Roles of surface forcing in the Southern Ocean temperature and salinity changes under increasing CO2: perspectives from model perturbation experiments and a theoretical framework

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Introduction

A rapid warming and freshening of the Southern Ocean have been observed over the past several decades and attributed to the anthropogenic climate change. In this study, ocean model perturbation experiments are conducted to separate roles of individual surface forcing in the Southern Ocean temperature and salinity changes. Model-based findings are compared with results from a theoretical framework including three idealized processes defined on the θ-S diagram.

FAFMIP experiments based on ACCESS-OM2

- Based on the global 1° ocean sea-ice model of ACCESS-OM2 (Kiss et al. 2020)
- Flux-form forcing anomalies of wind stress, heat flux and freshwater flux coming from Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP; Gregory et al. 2016)
- FAFMIP forcing anomalies applied individually to separate total responses in ocean states like temperature and salinity

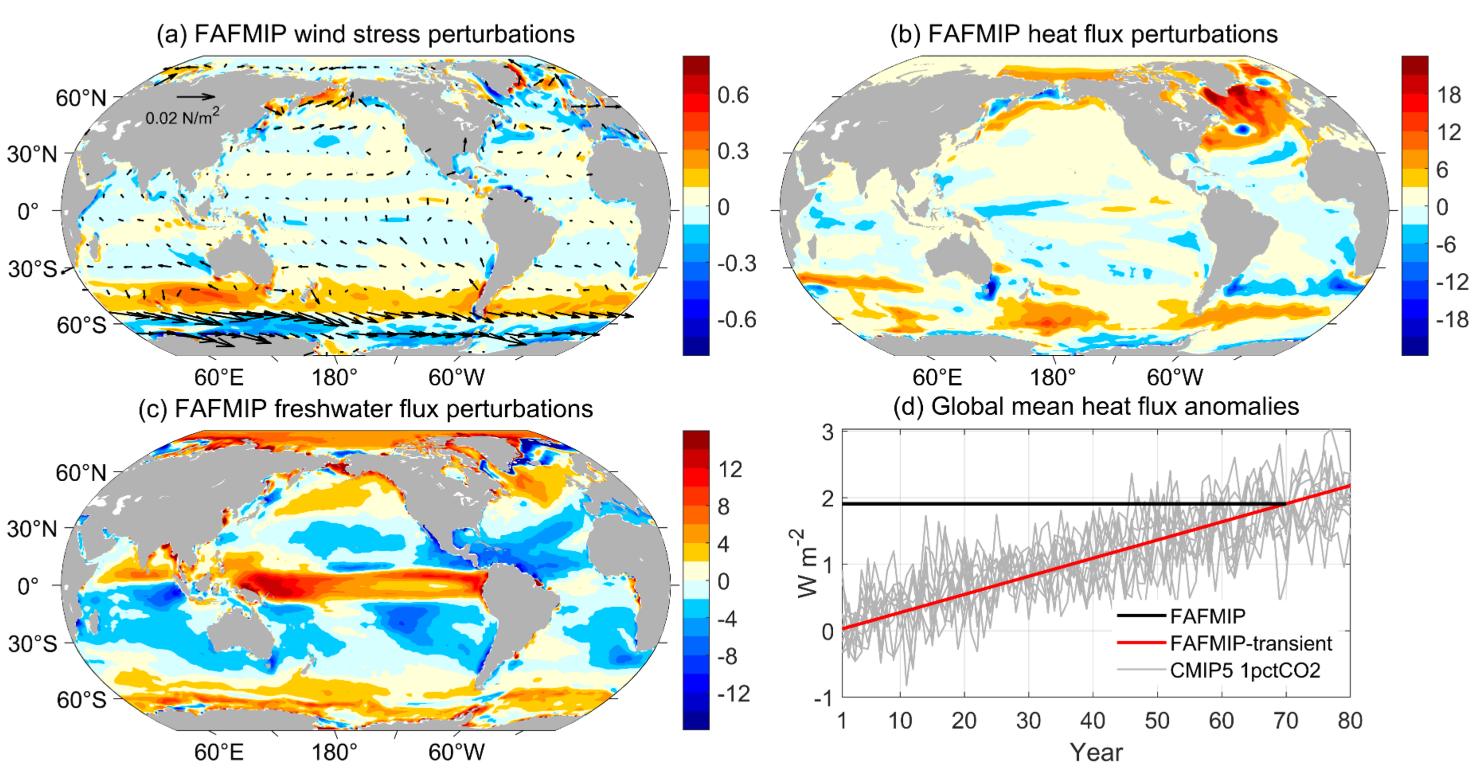


Fig. 1. Annual mean FAFMIP perturbations of surface (a) wind stress (N m^{-2}) and wind stress curl (10^{-7} N m^{-3}), (b) heat flux (W m^{-2}), (c) freshwater flux (10^{-6} kg m^{-2} s^{-1}), and (d) global mean heat flux anomalies for FAFMIP, transient FAFMIP and CMIP5 1pctCO2 experiments.

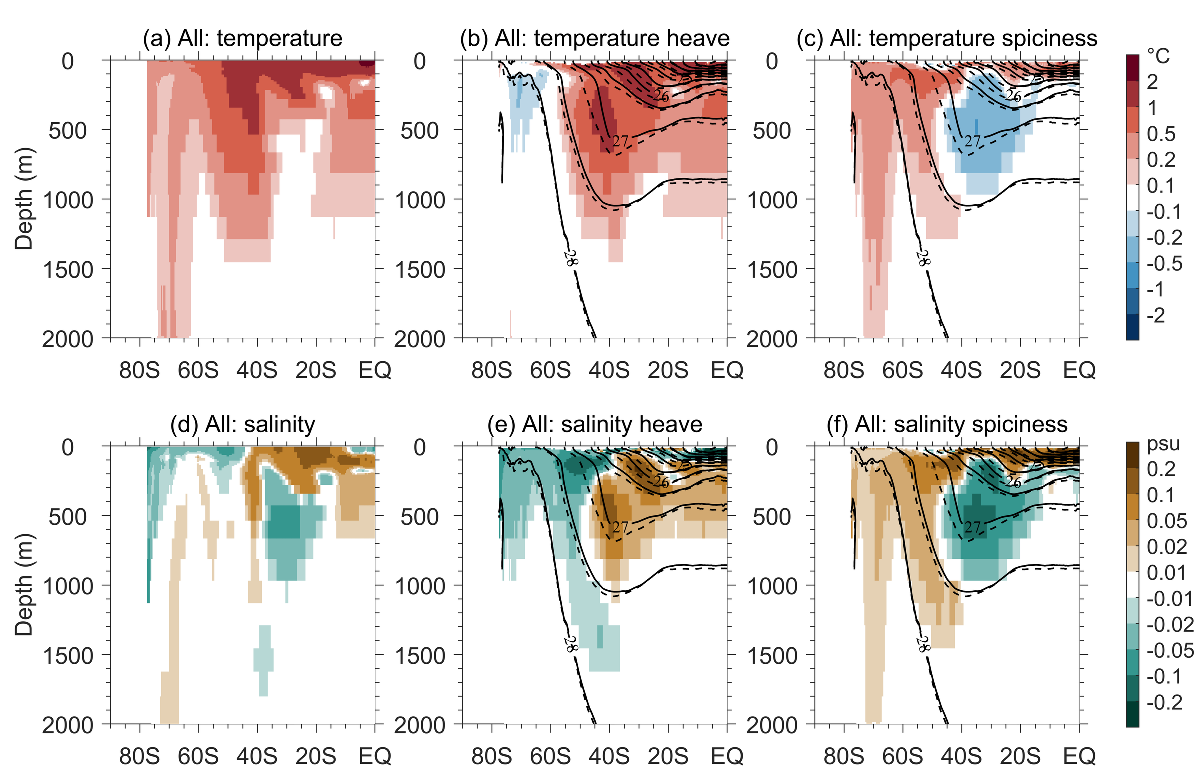


Fig. 2. Zonal averages of ocean (upper panels) temperature and (lower panels) salinity changes in the all-forcing experiment. (Left panels) changes at depth levels; (middle panels) changes related to the heave of isopycnals; (right panels) salinity spiciness changes along isopycnals mapped back to depth levels.

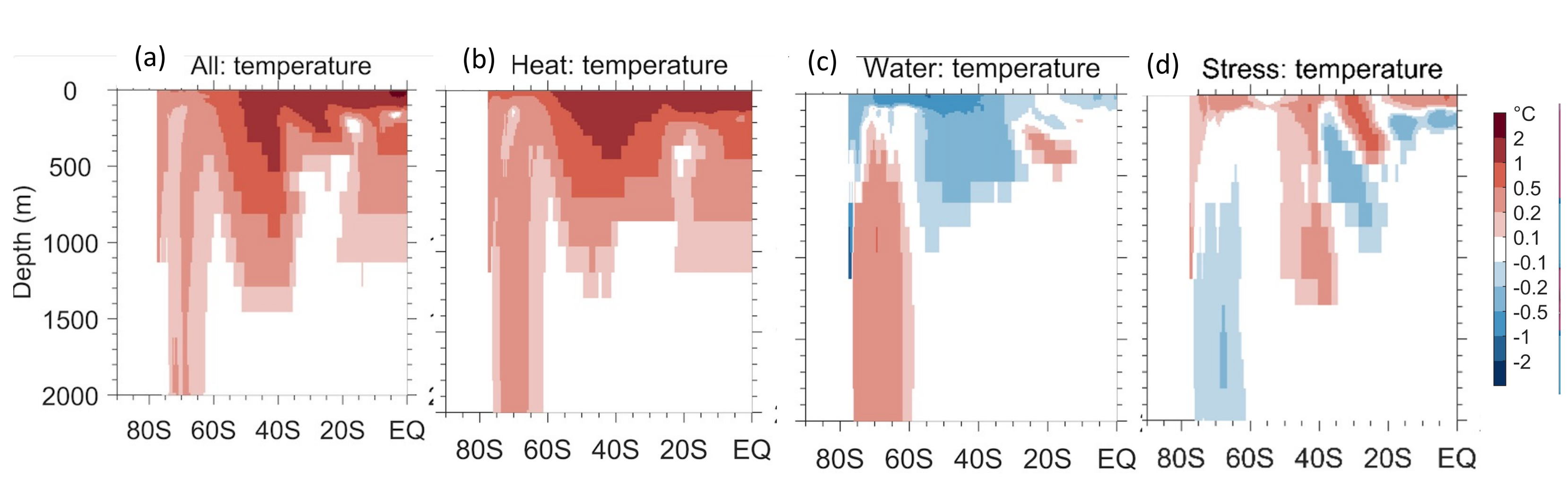


Fig. 3. Zonal averages of ocean temperature from (a) all-forcing (b) heat, (c) water and (d) stress FAFMIP experiments

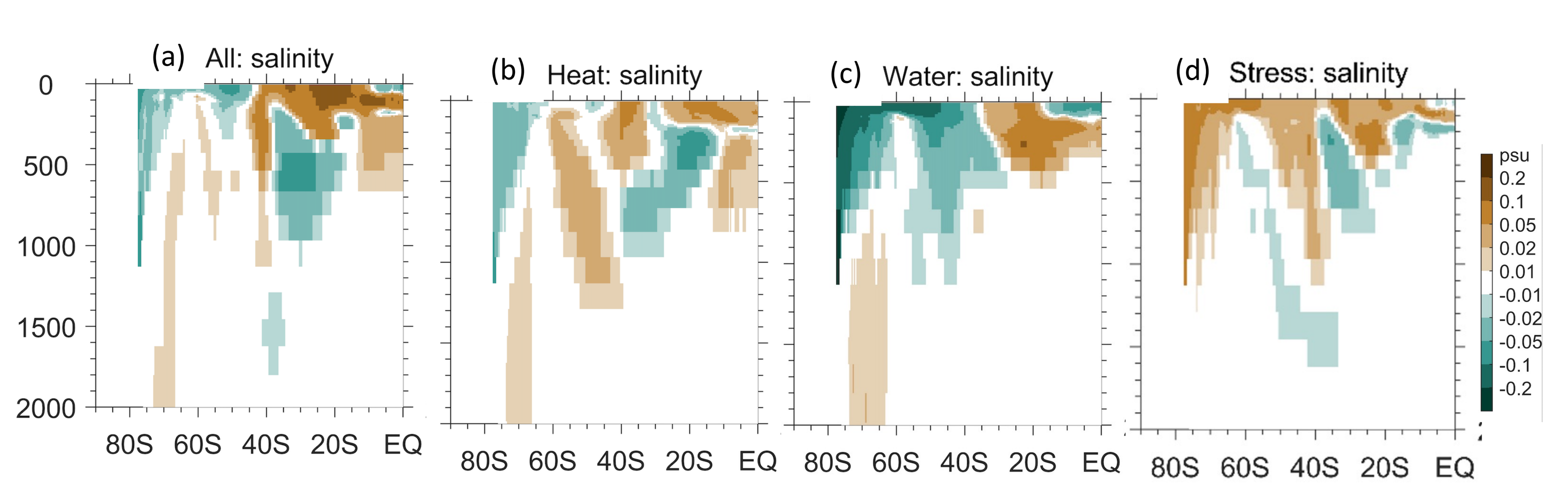


Fig. 4. Zonal averages of ocean salinity from (a) all-forcing (b) heat, (c) water and (d) stress FAFMIP experiments

Insights from a theoretical framework

- We use a theoretical framework from Bindoff and McDougall (1994, BM94) to separate subsurface temperature and salinity (T&S) changes into three processes on the T&S diagram
- **Pure warming**: no salinity change at depth level --- the warming might be traced back to surface heat flux input
- **Pure freshening**: no temperature change at depth level --- the salinity change might be traced back to surface freshwater input
- **Pure heave**: no spiciness signal, only isopycnal heave --- related to wind, wave propagation, eddy etc.

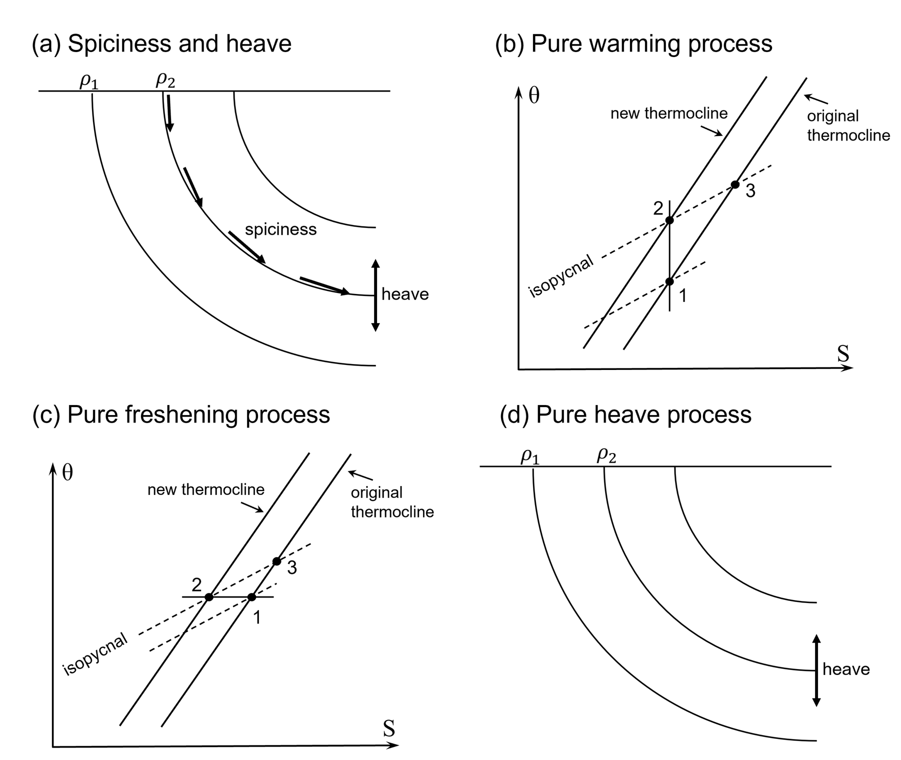
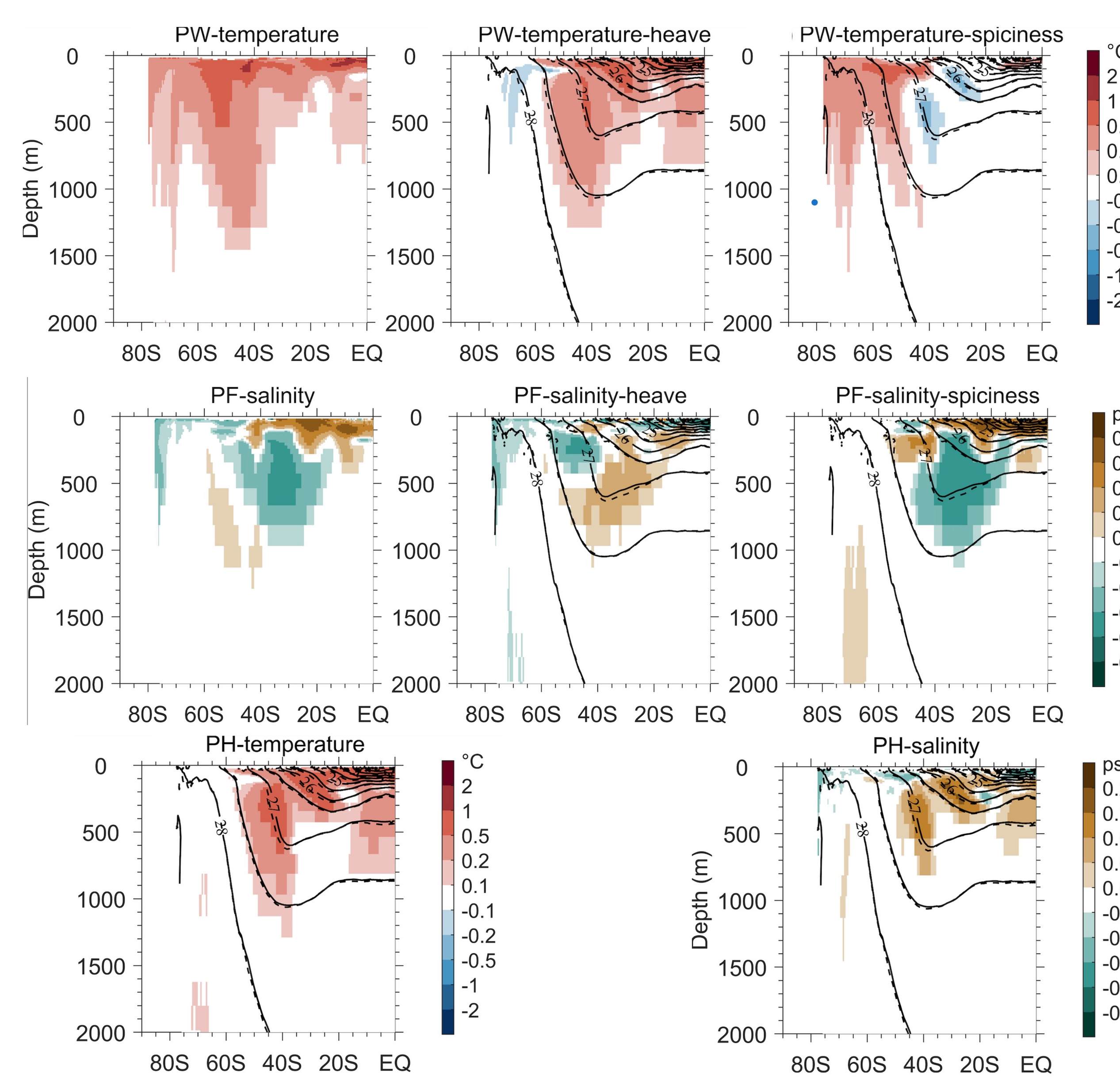


Fig. 5. Schematic diagrams for (a) the spiciness and heave components, (b) the pure warming process, (c) the pure freshening process, and (d) the pure heave process. These diagrams are redrawn from BM94 and Lyu et al. (2020).



Pure warming

Pure Freshening

Pure Heave

Fig. 6. Contributions of the pure warming (upper row), pure freshening (middle row) and pure heave (lower row) processes to zonal averages of ocean temperature and salinity changes in the all-forcing experiment, derived from the underdetermined Singular Value Decomposition solution based on BM94.

Conclusion

- Numerical model perturbation experiment is a powerful tool to separate and quantify distinct signatures of individual surface forcing in the interior ocean.
- While this theoretical framework is a useful tool to analyse subsurface ocean changes in terms of the three idealized processes, caution should be exercised when attempting to link each process to the individual surface flux forcing.
- The heave component arises from not only the dynamically induced adiabatic heave of isopycnals seen in the wind forcing perturbation experiment, but also the subduction and diffusion of heat and freshwater into the ocean interior which modify the density fields.
- Pure warming and pure heave processes can successfully represent some aspects of ocean responses as found in heat flux and wind stress perturbation experiments respectively, while pure freshening process cannot represent responses to freshwater flux well.

FOR FURTHER INFORMATION
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