Oceanic Drivers of Long-term Cooling in the Equatorial Pacific Cold Tongue

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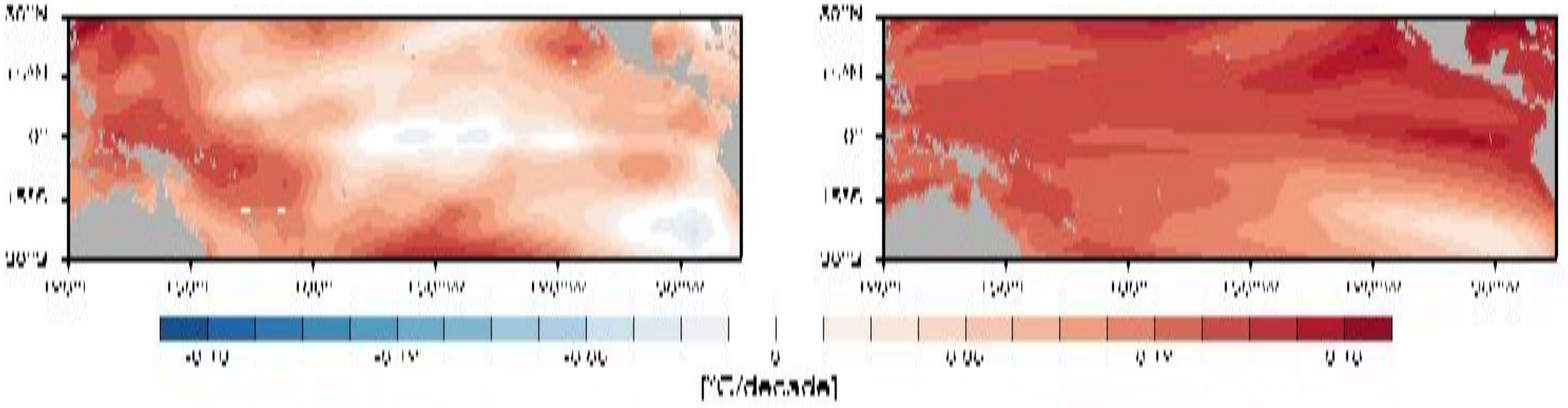
Tropical Pacific Warming Pattern:
A well-known OBS-Model Discrepancy

Observation

1958–2022 SST Trend
Composites of HadISST, ERSSTv5,
COBE and, and Kaplan

Model Simulations

1958–2022 SST Trend
Composites of 11 Large Ensemble Model
simulations with more than 10 members



Key Questions

1. How does the long-term cooling trend pattern in the tropical Pacific form in the real world?

2. Why do climate models generally fail to reproduce the real world?

3. How far are we from reaching a quantitative understanding of trend pattern formation?

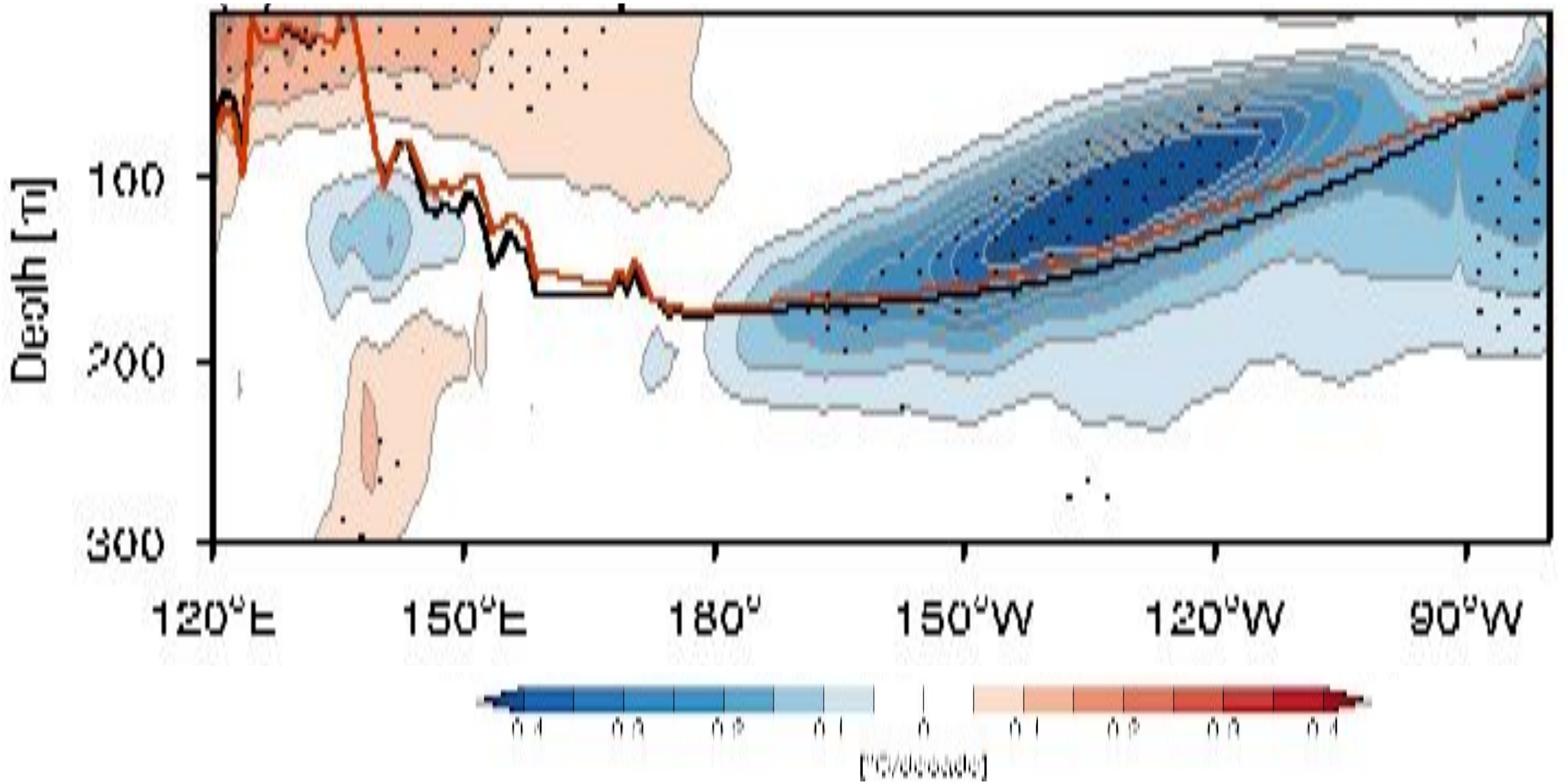
How does the forced climate change pattern in the tropical Pacific form in the real world?

– Not unexpected.

Wind-driven current and mixing change

Subsurface Cooling Powers the Lack of Surface Warming

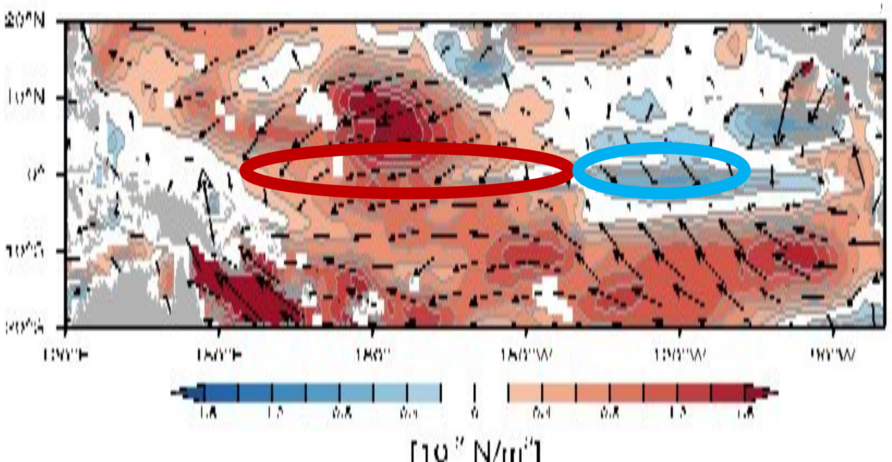
ORAS5 equatorial temperature trend during 1958-2022



Jiang et al., 2024a

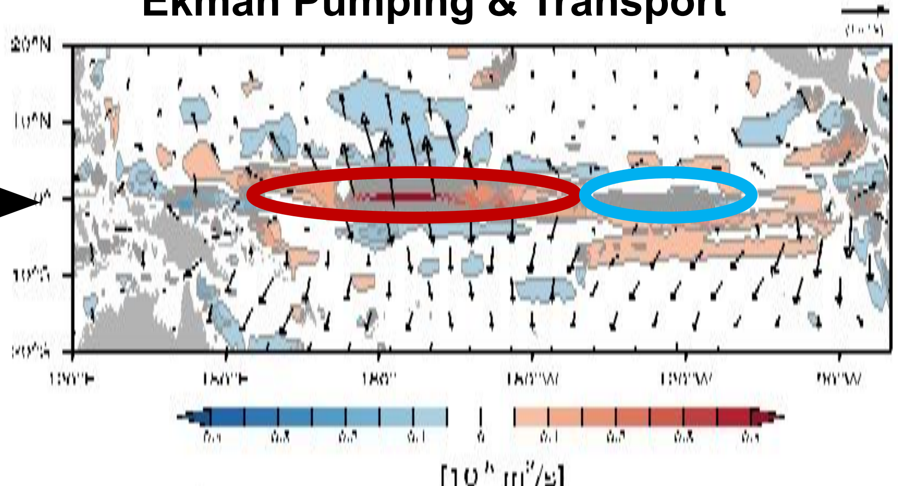
Wind-driven Ekman Pumping Response

Climate Change-related Wind Stress



Shading (surface wind stress magnitude)

Climate Change-related
Ekman Pumping & Transport



Shading (Ekman pumping change)

Ekman Transport (U_s, V_s)

$$U_s = (r_s\tau_x + \beta_s y\tau_y/(\rho(\beta_s{}^2y^2 + r_s{}^2))$$

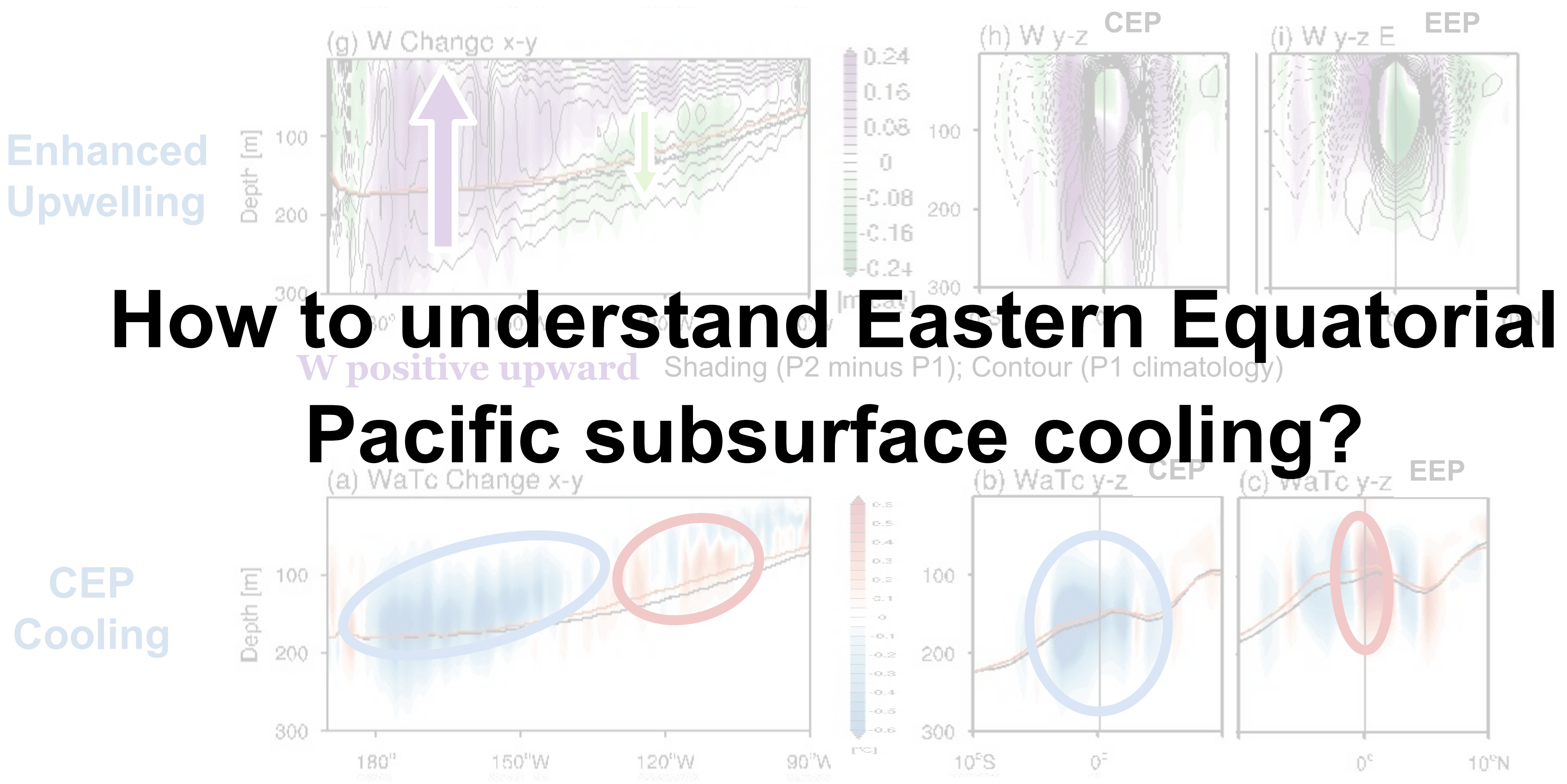
$$V_s = (r_s\tau_y - \beta_s y\tau_x)/(\rho(\beta_s{}^2y^2 + r_s{}^2))$$

r_s: *surface layer friction coefficient (0.5 day^{-1})*

Ekman Pumping (W)

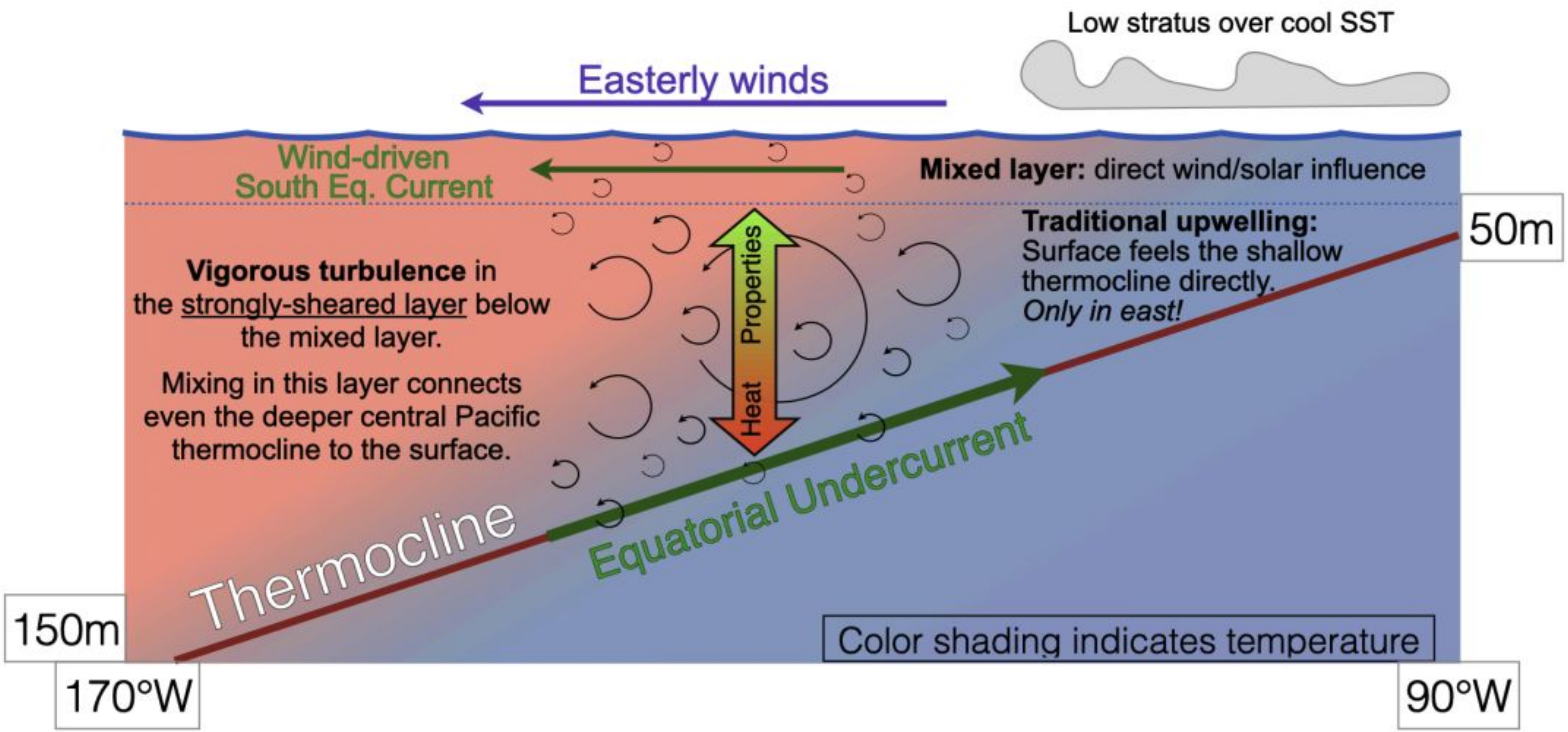
$$W = \frac{\partial U_s}{\partial x} + \frac{\partial V_s}{\partial y}$$

Central Equatorial Pacific (CEP): Enhanced Upwelling □ Cooling



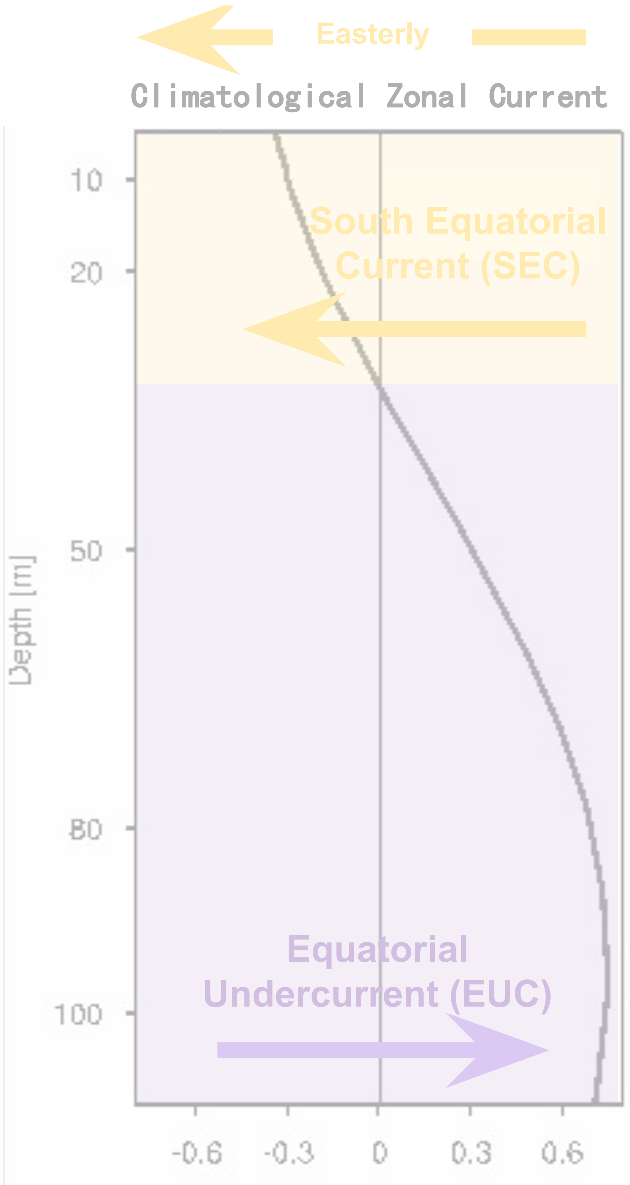
How to understand Eastern Equatorial Pacific subsurface cooling?

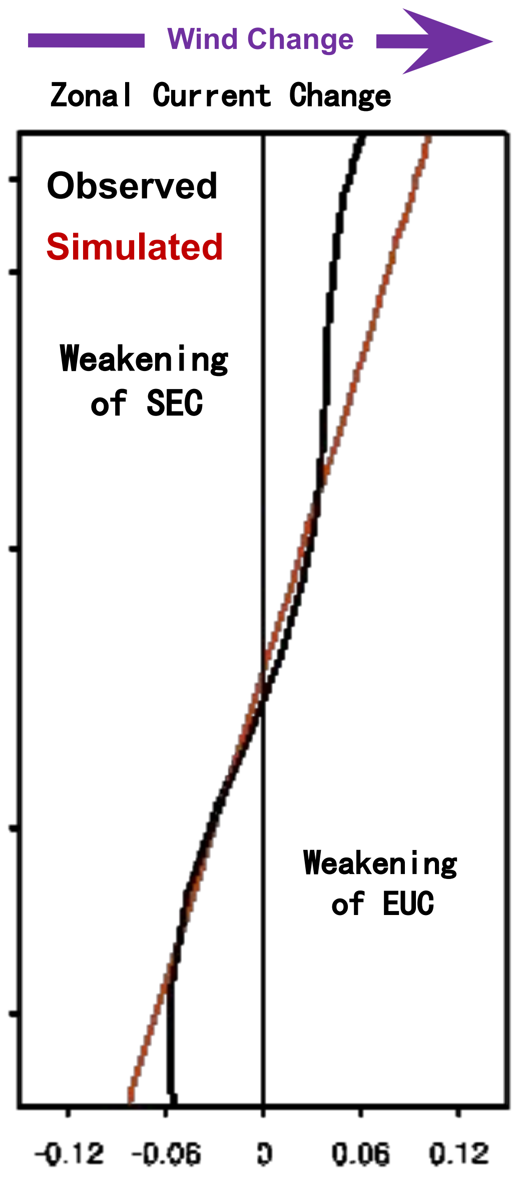
Eastern Equatorial Pacific (EEP): A Regime of Active Mixing



Upwelling and Mixing *(NOAA CVP TEPEX Science Plan)*

Eastern Equatorial Pacific (EEP): A Region of Active Mixing
Under Climate Change: Reduced Shear & Mixing





Under Historical Climate Change

Reduced Easterly

Weakening of SEC & EUC

Simulated by zeroth order model

Weakening of Current Shear $(\frac{\partial u}{\partial z})^2$

Increased Ri & Reduced Mixing

Less heat mixed down and

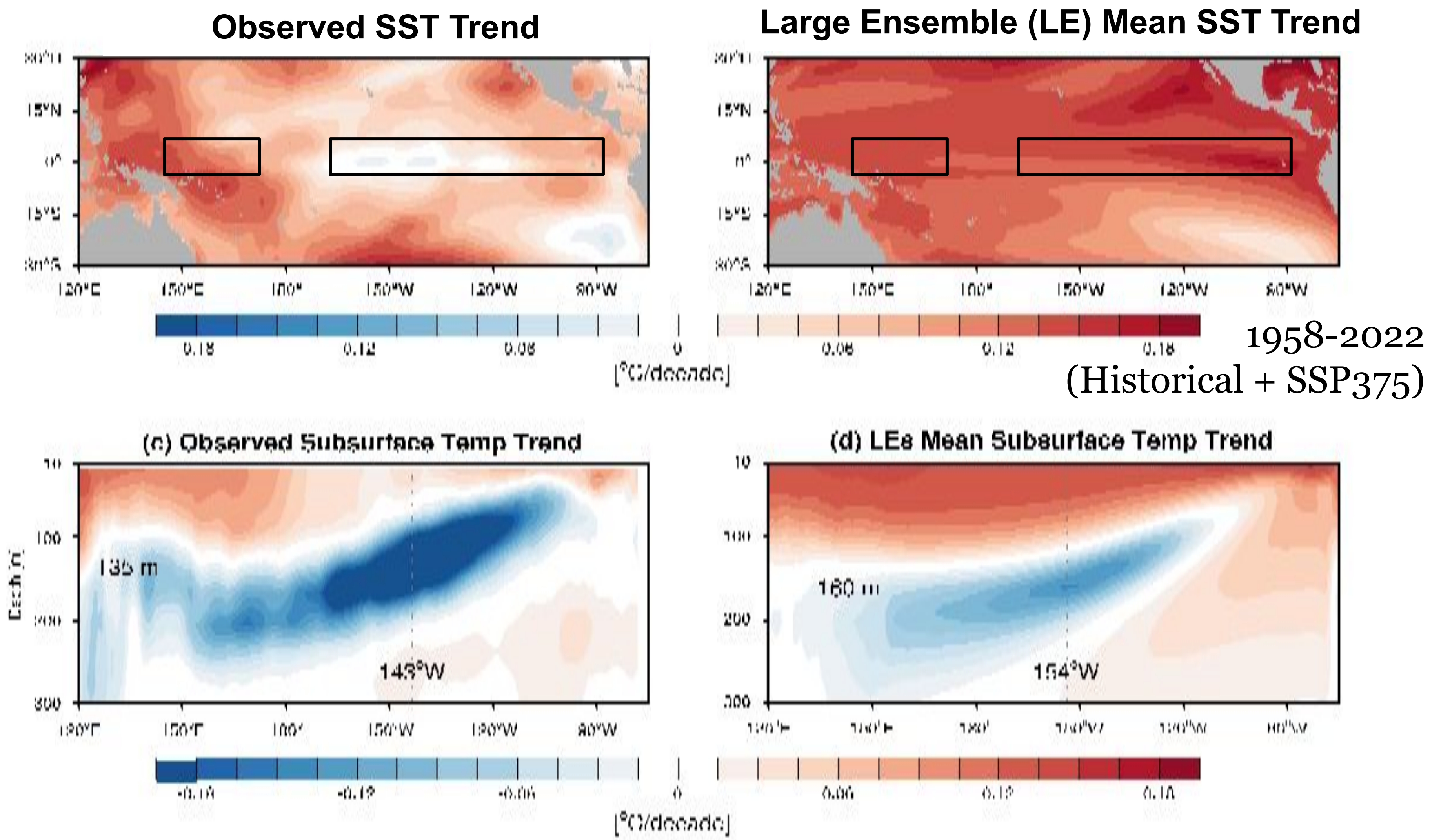
Subsurface Cooling

Why do climate models generally fail to reproduce the real world?

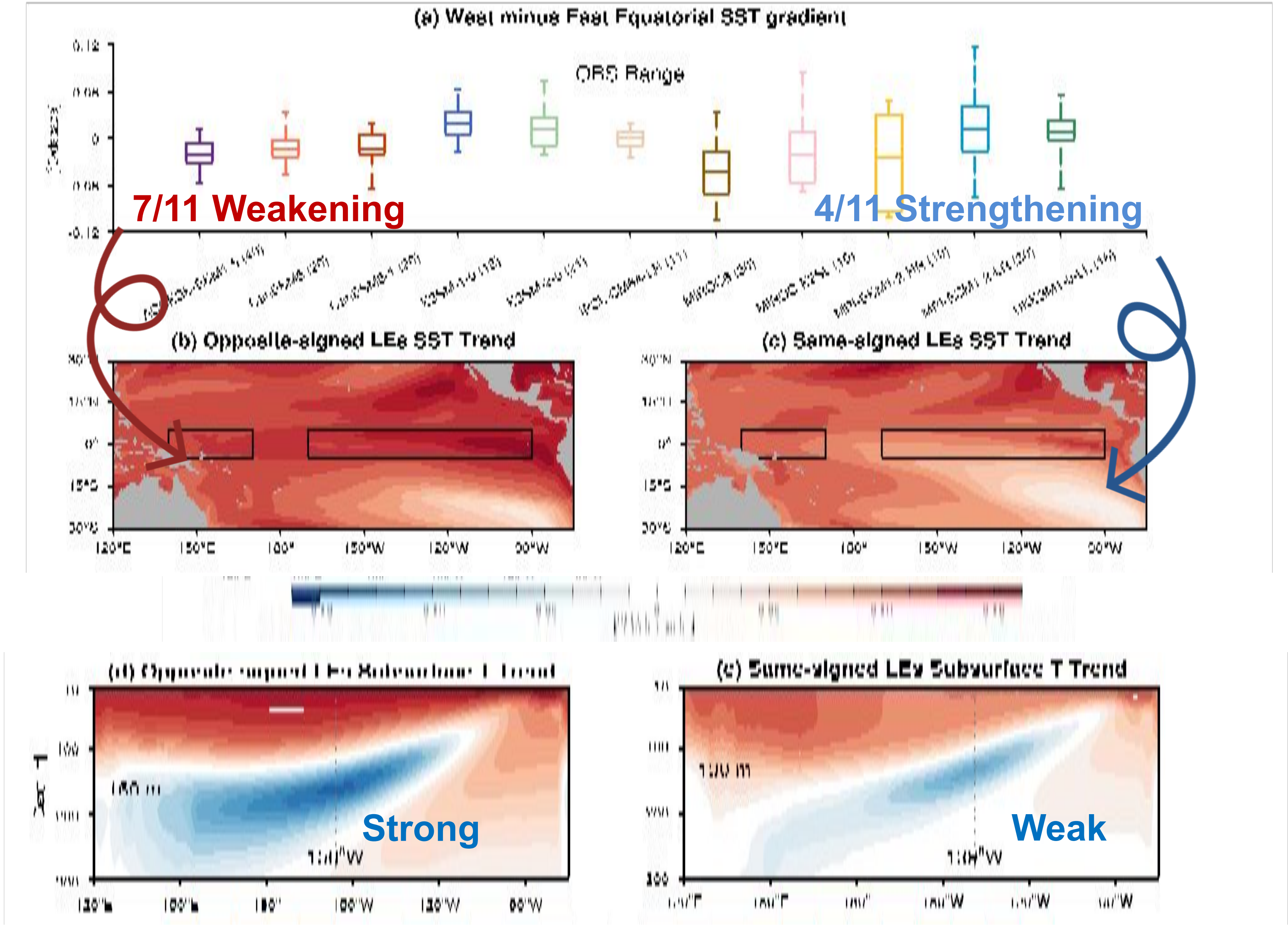
– **Weak subsurface signal cannot surface.**

Pacific Climate Change Pattern in Climate Models

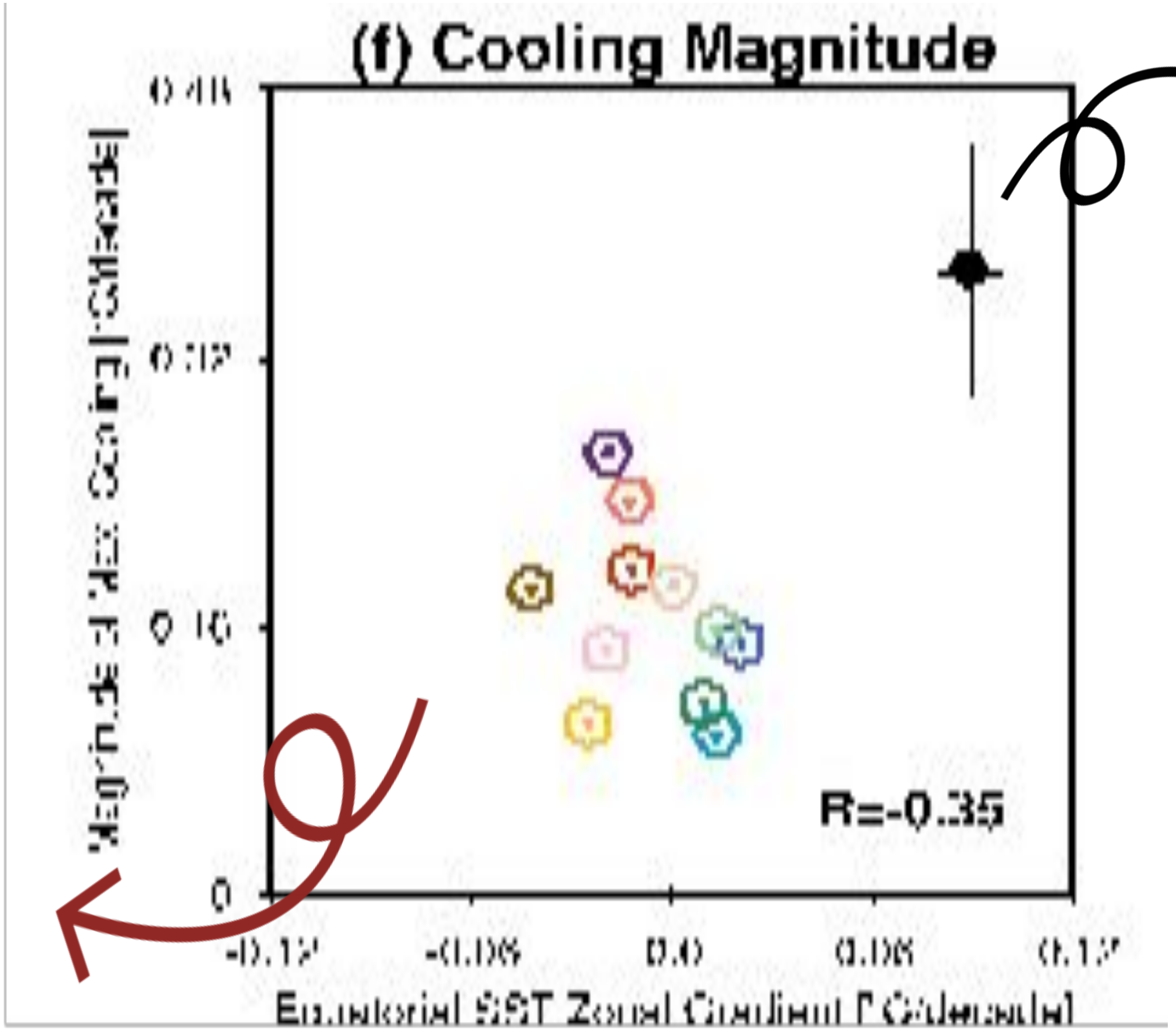
Subsurface cooling remains a prominent feature in model simulations despite distinct SST trend



Same-signed and Opposite-signed Models



A Systematic Underestimation of the Subsurface Cooling



Observation

CMIP6
LE Models

Subsurface Mixing Changes in LE Models and ORAs5

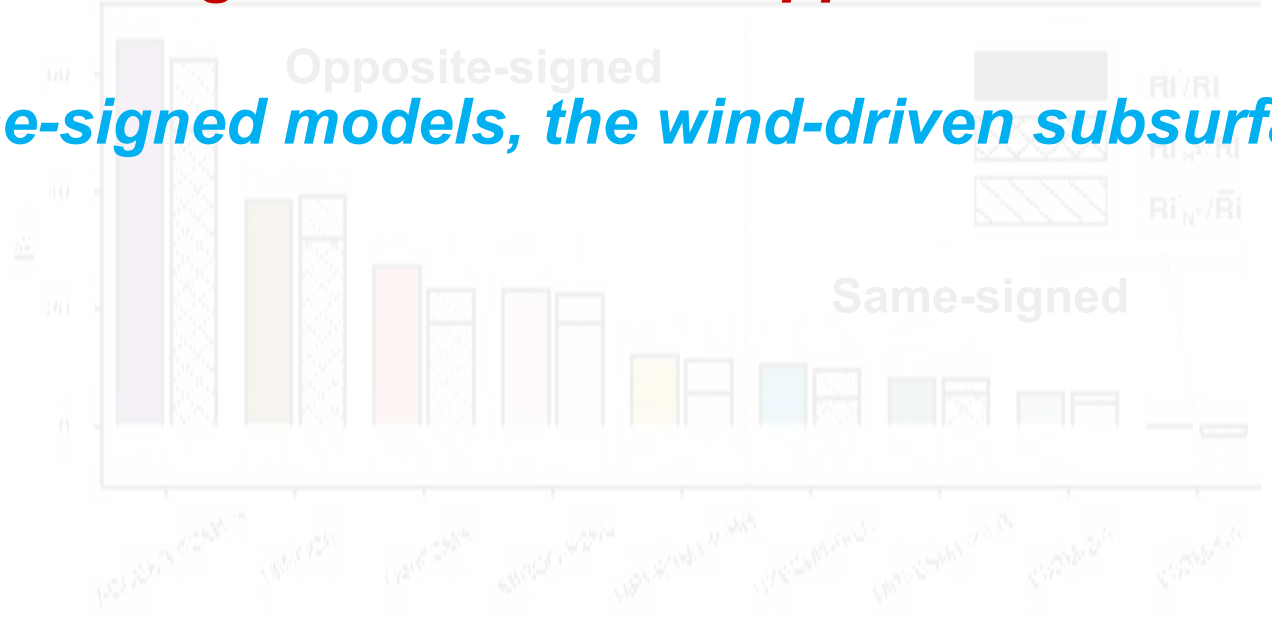
Quantifying upper ocean stability change based on Richardson number (0~250 m, 2°S~2°N, 150°E~90°W)

Why subsurface cooling doesn't just surface in models, especially in opposite-signed models?

$$Ri'/\overline{Ri} = Ri'_{N^{2\prime}}/\overline{Ri} + Ri'_{S^{2\prime}}/\overline{Ri} + \text{Residual}$$

Buoyancy-driven Shear-driven

- ***For opposite-signed models, the upper ocean stability significantly increase***
- ***For same-signed models, the wind-driven subsurface cooling is TOO weak.***

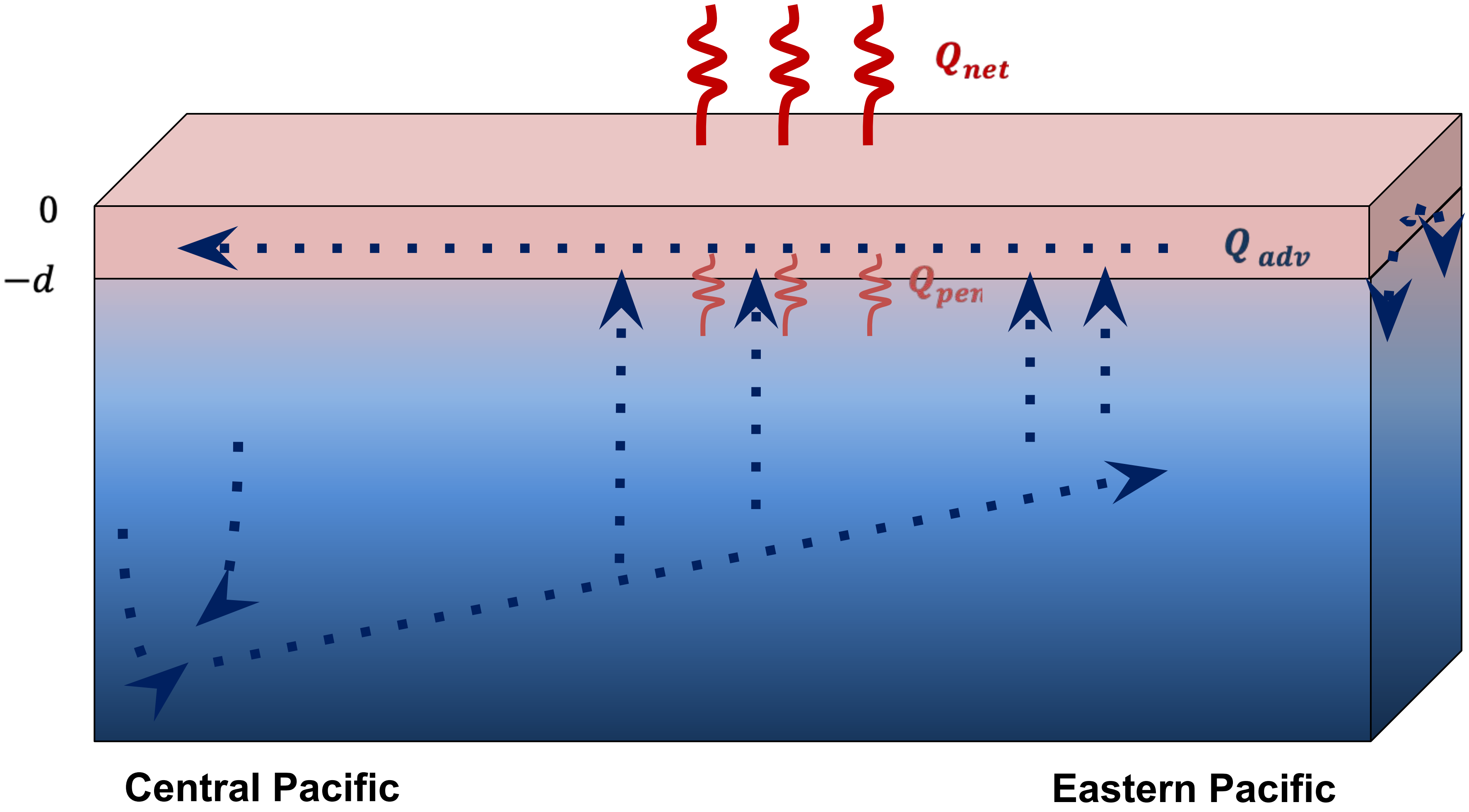


How far are we from reaching a quantitative understanding of trend pattern formation?

– Very far, at least when it comes to the the real world

Surface Layer Budget in Equatorial Pacific

Surface Layer Heat Budget $\frac{1}{d}\int_{-d}^{0}\left(\frac{\partial T}{\partial t}\right)dz = Q_{net} - Q_{pen} + \frac{1}{d}\int_{-d}^{0}(Q_{adv})dz + Q_{res}$



Challenges in Quantifying Heat Budget

Surface Layer Heat Budget

$$\frac{1}{d}\int_{-d}^{0}\left(\frac{\partial T}{\partial t}\right)dz = Q_{net} - Q_{pen} + \frac{1}{d}\int_{-d}^{0}(Q_{adv})dz + Q_{res}$$

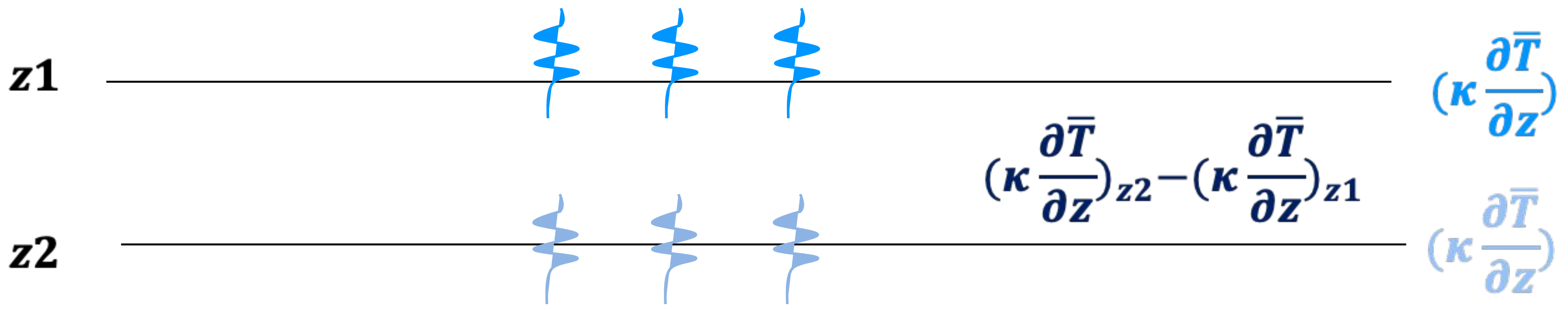
Mixing term is usually NOT resolved & NOT archived.

But we can estimate it, especially in regions with strong turbulence like the equatorial Pacific.

Quantifying Vertical Mixing

- **Turbulent heat flux can be parameterized as gradients of large-scale quantities:**

$$\overline{T'w'} = \kappa \frac{\partial \overline{T}}{\partial z} \qquad \kappa\text{: } \textit{Eddy diffusivity}$$

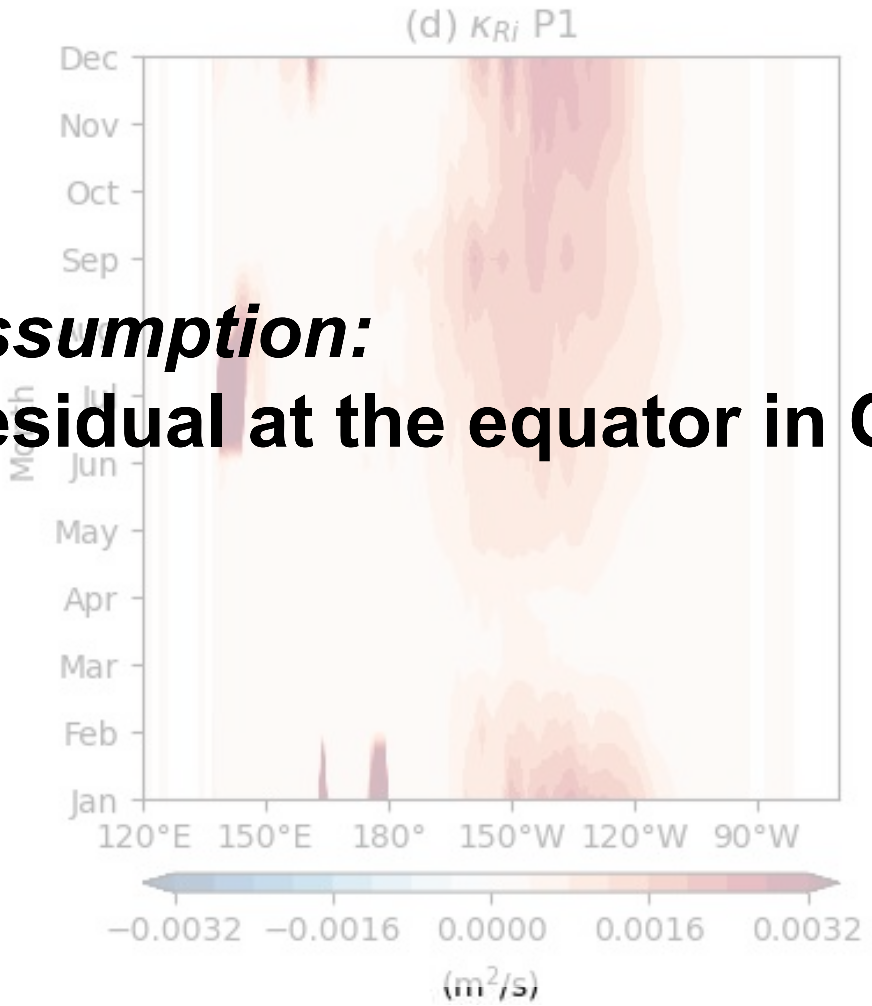


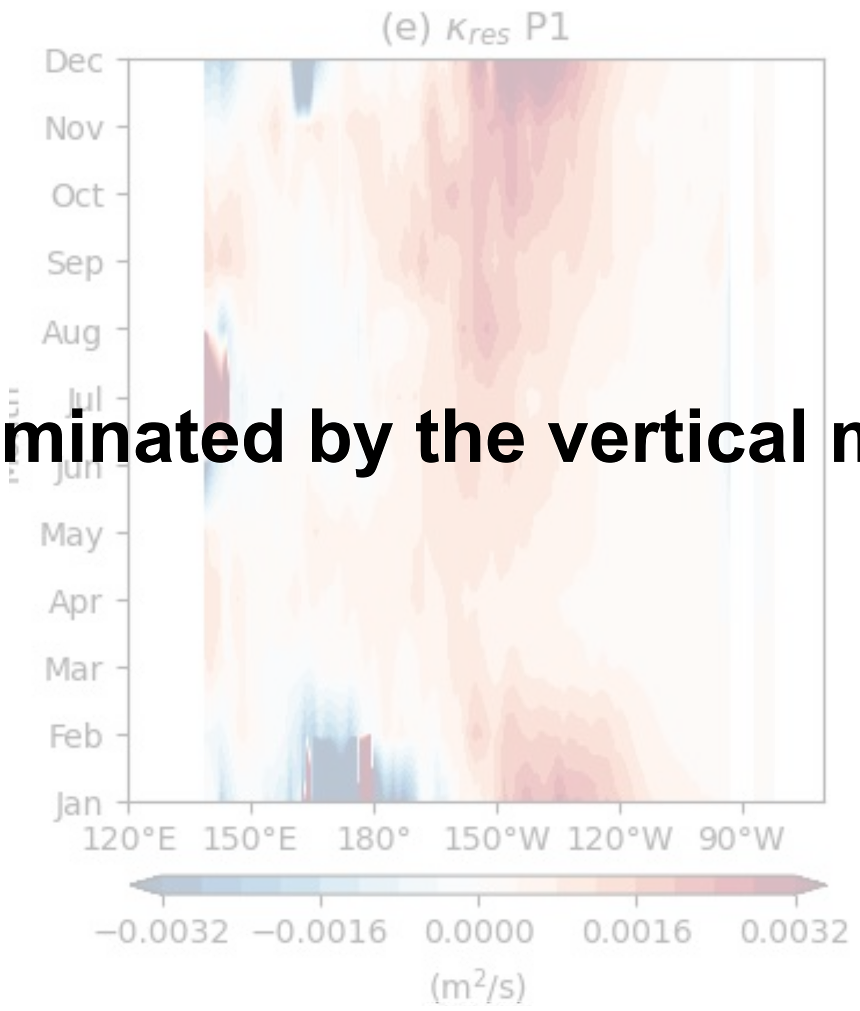
For the surface layer (-*d; d*=50 *m*), vertical diffusion (Q_{diffu}) can be inferred:

$$Q_{diffu} = -\frac{1}{d}\left(\kappa \frac{\partial T}{\partial z}\right)\Bigg|_{-d}$$

Quantifying Vertical Mixing

- **Parameterizing eddy diffusivity based on local Richardson number**
- **Inferring eddy diffusivity based on residual term**





Assumption:

Residual at the equator in ORAS5 is dominated by the vertical mixing

Challenges in Interpreting Heat Budget

Surface Layer Heat Budget on Climate Change Timescales

$$\frac{1}{d}\int_{-d}^{0}\left(\frac{\partial T}{\partial t}\right)dz = Q_{net} - Q_{pen} + \frac{1}{d}\int_{-d}^{0}(Q_{\,adv})dz + Q_{res}$$

$$\left(Q_{net} - Q_{pen} + \frac{1}{d}\int_{-d}^{0}(Q_{\,adv})dz + Q_{res}\right)Trend$$

$$\left(\frac{1}{d}\int_{-d}^{0}\left(\frac{\partial T}{\partial t}\right)dz\right)Tren$$

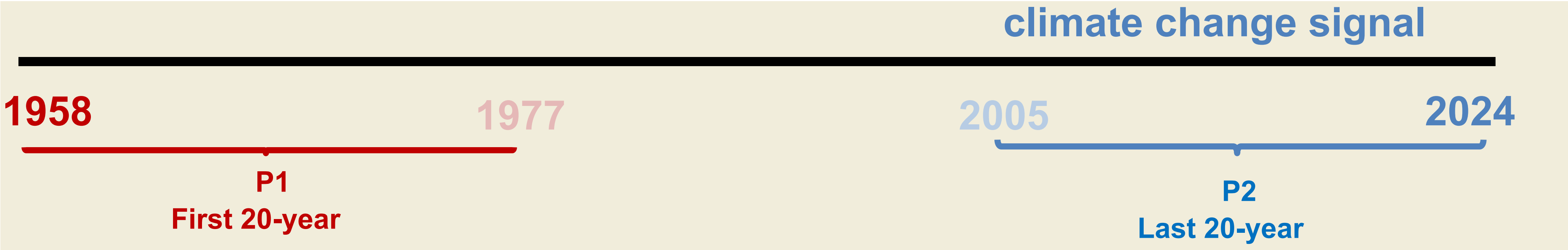
$$\frac{\left(\frac{\partial T}{\partial t}\right)P2 - \left(\frac{\partial T}{\partial t}\right)P1}{P2 - P1}$$

Second Derivative of Temperature

Alternative Approach

For a period that the climate change signal has not explicitly emerged $\overline{\frac{\partial T}{\partial t}}_{P1} \approx 0$

(1) We got a heat balance among individual terms



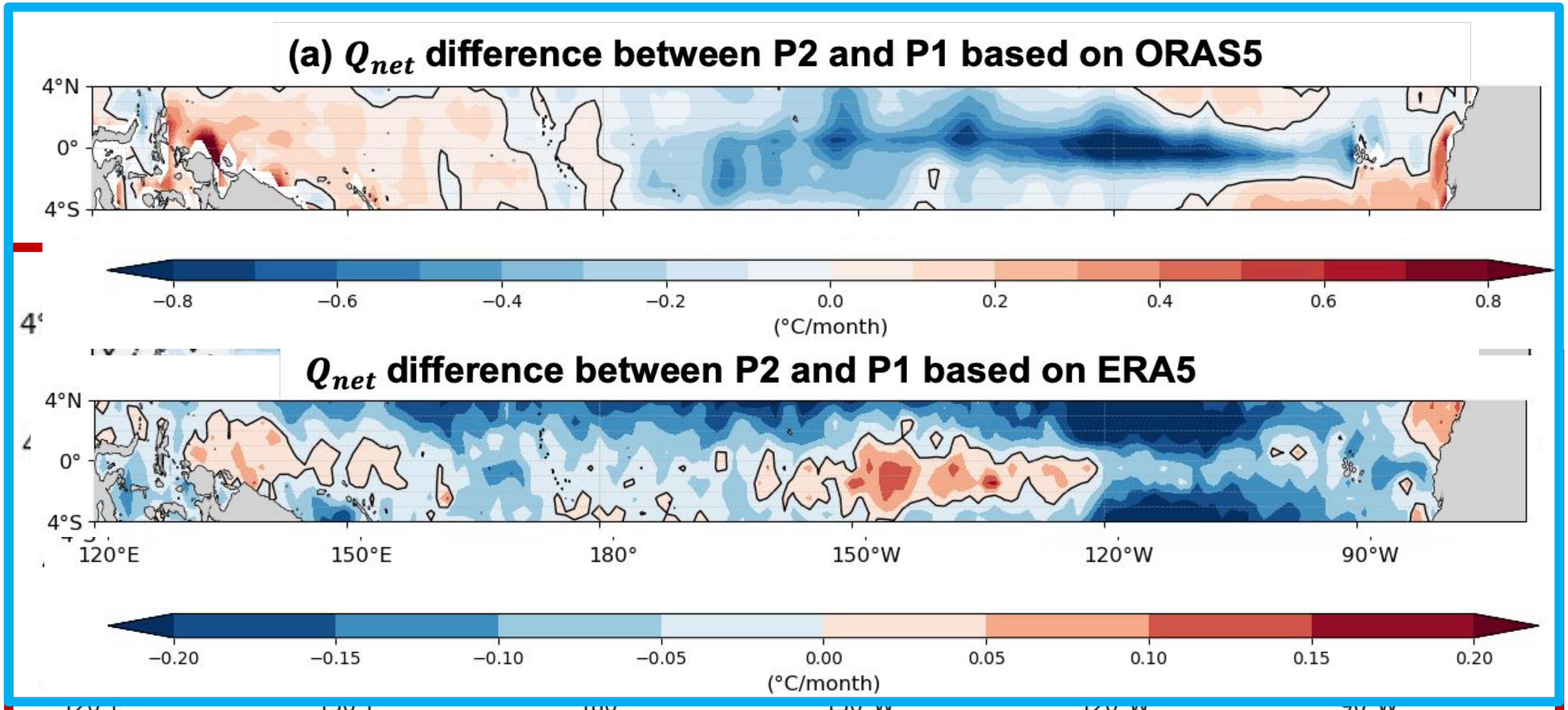
(2) By comparing the change in different terms between these two periods, we got to know what changes cause the temperature change

$$\overline{\frac{\partial T}{\partial t}}_{P2} \approx \overline{\frac{\partial T}{\partial t}}_{P2} - \overline{\frac{\partial T}{\partial t}}_{P1}$$

$$= \overline{Q_{net} - Q_{pen}}_{P2} - \overline{Q_{net} - Q_{pen}}_{P1} + \overline{\frac{1}{d}\int_{-d}^{0}(Q_{adv})dz}_{P2} - \overline{\frac{1}{d}\int_{-d}^{0}(Q_{adv})dz}_{P1} + \overline{Q_{res}}_{P2} - \overline{Q_{res}}_{P1}$$

Changes in Heat Budget Terms

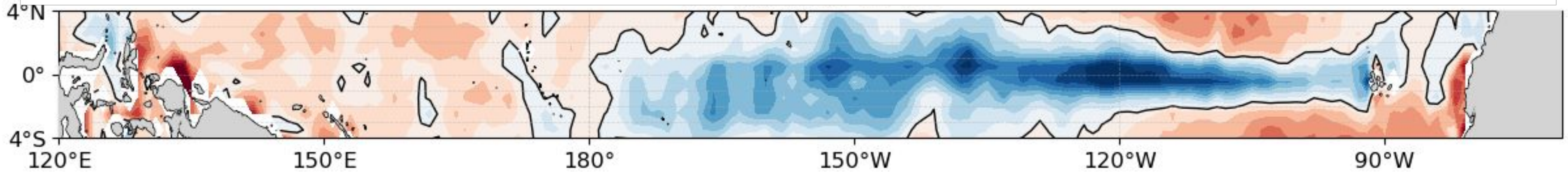
- Decrease in Q_{net} contribute to the cooling rate while it's balanced by warming rate due to residual Q_{res}



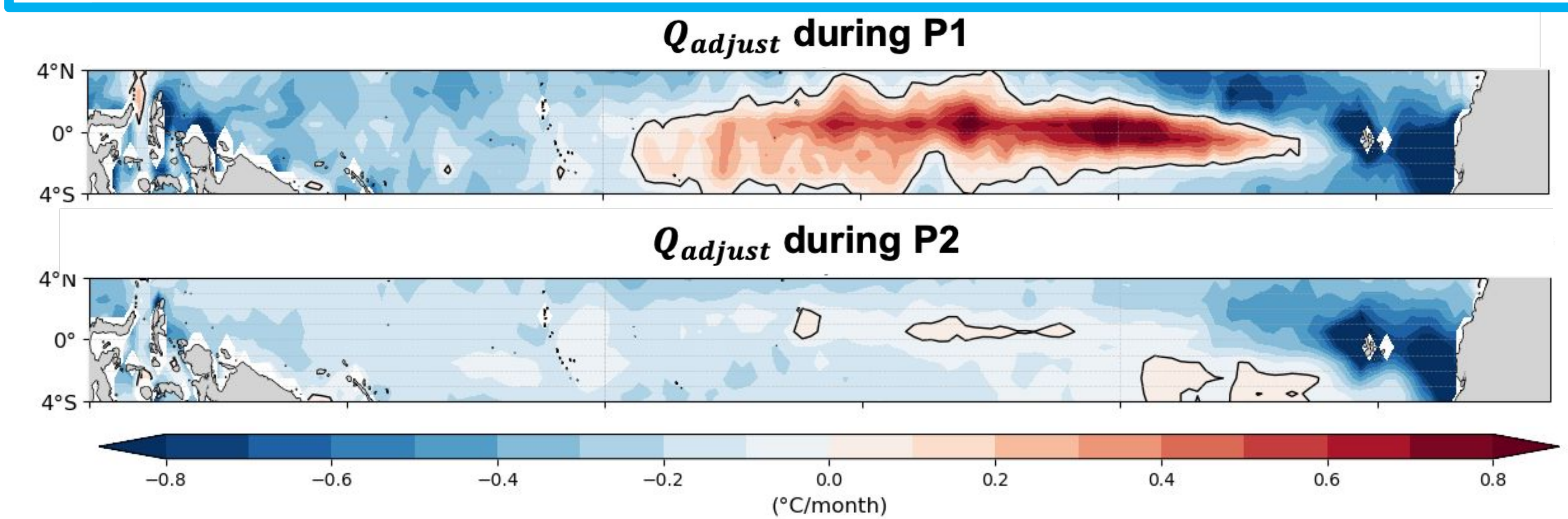
Q_{net} provided by ORAS5 does not reflect real-world air–sea fluxes and is not intended to do so

A Deus ex Machina Appears

Q_{adjust} difference between P2 and P1

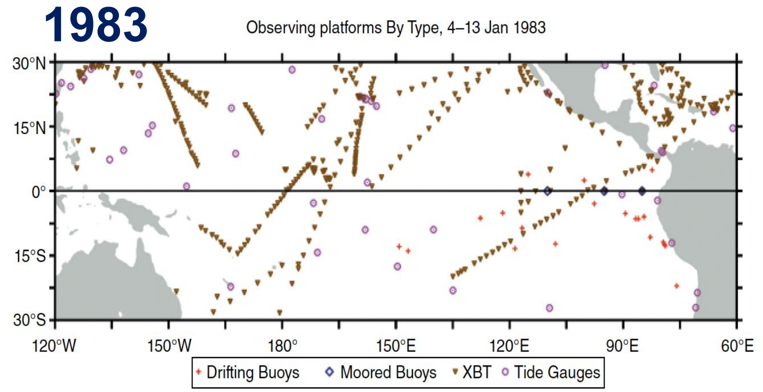


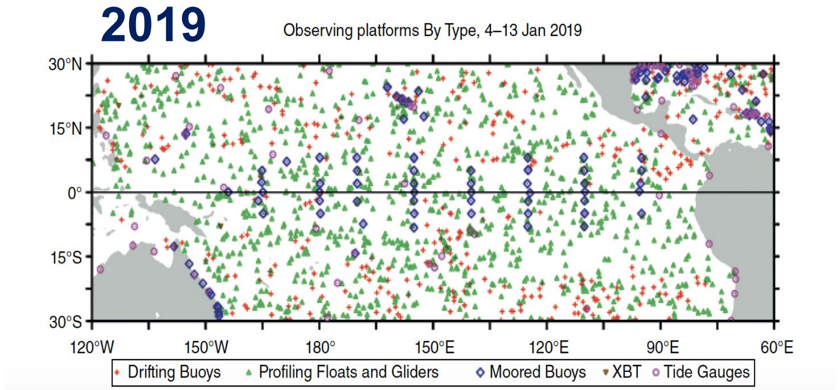
The decrease of Q_{adjust} over time, a deus ex machina, contributes to the cooling in the equatorial Pacific



Reduced Need for Adjustment?

- **Hypothesis#1: Reduced need for adjustment term is due to increase in observation data with time that our ocean model can assimilate**





McPhaden et al., 2020

- **Hypothesis#2: Reduced need for adjustment term is due to compensating error that emerges when the climate change signal becomes pronounced.**

Cold Bias in Climatology

Faster Warming Rate Under Climate Change

Summary

1. How does the long-term cooling trend pattern in the tropical Pacific form in the real world?

✔ Wind-driven and shear-driven current and mixing change.

2. Why do climate models generally fail to reproduce the real world?

✔ The weak subsurface cooling signal cannot surface.

3. How far are we from reaching a quantitative understanding of trend pattern formation?

✔ Very far, at least for understanding the real world.

F. Jiang, R. Seager, and M. A. Cane. Deus ex machina long-term cooling of the eastern Pacific cold tongue in ocean reanalysis data. Submitted.

F. Jiang et al. Subsurface cooling and sea surface temperature pattern formation over the equatorial Pacific. JGR Ocean

Thanks for listening

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Challenges in Quantifying Heat Budget

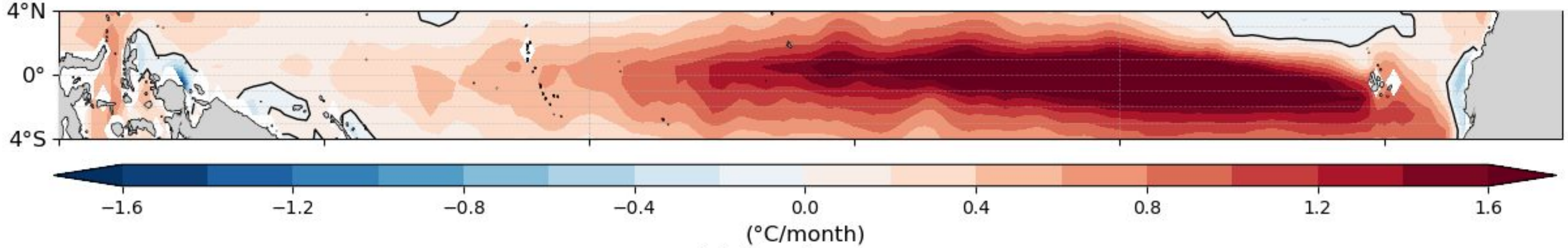
Surface Layer Heat Budget

$$\frac{1}{d}\int_{-d}^{0}\left(\frac{\partial T}{\partial t}\right)dz = Q_{net} - Q_{pen} + \frac{1}{d}\int_{-d}^{0}(Q_{adv})dz + Q_{res}$$

- **Challenge#1: Reliable quantification of air-sea fluxes is notoriously difficult, and its uncertainty is much larger than the climate change signal.**

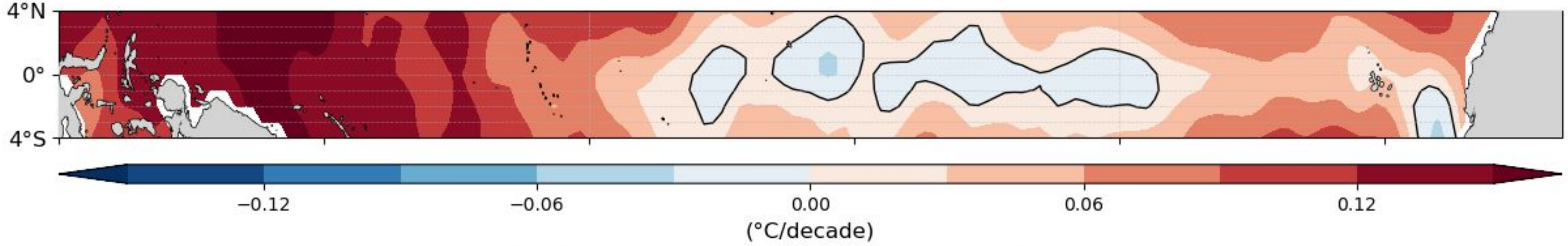
Q_{net} $\sim 1\ ^{\circ}C/month$

ORAS5 mean net surface heat flux during 1958-1977



SST Trend $\sim 10^{-3}\ ^{\circ}C/month$

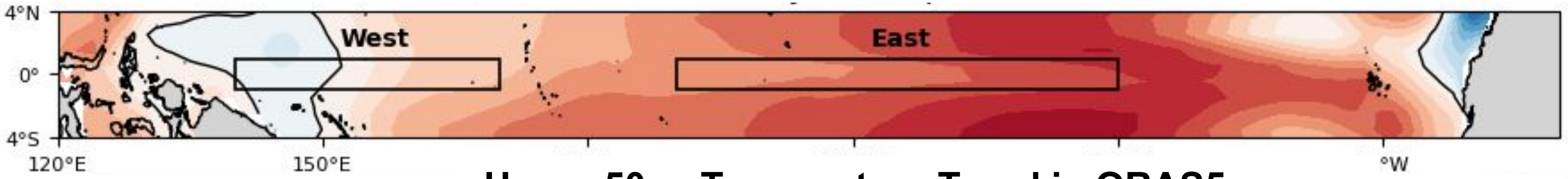
SST trend in HadISST during 1958-2024



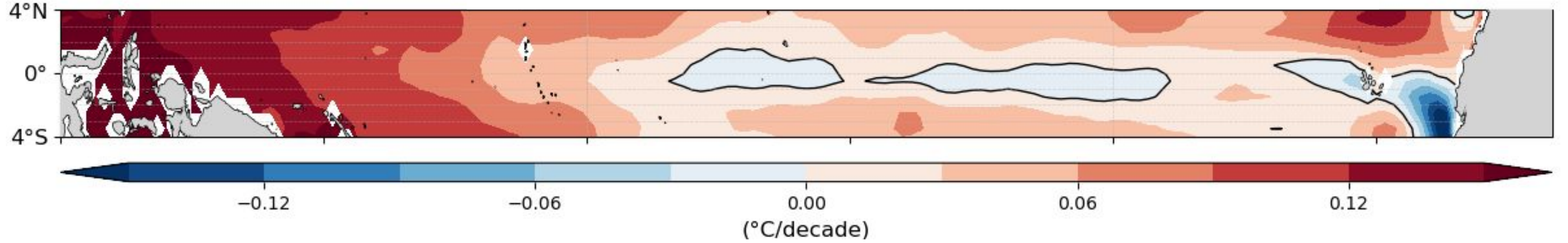
Exploring A Bit Further for Hypothesis#2

OMIP2 simulation (15 models): 1958-2018, forced with observed wind stress

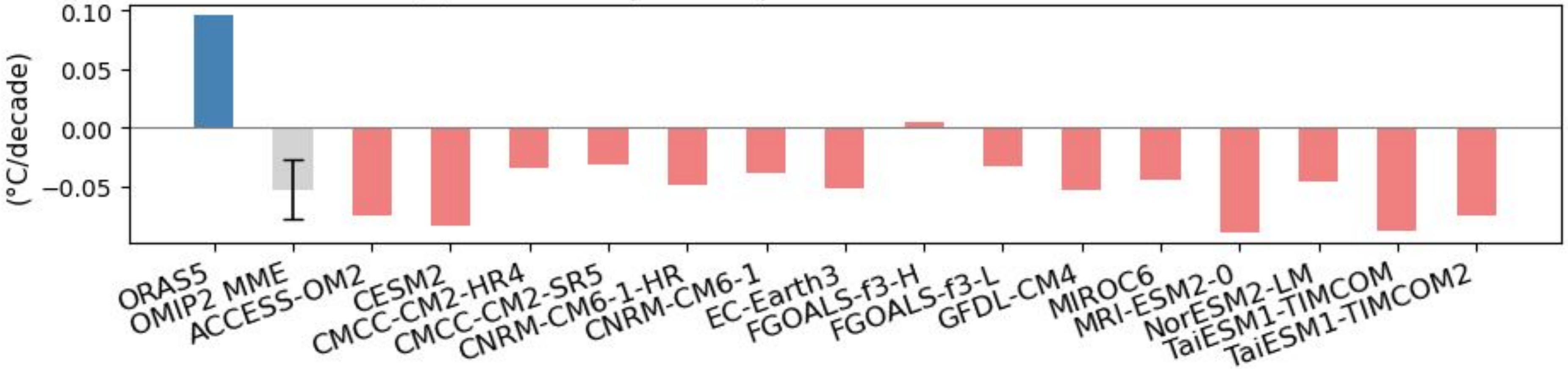
Upper 50 m Temperature Trend in OMIP2



Upper 50 m Temperature Trend in ORAS5



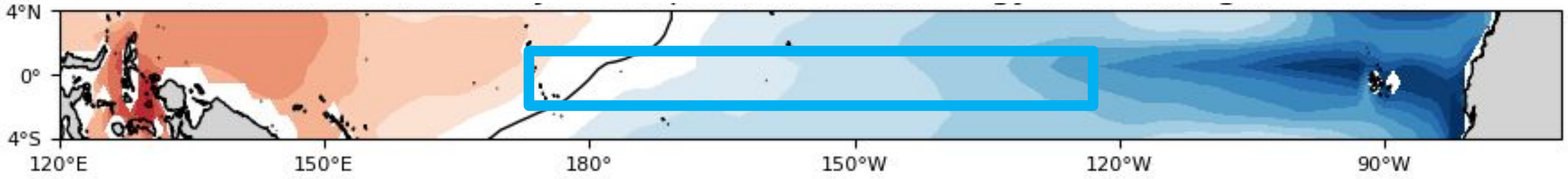
Upper 50 m Temperature West Minus East Trend



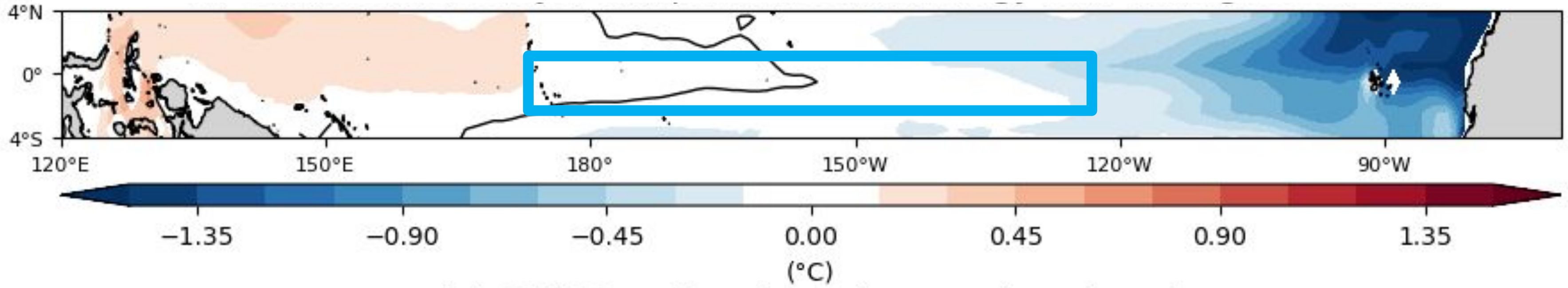
Exploring A Bit Further for Hypothesis#2

OMIP2 simulation (15 models): 1958-2018, forced with observed wind stress

Climatological Bias in OMIP2 Upper 50 m Temperature in P1



Climatological Bias in OMIP2 Upper 50 m Temperature in P2



Deus Ex Machina: God from the Machine

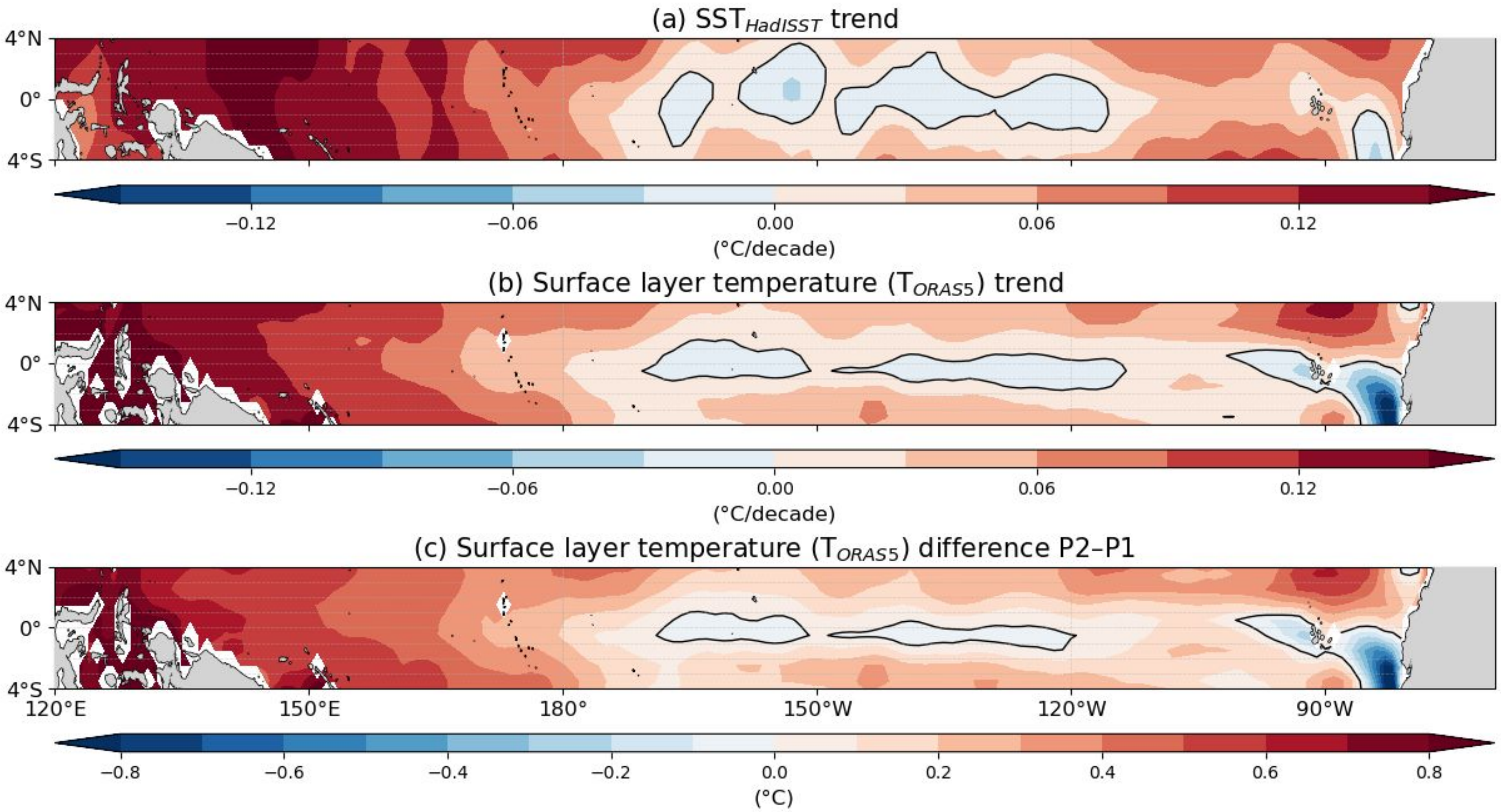
Deus ex machina is a storytelling technique where a character's conflict is solved by the sudden appearance of a new character or an implausible event. This event, or character, usually saves the hero from an otherwise hopeless situation.

Our Hopeless Situation:

Ocean model cannot cool the equatorial Pacific on its own under climate change even in an assimilating mode

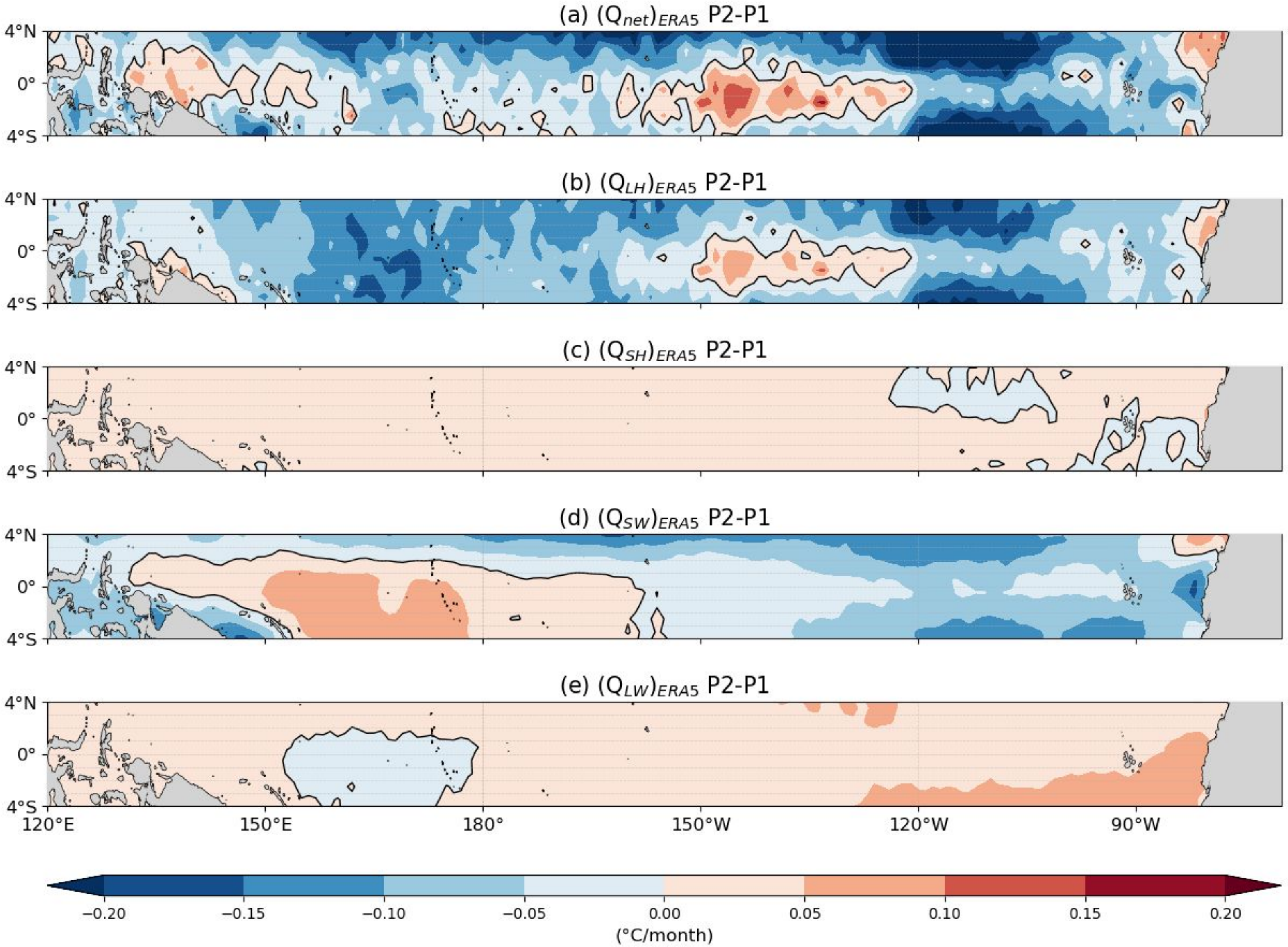
Supplementary Slides

SST



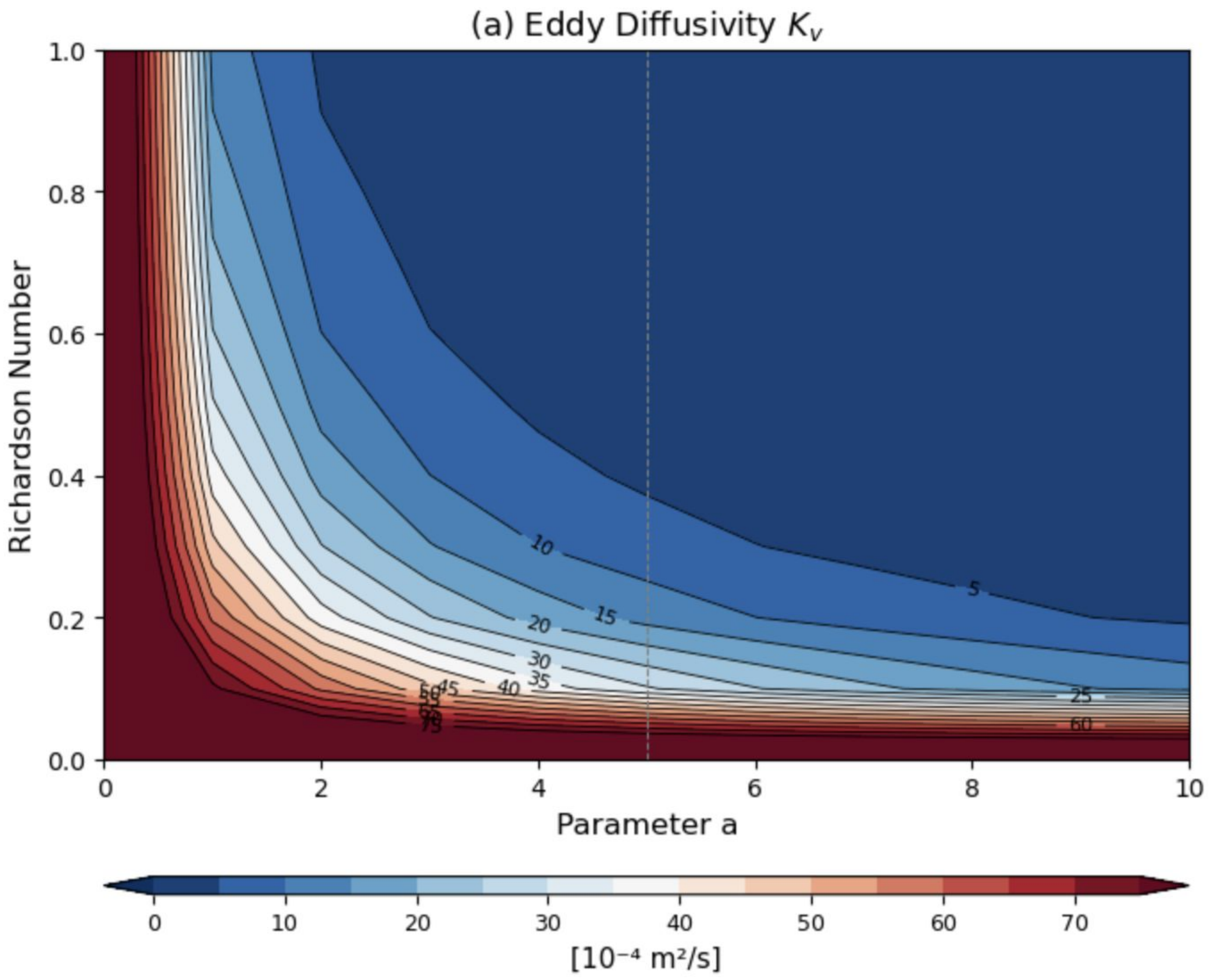
(a) SST$_{HadISST}$ trend
4°N
0°
4°S
−0.12
−0.06
0.00
0.06
0.12
(°C/decade)
(b) Surface layer temperature (T$_{ORAS5}$) trend
4°N
0°
4°S
−0.12
−0.06
0.00
0.06
0.12
(°C/decade)
(c) Surface layer temperature (T$_{ORAS5}$) difference P2–P1
4°N
0°
4°S
120°E
150°E
180°
150°W
120°W
90°W
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
(°C)

Q_{net} in ERA5

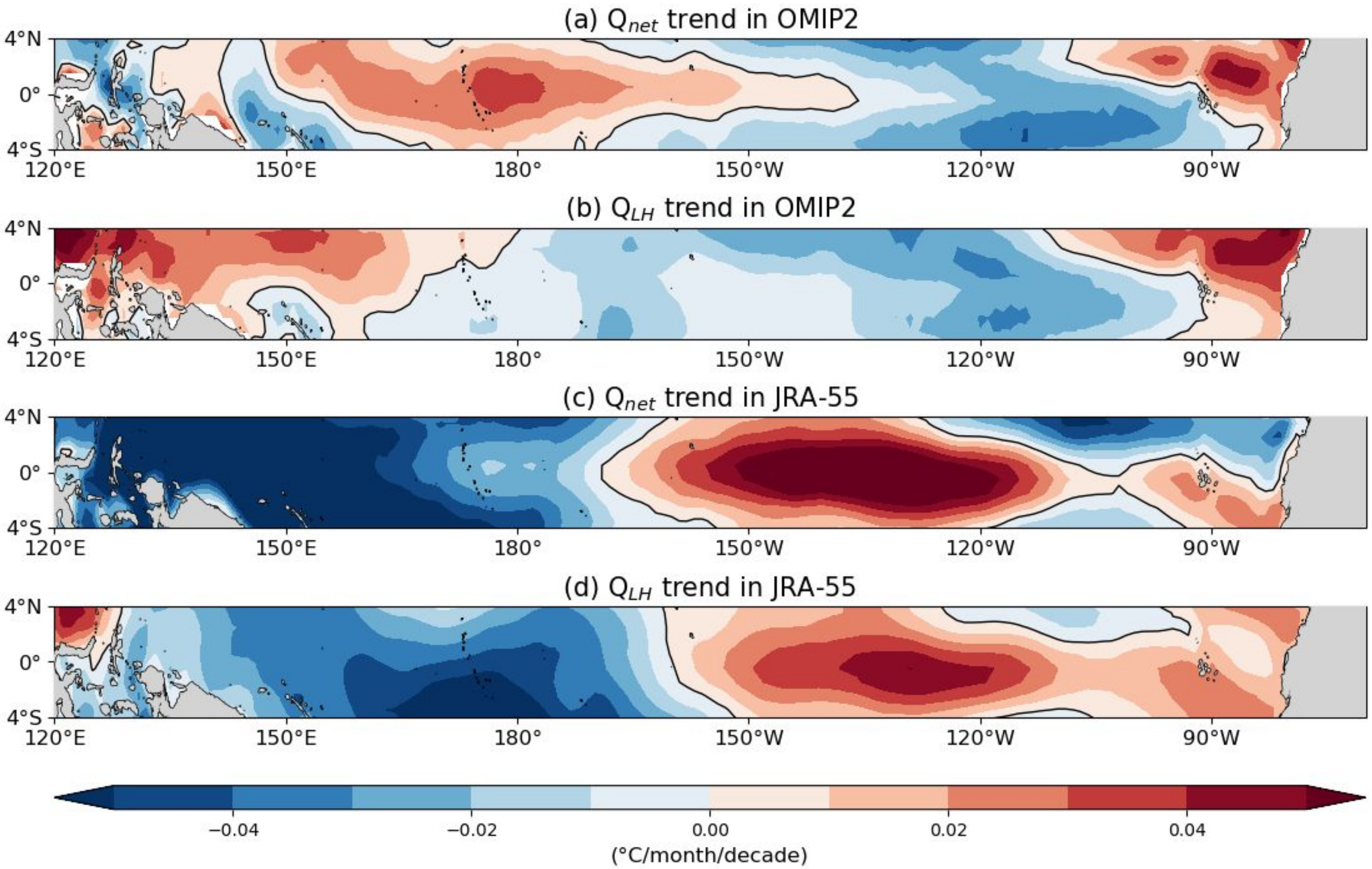


(a) $(Q_{net})_{ERA5}$ P2-P1
(b) $(Q_{LH})_{ERA5}$ P2-P1
(c) $(Q_{SH})_{ERA5}$ P2-P1
(d) $(Q_{SW})_{ERA5}$ P2-P1
(e) $(Q_{LW})_{ERA5}$ P2-P1
4°N
0°
4°S
120°E
150°E
180°
150°W
120°W
90°W
−0.20
−0.15
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
(°C/month)

Possibility of Changing Parameters in Vertical Mixing Scheme



OMIP2 heat flux



Hypothesis For Initial Response