

Historical and projected changes in the Southern Hemisphere surface westerlies

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Key points

1. Recent observational record is dominated by internal variability and is not a good indicator of forced changes in the westerlies
2. With reduced mean state biases compared to CMIP5, CMIP6 models provide a more credible estimate of past and future changes in surface westerlies.
3. There are significant regional and seasonal differences in wind changes that need to be considered when simulating past and future trends

Abstract

Changes to the Southern Hemisphere (SH) surface westerlies not only affect air temperature, storm tracks and precipitation; they are also pivotal in controlling global ocean circulation, ocean heat transport, and ocean carbon uptake. Wind-forced ocean perturbation experiments have commonly applied idealized poleward wind shifts ranging between 0.5 and 10 degrees of latitude, and wind intensification factors of between 10 and 300%. In addition, changes in winds are often prescribed ad-hoc without consistently accounting for physical constraints and can neglect important regional and seasonal differences. Here we quantify historical and future projected SH westerly wind changes based on examination of CMIP5, CMIP6 and reanalysis data. Under a high emission scenario, we find a projected end of 21st Century annual mean westerly wind increase of ~10% and a poleward shift of ~0.8° latitude, although there are also significant seasonal and regional variations.

Plain Language Summary

The westerly winds in the Southern Hemisphere have increased in speed and shifted towards Antarctica in the last few decades, and these are projected to intensify and move further poleward in the future. Changes in the westerly winds are of great importance because they control ocean carbon uptake, ocean circulation and ocean heat transport. To understand the impacts of changes in the westerlies on the Southern Ocean, ocean model simulations are often run by artificially increasing and shifting winds towards Antarctica to approximate future changes in the winds. However, there is no consistency in the way these changes are incorporated, with large variations in the applied shift and strengthening. In this study, we quantify recent observed and projected changes in the surface westerlies, aiming

to provide guidance as to what wind perturbations should be applied in ocean models. We further show that the latest generation of coupled climate models provides a more credible estimate of past and future changes in the surface westerly winds.

1. Introduction

The Southern Hemisphere (SH) surface westerlies are the strongest time averaged surface winds on the planet. The surface westerlies affect the distribution of clouds, precipitation and the position and intensity of storm tracks in the Southern Hemisphere high latitudes (e.g. Bracegirdle, 2013; Thompson et al., 2011) . Changes in these westerlies also have a strong imprint on ocean circulation including the Atlantic Meridional Overturning (Hall & Visbeck, 2002; Toggweiler et al., 2006; Waugh et al., 2013), water mass formation (Oke & England, 2004), Antarctic sea-ice and ice shelves (Holland et al., 2019) , oceanic uptake of heat and carbon (Sen Gupta & England, 2006; Lovenduski et al., 2007; Le Quere et al., 2007) and future changes in the western boundary current extensions (H. Yang et al., 2016) .

The surface westerlies in the SH mid-latitudes have intensified and shifted poleward over the past few decades through the combined influence of an increase in greenhouse gases and stratospheric ozone depletion (Arblaster & Meehl, 2006; Thompson et al., 2011), with the latter thought to be the dominant driver for the recent poleward intensification (Roscoe & Haigh, 2007; Drew T Shindell, 2004; Thompson, 2002). While ozone concentrations are expected to recover in the future, the westerly winds are projected to continue to shift poleward and intensify based on high emission climate model experiments. Under these

conditions, the effect of greenhouse gases is expected to dominate the opposing influence of ozone recovery (Thompson et al., 2011). Hence, understanding the impact of changing westerly winds on the ocean circulation remains an ongoing focus of research.

Several studies using ocean and coupled climate models ranging from coarse to eddy permitting resolutions have been conducted in the past to understand the influence of projected 21st Century poleward intensification of the surface westerlies on the Southern Ocean and Antarctica (e.g. Delworth & Zeng, 2008; Frankcombe et al., 2013; Spence et al., 2014). Most of these studies apply an idealized zonally symmetric intensification and/or poleward shift in the westerly winds in the SH extratropics (generally between 40-60°S). These prescribed changes cause significant impacts on various features of the SH, including the distribution of projected sea level rise (Frankcombe et al., 2013), subsurface warming and circulation changes around the Antarctic continental margin (Spence et al., 2014). However, the applied wind changes tend to be idealized and *ad hoc*, with no common protocol for applying these wind perturbations to ocean models, including the chosen magnitude of the wind shift and its intensification.

To examine the effect of future changes in surface westerlies, previous studies have applied a broad range of poleward shifts and intensifications, with the poleward shift ranging between 0.5 and 10 degrees latitude and wind intensification factors ranging from 10 up to 300%, and sometimes more. Given the wide range of perturbations that have been applied in past studies, some guidance regarding a reasonable estimate of the past and projected changes in the location and strength of the westerly winds in the SH is needed to better facilitate model intercomparison.

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95 In this study, we analyze the historical and projected intensification and poleward shift in
96 the SH surface westerlies across an ensemble of models from the Coupled Model Inter-
97 comparison Project 5 & 6 (CMIP5 and CMIP6) along with reanalysis products. We also
98 examine the seasonality and regional variations in these wind stress changes. These details
99 are important for correctly simulating certain aspects of change in the ocean and in
100 Antarctic sea ice. We also examine whether reanalysis products can be used to provide a
101 reliable estimate of the forced anthropogenic change in SH surface westerlies over the last
102 few decades.

103

104 **2. Data and Methods**

105 Surface monthly averaged zonal winds (at 10m elevation) from the CMIP5 and CMIP6
106 archives as well as reanalysis products are used to examine the latitude and strength of the
107 SH surface westerlies. Ocean model simulations employ surface winds to calculate both the
108 surface wind stress and air-sea turbulent heat fluxes; both are primary boundary conditions
109 for ocean models. Surface winds also determine sea-ice advection and wind-driven mixed
110 layer deepening and are therefore central to ocean-sea-ice model forcing fields.

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112 Data spanning 1850 through to 2099 from the first ensemble from each of multiple CMIP5
113 and CMIP6 models are used to provide equal weight to each climate model. Data from pre-
114 industrial control simulations (200-year runs from 27 CMIP5 and 23 CMIP6 models),
115 historical simulations (1850-2005 for CMIP5 and 1850-2014 for CMIP6) and future
116 projections (2006-2099 for CMIP5 and 2015-2099 for CMIP6) are used in this study (Table
117 S1, S2). For the future projections, data from both the intermediate emissions scenario

(Representative Concentration Pathway (RCP) 4.5 for CMIP5 and the Shared Socio-economic Pathway (SSP) 245 for CMIP6) and the high emissions scenario (RCP8.5 for CMIP5 and SSP585 for CMIP6) are analyzed. Both SSP585 (SSP245) and RCP8.5 (RCP4.5) scenarios are designed so that radiative forcing increases by 8.5W/m^2 (4.5 W/m^2) by 2100 relative to pre-industrial, although the emission rates of various greenhouse gases are different while achieving the same radiative forcing by 2100 (O'Neill et al., 2016). The differences in high emissions and moderate emissions scenarios arise because of differences in the projected concentrations of greenhouse gases, aerosols and stratospheric ozone.

Reanalysis datasets from 1979-2019 for monthly averaged surface zonal winds (at 10m elevation) from the European Centre for Medium Range Weather Forecasts (ECMWF) Reanalysis (ERA5, Hersbach et al., 2020), and the Japanese reanalysis (JRA-55, Kobayashi et al., 2015) are also analyzed. Because of sparse measurements over the Southern Ocean before the satellite era, reanalysis data before the year 1979 are not considered as they do not provide a reliable estimate of the westerly wind changes over the SH. Even though satellite measurements of winds only started in the late 1980s, satellite measurements of other physical quantities help to appreciably improve the quality of the reanalysis products post 1979. Therefore, the reanalysis wind fields from 1979 on are used in this study. Close agreement was found between ERA-5 and JRA-55 for all analyses presented in this study; hence for simplicity we only present results from the ERA5 reanalysis. We also considered the National Centre for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996), however, in agreement with Marshall (2003), we found that this dataset contains spuriously large trends in high latitude Southern Hemisphere winds that are inconsistent with station-based observations. All data are first

mapped to a common 1° x 1° latitude-longitude grid before conducting the analyses shown below.

The maximum jet strength is defined as the maximum surface zonal wind at each longitude in the SH extratropics between 30-70°S (consistent with the definition of Bracegirdle et al., 2013). The position of the westerly jet is then defined as the latitude where the maximum zonal surface wind speed is located at each longitude between 30-70°S.

3. Historical Era

A poleward intensification of the SH surface westerlies is found over the last few decades in both models and reanalysis (Fig. 1a, 1b). This poleward intensification can be described as a positive trend in the SAM (Fig. S1) over the last few decades. Based on single forcing experiments, this change has been attributed primarily to stratospheric ozone depletion, with greenhouse gases playing a secondary role (Thompson et al., 2011).

CMIP5 and older generation climate models are known to have a large equatorward bias (Fig. 1a) in the zonal mean location of the SH surface westerlies (Bracegirdle et al., 2013) possibly due to biases in the shortwave cloud forcing in the models as compared to reanalysis (Ceppi et al., 2012). Biases in the shortwave cloud forcing can induce surface temperature anomalies in the midlatitudes which affect the meridional temperature gradient, which in turn affects the mean latitude of the westerlies. Negative biases in shortwave cloud forcing correspond to equatorward biases in the latitude of the westerlies. There is a notable reduction in the equatorward bias (compared to ERA5) in the zonal mean

location of the maximum SH surface westerlies (see also Bracegirdle et al., 2020) reducing from 1.3° in CMIP5 models down to 0.3° in the CMIP6 multi-model mean, averaged over 1979 to 2005. While the bias has been reduced, two-thirds of models still have a zonal maximum situated further north than the reanalysis estimate (Fig. 1a). In contrast, the CMIP5 multi-model mean (MMM) has an almost identical mean strength for the SH surface westerlies as compared to ERA5, while the CMIP6 MMM is 4% too strong (see Fig. 1b). When limiting this inter-generational CMIP comparison to include just the subset of models that are common to both CMIP5 and CMIP6 (i.e., 12 models; see Table S1, S2), we again find a significant reduction in the equatorward bias (reduced bias of ~0.7° latitude; Fig. S2a). In contrast, we do not find any significant inter-generational difference in the strength of SH surface westerlies between CMIP5 and CMIP6 (Fig. S2b).

Studies examining the ocean response to historical changes in surface winds usually rely on atmospheric reanalyses for their forcing fields. However, changes over the relatively short reanalysis period may be strongly influenced by internal climate variability and may be a poor representation of the anthropogenic forced change. To test if the trends in the zonal mean location and strength in the ERA5 reanalysis lie outside the range of internal climate variability, a Monte-Carlo analysis was carried out by calculating trends over large numbers of random 41-year periods from the 200-year pre-industrial control simulations of 50 CMIP models (27 CMIP5 and 23 CMIP6; Fig. S3). This test assumes that the model variability is representative of the observed internal climate variability. The trend in the location of the SH westerlies calculated from the ERA5 reanalysis lies well within the distribution of trends associated with internal variability. However, the trend in the strength of the westerlies is unlikely to be explained by internal variability alone ($P < 0.1$). Given the model differences in

the representation of internal variability we repeat the analysis using individual CMIP5 and CMIP6 models. Similar results are obtained in more than 90% of the models for both the position and strength of the surface westerlies (Fig. S4-7). A seasonal analysis further finds that trends in both position and strength and for both model generations are significant in summer (DJF, Fig. S8, S9). In all other seasons and for both metrics, the reanalysis trends are within the range expected from internal variability. This is consistent with recent pacemaker model simulations by Schneider et al. (2015) and Yang et al. (2020), who found that a substantial component of recent multi-decadal westerly wind variability could be accounted for in model experiments forced by observed tropical SST variations, independent of anthropogenic forcing.

Most previous ocean model studies that have examined the effects of SH wind changes have done so by prescribing zonally symmetric changes in wind latitude and strength (e.g. Delworth & Zeng, 2008; Downes et al., 2017; Frankcombe et al., 2013; Hogg et al., 2017; Spence et al., 2014; Waugh et al., 2019). Zonal differences in the changes in SH westerlies has only been examined in a few studies (e.g. Bracegirdle et al., 2013; Waugh et al., 2020). The climatological zonal mean location of the surface westerlies is more poleward in the Pacific and western Indian Ocean compared to the Atlantic and eastern Indian basins (Fig. 2a). This is also a consistent feature in the climate models. In the ERA5 reanalysis, there is an 8° meridional difference in the most poleward (~56°S) and equatorward locations (~48°S) of the climatological mean surface westerlies observed over 2000-2019 (Fig. 2a). The CMIP5 MMM shows an equatorward bias in the latitude of the westerlies at all longitudes (Fig. 2a) consistent with the zonal average analysis (Fig. 1a). However, consistent with the improvement in the location of the zonal mean climatological surface westerlies, the CMIP6

MMM shows a better agreement with the ERA5 reanalysis at almost all longitudes compared to CMIP5 MMM, although biases of up to 0.9° persist in the region centered south of New Zealand (Fig. 2a).

We next examine recent regional trends in the ERA5 reanalysis to examine whether they can be accounted for by intrinsic variability, or whether they can provide a reliable estimate of the forced signal. To do this, we compute regional trends in the location and strength of surface westerlies in the ERA5 reanalysis, as well as in CMIP5 and CMIP6 models, for the modern period (1979-2019). Major regional differences between ERA5 and modelled trends in the meridional location of the westerlies can be seen (Fig 2b). Regional differences in trends in the meridional location of westerlies from either model generations are not consistent with the ERA5 trends. Indeed, even though the MMM averages over a large component of the internal variability inherent in individual models, we still find no consistency in the regional pattern of trends between the CMIP5 and CMIP6 MMM (Fig 2b). For example, in the east Pacific ERA5 shows a strong positive trend, in contrast to the CMIP5 MMM which shows a negative trend and CMIP6 MMM which has almost no trend (Fig. 2b). We conclude that over the relatively short reanalysis period (i.e. 41 years from 1979-2019), the regional differences in trends in both the latitude and the strength of westerlies are likely dominated by natural interannual to decadal climate variability. Indeed, because of large intermodel differences, presumably linked to each model's intrinsic variability, the MMM trends obtained from CMIP5 and CMIP6 are not significant at almost all longitudes (Fig. 2b, 2c).

For the models we extend the above analysis to cover the full 20th Century, to see if robust regional patterns in the trends emerge. Using the longer period for both the CMIP6 and CMIP5 models, similar regional patterns in MMM trends in the position of westerlies are found, with significant poleward trends identified everywhere except in the western Pacific, (Fig. 3b), with spatial correlation coefficient of 0.7 ($P < 0.05$) between CMIP5 and CMIP6 MMM trends. Similar regional patterns are also found in trends in the strength of the westerlies (spatial correlation coefficient of 0.8 ($P < 0.05$) between CMIP5 and CMIP6 MMM trends) with strong trends found in the eastern Indian and western Atlantic Oceans basins (Fig. 3c).

Changes in the zonal mean position and strength of the westerlies also show consistent seasonal differences over the historical time period (1900-1999, Fig. S10). While a poleward shift is found in all four seasons in both CMIP5 and CMIP6 MMM (Fig. S10a), the strongest trends are found during summer and weakest trends during winter (Fig. S10a). Similar seasonality is also found in the wind strength trends, with stronger trends in summer compared to winter (Fig. S10b).

4. Future Projections

Future changes in the SH surface westerlies are expected to be affected by the competing effects of increasing greenhouse gases (GHGs) and stratospheric ozone recovery (Thompson et al., 2011). While both GHGs and ozone have acted in concert in the past, as ozone recovers it is expected that the two effects will tend to cancel each other out in the future (e.g. Eyring et al., 2010; Goyal et al., 2019; Newman et al., 2006). After ozone recovery

stabilizes, it is expected that changes in the westerlies will be largely determined by changes in GHGs.

Projected 21st Century (2000-2099) changes in the high emissions scenario of CMIP5 and CMIP6 show a significant poleward shift (by $\sim 1.5^\circ/100\text{yr}$ latitude in CMIP5 & by $0.8^\circ/100\text{yr}$ in CMIP6 MMM) and intensification ($\sim 0.8\text{m/s}/100\text{yr}$ in CMIP6 MMM and $\sim 0.7\text{ m/s}/100\text{yr}$ in CMIP5 MMM) in the zonal mean location and strength of SH westerlies (Fig. 1, Table S3). As with the historical period, there are also major difference in these trends by season (Fig. 4). In particular, a poleward shift is found in all seasons with the largest shift projected during autumn and summer (compared to only in summer during the historical era), and a weaker shift projected for winter and spring (Fig. 4a, Fig. S10a). Strengthening of the westerlies is also projected in all seasons with the weakest trends in summer, in contrast to the historical era, when summertime trends were the strongest (Fig. 4b, Fig. S10b). As discussed earlier, the projected changes in the SH westerlies are expected to be affected by the competing effects of increasing GHGs and stratospheric ozone recovery. While the effect of GHGs acts in all seasons, stratospheric ozone primarily affects the SH during summer because of the breakdown of the stratospheric polar vortex during spring (Arblaster & Meehl, 2006). Weaker summertime trends in the 21st Century are therefore expected because of the opposing contributions of GHGs and stratospheric ozone forcing in that season (Fig. 4). This suggests that the role of GHGs becomes much more important in the future under a high emission scenario, particularly given the expected recovery of stratospheric ozone. Consistent results are found for projected changes in both the latitude and the strength of westerlies in CMIP5 models, although trends are stronger in the CMIP5 MMM (Fig. 4). It is interesting to note that the projected *strengthening* of westerlies in the high emission

scenarios of both CMIP5 and CMIP6 models during the 21st Century occurs throughout the year, but is strongest in winter and spring, whereas the projected *shift* in westerlies is considerably larger in summer and autumn compared to winter and spring (Fig. 4). This is counter to the expectation that the changes in the latitude and strength of westerlies operates in tandem (Bracegirdle et al., 2013), suggesting that different factors might be affecting the projected seasonal trends in both the poleward shift and the strengthening of westerlies in the SH.

In contrast to the high emission scenario, no significant trends are found in the moderate emissions scenario in both CMIP6 (SSP245) and CMIP5 (RCP45) MMM for both the latitude (except during autumn in CMIP5) and strength (except during autumn and spring in CMIP5) of the surface westerlies. In these cases, greenhouse forcing stabilizes at a much lower level and stratospheric ozone forcing can largely compensate the increase in greenhouse gases.

Projected 21st Century trends from CMIP6 models in the latitude of the maximum westerlies also show large regional differences, with the strongest poleward trends over the Atlantic and east Pacific Oceans, and somewhat weaker poleward trends in the Indian Ocean (Fig. 3b). Both CMIP5 and CMIP6 show similar regional patterns in the MMM trends in the meridional location of the westerlies (with a spatial correlation, $R=0.83$). However, CMIP6 MMM trends in the meridional location are weaker as compared to CMIP5 MMM trends (Fig. 3b). The weaker poleward shift in CMIP6 MMM as compared to CMIP5 MMM is consistent with the reduction in the equatorward bias in the meridional location of westerlies in CMIP6 MMM as compared to CMIP5 MMM, as models with a larger equatorward bias also tend to show a larger projected poleward shift (Bracegirdle et al.,

2013). Significant projected trends in the strength of westerlies under the SSP585 scenario of CMIP6 are evident at all longitudes, with stronger trends centered south of Australia and within the Drake Passage (Fig. 3c). Again, consistent regional patterns are found between both the model generations ($R=0.9$, Fig. 3c). However, the projected 21st Century trends are stronger in the CMIP5 MMM as compared to CMIP6 MMM in all regions except for the Atlantic (Fig. 3c).

5. Summary and Discussion

In the past a wide range of wind shifts and accelerations have been used to force ocean models in order to examine the response of the Southern Ocean and the Antarctic margin to past and projected changes in SH westerlies. Understanding future changes has also been hampered by the fact that CMIP5 models showed a significant equatorward bias in the location of the SH westerlies. Previous work has shown that projected wind changes are sensitive to the model's mean state. In particular, models with larger equatorward biases tend to show larger projected poleward wind shifts (Bracegirdle et al., 2013). As such, an anomalous wind shift based on a climate model projection (or from an ensemble of models) will retain a signature of the model's mean state bias (e.g. Duran et al., 2020).

In this study we found a significant reduction in the equatorward bias in the location of SH westerlies in CMIP6 models as compared to CMIP5 models, with the location of maximum surface westerlies in closer agreement with the position of maximum surface westerlies in the ERA5 reanalysis. Given the sensitivity of model projections to mean state biases, CMIP6 models thus likely offer a more credible estimate of past and future changes in SH westerlies for forcing ocean model simulations. We also found that the reanalysis time

period (41 years from 1979-2019) is too short to provide an estimate of the forced trends in the SH westerlies, as the trends over this multi-decadal period appear to be strongly influenced by internal climate variability (see also Schneider et al., 2015; D. Yang et al., 2020). Moreover, it is likely that any anthropogenic forced component of regional or seasonal differences in the reanalysis trends is dominated by internal variability. MMM regional and seasonal trend patterns in both the latitude and strength of the maximum winds only become consistent between CMIP5 and CMIP6 when considering centennial time-scale trends.

Based on the discussion above, we can provide a set of recommendations for forcing ocean model simulations with past and projected changes in SH surface winds: 1) Recent observed wind trends over the Southern Ocean likely include a substantial component of internal decadal variability, and thus should not be assumed to be indicative of forced changes alone. 2) CMIP6 models should be used instead of CMIP5 models for guiding the forcing used in ocean model simulations, for both past and future changes in the SH westerlies, given the much reduced mean state biases. 3) Seasonal variations in trends in both the location and the strength of the westerlies should be considered for simulations where seasonal changes are important (e.g., for studies examining seasonal changes in mode water formation, or Antarctic sea ice variability). 4) As ocean circulation is sensitive to the position of the wind maximum/wind stress curl, prescribed wind forcing should also include regional variations in surface wind trends. This is particularly relevant for projections where regional differences in trends can be as large as 150% for the location and 90% for the strength of the westerlies (Fig. 3b,3c).

While we have focused on ensemble average hindcasts and projections for CMIP5 and CMIP6 simulations, using the multi-model mean to construct zonal-mean wind forcing anomalies presents some problems. For example, only prescribing a zonal wind anomaly is not dynamically consistent if no changes are made to the meridional winds. In addition, the application of a zonal wind perturbation to daily reanalysis fields will distort the geometry of storms. Tapering regions by applying wind anomalies over a particular latitude band in the SH extratropics can also create spurious wind stress curl anomalies (e.g. Maher et al., 2018). One option to minimize these limitations is to use output from individual models as boundary forcing (e.g. Naughten et al., 2018), something commonly done for atmospheric downscaling projects (e.g. Evans et al., 2014). This is a more viable option now that CMIP6 models have minimal equatorward bias in the SH westerlies as compared to CMIP5. Using multiple models would also provide a means to estimate uncertainty in the projections.

Under a high emission scenario, a poleward intensification of the SH surface westerlies is projected to continue in the future despite the projected recovery of stratospheric ozone, because greenhouse gas forcing dominates the future trends across all seasons. We have provided quantitative information on the past and projected future changes in zonal mean position and strength of the surface westerlies over both annual and seasonal time scales (Table S3). This can be used to guide the forcing of idealized ocean model simulations with zonally averaged past and future changes in the SH westerlies.

Data Availability Statements

The datasets analyzed in this study are all publicly available. Data for CMIP5 and CMIP6 models can be obtained from the Earth Systems Grid Federation website

(CMIP5-<https://esgf-node.llnl.gov/projects/cmip5/> and CMIP6- <https://esgf-node.llnl.gov/projects/cmip6/>). ERA5 data can be downloaded from ECMWF website (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>).

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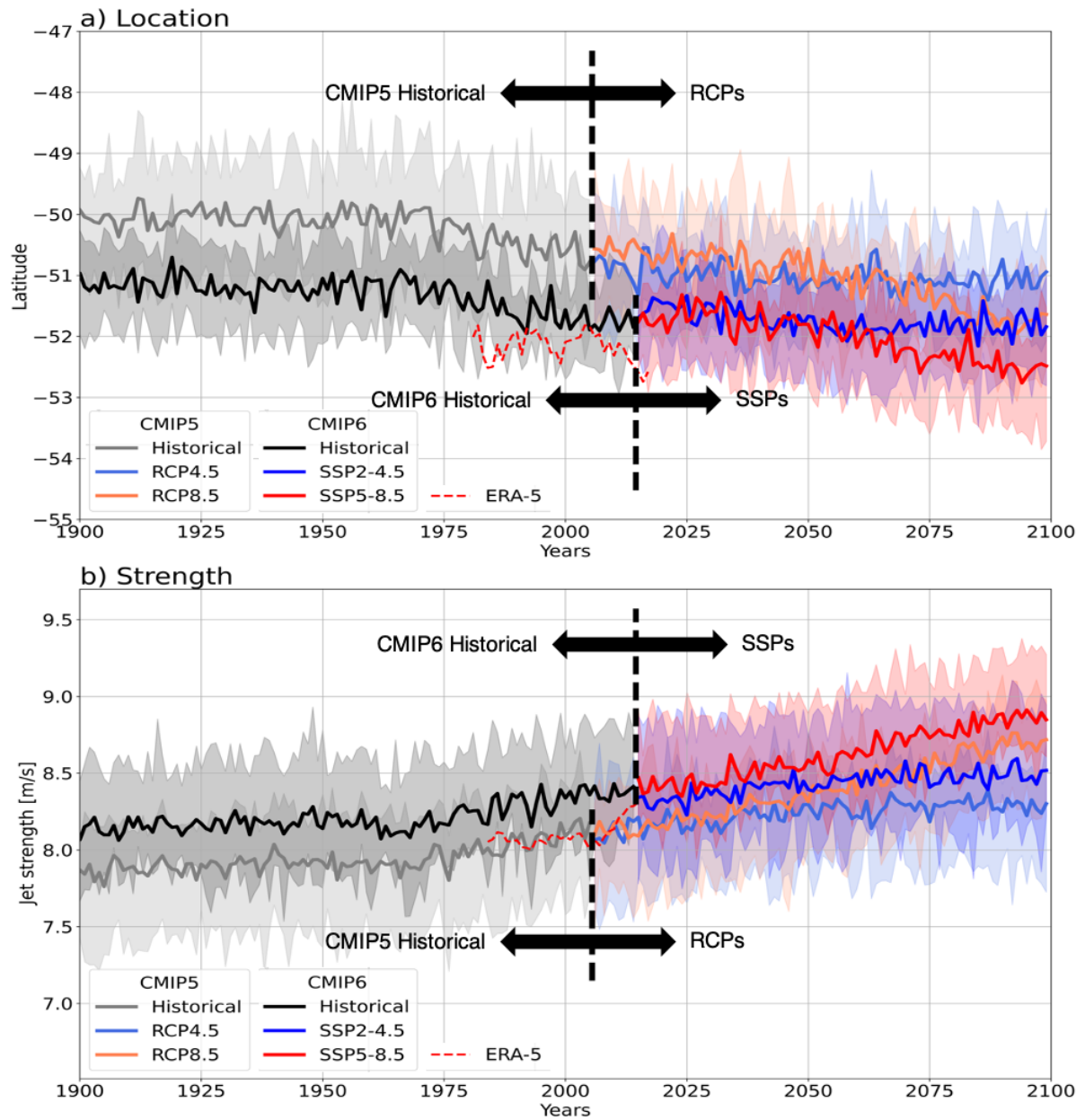


Figure 1 | Position (panel a) and strength (panel b) of maximum Southern Hemisphere surface westerly winds for CMIP5, CMIP6 models and ERA5. Thick lines represent multi-model mean and the shading indicates the inter-quartile range based on CMIP5 and CMIP6 ensembles. Red dotted line represents 5-year running mean jet latitude and strength from the ERA-5 reanalysis from 1979-2019.

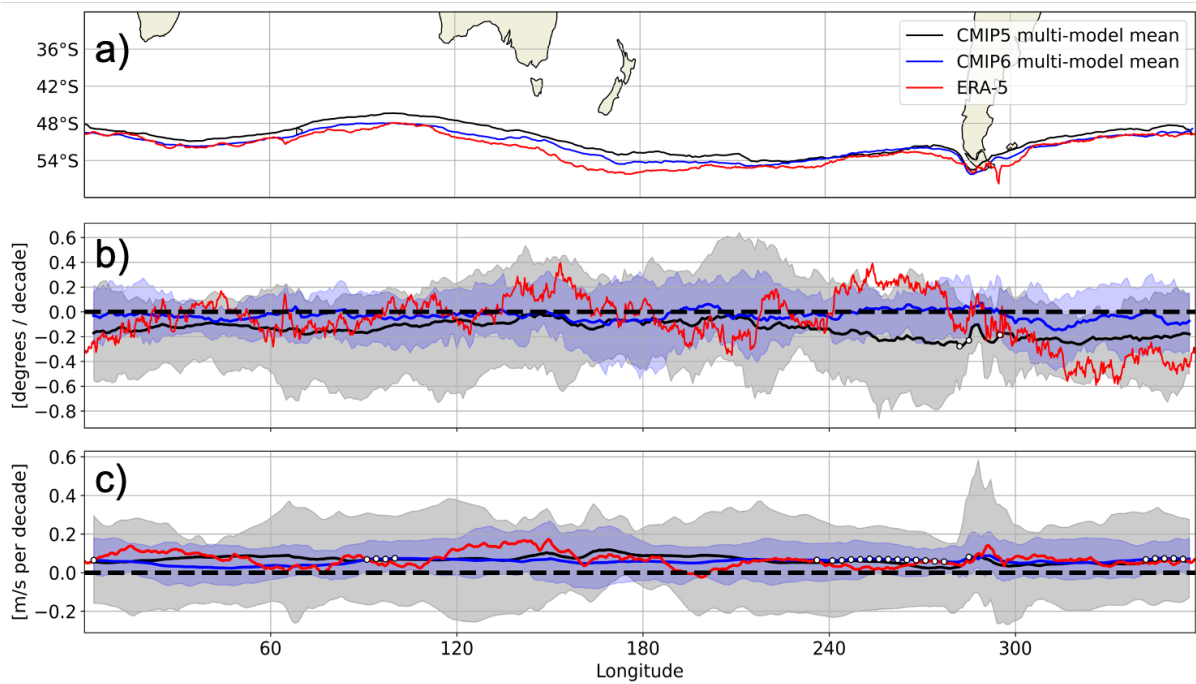


Figure 2 | Zonal differences in the wind latitude and strength in CMIP5, CMIP6 and ERA5. Panel a) shows the mean jet position for 2000-2019. Panel b) and c) respectively show the 1979-2019 trends in westerly jet shift and strength. Solid black and blue lines in panels b) and c) represent multi-model mean from CMIP5 and CMIP6 respectively and shading represents the inter-quartile range. White circles represent the regions where trends are significant.

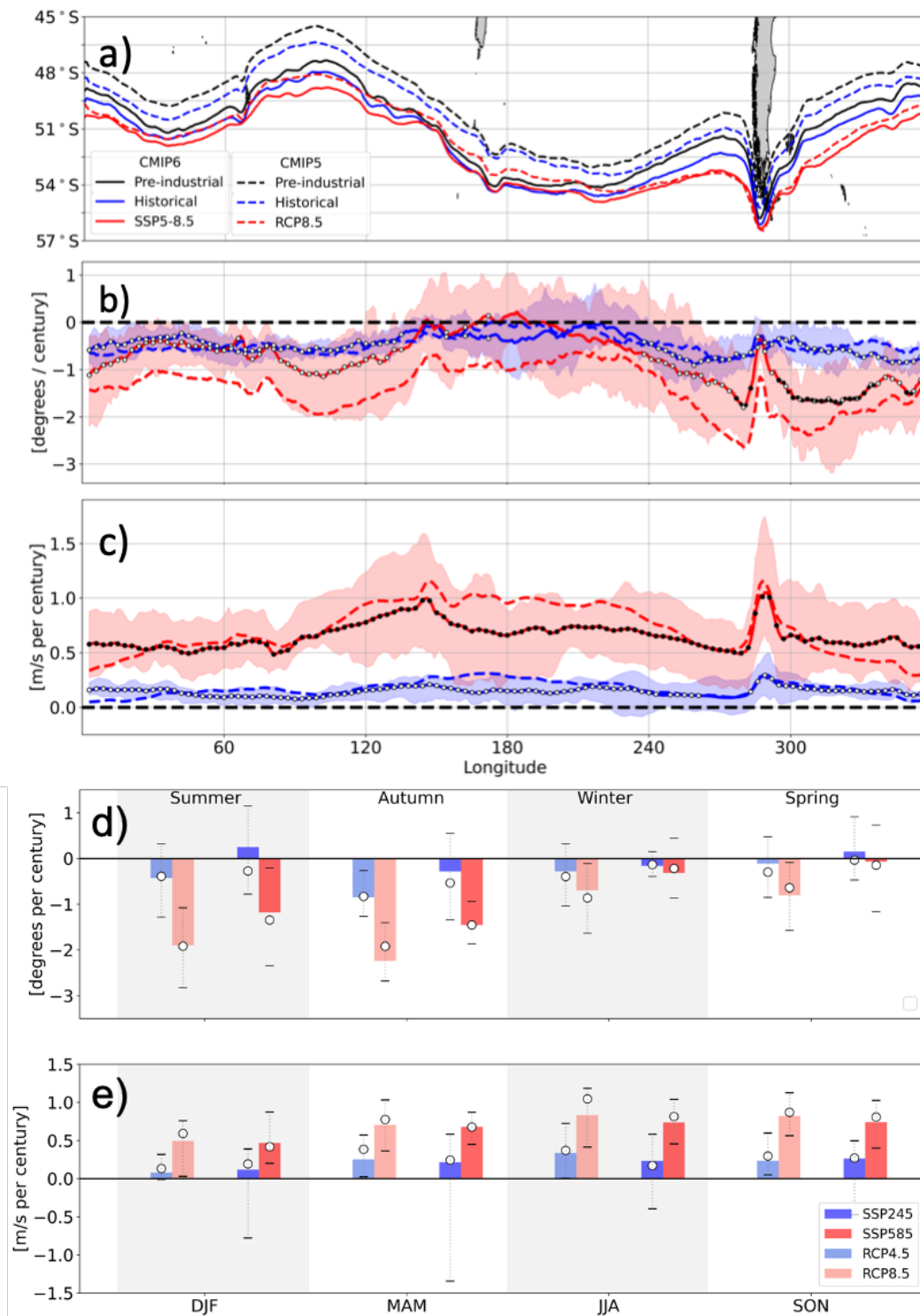


Figure 3 | Past and projected zonal and seasonal differences in wind latitude and strength in CMIP5 and CMIP6 models. Panel a) shows the multi-model mean jet position during the pre-industrial scenario (1860-1880 average), historical (1980-1999 average) and SSP5-8.5 (2080-2099 average). Panel b) and c) respectively show the trends in latitude and strength of

743 westerlies during the 20th (1900-1999) and 21st (2000-2099) Century. Solid lines in panels b)
744 and c) represent multi-model mean and shading represents inter-quartile range from CMIP6
745 models. White circles show the locations where trends are significant. Black dots on solid
746 red lines in panels b) and c) represent the locations where trends during the 21st Century are
747 significantly different from trends during the 20th Century. Panels d) and e) respectively
748 show trends in maximum zonally averaged zonal wind location and strength calculated over
749 2000-2099. Colored bars in panels d) and e) represent multi-model mean trends, circles
750 represent the multi-model median and dashed bars represent the inter-quartile range.

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