Large-scale ocean circulation and climate: Interannual climate variability

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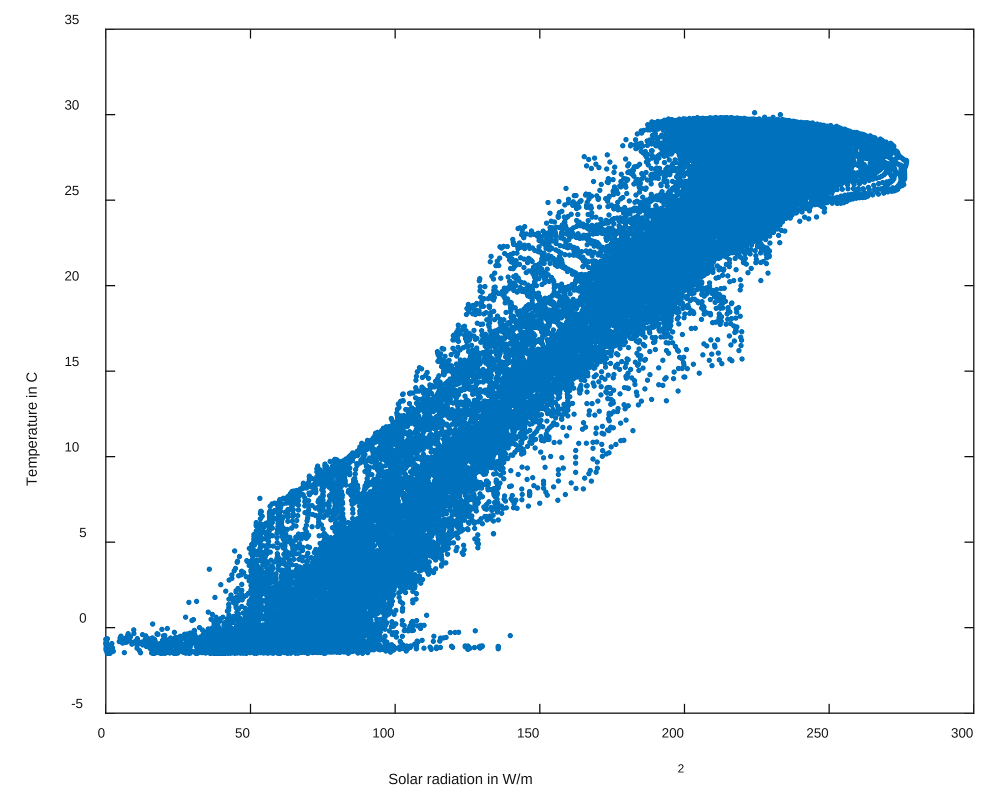
2023 ICTS Summer School on
Mathematical modeling of Climate Ocean
and Atmospheric Processes

We have already mentioned relationship between temperature and solar radiation

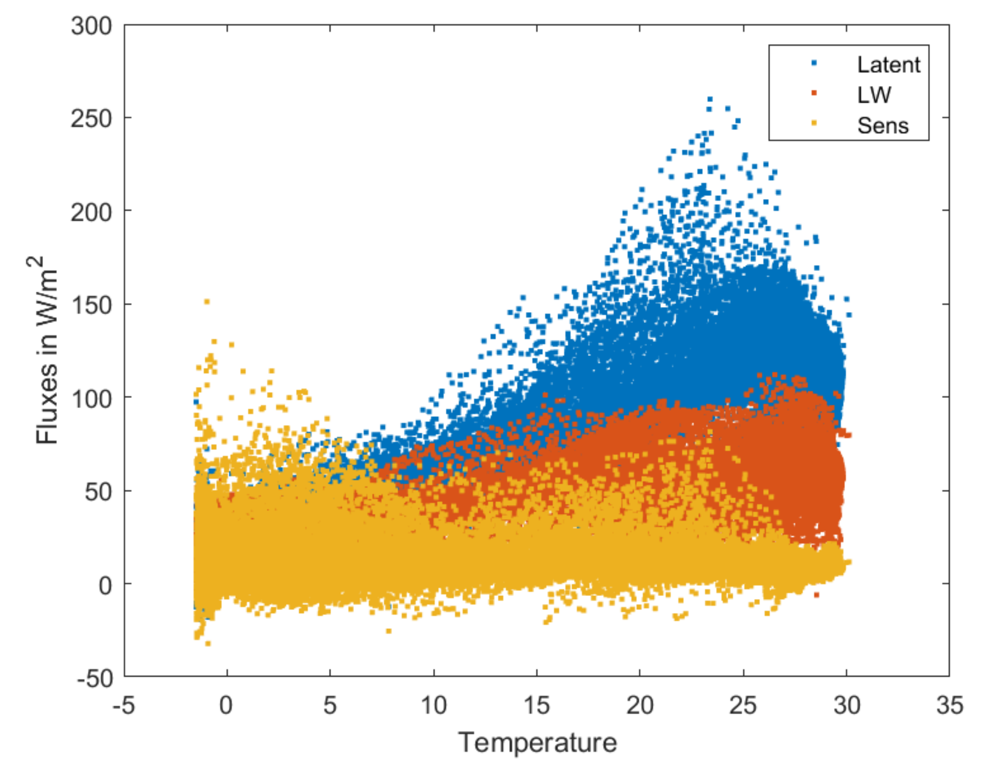
- Relationship from WHOI OAFlux dataset (Yu and Weller, 2009, updated).
- Fit is $T = 0.16 * Q_{sw} - 8.77$

with temperature in C.



Why is this?

- Heating surface leads to
  - More evaporation of water (latent heat loss, ~4 W/m²/K)
  - Larger upward flux of infrared radiation (longwave heat loss, ~2 W/m²/K)
  - More conductive heat to atmosphere (sensible heat loss, small)
  - Note- size of this damping depends on spatial scale, the larger the spatial scale, the weaker the damping.



Why do the oceans matter so much for long-term variability?

- Heat content.
- Heat capacity of 1 cubic meter of water is around 4×10^6 J/K
- Heat capacity of 1 cubic meter of air is around 10^3 J/K
- Nominal atmospheric thickness of 8km

- Means 2m of water holds as much heat as entire atmosphere.
- Winds stir ocean down to ~50m.

Implications of this for climate variability

Suppose the ocean receives fluxes from the atmosphere that behave like white noise.

$$\rho c_p H \frac{\partial T}{\partial t} = Q' - \lambda T'$$

We can perform a Fourier decomposition on each of these terms, letting

$$Q' = \hat{Q}\exp(i * \omega * t)\,, T = \hat{T} * \exp(i * \omega * t)$$

Solving, we get that

$$\left(i\omega\, 2\times 10^{8}\frac{J}{m^{2}K}+6\frac{W}{m^{2}K}\right)\hat{T}=\hat{Q}\rightarrow \hat{T}=\frac{\hat{Q}}{2\times 10^{8}J\,m^{-2}K^{-1}}\frac{1}{i\omega+\frac{1}{3\times 10^{7}s}}$$

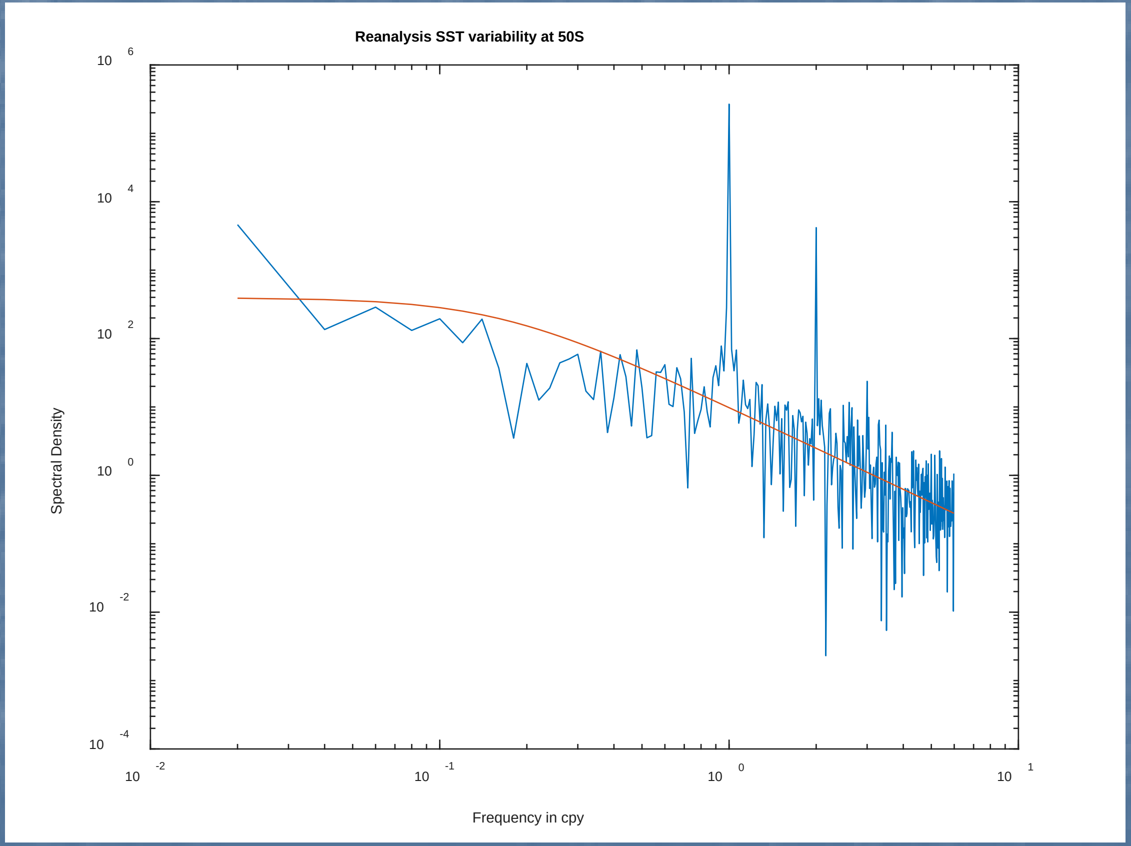
So when frequencies are very large..

Amplitude of temperature variation is determined by time of integration, is out of phase with flux, and drops as frequency increases.

When frequencies are very small ...

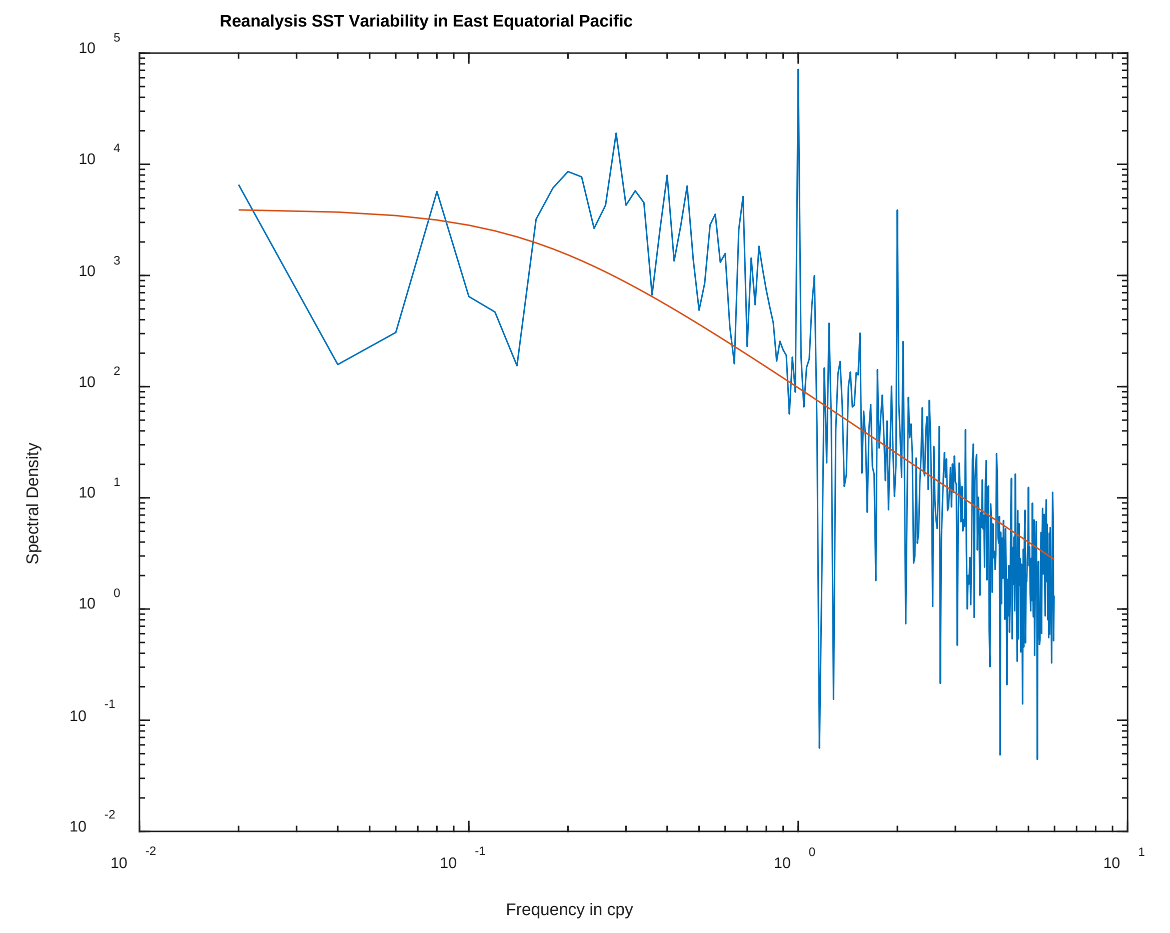
Amplitude of temperature variation is basically proportional to flux variation.

Example, temperature at 50S

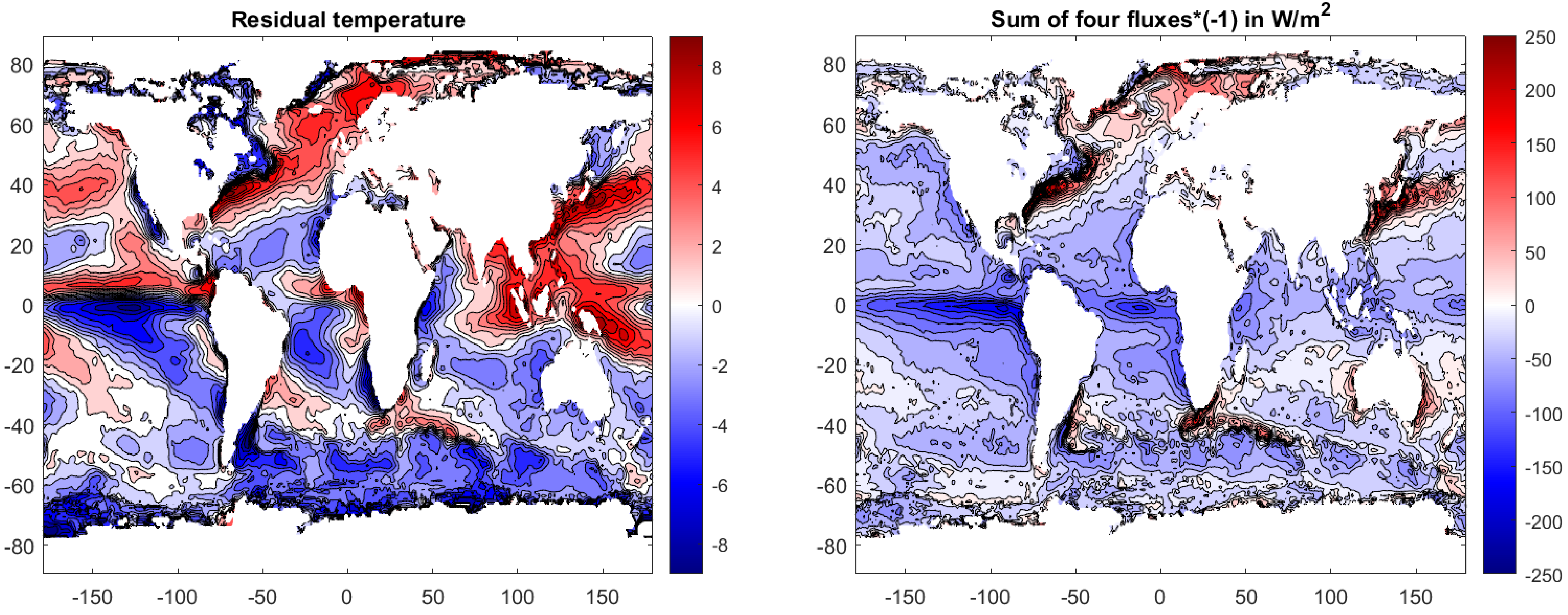


Pretty well described by ocean integrating white noise+ annual cycle (red line)

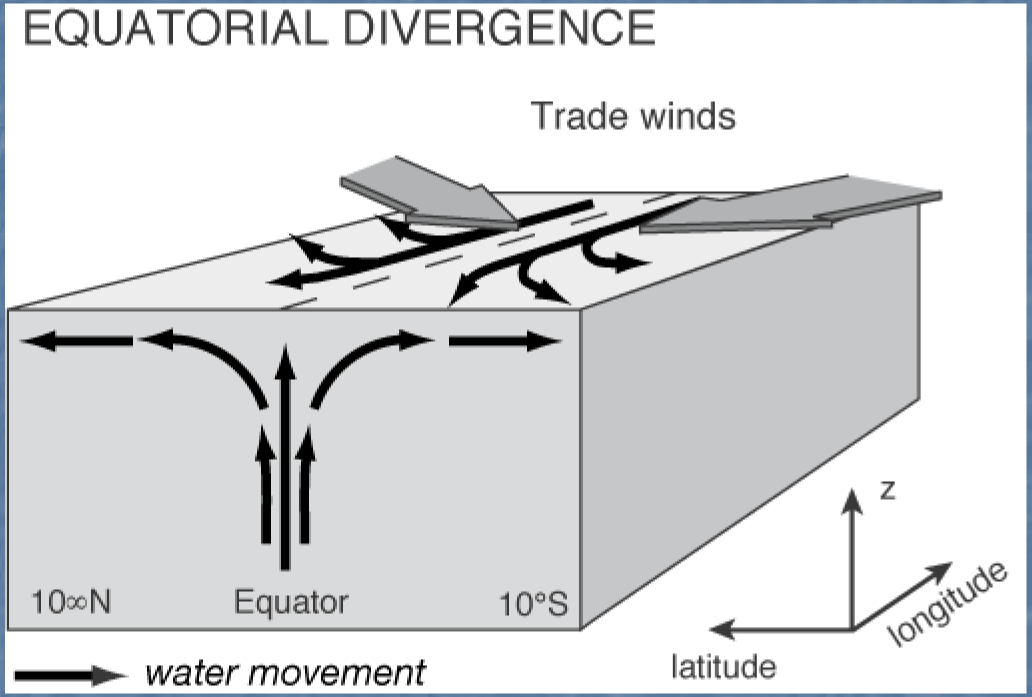
However, there are places where this doesn’t work as well..



How much of the temperature is not explained by Solar radiation

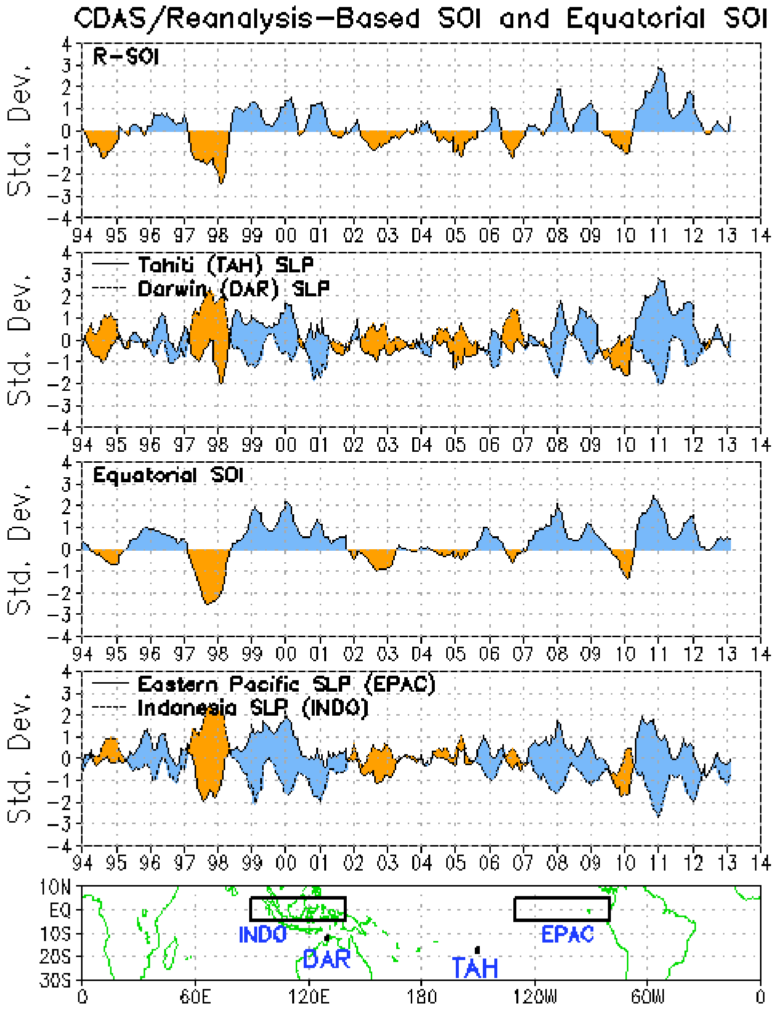


Why is the equator cold?

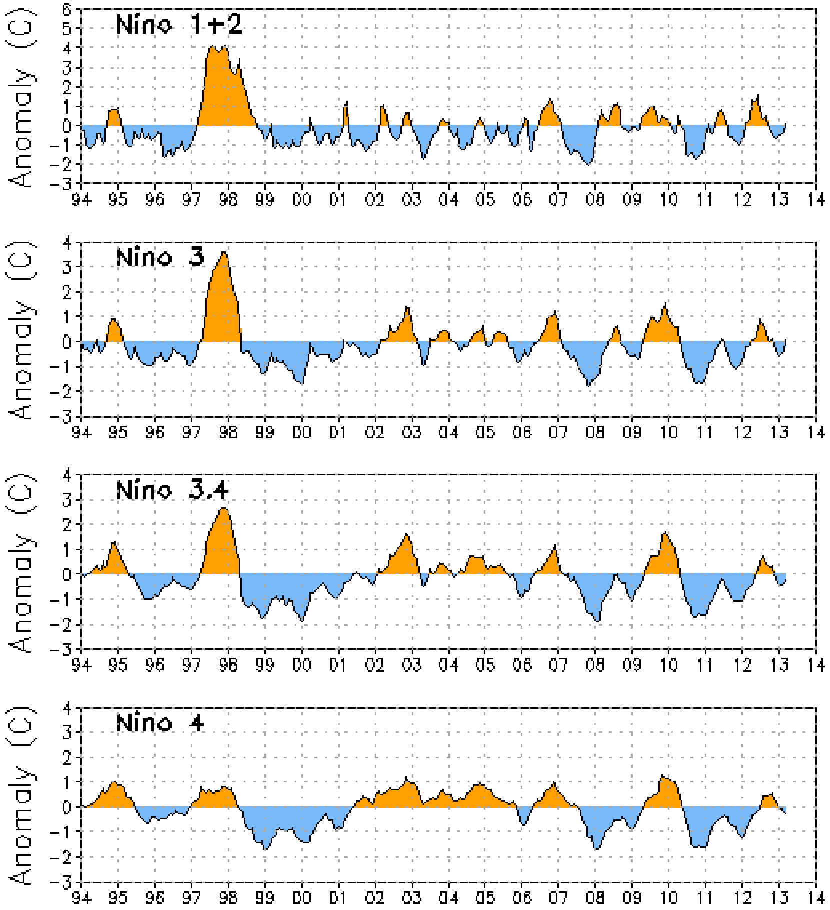


Winds slow down water on equator relative to earth's rotation.

Causes poleward drift, opposite directions on each side of equator.



Data updated through March 2013



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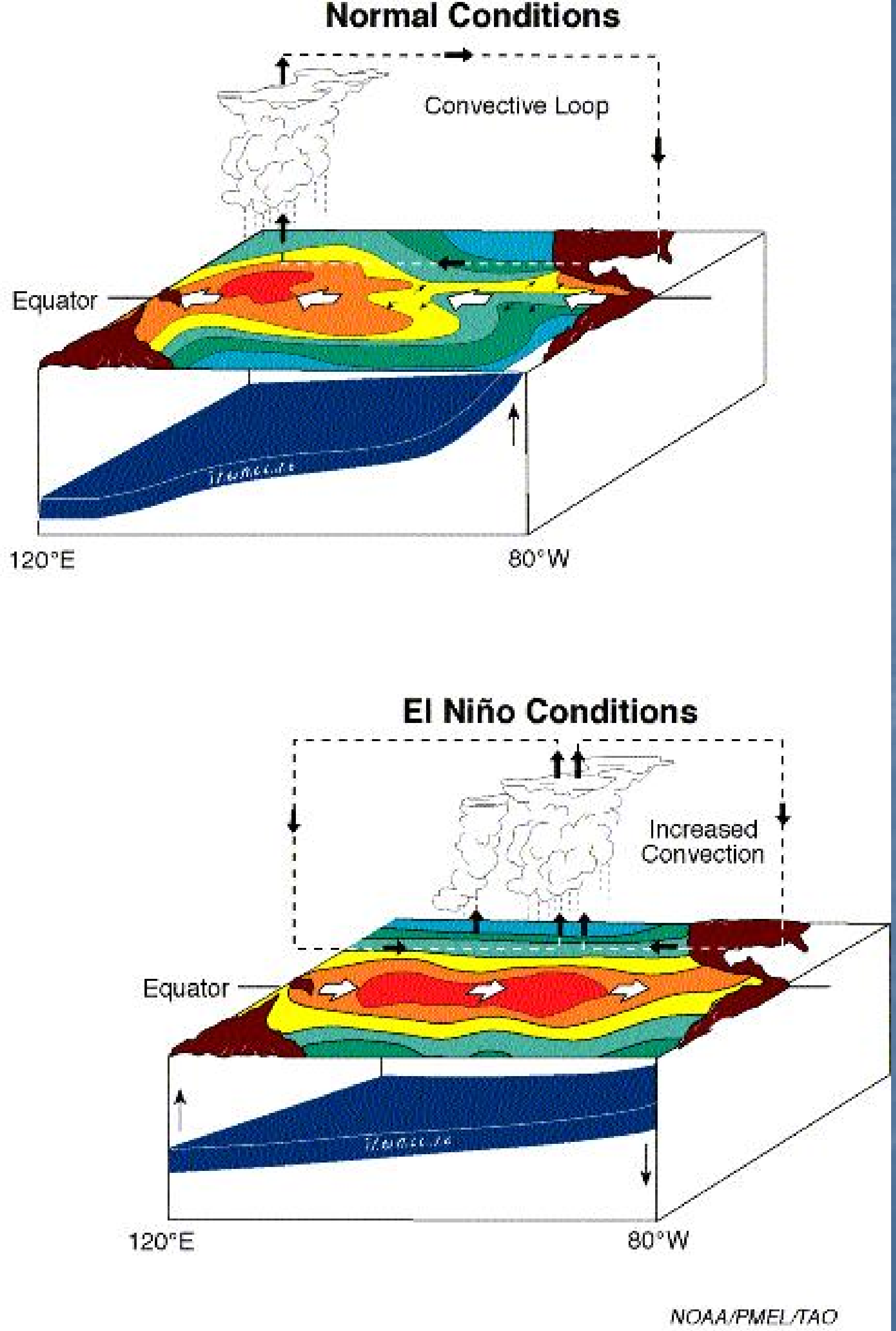


NOAA/PMEL/TAO

What's the link?

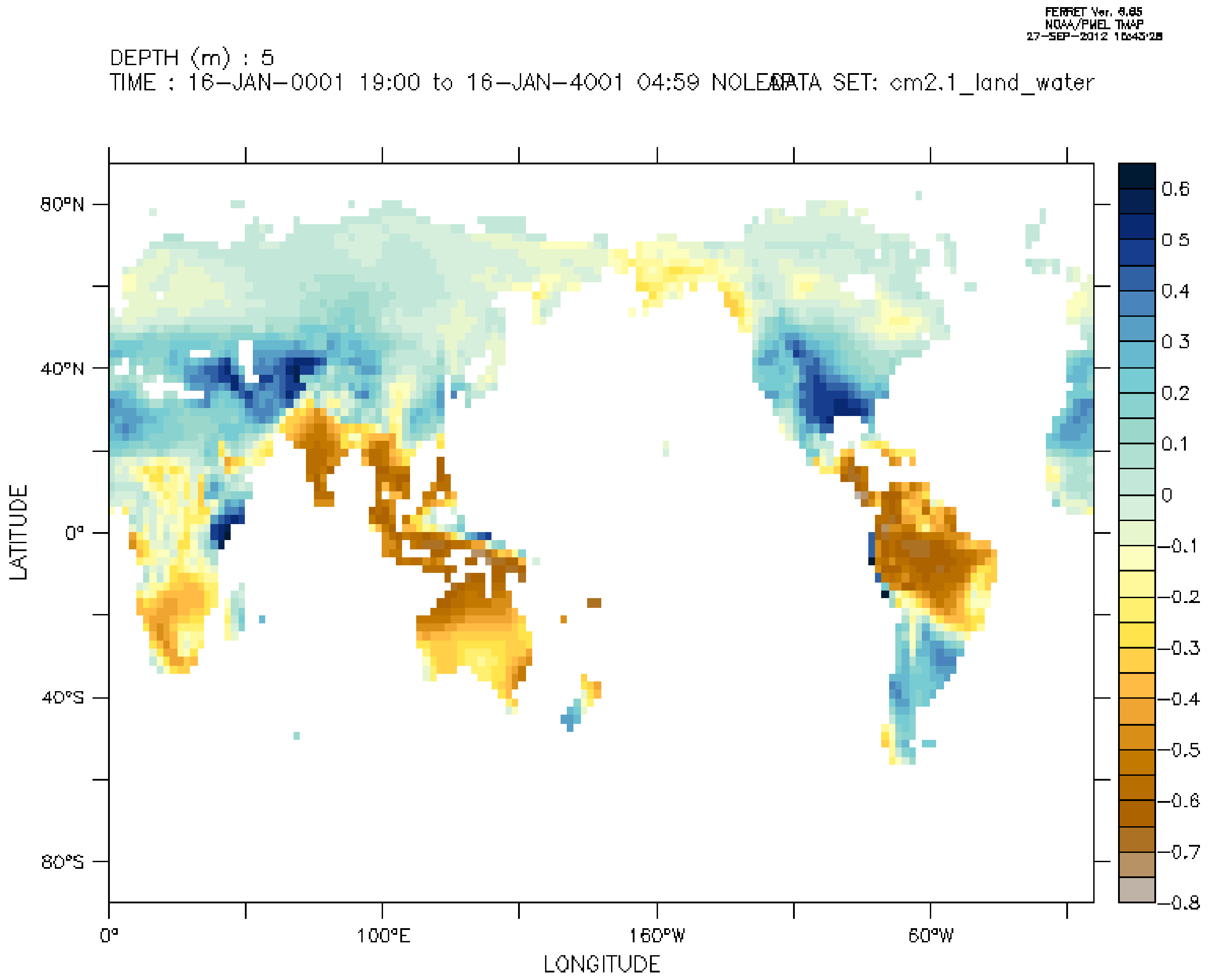
Weakening winds over Pacific...

Mean less upwelling of cold water.

Which then reduces the temperature gradient

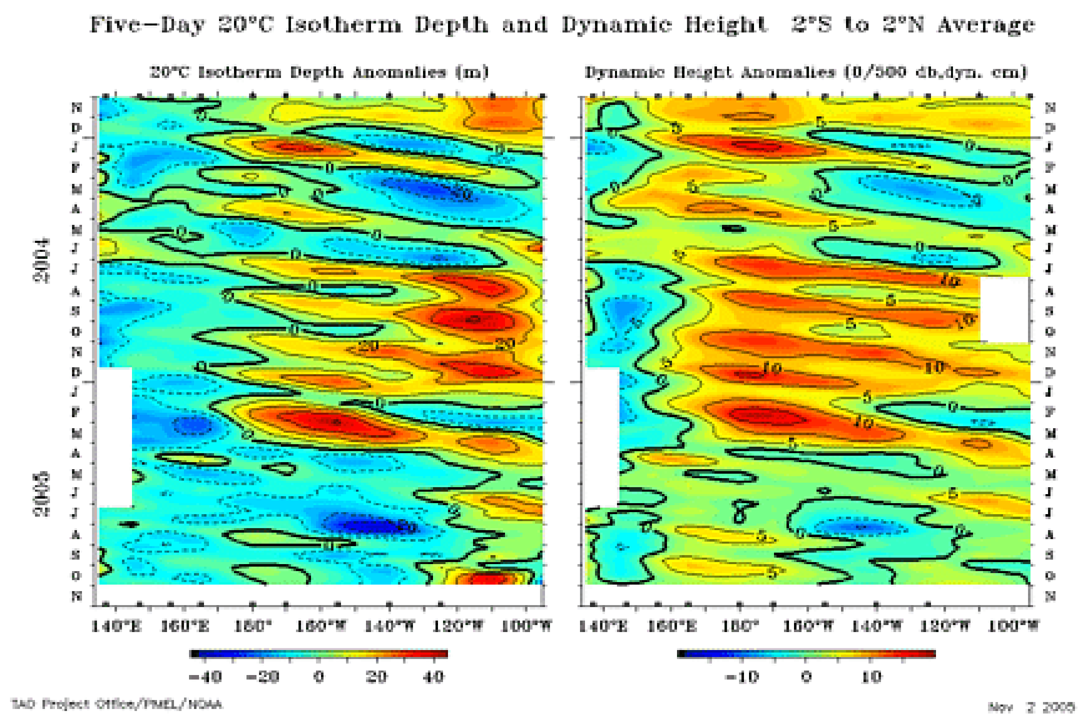
And reduces the winds further.

Why we might care...



Correlation between Soil Water and Previous Month's ENSO:CM2.1

High-resolution data from TAO array



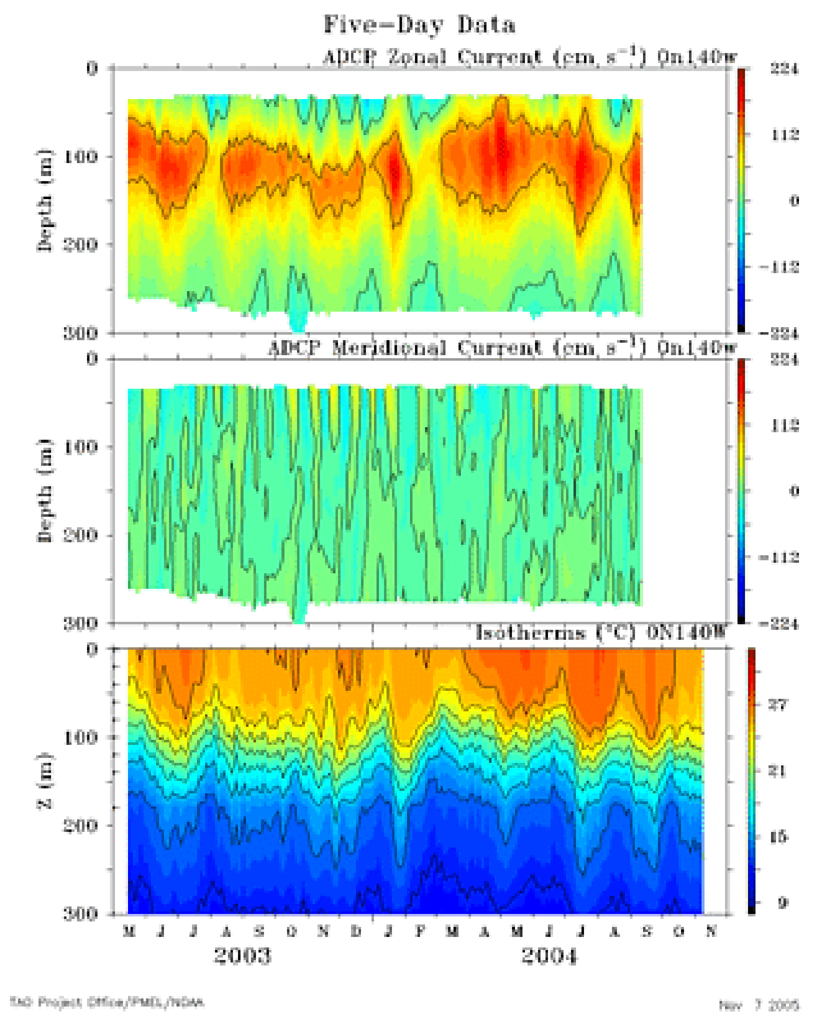
Five–Day 20°C Isotherm Depth and Dynamic Height 2°S to 2°N Average

20°C Isotherm Depth Anomalies (m)

Dynamic Height Anomalies (0/500 db,dyn. cm)

TAO Project Office/PMEL/NOAA

Nov 2 2005



Five–Day Data

ADCP Zonal Current (cm s^{-1}) 0n140w

ADCP Meridional Current (cm s^{-1}) 0n140w

Isotherms (°C) 0N140W

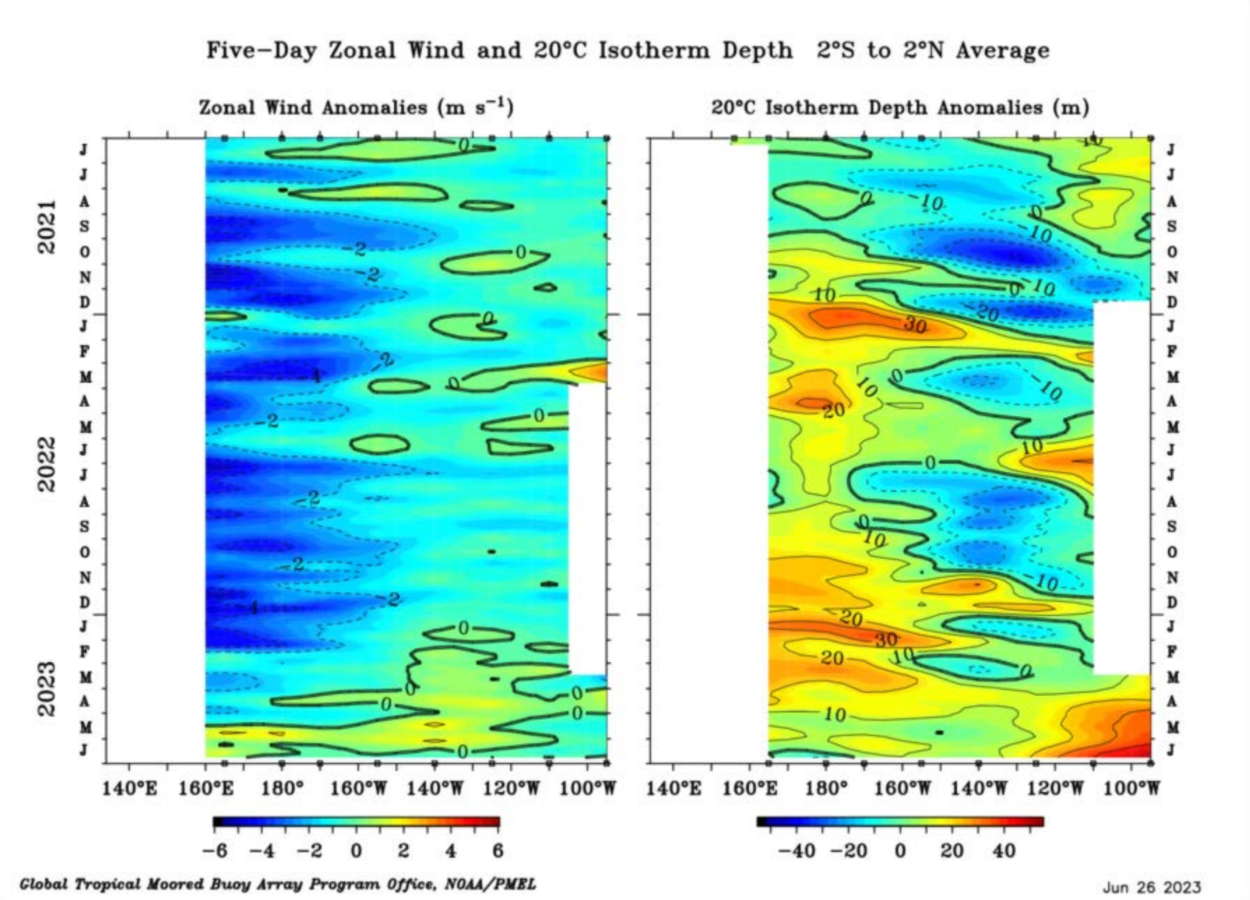
TAO Project Office/PMEL/NOAA

Nov 2 2005

What we see

- Strong compensation between dynamic height and 20C isotherm depth.
- Eastward propagation of waves.
- Waves start at about 160W.
- Speed is relatively fast.
- Deeper 20C isotherms correspond to high eastward velocities
- Some high-frequency variability involves both zonal and meridional velocities.

What’s going on along the equator?



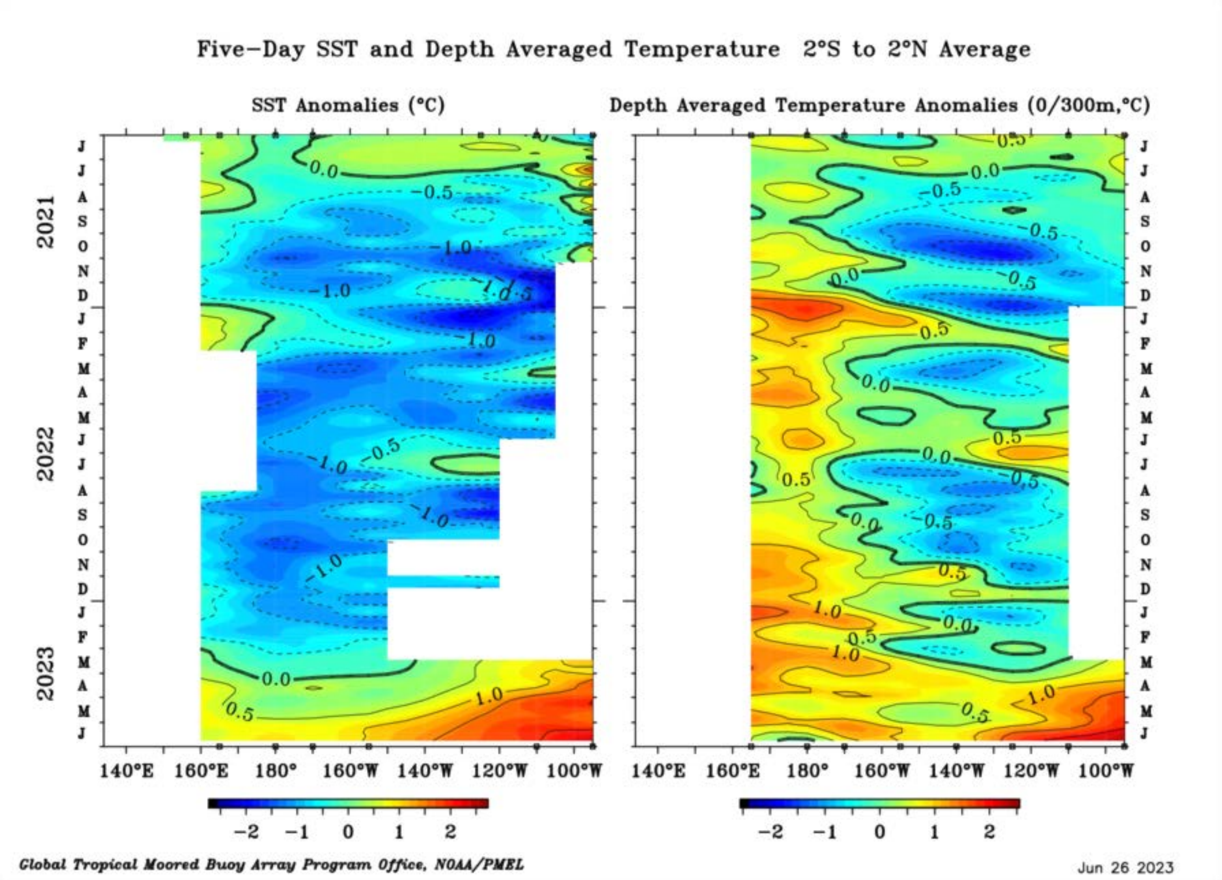
Five–Day Zonal Wind and 20°C Isotherm Depth 2°S to 2°N Average

Zonal Wind Anomalies (m s^{-1})

20°C Isotherm Depth Anomalies (m)

Global Tropical Moored Buoy Array Program Office, NOAA/PMEL

Jun 26 2023



Five–Day SST and Depth Averaged Temperature 2°S to 2°N Average

SST Anomalies (°C)

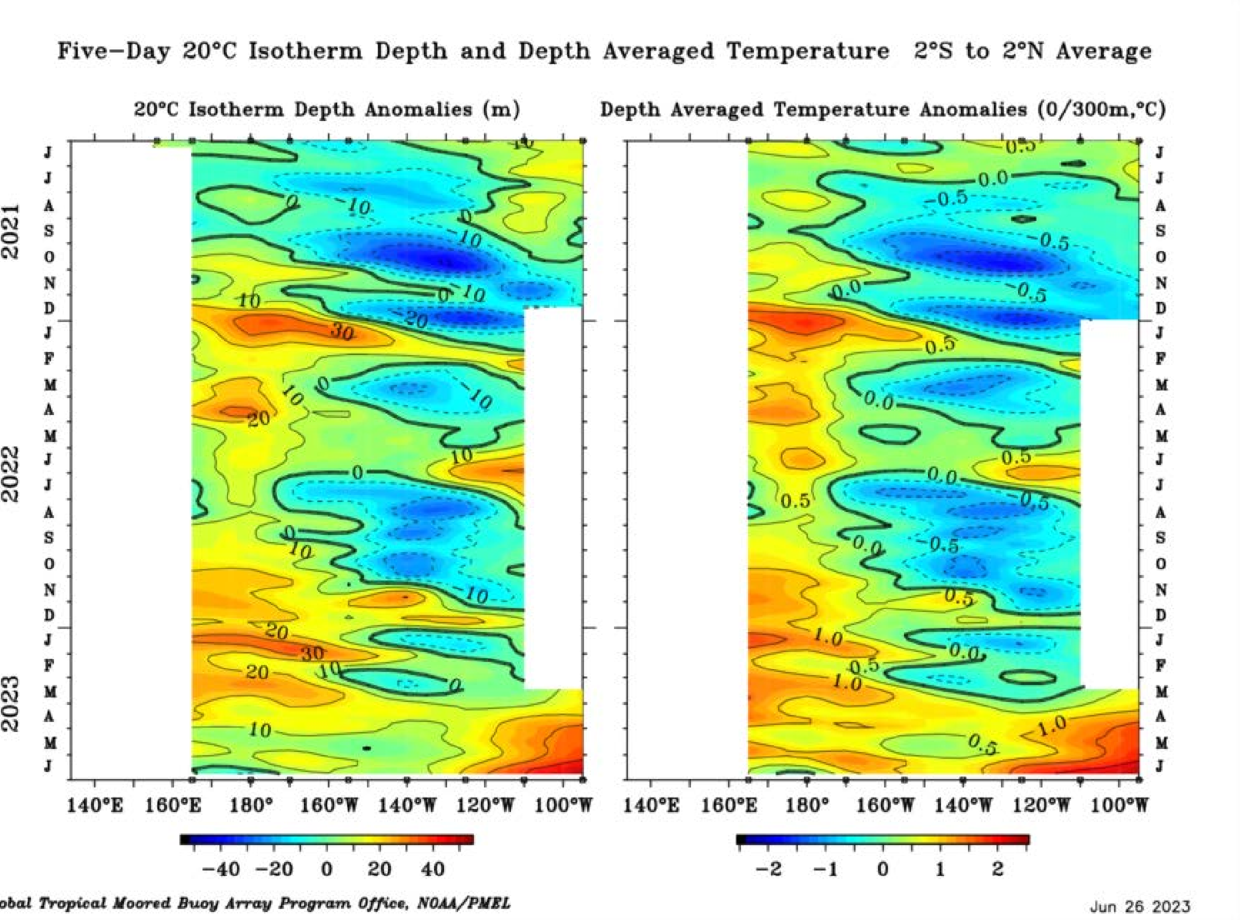
Depth Averaged Temperature Anomalies (0/300m,°C)

Global Tropical Moored Buoy Array Program Office, NOAA/PMEL

Jun 26 2023

Wind anomalies (westward in blue) have persisted for most of last couple of years
Temperatures in East Pacific lag winds, also reflect changes in isotherm depth.
Isotherm depth shows tilt, indicating eastward propagation.

However at 5N



Five−Day 20°C Isotherm Depth and Depth Averaged Temperature 2°S to 2°N Average

20°C Isotherm Depth Anomalies (m)

Depth Averaged Temperature Anomalies (0/300m,°C)

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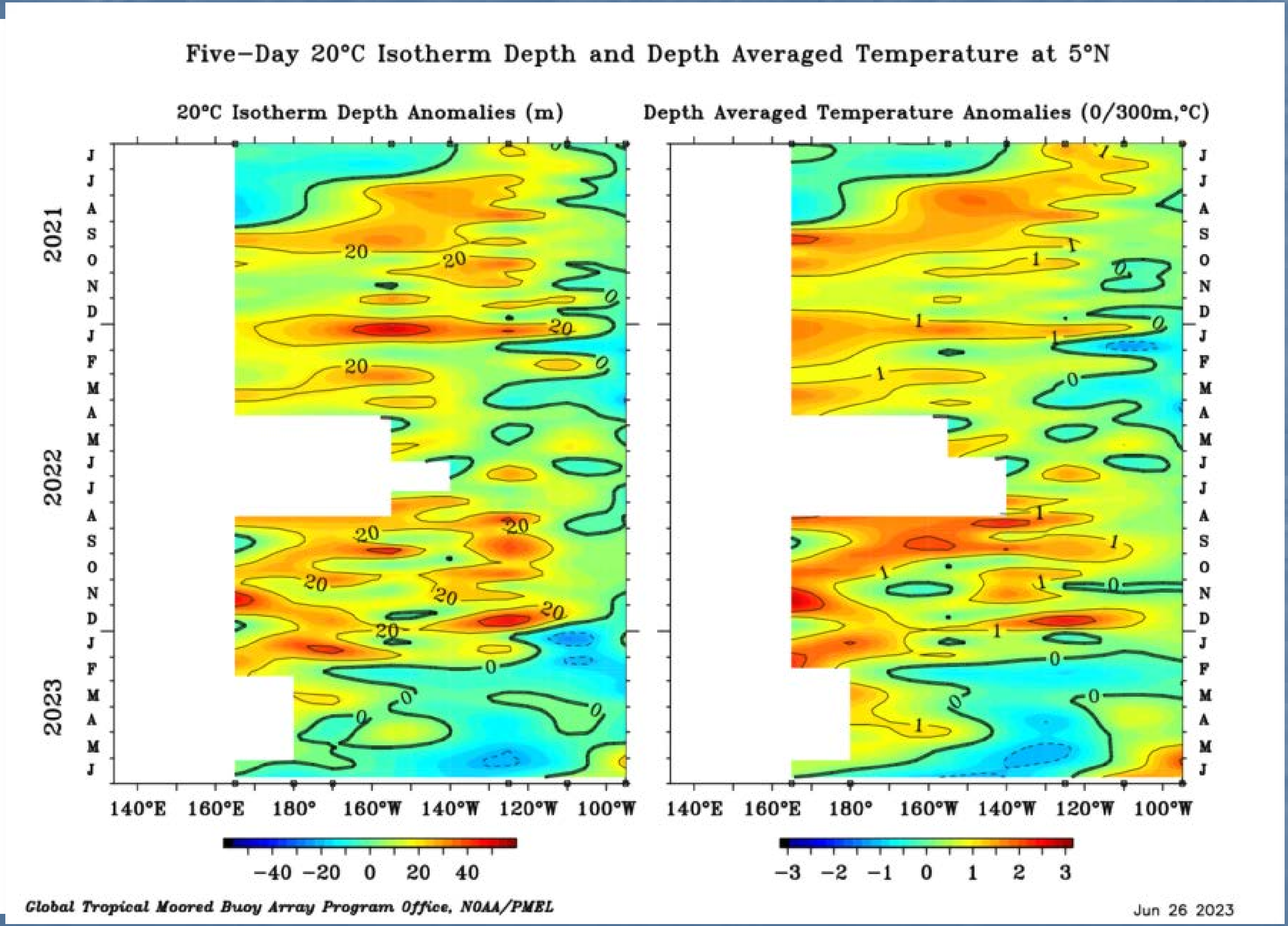

Five−Day 20°C Isotherm Depth and Depth Averaged Temperature at 5°N

20°C Isotherm Depth Anomalies (m)

Depth Averaged Temperature Anomalies (0/300m,°C)

Global Tropical Moored Buoy Array Program Office, NOAA/PMEL

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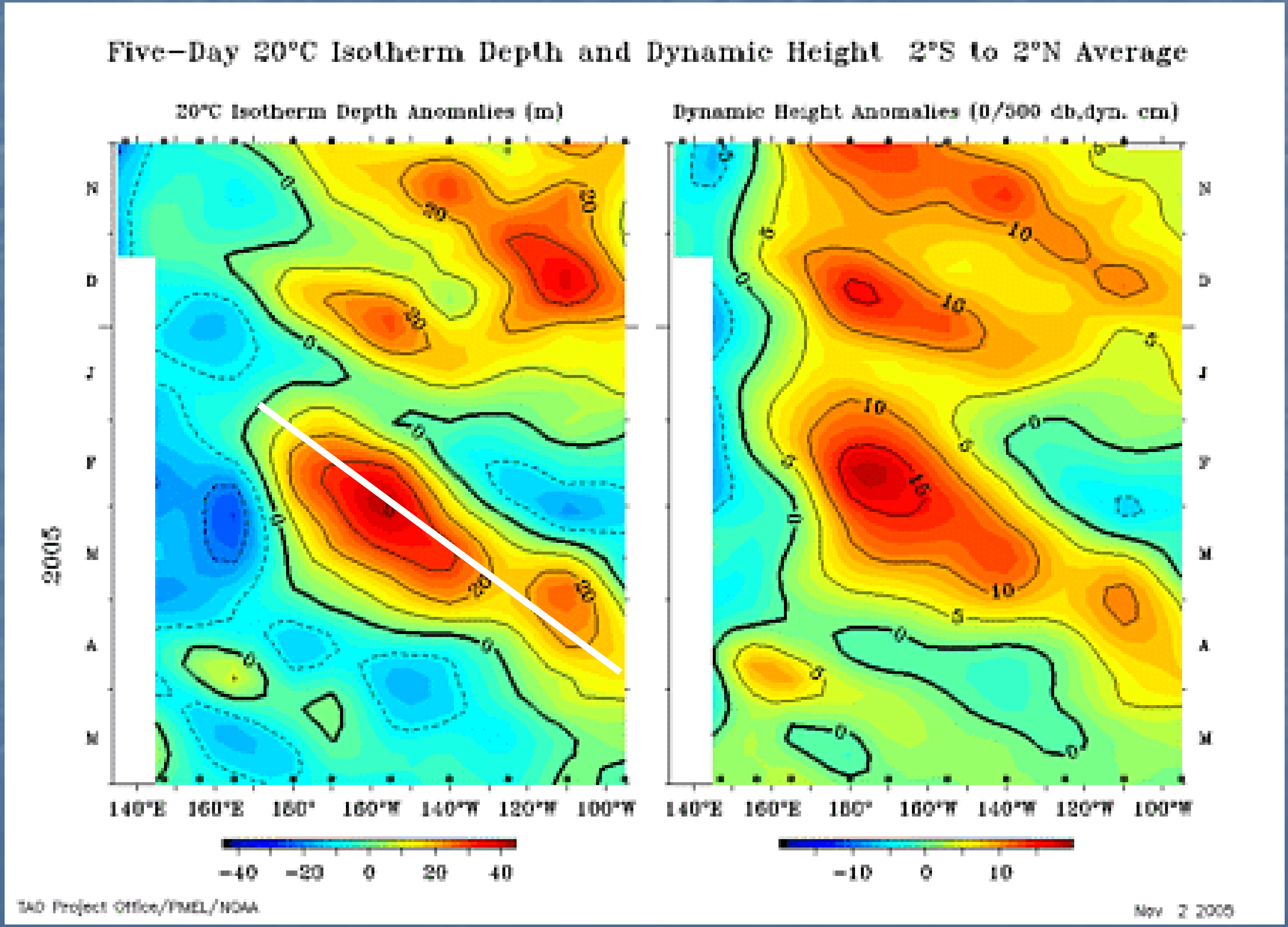
Example of a higher-resolution picture



Speed of disturbance

$$c = \frac{80\ degrees}{3\ months} = \frac{9.0\times10^6 m}{7\times10^6 s} = 1.2 m/s$$

So we are aiming to understand

1. Why the wave has a speed of only a few m/s.
2. What the associated structure should be (why is it trapped in surface layers), why is there an internal deformation countering the surface….
3. Why wave travels from west to east

Key reminder- on rotating earth velocity goes at right angles to pressure gradient

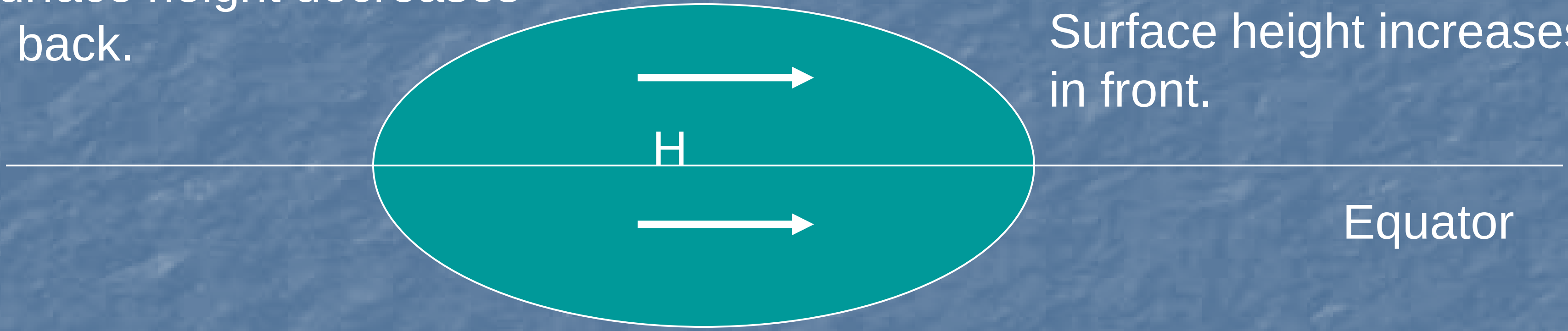
$$-f * v = -g\frac{\partial h}{\partial x}, \qquad f * u = -g\frac{\partial h}{\partial y}$$

Where Coriolis parameter $f = 2 * \Omega * \sin(\theta_{latitude})$

is negative in Southern Hemisphere, positive in Northern Hemisphere and goes to zero at equator.

Means that a given pressure gradient will drive a larger velocity near the equator.

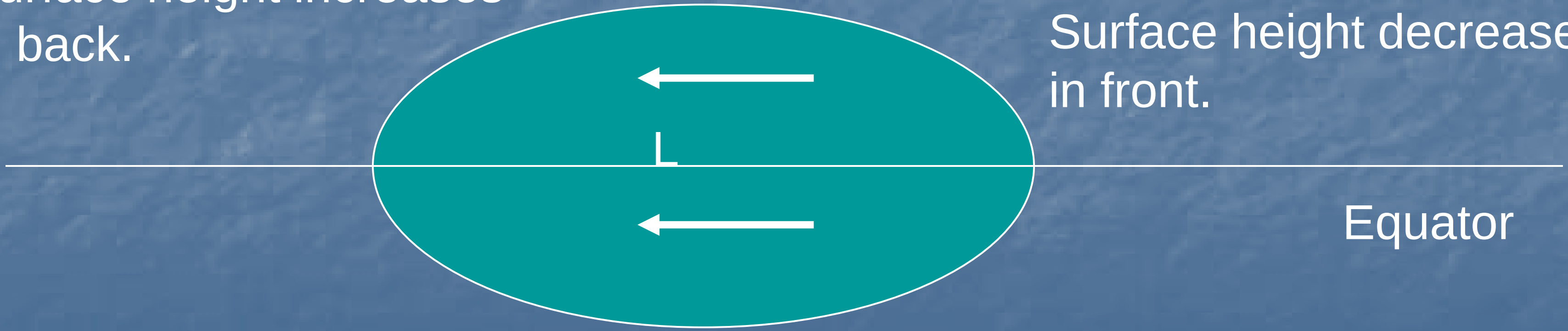
Schematic of what's going on



Surface height decreases in back.

Surface height increases in front.

Equator



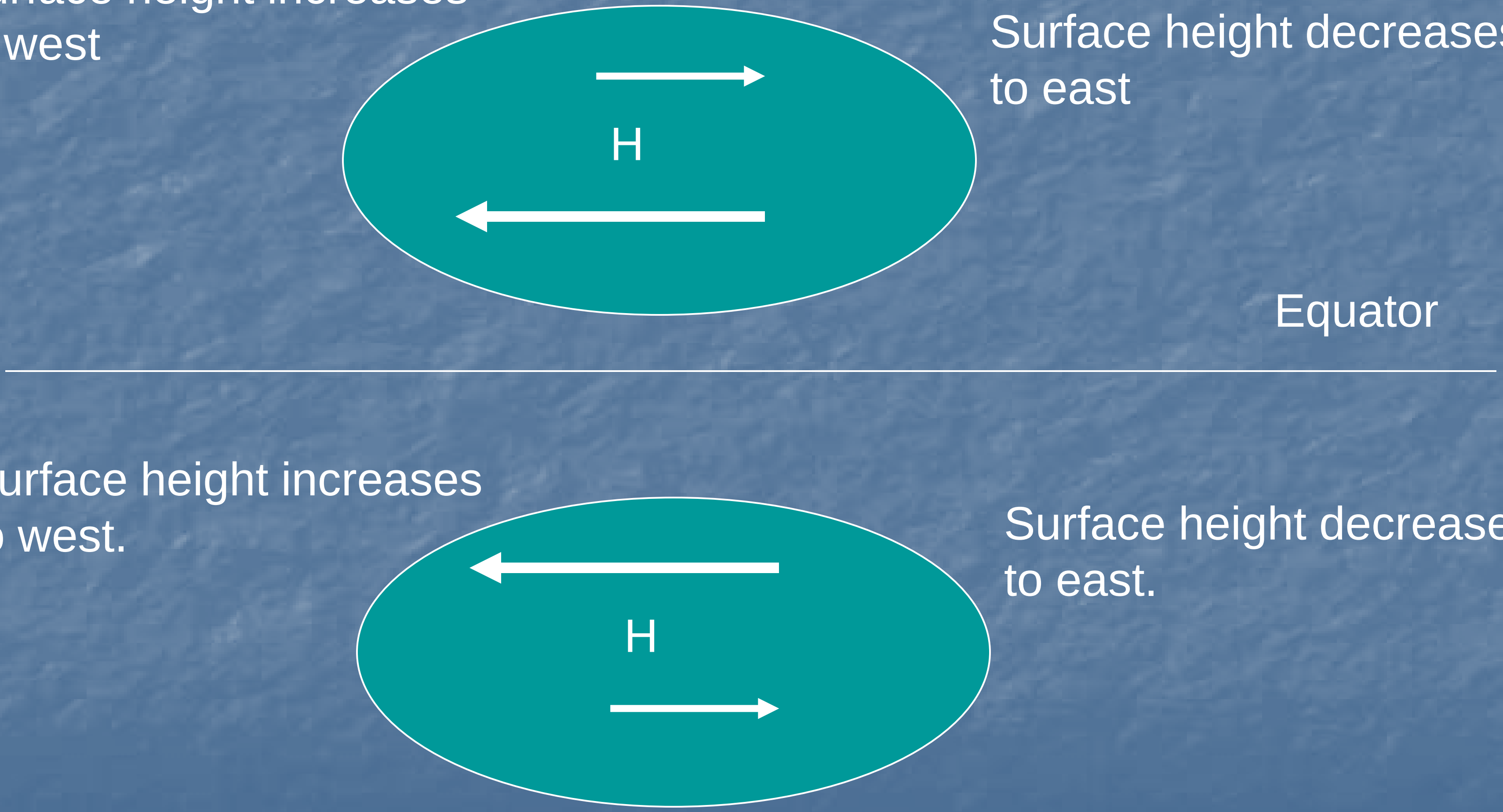
Surface height increases in back.

Surface height decreases in front.

Equator

Coastal Kelvin waves

Off-equatorial Rossby



Surface height increases
to west

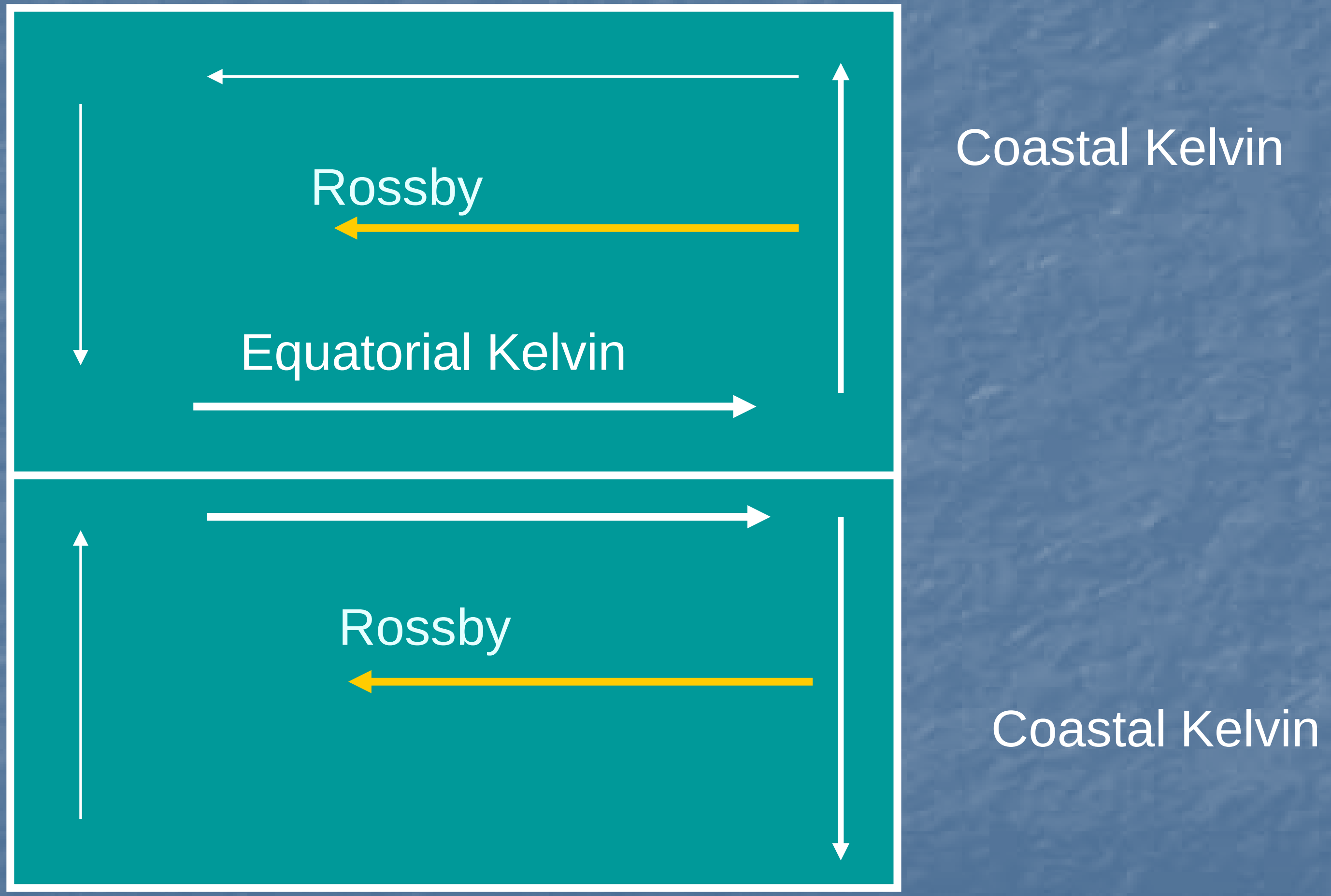
Surface height decreases
to east

Equator

Surface height increases
to west.

Surface height decreases
to east.

Sloshing mode of the equator



Eq Kelvin waves connected with establishment of El Nino, Rossby waves with its decay, transition to opposite phase.

Result.. Delay oscillator

$$T_{n+1} = a * T_n - b * T_{n-k} + \epsilon$$

Can do the same kind of decomposition we did for stochastic variability

$$\hat{T}(\exp(i * \omega * \Delta t) - a + b * \exp(-k * \omega * \Delta t)) = \hat{\epsilon}(\omega)$$

Note that for particular combinations of response and delay, coefficient on LHS can go to zero.

Complications and open questions

- How has El Nino changed in the past?
- How will it change in the future?

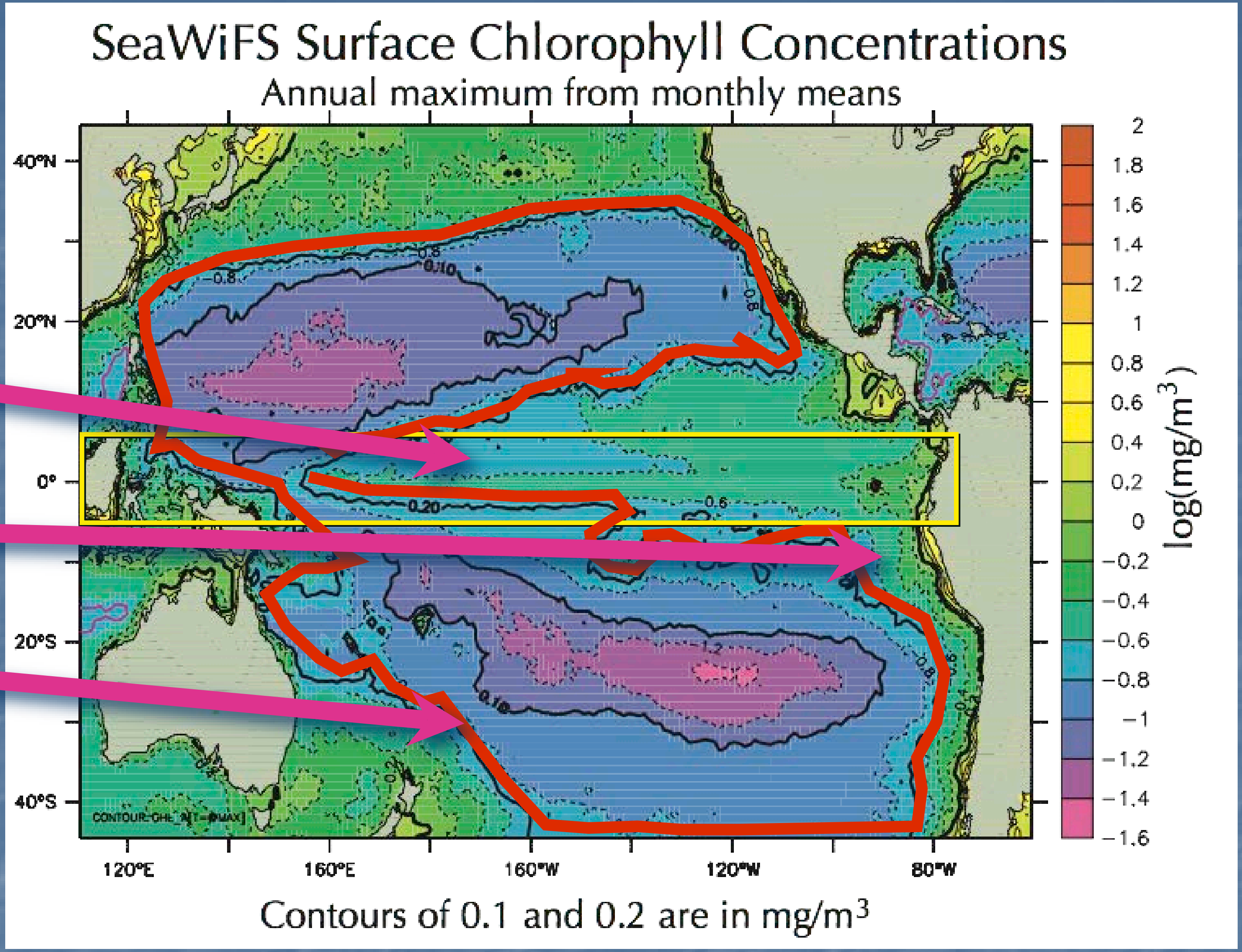
- Turns out we can fit multiple models of delay oscillator to present day conditions.
- Coefficients may not be consistent over time.
- What sets these coefficients may vary across models.

Turn ocean blue in different locations

-NoEqu

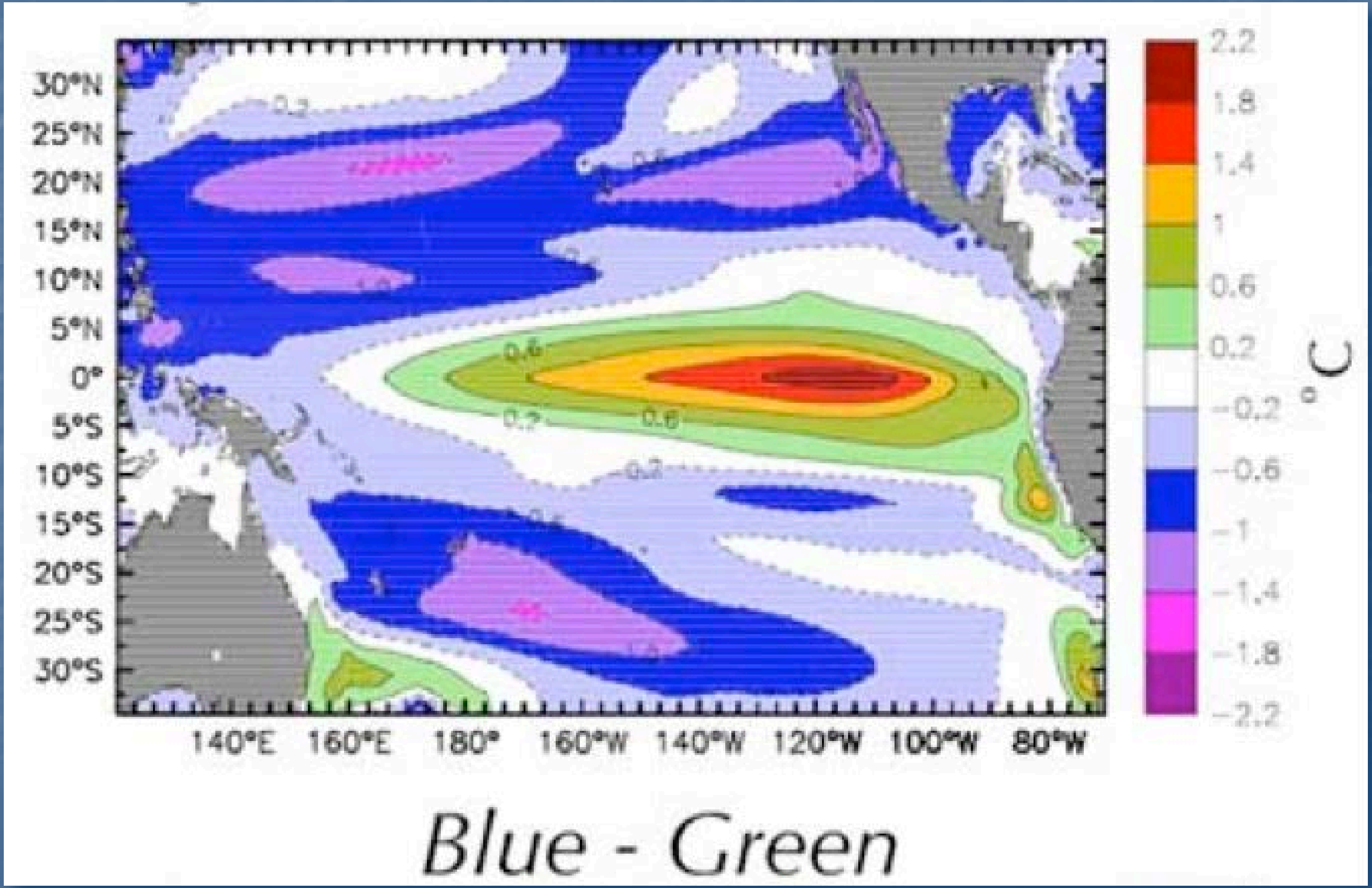
-Plus0.2

-Minus 0.2

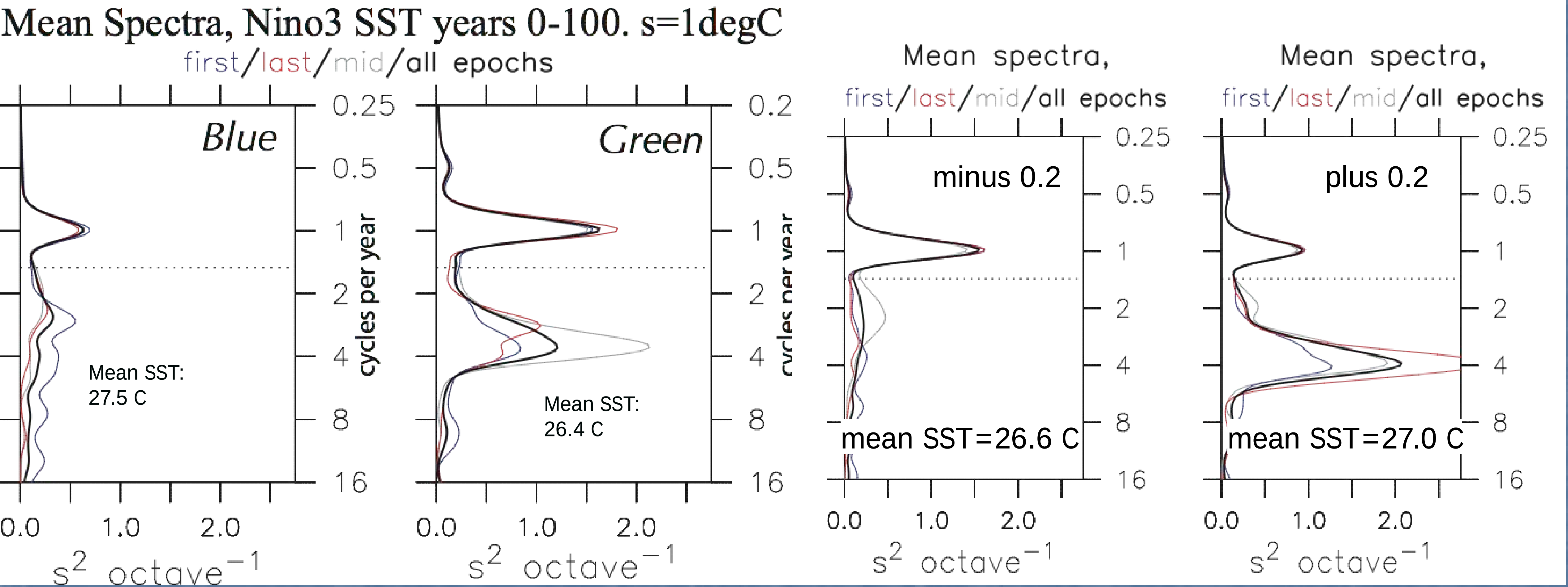


Green ocean, has chlorophyll-dependent absorption everywhere. Blue ocean turns it off everywhere.

Mean state change



Degree to which water is warmed as it moves towards equator (mixing, solar penetration) has big impacts on mean state. (Anderson et al., GRL, 2007)



Deeper penetration wipes out annual cycle, El Nino

Regional changes affect different parts of cycle.

Why does it depend where you push more heat into ocean?

- Answer- it changes the base state of the atmosphere.
- Changes that pin the convection to west Pacific (cooling off-equator) make it hard for winds to respond to warming, damp El Nino.
- Changes that warm East Pacific, moving winds out over ocean, make atmosphere more responsive to warming.
- Similar effects seen for increasing lateral mixing (Gnanadesikan et al., JGR, 2017)

Conclusions

- Ocean holds a lot of heat…
- Changes in how it stores and moves this heat around have potential to affect atmosphere.
- Simplest models of climate variability (ocean integrates noisy atmosphere) seem to work pretty well in some locations.
- But one region where they break down is the equator.
- Positive feedbacks between upwelling and winds, plus delayed “sloshing” response allow for variability (El Nino).
- This variability can be modulated by a large suite of processes, with effects crossing domains.