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Key Points:

- Interactive chemistry models project more 21st century Antarctic ozone than no-chemistry models
- Ozone differences arise from inconsistent forcings used by models with/without interactive chemistry
- Larger ozone increases lead to smaller increases in Southern Hemisphere surface westerlies

Supporting Information:

Supporting Information may be found in the online version of this article.

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Influence of Ozone Forcing on 21st Century Southern Hemisphere Surface Westerlies in CMIP6 Models

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Abstract The tropospheric westerly jet is a key feature of Southern Hemisphere climate. In recent decades the jet strengthened in austral summer (December–February [DJF]) and moved poleward owing to the Antarctic ozone hole. Future jet trends will be influenced by recovery of the Antarctic ozone hole and greenhouse gas (GHG) forcing. Here, we examine 21st century projections of ozone, temperature and winds in the sixth Coupled Model Intercomparison Project models with (CHEM) and without (NOCHEM) interactive chemistry. NOCHEM models use an ozone data set that was produced with GHG forcings inconsistent with those used by CHEM models, leading to less ozone recovery in the Antarctic springtime lower stratosphere. This propagates to different stratospheric temperature projections and DJF westerly winds: NOCHEM models project a $78 \pm 52\%$ stronger increase in DJF westerly wind speeds than CHEM models under the high GHG emissions scenario SSP585. Our results show the importance of simulating stratospheric ozone accurately for Southern Hemisphere climate change projections.

Plain Language Summary Global climate models must simulate Southern Hemisphere westerly winds accurately to simulate other key features of Southern Hemisphere midlatitude climate. During Southern Hemisphere summer, westerly winds are partly influenced by the Antarctic ozone hole. Global climate models simulate ozone in one of two ways: either they calculate ozone concentrations online via an interactive chemistry scheme, or they prescribe a precomputed ozone data set. The former approach is computationally expensive, yet the latter approach means that ozone cannot respond to internal changes in the model, potentially causing errors. In the sixth Coupled Model Intercomparison Project (CMIP6), most models prescribed ozone rather than calculating it online. Unfortunately, the ozone data set they prescribed is not consistent with other forcings used by the CMIP6 models, therefore models with and without interactive chemistry produce different 21st century Antarctic ozone projections, leading to differences in Southern Hemisphere westerly winds. This study adds another line of evidence as to why using interactive chemistry in a global climate model is important. It also acts as a cautionary tale for the next CMIP assessment, by showing that ozone forcing data sets must be produced in a way that is as consistent as possible with other CMIP forcings.

1. Introduction

The Southern Ocean is one of the windiest regions on the planet year-round. In the troposphere, the region of highest wind speed is known as the mid-latitude near-surface jet, or westerly jet. The westerly jet affects multiple aspects of Southern Hemisphere mid-latitude climate, such as air temperature, storm tracks and precipitation (Thompson et al., 2011), along with ocean circulation and carbon uptake and storage (Le Quéré et al., 2007). In recent decades, Antarctic ozone depletion and the associated stratospheric cooling and change in the thermal wind balance has caused the summertime westerly jet to strengthen and move poleward (Son et al., 2008, 2009; Thompson & Solomon, 2002).

Recently, it was shown that the poleward shift of the westerly jet has paused owing to the early stages of Antarctic ozone recovery (Banerjee et al., 2020; Solomon et al., 2016). Following the Montreal Protocol on Substances that Deplete the Ozone Layer, Antarctic springtime ozone abundances are projected to return to 1980 levels during the 2060s (Dhomse et al., 2018). Ozone recovery is leading to a reversal of late twentieth century Southern Hemisphere stratospheric circulation changes (Zambri et al., 2021), with the westerly jet expected to weaken and move equator-ward in response. However, the westerly jet is also influenced by greenhouse gas (GHG) forcing, which

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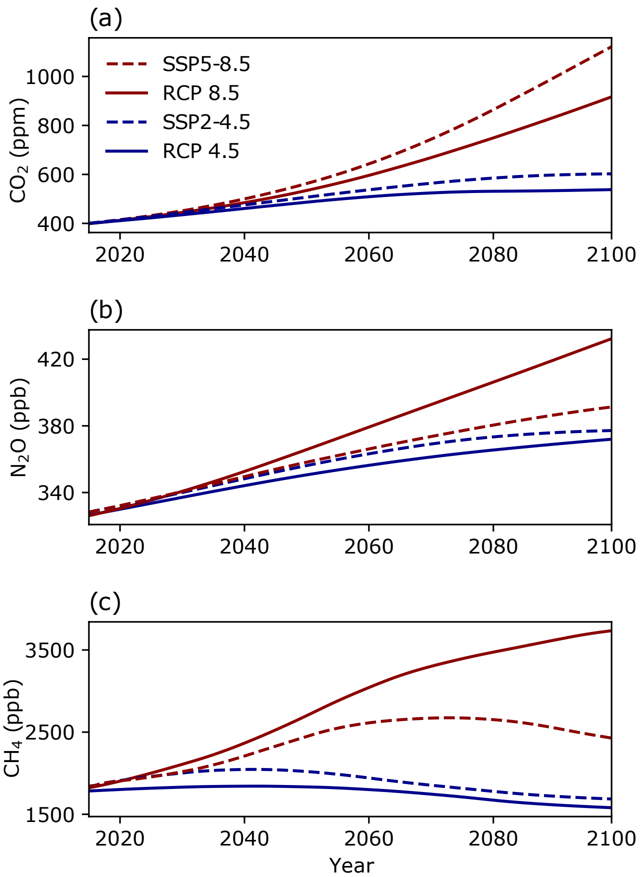

Figure 1. Global-, annual-mean greenhouse gas concentrations in selected Representative Concentration Pathways (RCPs, solid lines) and Shared Socioeconomic Pathways (SSPs, dashed lines). (a) CO_2; (b) N_2O; (c) CH_4. Data sourced from Meinshausen et al. (2011, 2020).

will play a key role in determining the jet strength and position through the 21st century, alongside ozone recovery (Bracegirdle, Krinner, et al., 2020; Thompson et al., 2011).

Global climate models that participated in the fifth Coupled Model Intercomparison Project (CMIP5) simulated biases in the position of the Southern Hemisphere westerly jet compared to reanalyses (Bracegirdle et al., 2013). Biases in the jet were linked to errors in shortwave cloud radiative forcing (Ceppi et al., 2012), with implications for the quality of regional climate change projections. Since CMIP5, substantial effort has been invested in reducing cloud-related errors over the Southern Ocean (Zelinka et al., 2020), and the present generation of models, those participating in the sixth Coupled Model Intercomparison Project (CMIP6), now have an annual-mean equatorward bias in the westerly jet of only 0.4°, compared with 1.9° in CMIP5 (Bracegirdle, Holmes, et al., 2020). It should be noted that despite improvements in the jet location, biases in the jet speed relative to the ERA-Interim reanalysis have increased from 0.31 m s^{-1} (2.42%) in CMIP5 to 0.51 m s^{-1} (3.98%) in CMIP6 (Bracegirdle, Holmes, et al., 2020). However, when comparing a subset of models common to both CMIP5 and CMIP6, Goyal et al. (2021) found no significant difference in the jet speed between the two groups.

Although reducing the jet location bias boosts confidence in future projections of Southern Hemisphere surface westerlies (Bracegirdle, Krinner, et al., 2020; Goyal et al., 2021), it is important to note that the CMIP6 models vary widely in their treatment of stratospheric ozone, which may also impact on surface westerlies. While some models calculated ozone online via interactive chemistry schemes, the majority prescribed a pre-calculated ozone data set (Section 2). Prior research has shown that prescribing stratospheric ozone leads to biases in simulated stratospheric dynamics (Haase et al., 2020; Ivanciu et al., 2021) and surface climate (Neely et al., 2014), with implications for Southern Ocean circulation and Antarctic sea ice (Li et al., 2016) along with the Southern Annular Mode (Morgenstern, 2021).

Here, we investigate whether the inclusion of interactive chemistry significantly influences 21st century Southern Hemisphere westerlies under a moderate and high GHG emissions scenario. We examine projections of springtime Antarctic ozone in models with and without interactive chemistry and explore how differences in ozone influence stratospheric temperature and near-surface westerly wind speeds.

2. Computational Methods

We analyzed the SSP245 and SSP585 simulations performed for CMIP6 (Eyring et al., 2016). Both experiments span 2015–2100 and are based on Shared Socioeconomic Pathways (SSPs; Riahi et al., 2017). As with the preceding Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) used in CMIP5, SSP245 and SSP585 yield an approximate global-mean increase in radiative forcing of 4.5 W m^{-2} and 8.5 W m^{-2} in 2100, respectively. However, the individual GHG concentration pathways taken to reach those radiative forcings differ (O'Neill et al., 2016). For example, SSP585 has a larger CO_2 concentration, and smaller N_2O and CH_4 concentrations, in 2100 compared with RCP85 (Figure 1).

Most CMIP6 models without interactive stratospheric chemistry used ozone data sets prepared for CMIP6 (Checa-Garcia, 2018; Checa-Garcia et al., 2018). These data sets, hereafter referred to as the CMIP6 ozone data sets, are based on Chemistry-Climate Model (CCM) simulations produced by the Canadian Middle Atmosphere Model and the Community Earth System Model-Whole Atmosphere Community Climate Model (CESM1-WACCM). Since the CCM simulations were performed for the Chemistry-Climate Model Initiative (Morgenstern et al., 2017), which pre-dates the SSPs, they used GHG concentrations following the RCPs (Figure 1). The

Table 1
The Sixth Coupled Model Intercomparison Project Models and Simulations Analyzed in This Study

Model	Experiments	Fully interactive stratospheric O_3?	Reference
CESM2-WACCM	ssp245 (5)	Yes	Danabasoglu (2019)
	ssp585 (5)		
CNRM-ESM2-1	ssp245 (10)	Yes	Seferian (2018)
	ssp585 (5)		
GFDL-ESM4	ssp245 (1)	Yes	Krasting et al. (2018)
	ssp585 (1)		
MRI-ESM2-0	ssp245 (1)	Yes	Yukimoto et al. (2019)
	ssp585 (1)		
UKESM1-0-LL	ssp245 (4)	Yes	Tang et al. (2019)
	ssp585 (5)		
ACCESS-CM2	ssp245 (3)	No	Dix et al. (2019)
	ssp585 (3)		
ACCESS-ESM1-5	ssp245 (10)	No	Ziehn et al. (2019)
	ssp585 (10)		
CAMS-CSM1-0	ssp245 (2)	No	Rong (2019)
	ssp585 (2)		
CanESM5	ssp245 (10)	No	Swart et al. (2019)
	ssp585 (10)		
CNRM-CM6-1	ssp245 (6)	No	Voldoire (2018)
	ssp585 (6)		
EC-Earth3	ssp245 (8)	No	EC-Earth-Consortium (2019)
	ssp585 (4)		
GISS-E2-1-G	ssp245 (10)	No	NASA/GISS (2018)
	ssp585 (10)		
HadGEM3-GC31-LL	ssp245 (1)	No	Ridley et al. (2019)
	ssp585 (4)		
IPSL-CM6A-LR	ssp245 (6)	No	Boucher et al. (2018)
	ssp585 (6)		
MIROC6	ssp245 (3)	No	Tatebe and Watanabe (2018)
	ssp585 (10)		
MPI-ESM1-2-LR	ssp245 (9)	No	Wieners et al. (2019)
	ssp585 (9)		
NESM3	ssp245 (2)	No	Cao and Wang (2019)
	ssp585 (2)		

Note. The number in brackets after the experiment name denotes the number of realizations analyzed.

CMIP6 ozone data sets specify stratospheric ozone concentrations as a monthly-mean, four-dimensional field (Checa-Garcia, 2018; Checa-Garcia et al., 2018).

We analyzed ozone concentration, temperature and near-surface (10 m) westerly wind speed in the SSP245 and SSP585 simulations for all models that had provided these fields at the time of data download (Table 1). All realizations for a model were combined to produce an ensemble mean, and ensemble means were then combined to produce a multi-model mean. For models with more than 10 realizations, only the first 10 were analyzed.

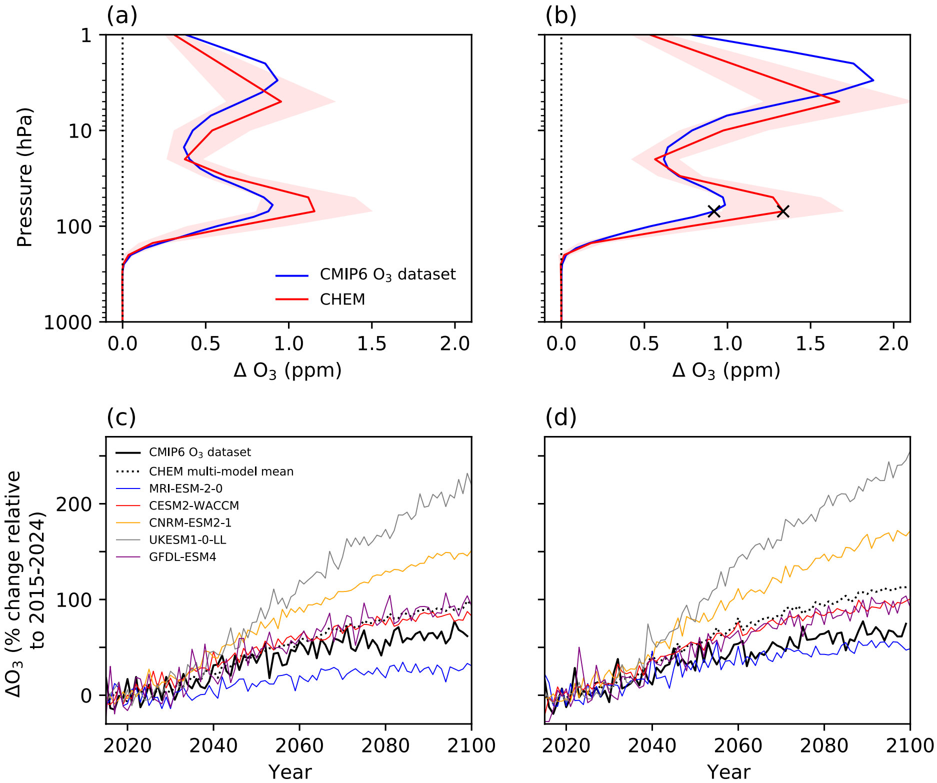

Figure 2. (a) Change in ozone concentration (2090–2099 minus 2015–2024) during September–November at 60–90°S in the CMIP6 ozone data set, and the multi-model mean ($\pm 1\sigma$) of interactive chemistry models (CHEM) in the SSP245 experiment. (b) As for (a) but for the SSP585 experiment. Crosses indicate 70 hPa, where the mean of the CHEM models is significantly different from the the sixth Coupled Model Intercomparison Project (CMIP6) ozone data set (95% level of confidence; one-sample *t*-test. No statistically significant differences were found for the SSP245 experiment shown in (a)). (c) Antarctic (60–90°S) ozone during September–November at 70 hPa, expressed as a percent change relative to the 2015–2024 mean in the SSP245 experiment. (d) As for (c) but for the SSP585 experiment.

3. Results and Discussion

Antarctic springtime ozone is projected to increase throughout the 21st century in response to decreasing stratospheric chlorine concentrations and increasing CO_2 concentrations (Braesicke et al., 2018; Dhomse et al., 2018). Ozone increases are seen in both the SSP245 and SSP585 simulations (Figure 2 and Figure S1 in Supporting Information S1). CMIP6 models with interactive chemistry (CHEM models) simulate on average a 1.15 ppm increase in springtime (September–November) lower-stratospheric (~70 hPa) ozone through the 21st century in SSP245; approximately an 80% increase (Figures 2a and 2c). In contrast, the CMIP6 ozone data set used by models without interactive chemistry (NOCHEM models) shows a ~0.90 ppm or 60% increase in lower stratospheric ozone. In the SSP585 experiment, the CHEM models and CMIP6 ozone data set show large ozone increases in the upper stratosphere, due to the effects of GHG-induced stratospheric cooling (Figures 3 and S2 in Supporting Information S1).

Recently, Keeble et al. (2021) evaluated ozone changes in CMIP6 models and identified no consistent bias in total column ozone between the CHEM and NOCHEM models. However, they identified that variability between CHEM models is high, with some models simulating more total column ozone than the multi-model mean, and others simulating less. In the springtime Antarctic lower stratosphere, which is a key region given its influence on surface climate, all CHEM models show larger projected ozone changes in the 21st century than the CMIP6 data set, with the exception of the MRI-ESM-2-0 model (Figures 2c and 2d). However, MRI-ESM-2-0 is known to underestimate Antarctic polar ozone depletion (Keeble et al., 2021; Morgenstern et al., 2020) therefore likely does not project future ozone changes accurately in this region.

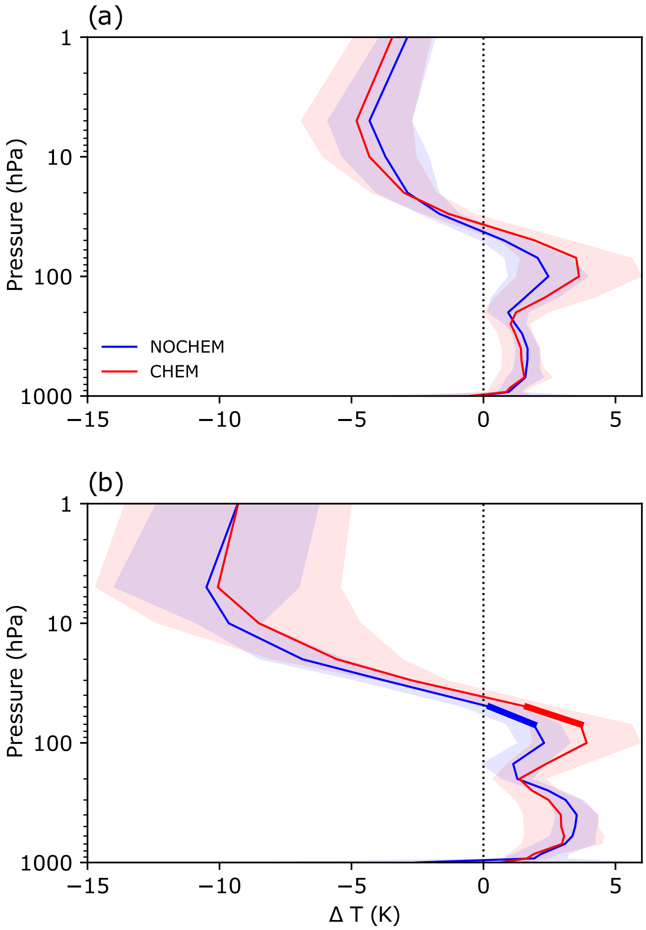

Figure 3. (a) Change in temperature (2090–2099 minus 2015–2024) during October–December at 60–90°S in CHEM models (multi-model mean $\pm 1\sigma$), and models without interactive chemistry (NOCHEM), in the SSP245 experiment. Thicker lines show regions where the difference between the CHEM and NOCHEM simulations is statistically significant at the 95% level of confidence (independent *t*-test). (b) As for (a) but for the SSP585 experiment.

The difference between ozone projections in the CHEM models and the CMIP6 ozone data set likely stems from the GHG scenarios used to produce the projections. The RCPs, which were used to produce the CMIP6 ozone data set (Checa-Garcia et al., 2018), follow different GHG concentration pathways than the SSPs, which ozone responds to in the CHEM models. In particular, SSP585 assumes much smaller CH_4 and N_2O concentrations by the end of the 21st century compared with RCP85 (Figures 1b and 1c). Consequently, the CHEM models simulate less ozone destruction via catalytic cycles involving reactive nitrogen and hydrogen oxides released from the photochemical breakdown of N_2O and CH_4 in the stratosphere (Butler et al., 2016; Revell et al., 2012), compared with simulations following RCP85.

Following the recovery of the Antarctic ozone hole through the 21st century, the lower stratosphere warms (notably during October–December [OND]) because UV-B absorption by ozone heats the stratosphere. Because lower stratospheric ozone projections differ in the CHEM models compared with the CMIP6 ozone data set, lower stratospheric temperature projections in the CHEM and NOCHEM models differ too (Figure 3). In the SSP245 experiment, the multi-model mean maximum lower stratospheric warming is 3.6 K in the CHEM models, compared with only 2.4 K in NOCHEM models (Figure 3a). In the SSP585 experiment, the lower stratosphere warms by 3.8 K in CHEM models but only 2.2 K in NOCHEM models (Figure 3b).

Changes in OND polar ozone and the resulting change in temperature and the thermal wind balance affect Southern Hemisphere surface winds in December–February (DJF; Thompson & Solomon, 2002). The lag arises due to the time it takes for the signal from the stratosphere to propagate to the surface (Son et al., 2008). The projected ozone recovery, along with GHG forcing, is expected to control the position and strength of the westerly jet in the 21st century. Projected changes in westerly winds are minimal in the SSP245 experiment in all CMIP6 models (Figures 4a and S3 in Supporting Information S1), consistent with previous studies (Bracegirdle, Krinner, et al., 2020; Goyal et al., 2021). This is because the influence of ozone recovery on winds is contradicted by increases in GHG forcing, and the amplitudes of these opposing factors almost compensate each other. With Antarctic springtime ozone concentrations projected to return to 1980 levels during the 2060s (Dhomse et al., 2018), much of the change in DJF zonal-mean westerly winds in the SSP245 experiment is projected to take place in the first half of the 21st century, whereas changes in the SSP585 experiment occur throughout the century (Bracegirdle, Krinner, et al., 2020).

In the SSP585 experiment, zonal-mean westerly wind speeds increase by 1.52 ± 0.52 m s^{-1} on average in NOCHEM models at 60°S (mean $\pm 1\sigma$), and by 0.88 ± 0.48 m s^{-1} in CHEM models. Therefore, the wind speed increase in the NOCHEM models is on average $78 \pm 52\%$ larger than in the CHEM models at 60°S, and the difference is statistically significant at the 95% level of confidence (as shown on Figure 4 by a student's *t*-test; statistical significance was also demonstrated by the Hotelling's T^2 and Mann-Whitney U tests, but these are not shown here for clarity). Because CHEM models simulate larger increases in lower stratospheric ozone and temperature through the 21st century than NOCHEM models, there is more opposition from ozone recovery to GHG forcing in CHEM models, and therefore smaller increases in westerly wind speeds are seen (Figure 4b). In terms of the westerly jet location, defined as the latitude of the maximum Southern Hemisphere zonal-mean 10 m wind speed (Bracegirdle et al., 2013; Goyal et al., 2021), in DJF the jet shifts $1.18 \pm 1.02°$ poleward in the SSP585 experiment between 2000 and 2099, and strengthens by 0.47 ± 0.43 m s^{-1} (averaged over all CMIP6 models; Goyal et al., 2021). Multi-model mean changes in the strength and the location of the westerly jet are not statistically significant between the CHEM and NOCHEM models (not shown), however these are both single-latitude

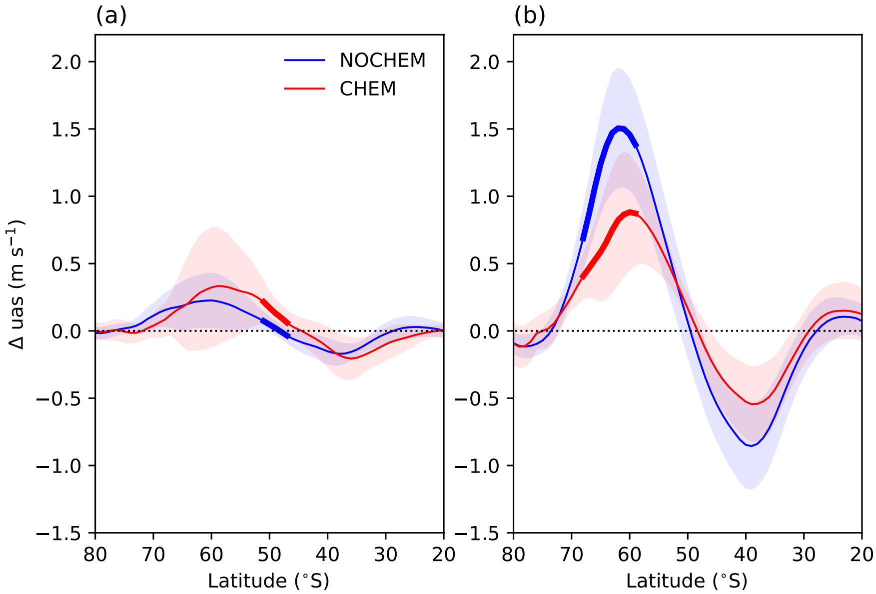

Figure 4. Change in near-surface (10 m) zonal wind speed (2090–2099 minus 2015–2024) during December–February for CHEM and NOCHEM models: multi-model mean $\pm 1\sigma$. Thicker lines show regions where the difference between the CHEM and NOCHEM simulations is statistically significant at the 95% level of confidence (independent *t*-test). (a) SSP245 experiment; (b) SSP585 experiment.

point metrics and do not convey all information regarding changes in zonal-mean Southern Hemisphere westerly winds, as shown in Figure 4.

Previously it was shown that the inclusion of interactive chemistry in the CMIP5 models made little difference to simulated historical trends in DJF near-surface westerly winds (Son et al., 2018). However, the CMIP5 models containing interactive stratospheric chemistry did not produce high-quality ozone simulations compared with models prescribing ozone (Eyring et al., 2013; Morgenstern, 2021). From analyzing CMIP6 models, our results show that prescribing a suitable ozone field is important for projections of Southern Hemisphere near-surface westerlies. Numerous other studies have shown the importance of interactive chemistry for producing accurate simulations of stratospheric ozone, dynamics, surface climate, ocean circulation, Antarctic sea ice and the Southern Annular Mode (Haase et al., 2020; Haase & Matthes, 2019; Ivanciu et al., 2021; Li et al., 2016; Morgenstern, 2021; Oehrlein et al., 2020; Rieder et al., 2019).

Despite many other studies recognizing the importance of interactive ozone chemistry, the majority (70%) of models that performed the SSP245 and SSP585 simulations for CMIP6 prescribed ozone rather than calculating it interactively. This is likely due to the high computational cost of including interactive chemistry. Our results show that for SSP245, in which GHG forcing is almost entirely counteracted by ozone recovery, relatively small wind speed changes are simulated, and differences between the CHEM and NOCHEM models are largely insignificant; likely because the differences between CO_2, N_2O and CH_4 in the SSPs and RCPs are relatively minor (Figure 1). Therefore for SSP245, the ozone forcing data set is consistent with ozone calculated by interactive chemistry models and the differences are not statistically significant (Figure 2a). For the high emissions scenario SSP585, the difference in projected ozone concentrations in the lower stratosphere (70 hPa) is statistically significant (Figure 2b), leading to statistically significant different changes in lower stratosphere temperatures (Figure 3b) and near-surface wind speeds (Figure 4b).

Over the historical period, the CMIP6 ozone data set compares relatively well to observations for the Southern Hemisphere (Morgenstern et al., 2021). This implies that even though NOCHEM models simulate surface winds accurately over the historical period with an improved jet location bias relative to CMIP5 (Bracegirdle, Holmes, et al., 2020; Goyal et al., 2021), this may just be a reflection of the good ozone forcing used in the historical period. It does not imply quality future simulations as the ozone field is inconsistent with other forcings applied in these simulations. For future CMIP efforts, the forcings used to produce precomputed ozone data sets for

NOCHEM models should be consistent with CMIP forcings, to produce an ozone data set that is as spatially and temporally consistent with the CHEM models as possible.

4. Conclusions

We have shown that CMIP6 models with interactive chemistry produce, on average, different projections of 21st century Antarctic springtime stratospheric ozone compared to the ozone forcing data set used by models without interactive chemistry. The differences exist because the precomputed ozone data set used by the NOCHEM models was based on CCM simulations performed using the RCP forcings for GHGs. In contrast, the CMIP6 models used the SSPs, and although the end-of-21st century radiative forcing is nearly the same in the RCPs and SSPs, the GHG concentrations followed to reach the specified radiative forcings are not. Because the GHGs CH_4 and N_2O are chemically reactive in the stratosphere, they influence ozone, leading to the different ozone projections between the CHEM and NOCHEM models.

As a consequence of different springtime ozone projections, Antarctic lower stratosphere temperature projections are also different in the CHEM and NOCHEM models. Differences in temperature propagate to differences in austral summertime near-surface westerly winds, with implications for many features of Southern Hemisphere climate connected to the westerly jet, such as temperature, precipitation and ocean circulation. Under the moderate GHG emissions scenario SSP245, ozone recovery and GHG forcing have contradictory influences on near-surface westerlies, the amplitudes of which lead to no significant change. Under the high emissions scenario SSP585, westerly winds strengthen through the 21st century and move poleward. However, the increase in wind speed is $78 \pm 52\%$ stronger in NOCHEM models than in CHEM models.

This study demonstrates, like many others before it, that an accurate representation of stratospheric ozone in global climate models is necessary for accurate simulations of the radiative and dynamical processes influenced by stratospheric ozone. Since it is often not feasible to perform large numbers of simulations with interactive chemistry due to computational cost, future model intercomparison projects must ensure that precomputed ozone data sets are produced as consistently as possible with recommended boundary conditions for the MIP simulations themselves, to provide ozone data that is as spatially and temporally consistent with the CHEM models as possible

Data Availability Statement

The sixth Coupled Model Intercomparison Project model data used in this study is available from https://esgf-node.llnl.gov/search/cmip6/ and via Danabasoglu (2019); Seferian (2018); Krasting et al. (2018); Yukimoto et al. (2019); Tang et al. (2019); Dix et al. (2019); Ziehn et al. (2019); Rong (2019); Swart et al. (2019); Voldoire (2018); EC-Earth-Consortium (2019); NASA/GISS (2018); Ridley et al. (2019); Boucher et al. (2018); Tatebe and Watanabe (2018); Wieners et al. (2019); Cao and Wang (2019). Representative Concentration Pathway and Shared Socioeconomic Pathway data were sourced from Meinshausen et al. (2011) and Meinshausen et al. (2020).

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References

Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D., & Chang, K.-L. (2020). A pause in Southern Hemisphere circulation trends due to the Montreal protocol. *Nature*, *579*(7800), 544–548. https://doi.org/10.1038/s41586-020-2120-4

Boucher, O., Denvil, S., Levavasseur, G., Cozic, A., Caubel, A., Foujols, M.-A., & Cheruy, F. (2018). *IPSL IPSL-CM6A-LR model output prepared for CMIP6 historical*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.5195

Bracegirdle, T. J., Holmes, C. R., Hosking, J. S., Marshall, G. J., Osman, M., Patterson, M., & Rackow, T. (2020). Improvements in circumpolar Southern Hemisphere extratropical atmospheric circulation in CMIP6 compared to CMIP5. *Earth and Space Science*, *7*(6), e2019EA001065. https://doi.org/10.1029/2019EA001065

Bracegirdle, T. J., Krinner, G., Tonelli, M., Haumann, F. A., Naughten, K. A., Rackow, T., & Wainer, I. (2020). Twenty first century changes in Antarctic and Southern Ocean surface climate in CMIP6. *Atmospheric Science Letters*, *21*(9), e984. https://doi.org/10.1002/asl.984

Bracegirdle, T. J., Shuckburgh, E., Sallee, J.-B., Wang, Z., Meijers, A. J. S., Bruneau, N., & Wilcox, L. J. (2013). Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: Historical bias, forcing response, and state dependence. *Journal of Geophysical Research: Atmospheres*, *118*(2), 547–562. https://doi.org/10.1002/jgrd.50153

Braesicke, P., Neu, J., & Fioletov, V. (2018). Update on global ozone: Past, present, and future. In *Scientific assessment of ozone depletion: 2018*, Global Ozone Research and Monitoring Project—Report No. 58, Chapter 3. World Meteorological Organization.

Butler, A. H., Daniel, J. S., Portmann, R. W., Ravishankara, A. R., Young, P. J., Fahey, D. W., & Rosenlof, K. H. (2016). Diverse policy implications for future ozone and surface UV in a changing climate. *Environmental Research Letters*, *11*(6), 064017. https://doi.org/10.1088/1748-9326/11/6/064017

Cao, J., & Wang, B. (2019). *NUIST NESMv3 model output prepared for CMIP6 historical version 20190703*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.8769

Ceppi, P., Hwang, Y.-T., Frierson, D. M. W., & Hartmann, D. L. (2012). Southern Hemisphere jet latitude biases in CMIP5 models linked to shortwave cloud forcing. *Geophysical Research Letters*, *39*(19), L19708. https://doi.org/10.1029/2012GL053115

Checa-Garcia, R. (2018). *CMIP6 ozone forcing dataset: Supporting information*. Zenodo. https://doi.org/10.5281/zenodo.1135127

Checa-Garcia, R., Hegglin, M. I., Kinnison, D., Plummer, D. A., & Shine, K. P. (2018). Historical tropospheric and stratospheric ozone radiative forcing using the CMIP6 database. *Geophysical Research Letters*, *45*(7), 3264–3273. https://doi.org/10.1002/2017gl076770

Danabasoglu, G. (2019). *NCAR CESM2-WACCM model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.10071

Dhomse, S. S., Kinnison, D., Chipperfield, M. P., Salawitch, R. J., Cionni, I., Hegglin, M. I., & Zeng, G. (2018). Estimates of ozone return dates from Chemistry-Climate Model Initiative simulations. *Atmospheric Chemistry and Physics*, *18*(11), 8409–8438. https://doi.org/10.5194/acp-18-8409-2018

Dix, M., Bi, D., Dobrohotoff, P., Fiedler, R., Harman, I., Law, R., & Yang, R. (2019). *CSIRO-ARCCSS ACCESS-CM2 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4271

EC-Earth-Consortium. (2019). *EC-Earth-Consortium EC-Earth3 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4700

Eyring, V., Arblaster, J. M., Cionni, I., Sedláček, J., Perlwitz, J., Young, P. J., et al. (2013). Long-term ozone changes and associated climate impacts in CMIP5 simulations. *Journal of Geophysical Research: Atmospheres*, *118*(10), 5029–5060. https://doi.org/10.1002/jgrd.50316

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Goyal, R., Sen Gupta, A., Jucker, M., & England, M. H. (2021). Historical and projected changes in the Southern Hemisphere surface westerlies. *Geophysical Research Letters*, *48*(4), e2020GL090849. https://doi.org/10.1029/2020GL090849

Haase, S., Fricke, J., Kruschke, T., Wahl, S., & Matthes, K. (2020). Sensitivity of the Southern Hemisphere circumpolar jet response to Antarctic ozone depletion: Prescribed versus interactive chemistry. *Atmospheric Chemistry and Physics*, *20*(22), 14043–14061. https://doi.org/10.5194/acp-20-14043-2020

Haase, S., & Matthes, K. (2019). The importance of interactive chemistry for stratosphere–troposphere coupling. *Atmospheric Chemistry and Physics*, *19*(5), 3417–3432. https://doi.org/10.5194/acp-19-3417-2019

Ivanciu, I., Matthes, K., Wahl, S., Harla, J., & Biastoch, A. (2021). Effects of prescribed CMIP6 ozone on simulating the Southern Hemisphere atmospheric circulation response to ozone depletion. *Atmospheric Chemistry and Physics*, *21*(8), 5777–5806. https://doi.org/10.5194/acp-21-5777-2021

Keeble, J., Hassler, B., Banerjee, A., Checa-Garcia, R., Chiodo, G., Davis, S., & Wu, T. (2021). Evaluating stratospheric ozone and water vapour changes in CMIP6 models from 1850 to 2100. *Atmospheric Chemistry and Physics*, *21*(6), 5015–5061. https://doi.org/10.5194/acp-21-5015-2021

Krasting, J. P., John, J. G., Blanton, C., McHugh, C., Nikonov, S., Radhakrishnan, A., & Zhao, M. (2018). *NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.8597

Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., & Heimann, M. (2007). Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science*, *316*(5832), 1735–1738. https://doi.org/10.1126/science.1136188

Li, F., Vikhliaev, Y. V., Newman, P. A., Pawson, S., Perlwitz, J., Waugh, D. W., & Douglass, A. R. (2016). Impacts of interactive stratospheric chemistry on Antarctic and Southern Ocean climate change in the Goddard Earth Observing System, version 5 (GEOS-5). *Journal of Climate*, *29*(9), 3199–3218. https://doi.org/10.1175/jcli-d-15-0572.1

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. (2020). The Shared Socio-Economic Pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L., Lamarque, J. F., et al. (2011). The RCP greenhousegas concentrations and their extensions from 1765 to 2300. *Climatic Change*, *109*(1), 213.

Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., & Weiss, R. (2017). Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geoscientific Model Development*, *10*(5), 2057–2116. https://doi.org/10.5194/gmd-10-2057-2017

Morgenstern, O. (2021). The Southern Annular Mode in 6th Coupled Model Intercomparison Project models. *Journal of Geophysical Research: Atmospheres*, *126*(5), e2020JD034161. https://doi.org/10.1029/2020JD034161

Morgenstern, O., Frith, S. M., Bodeker, G. E., Fioletov, V., & van der A, R. J. (2021). Reevaluation of total-column ozone trends and of the effective radiative forcing of ozone-depleting substances. *Geophysical Research Letters*, *48*, e2021GL095376. https://doi.org/10.1029/2021GL095376

Morgenstern, O., Hegglin, M. I., Rozanov, E., O'Connor, F. M., Abraham, N. L., Akiyoshi, H., & Zeng, G. (2017). Review of the global models used within phase 1 of the Chemistry–Climate Model Initiative (CCMI). *Geoscientific Model Development*, *10*(2), 639–671. https://doi.org/10.5194/gmd-10-639-2017

Morgenstern, O., O'Connor, F. M., Johnson, B. T., Zeng, G., Mulcahy, J. P., Williams, J., & Kinnison, D. E. (2020). Reappraisal of the climate impacts of ozone-depleting substances. *Geophysical Research Letters*, *47*(20), e2020GL088295. https://doi.org/10.1029/2020GL088295

NASA/GISS. (2018). *NASA-GISS GISS-E2.1G model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.7127

Neely, R. R., Marsh, D. R., Smith, K. L., Davis, S. M., & Polvani, L. M. (2014). Biases in Southern Hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone. *Geophysical Research Letters*, *41*(23), 8602–8610. https://doi.org/10.1002/2014GL061627

Oehrlein, J., Chiodo, G., & Polvani, L. M. (2020). The effect of interactive ozone chemistry on weak and strong stratospheric polar vortex events. *Atmospheric Chemistry and Physics*, *20*(17), 10531–10544. https://doi.org/10.5194/acp-20-10531-2020

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Revell, L. E., Bodeker, G. E., Huck, P. E., Williamson, B. E., & Rozanov, E. (2012). The sensitivity of stratospheric ozone changes through the 21st century to N_2O and CH_4. *Atmospheric Chemistry and Physics*, *12*(23), 11309–11317. https://doi.org/10.5194/acp-12-11309-2012

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., & Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M., & Andrews, T. (2019). *MOHC HadGEM3-GC31-LL model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.6109

Rieder, H. E., Chiodo, G., Fritzer, J., Wienerroither, C., & Polvani, L. M. (2019). Is interactive ozone chemistry important to represent polar cap stratospheric temperature variability in Earth-System Models? *Environmental Research Letters*, *14*(4), 044026. https://doi.org/10.1088/1748-9326/ab07ff

Rong, X. (2019). *CAMS CAMS_CSM1.0 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.9754

Seferian, R. (2018). *CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4068

Solomon, S., Ivy, D. J., Kinnison, D., Mills, M. J., Neely, R. R., & Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. *Science*, *353*(6296), 269–274. https://doi.org/10.1126/science.aae0061

Son, S.-W., Han, B.-R., Garfinkel, C. I., Kim, S.-Y., Park, R., Abraham, N. L., & Zeng, G. (2018). Tropospheric jet response to Antarctic ozone depletion: An update with Chemistry-Climate model Initiative (CCMI) models. *Environmental Research Letters*, *13*(5), 054024. https://doi.org/10.1088/1748-9326/aabf21

Son, S.-W., Polvani, L. M., Waugh, D. W., Akiyoshi, H., Garcia, R., Kinnison, D., & Shibata, K. (2008). The impact of stratospheric ozone recovery on the Southern Hemisphere westerly jet. *Science*, *320*(5882), 1486–1489. https://doi.org/10.1126/science.1155939

Son, S.-W., Tandon, N. F., Polvani, L. M., & Waugh, D. W. (2009). Ozone hole and Southern Hemisphere climate change. *Geophysical Research Letters*, *36*(15). https://doi.org/10.1029/2009GL038671

Swart, N. C., Cole, J. N., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., & Sigmond, M. (2019). *CCCma CanESM5 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.3610

Tang, Y., Rumbold, S., Ellis, R., Kelley, D., Mulcahy, J., Sellar, A., & Jones, C. (2019). *MOHC UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.6113

Tatebe, H., & Watanabe, M. (2018). *MIROC MIROC6 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.5603

Thompson, D. W. J., & Solomon, S. (2002). Interpretation of recent Southern Hemisphere climate change. *Science*, *296*(5569), 895. https://doi.org/10.1126/science.1069270

Thompson, D. W. J., Solomon, S., Kushner, P. J., England, M. H., Grise, K. M., & Karoly, D. J. (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, *4*, 741. https://doi.org/10.1038/ngeo1296

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1), 5. https://doi.org/10.1007/s10584-011-0148-z

Voldoire, A. (2018). *CMIP6 simulations of the CNRM-CERFACS based on CNRM-CM6-1 model for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4066

Wieners, K.-H., Giorgetta, M., Jungclaus, J., Reick, C., Esch, M., Bittner, M., et al. (2019). *MPI-M MPI-ESM1.2-LR model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.6595

Yukimoto, S., Koshiro, T., Kawai, H., Oshima, N., Yoshida, K., Urakawa, S., et al. (2019). *MRI MRI-ESM2.0 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.6842

Zambri, B., Solomon, S., Thompson, D. W. J., & Fu, Q. (2021). Emergence of Southern Hemisphere stratospheric circulation changes in response to ozone recovery. *Nature Geoscience*, *14*(9), 638–644. https://doi.org/10.1038/s41561-021-00803-3

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models ScenarioMIP. *Geophysical Research Letters*, *47*(1), e2019GL085782. https://doi.org/10.1029/2019GL085782

Ziehn, T., Chamberlain, M., Lenton, A., Law, R., Bodman, R., Dix, M., & Druken, K. (2019). *CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 ScenarioMIP*. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.4272