The intensification of winter mid-latitude storm tracks in the Southern Hemisphere

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The strength of mid-latitude storm tracks shapes weather and climate phenomena in the extra-tropics, as these storm tracks control the daily to multi-decadal variability of precipitation, temperature and winds. By the end of this century, winter mid-latitude storms are projected to intensify in the Southern Hemisphere, with large consequences over the entire extra-tropics. Therefore, it is critical to be able to accurately assess the impacts of anthropogenic emissions on these storms to improve societal preparedness for future changes. Here we show that current climate models severely underestimate the intensification in mid-latitude storm tracks in recent decades. Specifically, the intensification obtained from reanalyses has already reached the model-projected end-of-the-century intensification. The biased intensification is found to be linked to biases in the zonal flow. These results question the ability of climate models to accurately predict the future impacts of anthropogenic emissions in the Southern Hemisphere mid-latitudes.

Mid-latitude storms transfer momentum, moisture and heat across different latitudes and longitudes, thus controlling the distribution of winds, precipitation and temperature over the extra-tropics1–7. By the end of this century, climate models project a robust strengthening of winter mid-latitude storms in the Southern Hemisphere8–11, which will have large climate consequences for the entire Southern Hemisphere extra-tropics12,13. Over the 1980–2012 period, Southern Hemisphere winter cyclones were also found to intensify in one reanalysis16. However, whether this recent strengthening of winter mid-latitude storms is part of the emerged forced response or merely part of internal climate variability is still an open question. The answer to this question will reveal part of the impacts of anthropogenic emissions on the mid-latitude circulation in recent decades, which will allow policymakers to construct more-accurate adaptation strategies. Another motivation for investigating the recent changes in the mid-latitude flow comes from previous studies that documented model biases in the climatological (time mean) Southern Hemisphere winter circulation, including an equatorward bias in the climatological position of the mean zonal wind17–19 and an underestimation of the climatological strength of high-intensity cyclones20. Thus, investigating the recent changes in the intensity of winter mid-latitude storms in models will also allow us to evaluate how well climate models reproduce the trends of mid-latitude storms over the past decades and potentially discover biases in the projections of storms in current climate models. In this article, we focus on intensity changes of the storm tracks during winter, since during summer, the storm tracks are projected to shift poleward, which results in minor changes in their mid-latitude mean intensity21.

Recent trends in Southern Hemisphere winter storm tracks

We start by examining the recent changes in the intensity of Southern Hemisphere winter (June–August; results for September–November are shown in Supplementary Fig. 1) mid-latitude storm tracks using the transient eddy kinetic energy (EKE; Methods2,21,22). Specifically, we focus on the 40 yr trends (1979–2018) of mid-latitude EKE in 3 different reanalyses and 16 models (Fig. 1a) that participate in the Coupled Model Intercomparison Project Phase 623 (CMIP6), forced with the historical and the future Shared Socioeconomic Pathway scenario 5–8.5 (SSP5–8.5; Methods). We find that in reanalyses, the EKE have intensified over the past four decades at a mean rate of $1.8 \times 10^3$ J m$^{-2}$ yr$^{-1}$ (blue bar; varying between $1.4 \times 10^3$ and $2.5 \times 10^3$ J m$^{-2}$ yr$^{-1}$ across the reanalyses, black circles). By contrast, CMIP6 models simulate a much weaker strengthening, which varies across the models between $-315$ and $570$ J m$^{-2}$ yr$^{-1}$ (black circles), with a multimodel mean value of $210$ J m$^{-2}$ yr$^{-1}$ (grey bar). Thus, not a single model is able to capture the intensification of the EKE in reanalyses (not even when including the uncertainty in the mean reanalyses trend4; black bar). Not only is this models–reanalyses discrepancy evident over the entire 1979–2018 period, but also reanalyses show larger 10, 20 and 30 yr trends over the 1979–2018 period (Extended Data Fig. 1).

Examining the time evolution of EKE further reveals the large differences between reanalyses and climate models (Fig. 1b). First, climate models simulate a monotonic strengthening of the EKE over the twentieth and twenty-first centuries24. In particular, over the past decade, the EKE in CMIP6 models has intensified by ~2% (with s.d. of ±2% across the models), relative to the 1980–1999 period, while in reanalyses the EKE have intensified by ~12%; the percentage changes are calculated relative to the baseline period of each model/reanalysis separately (the time evolution of the different reanalyses is also shown in Supplementary Fig. 2). In CMIP6 models, a similar intensification by 12% is projected to occur only by 2080 (with s.d. of ±11 years across the models), which highlights that climate models may not only underestimate the recent storms’ intensification, but also severely under-predict the future intensification of the storms. Interestingly, the recent weakening of summer storms in the Northern Hemisphere in reanalyses was also found to occur in climate models only by the end of the twenty-first century21.

The intensification of the storm tracks also suggests a strengthening in the poleward eddy energy flux (flux by atmospheric perturbations, such as mid-latitude storms). To examine this, we plot in Fig. 1c the 1979–2018 trends in mid-latitude winter poleward transient eddy moist static energy flux ($v \phi'$, where $v$ is meridi-
Fig. 1 | Recent changes in Southern Hemisphere winter mid-latitude storm tracks. a, c. The 1979–2018 trends in EKE (a) and $v' m'$ (c) in reanalyses mean (blue) and CMIP6 mean (grey). The green bars show the AMIP6 mean trends over the 1979–2014 period. The black circles show the trends from the individual reanalyses/models. Filled (open) circles show trends that are (not) statistically significant at the 5% level based on a Student’s t test. The black bars show the 95% confidence interval of the mean reanalyses trend; red bars show the 2 s.d. across all 40 yr trends from pre-industrial runs, centred around the multimodel mean trend. b, d. Time evolution of EKE (b) and $v' m'$ (d) relative to the 1980–1999 period in reanalyses mean (blue) and CMIP6 mean (black). Thin lines show the evolution of individual reanalyses/models. The ensemble mean time evolution is smoothed with a three-point running mean for plotting purposes. Blue and brown lines show the 1979–2018 linear regressions in reanalyses and CMIP6 mean, respectively. The $v' m'$ trends are shown for 50°S, but similar results are evident throughout the mid-latitudes (Extended Data Fig. 2).

Does the large discrepancy between reanalyses and climate models hinder the detection of the intensification of winter storm tracks in climate models? To answer this question, we follow previous studies27–29 and analyse the time of emergence of the intensification, out of the internal climate variability, in both reanalyses and models. This is done using a signal/noise ratio approach, where the signal is defined as trends of different lengths, all starting from 1979 (the first year of the reanalyses). The noise is defined as 2 s.d. of all trends, with the same length as the signal, that arise only due to internal variability (estimated from pre-industrial control runs, Methods). The time of emergence is defined as the year when the signal (the trend) exceeds the noise.

To use the signal/noise ratio approach, we first ensure that climate models adequately capture the internal variability of the storm tracks’ trends and thus can be used to assess the ‘noise’. To compare the internal variability of the trends, we calculate the s.d. across all 10 yr, 20 yr and 30 yr trends in models and reanalyses over the detrended 1979–2018 period. Similarly, we calculate the s.d. across all trends of the same length from the pre-industrial control runs. We find that reanalyses and climate models have similar 10, 20 and 30 yr
trend variability (Extended Data Fig. 3). Thus, climate models can be used to evaluate the internal variability of the storm tracks’ trends.

The time of emergence of the intensification of mid-latitude EKE and $v'm'$ is shown in Fig. 2. The intensification signal of EKE in reanalyses emerged from the internal climate variability in the late 1990s to early 2000s (Fig. 2a). By contrast, the weaker strengthening in climate models considerably delays the emergence of the signal; the EKE intensification will emerge around 2050 in the multimodel mean, with s.d. of ±14 years. Similarly, the strengthening of $v'm'$ in reanalyses emerged around 2010 (Fig. 2b), while the emergence in climate models is projected to occur only around 2055 in the multimodel mean with s.d. of ±14 years. This highlights that, by underestimating the magnitude of the storm tracks’ changes, climate models may also underestimate the timing of executing adaption and mitigation strategies in Southern Hemisphere mid-latitudes.

The source of the models–reanalyses discrepancy

Next, we examine three possible sources of the larger intensification of mid-latitude storm tracks in reanalyses relative to models. First, the evolution of EKE and $v'm'$ in reanalyses is affected by both their response to external forcings and their internal variability\(^{24,30–32}\). We thus start by examining whether the size of the CMIP6 ensemble analysed here (16 model trends) might not be large enough to capture the internal variability of 40 yr trends, and thus also the trends in reanalyses (whether internal variability is mostly responsible for the strong trends in reanalyses). To evaluate the internal variability in 40 yr EKE and $v'm'$ trends, we calculate 2 s.d. of all 40 yr trends from the pre-industrial control runs\(^{34}\) (a total of 1,961 and 1,361 EKE and $v'm'$ trends, respectively) and centre it around the multimodel mean 1979–2018 trend (red error bars on top of grey bars in Fig. 1a,c). While increasing the ensemble size does increase the range of CMIP6 EKE trends (compare red bars and black dots), even with a substantially larger ensemble size, CMIP6 models still do not capture the recent trends in reanalyses (the overlap between the uncertainty in reanalyses $v'm'$ trends and the variability in the model trends suggests that internal variability could reduce, but not explain, the models’ $v'm'$ bias\(^{24,35}\); compare black and red error bars). Similarly, increasing the CMIP6 ensemble size by pooling together all 40 yr trends over the 1969–2028 period (a total of 320 trends), or examining the 1979–2018 trends using the Community Earth System Model (CESM) 40-member ensemble\(^{41}\), where the spread across its members represents the internal variability (Methods), yields similar results of smaller trends in models relative to reanalyses (Supplementary Figs. 5 and 6). Thus, from the preceding analyses, we conclude that the size of the CMIP6 ensemble is not likely to explain the smaller trends in models relative to reanalyses.

Second, the larger EKE and $v'm'$ trends in reanalyses relative to models might stem from the inability of climate models to simulate the recent cooling of the Southern Ocean surface\(^{34}\). This model bias was found to explain the models’ inability to capture the recent trends in annual mean eddy heat fluxes\(^{29}\). To evaluate the effect of recent observed changes in sea surface temperature (SST) in the models–reanalyses discrepancy, we calculate the EKE and $v'm'$ trends using the Atmosphere Model Intercomparison Project Phase 6 (AMIP6) runs; in these runs, there is no active ocean and sea ice, and the SST and sea ice are prescribed to observations (Methods). Although we find that correcting the simulated surface changes leads to slightly larger intensification in models, the intensification is relatively modest and we conclude that even AMIP6 runs do not capture the recent trends in reanalyses (green bars in Fig. 1a,c). This emphasizes that the inability of climate models to capture the recent winter EKE and $v'm'$ trends does not stem from biases in simulating SST trends. Interestingly, larger EKE trends relative to AMIP6 are also found in the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences–Department of Energy (NOAA-CIRES-DOE) reanalysis (Supplementary Fig. 7), which, similar to AMIP6, uses observed SST and sea ice but, unlike AMIP6, assimilates (only) surface pressure. This suggests, from geostrophic balance, that biases in the structure of the wind may affect the smaller EKE trends in models relative to reanalyses (as further shown in the following).

Third, since mid-latitude eddies arise from hydrodynamic instability, we follow previous studies\(^{22}\) and further investigate the source of the models–reanalyses discrepancy by conducting a linear normal-mode instability analysis. Such analysis allows one to examine the (maximum) growth rate of mid-latitude eddies for a given mean atmospheric conditions, which represents the extraction of energy from the mean flow by the eddies (Methods). In particular, we examine how changes in the vertical and meridional structures of the mean flow might explain the recent storm-track changes by modulating the eddy growth rate.

To examine the effect of changes in the vertical structure of the flow (baroclinicity), we conduct, at each year, a one-dimensional vertical linear normal-mode instability analysis to the quasi-geostrophic equations, using the mean zonal wind, static stability and tropopause height from each reanalysis and each model (Methods). Figure 3a shows the two-dimensional probability density function of the CMIP6 1979–2018 EKE trends and the resulting growth rate trends ($\sigma_n$ along with the corresponding trends in reanalyses (black dots). The EKE trends have low correlation with the growth rate trends across models ($r = 0.07$), and reanalyses not only show
negative growth rate trends (which are inconsistent with the EKE trends and stem from a reduced stability by the vertically dependent zonal flow and static stability), but also, in contrast to the EKE trends, do not show larger \( \sigma_b \) trends than the models. Examining simpler metrics for baroclinicity, such as the Eady growth rate or mean available potential energy (Methods), as was done in previous studies\(^{56,57} \), yields similar results (Supplementary Fig. 8).

However, examining the link between EKE and the meridional structure of the mean flow (variations in the barotropic component of the flow) by conducting, using the tropospheric averaged mean zonal wind (\( \bar{v} \)), a one-dimensional meridional linear normal-mode instability analysis to the absolute vorticity equation (Methods), reveals that the EKE trends are correlated with the growth rate trends (\( \sigma_b \)) across both models (\( r=0.63 \)) and reanalyses (Fig. 3b). Furthermore, similar to the EKE trends, reanalyses also show larger \( \sigma_b \) trends than the models. Similar results are found for the components of \( \bar{v} m' \) (eddy heat and moisture fluxes, Supplementary Fig. 9). This suggests that although baroclinicity drives the formation of mid-latitude storms, here both the changes in the storm tracks over recent decades and the models–reanalyses discrepancy seem to stem from the barotropic part of the flow. Note that changes in the meridional structure of the flow might result from the models–reanalyses discrepancy by affecting not only the barotropic growth of mid-latitude eddies, but also their baroclinic growth via, for example, the barotropic governor\(^{38,39} \) and by affecting the barotropic decay phase in eddy life cycles\(^{35} \).

To further demonstrate the different meridional structures of the wind in models and reanalyses, we next examine the 1979–2018 trends of the second meridional derivative of the mean zonal wind, \( \frac{\partial^2 \bar{v}}{\partial y^2} \) (Extended Data Fig. 4), which plays an important role in the growth of eddies\(^ {16} \) (Methods). For example, in barotropic instability, positive values of \( \frac{\partial^2 \bar{v}}{\partial y^2} \), which occur over the flanks of the zonal wind (the source regions for the instability), allow the necessary condition for instability to be met\(^ {17} \). Indeed, reanalyses exhibit an increase in \( \frac{\partial^2 \bar{v}}{\partial y^2} \) over the equatorward and far-equatorward flanks of the wind, which might explain the increased growth rate in recent decades. In addition, an increase in eddy generation over the flanks of the jet also suggests convergence of momentum by the eddies (\( -\frac{2 \bar{v} \partial^2 \bar{v}}{\partial y \partial y} \)) over the flanks of the jet, which results in a double peak of \( -\frac{2 \bar{v} \partial^2 \bar{v}}{\partial y \partial y} \) (Extended Data Fig. 5). The increase in \( \frac{\partial^2 \bar{v}}{\partial y^2} \) over the flanks of the jets and the double-peak behaviour of \( -\frac{2 \bar{v} \partial^2 \bar{v}}{\partial y \partial y} \) are not captured in most CMIP6 models (Extended Data Figs. 4 and 5), which suggests that the effect of changes in recent decades in the meridional structure of the mean zonal wind on the eddy flow are smaller in climate models relative to reanalyses, which might lead to the weaker EKE and \( \bar{v} m' \) intensification.

Last, previous studies found model biases in the climatological position of the zonal wind\(^{13,14} \) (which still exist, but have been improved, in CMIP6 models\(^ {15} \)), and they were argued to affect the future meridional structure of the wind (the shift of the zonal flow). Thus, it is conceivable that such biases might also affect the model bias in EKE trends. However, a third of the CMIP6 models used here show a poleward bias in the jet’s latitude, relative to reanalyses, while the other two-thirds show an equatorward bias (Supplementary Fig. 10; while a larger set of models might result in a larger bias in the jet’s position, still models show both poleward and equatorward biases\(^ {16,17} \)). Thus, since all models exhibit weaker EKE trends relative to reanalyses, the different zonal wind positions are probably not the source of the EKE discrepancy; reanalyses and models exhibit different relations between jet latitude and EKE trends.

**Discussion and conclusions**

Using multiple reanalyses, we find that mid-latitude storm tracks, including their associated poleward energy flux, have substantially intensified over recent decades in response to external forcing. Climate models, however, are found here to considerably underestimate this intensification, which is projected to occur in climate models only by the late twenty-first century. The inability of climate models to adequately capture the storm-track intensification, which delays the detection of the intensification in models by several decades, questions the skill of climate models to accurately assess the future changes in the Southern Hemisphere extra-tropics; mid-latitude storm tracks affect the distribution of heat, precipitation and weather events (including extreme events) from low subtropical regions to the high polar regions. We reveal that the biases in climate models probably arise from biases in the meridional structure of the zonal flow and not from a misrepresentation of internal variability in climate models nor from the models’ inability to simulate the recent cooling in the Southern Ocean. Our analysis highlights the importance of further investigating observation-based data to assess both the effects of human activity on mid-latitude climate and the limitations in climate models (especially the biased zonal wind changes) to form accurate climate change adaption and mitigation strategies for the Southern Hemisphere mid-latitudes.
Online content
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Eady growth rate and MAPE. The Eady growth rate $\gamma$ is calculated as $\sigma_{\text{ady}} = \frac{\partial \eta}{\partial x}$, where $\eta$ is the mean zonal wind shear and $N^2 = \frac{\partial \eta}{\partial x}$ is static stability. The Eady growth rate is averaged over the mid-latitudes and the extratropical troposphere (850–300 mb). The mean available potential energy is calculated as $\frac{\partial}{\partial y} \int \left( \frac{\partial \eta}{\partial x} - \frac{g}{\eta} \right) dp$, where $g = \frac{\partial \eta}{\partial y} \frac{\partial \eta}{\partial y}$ and tilde represents a mean over the mid-latitudes at constant pressure. Mean available potential energy is integrated over the mid-latitude troposphere.

Data availability

Any codes used in the manuscript are available at https://doi.org/10.5281/zenodo.634217.

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R.C. analysed the data and together with Y.M. and J.Y. discussed and wrote the paper.

Competing interests
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Extended Data Fig. 1 | Recent trends in Southern Hemisphere winter mid-latitude storm tracks. The mean of all 10-year, 20-year and 30-year trends over the 1979-2018 period in a, eddy kinetic energy and b, poleward eddy moist static energy flux in reanalyses mean (blue) and CMIP6 mean (gray). The black circles show the trends from the individual reanalyses/models.
Extended Data Fig. 2 | Latitudinal distribution of poleward eddy moist static energy flux trends. The 1979-2018 trends in poleward eddy moist static energy flux as a function of latitude in reanalyses mean (blue line) and CMIP6 mean (black line). Shadings show two standard deviations across reanalyses/CMIP6 models.
Extended Data Fig. 3 | Variability of winter mid-latitude storm tracks trends. One standard deviation across all 10-year, 20-year and 30-year trends in a, eddy kinetic energy and b, poleward eddy moist static energy flux in reanalyses mean (blue), CMIP6 mean (gray), and pre-industrial runs (red). The trends in CMIP6 and reanalyses were calculated over the detrended 1979-2018 period. The black circles show the results from individual reanalyses/models.
Extended Data Fig. 4 | Recent trends in the meridional structure of the zonal wind. The 1979-2018 trends in the second meridional derivative of the tropospheric (averaged between 850 mb – 300 mb) mean zonal wind, \( \frac{\partial \bar{u} \cos \phi}{\partial \phi} \), in mean reanalyses (blue lines) and CMIP6 models (black lines). Shadings show the 95% confidence interval of the trends. The vertical lines mark the climatological position of the mean zonal wind’s core in reanalyses mean (blue) and CMIP6 models (black). Green line marks the zero line. The latitudinal structure is smoothed with a 3-point running mean for plotting purposes.
Extended Data Fig. 5 | Recent trends in eddy momentum flux convergence. The 1979-2018 trends in vertically averaged eddy momentum flux convergence, \(-\frac{1}{\text{cos}^2 \phi} \frac{\partial^2 \cos^2 \phi}{\partial \phi^2}\), in mean reanalyses (blue lines) and CMIP6 models (black lines). Shadings show the 95% confidence interval of the trends. The vertical lines mark the climatological position of the mean zonal wind’s core in reanalyses mean (blue) and CMIP6 models (black). Green line marks the zero line. The latitudinal structure is smoothed with a 3-point running mean for plotting purposes.