Implications of the pattern effect for climate sensitivity and projections

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First Annual US CLIVAR Pattern Effect Workshop

Courtesy of NASA’s
Earth Observatory

The pattern effect and ECS

The Before Times

correspondence

Energy budget constraints on climate response

Alexander Otto[1*], Friederike E. L. Otto[1], Olivier Boucher[2], John Church[3], Gabi Hegerl[4], Piers M. Forster[5], Nathan P. Gillett[6], Jonathan Gregory[7], Gregory C. Johnson[8], Reto Knutti[9], Nicholas Lewis[10], Ulrike Lohmann[9], Jochem Marotzke[11], Gunnar Myhre[12], Drew Shindell[13], Bjorn Stevens[11] and Myles R. Allen[1,14]

ΔT = 0.75 ± 0.2 °C

ΔN = 0.65 ± 0.27 Wm^{-2}

ΔR = 2.3 ± 1 Wm^{-2}

(years 2000-2009 relative to 1860-1879)

Global-mean energy budget:

$$\Delta N = \lambda \Delta T + \Delta R$$

$$\lambda = -\frac{\Delta R - \Delta N}{\Delta T}$$

$$\mathrm{ECS} = -\frac{\Delta R_{2\times}}{\lambda}$$

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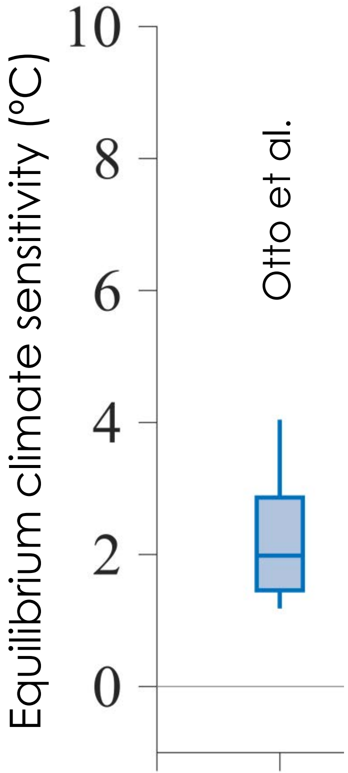

ECS from historical energy budget suggested ECS around 2°C

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IPCC AR5 in 2013:

"Equilibrium climate sensitivity is likely in the range 1.5°C to 4.5°C (*high confidence*)... No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies."

(Because other lines of evidence suggested ECS around 3°C)

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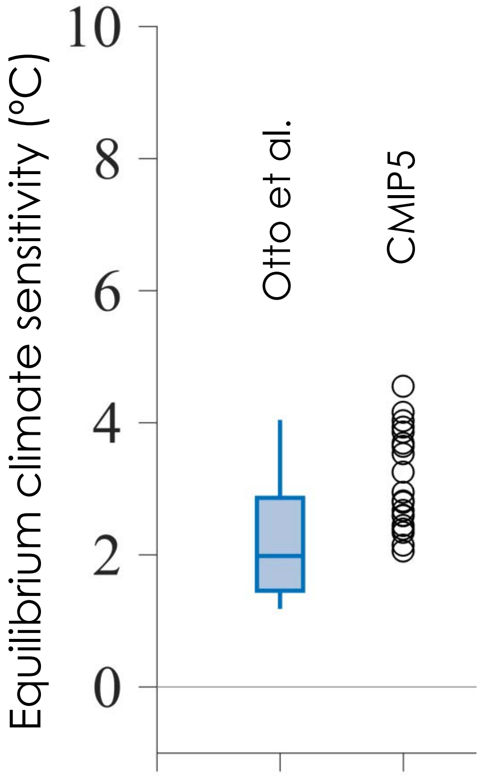

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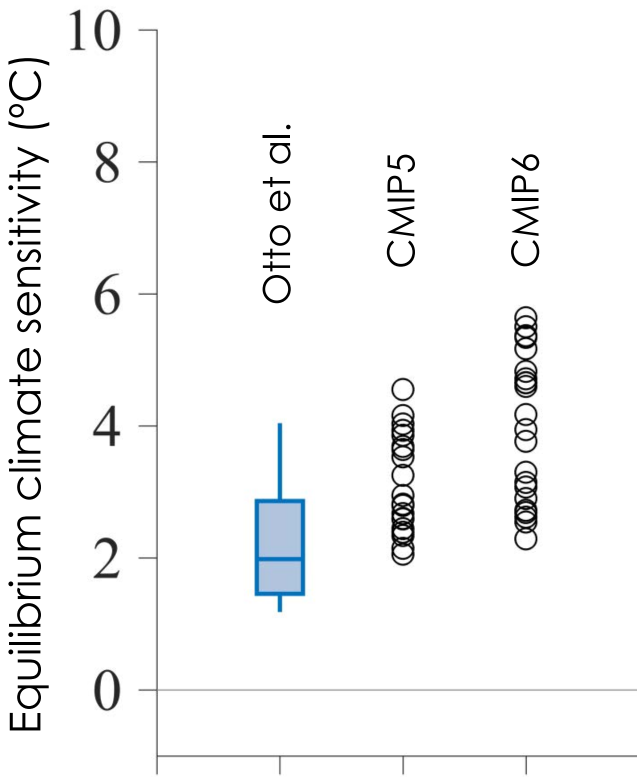
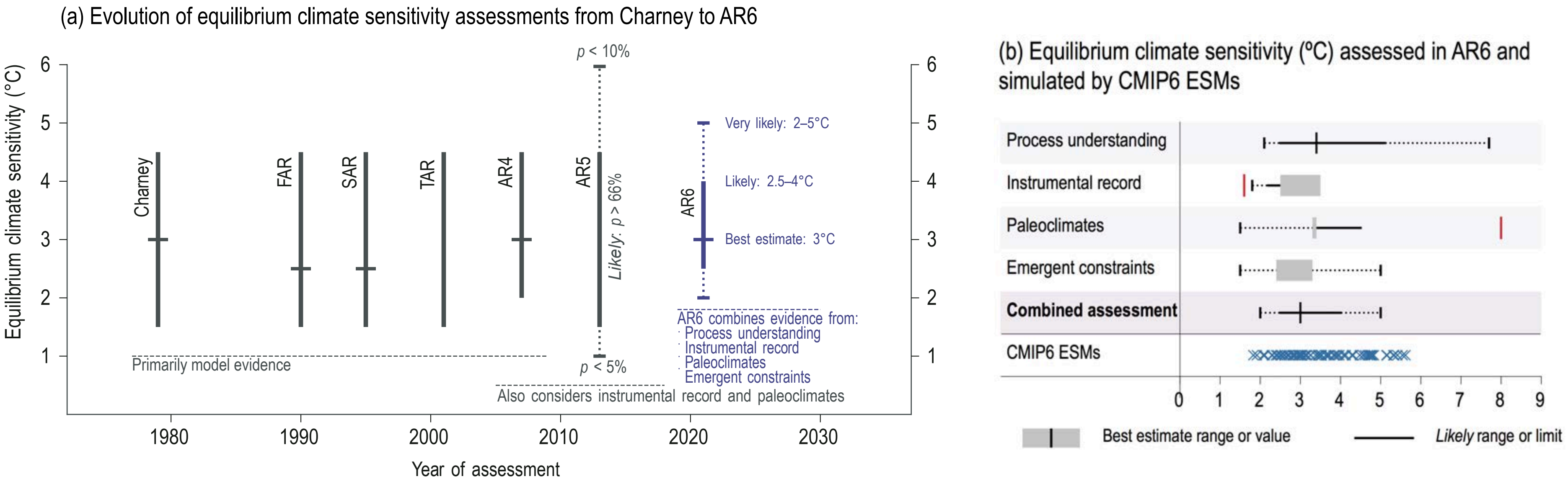
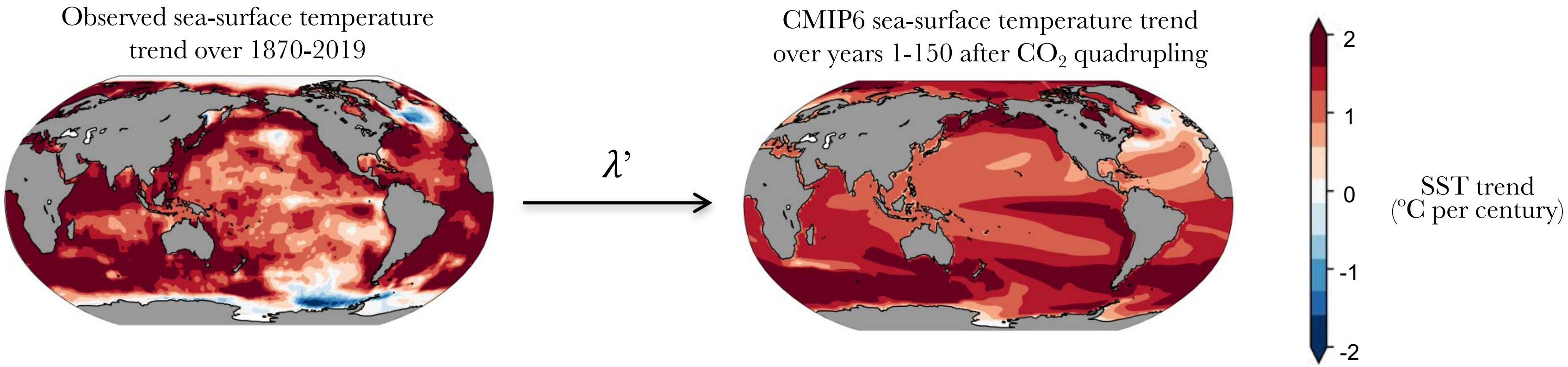


The view from 2021 (IPCC AR6)

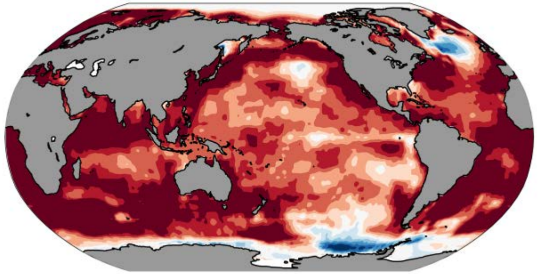


Pattern effect in the instrumental record



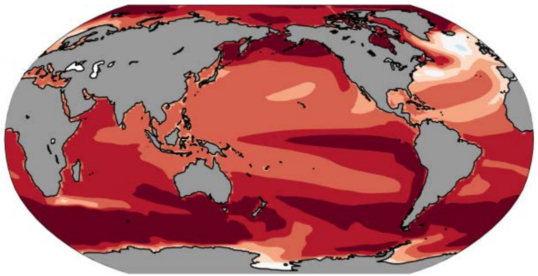
Pattern effect in the instrumental record

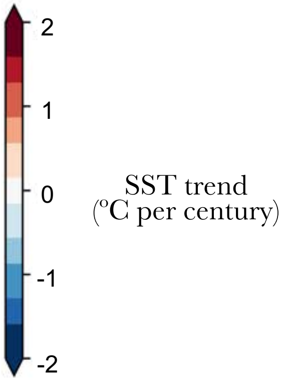
Observed sea-surface temperature trend over 1870-2019



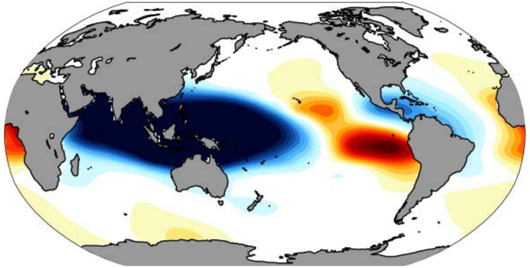
$\xrightarrow{\lambda'}$

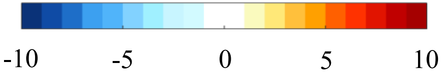
CMIP6 sea-surface temperature trend over years 1-150 after CO_2 quadrupling





Global radiative feedback in response to local warming patch in CAM4 (Dong et al. 2019)





Radiative feedback ($Wm^{-2}K^{-1}$)

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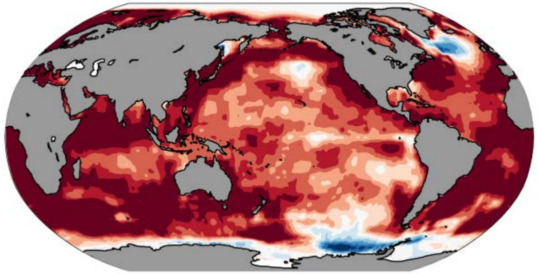

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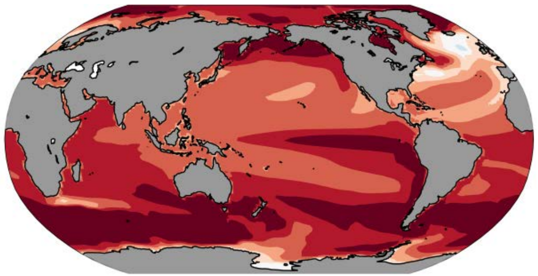
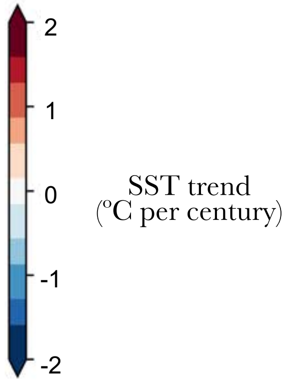
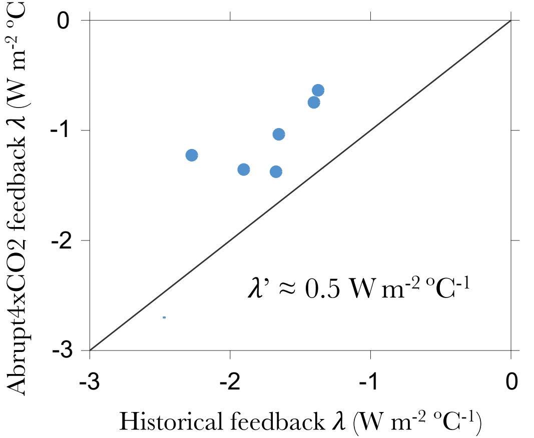




Atmosphere-only GCMs using observed historical warming patterns (Andrews et al. 2018)



The radiative feedback over the historical record is different (more negative) than that for the equilibrium response to CO_2 owing to the pattern effect

Thus, historical warming provides only an estimate of the effective climate sensitivity (EffCS) which may differ from ECS

$$\text{EffCS} = -\frac{\Delta R_{2\times}}{\lambda}$$

$$\text{ECS} = -\frac{\Delta R_{2\times}}{\lambda + \lambda'}$$

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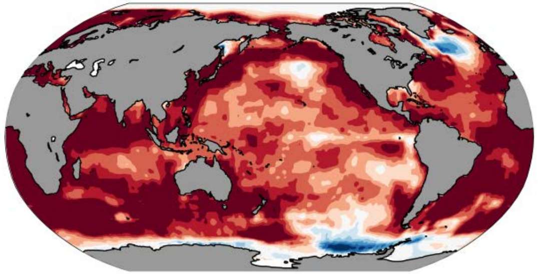

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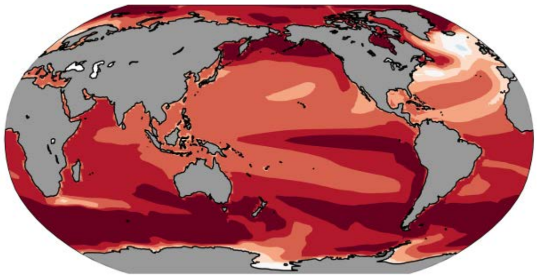

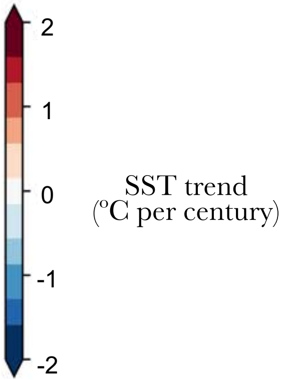

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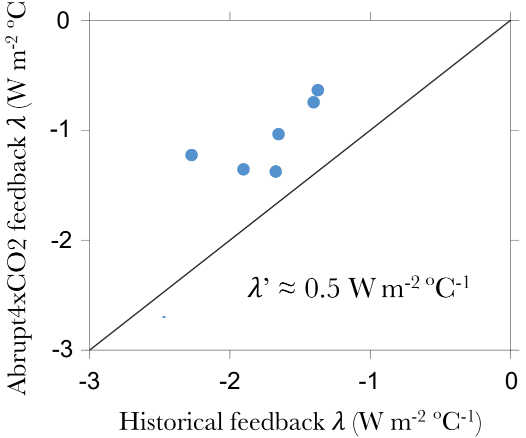

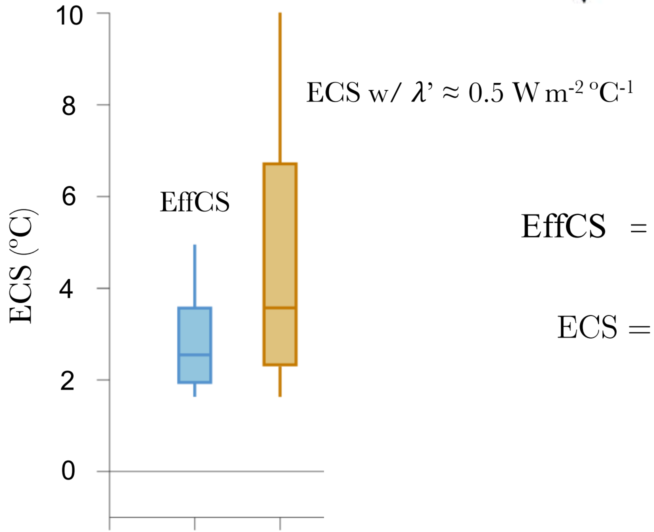

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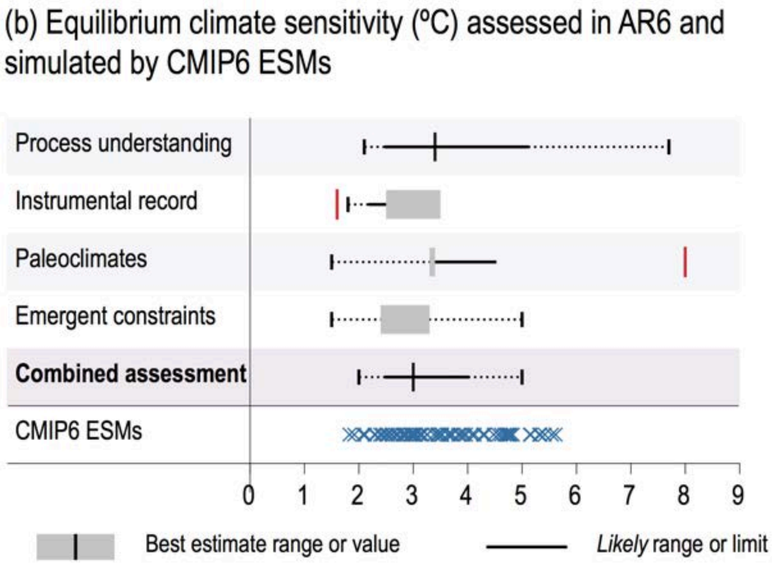

Outstanding questions on the pattern effect and ECS

- Can we produce better reconstructions of historical SSTs and sea ice (with uncertainty quantification), particularly for the 1800s reference period?
- Why do climate models generally fail to replicate observed patterns of warming (particularly since ~1980)?
- How confident are we in the models' radiative response to SST changes?
- Can we place observational constraints on the historical pattern effect?

- Fundamental issue: delayed warming (or cooling) has occurred preferentially in regions of most positive feedbacks, hiding potentially-high ECS from us; can we estimate what the radiative response (and thus ECS) will be to warming in these regions?

Outstanding questions on the pattern effect and ECS

- How does the pattern effect impact constraints on ECS based on the paleoclimate record?
- How confident are we in the equilibrium SST pattern of warming under CO_2 forcing? To what extent is the Pliocene a good analogue for the future warming pattern?

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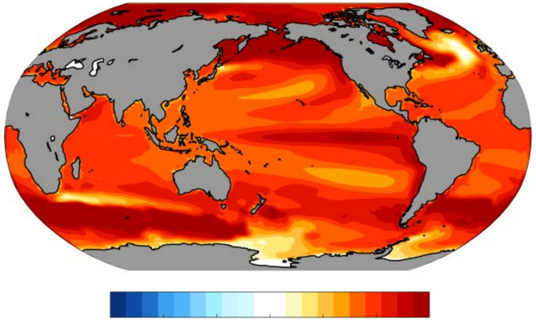
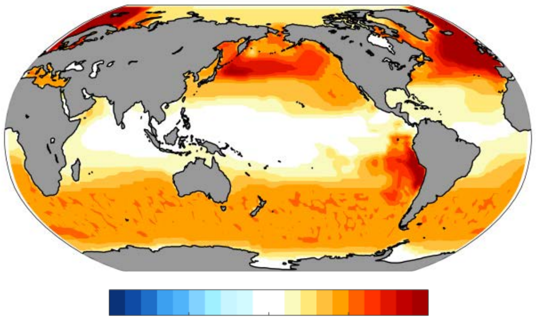
Pliocene SST reconstructions

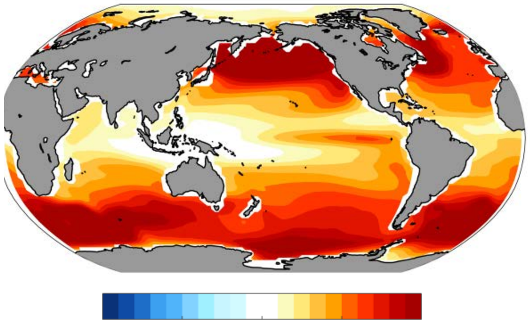
CMIP5 sea-surface temperature trend after CO_2 quadrupling (years 1-150)



Pliocene sea-surface temperature anomaly (PRISM)



Pliocene sea-surface temperature anomaly (Burls and Fedorov 2017)



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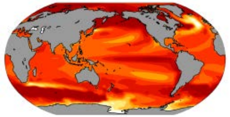

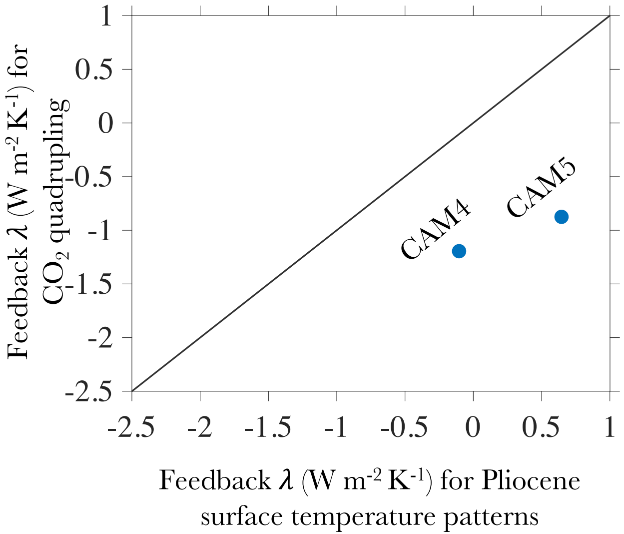

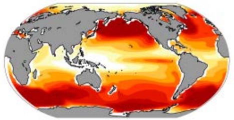

Pliocene SST patterns imply λ values near zero (near infinite EffCS), so a few possible interpretations:

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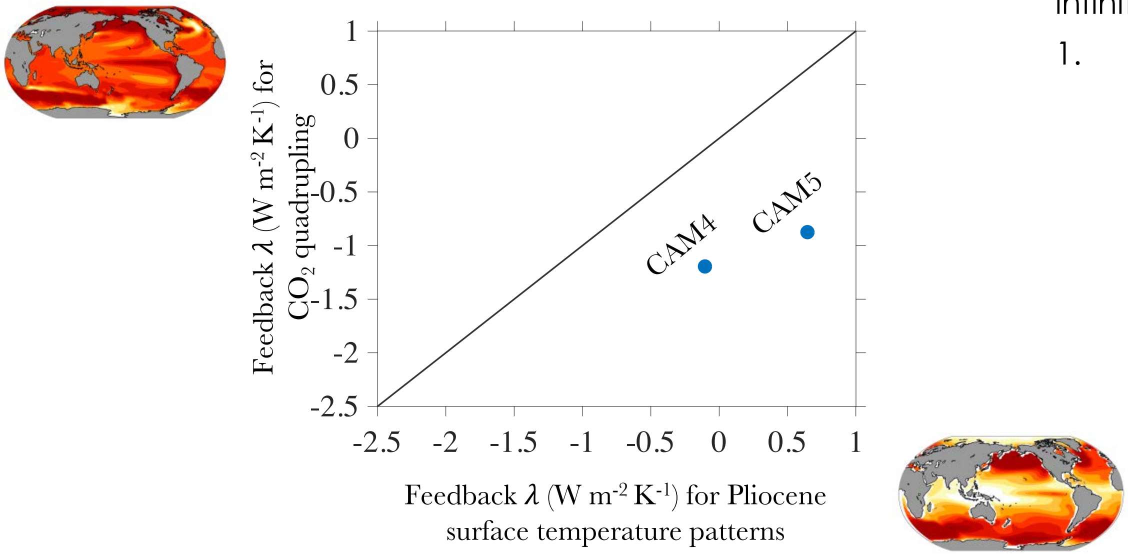

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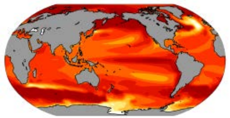

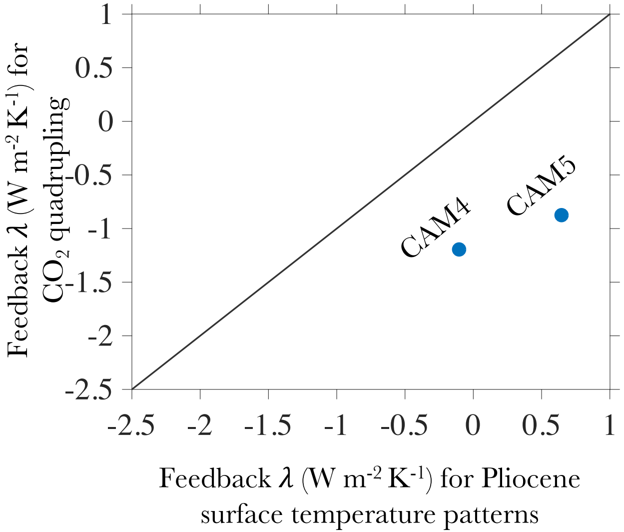

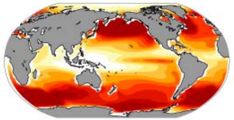

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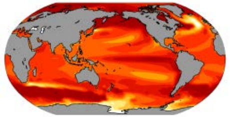

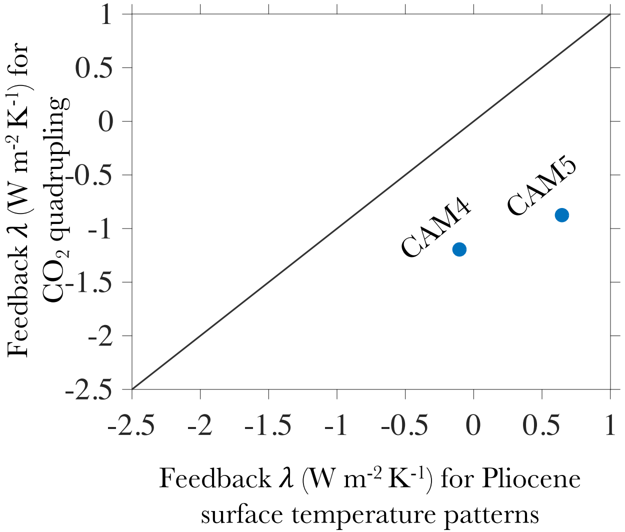

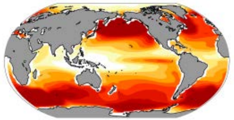

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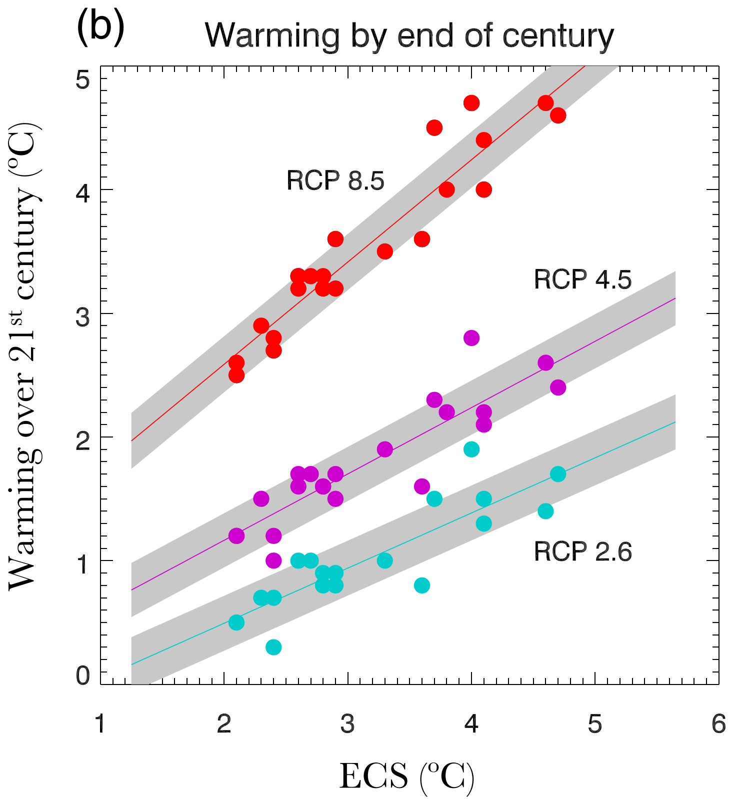
3. Pliocene pattern isn't accurate; we need better methods to reconstruct SSTs and quantify their uncertainty (e.g., Jess Tierney's data assimilation work)

Does the pattern effect matter for transient warming?

Transient warming is highly correlated with ECS



(Sherwood et al. 2020)

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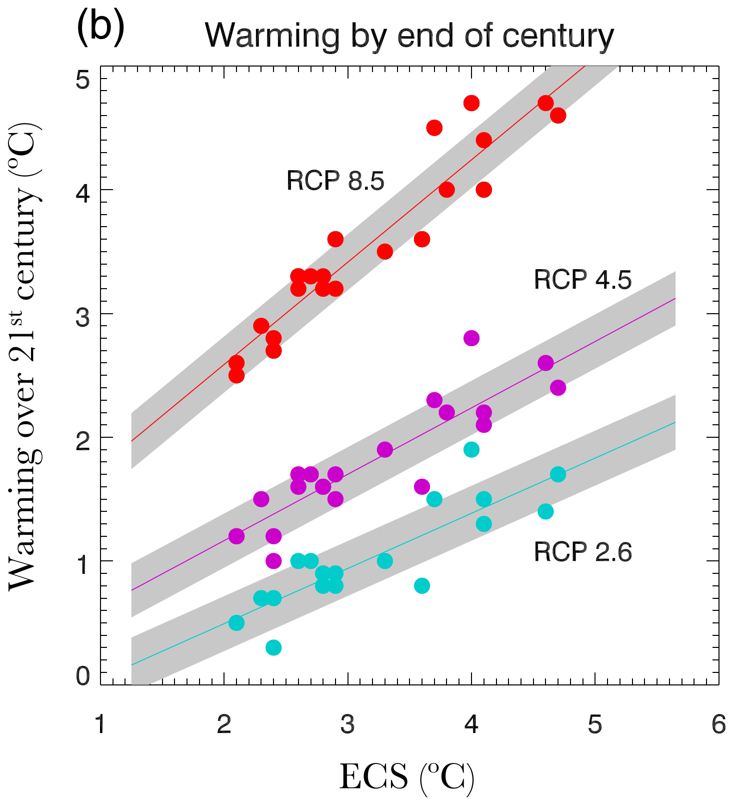

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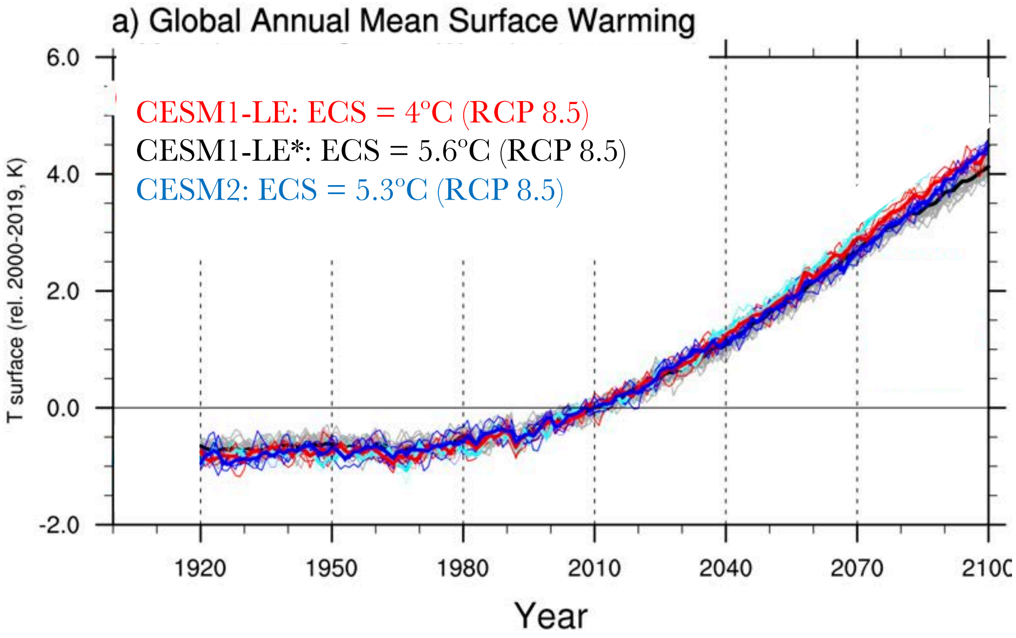
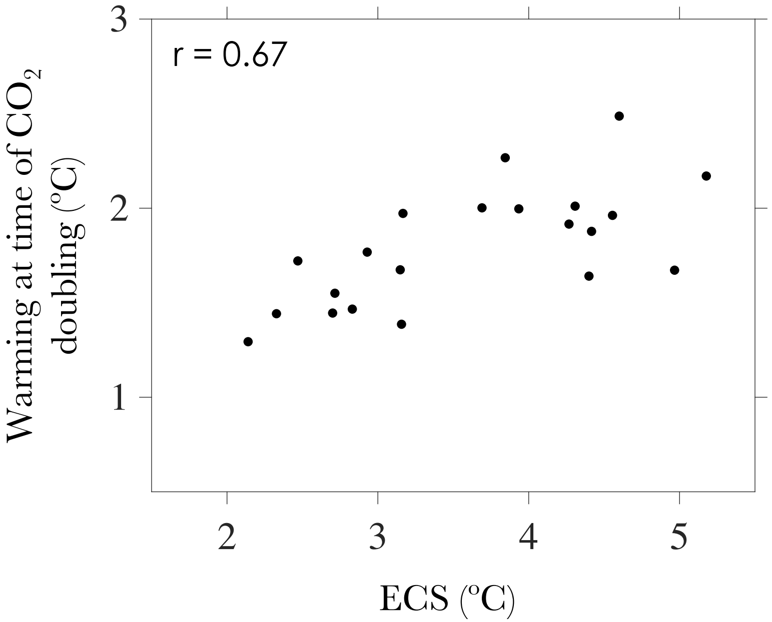
… or is it?



(modified from poster by David Schneider, Jen Kay, Cecile Hannay; see also Frey and Kay 2017)

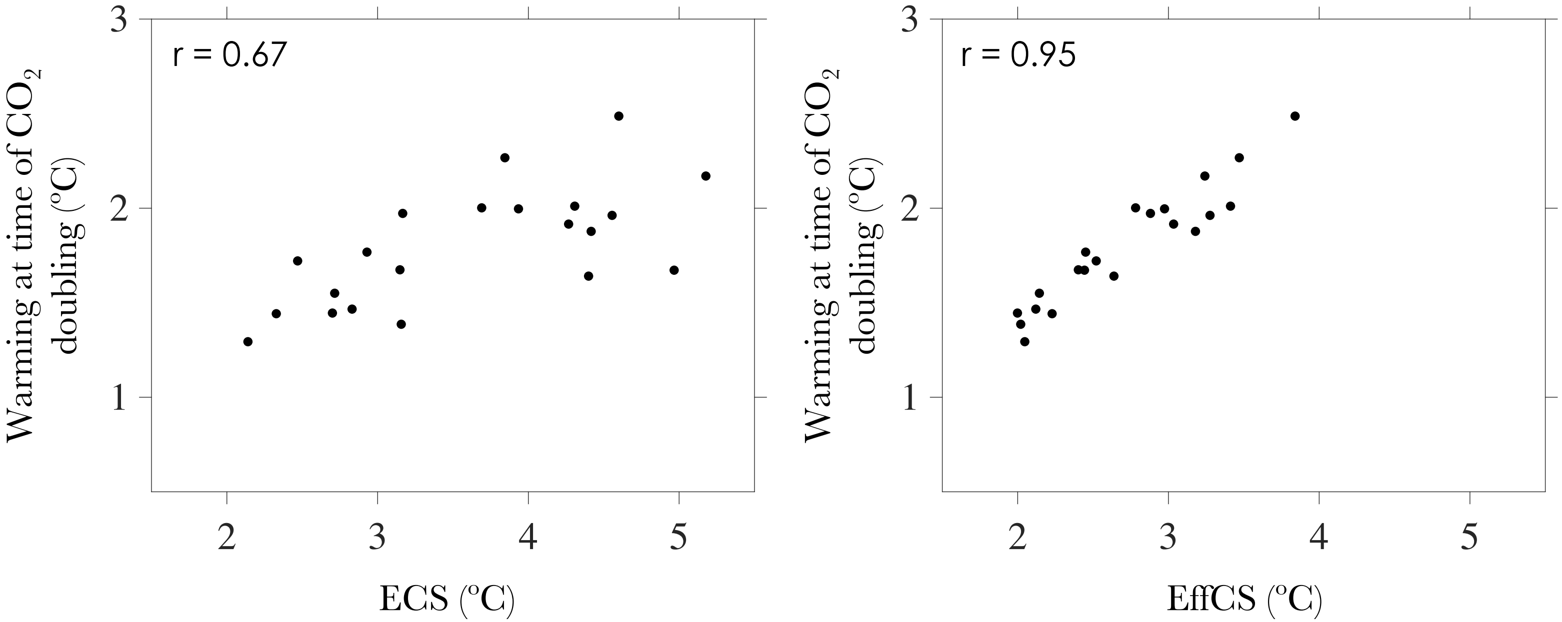
Transient warming is highly correlated with ECS

CMIP5 1%/yr CO_2 ramping simulations



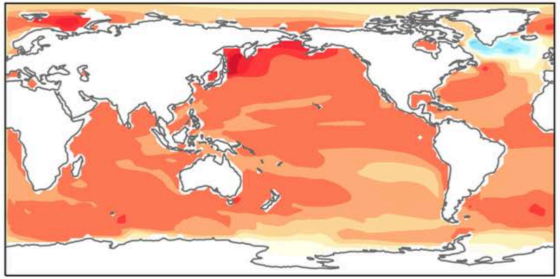
Transient warming is more highly correlated with EffCS

CMIP5 1%/yr CO_2 ramping simulations

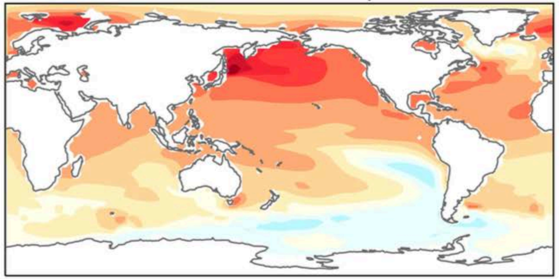


Transient warming and EffCS with freshwater forcing

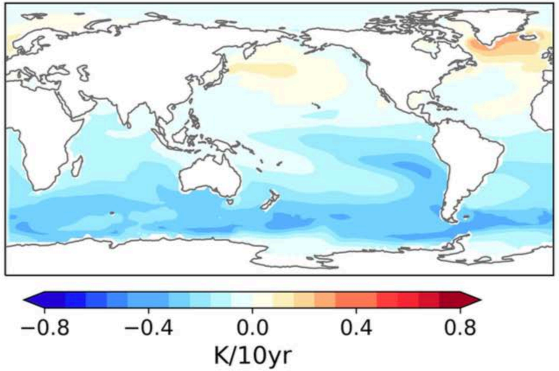
CESM1 21st century warming under RCP8.5



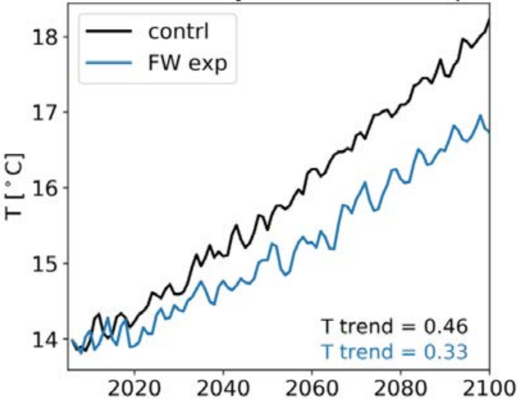
CESM1 21st century warming under RCP8.5 with Antarctic freshwater input



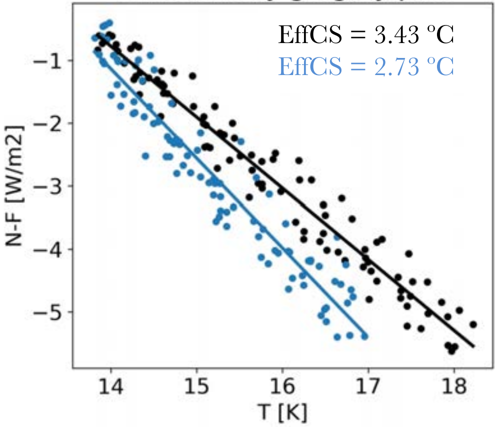
difference



21st century surface air temp

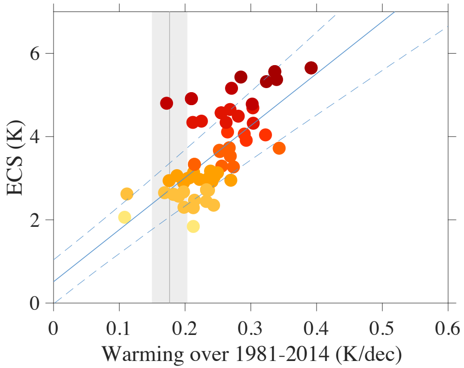


21st century gregory plot



(Work of Yue Dong and Shaina Sadai)

Transient warming and EffCS over recent decades



Correlation between ECS and transient warming over recent decades has been proposed as a strong emergent constraint on ECS (e.g., Jiménez-de-la Cuesta and Mauritsen 2019; Nijsse et al. 2020; Tokarska et al. 2020; Winton et al. 2020)

But shouldn’t it be EffCS (rather than ECS) that controls transient warming??

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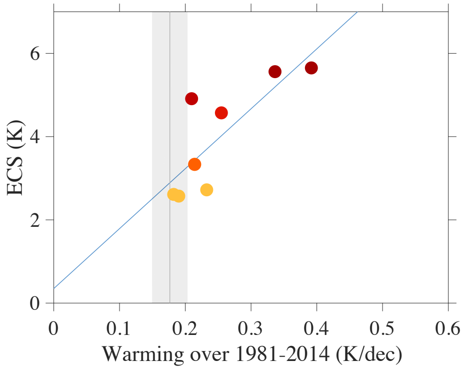

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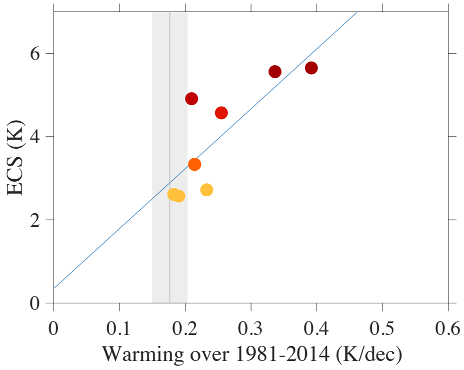

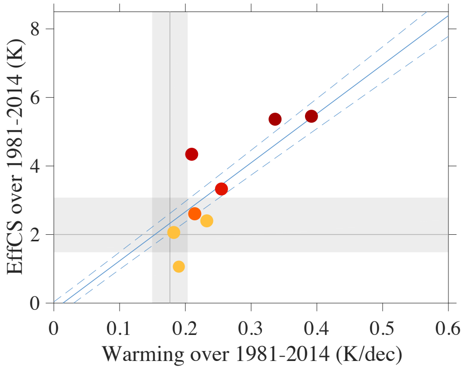

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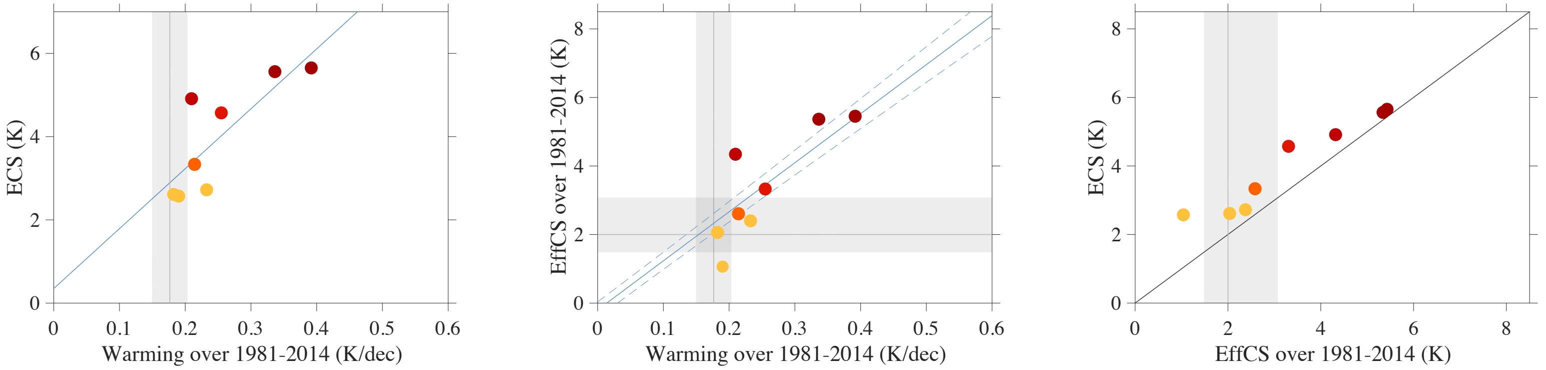
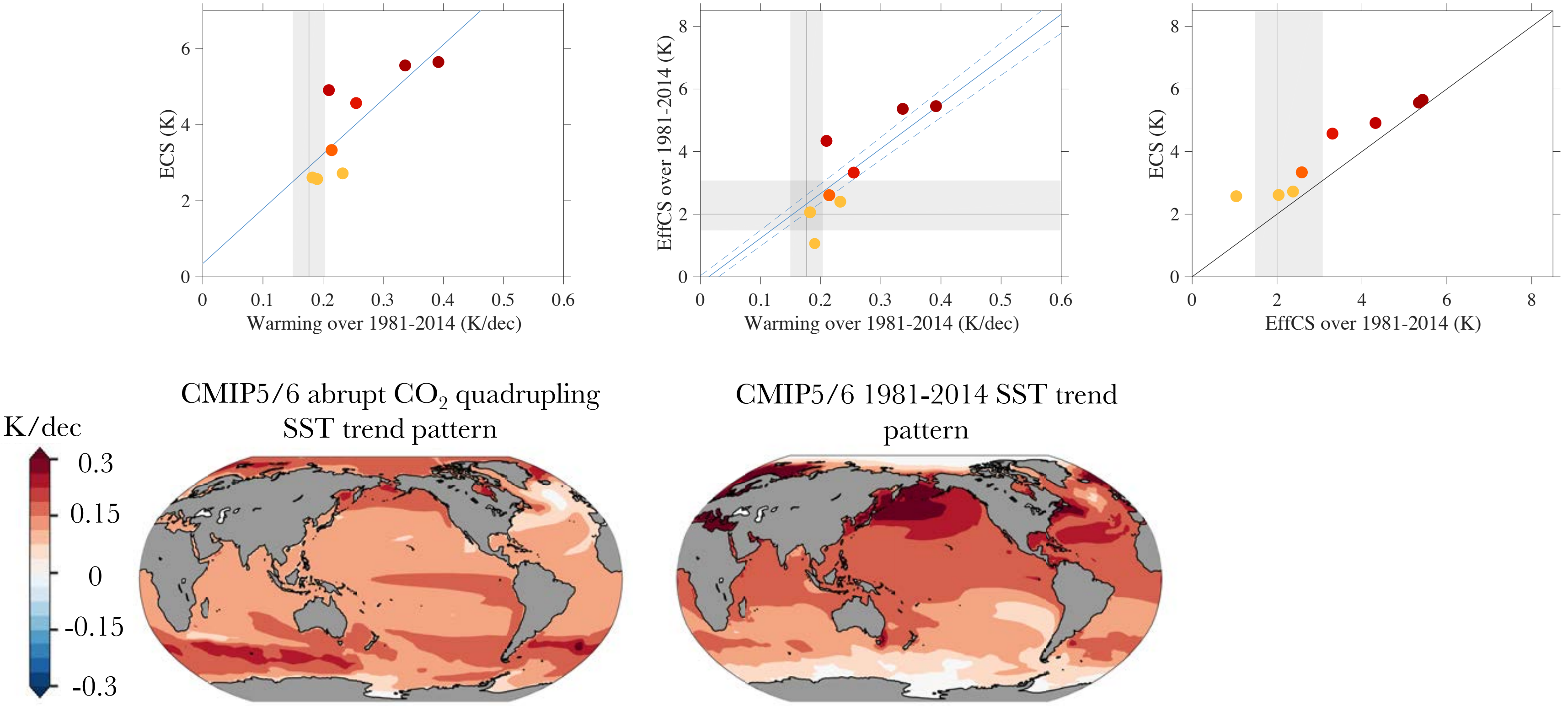
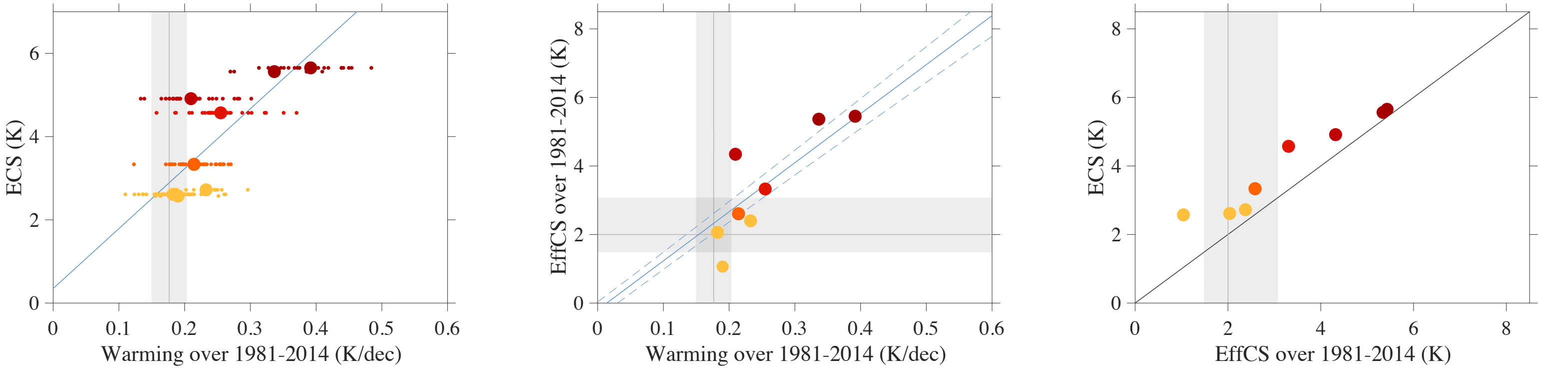


Transient warming and EffCS over recent decades

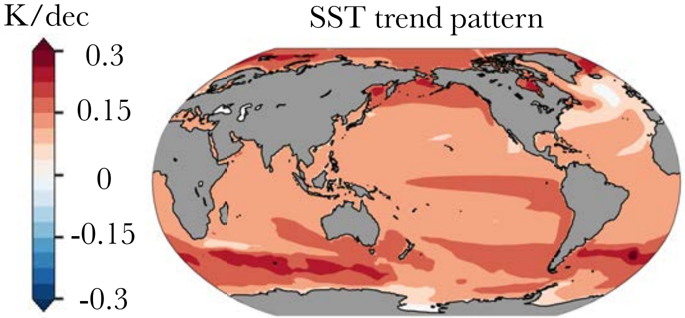


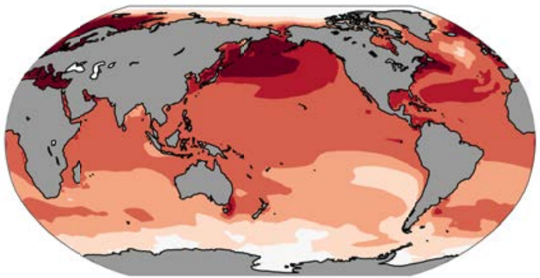
Transient warming and EffCS over recent decades



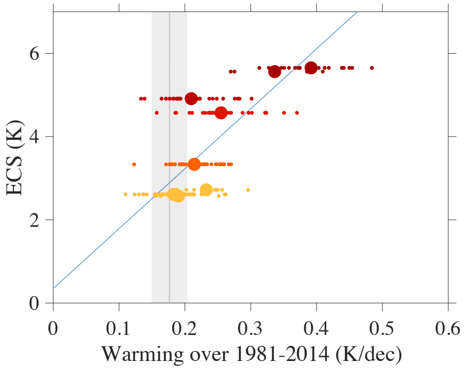
CMIP5/6 abrupt CO_2 quadrupling SST trend pattern

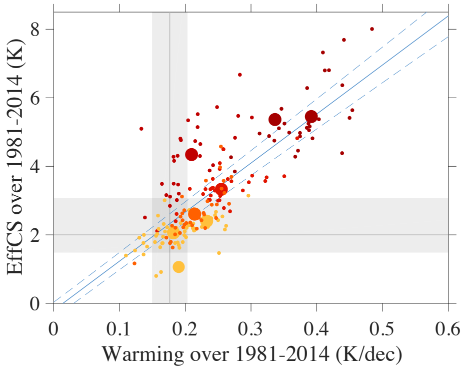
CMIP5/6 1981-2014 SST trend pattern

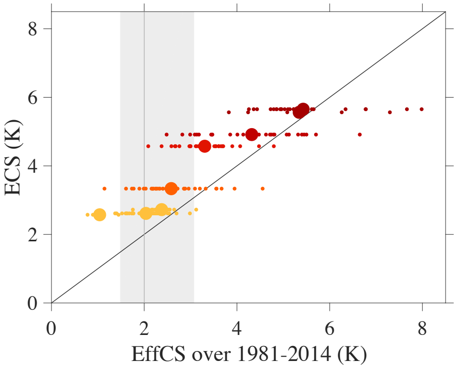


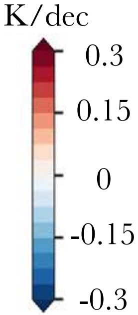


Transient warming and EffCS over recent decades

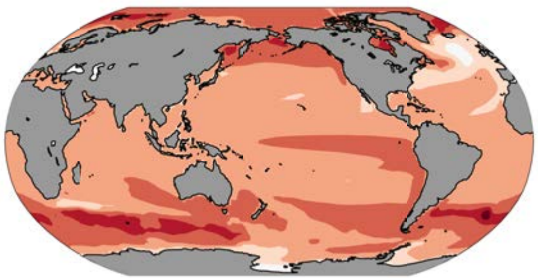




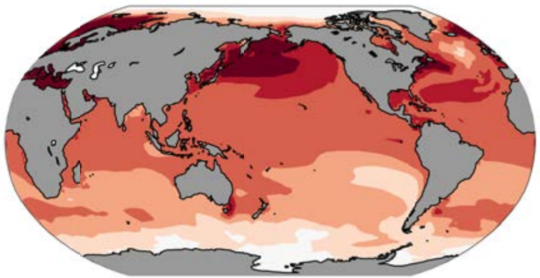




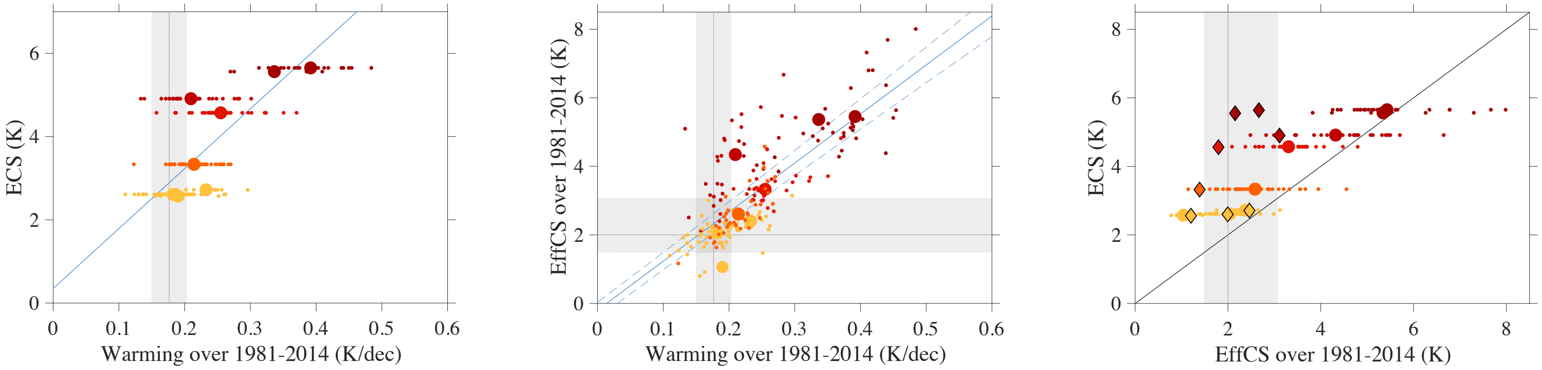
CMIP5/6 abrupt CO_2 quadrupling SST trend pattern



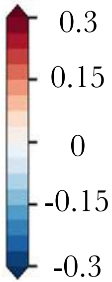
CMIP5/6 1981-2014 SST trend pattern



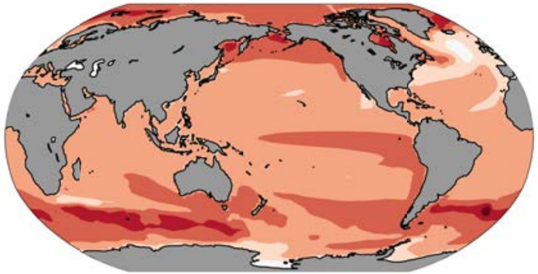
Transient warming and EffCS over recent decades



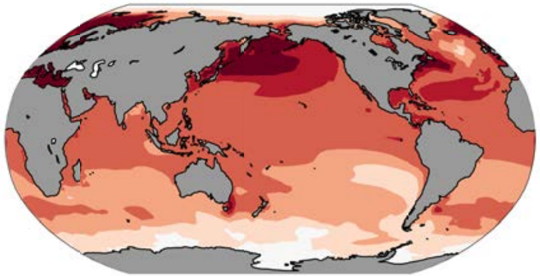
K/dec



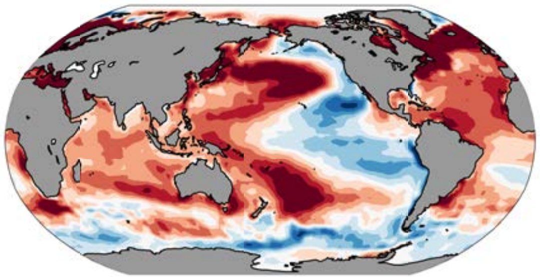
CMIP5/6 abrupt CO_2 quadrupling SST trend pattern



CMIP5/6 1981-2014 SST trend pattern

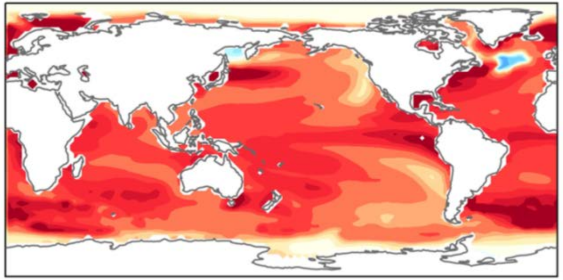


Observed 1981-2014 SST trend pattern

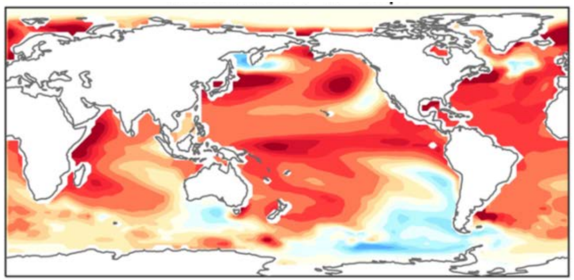


Transient warming and EffCS with freshwater forcing

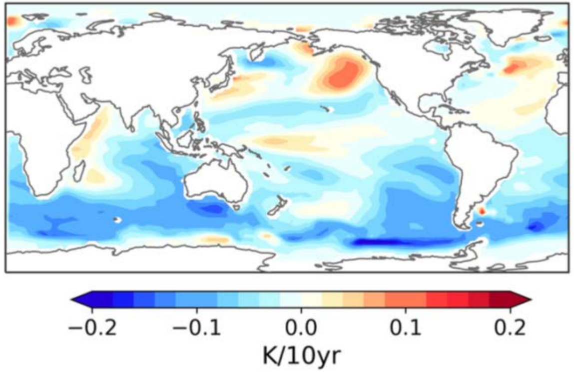
CESM1 historical warming over 1980-2013

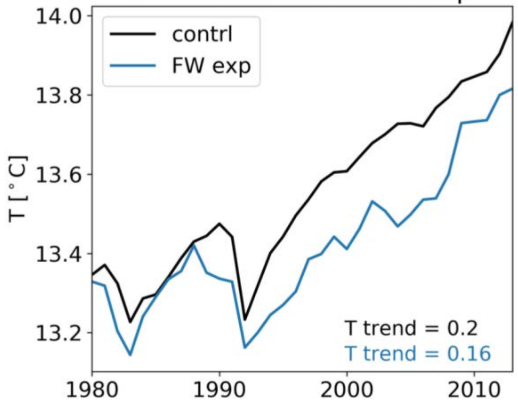


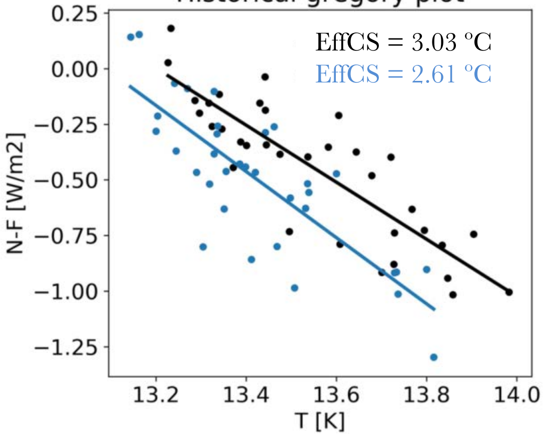
CESM1 historical warming over 1980-2013 with Antarctic freshwater input



difference





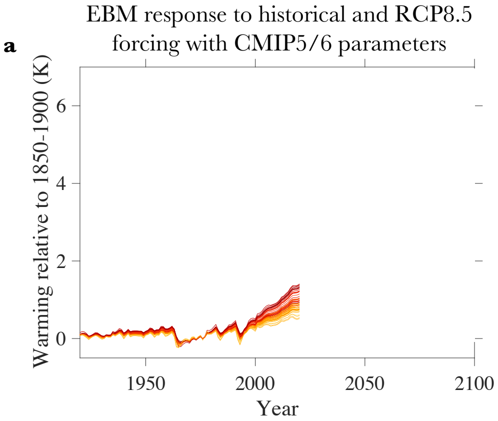


(Work of Yue Dong and Andrew Pauling)

Outstanding questions

- How will the pattern of warming evolve in the future, and on what timescale? (depends on mechanisms driving observed patterns, which we don't currently know)
- Fundamental issue: multiple potential mechanisms project onto same pattern of SST response (ENSO/PDO dynamics), yet all have different future evolutions. As summarized by Tim Andrews, candidate mechanisms are:
    - internal variability (originating in tropical Pacific and/or Southern Ocean?)
    - non-CO_2 forcing (ozone depletion, Southern Ocean freshwater forcing, tropospheric or stratospheric aerosols?)
    - role of teleconnections (from Southern Ocean or from Atlantic Ocean)
    - response to CO_2 forcing (delayed E Pacific warming or nonlinear ENSO mechanisms)

How does the pattern effect impact future warming?



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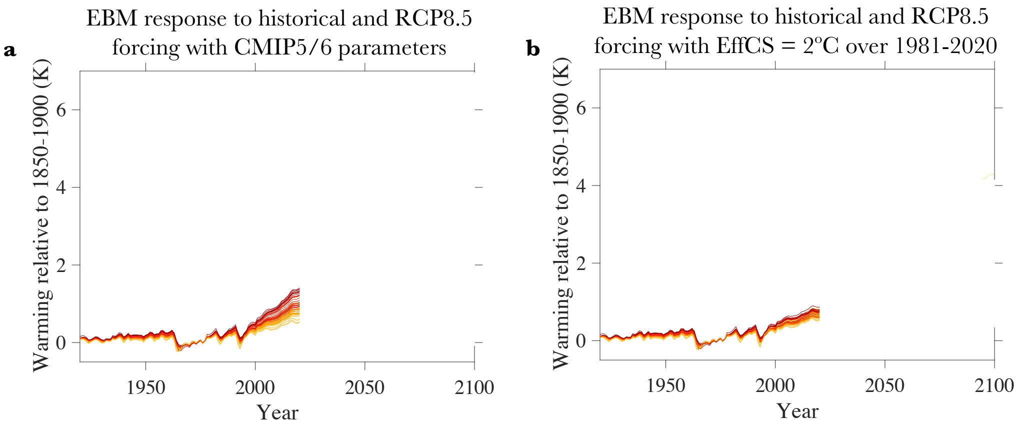

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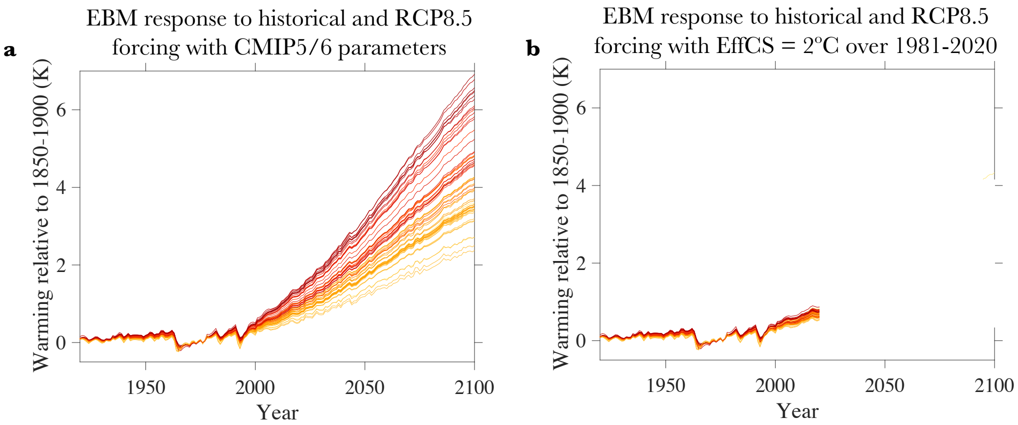

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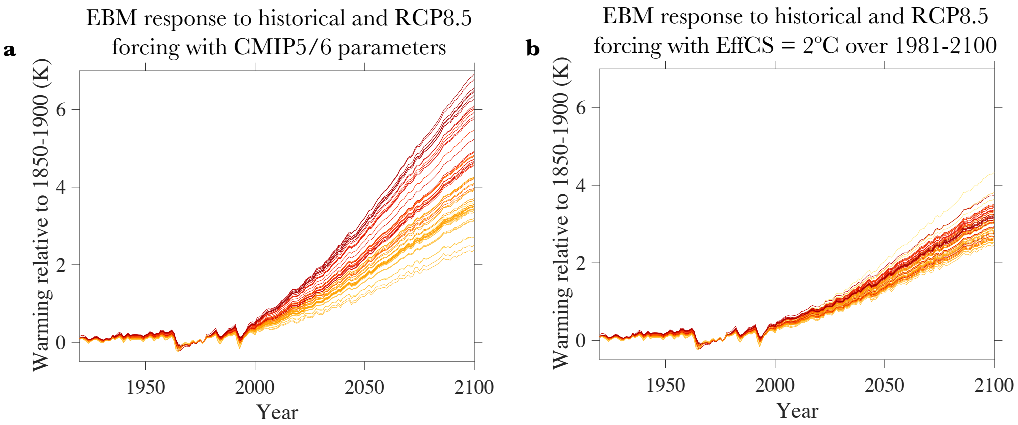
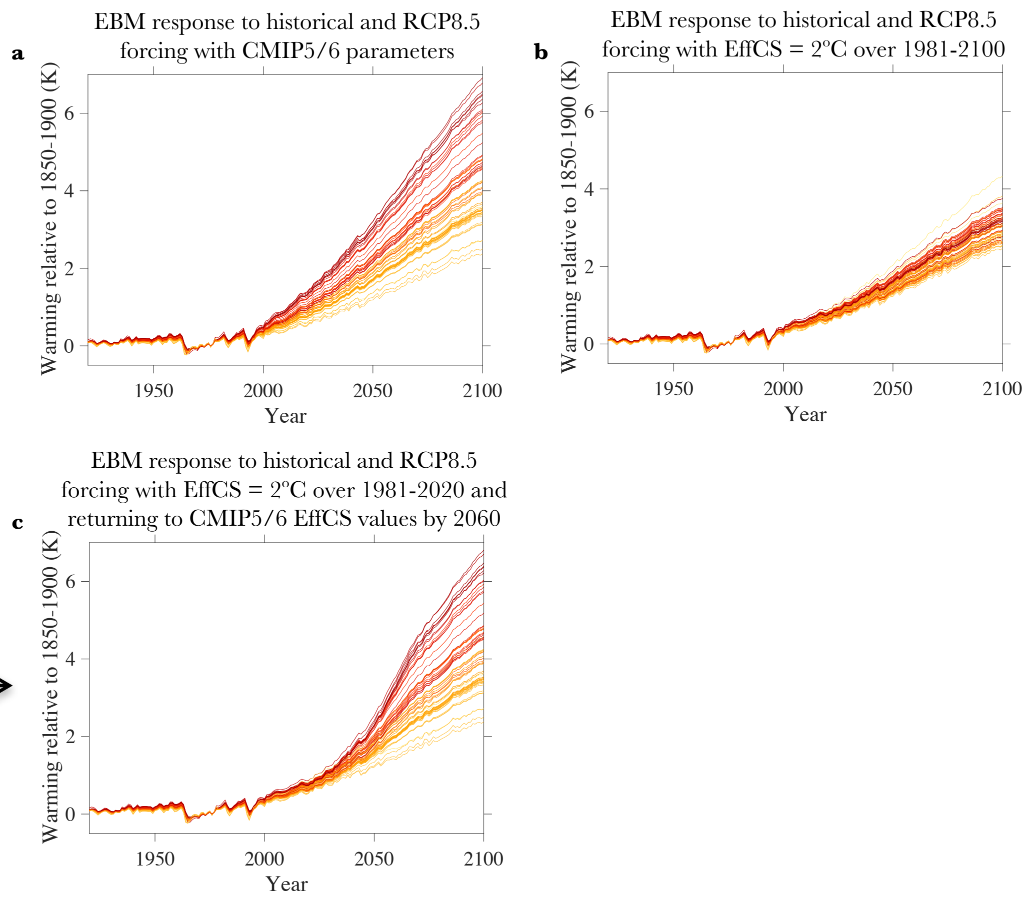


SST trend pattern since ~1980 continues indefinitely

How does the pattern effect impact future warming?

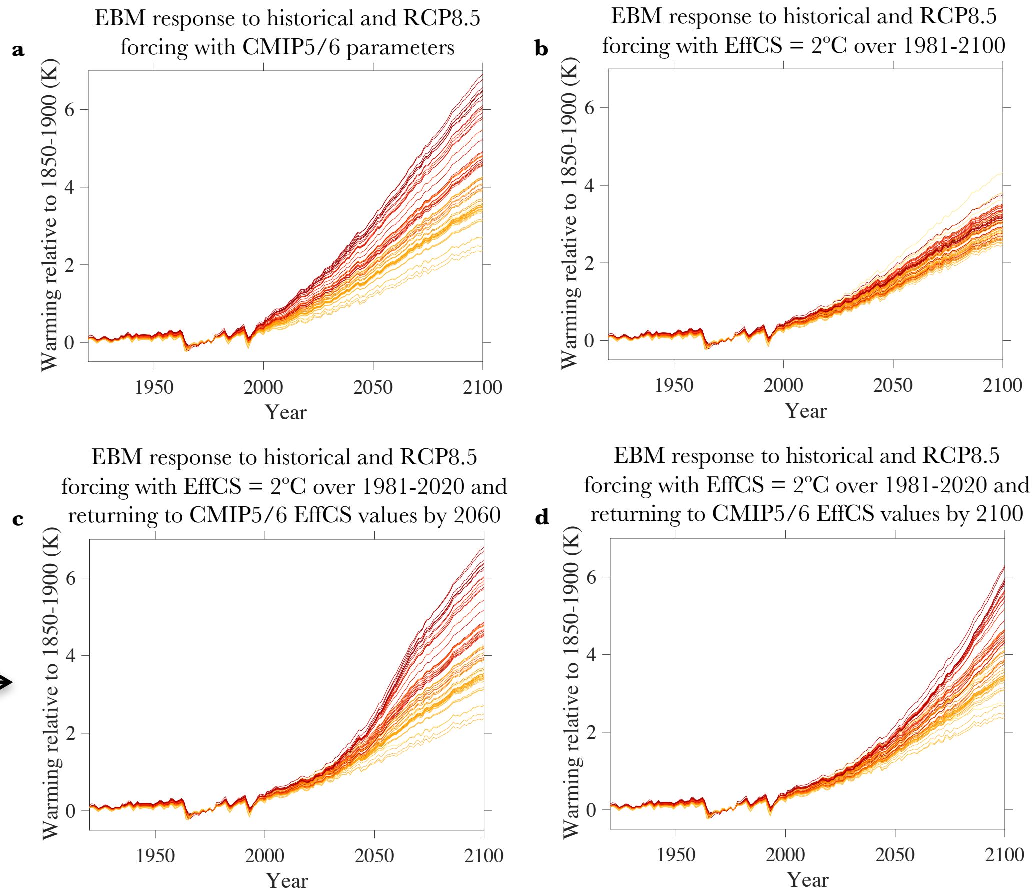


SST trend pattern since ~1980 continues indefinitely

SST trend pattern relaxes to CMIP5/6 patterns by 2060

How does the pattern effect impact future warming?

SST trend pattern since ~1980 continues indefinitely



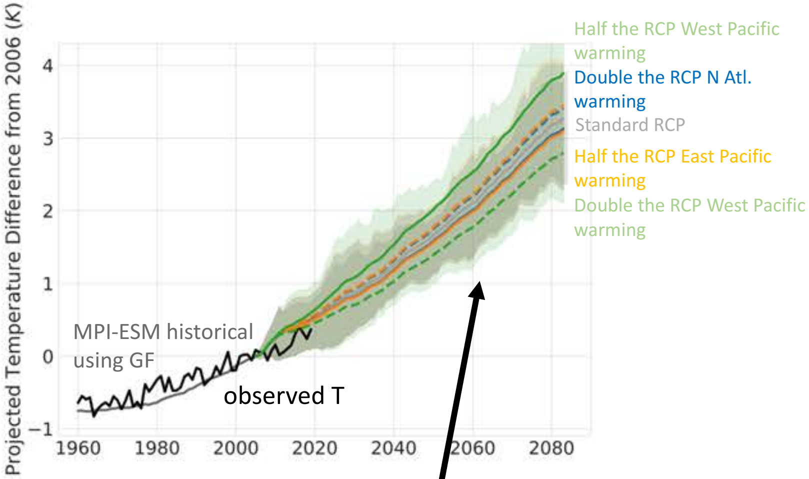
SST trend pattern relaxes to CMIP5/6 patterns by 2060

SST trend pattern relaxes to CMIP5/6 patterns by 2100

How does the pattern effect impact future warming?

Alternative SST pattern scenarios

Assume the coupled RCP/SSP scenarios are overall correct, except in the West Pacific, East Pacific, or North Atlantic – how much would alternative patters* reflect in global mean SSTs through changing radiative feedbacks?



By 2060, the spread of internal variability in the coupled model is ~1.3°C. This increases to ~2.0°C when considering SST pattern uncertainty

Work by Marc Alessi and Maria Rugenstein (see Marc's poster!)

* We redistribute SST warming/cooling. Global mean stays the same

Thank you Maria and Cristi!