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Eddy momentum-forcing redistribution accompanies an equatorward Southern Hemisphere jet response to Antarctic sea-ice–SST boundary perturbations

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Abstract

Antarctic sea-ice changes modify Southern Ocean lower-boundary conditions, yet the relation between eddy momentum deposition and jet displacement remains poorly constrained in within-model large ensembles. We analyze independent atmosphere-only Polar Amplification Model Intercomparison Project (PAMIP) ensembles from HadGEM3-GC31-MM and IPSL-CM6A-LR, each containing 100 present-day control and 100 treatment members under future Antarctic sea-ice boundary conditions (400 members total). Because the treatment changes sea ice together with prescribed sea surface temperature (SST) where ice retreats, it estimates a combined sea-ice–SST boundary response rather than a sea-ice-only effect. In the two-model equal-weight synthesis, 2–8-day poleward eddy heat flux decreases by 0.123 K m s^{-1} (95% interval -0.187 to $-0.059 \text{ K m s}^{-1}$; -0.380 control standard deviation [SD]). Seasonal-departure 250-hPa eddy momentum-flux convergence forms a meridional dipole, with enhanced deposition near $45\text{--}49^\circ\text{S}$ and reduced deposition near $55\text{--}60^\circ\text{S}$; the dipole increases by $0.159 \text{ m s}^{-1} \text{ day}^{-1}$ ($0.060\text{--}0.259$; $+0.325$ SD). The perturbation is accompanied by a negative Southern Annular Mode (SAM)-like response (-0.254 SD) and a 0.447° equatorward jet shift ($0.124\text{--}0.766^\circ$), while peak jet speed changes by only $+0.029 \text{ m s}^{-1}$ (-0.156 to $+0.211$). No latitude in the strict 2–8-day momentum-forcing profile passes false-discovery-rate correction, so evidence for redistribution is strongest for seasonal departures rather than for a fully resolved weather-scale mediation pathway. Momentum forcing, the SAM-like state, and jet latitude covary consistently across the four model–experiment ensembles. The response is therefore better characterized as co-occurring meridional redistribution of eddy momentum deposition and jet position than as uniform weakening of the Southern Hemisphere westerlies.

Keywords: Antarctic sea ice; sea surface temperature; eddy momentum-flux convergence; Southern Annular Mode; Southern Hemisphere jet; PAMIP large ensembles

1 Introduction

Antarctic sea ice modifies the lower boundary of the Southern Ocean atmosphere through surface albedo, turbulent heat exchange, and the thermodynamic consequences of freezing and melting, thereby affecting near-surface stability and the coupled high-latitude climate system (Pellichero et al. 2017; Smith et al. 2017; Ayres et al. 2022). Unlike the persistent long-term decline of Arctic sea ice, Antarctic sea ice exhibited a modest overall increase during much of the satellite era, followed by an abrupt decline around 2016 and several subsequent record-low states (Parkinson 2019; Meehl et al. 2019; Purich and Doddridge 2023; Hobbs et al. 2024). Changes in the latitude of the sea-ice edge and in adjacent SST can modify the lower-tropospheric meridional temperature gradient and baroclinicity over the Southern Ocean, with potential consequences for storm tracks and the midlatitude westerly jet (Smith et al. 2017; England et al. 2018; Ayres et al. 2022). The atmospheric response to Antarctic boundary changes therefore needs to be considered not only in terms of local surface energy exchange but also within an eddy–mean-flow dynamical framework (England et al. 2018; Purich et al. 2026).

Idealized and climate-model experiments have established that the Southern Hemisphere midlatitude jet is dynamically sensitive to Antarctic sea-ice boundary changes (Kidston et al. 2011; Ezber et al. 2025). Reduced sea ice has been associated with a negative SAM-like circulation anomaly and an equatorward adjustment of the midlatitude flow (Raphael et al. 2011), while multimodel experiments show that Antarctic sea-ice loss can produce both jet weakening and equatorward displacement, with their relative magnitudes depending on model structure and background state (Ayres and Screen 2019). PAMIP studies further show that eddy-feedback strength helps

determine the magnitude of the jet response (Screen et al. 2022). An equatorward jet response is therefore not itself the unresolved result. The narrower question addressed here is whether the boundary-condition response contains a reproducible latitude-by-latitude redistribution of upper-tropospheric eddy momentum deposition, and whether that redistribution co-occurs with changes in annular structure and jet position. This distinction matters because Southern Hemisphere westerly changes contain at least two dynamically different components—jet latitude and peak speed—and fixed-latitude-band averages can mix them when the jet axis moves (Bracegirdle et al. 2018; Williams et al. 2024).

From an eddy–mean-flow perspective, jet latitude is not determined passively by the local temperature gradient. Baroclinic eddies interact with the mean circulation through lower-tropospheric eddy heat transport and upper-tropospheric eddy momentum fluxes. In particular, the meridional structure of eddy momentum-flux convergence can shift the latitude of maximum zonal wind and is closely linked to the annular variability represented by the SAM (Lorenz and Hartmann 2001; Barnes and Hartmann 2010; Simpson et al. 2013). Consequently, diagnosing only whether total eddy kinetic energy increases or decreases is insufficient to characterize the dynamical response. It is also necessary to determine whether eddy heat transport and, especially, the latitude of eddy momentum deposition are reorganized, and whether those changes are dynamically consistent with the SAM-like circulation response and jet displacement.

Three issues are particularly relevant to this diagnosis. First, forced Southern Hemisphere circulation signals can be small relative to internal variability, so within-model large ensembles are useful for separating the ensemble-mean response from member-to-member variability and for comparing model-dependent responses without relying on small ensembles (Deser et al. 2020; Smith et al. 2019; Screen et al. 2022). Second, eddies defined as departures from the seasonal mean are not equivalent to strictly weather-scale transients: seasonal departures contain both synoptic disturbances and lower-frequency nonstationary variability, whereas a 2–8-day filter more directly isolates weather-scale fluctuations. Different time scales can contribute differently to eddy feedbacks on the mean flow (Lorenz and Hartmann 2001; Simpson et al. 2013). Third, the PAMIP future Antarctic sea-ice sensitivity experiment is not a single-factor sea-ice-concentration experiment. Prescribed SST is changed together with sea ice in retreat regions, so the experiment estimates the fast atmospheric response to a combined Antarctic sea-ice–SST boundary perturbation and does not isolate the contribution of sea ice alone (Smith et al. 2019; Screen et al. 2022).

Motivated by these issues, we ask whether the prescribed Antarctic sea-ice–SST boundary perturbation is accompanied by a meridional redistribution of Southern Hemisphere eddy momentum forcing and whether that redistribution is dynamically consistent with a negative SAM-like response and an equatorward shift of the jet axis. We analyze HadGEM3-GC31-MM and IPSL-CM6A-LR PAMIP atmosphere-only ensembles, each with 100 control and 100 treatment members. The analysis makes four distinctions that extend earlier jet-response studies: it resolves the latitude of eddy momentum deposition, separates jet latitude from peak speed, compares seasonal departures with a strict 2–8-day component, and keeps prescribed treatment effects distinct from post-treatment member-state covariation. Our central expectation is that a primarily geometric response should appear as a momentum-forcing dipole, a negative SAM-like anomaly, and an equatorward jet displacement, with comparatively little change in peak jet speed.

2 Data and methods

2.1 PAMIP experiments and data integrity

We use the 14-month atmosphere-only time-slice simulations pdSST-pdSIC (control) and pdSST-futAntSIC (treatment) from the PAMIP contribution to CMIP6 (Smith et al. 2019). Both simulations begin on 1 April 2000 and follow the PAMIP protocol of discarding the first 2 months for atmospheric spin-up, leaving 12 months for analysis. Each member therefore contributes its first complete Southern Hemisphere warm season, November 2000–March 2001 (NDJFM). HadGEM3-GC31-MM uses an N216 atmosphere with 85 vertical levels (Roberts et al. 2019), whereas IPSL-CM6A-LR uses a $2.5^\circ \times 1.3^\circ$ atmosphere with 79 levels (Boucher et al. 2020). For each model and experiment, the first 100 members satisfying the locked availability and integrity gates were retained, yielding 400 independent members (Table 1).

Relative to pdSST-pdSIC, pdSST-futAntSIC changes the prescribed Antarctic sea-ice boundary and applies the PAMIP SST treatment required where sea ice retreats. The estimand is therefore the fast atmospheric response to the combined sea-ice–SST lower-boundary perturbation. It cannot separate the individual contribution of SIC from the associated local SST treatment and excludes interactive ocean feedbacks. Control and treatment members are independent ensembles and are not paired by variant label.

The dynamical analysis uses 1,600 checksum-verified pressure-field subsets: ta, ua, va, and zg for each of the 400 members. The files retain the required 250-, 500-, 700-, and 850-hPa levels over 75–10°S; HadGEM3 daily pressure fields were sampled at every second latitude and third longitude, whereas IPSL fields were retained at the archived spacing. All files passed SHA-256 and NetCDF structure checks. Two additional monthly HadGEM3 siconca files verify the boundary contrast south of 45°S. Equivalent IPSL siconc output and a separate retreat-zone SST field were not available in the queried ESGF archive, so Fig. 1a is a HadGEM3 boundary-state check rather than a two-model forcing reconstruction. Dynamical diagnostics are calculated separately by model and combined with equal 50% model weights. The synthesis thus describes these two models and does not estimate a wider climate-model population.

Table 1 Model experiments and processed data used in the dynamical analysis

Model	Atmospheric configuration	Members	Archived fields and processing
HadGEM3-GC31-MM	N216 (432 × 324); 85 levels	100 control + 100 treatment; r1i1p1f2–r100i1p1f2	Daily ta/ua/va; monthly zg. Pressure fields south of 10°S; every second latitude and third longitude retained before diagnostics.
IPSL-CM6A-LR	2.5° × 1.3° (144 × 143); 79 levels	100 control + 100 treatment; r1i1p1f1–r100i1p1f1	Eday ta/ua/va/zg. Pressure fields south of 10°S retained on the archived horizontal grid.

Notes: Control is pdSST-pdSIC and treatment is pdSST-futAntSIC. PAMIP simulations run for 14 months from 1 April 2000, with the first 2 months discarded for spin-up; each member here contributes the complete NDJFM 2000/01 season. The HadGEM3 spatial stride is disclosed because it is part of the locked processing specification; all reported zonal diagnostics use the same retained grid within that model.

2.2 Boundary-condition effects and standardization

For model m and diagnostic Y , the raw boundary-condition effect is defined as

$$\Delta Y_m = \overline{Y_{m,T}} - \overline{Y_{m,C}} \quad (1)$$

where T denotes pdSST-futAntSIC and C denotes pdSST-pdSIC. To compare diagnostics with different physical units, the effect is standardized by the control-ensemble standard deviation:

$$\delta_m = \frac{\Delta Y_m}{s_{m,C}} \quad (2)$$

The two-model equal-weight standardized effect is then

$$\delta_{eq} = \frac{1}{2} (\delta_{\text{HadGEM3}} + \delta_{\text{IPSL}}) \quad (3)$$

Equal model weighting gives each model a weight of 50%. For diagnostics sharing physical units, we also report the arithmetic mean of the two model-specific raw effects. Standardized effects use each model’s full control-ensemble sample standard deviation, fixed before resampling. The synthesis summarizes these two models; its interval quantifies independent-member sampling uncertainty within them and does not include uncertainty from sampling the broader model population.

2.3 Eddy heat transport, kinetic energy, and momentum forcing

For each member, seasonal departures are defined by subtracting that member’s NDJFM mean field from its daily field:

$$x'(t, \varphi) = x(t, \varphi) - \bar{x}_{\text{NDJFM}}(\varphi) \quad (4)$$

A stricter transient component is obtained by applying a fourth-order zero-phase Butterworth high-pass filter with an 8-day cutoff separately to each member's complete NDJFM daily series. The implementation uses SciPy second-order sections and forward-backward filtering with its default odd-symmetric end padding. No incomplete season enters the calculation; model-native calendars yield 150 daily steps in HadGEM3 and 151 in IPSL. With daily sampling, 2 days is the Nyquist limit, so we refer to the retained high-frequency component as the approximately 2–8-day weather-scale component. Because a Butterworth response has a finite roll-off, this label denotes the operational high-pass band rather than an ideal rectangular filter. Seasonal departures, by contrast, also retain lower-frequency nonstationary variability. The 850-hPa poleward eddy heat flux in the Southern Hemisphere is defined as

$$H_e = -\langle [v'T'] \rangle_{55^\circ-75^\circ\text{S}} \quad (5)$$

Square brackets denote a zonal mean and angle brackets denote a cosine-latitude-weighted meridional average; the leading minus sign makes poleward transport positive in the Southern Hemisphere. The 250-hPa eddy kinetic energy is

$$K_e = \frac{1}{2} \langle [u'^2 + v'^2] \rangle_{45^\circ-65^\circ\text{S}} \quad (6)$$

The zonal-mean eddy momentum-flux convergence in spherical coordinates is

$$M(\varphi) = -\frac{1}{a \cos^2 \varphi} \frac{\partial}{\partial \varphi} \{ \cos^2 \varphi [u'v'] \} \quad (7)$$

where a is Earth's radius and positive M denotes an eastward acceleration of the zonal-mean westerly flow. The predefined seasonal-departure momentum-forcing dipole is

$$D_M = \langle M \rangle_{45^\circ-55^\circ\text{S}} - \langle M \rangle_{55^\circ-65^\circ\text{S}} \quad (8)$$

Positive values indicate that momentum deposition is shifted toward the equatorward side of the midlatitude jet region. To test sensitivity to the exact latitude-band definition, we additionally calculate the adjacent-band contrasts 40–50°S minus 50–60°S and 50–60°S minus 60–70°S. For both seasonal departures and the 2–8-day component, the full 40–70°S meridional momentum-forcing profile is also evaluated.

2.4 SAM-like and jet metrics

To avoid differences in archive frequency, 500-hPa geopotential height is first reduced to a member-level NDJFM seasonal zonal mean and linearly interpolated to a common 1° latitude grid from 74°S to 20°S. Within each model, the 100-member control-ensemble mean profile is subtracted from every control and treatment profile. An EOF analysis is then trained only on the area-weighted control anomalies, using the square root of cosine latitude as the weight and the covariance matrix implied by singular-value decomposition. The first control-trained EOF is treated as the model's dominant SAM-like annular mode and is referred to below as the SAM-like index. The standardized index is

$$\text{SAM}_t = \frac{\sum \varphi z'_{500,i}(\varphi) \sqrt{\cos \varphi} e_1(\varphi) - \mu_C}{\sigma_C} \quad (9)$$

where e_1 is the first control-ensemble EOF pattern, and μ_C and σ_C are the mean and standard deviation of control-ensemble projections, respectively. The EOF sign is fixed so that higher 500-hPa geopotential height over 35–50°S and lower height over 60–75°S corresponds to positive SAM. This index is intended to represent the model-consistent dominant annular state corresponding to the canonical SAM, rather than to assume exact equivalence with the observed SAM spatial structure. As an independent structural check, a simple 500-hPa midlatitude-minus-polar geopotential-height gradient proxy correlates at 0.992 and 0.998 with the EOF projection in HadGEM3 and IPSL, respectively; EOF1 explains 83.9% and 88.4% of control-ensemble variance.

Jet latitude is diagnosed from the maximum of the NDJFM zonal-mean 250-hPa zonal wind. To reduce discretization associated with the 1° latitude grid, a concave quadratic is fitted through the peak grid point and its two neighboring points, and the vertex is used as a continuous estimate of jet latitude. Jet latitude is stored as positive degrees south, so a negative standardized boundary-condition effect denotes an equatorward displacement. Peak jet speed is taken from the vertex of the same quadratic fit.

2.5 Statistical inference

For each model and diagnostic, 95% uncertainty intervals are estimated from 10,000 independent-member bootstrap resamples with seed 20260817. Control and treatment members are sampled independently; the control standard deviation used for standardization is held fixed, and the two-model interval is obtained by averaging the aligned model-specific bootstrap draws. Raw-unit effects are resampled from the same locked member arrays. Raw P values for primary treatment effects are obtained from 100,000 label permutations performed within model before equal-weight synthesis. Five predefined core diagnostics—the 2–8-day poleward eddy heat flux, seasonal-departure momentum-forcing dipole, control-trained SAM-like EOF index, jet latitude, and peak jet speed—form one hypothesis family and are jointly adjusted by the Holm procedure. Eddy kinetic energy, alternative latitude bands, time-scale sensitivities, and auxiliary diagnostics are adjusted within their stated families. Benjamini–Hochberg FDR correction is applied across the 31 latitudes of each full meridional profile. These procedures quantify member-sampling uncertainty and multiplicity, not structural uncertainty across climate models.

Within-ensemble state relationships are quantified using Spearman rank correlations, with member bootstrap intervals and label-permutation P values. We also fit standardized linear models containing a treatment indicator and the SAM-like index, using heteroskedasticity-consistent type-3 (HC3) robust standard errors, to examine the statistical overlap between the boundary-condition difference in jet latitude and the annular circulation variation represented by the SAM-like index. The prescribed-boundary ensemble contrast is used to estimate the treatment effect. Member-to-member correlations and SAM-adjusted regressions are used only to diagnose whether circulation metrics vary together; they are not used to infer a causal sequence or a mediation fraction.

2.6 Reproducibility and software

All processing, inference, and plotting were implemented in Python 3.12.13 using NumPy 2.5.2, pandas 3.0.5, SciPy 1.18.0, statsmodels 0.14.6, xarray 2026.7.0, netCDF4 1.7.4, and Matplotlib 3.11.1. The locked workflow records source identifiers, local SHA-256 checksums, member counts, pressure-level and temporal completeness, finite-value fractions, random seeds, and output dimensions. Figures and tables are generated from the same member-level result files used for the reported statistics. The complete reproducibility package is publicly archived on Zenodo (Tang 2026).

2.7 Use of generative AI in manuscript preparation

AI was used for English-language editing, consistency checking, and editorial restructuring of author-provided text. It did not generate scientific data or perform the numerical calculations or statistical tests reported here. The author reviewed all assisted text, independently verified the analyses, figures, tables, references, and interpretations, and takes responsibility for the manuscript.

3 Results and discussion

3.1 Prescribed boundary contrast and overview of the response

Figure 1 summarizes the prescribed Antarctic boundary perturbation and the principal eddy–SAM–jet responses examined in Sects. 3.2–3.6.

The independent HadGEM3 boundary check shows that area-weighted SIC south of 45°S is lower under pdSST-futAntSIC in every NDJFM month. The treatment-minus-control difference ranges from –3.98 percentage points in November to –1.91 points in February (Fig. 1a). This check verifies an archived SIC boundary-state contrast for one model; it does not reconstruct the unarchived IPSL field or separately quantify the retreat-zone SST treatment. The diagnosed circulation signal is therefore interpreted as the fast response to the combined prescribed ocean-surface boundary conditions, without separating SIC and SST contributions or including ocean-circulation adjustment.

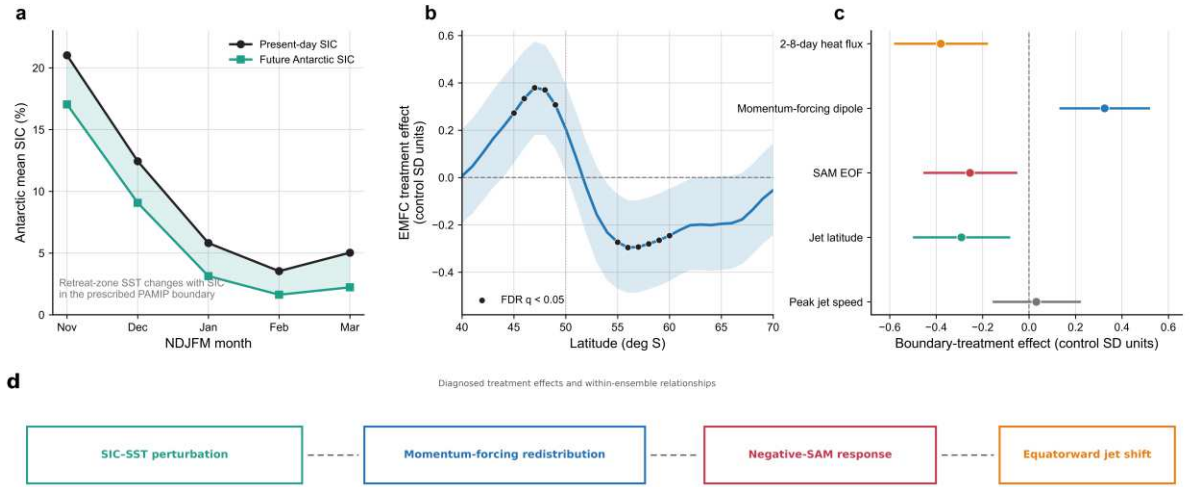


Fig. 1 Antarctic sea-ice–SST boundary perturbation and co-occurring eddy–SAM–jet responses. a, Area-weighted monthly SIC south of 45°S for the archived HadGEM3 control and treatment boundary states; this panel does not display an independent SST field or an IPSL forcing reconstruction. b, Two-model equal-weight standardized effect on the seasonal-departure 250-hPa eddy momentum-flux convergence profile. Black dots mark latitudes passing Benjamini–Hochberg FDR $q < 0.05$ across 31 latitudes. c, Two-model equal-weight standardized effects and 95% independent-member bootstrap intervals for the five core diagnostics. d, Schematic grouping of co-occurring treatment effects and member-state relationships; dashed connectors denote dynamical consistency, not identified causal mediation. SD denotes the model-specific control-ensemble standard deviation

3.2 Poleward eddy heat transport weakens without a coherent increase in overall eddy activity

The two-model equal-weight 2–8-day 850-hPa poleward eddy heat flux decreases by 0.123 K m s^{-1} (95% interval -0.187 to -0.059), equivalent to -0.380 control standard deviations (-0.581 to -0.177 ; permutation $P = 0.0002$; five-test Holm $P = 0.0010$; Figs. 1c and 2a). The model-specific raw effects are $-0.161 \text{ K m s}^{-1}$ in HadGEM3 and $-0.086 \text{ K m s}^{-1}$ in IPSL. All three adjacent latitude-band definitions yield negative standardized effects, indicating that the reduction is not an artifact of one band. The seasonal-departure estimate over 55–75°S is also negative (-0.288 control SD; -0.495 to -0.080 ; sensitivity-family Holm $P = 0.0496$).

In contrast, eddy kinetic energy does not show a coherent increase. The two-model equal-weight 2–8-day 250-hPa EKE effect is -0.209 control standard deviations; its unadjusted interval lies just below zero, but the sensitivity-family Holm-adjusted P value is 0.2330. Seasonal-departure EKE is $+0.070$ control standard deviations and its interval spans zero (Fig. 2a). The data therefore do not support an interpretation in which the Antarctic boundary perturbation uniformly intensifies storm-track eddy activity. This motivates examining where eddies deposit momentum rather than only how much eddy kinetic energy is present.

3.3 Eddy momentum forcing is redistributed meridionally

Seasonal-departure eddy momentum-flux convergence exhibits a clear dipole response: the two-model equal-weight profile is positive at approximately 45–49°S and negative at 55–60°S, with 11 latitude points passing FDR correction across the 31-latitude profile (Fig. 1b). The predefined 45–55°S minus 55–65°S dipole increases by $0.159 \text{ m s}^{-1} \text{ day}^{-1}$ (95% interval 0.060 to 0.259), equivalent to $+0.325$ control SD (0.130 to 0.521; permutation $P = 0.0014$; five-test Holm $P = 0.0056$). Raw model effects are $+0.092 \text{ m s}^{-1} \text{ day}^{-1}$ in HadGEM3 and $+0.226 \text{ m s}^{-1} \text{ day}^{-1}$ in IPSL. The alternative 40–50°S minus 50–60°S definition is also positive ($+0.306$ SD; sensitivity-family Holm $P = 0.0432$), so the main result does not depend on a single latitude boundary.

The strict 2–8-day profile has a similar overall shape, but no individual latitude passes the corresponding FDR threshold. For the 2–8-day component, the 40–50°S minus 50–60°S dipole is $+0.226$ control standard deviations (95% interval 0.020 to 0.429), but its P value becomes 0.1896 after adjustment across 14 sensitivity tests, while the 45–55°S minus 55–65°S definition has an interval that crosses zero (Fig. 2b,c). Because seasonal departures contain

lower-frequency nonstationary variability in addition to 2–8-day weather-scale fluctuations, the stronger seasonal-departure response indicates that time scales longer than 8 days may contribute to the total momentum-forcing anomaly. The present decomposition, however, does not isolate their separate contributions. The most defensible inference is therefore a meridional redistribution of momentum deposition around approximately 50°S, whereas the precise weather-scale contribution is more sensitive to the time-scale and latitude-band definition.

The momentum-forcing response occurs without a corresponding overall increase in eddy kinetic energy. This distinction is dynamically important: the mean-flow adjustment depends not only on the amplitude of eddy activity but also on where eddies converge momentum. The diagnosed dipole is consistent with the role of eddy momentum fluxes in maintaining and shifting the Southern Hemisphere jet discussed by Lorenz and Hartmann (2001) and Barnes and Hartmann (2010). It also clarifies why a fixed 45–65°S mean westerly can decrease even if peak jet speed does not: an equatorward displacement of the jet axis lowers the wind averaged over the original latitude band without requiring a uniform weakening of the jet.

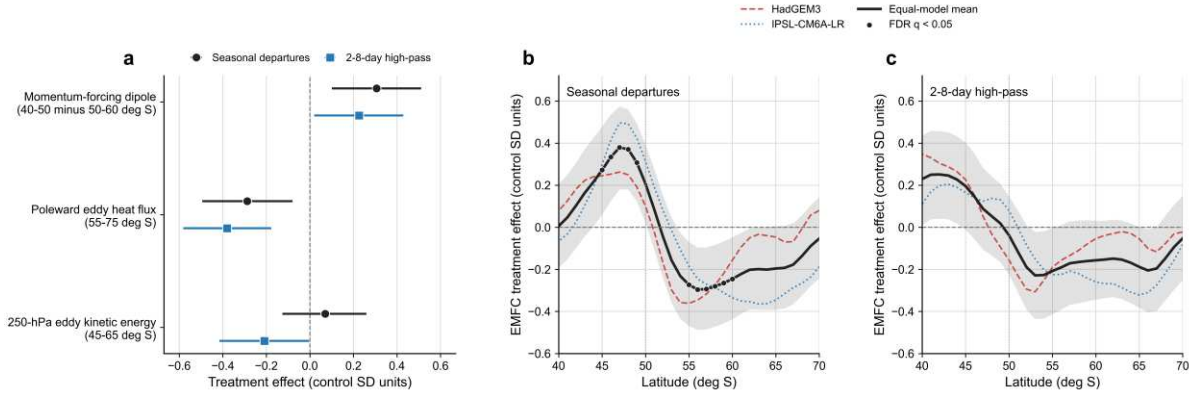


Fig. 2 Time-scale and latitude-band robustness of the eddy response. a, Two-model equal-weight standardized boundary-condition effects on the momentum-forcing dipole, poleward eddy heat flux, and 250-hPa eddy kinetic energy using seasonal departures and 2–8-day high-pass anomalies. b–c, Two-model equal-weight seasonal-departure and 2–8-day eddy momentum-forcing profiles. Dashed and dotted lines show model-specific effects, the solid black line shows the two-model equal-weight mean, shading denotes the 95% bootstrap interval, and dots identify latitudes passing within-profile FDR $q < 0.05$. No latitude in the strict 2–8-day profile passes the FDR threshold

3.4 The boundary perturbation projects onto a negative SAM-like annular response

In both models, the control-trained SAM-like spatial pattern consists of opposing 500-hPa geopotential-height anomalies between the midlatitudes and high southern latitudes, although the zero-crossing latitude and polar amplitude differ between models (Fig. 3a). The standardized SAM-like treatment effects are -0.246 in HadGEM3 and -0.262 in IPSL. The model-specific intervals each include zero, but the directions are consistent and the two-model equal-weight effect is -0.254 control standard deviations (95% interval -0.455 to -0.051 ; permutation $P = 0.0154$; five-test Holm $P = 0.0308$; Fig. 3b). The independent 500-hPa geopotential-height gradient proxy gives a nearly identical two-model equal-weight effect of -0.256 (95% interval -0.466 to -0.052).

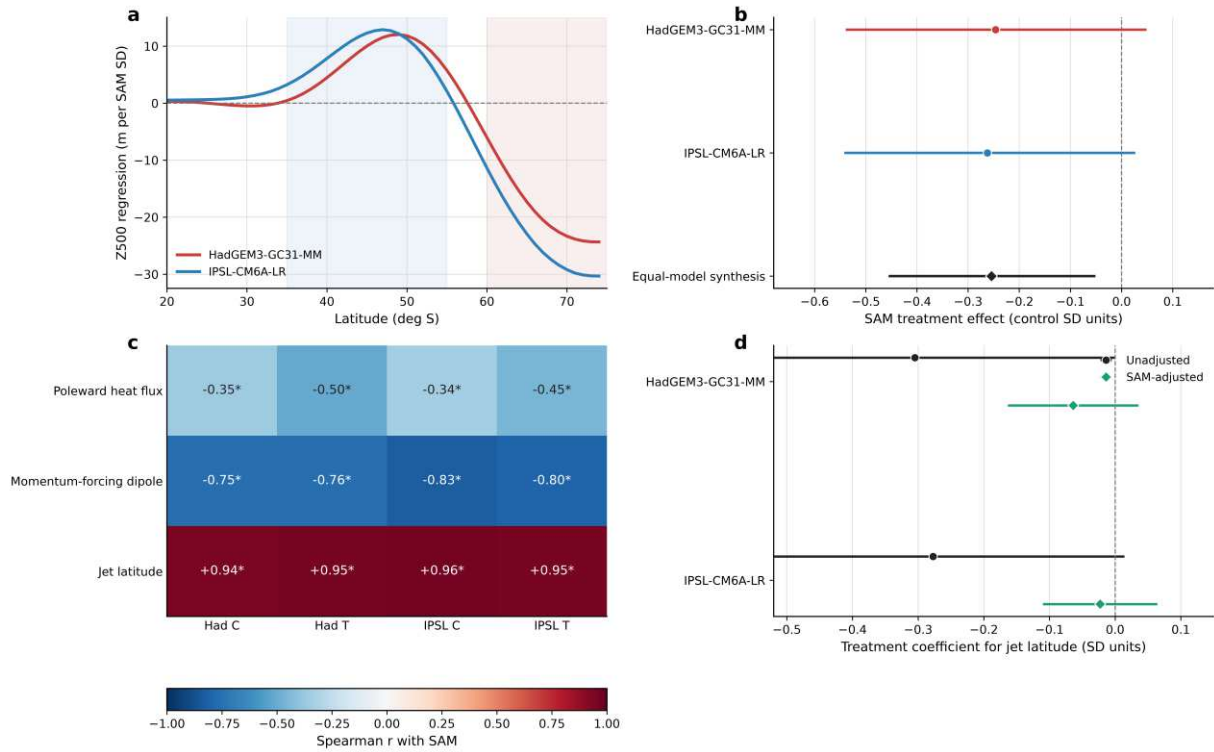


Fig. 3 Control-trained SAM-like response and relationships with jet displacement. a, Control-trained SAM-like 500-hPa geopotential-height regression patterns for the two models. b, Model-specific and two-model equal-weight SAM-like boundary-condition effects with 95% member-bootstrap intervals. c, Within-ensemble Spearman correlations of poleward heat flux, momentum-forcing dipole, and jet latitude with the SAM-like index. Asterisks indicate Holm-adjusted $P < 0.05$ across the 20 state-association tests. C and T denote control and treatment ensembles. d, Standardized jet-latitude treatment coefficients before and after adjustment for the post-treatment SAM-like index, with HC3 95% intervals. Panel d quantifies statistical overlap with the SAM-like index and is not interpreted as a causal mediation estimate

The negative SAM-like response should therefore be interpreted as a two-model equal-weight signal with consistent signs in the two large ensembles, not as a claim that each model independently reaches conventional significance or that the response generalizes to all climate models. The close agreement between the EOF-based index and the independent geopotential-height gradient proxy indicates that the result is not an artifact of EOF sign convention or training. Its direction is consistent with previous studies in which reduced Antarctic sea ice is associated with a negative SAM-like circulation response (Raphael et al. 2011; Ayres and Screen 2019; England et al. 2018), while the present large ensembles provide an explicit estimate of effect size and uncertainty within each model.

3.5 The jet shifts equatorward while peak speed remains nearly unchanged

The quadratic-interpolated raw jet-latitude shifts are -0.418° in HadGEM3 and -0.476° in IPSL. Their two-model equal-weight effect is -0.447° (95% member-bootstrap interval -0.766° to -0.124°), equivalent to -0.291 control SD (-0.500 to -0.082 ; permutation $P = 0.0070$; five-test Holm $P = 0.0210$; Fig. 1c). Because latitude is stored as positive degrees south, negative values denote an equatorward shift. Peak speed changes by -0.033 m s^{-1} in HadGEM3 and $+0.091 \text{ m s}^{-1}$ in IPSL; the equal-weight effect is only $+0.029 \text{ m s}^{-1}$ (-0.156 to $+0.211$), or $+0.031$ control SD (-0.157 to $+0.223$; permutation and Holm $P = 0.7589$).

Although the fixed $45\text{--}65^\circ\text{S}$ mean zonal wind decreases by 0.272 control standard deviations, standardized decompositions across the four model-experiment groups show much stronger coefficients for jet latitude (0.887–0.896) than for peak jet speed (0.210–0.409), and the fixed-band mean wind correlates strongly with jet latitude (0.873–0.926). The prescribed Antarctic boundary perturbation therefore changes the geometry of the jet primarily through a meridional displacement rather than by uniformly reducing the peak westerly wind. The equatorward

direction is consistent with earlier extreme sea-ice experiments and PAMIP multimodel results (Raphael et al. 2011; Screen et al. 2022). At the same time, Ayres and Screen (2019) found that under a 4×CO₂ background state the negative SAM response was expressed more strongly as jet weakening than as displacement. These differences across experimental designs and background states reinforce the need to distinguish jet position from jet intensity rather than infer both from a fixed-latitude-band wind average (Williams et al. 2024). The five predefined core diagnostics and their adjusted significance are summarized in Table 2.

Table 2 Two-model equal-weight boundary-condition effects for the core eddy–SAM–jet diagnostics

Diagnostic	Effect (control SD)	Physical-unit effect (95% interval)	95% bootstrap interval (SD)	Raw P	Holm P
2-8-day poleward eddy heat flux	−0.380	−0.123 K m s ^{−1} (−0.187 to −0.059)	−0.581 to −0.177	0.0002	0.0010
Seasonal momentum-forcing dipole	+0.325	+0.159 m s ^{−1} day ^{−1} (+0.060 to +0.259)	+0.130 to +0.521	0.0014	0.0056
Control-trained SAM EOF	−0.254	Not applicable (model-specific EOF scale)	−0.455 to −0.051	0.0154	0.0308
Jet latitude	−0.291	−0.447° (−0.766 to −0.124)	−0.500 to −0.082	0.0070	0.0210
Peak jet speed	+0.031	+0.029 m s ^{−1} (−0.156 to +0.211)	−0.157 to +0.223	0.7589	0.7589

Notes: The treatment contrast is pdSST-futAntSIC minus pdSST-pdSIC. Physical-unit effects are the equal-weight mean of model-specific raw effects; their intervals are independent-member bootstrap intervals. The SAM-like EOF is standardized separately within each model and therefore has no common raw unit. Negative jet-latitude effects indicate an equatorward shift because latitude is stored as positive degrees south. Raw P values use within-model independent-ensemble label permutations. Holm P values are adjusted jointly across the five predefined core metrics.

3.6 Covariation among eddy momentum forcing, the SAM, and jet latitude

Within both the control and treatment ensembles of each model, the SAM-like index is strongly negatively correlated with the 40–50°S minus 50–60°S momentum-forcing dipole (Spearman $r = -0.827$ to -0.755) and strongly positively correlated with jet latitude ($r = 0.943$ to 0.955); these relationships remain supported after Holm adjustment across the 20 state-association tests (Fig. 3c). The momentum-forcing dipole and jet latitude are also strongly negatively correlated for both time-scale definitions in all four model–experiment groups ($r = -0.887$ to -0.728). Under the sign conventions used here, a more positive momentum-forcing dipole, a more negative SAM-like index, and a smaller positive degree-south jet latitude all correspond to a more equatorward jet state. The three diagnostics therefore describe a consistent direction of member-to-member circulation variability.

When the SAM-like index is added to the jet-latitude regression, the standardized treatment coefficient decreases from -0.305 to -0.064 in HadGEM3 and from -0.277 to -0.023 in IPSL (Fig. 3d). This shows that much of the treatment–control difference in jet latitude statistically overlaps with the annular circulation variation represented by the SAM-like index. Because both the SAM-like index and jet latitude are post-treatment diagnostics derived from the same large-scale circulation, this coefficient reduction identifies shared statistical variation only and cannot establish a causal role for the SAM between the boundary perturbation and jet displacement.

Poleward eddy heat flux is negatively correlated with the SAM-like index in all four ensembles ($r = -0.502$ to -0.342), even though the boundary perturbation decreases both the heat flux and the SAM-like index. This within-ensemble relationship is not consistent with a simple linear chain in which reduced poleward heat transport directly causes the negative SAM-like response. The evidence therefore supports most directly the joint variation of the momentum-forcing redistribution, the SAM-like annular state, and jet latitude, rather than a complete causal sequence from lower-tropospheric heat transport to the SAM and then to the jet.

3.7 Relation to previous work and dynamical significance

Previous extreme sea-ice experiments, multimodel sensitivity studies, and PAMIP analyses have shown that reduced Antarctic sea ice can accompany a negative SAM-like response and an equatorward jet adjustment (Raphael et al. 2011; Ayres and Screen 2019; Screen et al. 2022). The present contribution is not the direction of the jet shift alone.

It resolves the latitude-by-latitude treatment response in 250-hPa eddy momentum deposition within two 100-member model ensembles, separates jet position from peak speed, and tests whether the result persists under a stricter weather-scale definition. The jet axis shifts equatorward while peak speed changes little and total EKE does not increase coherently; the most robust momentum signature is instead a seasonal-departure redistribution around approximately 50°S. A decline in fixed-band westerlies should therefore not automatically be interpreted as weakening of the entire jet.

This result connects the prescribed Antarctic boundary response to the classical eddy–mean-flow framework and refines the interpretation of earlier PAMIP work. Screen et al. (2022) showed that intermodel eddy-feedback differences influence the magnitude of the jet displacement. Here, within-model large ensembles diagnose where upper-level eddies deposit momentum and show that this meridional redistribution co-occurs with the SAM-like state and jet latitude. Screen et al. (2022) reported an observationally constrained equatorward austral-jet response using austral winter and an 850-hPa jet-latitude metric. Because that estimate is not directly comparable with the NDJFM 250-hPa shift diagnosed here, we do not interpret the difference in magnitude. The complementary results nevertheless emphasize why jet latitude, peak speed, and momentum-forcing structure should be reported separately. The present two-model synthesis does not represent the full PAMIP or CMIP population, because mean-state biases and eddy-feedback characteristics can alter both response magnitude and form (Smith et al. 2017; Screen et al. 2022; Williams et al. 2024).

3.8 Limitations and scope of inference

The interpretation is constrained by the experimental design, data reduction, and diagnostics. The treatment changes Antarctic sea ice and retreat-region SST simultaneously, so their individual contributions cannot be separated, and prescribed ocean-surface conditions exclude interactive ocean feedbacks. The HadGEM3 SIC check does not provide a two-model forcing reconstruction, while the pressure-field workflow retains every second latitude and third longitude for HadGEM3. That regular subsampling is suitable for the locked zonal diagnostics but may smooth smaller-scale eddy structure and should be tested against native resolution in a future replication. Seasonal departures include variability at periods longer than 8 days, whereas the strict 2–8-day momentum dipole is sensitive to latitude-band definition and has no FDR-supported latitude in its full profile. The analysis therefore does not assign a unique contribution to weather-scale transients. Member-state correlations and SAM-adjusted regressions describe shared post-treatment variation, not causal mediation. Finally, member-bootstrap intervals quantify internal sampling within two models and cannot characterize structural uncertainty across the PAMIP or CMIP population. In the real climate system, Antarctic sea ice, adjacent SST, and atmospheric circulation are jointly influenced by internal variability, ocean coupling, and multiple external forcings. The standardized effects diagnosed here therefore cannot be mapped directly onto a particular observed year or onto a long-term observed trend. A more appropriate observational test is whether the corresponding circulation diagnostics—especially the meridional structure of eddy momentum deposition, the annular state, and jet latitude—exhibit structural relationships comparable to those found in these controlled model experiments.

4 Conclusions

Using 400 PAMIP members from HadGEM3-GC31-MM and IPSL-CM6A-LR, we obtain four main conclusions.

1. The prescribed Antarctic sea-ice–SST boundary perturbation is accompanied by reduced 850-hPa poleward eddy heat transport, but not by a robust overall increase in 250-hPa eddy kinetic energy.
2. Seasonal-departure eddy momentum-flux convergence develops an FDR-supported dipole around approximately 50°S, indicating a meridional redistribution of momentum deposition toward the equatorward side of the jet region. The strict 2–8-day dipole is less robust across latitude definitions and does not establish a fully resolved weather-scale mediation pathway.
3. The two-model equal-weight response includes a negative SAM-like anomaly and an approximately 0.45° equatorward jet-axis displacement, while peak speed remains essentially unchanged. The response is

therefore better characterized as a change in jet geometry than as uniform weakening of the Southern Hemisphere westerlies.

4. The momentum-forcing dipole, SAM-like index, and jet latitude covary strongly and with consistent signs across the four model–experiment ensembles, indicating that they describe a common annular–jet state. These member-to-member relationships do not determine causal order.

Overall, the two large ensembles show that the fast atmospheric response to the prescribed Antarctic sea-ice–SST boundary perturbation is accompanied by a meridional reorganization of seasonal-departure eddy momentum deposition, a negative SAM-like circulation change, and an equatorward jet shift, rather than by a simple reduction in peak speed. These co-occurring responses are dynamically consistent with an eddy–annular-mode adjustment but do not identify a unique causal mediation sequence. Relative to a fixed-band wind metric, jointly diagnosing momentum forcing, annular structure, jet position, and jet intensity provides a more physically specific basis for comparing Antarctic boundary responses across models.

References

- Ayres HC, Screen JA (2019) Multimodel analysis of the atmospheric response to Antarctic sea ice loss at quadrupled CO₂. *Geophys Res Lett* 46:9861–9869. <https://doi.org/10.1029/2019GL083653>
- Ayres HC, Screen JA, Blockley EW, Bracegirdle TJ (2022) The coupled atmosphere–ocean response to Antarctic sea ice loss. *J Clim* 35:4665–4685. <https://doi.org/10.1175/JCLI-D-21-0918.1>
- Barnes EA, Hartmann DL (2010) Dynamical feedbacks of the Southern Annular Mode in winter and summer. *J Atmos Sci* 67:2320–2330. <https://doi.org/10.1175/2010JAS3385.1>
- Boucher O, Servonnat J, Albright AL et al (2020) Presentation and evaluation of the IPSL-CM6A-LR climate model. *J Adv Model Earth Syst* 12:e2019MS002010. <https://doi.org/10.1029/2019MS002010>
- Bracegirdle TJ, Hyder P, Holmes CR (2018) CMIP5 diversity in Southern westerly jet projections related to historical sea ice area: strong link to strengthening and weak link to shift. *J Clim* 31:195–211. <https://doi.org/10.1175/JCLI-D-17-0320.1>
- Deser C, Lehner F, Rodgers KB et al (2020) Insights from Earth system model initial-condition large ensembles and future prospects. *Nat Clim Chang* 10:277–286. <https://doi.org/10.1038/s41558-020-0731-2>
- England MR, Polvani LM, Sun L (2018) Contrasting the Antarctic and Arctic atmospheric responses to projected sea ice loss in the late twenty-first century. *J Clim* 31:6353–6370. <https://doi.org/10.1175/JCLI-D-17-0666.1>
- Ezber Y, Bozkurt D, Ilicak M (2025) Modeling the impacts of Antarctic sea ice decline: responses of atmospheric dynamics. *J Geophys Res Atmos* 130:e2024JD041558. <https://doi.org/10.1029/2024JD041558>
- Hobbs W, Spence P, Meyer A et al (2024) Observational evidence for a regime shift in summer Antarctic sea ice. *J Clim* 37:2263–2275. <https://doi.org/10.1175/JCLI-D-23-0479.1>
- Kidston J, Taschetto AS, Thompson DWJ, England MH (2011) The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream. *Geophys Res Lett* 38:L15804. <https://doi.org/10.1029/2011GL048056>
- Lorenz DJ, Hartmann DL (2001) Eddy-zonal flow feedback in the Southern Hemisphere. *J Atmos Sci* 58:3312–3327. [https://doi.org/10.1175/1520-0469\(2001\)058<3312:EZFFIT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<3312:EZFFIT>2.0.CO;2)
- Meehl GA, Arblaster JM, Chung CTY et al (2019) Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nat Commun* 10:14. <https://doi.org/10.1038/s41467-018-07865-9>
- Parkinson CL (2019) A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. *Proc Natl Acad Sci USA* 116:14414–14423. <https://doi.org/10.1073/pnas.1906556116>
- Pellichero V, Sallée JB, Schmidt S, Roquet F, Charrassin JB (2017) The ocean mixed layer under Southern Ocean sea ice: seasonal cycle and forcing. *J Geophys Res Oceans* 122:1608–1633. <https://doi.org/10.1002/2016JC011970>
- Purich A, Doddridge EW (2023) Record low Antarctic sea ice coverage indicates a new sea ice state. *Commun Earth Environ* 4:314. <https://doi.org/10.1038/s43247-023-00961-9>
- Purich A, Arblaster JM, Bosch G et al (2026) Southern Annular Mode dynamics, projections and impacts in a changing climate. *Nat Rev Earth Environ* 7:24–42. <https://doi.org/10.1038/s43017-025-00746-y>
- Raphael MN, Hobbs W, Wainer I (2011) The effect of Antarctic sea ice on the Southern Hemisphere atmosphere during the southern summer. *Clim Dyn* 36:1403–1417. <https://doi.org/10.1007/s00382-010-0892-1>
- Roberts MJ, Baker A, Blockley EW et al (2019) Description of the resolution hierarchy of the global coupled HadGEM3-GC3.1 model as used in CMIP6 HighResMIP experiments. *Geosci Model Dev* 12:4999–5028. <https://doi.org/10.5194/gmd-12-4999-2019>
- Screen JA, Eade R, Smith DM, Thomson S, Yu H (2022) Net equatorward shift of the jet streams when the contribution from sea-ice loss is constrained by observed eddy feedback. *Geophys Res Lett* 49:e2022GL100523. <https://doi.org/10.1029/2022GL100523>

445 Simpson IR, Shepherd TG, Hitchcock P, Scinocca JF (2013) Southern Annular Mode dynamics in observations
 446 and models. Part II: eddy feedbacks. *J Clim* 26:5220–5241. <https://doi.org/10.1175/JCLI-D-12-00495.1>
 447 Smith DM, Dunstone NJ, Scaife AA, Fiedler EK, Copsey D, Hardiman SC (2017) Atmospheric response to Arctic
 448 and Antarctic sea ice: the importance of ocean–atmosphere coupling and the background state. *J Clim* 30:4547–
 449 4565. <https://doi.org/10.1175/JCLI-D-16-0564.1>
 450 Smith DM, Screen JA, Deser C et al (2019) The Polar Amplification Model Intercomparison Project (PAMIP)
 451 contribution to CMIP6: investigating the causes and consequences of polar amplification. *Geosci Model Dev*
 452 12:1139–1164. <https://doi.org/10.5194/gmd-12-1139-2019>
 453 Tang S (2026) Eddy momentum-forcing redistribution accompanies an equatorward Southern Hemisphere jet
 454 response to Antarctic sea-ice–SST boundary perturbations. Zenodo. <https://doi.org/10.5281/zenodo.22057819>
 455 Williams RS, Marshall GJ, Levine X et al (2024) Future Antarctic climate: storylines of midlatitude jet
 456 strengthening and shift emergent from CMIP6. *J Clim* 37:2157–2178. <https://doi.org/10.1175/JCLI-D-23-0122.1>

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462 **Author Contributions**

463 Shulin Tang conceived and designed the study, performed the data processing and statistical analyses, interpreted
464 the results, prepared the figures and tables, and wrote and approved the manuscript.

465 **Data Availability**

466 The original PAMIP model output is available through the CMIP6 Earth System Grid Federation and is not
467 redistributed here. A reproducibility package containing the exact 400-member inventory, source identifiers,
468 SHA-256 manifest, processed member-level diagnostics, raw and standardized effect tables, statistical and
469 plotting scripts, and software environment is publicly archived on Zenodo at
470 <https://doi.org/10.5281/zenodo.22057819>.

471 **Code Availability**

472 The analysis and figure-generation scripts are included in the same reproducibility package:
473 <https://doi.org/10.5281/zenodo.22057819>.