Change in Occurrence Frequency of Stratospheric Sudden Warmings
with ENSO-like SST Forcing as Simulated WACCM

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Abstract

Change in occurrence frequency of stratospheric sudden warmings (SSWs) associated with El Niño/Southern Oscillation (ENSO) is explored through idealized experiments with Whole Atmosphere Community Climate Model (WACCM) under perpetual January conditions that include ENSO-like perturbations of sea-surface temperatures (SSTs) in the tropical Pacific. The experiments show greater frequency of SSWs for an El Niño-like condition than for a La Niña-like counterpart, producing a change in shape of probability distribution functions (PDFs) of stratospheric variability. The El Niño-like forcing induces the familiar Pacific-North America (PNA) pattern, which results in an enhanced planetary wave of zonal wavenumber 1 in the upper troposphere and stratosphere of high latitudes. This contributes to a shift of PDFs of poleward eddy heat flux in the lower stratosphere, including an increase of extreme wave events that induce more frequent SSWs.
1. Introduction

The large interannual variability observed in the Northern winter extratropical stratosphere and troposphere arises from external forcings that vary from year to year, as well as from internal processes that generate unforced variability [Yoden et al., 2002]. The external forcings to the extratropical stratosphere and troposphere include the solar cycle, volcanic eruptions, quasi-biennial oscillation (QBO), ENSO, anthropogenic effects, and so on [Labitzke and van Loon, 1999]. This study focuses on impact of the ENSO on the Northern extratropical stratosphere and troposphere.

It has been observed that the Northern stratospheric polar vortex tends to be weaker for El Niño winters than for La Niña winters on monthly and seasonal means [van Loon and Labitzke, 1987]. Baldwin and O’Sullivan [1995] also examined stratospheric variability in relation to tropospheric teleconnections associated with ENSO. Although it is difficult to separate effect of ENSO from that of the QBO in observations because of the overlap between their phases [Hamilton, 1993], a couple of idealized GCM simulations [Hamilton, 1995; Sassi et al., 2004] that include ENSO SST forcings support the earlier observational result of van Loon and Labitzke [1987].

While the observational and modeling studies examined monthly and seasonal means, the ENSO-induced change in the stratospheric circulation may not be merely a change in the mean states (shift of PDFs), but may reflect a change in frequency of SSWs (change in shape of PDFs) that characterizes stratospheric variability during winter. This study shows ENSO-induced change in frequency of SSWs and explores the mechanism through dynamical diagnostics by using idealized GCM experiments similar to those of Hamilton [1995] and Sassi et al. [2004]. Possible changes in frequency of SSWs with those external forcings remain relatively unexplored. Such a perspective will be useful for
understanding dynamical processes that govern the troposphere-stratosphere climate system.

Taguchi and Hartmann [2005, hereafter TH] used the same experiments for a shorter period to examine ENSO-extratropical atmosphere connection from a quite different perspective. They argued that ENSO and SSW signals in the extratropical surface climate, though distinct in their hemispheric structures, nonetheless interfere positively over the Southeastern United States and northern Mexico to enhance colder and wetter winter climate anomalies.

2. Model and Experiments

The model used in this study and TH is Whole Atmosphere Community Climate Model (WACCM), a version of NCAR Community Climate Model that is extended to include the middle and upper atmosphere up to about 110 km altitude [Sassi et al., 2002]. The horizontal resolution is T63, with 66 vertical levels. Our experiments consist of two perpetual simulations forced with climatological January conditions including SST and ozone distributions. The two runs are different only in SSTs in the tropical Pacific. The SSTs are lowered for a La Niña-like condition in one run called COLD, while raised for an El Niño-like condition in the other called WARM. The SST difference peaks in the eastern equatorial Pacific at about 2.5 K (Fig. 1a). The model runs each are conducted for 25 years (100 winters) in this study, and thus afford a large sample enough to examine change in frequency of the episodic stratospheric warming phenomenon. Since most of SSWs in the NH occur during mid-winter, the perpetual January experiments are a reasonable first step to study impact of external forcings on their frequency. The imposed SST forcing induces a change in atmospheric heating as implied in a change in
precipitation (Fig. 1b). The precipitation response, including increase over the equator and decrease in its neighboring latitudes in the central Pacific, is in general agreement with observations [e.g., Philander, 1990]. We here show that the familiar PNA response in the El Niño-like condition resulting from the anomalous heating enhances zonal wavenumber 1 signal in high latitudes, putting more wave energy into the polar stratosphere and hence driving more frequent SSWs.

3. Results

We first examine a significant climatological response in our simulations. Our experiments show that the extratropical stratosphere is climatologically warmer for the run WARM than for the run COLD, together with a weaker polar night jet (Fig. 2a,b). The changes in the zonal mean states are driven by the enhanced upward propagation of wave activity in the high latitude stratosphere poleward of about 60°N, as measured by the Eliassen-Palm (EP) flux (Fig. 2c). The EP flux used here is the quasi-geostrophic scaling [Andrews et al., 1987], which is useful to diagnose planetary wave activity that can propagate to the stratosphere. The increasing EP flux in the stratosphere can be traced down to the troposphere in lower latitudes around 45°N. These features are very consistent with the results of Sassi et al. [2004].

To examine the occurrence of SSWs, we use daily time series of the zonal mean temperature [T] in the polar middle stratosphere (88°N and 11 hPa, denoted by X in Fig. 2a) as an indicator of dynamical conditions in the extratropical stratosphere. Square brackets denote the zonal mean. The polar stratospheric temperature is used because it shows a large climatological difference (Fig. 2a) and day-to-day variation in both runs (not shown). It is very clear that occurrence of SSWs, or extreme stratospheric anomalies,
as seen in large spikes of the temperature time series, is more frequent for the run WARM (Fig. 3). This feature is robust throughout the runs.

We use the same criteria of SSWs as in TH for a quantitative comparison of their frequency between the two runs. We searched for periods when the polar temperature becomes warmer than 205 K and defined key day of each SSW period as the day on which the temperature achieved its maximum value higher than 235 K. Based on this definition, SSWs are twice as likely to occur for the run WARM (52 events identified in the 25-year period) as for the run COLD (26 events). The thresholds and defined key days are denoted in Fig. 3 for the 2000-day period. Our following analysis pays attention not only to the exact SSW events but also to when the extratropical stratosphere is highly disturbed as seen in higher temperatures than 230 K for example.

The difference of the frequency of the SSWs is highly statistically significant according to our Monte Carlo simulation. It shows that such a bias (26 vs. 52) of the events occur by chance in only 22 of total 10,000 trials if the probability of the events are equal between the two runs. Although the definition of the SSWs includes a few subjective values, the change in the frequency of SSWs (or highly disturbed periods) is robust as clearly seen in the temperature time series (Fig. 3). The temperature is a good index for SSWs and closely related to possible alternative indices, such as the zonal mean zonal wind at 60°N and 11 hPa (also plotted in Fig. 3). The variability of the wind corresponds well (though not perfect) to that of the temperature, so that the difference in the frequency of SSWs is also clear in the zonal wind time series.

The occurrence of SSWs can be related to poleward eddy heat flux in the lower stratosphere of high latitudes (45-75°N), as observed by Polvani and Waugh [2004] for Northern winter. The heat flux is proportional to the vertical component of the
quasi-geostrophic EP flux. Figure 3 also plots the heat flux on each day that is averaged for the prior 40 days (denoted by G), since Polvani and Waugh [2004] also showed that stratospheric anomalies are best correlated with the lower stratospheric heat flux when it is averaged (or cumulated) for the prior 40 days or longer, implying importance of low-frequency component of planetary wave variability. As expected, temperatures higher than 230 K are well related to strong heat fluxes more than about 20 mK/s in each run. Such strong wave events are more frequent for the run WARM.

To relate the two quantities more clearly, two-dimensional PDFs are plotted in Fig. 4 for the two runs, as well as one-dimensional PDFs for each quantity. The change in the frequency of SSWs is reflected in different shapes of 1D PDFs for the temperature. The run WARM has more samples for very high temperatures, while the mode values are similar for the two runs (around 200 K). The shapes of the 2D PDFs are similar between the two runs, and confirm that the samples of such high temperatures correspond well to those of strong eddy heat flux for both runs as examined in Fig. 3. The 1D PDFs for the heat flux also ensure greater frequency of strong wave events for the run WARM. Note that the shapes of the PDFs are almost the same between the two runs. As a result, the 2D PDF for the run WARM has more samples for high temperatures and strong heat fluxes than that of the run COLD. To summarize, the El Niño-like SST forcing shifts the PDF of the heat flux to the positive side, which is consistent with the increase in frequency of strong wave events and hence SSWs.

Figure 5a plots difference of the 25-year mean poleward eddy heat flux in the lower stratosphere (101 hPa) between the two runs as a function of zonal wavenumber and latitude. The difference shows that the shift of the 1D PDFs of the total heat flux (Fig. 4) is attributable to planetary wave of zonal wavenumber 1 (wave 1) around 60°N. The
increase of wave 1 heat flux is also noticeable in the upper troposphere at 266 hPa (Fig. 5b). Since extratropical low-frequency variations, including the PNA, are equivalent barotropic as is well known [Horel and Wallace, 1981; Hoskins and Karoly, 1981], the upper tropospheric level is chosen as a representative level to characterize the tropospheric response. The difference of the time mean heat flux at the two levels is basically statistically significant at a confidence level of 95% (denoted by shading in Fig. 5) according to a Student’s t test. In the test, we took account of actual temporal degree of freedom for the heat flux at each wavenumber and latitude. Difference of wave 1 amplitude of geopotential height has similar patterns to Fig. 5 at both levels (not shown). The increased wave 1 activity in high latitudes is important for the increase in frequency of SSWs, since it can propagate to the stratosphere most easily [Charney and Drazin, 1961] and be directed toward the polar region as inferred from Fig. 2c. Heat flux and amplitude of wave 2 basically decrease for the run WARM, so that relative importance of wave 1 to wave 2 increases.

To understand how the SST forcing induces the wave 1 amplification, Fig. 6 plots stationary wave patterns of geopotential height in the upper troposphere (300 hPa) for the two runs, together with a difference field. Figure 7 extracts longitudinal structure of the geopotential height waves averaged 50 and 70°N where the heat flux of wave 1 shows the large response (Fig. 5). The difference (Fig. 6c) shows a familiar wave train that corresponds to the PNA pattern [e.g., Horel and Wallace, 1981]. The PNA response is robust throughout the troposphere (not shown). The wave response includes wave 1 component, with ridge and trough around 30°W and 150°E near 60°N, respectively (Figs. 6c and 7b). The superposition of this wave 1 response to the wave 1 in the reference run COLD increases the amplitude in the run WARM, since their phase locations are roughly
similar in those latitudes (Fig. 7b).

If we return to a stratospheric aspect, the change in relative importance of wave 1 to wave 2 (Fig. 5) implies a change in dominant synoptic patterns of SSWs between the two runs. To examine this possibility, we obtain amplitude of waves 1 and 2 at 60°N for a mature stage (between 2 days before and after the key days) for all SSWs (Fig. 8). Consistent with the increase of wave 1 activity (Fig. 5), the plot shows that the run WARM favors wave 1-type SSWs (polar vortex shift), while wave 2-type SSWs (vortex split) occur more frequently for the run COLD.

While our result (greater frequency of SSWs for the run WARM, as confirmed in Fig. 9a) is obtained for the idealized situation, a more realistic 50-year WACCM simulation forced with observed SSTs from 1950 to 1999 [Sassi et al., 2004] shows a similar tendency, having more frequency in high temperatures for El Niño conditions (solid line) than for La Niña conditions (shading) as shown in Fig. 9b. The La Niña and El Niño conditions are defined here as DJF winters when DJF mean SSTs averaged over 180°W-90°W and 6°N-6°S are in bottom and top 15 of 50 values, respectively (each groups therefore includes 15x90=1350 days). A similar feature is also found for NCEP/NCAR reanalysis data [Kalnay et al., 1996] from 1979 to 1999 (Fig. 9c). In this case, the La Niña and El Niño groups are each defined with the same SST index to include 6 DJF seasons (540 days) of 21 years. It will be difficult however to obtain statistical significance in the change in frequency of SSWs for both the 50-year WACCM run and observations, because the samples are not large enough. As mentioned in Introduction, another problem in attributing the observed difference in the PDFs to the ENSO is the phase overlap between the ENSO and QBO.
4. Summary

Intermittent occurrence of SSWs is a vital aspect to the troposphere-stratosphere climate system especially in the Northern Hemisphere during winter. Possible changes in frequency of SSWs with external forcings nonetheless remain relatively unexplored. Our analysis of the WACCM experiments under the perpetual conditions has made a clear case for the increase of frequency of SSWs during El Niño. The El Niño-like SST condition induces an increase in planetary wave 1 forcing from the troposphere to the stratosphere in high latitudes, compared to the La Niña-like condition. The changes in the PDFs for the troposphere (planetary wave forcing) and stratosphere (frequency of SSWs) emerge differently. The increase of the wave 1 forcing appears as a shift of their PDFs, including an increase of frequency of extreme wave events. Since such extreme wave events often induce SSWs, this results in the increase of frequency of SSWs, changing the shape of the PDF of stratospheric variability.

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Reference List


Charney, J. G., and P. G. Drazin, Propagation of planetary-scale disturbances

Baldwin, M. P., and D. O’Sullivan, Stratospheric effects of ENSO-related

Hamilton, K., An examination of observed Southern Oscillation effects in the

Hamilton, K., Interannual variability in the Northern Hemisphere winter middle
atmosphere in control and perturbed experiments with the GFDL SKYHI general

Horel, J. D., and J. M. Wallace, Planetary-scale atmospheric phenomena

Hoskins, B. J., and D. J. Karoly, The steady linear response of a spherical

Kalnay, M. E. et al., The NCEP/NCAR 40-year reanalysis project, Bull. Am. Soc.,
77, 437-472, 1996.

Labitzke, K., and H. van Loon, The stratosphere, 179 pp., Springer-Verlag, New
York, 1999.

in the lower stratosphere of the Northern Hemisphere in winter and a comparison with the

Philander, S. G. H., El Niño, La Niña, and the Southern Oscillation, Academic

Polvani, L. M., and D. W. Waugh, Upward wave activity flux as precursor to
extreme stratospheric events and subsequent anomalous weather regimes, J. Climate, 17,


Figure Captions

Figure 1: (a) Imposed SST difference in K, run WARM minus run COLD. Contours are drawn from 1 K at a 0.5 K interval. (b) Climatological difference in precipitation rate. Contour interval is 2mm/day.

Figure 2: Climatological difference, run WARM minus run COLD: (a) zonal mean temperature [T] in K, (b) zonal mean zonal wind [U] in m/s, and (c) EP flux F (arrows) and its divergence DF (contours and shades) in m/s/day. The EP flux is divided by the square root of 1000/pressure.

Figure 3: Daily time series for the first 2000 days in (a) run COLD and (b) run WARM. The panels (a,b) each include the zonal mean temperature [T] at 88ºN and 11 hPa in top, the zonal mean zonal wind at 60ºN and 11 hPa in middle, and poleward eddy heat flux averaged 45-75ºN at 101 hPa in bottom. The heat flux plotted on each day is averaged for 40 days prior to the day (denoted by G). In the panel (a), two horizontal lines are drawn at 205 and 235 K, and the shading denotes a temperature range higher than 230 K. The panels (b,c) include thresholds of 0 m/s and 20 mK/s, respectively. Dots in (c) indicate days when the temperature is in the shaded range.

Figure 4: Two-dimensional PDFs in % with respect to the polar stratospheric temperature and lower stratospheric time-averaged heat flux. Contours are drawn for 0.1, 0.2, 1, 2, and 4 %. One-dimensional PDFs are also drawn for each quantity. Black contours and lines are used for the run WARM in both 2D and 1D PDFs. Broken lines denote 230 K and 20 mK/s.

Figure 5: Difference, run WARM minus run COLD, of 25-year mean poleward eddy heat flux as functions of zonal wavenumber and latitude at (a) 101 hPa and (b) 266 hPa. Contour interval is 0.5 mK/s in (a) and 0.2 mK/s in (b). Shading indicates that the
difference is statistically significant at a 95% confidence level.

Figure 6: Stationary wave patterns of geopotential height at 300 hPa. The panels (a) and (b) are for runs COLD and WARM, respectively. The panel (c) shows (b) minus (a). Contours are for all waves. Dark and light shadings denote values larger than 25 m and smaller than -25 m for wave 1 component, respectively, in all panels. Outermost circle is 30°N, and broken lines denote latitudes of 50 and 70°N.

Figure 7: Geopotential height waves averaged between 50 and 70°N at 300 hPa as functions of longitude for (a) all waves and (b) wave 1. Thin and thick solid lines are for runs COLD and WARM, respectively. Broken line is for difference, run WARM minus run COLD.

Figure 8: Scatter plot between amplitude of waves 1 and 2 of geopotential height at 11 hPa for a mature stage of 26 and 52 SSWs in the runs COLD (dots) and WARM (crosses), respectively. Average is denoted by the big symbol for each run.

Figure 9: (a) PDFs in % of the zonal mean temperature at 88°N and 11 hPa for the runs COLD (shading) and WARM (solid line). The temperature values are normalized with the mean and standard deviation of all data combined for the two runs. (b) As in (a), but for the zonal mean temperature at the same gridpoint in a 50-year WACCM simulation forced with observed SSTs from 1950 to 1999 [Sassi et al., 2004]. Shading and solid line are for 15 La Niña and El Niño DJF winters, respectively, which are determined with DJF mean SSTs averaged over 180°W-90°W and 6°N-6°S. The temperatures on each calendar day are normalized with the mean and standard deviation for the day calculated from the 50-year data. (c) As in (b), but for the temperature at NP and 10 hPa in the NCEP/NCAR reanalysis data from 1979 to 1999. The La Niña and El Niño winters include 6 DJF seasons when the SSTs in the region are in the bottom and top 6 of 21
values, respectively.
Fig. 2
Fig. 3
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Fig. 8