This study examines recent observed trends in near-surface winds over the Southern Ocean using multiple reanalysis products and an observational SAM index. Historical and future forcing runs with UKESM1 are used to attribute the recent trends using scenarios with/without ozone depletion and with two levels of greenhouse gas emissions. Consistent with prior studies, ozone depletion and recovery strongly affect the wind trends prior to 2050, with subsequent trends being dominated by increasing greenhouse gases.

This is a sound scientific study, but at the same time, isn't terribly novel. Apart from examination of observed trends in the newest reanalysis data sets, the relative importance of ozone and greenhouse gas forcings in circulation trends over the 1950-2100 trend has already been well established by previous studies. As the other reviewer notes in detail, this study lacks good contextualization of its results within the previous literature on the subject. Another weakness of the study is that only one model is examined (UKESM1). Given that there are known biases in how this model captures observed ozone depletion (as the authors discuss), I think the study would benefit from the inclusion of results from CMIP6 DAMIP experiments to put the UKESM1 results in better context. For this reason, I'm suggesting major revisions.

Major comment:

2.1 Given that the interactive ozone chemistry in UKESM1 may lead to too strong ozone depletion and exaggerated circulation trends, I think these results should be placed in the context of other simulations. As the authors acknowledge, the CMIP6 DAMIP hist-stratO3 simulations are also problematic in how they prescribe ozone, but I think it would be useful to contrast the trends simulated in UKESM1 with those from prescribed ozone simulations. While neither set-up may be correct, it would give readers a sense of the spread of possible circulation trends due to ozone. Unfortunately, many authors unfamiliar with the ozone problem just assume that the DAMIP simulations accurately capture ozone-induced circulation trends. My personal opinion is that the circulation trends in the hist-stratO3 simulations are way too weak, so the authors' simulations from UKESM1 may be a nice way to illustrate this.

We have included a new section where we compare UKESM1 to other CMIP6 models that use interactive chemistry and have the required data available on the ESGF (please see below). This nicely places UKESM1 in the context of similar models. It does show that the UKESM1 TCO trend over 1980 to ~1995 is stronger than observed. We have added some sentences to point this out and also point out that the accurately simulated trends in wind speed are associated with too strong ozone loss in UKESM1.

With respect to comparing our results to DAMIP simulations, given the different set up of our experiments and DAMIP, we prefer to only compare to other interactive chemistry models for full historical runs. In motivating our experimental design (sec 2.6) we discuss some earlier studies looking at DAMIP runs with respect to stratospheric ozone and (partly) use these findings as a motivation for using UKESM1 with interactive treatment of ozone in our study.

Proposed new text:
This text is comprised of a short methods section and section 3.3, which shows the results of the intercomparison. We also include some new figures.

2.5 CMIP6 model intercomparison

To contextualize UKESM1 results, we report trends in the winds and the SAM index, as well as in total column ozone (TCO), for other CMIP6 models with interactive chemistry for which SAM, TCO, and (at least) daily-resolution wind fields are available (Table 2). Spatiotemporal standardization and SAM index calculation is performed as described in sections 2.2 and 2.3. For the intercomparison of the subset of CMIP6 models, we use the historical run for the period 1980-2014 and the SSP 3-7.0 run for the period 2015-2019. We calculate trends in SAM, 10-m wind speed, and total column ozone (TCO) for the band 70°S- 90°S, for 1980-1999 and 1980-2019.We compare CMIP6 TCO trends to an observational dataset (Bodeker et al., 2021). For this intercomparison, to maintain consistency in method, only one ensemble member of each model, including UKESM1, is used.

Table 2

Model	Reference
UKESM1-0-LL	Sellar et al., 2019
CNRM-ESM2-1	Séférian et al., 2019
GISS-E2-1-G	Kelley et al., 2020
MRI-ESM2-0	Yukimoto, Kawai, et al., 2019
GFDL-ESM4	Dunne et al., 2020

Table 2: CMIP6 models with interactive chemistry used in the intercomparison. *Only models with both interactive chemistry and 10-m wind fields available at (at least) daily resolution are used. One ensemble member is used per model.*

2.6 Experimental Design

Morgenstern (2020), Revell et al. (2022) and Zeng et al., (2022) emphasize that to simulate forced trends in Southern Ocean winds models need to interactively simulate ozone chemistry, GHGs and ODS. This is to capture multiple interactions between GHGs (e.g. CO_2, CH_4, N_2O), ozone, and their combined impact on model dynamics. Prescribing an externally generated ozone field risks it being chemically inconsistent with other time-evolving GHGs (Zeng et al., 2022), and potentially be offset with respect to the model thermodynamical fields (Morgenstern, 2020). Morgenstern (2020) shows that the CMIP6 DAMIP (Detection and Attribution Model Intercomparison Project) experiments (Gillett et al., 2016); *hist-GHG* (historical GHG forcings with all other forcings pre-industrial) and *hist-stratO3* (prescribed historical ozone and all other forcings pre-industrial) do not combine to give the (forced) time evolution of the SAM index seen in full historical simulations. This is due to feedbacks between the time-varying GHGs and ozone leading to a different impact on model dynamics compared to the combination of the two individual drivers. This feedback is captured in models that run with interactive chemistry.

Motivated by these studies, we use UKESM1 with interactive chemistry to study the role of stratospheric ozone loss and recovery on Southern Ocean winds. We control the evolution of stratospheric ozone in UKESM1 by modifying surface mixing ratios of ozone depleting substances (ODS, e.g. chlorofluorocarbons and hydrochlorofluorocarbons), which play a central role in driving stratospheric ozone loss (Farman et al., 1985; Solomon et al., 1986). We perform simulations for 1950 to 2100 using two ODS surface mixing ratio scenarios: (i) ODS use the standard CMIP6 surface mixing ratios (historical followed by a projection), and (ii) ODS are fixed at 1950 values. We refer to these two experiments as OZONE-HIST and OZONE-1950. OZONE-HIST results in ozone loss from approximately 1970 to 2000, followed by a slow recovery through to 2100 (Keeble et al. 2021, Fig. 7). OZONE-1950 minimizes stratospheric ozone loss throughout the simulation as only trace amounts of ODS, emitted or produced in the atmosphere before 1950, are available for ozone destruction in the stratosphere.The two ODS scenarios are combined with two CMIP6 SSP scenarios (SSP 3-7.0 and SSP 1-2.6; Gidden et al., 2019) that represent a high and low GHG emission scenario.

This configuration results in four experiments that allow us to isolate the effects of simulated stratospheric ozone and GHG on wind trends; see Table 3 for a summary. Following McLandress et al. (2011), we assume that ozone-driven trends (resulting from the different ODS surface mixing ratios) and GHG-driven trends are additive; that is, the OZONE-HIST run demonstrates a linear addition of ODS-driven trends and GHG-driven trends, so [OZONE-HIST – OZONE-1950] will isolate the ODS-driven trend, while any trends in the OZONE-1950 runs are due to GHG emissions alone. We acknowledge the potential for some non-linear interactions that may weaken this assumption but suggest to first order it is a reasonable approximation for attributing the primary differences identified either to ODS or GHG differences in the respective experiments.

For each UKESM1 experiment, we run three ensemble members, each branched in 1850 from the CMIP6 UKESM1 piControl following the procedure for generating initial conditions outlined in section 4 of Sellar et al., (2020). With respect to means and trends, we report the ensemble mean value, calculated at daily 1°x1° resolution. When reporting extreme values, interannual variability, jet position, and standard deviation in the jet position, we calculate them for each ensemble member separately and give the mean of these calculations.

3.3 UKESM1 in the context of CMIP6 models with interactive chemistry

The CMIP6 models with interactive ozone show substantial spread (~1 m/s) in their representation of the mean wind speed over the Southern Ocean (Fig. 6 a)-c)). All models, except GISS-E2-I-G, overestimate the climatological mean wind speed with respect to ERA5. Agreement across the models in wind speed trends is also generally weak. Most models (except MRI-ESM2-0) show larger DJF trends for 1980–1999 than 1980–2019, with GFDL_ESM4 and UKESM1 being notably accurate for both time periods. Furthermore, all models except UKESM1 underestimate the JJA wind speed trend during 1980-1999, though trends in this season are not expected to be strongly forced by ozone trends. UKESM1 performs well in capturing wind trends compared to other CMIP6 models, reproducing relatively well the wind speed trends seen in ERA5, for both DJF and JJA, as well as for the two time periods considered, including differences between these two periods. UKESM1 falls within the range of CMIP6 models with respect to mean wind speed biases (Fig. 6).

On average, the models overestimate TCO depletion (for the area 70°S- 90°S), though with considerable inter-model variation: MRI-ESM2-0 underestimates depletion, GFDL-ESM4 and CNRM-ESM2-1 are quite accurate, while UKESM1 and GISS-E2-1-G substantially overestimate ozone loss across all seasons and time periods (Fig. 6 lower panels, Fig. S1). Though stronger ozone depletion is expected to correlate with larger wind speed trends, this relationship holds only partially in austral summer. GISS-E2-1-G substantially overestimates ozone depletion in 1980–1999 but fails to produce a correspondingly strong wind speed trend, even in summer. Similarly, CNRM-ESM2-1 reasonably captures the observed ozone loss but underestimates wind speed trends. GFDL-ESM4 best matches both metrics in austral summer but not winter. While the strongest ozone loss typically occurs in austral spring (SON), inter-model TCO trends and their relationship with wind speed trends are consistent whether wind speed trends in DJF are plotted relative to TCO trends in SON or DJF (Fig. S2). To maintain consistency with the rest of this study, we therefore present only DJF results in Figure 6.

UKESM1 overestimates ozone depletion, primarily in the 1980-1999 period, but accurately reproduces the ERA5 wind speed trends for both periods, suggesting the dynamical link between Antarctic ozone loss and near-surface westerlies is weaker in UKESM1 than in reality. The weak TCO–wind relationship across models in austral winter (JJA) for 1980–1999 indicates observed wind increases during this period are very likely not ozone-driven. As in the reanalyses (Fig. 5), SAM trends correlate strongly with wind speed trends across CMIP6 models (Fig. S3), due to the mechanistic link between these metrics. While acknowledging recent trends in Antarctic TCO are larger than observed in UKESM1, our analysis of wind speed and SAM trends, and the implied response to ozone forcing, suggests UKESM1 is suitable for studying (and attributing) past and future changes in Southern Ocean winds, and by extension the drivers of past and future changes in Southern ocean carbon uptake, as carried out in our earlier study (Jarníková et al., 2025).

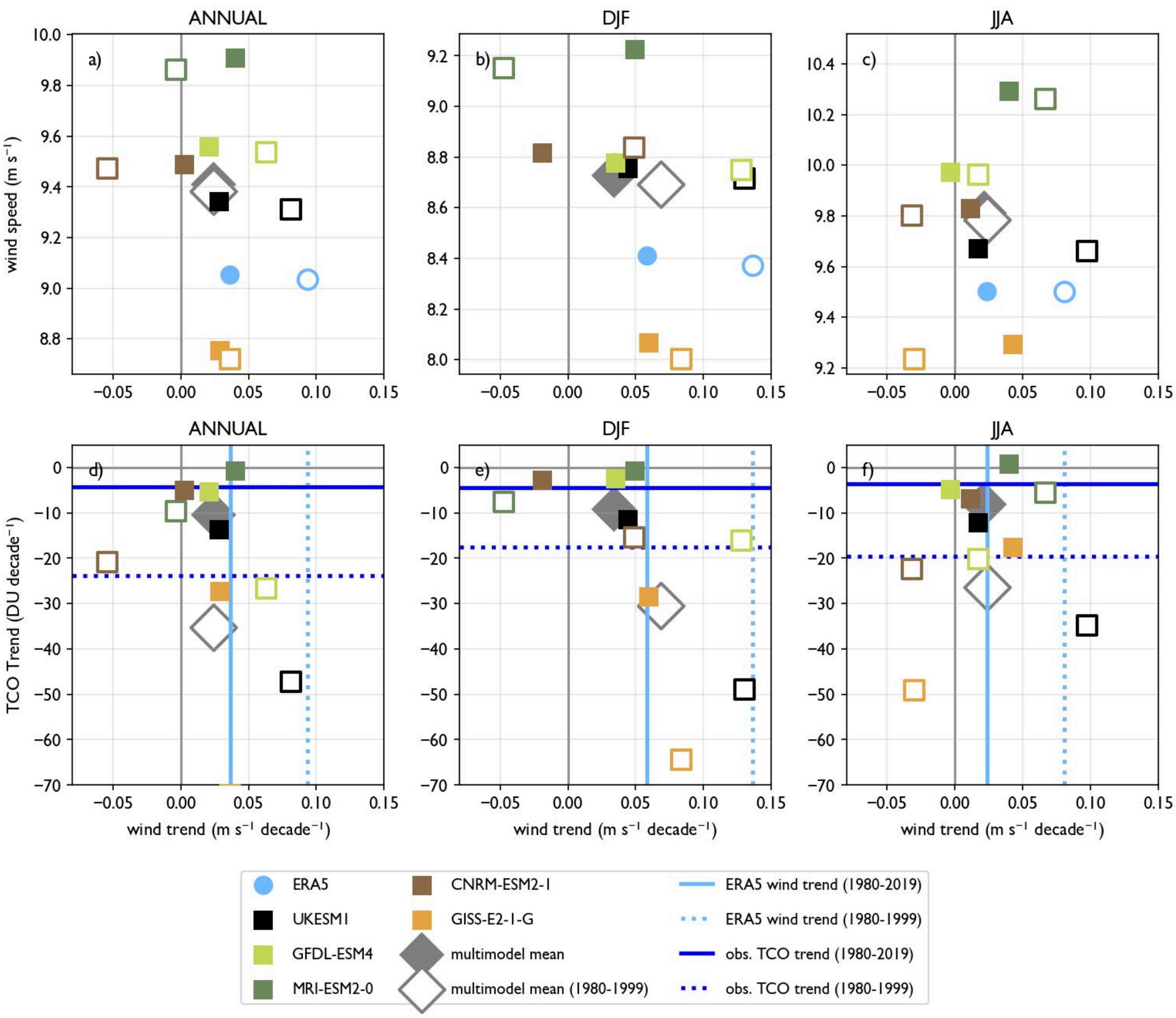

Fig. 6: 10-m wind speed, decadal wind speed trend, and decadal TCO trend for CMIP models with interactive chemistry. *For each model, one ensemble member is used (see Table 2)**.***

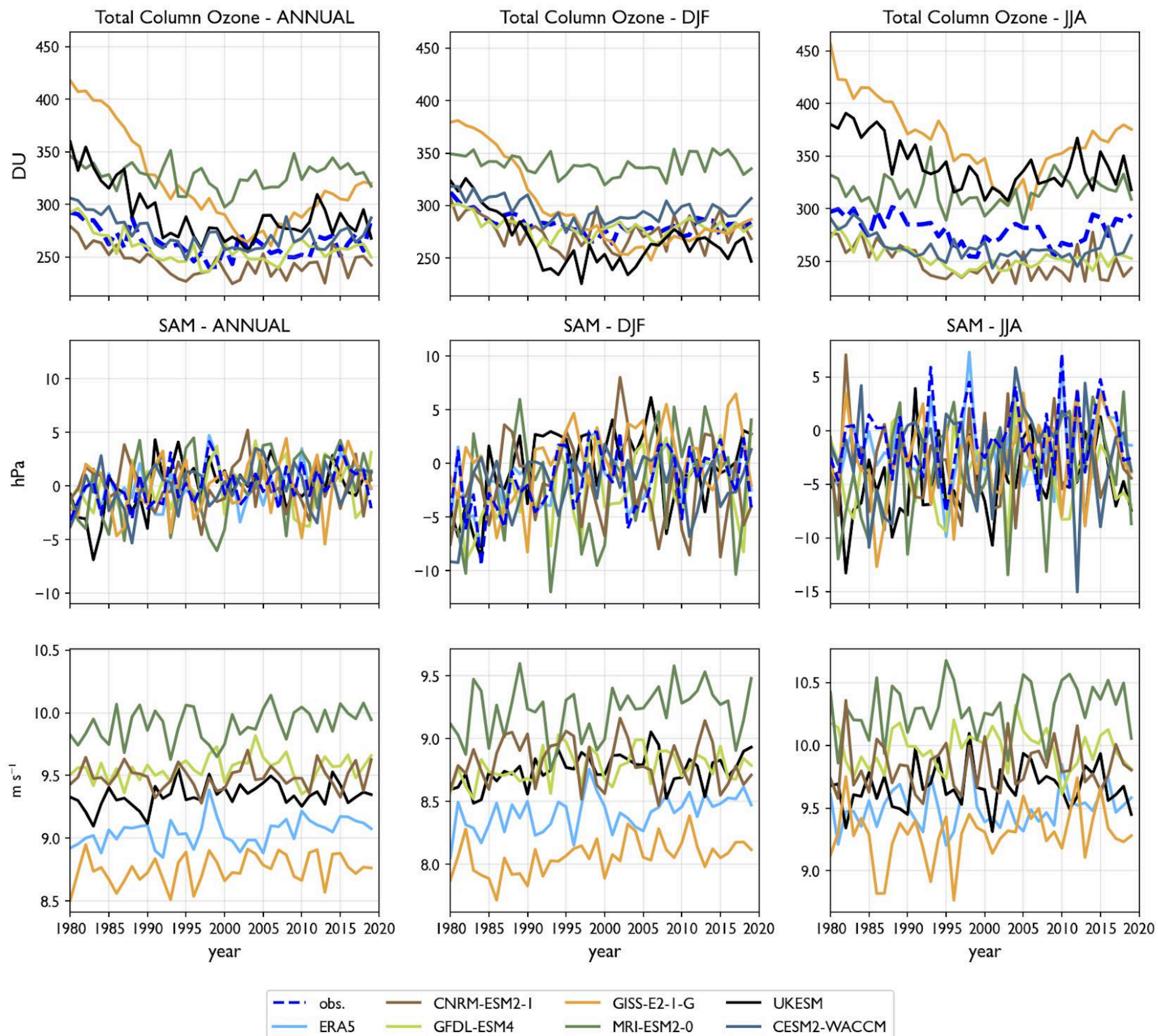

Fig. S1: Timeseries of Total Column Ozone (TCO) for 70-90°S, SAM index, and 10-m wind speed (40-60°S) for CMIP6 models with interactive chemistry. *Relevant observations and reanalyses are shown as follows: the Bodecker observational TCO is shown in dashed blue in the top row. The Marshall station-based SAM index is shown in dashed blue in the middle row, and the ERA5 wind speed is shown in light blue in the bottom row.*

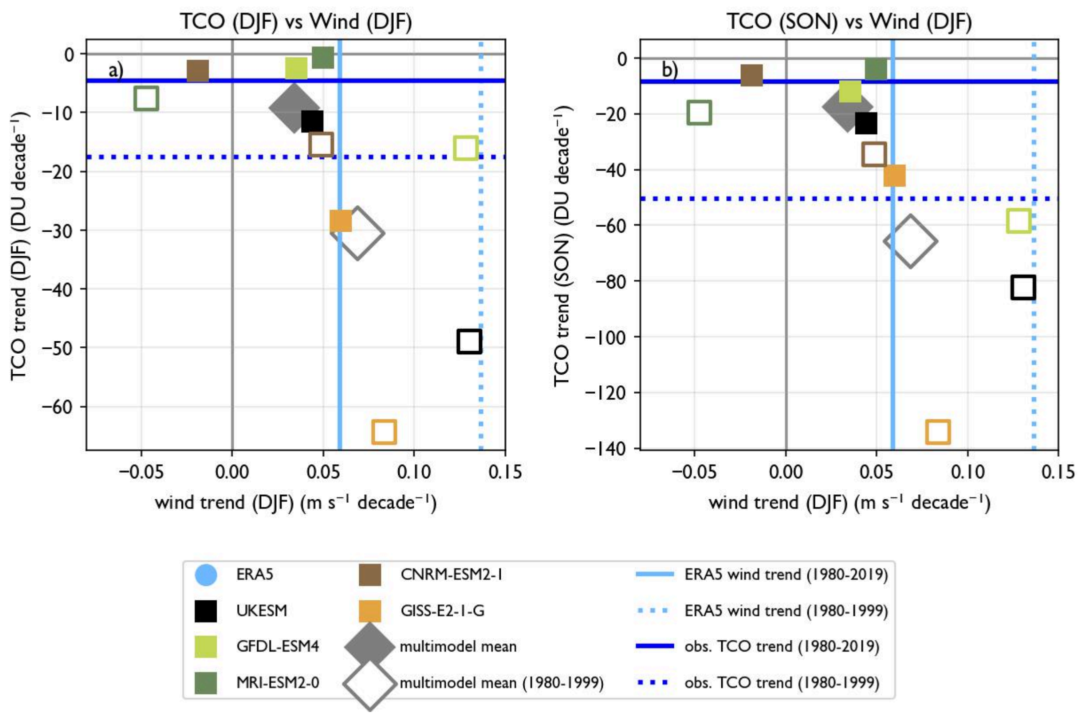

Fig. S2: Trends in TCO (DJF and SON) vs. trends in 10-m winds in DJF. *Though maximum ozone depletion is seen in SON, inter-model TCO trends and their relationship with wind speed trends are consistent whether wind speed trends in DJF are plotted relative to TCO trends in SON or DJF.*

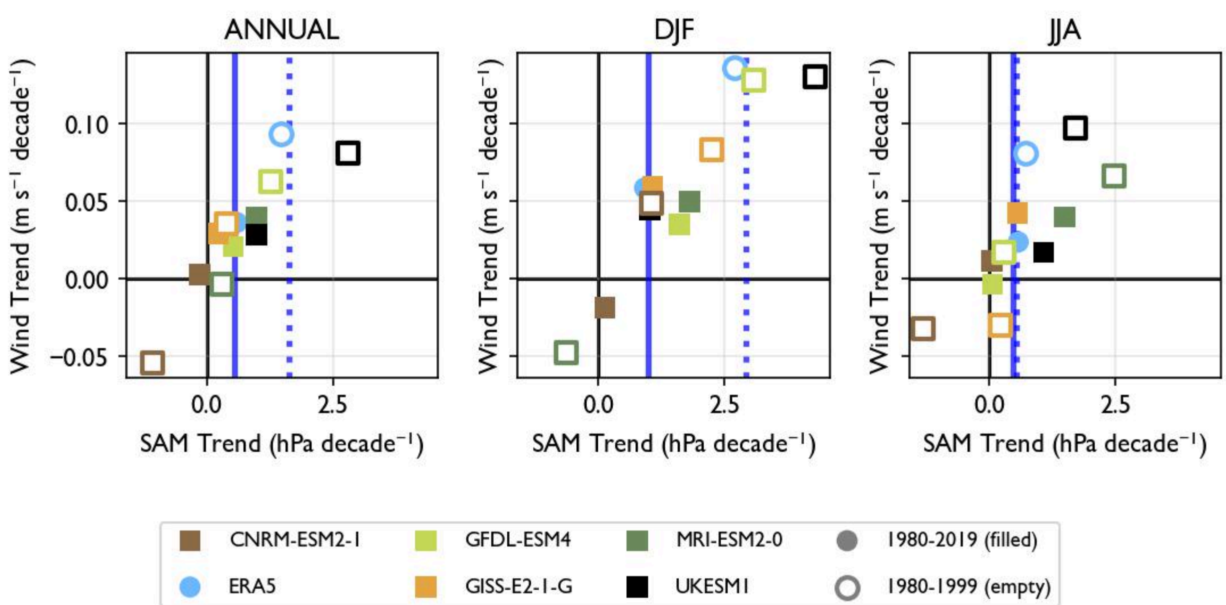

Fig. S3: Trends in 10-m winds vs SAM trends for CMIP6 models with interactive chemistry and ERA5. *See also Fig. 5. For this intercomparison, one ensemble member is used for each model, including UKESM1, so SAM trends here are somewhat higher than in the ensemble mean shown in Fig. 5*

Minor comments

2.2 Line 16: R1 is not a common abbreviation for the NCEP-NCAR reanalysis. In the abstract, please use NCEP-NCAR, or define the acronym R1.

We have changed R1 to NCEP-NCAR in the abstract. Throughout the paper, we keep R1, but define it in the methods. Proposed amendment:

We also include the older, but still commonly used, NCEP-NCAR reanalysis (R1), as a comparison.

2.3 Lines 48-52: Another paper to consider in the literature review is Barnes et al. (2014):

Barnes, E. A., N. W. Barnes, and L. M. Polvani, 2014: Delayed Southern Hemisphere Climate Change Induced by Stratospheric Ozone Recovery, as Projected by the CMIP5 Models. J. Climate, 27, 852–867, https://doi.org/10.1175/JCLI-D-13-00246.1.

In the proposed new text, we discuss Barnes in both the introduction and Discussion:

Introduction:

Barnes et al. (2014) showed that ozone recovery delays the effect of greenhouse gas driven climate change on multiple Southern Hemisphere climate indicators, including the position of the jet stream, and that the historical ozone-driven circulation changes are larger than those projected to the end of the twenty-first century.

Discussion:

This control shift is consistent with the general understanding. As in Barnes et al. (2014), we find historical wind speed trends due to ozone depletion are stronger than greenhouse gas driven trends seen in the twenty first century. Similar to Barnes et al (2014)., Gerber and Son (2014.), McLandress et al. (2011), and Simpkins and Karpechko (2012), we observe a cancellation of effects in the first half of the twenty first century, as ozone recovery competes with greenhouse gas emissions, leading to only weak wind trends in this period.

2.4 Lines 88-94: I don't think it's good practice to continue using the NCEP-NCAR reanalysis. This is a very old reanalysis that is known to perform poorly in many applications (as indeed you show here). I would recommend focusing on the three more modern reanalyses that were formulated in the past decade (as opposed to in the 1990s).

I agree that the NCEP-NCAR reanalysis is old and has been superseded by more modern reanalyses. We include it primarily for two reasons: 1) it is still used in a number of applications; for example, some models in the Global Carbon Budget use it for atmospheric forcing, and an illustration that other reanalyses are better suited is therefore relevant 2) the state-of-the-art MERRA2 reanalysis doesn't perform much better when simulating SAM and wind trends (see, eg, Fig. 5), so NCEP-NCAR acts as a comparison.

I've added a line making it clear that R1 is older in the paper:

We use a subset of the latest generation of products that are commonly used in earth system research: ERA5, JRA3Q and MERRA2. We also include the older, but still commonly used, NCEP-NCAR reanalysis (R1), as a comparison.

2.5 Line 177: For easy reference for readers, it might be nice to have a table describing what these four experiments are with associated ozone and greenhouse gas forcings listed for each one.

I've added an extra table, Table 3, with this information.

Experiment	Ozone forcing	GHG forcing
OZONE-HIST SSP 1-2.6	Standard CMIP-6 surface mixing ratios for ODS (historical to 2015, followed by specific SSP pathway projection) (Meinshausen et al., 2017)	SSP 1-2.6 (Gidden et al., 2019)
OZONE-HIST SSP 3-7.0	as above	SSP 3-7.0 (Gidden et al., 2019)
OZONE-1950 SSP 1-2.6	ODS surface mixing ratios fixed at 1950 values from 1950 onwards	SSP 1-2.6 (Gidden et al., 2019)
OZONE-1950 SSP 3-7.0	as above	SSP 3-7.0 (Gidden et al., 2019)

Table 3: Summary of experiments with description of ozone and GHG forcing.

2.6 Line 241: You need to define how the jet position is located. Presumably this is just a wind maximum in latitude, but there are often assumptions about how to locate the maximum between grid points (interpolation, etc.).

I believe this text somehow got cut off during the editorial formatting process; our original draft section 2.2 (spatiotemporal standardization) is much more detailed than shown in the uploaded version. Please see the full section 2.2 in the revised draft, which includes the following definition of the jet position:

We use the 1°×1° gridded products to calculate the wind jet position. At each longitude, for each day, we record the jet position as the location of the maximum of the u-component of the 10-meter wind speed between 30°S and 70°S, following Bracegirdle et al. (2013). We then use this daily wind jet position at each longitude to calculate the zonal average and the seasonal average.

2.7 Line 382: Figure 7 should not be cited here, as it only shows trends for the historical period not the 2000-2049 period.

I have removed this reference in the proposed new text.

2.8 Line 385: Why is the effect of ozone recovery stronger when greenhouse gas levels are larger? Is this expected from prior studies? If so, they should be cited here.

Liu et al (2025) discuss the importance of other GHGs (in particular CH4) in impacting ozone loss and recovery, while Revell et al (2022) compare CMIP6 models with prescribed ozone (where the future ozone scenarios are generated based on the CMIP5 RCPs) versus CMIP6 models with interactive chemistry. In the latter set of models the future GHG scenarios are based on the SSPs (i.e. SSP5-85 compared to RCP8.5). SSP5-85 has lower CH4 and N2O than the RCP8.5 scenario. As a result ozone loss is smaller, and recovery greater, in the CMIP6 interactive chemistry models than in the prescribed ozone models due to the influence of CH_4 and N_2O on ozone chemistry.

SSP 3-7.0 has higher CH_4 concentrations than SSP 1-2.6 and the UKESM1 ozone chemistry responds to this difference, resulting in a more rapid recovery of the ozone hole in SSP370 versus SSP126. We have added the text below in the proposed new manuscript to explain this point.

The sensitivity of ozone recovery to SSP pathway reflects the interaction of other GHGs (e.g. CH_4 and N_2O) with ozone chemistry. SSP 3-7.0 has higher CH_4 concentrations in the future than SSP 1-2.6, and UKESM1 has a significant ozone response to increasing CH_4 (see figure 14 in Zeng et al., 2022). Ozone recovery will therefore be accelerated in SSP 3-7.0 relative to SSP 1-2.6, with a concomitant stronger forcing of surface winds.

Liu, N., *et al.* “Impact of Methane Emissions on Future Stratospheric Ozone Recovery.” *Adv. Atmos. Sci.* 42, 1463–1482 (2025). https://doi.org/10.1007/s00376-024-4142-6

Revell, L. E., et al. "Influence of ozone forcing on 21st century Southern Hemisphere surface westerlies in CMIP6 models." *Geophysical Research Letters* 49.6 (2022): e2022GL098252.

2.9 Line 388: Why is the GHG-driven wind acceleration larger in winter and spring? Is this expected from prior studies? If so, they should be cited here.

We were unable to find any earlier studies directly discussing this point. Here we make some speculations on what may be driving this. We have not included any of this in the paper because more analysis is needed to have any confidence in these speculations.

The meridional pattern of warming under increased GHGs in the S. Hemisphere is one of warming in the tropics and subtropics, a warming minimum at ~55-65S (due to upwelling along the ACC and active ocean heat uptake) and then increased warming again south of the ACC. This is the basic climate change pattern that gives rise to the GHG-forced changes in surface winds (e.g. poleward shift of the jet and increased westerly wind speeds). In the austral winter and spring this pattern may be amplified relative to other seasons through increased ocean heat uptake in the 55-65S band as the mixed layer deepens under stronger background winds. In addition, warming over the region south of the ACC may be stronger in winter due to the frequent occurrence of a stable boundary constraining warming to near surface. In addition, summer warming is constrained through excess heat primarily going into sea ice melt. A seasonally amplified climate change pattern may therefore allow a larger response in the surface winds.

2.10 Table 1, NCEP-NCAR: I think the proper citation here would be Kalnay et al. (1996):

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc., 77, 437–472, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Thanks! I fixed the citation mismatch.

2.11 Figure 1 caption: Please list the time period used to construct climatology in the caption (1980-2019).

Thanks! I've added this clarification.

Fig. 1: Climatological wind speed for 1980-2019. *For ERA5, the climatological wind speed for the full year and austral summer (DJF) and winter (JJA) is shown. For the other 3 reanalyses and UKESM1, differences from ERA5 are shown as [product x – ERA5]; i.e. positive (red) values indicate higher winds than ERA5. See also Table 2.*