The role of the stratosphere in future mid-latitude climate projections

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One of the greatest uncertainties when it comes to future projections of regional climate is how the large-scale atmospheric circulation will change (Shepherd 2014). While there is a general consensus among models on a zonal mean poleward shifting of the mid-latitude westerlies and associated storm tracks (Yin 2005; Kidston and Gerber 2010; Chang et al. 2012; Swart and Fyfe 2012; Wilcox et al. 2012; Barnes and Polvani 2013), there is a large spread in the magnitude of this response. In addition to this zonal mean, poleward shifting view, there are more localized changes in the circulation associated with altered stationary wave patterns (Stephenson and Held 1993; Joseph et al. 2004; Simpson et al. 2014). For many of these predicted changes, we do not have a good physical understanding of the mechanisms that produce them, or the factors that govern their uncertainty. The stratosphere and how it is expected to change in the future is one source of uncertainty, among many, in future tropospheric mid-latitude circulation change. There are a variety of ways in which the stratosphere's mean state, variability and composition may impact on tropospheric climate change. Instead of providing an exhaustive review of this topic, we focus on the role of changes in the extra-tropical mean state of the stratosphere in future projections of tropospheric mid-latitude climate by considering two particular aspects. For the Northern Hemisphere we discuss the impact of uncertainty in future changes in the stratospheric polar vortex on tropospheric climate change. For the Southern Hemisphere we discuss the relative roles of stratospheric ozone depletion and changing greenhouse gas concentrations on the future evolution of the Southern Hemisphere mid-latitude jet stream.

The uncertain future of the Northern Hemisphere stratospheric polar vortex

Since multi-model assessments of future climate change began, models have improved considerably in their representation of the stratosphere. Many models now have high top and increased vertical resolution (Gerber et al. 2012; Charlton-Perez et al. 2013). However, improvement in stratospheric representation has not been accompanied by a greater consensus among models in how the Northern Hemisphere stratospheric circulation will change in the future. Nevertheless, we are starting to gain a quantitative understanding of the impact that this stratospheric uncertainty may have on tropospheric projections.

One important way in which the Northern Hemisphere (NH) stratosphere can influence tropospheric circulation change is through the influence of changes in the strength of the wintertime stratospheric polar vortex, resulting in a downward influence on the tropospheric circulation. Earlier studies on this topic focused on comparisons

between high-top and low-top configurations within one model, but they failed to reach a consensus as to the impact of stratospheric resolution. This began with Shindell et al. (1999) who found that historical negative trends in sea level pressure (SLP) over the Arctic could only be reproduced in response to greenhouse gas forcing in their high-top model. This result was in contrast to the subsequent studies of Sigmond et al. (2008), Karpechko and Manzini (2012), and Scaife et al. (2012), who found that their high-top models produced less of a reduction in Arctic SLP, and Gillett et al. (2002) who found no significant influence of stratospheric representation on the tropospheric circulation response to rising greenhouse gases.

Through the use of multi-model intercomparisons in which models vary widely in their representation of the stratosphere (Charlton-Perez et al. 2013), it has now become clear that there is no direct link between vertical resolution and how the Northern Hemisphere polar vortex, together with its downward influence on the troposphere, is predicted to change in the future (Manzini et al. 2014; Simpson et al. 2018). This is illustrated in Figure 1a, reproduced from Simpson et al. (2018). This shows the predicted late 21st century change in December-January-February (DJF) averaged zonal mean zonal wind at 10 hPa averaged over 60ºN to 75ºN, for the Coupled Model Intercomparison Project, phase 5 (CMIP5) models, under the RCP8.5 scenario (Taylor et al. 2012). Firstly, there is a complete lack of consensus among the models, with roughly half the models exhibiting a weakening and half exhibiting a strengthening. Secondly, it is clear that there is no link between model lid-height and the polar vortex response, with high- and low-top models sitting on both ends of the scale.

Figures 1c and d provide an indication of the variety of polar vortex responses that occur among the models. The model MRI-CGCM3 (Figure 1c) exhibits the greatest weakening of the polar vortex while MIROC5 (Figure 1d) exhibits the greatest strengthening. These are both high-top models, by the definition of Charlton-Perez et al. (2013), and differ in the zonal wind anomalies in the

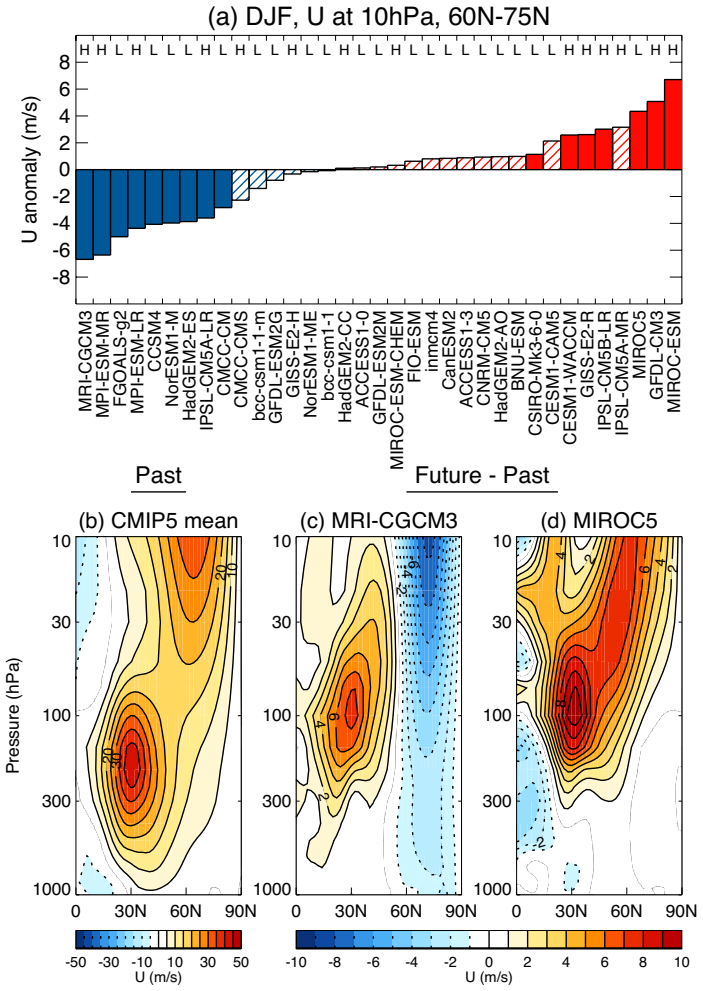

Figure 1. (a) Future-Past difference in zonal mean zonal wind at 10hPa area averaged from 60ºN to 75ºN for each of the CMIP5 models (equivalent to figure 1e of Simpson et al. (2018)). All available ensemble members for the historical simulations and RCP8.5 simulations are used. Solid bars depict anomalies that are significantly greater than expectations from the sampling of internal variability at the 95% level. Hatched bars are not. Significance is determined using a bootstrapping methodology as described in Simpson et al. (2018). H's and L's depict whether a model is high- or low- top by the Charlton-Perez et al. (2013) definition. (b) The CMIP5 multi-model mean DJF averaged zonal mean zonal wind (ms-1). (c) The Future-Past difference in DJF zonal mean zonal wind for the model MRI-CGCM3 where Future = years 2070-2099 of the RCP8.5 scenario and Past= years 1979-2005 of the historical simulations. This makes use of three historical members and one RCP8.5 member. (d) Same as (c) but for MIROC5 using five historical members and three RCP8.5 members.

polar vortex by roughly 14 m/s. A variety of processes likely contribute to this spread among models. The mean stratospheric circulation is strongly influenced by wave-mean flow interaction involving resolved waves, such as vertically propagating Rossby waves, and unresolved gravity waves that must be parameterized. Gravity wave parameterizations are not well constrained by observations, resulting in the mean flow varying across models or with different influences of resolved and parameterized waves. Models can vary in their predicted future changes because they have different climatological states in the present day that then respond differently (Sigmond et al. 2008). Alternatively, variations in the relative contributions from resolved and gravity wave drags could lead to different mean state responses as these two wave components respond. Another possible source of inter-model spread is that the polar vortex response may rely heavily on tropospheric processes that govern the changes in upward propagating wave activity (Karpechko and Manzini 2017). These tropospheric processes could differ among models for a multitude of reasons, which may make it challenging to find systematic relationships that explain the spread in stratospheric vortex change. Currently, we have little understanding of the relative roles of these processes in contributing to the wide inter-model spread shown in Figure 1a. Based on our current model projections, it is unknown as to how the NH stratospheric polar vortex will change in the future.

What extent does this wide spread in stratospheric polar vortex responses impact on our future projections of tropospheric circulation change? Manzini et al. (2014) were the first to comprehensively investigate this among the CMIP5 models. They used a regression approach, whereby they linearly regressed measures of tropospheric change across models onto an index of change in the strength of the NH stratospheric polar vortex. They found that with a relative weakening of the stratospheric polar vortex, there is a relative increase in Arctic SLP and a reduced poleward shifting of the tropospheric westerlies.

Similar results are reproduced in Figures 2 (a)-(c) based on the analysis of Simpson et al. (2018). Figure 2b shows the CMIP5 multi-model mean, Future – Past, difference in SLP and Figure 2c shows the regression of SLP onto the polar vortex response (that was shown in Figure 1a). This regression has been multiplied by -10 m/s so that it depicts the anomalies associated with a relative weakening of the polar vortex corresponding roughly to the difference between the models that lie at the 5th and 95th percentiles of the CMIP5 distribution (i.e., models that have a weakening of the vortex of 5 m/s and models that have a strengthening of the vortex of 5 m/s). The CMIP5 multi-model mean displays reduced SLP over the Arctic and an increase to the South (Figure 2b). The regression of SLP onto the polar vortex suggests that models on opposite ends of the scale, in terms of their

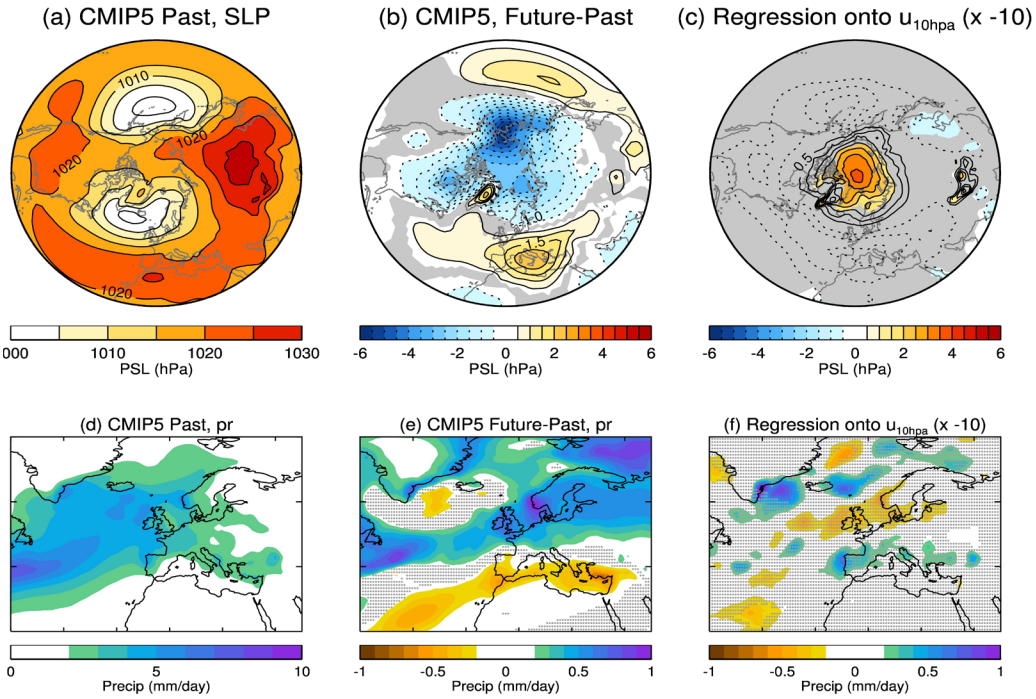

Figure 2. (a) CMIP5 multi-model mean DJF SLP (hPa) climatology (same models as in Figure 1d). (b) The CMIP5 multi-model mean Future-Past difference in SLP where Future = years 2070-2099 of the RCP8.5 scenario and Past = years 1979-2005 of the historical simulations. (c) The regression of SLP onto the change in stratospheric vortex strength (that shown in Figure 1d) multiplied by -10. In (b) and (c) gray shaded regions are not statistically significant at the 95% level by a bootstrapping methodology (see Simpson et al. 2018). (d)-(f) are as (a)-(c) but for precipitation rate (mm/day). In (e) and (f) stippling indicates regions that are not statistically significant at the 95% level by a bootstrapping methodology (see Simpson et al. 2018). Panels (b, c, e and f) are equivalent to figures shown in Simpson et al. 2018 except a prior regression onto globally average surface temperature has not been performed, which makes little difference.

polar vortex response, could differ in their SLP response by a magnitude that is similar to the multi-model mean CMIP5 response. Causality cannot be inferred from this form of regression analysis alone. To address this issue, Simpson et al. (2018) performed idealized experiments where, via relaxation, stratospheric anomalies consistent with polar vortex responses on opposite ends of the CMIP5 range were imposed within one model. It was found that the tropospheric response to the imposed vortex anomalies was quantitatively in agreement with the inferences from linear regression across models, which supports the conclusion that the pattern found in Figure 2c represents a downward influence of the stratospheric uncertainty onto the troposphere below. Simpson et al. (2018) estimated that eliminating the uncertainty in the stratospheric polar vortex response would reduce the inter-model spread in Arctic SLP found in the CMIP5 models by roughly 15-20%, where "spread" is defined as the 4σ range (σ being the across-model standard deviation). Thus, the stratospheric influence is a non-negligible component of the inter-model spread in Arctic SLP.

In terms of regional impacts, the Northern Hemisphere stratospheric vortex response is likely to have the greatest influence on European climate. In particular, associated with the weakening of the jet stream in the North Atlantic and the strengthening to the south that accompanies the SLP pattern in Figure 2c, is a decrease in precipitation over Northern Europe and an increase to the south (Figure 2f). While the regression of precipitation onto the polar vortex response is only marginally significant in Southern Europe, the idealized experiments of Simpson et al. (2018) exhibited a similar precipitation response to the stratospheric polar vortex anomalies, with greater significance given the greater length of the simulations. These precipitation anomalies are of particular relevance to the Mediterranean region where the CMIP5 multi-model mean suggests a considerable wintertime drying

in the future (Seager et al. 2014; Figure 2e). Figure 2f suggests that models with a strengthening of the polar vortex would become considerably drier than those with a weakening (see also Zappa and Shepherd 2017) and the magnitude of the difference between models on opposite ends of the scale in terms of their polar vortex response is roughly 10% of the present day precipitation climatology of the Mediterranean (compare Figure 2f with Figure 2d). However, there are many other sources of uncertainty in Mediterranean precipitation projections, and Simpson et al. (2018) estimated that if stratospheric spread were eliminated, the spread in precipitation projections over Europe would only be reduced by around 5%. Nevertheless, the magnitude of the precipitation difference between models that exhibit a strong strengthening of the polar vortex and those that exhibit a strong weakening of the polar vortex is large and would considerably affect precipitation projections in a region that is highly vulnerable to climate change. This motivates an improved understanding and a narrowing of the uncertainty in future Northern Hemisphere polar vortex change.

The relative roles of ozone recovery and increasing greenhouse gas concentrations on the southern hemisphere jet stream change

In the Southern Hemisphere, the stratosphere is projected to play a key role in the future evolution of the mid-latitude circulation due to the influence of ozone recovery on the mid-latitude westerly jet. Over the late 20th century, the austral springtime cooling of the Southern Hemisphere polar stratosphere in association with ozone loss was accompanied by a southward shifting of the tropospheric mid-latitude westerly jet during the austral summer season in both observations (Thompson and Solomon 2002) and model simulations (Son et al. 2010). Rising greenhouse gas concentrations are also thought to have contributed to a poleward shifting of the mid-latitude jet (Fyfe et al. 1999; Yin 2005; Kidston and Gerber 2010; Barnes and Polvani 2013), although much remains to be understood about the mechanisms behind this poleward shift. It has been shown that a dominant influence on the poleward shift associated with rising greenhouse gases is the sea surface temperature (SST) mediated warming. However, the direct radiative effects of increasing CO2 also play a lesser role (Grise and Polvani 2014), with Sigmond et al. (2004) suggesting a portion of this effect is due to the rising CO2 in the stratosphere, which induces stratospheric cooling and associated circulation changes.

During the late 20th century, ozone depletion, rising greenhouse gas concentrations and accompanying stratospheric cooling and SST warming were likely conspiring to shift the mid-latitude westerlies poleward during DJF. This has been demonstrated in single forcing model simulations in which only greenhouse gas concentrations or only ozone/ozone depleting substances were allowed to evolve transiently in time (Arblaster and Meehl 2006; McLandress et al. 2010; Polvani et al. 2010). However, as the ozone hole recovers, the associated warming of the polar stratosphere is expected to give rise to an equatorward shifting of the mid-latitude jet, competing with the continued poleward shifting associated with rising greenhouse gas concentrations in the coming decades. This is illustrated in Figure 3 for the CMIP5 models, many of which have prescribed stratospheric ozone but some of which have interactive stratospheric chemistry (Eyring et al. 2013). Over the historical period, as the springtime stratosphere cooled from 1960 to around 2000 (Figure 3a), the CMIP5 ensemble mean simulates a poleward shifting of the DJF southern hemisphere westerlies by about 1° latitude (Figure 3b). However, in the coming decades, as the ozone hole recovers and the springtime stratosphere warms (Figure 3a), the poleward shifting of the westerlies stalls, with the CMIP5 ensemble mean exhibiting only a minor poleward shifting of the westerlies between around 2000 and 2050 (Figure 3b). This is likely due to the poleward shifting associated with rising greenhouse gases, which is offset by an equatorward shifting associated with ozone recovery (McLandress et al. 2010; Polvani et al. 2010). The degree to which these two forcings offset each other is sensitive to the future greenhouse gas emissions scenario used in the simulations. Simulations performed

with lower future emissions scenarios suggest that the southern hemisphere jet may even shift equatorward in the coming decades as ozone recovery dominates the forced trends (Eyring et al. 2013). However, there have been reports that in violation of the Montreal Protocol, CFC-11 emissions are now increasing again (Montzka et al. 2018), and hence the rate of ozone recovery is also uncertain. Therefore, the stratosphere is likely to play an important role in the future evolution of the Southern Hemisphere mid-latitude circulation, particularly during the DJF season as it responds to past and ongoing human activities.

In summary, there are a variety of ways in which the stratosphere may impact future tropospheric climate change. In the Southern Hemisphere, the stratosphere has already played a key role in historical climate trends as the cooling of the polar stratosphere accompanying ozone loss has contributed to a poleward shifting of the Southern Hemisphere westerlies during DJF. It is expected that as ozone recovers, an equatorward shifting of the Southern Hemisphere westerlies associated with a warming of the polar stratosphere will offset, to some extent, the poleward shifting of the westerlies induced by greenhouse gas warming during DJF. In the Northern Hemisphere, the role of the stratosphere in future climate change remains to be seen. Changes in the strength of the polar vortex as the planet warms could impact substantially on tropospheric circulation change in the mid-latitudes, particularly in the North Atlantic sector, with important implications for European climate change. However, models currently disagree on how the stratospheric vortex will change in the future. A narrowing down of this uncertainty would help to improve our confidence in future projections of wintertime climate over Europe. There is hope that progress can be made in the near future in this regard through the DynVarMIP initiative as part of the Coupled Model Intercomparison Project Phase 6, where targeted diagnostics will be made available that could help to shed light on the reasons behind the large inter-model spread in stratospheric vortex responses (Gerber and Manzini 2016).

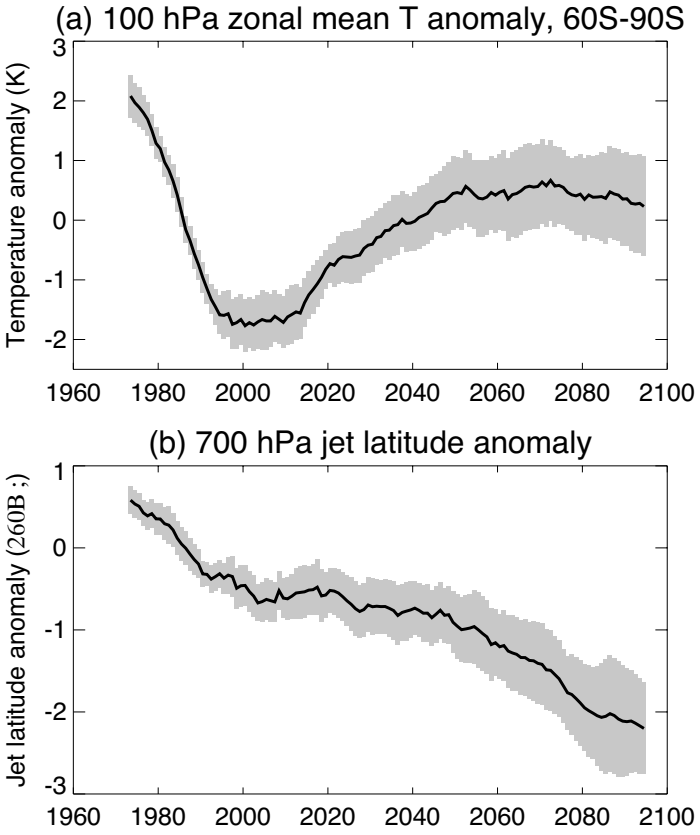

Figure 3. The ensemble mean of 23 CMIP5 models using only the first available member for each model. The historical simulation for years 1969-2005 is combined with the RCP8.5 simulation from years 2006 to 2099. (a) October – January, polar cap averaged temperature anomaly (K) at 100 hPa (area average from 60S to 90S) and (b) DJF jet latitude anomaly where jet latitude is defined as the latitude of the maximum zonal mean zonal wind at 700 hPa. Jet latitude is determined by a quadratic fit to the values at the grid point with the maximum zonal mean zonal wind and the two adjacent grid points. Anomalies are defined relative to the 1969-2005 climatology for each model before calculating the ensemble mean. The black line depicts 10 year running mean values and the gray shading depicts +/- 2 standard errors about the mean where standard error = σ/sqrt(N), σ = across-model standard deviation of the 10 year averaged climatology and N is the number of models (23).

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