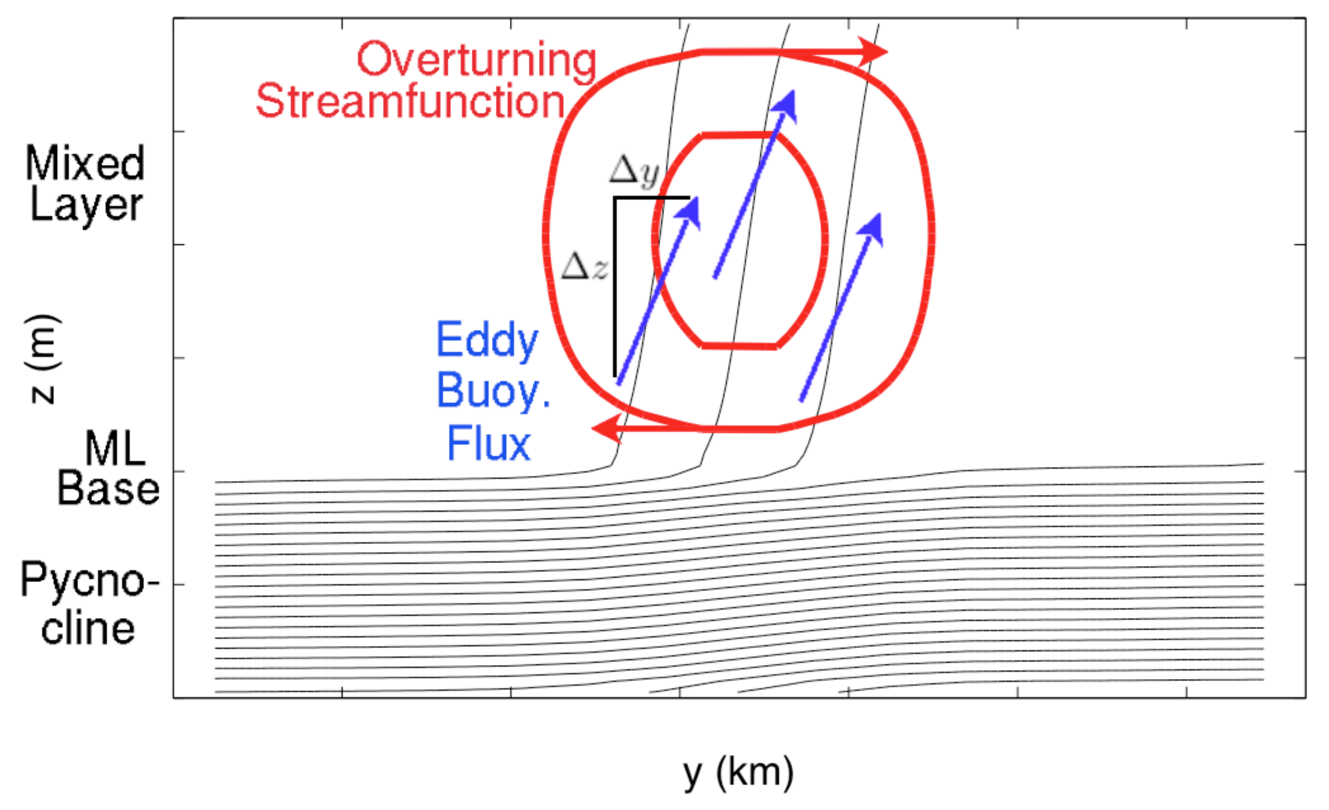
$$\overline{w'b'}$$

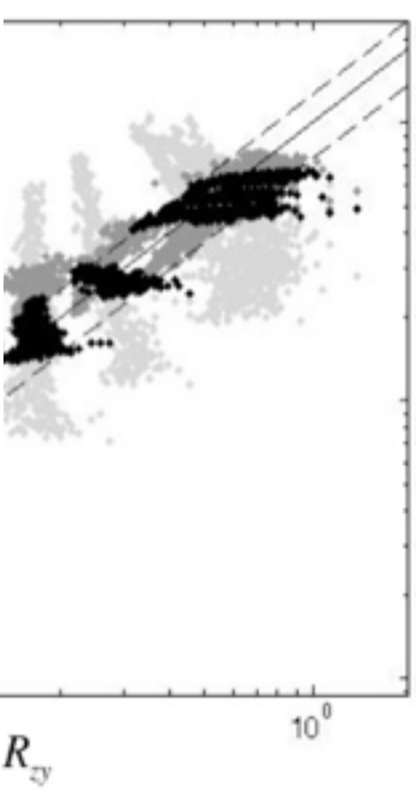
$|f|$

and horizontally downgradient flux.

$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b}$$



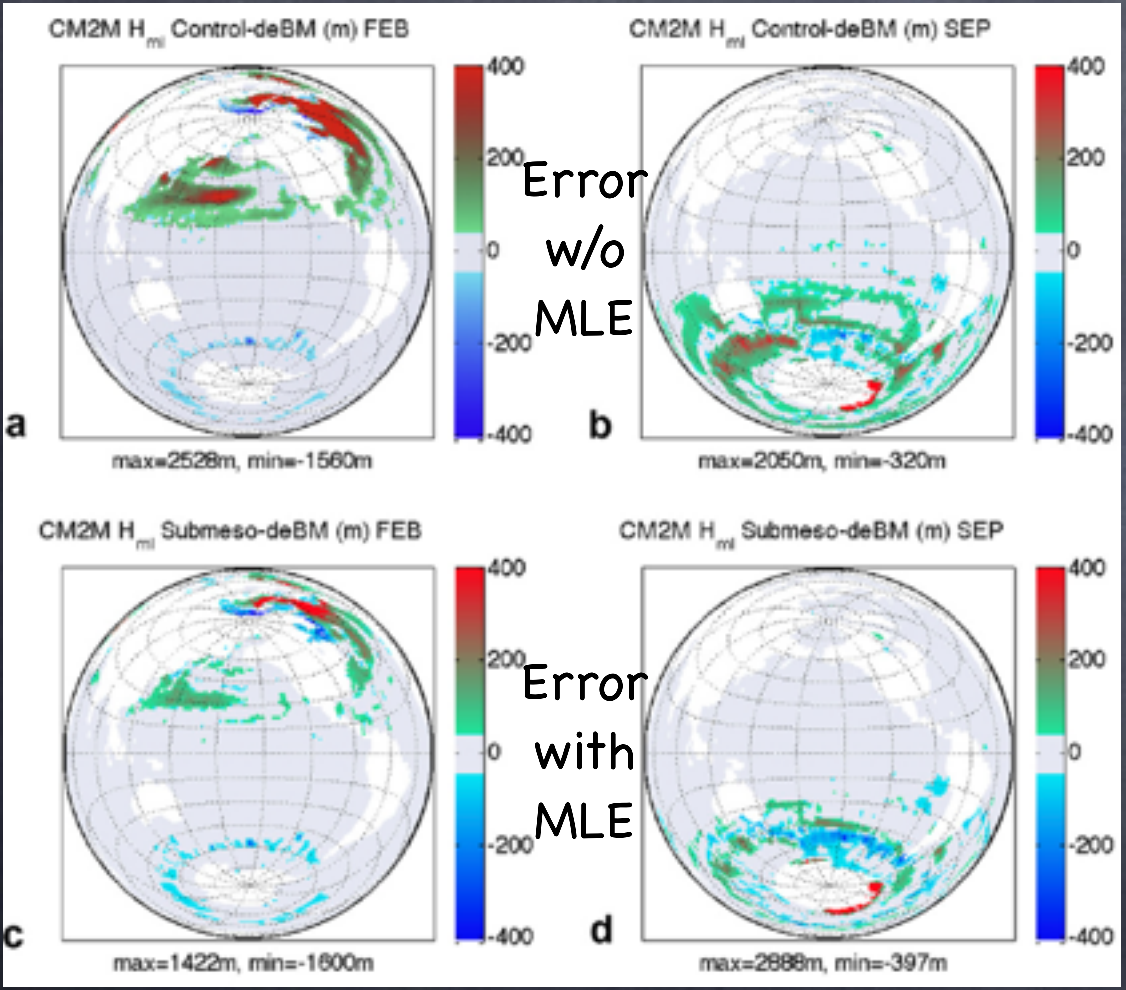




S. Bachman and B. Fox-Kemper. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Physical Sensitivity of Ocean Climate to MLE: (submeso) Mixed Layer Eddy Restratification

Improves CFCs (water masses)

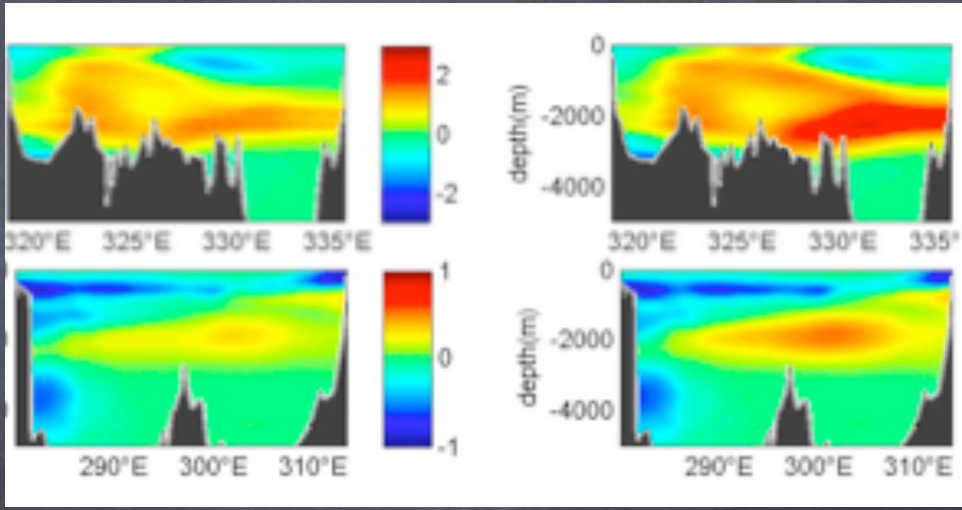


Error w/o MLE

Error with MLE

Bias with MLE

Bias w/o MLE



A consistently restratifying,

$$\overline{w'b'} \propto \frac{H^2}{|f|}\left|\nabla_H \bar{b}\right|^2$$

and horizontally downgradient flux.

$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|}\nabla_H \bar{b}$$

B. Fox-Kemper, 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.

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

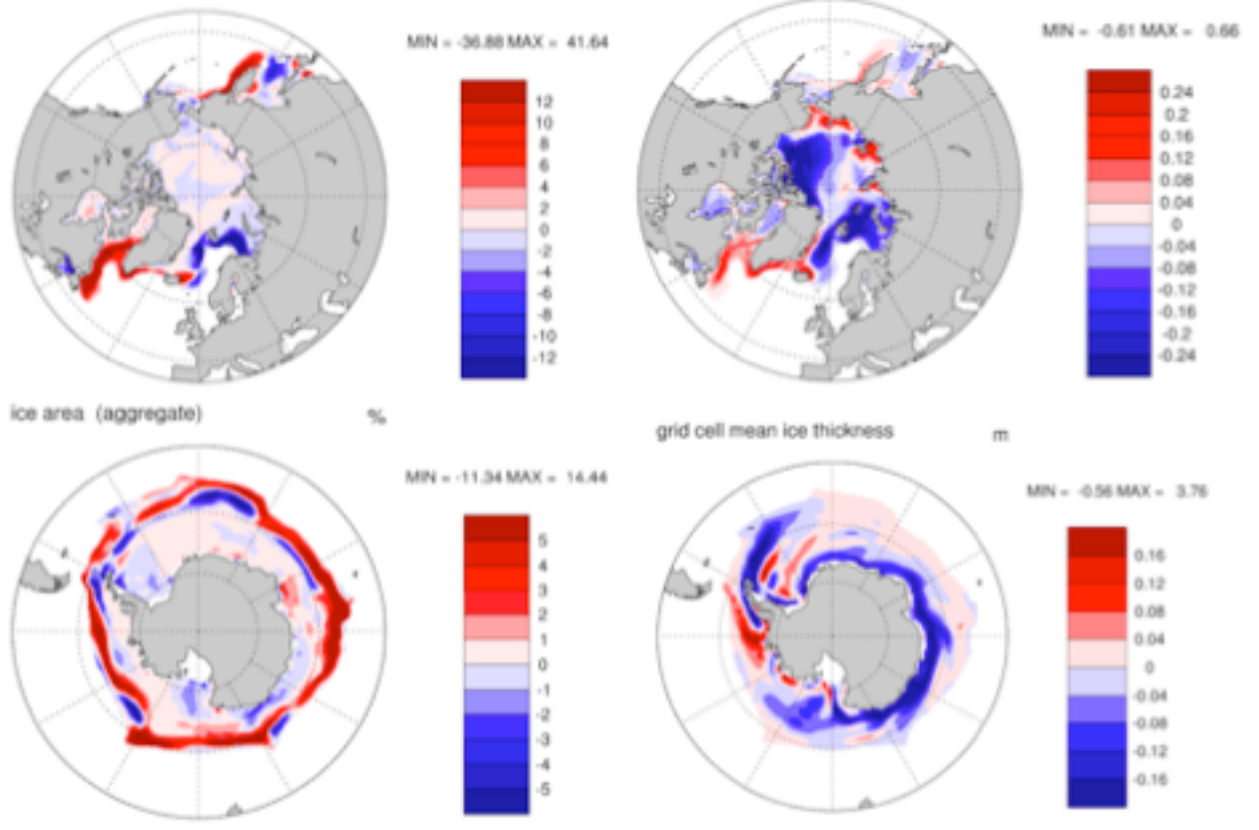
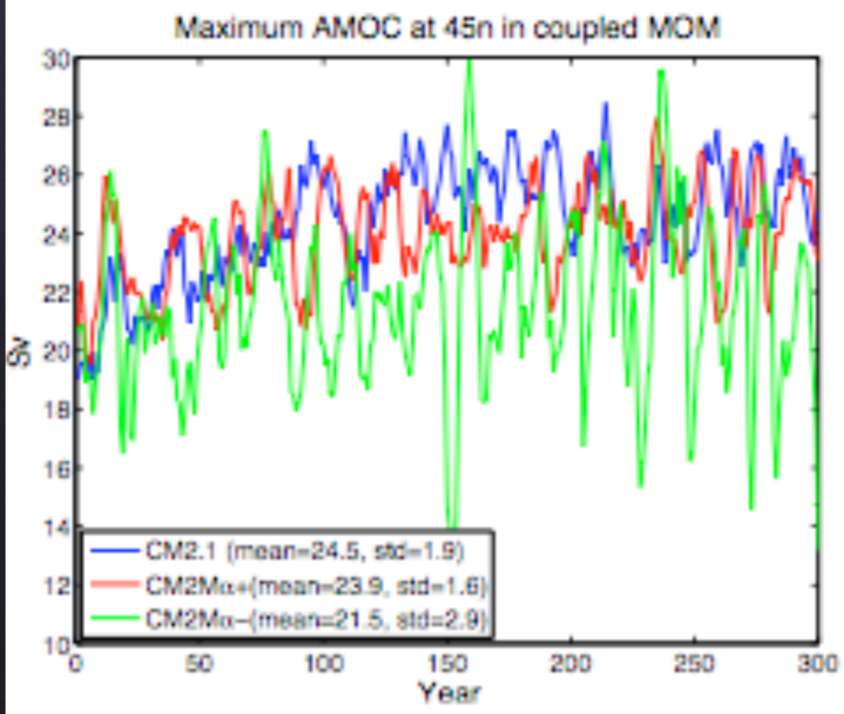


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization (CCSM$^+$ minus CCSM$^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

May Stabilize AMOC

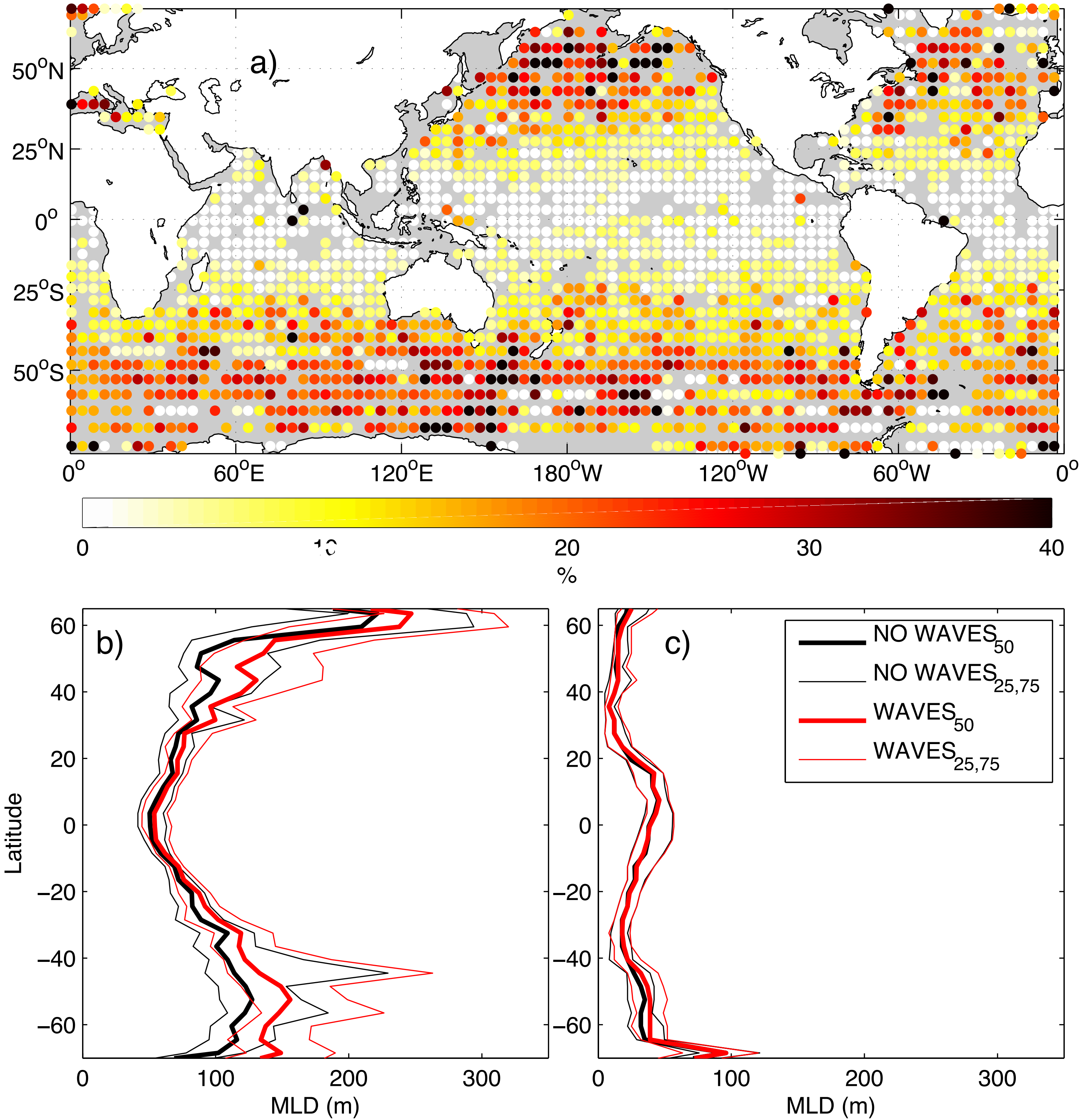


Affects sea ice

NO RETUNING NEEDED!!!

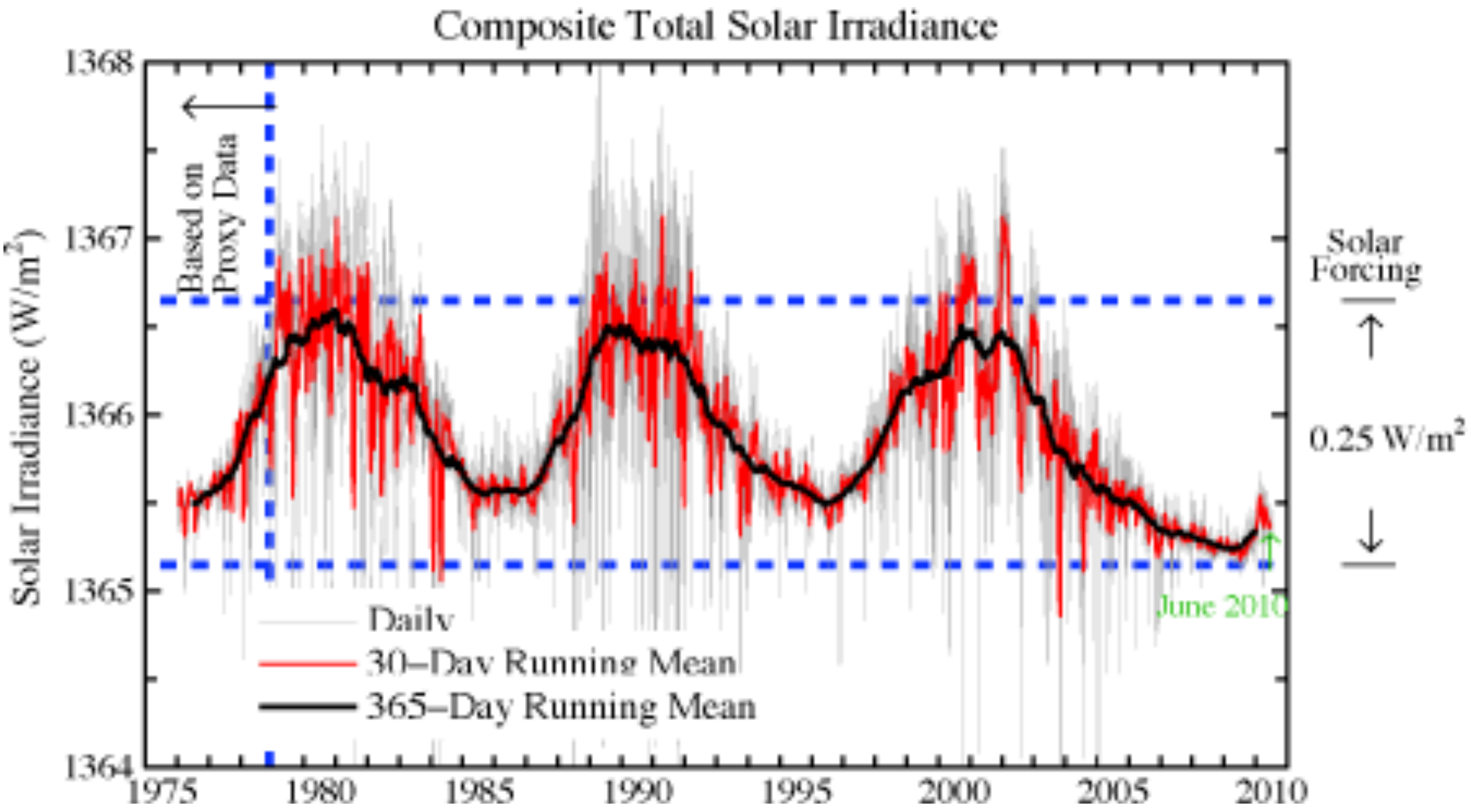
These are impacts: bias change unknown

Including Wave-driven Mixing (Harcourt 2013 parameterization) Deepens the Mixed Layer!



M. A. Hemer, B. Fox-Kemper, & R. R. Harcourt. Quantifying the effects of wind waves the the coupled climate system, in prep. 2013.

Solar “Constant” varies by 0.02%, changing T_e & T_s by about 0.005%=0.01K



Solar irradiance through June 2010 (from Fröhlich & Lean 2004, and PMOD/WRC).