Causes and consequences of the unique Pacific Ocean sea-surface temperature trend pattern

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The pattern of Pacific SST and SLP trends since ~1980 has been unique.

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Wills et al. 2022 (GRL)
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As summarized in Andrews et al. 2022 (JGR) and Ulla’s talk, candidate mechanisms are:

- internal variability (originating in tropical Pacific 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)
- or some combination of these

Fundamental issue: multiple potential mechanisms project onto same pattern of SST response (ENSO/PDO dynamics), yet all imply different future evolutions

Perhaps the most important unsolved problem in climate dynamics
What’s driven the pattern and why do models fail to replicate it?

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Two-way teleconnections between the Southern Ocean and the tropics

Response to localized patches of heat uptake in a slab ocean model (CAM4)

The tropical Pacific and Southern Ocean influence each other through atmospheric teleconnections, making it difficult to determine which is driving which.

But that the Southern Ocean has cooled more than the tropical Pacific in observations is at least consistent with the Southern Ocean driving the tropics.

Dong et al. 2022 (J Climate); see also Kang et al. 2023 (PNAS) and Sally Zhang's talk from yesterday.
One potential mechanism: Southern Ocean freshening

Response to adding Antarctic meltwater to the Southern Ocean in a coupled model (CESM1-CAM5)

Dong et al. 2022 (J Climate) and 2022 (GRL)
Another potential mechanism: Southern hemisphere atmospheric circulation

Response to nudging tropospheric winds to reanalysis over the Southern Ocean in a coupled model (CESM1-CAM5)

Dong et al. 2022 (J Climate); see also Hartmann 2022 (PNAS)
Impact of the SST trend pattern on global warming

Armour et al. (submitted)

Ensemble members that warm more show enhanced warming in the eastern tropical Pacific (El Niño-like) and Southern Ocean.
Impact of the SST trend pattern on global warming

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Ensemble members that warm less show reduced warming in the eastern tropical Pacific (La Niña-like) and Southern Ocean.
Impact of the SST trend pattern on global warming

Ensemble members that have a higher effective climate sensitivity (EffCS) over this period show enhanced warming in the eastern tropical Pacific (El Niño-like) and Southern Ocean.
Impact of the SST trend pattern on global warming

Armour et al. (submitted)

CESM1-LENS regression of local SST trend on effective climate sensitivity (EffCS) over 1981-2014

DONG ET AL. 10.1029/2021GL095778

The historical pattern effect that leads to lower values of EffCS may partially result from various non-CO₂ forcing agents that have operated in the historical period (e.g., Forster, 2016; Marvel et al., 2016). Gregory et al. (2020) suggest that volcanic forcing may bias estimate of EffCS from CO₂ quadrupling by causing different surface warming patterns in CMIP5 models. Winton et al. (2020) find that a large portion of the EffCS underestimate in GFDL-CM4 is attributable to its large efficacy of aerosol forcing. To test this possibility within other CMIP6 models, we make use of the DAMIP non-GHG forcing simulations, namely, hist-aer and hist-nat (Figure S2 in Supporting Information S1). Within all but one model, natural forcing alone produces even lower values of EffCS than those from historical simulations (i.e., a larger historical pattern effect). In comparison, when forced by anthropogenic aerosol forcing alone, four models show a larger historical pattern effect while three models show a reduced pattern effect. These results suggest that non-GHG forcing may largely account for the historical pattern effect, though the impact of aerosol forcing is less robust across models.

Figure 2. Historical and equilibrium SST trend patterns. Annual-mean SST linear trends over (a) 1870–2014, (b) 1979–2014, and (c) 150 years of abrupt-4xCO₂ simulations. The observed SST trend patterns in (a), (b) are calculated using AMIPII dataset (Hurrell et al., 2008). Note that the color scales in (a) and (b and c) are different.

CAM5 Green’s function showing global TOA radiative response to local surface warming (Zhou et al. 2017)
The unique SST trend pattern has slowed global warming

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CESM1 nudged toward observed SST trend pattern with Antarctic meltwater or southern hemisphere wind nudging produces a lower global warming rate.

Armour et al. (submitted)
Key takeaways so far

- The observed warming pattern since ~1980 has been unique, and CMIP5/6 models are not able to replicate its key features.

- The pattern implies low effective climate sensitivity (EffCS) over this period, even in models with high ECS. This lower EffCS implies slower global warming (relative to what it could have been had the pattern been more uniform).
  - CMIP5/6 models likely overestimate global warming over recent decades because they fail to replicate its spatial pattern (not because they have too-high values of ECS).

- Fundamental issue: multiple potential mechanisms project onto the same pattern of historical SST pattern trends, yet all have different future evolutions.
  - e.g., low-frequency internal variability, Antarctic meltwater and teleconnections to the tropics, southern hemisphere atmospheric circulation trends, response to aerosol or CO$_2$ forcing...
How does the pattern effect impact future warming?
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a. EBM response to historical and RCP8.5 forcing with CMIP5/6 parameters

b. EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2020
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- **EBM response to historical and RCP8.5 forcing with CMIP5/6 parameters**

- **EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2100**

SST trend pattern since ~1980 continues indefinitely.
How does the pattern effect impact future warming?

**EBM response to historical and RCP8.5 forcing with CMIP5/6 parameters**

**EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2100**

**EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2020 and returning to CMIP5/6 EffCS values by 2060**

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?

EBM response to historical and RCP8.5 forcing with CMIP5/6 parameters

EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2010

EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2020 and returning to CMIP5/6 EffCS values by 2060

EBM response to historical and RCP8.5 forcing with EffCS = 2°C over 1981-2020 and returning to CMIP5/6 EffCS values by 2100

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
Parting thoughts

- The unique Pacific Ocean sea-surface temperature trend pattern has likely slowed global-mean warming since ~1980

- Future warming will depend on how the pattern of warming evolves, and on what timescale... which in turn depends on what has driven the historical pattern
  - This is a major source of uncertainty in climate prediction
  - Caution is needed when devising model weighing schemes or "emergent constraints" based on historical warming
Our recent papers

- Armour, Proistosescu, Dong, Hahn, et al.: Sea-surface temperature pattern effects have slowed recent global warming and biased emergent constraints on climate sensitivity, submitted


