The intensification of winter mid-latitude storms in the Southern Hemisphere

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The strength of mid-latitude storms shapes weather and climate phenomena in the extratropics, as these storms 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 extratropics. It is thus critical to accurately assess the impacts of anthropogenic emissions on winter-time mid-latitude storms, in order to improve our preparedness to future climate changes. However, here we find that climate models severely underestimate the intensification in mid-latitude storms in recent decades. Specifically, the intensification obtained from reanalyses has already reached the model-projected intensification by the end of the century. Our results question the ability of climate models to accurately predict the future climate impacts of anthropogenic emissions in the Southern Hemisphere mid-latitudes.
Main

The atmospheric flow has important climate and weather impacts for the mid-latitudes. In particular, mid-latitude storms transfer momentum, moisture and heat across different latitudes and longitudes, thus controlling the distribution of winds, precipitation and temperature over the extratropics\textsuperscript{6–9}. By the end of this century, climate models project a robust strengthening of winter mid-latitude storms in the Southern Hemisphere\textsuperscript{1–5,10,11}, which will thus have large climate consequences for the entire Southern Hemisphere extratropics\textsuperscript{12,13}.

Over the 1980-2012 period, Southern Hemisphere winter cyclones were also found to intensify in one reanalysis\textsuperscript{14}. 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 (e.g., time of emergence of the intensification of the storms), which will allow policymakers to construct more accurate adaption strategies. Another motivation for investigating the recent changes in the mid-latitude flow comes from previous studies who documented model biases in the climatological (time mean) Southern Hemisphere winter circulation, including an equatorward bias in the climatological position of the mean zonal wind \textsuperscript{15,16}, and an underestimation of the climatological strength of high-intensity cyclones\textsuperscript{17}. Thus, investigating the recent changes in mid-latitude storms in models will also allow us to evaluate how well climate models reproduce the trends of mid-latitude storms over the last decades, and potentially discover alarming biases in the projections of storms in current climate models.
Recent trends in Southern Hemisphere mid-latitude winter storms

We start by examining the recent changes in the intensity of Southern Hemisphere winter (June-August) mid-latitude storms using the transient eddy kinetic energy (EKE, Methods; EKE is commonly used to describe the intensity of mid-latitude storm tracks\textsuperscript{2,4,18,19}). Specifically, we focus on the 40-year 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 6\textsuperscript{20} (CMIP6), forced with the Historical and the SSP5-8.5 future scenario (Methods). We find that in reanalyses, winter storms have intensified over the last four decades in a mean rate of $1.8 \times 10^3 \text{ J m}^{-2} \text{ yr}^{-1}$ (blue bar; varying between $1.4 \times 10^3 - 2.5 \times 10^3 \text{ J m}^{-2} \text{ yr}^{-1}$ across the reanalyses, black circles)\textsuperscript{14}. In contrast, CMIP6 models simulate a much weaker strengthening which varies across the models between $-315 \text{ J m}^{-2} \text{ yr}^{-1}$ and $570 \text{ J m}^{-2} \text{ yr}^{-1}$ (black circles), with a multi-model mean value of $210 \text{ J m}^{-2} \text{ yr}^{-1}$ (gray bar). Thus, not a single model is able to capture the intensification of the storms in reanalyses. This models-reanalyses discrepancy is not only evident over the entire 1979-2018 period, but also reanalyses show larger 10-, 20- and 30-year trends over the 1979-2018 period (Supplementary Fig. 1).

Examining the time evolution of the storms’ intensity further reveals the large differences between reanalyses and climate models (Fig. 1b). First, climate models simulate a monotonic strengthening of winter storms over the 20th and 21st centuries\textsuperscript{1-5,10,11}. In particular, over the last decade, winter storms in CMIP6 models have intensified by $\sim 2\%$ (with standard deviation of $\sim \pm 2\%$ across the models), relative to the 1980-1999 period, while in reanalyses the storms have intensified by $\sim 9\%$ (the time evolution of the different reanalyses is shown in Supplementary
Fig. 2). In CMIP6 models, a similar intensification by 9% is only projected to occur by 2080 (with standard deviation of ±17 years across the models), which highlights that climate models might not only underestimate the recent storms’ intensification, but might 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 21st century\textsuperscript{18}.

The intensification of winter storms 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 wintertime poleward transient eddy moist static energy flux ($v'm'$, where $v$ is meridional velocity, $m$ is moist static energy and prime denotes eddy terms, Methods) at mid-latitudes; this energy flux accounts for the poleward eddy flux of heat, moisture and geopotential (Methods). Similar to the EKE trends, over the last four decades $v'm'$ has intensified faster in reanalyses than in climate models; reanalyses show an intensification in a mean rate of $6 \times 10^{12} \text{TWyr}^{-1}$, varying between $4.9 \times 10^{12} \text{TWyr}^{-1}$ and $7 \cdot 10^{12} \text{TWyr}^{-1}$ across the reanalyses, while CMIP6 models show a mean intensification of only $1 \times 10^{12} \text{TWyr}^{-1}$, where not a single model is able to capture the intensification in the reanalyses. Decomposing the $v'm'$ trends reveals that the discrepancy between models and reanalyses is found in the poleward eddy heat and moisture fluxes, but not in the poleward eddy geopotential flux (Supplementary Fig. 4).

Similar to the time evolution of EKE, $v'm'$ is also projected to monotonically intensify over the 21st century (Fig. 1d). In particular, over the last decade, climate models simulate a $\sim 4\%$ increase in $v'm'$ (with standard deviation of $\sim \pm 5\%$ across the models), relative to the 1980-1999
period, while reanalyses show a $\sim 16\%$ increase (time evolution of different reanalyses is shown in Supplementary Fig. 2). A similar $16\%$ increase in climate models is only projected to occur by 2090 (with standard deviation of $\pm 11$ years across the models), which again stresses that climate models might under-predict the future changes in Southern Hemisphere eddy energy fluxes, and thus also their large impacts on the distribution of climate zones in the extra-tropics. Lastly, note that while biases in long-term trends might be found in reanalyses$^{21}$, due to the inclusion of new observed products, the use of several reanalyses which all show very similar monotonic increase in EKE and $\nu'\mu'$ over the last four decades, together with the fact that the larger 1979-2018 trends in reanalyses, relative to models, are evident also on shorter trends (Supplementary Fig. 1), provide us confidence to use these datasets to evaluate the recent changes in storms’ activity.

Detection analysis for the intensification of winter storms

Does the large discrepancy between reanalyses and climate models hinder the detection of the intensification of winter storms in climate models? To answer this question we follow previous studies$^{22–24}$ and analyze the time of emergence of the intensification of the storms, out of the internal climate variability, in both reanalyses and models. This is done using a signal-to-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 two standard deviations of all trends, with the same length as the signal, that arise only due to internal climate variability (estimated from long pre-industrial control runs, Methods). The time of emergence is defined as the year when the signal (i.e., the trend) exceeds the noise.

In order to use the signal-to-noise ratio approach we first ensure that climate models ade-
quately capture the internal variability of the storms’ trends, and thus can be used to assess the ‘noise’. To compare the internal variability of the storms’ trends we calculate the standard deviation across all 10-year, 20-year and 30-year trends in models and reanalyses over the detrended 1979-2018 period. Similarly, we calculate the standard deviation across all trends of the same length from the long pre-industrial control runs. We find that reanalyses and climate models have similar 10-, 20- and 30-year trends variability (Supplementary Fig. 5). Thus, climate models can be used to evaluate the internal variability of the storms’ 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 ’90s-early ’00s (Fig. 2a). In contrast, the weaker strengthening in climate models significantly delays the emergence of the signal; the EKE intensification will emerge around 2050 in the multi-model mean, with standard deviation of $\pm 14$ 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 multi-model mean with standard deviation of $\pm 14$ years. This highlights that, by underestimating the magnitude of the storms’ changes, climate models may also underestimate the timing of executing adaption and mitigation strategies in Southern Hemisphere mid-latitudes.

**The source of the different intensification in models and reanalyses**

Next, we examine three possible sources of the larger intensification of mid-latitude storms in reanalyses, relative to climate models. First, the size of the CMIP6 ensemble analyzed here (i.e., 16 model trends) might not be large enough to capture the trends in reanalyses, i.e., the 16 model
trends might not capture the internal variability of 40-year trends. To evaluate the internal variability in 40-year EKE and $v' m'$ trends we calculate two standard deviations of all 40-year trends from the pre-industrial control runs (total of 1961 and 1361 EKE and $v' m'$ trends, respectively), and center it around the multi-model mean 1979-2018 trend (red error-bars on top of gray bars in Fig. 1a and 1c). While increasing the ensemble size does increase the range of CMIP6 EKE trends (compare red bars and black dots), even with a significantly larger ensemble size CMIP6 models still do not capture the recent trends in reanalyses. Thus, 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\textsuperscript{25,26}. This model bias, was found to explain the models’ inability to capture the recent trends in annual mean eddy heat fluxes\textsuperscript{24}. To evaluate the effect of recent observed changes in sea surface temperature in the recent storms’ trends 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 sea surface temperature 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 and 1c). This emphasizes that the inability of climate models to capture the recent wintertime EKE and $v' m'$ trends does not stem from biases in simulating surface temperatures. Interestingly, larger EKE trends, relative to AMIP6, are also found in NOAA-CIRES-DOE reanalysis (Supplementary Fig. 6), which, similar to AMIP6,
uses observed sea surface temperature and sea-ice, but, unlike AMIP6, it only assimilates 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 below).

Third, since mid-latitude eddies arise from hydrodynamic instability, we follow previous studies\textsuperscript{19,27,28}, 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 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 maximum baroclinic and barotropic growth rates might explain the recent changes in the storms.

For the baroclinic growth rate, we conduct, at each year, a 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). Fig. 3a shows the two-dimensional probability density function of the CMIP6 1979-2018 EKE trends and baroclinic growth rate trends ($\sigma_{bc}$), along with the corresponding trends in reanalyses (black dots). The EKE trends have low correlation with the baroclinic growth rate trends across models ($r = 0.07$), and reanalyses not only show negative growth rate trends (inconsistent with the EKE trends), but also, in contrast to the EKE trends, reanalyses do not show larger $\sigma_{bc}$ 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\textsuperscript{1–3,5,10}, yields similar results (Supplementary Fig. 7).

On the other hand, examining the link between EKE and the barotropic growth rate ($\sigma_{bt}$), by conducting, using the tropospheric averaged mean zonal wind ($\bar{u}$), a linear normal-mode instability
analysis to the absolute vorticity equation (Methods), reveals that the EKE trends are correlated with $\sigma_{bt}$ trends across both models ($r = 0.63$) and reanalyses (Fig. 3b). Furthermore, similar to the EKE trends, reanalyses also show larger $\sigma_{bt}$ trends than the models. Similar results are found for the components of $v'm'$ (eddy heat and moisture fluxes, Supplementary Fig. 8). This suggests that changes in the meridional structure of the mean zonal wind, which drives barotropic instability, might play an important role in the models-reanalyses discrepancy.

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, $\frac{\partial^2 \pi}{\partial y^2}$ (Supplementary Fig. 9); recall that in barotropic instability positive values of $\frac{\partial^2 \pi}{\partial y^2}$, which occur over the flanks of the zonal wind, allows the necessary condition for barotropic instability to be met. Reanalyses exhibit an increase in $\frac{\partial^2 \pi}{\partial y^2}$ over the equatorward and far-end poleward flanks of the wind (the flanks of the wind are the source regions for barotropic instability), which suggests that barotropic instability might be more prevalent with time in reanalyses. Another support for the importance of barotropic instability in reanalyses is the double peak of the eddy momentum flux convergence trends, $-\frac{\partial u'v'}{\partial y}$ (Supplementary Fig. 10); in barotropic instability the eddies converge momentum over the flanks of the jets, resulting in a double peak of $-\frac{\partial u'v'}{\partial y}$\textsuperscript{30,31}. In contrast, the multi-model mean shows a very small intensification in $\frac{\partial^2 \pi}{\partial y^2}$ across most of the mid-latitudes, with only a single peak of $-\frac{\partial u'v'}{\partial y}$ over the poleward flank of the wind, as different models exhibit different variations in $\frac{\partial^2 \pi}{\partial y^2}$ and $-\frac{\partial u'v'}{\partial y}$. This suggests that barotropic instability processes in climate models may not be as pronounced as in reanalyses, which might lead to the weaker EKE intensification. Lastly, note that while previous studies found model biases in the climatological position
of the zonal wind, which were argued to affect the future meridional structure of the wind (i.e., the shift of the zonal flow), here, on the other hand, CMIP6 models adequately capture the position of the zonal wind in reanalyses (Supplementary Fig. 11), which suggests that different zonal wind positions are likely not the source of the EKE discrepancy.

In summary, using multiple reanalyses, we find that mid-latitude storms, including their associated poleward energy flux, have substantially intensified over recent decades in response to external forcing. Climate models, on the other hand, are found here to significantly underestimate this intensification, which is only projected to occur in climate models by the late 21st century. The inability of climate models to adequately capture the changes in mid-latitude storms questions the skill of climate models to accurately assess the future climate changes in the entire Southern Hemisphere extra-tropics; mid-latitude storms affect the distribution of heat, precipitation and weather events (including extreme events) from low subtropical regions to the high polar regions. This highlights the importance of further investigating observation-based data to assess both the impacts of human activity on mid-latitude climate, and the limitations in climate models to form accurate climate-change adaption and mitigation strategies for the Southern Hemisphere mid-latitudes.
Methods

EKE

The Southern Hemisphere wintertime storms’ intensity is defined, following previous studies\textsuperscript{1–3,5,18}, as the column integrated June-August (JJA) transient eddy kinetic energy, $EKE = \frac{1}{g} \int_0^{p_s} u'^2 + v'^2 dp$, where $g$ is gravity, $p_s$ surface pressure, $u$ and $v$ are the zonal and meridional winds, respectively, $p$ is pressure and prime denotes eddy terms, calculated using a bandpass filter of 2-6 days. Using a different bandpass filter to define the transient eddies (e.g., 3-10 days) yields similar results (Supplementary Fig. 12). We analyze here the column integrated mid-latitude mean (i.e., averaged zonally and over $40^\circ S - 70^\circ S$) EKE (as was done in previous studies\textsuperscript{2,4,18,19}) as the different intensification in models and reanalyses appears throughout the troposphere (Supplementary Fig. 13) and across most of the mid-latitudes (Supplementary Fig. 14).

Eddy moist static energy flux

The poleward transient eddy moist static energy flux is defined as $v' m' = \frac{2 \pi a \cos \phi}{g} \int_0^{p_s} c_p v'T' + L_v v'q' + v'\Phi' dp$, where $v'T'$, $v'q'$ and $v'\Phi'$ are the meridional eddy heat, moisture and geopotential fluxes, respectively, $T$ is temperature, $q$ is specific humidity, $\Phi$ is geopotential, $c_p = 1004 \text{ Jkg}^{-1}\text{K}^{-1}$ is specific heat capacity and $L_v = 2.5 \cdot 10^6 \text{ Jkg}^{-1}$ is latent heat of vaporization.

CMIP6 models

We use daily and monthly output from 16 models that participate in the Coupled Model Intercomparison Project Phase 6\textsuperscript{20} (CMIP6, Supplementary Table 1; we use all models that have available daily data for the analysis), and in order to weigh all models equally, we select only the ‘r1i1p1f1’ member in four experiments: historical (through 2014), future scenario SSP585 (through 2100),
historical with prescribed sea surface temperature and sea-ice (AMIP6, through 2014), and pre-industrial control run (with constant 1850 forcings). The constant external forcings in the control run allows one to evaluate the internal climate variability. Following previous studies\textsuperscript{23,32,33}, before assessing the internal climate variability, we first concatenate the last 200 years of each model’s pre-industrial run, which yields $\sim 2,000$ years of control data. Lastly, we here use the long pre-industrial runs to assess the internal climate variability, rather than reanalyses data, since the length of the control runs not only allows one to gather enough statistics to adequately evaluate the internal variability, but also to account for the variability of 40-year trends, which cannot be estimated in reanalyses (as there is only one trend over the 1979-2018 period).

**Reanalyses**

Reanalyses provide the best approximation for the state of the atmosphere, as they assimilate air and surface observations in general circulation models, and thus are used here to examine the recent changes in mid-latitude storms. Four reanalyses are examined in this study including JRA-55\textsuperscript{34}, NCEP2\textsuperscript{35}, Era-Interim\textsuperscript{36} and NOAA-CIRES-DOE\textsuperscript{37}. We here analyze the Era-Interim, rather than ERA5\textsuperscript{38}, for consistency with the large body of work done using Era-Interim; nevertheless, similar results are also evident in ERA5 (Supplementary Fig. 15). Unlike the other reanalyses, the NOAA-CIRES-DOE reanalysis only assimilates surface pressure, and uses observed sea surface temperature and sea-ice. We thus analyze the NOAA-CIRES-DOE in comparison with AMIP6 runs. We use 6-hourly data from JRA-55, NCEP2 and ERA5, and daily data from Era-Interim and NOAA-CIRES-DOE of zonal and meridional winds, temperature, specific humidity and geopotential over the 1979-2018 period; the NOAA-CIRES-DOE (20CRv3.MO) is available over the
1981-2015 period.

Linear normal-mode instability analysis

For calculating the baroclinic and barotropic growth rates of mid-latitude eddies we follow previous studies\textsuperscript{27, 28, 39–43} and conduct a linear normal-mode instability analysis. For the baroclinic growth rate we use the quasigeostrophic equations (simplified set of equations for the mid-latitude flow that include conservation of vorticity in the interior and of buoyancy in the vertical boundaries) linearized about a zonal mean state (represented by an overbar), which can be written (for simplicity in Cartesian coordinates) as follows,

\[
\begin{align*}
\frac{\partial q'}{\partial t} + \bar{u} \frac{\partial q'}{\partial x} + \frac{\partial \psi'}{\partial x} \frac{\partial \bar{p}}{\partial y} &= 0, 
H_p < p < p_s, \\
\frac{\partial \psi'}{\partial t} \frac{\partial \psi'}{\partial p} + \bar{u} \frac{\partial \psi'}{\partial x} \frac{\partial \psi'}{\partial p} - \frac{\partial \psi'}{\partial x} \frac{\partial \bar{p}}{\partial p} &= 0, 
\psi' = \hat{\psi}'(p) e^{i(kx - \omega t)}, 
\end{align*}
\]

where \(q' = \nabla^2 \psi' + \Gamma \psi'\) is the eddy quasigeostrophic potential vorticity, \(u' = -\frac{\partial \psi'}{\partial y}\) and \(v' = \frac{\partial \psi'}{\partial x}\), 
\(\Gamma = \frac{\partial}{\partial p} \frac{f^2}{S^2} \frac{\partial S^2}{\partial p}\), \(S^2 = -\frac{1}{\rho_0} \frac{\partial \theta}{\partial p}\) is static stability, \(\theta\) is potential temperature, \(\rho\) is the density, \(\frac{\partial \bar{p}}{\partial y} = \beta - \Gamma \bar{\pi}\) is the mean quasigeostrophic potential vorticity gradient (the instability analysis is conducted locally for the mid-latitudes and hence the mean flow is only vertically dependent), \(\beta\) is the meridional derivative of the Coriolis parameter \(f\) and \(H_p\) is the tropopause height (defined, following the WMO, as the lowest level where the vertical temperature gradient crosses the 2 K km\(^{-1}\) value).

Eq. 1 can be written in the form of an eigenvalue problem by substituting a plane-wave solution, \(\psi' = \text{Re} \hat{\psi}'(p) e^{i(kx - \omega t)}\), where \(\hat{\psi}'\) represents the normal modes (the eigenvectors), \(k\) is the zonal wavenumber and \(\omega\) is frequency (the eigenvalues). The waves will thus exponentially grow for any non-zero imaginary component of the eigenvalues. The resulting vertical eigenvalue prob-
lem is then solved for each year using the vertically dependent wintertime zonal mean mid-latitude fields (velocity, temperature, tropopause height), and we analyze the resulting fastest growth rate each year.

For the barotropic growth rate we use the linearized absolute vorticity ($\eta = \nabla^2 \psi + f$) equation for two-dimensional flow,

$$\frac{\partial \nabla^2 \psi'}{\partial t} + \bar{u} \frac{\partial \nabla^2 \psi'}{\partial x} + \frac{\partial \psi'}{\partial x} \frac{\partial \eta}{\partial y} = 0,$$

where $\frac{\partial \eta}{\partial y} = \beta - \frac{\partial^2 \bar{u}}{\partial y^2}$, and $\psi' = 0$ at the meridional boundaries. A plane-wave solution of the form, $\psi' = \text{Re} \hat{\psi}'(y)e^{i(kx-\omega t)}$, transforms Eq. 2 to an eigenvalue problem, only here, unlike in the baroclinic case, the normal modes are a function of latitude. The latitudinally dependent wintertime vertically averaged (between 850 – 300 mb) zonal mean winds are used to solve the resulting eigenvalue problem each year.

**Eady growth rate and MAPE**

The Eady growth rate\(^{29,44}\) is calculated as $\sigma_{\text{Eady}} = f \frac{\partial \bar{u}}{\partial z}$, where $\frac{\partial \bar{u}}{\partial z}$ is the mean zonal wind shear and $N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z}$ 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 (MAPE) is calculated as $\frac{c_p}{2g} \int \gamma \left( \bar{T}^2 - \tilde{T}^2 \right) dp$\(^{45}\), where $\gamma = \frac{-\kappa \theta}{\rho T} \left( \frac{\partial \tilde{T}}{\partial p} \right)^{-1}$ and tilde represents a mean over the mid-latitudes at constant pressure. MAPE is integrated over the mid-latitude troposphere.

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**Data Availability:** The data used in the manuscript is publicly available for CMIP6 data (https://esgf-node.llnl.gov/projects/cmip6/), NCEP (https://psl.noaa.gov/), JRA55 (https://rda.ucar.edu/), ERA-I and ERA5 (https://www.ecmwf.int) and NOAA-CIRES-DOE (https://www.psl.noaa.gov).

**Code Availability:** Any codes used in the manuscript are available upon request from rei.chemke@weizmann.ac.il.

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Figure 1: **Recent changes in Southern Hemisphere winter mid-latitude storms.** The 1979-2018 trends in **a**, EKE and **c**, $v'm'$ in reanalyses mean (blue) and CMIP6 mean (gray). The green bars show the AMIP6 mean trends over the 1979-2014 period (green). The black circles show the trends from the individual reanalyses/models, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test. The red bars show two standard deviation across all 40-year trends from pre-industrial runs. Time evolution of **b**, EKE and **d**, $v'm'$, relative to the 1980-1999 period, in reanalyses mean (blue) and CMIP6 mean (black). Shadings show two standard deviations across reanalyses/CMIP6 models. The time evolution is smoothed with a 3-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 $50^\circ$S, but similar results are evident throughout the mid-latitudes (Supplementary Fig. 3).
Figure 2: **Time of emergence of mid-latitude storms.** The occurrence frequency of the time of emergence of \( a \), EKE and \( b \), \( v' m' \) across CMIP6 models (gray). The vertical blue and black lines show the emergence in each reanalysis (different shades of blue) and in CMIP6 mean, respectively.
Figure 3: **Linear normal-mode instability analysis.** The 1979-2018 EKE trends plotted against the trends in a, baroclinic and b, barotropic growth rates of mid-latitude eddies, calculated from a linear normal-mode instability analysis. Contours show the two-dimensional probability density function of the trends in CMIP6 models, estimated by fitting a kernel distribution, and the correlation appears in each panel. The black circles show the trends from reanalyses.
The intensification of winter mid-latitude storms in the Southern Hemisphere

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Table 1: List of the 16 CMIP6 models analyzed in this study and their availability (marked by asterisks).

| Model               | EKE | MSE | PI | AMIP6 |
|---------------------|-----|-----|----|-------|
| ACCESS-CM2          | *   | *   | *  |       |
| ACCESS-ESM1-5       | *   |     | *  |       |
| CanESM5             | *   | *   | *  |       |
| CESM2-WACCM         | *   | *   | *  |       |
| CMCC-CM2-SR5        | *   |     | *  |       |
| EC-Earth3-Veg       | *   |     |   |       |
| FGOALS-g3           | *   |     |   |       |
| GFDL-CM4            | *   | *   |   |       |
| INM-CM4-8           | *   | *   | *  |       |
| INM-CM5-0           | *   | *   | *  |       |
| IPSL-CM6A-LR        | *   | *   | *  |       |
| MPI-ESM1-2-HR       | *   | *   | *  |       |
| MPI-ESM1-2-LR       | *   | *   | *  |       |
| MRI-ESM2-0          | *   | *   | *  |       |
| NorESM2-LM          | *   | *   |   |       |
| NorESM2-MM          | *   | *   |   |       |
Fig. S1. The mean of all 10-year, 20-year and 30-year trends over the 1979-2018 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.
**Fig. S2.** Time evolution of **a**, eddy kinetic energy and **b**, poleward eddy moist static energy flux, relative to the 1980-1999 period, in each reanalysis (blue lines) and CMIP6 mean (black). Shading shows two standard deviations across CMIP6 models. The time evolution is smoothed with a 3-point running mean for plotting purposes.
Fig. S3. 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.
**Fig. S4.** The 1979-2018 trends in poleward eddy moist static energy flux, decomposed to eddy heat flux ($v'T'$), eddy moisture flux ($v'q'$) and eddy geopotential flux ($v'\Phi'$) in reanalyses mean (blue) and CMIP6 mean (gray). The black circles show the trends from the individual reanalyses/models, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test.
Fig. S5. 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 models and reanalyses were calculated over the detrended 1979-2018 period. The black circles show the results from individual reanalyses/models.
Fig. S6. The 1981-2014 trends in eddy kinetic energy in NOAA-CIRES-DOE (blue) and AMIP6 mean (green). The black circles show the trends from the individual models/NOAA-CIRES-DOE, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test.
**Fig. S7.** The 1979-2018 eddy kinetic energy trends plotted against the trends in **a**, Eady growth rate and **b**, MAPE. Contours show the two-dimensional probability density function of the trends in CMIP6 models, estimated by fitting a kernel distribution, and the correlation appears in each panel. The black circles show the trends from reanalyses.
Fig. S8. The 1979-2018 trends in eddy heat flux ($v'T'$, upper row) and eddy moisture flux ($v'q'$, bottom row) plotted against the trends in baroclinic (left column) and barotropic (right column) growth rates of mid-latitude eddies, calculated from a linear normal-mode instability analysis. Contours show the two-dimensional probability density function of the trends in CMIP6 models, estimated by fitting a kernel distribution, and the correlation appears in each panel. The black circles show the trends from reanalyses.
Fig. S9. The 1979-2018 trends in the second meridional derivative of the tropospheric (averaged between 850mb − 300mb) mean zonal wind, $\frac{\partial}{\partial \theta} \left[ \frac{1}{r \cos \theta} \frac{\partial \mathbf{u} \cos \theta}{\partial \theta} \right]$, in mean reanalyses (blue line) and CMIP6 (black line). Shadings show two standard deviations across reanalyses/CMIP6 models. The vertical lines mark the climatological position of the mean zonal wind’s core in reanalyses mean (blue) and CMIP6 mean (black). Green line marks the zero line. The latitudinal structure is smoothed with a 3-point running mean for plotting purposes.
**Fig. S10.** The 1979-2018 trends in vertically averaged eddy momentum flux convergence, \(-\frac{1}{r \cos \theta} \frac{\partial u' v' \cos \theta}{\partial \theta}\), in mean reanalyses (blue line) and CMIP6 (black line). Shadings show two standard deviations across reanalyses/CMIP6 models. The vertical lines mark the climatological position of the mean zonal wind’s core in reanalyses mean (blue) and CMIP6 mean (black). Green line marks the zero line. The latitudinal structure is smoothed with a 3-point running mean for plotting purposes.
Fig. S11. The occurrence frequency of the climatological (averaged over the 1979-2018 period) position of the mean zonal wind’s core across CMIP6 models (gray). The vertical blue and black lines show the position of the jet in each reanalysis and in CMIP6 mean, respectively.
Fig. S12. The 1979-2018 trends in eddy kinetic energy in reanalyses mean (blue) and CMIP6 mean (gray). The black circles show the trends from the individual reanalyses/models, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test. Here the eddy kinetic energy is defined using a bandpass filter of 3-10 days.
**Fig. S13.** The low-level (850mb), mid-level (500mb) and high-levels (300mb) 1979-2018 trends eddy kinetic energy in reanalyses mean (blue) and CMIP6 mean (gray). The black circles show the trends from the individual reanalyses/models, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test.
**Fig. S14.** The distribution of the 1979-2018 eddy kinetic energy trends in **a**, reanalyses mean and **b**, CMIP6 mean. The small black dots indicate regions where two thirds of the models/reanalyses agree on the sign.
Fig. S15. The 1979-2018 trends in a, eddy kinetic energy and b, poleward eddy moist static energy flux in ERA5 (blue) and CMIP6 mean (gray). The black circles show the trends from the individual models/ERA5, where filled (open) circles show trends that are (not) statistically significant at the 95% level based on a Student’s t-test.