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ACCESS-CM2-Chem: evaluation of southern hemisphere ozone and its effect on the Southern Annular Mode

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ABSTRACT

Chemistry–climate models are important tools for forecasting the evolution of climate. Of particular importance is the simulation of Antarctic ozone depletion due to its effect on the Southern Annular Mode (SAM). In this paper we evaluate the chemistry–climate model ACCESS-CM2-Chem. We find the simulation of stratospheric ozone by ACCESS-CM2-Chem to be significantly improved relative to its predecessor, and as good as the best of the contemporary chemistry–climate models – the ensemble of which displays considerable variation. We also find that the trend in summertime SAM is simulated well by ACCESS-CM2-Chem compared to the ERA5 reanalysis. Further, we show that this trend is more sensitive to changes in ozone depletion forcing in ACCESS-CM2-Chem than the equivalent model with prescribed ozone. However, a downside of the interactive chemistry of ACCESS-CM2-Chem, relative to the prescribed chemistry version, is an increase in the bias towards later vortex break-ups. Many recent studies have identified the important role of feedbacks between interactive ozone chemistry and climate. This phenomenon will be crucial to understand future projections where the recovery of stratospheric ozone will interact with increasing greenhouse gas driven warming. Based on the performance demonstrated here, ACCESS-CM2-Chem is a promising model with which to further this line of research, although the delay in the vortex break-up induced by the interactive chemistry is an issue that requires further work.

Keywords: chemistry, climate, interactive, model, ozone, SAM, Southern Annular Mode, southern hemisphere.

1. Introduction

ACCESS-CM2-Chem is the latest chemistry–climate configuration released for the Australian Community Climate and Earth System Simulator (ACCESS). ACCESS-CM2-Chem is based on the atmosphere–ocean coupled model ACCESS-CM2 (Bi *et al.* 2020) extended to include tropospheric and stratospheric chemistry utilising the United Kingdom Chemistry and Aerosol (UKCA) module. ACCESS-CM2-Chem is the first interactive chemistry enabled version of the model for which model output is publicly available since ACCESS-CCM (Stone *et al.* 2016). ACCESS-CCM contributed model runs to the Chemistry–Climate Model Initiative's first intercomparison project (CCMI-1) (Eyring *et al.* 2013).

Of particular importance for simulation of southern hemisphere climate is the model's simulation of the ozone hole – the very low ozone concentration observations over the Antarctic during spring, which was caused by the release of ozone-depleting substances beginning in the mid-20th century. Stone *et al.* (2016) finds the Antarctic October mean total column ozone (TCO) simulated by ACCESS-CCM to be ~20–30 DU higher than observed. In general, the quality of the simulation of Antarctic ozone depletion by chemistry models of that generation is mixed; looking at the complete set of the CCMI-1 generation of models, Dhomse *et al.* (2018) finds the ±1 standard deviation range from the ensemble mean October TCO to be ~100 DU during the period of peak ozone depletion. In this paper, we assess improvements in the simulation of ozone by

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ACCESS-CM2-Chem compared to ACCESS-CCM. The ACCESS-CM2-Chem runs have also been submitted to the latest Chemistry–Climate Model Initiative (CCMI) activity, CCMI2022 (Plummer *et al.* 2021), to facilitate the assessment of the current generation of chemistry–climate models (CCMs) more broadly.

The primary dynamical effect of ozone depletion can be seen in the Southern Annular Mode (SAM), the dominant mode of variability in the southern extra-tropics. Dynamical anomalies, caused by the radiative cooling resulting from the spring ozone depletion in the stratosphere, propagate downward (e.g. Thompson *et al.* 2005) and drive a trend toward the positive polarity of summer SAM, which represents a strengthening and poleward shift of the tropospheric jet. The southern hemisphere storm track shifts southward with the tropospheric jet and thus changes in ozone can be shown to have a clear influence on temperature and precipitation in many southern mid- and high-latitude regions (Previdi and Polvani 2014 and references therein). Ozone depletion has also been shown to influence sea surface temperature (SST) and sea ice extent (SIE), although the effect is more complicated. Ferreira *et al.* (2015) propose a mechanism with offsetting effects operating on different timescales: on interannual timescales the SAM-driven enhancement of the Ekman drift drives cooler SST and greater SIE, whereas on longer timescales it causes increased upwelling of warm water which offsets the faster response and eventually dominates, resulting in overall warmer SSTs and lesser SIE. The recovery of the ozone layer over the 21st century is expected to exert the opposite influence on the SAM, although it is possible this may be offset by increasing greenhouse gas (GHG) forcing which will drive a positive trend in the SAM (Thompson *et al.* 2011).

The accurate simulation of ozone is important to more accurately model the direct effect on climate, but of course such effects are also plausibly captured by climate models with a prescribed ozone field rather than interactive chemistry. However, recent studies found that modelling the chemistry interactively enables the model to capture more subtle effects on the atmospheric dynamics. Studies comparing individual models with and without chemistry find that the polar night jet, in both the southern and northern hemisphere is stronger when interactive chemistry is included (Li *et al.* 2016; Haase and Matthes 2019; Haase *et al.* 2020; Oehrlein *et al.* 2020; Ivanciu *et al.* 2021). Li *et al.* (2016) find interactive chemistry to result in stronger dynamical coupling between the stratosphere and troposphere and an enhancement of the effect on SST and SIE identified by Ferreira *et al.* (2015). Haase and Matthes (2019) identify a feedback mechanism mediated by the background strength of the vortex – low polar stratospheric ozone and hence temperature strengthens the vortex – depending on the background strength of the vortex this may negate or promote planetary wave propagation (Charney and Drazin 1961), making the vortex more or less stable respectively. A less stable vortex allows more mixing of ozone-rich air from outside of the vortex (i.e. a negative feedback) and a more stable vortex allows less of this mixing (a positive feedback). Haase *et al.* (2020) demonstrate this for the southern hemisphere by showing a negative correlation between polar cap ozone at 50 hPa and the dynamical heating rate lagged by 15 days throughout the stratosphere during summer (i.e. as the vortex breaks up) which is much stronger in a simulation with interactive chemistry. Conversely, there is a small positive correlation in the lower stratosphere during spring (i.e. when the vortex is strong) in the model with interactive chemistry, which is absent in the model without chemistry. Morgenstern (2021) examines the effect of interactive chemistry on trends in the SAM and finds that GHG-driven strengthening of SAM is likely to be offset to a large degree by the effect of ozone increases resulting from the GHG warming. Therefore, models without interactive chemistry will tend to predict a more positive summer SAM trend over the 21st century. The effect of interactive chemistry is also important on a global scale; for example, Nowack *et al.* (2018) find that switching the interactive chemistry off in the stratosphere results in larger climate sensitivity due to a feedback between stratospheric water vapour and ozone.

It is important for CCMs to accurately simulate ozone depletion both because of the important role it plays in projections of southern hemisphere climate and because minimising the baseline bias in ozone gives greater confidence when investigating the subtle effects of interactive chemistry on the climate. In this paper we evaluate the ACCESS-CM2-Chem simulation of stratospheric ozone against an observational dataset and compare simulated stratospheric ozone to the predecessor ACCESS-CCM model and an ensemble of CMIP6 models that have interactive chemistry. We also evaluate the simulation of the SAM in ACCESS-CM2-Chem and compare this to ACCESS-CM2 without interactive chemistry.

2. Model description

ACCESS-CM2-Chem is an extension of ACCESS-CM2, a detailed description of which is provided in Bi *et al.* (2020). ACCESS-CM2 combines the United Kingdom Met Office (UKMO) Unified Model (UM) atmospheric model (ver. 10.6), in the GA7.1 configuration (Walters *et al.* 2019), at N96 (1.875° × 1.25°) and 85 vertical level resolution; the Community Atmosphere Biosphere Land Exchange (CABLE2.5) land surface model (Haverd *et al.* 2018); the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (ver. 5, MOM5) at 1° resolution (Griffies 2012); the Los Alamos National Laboratory (LANL) CICE5.1 sea ice model (Hunke *et al.* 2015); and the OASIS-MCT coupler (Craig *et al.* 2017). In ACCESS-CM2,

UKCA is run with an offline oxidants configuration to enable aerosol precursor chemistry, whereas ACCESS-CM2-Chem utilises a full stratosphere–troposphere (StratTrop) chemistry configuration. The details of the StratTrop configuration are similar to those detailed in Archibald *et al.* (2020) with the following additions: the stratospheric heterogeneous chemistry has been updated and extended to include bromine reactions as detailed in Dennison *et al.* (2019); and the dry deposition of ozone has been modified following Luhar *et al.* (2017, 2018).

Although ACCESS-CM2 has the capability of running with coupled ocean and sea ice components, the results presented in this paper are produced using prescribed SSTs and sea ice concentrations (SICs).

3. Datasets and methods

3.1. Models

We use three historical runs of ACCESS-CM2-Chem spanning 1960–2018. These are produced following the specifications of the CCMI2022 'Ref-D1' experiment (Plummer *et al.* 2021), which uses GHG forcing following the CMIP6 historical database up to 2014 (Meinshausen *et al.* 2017) and the SSP2-4.5 scenario (Meinshausen *et al.* 2020) for the remaining years. Concentrations of ozone-depleting substances follow the World Meteorological Organization's (WMO) 2018 baseline scenario (Carpenter *et al.* 2018), and are specified at surface level.

We additionally use data from the ACCESS-CCM (Stone *et al.* 2016) and the set of models participating in the 'AerChemMIP' activity of the sixth Coupled Model Intercomparison Project (CMIP6) as comparison points for the performance of ozone depletion in the model.

ACCESS-CCM is the previous iteration of ACCESS with interactive chemistry from which data have been released (Stone *et al.* 2016). ACCESS-CCM combined UM at version 7.3 and the United Kingdom Meteorological Office's Surface Exchange Scheme-II (MOSES-II) land model and used prescribed SSTs and SICs. It was run at lower horizontal (N48) and vertical (60 level) resolution than ACCESS-CM2-Chem. The runs from this model were produced as part of the CCMI-1.

AerChemMIP is the subproject of CMIP6 focused on chemistry and aerosols (Collins *et al.* 2017), and represents the state of the art in CCMs. We use one run of the historical experiment from each of six models (Table 1) for which data were available.

To assess the impact of chemistry on atmospheric dynamics we compare ACCESS-CM2-Chem to an ensemble of five atmosphere-only (i.e. the 'AMIP' experiment) runs of ACCESS-CM2 that have been submitted to CMIP6 (Bodman *et al.* 2020). The ACCESS-CM2 runs span the period 1979–2014.

Table 1. CMIP6 models.

Model	References
CESM2-WACCM	Danabasoglu (2019), Gettelman *et al.* (2019)
CNRM-ESM2-1	Séférian (2018, 2019)
GFDL-ESM4	Krasting *et al.* (2018), Dunne *et al.* (2020)
GISS-E2-1-G	NASA Goddard Institute for Space Studies (2018), Kelley *et al.* (2020)
IPSL-CM5A2-INCA	Boucher *et al.* (2020), Sepulchre *et al.* (2020)
MRI-ESM2-0	Yukimoto *et al.* (2019*a*, 2019*b*)
UKESM1-0-LL	Tang *et al.* (2019), Sellar *et al.* (2019)

3.2. Observations and reanalysis

For evaluations of TCO, we use the Bodeker Scientific filled (BS-filled) dataset version 5.3.1. This dataset combines various satellite measurements, uses ground based measurements to bias correct and algorithmically fills in regions not observed by the satellites (Bodeker *et al.* 2021).

For evaluations of the vertical profile of ozone, we use OzoneSondes launched from four stations covering the southern mid- and high-latitudes: South Pole (90°S, 169°E) (National Oceanic and Atmospheric Administration Earth System Research Laboratories 2021), Davis (68.5°S, 79°E), Macquarie Island (54.6°S, 158.9°E) and Melbourne (Broadmeadows, 37.5°S, 145°E) (Australian Antarctic Division and Australian Bureau of Meteorology 2021).

For analysis of the atmospheric dynamics we use ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach *et al.* 2020). The SAM is used to evaluate the large-scale dynamics. Here we calculate the SAM as the first empirical orthogonal function (EOF) of the monthly zonal mean geopotential height south of 20°S at a given pressure level. The SAM index is the principal component associated with the first EOF, normalised to have zero mean and unit standard deviation (Thompson and Wallace 2000).

4. Results

4.1. Ozone

Fig. 1 shows the 1996–2018 mean annual cycle of TCO for the ACCESS-CM2-Chem ensemble compared to BS-filled. Generally, the model simulates TCO well at northern mid- and high-latitudes and simulates too much ozone in the equatorial and southern mid-latitude regions. At high southern latitudes there is an overabundance of ozone during the austral winter. A notable problem in ACCESS-CCM was the very gradual depletion of Antarctic ozone over July–October culminating in ozone minima much higher than observed (as shown in Stone *et al.* 2016). By contrast, ACCESS-CM2-Chem shows rapid ozone depletion in August–September, in good

agreement with BS-filled. The ozone minimum is now slightly lower than that of the BS-filled dataset. A persistent problem with the simulation of ozone is the depleted Antarctic ozone lasting too long into summer, which is a common problem of CCMs (Hurwitz *et al.* 2010; McLandress *et al.* 2012).

We now assess the performance of ACCESS-CM2-Chem relative to other models during the springtime Antarctic ozone depletion peak. Fig. 2 shows the September–October polar cap (60–90°S) mean TCO for each ACCESS-CM2-Chem run compared to ACCESS-CCM, the CMIP6 ensemble and BS-filled dataset. ACCESS-CM2-Chem simulates the rapid decline of polar ozone well throughout the 1980s and 1990s. This is an improvement over the ACCESS-CCM model which has a high ozone bias of 20–30 DU for the portion of the run that can be compared to the BS-filled dataset. Several of the CMIP6 ensemble simulate ozone

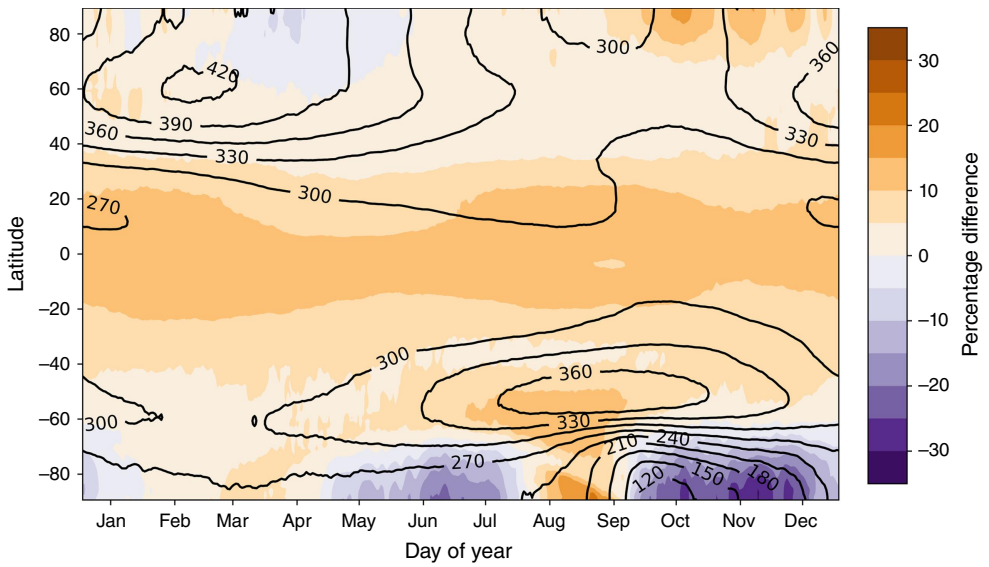

Fig. 1. Total column ozone 1996–2018 mean annual cycle. ACCESS-CM2-Chem ensemble mean is shown with contours and the anomaly relative to the BS-filled ozone dataset shown with shading.

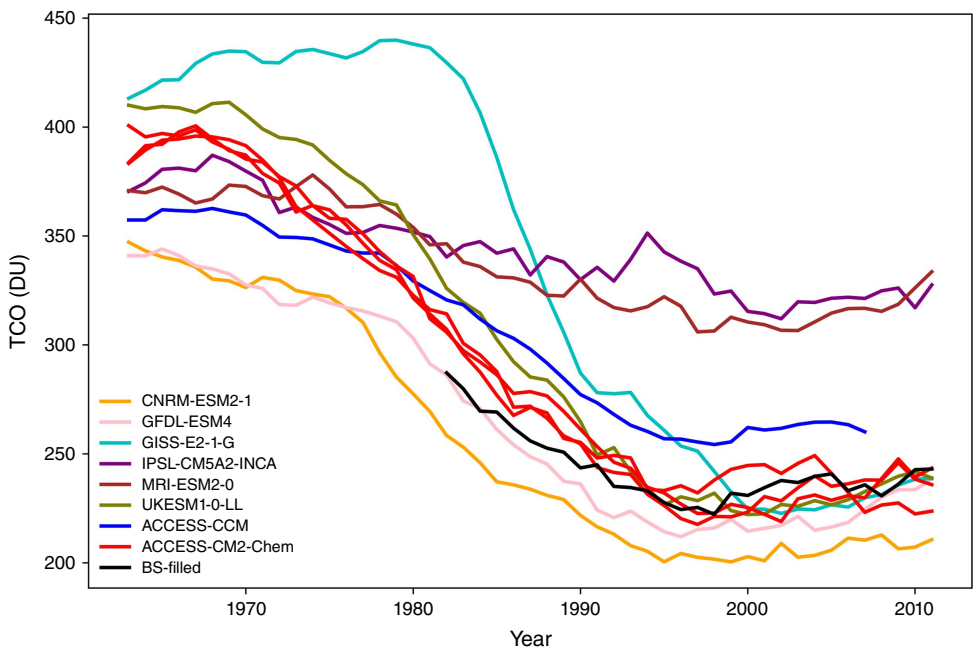

Fig. 2. Polar cap (60–90°S) September–October mean total column ozone (TCO) for the CMIP6, ACCESS-CM2-Chem and ACCESS-CCM model runs and BS-filled ozone dataset, smoothed with a 7-year moving mean.

depletion as competently as ACCESS-CM2-Chem, although MRI-ESM2.0 and IPSL-CM5A2-INCA severely underestimate the amount of ozone depletion, whereas GISS-E2.1 G over-estimates the amount of ozone pre-1990. Although most of the models do a reasonable job of simulating ozone in the later half of the runs, there is a large spread in the pre ozone-hole period. For example, GFDL-ESM4, which simulates polar ozone as well as ACCESS-CM2-Chem compared to the BS-filled dataset, starts from a point ~50 DU lower. The lack of satellite-based observation prior to 1979 make it difficult to assess the models in this period.

Fig. 3 shows the vertical profile of ozone in the ACCESS-CM2-Chem and ACCESS-CCM models compared to OzoneSonde measurements at four southern hemisphere stations: South Pole, Davis, Macquarie Island and Melbourne (Broadmeadows). At Davis, the ozone peak is over-estimated in late winter; the onset of ozone depletion is well simulated with both the mean and standard deviation matching the observations; throughout the remainder of the year the over-estimation of ozone depletion is located at the lowest levels of the stratosphere. At Macquarie Island, the ozone peak is over-estimated by the model for all

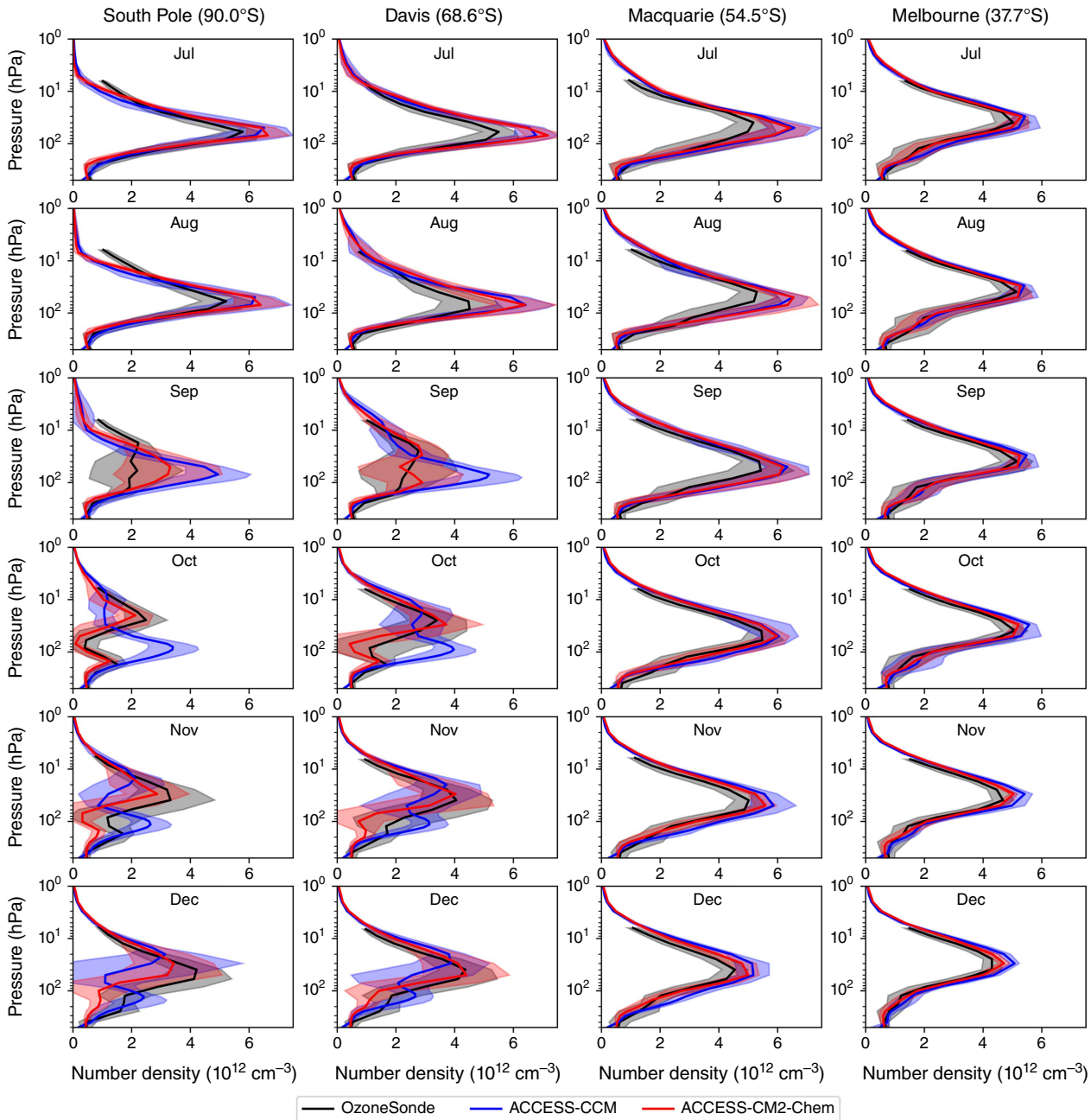

Fig. 3. Ozone profiles from ACCESS-CM2-Chem compared to OzoneSonde measurements at four stations.

months, with the largest discrepancies occurring in July and August. At Melbourne, the model matches the observation well for all months. Comparison with the ACCESS-CCM run shows a vast improvement in simulating the height at which ozone depletion occurs; at the South Pole and Davis stations the most pronounced ozone depletion occurs at a pressure level ~10–40 hPa compared to 30–100 hPa for ACCESS-CM2-Chem and the observations. This improvement is likely due to the introduction of the bromine chemistry described in Dennison *et al.* (2019), in particular the $BrONO_2$ + HCl bromine activation reaction that occurs readily on sulfate aerosols which are abundant in the lower stratosphere. Another potential factor is that the resolution of ACCESS-CM2-Chem is higher than ACCESS-CCM. Stock *et al.* (2014) examined the effect of horizontal resolution on tropospheric ozone and found little impact at global scale; the horizontal resolution is likely even less important in the stratosphere where smaller scale dynamics are less salient. However, the improved vertical resolution may play more of a role. Austin *et al.* (1997) demonstrated the importance of vertical resolution in very early coupled models, finding a much-improved ozone simulation at 49 compared to 19 levels.

4.2. Southern Annular Mode

We now shift focus to evaluation of the SAM, an important feature of southern hemisphere atmospheric dynamics. Fig. 4 shows the SAM index in the stratosphere and troposphere (50 and 500 hPa respectively) for the ACCESS-CM2-Chem ensemble compared to the ACCESS-CM2 ensemble

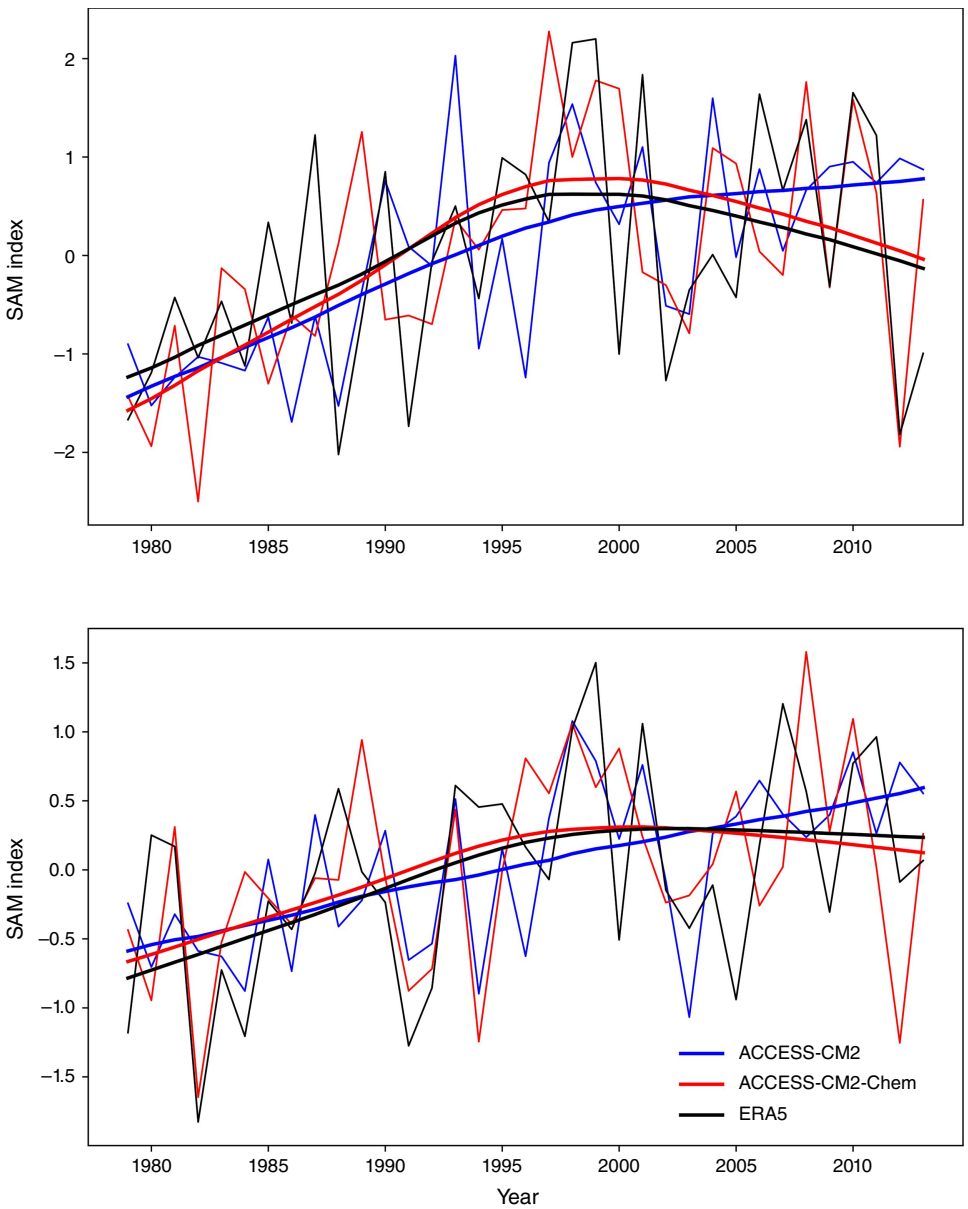

Fig. 4. SAM index for NDJ at 50 hPa (top) and DJF at 500 hPa (bottom) for ACCESS-CM2 ensemble (blue), ACCESS-CM2-Chem ensemble (red) and ERA5 reanalysis (black). The thick lines show the multiple linear regression fit using EESC and CO_2eq.

and the ERA5 reanalysis. We examine the tropospheric SAM in the austral summer (DJF), as it is known to be influenced by changes in ozone during this period (Fogt *et al.* 2009), along with the stratospheric SAM at a 1-month lead (NDJ) as SAM anomalies are known to propagate from the stratosphere to the troposphere on this timescale (Thompson *et al.* 2005). In the stratosphere, the influence of ozone is quite apparent in the change in trend *c*. 2000, coinciding with the slowdown in ozone depletion. This effect is much stronger in ACCESS-CM2-Chem and somewhat stronger than what is observed in the reanalysis. The same characteristics can be seen in the tropospheric SAM although the effect is more muted.

In the troposphere, ACCESS-CM2-Chem matches the reanalysis quite well; the trend in SAM index over the ozone depletion period (1979–2000) for ACCESS-CM2-Chem (0.062 ± 0.044) does not differ significantly from the ERA5 trend (0.063 ± 0.050), whereas the trend is too small for ACCESS-CM2 (0.046 ± 0.034). Modelling studies have shown that the positive SAM trend in summer is driven by both ozone depletion and increased GHG forcing, whereas ozone recovery is projected to drive a negative trend, competing against the continued positive trend forced by increasing GHGs (Thompson *et al.* 2011). Considering this, we analyse the trends further by applying a multiple linear regression to each SAM index record using normalised equivalent effective stratospheric chlorine (EESC) and equivalent carbon dioxide (CO_2eq) as explanatory variables. We use EESC rather than ozone here as it represents just the chemistry-based influence, whereas using ozone would capture both chemical and dynamical changes in the atmosphere, and therefore potentially have some correlation with CO_2eq. The multiple linear regression function is described in Eqn 1, where b_{ODS} and b_{GHG} are the regression coefficients associated with EESC and CO_2eq respectively, and ε is the residual.

$$\mathrm{SAM} = b_{\mathrm{ODS}}\,\mathrm{EESC} + b_{\mathrm{GHG}}\,\mathrm{CO_2eq} + \varepsilon \qquad (1)$$

The EESC is calculated using concentrations from the WMO 2018 A1 scenario (Carpenter *et al.* 2018) following the procedure of Newman *et al.* (2007) with an age of air of 5.5 years, as is appropriate for the high latitudes. The CO_2eq is calculated with concentrations from the CMIP6 historical scenario (Meinshausen *et al.* 2017) and 100 year global warming potentials (GWP100) from the WMO 5th Assessment Report (Myhre *et al.* 2013). The EESC and CO_2eq are normalised such that they have zero in 1979 and a range of one over the 1979–2014 period. The regressions are illustrated by thick lines in Fig. 4 and the regression coefficients are listed in Table 2. The multiple linear regression shows that the summertime SAM is more sensitive to ozone in ACCESS-CM2-Chem than the version without chemistry, with a notable change in the trend associated with ozone recovery. This is most clear in the stratosphere where the regression coefficient associated with ozone depletion is significant ($P > 0.05$) for both ACCESS-CM2-Chem and ERA5. The ACCESS-CM2-Chem ($b_{ODS} = 2.94$) matches ERA5 (2.44) well, whereas in ACCESS-CM2 the influence is somewhat weaker (1.35), although the broad confidence interval on these coefficients means one cannot definitively say ACCESS-CM2-Chem simulates this ozone-driven effect better than ACCESS-CM2 in this respect. The explained variance of the linear regression (r^2) for both ACCESS-CM2 and ACCESS-CM2-Chem models (0.40 and 0.50 respectively) is higher than that of ERA5 (0.22) suggesting an underestimation of the SAM variability by the models. In the troposphere, the apparent influence of ozone depletion is much smaller, and ACCESS-CM2-Chem and ERA5 show similar small changes in trend, whereas ACCESS-CM2 displays no discernible change in trend. As such, no statistically robust conclusions can be drawn given the amount of variability and the limited run length. However, this effect on dynamics from the changes in ozone depletion was well established by other studies (Banerjee *et al.* 2020, Zambri *et al.* 2021), so it is encouraging that ACCESS-CM2-Chem at least shows some sign of this effect.

Fig. 5 shows the climatology of the standard deviation in the SAM index over the period 1979–2014. At 50 hPa, the seasonal cycle peaks *c*. October–November, which reflects the break-up of the polar vortex. This peak occurs later for ACCESS-CM2, and to an even greater degree for ACCESS-CM2-Chem. For the majority of the year, the variance in ACCESS-CM2-Chem is lower than ACCESS-CM2 but is larger in summer due to this delayed peak. The difference in variance between the two models is significant only in January

Table 2. SAM regression coefficients (*b*) with 95% confidence intervals as well as the coefficient of determination (r^2) for the regression.

Pressure level	Model	b_{ODS}	Conf. int.	b_{GHG}	Conf. int.	r^2
50 hPa (NDJ)	ACCESS-CM2-Chem	2.94	[1.15, 4.73]	−1.02	[−3.00, 0.97]	0.40
	ACCESS-CM2	1.35	[−0.12, 2.82]	1.05	[−0.58, 2.67]	0.50
	ERA5	2.44	[0.97, 3.78]	−1.01	[−3.39, 1.37]	0.22
500 hPa (DJF)	ACCESS-CM2-Chem	1.04	[−0.27, 2.36]	−0.12	[−1.57, 1.33]	0.19
	ACCESS-CM2	0.19	[−0.77, 1.15]	1.02	[−0.04, 2.08]	0.36
	ERA5	0.98	[−0.39, 2.35]	0.17	[−1.35, 1.69]	0.22

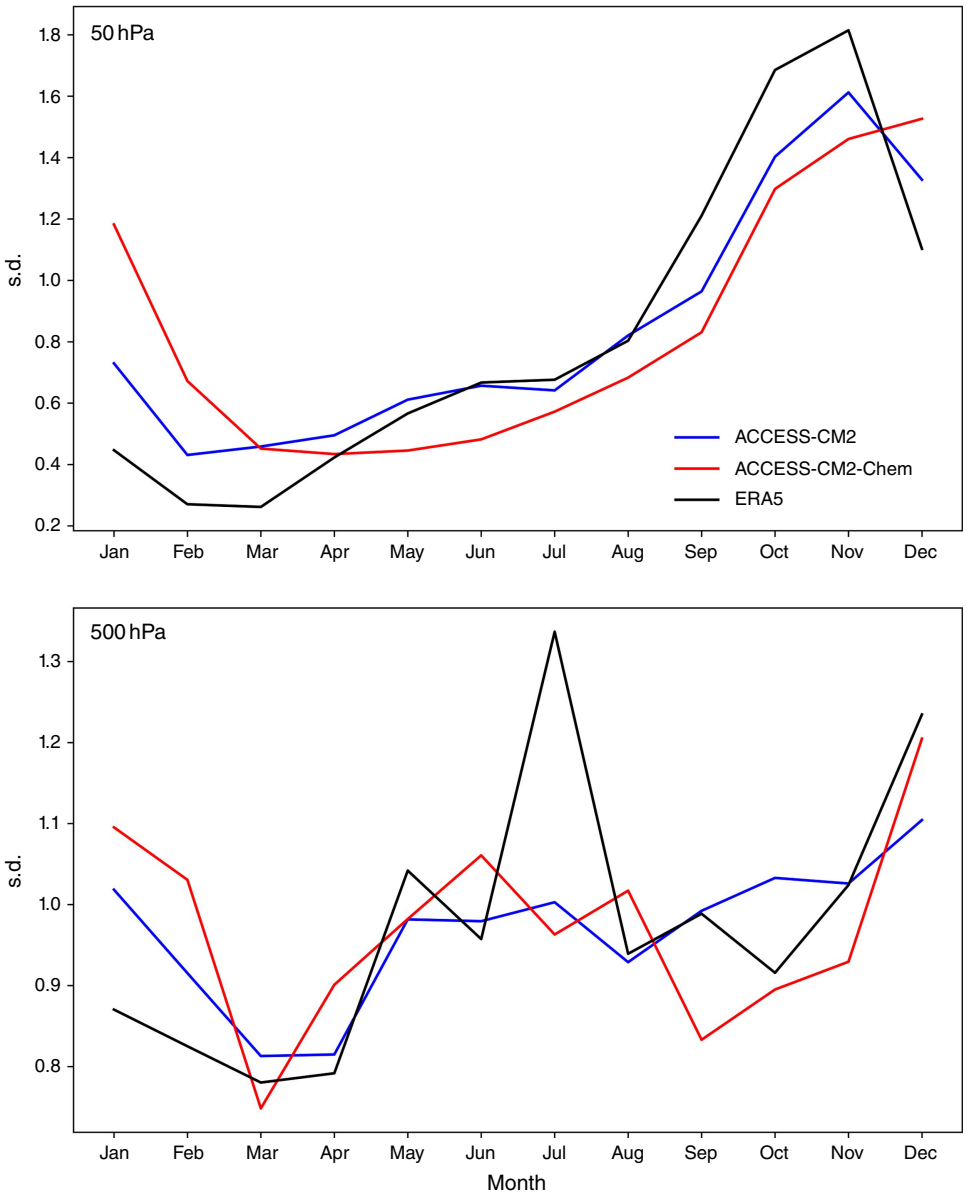

Fig. 5. Standard deviation of SAM index over the period 1979–2014 at 50 (top) and 500 hPa (bottom) for ACCESS-CM2 ensemble (blue), ACCESS-CM2-Chem ensemble (red) and ERA5 reanalysis (black).

and February according to Levene's test (Levene 1960). We examine this difference further in the next section, which focuses on the vortex break-up. At 500 hPa, the ERA5 reanalysis shows a clear annual cycle with increased variance in the austral winter, possibly due to increased baroclinic activity, and a summer peak due to the downward propagation of stratospheric anomalies (Thompson *et al.* 2005). Both versions of the model generally simulate this annual cycle although they do not capture the large July peak in ERA5. The elevated summer variance lasts too long into summer due to the model's overly persistent polar vortex. Using Levene's test (Levene 1960) shows no significant ($P < 0.05$) difference in variance between the model ensembles in any month.

4.3. Vortex break-up

We examine the difference between ACCESS-CM2 and ACCESS-CM2-Chem further by looking specifically at the polar vortex. Fig. 6 shows seasonal evolution of the polar vortex as represented by the zonal mean zonal wind at 60°S and 10 hPa averaged over the years 1979–2014. The models both overestimate the peak strength of the vortex, but there is no difference between the models in this regard. The tendencies of the models begin to diverge in November and ultimately differ in mean break-up date (defined as the date at which the wind turns easterly; Hurwitz *et al.* 2010) by 10 days. Fig. 7 shows the break-up dates over the length of the model runs. As was the case of the SAM, the change in the break-up date in the ACCESS-CM2-Chem

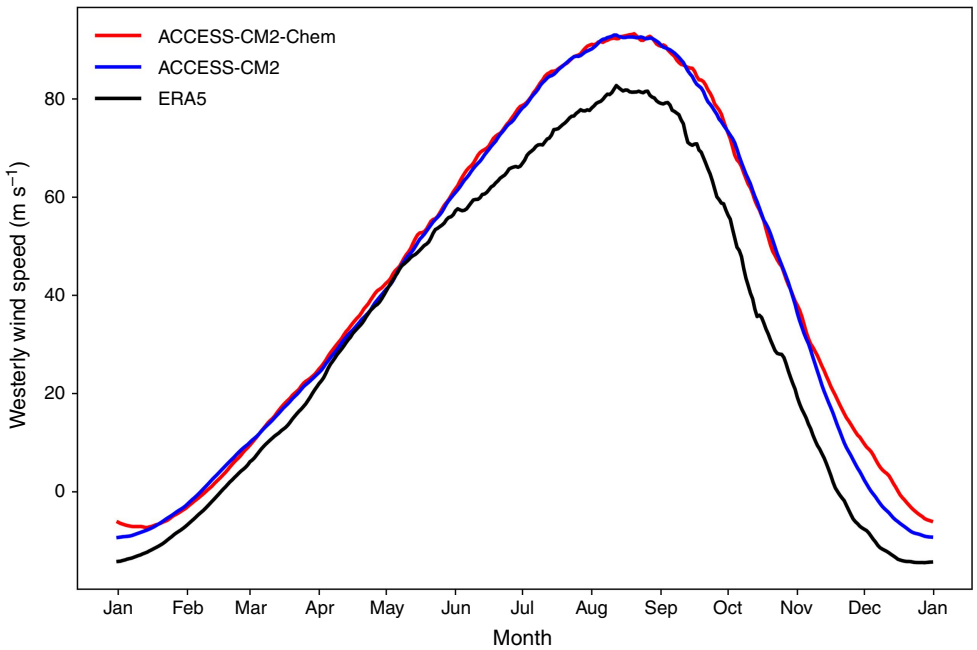

Fig. 6. Seasonal cycle of the polar vortex as measured by the zonal mean zonal wind at 60°S and 10 hPa over the period 1979–2014 for the ACCESS-CM2 ensemble (blue), ACCESS-CM2-Chem ensemble (red) and ERA5 reanalysis (black).

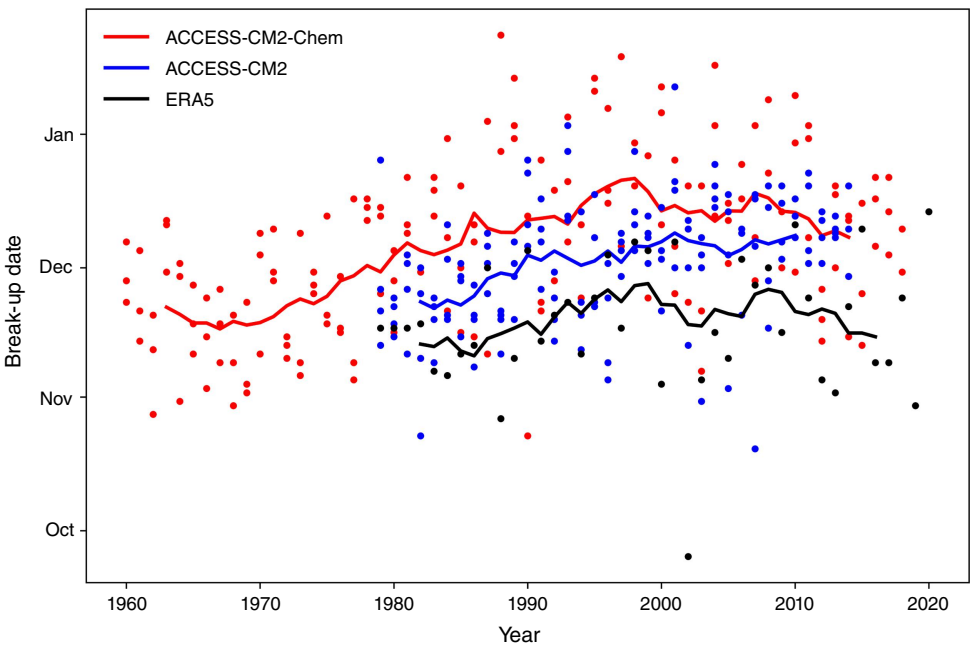

Fig. 7. Vortex break-up date as measured by the date at which the zonal wind at 60°S and 10 hPa turns easterly for the ACCESS-CM2 ensemble (blue), ACCESS-CM2-Chem ensemble (red) and ERA5 reanalysis (black). Lines show the 7-year running mean, in the case of ERA5 this excludes the 2002 outlier.

model shows the distinctive change in trend *c*. 2000 characteristic of the influence of changes in ozone. However, it is not clear whether the same is true for either ACCESS-CM2 or ERA5 given the more limited run lengths.

5. Summary and discussion

In this paper, we introduced and described the ACCESS-CM2-Chem model. The ability of ACCESS-CM2-Chem to

simulate stratospheric ozone and the associated effects on atmospheric dynamics has been evaluated and placed into context with other models of similar capabilities.

ACCESS-CM2-Chem gives a much-improved simulation of ozone relative to its predecessor ACCESS-CCM. The depth of polar ozone depletion during September and October closely matches that of the BS-filled dataset, removing almost entirely the 20–30 DU bias present in ACCESS-CCM. This bias is in large part due to the lack of bromine activation on sulfate aerosols (Dennison *et al.* 2019) as evidenced by the large increase in ozone depletion in the lower stratosphere (where sulfate aerosols are abundant) at the South Pole and Davis stations. ACCESS-CM2-Chem also performs well relative to the CMIP6 ensemble, which is hampered by some outlier models.

Given the wide spread in ozone simulation that is typical of CCMs, estimating ozone return dates is not a trivial exercise. Dhomse *et al.* (2018), undertaking this task using the CCMI-1 set of models, dealt with this in two ways: first, by bias correcting each model relative to observations for the 1980–1984 period; and second, by calculating – in addition to the multi-model mean (MMM), 'MMM1S' – a multi-model mean excluding points outside of ±1 standard deviations from the MMM. They found that the MMM1S return date to the 1980 baseline for the South Pole region (2060) to be similar to that of the MMM (2062) due to there being an approximately equal amount of positive and negative outliers; however, the ±1 standard deviation range narrowed appreciably (2055–2066 and 2051–2082 respectively). In general, the improvement in ACCESS-CM2-Chem over its CCMI-1 predecessor ACCESS-CCM should be beneficial for a similar exercise using the CCMI-2022 set of models. However, assuming the bias is constant over the model run is perhaps too crude given that any ozone bias may well be a function of temperature and ODS concentrations. For example, Fig. 2 shows that the two iterations of the ACCESS model happen to have a similar amount of ozone *c*. 1980, but the changes to the chemistry scheme that have resulted in much larger ozone depletion are likely to have changed the nature of the ozone bias inherent to each model, which would mean that the bias would manifest differently in 2060 conditions than 1980 conditions and thus introduce uncertainty into the estimation of the return date. The cause of the large variation in ozone simulated by different models likely requires more examination which should lead to greater confidence in estimated ozone return dates.

The improved simulation of ozone paves the way for improved simulation of atmospheric dynamics, and their evolution over time. The key feature of ozone depletion on climate is the trend toward a positive SAM in the austral summer. This trend is captured by versions of the model with and without chemistry; however, ACCESS-CM2-Chem responds more strongly to changes in ozone, showing the expected abatement of this trend as ozone begins to recover. Given the limited timespan of the model runs, the regressions on EESC and CO_2eq presented here are not particularly strong, but this result aligns with other recent work demonstrating feedbacks between interactive ozone chemistry and atmospheric dynamics. For example, Revell *et al.* (2022) finds that in CMIP6 models with interactive chemistry the increase in the strength of the mid-latitude jet (i.e. an expression of a positive SAM index) over the 21st century is less than in models without interactive chemistry. This, and other recent studies (e.g. Nowack *et al.* 2018; Haase *et al.* 2020; Morgenstern 2021) identifying ozone feedbacks, demonstrate the importance of modelling interactive ozone for climate projections. One downside of the ACCESS-CM2-Chem, relative to the version without interactive chemistry, is the exacerbation of the delay in vortex break-up. Morgenstern *et al.* (2022) finds a related problem, namely the overly long persistence of cold polar stratospheric temperatures, in many CCMI-2022 models relative to their non-interactive chemistry counterpart. Noting the exceptions to this finding that occur in model pairings where there are also some additional non-chemistry differences (e.g. more model levels, a different gravity wave scheme), they propose that re-tuning the model after the introduction of interactive chemistry (as opposed to simply adding on interactive chemistry to a model that has been tuned in its absence), could be a solution to this problem. This is an area where more research would be useful.

Because the SAM is such an important driver of regional climate, e.g. explaining up to 15% of the variation in rainfall in western Tasmania and on the south-eastern coast (Hendon *et al.* 2007), it may also be useful to analyse the impact of interactive chemistry on projections of regional climate. Similarly, it may also be beneficial to further study the impact of interactive chemistry on seasonal forecasts given established benefits of including prescribed ozone (e.g. Son *et al.* 2013). In particular, during the stratospheric sudden warmings of 2002 (Hendon *et al.* 2020) and 2019 (Jucker and Goyal 2022), the only two events of this kind observed in the southern hemisphere, ozone appears to have played a key role. We believe ACCESS-CM2-Chem is a promising model to further these areas of research due to its good simulation of southern hemisphere ozone depletion and the ozone depletion's influence on the SAM, as demonstrated in this paper. However, the delay in vortex break-up remains an important issue to address in this and other CCMs. ACCESS-CM2-Chem is available to anyone in the Australian community.

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Data availability. The ACCESS-CM2-Chem model runs can be found on the Centre for Environmental Data Analysis (CEDA) archive https://archive.ceda.ac.uk/.

Conflicts of interest. The authors declare that they have no conflicts of interest.

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