UC RIVERSIDE

EVALUATING SOUTHERN OCEAN HEAT UPTAKE IN HIGH- AND LOW-RESOLUTION CLIMATE MODELS

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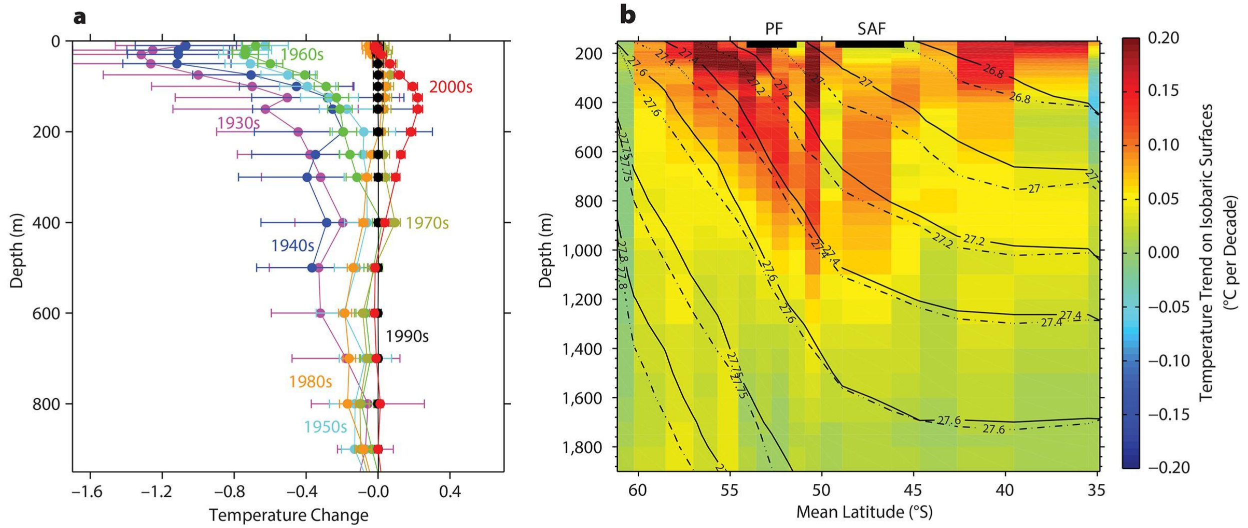
30TH ANNUAL CESM WORKSHOP 2025

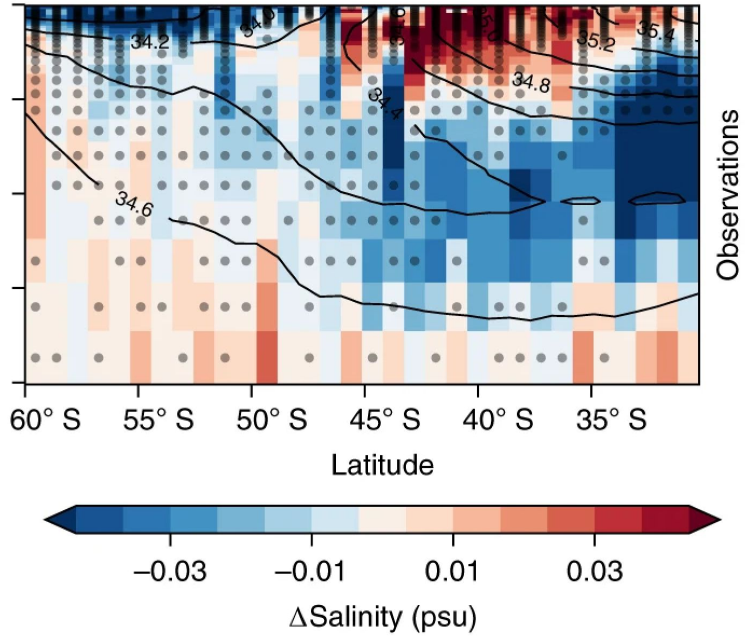
Motivation

Recent Observed Changes in the Southern Ocean



Southern Ocean within and north of the Antarctic Circumpolar Current has warmed at all depths in the upper 2,000 m.

(Gille, 2008); (Böning et al., 2008)

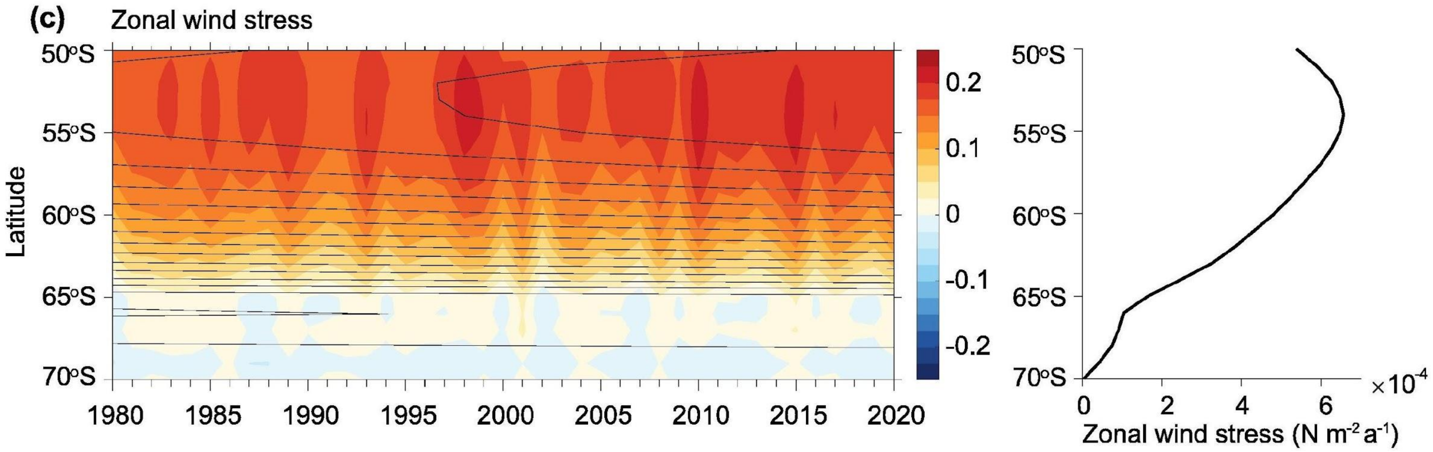


Southern Ocean also shows strong surface freshening south of 45°S which extends into ocean interior

(Swart et al., 2018)

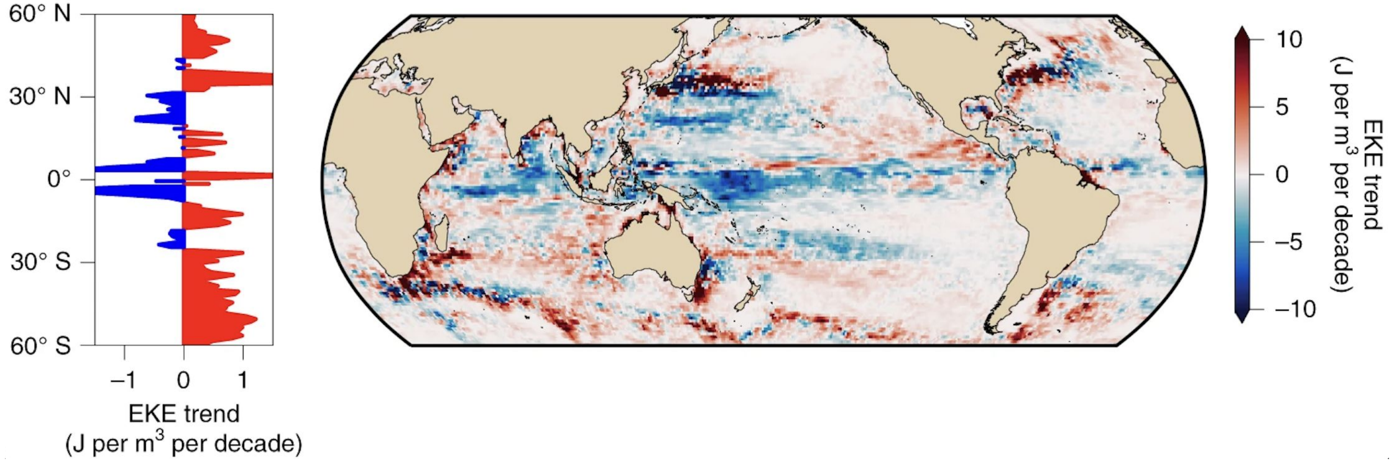
Motivation

Recent Observed Changes in the Southern Ocean



Southern Ocean also exhibits poleward strengthening of westerlies

(Cai et al., 2023)



Observational studies suggest a rise in eddy kinetic energy (EKE) in the ACC since the 1990s

(Martínez-Moreno et al., 2021)

Motivation

- It was found that explicitly resolved mesoscale eddies reduce subsurface ocean model warming drifts, improving the realism of water masses relative to those in standard models.

- Accurate simulation of climate change responses in the Southern Ocean was reported to be critically dependent on mesoscale eddies.

(Hewitt et al., 2017)

Methods

I. Datasets

- **Period analyzed:** 1958–2014
- **Region:** 30°S–70°S, upper 0–1800 m layer

i. Observational Datasets

Ishii et al. (2005)

IAP (Cheng et al., 2017)

EN4.2.2 (Good et al., 2013)

- All observational data interpolated to Ishii vertical levels for consistency

Methods

ii. Climate Model Simulations

- **Models used:**

•**HadGEM3-GC31** (UK Met Office) and **CESM1.3** (NCAR/iHESP)

•**Participating in: CMIP6 HighResMIP**

•**Simulations:** control-1950 and hist-1950

•**Drift correction:** linear trend removed using 100-yr control-1950 simulation

HadGEM3-GC31:

- **Low resolution (LL):**

ORCA1 (~1° ocean), N96 (~135 km) atmosphere

- **High resolution (HH):**

•ORCA12 (~0.1° ocean), N512 (~25 km) atmosphere

•Ocean: 75 vertical levels
•Ocean components: GA7.1 atmosphere, GO6 ocean (NEMO v3.6), GSI8.1 sea ice (CICE5.1), GL7.1 land
•Coupled via OASIS-MCT

CESM1.3:

- **Low resolution (LR):**

~1° POP2 ocean, 0.25° CAM5-SE atmosphere

- **High resolution (HR):**

~0.1° POP2 ocean, 0.25° atmosphere (same as LR)

•Ocean: 62 vertical levels, max depth 6000 m
•No eddy parameterization in HR – explicitly resolves mesoscale eddies
•CAM5 atmosphere, CICE4 sea ice, CLM4 land, updated physics

Methods

iii. Spiciness–Heave Decomposition Method

- *To separate temperature changes into components arising from along-isopycnal variations and vertical displacement of isopycnal surfaces*

Temperature:

$$T'|_z \cong T'|_n + N' T_z$$

• **Terms:**

$T'|_n$: Spiciness — changes **along** isopycnals

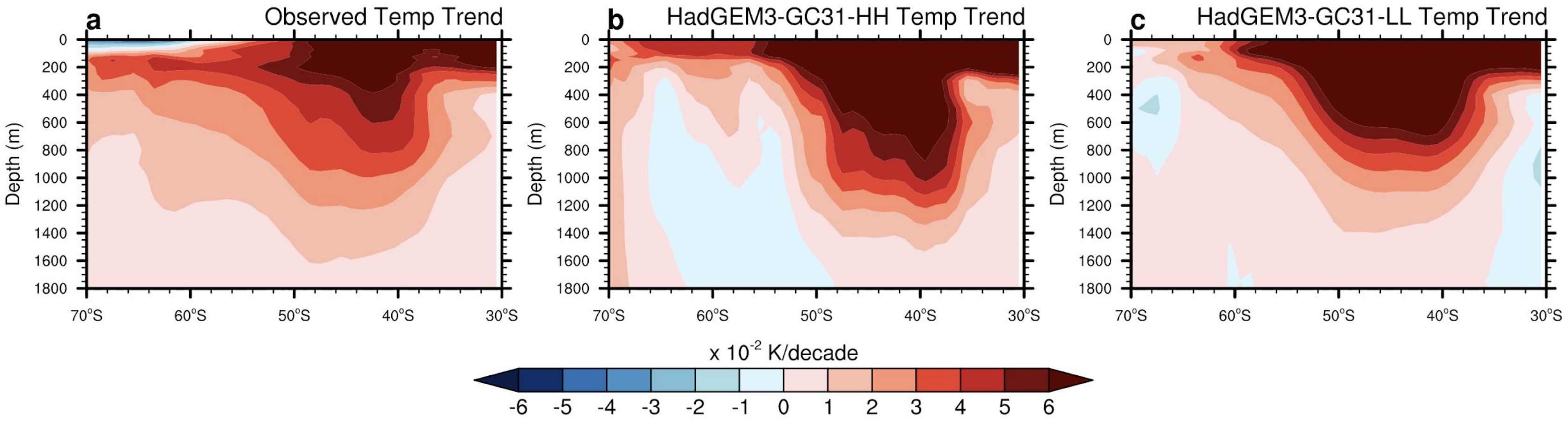
• $N' T_z$: Heave — changes **due to vertical displacement** of density surfaces

• N’: Depth change of neutral density surface (positive = deeper)

Bindoff et al. (1994); Lyu et al. (2020)

Results

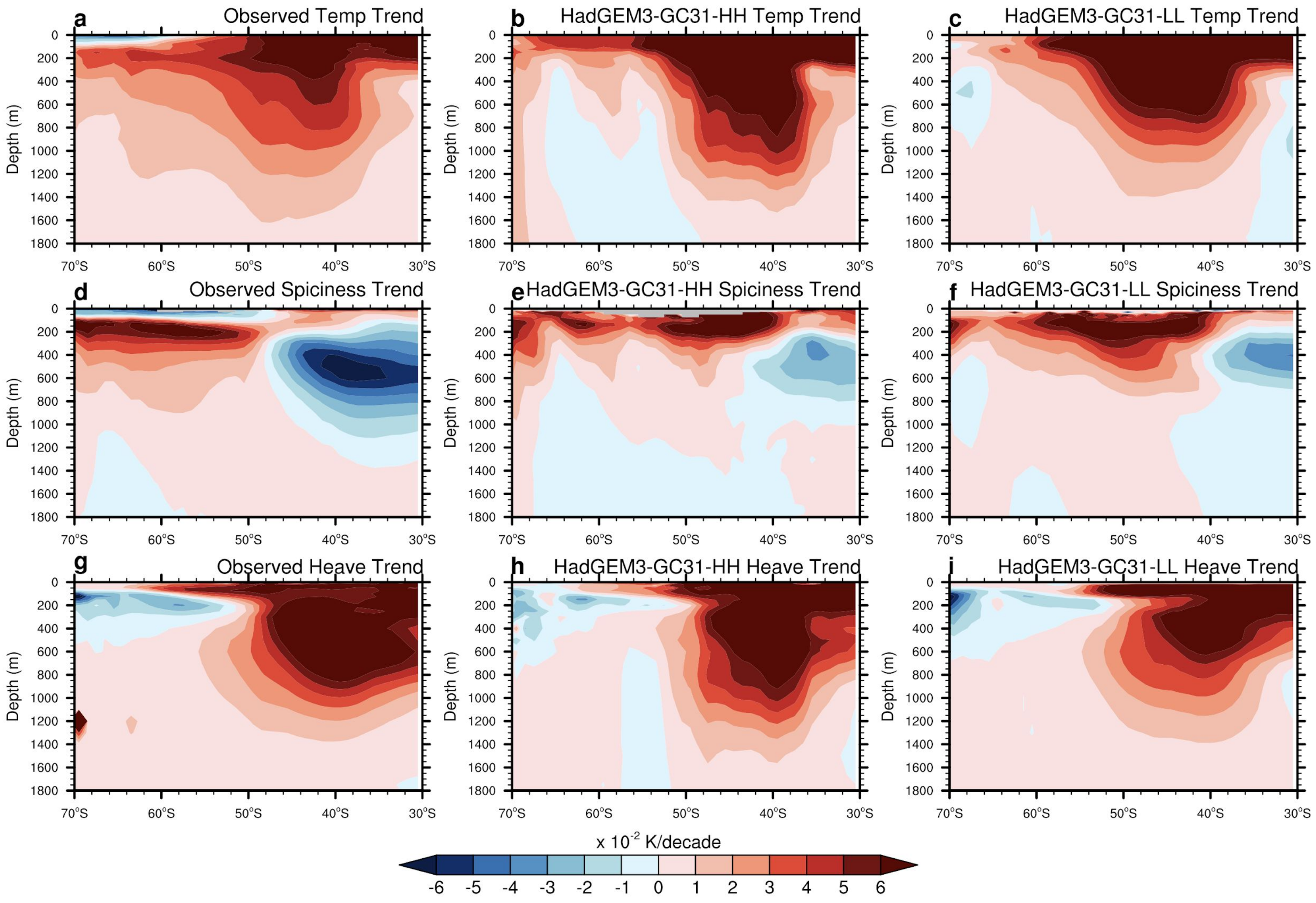
Temperature Trends – Observation vs HadGEM3-GC31



- **Observation-based datasets** consistently show **surface cooling and subsurface warming south of 55°S**, and **a deep-reaching warming north of 55°S**
- **HadGEM3-GC3.1** simulations **show resolution-dependent biases**, with the **high-resolution version producing deeper and stronger warming north of 55°S** and **both resolutions failing to capture the observed surface cooling south of 55°S**

Results

Temperature Trends – Observation vs HadGEM3-GC31



Observations:

Surface cooling south of 55ºS is driven by **negative spiciness trends**

Subsurface warming north of 50ºS arises from **positive heave contributions**

HadGEM3-GC3.1 High & Low Res:

South of 55ºS:

Both resolutions **fail to capture observed cooling**

Simulate **spiciness-driven warming** instead of cooling

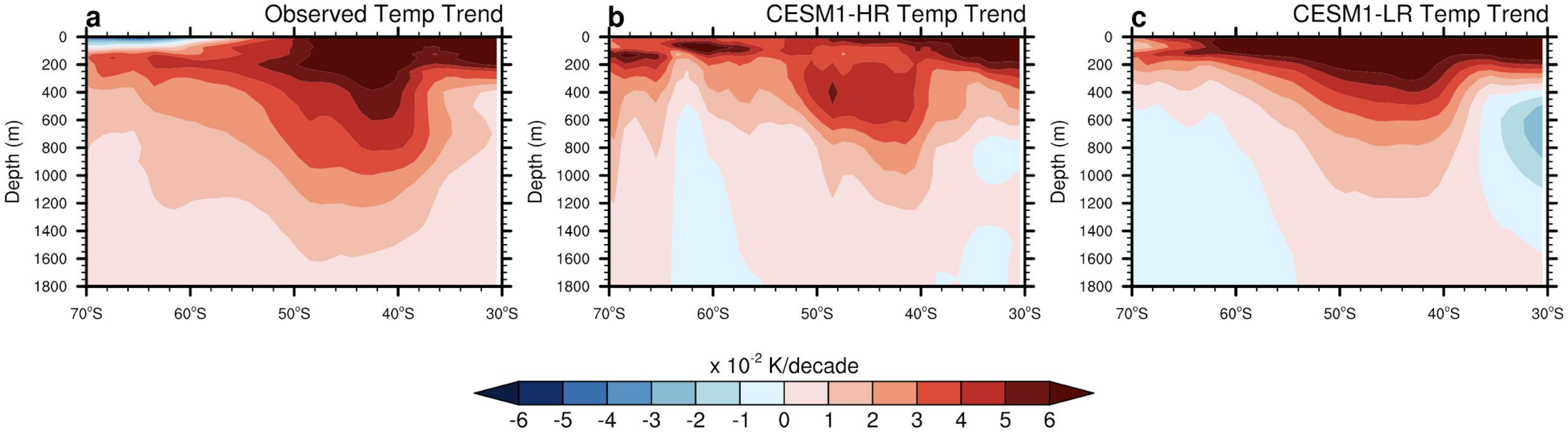
North of 50ºS:

Warming tongue driven by heave in both versions

High-res model shows **stronger and deeper heave**, closer to observations

Results

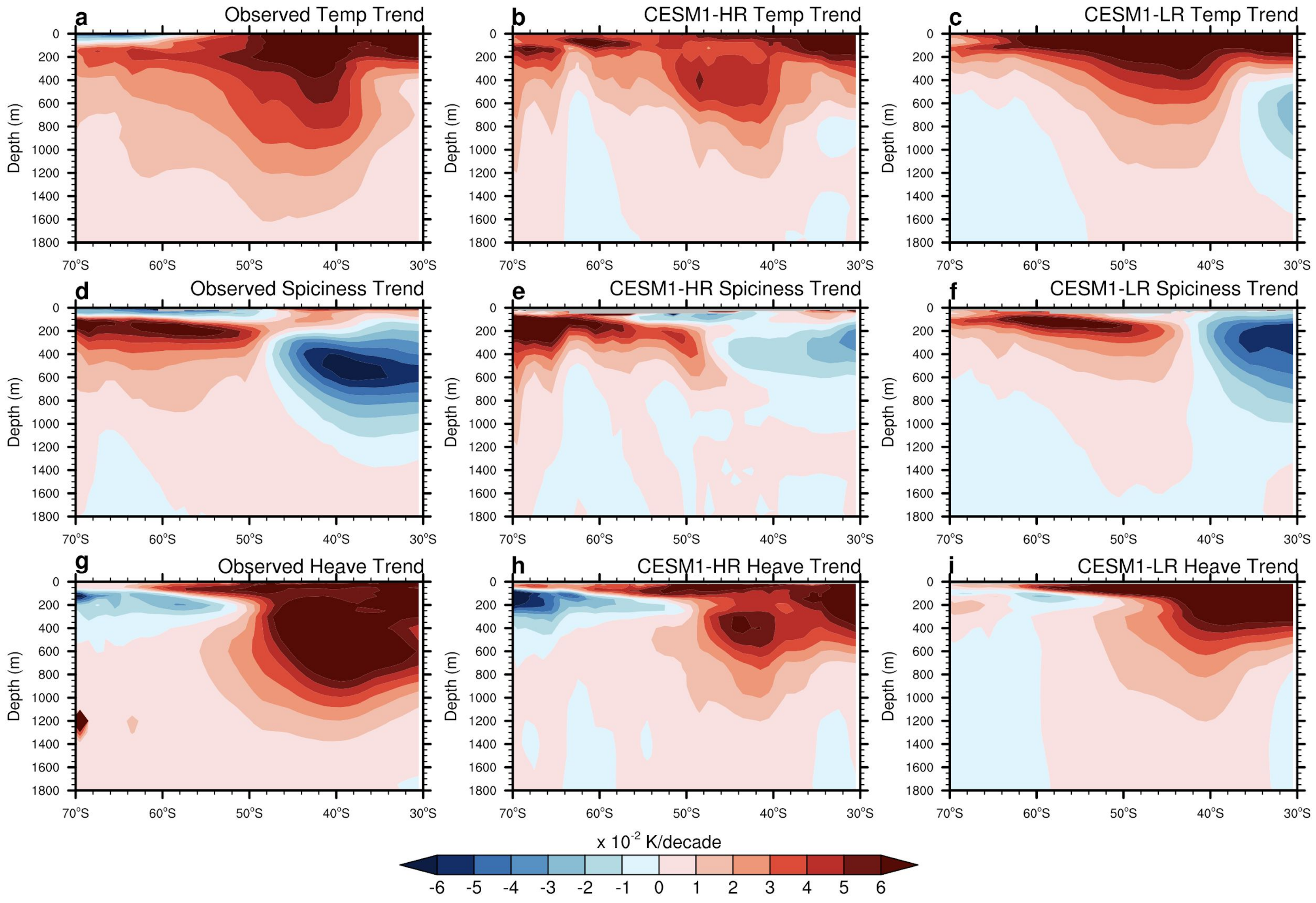
Temperature Trends – Observation vs CESM1.3



- Both **CESM1.3** resolutions **fail to capture** observed **surface cooling south of 55ºS**
- **Underestimate warming north of 55ºS** in both resolutions
- **High-resolution version** shows a **deeper warming tongue**, but with **weaker magnitude** than both **low-resolution** and **observations**

Results

Temperature Trends – Observation vs CESM1.3



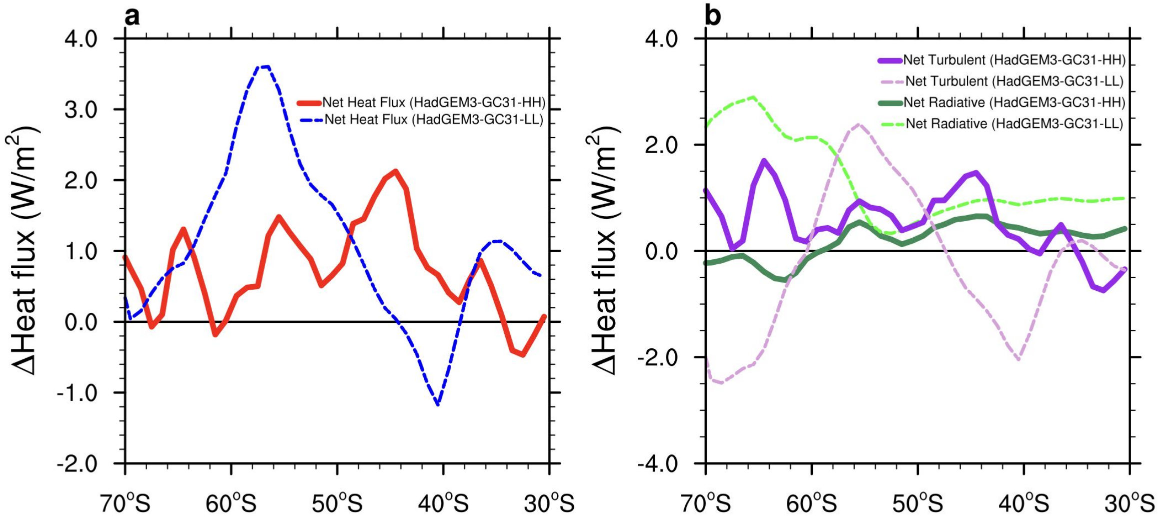
Spiciness: **Overestimates warming south of 55ºS** (compared to observed cooling).

Heave: **Dominates warming north of 50ºS**, but remains **too weak and shallow**, leading to **underestimated subsurface warming** compared to observations.

Results

Physical Mechanisms– HadGEM3-GC31

1. Surface Flux



HadGEM3-GC31 High-Resolution

- **Net surface heat flux anomalies: +ve** from **70°S- 35°S**
- Positive anomalies are largely due to **enhanced turbulent fluxes** (latent + sensible), especially **south of 60°S** (Panel b).
- Explains the **positive spiciness trend** and **absence of observed surface cooling** in high-res simulation
- **North of 60°S (ACC and beyond)**: Continued positive net flux driven by **turbulent + radiative contributions**, aligning with upper ocean warming in spiciness.

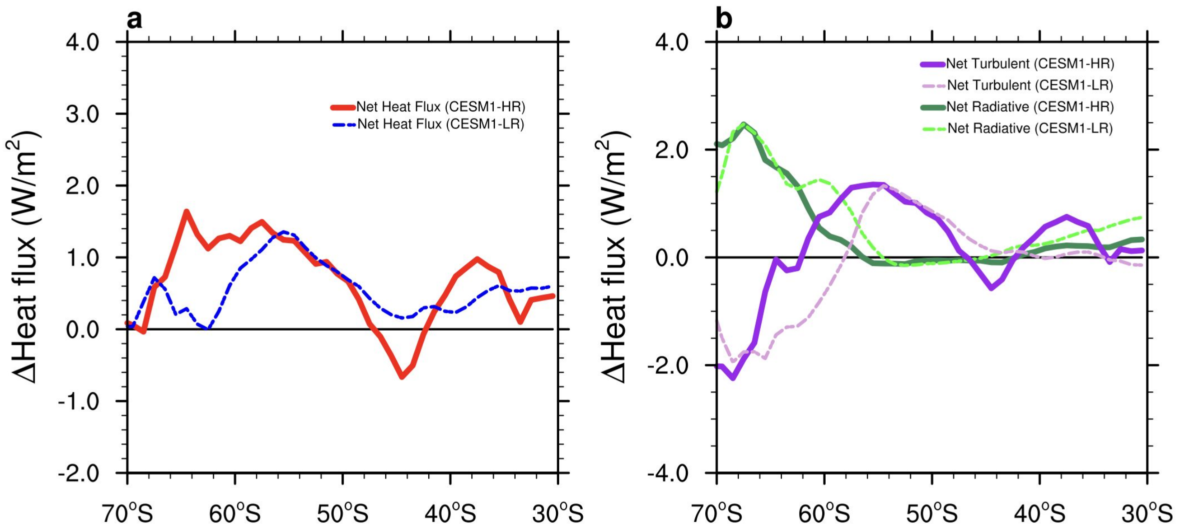
HadGEM3-GC31 Low-Resolution

- Shows **weaker net heat flux anomalies south of 64°S** compared to high-res.
- This is because, positive radiative fluxes are **offset by stronger negative turbulent fluxes**, leading to **weaker surface warming** and **spiciness trends south of 64ºS.**
- From **64°S to 45°S**, net heat flux **increases**, peaking around 57°S due to **turbulent fluxes**.

Results

Physical Mechanisms– CESM1.3

1. Surface Flux



CESM1.3 High-Resolution

Positive net heat flux from **68°S to 47°S**, peaking at **58°S**.

Radiative flux dominates south of 61°S; **turbulent warming dominates** north of 61°S.

CESM1.3 Low-Resolution

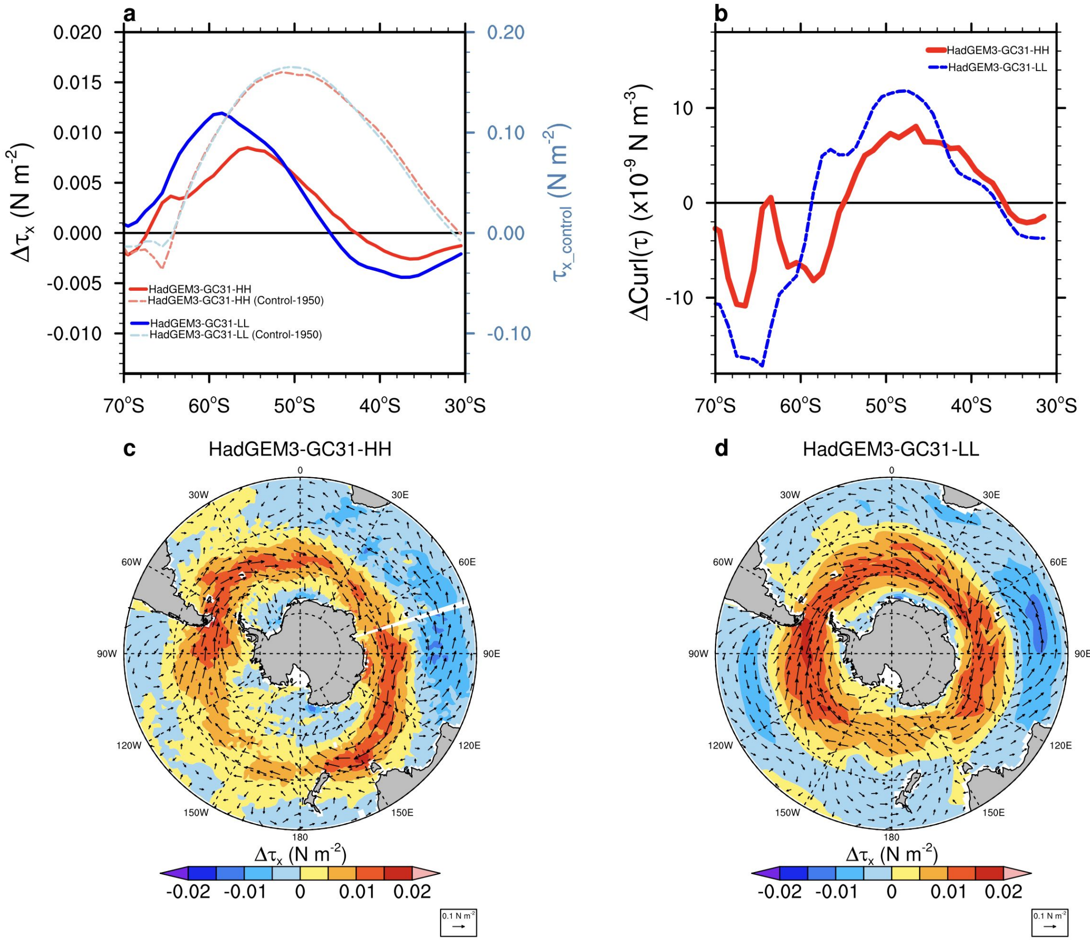
Positive net heat flux from **70°S to 30°S**, peaking near **56° S,** driven by **turbulent fluxes**.

South of 60°S, **positive radiative flux** nearly **cancelled** by **negative turbulent fluxes**.

Results

Physical Mechanisms– HadGEM3-GC31

III. Zonal Wind Changes



High-Resolution:

- **Zonal Wind Stress Anomaly:**
- Dipole centered near **42°S**: positive anomaly south, negative north (Panel. a, red line).
- Indicates **poleward intensification of westerlies**.

- **Wind Stress Curl:**
- Positive curl anomalies **north of 55°S**, peaking **~9×10^{-9} N/m^3** at 46°S.
- Negative curl anomalies **south of 55°S** (Panel. b, red line).

Low-Resolution:

- **Zonal Wind Stress Anomaly:**
- Dipole **centered farther south (~46°S)**: positive south, negative north (Panel. a, blue line).

- **Wind Stress Curl:**
- Positive anomalies begin at **~58°S**, peaking **~11×10^{-9} N/m^3** near 48°S (Panel. b, blue dashed line).
- Negative anomalies poleward of 58°S.

Conclusion

- **Subsurface warming patterns** (e.g., warm tongue north of 55°S) are captured by all models, but:
- **High-resolution versions** reproduce **deeper warming tongues**, due to stronger **heave** contributions associated with positive wind stress curl anomalies.

- **Surface cooling south of 55°S is absent** in all models
- All simulate **spiciness-driven surface warming** instead.
- Linked to **underestimated sea ice expansion**, causing excess **surface heat uptake**.

- **Turbulent heat fluxes** acts the **main driver** of spiciness induced surface warming; radiative fluxes play a contributing **role**.

- Each resolution shows **region- and process-specific strengths/limitations**.

- Highlights the need for improved:
  - **Surface turbulent flux simulation**
  - **Sea ice dynamics**
  - **Wind forcing representation**

References

Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., & Schwarzkopf, F. U. (2008). The response of the Antarctic Circumpolar Current to recent climate change. Nature Geoscience, 1(12), 864–869. https://doi.org/10.1038/ngeo362

Gille, S. T. (2008). Decadal-scale temperature trends in the Southern Hemisphere Ocean. Journal of Climate, 21(18), 4749–4765. https://doi.org/10.1175/2008jcli2131.1

Hewitt, H. T., Bell, M. J., Chassignet, E. P., Czaja, A., Ferreira, D., Griffies, S. M., Hyder, P., McClean, J. L., New, A. L., & Roberts, M. J. (2017). Will high-resolution global ocean models benefit coupled predictions on short-range to climate timescales? Ocean Modelling, 120, 120–136. https://doi.org/10.1016/j.ocemod.2017.11.002

Martínez-Moreno, J., Hogg, A. McC., England, M. H., Constantinou, N. C., Kiss, A. E., & Morrison, A. K. (2021). Global changes in oceanic mesoscale currents over the satellite altimetry record. Nature Climate Change, 11(5), 397–403. https://doi.org/10.1038/s41558-021-01006-9

Swart, N. C., Gille, S. T., Fyfe, J. C., & Gillett, N. P. (2018b). Recent southern ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. Nature Geoscience, 11(11), 836–841. https://doi.org/10.1038/s41561-018-0226-1

Acknowledgment

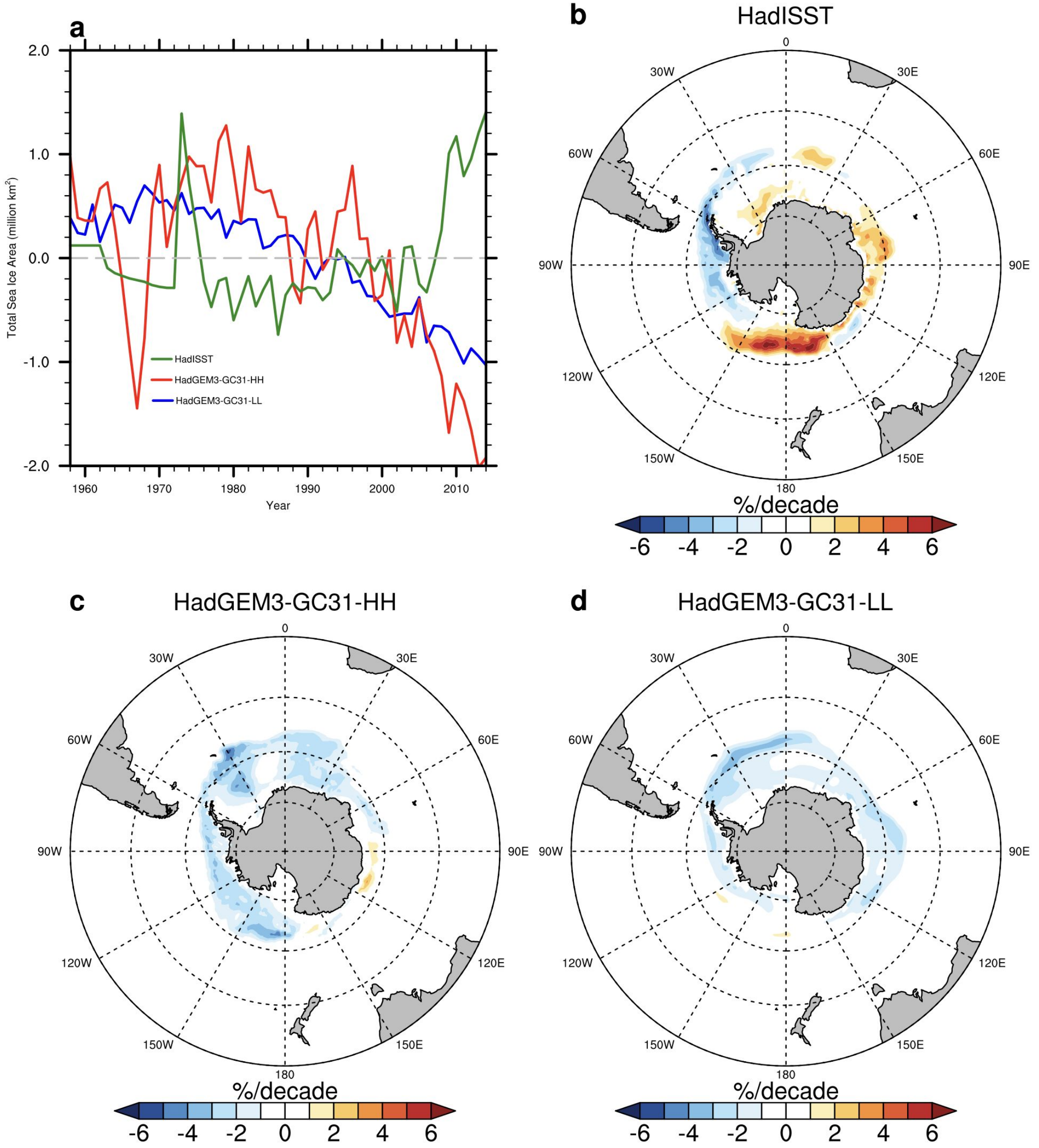
We acknowledge the International Laboratory for High-Resolution Earth System Prediction (iHESP) and the National Center for Atmospheric Research for providing the high-resolution CESM1.3 data, and the UK Met Office for making the Hadley Centre Global Environment Model version 3 (HadGEM3) data publicly available.

Thank you for listening!!!

Supplementary Info

Physical Mechanisms– HadGEM3-GC31

II. Sea Ice Variability



- **Observed (HadISST.2):**
- Southern Hemisphere sea ice area **increased** from 1958–2014, especially post-1990s.
- Regional **sea ice concentration increased** in Ross Sea, Prydz Bay, Davis Sea, and Weddell Sea.
- Some local **decreases** in Amundsen, Bellingshausen, and western Weddell Sea.

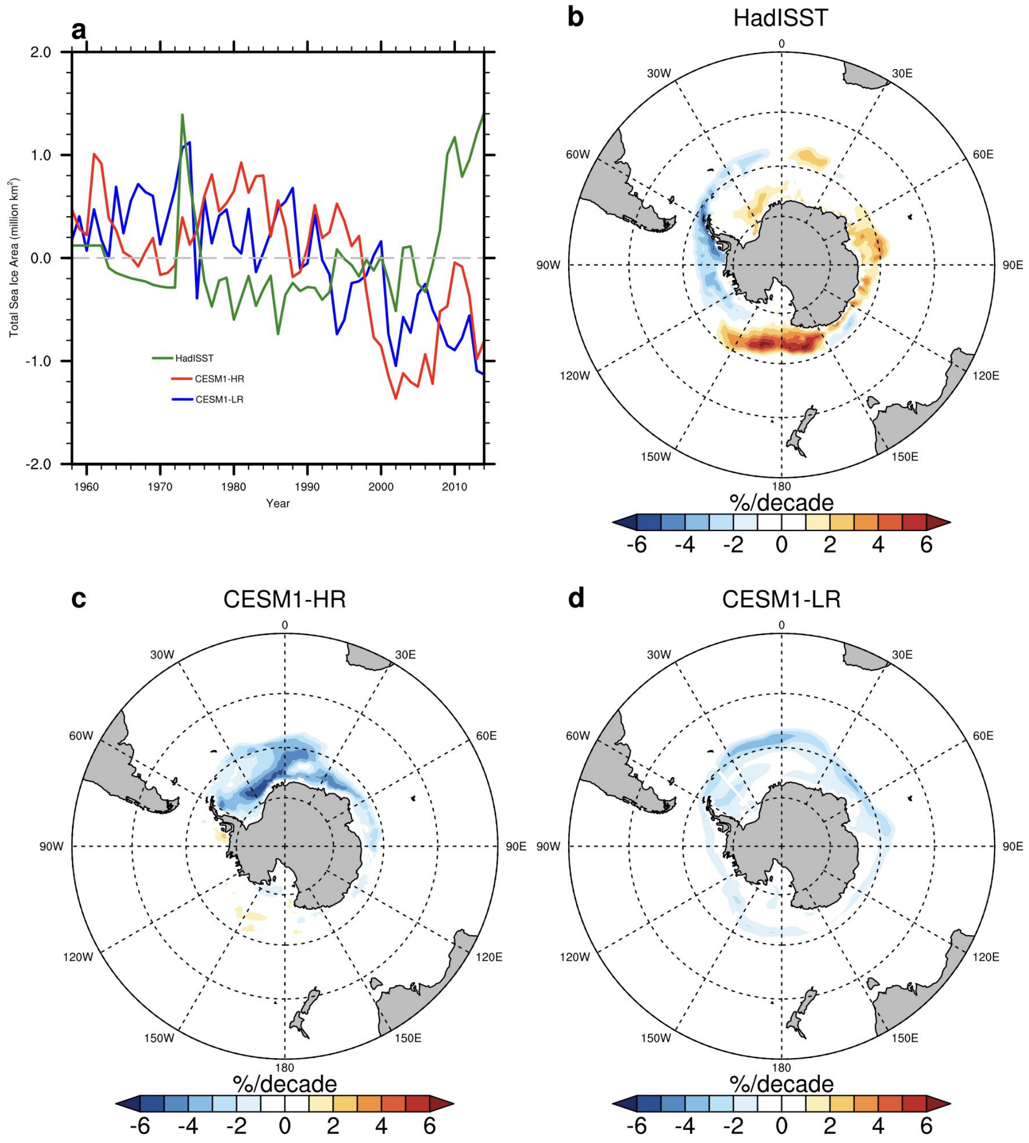
- **HadGEM3 Simulations:**
- Both **high- and low-res simulate decreasing sea ice area**, opposite to observations.
- **Spatially**, both versions simulate **widespread sea ice loss**, especially high-res.

- **Observed sea ice increase limits air–sea heat exchange**, helping to explain **surface cooling** south of 55°S.
- **Model sea ice decline exposes open ocean**, enhancing **surface warming via increased heat flux**.
- Hence, **sea ice trend mismatch** explains why **models fail to capture observed surface cooling**.

Supplementary Info

Physical Mechanisms– CESM1.3

II. Sea Ice Variability

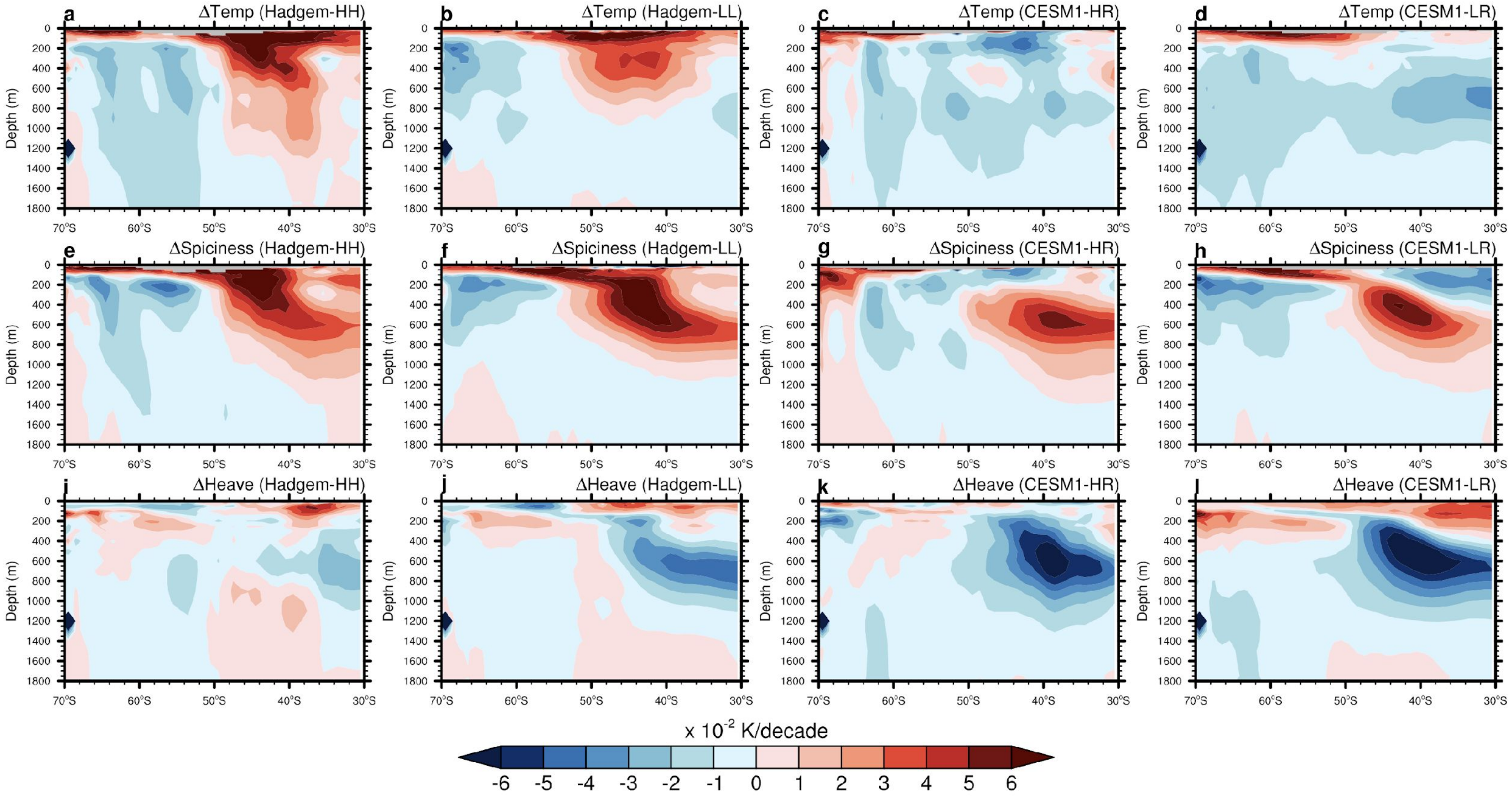


- **CESM1.3 Simulations:**
- Both **high- and low-resolution versions simulate declining sea ice area** from 1958–2014.

- **Spatial Sea Ice Concentration Trends:**
- **Widespread sea ice loss** across Southern Ocean in both configurations.

Supplementary Info

I. Model Temperature bias



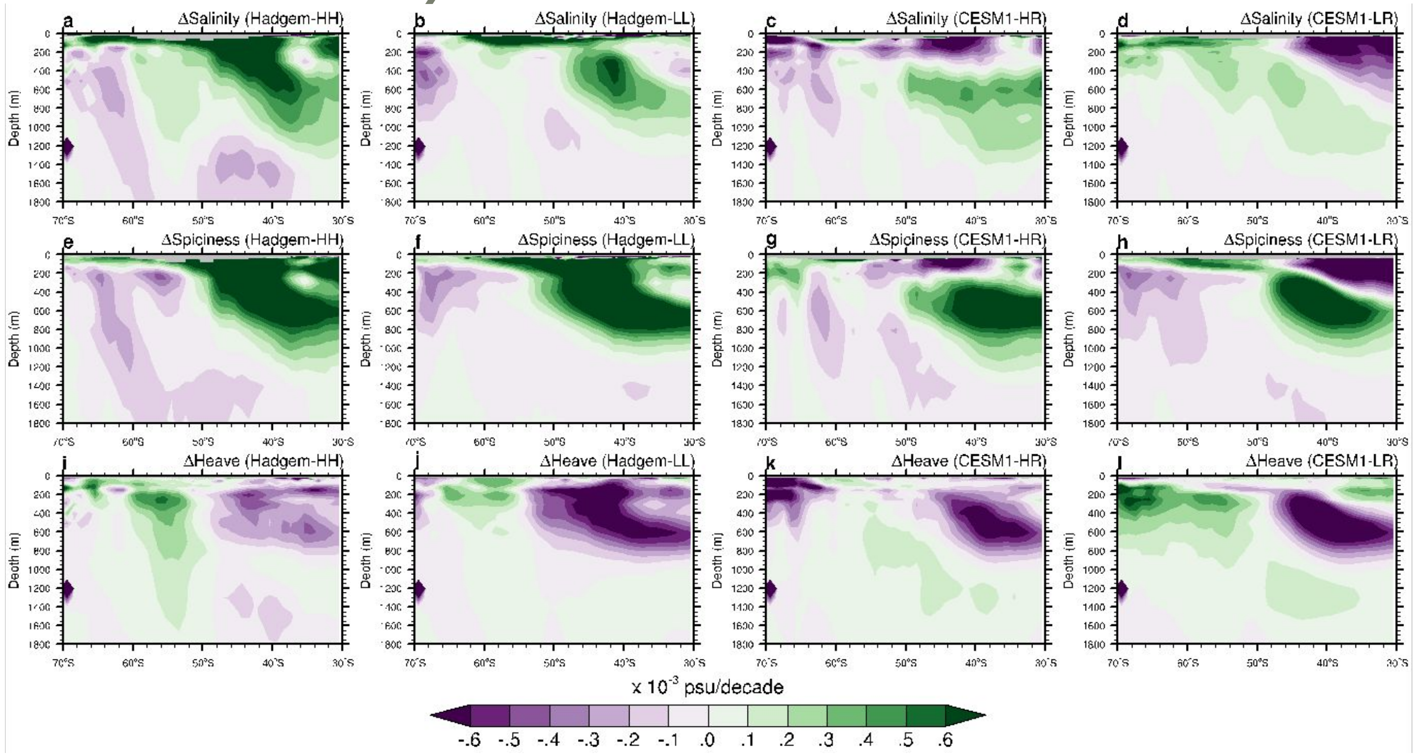
- **North of 55ºS:**
  - *HadGEM3-GC3.1 (HH & LL)* simulates **higher temperatures than observations**, with **HH showing deeper warming** due to stronger heave.
  - Though **surface warming** is overestimated, the **subsurface shows less intensity** — reflecting **weaker spice-related cooling** than observed.
- **South of 55ºS (especially near Antarctica):**
  - Both HadGEM3-GC3.1 simulations show **excess warming** relative to observations.
  - This warm bias is **mostly from spiciness**, indicating models simulate **too much along-isopycnal warming**.
- **Heave contribution** in HH aligns more closely with observations, suggesting it better captures **isopycnal displacement-driven warming**.

CESM1.3:

- Shows **smaller temperature anomalies** compared to HadGEM, especially **north of 55ºS**.
- This is due to **weaker heave-induced warming** and **underestimated spice-related cooling**, especially in the **low-resolution version**.
- The combination of reduced heave and weaker spice anomalies results in **less total warming** than HadGEM.

Supplementary Info

II. Model Salinity bias

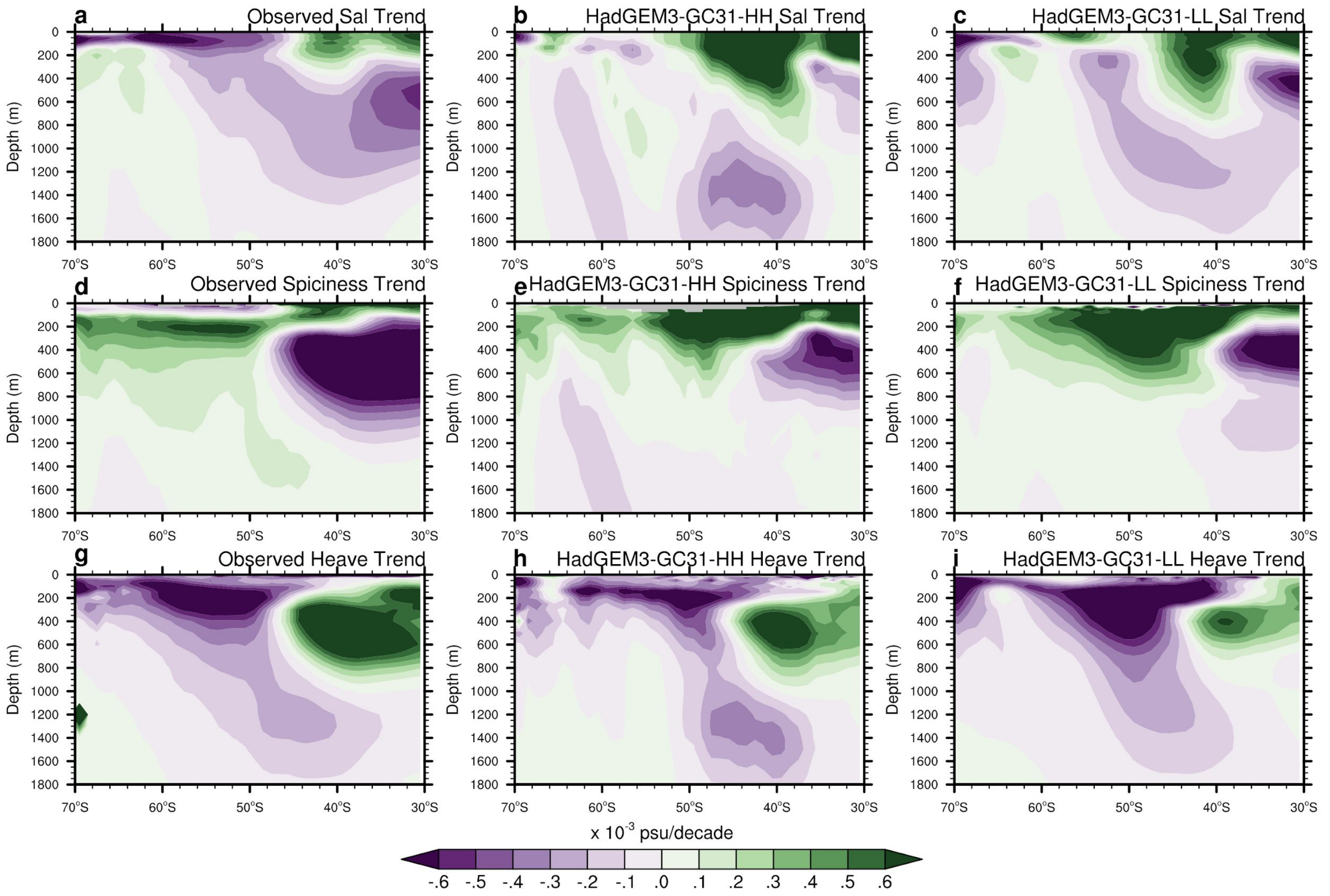


HadGEM3-GC3.1 High-Resolution (HH):
Shows **over-salinification of SAMW**, mainly driven by **spiciness** (along-isopycnal changes).
Near-Antarctic **surface freshening** is present and comes from **both heave and spice** contributions.
HadGEM3-GC3.1 Low-Resolution (LL):
Shows a **similar spatial pattern** to HH but with **smaller magnitude trends**.
The **total salinity trend** in LL **matches observations more closely**, especially in near-Antarctic and AAIW layers.

CESM1.3:
High-resolution version aligns **better with observations**, especially near-Antarctica.
Low-resolution CESM shows **strong salinification in the SAMW region**, opposite to the **observed freshening**.
This bias is mainly due to the **spice component** (along-isopycnal salinity increase).

Supplementary Info

Salinity Trends – Observation vs HadGEM3-GC31



- **Observation-based datasets**

Surface freshening south of 55°S, co-located with cooling.

Clear freshening of AAIW (400–800 m, 40°–50°S).

Salinification of SAMW (0–300 m, 30°–40°S) and CDW.

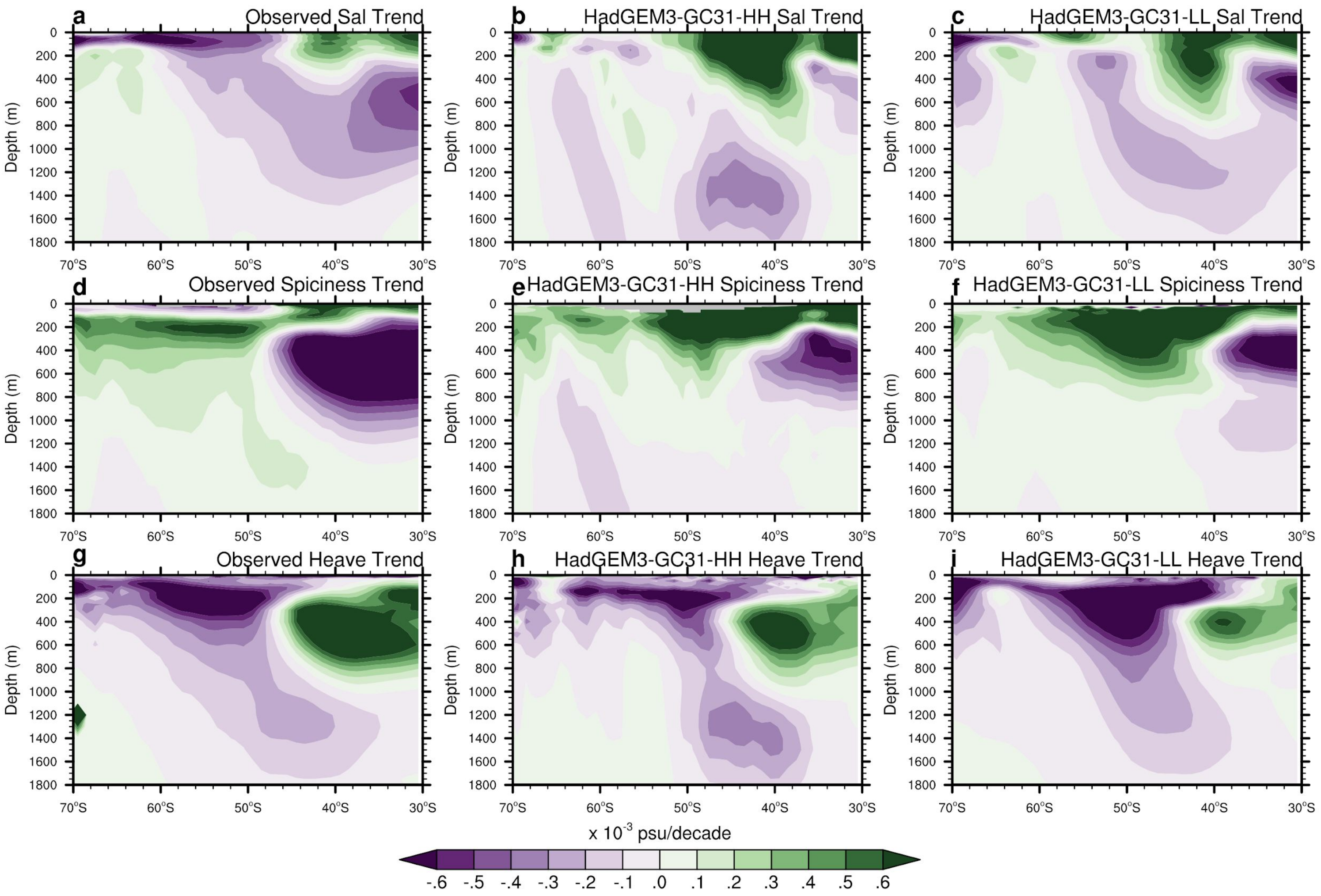
- **HadGEM3-GC3.1 simulations**

High-resolution:
Captures overall pattern but **overestimates SAMW salinification**.
Underestimates surface and AAIW freshening.

Low-resolution:
Better reproduces **near-Antarctic surface freshening** (but extends too deep).
Simulates SAMW and AAIW trends more accurately.
Shows **reduced biases** across regions compared to high-res.

Supplementary Info

Salinity Trends – Observation vs HadGEM3-GC31



Observations:

Surface freshening south of 55ºS is driven by **negative spiciness and heave trends**
SAMW salinification arises from **positive heave and spice contributions**

HadGEM3-GC31 High Res:

South of 55ºS:

- **Freshening**, primarily due to **heave**, but is heavily **compensated by spice**

North of 50ºS (SAMW):

- **Captures observed salinification** fairly well, with **positive contributions from both heave and spice**

HadGEM3-GC31 Low Res:

South of 55ºS:

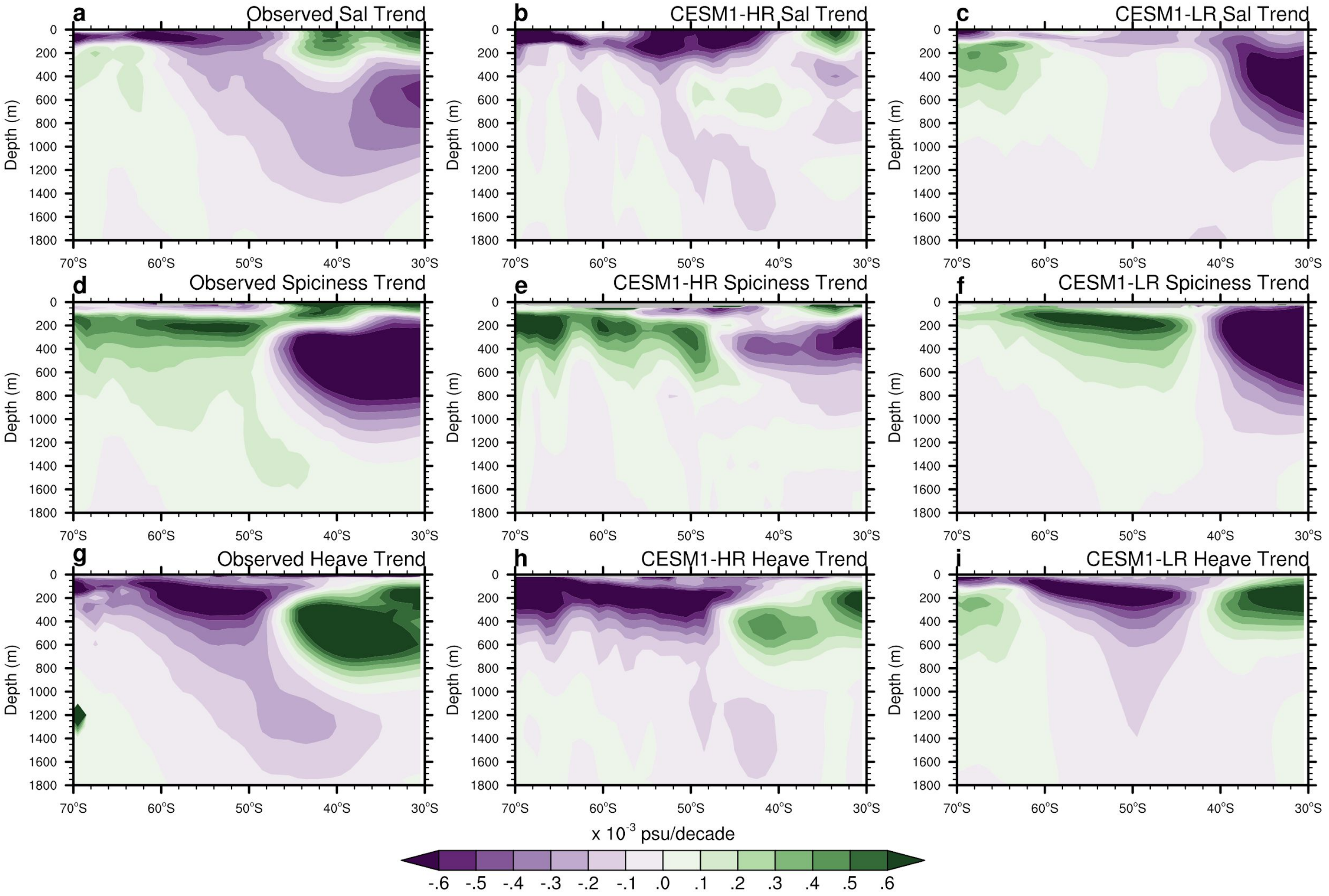
- **Overestimates freshening**, due to **stronger heave**, with **spice lightly compensating**

North of 50ºS (SAMW):

- Simulates salinification, contributed by spiciness and heave

Supplementary Info

Salinity Trends – Observation vs CESM1.3



Observations:

Surface freshening south of 55°S is driven by **negative spiciness and heave trends**
SAMW salinification arises from **positive heave and spice contributions**

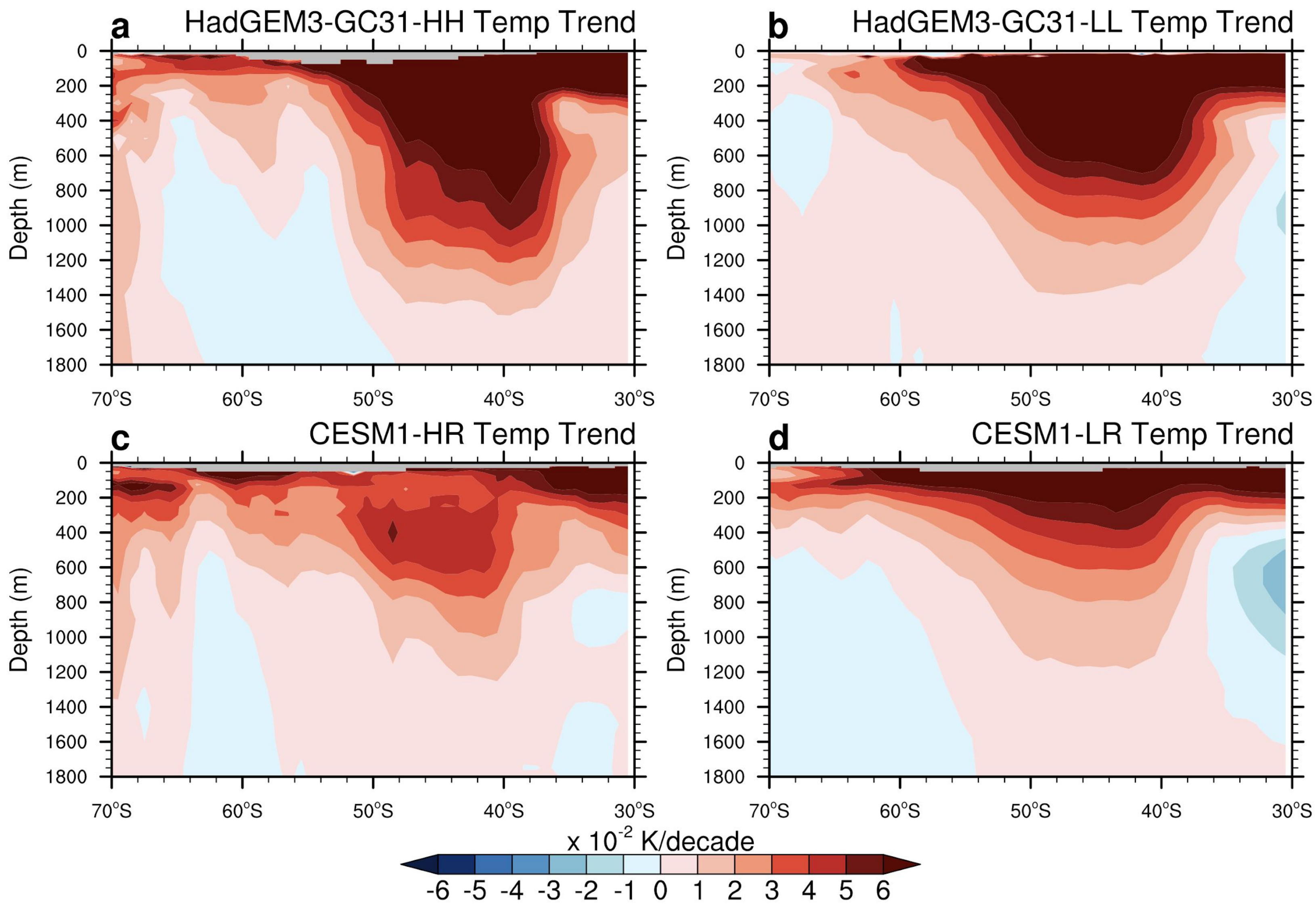
CESM1.3 High Res:

South of 55°S:
‣ **Overestimates freshening**, primarily due to **heave**, partially **compensated by spice**
North of 50°S (SAMW):
‣ **Captures observed salinification** fairly well, with **positive contributions from both heave and spice**

CESM1.3 Low Res:

South of 55°S:
‣ **Underestimates freshening**, due to **weaker heave**, with **spice partially compensating**
North of 50°S (SAMW):
‣ Simulates **freshening instead of salinification, driven by spiciness, not heave**

Supplementary Info



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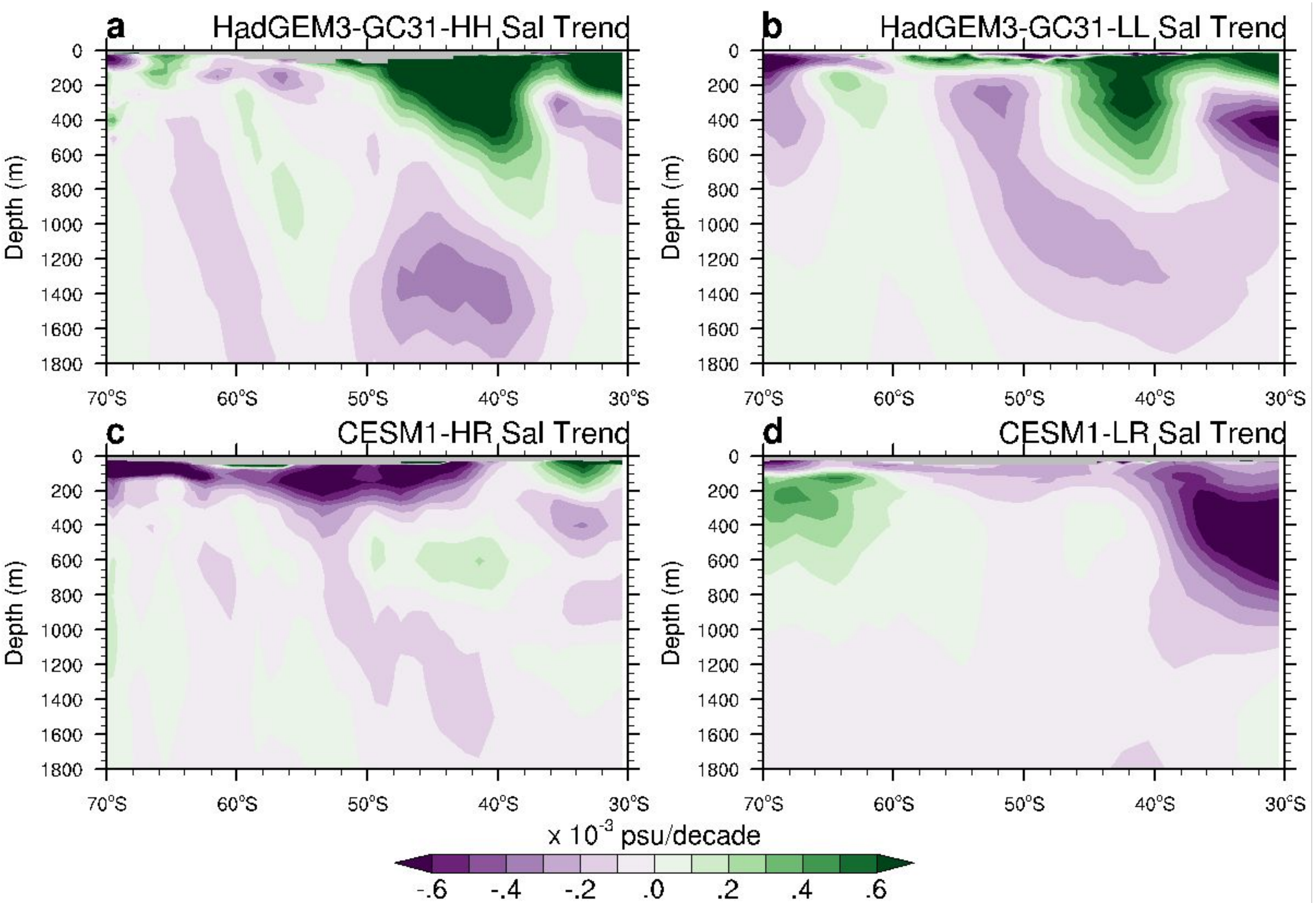

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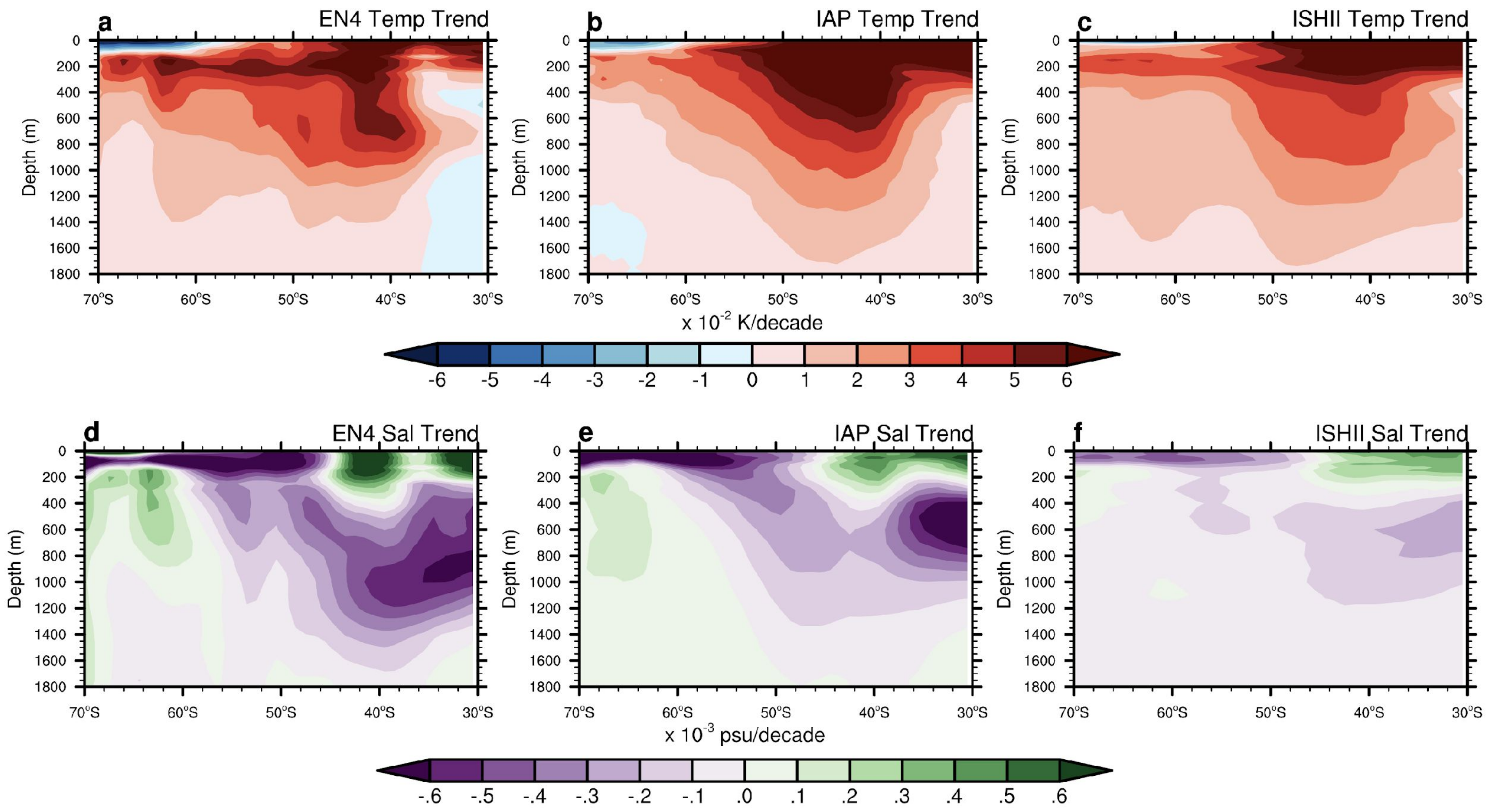

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