Global Impacts of Recent Southern Ocean Cooling

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The Southern Ocean (SO) surface has cooled since late 1970s.
Paleoclimate proxy shows SO SST multi-decadal variability

With tree ring records from Tasmania

Consistent with the instrumental SSTs (Fig. 2a) and reconstructed Tasmanian summer temperature (Fig. 6), the model simulates pronounced SOCV (Fig. 2c). An SOCV index was computed from the model in the same way as from the observed SSTs. The standard deviation...
Previous studies suggest a robust response due to SH extratropical forcing.
Previous studies suggest a robust response due to SH extratropical forcing

- Slab ocean

- Dynamic ocean

Hwang et al. (2017)

Dong et al. (2022)

Bronsemaer et al. (2018)

Kang et al. (2019)
Climate models are unable to capture observed SO SST trends

Observed trends 1979-2013

Stippling shows significant trends at 95% level

Data: ERSSTv3b; Zhang et al. (2021)
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Figure S3. Box-and-whisker plot of SST trends averaged over (a) tropical South Atlantic (gray box in Figure 1f) and (b) the Southern Ocean (40S-65S) for each model ensemble. Green stars show the EM values. Orange lines show the median values. Gray horizontal lines show the observed values from various data sets: NOAA Extended Reconstruction SSTs version 3b and 5 (ERSSTv3b & ERSSTv5, Huang et al. 2017), Centennial in situ Observation-Based Estimates (COBE, Ishii et al. 2005), and the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST, Rayner et al. 2003).

How much can be driven by SO cooling?
SO-induced teleconnection can affect the tropical warming patterns and climate sensitivity

Projected warming pattern

- Weakened Walker circulation
- Remote tropospheric warming
- Decreased inversion strength
- Decreased low-cloud cover

Atmospheric temperature profile

CMIP6 sea-surface temperature trend over years 1-150 after abrupt CO₂ quadrupling (°C per century)

IPCC AR6 WG I; Zhou et al. (2016); Zhang et al. (2021)
SO-induced teleconnection can affect the tropical warming patterns and climate sensitivity

Projected warming pattern

- Positive Feedback

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Observed pattern 1979-2013

- Atmospheric response to observed and projected Pacific Ocean sea surface temperature trends.
- Positive Feedback

Figure 7.14 | Illustration of tropospheric temperature and low-cloud feedbacks associated with SST changes. (a) Atmospheric response to linear sea-surface temperature trend observed and projected for the period 1870-2019 (°C per century). (b) Atmospheric response to projected Pacific Ocean warming trends. (a) Positive Feedback

IPCC AR6 WG I; Zhou et al. (2016); Zhang et al. (2021)
SO-induced teleconnection can affect the tropical warming patterns and climate sensitivity

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**Observed pattern 1979-2013**

- Increased inversion-strength
- Increased low-cloud cover

CMIP6 sea-surface temperature trend over years 1-150 after abrupt CO₂ quadrupling (°C per century)

Positive Feedback
SO-induced teleconnection can affect the tropical warming patterns and climate sensitivity

**Projected warming pattern**

- Increased inversion strength
- Decreased low-cloud cover
- Remote tropospheric warming
- Weakened Walker circulation

**Observed pattern 1979-2013**

- Increased inversion strength
- Increased low-cloud cover

IPCC AR6 WG I; Zhou et al. (2016); Zhang et al. (2021)
SO surface cooling may explain model’s inability to simulate observed Antarctic sea ice expansion

Observed SST (colors), wind (vectors), and sea ice (contours) trends

(a) Observed sea ice extent trend is positive
Using Southern Ocean pacemaker experiment (SOPACE) to study SO teleconnection
By including observed SO SST evolution in historical simulations

We nudge SST at each grid point in SO to **observed monthly anomaly** + CESM1 mean state.
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By including observed SO SST evolution in historical simulations

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Global SST response to observed SO cooling

Results from CESM1

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Radiatively-forced response + SO-driven response

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SO-driven response

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Zhang et al. (2021); Kang et al. (2023)
Why is the response so weak in the tropical Pacific?

Pacemaker experiment

Idealized experiment

Zhang et al. (2021); Kang et al. (2023); Kang et al. (2019)
CESM1 has a subtropical low cloud bias in the Pacific

Subtropical stratocumulus cloud feedback west of South America

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- CESM1’s stratocumulus cloud feedback is too weak
- CESM2 has much stronger stratocumulus cloud feedback
- Will SOPACE with CESM2 show a stronger tropical Pacific response?
Global SST response to observed SO cooling

CESM1 vs CESM2

Materials and Methods

Zhang et al. (2021); Kang et al. (2023)

Stippling: trends NOT significant at 95% confidence level

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Global SST response to observed SO cooling

CESM1 vs CESM2

Radiatively-forced only

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Zhang et al. (2021); Kang et al. (2023)
Global SST response to observed SO cooling

**CESM1 vs CESM2**

**A** [HIST1] Radiatively-forced only

**B** [SOPACE1] Radiatively-forced + SO-driven

**C** SO-driven1

**D** [HIST2] Radiatively-forced only

**E** [SOPACE2] Radiatively-forced + SO-driven

**F** SO-driven2

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Zhang et al. (2021); Kang et al. (2023)
Decomposition of SST trends via surface energy budget

\[ \rho c_p H \frac{\partial T}{\partial t} = SW + LW - LH - SH + OHT \]
Decomposition of SST trends via surface energy budget

\[ \rho c_p H \frac{dT}{dt} = SW + LW - LH - SH + OHT \]
Comparison with observations:
Differences in radiatively-forced response

Zhang et al. (2021); Kang et al. (2023)
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What are the processes that contribute to the intermodel difference in the remote Southeast Pacific response to Southern Ocean cooling? We address this question by examining the surface energy budget in SO-driven (Fig. 2; Materials and Methods).

In response to observed Southern Ocean cooling, the southeast-easterlies in the eastern basin of the South Pacific strengthen in conjunction with increased sea level pressure over southern high-latitudes, enhancing the evaporative cooling, thereby promoting equatorward propagation of a surface cooling response (Fig. 2 G and H). The wind-evaporation-SST (WES) feedback is likely to trigger cooling in the Southeast Pacific, which then stabilizes the atmospheric boundary layer aloft. The resultant increase in the lower tropospheric stability enhances subtropical low clouds that amplify the surface cooling via the shortwave radiative feedback (Fig. 2 C and D and SI Appendix, Fig. S5). Indeed, the shortwave radiative effect and the WES feedback are the dominant drivers of the Southeast Pacific cooling in both models (Fig. 2 K).

However, the contributions from the shortwave fluxes show a large intermodel difference: the shortwave flux (i.e., $T_{SW}$ in Fig. 2 K)
Comparison with observations: Differences in radiatively-forced response

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Zhang et al. (2021); Kang et al. (2023)

3 of 10
Comparison with observations: Differences in radiatively-forced response

- CESM1 + CMIP5 forcing
  - [HIST1]
  - [SOPACE1]

- CESM2 + CMIP6 forcing
  - [HIST2]
  - [SOPACE2]

- CESM2 + CMIP5 forcing
  - [HIST2-C5]
  - [SOPACE2-C5]

Southwest Pacific SST trend

K

ERSSTv5

Stippling: trends NOT significant at 95% confidence level

Zhang et al. (2021); Kang et al. (2023)
Observed Antarctic sea ice trends are also better represented in SOPACE2.
Summary

• The global response of observed SO surface cooling includes cooling of the southeastern tropical Pacific and Atlantic, as well as Antarctic sea ice expansion

• Observed SO surface cooling from 1979 to 2013 is partly responsible for driving cooling of the southeastern tropical Pacific SST

• The SO-tropical teleconnection is highly sensitive to the strength of the subtropical low cloud feedback

• There are implications for future warming patterns as the SO transitions from cooling to warming under increasing greenhouse gases
Challenges and open questions

• Uncertainties in historical radiative forcing hinder our understanding of the SO-tropical teleconnection (especially in the northern extratropics)

• Can we quantify the causes of SO SST multi-decadal variability (e.g., internal variability, CO2 or ozone, ice melt...)?

• What other model/resolution-dependent feedbacks can influence the SO-driven teleconnection?

Questions and feedbacks? 📧 sallyz@jhu.edu
Extra Slides
SO cooling’s impact on tropical precipitation

The interhemispheric contrast in SST (Fig. 1), giving rise to a northward displacement of the cross-equatorial Hadley circulation in [HIST2], as a way to restore the interhemispheric energy balance (36) (Fig. 3). As a result, [HIST2] shows a clear northward shift of zonal-mean tropical precipitation, distinct from the highly equatorially symmetric response in [HIST1] and Fig. 3.

**Figures:**
- (A) [HIST1], (B) [SOPACE1], (C) SO-driven1, (D) [HIST2], (E), [SOPACE2], (F) SO-driven2, (G) [HIST2-C5], (H) [SOPACE2-C5], and (I) ERA5 reanalysis (37), with the climatological mean in contours (solid: clockwise, dashed: counter-clockwise).
- (J) Zonal-mean precipitation trends between 30°S and 30°N in [HIST1] (red), [HIST2] (blue), and [HIST2-C5] (green), (K) [SOPACE1] (red), [SOPACE2] (blue), and [SOPACE2-C5] (green), and (L) SO-driven1 (red) and SO-driven2 (blue), with the observed estimate from GPCP data (38) in black lines in (J and K).
- Local trend that is not statistically significant at 95% confidence level is stippled in (A–I) and is plotted in thinner lines in (J–L).
SO cooling’s impact on tropical circulation
Schematic of SO teleconnection
Antarctic sea ice trends are better captured when observed SO SST trends are included.

Blanchard-Wrigglesworth et al. (2022)
Origin of SO SST variability is under debate

**Forced response**

- Ocean heat uptake (Marshall et al., 2015; Armour et al., 2016)
- Ozone (e.g., Ferreira et al., 2015; Hartmann 2022)
- Antarctic meltwater (e.g., Bronselaer et al., 2018)
Origin of SO SST variability is under debate

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**Internal variability**
- Linked to tropical variability (e.g., Schneider and Deser 2018; Chung et al., 2022)
- Ocean deep convection (Latif et al., 2013; Zhang et al., 2017; Cabré et al., 2017)
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**Observations**: limited coverage; some evidence from paleo records (Latif et al., 2013)
**Models**: sensitive to parameterization; captured in high-resolution models (Chang et al., 2020)
Sea level pressure

Fig. S10. Global sea level pressure trend maps. Annual-mean sea level pressure trends between 1979-2013 in (A) [HIST1], (B) [SOPACE1], (C) SO-driven1, (D) [HIST2], (E) [SOPACE2], (F) SO-driven2, (G) [HIST2-C5], (H) [SOPACE2-C5], and (I) ERA5 reanalysis (52). Stippling indicates a local trend that is not statistically significant at 95% confidence level.