Hyperthermals, Heat Death, and Hurricanes: Implications of a Hotter Eocene Hothouse

Matthew Huber, Purdue

KITP   Physics of Climate Change   May 14-16, 2008

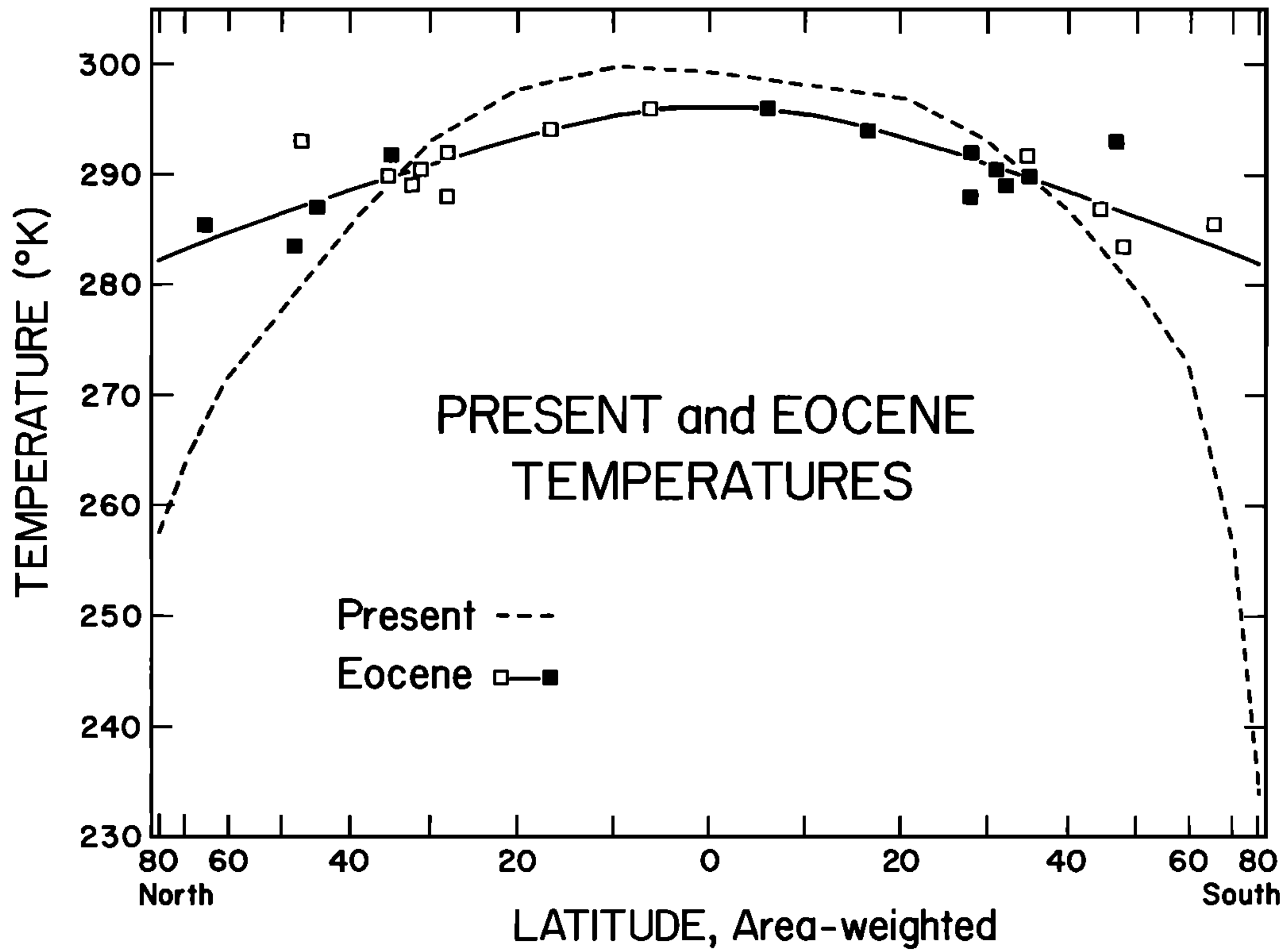
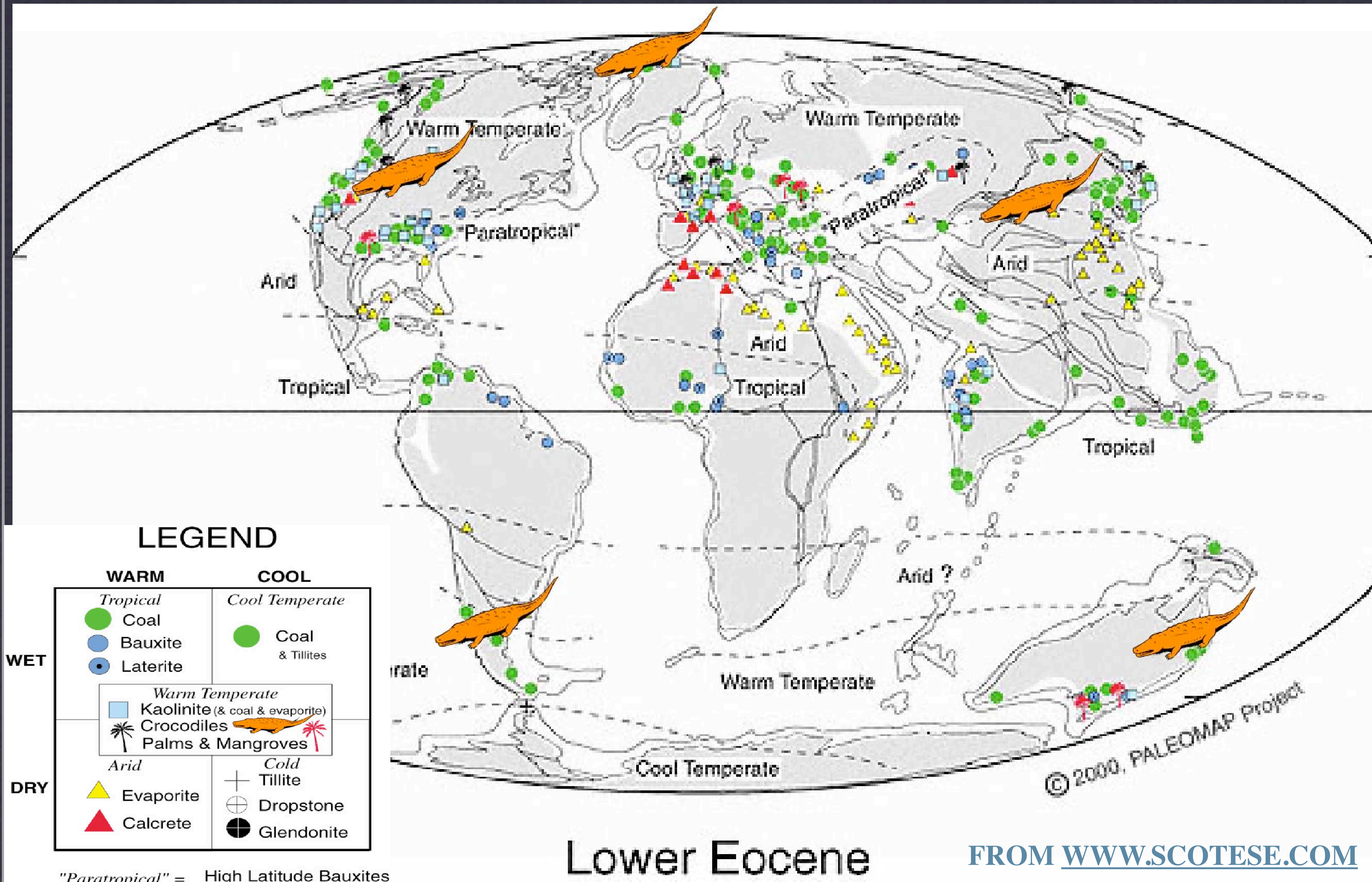


Fig. 1. Isotopic paleotemperatures of the Eocene surface ocean from Shackleton and Boersma [1981] in comparison with modern values. Northern and Southern hemisphere isotopic values are plotted in both hemispheres (mirror data sites are plotted as open squares) in order to draw a temperature distribution with respect to latitude. The latitude scale is area weighted.

THE LOW GRADIENT "PROBLEM"

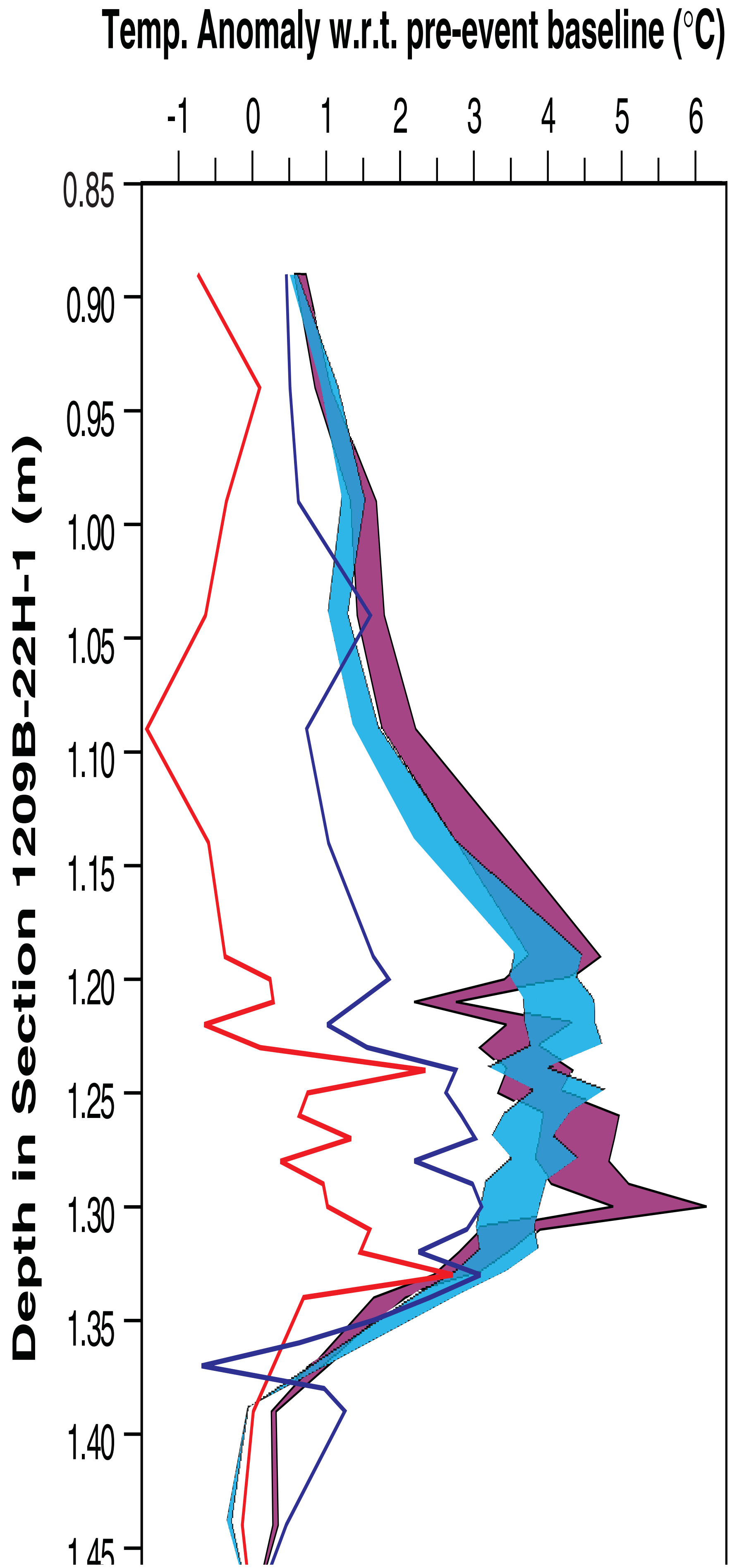
HAS THERE BEEN PROGRESS?

BARRON, 1987

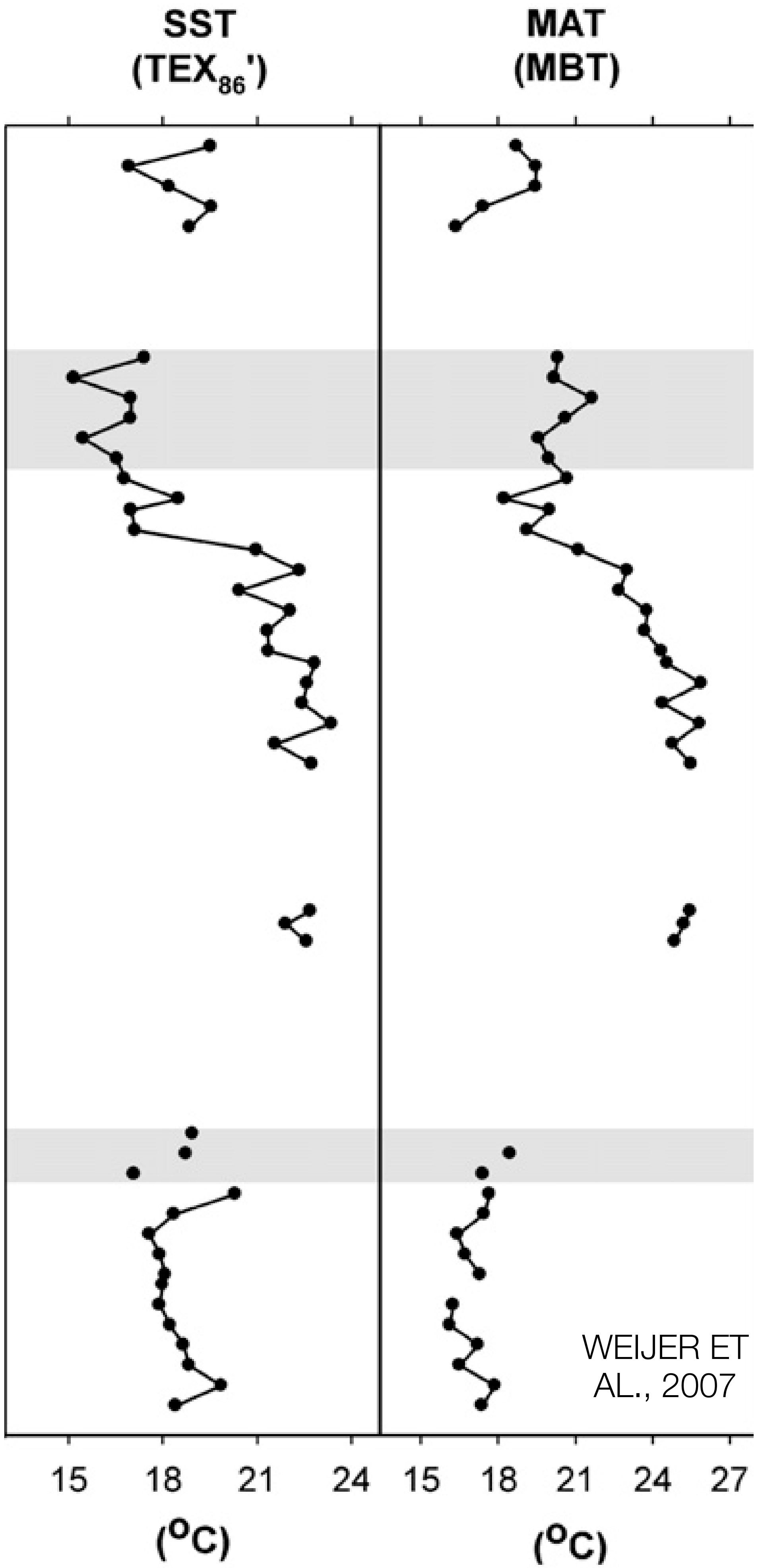


DISTRIBUTION OF FAUNAL AND FLORAL CLIMATE PROXIES


Stump spacing provides estimates of tree biomass of ~700m3/ha and annual productivity of 5.5m3/ha/yr, similar to modern temperate forests
courtesy of Jane Francis



PETM



A 100 kyr global warming event at 55.5 mya

Paleocene-Eocene

Paleocene-Eocene

Vol 442|10 August 2006|**doi:10.1038/nature05043** nature

LETTERS

Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum

Mark Pagani[1*], Nikolai Pedentchouk[1*], Matthew Huber[2*], Appy Sluijs[3], Stefan Schouten[4], Henk Brinkhuis[3], Jaap S. Sinninghe Damsté[4,5], Gerald R. Dickens[6] & the Expedition 302 Scientists†

Paleocene-Eocene

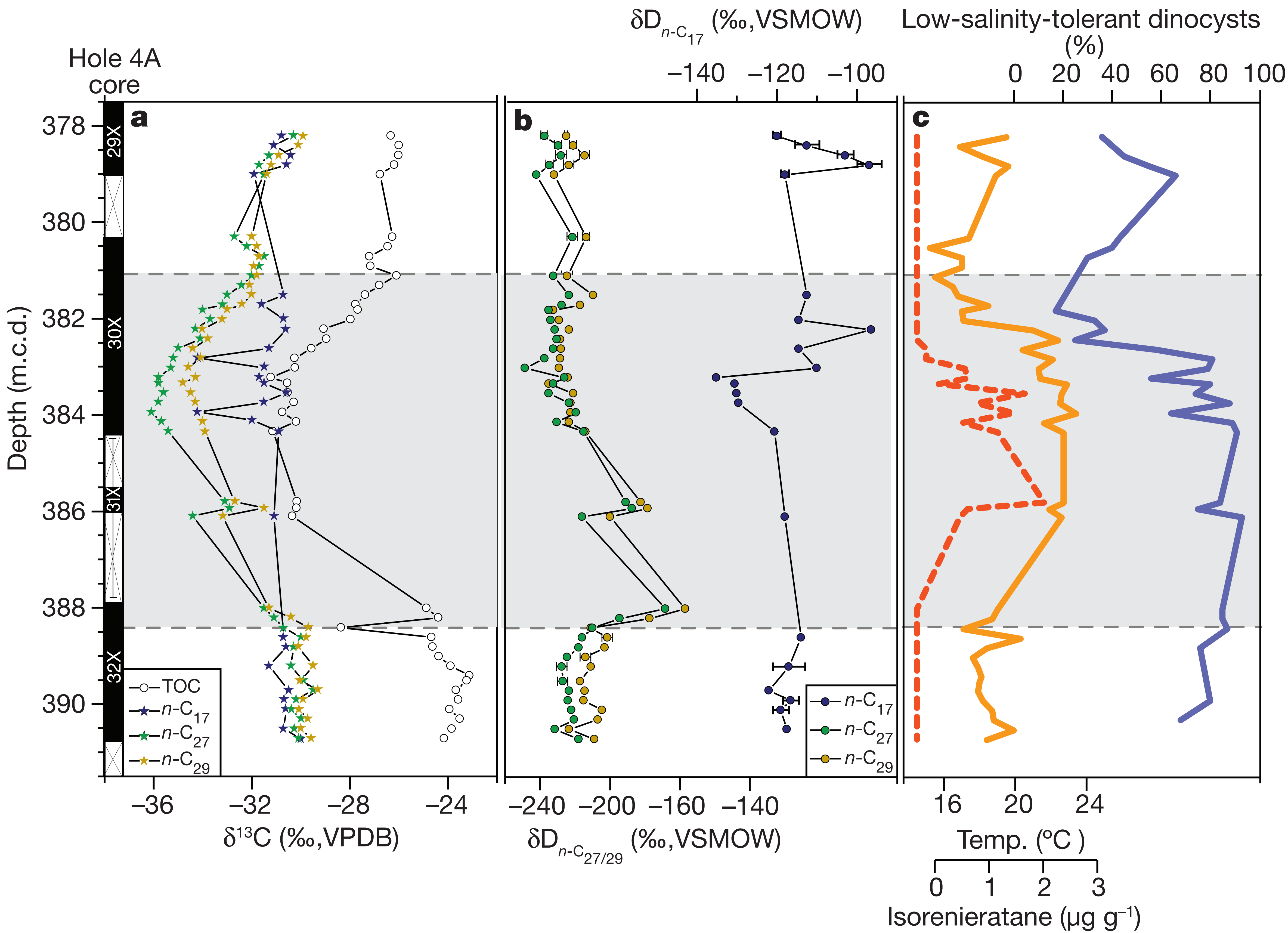
nature Vol 441|1 June 2006|**doi:10.1038/nature04668**

LETTERS

Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum

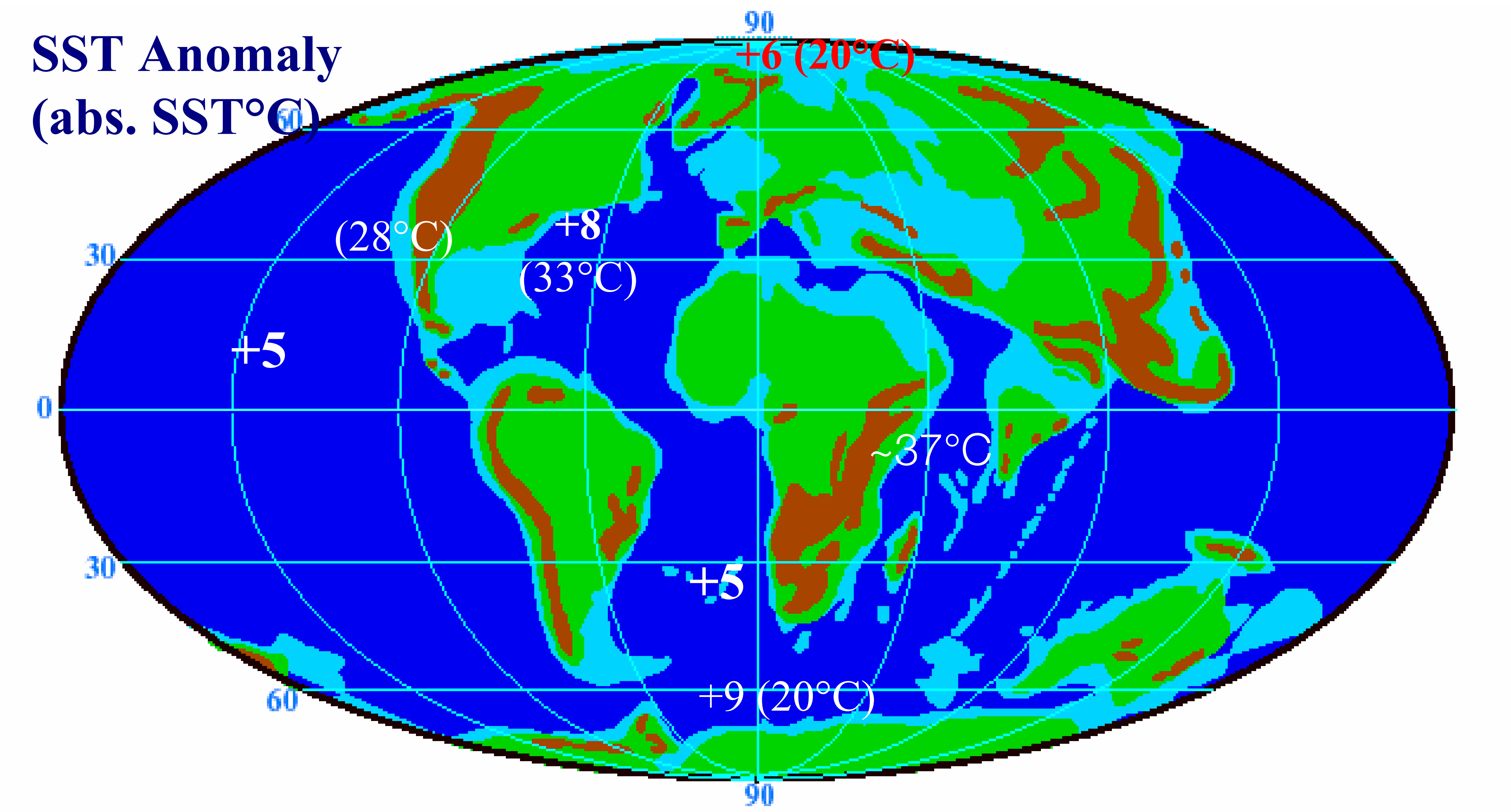
Appy Sluijs[1*], Stefan Schouten[2*], Mark Pagani[3], Martijn Woltering[2], Henk Brinkhuis[1], Jaap S. Sinninghe Damsté[2,4], Gerald R. Dickens[5], Matthew Huber[6], Gert-Jan Reichart[4], Ruediger Stein[7], Jens Matthiessen[7], Lucas J. Lourens[4], Nikolai Pedentchouk[3], Jan Backman[8], Kathryn Moran[9] & the Expedition 302 Scientists†

Paleocene-Eocene



Paleocene-Eocene

early Eocene temperature proxy records



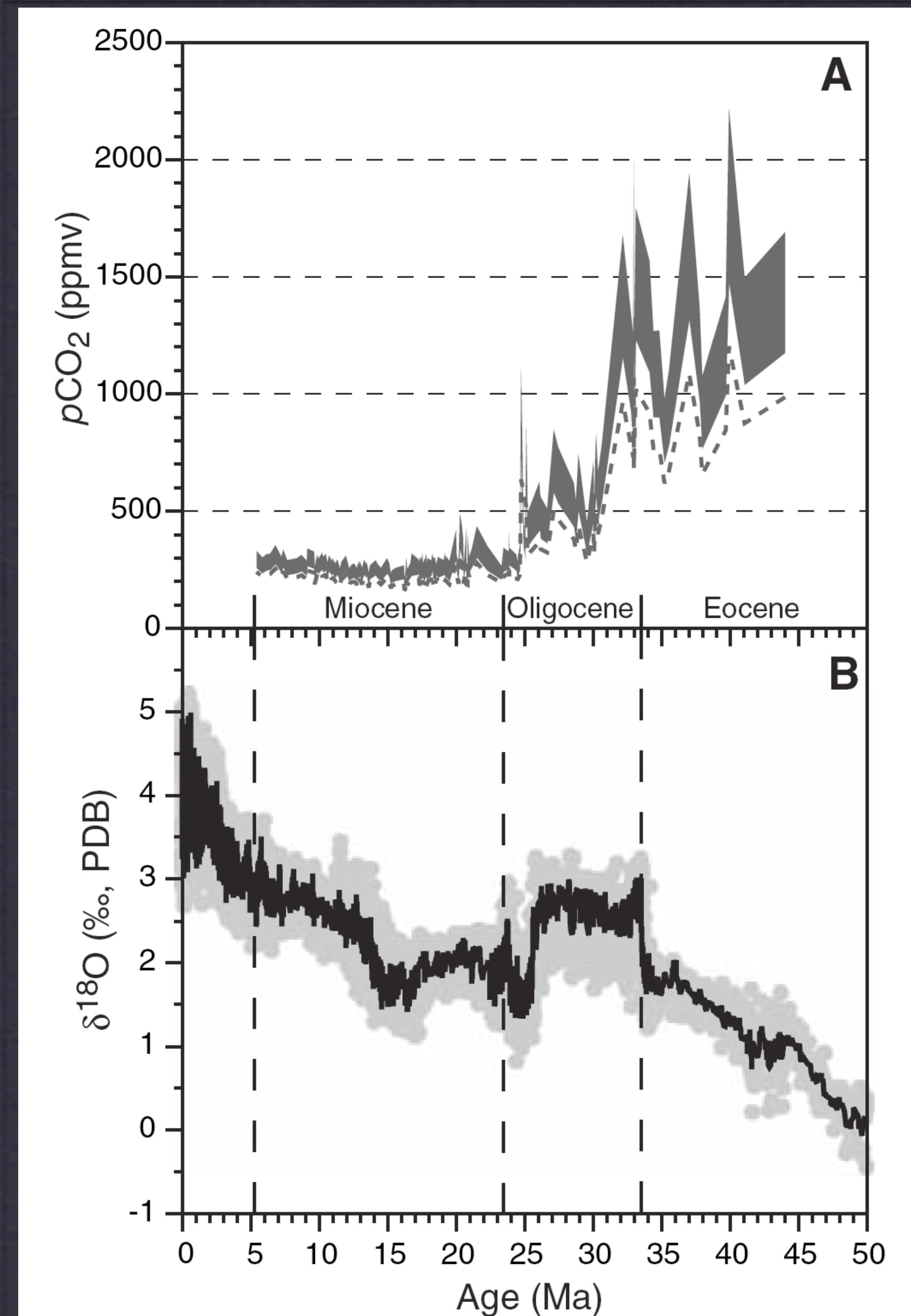
courtesy of J. Zachos

Five main hypothesis

- Ocean Heat transport was higher with closed high latitude gateways
- Atmospheric heat transport was greater because of a ‘permanent El Niño’
- Polar stratospheric clouds maintained a strong polar greenhouse effect, warming the poles
- Or enhanced poleward latent heat fluxes warmed the poles and cooled the tropics
- Let’s also not forget vegetation feedbacks

One set of high resolution estimates of atmospheric CO_2

PAGANI ET AL., 2005



Loosely correlated with greenhouse/Icehouse Transition

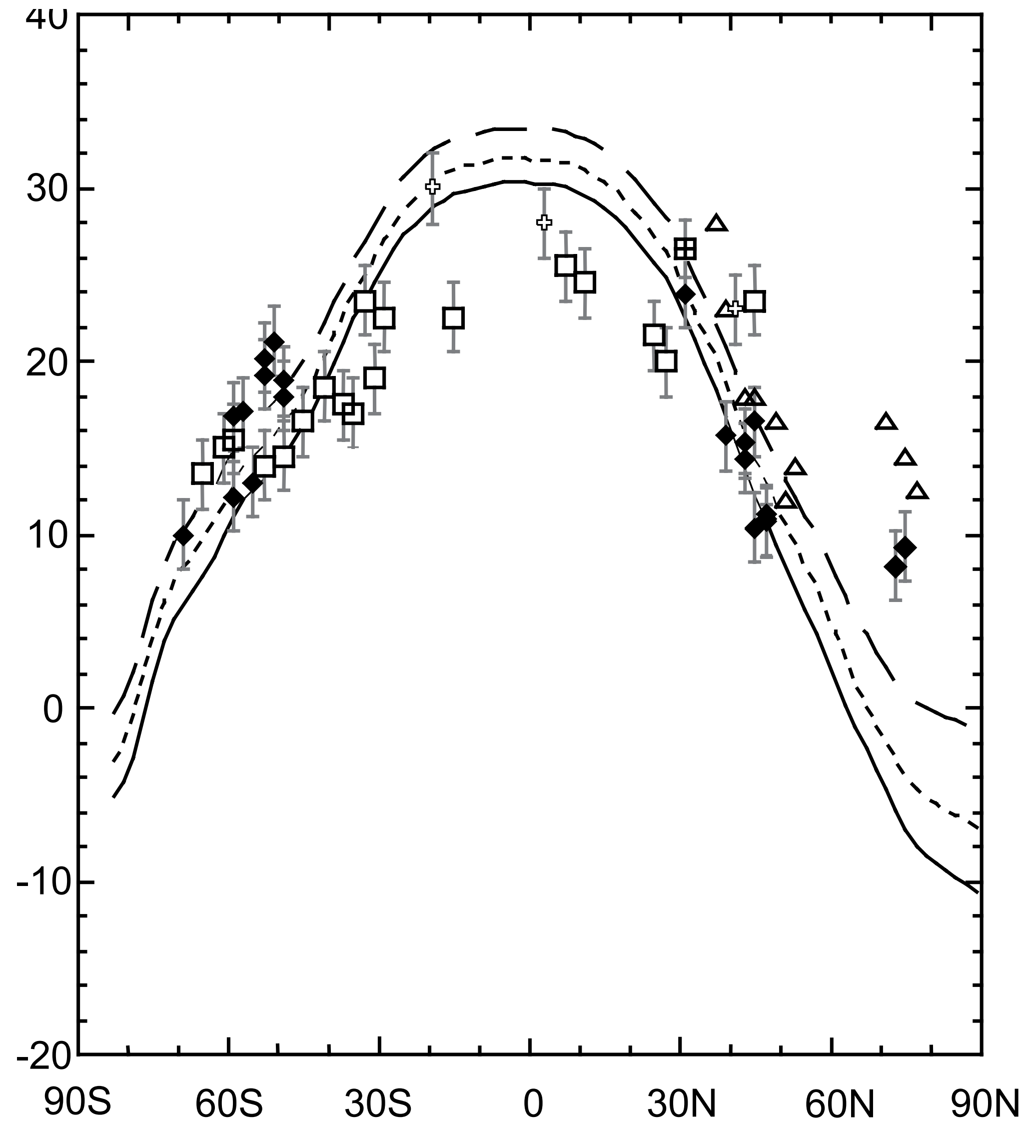
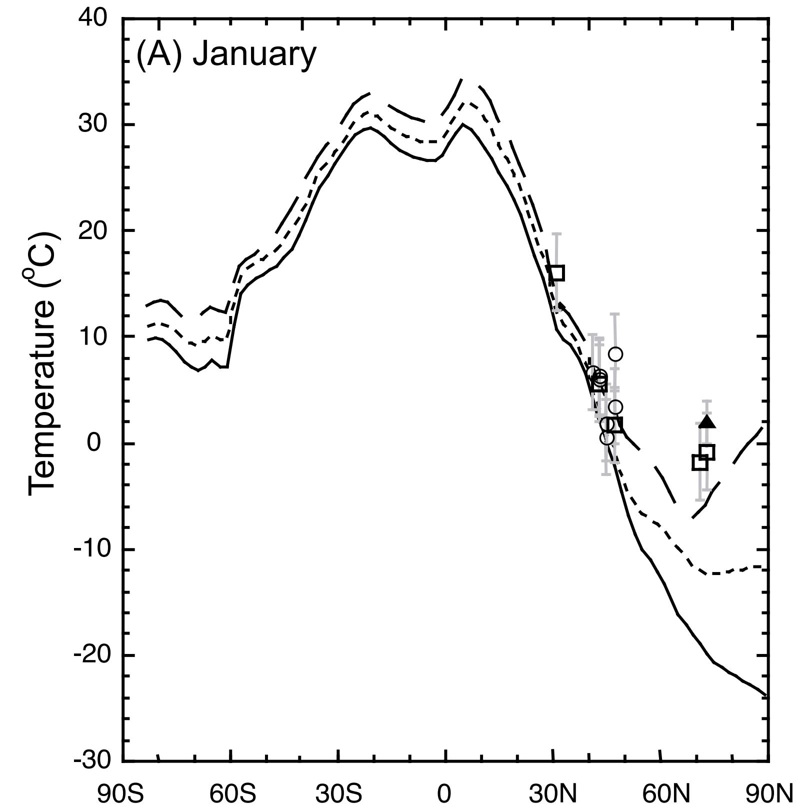
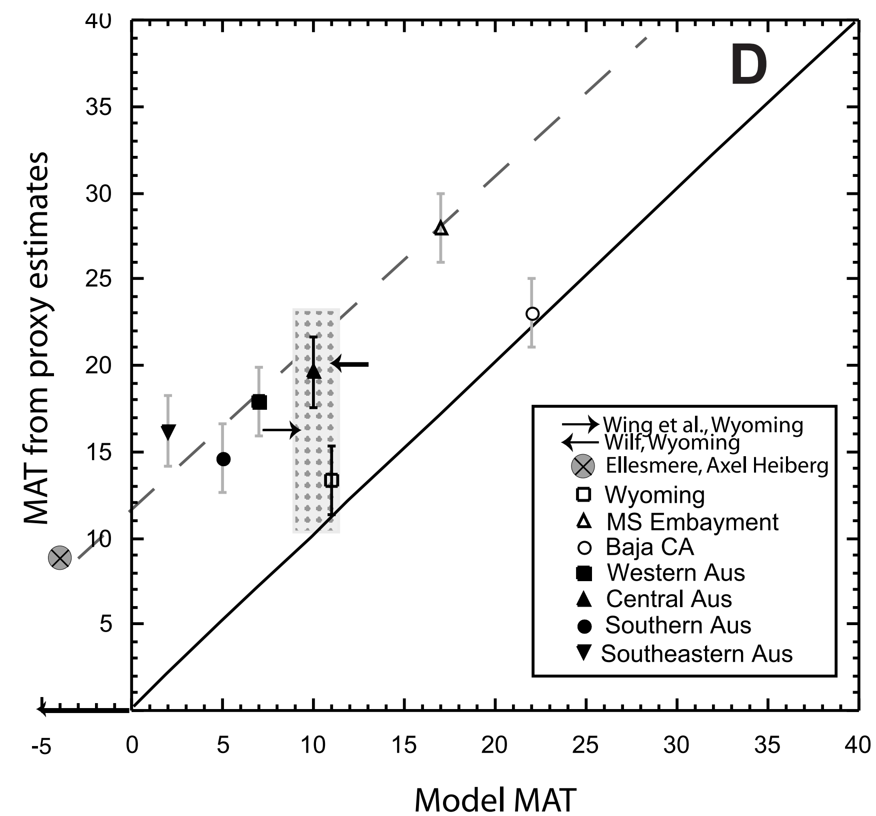


Fig. 1. Mean annual and zonally averaged surface temperatures over land and ocean for three modeling scenarios: $LoCO_2$ (solid line), $MidCO_2$ (short-dashed line), and $HiCO_2$ (long-dashed line). Also included are Eocene temperature estimates from proxies: triangles, from Sloan and Barron (1992); open squares, ocean surface temperature data from Zachos et al. (1994); diamonds, Eocene flora temperature estimates from Greenwood and Wing (1995); hatched square, ocean surface temperature from Kobashi et al. (2001); plus markers, ocean surface temperature data from Pearson et al. (2000).

Shellito, Sloan, Huber, 2003





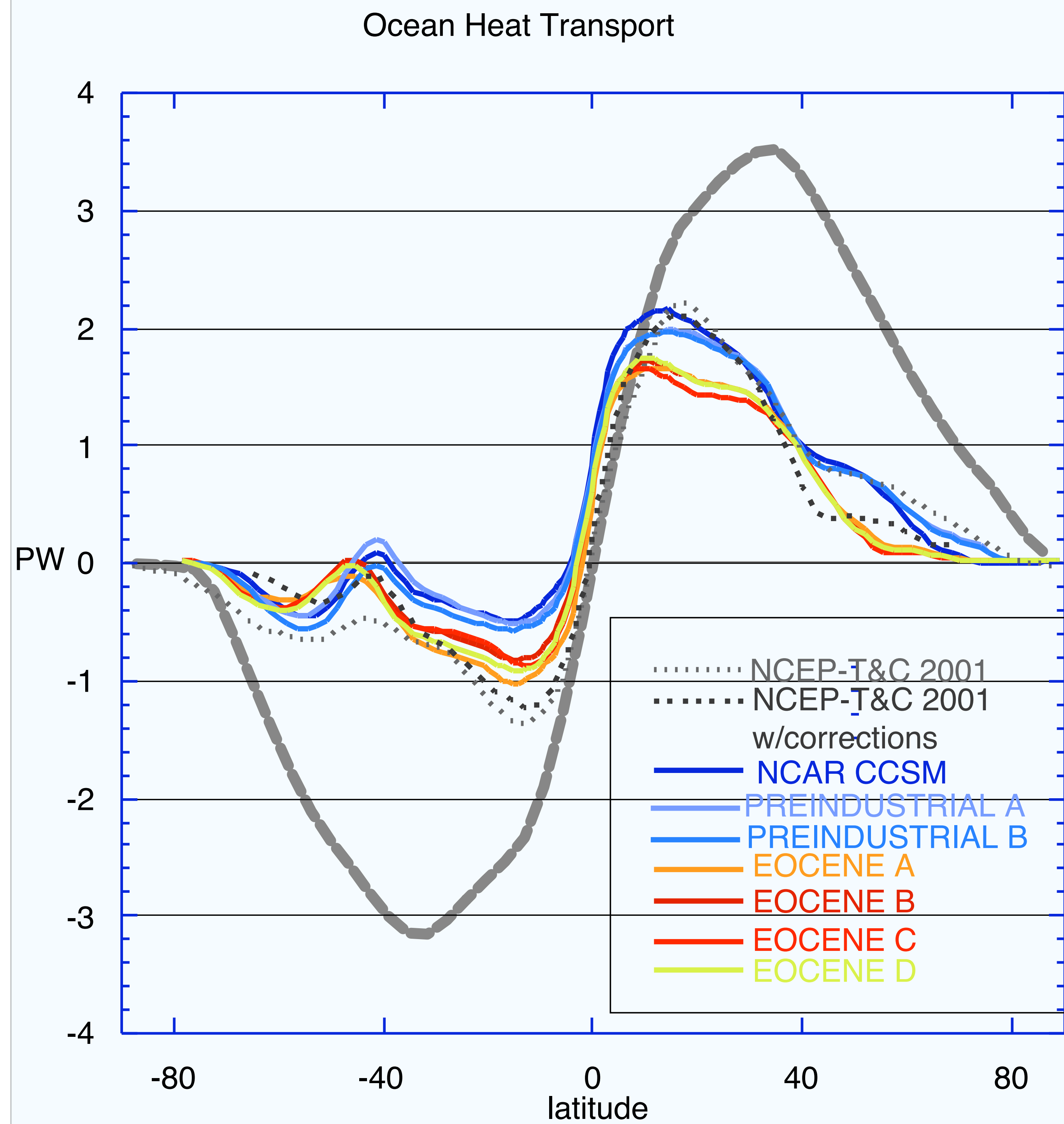
Huber, Sloan, Shellito, 2003

MAT and CMM problems

- No evidence for increased ocean heat transport to account for small gradients, even with closed ocean gateways

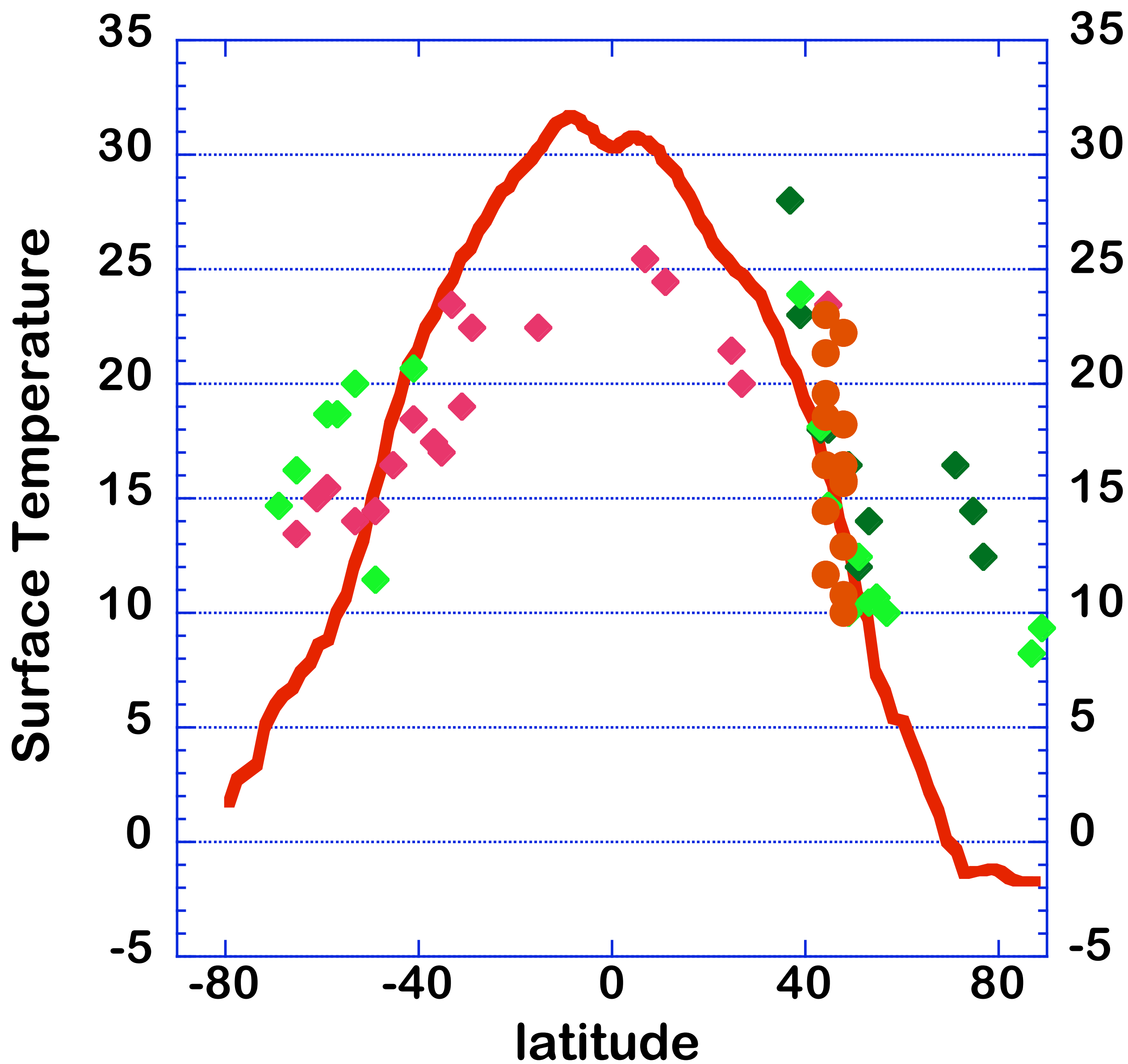
- More than a 3-fold increase in ocean heat transport is necessary to reproduce small equator-to-pole temperature gradient

- Perhaps the data can be reinterpreted to high tropical temperatures and slightly cooler ones at the poles

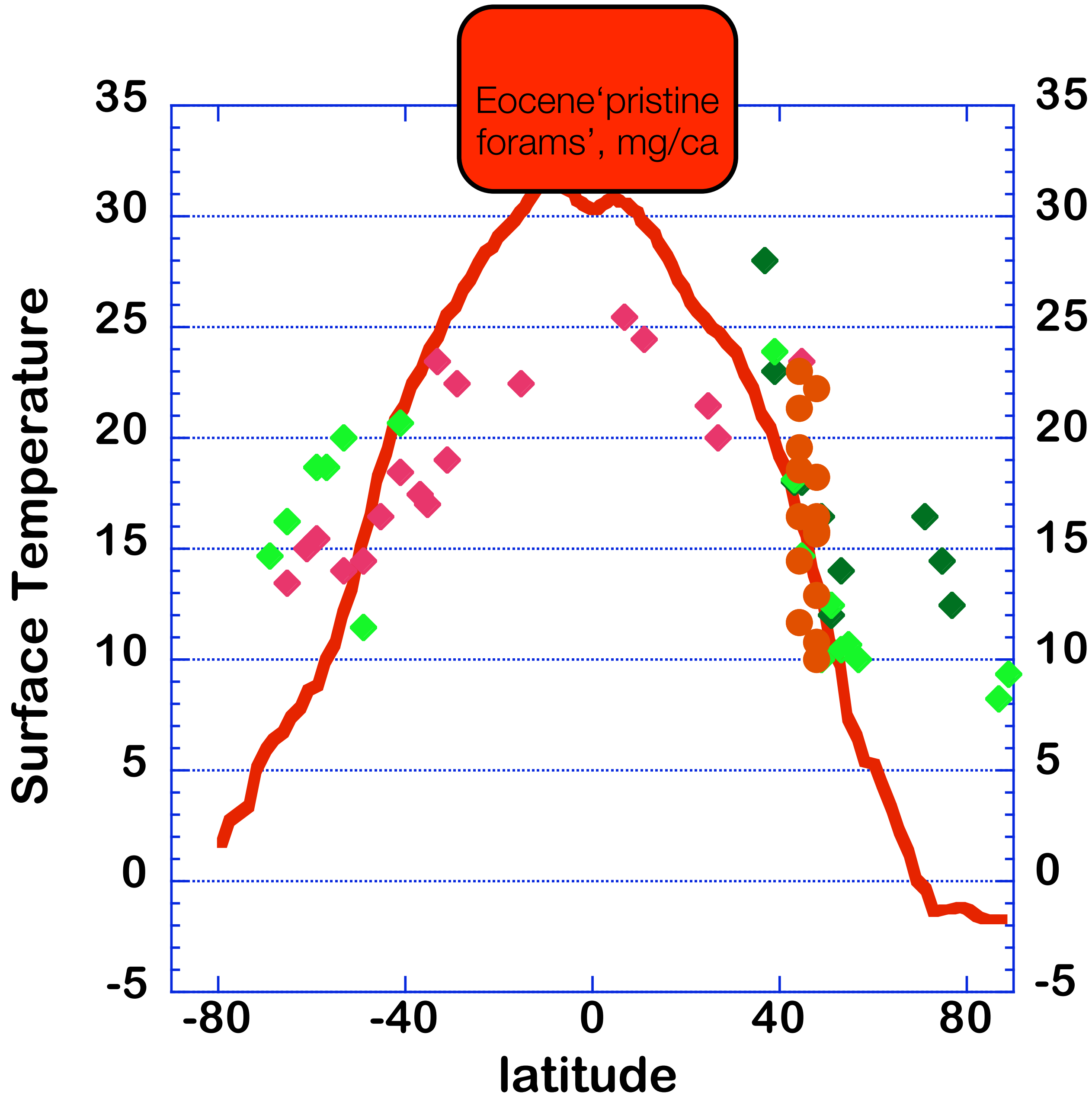


Huber et al., 2004

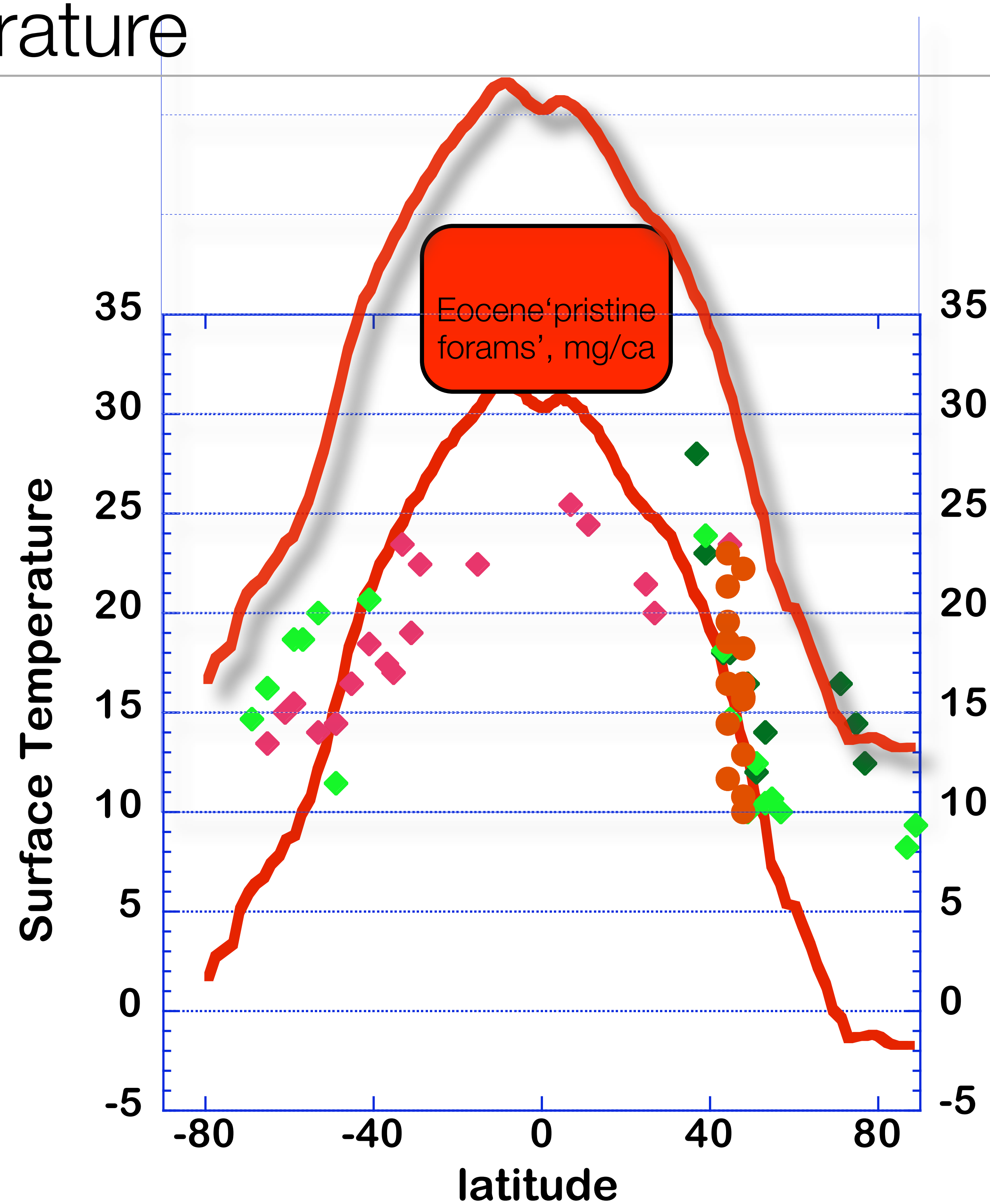
Surface Temperature



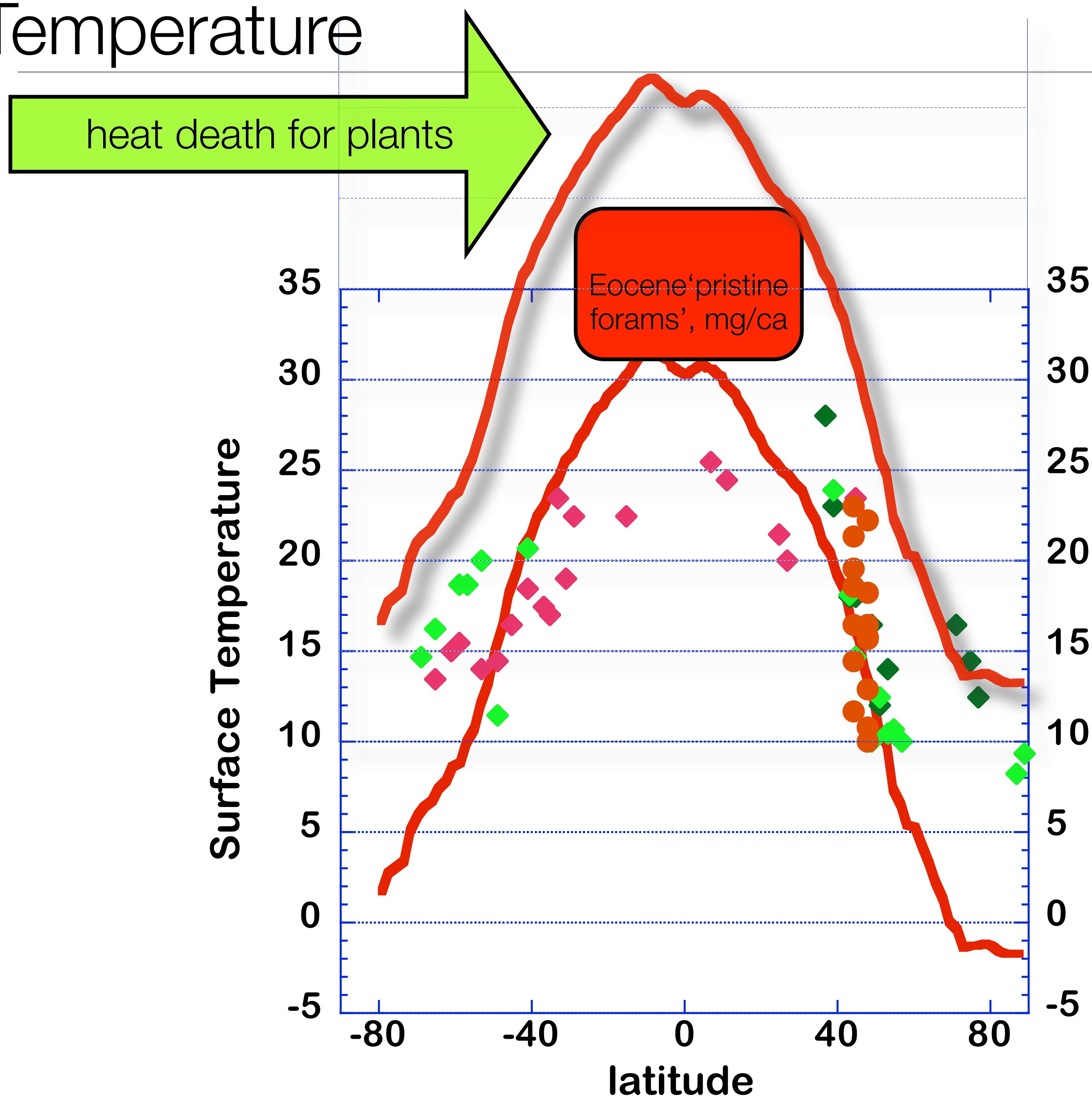
Surface Temperature



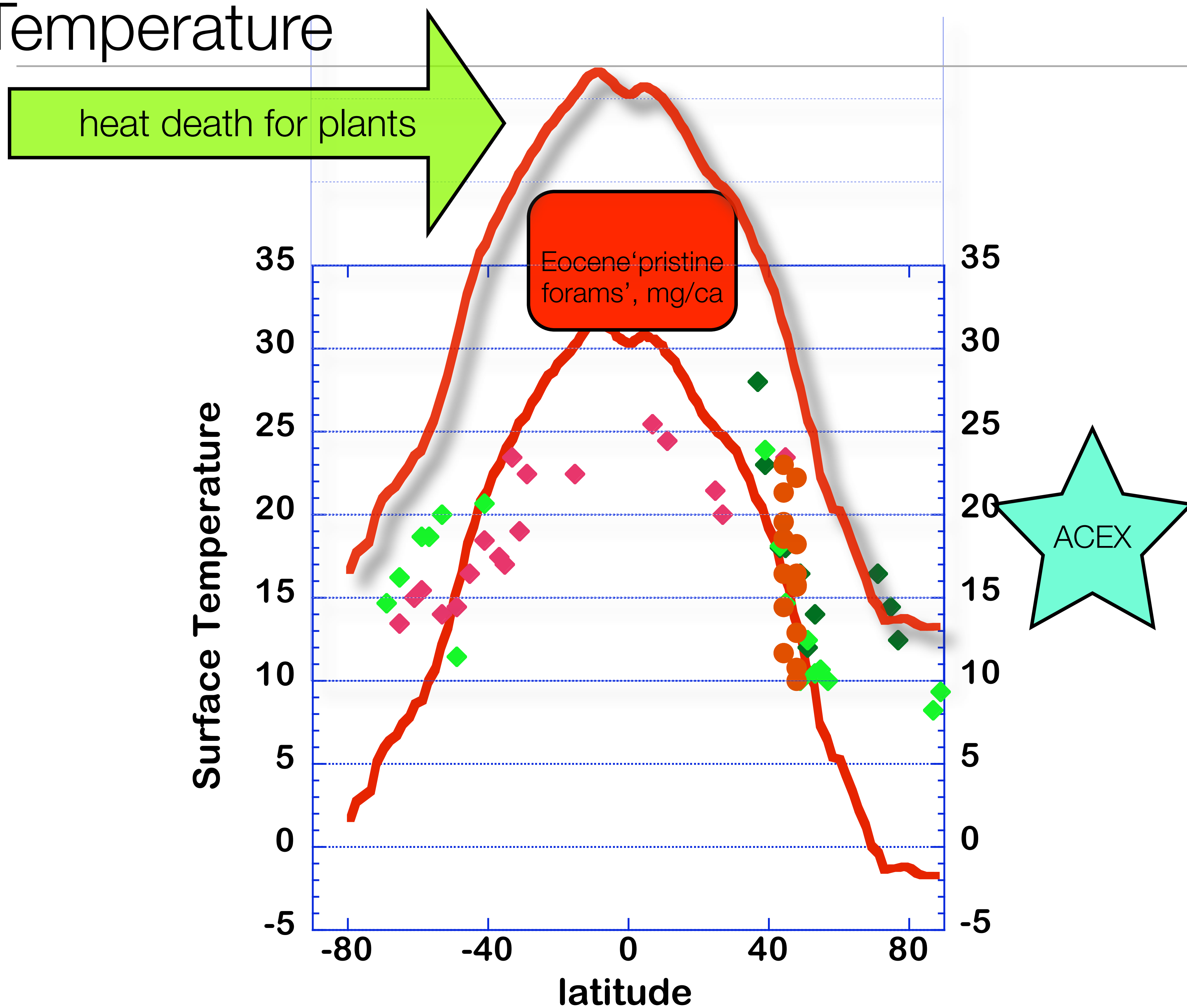
Surface Temperature



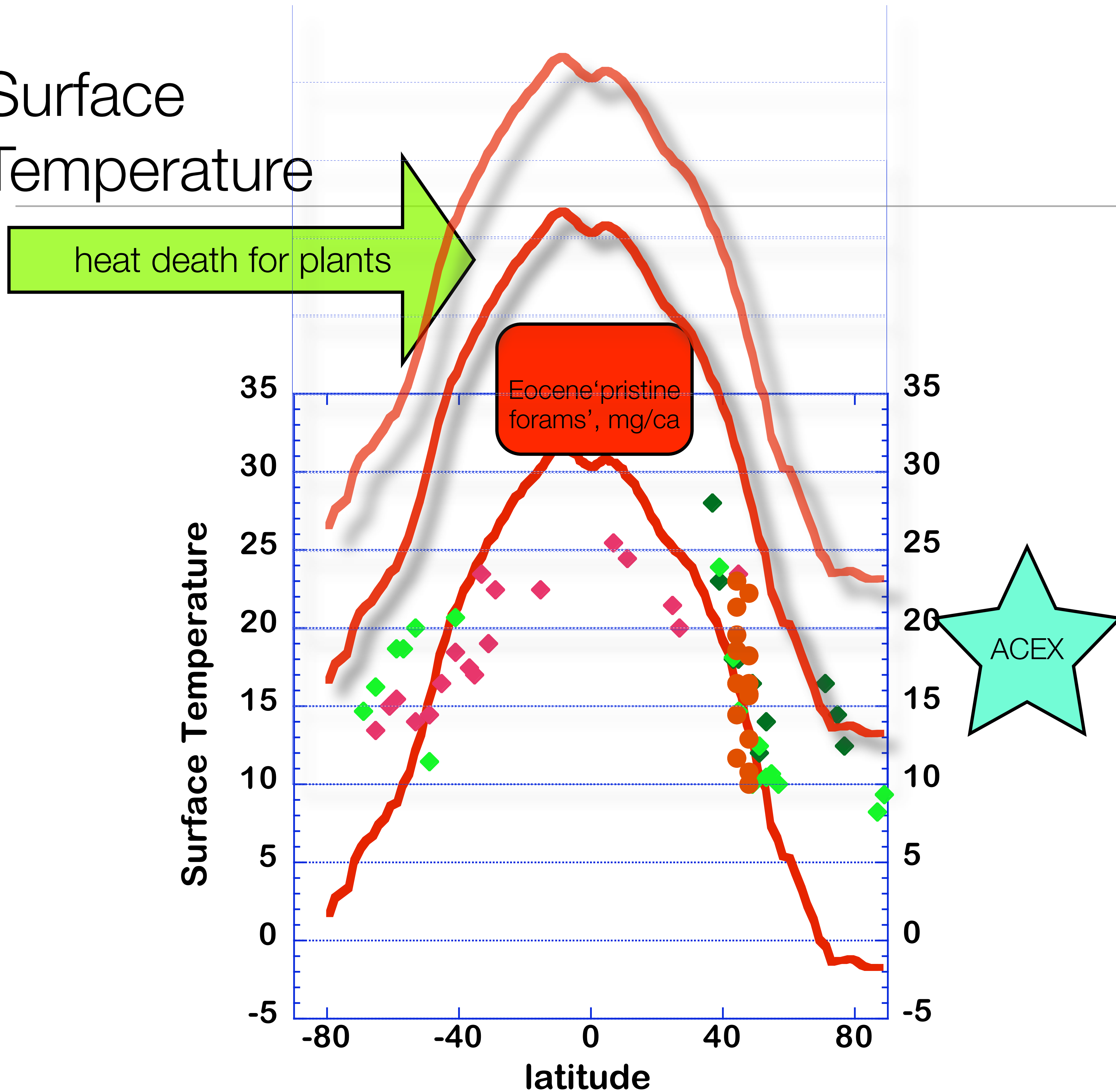
Surface Temperature



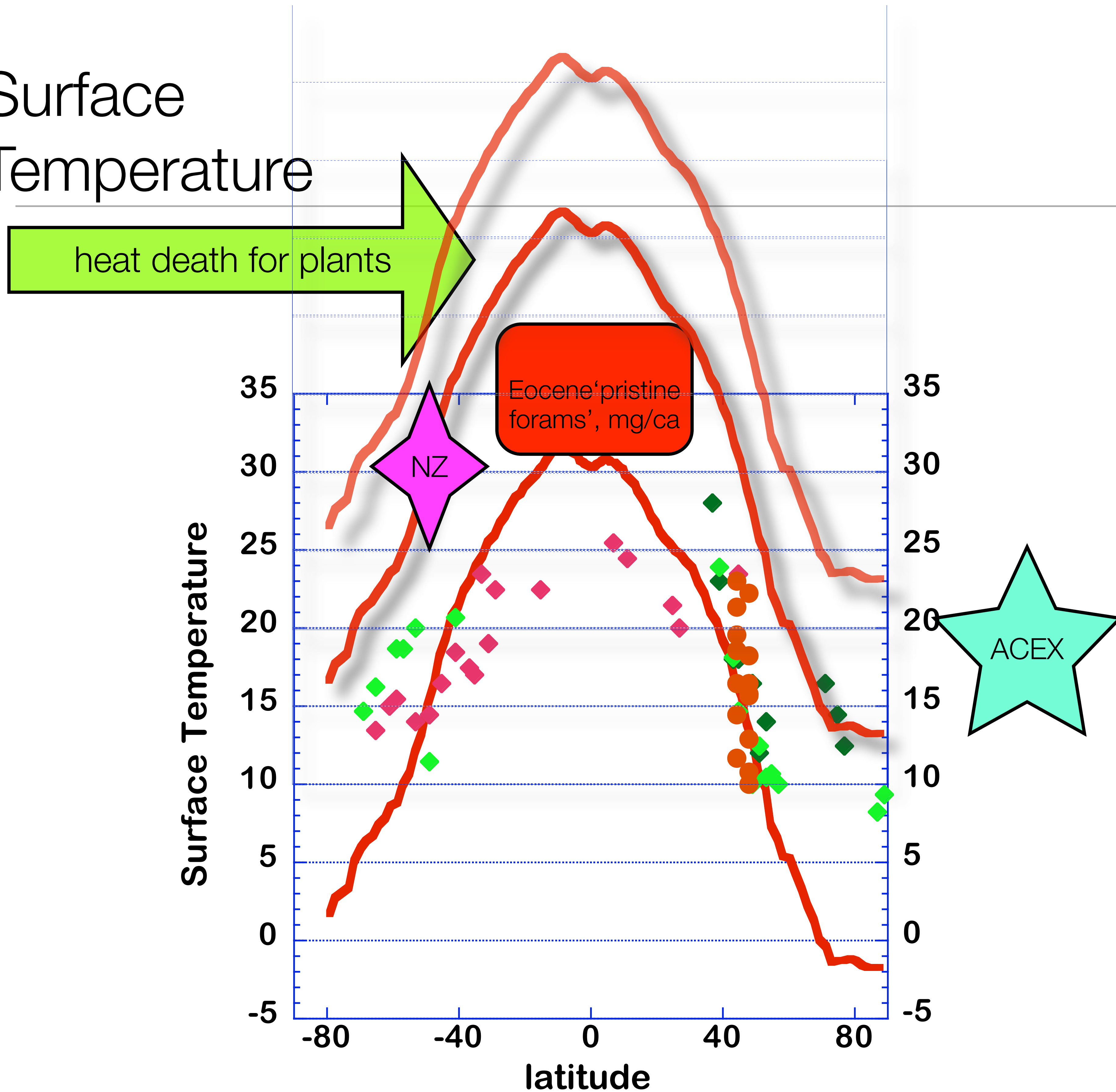
Surface Temperature



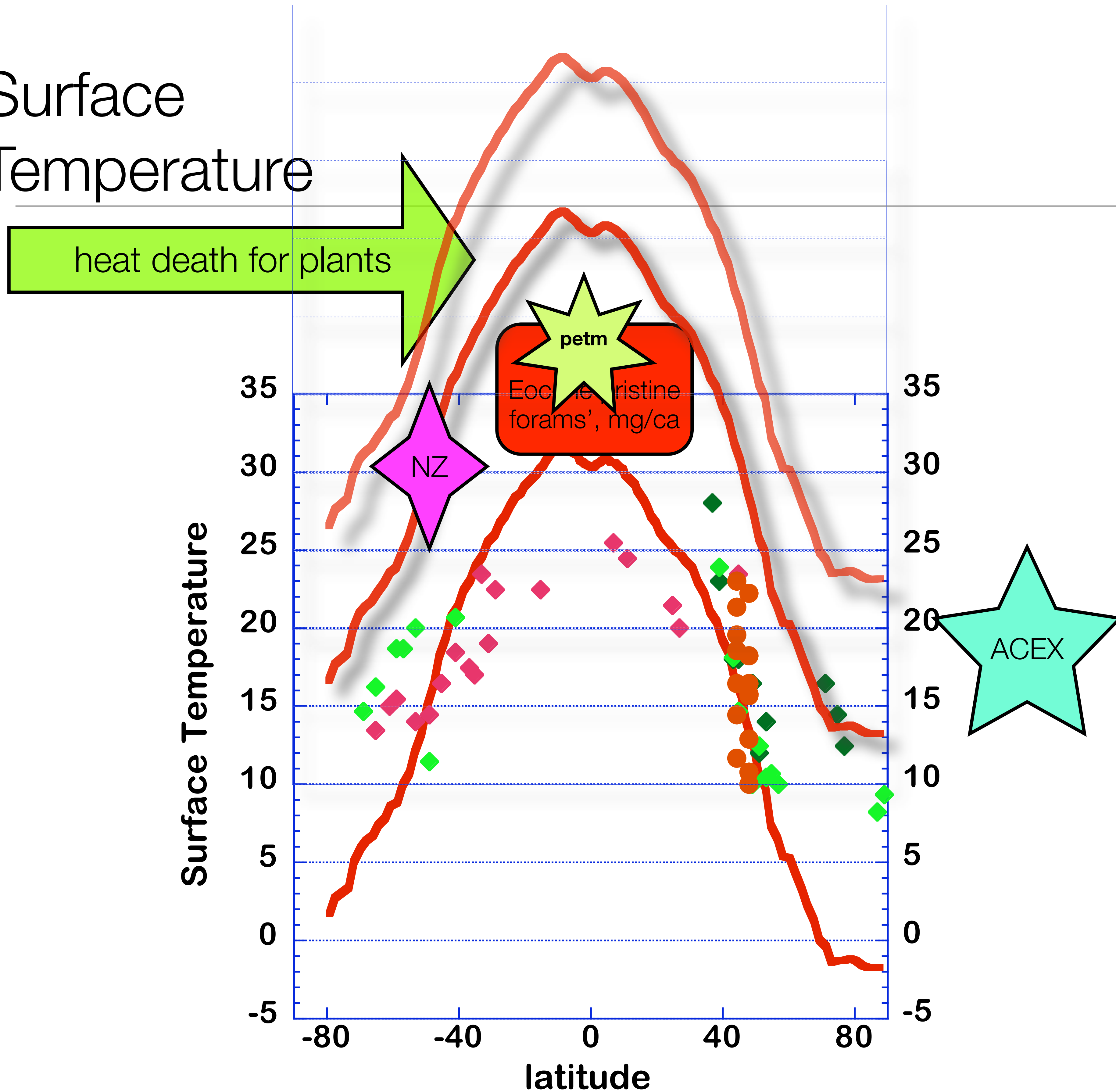
Surface Temperature

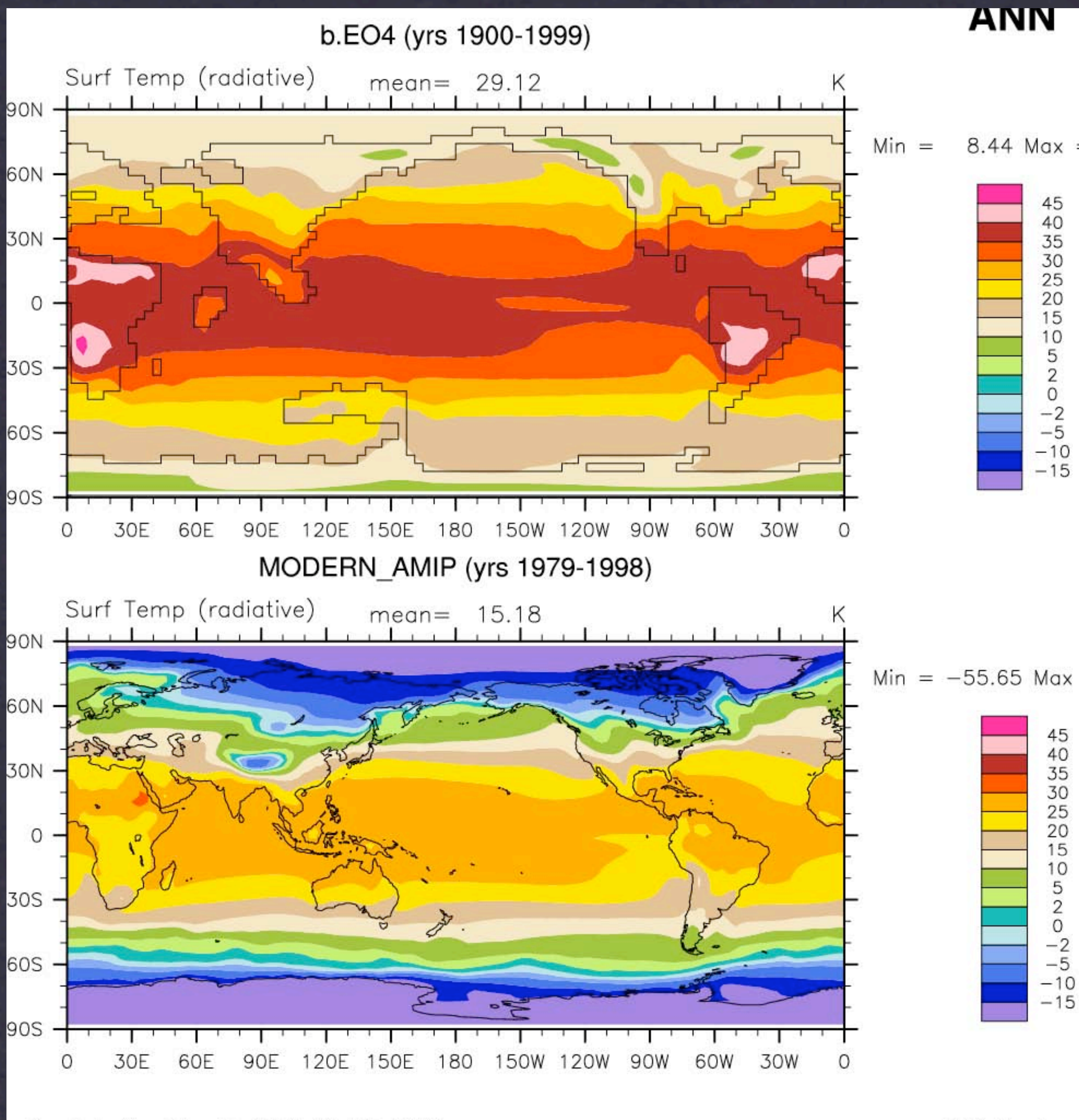


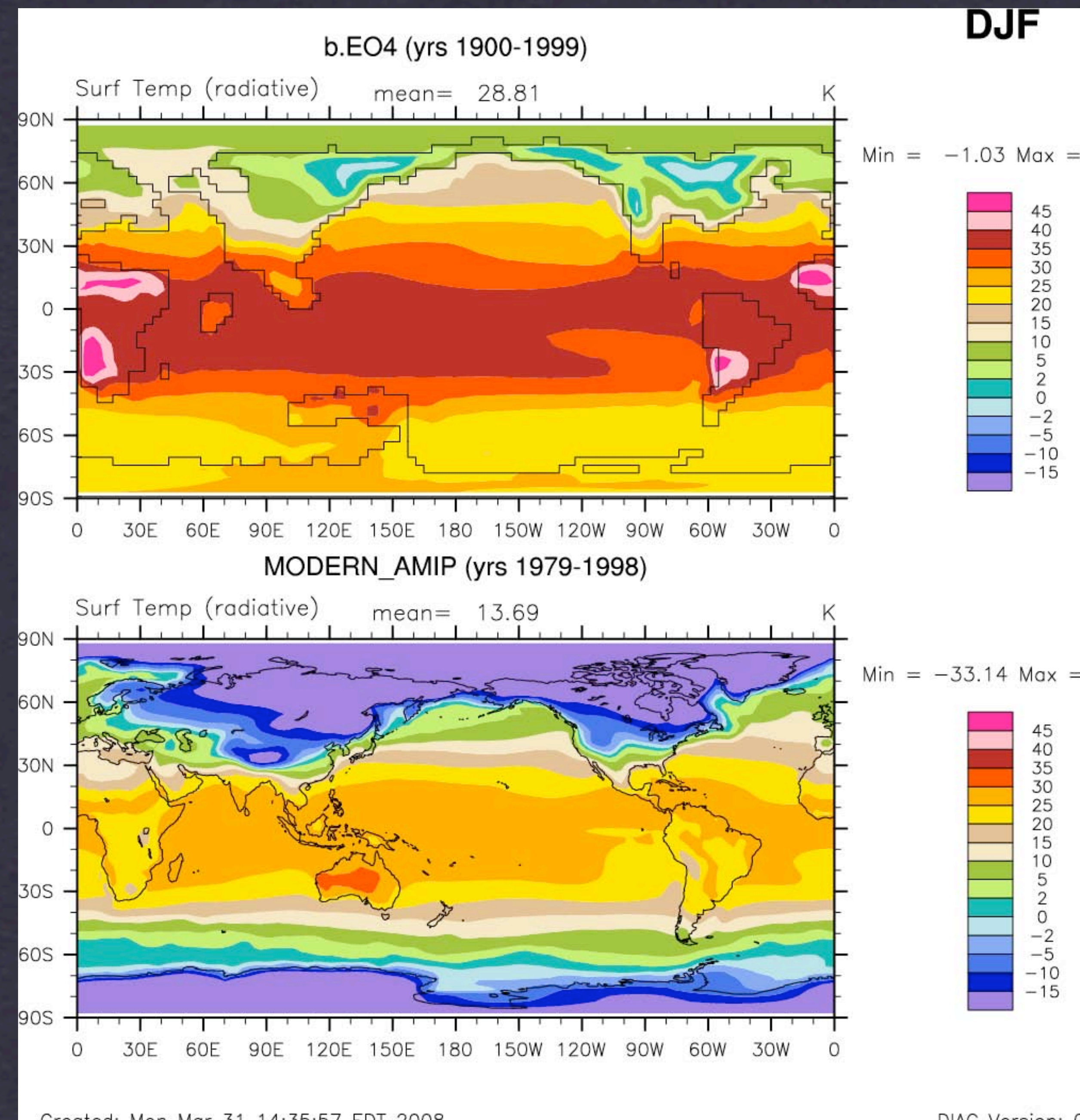
Surface Temperature



Surface Temperature





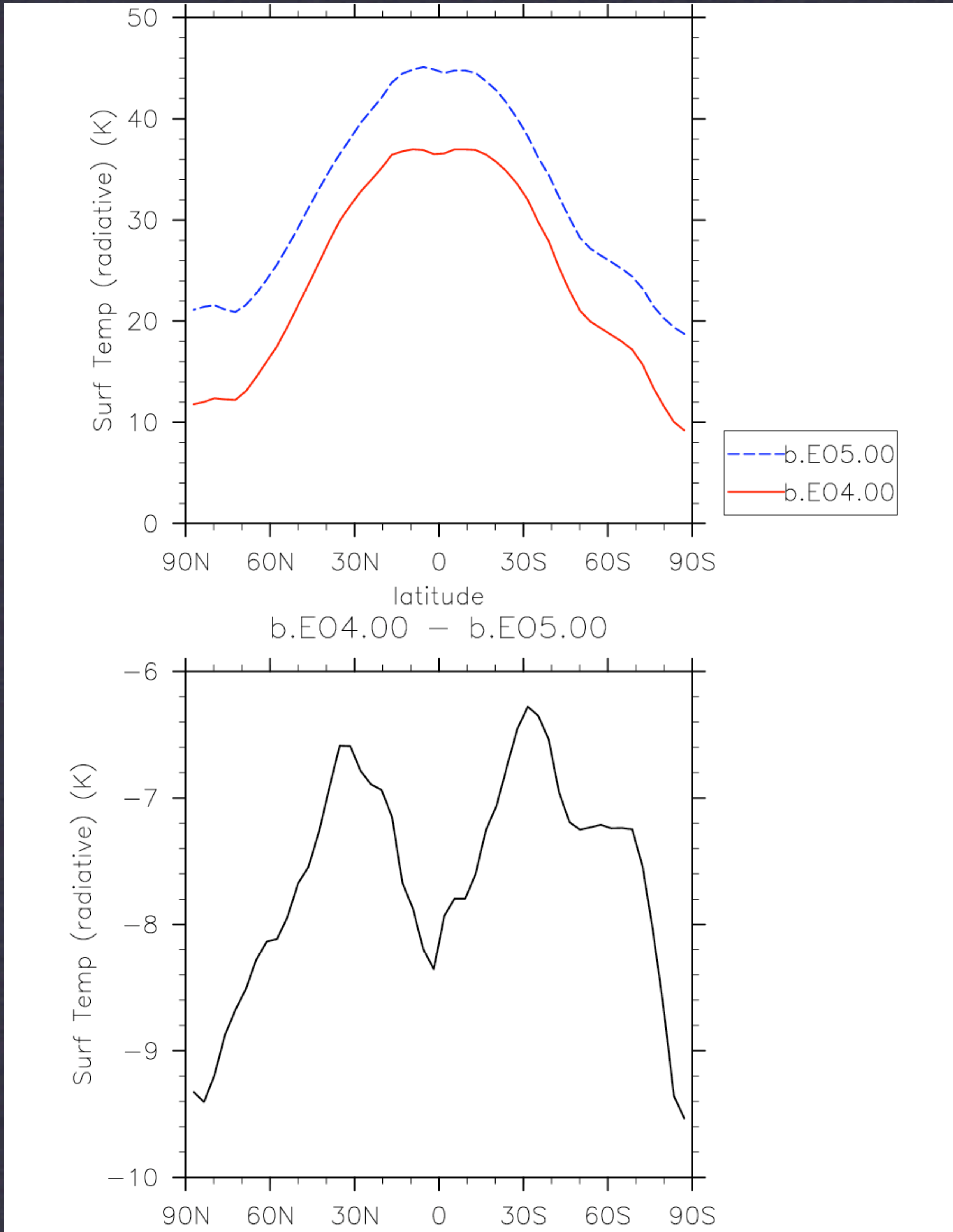


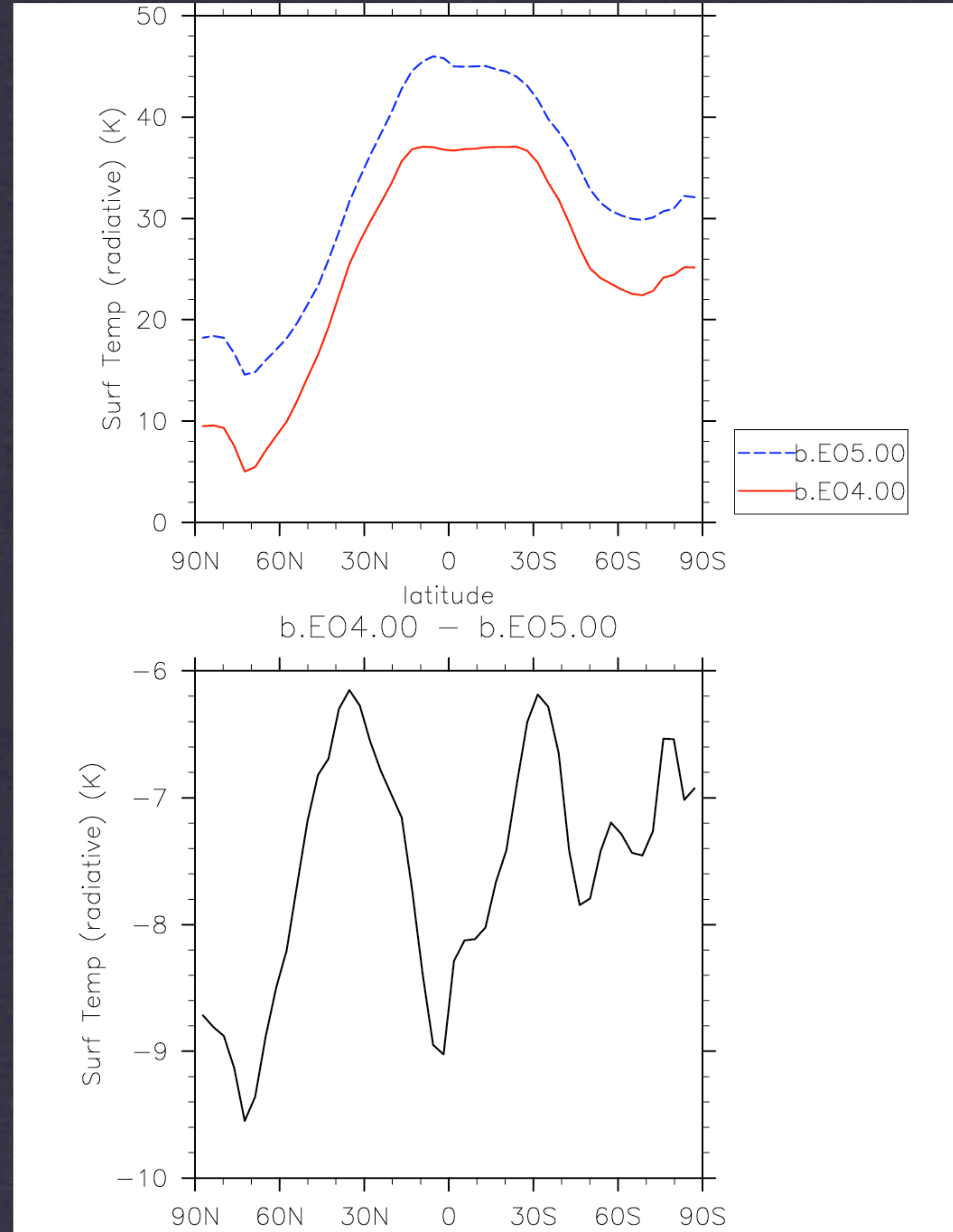
FIRST EOCENE SIMULATIONS TO APPROACH MIDDLE EOCENE CONDITIONS

HUBER IN PREP

temperature change for 5 doublings

REALLY HOT
temperature hot enough to kill plants in tropics





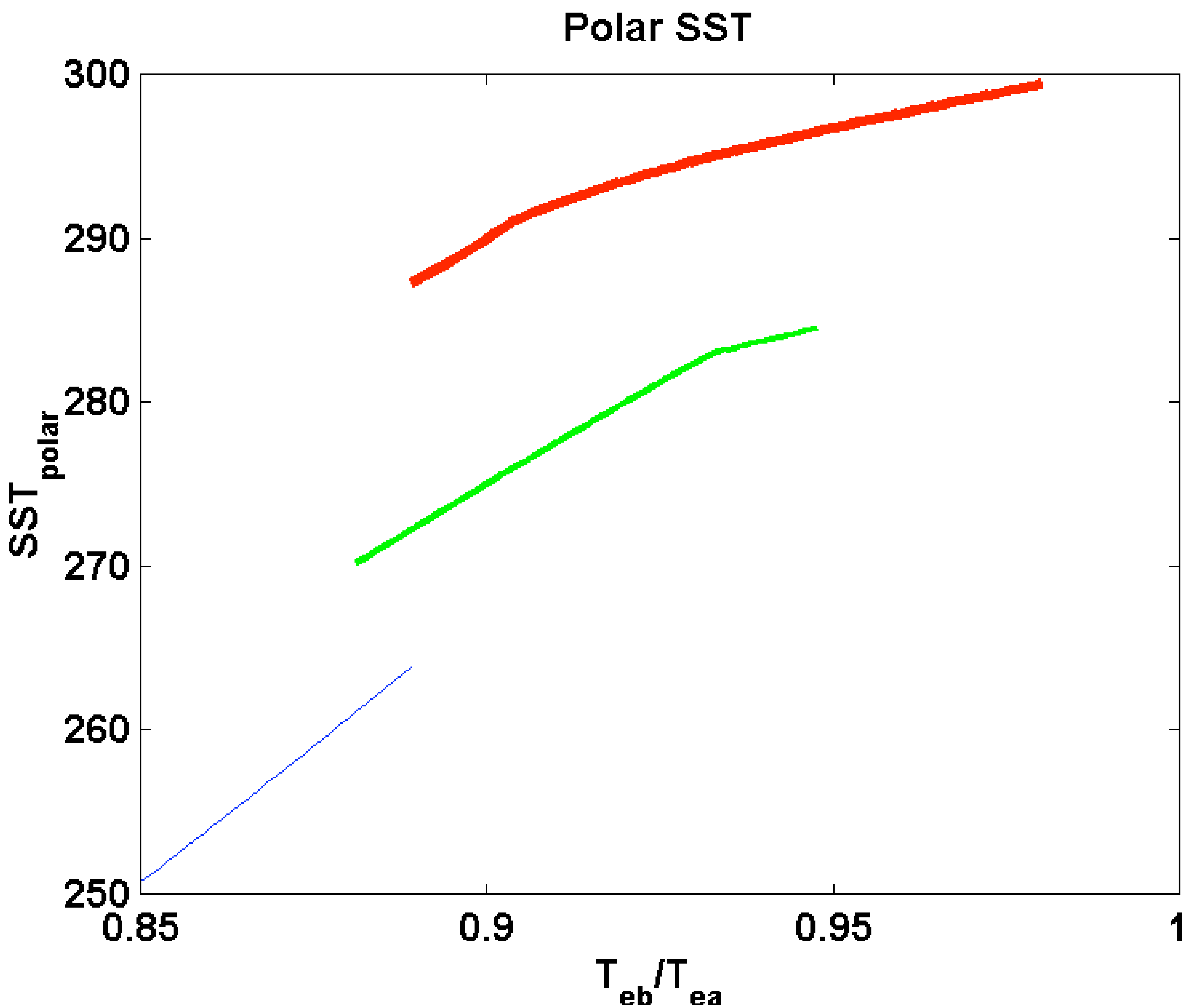
HOT MAT, HOT CMM

JUST PLAIN HOT, HOT, HOT

Increased poleward heat transport (or something else?) now required (once again) by the data

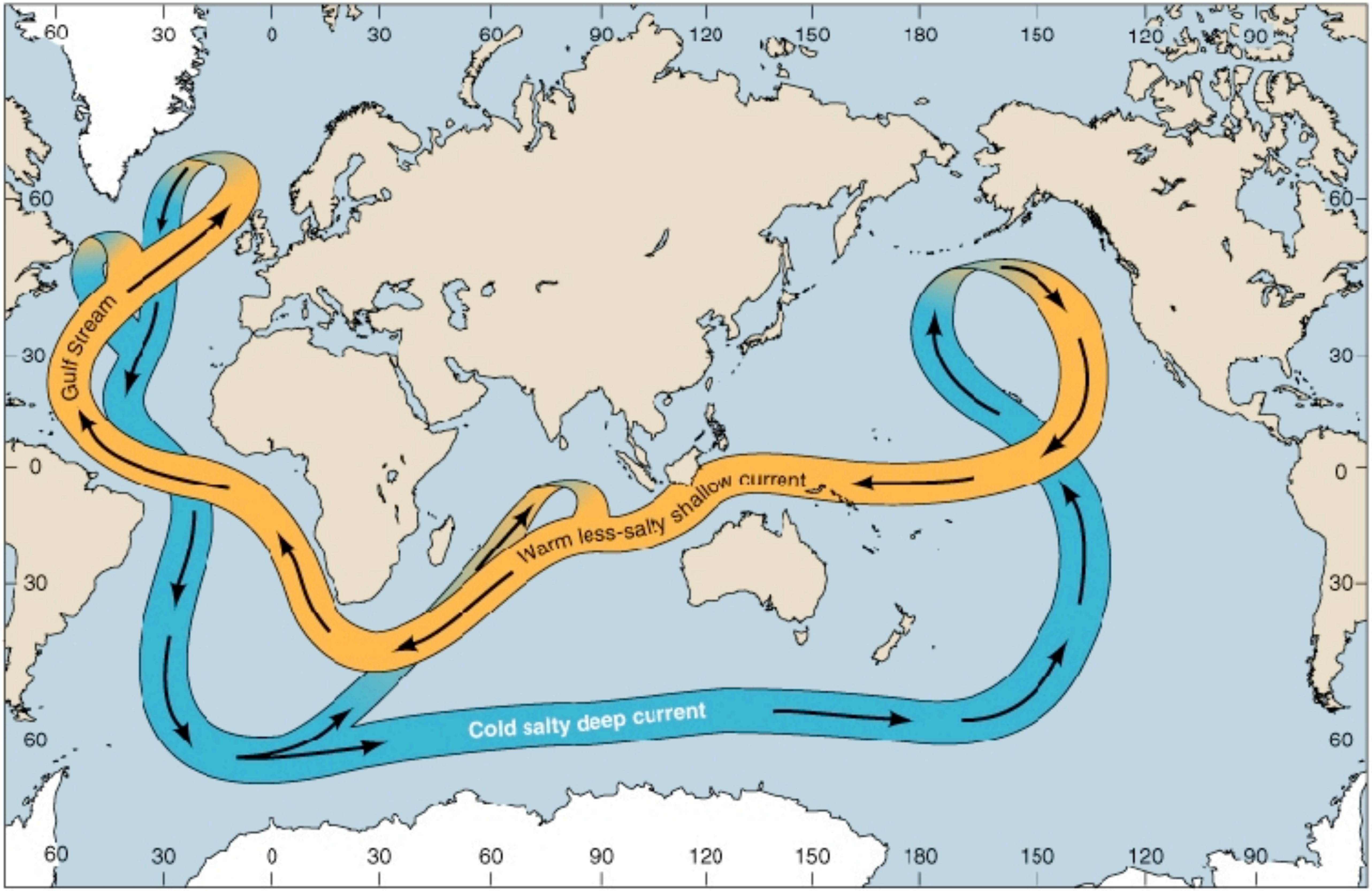
- Models and theory have not produced strong latent feedbacks sufficient to maintain small equator-to-pole temperature gradients.
- Revisit the ocean heat transport argument
- Pursue Kerry Emanuel’s Tropical Cyclone--Ocean Heat Transport Hypothesis, which provides a mechanism for Mitch Lyle’s 1997 ocean vertical mixing/climate hypothesis

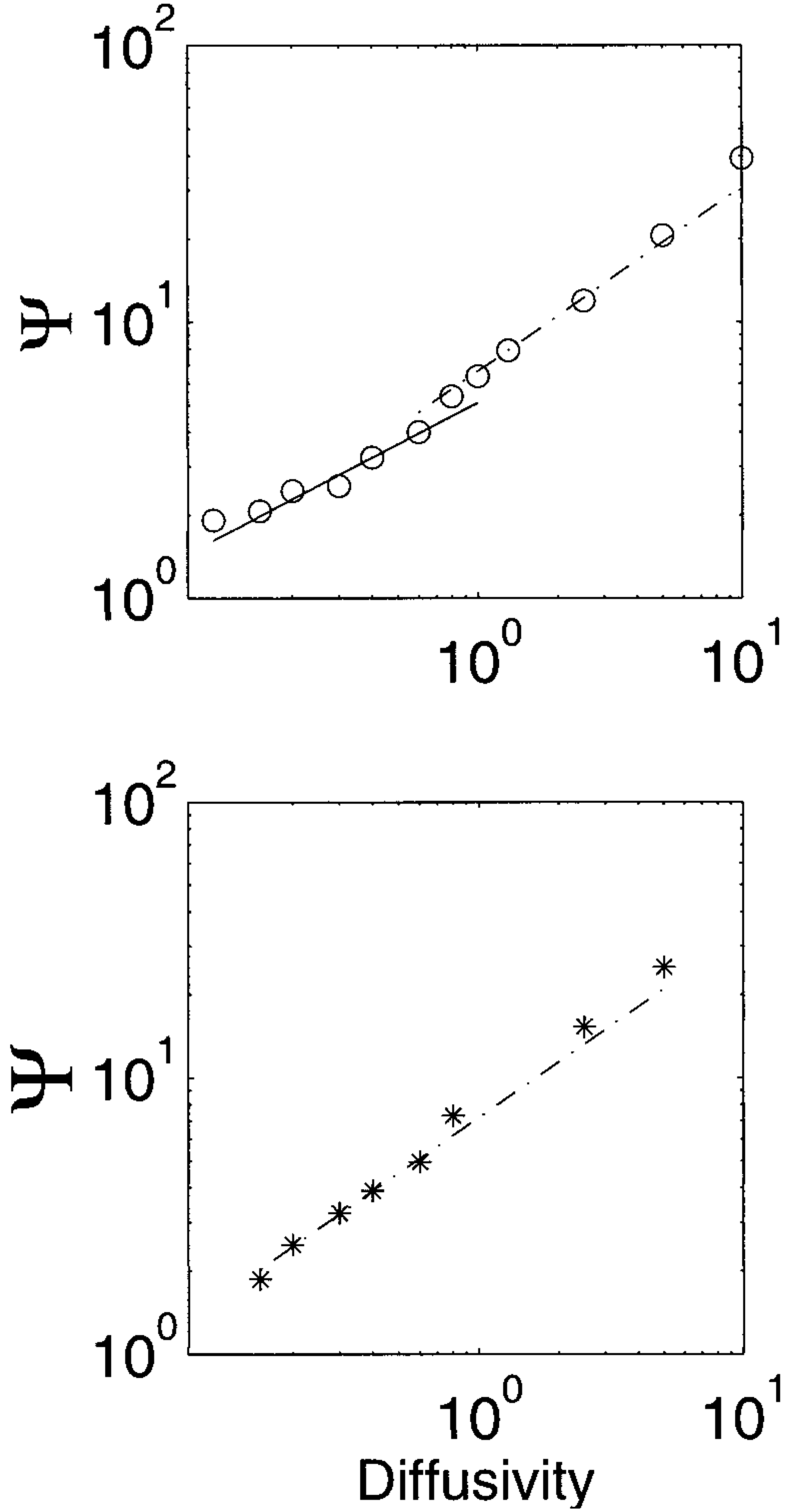
Simple climate model shows thresholded nonlinearity due to dramatic increases in ocean mixing/heat transport



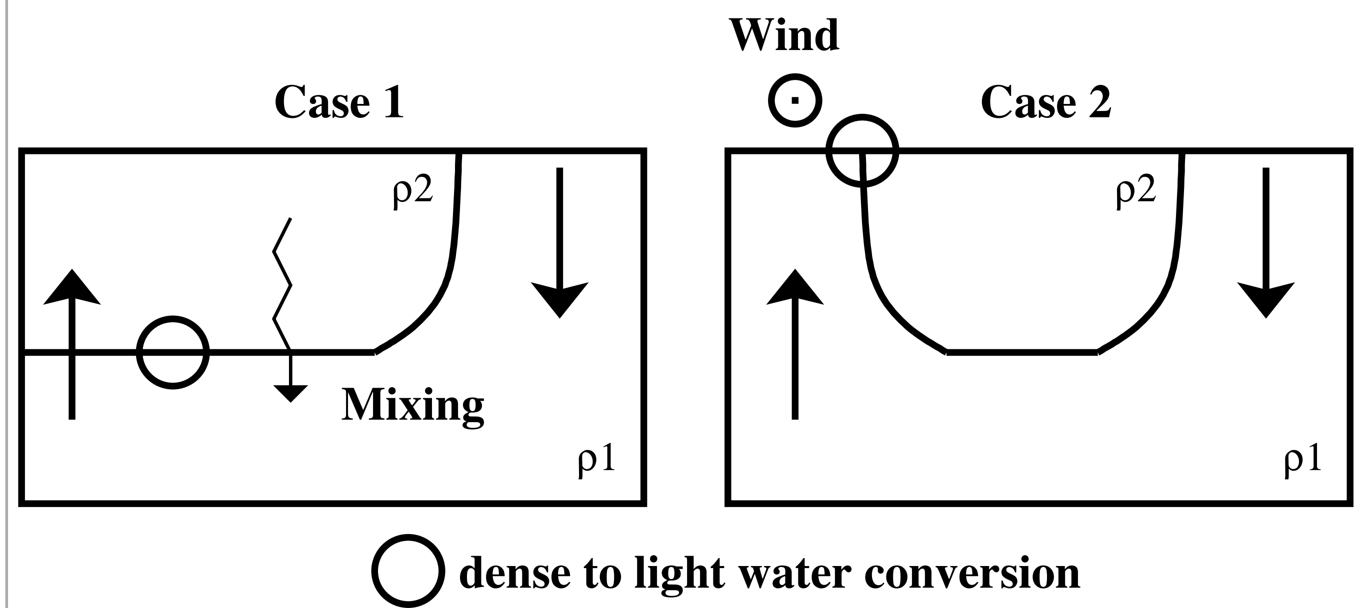
Emanuel 2002

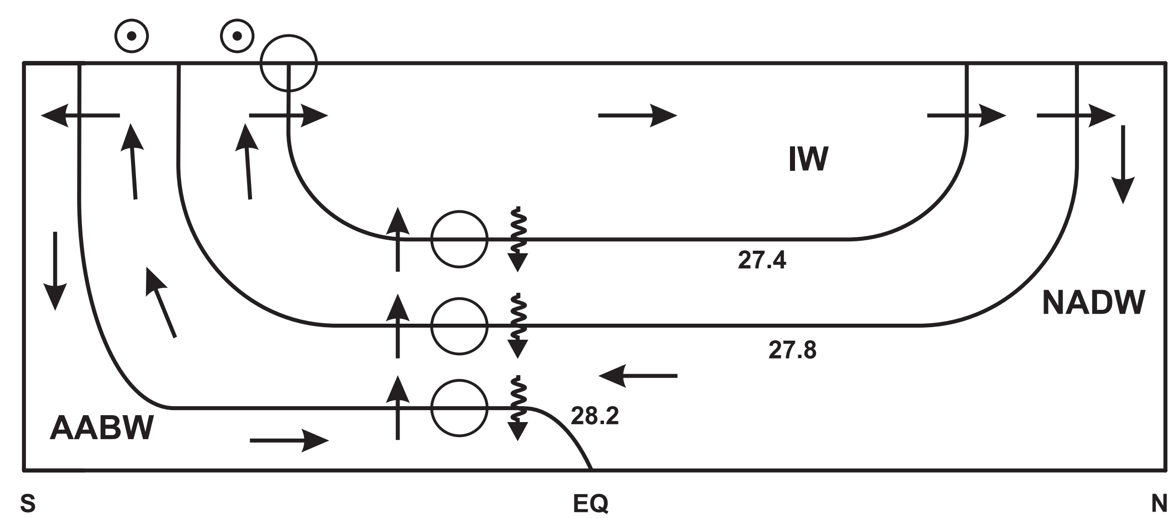
Thermohaline Circulation--Why does dense water rise?





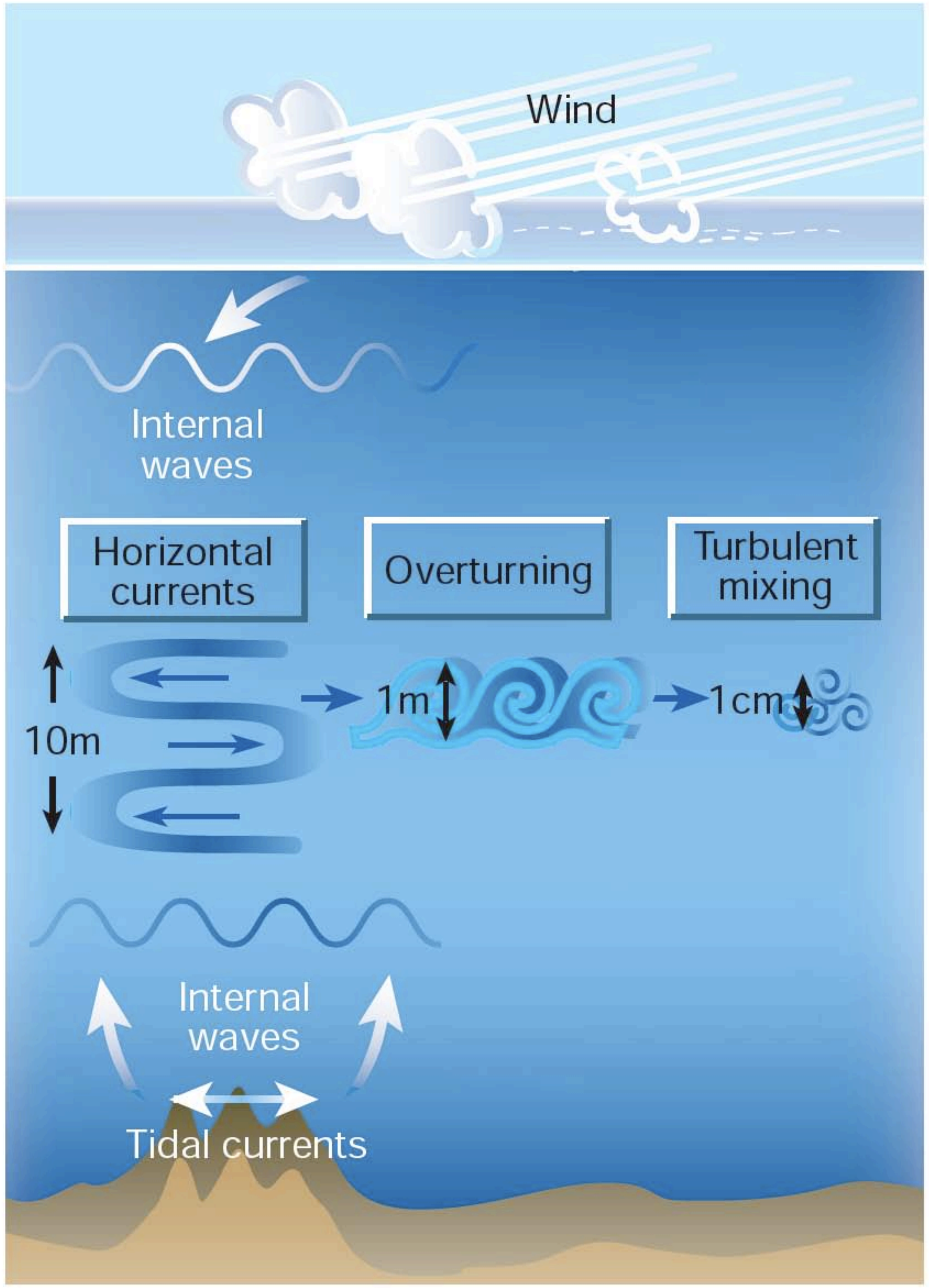
Vallis, 2000

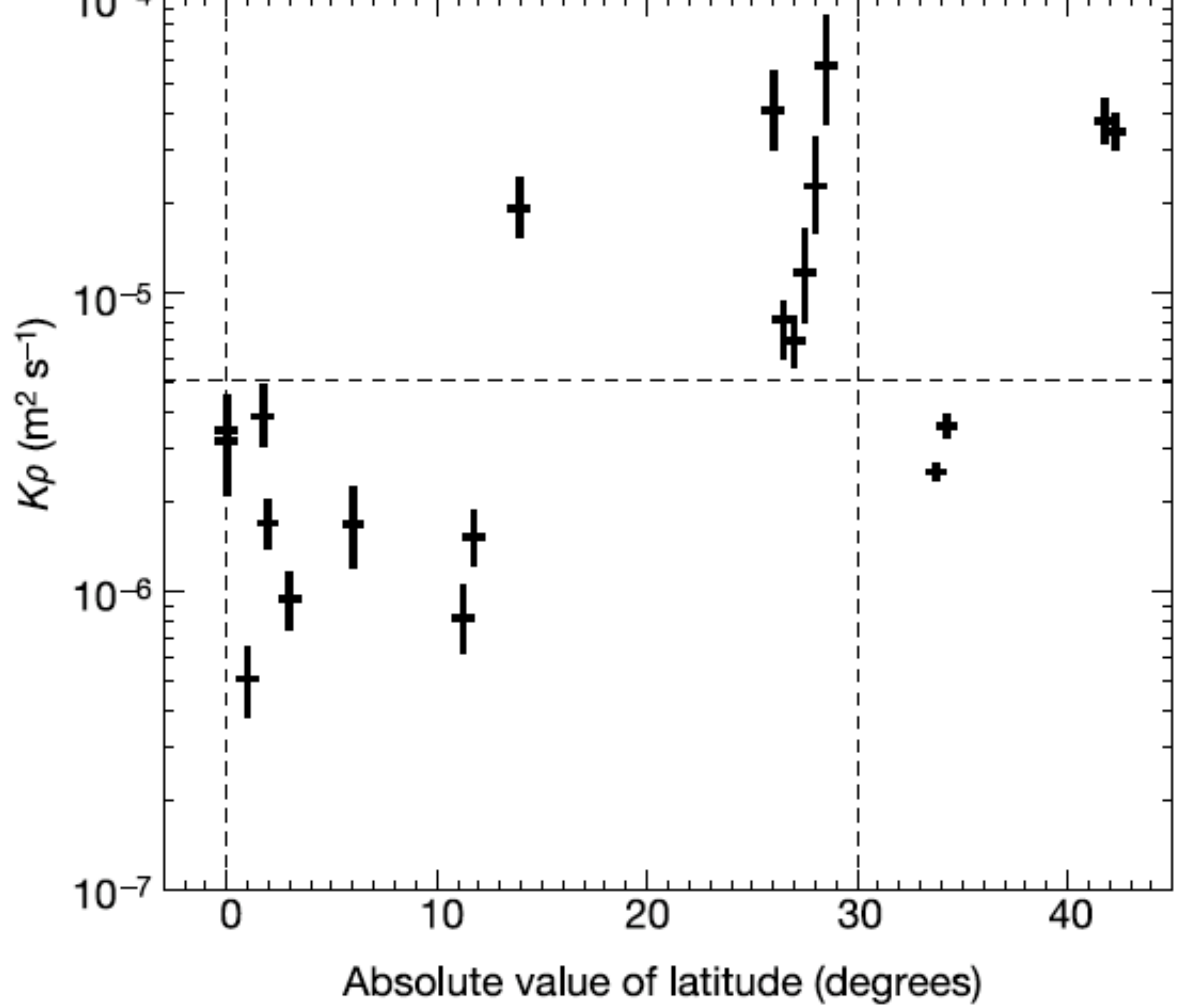


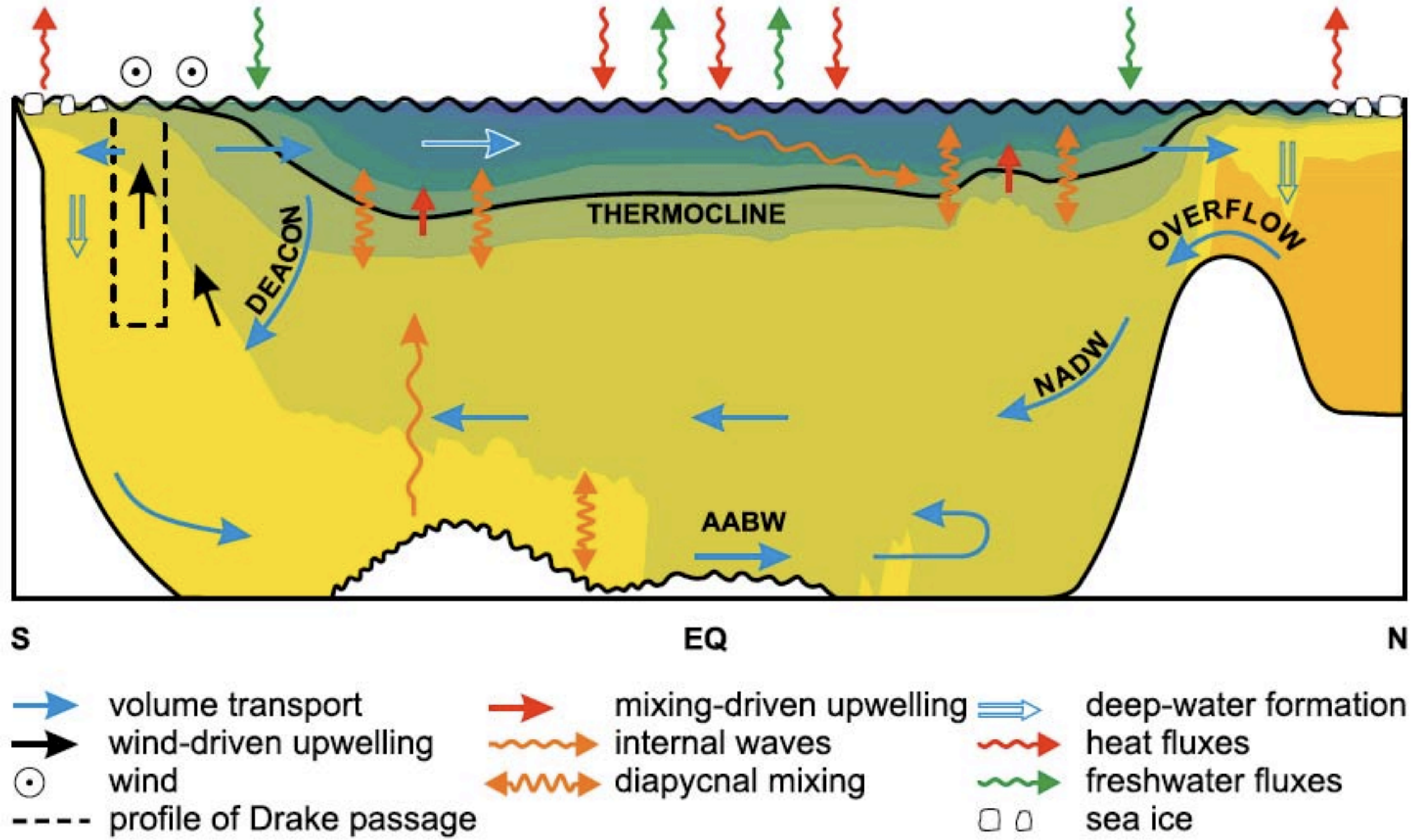


Kulbrodht et al, 2007

Meridional overturning streamfunction strong function of vertical diffusion


Wind
Internal waves
Horizontal currents
Overturning
Turbulent mixing
10m
1m
1cm
Internal waves
Tidal currents


10^{-4}
10^{-5}
10^{-6}
10^{-7}
Kρ (m² s⁻¹)
0
10
20
30
40
Absolute value of latitude (degrees)



Kulhbrodt et al., 2007

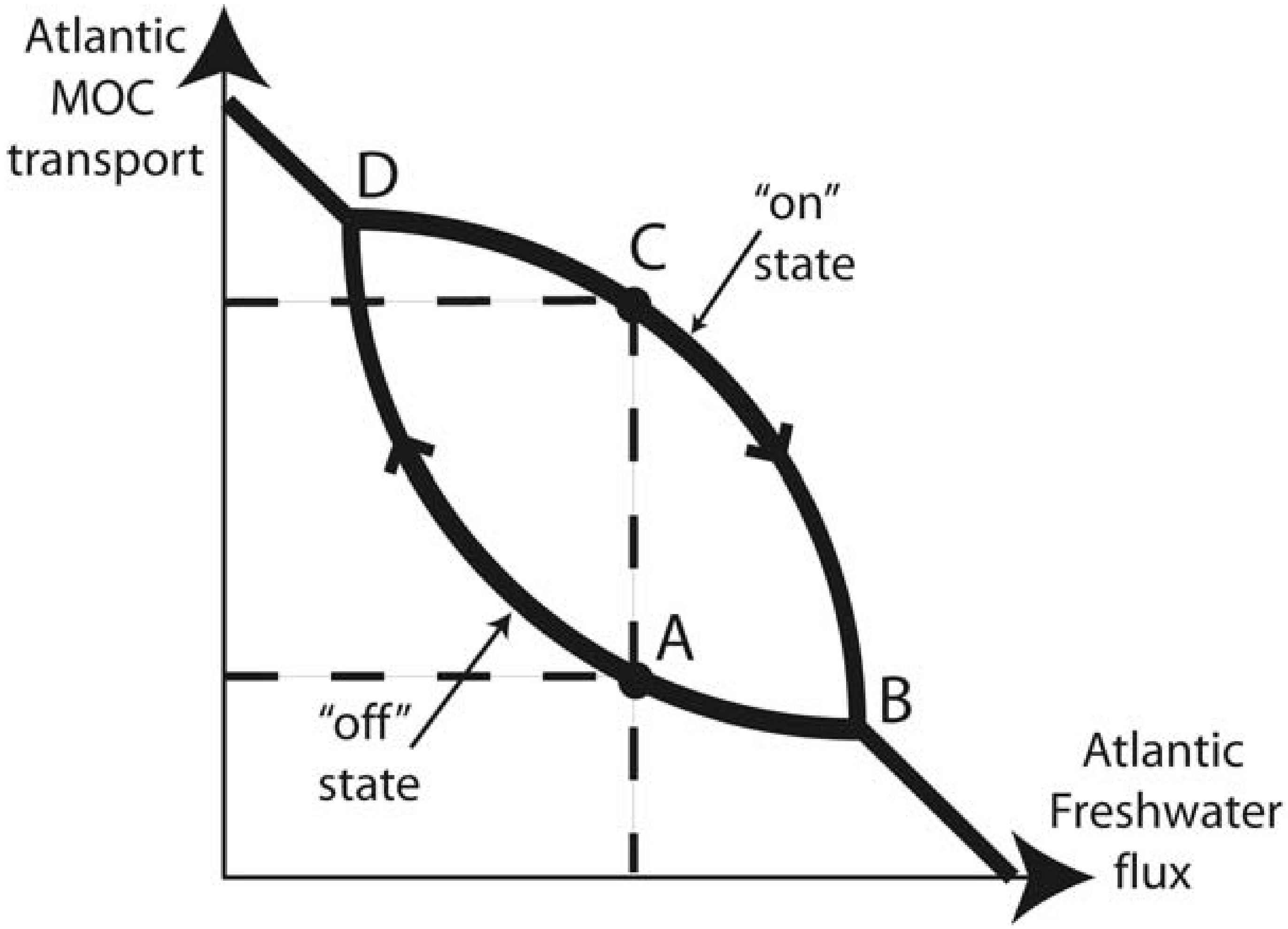


Fig. 1a: Schematic diagram of the familiar hysteresis associated with the MOC. For each freshwater flux, there are two different transports corresponding to two distinctly different stable solutions (points C and A). In a typical "hosing" numerical experiment, the upper branch is followed when the freshwater flux is gradually increased. On the other hand, the lower curve is followed when the freshwater flux is gradually decreased. See, for example, Rahmstorf (2002) for details.

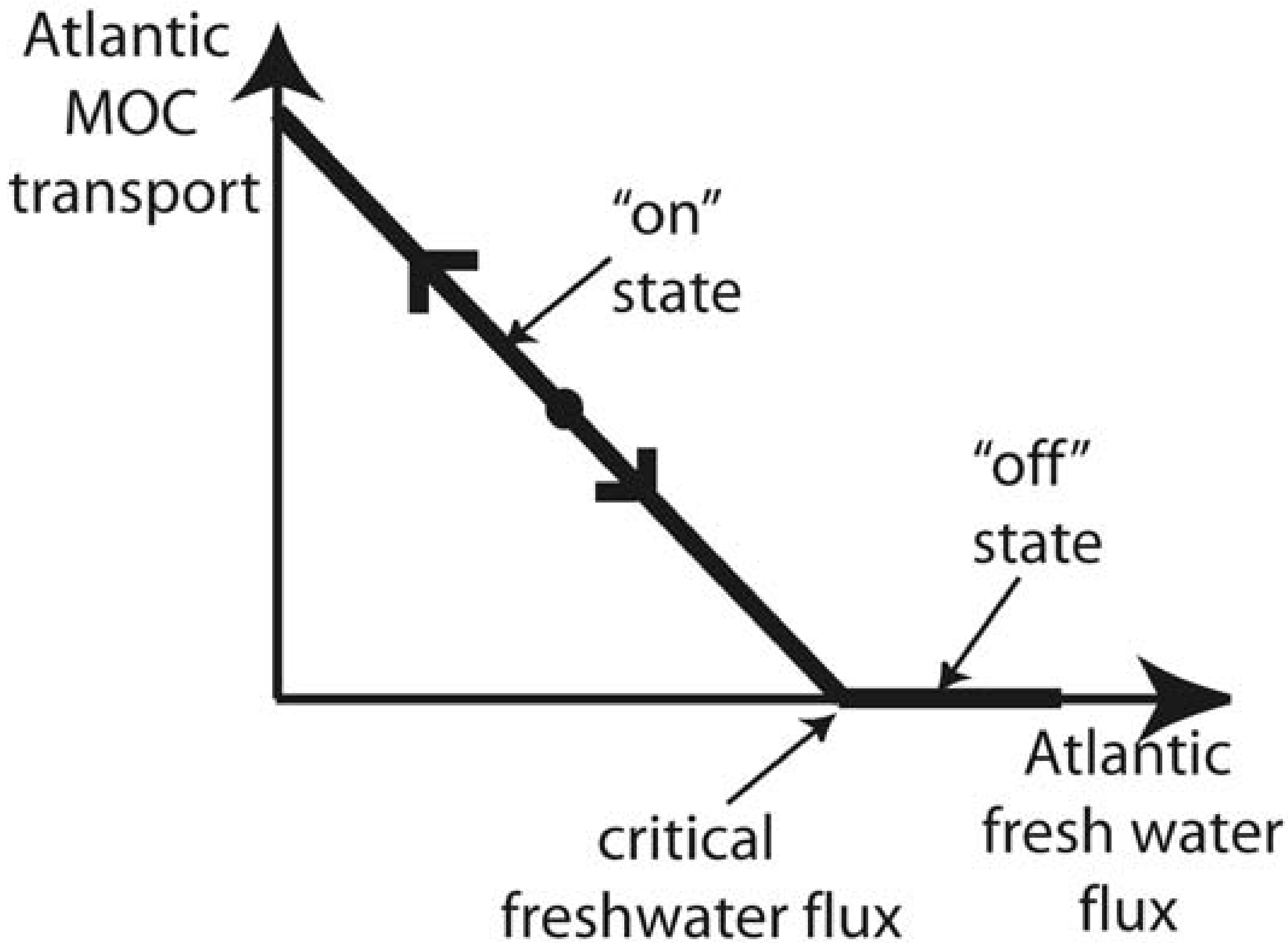


Fig. 1b: Schematic diagram of our perception of the MOC. There are no two states for the same freshwater flux. Rather, the “on” and “off” modes are actually a part of one continuous solution, involving no hysteresis.

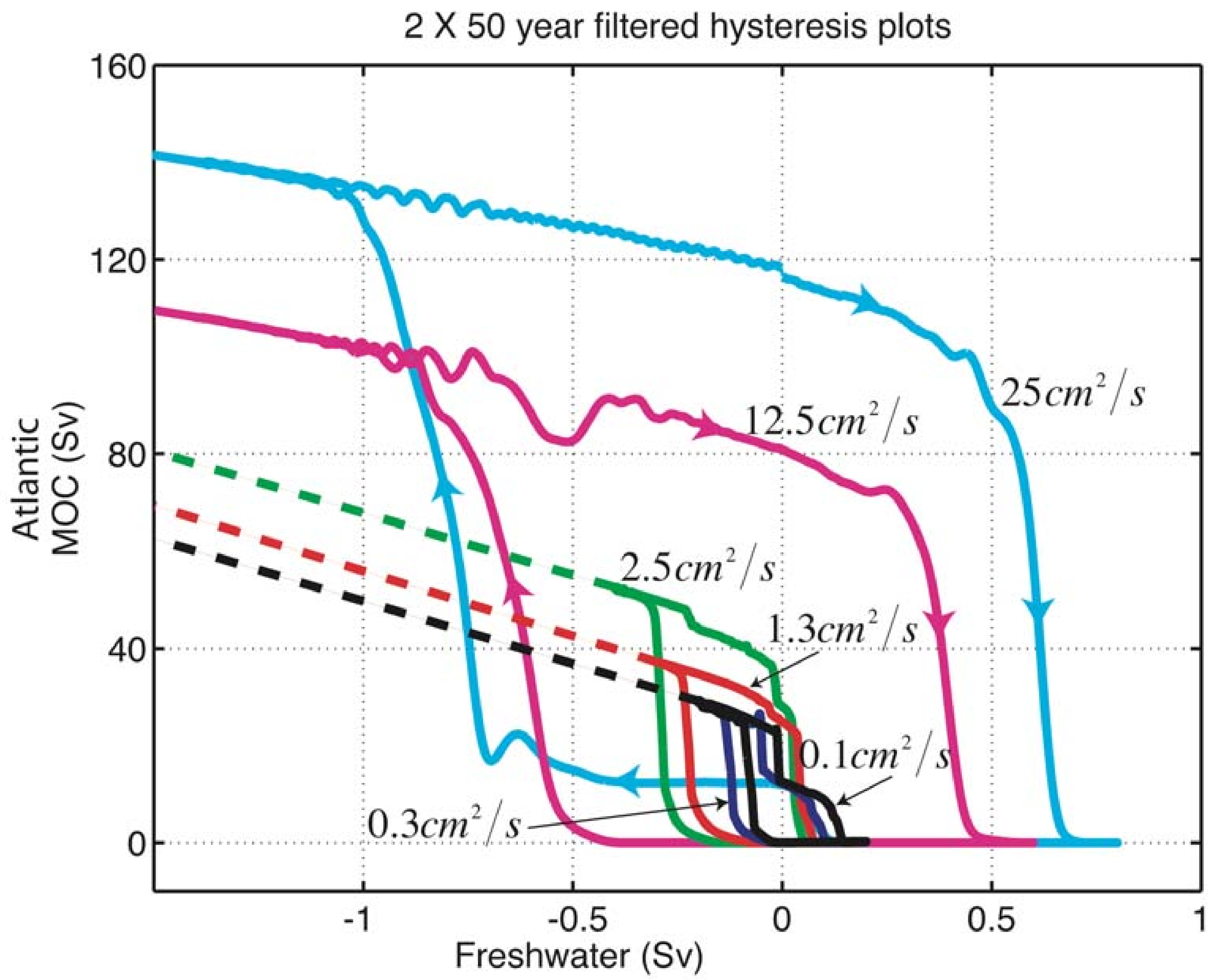


Fig. 6b: Plots of the maximum value of the North Atlantic meridional overturning mass flux (Sv) as a function of the freshwater flux perturbation applied to the 50-70 degree North longitude band for each of the 6 experiments. The model output was filtered with two passes of a 50-year running mean filter to remove some oscillations especially in the very high diffusivity experiments 4 & 5. The size of the hysteresis loops increases with increasing vertical diffusivity.

Steady State Energy Balance

Outflow temperature
Enthalpy exchange coefficient
Drag coefficient

$$\mathcal{P} = 2\pi \frac{T_s - T_o}{T_s} \int_a^b \left[C_k \rho |V| \left(k_0^* - k \right) + C_D \rho |V|^3 \right] r\,dr$$

Power generation
Surface temperature
Air-sea enthalpy disequilibrium
Dissipative heating

$$\mathcal{D} = 2\pi \int_a^b C_D \rho |V|^3 r\,dr$$

Dissipation

$$\rightarrow |V_{max}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left(k_0^* - k \right)$$

courtesy of K. Emanuel

Theoretical Upper Bound on Hurricane Maximum Wind Speed:

$$|V_{max}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left(k_0^* - k \right)$$

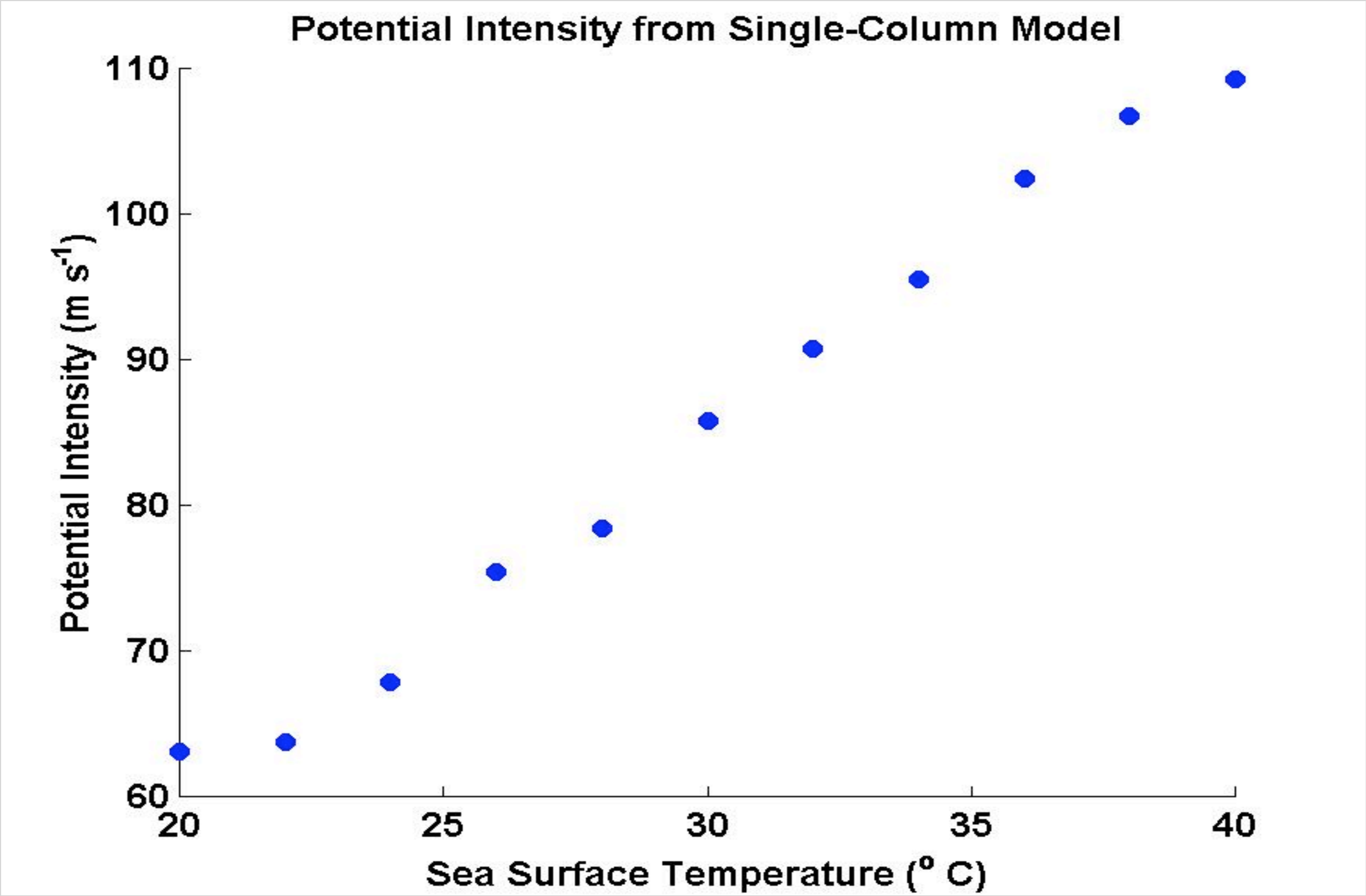
Surface temperature

Ratio of exchange coefficients of enthalpy and momentum

Outflow temperature

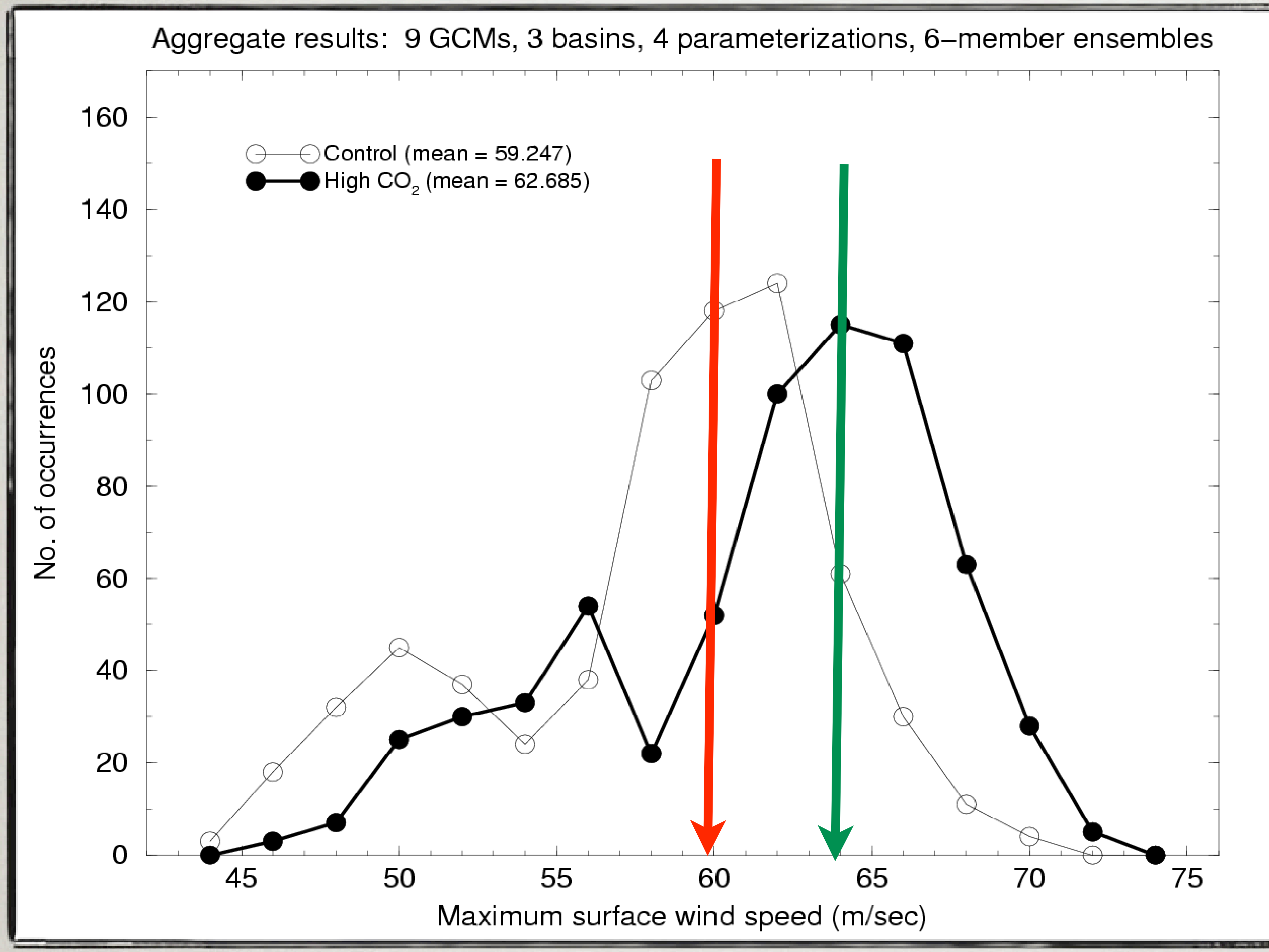
Air-sea enthalpy disequilibrium

courtesy of K. Emanuel



Maximum Potential Intensity as a function of SST (Emanuel, 1987)

Warmer water = more intense storms



Will global warming lead cyclones with stronger winds?

All models show increased maximum wind speeds

adapted from Knutson, 2005

Tropical Cyclone Power Dissipation

A measure of the potential destructiveness of a tropical cyclone based on integrated surface wind speed

$$PD = 2\pi \int_0^{\tau} \int_0^{r_0} C_d \rho |V^3| r \, dr \, dt$$

C_D - surface drag coeffiecient
ρ - surface air density
$|V|$ - magnitude of the surface wind

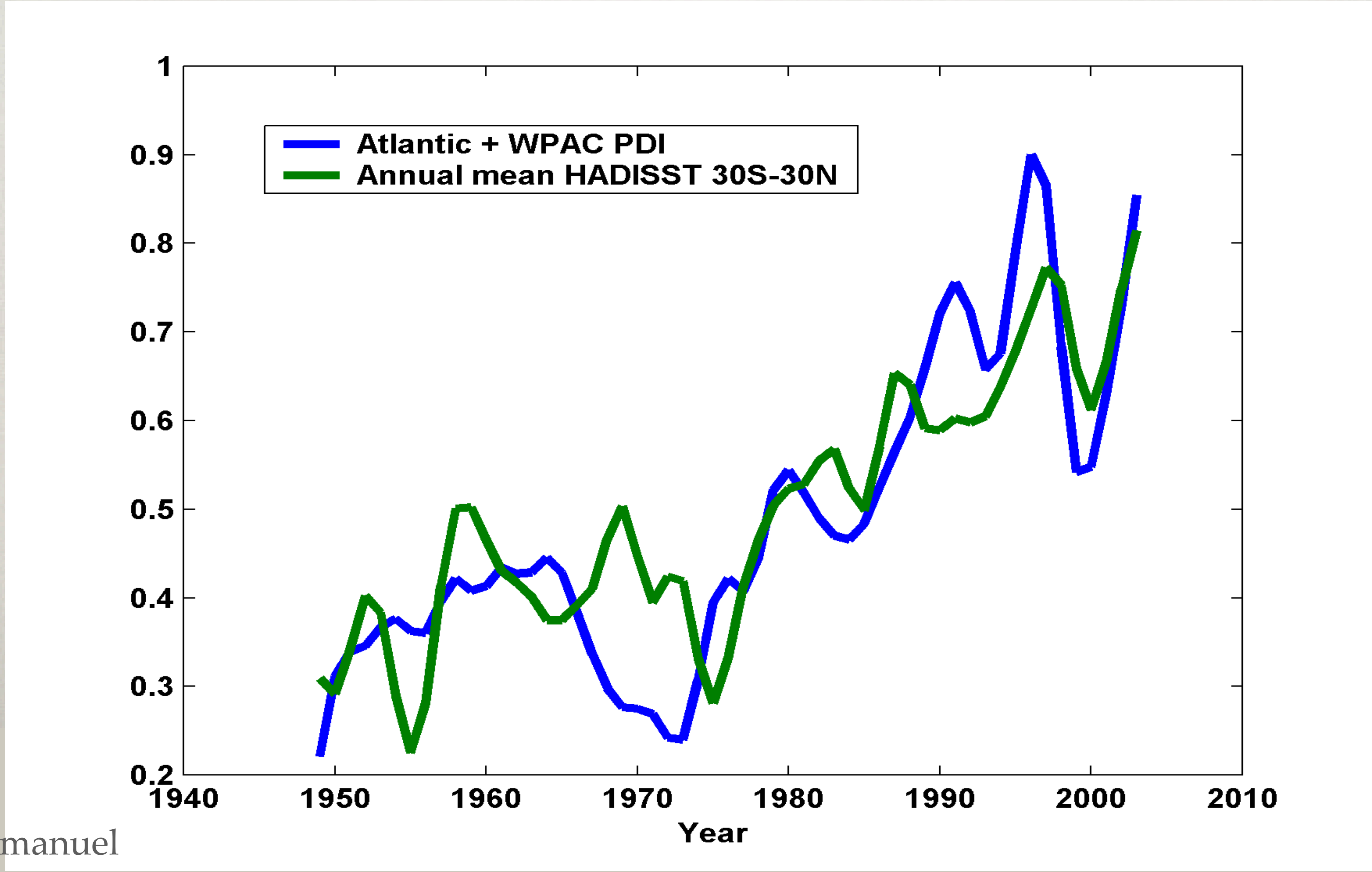
PD has units of Joules and represents the total amount of energy dissipated over the lifetime of a tropical cyclone.

Measures of tropical cyclone activity:

$$\textit{Power dissipation} = 2\pi \int_0^{\tau} \int_0^{r_0} C_D \rho \, |\mathbf{V}|^3 \, r dr dt.$$

Simplified "Power Dissipation Index":

$$PDI \equiv \int_0^{\tau} V_{max}^3 dt$$



courtesy of K. Emanuel

Emanuel (05) approximates the Power Dissipation (PD) as the Power Dissipation Index (PDI):

$$PDI \equiv \int_0^{\tau} |V_{max}|^3 \, dt$$

V_{max} is the maximum sustained winds at 10 meters and the area integral is avoided.

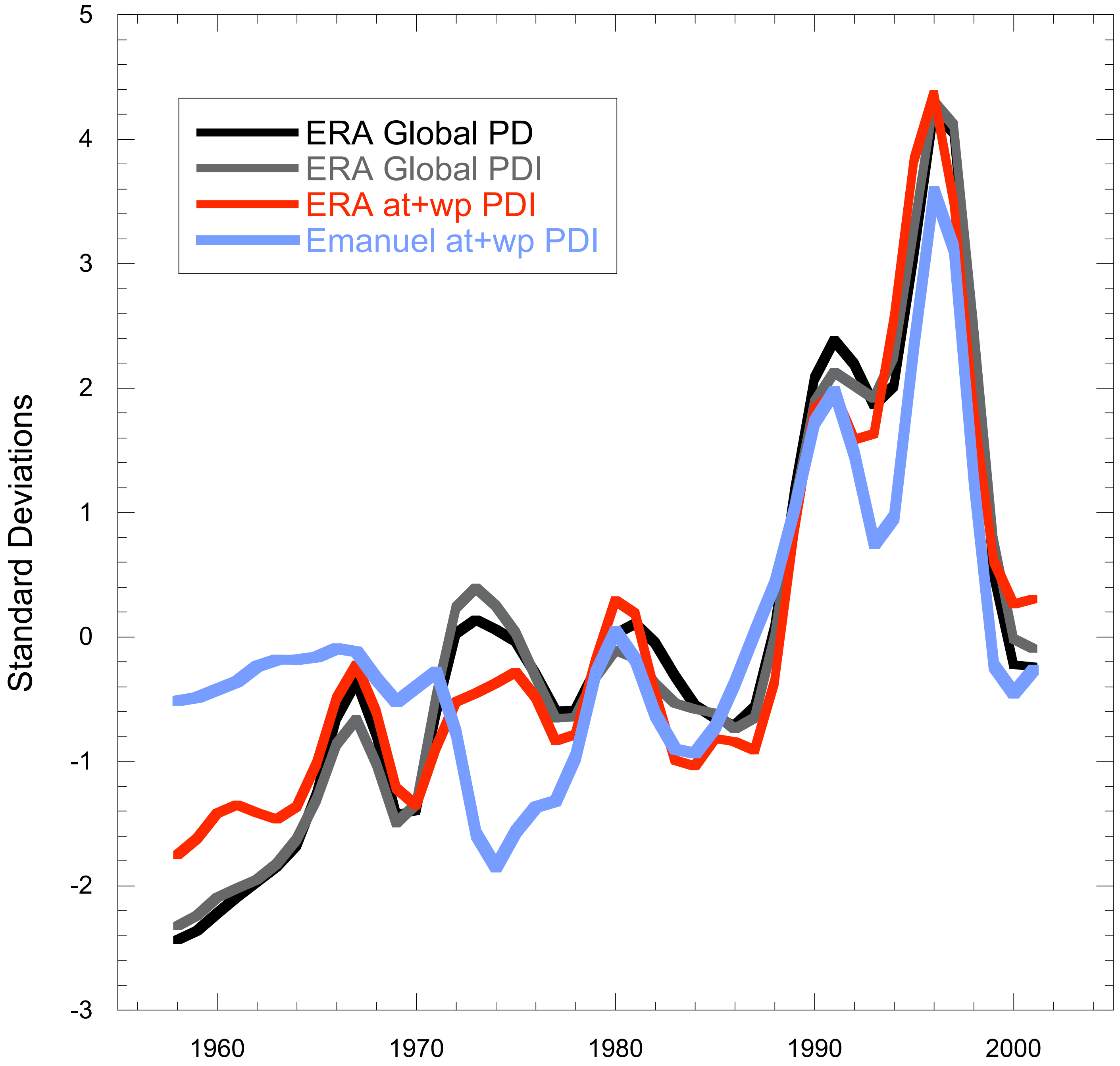
Implementation of high-resolution ERA-40 global winds (1.125x1.125 degrees, 4 times daily) allows us to calculate PD more explicitly:

$$PD \approx 2\pi C_d \rho \int_0^{\tau} \int_0^{r_0} |V^3| r \, dr \, dt$$

The product $C_d \rho$ is assumed constant and now the geometric dimensions of the storm are included in the integral.

Power Dissipation from ERA-40

Figure 1



Sriver and Huber, GRL, 2006

Trends in Power Dissipation (PD) quantities for the ERA40 project period , 1958-2001.

Key Points:

- PDI is a good approximation for PD.

- TC records for the Atlantic and western Pacific are adequate indicators for global TC activity.

$$PDI \equiv \int_0^{\tau} |V_{max}|^3 \, dt$$

$$PD \approx 2\pi C_d \rho \int_0^{\tau} \int_0^{r_0} |V^3| r \, dr \, dt$$

Reanalysis-derived PD (integrated intensity) and mean annual tropical temperature

Figure 2

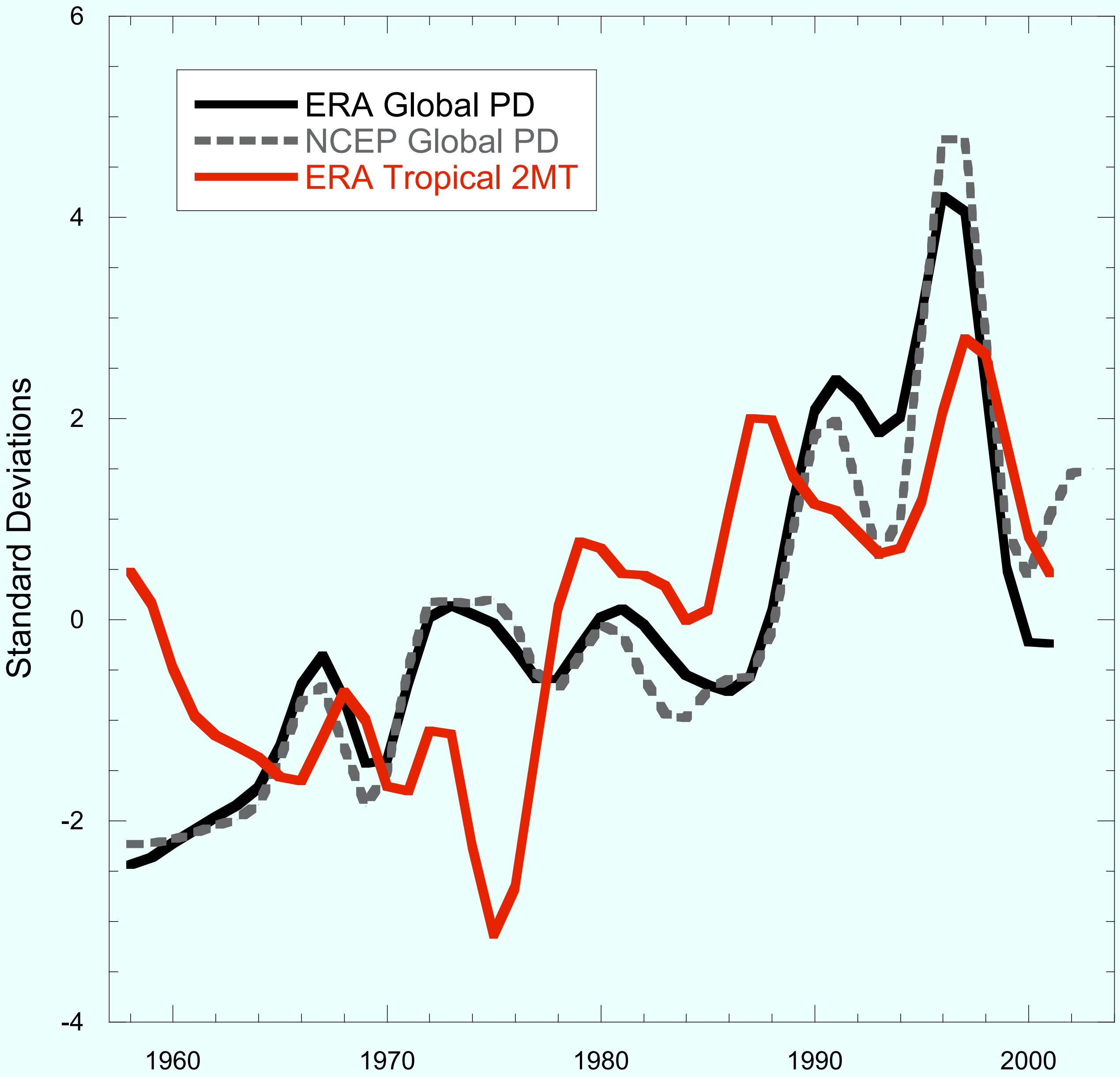
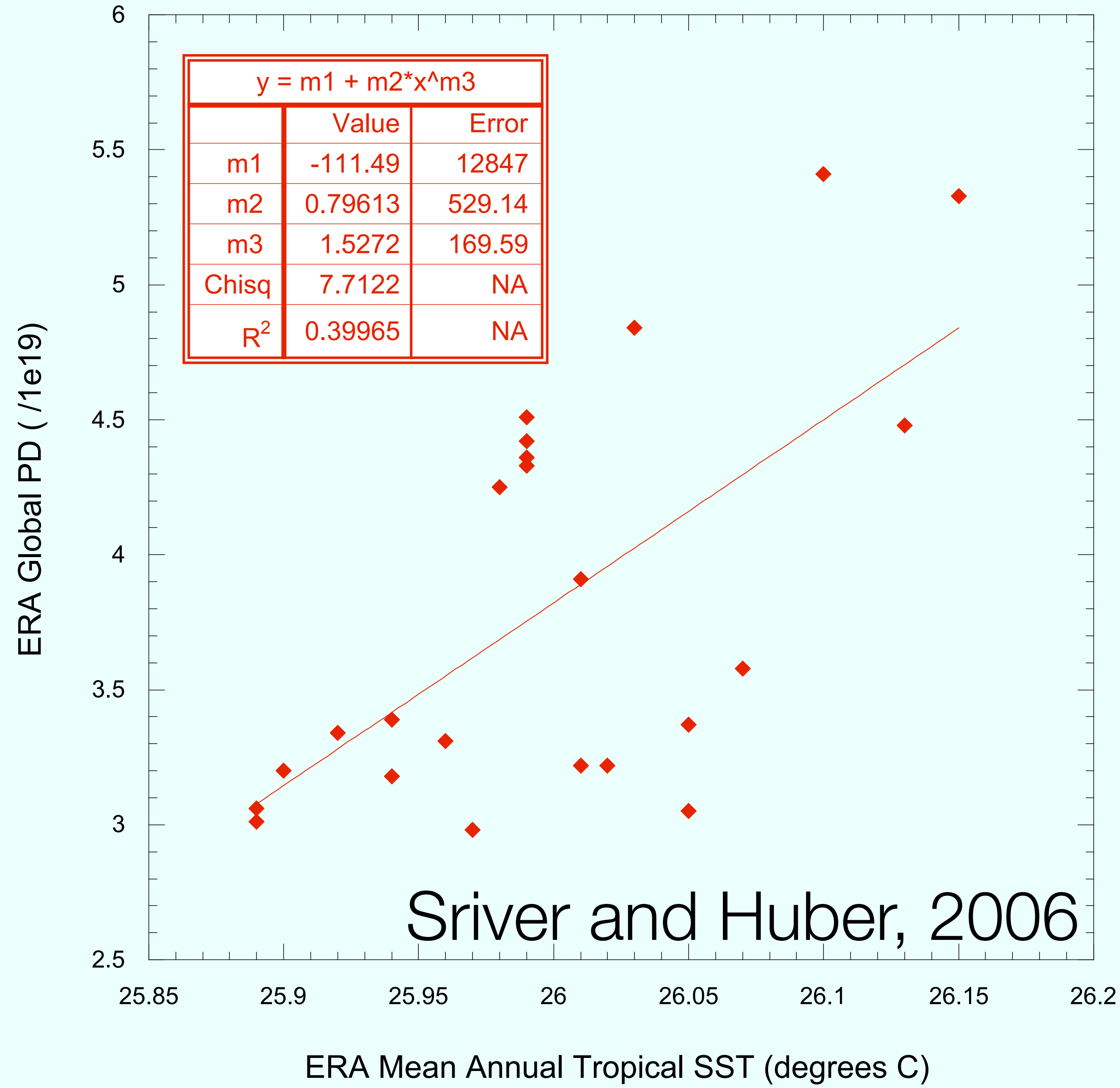


Figure S.4

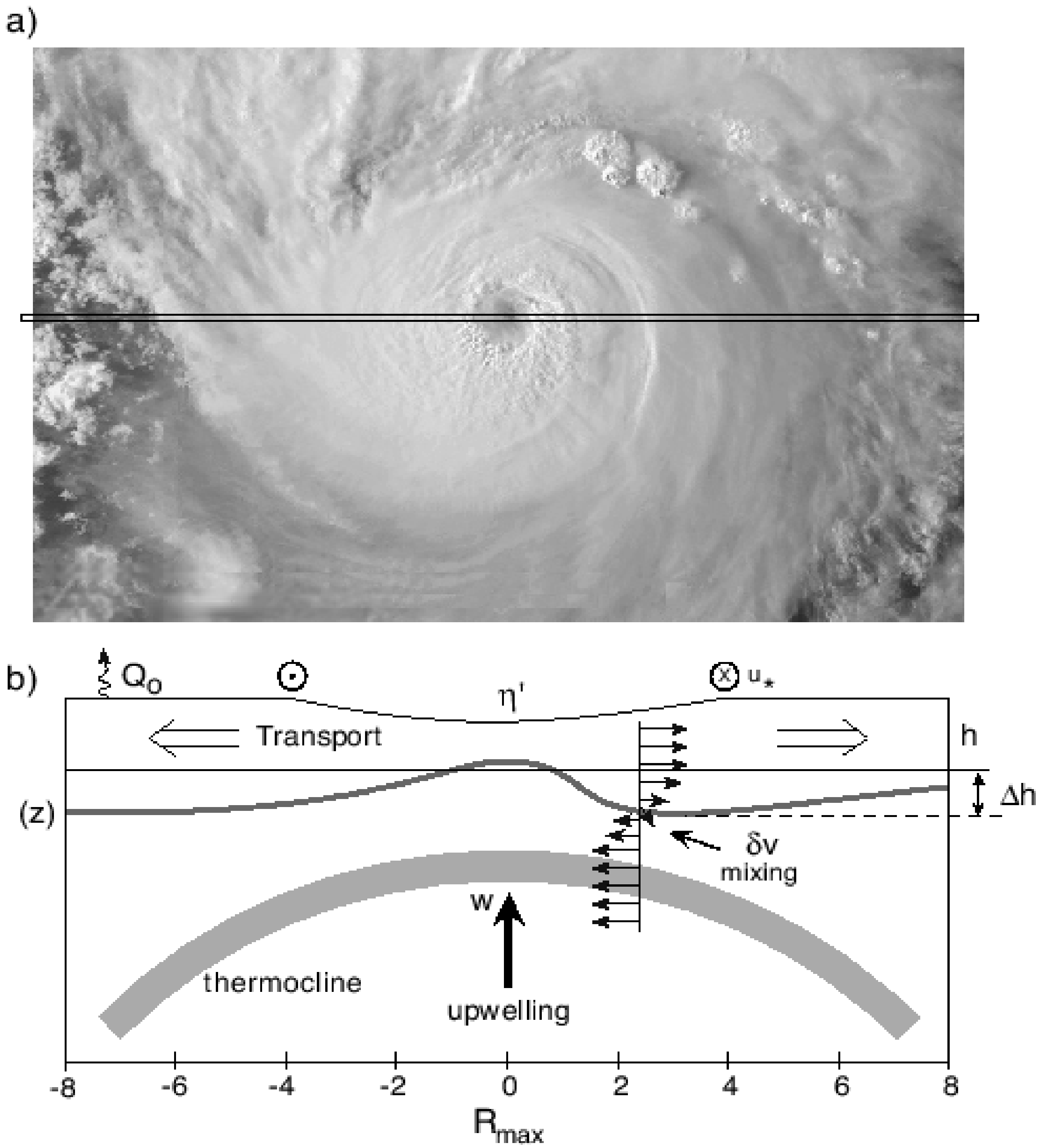


0.25 degree C increase in mean annual tropical temperature may lead to a ~ 80% increase in tropical cyclone integrated intensity

Higher temperatures => higher integrated TC intensity->MOC increase

Dynamic response of the upper ocean to tropical cyclone winds

- Extreme surface wind forcing can excite the background wave field
- - generating near-inertial internal gravity waves
- - producing geostrophic currents
- - leading to baroclinic ridges from elevated isopycnals
- Entrainment fluxes at the base of the mixed layer account for 60-85% of upper ocean cyclone-induced cooling. (Jacob et al., 2000; Shay, 2006)



Shay, 2006

Penetration depth of mixing and energetics of geostrophic currents

Froude # $$F_r = \frac{U_h}{c_n}$$

Aspect ratio $$\frac{L}{R_n}$$

U_h - translational speed of storm

$c_n = \sqrt{gH}$ - speed of normal mode (n) long gravity waves

L - horizontal length scale of storm

$R_n = \frac{c_n}{f}$ - radius of deformation

$$F_r = \frac{U_h}{c_n} \qquad\qquad \frac{L}{R_n}$$

Slow moving storms, $F_r \leq 1$

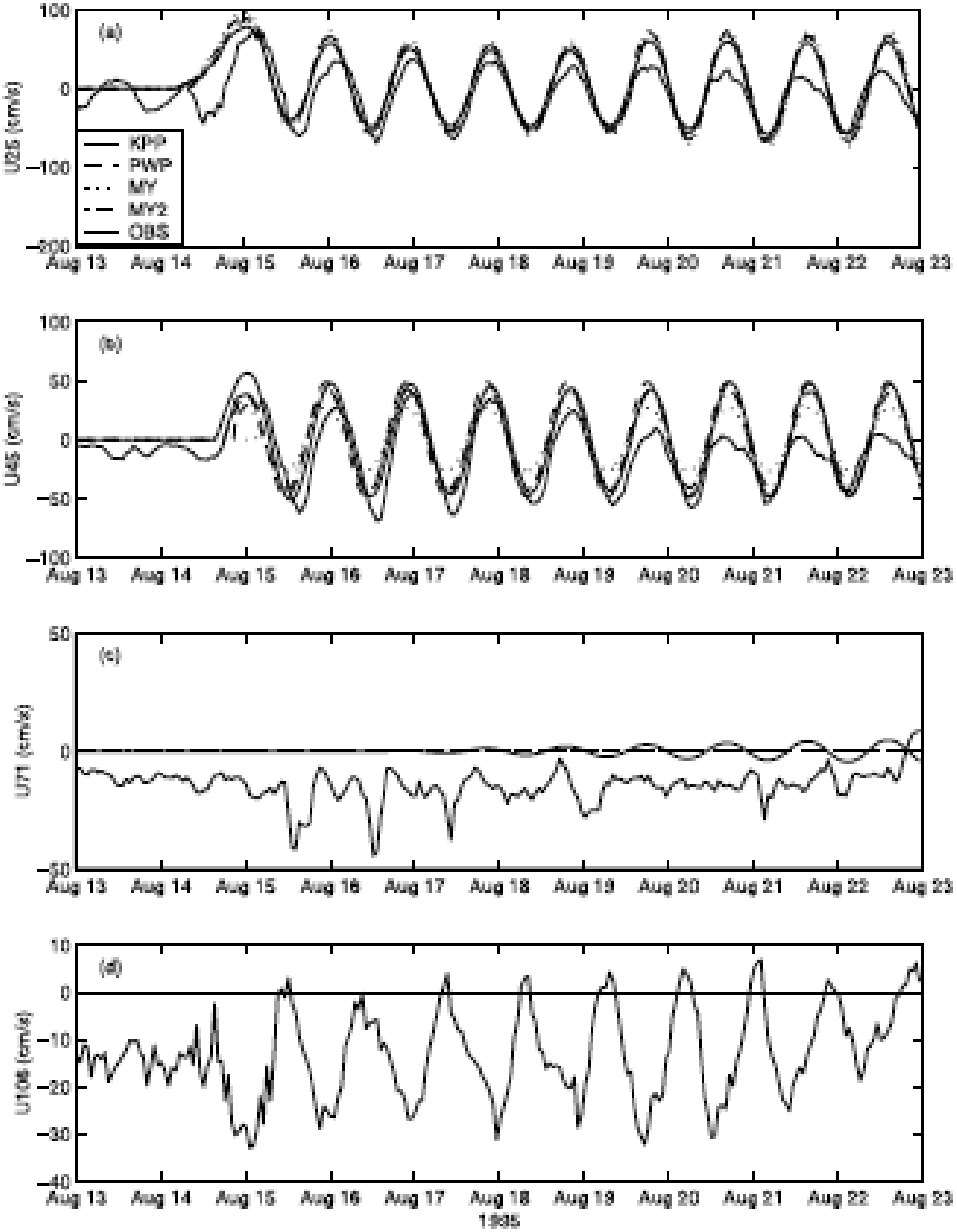
Produce more energetic geostrophic response and larger values of $\frac{L}{R_n}$, causing deeper penetration of mixing and elevated isopycnals.

- Orlanski and Polinsky, 1983

Fast moving storms, $F_r \geq 1$

More energy is supplied to the near-inertial wave field and less to geostrophic currents.

Excitation of inertial waves



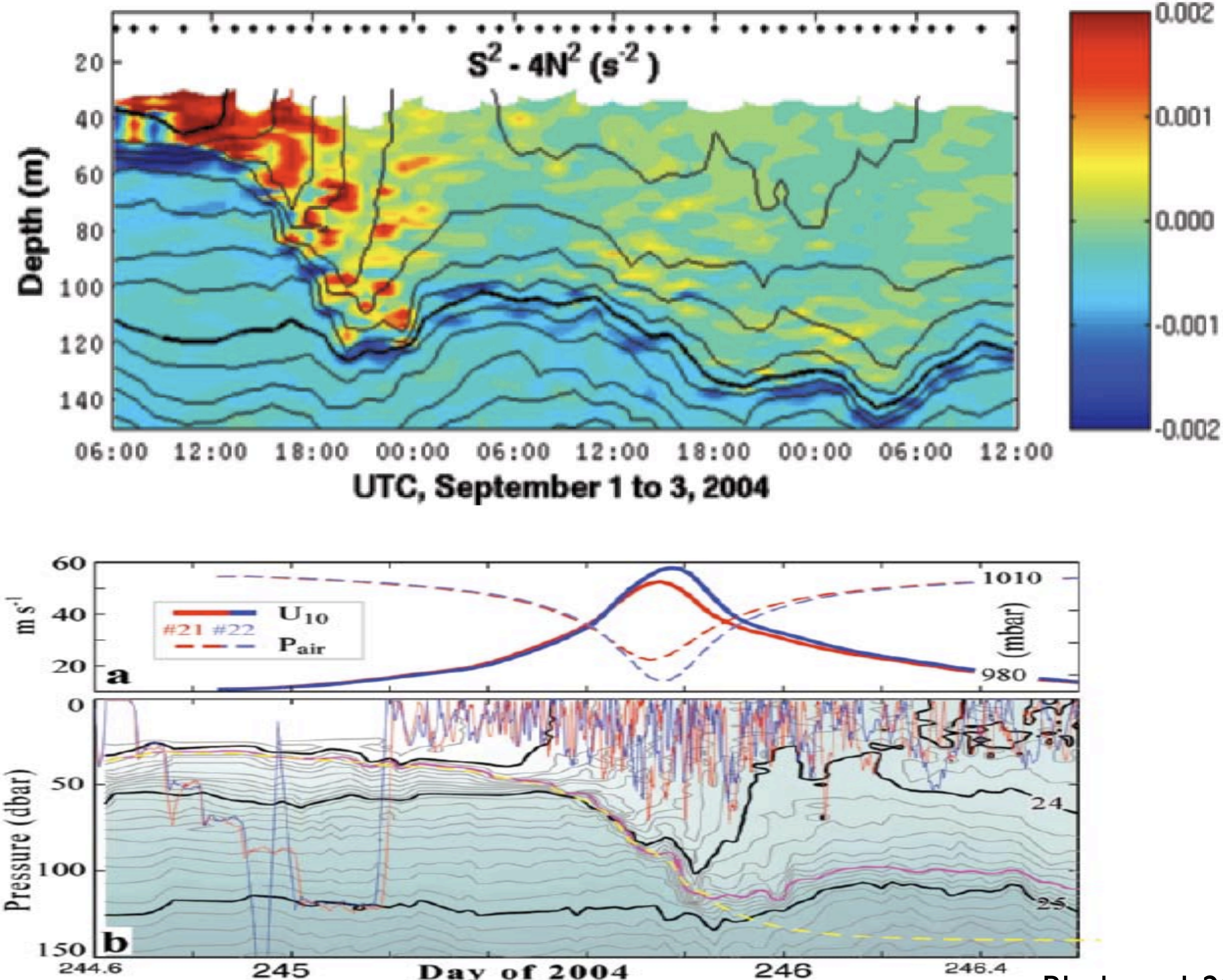
Hurricane Felix 1995

Vertical profiles of horizontal velocities prior to, during, and after passage of storm from observations and model results.

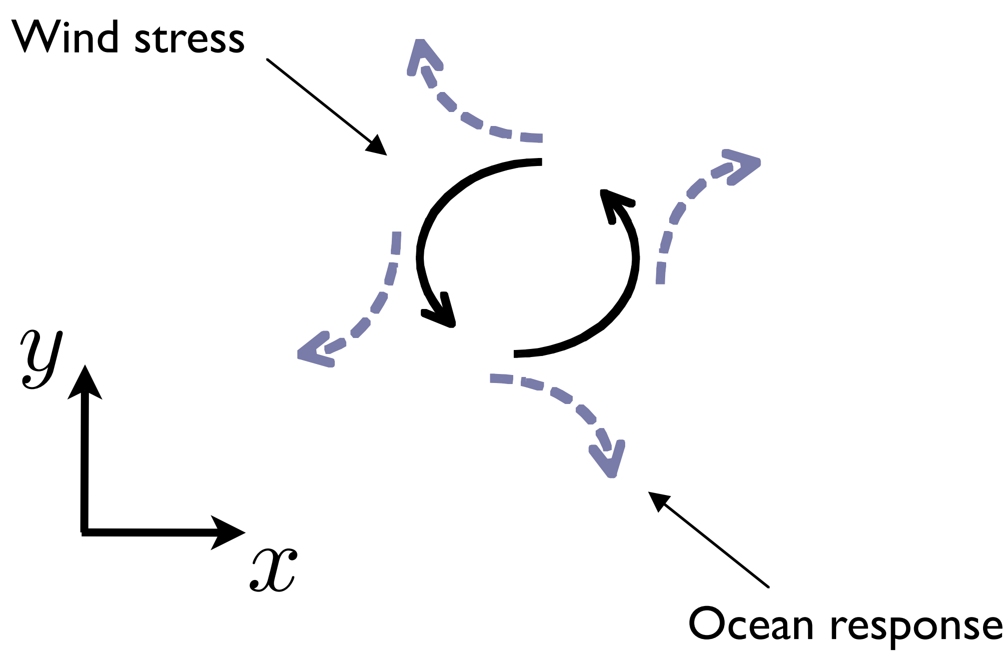
Observations are from the Bermuda testbed mooring site (denoted in plots by thick black line).

Surface wind forcing excites the background wave field producing a near-inertial response.

Zedler et al., 2002



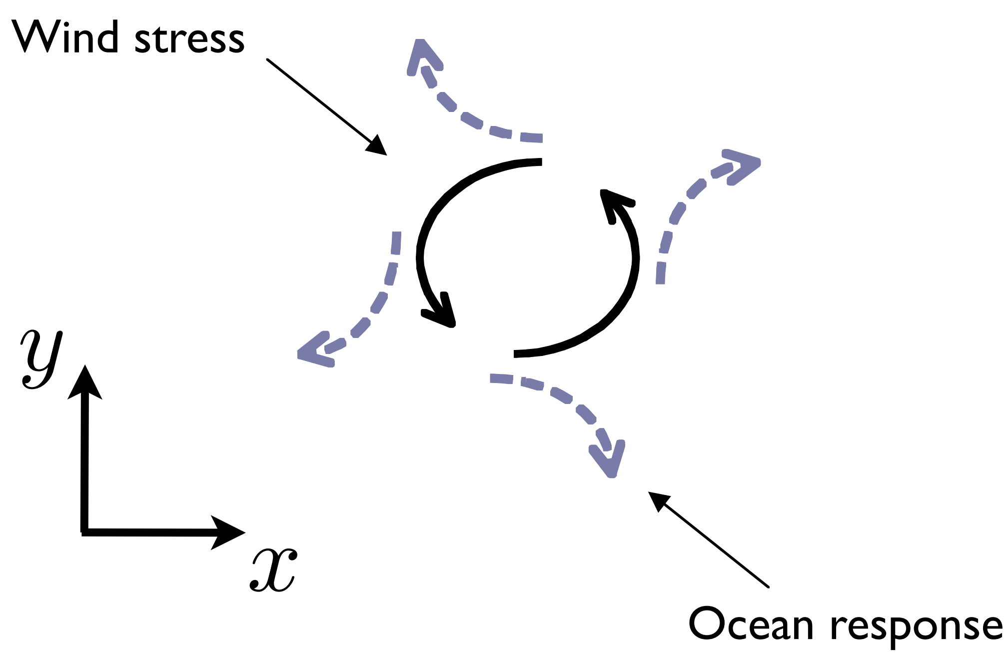
Black et al. 2007



In addition to generating near-inertial gravity waves, TCs generate geostrophic ocean currents.

The geostrophic response of the upper ocean to TC-wind forcing is divergent flow.

Cyclonic forcing by the atmosphere => anticyclonic response by the ocean



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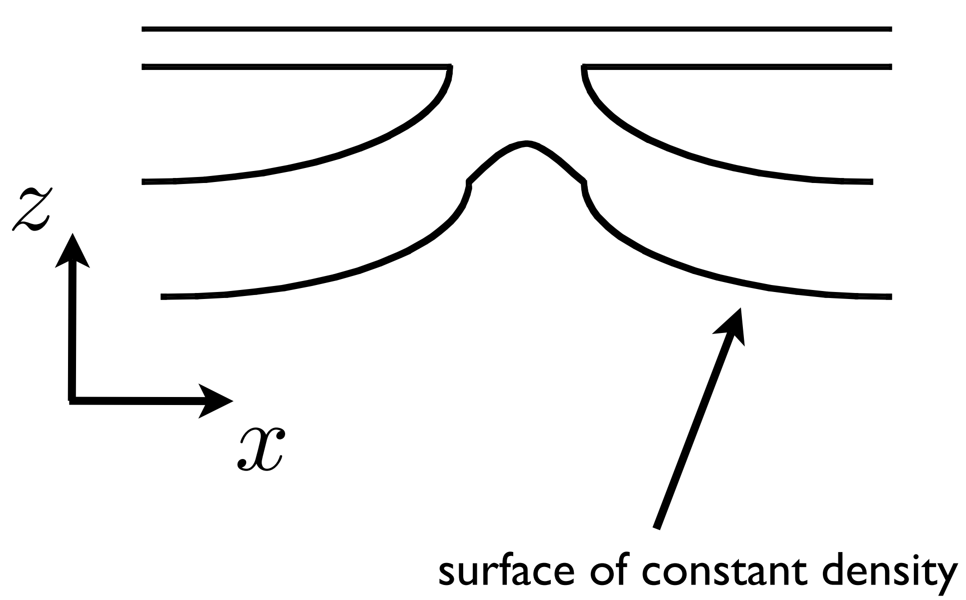
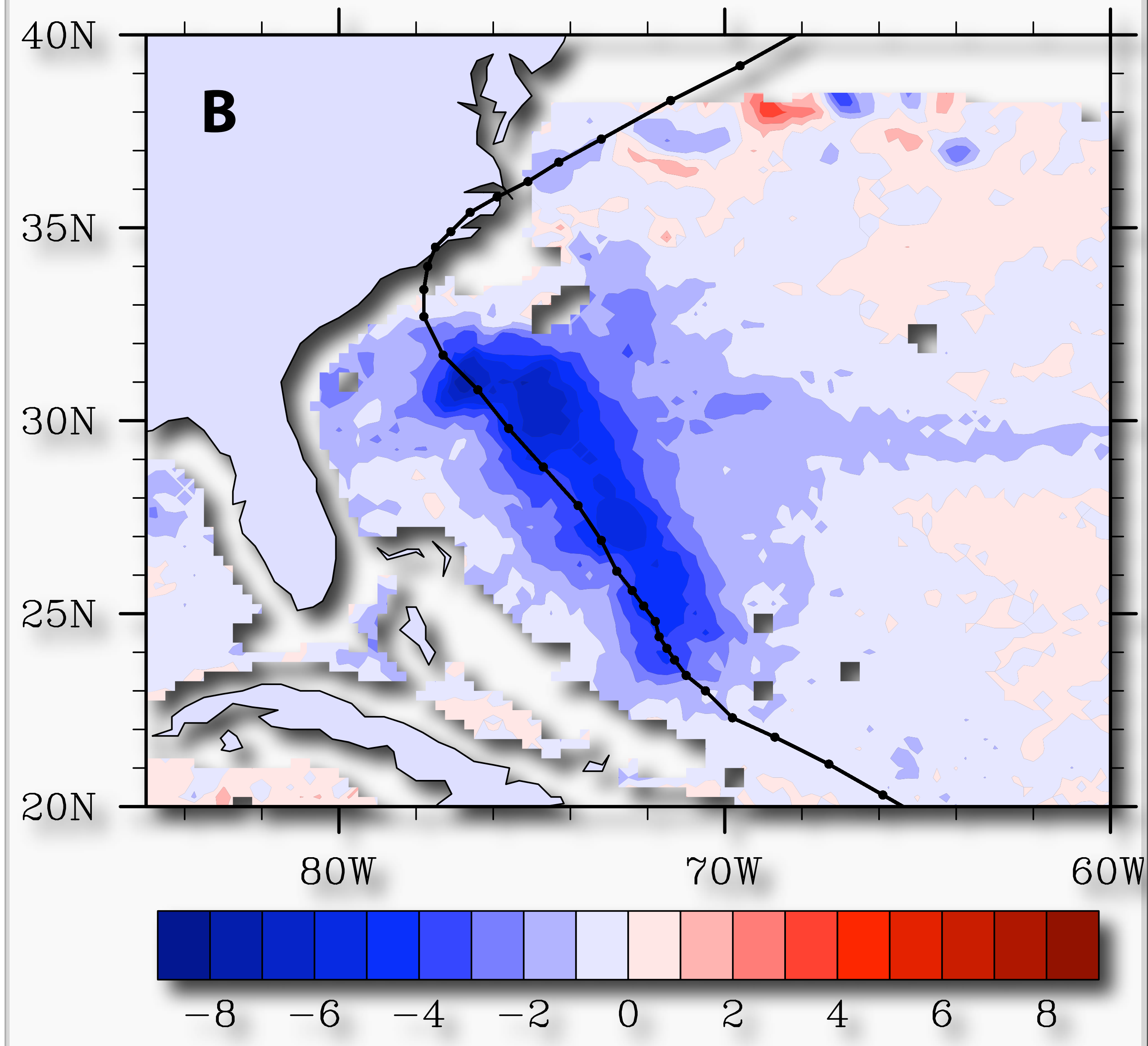


Divergence leads to upward deflection of isopycnals
=> upwelling of cold water from within thermocline.

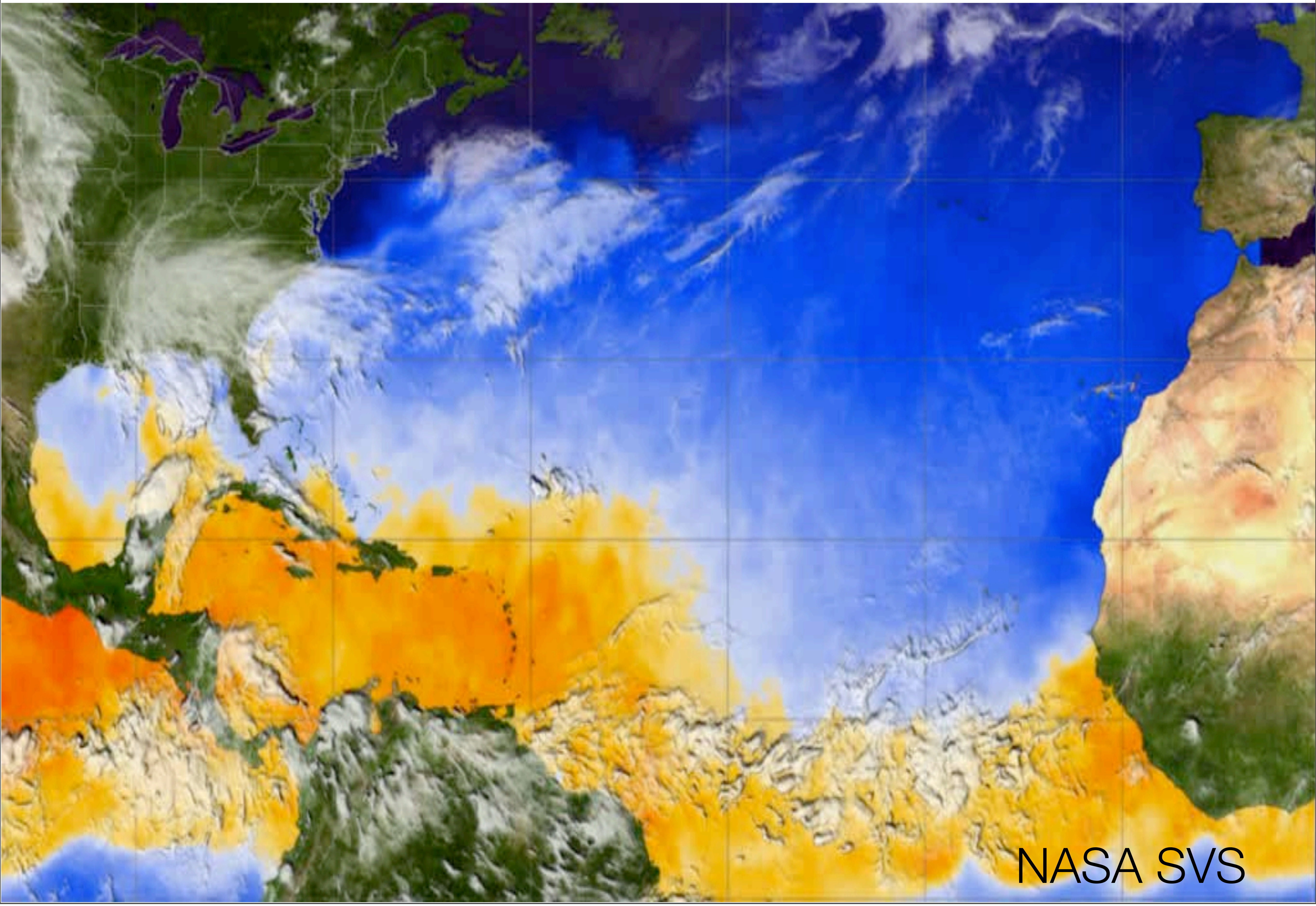
Uplift of isopycnals (or the change in mixed layer depth) may be up to 100 meters.

The TC-OHT Hypothesis (Emanuel, 2002)

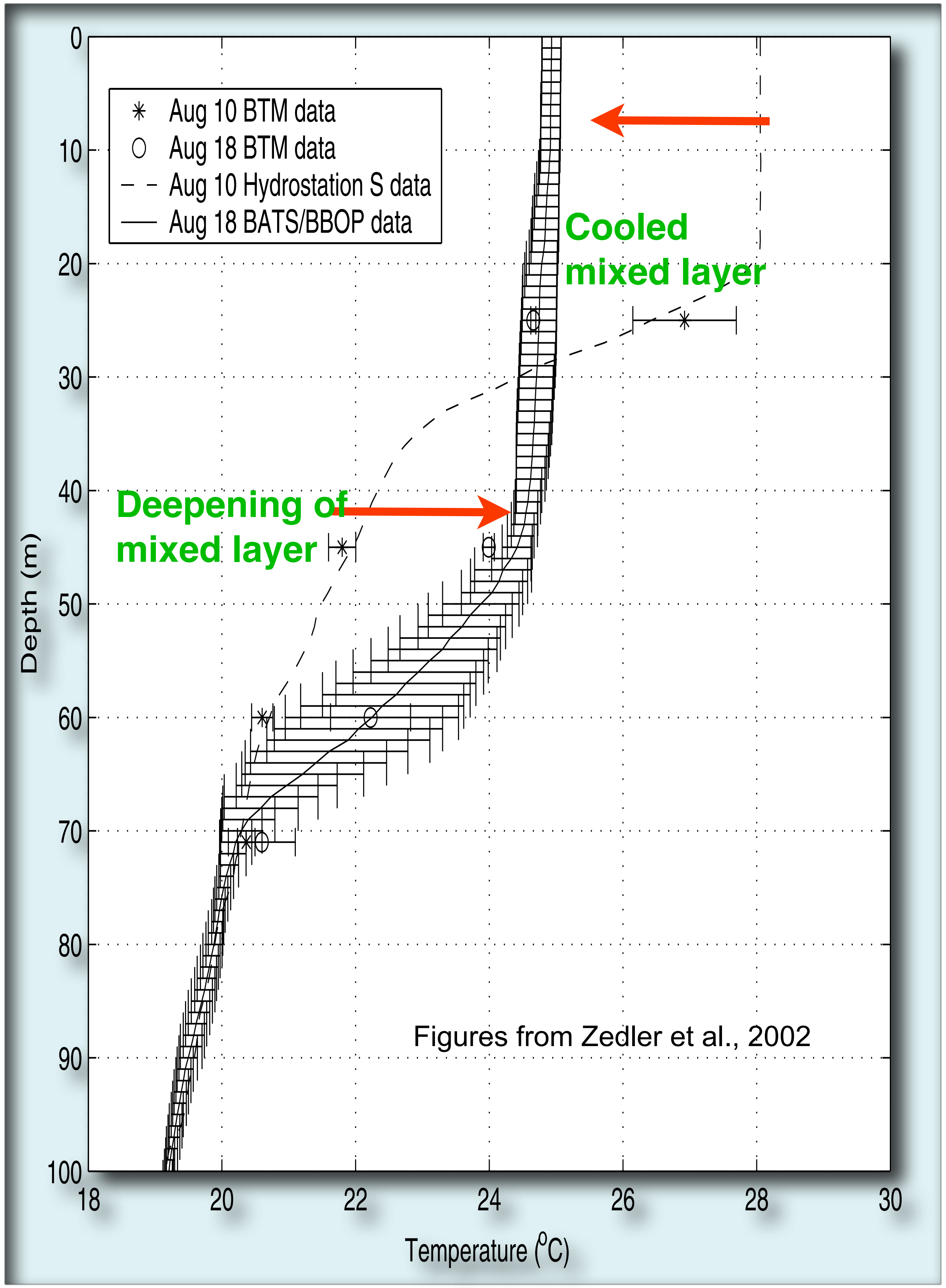
- Tropical cyclones induce strong ‘cold wakes’ via vertical mixing upwards of colder denser water from below
- This vertical mixing is hypothesized to drive the meridional overturning circulation of the ocean and ocean heat transport
- This process may represent the ocean’s ‘missing mixing’ and it may be--itself--a function of tropical temperatures

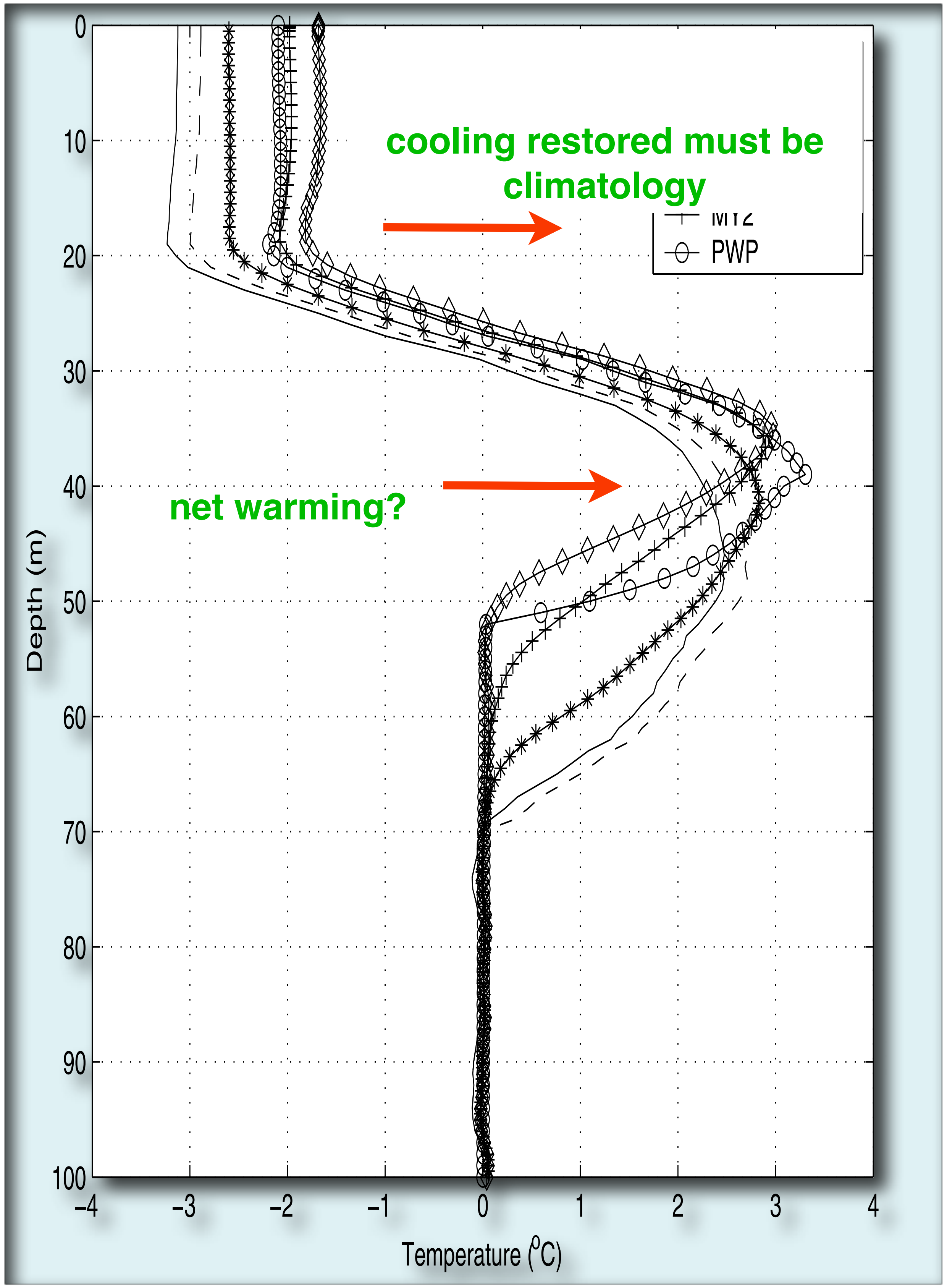


Hurricanes of 2005



Observations and model results for Hurricane Felix, 2001

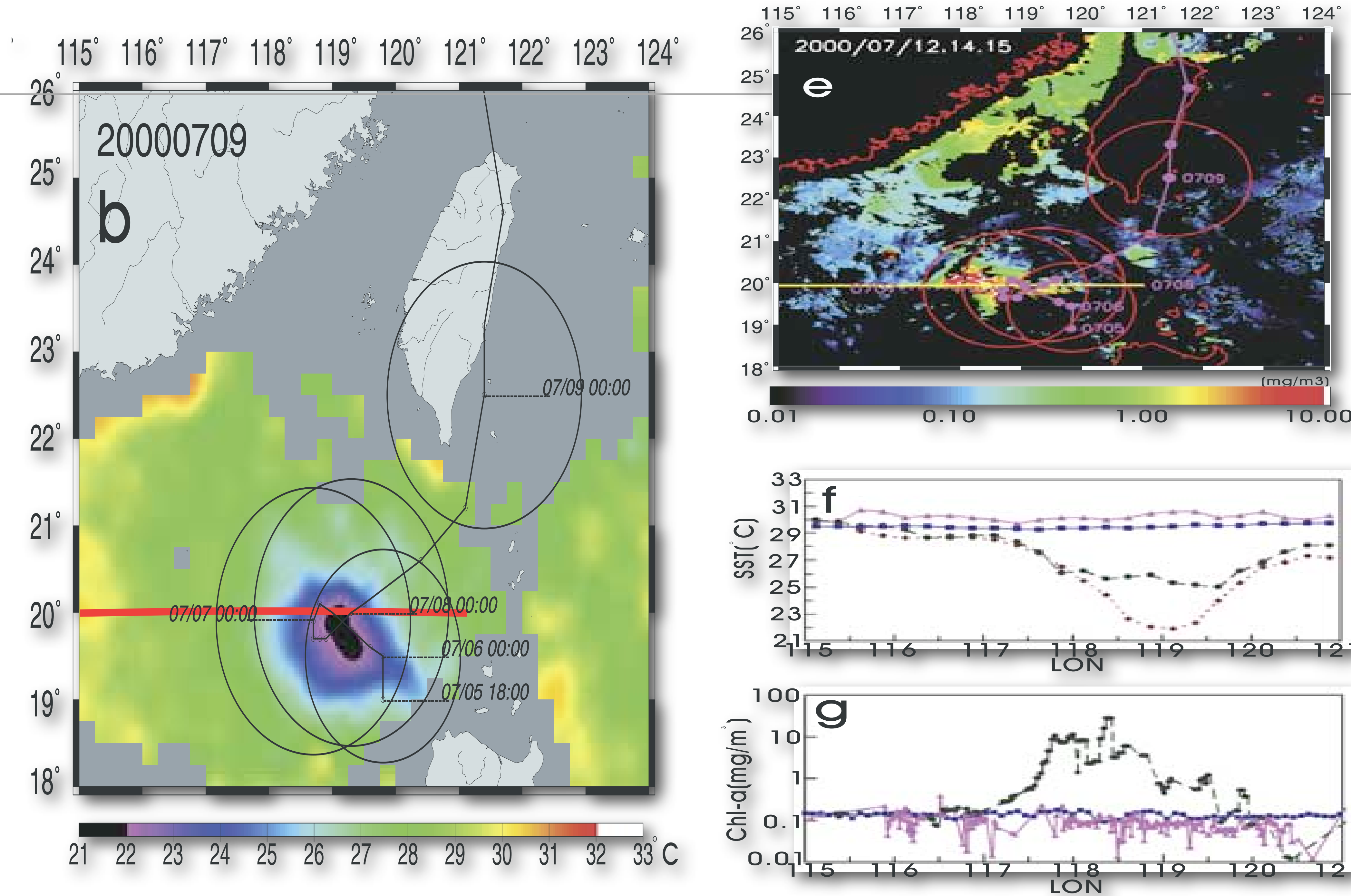




Deepened mixed layer leads to anomalous warming within the thermocline.

If mixed layer is restored to climatology by surface fluxes, then column integrated heating must represent a net poleward heat flux in steady state.

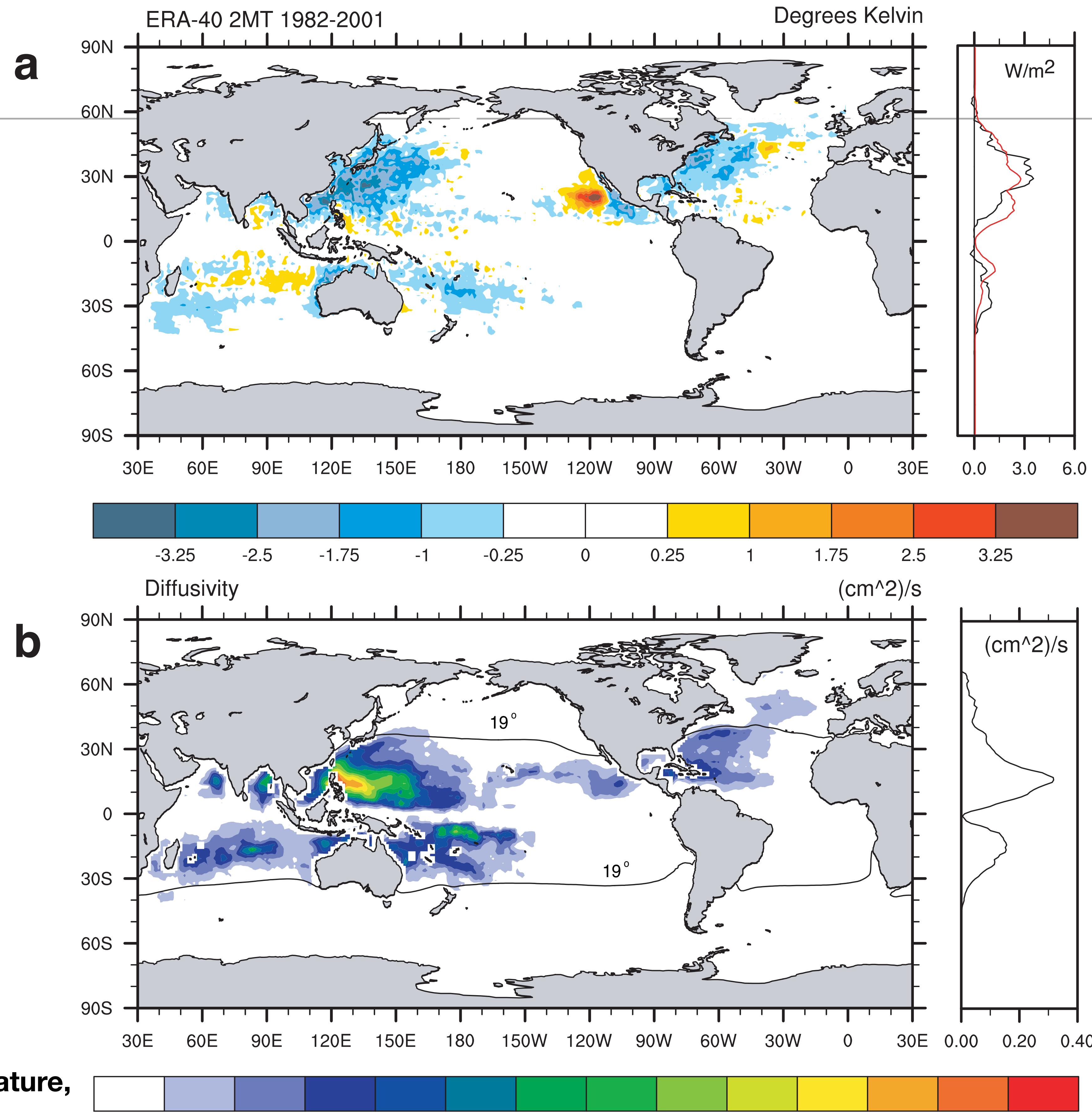
40



Tropical cyclones mix the upper ocean--causing cooling and plankton blooms (~30% of new production in the oligotrophic gyres)

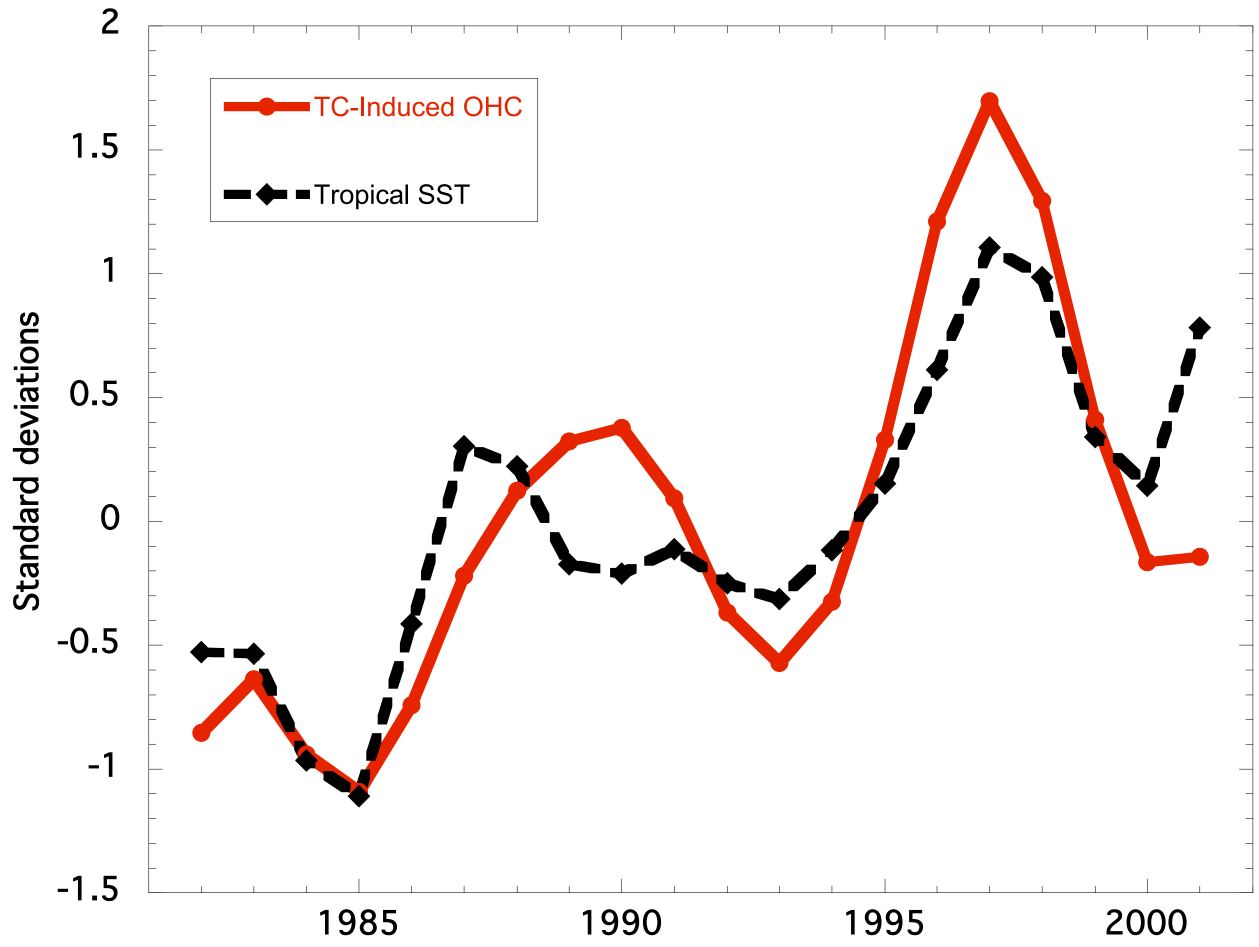
Lin et al., GRL 2003

Surface cooling and estimated effective vertical diffusivity



Sriver and Huber, Nature, 2007

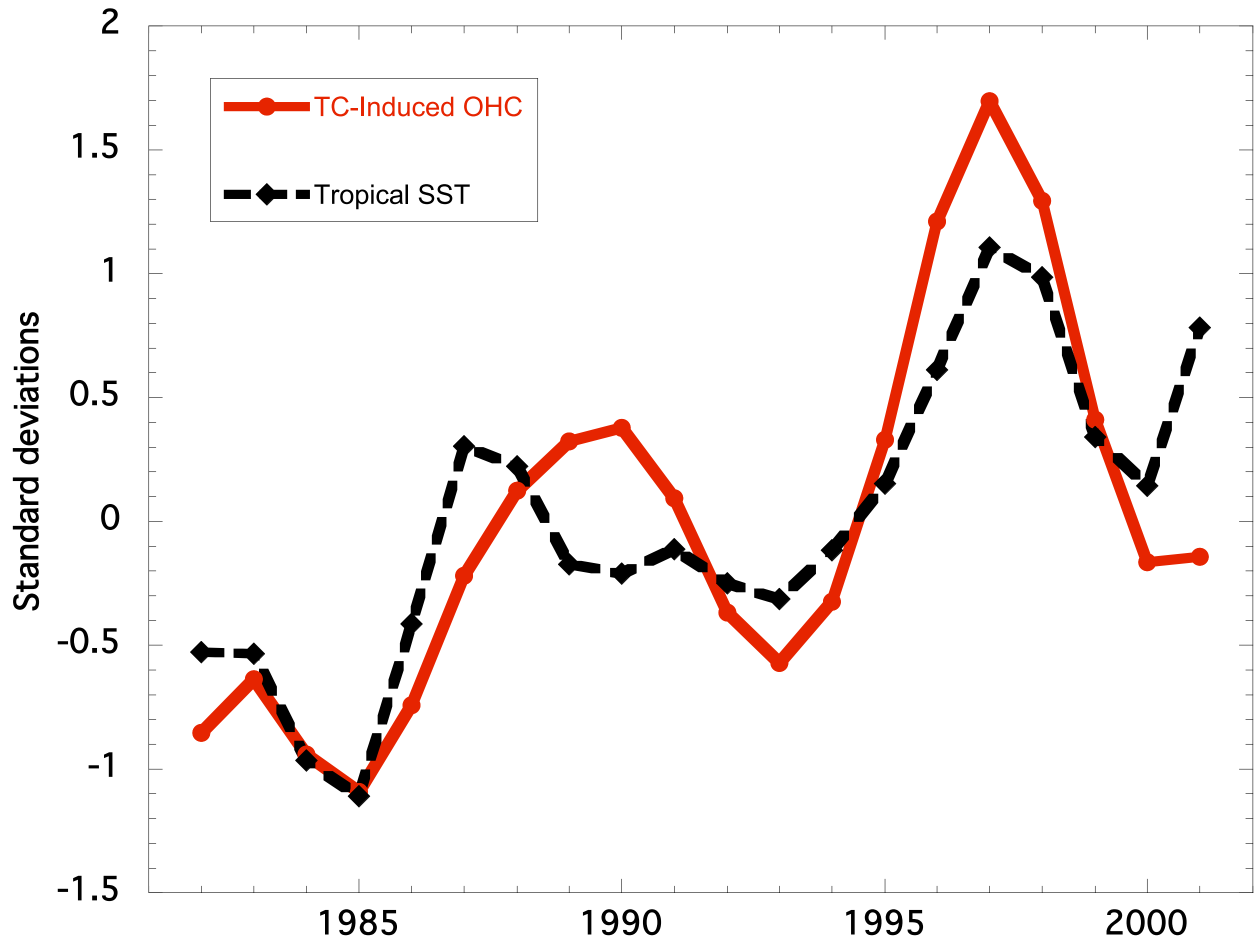
TC-induced OHC anomalies and tropical SST



ERA-40 derived, low pass filtered time series of TC-induced OHC anomalies (Red line) and mean annual tropical SST (Black line).

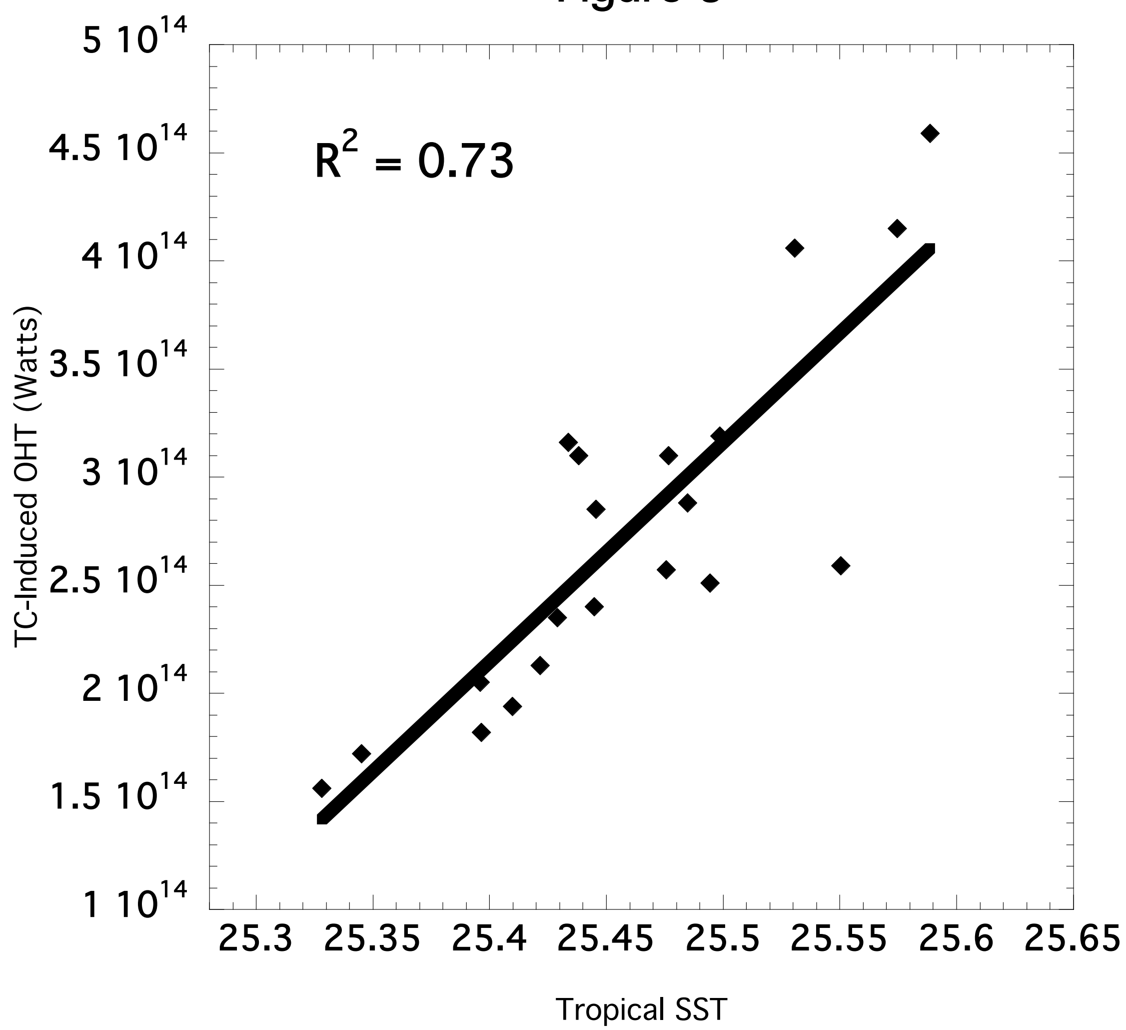
Sriver and Huber, Nature, 2007

TC-induced OHC anomalies and tropical SST



ERA-40 derived, low pass filtered time series of TC-induced OHC anomalies (Red line) and mean annual tropical SST (Black line).

Figure 3

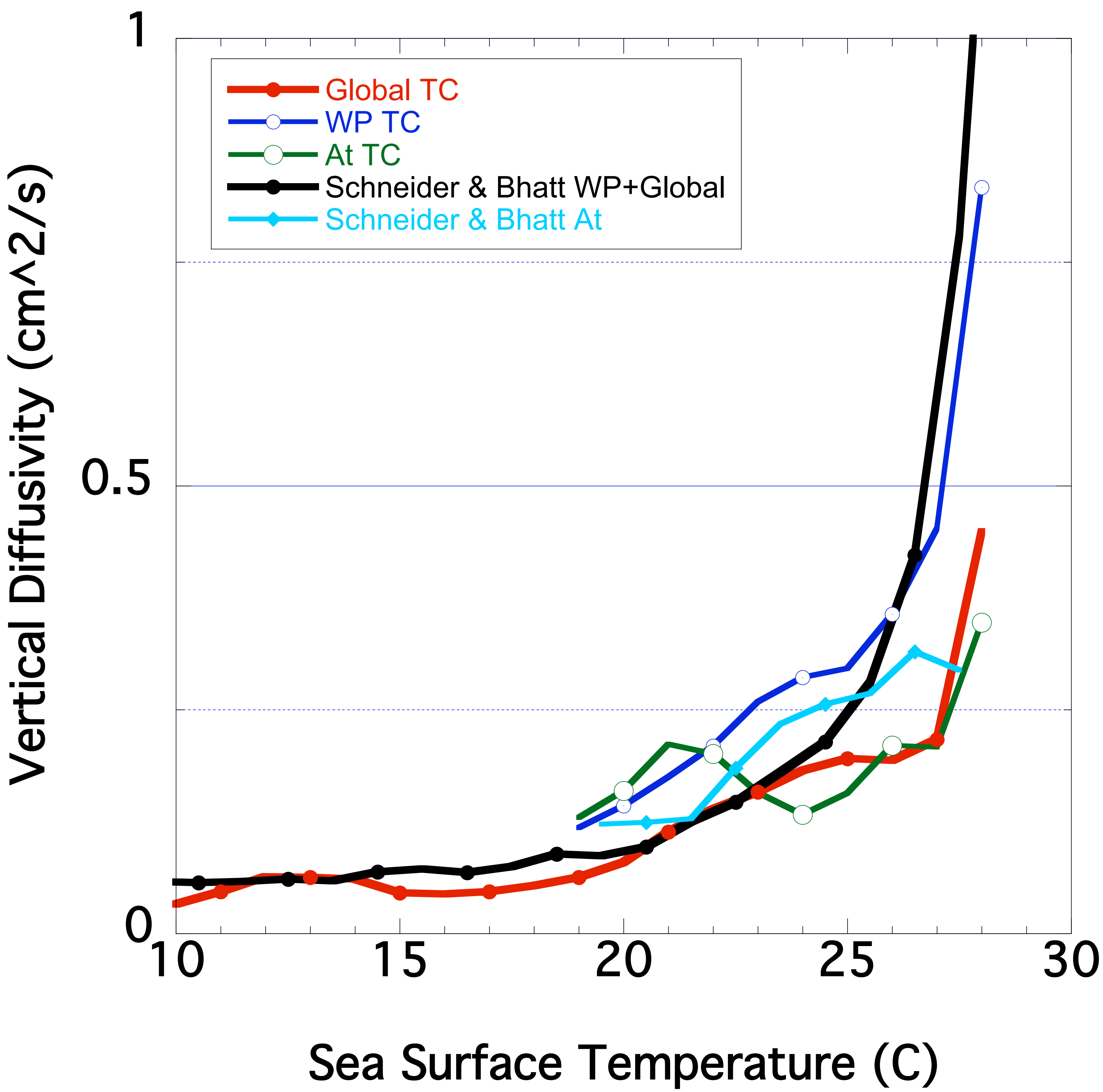


TC-induced OHC anomalies appear to be extremely sensitive to changes in tropical SST.

0.25 C increase in tropical SST
=> more than a doubling of TC-induced OHC anomalies.

Sriver and Huber, Nature, 2007

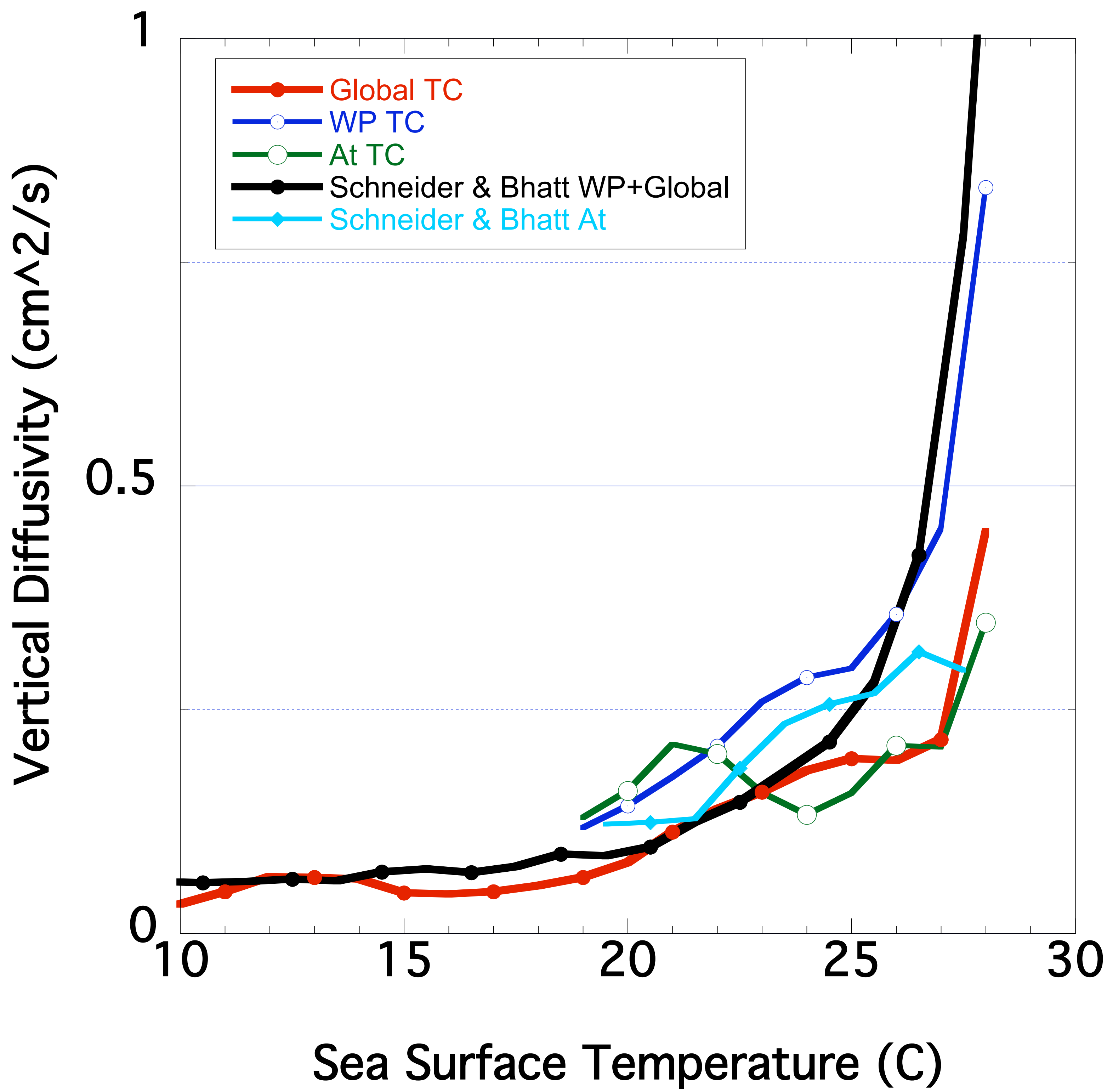
Vertical Diffusivity and SST



Diffusivity data courtesy of Ed Schneider
(Schneider and Bhatt, 2000)

Sriver and Huber, Nature, 2007

Vertical Diffusivity and SST

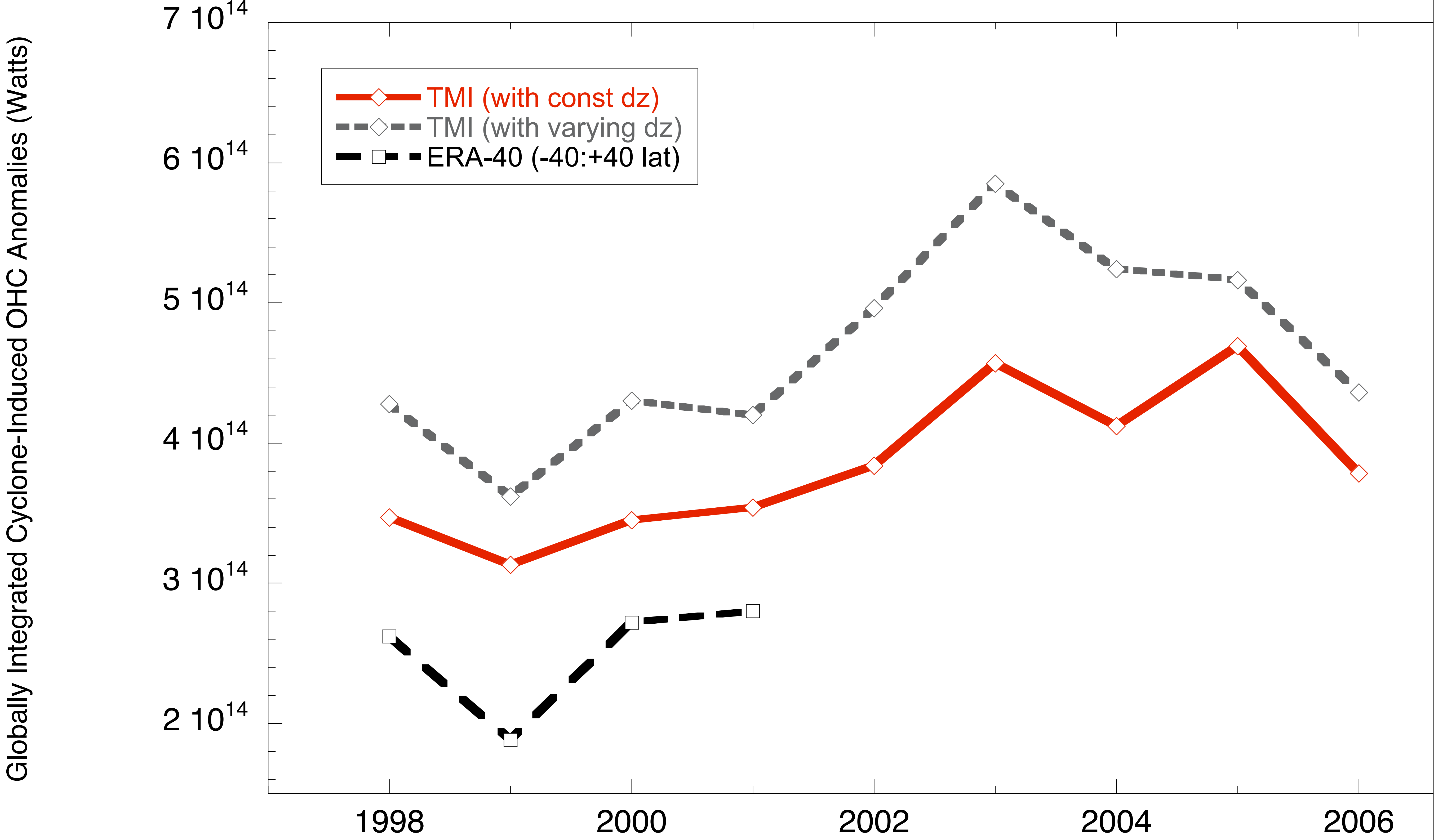


- Agreement suggests all upper ocean vertical mixing in the tropics is due to TCs.
- In each location, all annual mixing in upper tropical oceans occurs during 1-2 TC events.

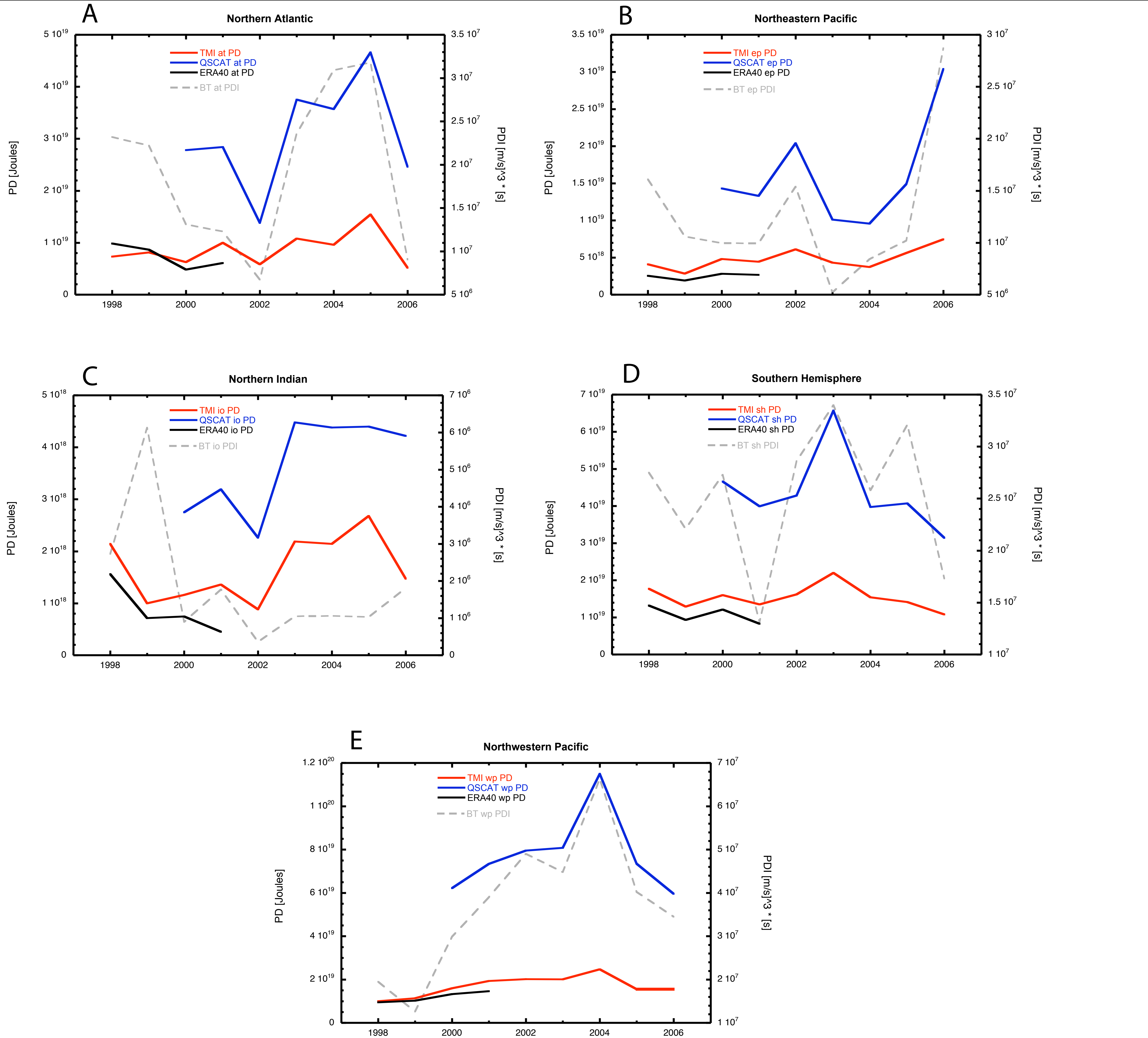
Diffusivity data courtesy of Ed Schneider (Schneider and Bhatt, 2000)

Sriver and Huber, Nature, 2007

Figure 3



Globally Integrated Cyclone-Induced OHC Anomalies (Watts)
7 10^14
6 10^14
5 10^14
4 10^14
3 10^14
2 10^14
1998
2000
2002
2004
2006
TMI (with const dz)
TMI (with varying dz)
ERA-40 (-40:+40 lat)


A
Northern Atlantic
TMI at PD
QSCAT at PD
ERA40 at PD
BT at PDI
PD [Joules]
PDI [m/s]^3 * [s]
B
Northeastern Pacific
TMI ep PD
QSCAT ep PD
ERA40 ep PD
BT ep PDI
C
Northern Indian
TMI io PD
QSCAT io PD
ERA40 io PD
BT io PDI
D
Southern Hemisphere
TMI sh PD
QSCAT sh PD
ERA40 sh PD
BT sh PDI
E
Northwestern Pacific
TMI wp PD
QSCAT wp PD
ERA40 wp PD
BT wp PDI
1998
2000
2002
2004
2006

TMI SST

-3.5° 3.5°

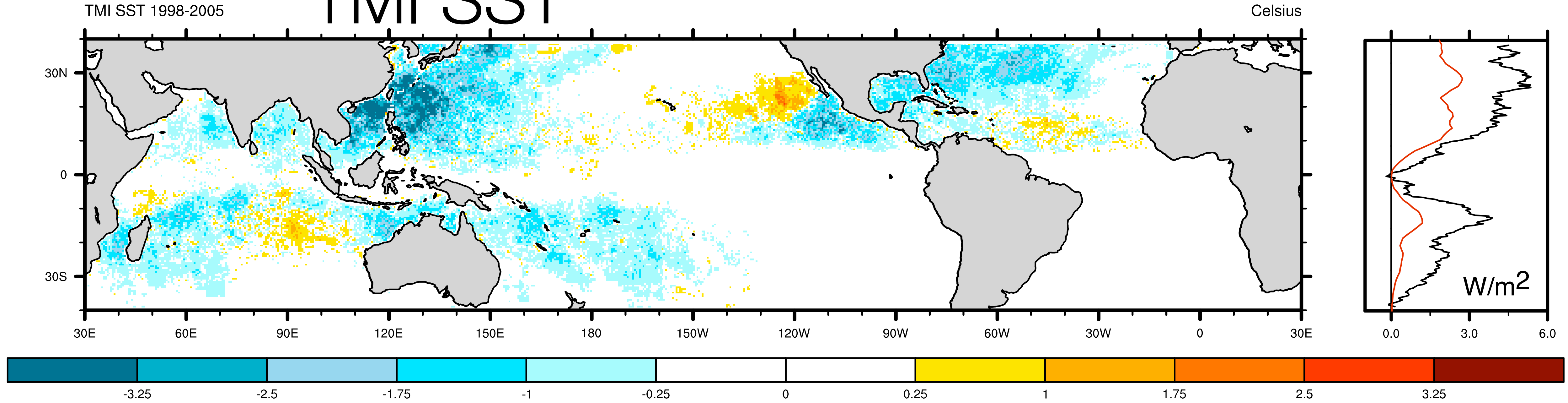
TMI PD

0 J/m^2*10^6 2.6 J/m^2*10^6

Satellite (TMI) derived SST (top) and Power Dissipation(bottom)

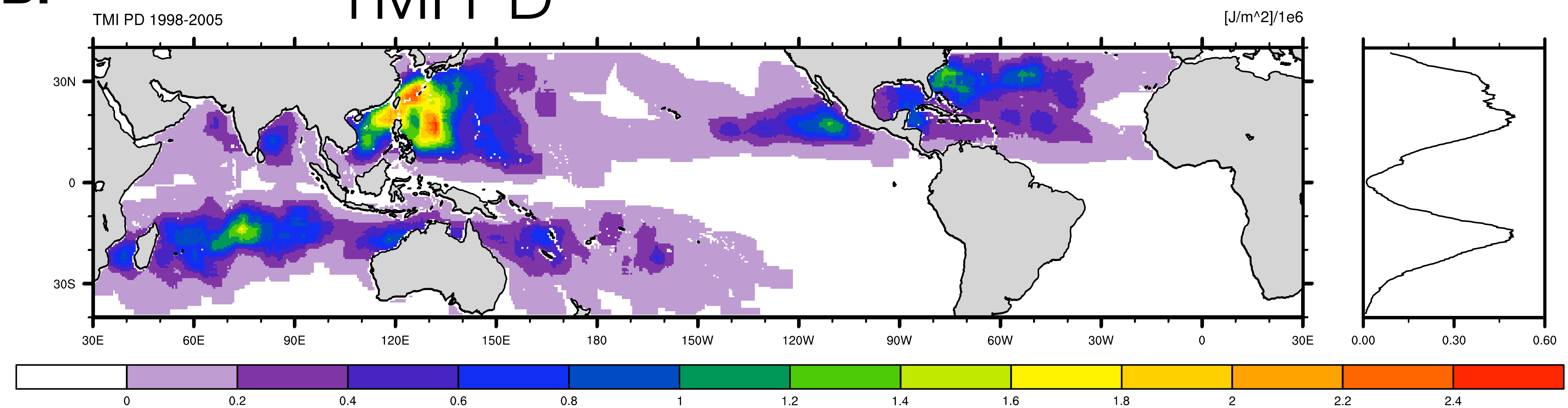
Sriver et al, submitted

A. TMI SST



-3.5° 3.5°

B. TMI PD



0 J/m^2*10^6 2.6 J/m^2*10^6

Satellite (TMI) derived SST (top) and Power Dissipation(bottom)

Sriver et al, submitted

TMI MLDD

0 m

85 m

TMI Diffusivity

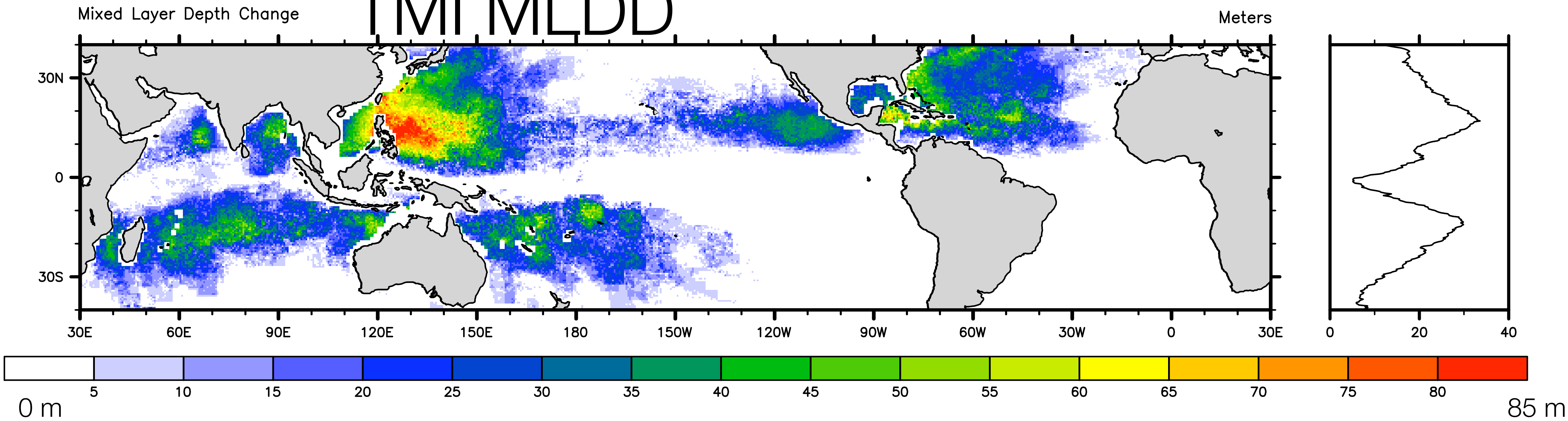
0 cm^2/s

2.5 cm^2/s

Mixed layer depth depression (top) and effective vertical diffusivity (bottom)

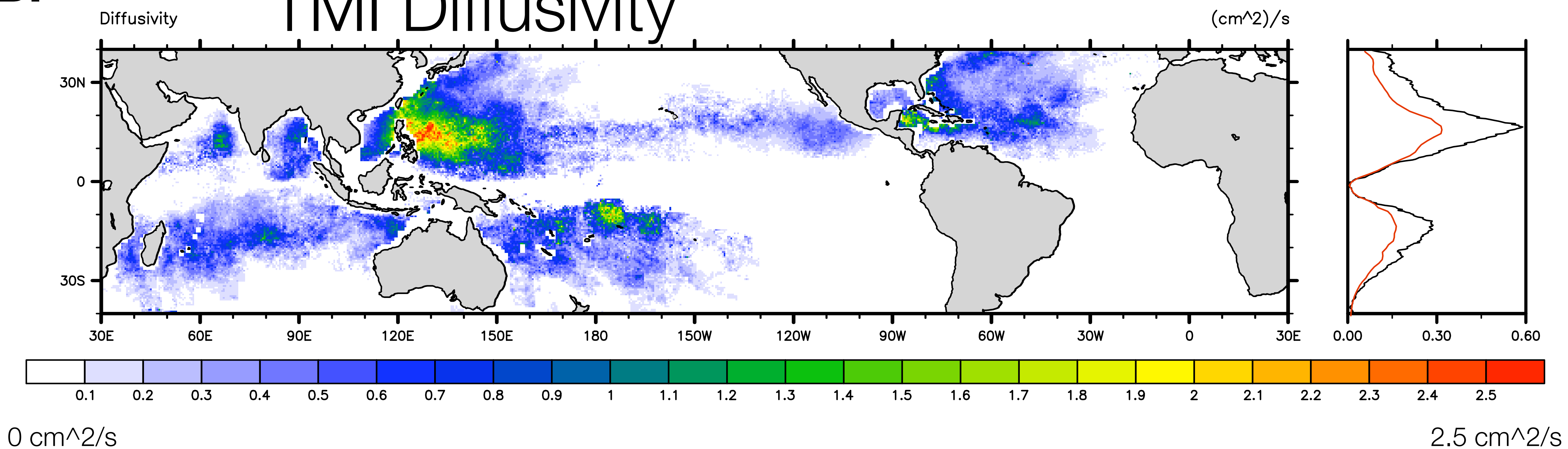
Sriver et al, submitted

TMI MLDD



B.

TMI Diffusivity



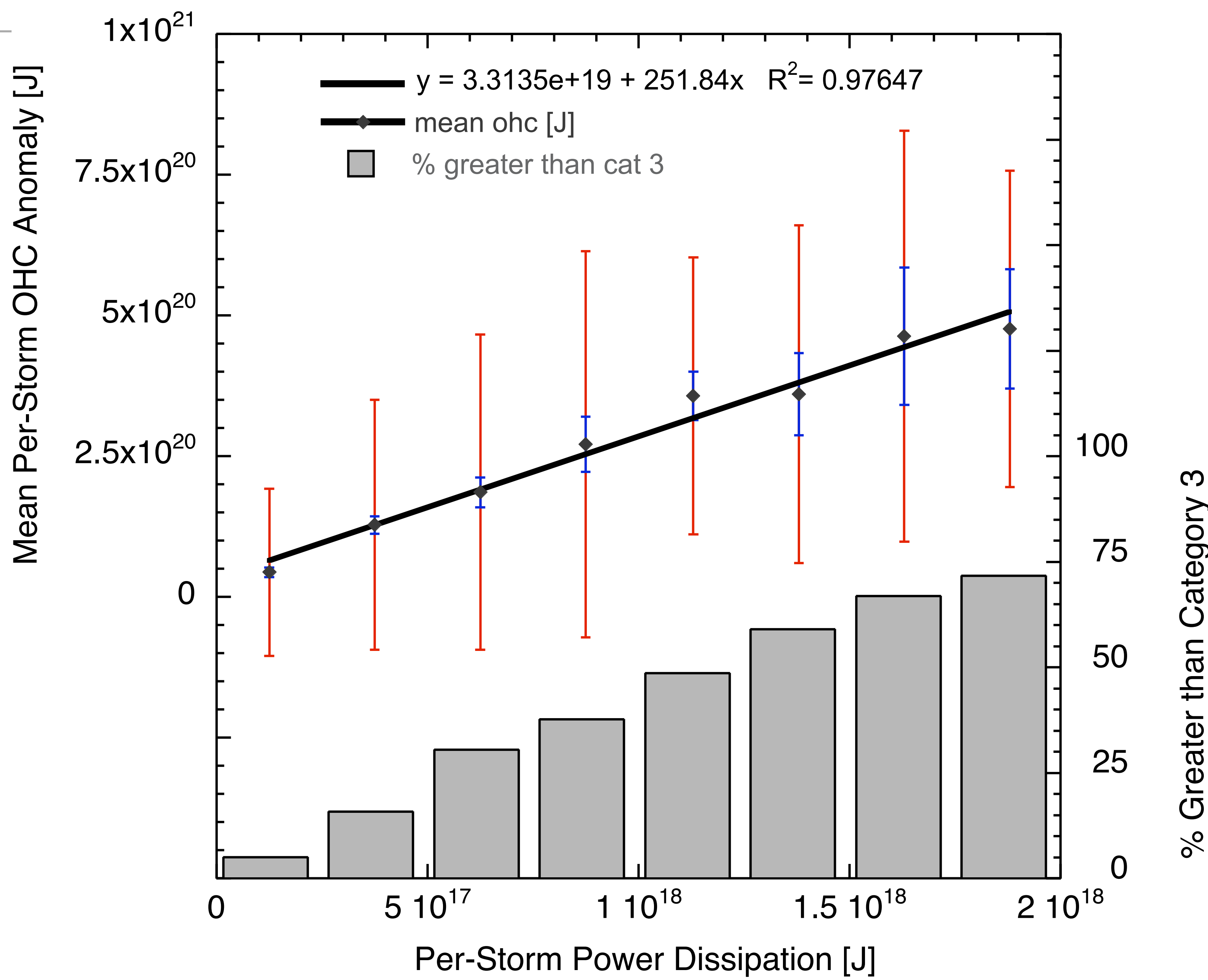
Mixed layer depth depression (top) and effective vertical diffusivity (bottom)

Sriver et al, submitted

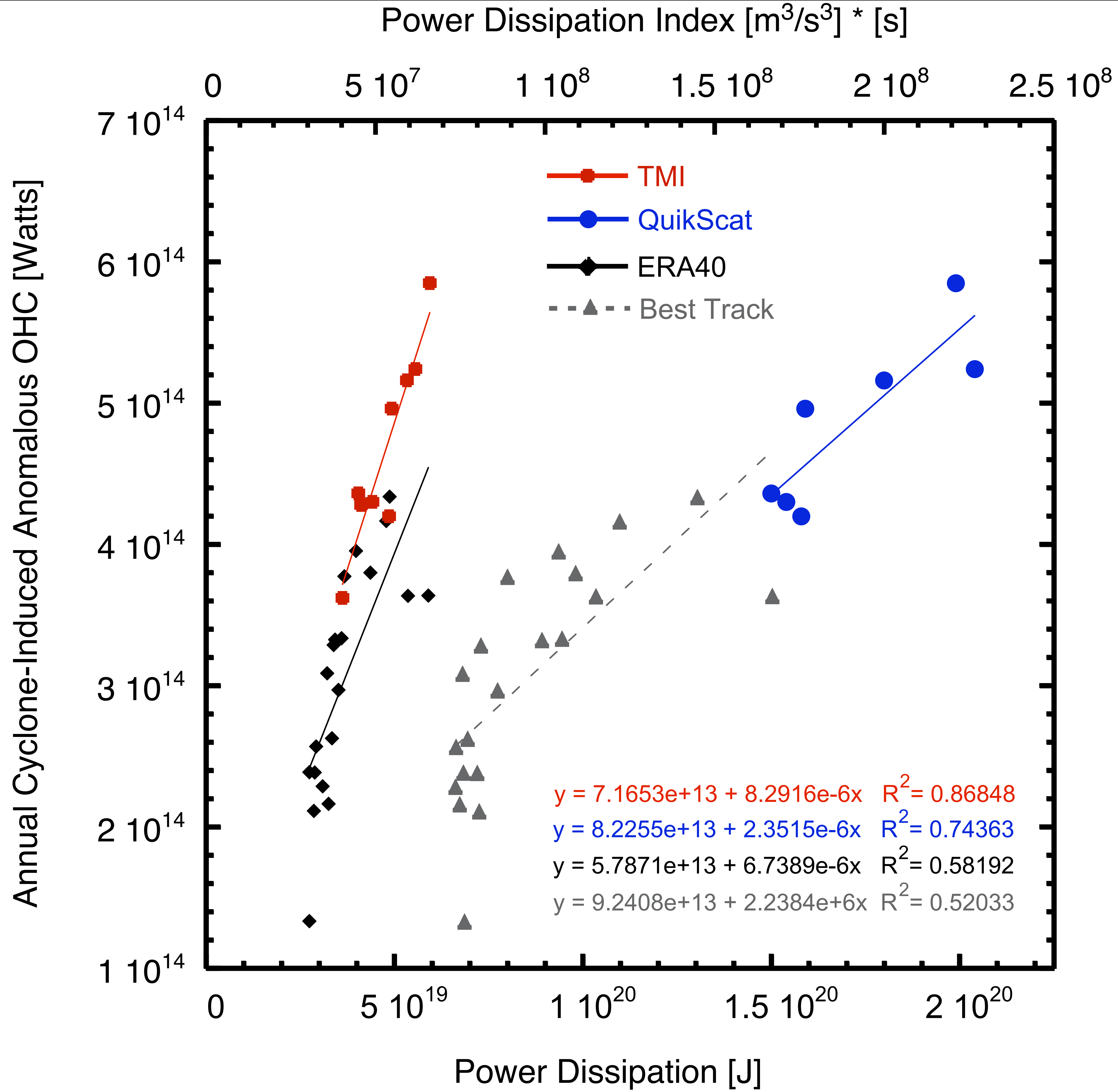
Binned Analysis of per storm heat convergence

- We calculate the integrated OHC (magnitude of cold wake) for each tropical cyclone
- Each storm is put into a bin based on its integrated power dissipation
- The per storm OHC scales linearly with per storm PD.
- Interestingly, per storm PD scales linearly with the fraction of storms that reach Cat 3 in each bin
- In other words, it's the strong storms that do the 'heavy lifting'

Figure 5

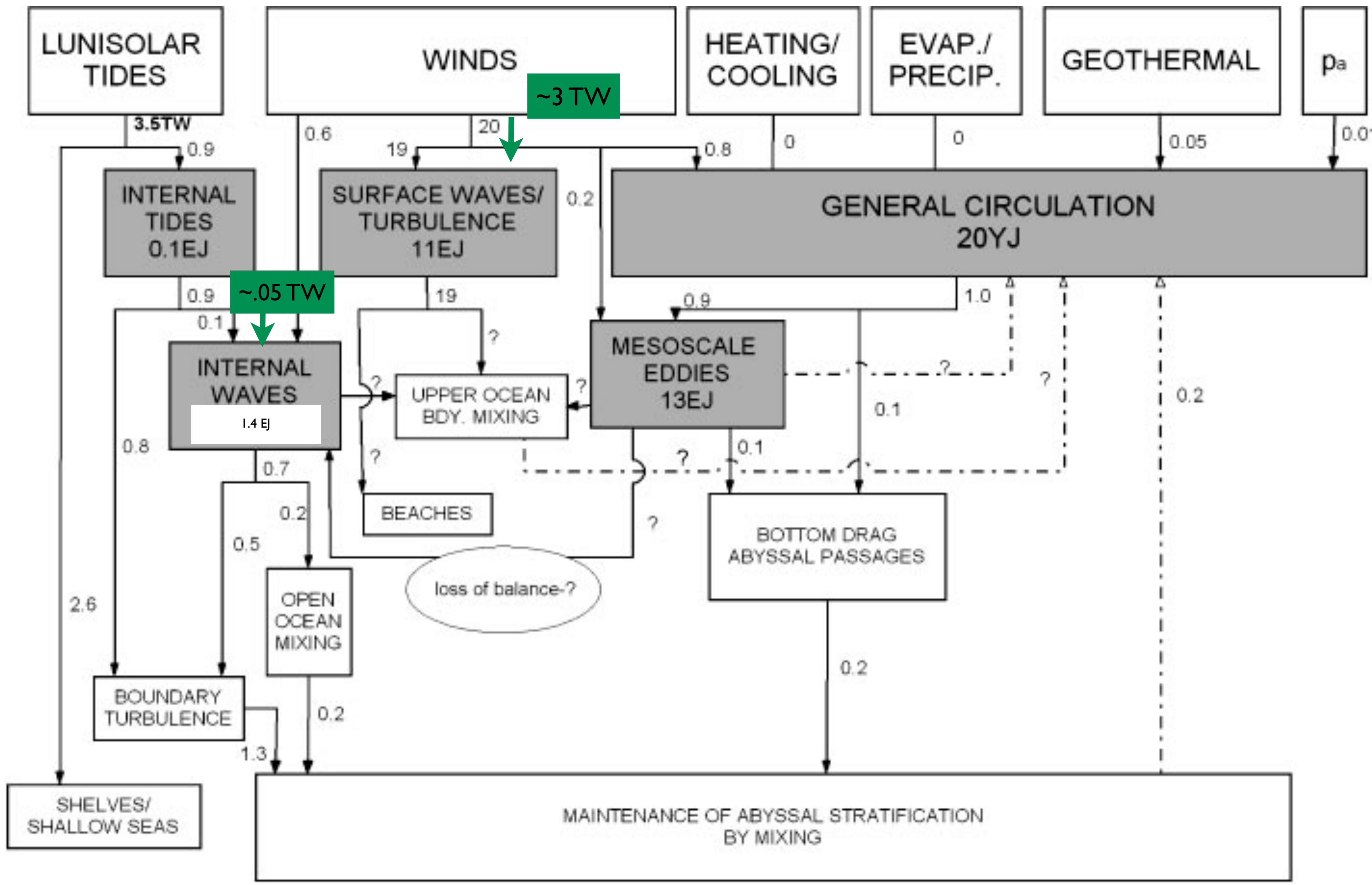


Sriver et al, submitted


Power Dissipation Index [m^3/s^3] * [s]
0
5 10^7
1 10^8
1.5 10^8
2 10^8
2.5 10^8
Annual Cyclone-Induced Anomalous OHC [Watts]
7 10^14
6 10^14
5 10^14
4 10^14
3 10^14
2 10^14
1 10^14
TMI
QuikScat
ERA40
Best Track
y = 7.1653e+13 + 8.2916e-6x R^2= 0.86848
y = 8.2255e+13 + 2.3515e-6x R^2= 0.74363
y = 5.7871e+13 + 6.7389e-6x R^2= 0.58192
y = 9.2408e+13 + 2.2384e+6x R^2= 0.52033
0
5 10^19
1 10^20
1.5 10^20
2 10^20
Power Dissipation [J]

- Vertical diffusivity is enhanced under regions with strong TCs.
  - areas of warmest SST

- TC activity provides a physical mechanism for strong positive relationship between vertical diffusivity and SST.

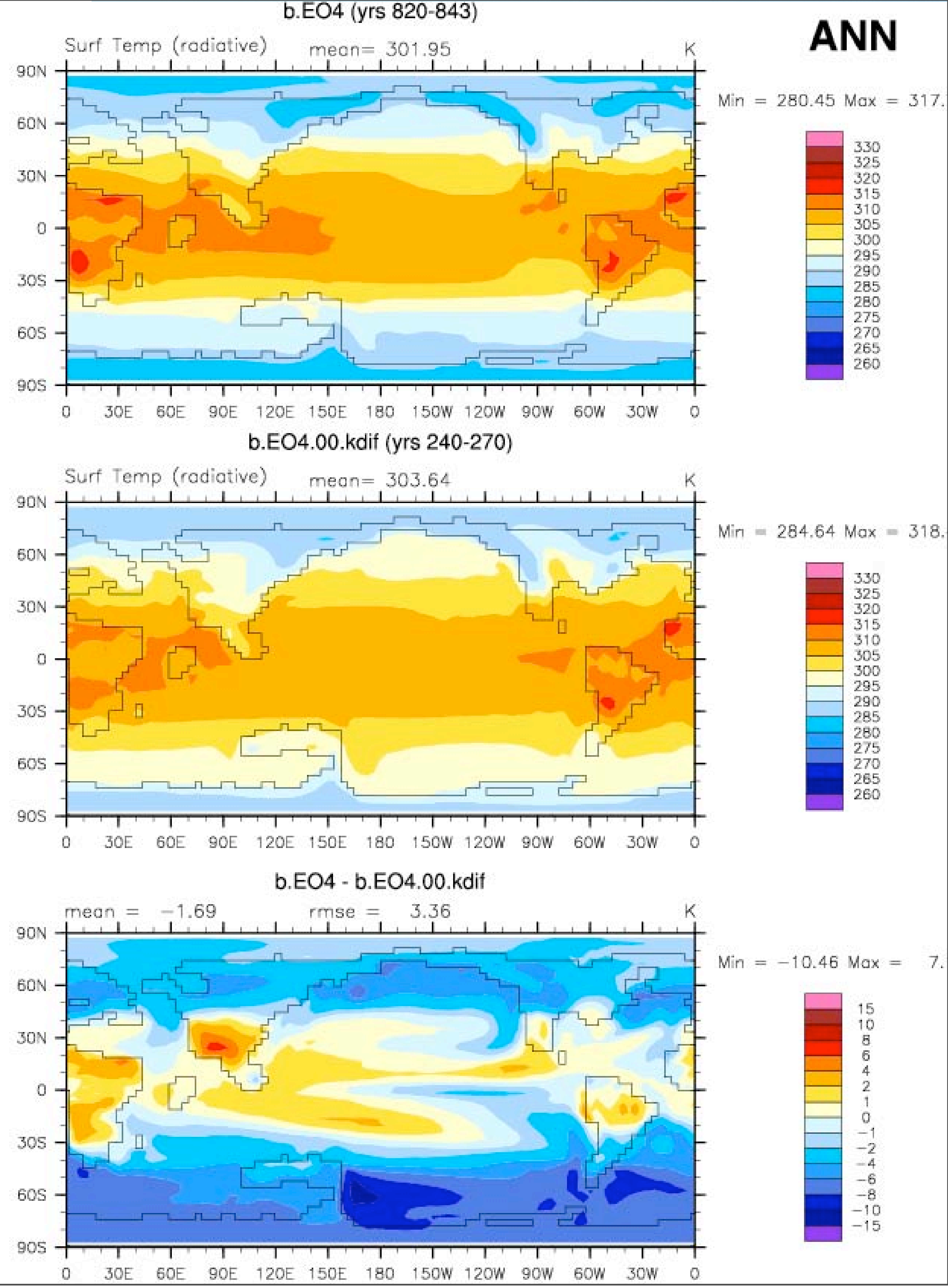

LUNISOLAR TIDES
WINDS
HEATING/ COOLING
EVAP./ PRECIP.
GEOTHERMAL
pa
3.5TW
~3 TW
INTERNAL TIDES 0.1EJ
SURFACE WAVES/ TURBULENCE 11EJ
GENERAL CIRCULATION 20YJ
~.05 TW
INTERNAL WAVES
1.4 EJ
UPPER OCEAN BDY. MIXING
MESOSCALE EDDIES 13EJ
BEACHES
loss of balance-?
BOTTOM DRAG ABYSSAL PASSAGES
OPEN OCEAN MIXING
BOUNDARY TURBULENCE
SHELVES/ SHALLOW SEAS
MAINTENANCE OF ABYSSAL STRATIFICATION BY MIXING

Effect of increased vertical diffusion on surface temperature

- Increased vertical mixing causes cooling of tropics and warming of high latitudes

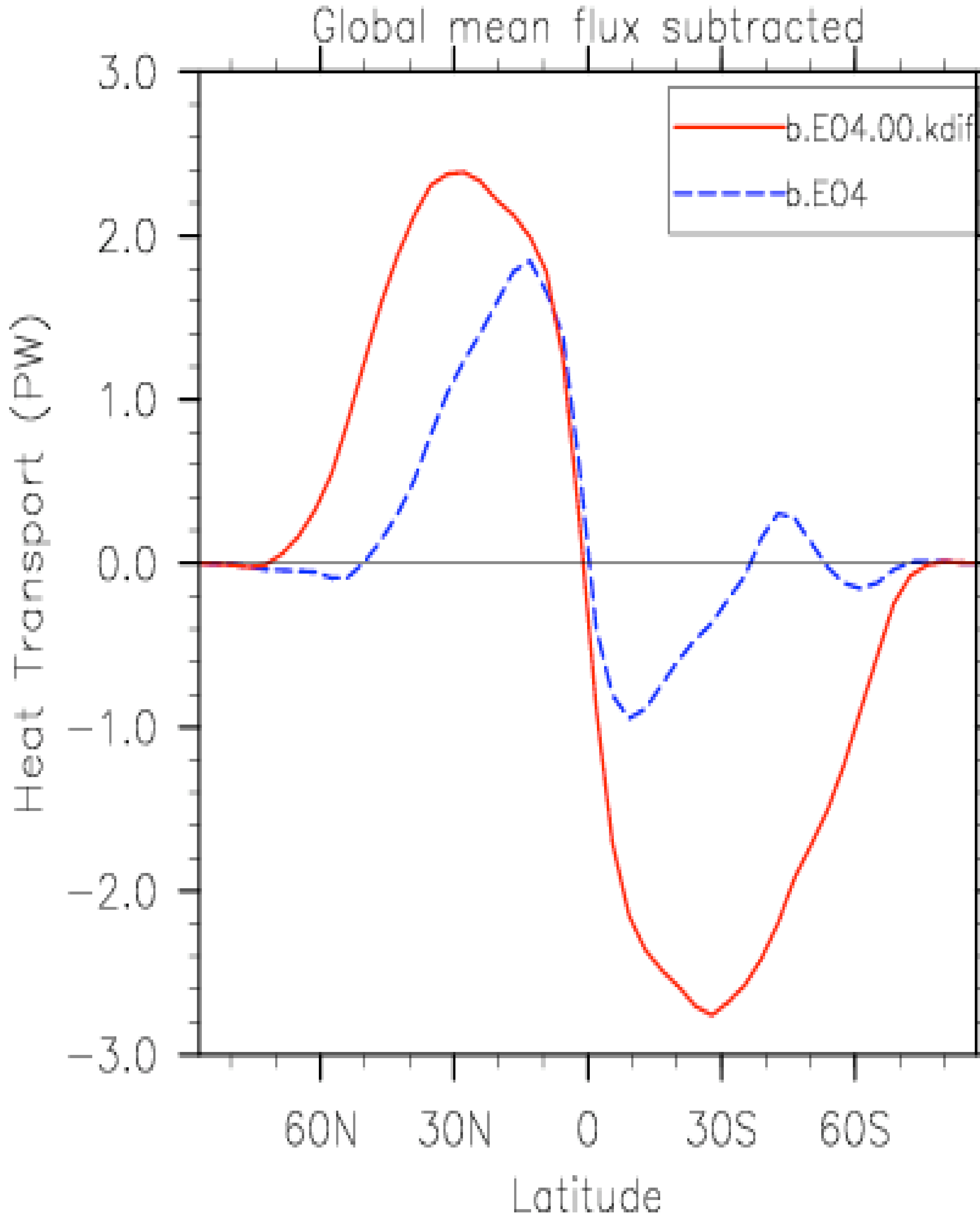
- Global mean temperature increases by 1.7°C

- can explain low gradient paradox and add extra global mean sensitivity in a warmer world



Effect of Increased vertical diffusivity on ocean heat transport

- A five-fold increase in diffusivity leads to >doubling of OHT.



* with some more work we can either resolve this process or stochastically parameterize it!

Climate & Biota of the Early Paleogene

CBEP 2009: January, Wellington, New Zealand

World's leading paleobotanists, palynologists, micropaleontologists, vertebrate paleontologists, stratigraphers, sedimentologists, geochemists, paleomagnetists, paleoceanographers, climate modellers

understanding climate dynamics and biotic response in a greenhouse world

GNS