Southern Hemisphere Stationary Wave Response to Changes of Ozone and Greenhouse Gases

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ABSTRACT

The Southern Hemisphere (SH) stratospheric stationary wave amplitude increased significantly in late spring and early summer during the last two decades of the twentieth century. A suite of chemistry climate model simulations are examined to explore the underlying cause and the separate effects of anthropogenic forcing from ozone depleting substances (ODSs) and greenhouse gases (GHGs) in the past and projected SH stationary wave evolution. The model simulations produce trends in the wave amplitude similar to that observed, although somewhat weaker. In simulations with changing ODSs, this increase in amplitude is reproduced during the ozone depletion period and is reversed during the ozone recovery period. This response is related to changes in the strength and timing of the breakdown of the SH polar vortex associated with ozone depletion and recovery. GHG increases have little impact on the simulated stratospheric stationary wave amplitude but are projected to induce an eastward phase shift of the waves. This phase shift is linked to the strengthening of the subtropical jets driven by GHG forcing via sea surface warming.

1. Introduction

Stationary waves play an essential role in many aspects of the climate system. For example, regional climate is closely related to tropospheric stationary waves; stratospheric stationary waves have important impacts on stratospheric ozone that directly influences surface ultraviolet radiation (e.g., Gabriel et al. 2011; Ialongo et al. 2012); and there is also increased evidence of downward dynamical links between the stratosphere and troposphere possibly involving stationary planetary waves (e.g., Hartmann et al. 2000; Song and Robinson 2004; Harnik et al. 2011; Smith and Kushner 2012). Stratospheric stationary waves have not been explored thoroughly, especially in the Southern Hemisphere (SH), and there remain many issues in debate (e.g., Lin 1982; Smith 1983; Plumb 1989; Wirth 1991; Quintanar and Mechoso 1995a,b; Scott and Haynes 2002; see also a review by Haynes 2005).

Stratospheric stationary waves play an important role in the SH stratospheric ozone depletion and the associated climate impacts. For example, the zonally asymmetric ozone is responsible for a considerable portion of the observed stratospheric cooling over the Antarctic (e.g., Crook et al. 2008; Gillett et al. 2009; Waugh et al. 2009; Gabriel et al. 2011).

The dynamics of the NH stratospheric stationary wave response to greenhouse gas (GHG) forcing has been primarily linked to changes to the subtropical tropospheric jet that are radiatively forced by GHG increases (Wang and Kushner 2011). On the other hand, ozone depletion is the dominant anthropogenic forcing in the SH stratosphere during the past decades. Hu and Fu (2009) have shown that there is a marked zonally asymmetric component of the SH lower stratospheric temperature trend in the observations and the associated geopotential
height trend in September and October. SPARC CCMVal (2010) has also shown a statistically significant trend of SH stratospheric stationary wave amplitude in reanalysis datasets and the ensemble mean of CCMs in 1980–99. Connections between ozone zonal asymmetries and stationary/ transient waves have also been explored (e.g., Malanca et al. 2005; Grytsai et al. 2007; Canziani et al. 2008). Apart from these studies, there are few investigations on observed and projected stratospheric stationary wave trends in the SH and the underlying dynamics. Here we address the following questions.

1) Is there a robust stationary wave response in the SH stratosphere to anthropogenic forcing?
2) What are the separate effects of ozone and GHG radiative forcing on the SH stationary wave field?
3) What is the dynamical origin of the stationary wave response for each forcing?

The data and methods used for this study are described in the next section. The diagnosis of reanalysis data and CCM simulations is presented in section 3. In section 4 we discuss the underlying dynamics of the stationary wave responses. Results are summarized in section 5.

2. Data and methods

a. Data and models

Monthly reanalysis data and modeling output are used in this study, and we treat the reanalysis data as observations. The reanalysis data include European Center for Medium range Weather Forecasting (ECMWF) 40-Year Re-Analysis (ERA-40) (Uppala et al. 2005), ECMWF Interim Reanalysis (ERA-Interim) (Simmons et al. 2006), and National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996).

The modeling output is from the second phase of the Chemistry Climate Model Validation (CCMVal-2) project (Eyring et al. 2008; Morgenstern et al. 2010). We examine output from simulations where both ozone depleting substance (ODS) and GHG change (REF-B2 in CCMVal-2 nomenclature, but referred to as GHG+ODS here) as well as simulations where only GHGs change (SCN-B2b or GHG-only) or only ODSs change (SCN-B2c or ODS-only). The prescribed GHGs follow the Houghton et al. (2001) Special Report on Emissions Scenarios (SRES) A1b scenario, while the ODSs follow the adjusted WMO (2007) A1 scenario.

The CCMVal-2 models feature a relatively high vertical resolution in the stratosphere and prognostic stratospheric chemistry. All of the models prescribe sea surface temperature (SST) output from coupled atmosphere–ocean models as boundary conditions, except the Canadian Middle Atmosphere Model (CMAM) which has a fully coupled ocean component. Details of the scenarios and the CCMs can be found in Eyring et al. (2008) and Morgenstern et al. (2010).

GHG+ODS simulations by 13 CCMs are diagnosed here (the other 5 CCMs in CCMVal-2 did not provide the zonally asymmetric geopotential height data required in this study). The ensemble mean of GHG+ODS simulations from all 13 models is referred to as “EM13” and each model is given the same statistical weight regardless of its ensemble size. Three of these CCMs also performed the GHG-only and ODS-only simulations: the Center for Climate-Systems Research–National Institute of Environmental Studies (CCSRNIES) (Akiyoshi et al. 2004; Kurokawa et al. 2005), CMAM (Beagley et al. 1997; de Grandpré et al. 2000; Scinocca et al. 2008), and Solar-Climate-Ozone Links (SOCOL) (Egorova et al. 2005; Rozanov et al. 2005) models. The ensemble mean of CCSRNIES, CMAM, and SOCOL is referred to as “EM3.” For some of the results in section 3, these three models are analyzed individually because they treat SSTs in distinctive ways. CMAM has a fully coupled ocean module and thus does not rely on prescribed SSTs. CCSRNIES follows the standard protocol in employing SSTs, using SSTs with fixed GHGs for the ODS-only scenario and SSTs with GHG increases for GHG+ODS and GHG-only scenarios. SOCOL uses the same SSTs with GHG increases for all three scenarios.

b. Methods

The stationary wave field is defined as the zonally asymmetric geopotential height (denoted \( Z^* = Z - \bar{Z} \)), where brackets represent zonal mean; the overbar for time mean is omitted for simplicity). The stationary wave amplitude (denoted \( |Z^*(p, \theta)| \)) is defined as the root mean square of \( Z^* \) at each latitude and pressure level:

\[
|Z^*(p, \theta)| = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} [Z^*(p, \theta, \lambda)]^2 d\lambda},
\]

where \( \lambda \) is longitude, \( \theta \) is latitude, and \( p \) is pressure. Geopotential height \( Z^* \) can be decomposed into wave-numbers:

\[
Z^* = \sum_k A_k \cos[k(\lambda - \lambda_k)],
\]

where \( A_k \) and \( \lambda_k \) represent the amplitude and phase for the \( k \)th wavenumber (\( k = 1, 2, 3, \ldots \)).

Data between 1979 and 2001 are used to calculate SH stationary wave trends when we directly compare
models and observations. The period is chosen to account for the quality of the reanalysis datasets and the time evolution of ozone in the SH stratosphere. The SH stratosphere observations are of poorer quality prior to the satellite era (before 1979). The SH stratospheric ozone has started to recover since early 2000s because most ODSs started to decrease in late 1990s and the major sudden stratospheric warming event significantly reduced ozone depletion in 2002.

For the model simulations we also calculated the monthly climatology of $Z^*$ for each of three 20-yr periods: 1960–79, 2000–19, and 2080–99. Regarding the two major external forcing factors, GHGs increase monotonically, while ODSs increase in the late half of the twentieth century but drop back almost to their background levels by the end of the twenty-first century. Most simulations span from 1960 to 2099, which is divided into the ozone depletion period and the ozone recovery period. When both GHGs and ODSs changes are prescribed, the difference between the 1960–79 and 2000–19 periods is considered as the response to ozone depletion, and similarly the response to ozone recovery is the difference between 2000–19 and 2080–99. The difference between 1960–79 and 2080–99 isolates the effect of GHG forcing, as ODSs in 2000s are similar to in their values in 1960s.

The response of the eddy heat flux (the covariance of the zonally asymmetric component of meridional velocity and temperature) from stationary and transient waves is also analyzed. This field is calculated from 6-h data and is only available from CMAM GHG+ODS and GHG-only simulations. The temporal coverage of the heat flux is missing from 2000 to 2079 in the CMAM GHG+ODS simulations. Therefore, the period of 1990–99 is used to replace the period of 2000–19 for the analysis of heat flux.

We also associate the changes in $|Z^*|$ with the changes in the zonal-mean zonal wind (denoted $|U|$) and zonally asymmetric ozone (denoted $O_3^\Delta$) to explore possible dynamical connections. Monthly mean $|U|$ is available from all simulations analyzed in this study. We focus on $O_3^\Delta$ from CMAM ODS-only simulations as an example. Linear trend analysis based on least squares estimation is applied to interannually varying $|Z^*|$ and $|U|$ for both observational and simulated data. The multidecadal trend in $|Z^*|$ represents long term changes in the amplitude of the climatological stationary wave field.

Two different types of statistical significance are examined in this manuscript: one tests the significance of temporal changes (response or trend) in a single dataset (reanalysis, individual models, or multimodel means) and the other quantifies the consistency or robustness of the responses among models. The first type of statistical significance is evaluated using the one-sample or two-sample Student’s $t$ test. The one-sample Student’s $t$ test is used to detect the statistical significance of the $|Z^*|$ and $|U|$ trends at 10% and 5% significance levels (e.g., section 2.3.1 in Montgomery et al. 2012). The null hypothesis is that there is no trend in the time series of $|Z^*|$ or $|U|$ from 1979 to 2001. The number of degrees of freedom is the length of time series minus 2 ($23–2 = 21$ here). The two-sample $t$ test is used to examine the statistical significance of the $|Z^*|$ and $|U|$ responses (e.g., section 5.2.2 in Wilks 2005). The null hypothesis is the equality of the climatologies of two periods. The number of degrees of freedom is the total number of data points minus 2 ($20 + 20 – 2 = 38$, as each period consists of 20 years). For comparisons involving responses over multiple time periods we use the standard deviation of $|Z^*|$ and $|U|$ of each period to represent their interannual variability and compare the responses with the standard deviation.

The second type of statistical significance, that is, the robustness of responses among models, is evaluated by the standard deviation of the responses in models. The standard deviation is a simple but useful measure of the spread in the responses, which can represent the confidence in the ensemble mean responses. The ensemble mean response is considered “robust” (to distinguish from the first type of statistical significance) if it is greater than one standard deviation of the responses in all ensemble members.

3. Results

a. Observed and simulated SH stationary wave changes

The observed SH stationary wave amplitude shows a positive trend in the stratosphere in the austral late spring and early summer during the last two decades of the twentieth century (Fig. 1 for 10-hPa $|Z^*|$ trends; see also Fig. 4.8 in SPARC CCMVal 2010). For the months November–December (ND), this trend is robust and statistically significant in all three reanalysis products over the period 1979–2001. The trend and its statistical significance are not sensitive to the ending year before 2002 (not shown). When the ensemble mean of 13 CCMVal-2 models (EM13) is analyzed over the same period, an increasing trend in amplitude is also seen (Fig. 1d) that is statistically significant in November. The EM13 ND trends are weaker owing to a relatively large spread among models (not shown) and thus not strictly robust, but all trends agree in sign with observed trends in ND. In August–October none of the observed and EM13 trends are statistically significant because of large
interannual variability in the austral winter and early spring. In these months there is also a pronounced spread in the trends among individual models: some models show trends similar to the observations whereas others show negative trends (not shown).

The climatology of the ERA-40 SH November–December mean stationary waves is dominated by the wave-1 component and the stationary waves show a clear increase in amplitude (Figs. 2a,b; ERA-40 is chosen to represent the reanalysis for simplicity hereafter because the three reanalysis datasets analyzed here are similar to each other). This predominant wave-1 feature represents a displacement of the stratospheric polar vortex off the pole toward the Atlantic sector. Trends in ERA-40 wave-1 amplitude ($A_1$) and phase ($\lambda_1$) have been diagnosed separately: the trend in $A_1$ (6.1 ± 2.4 m yr$^{-1}$) is statistically significant at the 5% level, but the trend in $\lambda_1$ (0.8° ± 1.1° yr$^{-1}$) is not. The CCMVal-2 models over the same period show a trend whose zonal structure is similar to the observed, although the amplitude of the trend is weak compared to the observations (Fig. 2c). Individual CCMs have some difficulty in accurately capturing the observed stationary wave zonal structure (e.g., SPARC CCMVal 2010), whereas the EM13 reproduces the observed zonal structure reasonably well (Fig. 2c). The EM3 GHG+ODS climatology and trend (Fig. 2d) are generally similar to their counterparts in EM13 and ERA-40, except their wave-1 phases are about 20° westward of those of EM13 and ERA-40.

b. GHG and ODS influence on stationary waves in CCMs

We have established that recent observed stationary wave trends are captured by the CCMVal-2 simulations well enough to justify using the simulations to analyze the cause of past and projected stationary wave evolution. Here we focus on the CCM output and calculate differences between 20-yr climatologies, as described in section 2, to isolate the effects of ozone depletion, ozone recovery, and GHG forcing. The SH stationary wave amplitude response over the ozone depletion period, expressed as the difference 2000–19 minus 1960–79, is robust in the austral late spring and early summer in the EM13 GHG+ODS simulations (shaded area in Fig. 3a, indicating that the ensemble mean response is greater than one standard deviation of the responses from 13 CCMs) and is similar to the observed trends (Fig. 1). This response reverses in the projected ozone recovery period (2080–99 minus 2000–19, Fig. 3b). The opposite responses in the two periods almost cancel out and result in a weak and unrobust response in these months for the GHG forcing period (2080–2099 minus 1960–1979,
Fig. 3c). Note that there are two types of statistical significance that apply to the ensemble mean responses, but it is not straightforward to show them on the same plot. Therefore, in Fig. 3 we only show the robustness of the ensemble-mean response in amplitude to ozone depletion and recovery. Although not shown, the response is generally statistically significant at the 10% level by t test and most of the shaded responses (shading for robustness) are usually significant at the 5% level (see shading in 10 hPa in Fig. 4 below for the 5% level of statistical significance).

Sensitivity simulations from ODS-only and GHG-only scenarios from three of the EM13 models (EM3, see Section 2) are used to separate the roles of ODS and GHG forcing in the stationary wave amplitude response. The EM3 GHG+ODS responses (Figs. 3d–f) are generally similar to the EM13 GHG+ODS responses (Figs. 3a–c). Therefore, EM3 is a good representation of EM13. The SH stationary wave amplitude response to ODS forcing explains most of the total response to both forcings during austral late spring and early summer for the ozone depletion and recovery periods (cf. Figs. 3g,h to Figs. 3d,e). Overall, the stationary wave amplitude response to GHG forcing is either relatively weak (e.g., around 60°S in January–March) or not robust among models. We note evidence of a slight increase in stationary wave amplitude in response to GHG increases in June–July in Fig. 3l but this feature is more evident in the earlier period (Fig. 3j) than the later period (Fig. 3k) and is sensitive to the time period chosen.

The meridional structure shown in Fig. 3 indicates that the $|Z^*|$ responses are strongest near the position of the climatological stratospheric jet maximum ($\sim 60°S$). The vertical structure of the $|Z^*|$ responses can provide information on the underlying dynamics. The relative role of GHG and ODS forcing is similar at all levels in the stratosphere, that is, the ODS forcing dominates the $|Z^*|$ responses in the austral late spring and early summer (Fig. 4). In October and November, the $|Z^*|$ responses to ODS forcing are strongest around 5 hPa. A downward progression of the $|Z^*|$ responses can be found from November to January. The amplitude of the $|Z^*|$ responses diminishes as the responses approach the lowermost stratosphere (Figs. 4g,h). The stratospheric $|Z^*|$ responses above 20 m are usually statistically significant at 5% level, while the tropospheric responses are
generally weak and statistically less significant. We notice a strong fall-to-spring response to GHG forcing in EM3 over the GHG period (Fig. 4l), but this is not prominent in EM13 (Fig. 4c). Although the robustness is not explicitly shown on the plots, we can still infer the robustness by comparing the first two rows of Fig. 4. Any feature shown in both EM13 and EM3 responses can be considered robust.

To focus on the most robust aspects of the response in context of the observed trends, the GHG + ODS EM13 and EM3 SH October–December climatological stationary waves for the three 20-yr periods are compared with ERA-40 stationary waves (Figs. 5a–c). The observed and simulated SH stationary waves all show a general eastward shift over time. Again, the EM3 responses are generally similar to the EM13 responses (Figs. 5b,c). The ERA-40 $|Z^*|$ and wave-1 phase responses are statistically significant at 7% and 9% levels, respectively, due to the relatively short period of record. The EM13 and EM3 $|Z^*|$ responses are significant at the 1% level for ozone depletion and recovery periods, and the corresponding wave-1 phase responses are also significant at the 1% level for periods longer than 80 yr. A more detailed look at the response to GHG and ODS in the EM3 models is shown in Fig. 6, which plots the total stationary wave fields in the three periods for each model and forcing scenario.

As introduced in section 2a, the three CCMs (CMAM, SSCRNIES, and SOCOL) incorporate SSTs differently, and it is thus more appropriate to diagnose them...
separately because the stationary wave response might be sensitive to this. In the GHG+ODS scenario in all three models, the SH stationary wave amplitude increases from 1960–79 to 2000–19 and decreases in amplitude and shifts eastward from 2000–19 (Figs. 6a,d,g), similar to the EM13 responses in Fig. 5b. In the CCSRNIES model, the amplitude increases from 1960–79 to 2000–19 is less pronounced than in the other two models. In the ODS-only scenario in all three models, ozone depletion (recovery) induces an increase (decrease) in amplitude. In the GHG-only scenario in all three models, forcing associated with GHG increases induce an eastward shift of the stationary waves from 2000–19 to 2080–99. A statistically significant eastward shift of the stationary wave-1 phase can also be found in most of the 13 GHG+ODS simulations over 2000–99 but not over 1960–99 (not shown), indicating that this phase shift is a robust response to GHG increases. There is also a less robust increase in stationary wave amplitude from 1960–79 to 2000–19.

Fig. 4. EM13 stationary wave amplitude response averaged over 50°–70°S at all pressure levels during (a) the ozone depletion period, (b) the ozone recovery period, and (c) the entire simulation period. (d)–(f) As in (a)–(c) but for EM3 GHG+ODS simulations, (g)–(i) as in (d)–(f) but for ODS-only scenario, and (j)–(l) as in (d)–(f) but for GHG-only scenario. The contour interval is 20 m. The gray shading indicates responses statistically significant at 5% level by the two-sample t test, which means that the climatologies of the two periods are distinguishable over their interannual variability. The responses are generally significant at 10% level and thus the corresponding shading is omitted.
A key question is whether changes in the stationary wave field are important for stratospheric wave driving compared to changes in the transient wave field. Stationary and transient waves might respond differently to the GHG and ODS forcing and their response can be isolated by diagnosing their contribution to the wave activity response. Note that only CMAM provides the data required to carry out the stationary–transient
decomposition, and this data is only available for the GHG+ODS and GHG-only integrations. The data are missing over 2000–79 in the GHG+ODS simulations and thus the period 2000–19 is replaced by 1990–99 for the heat flux diagnosis. We focus on the SH 10-hPa November climatological heat flux because in this month the response to ozone depletion is most robust across the models. In November the SH transient waves have a greater contribution to the climatological total heat flux than the stationary waves (Fig. 7). The stationary wave heat flux amplitude increases by about 60% during the ozone depletion period and falls back during the ozone recovery period in the GHG+ODS scenario (dark bars in Fig. 7a). Strikingly, during the ozone depletion period, the stationary wave contribution becomes larger than the transient wave contribution, which is the opposite of the pre-ozone hole situation. This reversed change is much weaker in the GHG-only scenario (dark bars in Fig. 7b) and thus is likely a response to ozone forcing (the ODS-only case is not shown due to data nonavailability). Therefore, the stationary wave activity dominates the total heat flux changes in the GHG+ODS scenario in the SH midstratosphere, which is linked to ozone changes.

4. Discussion

The analysis above has shown responses in the SH stationary wave amplitude and phase that can be linked to the changes in ozone depleting substances and greenhouse gases. We now discuss the dynamics of these linkages.

a. Dynamics of changes in stationary wave amplitude

At the same time as there was an increase in SH stationary wave amplitude in November–December between 1979 and 2001 (4.7 ± 1.8 m yr⁻¹ around 60°S at 10 hPa in ERA-40), there was an observed strengthening of the spring Antarctic polar vortex (ERA-40 maximum zonal wind around 60°S at 10 hPa increases by 0.32 ± 0.20 m s⁻¹ yr⁻¹) and the delay in the breakdown of the vortex (e.g., Waugh et al. 1999; Karpetchko et al. 2005). This association between strengthening of the vortex and stationary wave amplitude is also found in the CCMs. In the EM13 GHG+ODS simulations there is a strengthening of the vortex and increase in wave amplitude during the ozone depletion period (e.g., 0.46 ± 0.17 m s⁻¹ yr⁻¹ and 2.2 ± 1.9 m yr⁻¹ around 60°S at 10 hPa during 1979–2001), with both trends reversing as the ozone recovers.

This tight relationship between vortex strength and wave amplitude suggests that changes in the stationary wave amplitude might be attributed to changes in the strength of the vortex. In idealized general circulation model simulations with fixed topography and a polar vortex whose strength can be tuned, the stratospheric stationary wave amplitude increases with polar vortex strength (Fig. 7b of Gerber 2012). Gerber (2012) related this relationship to a colder vortex causing a resonant cavity in the stratosphere that leads to larger wave amplitudes (Matsuno 1970). A linear diagnosis of the zonal mean state [the so-called “downward wave coupling,” Harnik and Lindzen (2001)] also confirms that this mechanism is applicable to observations (Harnik et al. 2011). An increased wave reflection from the stratosphere is linked to strengthening of the stratospheric vortex owing to ozone depletion using CCM simulations (Shaw et al. 2011).

Another possible cause for the changes in wave amplitude is change in the ozone zonal asymmetries driving asymmetries in shortwave radiative heating. The zonally asymmetric components of ozone and geopotential height are usually observed to be in phase (e.g., Gabriel et al. 2011; Ialongo et al. 2012), and ozone zonal asymmetries can produce zonally asymmetric radiative heating to force a wave component in the circulation. Thus changes in the former could lead to changes in the latter. Here we compare changes in stationary wave amplitude with changes in polar vortex strength and in ozone asymmetries to find out the dominant mechanism of the stationary wave amplitude response. As shown in Fig. 8, the stationary wave amplitude and the polar jet strength start from their minima at the pre-ozone-hole conditions in the ODS-only simulations (blue dots in Fig. 8) and reach their maxima at the ozone depleted stage (dark green dots in Fig. 8). The increase of stationary wave amplitude is reversed as the zonal mean state is restored close to pre-ozone-hole conditions in the ozone recovery period (red dots in Fig. 8). Other periods fall in between these stages in an orderly manner. The increase and decrease in the strength of the Antarctic polar jet can
also be found in all GHG + ODS simulations in austral late spring–early summer, but in the GHG-only simulation there are only small and uncorrelated changes in these two quantities (not shown). On the other hand, the relationship between ozone asymmetries and stationary wave amplitude is much weaker than the vortex strength–wave amplitude relationship. For example, in the CMAM ODS-only simulation the stationary wave amplitude increases by more than 30% during the ozone depletion period whereas the ozone zonal asymmetry only increases by about 10% (Fig. 9a). The ratio of their percentage changes slightly reduces to 2:1 in the ozone recovery period. Furthermore, whereas the stationary wave-1 phase remains steady over the entire simulation, the ozone wave-1 phase varies up to 60° (Fig. 9b). This analysis provides no evidence that ozone asymmetries cause changes in stationary wave amplitude.

Further evidence that ozone asymmetries are not playing a major role can be seen in the prescribed zonal-mean ozone simulations in Waugh et al. (2009). In these simulations the vortex strengthens and stationary wave amplitudes increase during the ozone depletion period and both of these trends reverse during ozone recovery (not shown), even though there are no zonal asymmetries in the ozone forcing. This further supports the hypothesis that changes in the polar vortex strength is the primary cause of changes in the SH stationary wave amplitude.

b. Dynamics of the eastward shift of the SH stratospheric stationary wave

Wang and Kushner (2011) have discussed a connection between the strength of the subtropical westerly jet and the phase of NH stratospheric stationary waves in

![Figure 8](image_url)

**Fig. 8.** Scatterplots of October–December seasonal mean climatological (20 year) mean SH 10-hPa stationary wave amplitude vs polar vortex strength (maximum zonal mean zonal wind) for (a) CMAM, (b) CCSRNIES, and (c) SOCOL in the ODS-only scenario. The error bar in (a) represents one standard deviation of the interannual variability.

![Figure 9](image_url)

**Fig. 9.** (a) Scatterplots of CMAM SH 10-hPa stationary wave-1 amplitude (relative to 1960–1979 climatology) vs ozone wave-1 amplitude in the ODS-only scenario. (b) As in (a) but for the wave-1 phase. The horizontal and vertical axes have the same scale.
idealized stationary wave models. We find evidence of such a connection in this work. In Fig. 10, the phase of the wave-1 component of stationary waves from GHG-only simulations is plotted against the SH subtropical upper-tropospheric jet strength. In all three models, as the jet strengthens with greenhouse gas forcing, the phase shifts eastward, albeit with occasional decadal variations. Similar relationships are seen in the NH (not shown). The GHG+ODS simulations also show a similar relationship between the phase and jet strength (circles in Fig. 11). In two of the ODS-only integrations, the stationary wave phase does not change over the three periods (Figs. 11a, b), but in SOCOL there is a pronounced jet strengthening and eastward phase shift (Fig. 11c, red triangle). This arises, we expect, because the SOCOL ODS-only integration includes the SST warming response to GHG increases.

The observed SH late winter planetary waves have exhibited longitudinal phase shifts on interannual time scales, associated with the subtropical tropospheric jet strength changes. For example, Hio and Hirota (2002) showed that in the NCEP–NCAR reanalysis an eastward (westward) shift of the SH stratospheric planetary waves corresponds to the strengthening (weakening) of the subtropical tropospheric jet. Agosta and Canziani (2011) further related the strengthening (weakening) of the subtropical tropospheric jet to the anomalous meridional (longitudinal) gradient of sea surface diabatic heating. There are also other changes that can lead to a phase shift in the SH stratospheric planetary waves. For example, Lin et al. (2012) have shown that a La Niña–like tropical SST anomaly can induce a westward shift and a central Pacific El Niño–like tropical SST anomaly can lead to an eastward shift. These tropical SST anomalies can influence the planetary waves by generating zonally asymmetric heating. The pattern of the tropical SST response to GHG increases varies among models (e.g., Zhu and Liu 2009), and thus the long-term impact of the longitudinal structure of the sea surface warming on the SH stratospheric stationary wave is inconclusive. Therefore, the strengthening of the subtropical

![Figure 10](image1.png)

**FIG. 10.** As in Fig. 8 but for scatterplots of the SH 10-hPa stationary wave-1 phase vs SH subtropical tropospheric jet strength (zonal mean zonal wind on 100 hPa at 30°S) in the GHG-only scenario. The error bar in (a) represents one standard deviation of the interannual variability.

![Figure 11](image2.png)

**FIG. 11.** Scatterplots of SH 10-hPa stationary wave-1 phase vs SH subtropical tropospheric jet strength for the three periods 1960–79, 2000–19, and 2080–99 and all three scenarios.
jet is a likely important factor in producing such an eastward shift in the long term—in simulations with increasing GHGs (and hence warming SSTs).

5. Conclusions

An increase of stationary wave amplitude is found in the SH stratosphere in the late spring and early summer over the period from 1979 to 2001 in reanalysis datasets, in agreement with previous findings in temperature and ozone zonal asymmetries (e.g., Malanca et al. 2005; Grytsai et al. 2007; Canziani et al. 2008; Hu and Fu 2009; SPARC CCMVal 2010). CCMVal-2 simulations also show a robust increase of SH stratospheric stationary wave amplitude during the last four decades of the twentieth century, which is reversed during the twenty-first century. Secular changes in ozone (ozone depletion and recovery) are responsible for the changes in stationary wave amplitude, as illustrated by sensitivity simulations with isolated GHG and ozone forcing. Diagnosis on heat flux changes shows that transient waves contribute little to these changes, but stationary waves dominate the heat flux changes. This implies that the dynamics of the zonally asymmetric circulation response to ozone changes is separable between stationary and transient components. The increase (decrease) in the SH stratospheric stationary wave amplitude is linked to the strengthening (weakening) of the spring Antarctic polar vortex, associated with ozone depletion (recovery). A downward progression of the stationary wave response to changes in ozone is found from the austral late spring to summer. The signal can reach the lowermost stratosphere but not into the troposphere, where response is either weak or statistically insignificant.

The SH stratospheric stationary wave amplitude does not show a consistent trend among models when only forced by GHG increases, but in these simulations an eastward shift of the stationary wave phase is found. This eastward phase shift is also found in simulations with both GHG and ozone changes, not only from the CCMs shown above, but also from most of the other CCMs (not shown). No significant phase shift is found in simulations with ozone changes alone. The eastward phase shift of stationary waves is associated with the strengthening in the subtropical tropospheric jet, which is a well-known response to GHG increases via SST warming. This phase shift is significant over centennial time scales and might be masked by natural variability over shorter time scales. For instance, the phase shift found in the re-analysis datasets can result from GHG increases as well as interannual or decadal variability in tropical SSTs. It might be possible to separate these effects in the observations if the sensitivity of the phase shift to GHG increases can be determined accurately in models.

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