Stratospheric circulation trends and their impact on the climate system

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Abstract

This chapter reviews trends in the large-scale circulation of the stratosphere, during the recent past (mid-20th century to present) and the remainder of the 21st century, with a focus on their representation in climate model simulations. We discuss three major aspects of stratospheric circulation: the Brewer-Dobson circulation, the quasi-biennial oscillation, and the polar vortices. Trends are driven by both rising greenhouse gas concentrations and stratospheric ozone depletion. These two drivers have reinforced each other during the recent past, but as ozone recovers in the future they will act in opposition. Finally, we discuss the impact of stratospheric trends on tropospheric circulation, the ocean, and cryosphere.

Keywords

Atmospheric circulation; Brewer-Dobson circulation; Ozone depletion; Polar vortex; Quasi-biennial oscillation; Stratosphere; Stratosphere-troposphere coupling

Key points

- The latest generation of climate models have a much improved representation of the stratosphere, can capture several aspects of observed circulation trends, and give robust projections of future trends.
- Stratospheric circulation trends have been shown to have significant impacts on broader climate, including on the jet streams and precipitation patterns.
- Despite recent progress, large model uncertainty remains in some aspects of future stratospheric trends, particularly the Arctic polar vortex and the quasi-biennial oscillation.

Introduction

The stratosphere is the lowermost layer of the 'middle atmosphere', lying above the troposphere and below the mesosphere, and it makes up roughly 10% of the total atmospheric mass. Unlike the troposphere, it is characterized by stable stratification, determined largely by radiative processes, most notably the absorption of solar radiation by ozone which leads to a mean temperature that increases with height. This stability results in a quasi-horizontal circulation with dynamical variability generally occurring over both large spatial and time scales. Despite its remote and rarefied nature, work over the last three decades has shown increasingly robust evidence that long-term changes in stratospheric circulation can play a major role in surface climate trends. This chapter reviews progress in simulating both the recent historical and projected future trends in the major features of stratospheric circulation, as well as our understanding of the impacts of these trends on the broader climate system.

Stratospheric circulation results from a three-way balance between dynamical, radiative, and chemical processes. Because of the stratosphere's lack of baroclinic instability, dynamical driving originates largely, though not exclusively, from below. Both small-scale inertio-gravity waves and large-scale Rossby and Kelvin waves are excited in the troposphere and can propagate vertically into the stratosphere to eventually break and dissipate, depositing momentum onto the mean flow. Radiative forcing is largely dominated by ultraviolet-absorbing ozone, resulting in strong cooling and a large meridional temperature gradient during the polar night, when this incoming radiation is absent. Water vapor, although much scarcer than in the troposphere, also plays an important role through radiative cooling. The most significant chemical processes in the stratosphere are those related to ozone. The formation of ozone occurs largely by photolysis of oxygen, while its destruction comes through catalytic reactions with nitrogen-, hydrogen-, or halogen-containing species. These reactions are highly-temperature dependent, and particularly effective when cold enough for polar stratospheric clouds to form, which provide sites for heterogeneous reactions.

Long-term trends in stratospheric circulation can be driven by any processes that upset this delicate dynamical-radiative--chemical balance. The most significant driver of stratospheric change over recent decades has been stratospheric ozone depletion, caused by the anthropogenic emission of ozone depleting substances (ODSs) such as chlorofluorocarbons (CFCs). Over the period 1970–2000, total column ozone declined by approximately 5% in midland low-latitudes, but more than 40% in the Antarctic (WMO, 2022). The latitudinal difference in the extent of ozone depletion has, in turn, resulted in a strengthening of the temperature gradient between mid- and high-latitudes. As a result of the Montreal protocol and its amendments, concentrations of ODSs are now declining, and there is early evidence for recovery of the ozone layer, a trend which is projected to continue for the remainder of this century. During this same period, forcing due to increasing greenhouse gas (GHG) concentrations is likely to increase. GHGs impact stratospheric trends by both a direct radiative cooling effect on the stratosphere, and also by their influence on tropospheric dynamics and so on the wave-driving of the stratospheric circulation from below. As we will discuss in this chapter, the stratospheric effects of increasing GHGs and ozone recovery are often opposite in sign, making their net impact challenging to predict.

Our discussion will focus on trends in the three major phenomena of the large-scale stratospheric circulation: (i) the Brewer-Dobson circulation (BDC), (ii) the quasi-biennial oscillation (QBO), and (iii) stratospheric polar vortices. A full treatment of these phenomena is beyond the scope of this chapter, but we will here set the scene with a brief description of each.

i. The BDC is the net transport circulation of heat and constituents in the stratosphere. It is typically separated into zonal mean advection by the residual circulation and two-way isentropic mixing. The residual circulation consists of upwelling in the topics, poleward transport, and downwelling at high latitudes, driven by a drag due to Rossby and gravity waves. In addition to this advection, mixing occurs mainly following large scale stirring of the flow associated with breaking waves outside the polar vortex.
ii. The QBO is the dominant zonal circulation feature of the tropical stratosphere, consisting of alternating and descending bands of easterly and westerly winds, with a strikingly regular period of approximately 28 months. The oscillation is an emergent phenomenon, arising from the interaction of equatorial Kelvin and gravity waves with the mean zonal flow in the tropical lower stratosphere.
iii. Stratospheric polar vortices are regions of intense westerly winds encircling the pole and are the dominant feature of the extratropical stratosphere during winter. The strong winds result from thermal wind balance in concert with the steep temperature gradient that forms between polar and mid-latitudes during the polar night. Polar vortices can display high variability on short time scales, as a result of wave breaking. This variability is significantly larger in the Artic than the Antarctic, owing to stronger wave driving from topography and land-sea temperature contrasts. The archetypal example of this variability is a Sudden Stratospheric Warming (SSW), during which the vortex breaks down, the westerly winds reverse in direction, and stratospheric temperatures can rise by as much as 50 K within a few days.

Trends in these stratospheric phenomena can have far-reaching consequences beyond the stratosphere. It has now become well-established that stratospheric polar vortex variability can significantly impact large-scale modes of surface climate variability, such as the Northern and Southern Annular Modes (NAM, SAM) and the North Atlantic Oscillation (NAO), with subsequent effects on the probability of weather extremes (Kidston et al., 2015). This downward coupling has been attributed to both large-scale balance arguments (Black, 2002), as well as eddy feedback mechanisms (Song and Robinson, 2004), and is particularly strong following SSW events. More recently, work on stratosphere-troposphere coupling has extended to include the tropics (Haynes et al., 2021), through an impact on deep convection by modulation of upper tropospheric static stability. Coupling to the ocean has also been explored, including impacts on sea-surface temperatures and ocean circulation. Given these results it can be expected that uncertainty in stratospheric circulation trends will project onto uncertainty in surface climate trends.

The growing understanding of the stratospheric influence on surface climate has motivated a widespread increase in the vertical resolution and top level altitude of climate models. In the fifth Coupled Model Intercomparison Project (CMIP5), less than half of the models had an uppermost level above the stratopause (about 1 hPa), resulting in a poor representation of stratospheric circulation (Charlton-Perez et al., 2013). However, in CMIP6 the vast majority have a lid above the stratopause and about two-thirds of models resolve above 0.1 hPa (Ayarzagüena et al., 2020). Outstanding progress has also been made in the number of models able to simulate an internally-generated QBO; rising from about 10% of models in CMIP5 to 50% in CMIP6 (Kim et al., 2020), although still with a significant spread in their periods and amplitudes. Despite these advances, several key stratospheric processes remain poorly-represented in most climate models. For instance, the vast majority of models do not include interactive ozone chemistry and so prescribe ozone concentrations generated by other models, preventing feedbacks between chemistry, radiation and dynamics (Keeble et al., 2021).

Although the focus of this chapter is on the representation of historical and future trends in climate models, it is important to note that we now have approximately 45 years of global satellite observations of the stratosphere. These observations include atmospheric composition, most notably ozone and water vapor, as well as temperature, and most recently direct wind observations with the ESA Aeolus instrument. An even longer, though spatially much sparser, record exists for radiosonde observations. However, due to changes in instrumentation over this period, directly reconstructing trends from observational data is not trivial (Maycock et al., 2018; Steiner et al., 2020). Deriving trends in circulation from tracers or from reanalysis products has proven particularly challenging (Ploeger et al., 2019; Garny et al., 2024). Therefore climate models remain a vital tool for understanding stratospheric trends even over the historical period.

The remainder of this chapter is organized as follows. The next three sections will discuss the current understanding of historical and projected future trends in the BDC (Section "Brewer-Dobson circulation trends"), QBO (Section "Quasi-Biennial oscillation trends"), and stratospheric polar vortices (Section "Polar vortex trends"). We will then discuss the impact of these trends on the broader climate system, including the troposphere and ocean (Section "Impact of stratospheric circulation trends on the troposphere, surface, and ocean"). Finally, we will discuss the outlook for the projection of stratospheric circulation trends and their impacts, as well as potential new drivers of future trends (Section "Summary and outlook").

Brewer-Dobson circulation trends

The advective component of the Brewer-Dobson circulation, called the residual circulation, is driven by deposition of westward momentum, or wave drag associated with the dissipation of Rossby and gravity waves (Andrews et al., 1987). Two branches of the residual circulation are typically considered; the deep branch extending to polar latitudes and the shallow branch limited to levels below 50 hPa and latitudes equatorward of 60° (Birner and Bönisch, 2011).

In addition to being advected by the residual circulation, air parcels are mixed, and this occurs mainly following large scale stirring of the flow associated with breaking waves just outside of the polar vortex (McIntyre and Palmer, 1983). A measure of the net tracer transport is the mean age of air, which constitutes the mean residence time of an air parcel in the stratosphere since it enters through the tropical tropopause (Waugh and Hall, 2002; Garny et al., 2024).

Climate models project an acceleration of both branches of the residual circulation in response to GHG increases (Butchart, 2014; Abalos et al., 2021). Fig. 1 shows the change from the present to the end of the century in the vertical component of the residual circulation, $\overline{w}^*$, for the high emission scenario ssp5–8.5 of CMIP6. Tropical upwelling and extratropical downwelling are strengthened, except in the SH polar lower/middle stratosphere. A decrease in the mean age of air is robustly projected by models throughout the stratosphere due to the acceleration of the residual circulation, while changes in mixing are more uncertain across models (Eichinger et al., 2019).

In addition to increasing GHG, ozone depleting substances (ODS) are a major anthropogenic forcing of the Brewer-Dobson circulation. In particular, stratospheric ozone depletion has substantially contributed to accelerate the residual circulation, especially in the SH, over the last decades of the 20th century (Li et al., 2008; Oman et al., 2009; McLandress et al., 2010; Oberländer et al., 2013; Polvani et al., 2018). The projected recovery of stratospheric ozone over the 21st century is associated with a weakening of the BDC that will partly compensate the acceleration due to GHG increase, leading to an estimated average reduction by a factor of a half in the global mean age of air trend over the 21st century as compared to the ozone depletion period (Polvani et al., 2019). The effect of ozone recovery is evidenced by the weakening of the residual circulation in the SH (Fig. 1). Still, in experiments driven only by CO_2 increase there is no acceleration in the SH polar lower stratosphere (Abalos et al., 2021) due to the changes in the polar vortex (Section "Polar vortex trends").

Regarding mechanisms for projected BDC trends, the acceleration of the shallow branch of the residual circulation is explained by enhanced wave propagation and dissipation in the subtropical lower stratosphere due to the strengthening of the upper flanks of

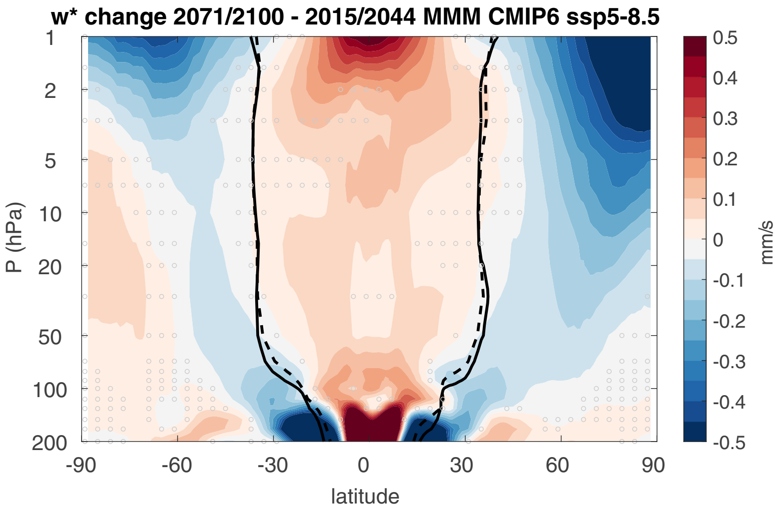

Fig. 1 Change in the vertical component of the residual circulation $\overline{w}^*$ (in mm s^{-1}) averaged over the periods 2015–2044 and 2071–2100. Thick black solid (dashed) lines show the turnaround latitudes in the first (second) period. Multi-model mean computed from ensemble means of the CMIP6 high top models with DynVarMIP output (3 members each): CESM2-WACCM, HadGEM3-GC31-LL, MRI-ESM2–0 and UKESM1–0-LL. Gray circles indicate regions where at least one model does not agree on the sign of the change.

the subtropical jets linked to tropical upper tropospheric warming and stratospheric cooling under increasing GHG (Garcia and Randel, 2008; Shepherd and McLandress, 2011). Both resolved Rossby waves and orographic gravity waves are responsible for the acceleration, with different relative contributions across models (Butchart et al., 2011). For the deep branch, there are larger uncertainties in the magnitude of the trends and the contributions of different waves. In particular, the models disagree on the contribution from resolved Rossby waves and parameterized orographic and non-orographic gravity waves (Butchart et al., 2011; Abalos et al., 2021). The relative contribution of different types of waves is further complicated by the compensation mechanism that occurs between resolved and parameterized waves in both the climatology and the externally forced changes (Cohen et al., 2013; Sigmond and Shepherd, 2014).

Another important consideration is that the acceleration of the BDC reflects in part the upward shift of the tropopause due to tropospheric thermal expansion under global warming (Oberländer-Hayn et al., 2016). Consequently, the trends in residual circulation are reduced in tropopause-relative coordinates. Moreover, it has been recently pointed out that the stratospheric cooling associated with GHG forcing leads to a shrinking of the stratosphere, which implies that the use of a constant scale height as usually done in modeling studies leads to an overestimation by about 20% in the acceleration of the residual circulation (Eichinger and Šácha, 2020; Pisoft et al., 2021).

There is observational evidence to support the trends in the shallow branch over the last 40 years or so (Fu et al., 2019; Ray et al., 2014). The observational estimates of mean age of air in the middle to upper stratosphere show non-significant positive values, in contrast to the model simulations (Engel et al., 2017). However, given the large uncertainties in obtaining the estimates, the spatio-temporal limitations of the data, the latest results show that these observational trends are not inconsistent with the model trends (Garny et al., 2024). While some studies based on model results have concluded that a statistically significant trend should emerge over 40 years or even shorter periods, depending on the circulation metric and the region of the stratosphere (Hardiman et al., 2017; Abalos et al., 2021), observational limitations including poor sampling hamper the detection of trends (Garcia et al., 2011; Rivoire et al., 2024; Garny et al., 2024).

Quasi-Biennial oscillation trends

Given the difficulty of representing the QBO accurately in climate models, largely due to its dependence on parameterized non-orographic gravity waves excited by deep convection, projecting its future changes in response to increasing greenhouse gases remains challenging. Over the last years, substantial progress has been made in simulating the QBO (Anstey et al., 2022a) which has allowed evaluation of its response to a warming climate. A robust weakening of QBO amplitude has been identified across models, as shown in Fig. 2. This is associated with increased tropical upwelling in the lower stratosphere (Butchart et al., 2020; Richter et al., 2022) counteracting the descent of the QBO phases, consistent with the observational findings of Kawatani and Hamilton (2013). In the middle-upper stratosphere, changes in non-orographic GWs dominate the amplitude change. In comparing observed and simulated trends, as in Fig. 2, it is important to also take into account internal variability; although the observed trend lies outside the uncertainty of the multi-model mean in the mid-stratosphere, it may still may be encompassed by the model ensemble spread.

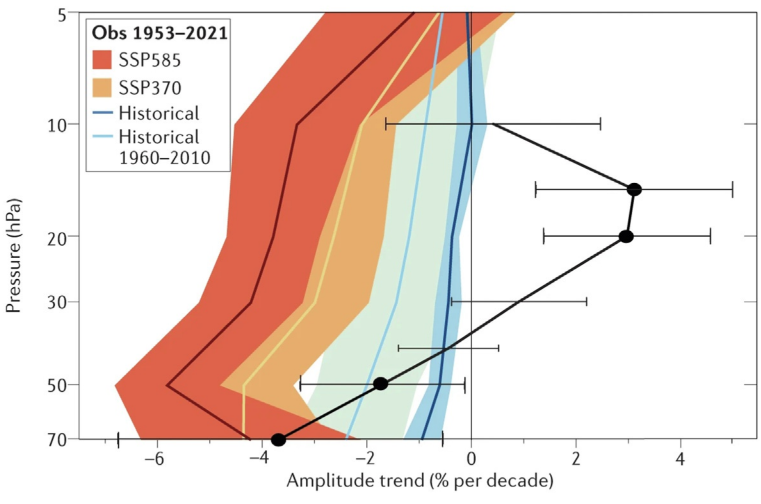

Fig. 2 CMIP6 multi-model mean trend in QBO amplitude in historical and two future scenario simulations. Shading represents the ±2 standard error uncertainty in the multi-model mean. Also shown are observed trends from the FUB radiosonde data set (https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html) (black line, error bars represent range of 95% significance, filled circles denote significant trends). Adapted from Butchart N, Anstey JA, Kawatani Y, Osprey SM, Richter JH, and Wu T (2020) QBO changes in CMIP6 climate projections. *Geophysical Research Letters* 47: e2019GL086903.

In contrast, changes in the periodicity of the QBO are not robust, with some models displaying increased and others decreased period. Changes in periodicity are correlated with changes in gravity wave momentum flux entering the stratosphere (Butchart et al., 2020; Richter et al., 2022), with larger fluxes resulting in shorter QBO periods. Increased gravity wave drag of westward and eastward propagating gravity waves, including resolved Kelvin waves, accelerates the descent of the respective QBO phases (Lee et al., 2024).

It is important to consider the limitations of the QBO representation in global climate models, including its systematically weak amplitude in the lowermost stratosphere (Anstey et al., 2022b), partly due to the low vertical resolution. Moreover, as the QBO is tuned for the present climate and reliant on gravity wave parametrizations, its future evolution may not be correctly represented (Anstey et al., 2022b). Most models underestimate gravity wave drag in the present climate (Holt et al., 2022), and there is large uncertainty on how resolved waves will change in a warming climate, largely due to uncertainties in convective parametrizations.

Two disruptions of the highly regular QBO have been recently observed in the boreal winter of 2015/2016 and 2019/2020 (Newman et al., 2016; Osprey et al., 2016; Anstey et al., 2021), unprecedented in the observational record of over 50 years. These extremely anomalous events raise the question whether the QBO may undergo more frequent disruptions in the future, especially considering its expected weakening and the shift of the critical line towards the equator which may facilitate extratropical wave penetration into the deep tropics (Anstey et al., 2021). However, models simulate a QBO that is more regular than that observed and generally fail to capture disruption events.

Polar vortex trends

Arctic

In the NH, dynamical variability of the stratospheric polar vortex is much larger than in the SH, owing to the stronger tropospheric wave driving. This large internal variability makes detecting and attributing trends challenging. In the observational record, there has been no clear trend in the mean strength or variability of the NH polar vortex. While there has been an increase in the frequency of SSW events since the 1990s, when very few events were observed, work inferring historical SSW frequencies from NAO records has shown that the 1990s likely had the longest absence of SSWs during the past 150 years (Domeisen, 2019). Hence the subsequent increase in SSWs can be attributed to a return to climatological frequencies, likely associated to low frequency internal variability, rather than an externally-driven trend.

Several studies have investigated simulated trends in SSW frequency under increased GHG forcing, all of which have found the trends to be highly model-dependent. Ayarzagüena et al. (2020) found approximately equal numbers of CMIP6 models simulating either a statistically significant decrease, no significant change, or a statistically significant increase in SSW frequency under a quadrupling of CO_2. In some models, the change was not only statistically significant but also large, with as much as a doubling or halving in SSW frequency. Similar disagreement as to the sign of the SSW change has been found in CMIP5/6 simulations with more realistic transient forcing (Rao and Garfinkel, 2021) and in models with interactive chemistry (Ayarzagüena et al., 2018). As for SSWs, changes in the mean NH polar vortex strength (typically measured by winter-mean zonal-mean zonal wind at 10 hPa and 60°N) are also highly model-dependent (Wu et al., 2019; Karpechko et al., 2022). Among CMIP6 models there is an approximately 50/50 split between those that predict a strengthening or a weakening of the vortex under increasing GHG concentrations, many of the changes being highly statistically significant (Fig. 3). The model dependence of these projected trends is such that, by the end of this century, it dominates all other sources of spread including internal variability and scenario uncertainty (Karpechko et al., 2022). Moreover, the uncertainty in trends increases as the GHG forcing increases.

Despite the uncertainty discussed above, some aspects of NH polar vortex trends have been found to be broadly consistent among model projections. Ayarzagüena et al. (2020) found CMIP6 models to robustly predict an earlier formation date and a later decay date (known as *final warming* date) under increased GHG forcing, meaning a longer fraction of the year during which polar vortex variability is coupled with the surface. This robustness can be understood in terms of the radiative effect of GHGs cooling the polar vortex and leading to it being longer-lived (the competing influence of changes in wave driving, which dominates uncertainty in mid-winter vortex projections, is much smaller in the shoulder seasons). An eastward shift in the mean central location of the vortex is also a consistent trend in both CMIP5 (Matsumura et al., 2021) and CMIP6 (Karpechko et al., 2022) models; a trend which is also seen, though not statistically significant, in reanalysis data (Zhang et al., 2016; Seviour, 2017). This shift has been attributed to zonal asymmetries in the pattern of surface temperature warming, with subsequent effects on stationary waves.

Beyond the direct impact of increasing GHG concentrations, several studies have investigated how GHG-driven changes in other climate system components might impact the stratospheric polar vortex. The topic of most interest has been the impact of melting Arctic sea-ice, which has been linked to a weakening of the polar vortex through enhanced upward wave propagation from the troposphere to the stratosphere (Kim et al., 2014; Kretschmer et al., 2020; Zheng et al., 2023; Liang et al., 2024). The impacts of sea-ice loss in different Arctic regions can interact either constructively or destructively with the climatological stationary wave pattern, such that some regions have a larger overall effect on weakening the polar vortex (Screen, 2017; McKenna et al., 2018); a region identified as particularly important is the Barents-Kara Sea (De and Wu, 2019; Zhang et al., 2018; Kretschmer et al., 2020). However, several modeling studies have also found the overall sea-ice impact on the polar vortex to be weak (Cai et al., 2012; Seviour, 2017) and modeldependent (Smith et al., 2022), and so potentially contributing to the total uncertainty in the GHG forcing response discussed above. A further confounding factor is the possibility that the vortex response to sea-ice loss may be dependent upon the state of internal climate variability, for example to the phases of the QBO (Labe et al., 2019) and Pacific Decadal Oscillation (PDO) (Simon et al., 2022). These results may reflect the importance of the basic stratospheric state in the

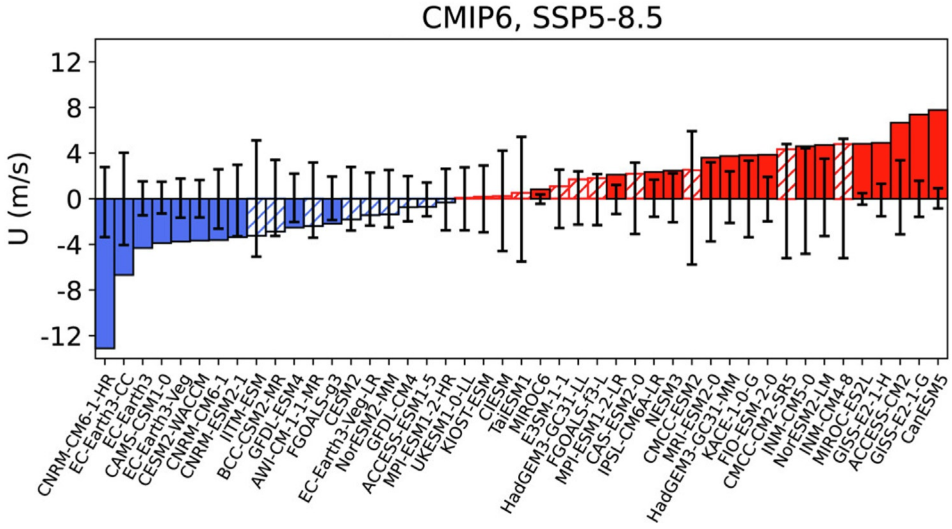

Fig. 3 Changes in the strength of the NH polar vortex, measured by the DJF-mean zonal-mean zonal wind at 10 hPa, averaged from 60°N to 75°N, in CMIP6 models. The difference is shown between 2070 and 2099 and 1980–2009 under the SSP585 experiment. Error bars show the 95% confidence interval, obtained from sampling model pre-industrial control simulations with an equivalent sample size to that used for the bars. Hatching indicates where the simulated trend is not significant. Adapted from Karpechko AY, Afargan-Gerstman H, Butler AH, Domeisen DI, Kretschmer M, Lawrence Z, Manzini E, Sigmond M, Simpson IR, and Wu Z (2022) Northern hemisphere stratosphere-troposphere circulation change in CMIP6 models: 1. Inter-model spread and scenario sensitivity. *Journal of Geophysical Research: Atmospheres* 127: e2022JD036992.

response (discussed further below) since, for instance, the phase of the QBO impacts the mean vortex strength (Holton and Tan, 1980), but also may be related to other nonlinear interactions between the QBO/PDO and the impact of sea-ice loss.

Stratospheric ozone changes are another potential driver of NH polar vortex trends. The NH polar vortex is warmer than its SH counterpart due to larger wave activity, resulting in much more limited ozone depletion over the last decades of the 20th century. Future projections show that ozone will recover and potentially surpass historic concentrations by the end of the present century as a result of both reductions in ODS and stratospheric cooling caused by increased GHG concentrations (WMO, 2022). This *super recovery* of ozone has been shown in coupled chemistry models to drive a slight reduction in the lower-stratospheric meridional temperature gradient, and so, by thermal wind balance, a small weakening of the polar vortex (Chiodo and Polvani, 2019; Li and Newman, 2023), along with a dampening of the BDC acceleration (Hufnagl et al., 2023). The impact of ozone recovery is likely to be greater in springtime than in winter since the presence of sunlight in spring has led to greater Arctic ozone depletion in this season, meaning that larger ozone changes are involved in its recovery. However, even though coupled chemistry models consistently show that isolated effect of ozone recovery is a weakening of the springtime polar vortex, this consistency is not sufficient to overcome the inconsistency in the response to GHG forcing, such that the net trend remains uncertain among these models (Chiodo et al., 2023). The weakening effect of ozone recovery is also not sufficient to reverse the GHG-driven delay of the vortex breakdown; a small delay in the breakdown date is still seen in future CMIP5 and CMIP6 simulations which include prescribed ozone recovery (Rao and Garfinkel, 2021).

A consistent theme of the discussion above is the extent of model-dependency in most, though not all, aspects of the NH polar vortex response to climate forcings; a situation that has unfortunately not significantly improved from one model generation to the next, even as vertical resolution has increased. However, several recent studies give cause for optimism by bringing some physical insight into the model-dependency and so indicating how it might be reduced. In particular, studies have pointed towards a key role for biases in the basic state of zonal winds in the so called *neck region* in the lower stratosphere, between the subtropical jet and the polar vortex (Karpechko et al., 2024; Sigmond and Sun, 2024; Mudhar et al., 2024). This region is particularly important in modulating the propagation of planetary waves from the troposphere to the stratosphere, such that biases in its mean winds can significantly impact the ability of changes in tropospheric wave activity to influence the stratosphere. Using this metric Karpechko et al. (2024) were able to construct an 'emergent constraint' on the CMIP6 polar vortex future projections, but this only marginally reduced uncertainty and the constraint was not found for CMIP5 models. It remains to be seen whether model improvements in this area–for instance, through changes to gravity wave parametrizations–may be able to reduce spread in future model intercomparisons.

Antarctic

Trends in the SH stratospheric polar vortex are much more easily detected than those in the NH because both the signal of historical forcing due to ozone depletion is larger, and the noise of internal variability is lower. Ozone depletion causes a cooling of the polar stratosphere which is strongest in springtime, resulting in a stronger meridional temperature gradient in the lower stratosphere and, through thermal wind balance, a stronger and longer-lived polar vortex (e.g. Gillett and Thompson, 2003). Trends of both an increasing mean strength and delayed break-up date of the SH polar vortex have been robustly identified in the observational record, although the latter has been highly variable over the last two decades (Langematz and Tully, 2018; WMO, 2022).

In contrast to results for the NH, the simulated response of the SH polar vortex to increasing GHG concentrations is a robust strengthening, which is largest in November–December (Ceppi and Shepherd, 2019). Here the dominant mechanism is radiative, with greater GHG concentrations cooling and therefore strengthening the polar vortex (McLandress et al., 2010), however GHG-driven changes in dynamical forcing have also been shown to be important, and lead to significant model spread in the magnitude of the response (Ceppi and Shepherd, 2019). Along with this strengthening, a reduction in wave-driving at southern high latitudes, and so a reduction in residual circulation downwelling is also simulated (Abalos et al., 2021, Section "Brewer-Dobson circulation trends"). A further effect of the polar vortex strengthening is a delayed vortex break-up date (Wilcox and Charlton-Perez, 2013), though the magnitude of this delay varies from about 5 to 30 days in CMIP6 simulations (Ceppi and Shepherd, 2019).

The results described above show qualitatively similar impacts of ozone depletion and increased GHG concentrations on the SH polar vortex. Ozone and GHG changes have therefore worked together during the period of rapid Antarctic ozone depletion (approximately 1980–2000). However, Antarctic column ozone is projected to recover at least to 1980 levels during the remainder of the 21st century (WMO, 2022), a trend of which there are already some indications in the observational record (Solomon et al., 2016; Wang et al., 2025). Hence GHG and ozone driven trends are projected to be of opposite sign in this time period, leading to a large cancellation in the net trend (Polvani et al., 2011). As a result, the date of the SH polar vortex break-up is not projected to be significantly further delayed beyond the trend already observed during the ozone depletion period (Rao and Garfinkel, 2021; Mindlin et al., 2021).

While the combined effects of ozone and GHG forcing on the mean strength of the SH vortex are relatively well known, impacts on vortex variability are more uncertain. There has only been one SH SSW (in September 2002) meeting the definition of a reversal of zonal-mean zonal wind at 60°S and 10 hPa, but recent years have seen significant SH vortex variability, with a very near SSW in 2019 and very strong, long-lasting vortices in 2020 and 2021. This has motivated research into whether such increased variability may be externally-driven. Given their rarity the probability of SH SSWs is difficult to determine, but has been estimated from historical climate model simulations at approximately 1 in 25 years (Wang et al., 2020; Jucker et al., 2021), meaning that the two observed (if we count 2019) are not unexpected. Jucker et al. (2021) also found a large reduction in SH SSW frequency by the end of the 21st century in high-emission CMIP6 simulations, a trend driven by a strengthening of the vortex caused by GHG concentrations continuing to increase beyond the time of ozone recovery. In summary, there is not any evidence that recent large SH polar vortex variability is anthropogenically driven, although there has been relatively little research in this area.

Impact of stratospheric circulation trends on the troposphere, surface, and ocean

Northern Hemisphere extratropics

Anomalies in the strength of the stratospheric polar vortex are known to significantly influence extratropical tropospheric circulation, particularly the jet streams and storm tracks and related annular modes (Kidston et al., 2015). A result of this coupling is that the large uncertainty, discussed above, in simulated future NH stratospheric polar vortex trends, has been shown to contribute to the total uncertainty in extratropical tropospheric circulation trends. Specifically, models with a strengthened polar vortex simulated a more positive trend in the NAO and NAM than models in which the polar vortex weakens (Karpechko et al., 2022). The importance of uncertainty in NH polar vortex trends in overall trends of sea-level pressure has been identified by both regression across CMIP5 (Manzini et al., 2014) and CMIP6 (Karpechko et al., 2022) simulations as well as by directly imposing stratospheric perturbations, representative of the inter-model spread, in a single model (Simpson et al., 2018).

Future projections of North Atlantic circulation change have been commonly viewed as resulting from a 'tug-of-war' between the effects of near-surface polar and upper-tropospheric tropical amplification, which have opposing effects on the meridional temperature gradient (e.g. Harvey et al., 2014). More recently, uncertainty in NH polar vortex trends has been shown to contribute the total uncertainty by an approximately equal amount as these two factors (Zappa and Shepherd, 2017), and so polar vortex trends have been proposed to ultimately decide the winner in the tug-of-war (Peings et al., 2019). The relative roles of model uncertainty in polar and tropical warming as well as polar vortex strength are illustrated in Fig. 4. Here the uncertainty in polar vortex strength can be seen to project onto 850 hPa zonal wind which is informative of jet stream location and storm track activity. The stratospheric impact is strongest in the North Atlantic basin, with a strengthened polar vortex favoring a poleward jet shift, consistent with a positive phase of the NAO. Further highlighting the importance of uncertainty in polar vortex trends is the result that this uncertainty also significantly contributes to uncertainty in precipitation projections, particularly in Europe where a weakening of the vortex is associated with a relative drying in the north and a wetting in the south, and conversely for a vortex strengthening (Scaife et al., 2012; Karpechko et al., 2022).

In addition to changes in vortex strength, trends in polar vortex morphology may also have significant surface climate impacts. SSWs can be classified as those characterized by a splitting of the polar vortex and those in which the vortex remains intact but displaces significantly from the pole (Charlton and Polvani, 2007). Some studies have found that the different types of event may have different surface impacts (Mitchell et al., 2013; Hall et al., 2021b), although there remains significant uncertainty in the

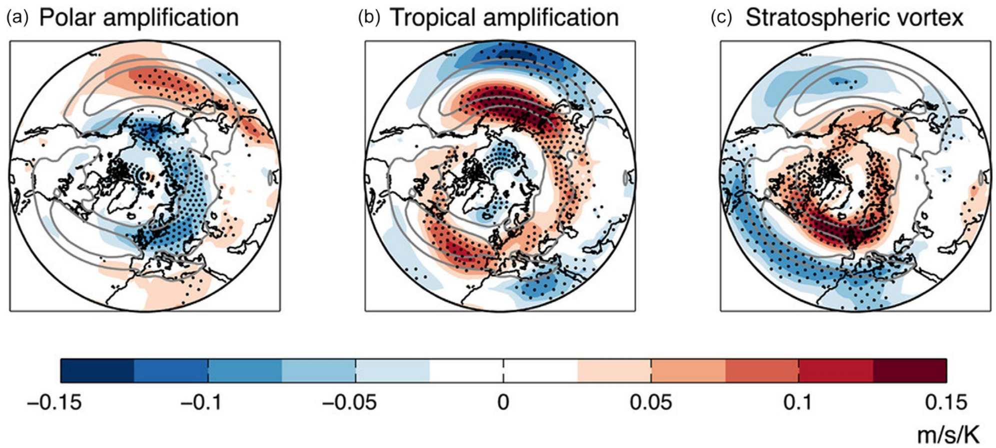

Fig. 4 Sensitivities, derived through a regression framework, of CMIP5 climate change projections (2070–2100 minus 1960–90 under the RCP8.5 scenario) of zonal wind at 850 hPa to a one standard deviation positive anomaly in lower-tropospheric polar warming (a), upper tropospheric tropical warming (b), and zonal-mean zonal wind at 20 hPa averaged from 70°N to 80°N. The gray contours mark the 8 m s^{-1} (inner) and 4 m s^{-1} (outer) 850 hPa zonal wind in the multimodel mean of the historical simulations. Stippling indicates areas with significant regression coefficients at the 5% level. From Zappa G and Shepherd TG (2017) Storylines of atmospheric circulation change for European regional climate impact assessment. *Journal of Climate* 30: 6561–6577. ©American Meteorological Society. Used with permission.

magnitude of any difference due to inter-model spread (Seviour et al., 2016b) and the relatively limited number of each type of SSW in the observational record (Maycock and Hitchcock, 2015). Mitchell et al. (2012) found an increase in vortex displacement events in a high-emission future simulation, although no overall change in SSW frequency. Models, however, have very large biases in their representation of split and displaced vortex events (Hall et al., 2021a), and so the results from a single model should be treated with caution. As discussed above, a more robust model projection is an eastward shift in the vortex center. This shift has been related to changes in tropospheric stationary wave patterns that may drive a surface cooling over central Siberia and northern Canada, with the potential to offset some of the climate change-driven warming in these regions (Zhang et al., 2016).

The effects of 21st century ozone recovery on the NH polar vortex have also been shown to have significant surface impacts that are particularly strong in spring. Chiodo et al. (2023) showed that ozone super recovery cancels approximately 20% of the GHG-driven springtime trend in NH sea-level pressure over the 21st century, with the ozone-driven weakening of the polar vortex favoring a more negative phase of the NAM. Neglecting this feedback has been shown to lead to a significant overestimation of the strength of GHG-driven circulation trends (Li and Newman, 2023), including impacts on precipitation patterns (Chiodo and Polvani, 2019).

Beyond the impact of long-term NH polar vortex trends, it is plausible that the strength of subseasonal stratosphere-troposphere coupling may be affected by climate change, for instance due to changes in the mean strength or location of the jet stream. This possibility was investigated by Ayarzagüena et al. (2020) who compared sea-level pressure anomalies following SSWs in pre-industrial and CO_2 quadrupling experiments. They found generally small changes in the surface anomalies following SSWs in the two scenarios, with little model agreement on any change in the North Atlantic, but some indication of a consistent trend towards stronger anomalies in the North Pacific. Overall however, the possibility of climate change-driven changes to the strength of stratosphere-troposphere coupling remains relatively little investigated.

Some studies have investigated the role of the NH polar vortex not just on surface climate but on deep ocean circulation and associated long-term climate variability. It has been proposed, using coupled model simulations, that there is co-variability between the Atlantic Meridional Overturning Circulation (AMOC) and Arctic stratosphere, with the stratosphere acting to enhance multi-decadal AMOC variability (Schimanke et al., 2011; Reichler et al., 2012). This coupling was further investigated by Dimdore-Miles et al. (2022), who proposed, using a spectral analysis method, that the lack of SSWs in the 1990s contributes approximately 30% of the recent slowing trend in the AMOC. However, understanding of the physical mechanisms linking NH stratospheric and ocean variability remains relatively poorly understood.

Southern Hemisphere extratropics

Relative to the NH, there is much greater confidence in the role of the stratosphere in historical and future SH surface climate trends. Most notably, Antarctic ozone depletion and its associated SH polar vortex strengthening has been demonstrated to drive a poleward intensification of the extratropical jet and a poleward expansion of the Hadley cell, consistent with the positive phase of the SAM (e.g. Son et al., 2018). The magnitude of this SAM trend from 1980 to 2000 is such that it lies outside the range of natural internal variability inferred from climate reconstructions of the last millenia (Fogt and Marshall, 2020).

There is now also evidence that the emerging recovery of the Antarctic ozone hole since 2000 has had an effect on the troposphere, with a notable leveling or slight reversal of summertime trends in the SAM and jet and Hadley cell latitudes during this period (Banerjee et al., 2020). The attribution of the leveling of these trends to ozone recovery is further supported by coupled chemistry-climate and prescribed-ozone simulations (Banerjee et al., 2020; Zambri et al., 2021). Continued ozone recovery during the next century is projected to act to oppose and reduce a GHG-driven positive trend in the SAM (Mindlin et al., 2021). Although GHG forcing is projected to be dominant, such that the overall trend is very likely to remain positive even in low-emission scenarios, the strength of projected ozone recovery has been shown to have a significant impact on overall 21st century circulation trends (Revell et al., 2022).

Although the studies discussed above have focused on ozone-driven changes in zonal-mean circulation, the observed poleward jet shift from 1980 to 2018 is not zonally-symmetric, being only present in the Atlantic and Indian Ocean sectors, not in the Pacific (Waugh et al., 2020). There is evidence from climate model simulations that this zonal asymmetry is consistent with internal variability rather than a direct result of ozone forcing (Waugh et al., 2020). Uncertainties in even zonally-symmetric circulation changes can also imprint on regional scales. For example, Mindlin et al. (2021) showed that model uncertainty in the projected delay of the vortex breakup date can explain a significant fraction of uncertainty in precipitation trends in South America, Southern Africa and Australia.

Moving down from the troposphere, several recent studies have investigated ozone impacts on the ocean and cryosphere. A positive SAM is associated with poleward shift and increase in westerly wind stress over the Southern Ocean, which, in turn, results in equatorward Ekman transport and upwelling at high latitudes. The impacts of these two ocean circulation responses can have opposing influences on sea-surface temperature (SST), since Ekman transport acts to move cold polar water equatorward thereby cooling the Southern Ocean, and upwelling brings warm water from depth, warming the surface. Some modeling studies have found these two responses to act on different time scales, with a short-term cooling preceding a long-lived warming in response to an abrupt ozone perturbation (Ferreira et al., 2015; Seviour et al., 2016a). This two time scale response appears similar to observed Southern Ocean SST trends, which have displayed a cooling from about 1980–2016, followed by a warming in more recent years. However, the two time scale response is not robustly seen under more realistic transient ozone forcing (Seviour et al., 2019), and high-resolution simulations have shown the upwelling associated with long-term warming to be damped by mesoscale eddy compensation (Doddridge et al., 2019). Overall, there is relatively low confidence about the role of ozone depletion and associated stratospheric trends in observed Southern Ocean SST trends.

A similar two time scale response to SAM forcing has been found in several models for Southern Ocean sea ice, with a short-term expansion and longer-lived contraction (Holland et al., 2017). However, the summertime SAM explains only 15% of interannual variability in autumn sea-ice extent, and so ozone-driven SAM trends are unlikely to have been a major driver of observed sea-ice trends (Polvani et al., 2021). Modeling results indicate that ozone recovery may act to compensate for some of the GHG-driven warming and sea-ice melting over the 21st century (Li et al., 2023). However, this compensation may not occur in the summer when the sea-ice edge has retreated from the region of strengthened westerly winds (Li et al., 2025), and there remains large uncertainty in the magnitude of any compensation due to significant model biases in the representation of ocean-atmosphere thermodynamic coupling (Chemke and Polvani, 2020).

Below the mixed layer, the Southern Ocean has seen a large-scale warming and freshening since the 1950s (Swart et al., 2018). There is modeling evidence that this trend has been significantly driven by the poleward intensifying zonal winds (Bronselaer et al., 2020). However, detection and attribution studies have found that the warming associated with GHG increases over this period is the dominant driver, and ozone depletion-related circulation changes have a smaller role (Solomon et al., 2015; Swart et al., 2018). The exact size of the ozone contribution to historical trends remains highly uncertain due to both model uncertainty and the fact that ozone and GHG signatures on ocean temperature are similar and therefore challenging to separate.

Tropics

The stratosphere influences the tropical troposphere climate through several pathways, which are less extensively studied than stratosphere-troposphere coupling in the extratropics (Haynes et al., 2021). There is evidence that transient intensification of the Brewer-Dobson circulation associated with Sudden Stratospheric Warmings can affect tropical upper tropospheric stability and thus deep convection (Kodera, 2006; Eguchi et al., 2015). It is now well established that the phase of the QBO influences the deep convection and precipitation in the tropics, mainly by modulating the Madden-Julian Oscillation (MJO) (Martin et al., 2021). In particular, a stronger and slower-propagating MJO in winter has been connected to the easterly phase of the QBO in the lower stratosphere (Yoo and Son, 2016; Martin et al., 2021; Hood and Hoopes, 2023). Such influence is largely due to the QBO temperature and static stability anomalies in the tropical lower stratosphere induced by the residual circulation anomalies. However, additional mechanisms such as cirrus clouds radiative feedbacks, wind shear effects and others are likely contributing (Martin et al., 2021). While this connection is robust in observations, it is poorly represented in climate models. This has been proposed to be due to their mis-representation of QBO anomalies in the lower stratosphere (Kim et al., 2020), however, nudging experiments that remove model QBO biases have also been found to have the same problem (Martin et al., 2023), and so the causes of the lack of QBO-MJO connection in models remain unclear. Therefore, the future evolution of this MJO-QBO connection is highly uncertain. More in general, future changes in stratosphere-troposphere coupling in the tropics remain largely unexplored and present substantial challenges due to the limitations in modeling of cloud feedbacks and convective parameterizations.

Stratosphere-troposphere exchange

An important effect of the acceleration of the Brewer-Dobson circulation is to enhance the exchange of chemical constituents between the troposphere and stratosphere. The transport of ozone from the stratosphere into the troposphere is projected to increase over the 21st century (Wang and Fu, 2023). This enhancement is mainly due to the increase in ozone concentration in the extratropical lower stratosphere, which is in turn due to both the acceleration of the Brewer-Dobson circulation and the decline in ODS and subsequent recovery of the ozone layer (Banerjee et al., 2016; Meul et al., 2018; Abalos et al., 2020). While the stratospheric ozone contribution will increase in the future, the evolution in tropospheric ozone concentrations depends largely on the emissions of ozone precursors (Archibald et al., 2020; Griffiths et al., 2020).

Summary and outlook

Overall, we have seen that both rising GHG concentrations and ozone depletion have been the dominant drivers of significant historical trends in many of the large-scale features of stratospheric circulation. The latest generation of climate models are generally able to well capture these historical trends, although significant uncertainty remains in the attribution to forcing versus internal climate variability. Our understanding is less clear when it comes to projected future trends. This is due in part to the fact that the effects of rising GHG concentrations and recovering ozone levels are usually in opposition, adding to uncertainty in the net overall trend.

Table 1 summarizes current understanding of the effects of 21st century changes to stratospheric circulation. This shows that for some circulation features–the strength of the BDC, the seasonal duration of the NH polar vortex, and the strength of the SH polar vortex–GHG forcing is likely to dominate the counteracting impact of ozone recovery. In the case of the SH polar vortex duration, where ozone has a larger impact, the two effects are predicted to approximately cancel. Large uncertainties remain for other aspects, particularly the NH polar vortex strength, which has large model dependence in the response to GHG forcing, and both the amplitude and period of the QBO.

We have shown that there is substantial evidence from recent modeling experiments that stratospheric circulation changes are capable of driving significant changes in tropospheric circulation, including in the strength and location of the jet streams in the extratropics, as well as in tropical convection. Where the sign of historical and future stratospheric change is relatively well-known, such as in the Antarctic, this stratosphere-troposphere coupling can help explain surface trends. However, where stratospheric change is poorly-understood, such as in the Arctic and tropics, the stratosphere adds significant uncertainty to surface projections.

In the last decade, moving from CMIP5 to CMIP6, there has been rapid progress in models' stratospheric resolution and ability to represent important stratospheric processes such as interactive ozone chemistry. This has led to more accurate simulations of stratospheric circulation, and thus a greater understanding of circulation trends. Future model improvements, for instance in the ability to resolve rather than parameterize gravity waves, are likely to further understanding in coming years (Franke et al., 2023). Machine learning methods have also shown promise in quantifying and understanding uncertainty due to model parameterizations (Mansfield and Sheshadri, 2024). In contrast, a cause for concern in the near future is the upcoming "data desert" caused by the end of the operational lifetimes of the Atmospheric Chemistry Experiment–Fourier Transform Spectrometer (ACE-FTS) and Microwave Limb Sounder (MLS) satellite instruments (Salawitch et al., 2025). This will lead to a gap in global measurements of stratospheric composition and transport, posing challenges for observational calibration and model verification.

This chapter has discussed stratospheric circulation trends driven by GHG and ozone changes, but there are several other contributors to stratospheric circulation change. In the historical period, perturbations to stratospheric circulation have been caused by volcanic eruptions (Coy et al., 2022), powerful wildfires (Solomon et al., 2023), and solar cycle variability (Gray et al., 2010). A major potential driver of future stratospheric circulation change is the prospect of Stratospheric Aerosol Injection (SAI) geoengineering. If SAI were to be implemented, it is projected by modeling experiments to strengthen the polar vortices and accelerate the BDC, although the magnitude of these impacts is highly sensitive to the location of injection, being greater for injection at low

Table 1 Summary of changes in stratospheric circulation discussed in this chapter caused by rising GHG concentrations, ozone recovery, and the projected net trend at the end of the 21st century.

	GHG ↑	*ODS* ↓	*Net*
BDC strength	↑	↓	↑
QBO amplitude	↓	?	↓?
QBO period	?	?	?
NH PV strength	?	↓	?
NH PV duration	↑	↓	↑
SH PV strength	↑	↓	↑
SH PV duration	↑	↓	≈

Up and down arrows indicate increasing and decreasing trends respectively, '?' indicates a highly uncertain/unknown trend, '≈' indicates little/no projected trend.

latitudes (Bednarz et al., 2023). Given the impacts of stratospheric circulation change on broader climate discussed in Section "Impact of stratospheric circulation trends on the troposphere, surface, and ocean," it is unsurprising that SAI-driven stratospheric changes are also projected to have large and potentially unwanted surface impacts (Wunderlin et al., 2024). A greater understanding of stratospheric change and stratosphere-troposphere coupling, along with greater fidelity in their representation in models, will allow this uncertainty to be narrowed and enable better-informed policy making decisions.

Conclusion

Although the stratosphere exists far above our heads and makes up only about 10% of the total mass of the atmosphere, changes in its large-scale circulation, externally forced by ODS and GHG, can have significant impacts on global climate. State-of-the-art climate model simulations have given us a good understanding of historical trends and robust projections of some aspects of future trends; progress that has been enabled by a focus on better resolving and representing stratospheric processes in models. However, in some areas large disagreement among simulated trends persists, most notably in the Arctic polar vortex and the QBO. High resolution simulations and the use of machine learning to constrain or replace parameterizations may help narrow uncertainty in these areas in coming years. Continuing to improve models is particularly important given the increasing likelihood that new natural or anthropogenic drivers of stratospheric change may emerge.

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