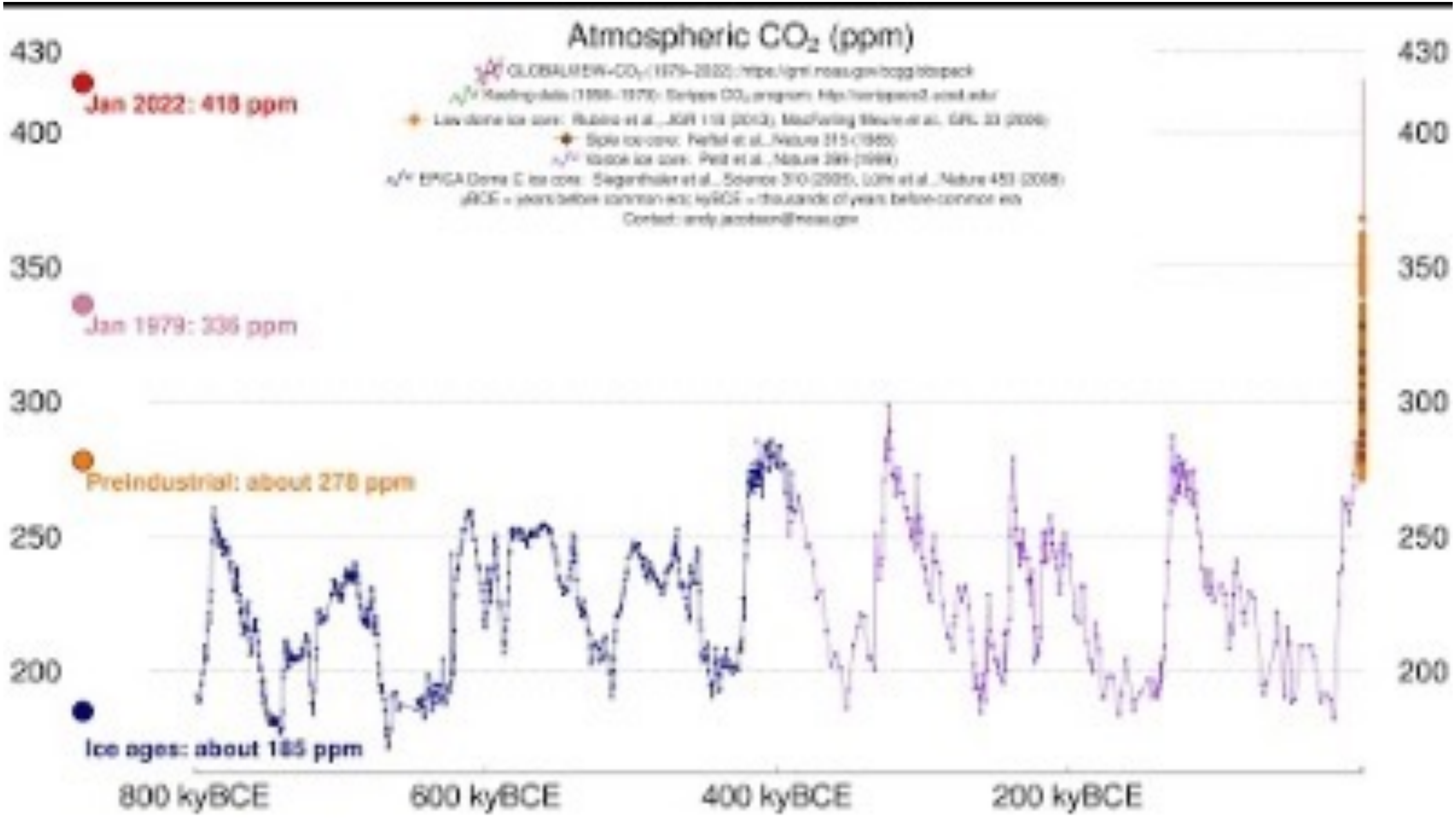
Tropical Pacific Climate Change

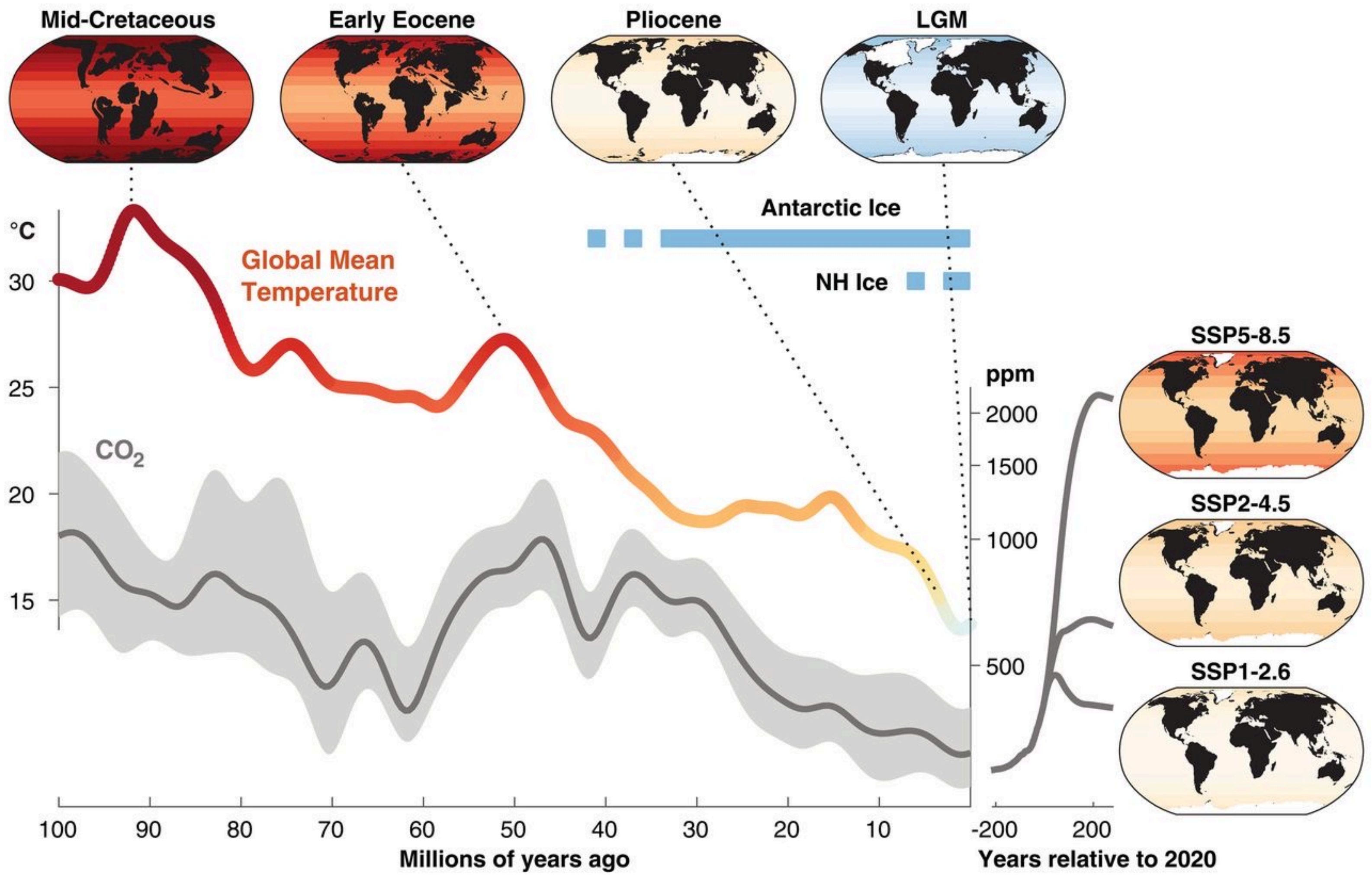
Natalie Burls
Center for Ocean-Land-Atmosphere Studies
Dept. of Atmospheric, Oceanic, & Earth Sciences
George Mason University

ICTP Summer School on Atlantic Variability and Tropical Basin Interactions at Interannual to Multi-Decadal Time Scales



https://www.youtube.com/watch?v=Yb3NsMJ-YQ8

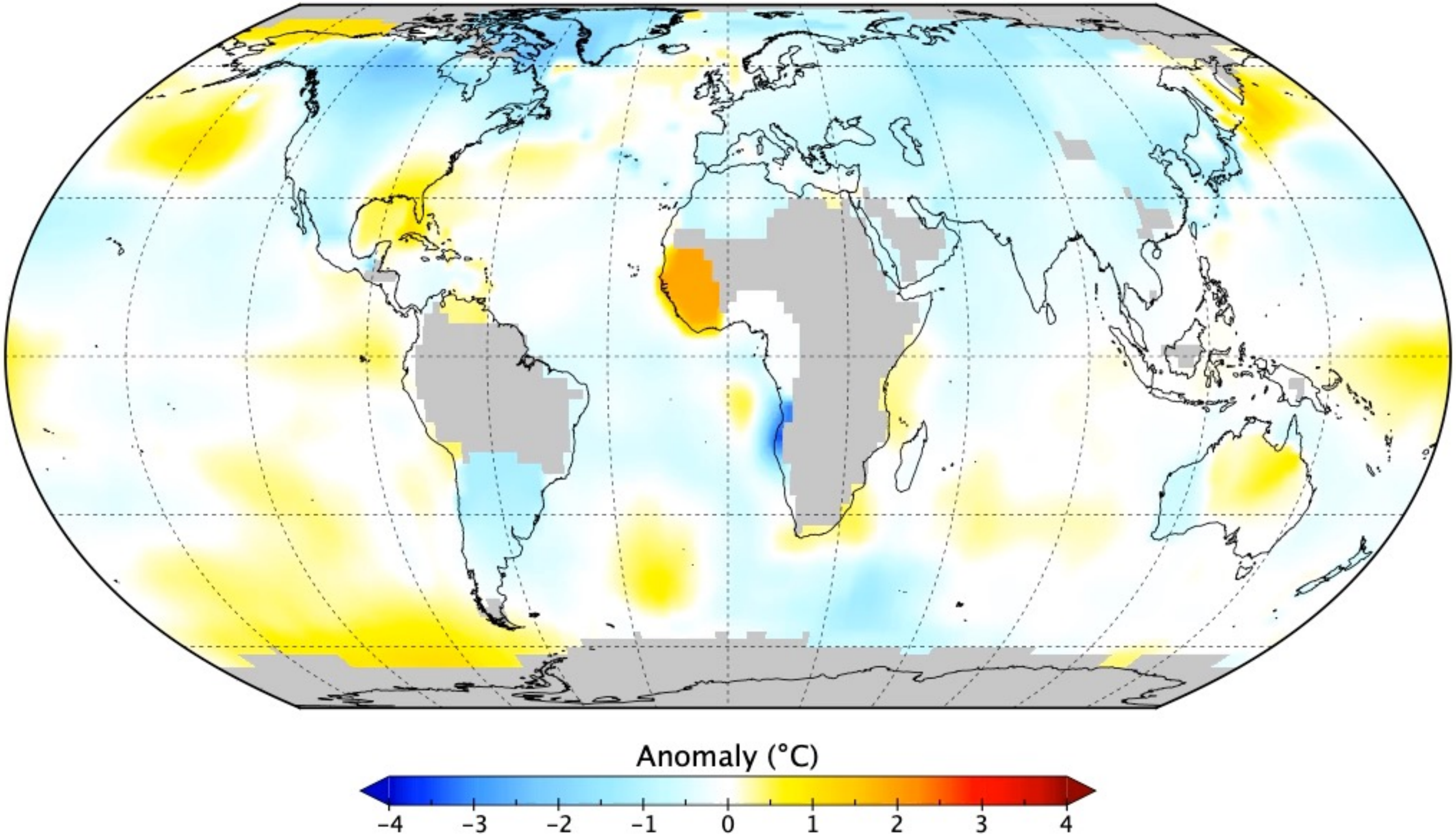
High CO_2 Climates of the Past



Tierney et al. *Science* 2020

GISTEMP 5-Year Annual LOTI Anomaly

1880–1884



Base Period: 1951–1980

Data Min = −3.47, Max = 1.92, Mean = −0.18

NASA/GISS/GISTEMP/v4

Outline

- Climate Sensitivity and the importance of the Tropics
- Theories of Tropical Climate Change
- The equilibrium response and insights from past warm climates
- The transient response, observed Tropical Climate Change
    - A model-data mismatch?
- ~~Changes in ENSO with warming~~ (a topic for another day)

What is Climate Sensitivity?

The "Charney Report"

Carbon Dioxide and Climate: A Scientific Assessment

Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23–27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

The conclusions of this brief but intense investigation may be comforting to scientists but disturbing to policymakers. If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible. The conclusions of prior studies have been generally reaffirmed. However, the study group points out that the ocean, the great and ponderous flywheel of the global climate system, may be expected to slow the course of observable climatic change. A wait-and-see policy may mean waiting until it is too late.

The "Charney Report"

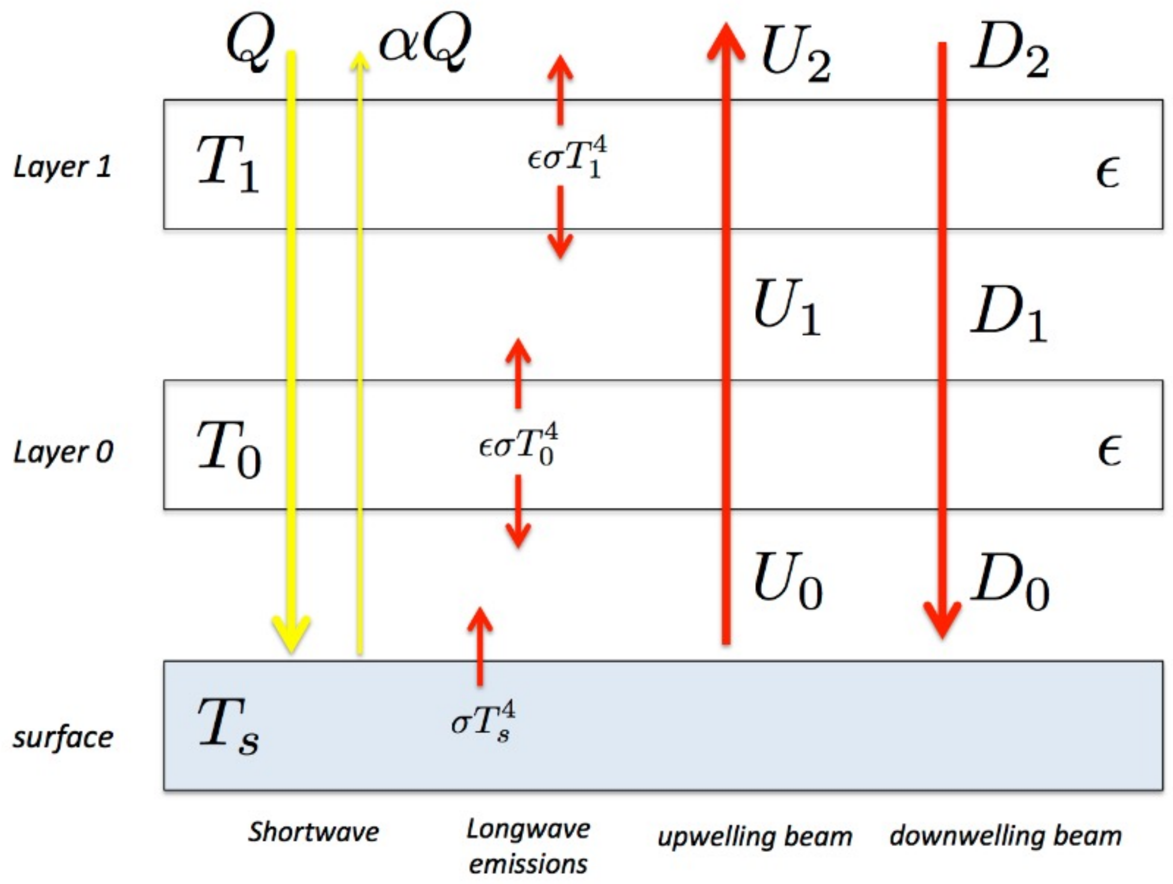
Carbon Dioxide and Climate:
A Scientific Assessment

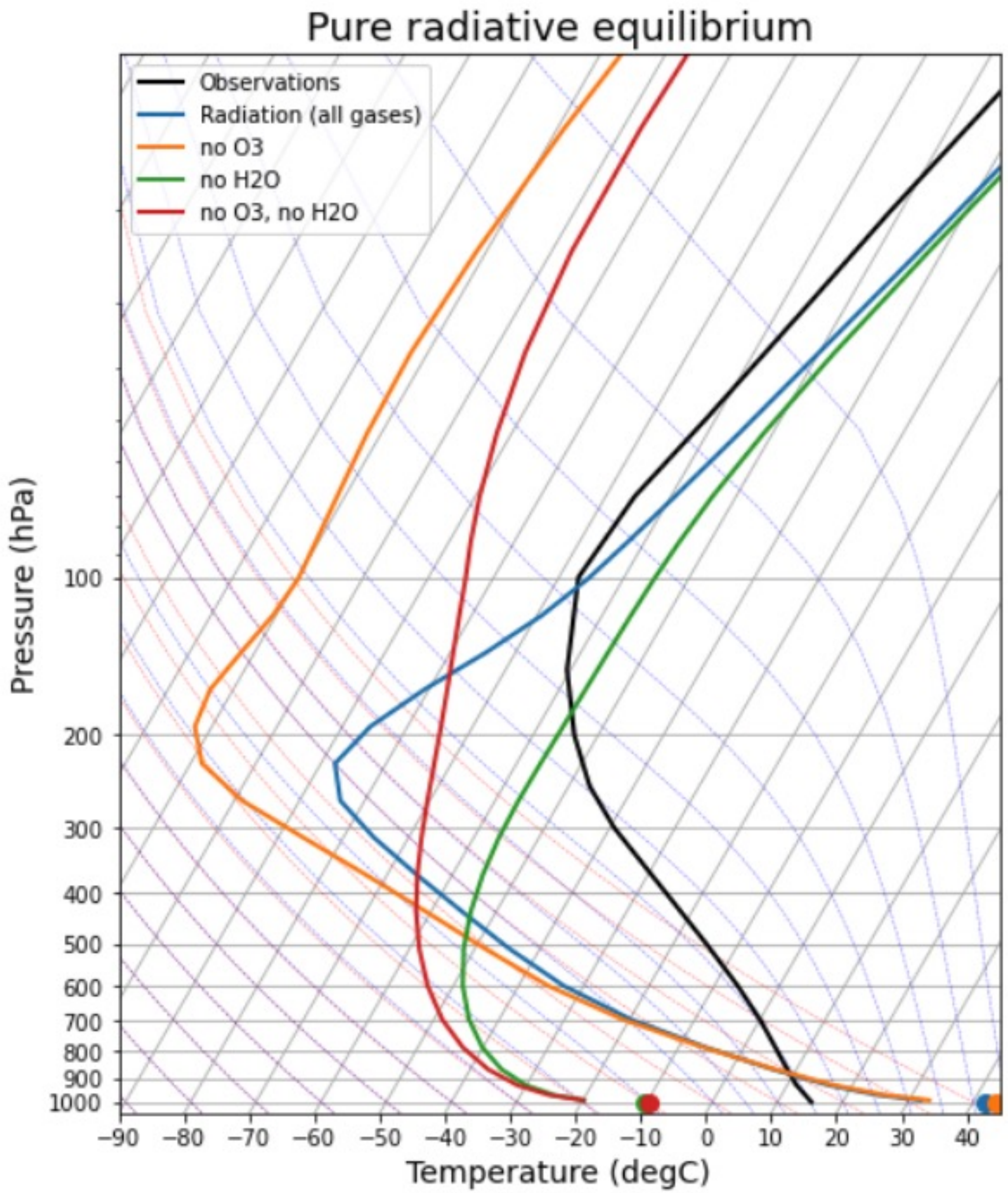
Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23–27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

The conclusions of this brief but intense investigation may be comforting to scientists but disturbing to policymakers. If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible. The conclusions of prior studies have been generally reaffirmed. However, the study group points out that the ocean, the great and ponderous flywheel of the global climate system, may be expected to slow the course of observable climatic change. A wait-and-see policy may mean waiting until it is too late.

When it is assumed that the CO_2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, the more realistic of the modeling efforts predict a global surface warming of between 2°C and 3.5°C, with greater increases at high latitudes. This range reflects both uncertainties in physical understanding and inaccuracies arising from the need to reduce the mathematical problem to one that can be handled by even the fastest available electronic computers. It is significant, however, that none of the model calculations predicts negligible warming.

Radiative Equilibrium





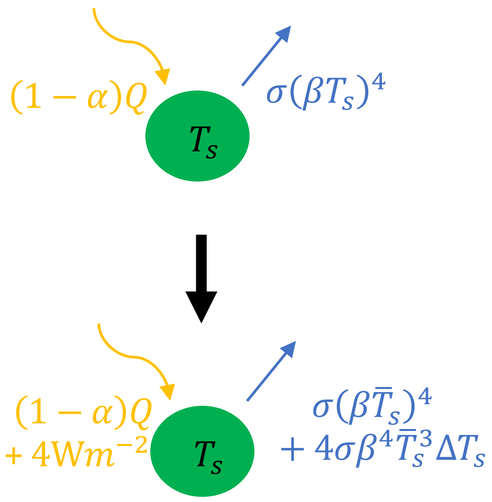
https://brian-rose.github.io/ClimateLaboratoryBook/courseware/radeq.html, Rose 2018

Climate Sensitivity

0 Dimension – Global Mean Top of the Atmosphere Energy Balance Model (EMB)

$R \sim 4Wm^{-2}$ per CO_2 doubling

Simplest 0D EMB with only the Planck Feedback to come back into equilibrium



$$C\frac{dT_s}{dt} = (1-\alpha)Q - \sigma(\beta T_s)^4 + R$$

$R \sim 4Wm^{-2}$ per CO_2 doubling

$\lambda = -4\sigma\beta^4\bar{T}_{s_o}^3 = \mathbf{3.3\ Wm^{-2}K^{-1}}$

ΔT_s = 1.2

$T_{e(mission)} = \beta T_{s(urface)}$
$T_e = 255$
$T_s = 288$
β = 225/288 = 0.885

Climate Sensitivity with just the Planck Feedback

****See David Hartmann's textbook & Brian Rose's online course notes for detailed derivation -** https://www.atmos.albany.edu/facstaff/brose/classes/ATM623_Spring2015/Notes/Lectures/Lecture02%20--%20Solving%20the%20zero-dimensional%20EBM.html*

Climate Sensitivity

0 Dimension – Global Mean Top of the Atmosphere Energy Balance Model (EMB)

$R \sim 4\mathrm{W}m^{-2}$ per CO_2 doubling

Simplest 0D EMB with all the fast feedbacks

$$C\frac{d\Delta T_s}{dt} = R + \Delta F_{TOA} = R + \lambda\,\Delta T_s$$

$$-R = \Delta F_{TOA} = \lambda\,\Delta T_s \quad \longrightarrow \quad \lambda = \frac{\partial}{\partial T_s}(\Delta F_{TOA})$$

*Lambda the **Climate Feedback Parameter***
($Wm^{-2}K^{-1}$)

$$\lambda_i = \frac{\partial \Delta F_{TOA}}{\partial x_i}\frac{\Delta x_i}{\Delta T_s}$$

Δx_i =*"Fast Feedbacks"*

- *Planck feedback*
- *Lapse rate feedback*
- *Surface (sea-ice) albedo feedback*
- *Water vapor feedback*
- *Net cloud feedback*

AGU ADVANCING EARTH AND SPACE SCIENCE

Reviews of Geophysics

REVIEW ARTICLE
10.1029/2019RG000678

Key Points:

- We assess evidence relevant to Earth's climate sensitivity *S*: feedback process understanding and the historical and paleoclimate records
- All three lines of evidence are difficult to reconcile with *S* < 2 K, while paleo evidence provides the

An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence

S. C. Sherwood[1], M. J. Webb[2], J. D. Annan[3], K. C. Armour[4], P. M. Forster[5], J. C. Hargreaves[3], G. Hegerl[6], S. A. Klein[7], K. D. Marvel[8,9], E. J. Rohling[10,11], M. Watanabe[12], T. Andrews[2], P. Braconnot[13], C. S. Bretherton[4], G. L. Foster[11], Z. Hausfather[14], A. S. von der Heydt[15], R. Knutti[16], T. Mauritsen[17], J. R. Norris[18], C. Proistosescu[19], M. Rugenstein[20], G. A. Schmidt[9], K. B. Tokarska[6,16], and M. D. Zelinka[7]

Abstract We assess evidence relevant to Earth's equilibrium climate sensitivity per doubling of atmospheric CO_2, characterized by an effective sensitivity *S*. This evidence includes feedback process understanding, the historical climate record, and the paleoclimate record. An *S* value lower than 2 K is difficult to reconcile with any of the three lines of evidence. The amount of cooling during the Last Glacial Maximum provides strong evidence against values of *S* greater than 4.5 K. Other lines of evidence in combination also show that this is relatively unlikely. We use a Bayesian approach to produce a probability density function (PDF) for *S* given all the evidence, including tests of robustness to difficult-to-quantify uncertainties and different priors. The 66% range is 2.6–3.9 K for our Baseline calculation and remains within 2.3–4.5 K under the robustness tests; corresponding 5–95% ranges are 2.3–4.7 K, bounded by 2.0–5.7 K (although such high-confidence ranges should be regarded more cautiously). This indicates a stronger constraint on *S* than reported in past assessments, by lifting the low end of the range. This narrowing occurs because the three lines of evidence agree and are judged to be largely independent and because of greater confidence in understanding feedback processes and in combining evidence. We identify promising avenues for further narrowing the range in *S*, in particular using comprehensive models and process understanding to address limitations in the traditional forcing-feedback paradigm for interpreting past changes.

Climate Sensitivity is Model, Time and State Dependent

Climate Sensitivity

Regional structure to Fast Feedbacks

$$C\frac{d\Delta T_s}{dt} = R + \Delta F_{TOA} + \Delta OHT + +\Delta AHT = R + \lambda\,\Delta T_s$$

$$-R = \Delta F_{TOA} = \lambda\,\Delta T_s \quad \rightarrow \quad \lambda = \frac{\partial}{\partial T_s}(\Delta F_{TOA})$$

$$\lambda_i = \frac{\partial \Delta F_{TOA}}{\partial x_i}\frac{\Delta x_i}{\Delta T_s}$$

Δx_i ="Fast Feedbacks"

- *Planck feedback*
- *Lapse rate feedback*
- *Surface (sea-ice) albedo feedback*
- *Water vapor feedback*
- *Net cloud feedback*

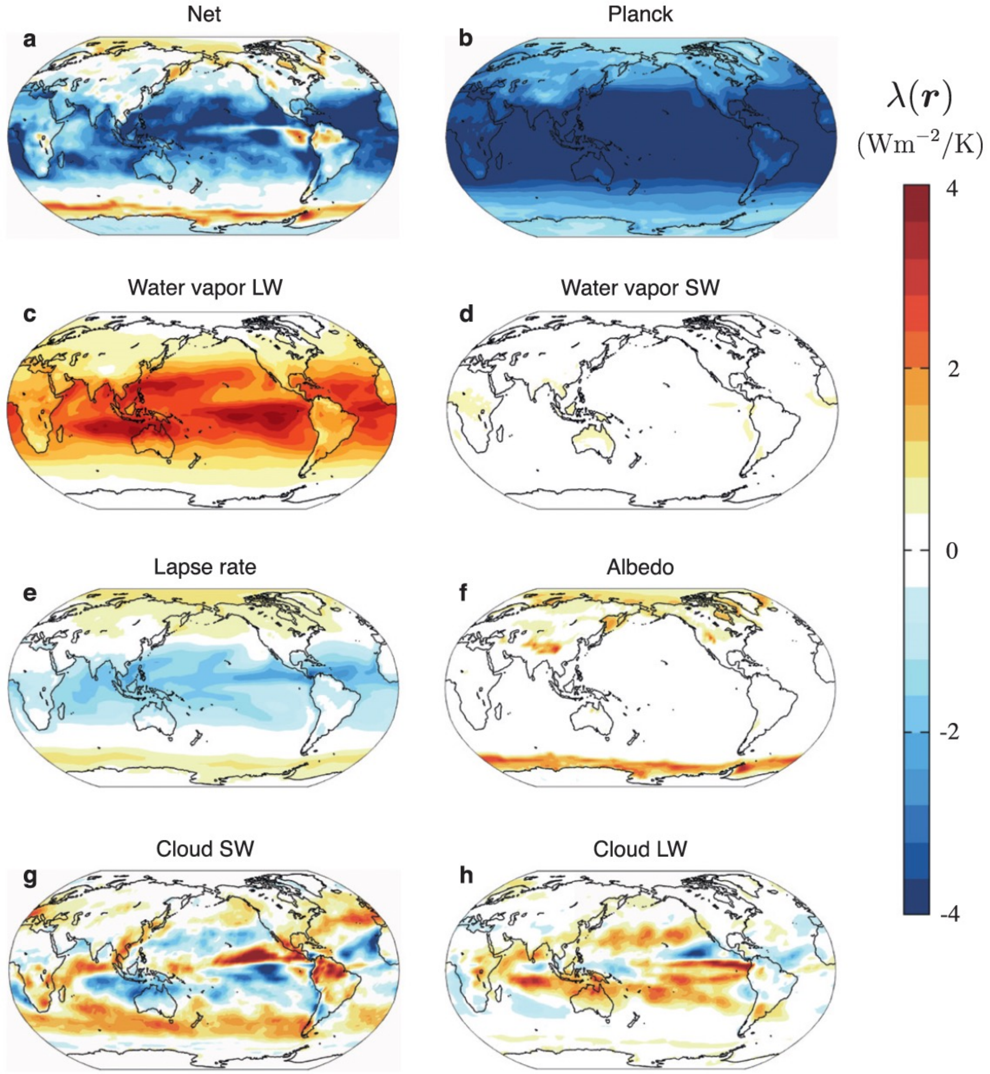
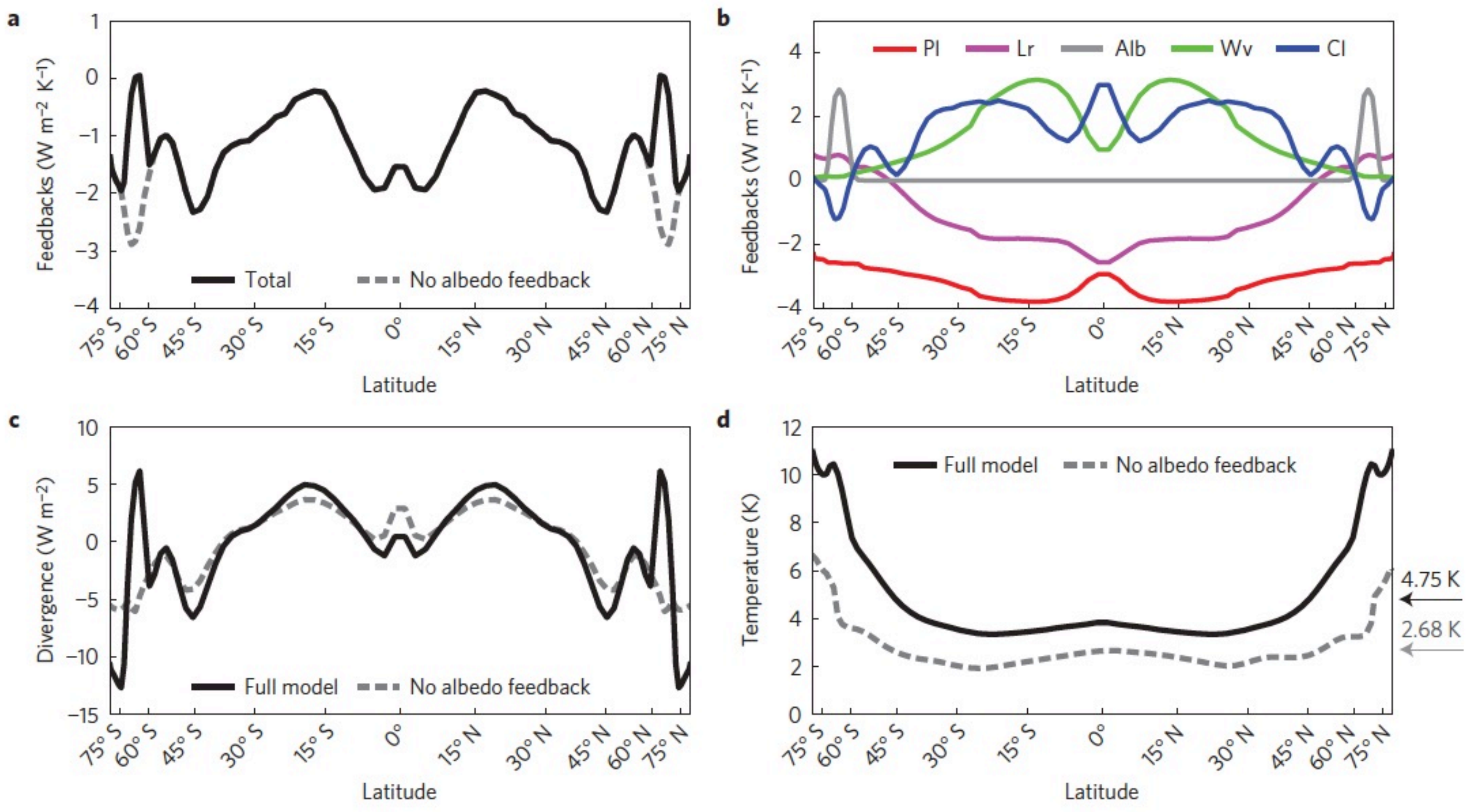


FIG. 5. Spatial patterns of net and individual local feedbacks within CCSM4: local feedbacks (local TOA response per degree local surface temperature change) separated into (a) net (sum of all individual feedbacks), (b) Planck, (c) LW water vapor, (d) SW water vapor, (e) lapse rate, (f) surface albedo, (g) cloud SW, and (h) cloud LW feedbacks.

Armour et al., 2015

The State Dependence of Climate Feedbacks

A climate with sea-ice versus one without sea-ice



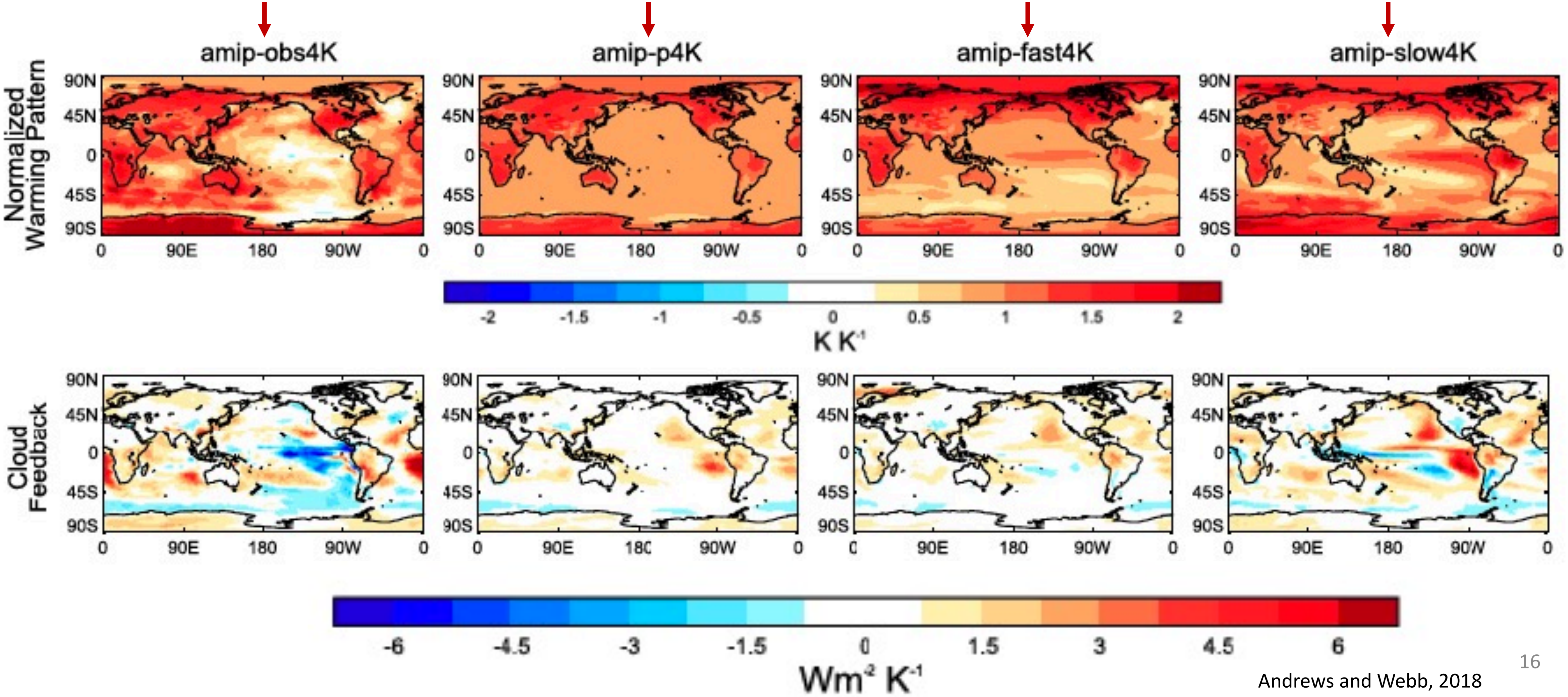
Roe et al., 2015

The Time Dependence of Climate Feedbacks

amip-obs4K SSTs are subject 20th century trends, normalized and then scaled to ensure a global-mean SST increase of 4K

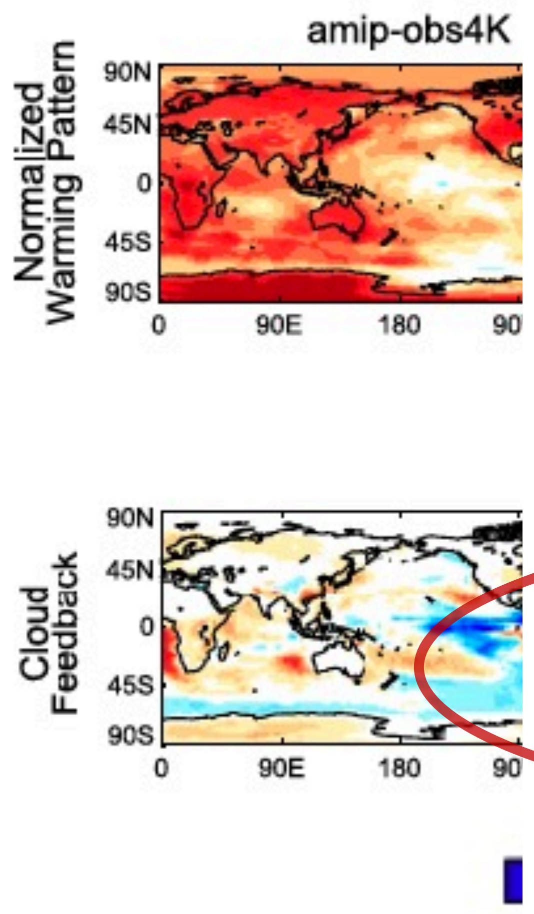
SSTs are subject to a uniform warming of 4K

The CMIP5 AOGCM-mean response to an abrupt quadrupling of CO_2 averaged over years 1–20 (amip-fast4k) and years 21–150 (amip-slow4K)



Andrews and Webb, 2018

The Time Dependence of Climate Feedbacks



The Dependence of Global Cloud and Lapse Rate Feedbacks on the Spatial Structure of Tropical Pacific Warming

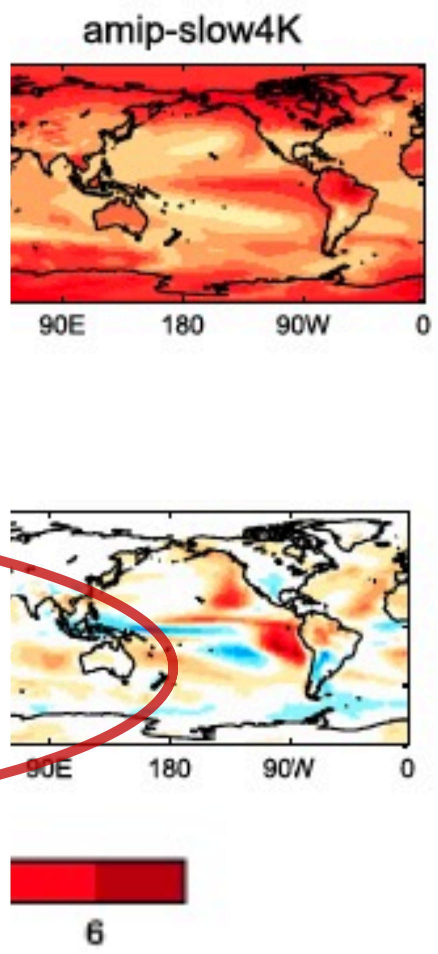
TIMOTHY ANDREWS AND MARK J. WEBB

Met Office Hadley Centre, Exeter, United Kingdom

(Manuscript received 10 February 2017, in final form 29 September 2017)

ABSTRACT

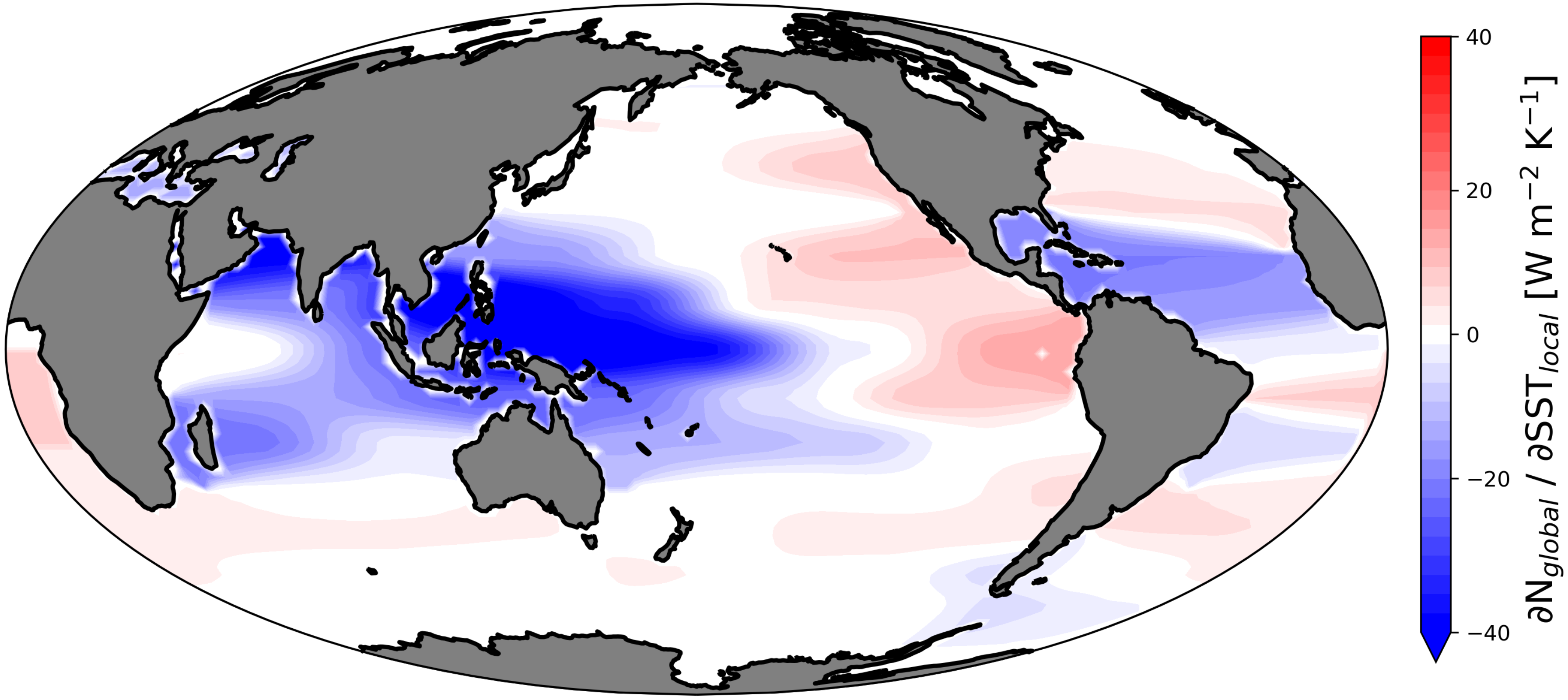
An atmospheric general circulation model (AGCM) is forced with patterns of observed sea surface temperature (SST) change and those output from atmosphere–ocean GCM (AOGCM) climate change simulations to demonstrate a strong dependence of climate feedback on the spatial structure of surface temperature change. Cloud and lapse rate feedbacks are found to vary the most, depending strongly on the pattern of tropical Pacific SST change. When warming is focused in the southeast tropical Pacific—a region of climatological subsidence and extensive marine low cloud cover—warming reduces the lower-tropospheric stability (LTS) and low cloud cover but is largely trapped under an inversion and hence has little remote effect. The net result is a relatively weak negative lapse rate feedback and a large positive cloud feedback. In contrast, when warming is weak in the southeast tropical Pacific and enhanced in the west tropical Pacific—a strong convective region—warming is efficiently transported throughout the free troposphere. The increased atmospheric stability results in a strong negative lapse rate feedback and increases the LTS in low cloud regions, resulting in a low cloud feedback of weak magnitude. These mechanisms help explain why climate feedback and sensitivity change on multidecadal time scales in AOGCM abrupt4xCO_2 simulations and are different from those seen in AGCM experiments forced with observed historical SST changes. From the physical understanding developed here, one should expect unusually negative radiative feedbacks and low effective climate sensitivities to be diagnosed from real-world variations in radiative fluxes and temperature over decades in which the eastern Pacific has lacked warming.



Andrews and Webb, 2018

Global Radiative feedback response to local warming

CAM5 Green's Function (Zhou et al. 2017)



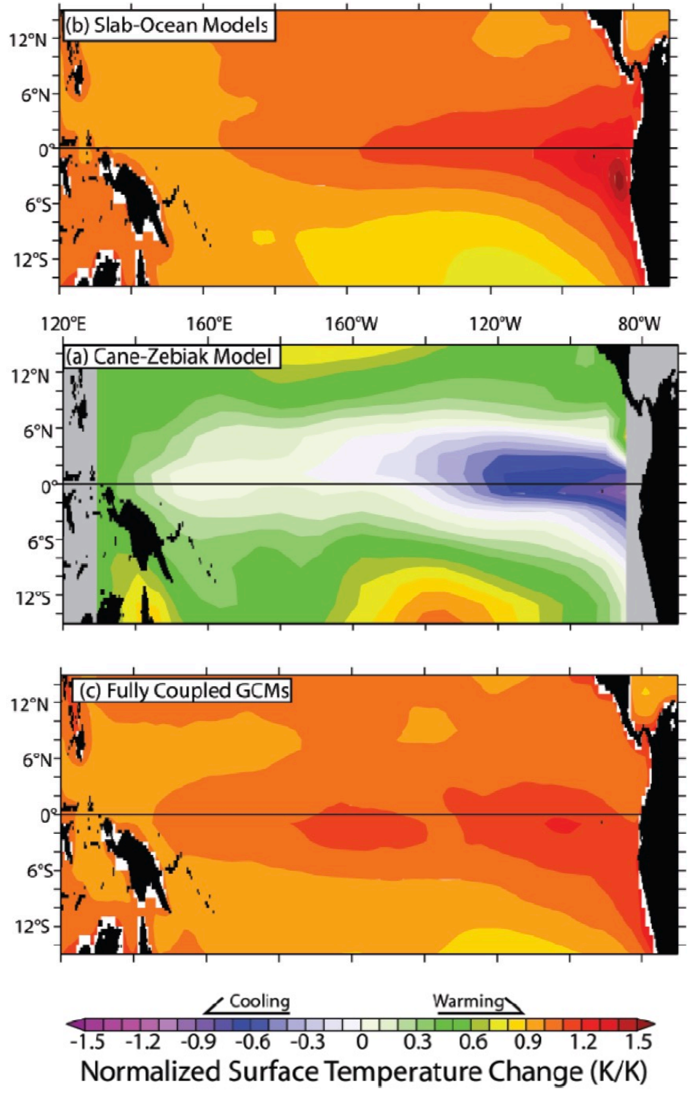
How will the tropical Pacific respond to global warming?

The Response of Tropical Climate to Warming

Thermodynamic Arguments

Accounting for Ocean Dynamics

Accounting for Extratropical Influences

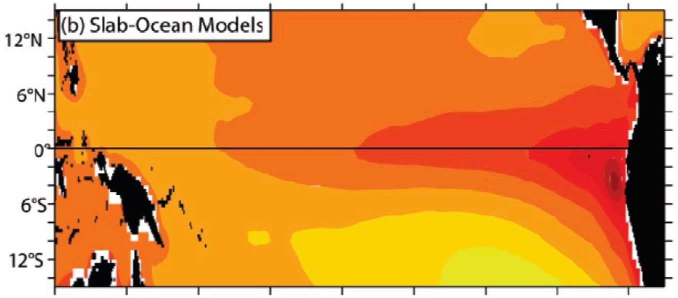


Vecchi et al., 2008

The Response of Tropical Climate to Warming

Thermodynamic Arguments

1) The thermodynamically driven weakening of atmospheric circulation in a warmer climate resulting in weaker SST gradients via ocean-atmosphere coupling (Betts and Ridgway, 1989; Held and Soden, 2006, Vecchi and Soden, 2007, Ma et al., 2012) .



A global budget:

$$P = Mq$$

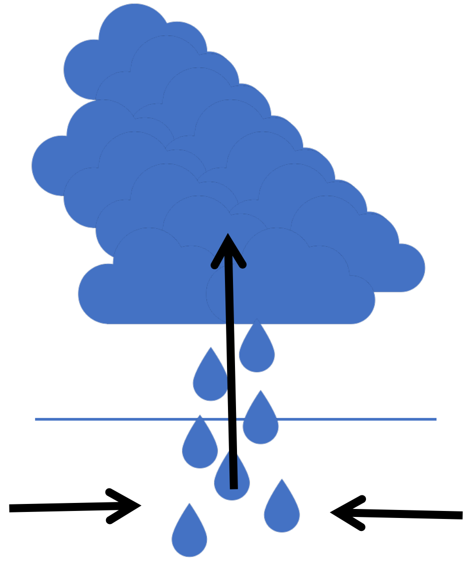
Precipitation = Mass exchange between the boundary layer and free troposphere – **the Circulation Strength** x **Humidity**

+ 2% per Kelvin
***Radiatively constrained as global P-E = 0**

- 5% per Kelvin

+ 7% per Kelvin
Clausius Clapeyron

$$\frac{d \ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T),$$



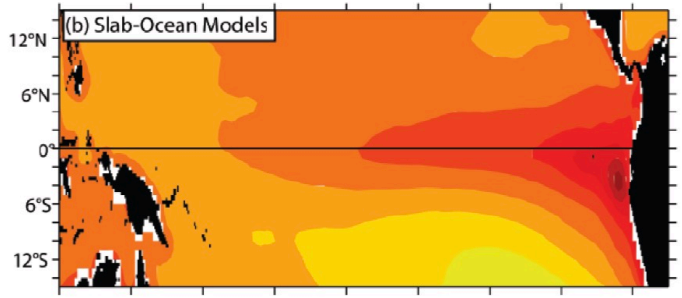
The Response of Tropical Climate to Warming

Thermodynamic Arguments

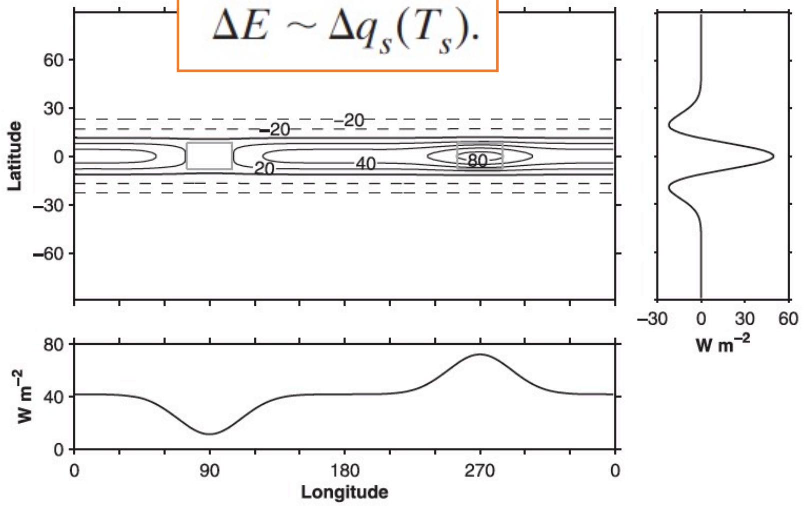
1) The thermodynamically driven weakening of atmospheric circulation in a warmer climate resulting in weaker SST gradients via ocean-atmosphere coupling (Betts and Ridgway, 1989; Held and Soden, 2006, Vecchi and Soden, 2007, Ma et al., 2012) .

2) “Evaporative damping” leads directly to weaker SST gradients (Knutson and Manabe, Merlis and Schneider, 2011)

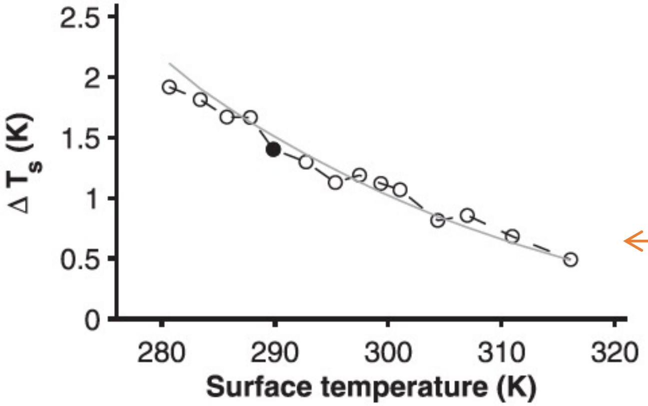
***Merlis and Schneider (2011), SOM experiments with ocean heat transport is held fixed and no clouds**



$$\Delta E \sim \Delta q_s(T_s).$$



$$\Delta T_s \sim \Delta q_s \left(\frac{\partial q_s}{\partial T} \right)^{-1}$$



a 30% reduction in the zonal SST gradient would require a global mean temperature increase of some 10°C

The Response of Tropical Climate to Warming

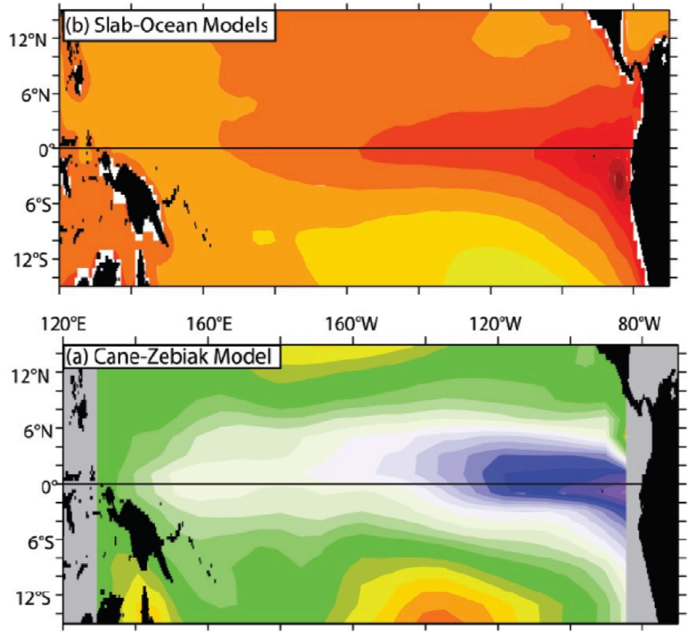
Thermodynamic Arguments

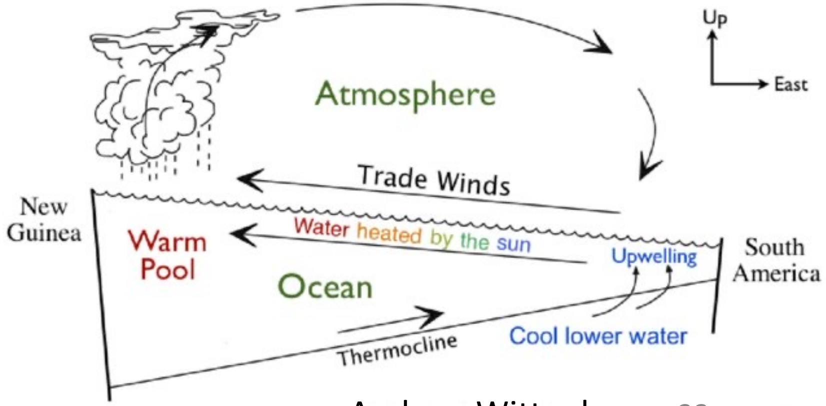
The weakening of atmospheric circulation in a warmer climate resulting in weaker SST gradients via ocean-atmosphere coupling (Betts and Ridgway, 1989; Held and Soden, 2006, Vecchi and Soden, 2007, Ma et al., 2012) .

“Evaporative damping” leads directly to weaker SST gradients (Knutson and Manabe, Merlis and Schneider, 2011)

Accounting for Ocean Dynamics

The “ocean thermostat” leads to an increase in the zonal SST gradient as upwelling in the eastern Pacific opposes surface heating (Clement et al., 1996, Sun and Liu 1996).





The Response of Tropical Climate to Warming

Thermodynamic Arguments

The weakening of atmospheric circulation in a warmer climate resulting in weaker SST gradients via ocean-atmosphere coupling (Betts and Ridgway, 1989; Held and Soden, 2006, Vecchi and Soden, 2007, Ma et al., 2012) .

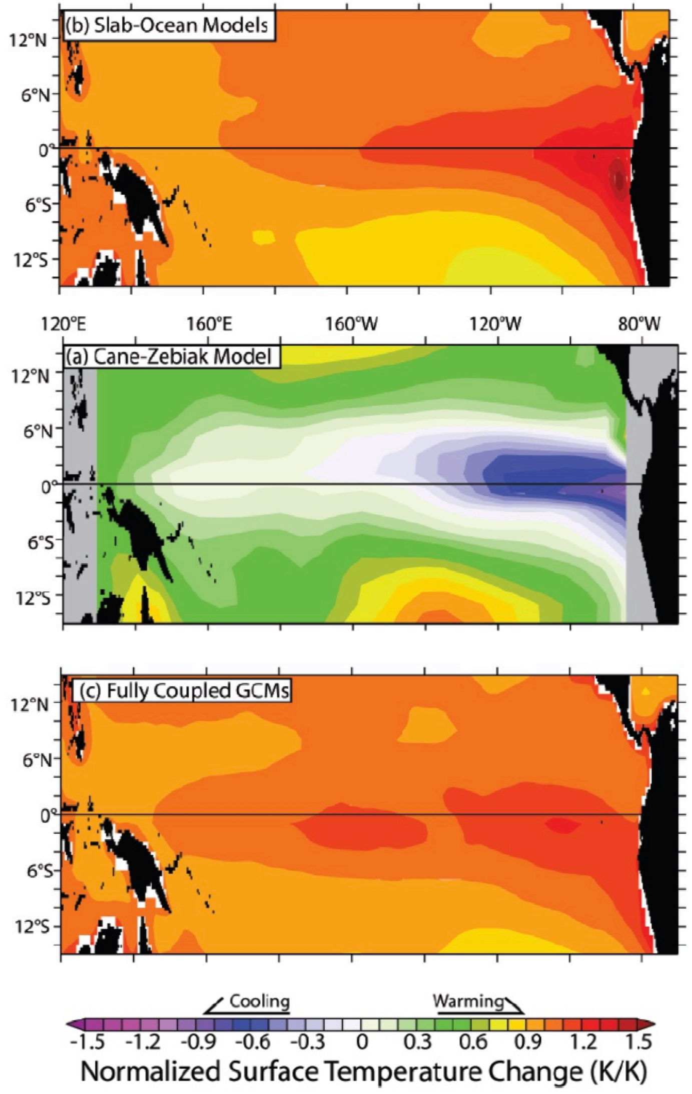
“Evaporative damping” leads directly to weaker SST gradients (Knutson and Manabe, Merlis and Schneider, 2011)

Accounting for Ocean Dynamics

The “ocean thermostat” leads to an increase in the zonal SST gradient as upwelling in the eastern Pacific opposes surface heating (Clement et al., 1996, Sun and Liu 1996).

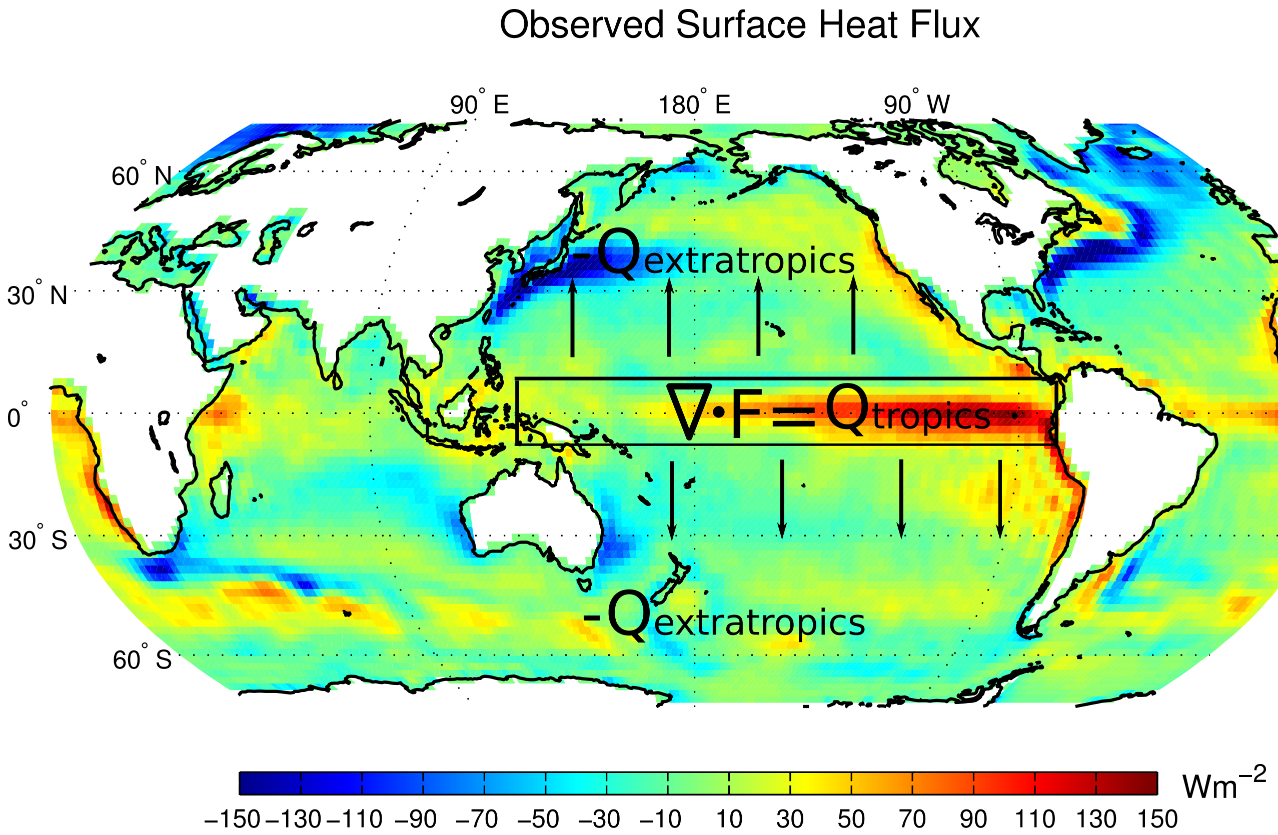
Accounting for Extratropical Influences

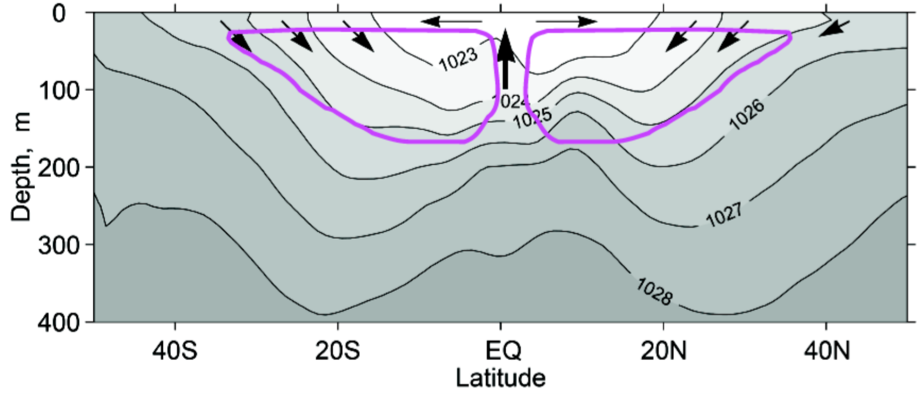
A couple ocean-atmosphere theory that includes the influence of the extra-tropics (Liu and Huang 1997; Liu 1998, Burls and Fedorov 2014a).

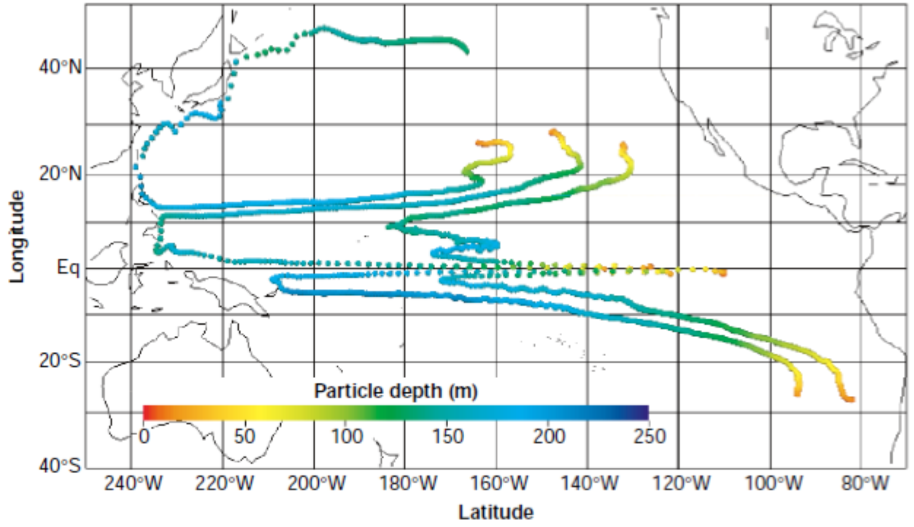


Vecchi et al., 2008

Accounting for Extratropical Influences







Gu and Philander, 1997

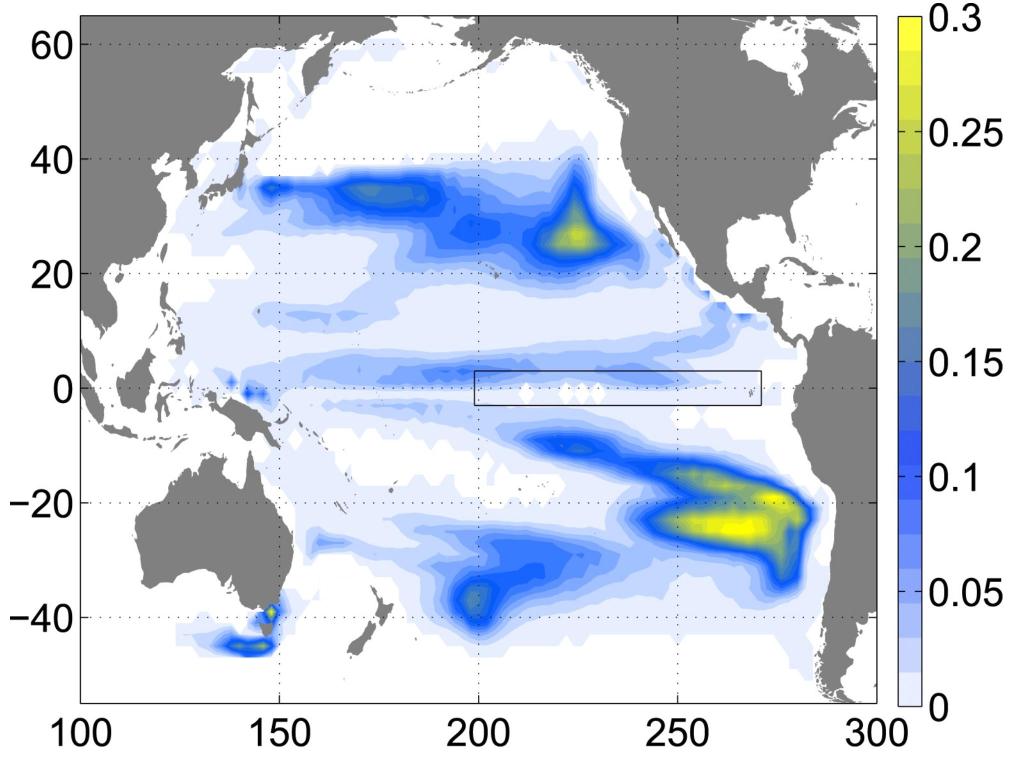
In the steady state:

$$\Delta SST \propto Q_{tropics} = \nabla \cdot F_o = -Q_{extratropics}$$

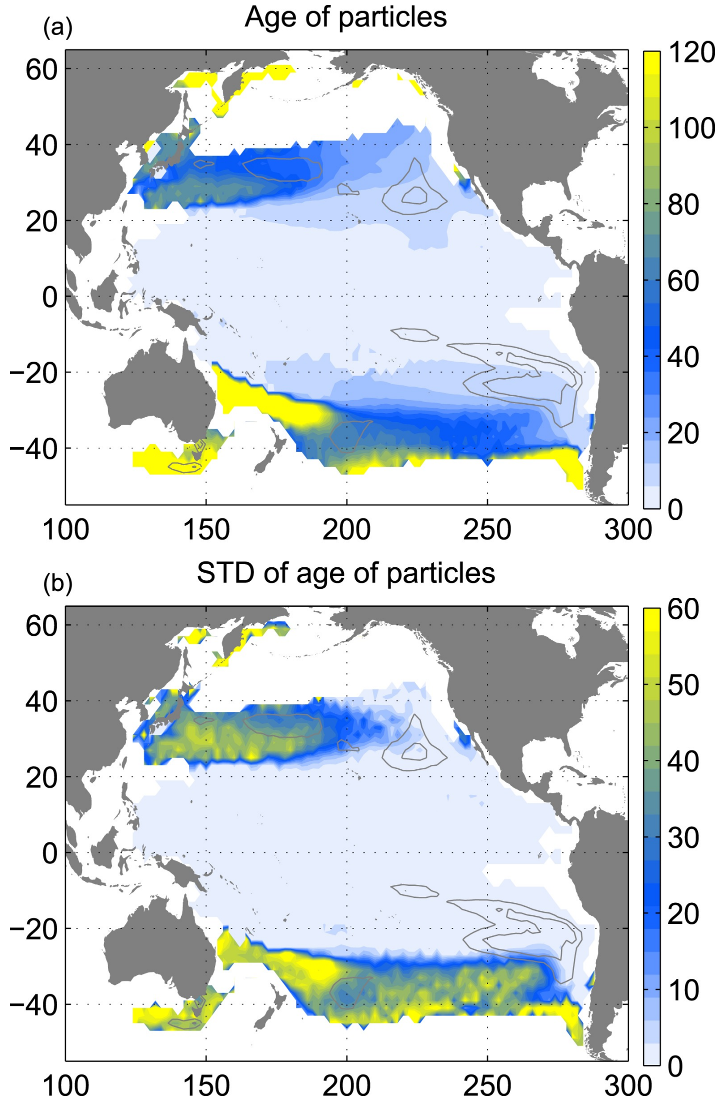
under the constraint of a balanced heat budget (Boccaletti et al., 2004).

Lagrangian analysis of the origin of water upwelled along the equator in the Pacific (IPSL Model)

Subduction Regions

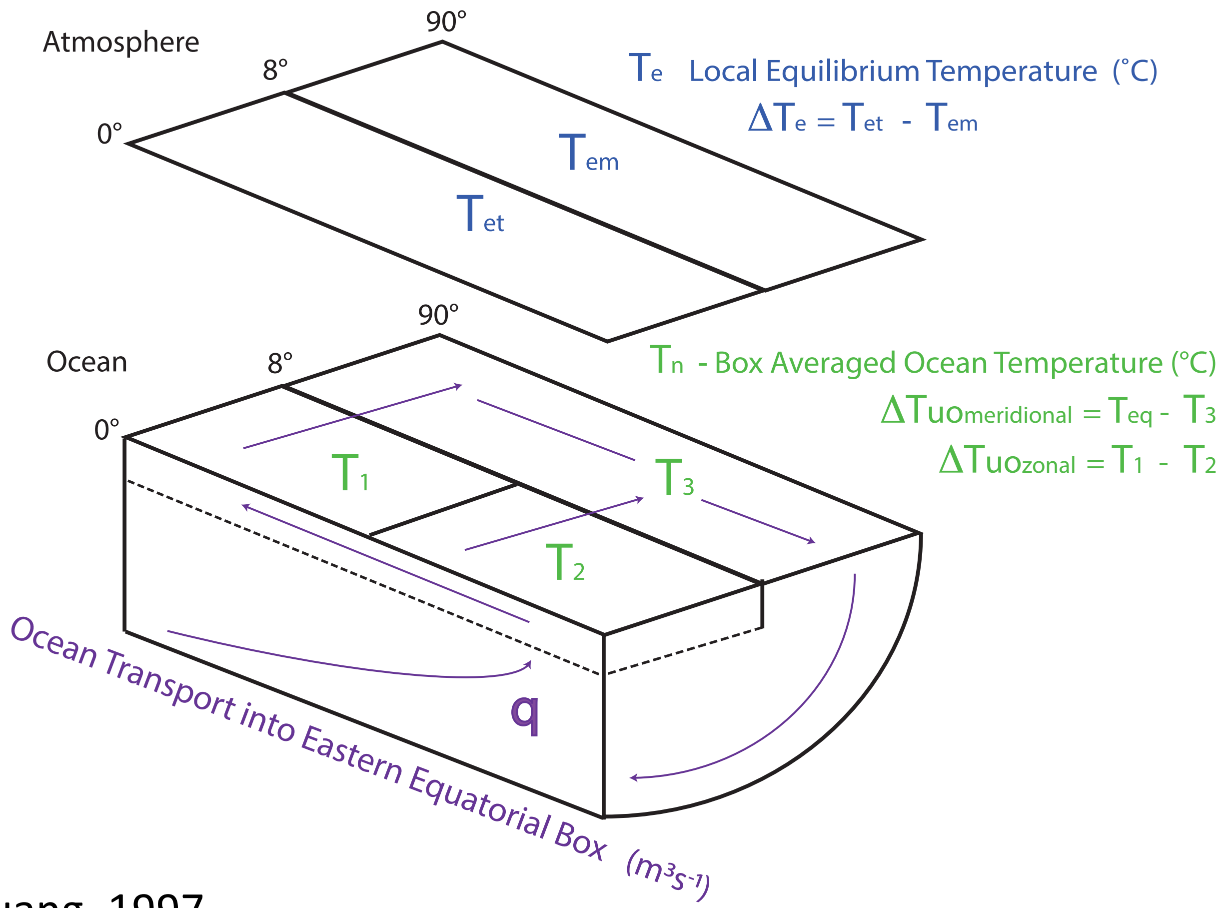


Probability density function showing the origins of upwelled EEP water in the model

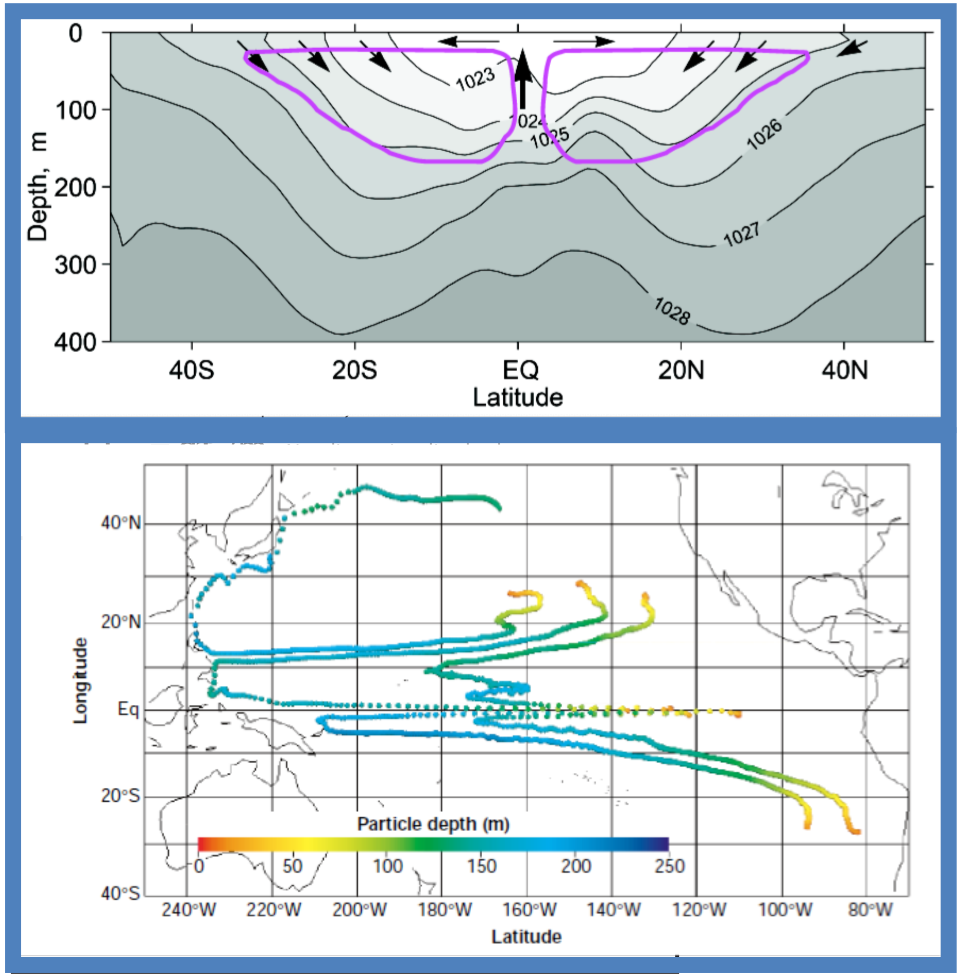


Thomas and Fedorov, 2017

A couple ocean-atmosphere theory that includes the influence of the extra-tropics

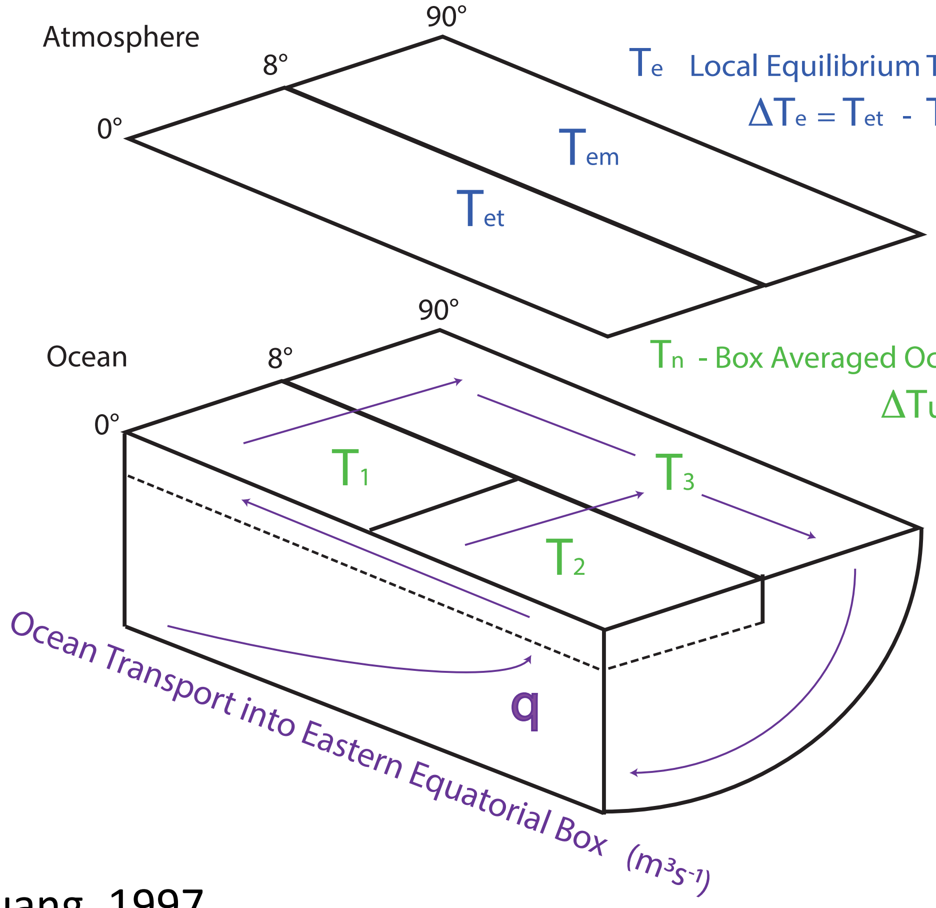


Liu and Huang, 1997



Gu and Philander, 1997

A couple ocean-atmosphere theory that includes the influence of the extrat-ropics



T_e Local Equilibrium Temperature (°C)

$\Delta T_e = T_{et} - T_{em}$

T_n - Box Averaged Ocean Temperature (°C)

$\Delta Tuo_{meridional} = T_{eq} - T_3$

$\Delta Tuo_{zonal} = T_1 - T_2$

m_n The volume of each Box (m^3)

$m = m_3/m_1$

τ_r Restoring time of local negative air-sea feedback (s)

A_w Walker Coupling Parameter ($m^3s^{-1}K^{-1}$)

A_h Hadley Coupling Parameter ($m^3s^{-1}K^{-1}$)

ϵ Branching Parameter

$T_{eq} = 1/2(T_1 + T_2)$

$Q = q\tau_r/m_1$ Nondimensionalized volume transport

Q_i 1/Q

$$q = A_h(T_{eq} - T_3) + A_w(T_1 - T_2)$$

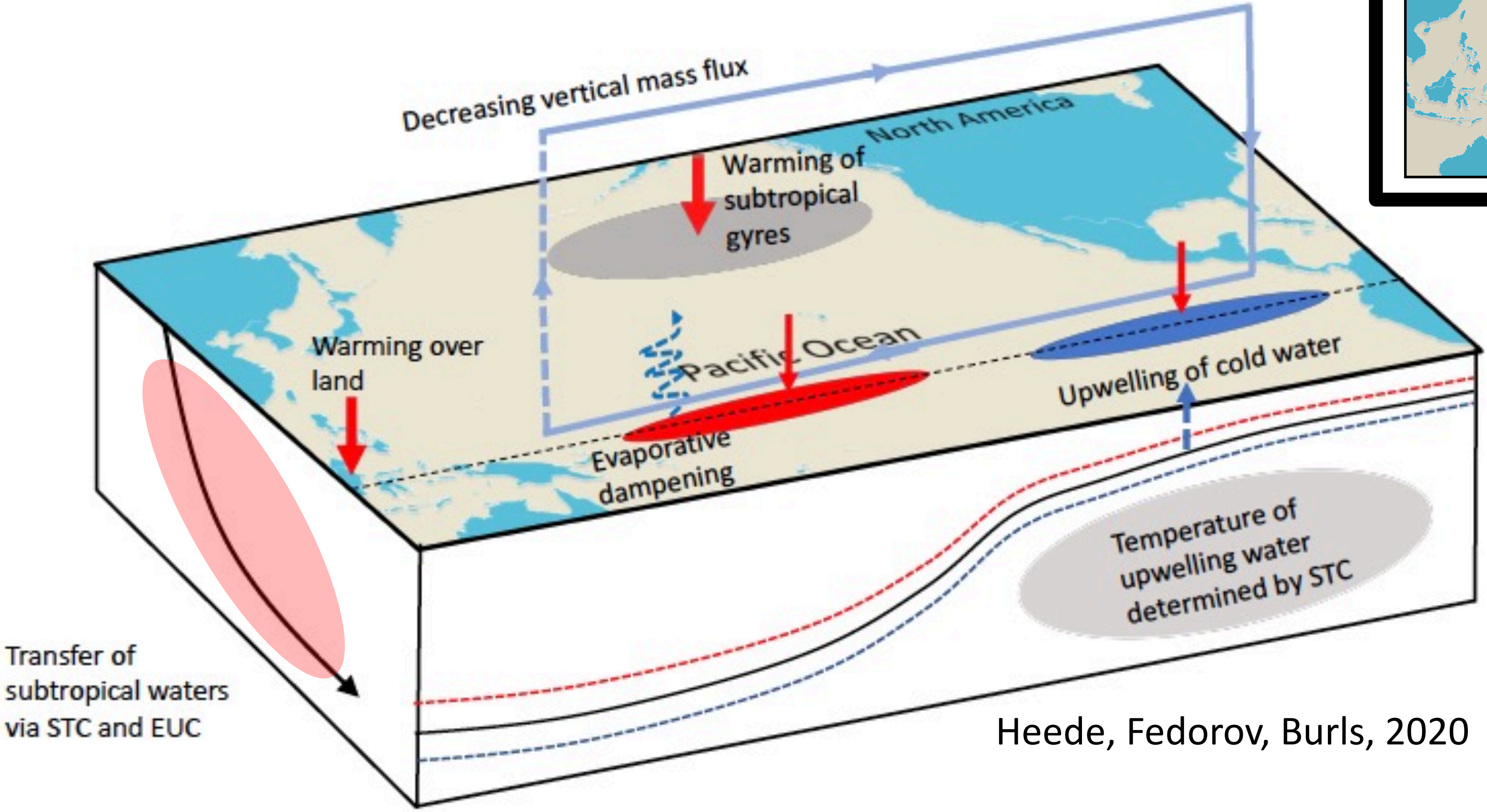
$$m_1 dT_1/dt = m_1(T_{et} - T_1)/\tau_r + (1-\epsilon)q(T_2 - T_1)$$

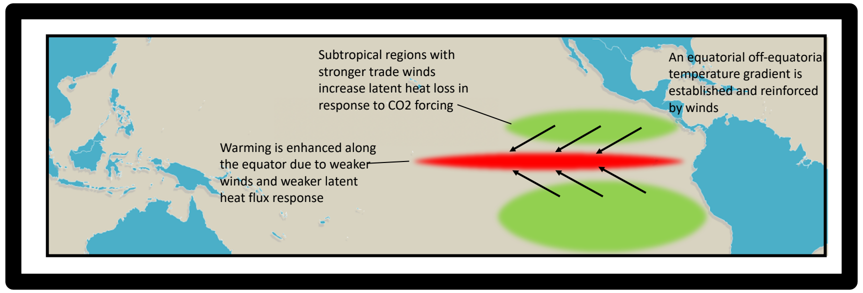
$$m_2 dT_2/dt = m_2(T_{et} - T_2)/\tau_r + q(T_3 - T_2)$$

$$m_3 dT_3/dt = m_3(T_{em} - T_3)/\tau_r + \epsilon q(T_2 - T_3) + (1-\epsilon)q(T_1 - T_3)$$

Liu and Huang, 1997

The Response of Tropical Climate to Warming





Plus wind-evaporation-SST feedback e.g. Xie et al., 2010

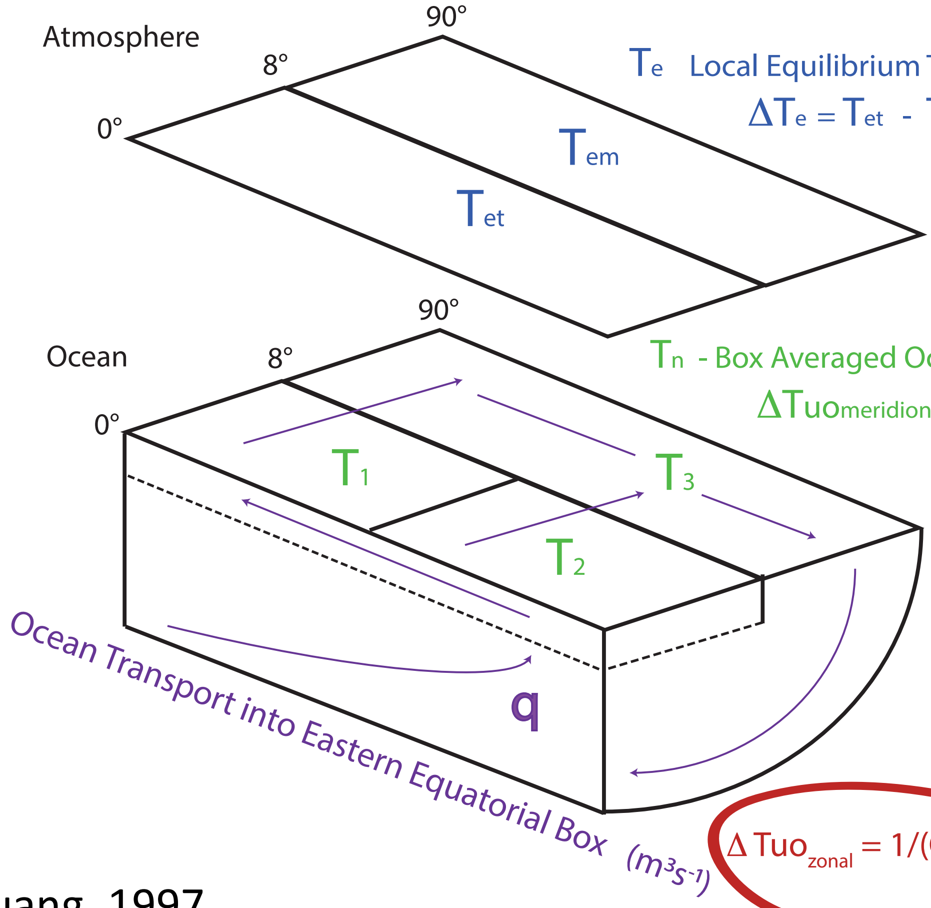
Amplified by cloud feedbacks e.g. Kang et al., 2020, Luongo et al. 2023

Heede, Fedorov, Burls, 2020

These mechanisms operate on different timescales

Equilibrium Arguments

A couple ocean-atmosphere theory that includes the influence of the extratropics



T_e Local Equilibrium Temperature (˚C)

$\Delta T_e = T_{et} - T_{em}$

T_n - Box Averaged Ocean Temperature (°C)

$\Delta Tuo_{meridional} = 1/2(T_1 + T_2) - T_3$

$\Delta Tuo_{zonal} = T_1 - T_2$

$\Delta Tuo_{zonal} = 1/(Q_i + 3/2 - \varepsilon)\, \Delta Tuo_{meridional}$

- m_n The volume of each Box (m^3)
- $m = m_3/m_1$
- τ_r Restoring time of local negative air-sea feedback (s)
- A_w Walker Coupling Parameter ($m^3s^{-1}K^{-1}$)
- A_h Hadley Coupling Parameter ($m^3s^{-1}K^{-1}$)
- ϵ Branching Parameter
- $T_{eq} = 1/2(T_1 + T_2)$
- $Q = q\tau_r/m_1$ Nondimensionalized volume transport
- Q_i 1/Q

$$q = A_h(T_{eq} - T_3) + A_w(T_1 - T_2)$$

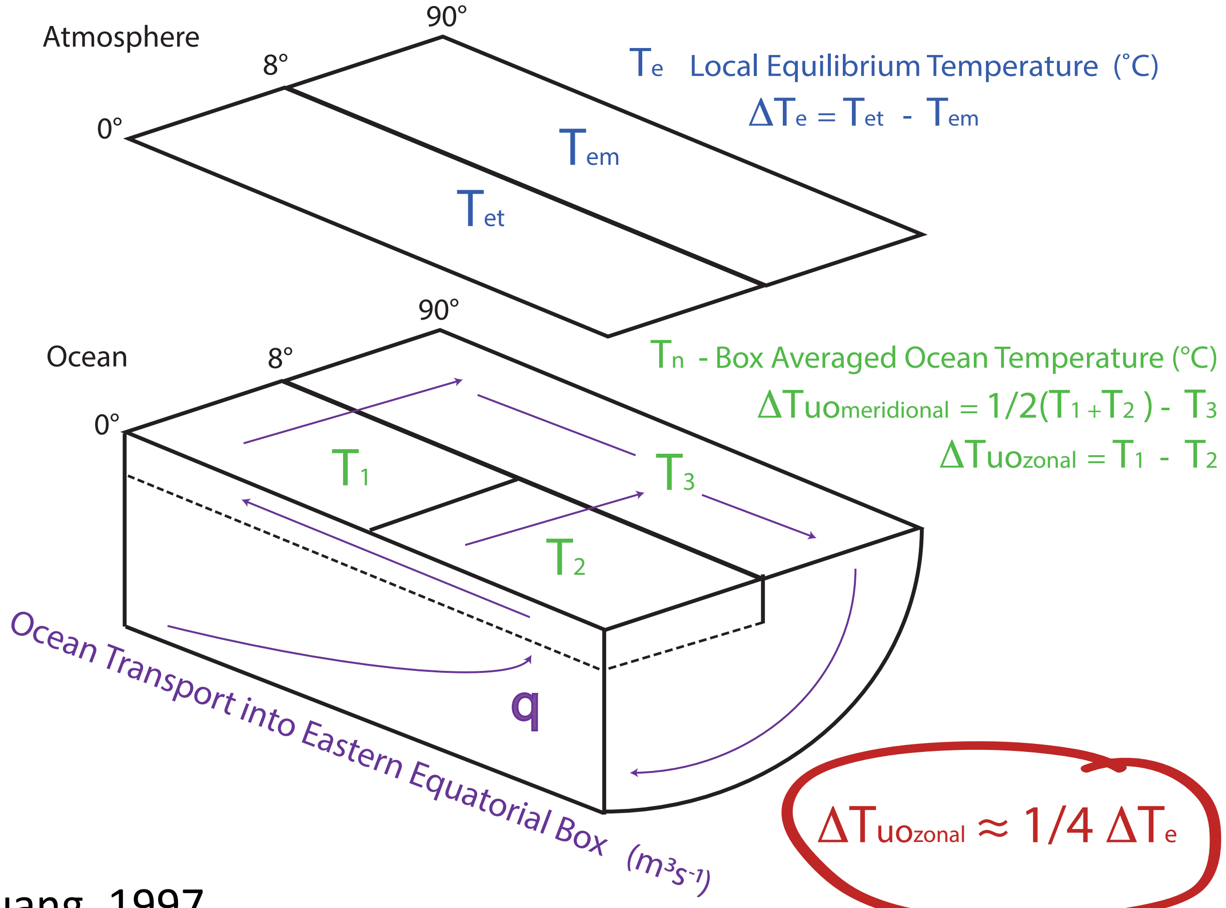
$$m_1 dT_1/dt = m_1(T_{et} - T_1)/\tau_r + (1-\epsilon)q(T_2 - T_1)$$

$$m_2 dT_2/dt = m_2(T_{et} - T_2)/\tau_r + q(T_3 - T_2)$$

$$m_3 dT_3/dt = m_3(T_{em} - T_3)/\tau_r + \epsilon q(T_2 - T_3) + (1-\epsilon)q(T_1 - T_3)$$

Liu and Huang, 1997

A couple ocean-atmosphere theory that includes the influence of the extratropics



m_n The volume of each Box (m^3)

$m = m_3/m_1$

τ_r Restoring time of local negative air-sea feedback (s)

A_w Walker Coupling Parameter ($m^3s^{-1}K^{-1}$)

A_h Hadley Coupling Parameter ($m^3s^{-1}K^{-1}$)

ϵ Branching Parameter

$T_{eq} = 1/2(T_1 + T_2)$

$Q = q\tau_r/m_1$ Nondimensionalized volume transport

Q_i 1/Q

$$q = A_h(T_{eq} - T_3) + A_w(T_1 - T_2)$$

$$m_1 dT_1/dt = m_1(T_{et} - T_1)/\tau_r + (1-\epsilon)q(T_2 - T_1)$$

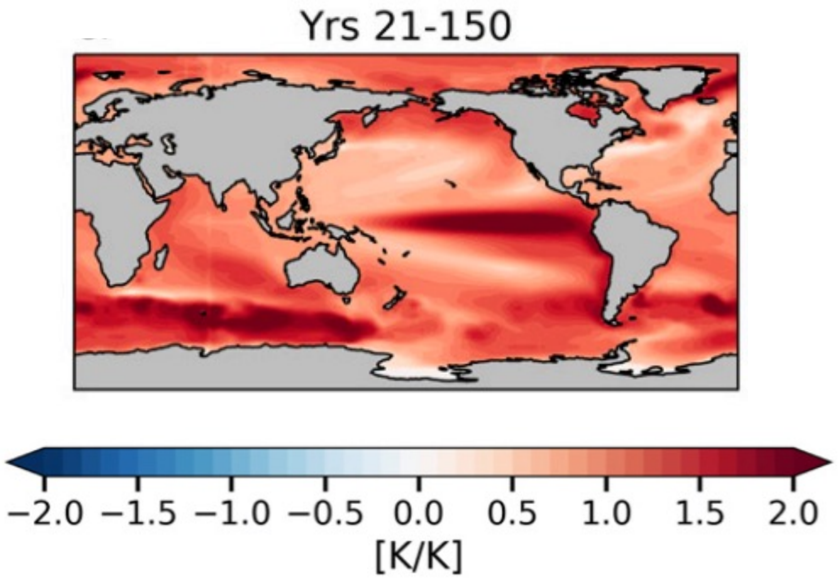
$$m_2 dT_2/dt = m_2(T_{et} - T_2)/\tau_r + q(T_3 - T_2)$$

$$m_3 dT_3/dt = m_3(T_{em} - T_3)/\tau_r + \epsilon q(T_2 - T_3) + (1-\epsilon)q(T_1 - T_3)$$

Liu and Huang, 1997

Equilibrium Response

CMIP6 abrupt 4xCO2 simulations



Dong et al., 2020

Modified Cloud Albedo and Abrupt CO_2 Sensitivity Experiments

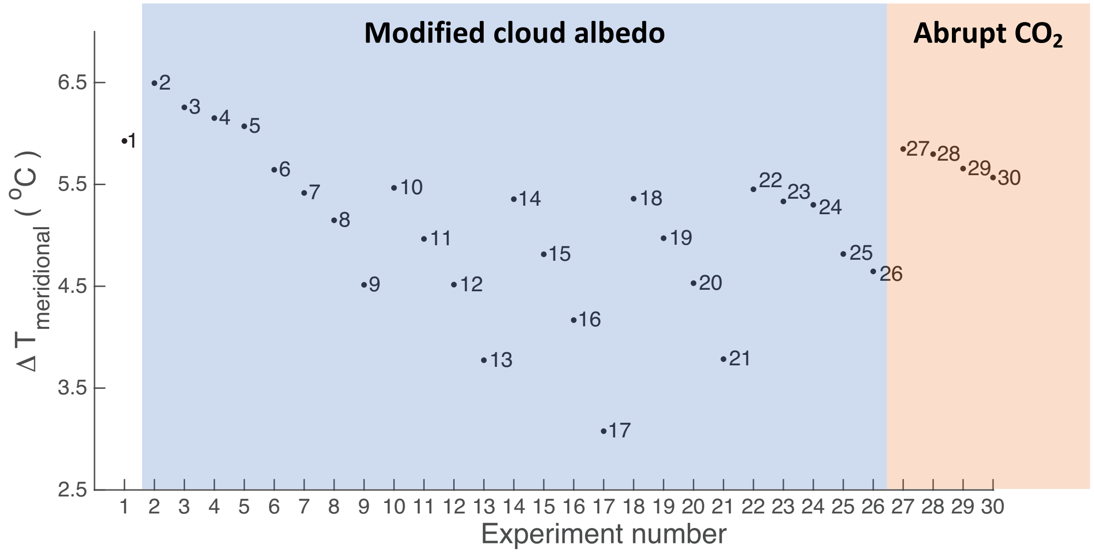
Experimental Setup

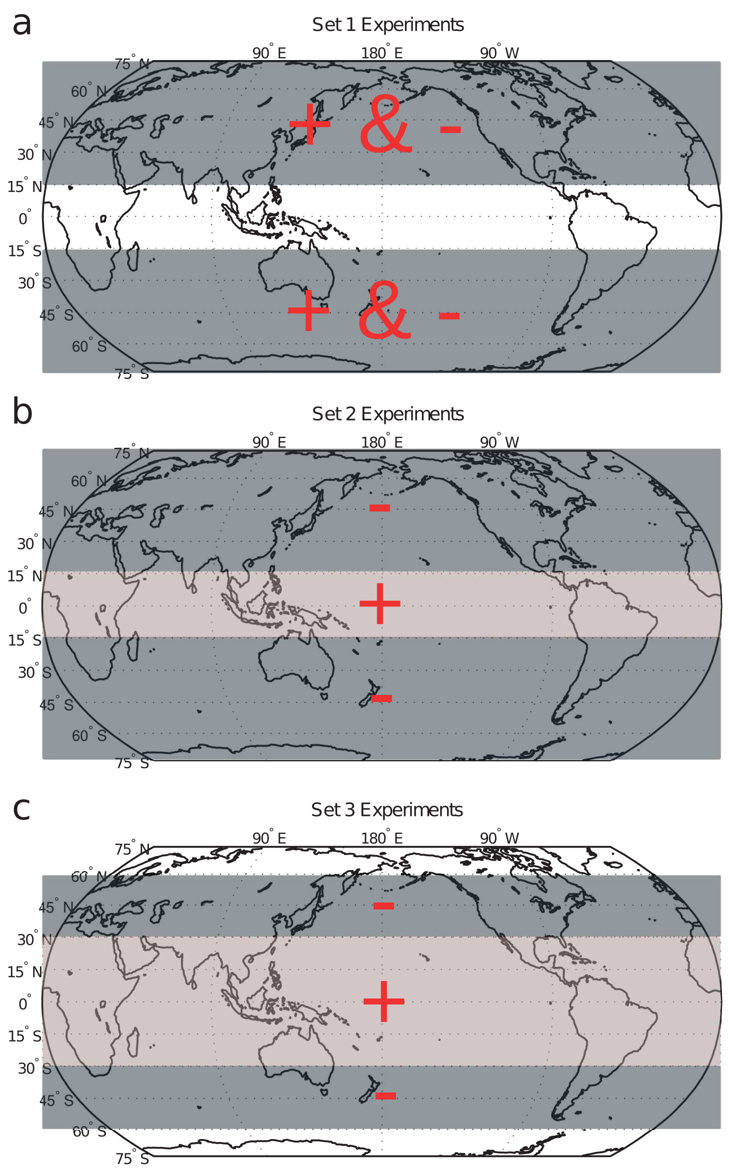
- The Community Earth System Model (CESM)
- Modified Cloud albedo experiments

  Reflectivity of clouds changed by modifying the atmospheric liquid and ice water path, but only in the shortwave radiation scheme. The changes imposed are hypothetical.

- Abrupt 2x, 4x, 8x and 16x CO_2 experiments

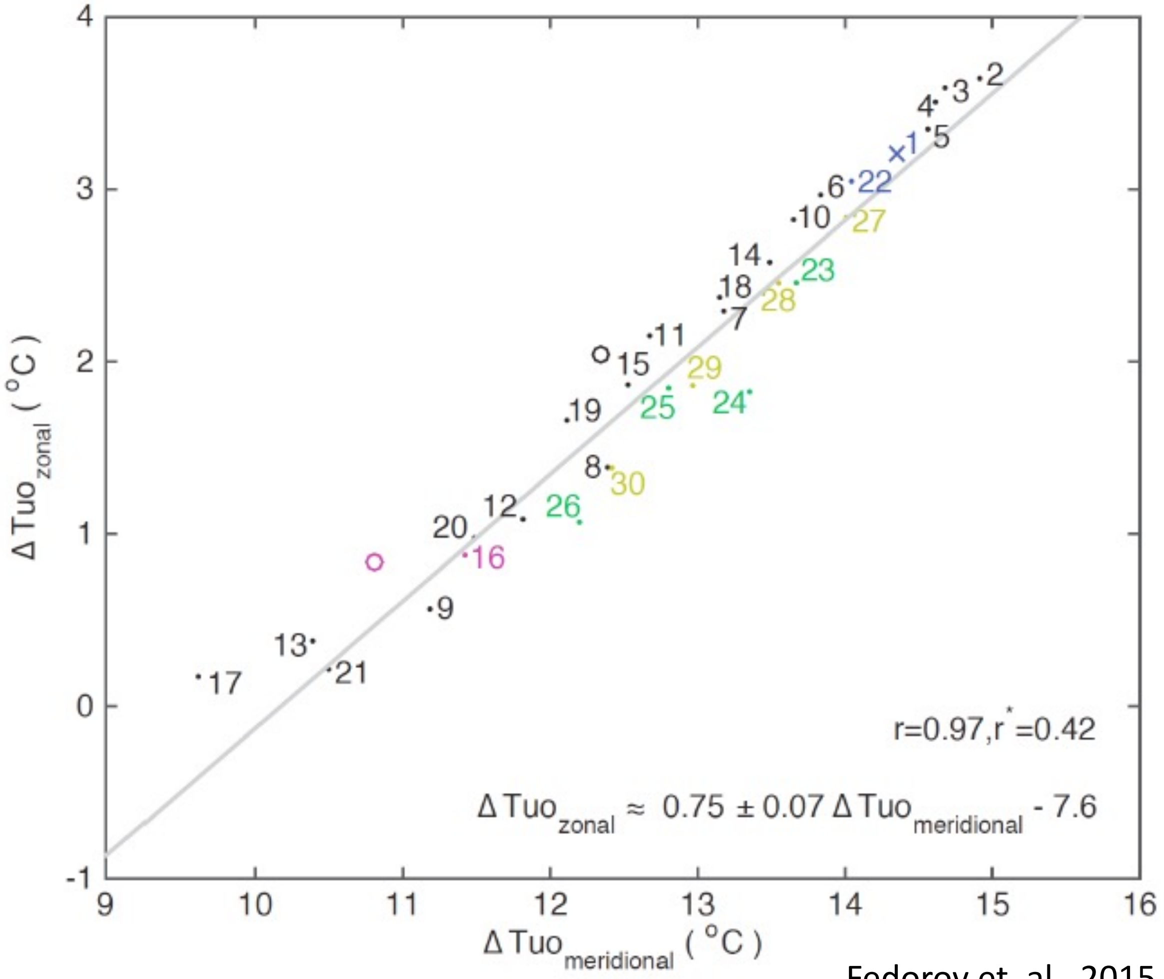
Simulating a broad range of meridional SST gradients





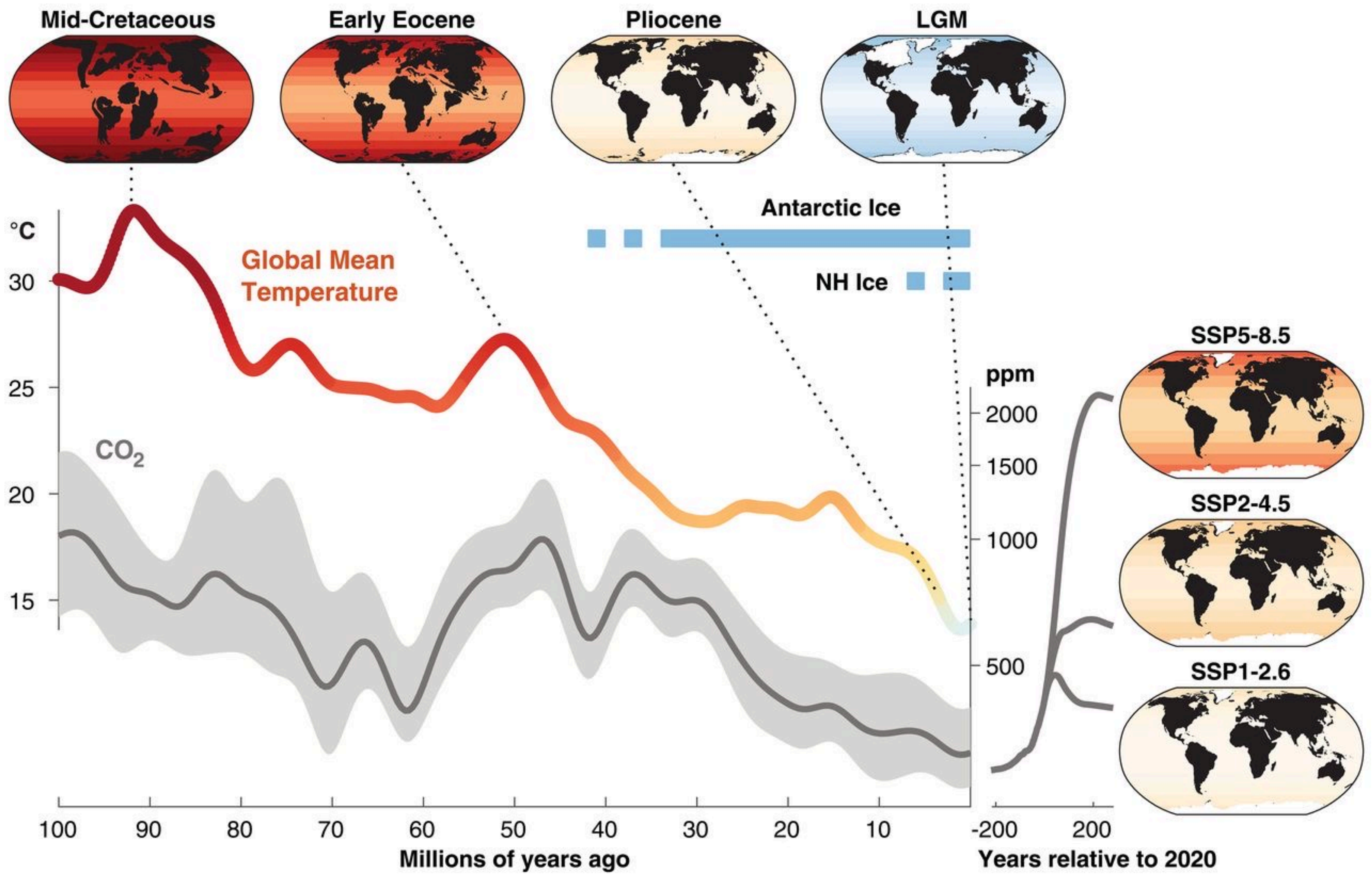
Burls and Fedorov, 2014a

Tightly linked zonal and meridional upper ocean temperature gradients



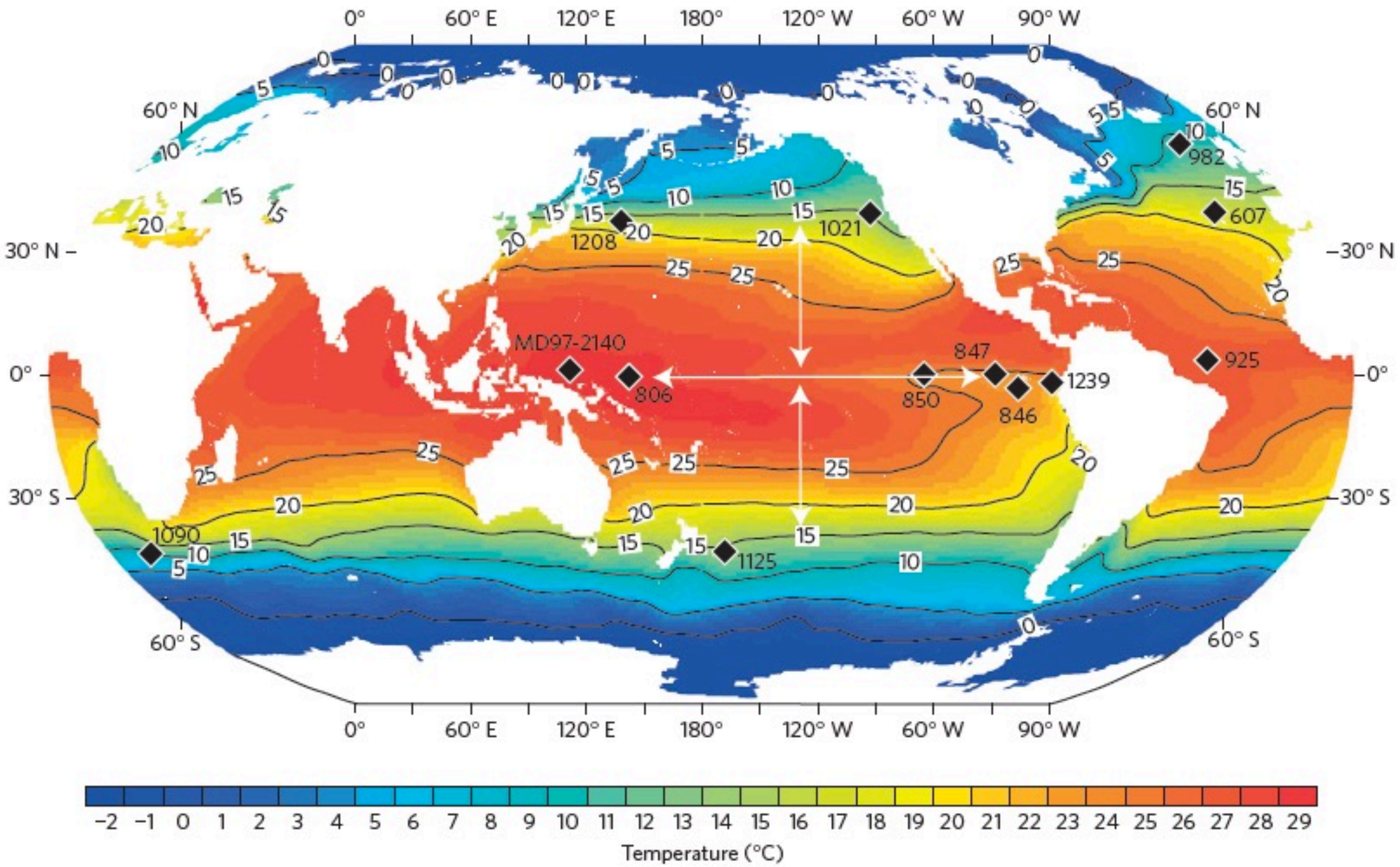
Fedorov et. al., 2015

Past warm climate analogues



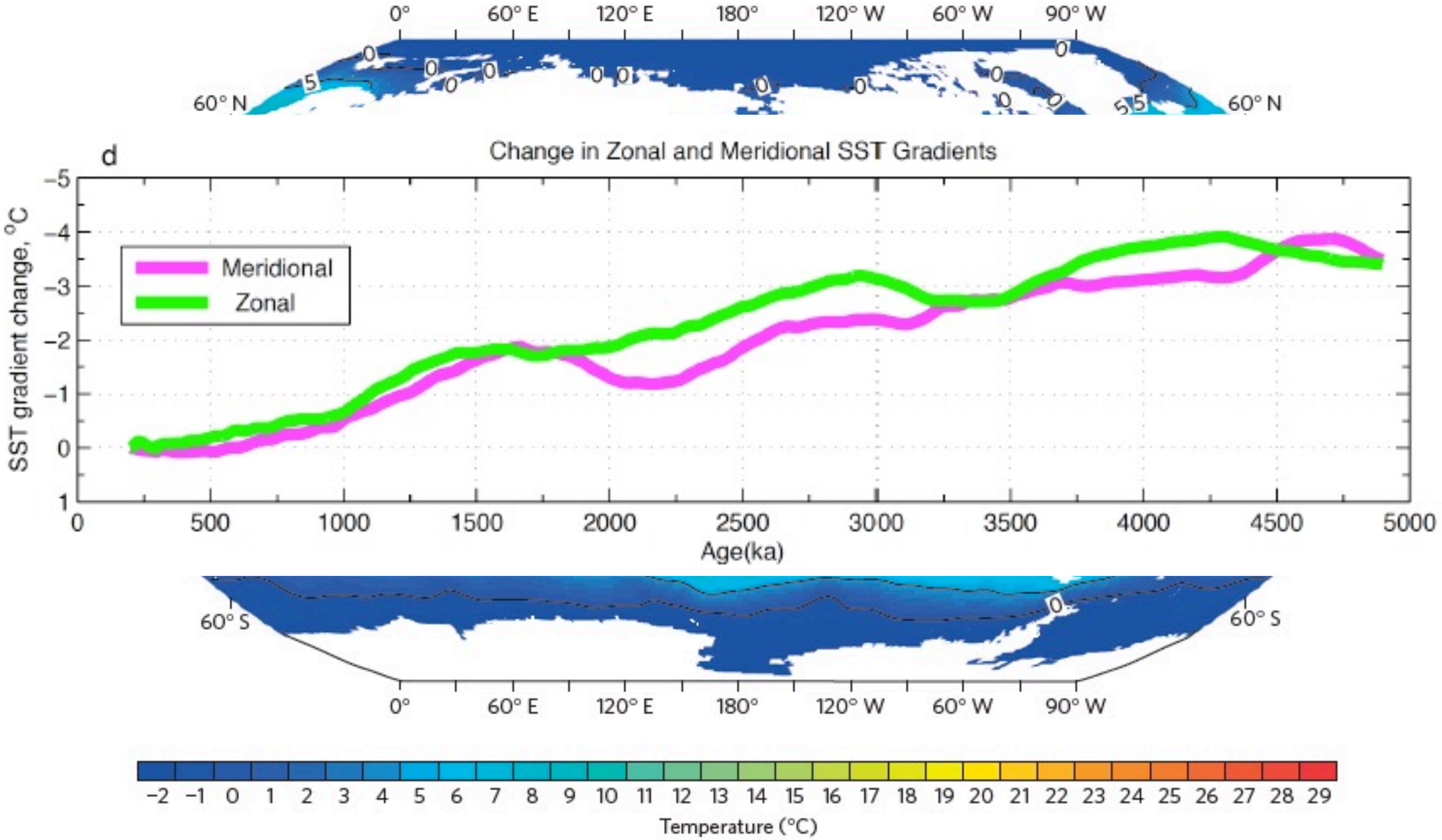
Tierney et al. *Science* 2020

Tightly linked ocean zonal and meridional temperature gradients over the past 5 million years



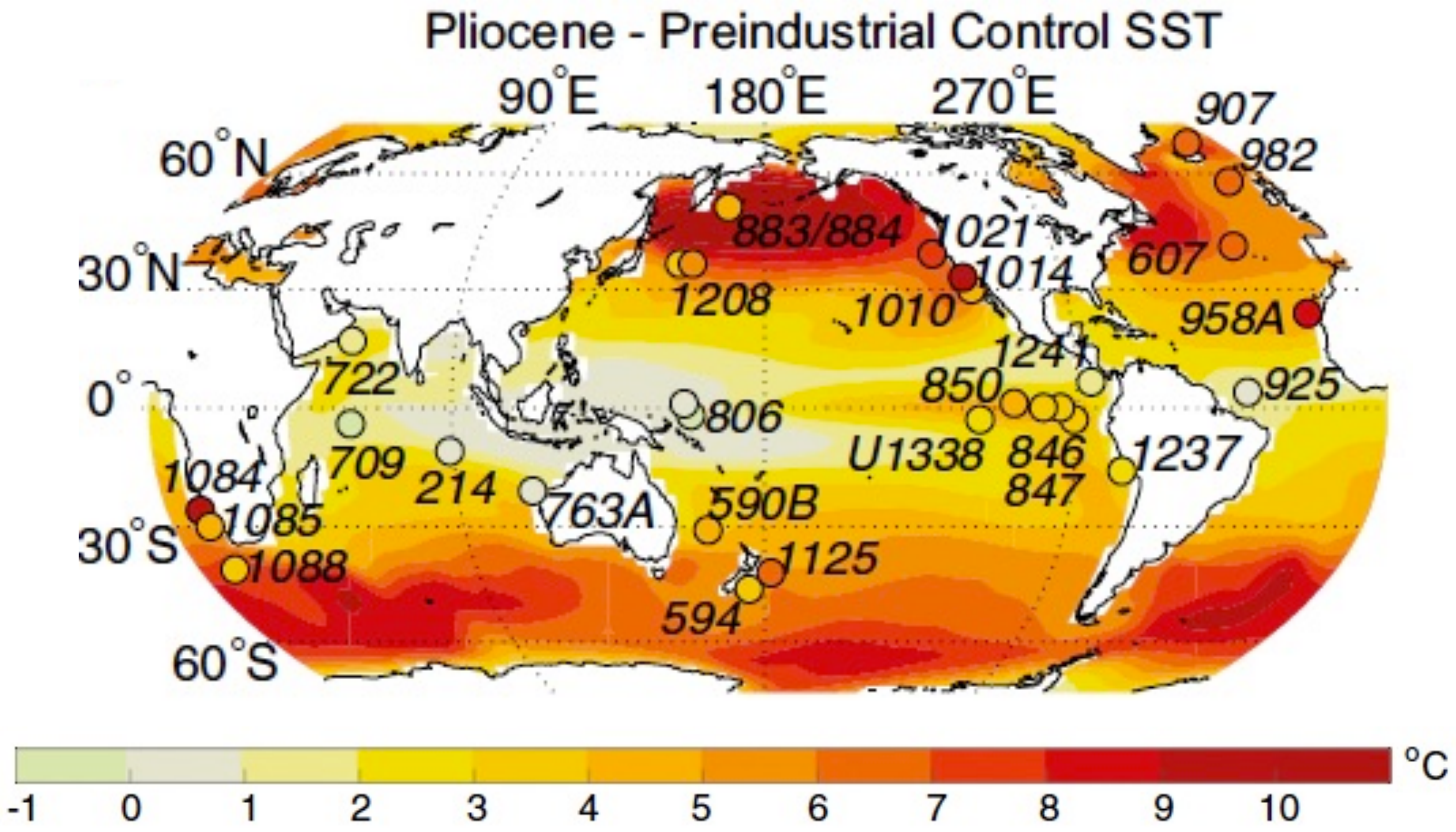
Fedorov et. al., *2015*

Tightly linked ocean zonal and meridional temperature gradients over the past 5 million years



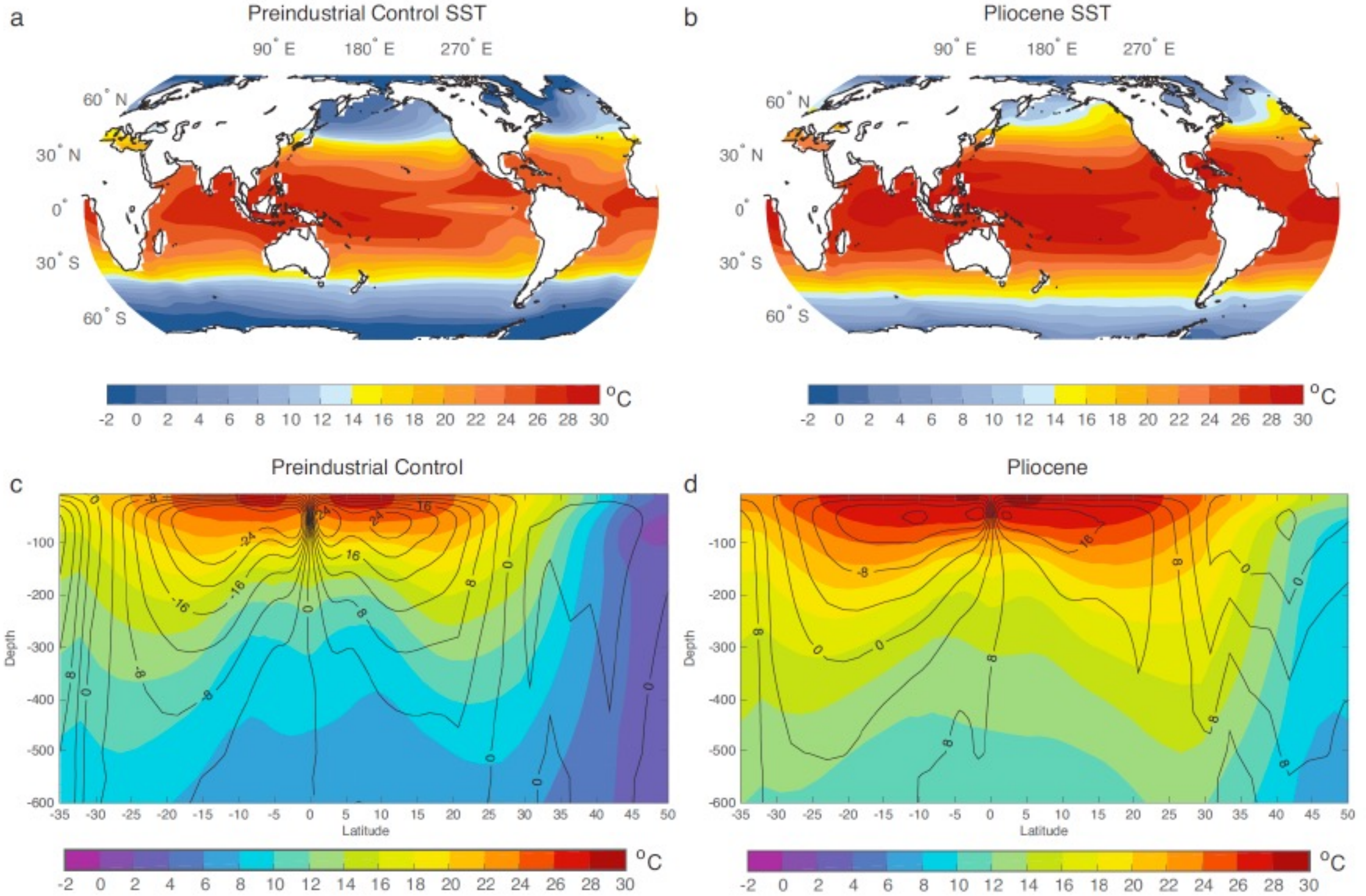
Fedorov et. al., *2015*

Simulating Pliocene conditions



Burls & Fedorov, *PNAS*, 2017

Thermal Structure of the Early Pliocene Ocean

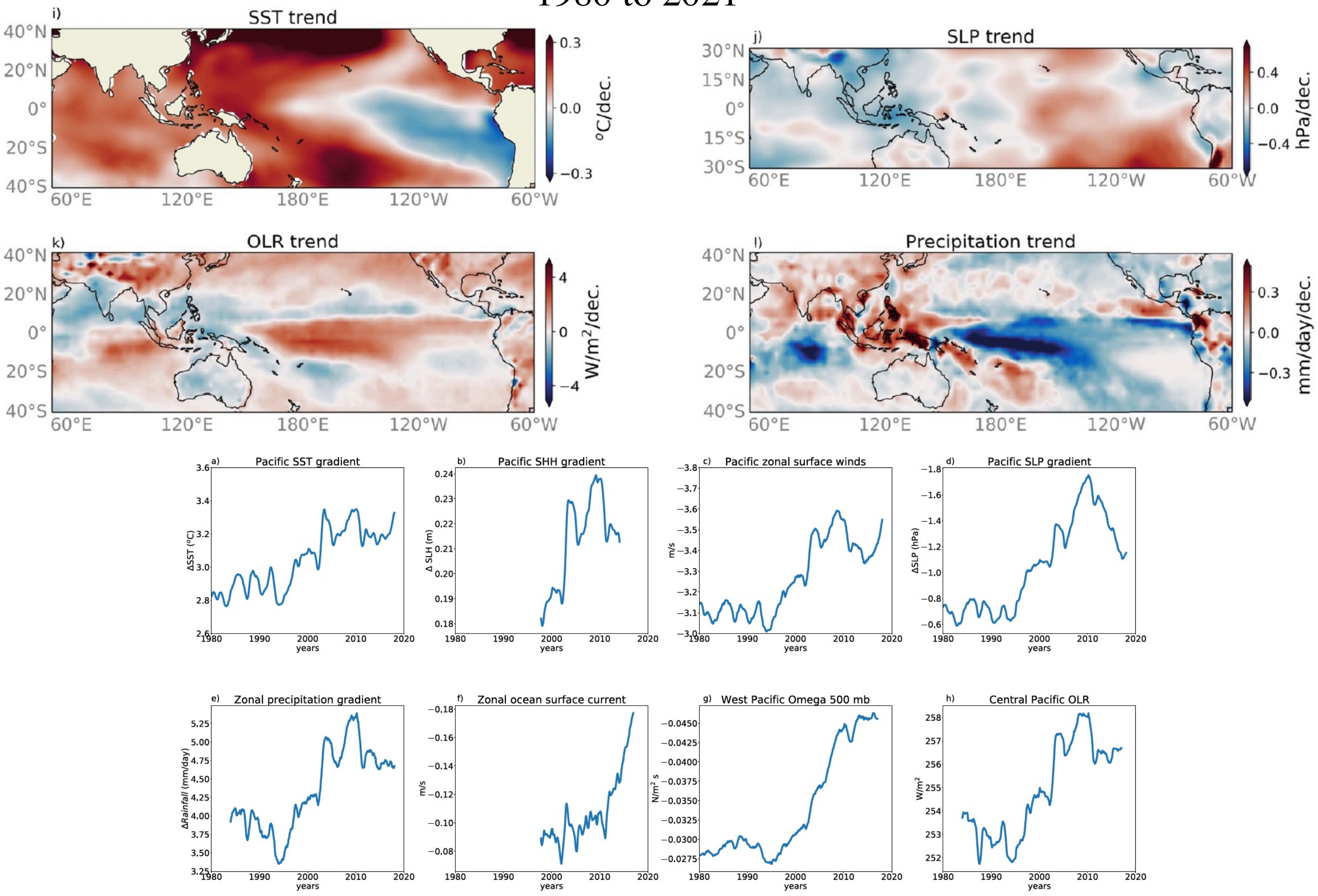


Burls & Fedorov, *Paleoceanography*, 2014

Transient Response

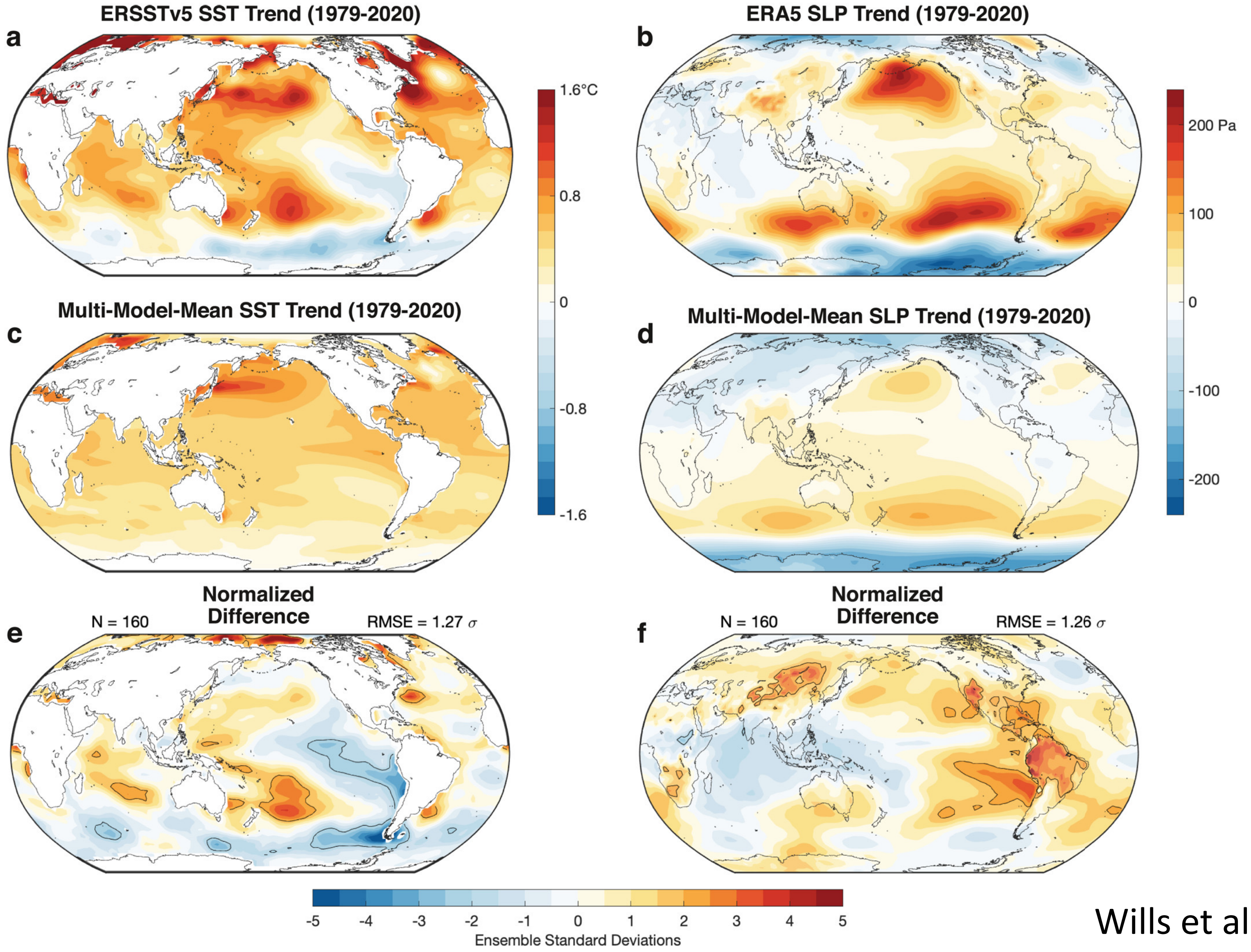
Historical Trends

1980 to 2021



Heede and Fedorov, 2022

Historical Trends



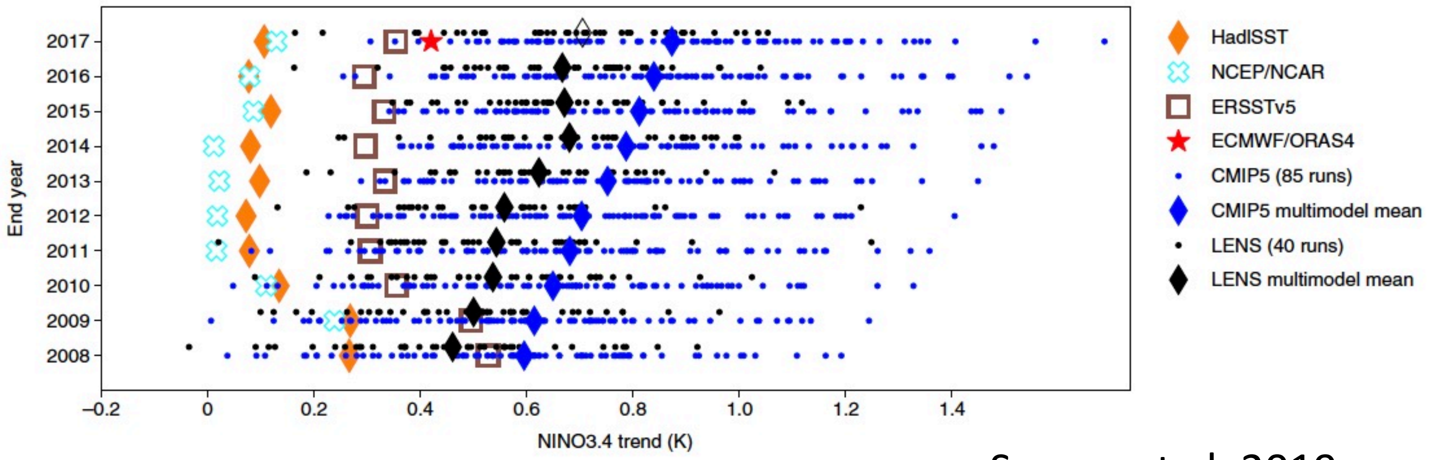
Wills et al., 2022

Why the model-data mismatch

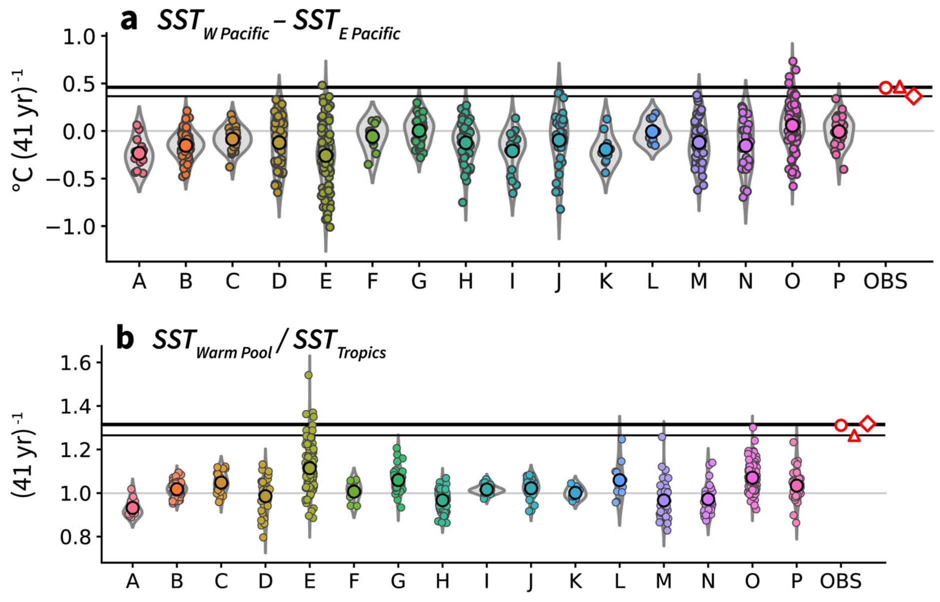
- Pacific multi-decadal variability (internal variability, a.k.a. natural variability) e.g. McPhaden et al, 2011; England et al., 2014
- Remote influence of Atlantic multi-decadal variability e.g. McGregor et al., 2014
- Missing aerosol forcing e.g. Takahashi and Watanabe 2016
- Tropical Pacific Biases e.g. Seager et al., 2019
- Southern Ocean forcing e.g. Huang et al., 2017

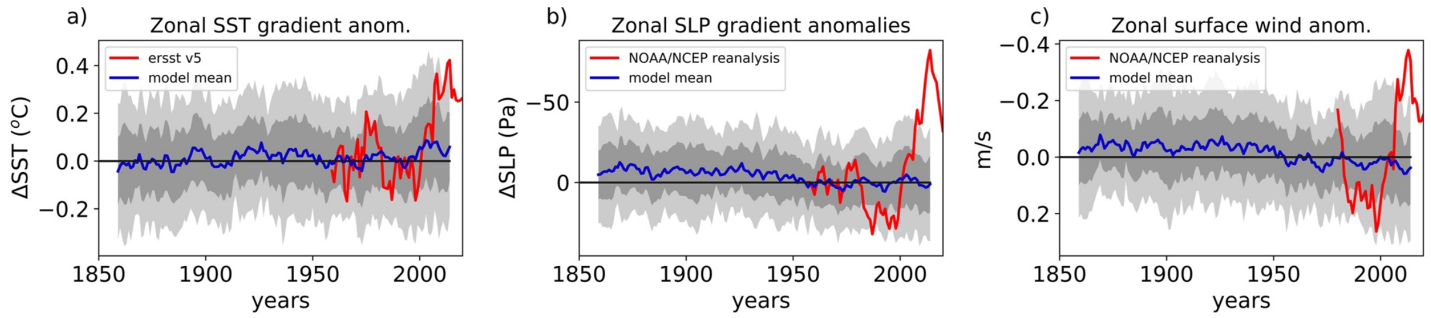
Historical Trends

***60 year trends in Nino 3.4,* (1958–2017)**



Seager et al. 2019





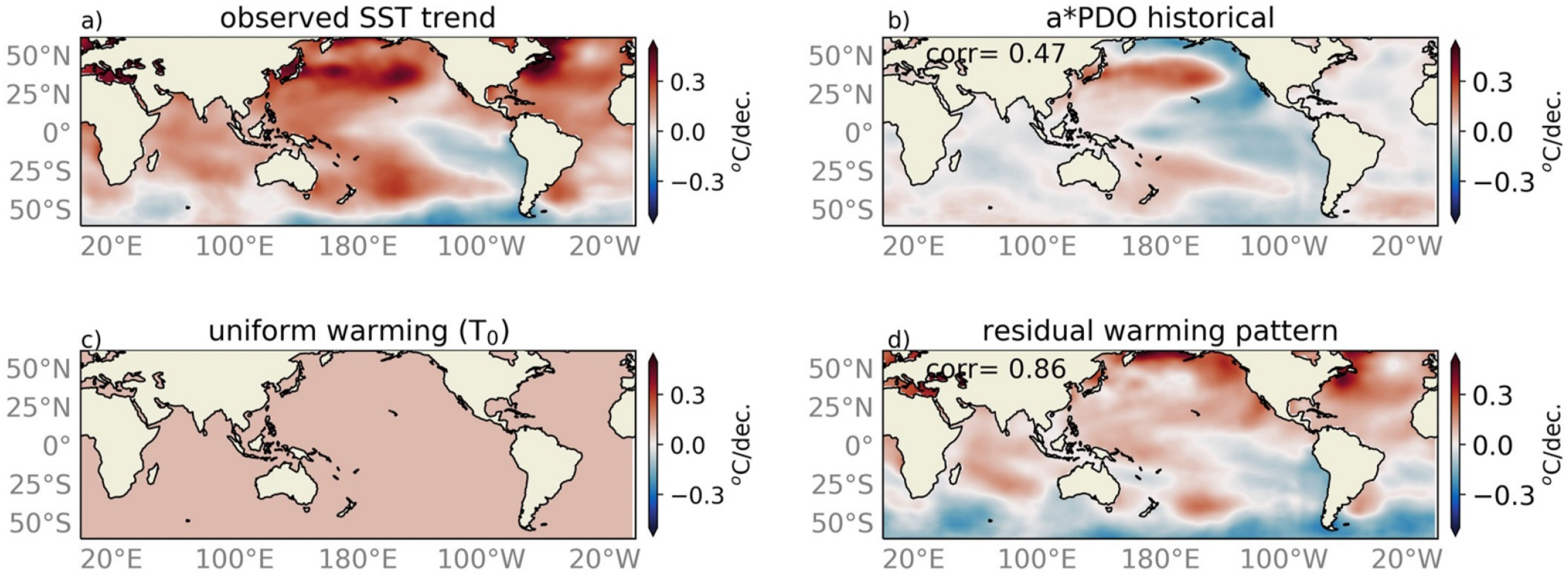
Heede and Fedorov, 2022

○ ERSSTv5
△ AMIPII
◇ COBE
○ ERA5
△ JRA55
○ ERSSTv5, ERA5
△ ERSSTv5, OBS-mean PSL
◇ OBS-mean SST, ERA5

A: ACCESS-ESM1.5
B: CanESM2
C: CanESM5
D: CESM1
E: CESM2
F: CNRM-CM6.1
G: CSIRO-Mk3.6
H: EC-Earth3
I: GFDL-CM3
J: GFDL-ESM2M
K: GISS-E2.1-G
L: IPSL-CM6A-LR
M: MIROC6
N: MIROC-ES2L
O: MPI-ESM
P: NorCPM1

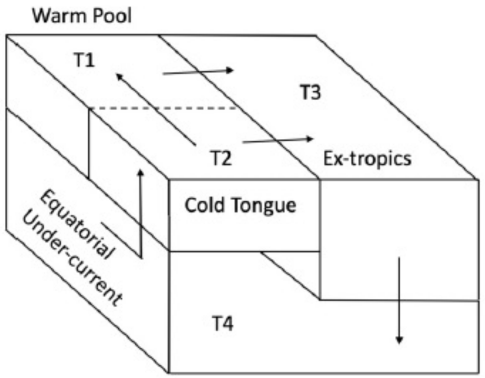
Wills et al., 2022

Transient versus Equilibrium



Heede and Fedorov, 2022

Transient Response in the Idealized Box Model



$$\frac{dT_1}{dt} = m_1 H_1 + q(1-\varepsilon)(T_2 - T_1)$$

$$m_2 \frac{dT_2}{dt} = m_2 H_2 + q(T_4 - T_2)$$

$$m_3 \frac{dT_3}{dt} = m_3 H_3 + q\varepsilon(T_2 - T_3) + q(1-\varepsilon)(T_1 - T_3)$$

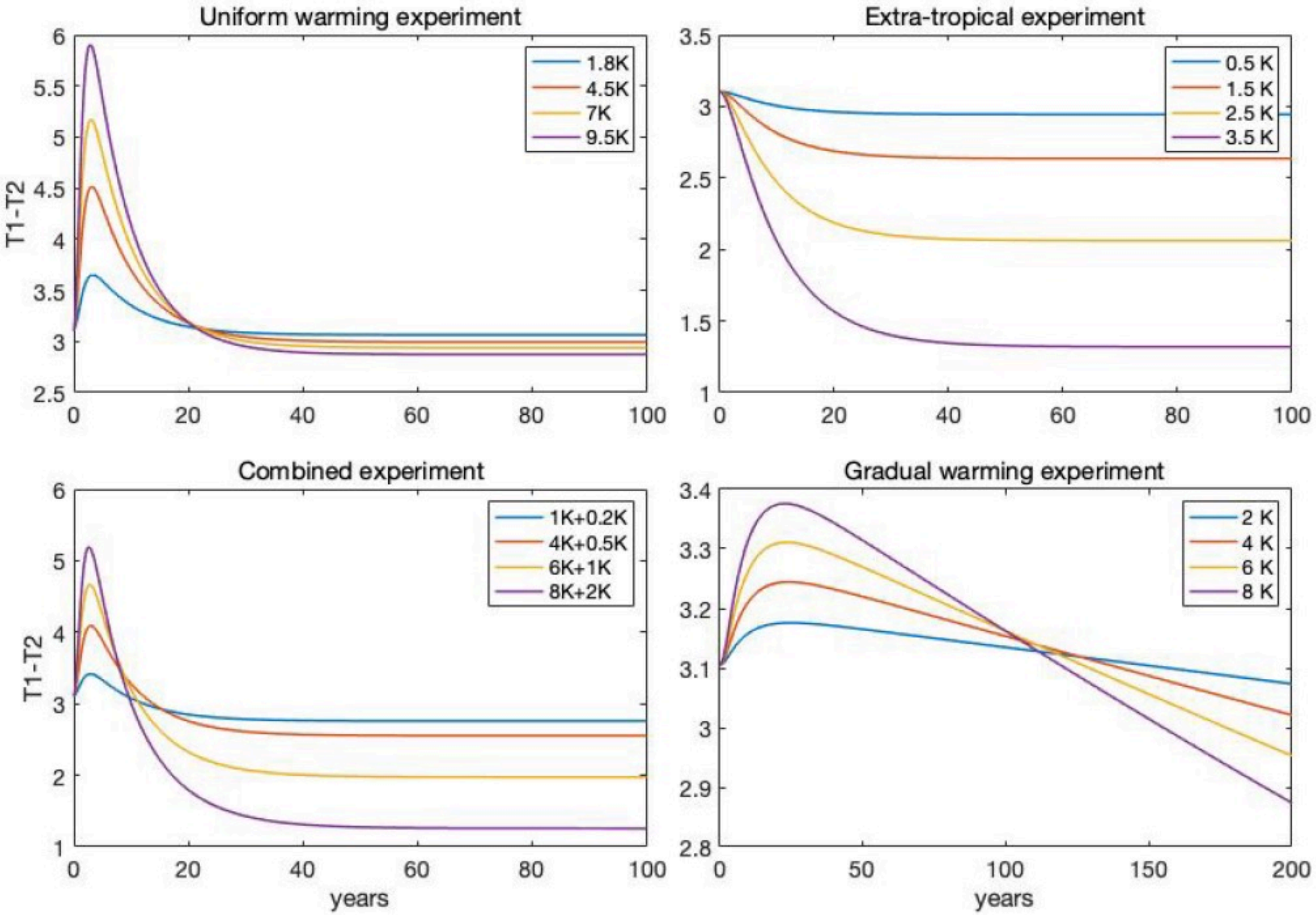
$$m_4 \frac{dT_4}{dt} = q(T_3 - T_4)$$

$$q = A_H(T_{eq} - T_3) + A_W(T_1 - T_2)$$

$$H_i = \frac{1}{C_p \rho h_i}(H_{sw} - (H_{latent} + H_{sensible} + H_{OLR})), \quad i = 1,2,3$$

$$H_{iOLR} = E\sigma T_i^4, \quad i = 1,2,3$$

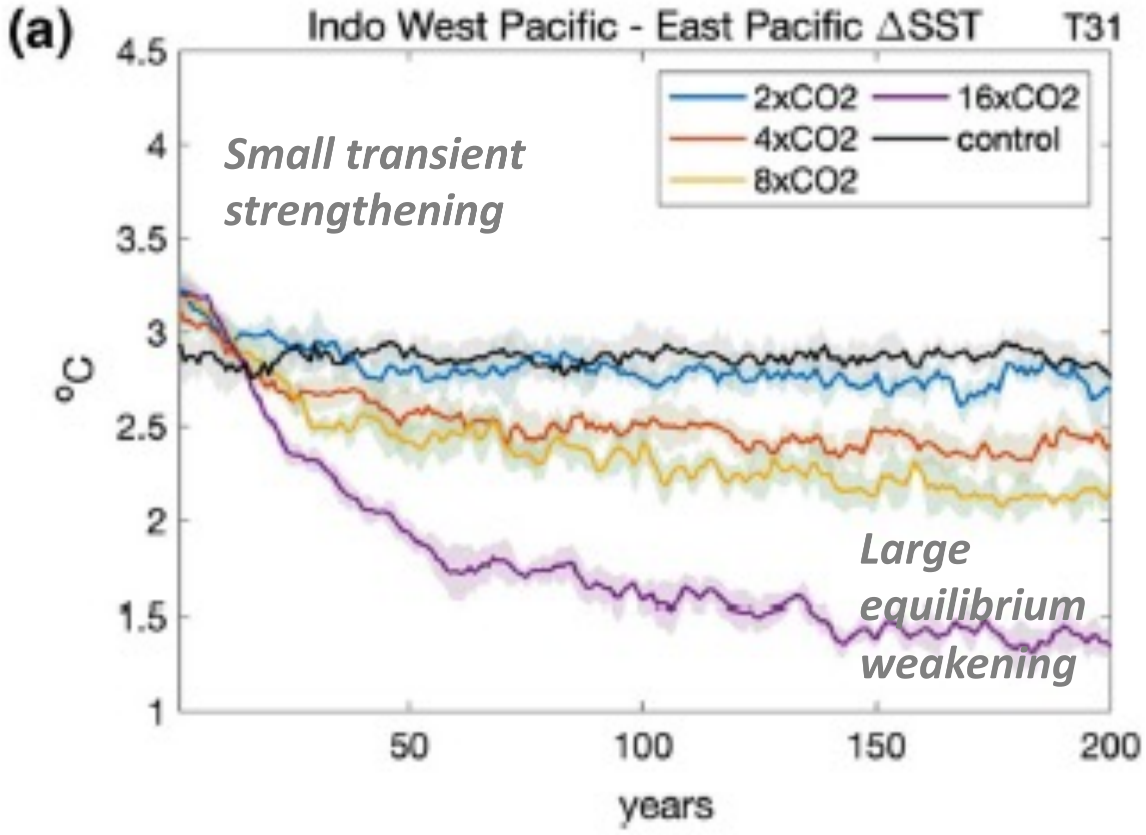
$$H_{i_{Latent}} = LV_{a_i} C_L \frac{0.622}{\rho_{air}} e_s(T_i)(1 - RH), \quad i = 1,2,3$$



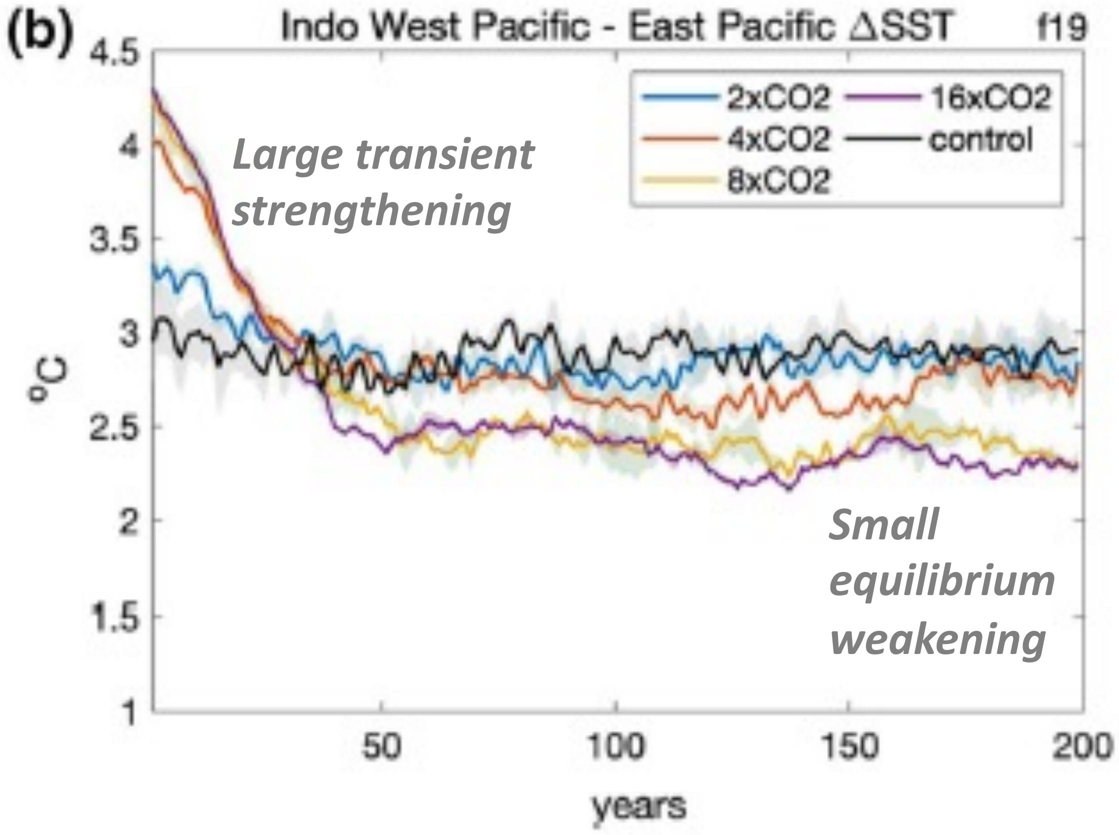
Heede, Fedorov, Burls, 2020

Model Dependance of Transient and Equilibrium Response

Low Res CESM (T31)



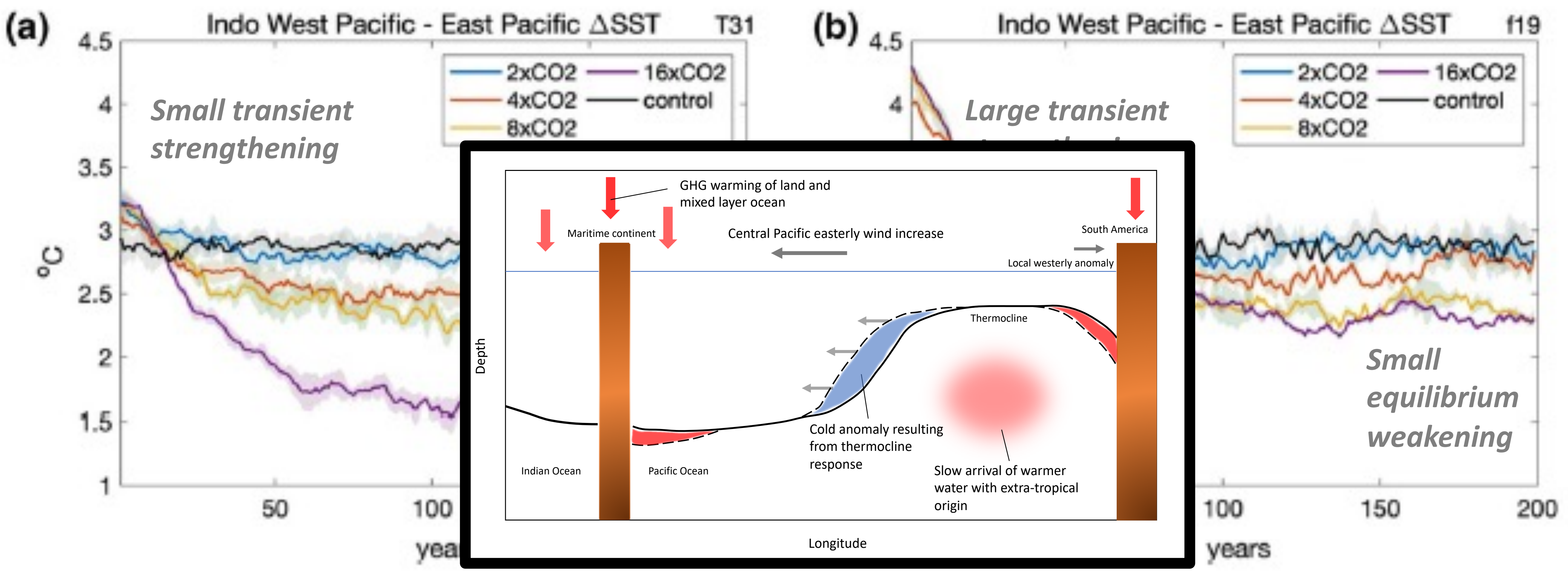
High Res CESM (f19)



Heede, Fedorov, Burls, 2021

Model Dependance of Transient and Equilibrium Response

Low Res CESM (T31) **High Res CESM (f19)**

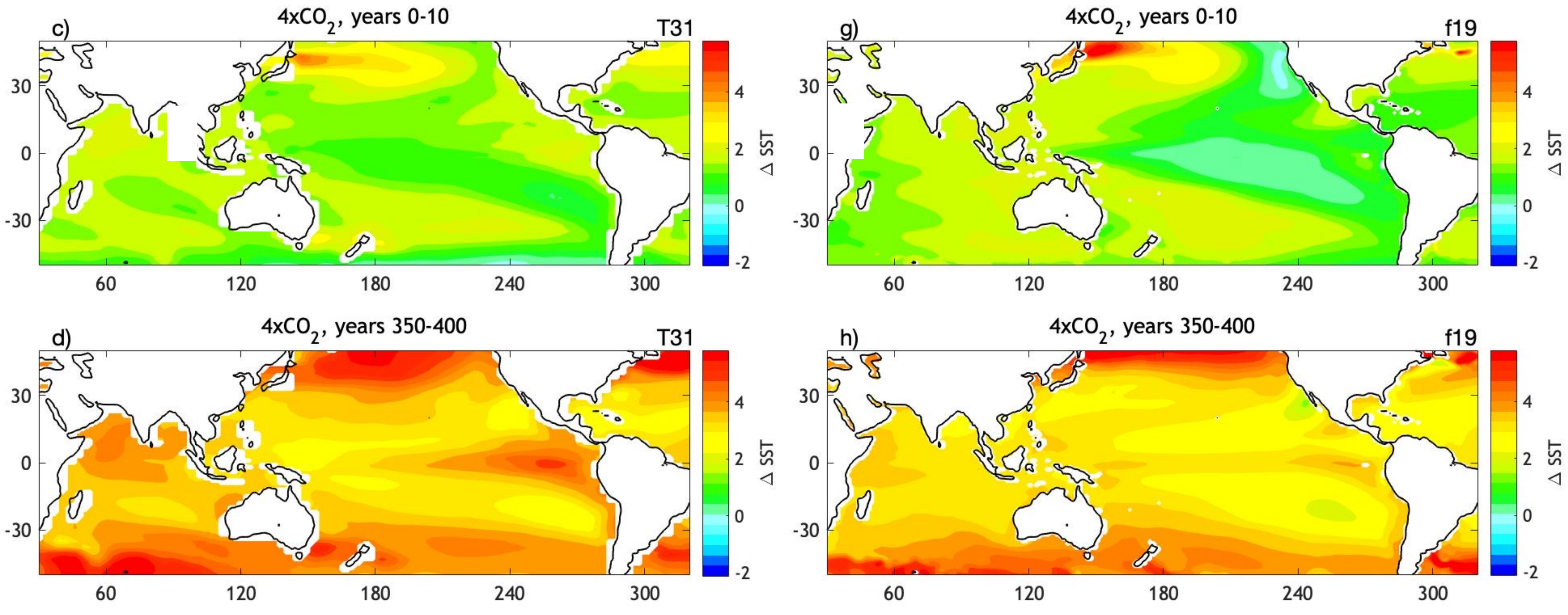


Heede, Fedorov, Burls, 2021

Model Dependance of Transient Response

Low Res CESM

High Res CESM

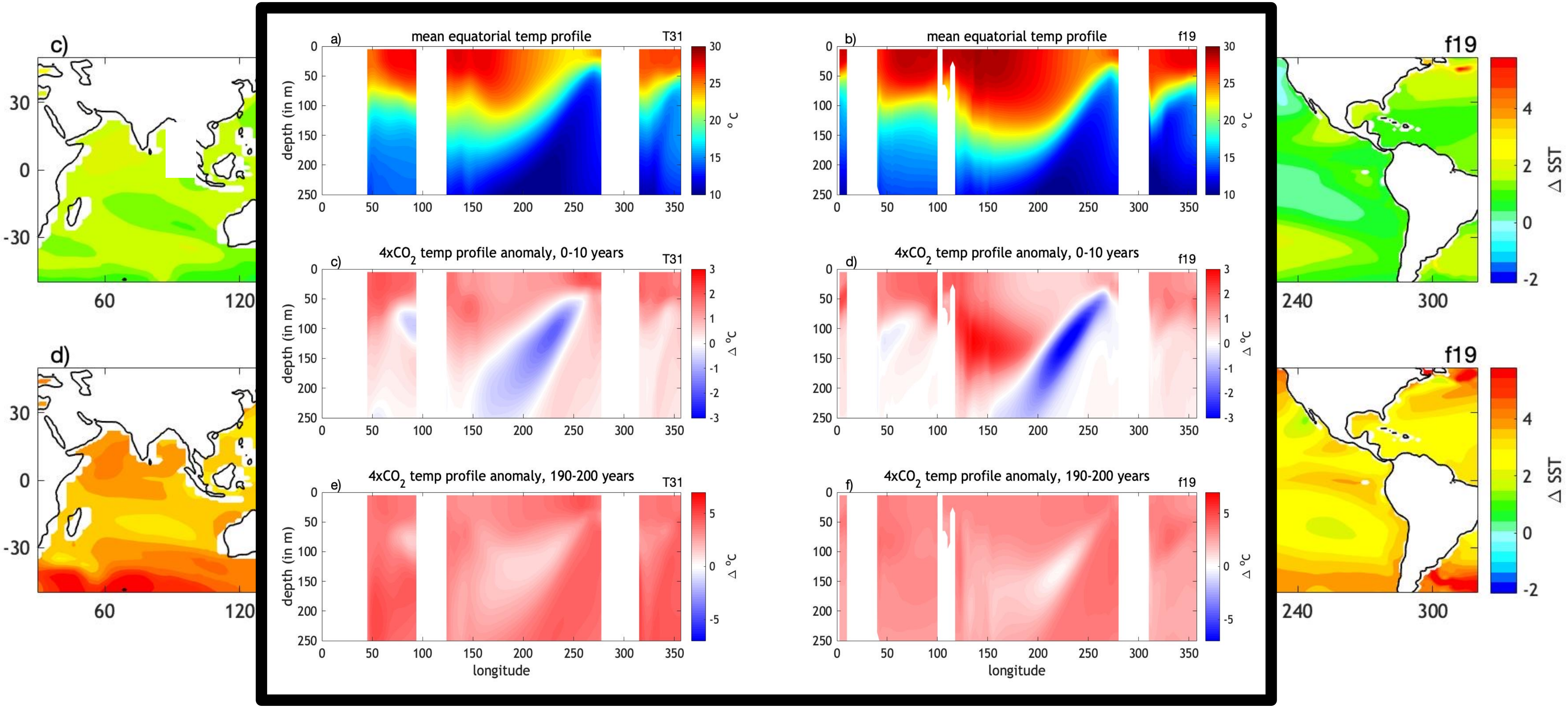


Heede, Fedorov, Burls, 2021

Model Dependance of Transient Response

Low Res CESM

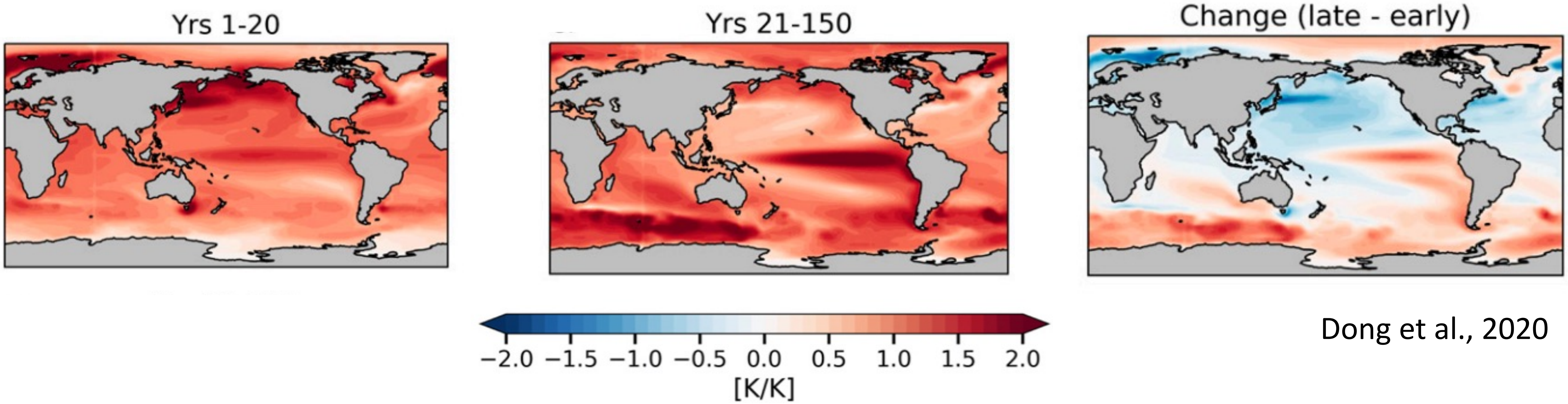
High Res CESM



Heede, Fedorov, Burls, 2021

Transient versus Equilibrium

CMIP6 abrupt 4xCO2 simulations



Dong et al., 2020

Summary

- Tropical Pacific warming patterns play a crucial role in setting global climate sensitivity
- Opposing theories exist for the response of the tropical Pacific to global warming – “Weaker Walker vs Thermostat)
- This discrepancy can be addressed by including the influence of the extra-tropics and paying attention to time scale
- Coupled climate models struggle to capture the historical tropical Pacific warming pattern
- Past high-CO_2 warm climates suggest a weakening of large-scale SST gradients once equilibrium is reached

References

- Andrews, T., & Webb, M. J. (2018). The dependence of global cloud and lapse rate feedbacks on the spatial structure of tropical Pacific warming. Journal of Climate, 31(2), 641-654.
- Armour, K. C., Bitz, C. M., & Roe, G. H. (2013). Time-varying climate sensitivity from regional feedbacks. Journal of Climate, 26(13), 4518-4534.
- Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of climate*, *19*(21), 5686-5699.
- Ma, J., Xie, S. P., & Kosaka, Y. (2012). Mechanisms for tropical tropospheric circulation change in response to global warming. Journal of Climate, 25(8), 2979-2994.
- Merlis, T. M., & Schneider, T. (2011). Changes in zonal surface temperature gradients and Walker circulations in a wide range of climates. Journal of climate, 24(17), 4757-4768.
- Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg, 2010: Global warming pattern formation: Sea surface temperature and rainfall. J. Climate, 23, 966–986.
- Liu, Z., & Huang, B. (1997). A coupled theory of tropical climatology: Warm pool, cold tongue, and Walker circulation. Journal of climate, 10(7), 1662-1679.
- Roe, G. H., Feldl, N., Armour, K. C., Hwang, Y. T., & Frierson, D. M. (2015). The remote impacts of climate feedbacks on regional climate predictability. Nature Geoscience, 8(2), 135-139.
- Tierney, J. E., Poulsen, C. J., Montañez, I. P., Bhattacharya, T., Feng, R., Ford, H. L., ... & Zhang, Y. G. (2020). Past climates inform our future. *Science*, *370*(6517), eaay3701.

References

- Dong, Y., Armour, K. C., Zelinka, M. D., Proistosescu, C., Battisti, D. S., Zhou, C., & Andrews, T. (2020). Intermodel spread in the pattern effect and its contribution to climate sensitivity in CMIP5 and CMIP6 models. Journal of Climate, 33(18), 7755-7775
- Xie, S. P., Deser, C., Vecchi, G. A., Ma, J., Teng, H., & Wittenberg, A. T. (2010). Global warming pattern formation: Sea surface temperature and rainfall. Journal of Climate, 23(4), 966-986.
- Erfani, E., & Burls, N. J. (2019). The strength of low-cloud feedbacks and tropical climate: A CESM sensitivity study. Journal of Climate, 32(9), 2497-2516.
- Wills, R. C. J., Dong, Y., Proistosecu, C., Armour, K. C., & Battisti, D. S. (2022). Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change. Geophysical Research Letters, 49(17), e2022GL100011. https://doi.org/10.1029/2022GL100011
- McPhaden, M. J., Lee, T., & McClurg, D. (2011). El Niño and its relationship to changing background conditions in the tropical Pacific Ocean. Geophysical Research Letters, 38(15).
- Fedorov, A. V., Burls, N. J., Lawrence, K. T., & Peterson, L. C. (2015). Tightly linked zonal and meridional sea surface temperature gradients over the past five million years. Nature Geoscience, 8(12), 975-980.
- England, M. H., McGregor, S., Spence, P., Meehl, G. A., Timmermann, A., Cai, W., ... & Santoso, A. (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. Nature climate change, 4(3), 222-227.
- Burls, N. J., & Fedorov, A. V. (2014). What controls the mean east–west sea surface temperature gradient in the equatorial Pacific: The role of cloud albedo. *Journal of Climate*, *27*(7), 2757-2778.

References

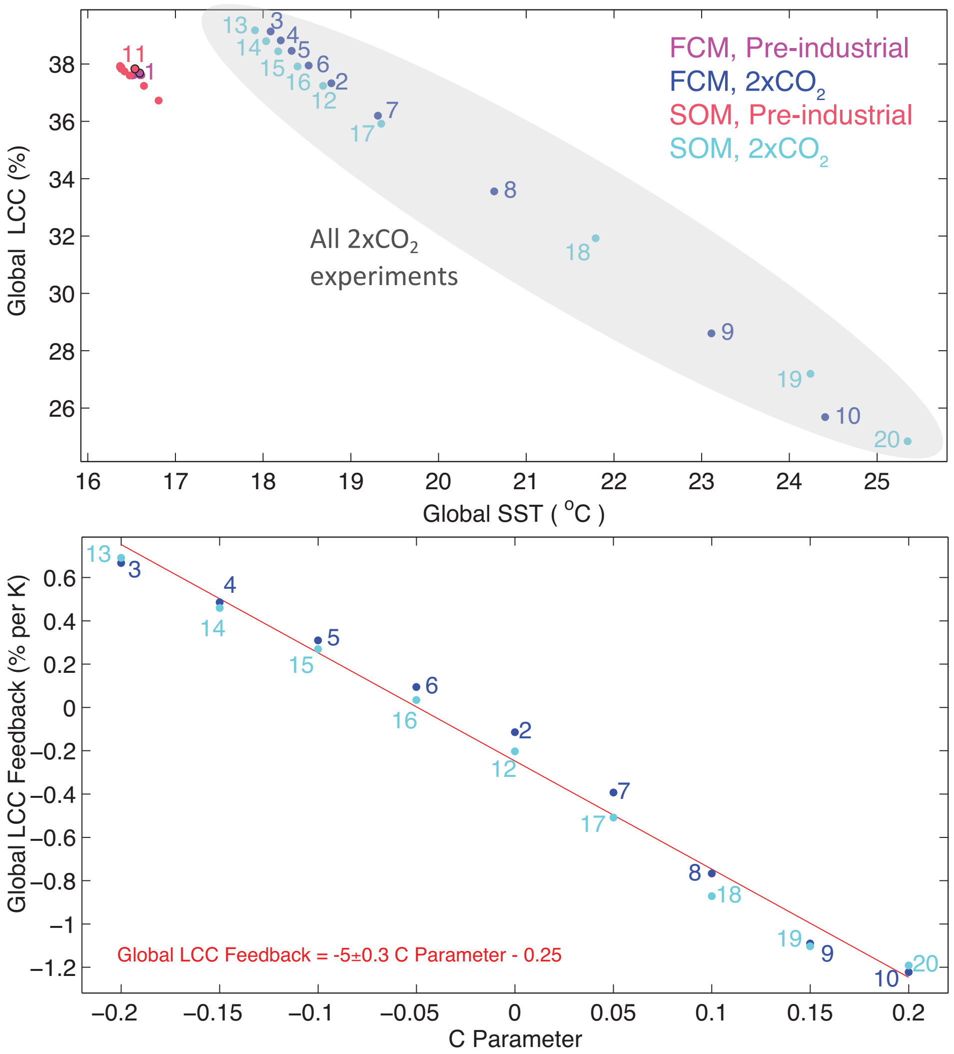
- McGregor, S., Timmermann, A., Stuecker, M. F., England, M. H., Merrifield, M., Jin, F. F., & Chikamoto, Y. (2014). Recent Walker circulation strengthening and Pacific cooling amplified by Atlantic warming. Nature Climate Change, 4(10), 888-892.
- Takahashi, C., & Watanabe, M. (2016). Pacific trade winds accelerated by aerosol forcing over the past two decades. Nature Climate Change, 6(8), 768-772.
- Seager, R., Cane, M., Henderson, N., Lee, D. E., Abernathey, R., & Zhang, H. (2019). Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases. Nature Climate Change, 9(7), 517-522.
- Hwang, Y. T., Xie, S. P., Deser, C., & Kang, S. M. (2017). Connecting tropical climate change with Southern Ocean heat uptake. Geophysical Research Letters, 44(18), 9449-9457.
- Kohyama, T., Hartmann, D. L., & Battisti, D. S. (2017). La Niña–like mean-state response to global warming and potential oceanic roles. Journal of Climate, 30(11), 4207-4225.
- Kang, S. M., I. M. Held, D. M. W. Frierson, and M. Zhao (2008), The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM, J. Clim., 21(14), 3521–3532.
- Kang, S. M., Xie, S. P., Shin, Y., Kim, H., Hwang, Y. T., Stuecker, M. F., ... & Hawcroft, M. (2020). Walker circulation response to extratropical radiative forcing. *Science advances*, *6*(47), eabd3021.
- Luongo, M. T., Xie, S. P., Eisenman, I., Hwang, Y. T., & Tseng, H. Y. (2023). A pathway for northern hemisphere extratropical cooling to elicit a tropical response. Geophysical Research Letters, 50(2), e2022GL100719.
- Vecchi, G. A., Clement, A., & Soden, B. J. (2008). Examining the tropical Pacific's response to global warming. Eos, Transactions American Geophysical Union, 89(9), 81-83

References

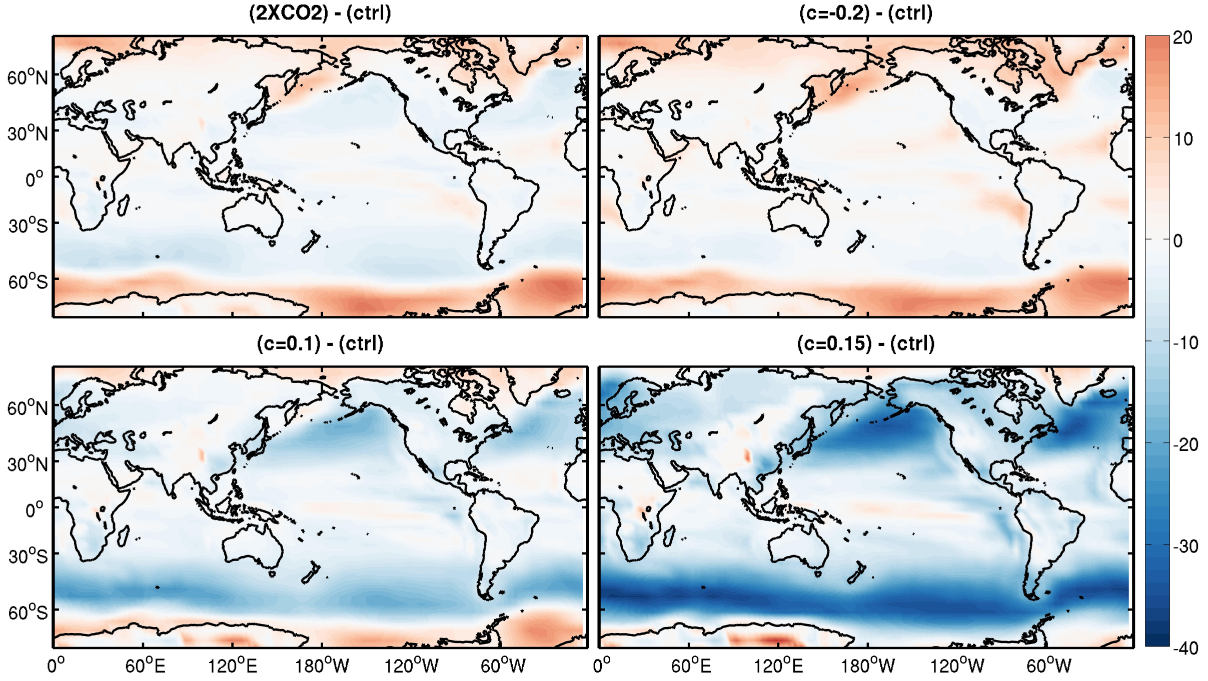
- Andrews, T., & Webb, M. J. (2018). The dependence of global cloud and lapse rate feedbacks on the spatial structure of tropical Pacific warming. Journal of Climate, 31(2), 641-654.
- Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., ... & Zelinka, M. D. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. Reviews of Geophysics, 58(4), e2019RG000678.
- Thomas, M. D., & Fedorov, A. V. (2017). The eastern subtropical Pacific origin of the equatorial cold bias in climate models: A Lagrangian perspective. Journal of Climate, 30(15), 5885-5900.
- Gu, D., & Philander, S. G. (1997). Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. Science, 275(5301), 805-807.
- Betts and Ridgway, 1989; Held and Soden, 2006, Vecchi and Soden, 2007, Ma et al., 2012
- Zhou, C., Zelinka, M. D., & Klein, S. A. (2017). Analyzing the dependence of global cloud feedback on the spatial pattern of sea surface temperature change with a G reen's function approach. Journal of Advances in Modeling Earth Systems, 9(5), 2174-2189.
- Heede, U. K., & Fedorov, A. V. (2023). Colder eastern equatorial Pacific and stronger Walker circulation in the early 21st century: separating the forced response to global warming from natural variability. Geophysical Research Letters, 50(3), e2022GL101020.

Extra Slides

Scaling the strength of the low cloud amount feedback



Low Cloud Fraction Changes



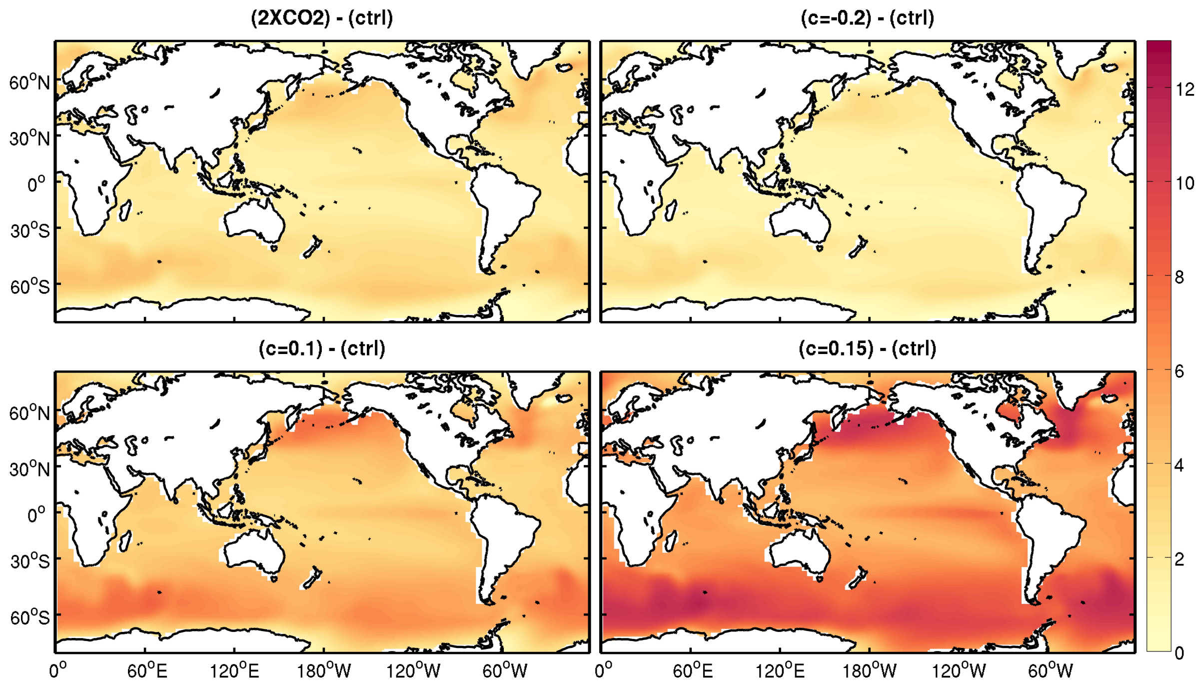
$$CF(SST) = CF_o\,(1-c)^{\overline{SST}-\overline{SST_0}}$$

where CF_o = cloud fraction before modification
SST = globally-averaged sea surface temperature at each time step
SST_o = globally-averaged SST for the last 100 years of the control
c = arbitrary constant to control the strength of the feedback modification

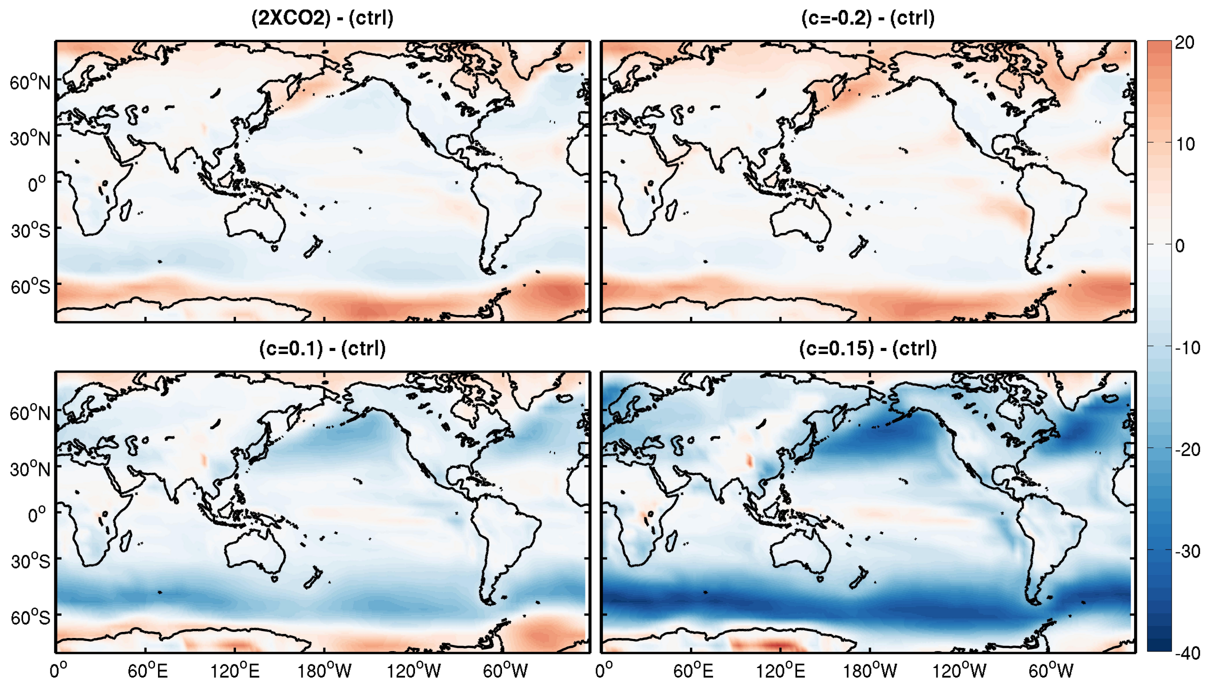
Erfani and Burls, JOC, 2019

Scaling the strength of the low cloud amount feedback

Sea Surface Temperature Changes



Low Cloud Fraction Changes

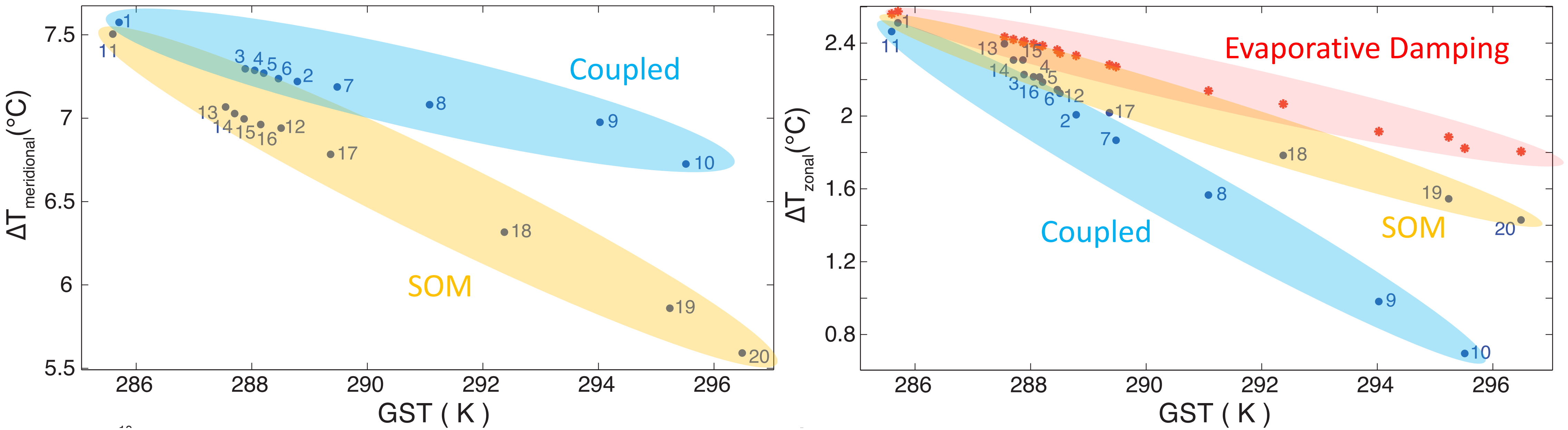


	SST (°C)		LCC (%)		TOA imbalance (W m^{-2})		
c parameter	Preindustrial CO_2	$2\times CO_2$	Preindustrial CO_2	$2\times CO_2$	Preindustrial CO_2	$2\times CO_2$	ECS (°C)
No modification	16.59	18.78	37.65	37.33	0.0465	0.0350	3.08
−0.2	16.53	18.08	37.62	39.14	0.0699	−0.0054	2.18
−0.15	16.51	18.20	37.60	38.82	0.0923	0.0352	2.35
−0.1	16.53	18.32	37.63	38.46	0.0596	0.0349	2.50
−0.05	16.53	18.52	37.64	37.94	0.0751	0.0350	2.76
0.05	16.60	19.31	37.65	36.20	0.0968	0.0722	3.77
0.1	16.61	20.63	37.61	33.60	0.0725	0.2009	5.37
0.15	16.59	23.11	37.66	28.61	0.0932	0.4364	8.32
0.2	16.60	24.41	37.61	25.69	0.0928	0.4733	9.81

Erfani and Burls, JOC, 2019

Scaling the strength of the low cloud amount feedback

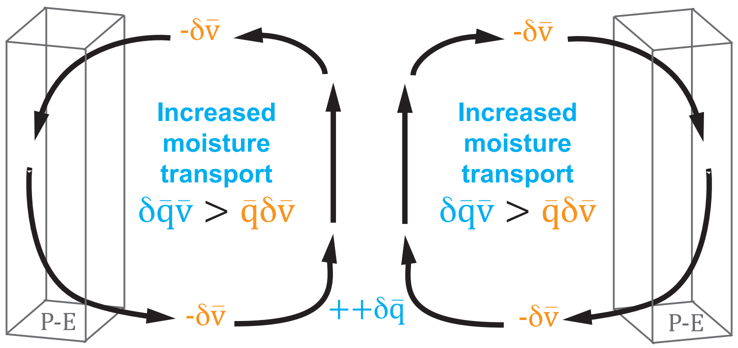
Changes in Large Scale Meridional and Zonal SST Gradients



Erfani and Burls, JOC, 2019

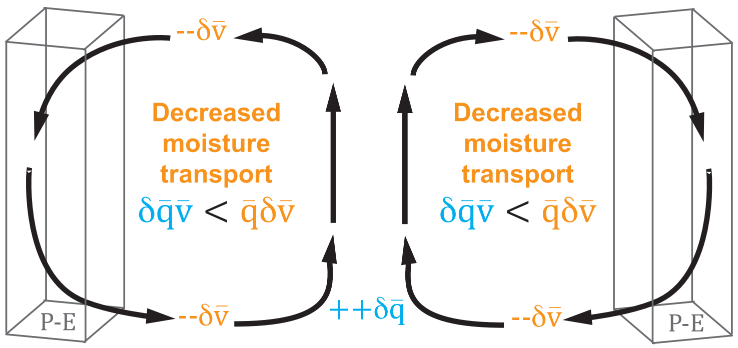
Wetter Subtropics in a Warmer World

$4xCO_2$

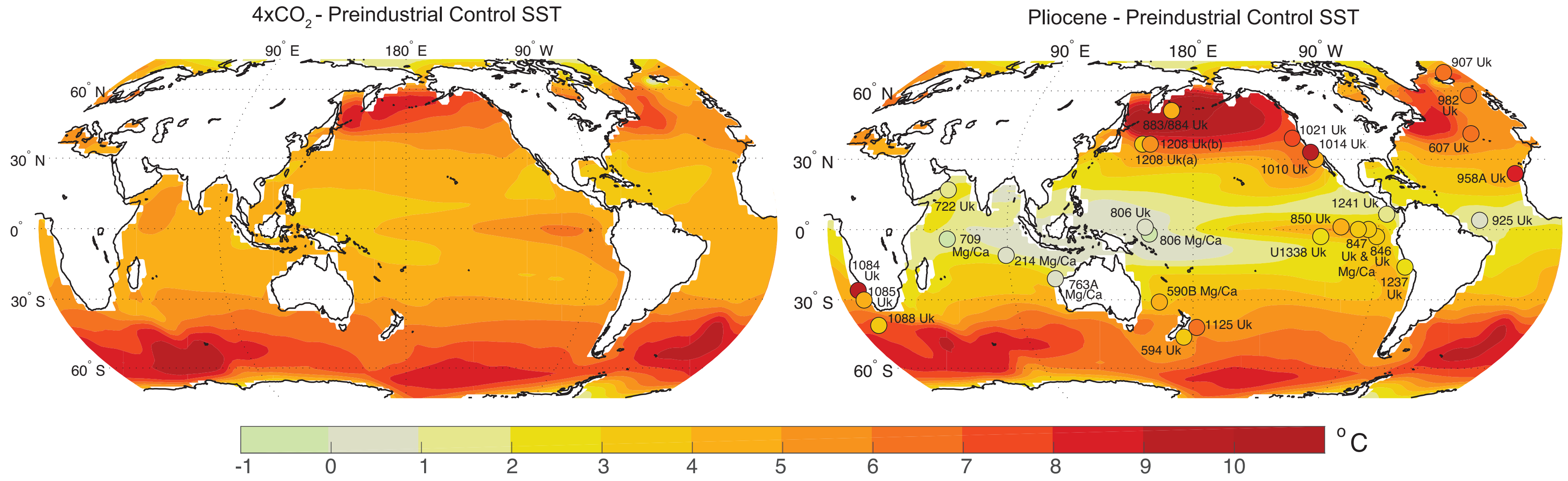


Wet gets wetter, Dry gets drier

Pliocene



Dry gets wetter, Wet gets drier



Burls & Fedorov, *PNAS*, 2017