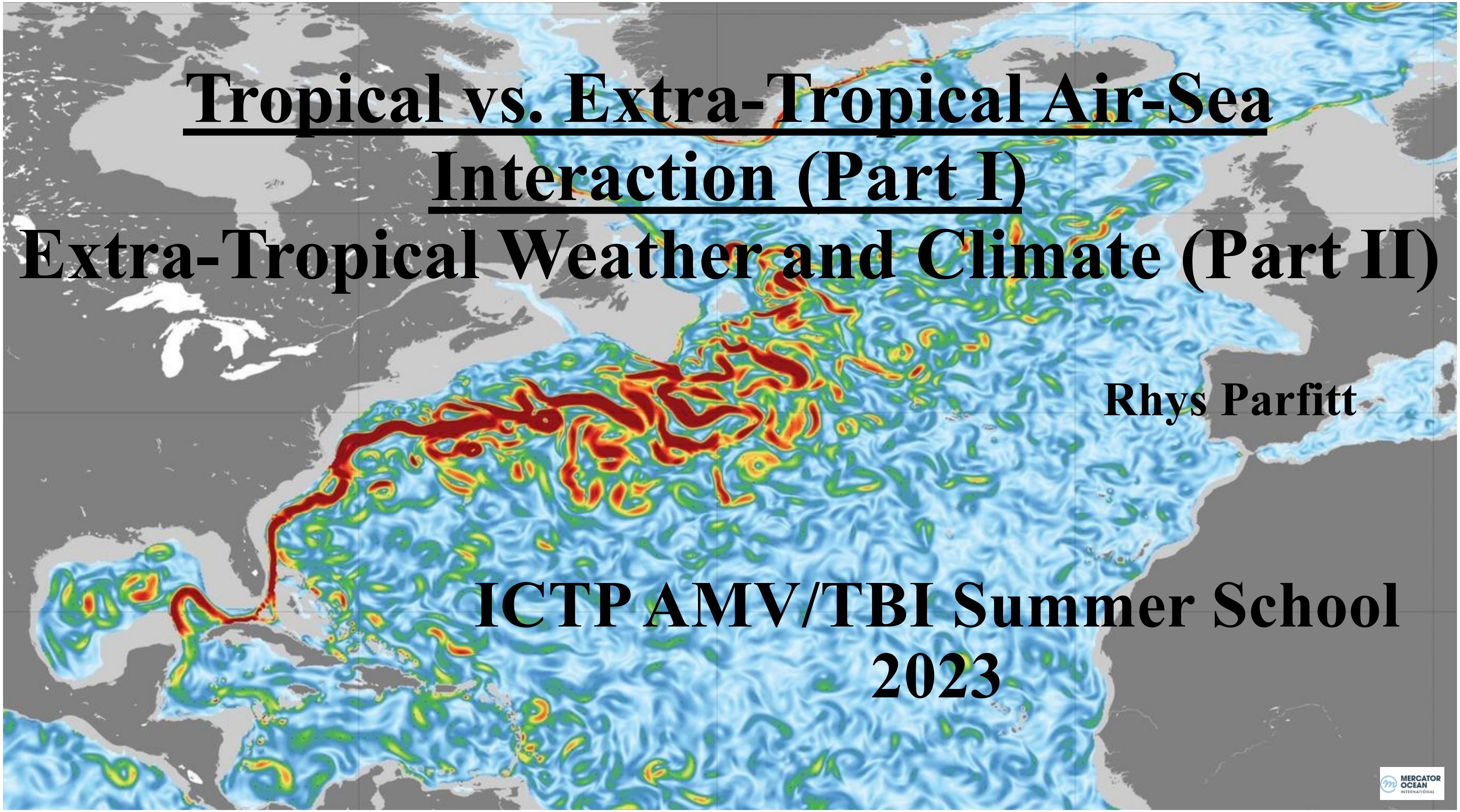
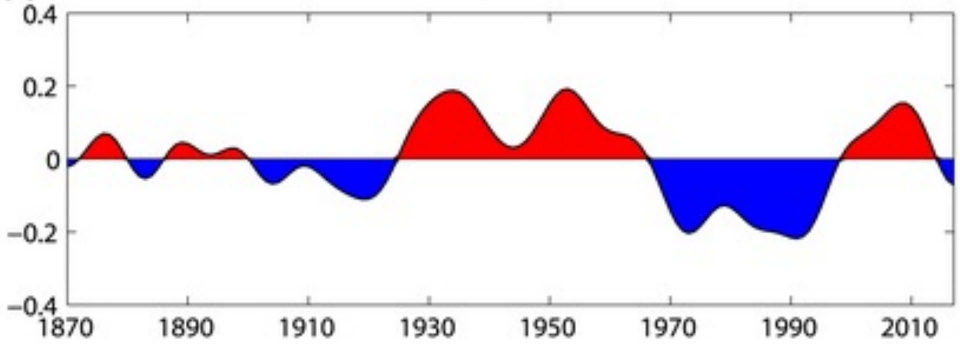


Tropical vs. Extra-Tropical Air-Sea Interaction (Part I)

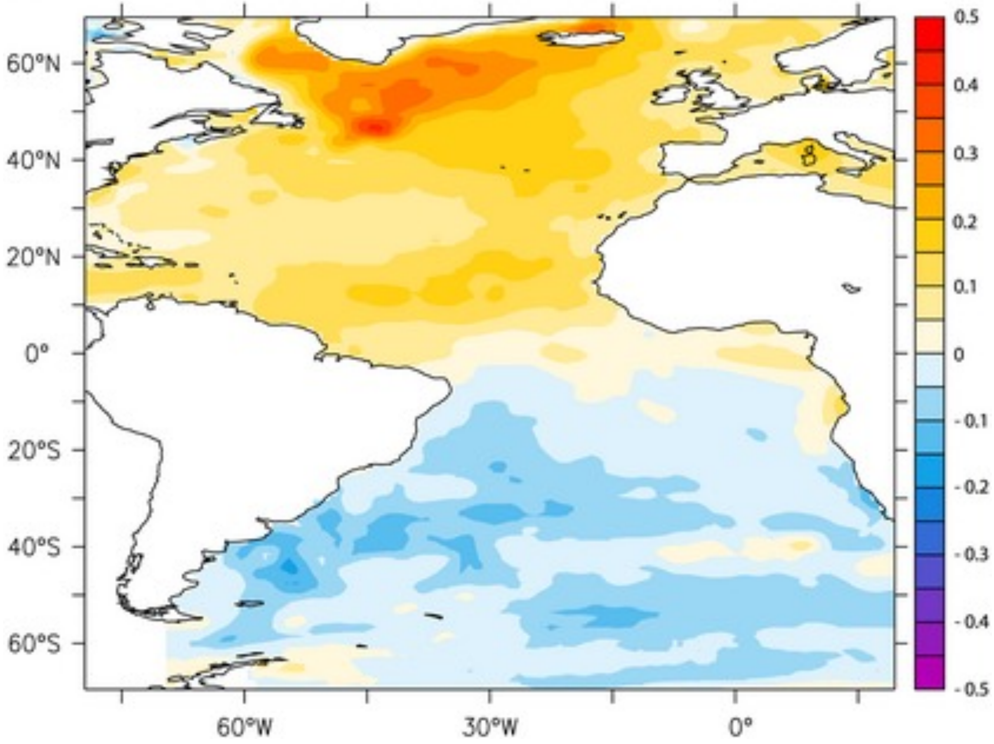
Extra-Tropical Weather and Climate (Part II)

Rhys Parfitt

ICTP AMV/TBI Summer School
2023



(a) Observed AMV Index



(b) Observed SST Pattern Associated with the AMV

Sea-surface temperature anomalies (here associated with Atlantic Multi-Decadal Variability) –

How might they influence the atmospheric circulation ?

Zhang et al. (2019)

Well accepted that *tropical* ocean / SSTs play a first order role in atmospheric circulation *in the tropics*

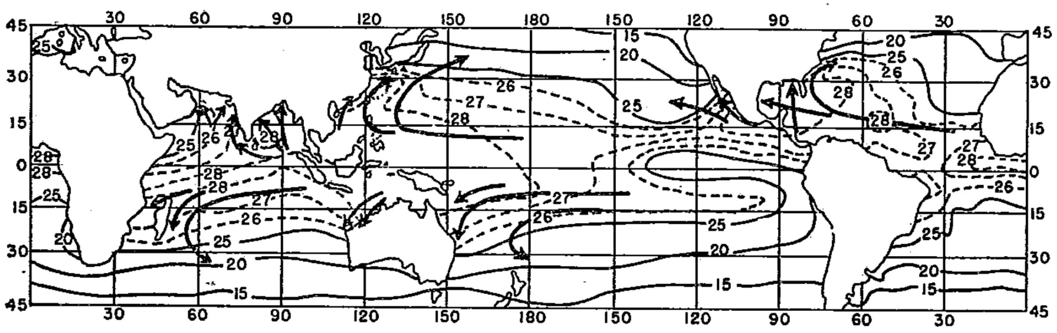


Fig. 4. Principal hurricane paths and surface water temperature during the warmest season.

Palmen (1948)

(above) Impact on tropical cyclones

(right) Coupled ocean-atmosphere processes associated with ENSO

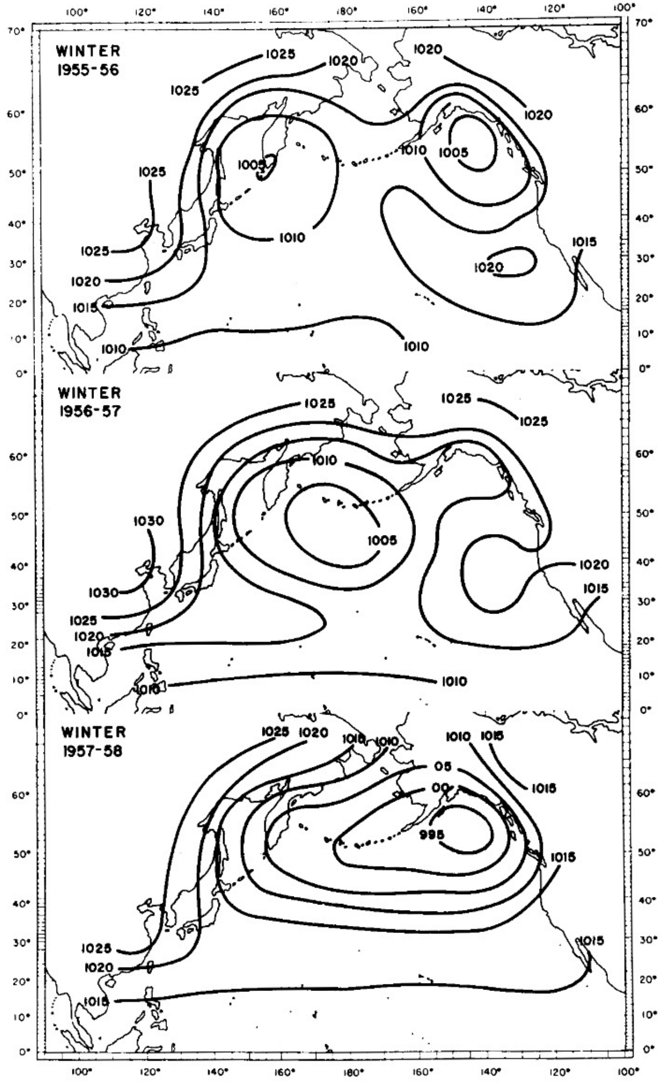
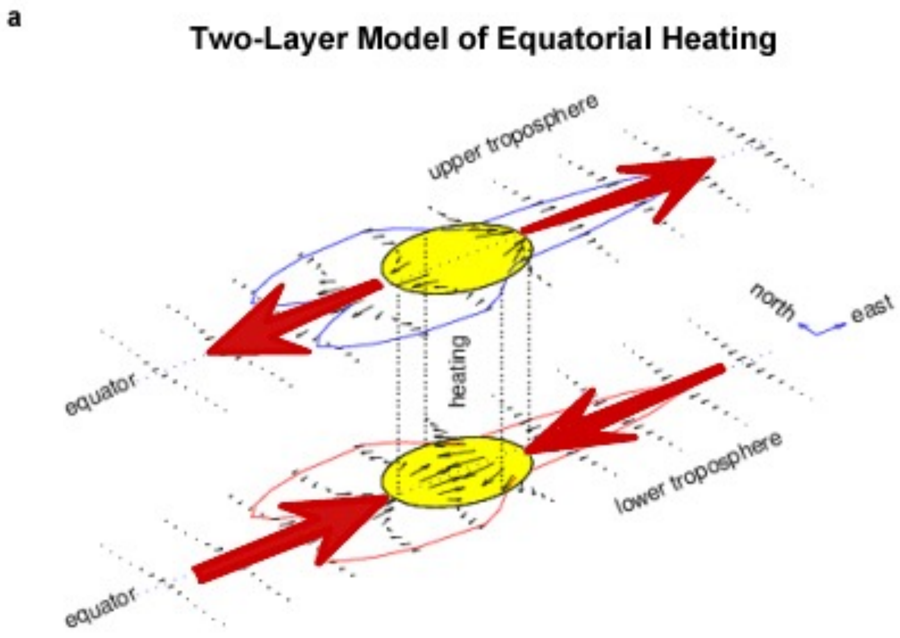
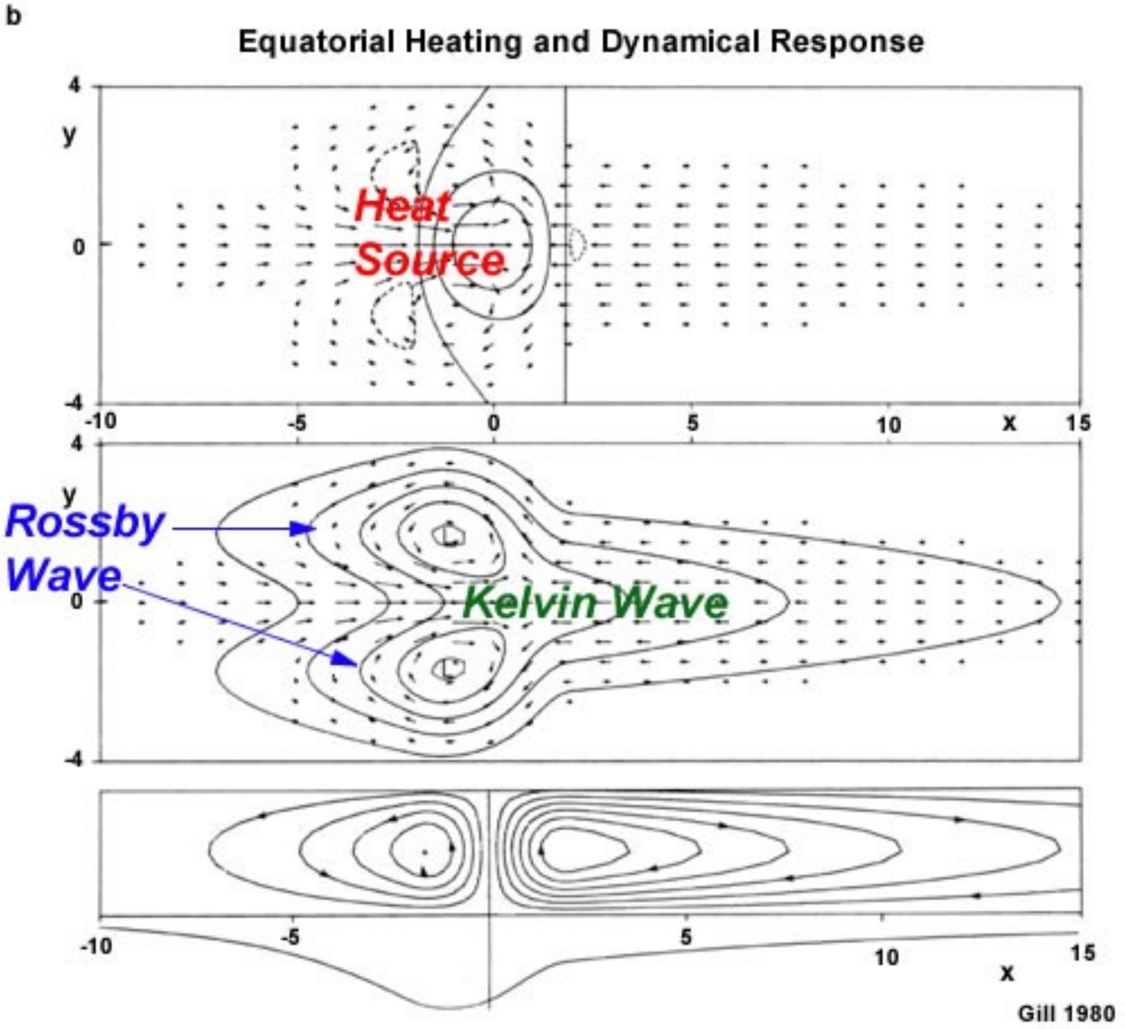


Fig. 6. Average distribution of atmospheric pressure at sea level during the winter seasons, December to February inclusive, of 1955–56 and 1956–57, before the East Pacific equatorial warming, and 1957–58 at the peak of that warming.

Bjerknes (1966)

Basic character of the local atmospheric response to tropical SST anomaly well explained by simple theoretical models of Matsuno (1966) and Gill (1980)



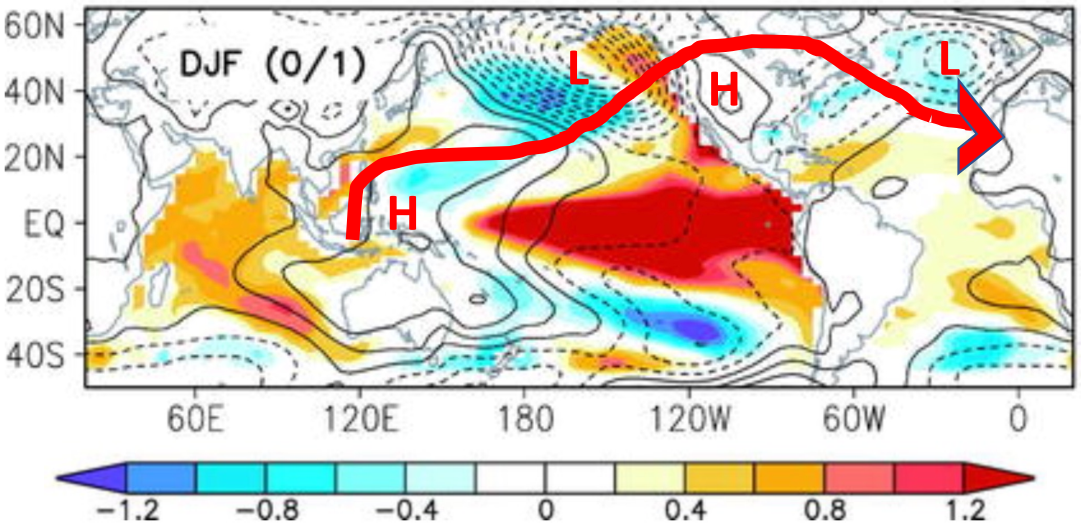


Gill 1980

Gill, 1980

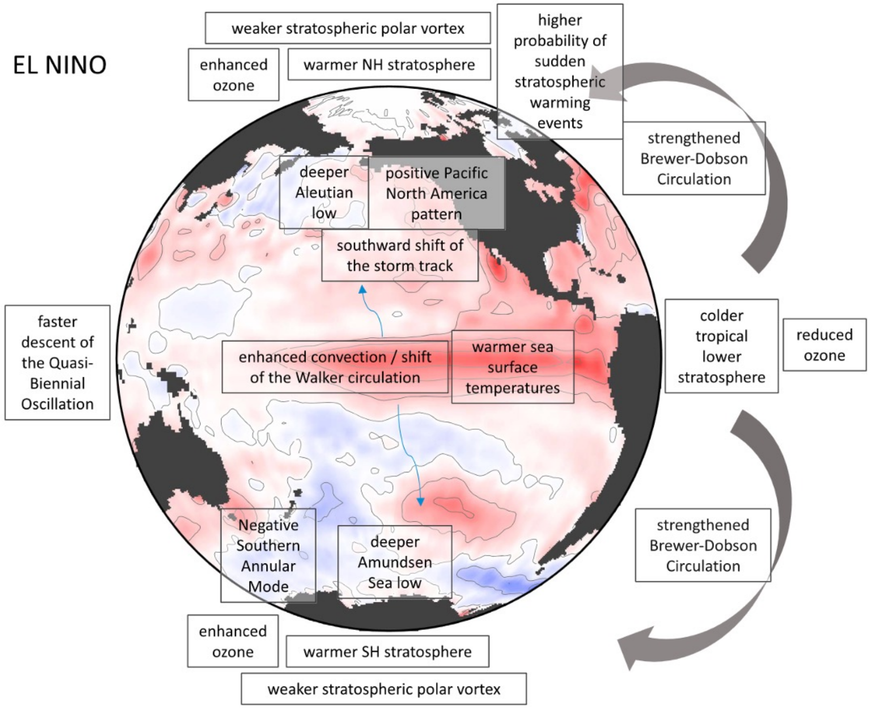
Well accepted that *tropical* ocean / SSTs play a first order role in atmospheric circulation *in the extra-tropics*

Observed SLP (El Nino – La Nina)



“Atmospheric Bridge”

Alexander et al. (2002)



EL NINO

weaker stratospheric polar vortex

enhanced ozone

warmer NH stratosphere

higher probability of sudden stratospheric warming events

strengthened Brewer-Dobson Circulation

deeper Aleutian low

positive Pacific North America pattern

southward shift of the storm track

faster descent of the Quasi-Biennial Oscillation

enhanced convection / shift of the Walker circulation

warmer sea surface temperatures

colder tropical lower stratosphere

reduced ozone

strengthened Brewer-Dobson Circulation

Negative Southern Annular Mode

deeper Amundsen Sea low

enhanced ozone

warmer SH stratosphere

weaker stratospheric polar vortex

Domeisen et al. (2019)

Via stratosphere – sudden stratospheric warmings

What about the role of the *extra-tropical* ocean / SSTs in the *extra-tropical* atmospheric circulation ?

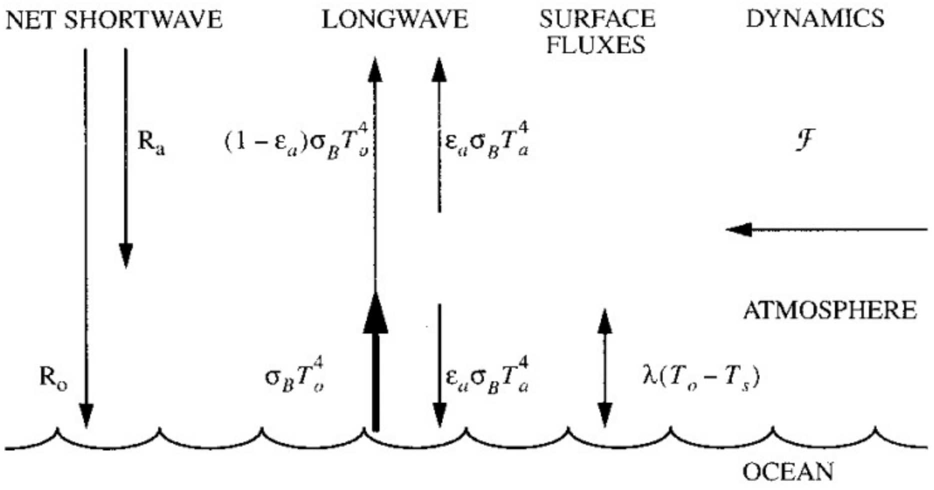
Basic character – low-level convergence (cyclonic) and upper-level divergence (anticyclonic). Cyclone shifted downstream due to cold-air advection - “linear baroclinic response” (Hoskins and Karoly, 1981). Linear response can cause remote impacts (e.g. Sato et al., 2014).

Involvement of eddies induces a more barotropic response.

Forcing estimate of 20 m K^{-1} at 500 hPa, vs. observed monthly - interannual std. 50 – 100 m, lead to assertion that “*direct linear forcing [from extra-tropical SST] will rarely be relevant in the extra-tropics*” (Kushnir et al., 2002).

<u>Traditional view is that extra-tropical ocean is passive to atmospheric variability</u>

Traditional view reinforced by consistency of a linear stochastic framework with general circulation models at the time -



$$\gamma_a \frac{d\tilde{T}_a}{dt} = -\lambda_{sa}(\tilde{T}_s - \tilde{T}_o) - \lambda_a \tilde{T}_a + \tilde{\mathcal{F}}$$

$$\gamma_o \frac{d\tilde{T}_o}{dt} = -\lambda_{so}(\tilde{T}_s - \tilde{T}_o) - \lambda_o \tilde{T}_o.$$

<u>Barsugli and Battisti (1998)</u>

Slab ocean coupled to grey atmosphere

Some manipulation + assume a few things… (e.g. forcing has deterministic SST-forcing and random component that is inherent to atmosphere)

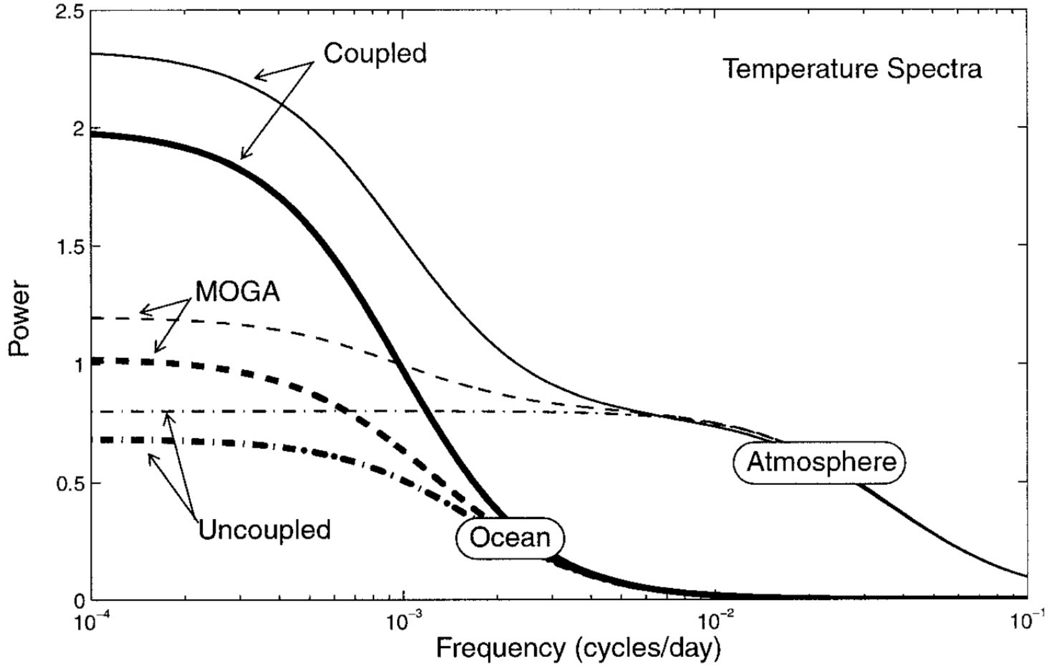


FIG. 4. Power spectra of atmosphere and ocean temperature for the coupled, MOGA, and uncoupled cases. The standard parameters (see Table 1) are used.

$$i\sigma T_a = -aT_a + bT_o + N$$

$$i\beta\sigma T_o = cT_a - dT_o.$$

Solve numerically for:

- Coupled
- Uncoupled ($T_o = 0$ in equation for T_a)
- MOGA ($T_o = T_o$(solved from coupled equations) in in equation for T_a)

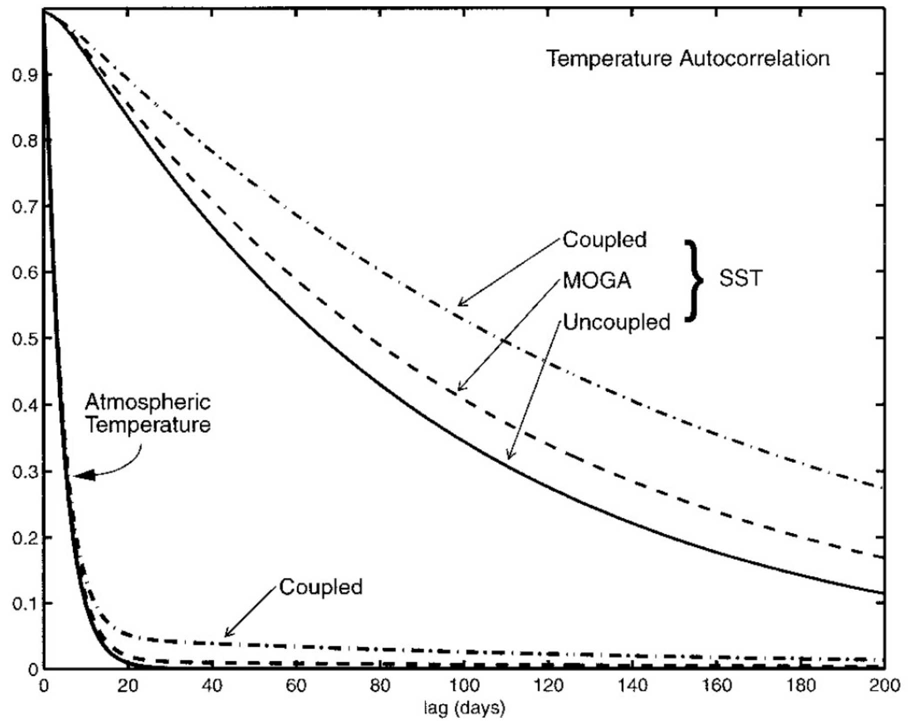


FIG. 8. Autocorrelation function for atmospheric temperature (thick lines) and SST (thin lines) for the coupled (dash–dot), MOGA (dashed), and uncoupled (solid) cases.

Autocorrelation falls less sharply to zero for both SST and atmospheric temperature, with coupling

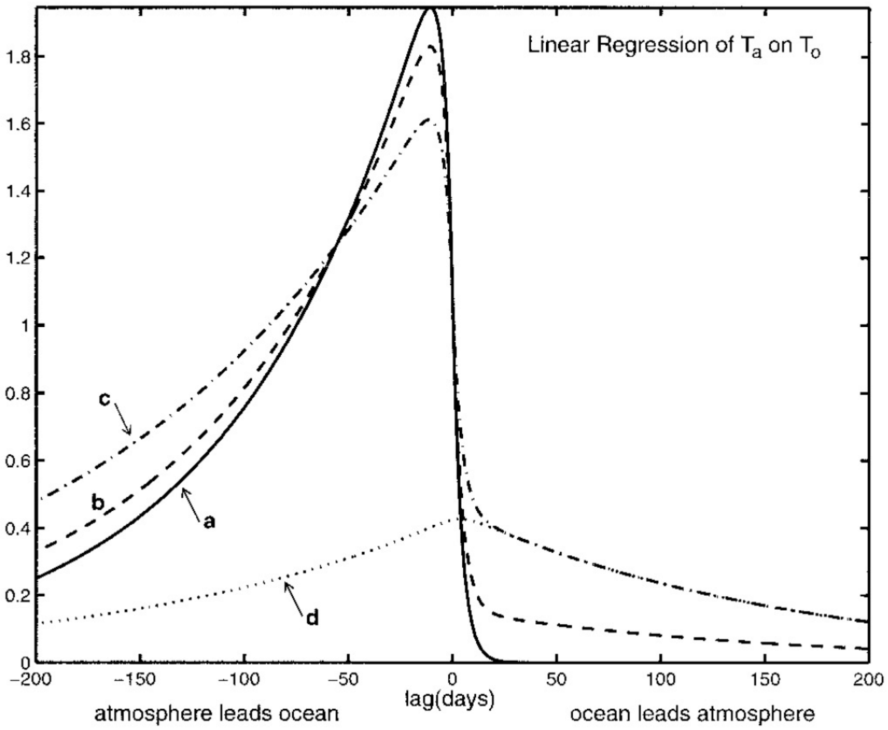
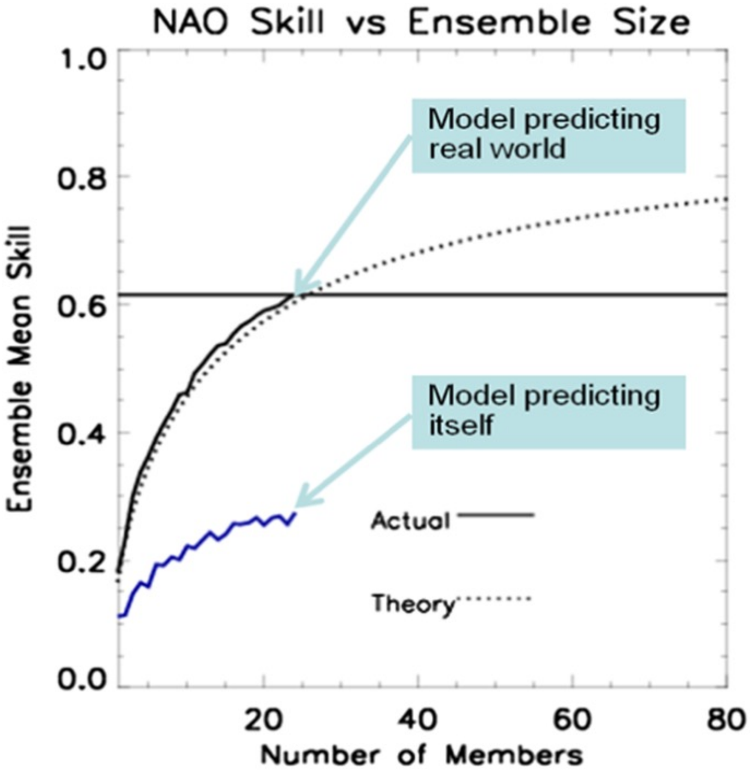


FIG. 9. Lagged linear regression between T_a and T_o. Curve **a**: T_a^U, T_o^U; curve **b**: T_a^M, T_o^M; curve **c**: T_a^C, T_o^C; curve **d**: T_a^M, T_o^C.

Coupled system shows a larger component that is symmetric in lag

Traditional view is that extra-tropical ocean is passive to atmospheric variability

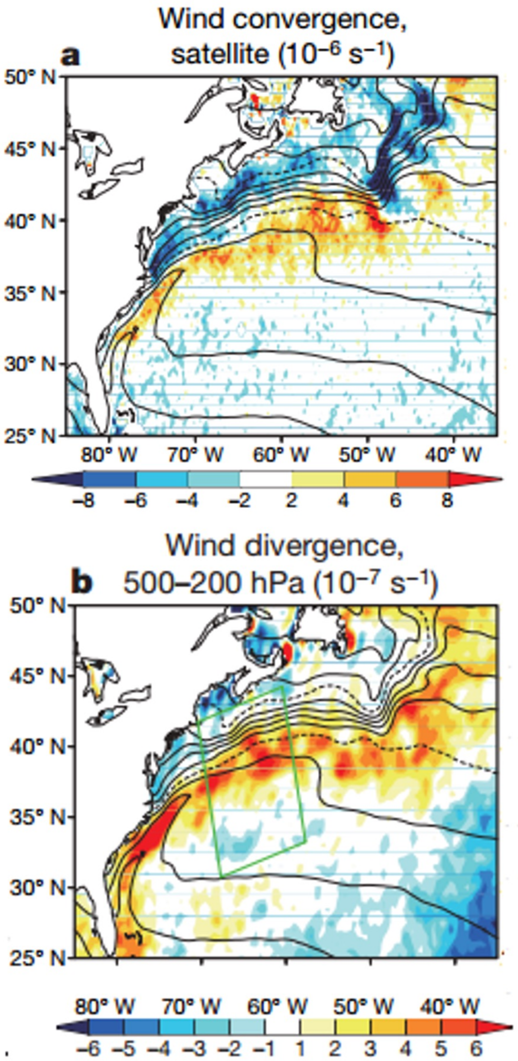
"It is important to emphasize that the prevailing paradigm is that storm-track response is well captured by dry quasi-geostrophic (QG) dynamics … since even very low-resolution QG models have been able to reproduce features of the eddy mean flow feedback generated by low-resolution AGCMs" (Czaja et al., 2019).

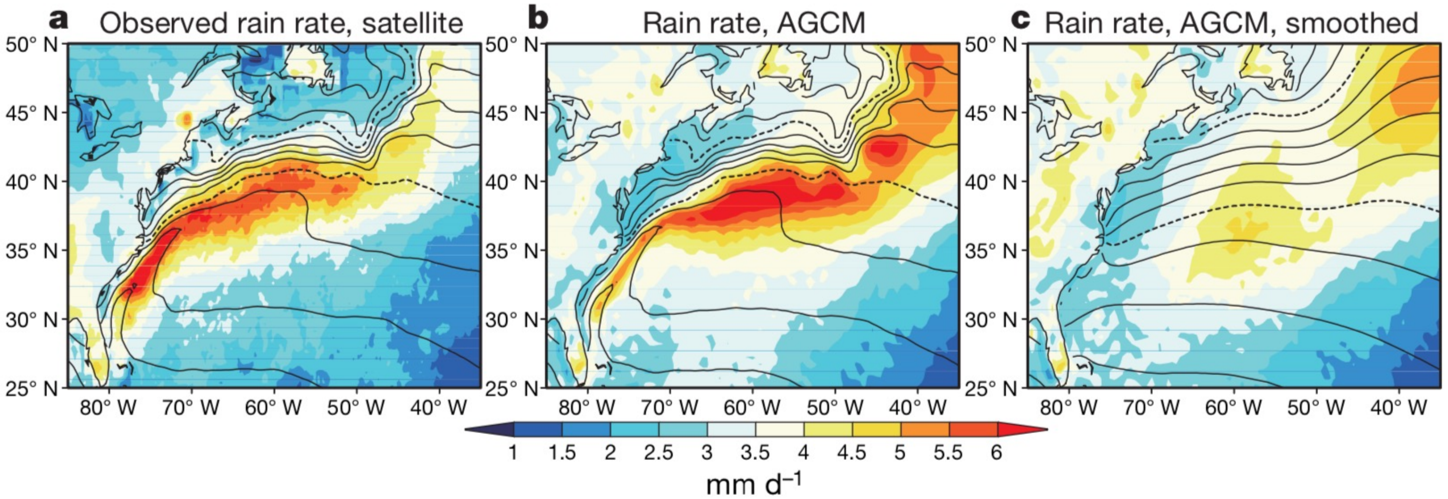


However, AGCMs (and coupled seasonal forecasting systems based on them) show less predictability than nature in midlatitudes (*left,* Scaife et al., 2018).

Also, AGCMs cannot simulate (even when forced with observed SST anomalies), 20th century multidecadal variability in the North Atlantic Jet Stream (Simpson et al., 2018).

A different picture has emerged with higher-resolution models and data

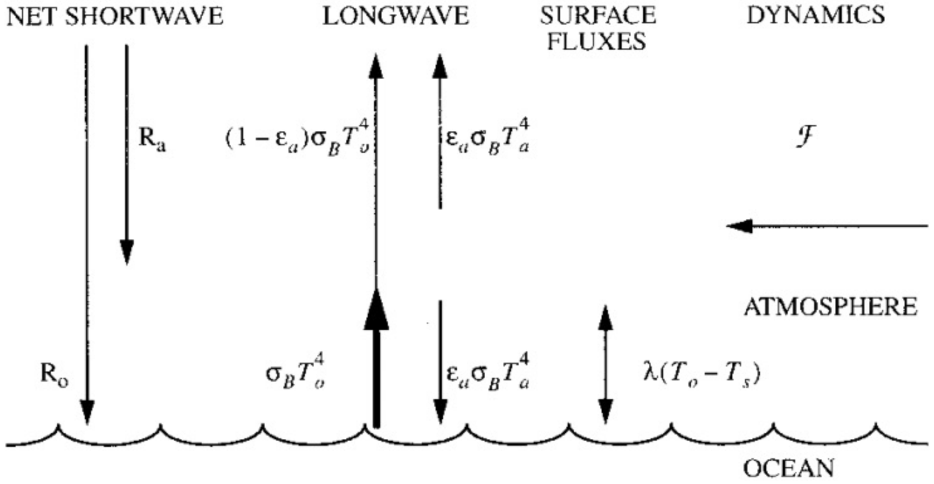




Meandering Gulf Stream imprint throughout troposphere – imprint removal with smoothing of sea-surface temperature gradient (*left and above*, Minobe et al., 2008).

Estimates with newer reanalyses place oceanic forcing at > 50 m K^{-1} at 500hPa (e.g. Frankignoul et al., 2011).

Extend framework to include stochastic forcing arising in the ocean



$$\gamma_a \frac{d\tilde{T}_a}{dt} = -\lambda_{sa}(\tilde{T}_s - \tilde{T}_o) - \lambda_a \tilde{T}_a + \tilde{\mathcal{F}}$$

$$\gamma_o \frac{d\tilde{T}_o}{dt} = -\lambda_{so}(\tilde{T}_s - \tilde{T}_o) - \lambda_o \tilde{T}_o.$$

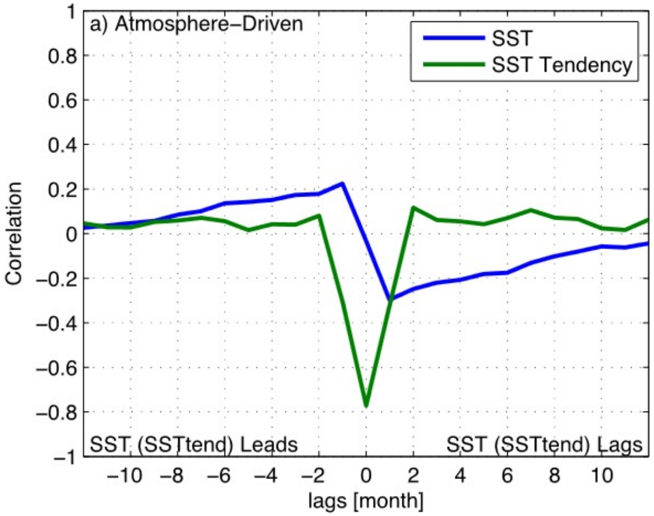
Barsugli and Battisti (1998)

$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a,$$

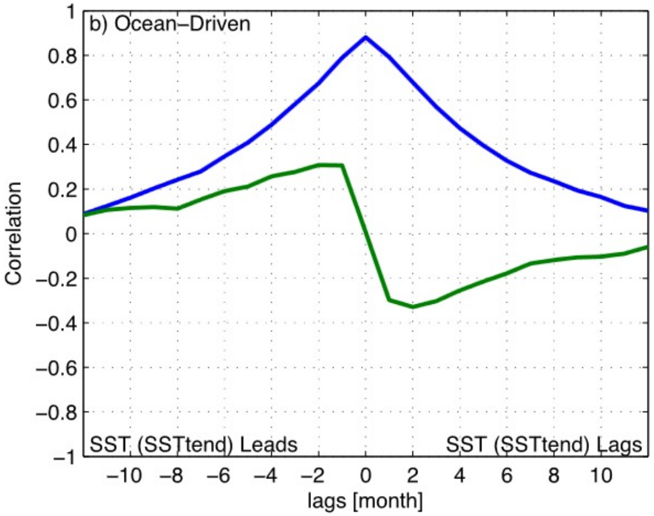
$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o,$$

Wu et al. (2006)

Lagged correlation between SST and SHF, and SST tendency and SHF, **with variability driven by atmospheric noise**.



Lagged correlation between SST and SHF, and SST tendency and SHF, **with variability driven by oceanic noise**.

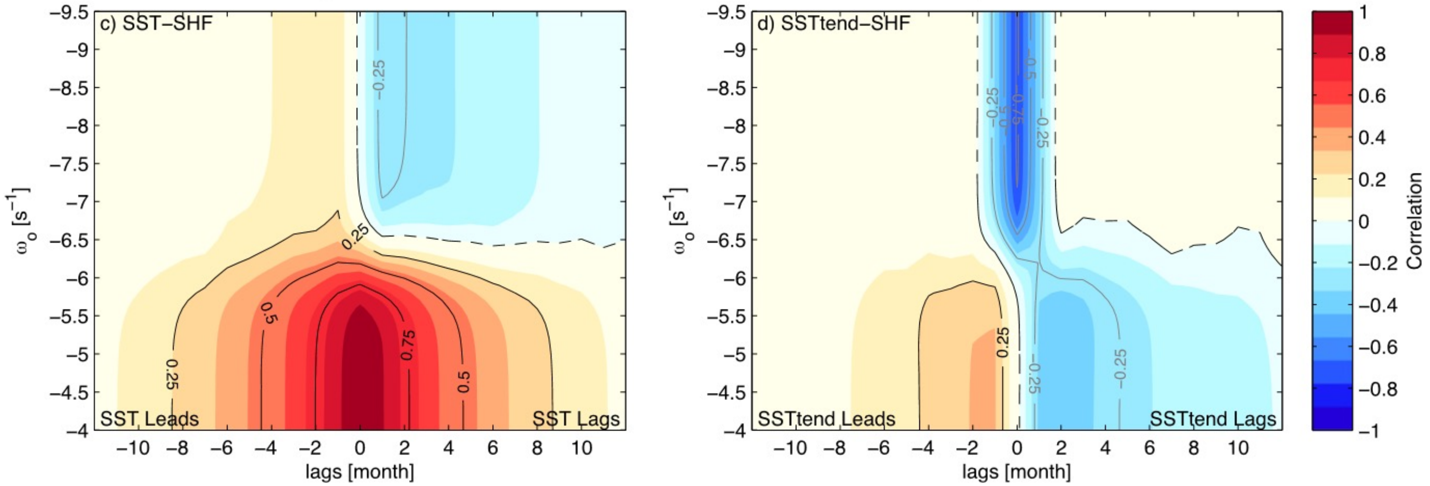


$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a,$$

$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o,$$

Stochastic forcing:
Forcing frequency times Gaussian rng for temperature anomalies ±1°C

Atmospheric forcing frequency: 1 day^{-1}
Ocean forcing frequency: 1/500 day^{-1} for atmosphere-driven, 1/5 day^{-1} for ocean-driven.



Vary ocean forcing frequency

Figures from Bishop et al. (2017)

Atmosphere-driven

Near-zero simultaneous correlation SST-SHF, asymmetrical lead-lag

Strongly negative simultaneous correlation SST tendency-SHF, symmetrical lead-lag

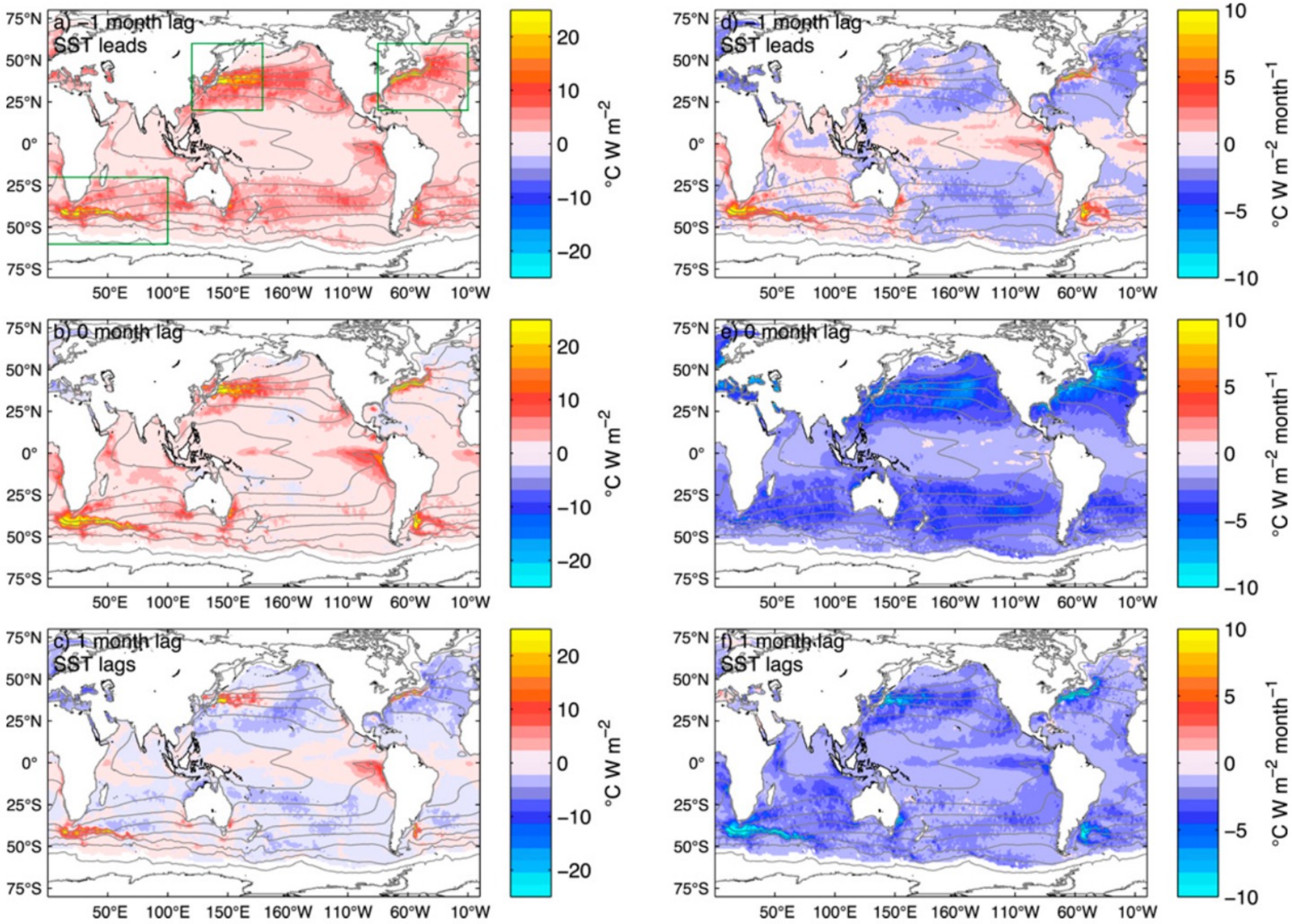
Ocean-driven

Positive simultaneous correlation SST-SHF, symmetrical lead-lag

Zero simultaneous correlation SST tendency-SHF, asymmetrical lead-lag structure

Where do we see each of these?

SST-SHF covariance **SST tendency -SHF covariance**



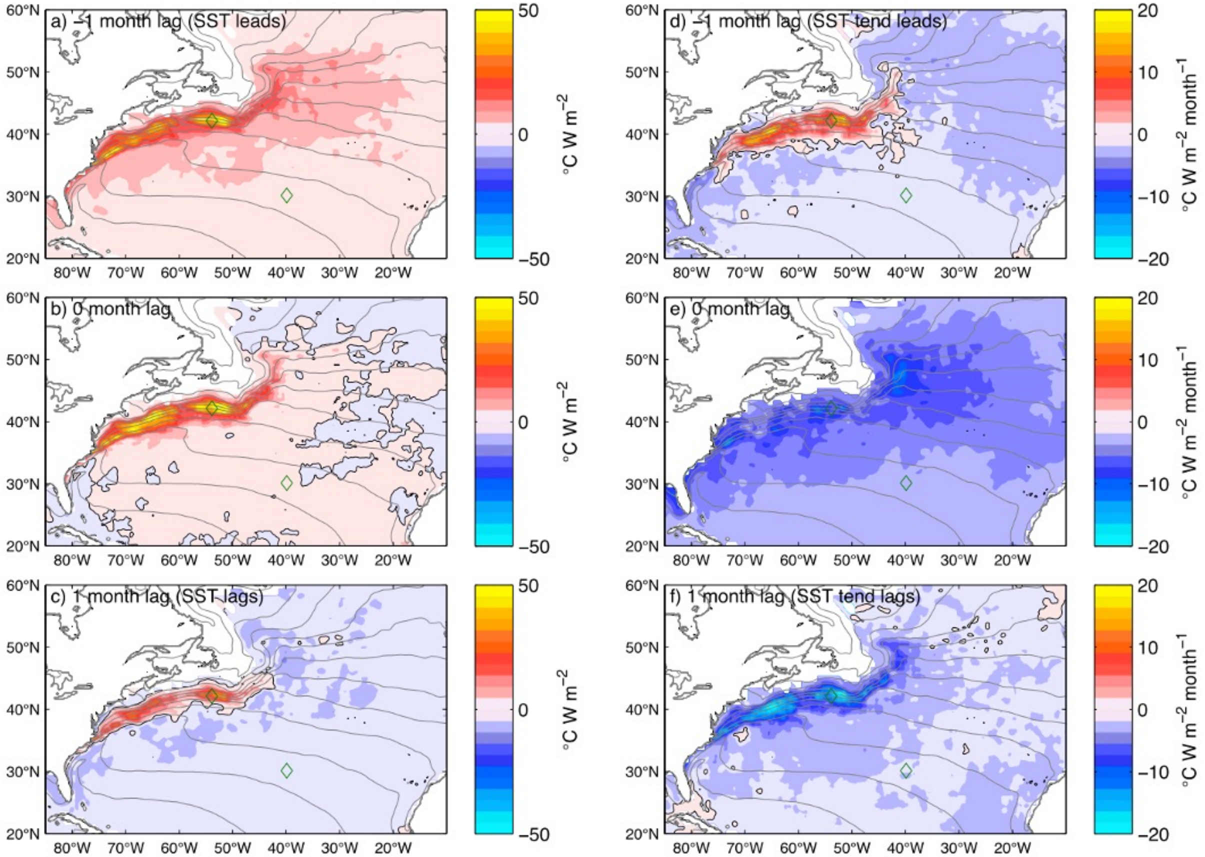
NOAA OISST (1/4^o), OAFLUX(1^o) products

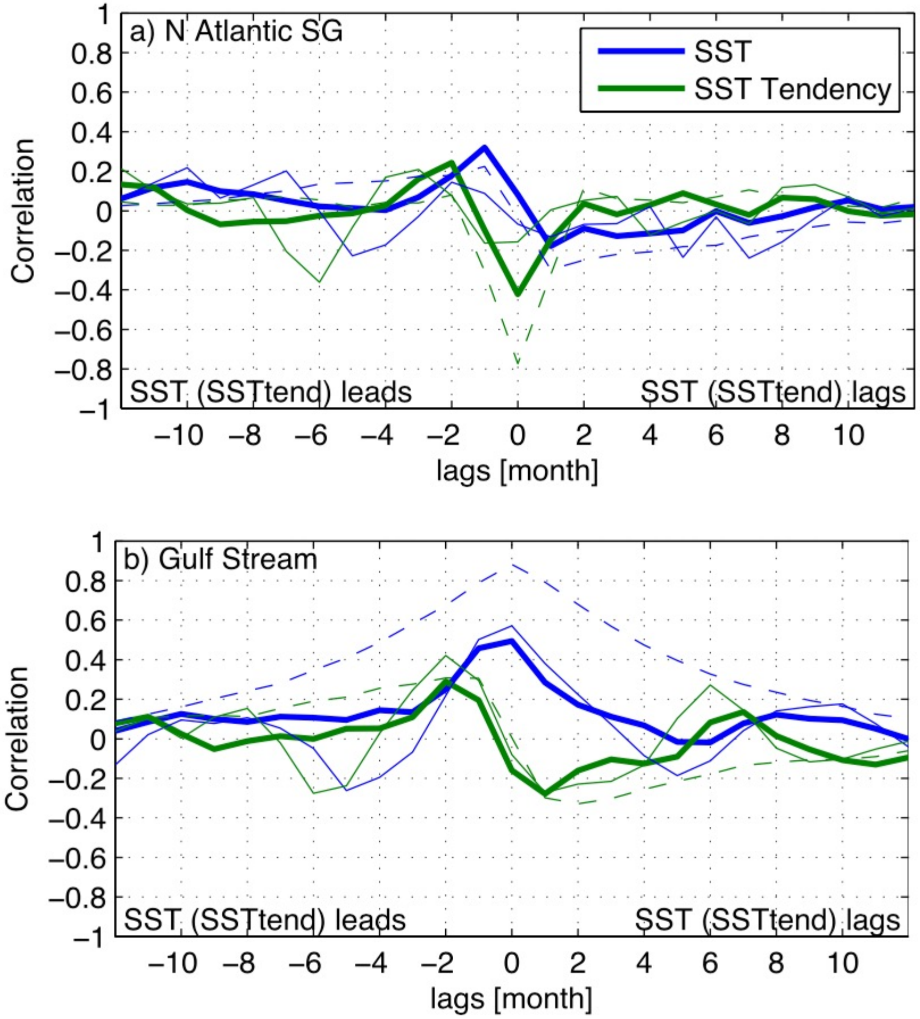
Figures from Bishop et al. (2017)

North Atlantic

SST-SHF covariance

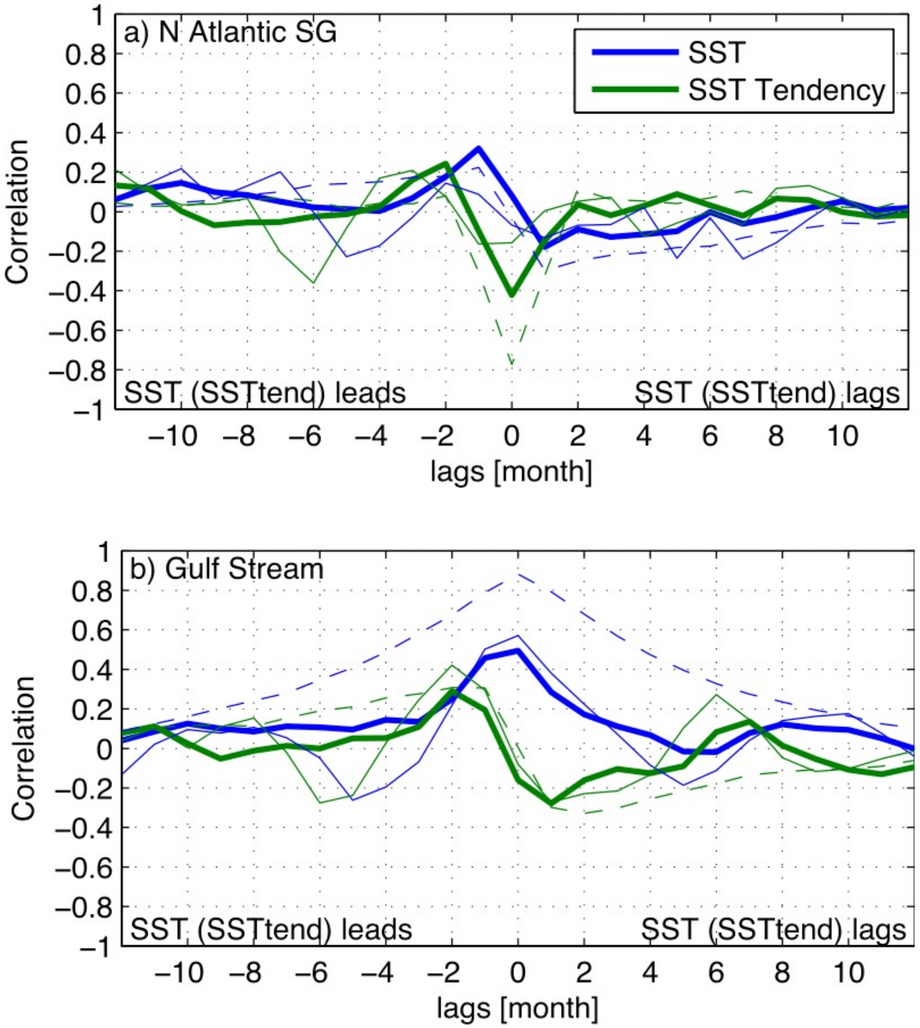
SST tendency -SHF covariance





Figures from Bishop et al. (2017)

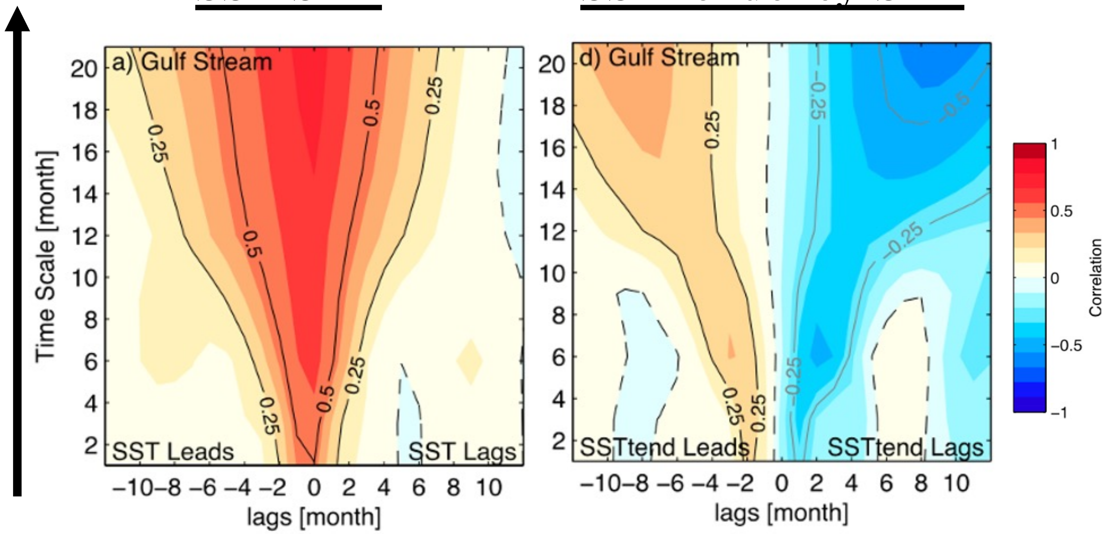
These relationships are dependent on both the spatial and temporal scale



Increasing *temporal* scale

SST-SHF

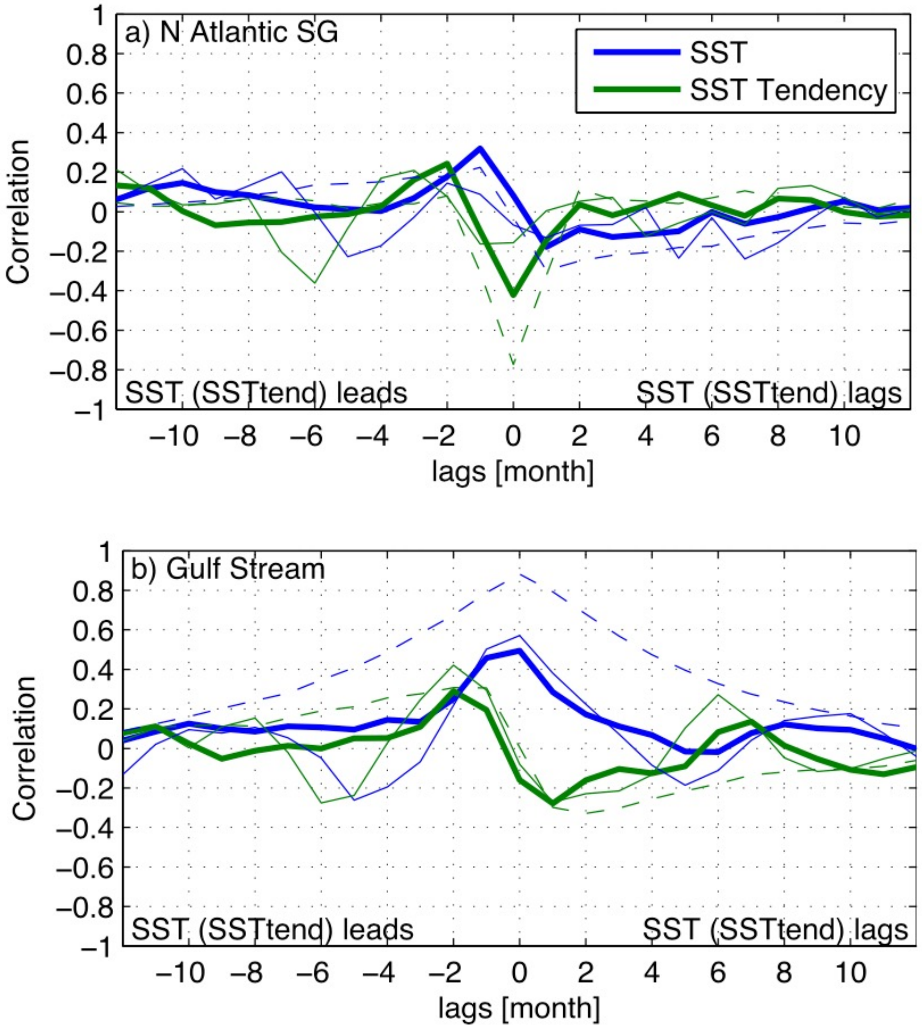
SST tendency-SHF



Longer time-scale transitions into ocean-driven regime

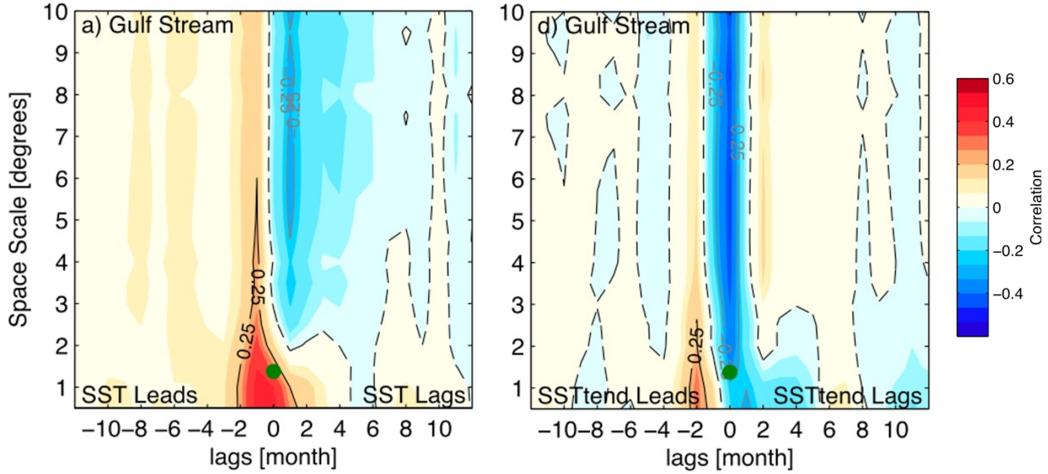
Figures from Bishop et al. (2017)

These relationships are dependent on both the spatial and temporal scale



Increasing *__spatial__* scale

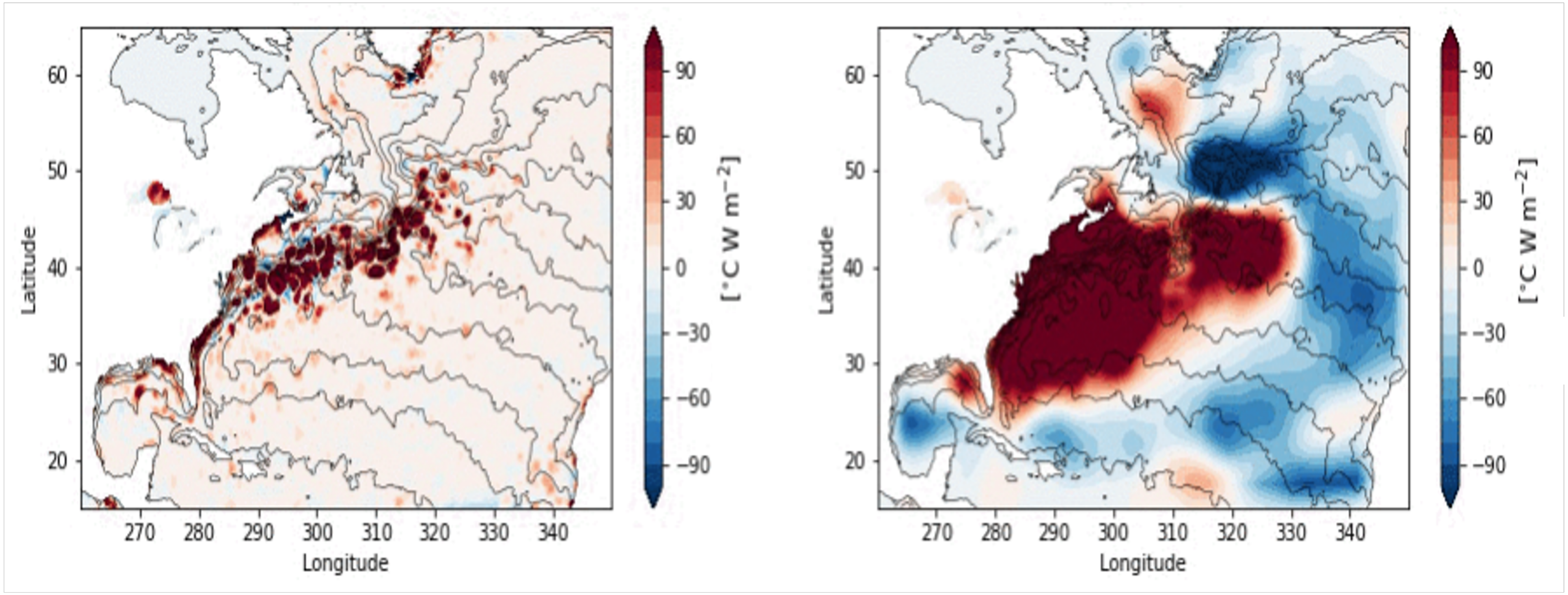
__SST-SHF__ **__SST tendency-SHF__**



__Shorter spatial-scale__ transitions into ocean-driven regime

__Figures from Bishop et al. (2017)__

Q’T’ – Latent heat flux, SST co-variability
Daily Snapshots, January – March 2009, J-OFURO3 product



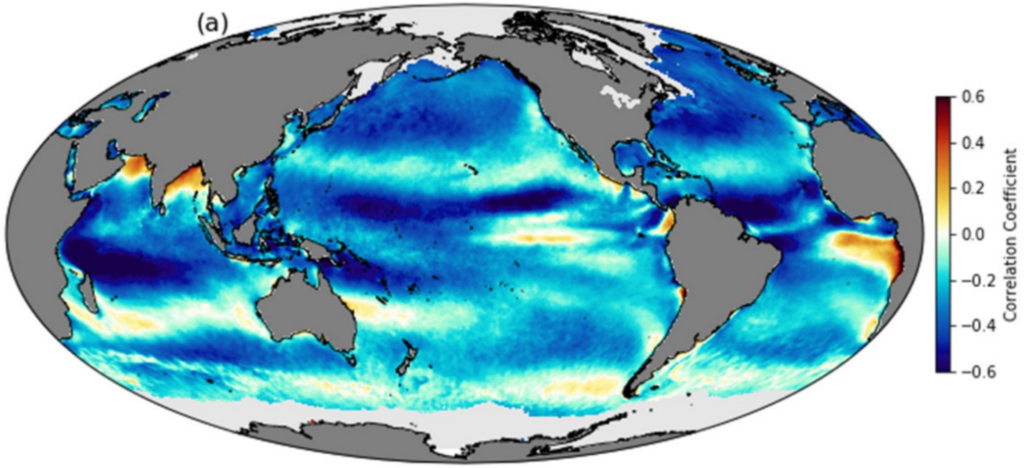
Ocean mesoscale (< 500km)

Synoptic scale

<u>Animation courtesy of Stuart Bishop</u>

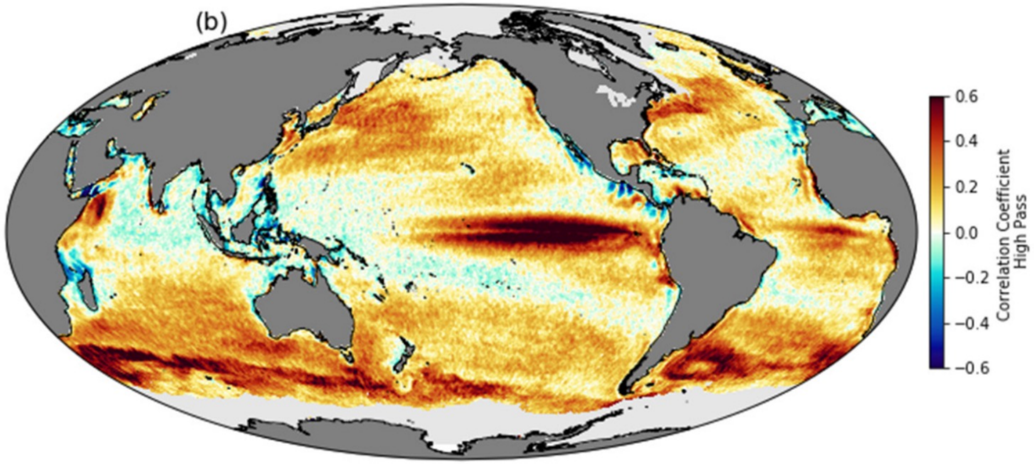
Daily correlation between wind speed and SST

QuikScat, NOAA OISST (25km gridded).
Gentemann et al., 2020



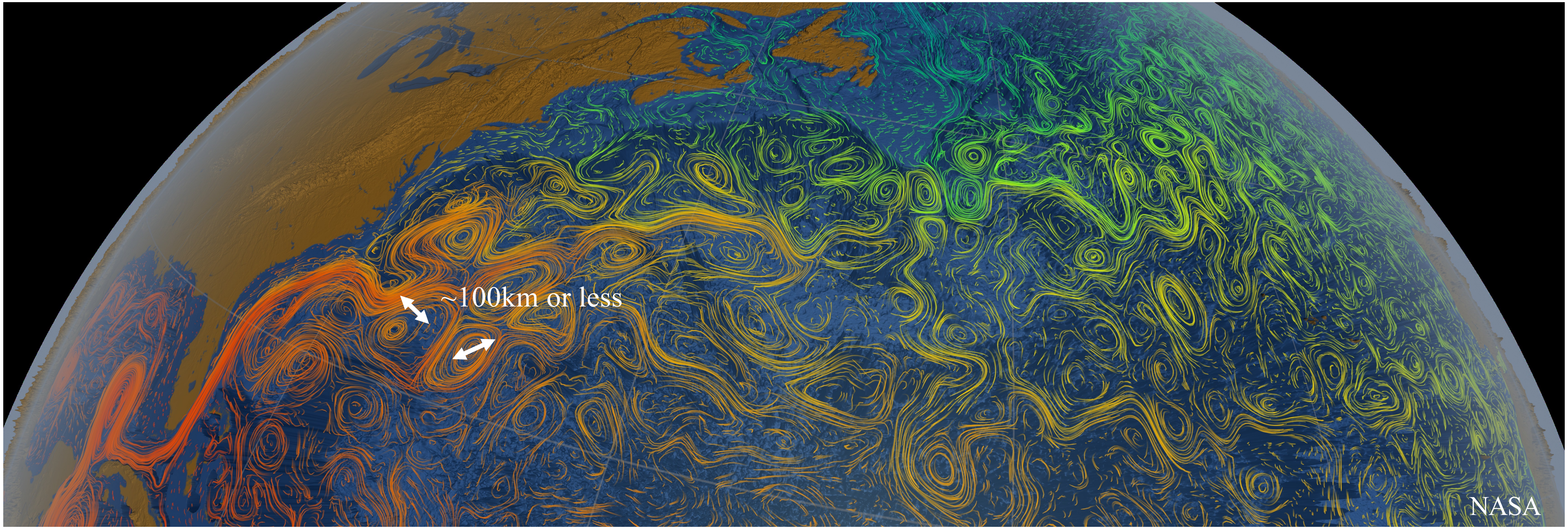
Negative correlation – increase in wind speed reduces SST by enhancing ocean-atmosphere heat flux / mixing warm surface water with cooler waters below

With 1000km high-pass filter applied

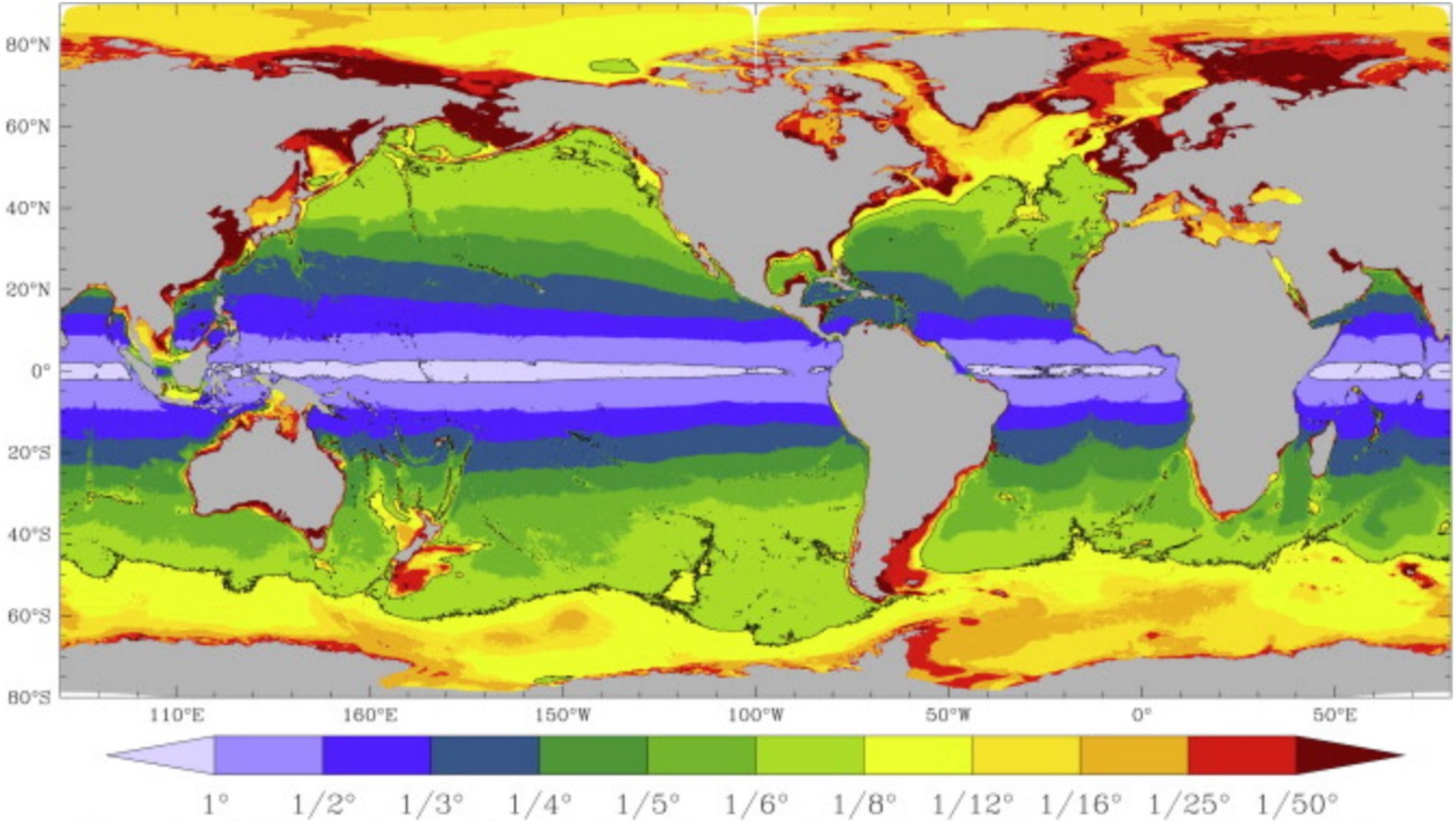


Positive correlation – increase in SST increases vertical mixing of momentum in atmosphere, drawing stronger winds from aloft

Western boundary currents - energetic fronts and mesoscale eddies



Resolution required to resolve first baroclinic deformation radius with 2Δx



Hewitt et al. (2017)

Climate model CCSM 4.0, eddy-resolving (~10km) ocean vs. parameterized (~100km)

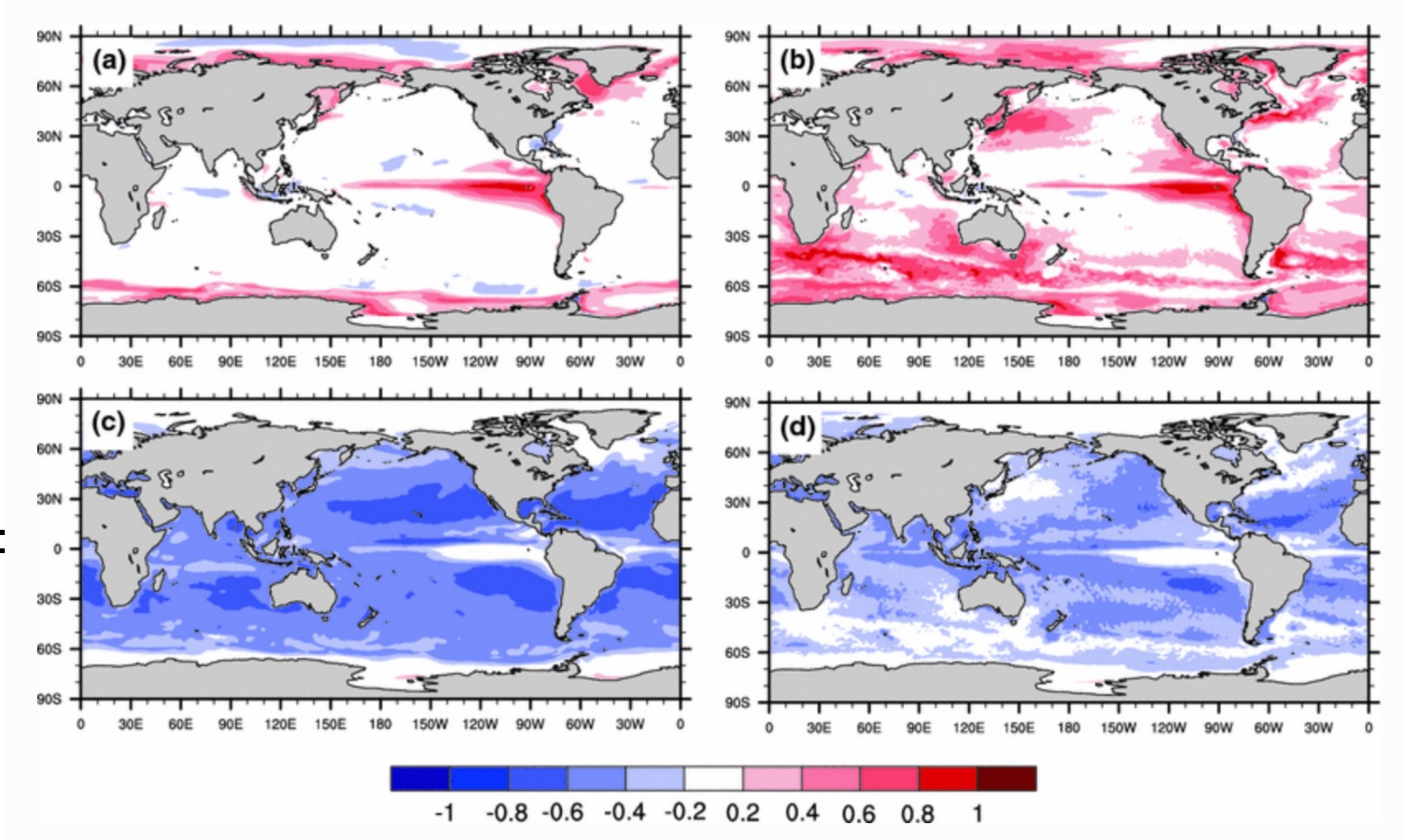
Simultaneous Correlations

Low-resolution

High-resolution

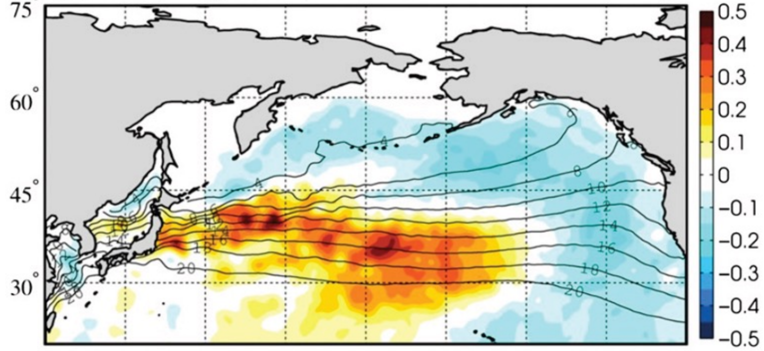
SST-SHF

SST tendency-SHF

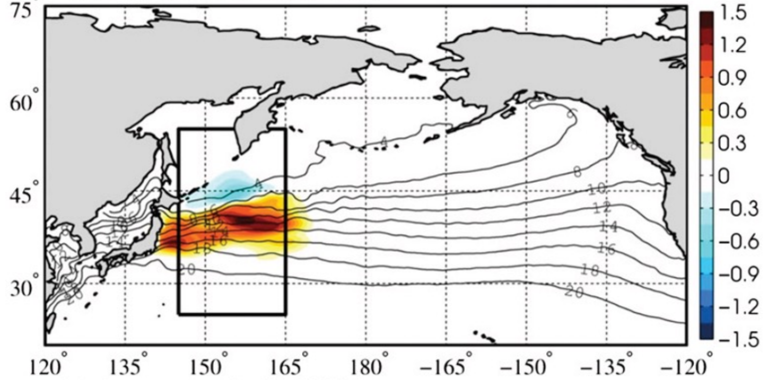


Kirtman et al. (2012)

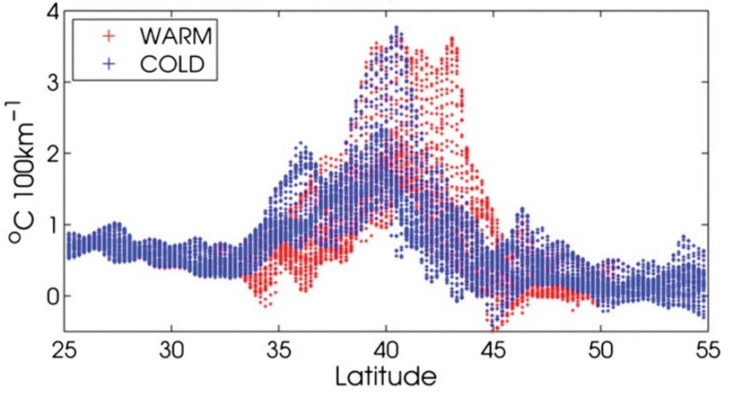
Resolving frontal and mesoscale variability in the extra-tropical ocean significantly changes the nature of air-sea interaction in the extra-tropics – why?



(a) OEI SST regression, Nov–Mar



(b) SST anomaly for model



(c) Across-front −1*dSST/dy

(top) Regression of monthly SST anomalies onto the Oyashio Extension Index of Frankignoul et al. (2011), Nov-Mar 1982-2008

(middle) Regression after filter application to remove basin-wide signal that may reflect SST response to atmosphere

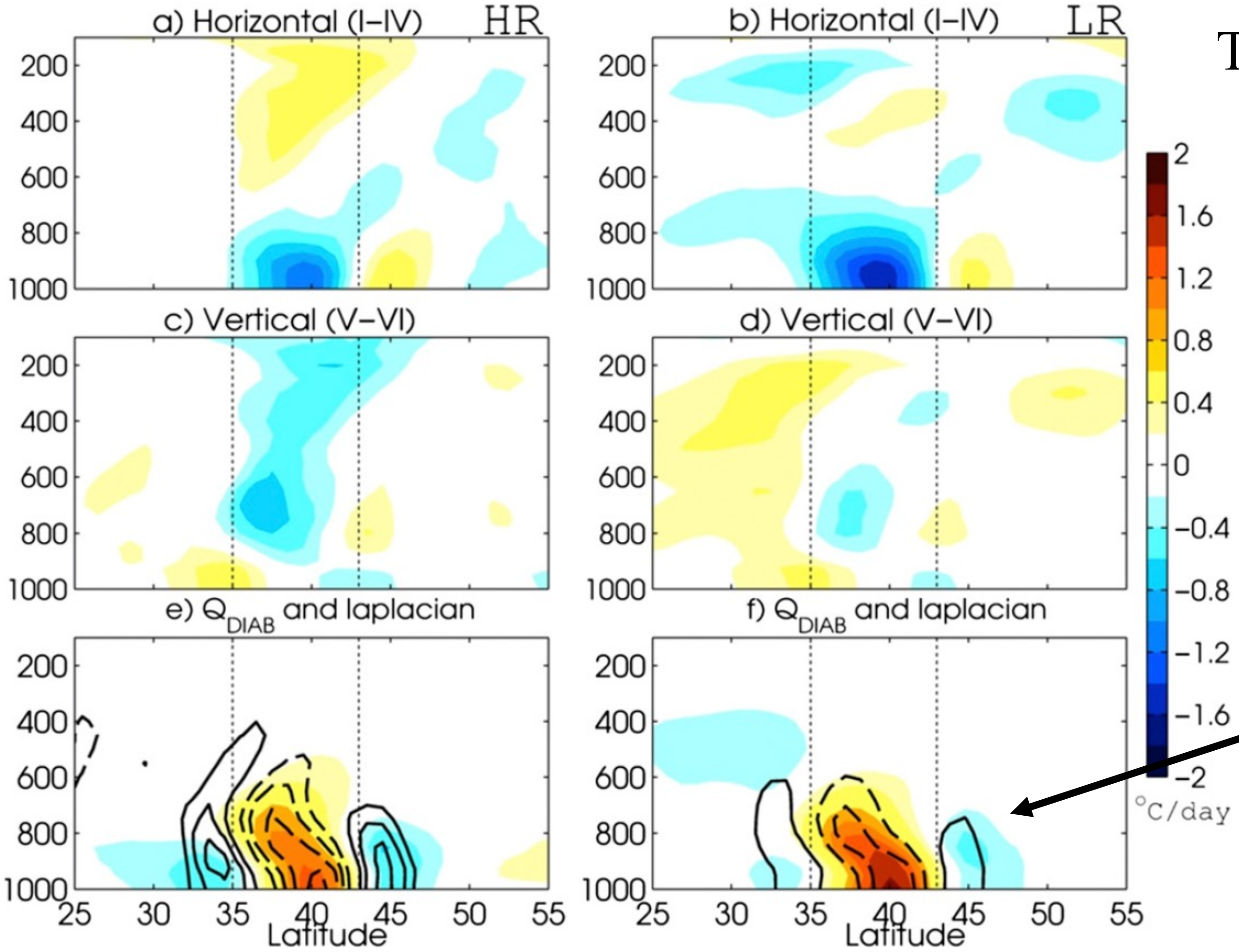
Prescribed SST experiments, 25-member ensemble, CAM5; 0.25^{o} and 1^{o},1st November – 31st March

- 1982-2011 monthly average SST (NOAA OISST)
- Addition of anomaly *(warm phase)*
- Subtraction of anomaly *(cold phase)*

(bottom) Scatter of point-by-point $-d$(SST)/dy from 145° to 165°E as a function of latitude (dots) for the "warm" (red) and "cold" (blue) experiments.

From Smirnov et al. (2015)

Difference between warm and cold experiments in HR and LR



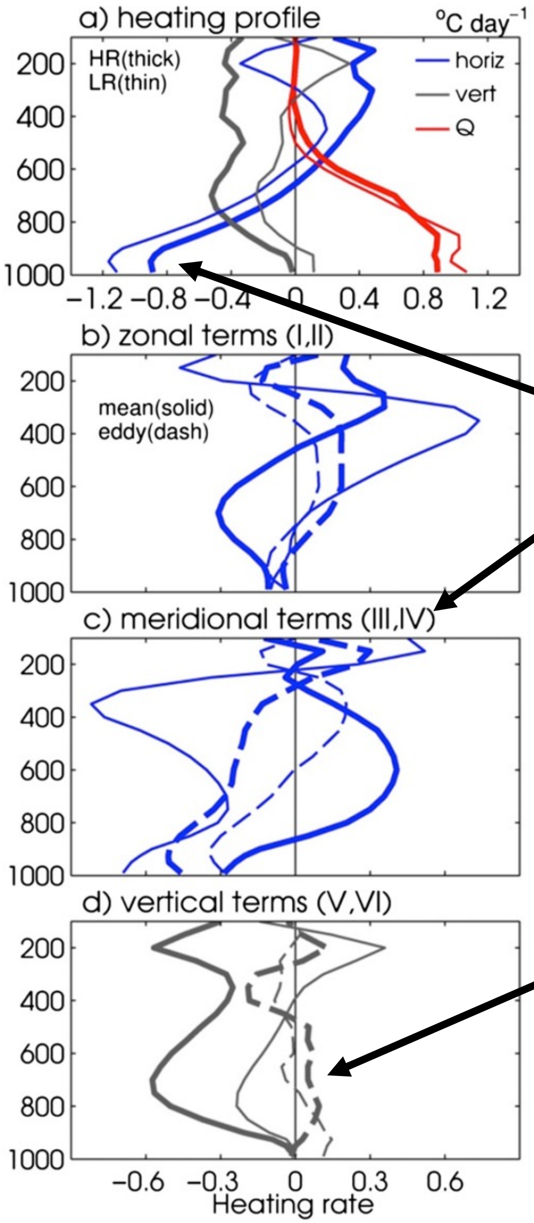
From Smirnov et al. (2015)

Time-mean thermodynamic equation

$$\underset{\text{I}}{\overline{u}\frac{\partial \overline{T}}{\partial x}} + \underset{\text{II}}{\frac{\partial}{\partial x}\overline{u'T'}} + \underset{\text{III}}{\overline{v}\frac{\partial \overline{T}}{\partial y}} + \underset{\text{IV}}{\frac{\partial}{\partial y}\overline{v'T'}}$$

$$+ \underset{\text{V}}{\left(\overline{\omega}\frac{\partial \overline{T}}{\partial p} - \frac{\kappa}{p}\overline{\omega}\,\overline{T}\right)} + \underset{\text{VI}}{\left(\overline{\omega'\frac{\partial T'}{\partial p}} - \frac{\kappa}{p}\overline{\omega' T'}\right)} = \underset{\text{VII}}{\overline{\dot{Q}}},$$

Notice how profile of diabatic heating is almost the same between HR and LR in response to the SST anomaly



Averaged over region 35°-43°N, 145°-165°E

Compare:
Eddy heat flux divergence (*dashed*) and mean thermal advection (*solid*); HR (*thick*), LR (*thin*)

Near the surface the meridional heat transport terms largely balance $\bar{\dot{Q}}$, however…

For LR, the mean transport dominates the eddy transport

For HR, the eddy transport is about 60% larger than the mean transport and has much greater vertical extent

Also note large difference in vertical transport at mid-levels due to mean ω circulation

→Horizontal eddy transports (lower troposphere) and strong vertical motion (middle troposphere) much more important for balancing $\dot{Q}$ in HR than in LR

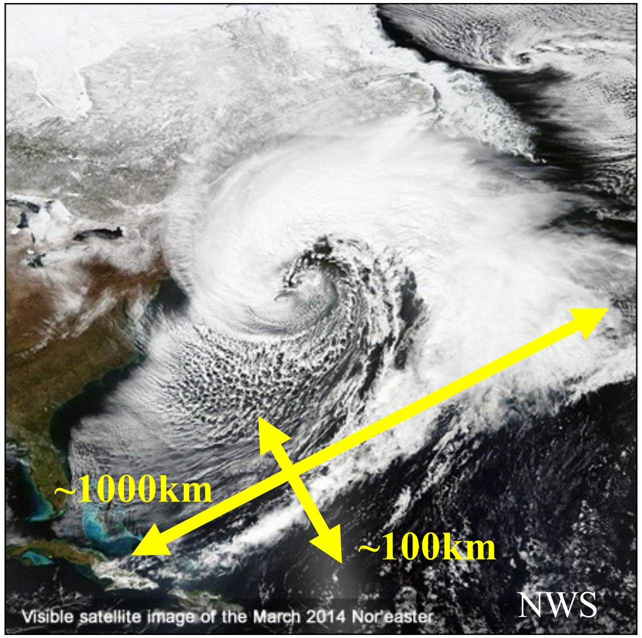
In other words:

At 1º —> Anomalous heating is balanced by **horizontal cold air advection**. This is what one expects from linear dynamics (traditional paradigm - Hoskins and Karoly, 1981).

At 0.25º —> The forcing is instead balanced by **transient eddy fluxes**.

This is a new paradigm where the atmospheric eddies and ocean can "see" each other…

What atmospheric and ocean features scale match at ~ 0.25º?



Tropical vs. extra-tropical:

- Tropical SST anomalies reach free troposphere more easily than extra-tropical anomalies due to more significant role of vertical advection
- Response to tropical SST anomalies much less sensitive to background climatology
- Mid-latitude SST anomalies exist in an environment with high internal variability
- Tropical SST anomalies persist much longer than extra-tropical SST anomalies

→ Tropical SSTs more important for seasonal predictability

However:

- “Passive paradigm” of extra-tropical ocean is likely a gross underestimation
- Direct extra-tropical oceanic forcing only truly revealed at resolutions high enough to resolve the oceanic mesoscale
- These resolutions allow the ocean to interact with atmospheric transients

How many studies looking at AMV have this resolution ?