On the Life Cycle of Northern Hemisphere Stratospheric Sudden Warming

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ABSTRACT

This study examines the evolution of the atmospheric flow and wave fluxes during the life cycle of a stratospheric sudden warming (SSW) in the Northern Hemisphere. Previous studies of SSWs have focused on the evolution of the flow and wave fluxes at stratospheric levels. Motivated by recent evidence of strong coupling between the circulations of the stratosphere and troposphere during the Northern Hemisphere winter, we provide here a comprehensive analysis of the evolution of the flow and wave fluxes during a SSW at levels throughout the depth of the stratosphere and troposphere.

During the onset of a SSW, the polar stratosphere is disturbed by poleward heat and momentum flux anomalies associated mainly with waves of zonal wavenumber one and two. When the waves break in the lower stratosphere, they act to weaken the strength of the circumpolar flow there, and drive an anomalous mean meridional circulation that gives rise to anomalously high polar stratospheric temperatures. As the SSW progresses, the induced stratospheric circulation anomalies descend to the lower stratosphere, where they coincide with the growth of anomalous equatorward momentum fluxes by waves in the upper troposphere centered near 50°N, and by anomalous equatorward heat fluxes by waves in the lower troposphere centered near 60°N. The anomalies in tropospheric wave activity are mainly associated with waves of zonal wavenumber four and higher, and are concentrated over the Atlantic half of the hemisphere. The anomalous upper tropospheric momentum fluxes drive anomalies in the tropospheric mean meridional circulation that transport easterly zonal wind anomalies from the upper troposphere to the surface where they compose negative polarity of the Northern Hemisphere Annular Mode (NAM).

1. Introduction

Sudden stratospheric warmings (SSWs) dominate the variability of the Northern Hemisphere (NH) wintertime stratospheric circulation (for example, see Andrews et al., 1987). During a SSW, polar stratospheric temperatures rise and the zonal mean zonal flow weakens dramatically over a short time period. As the zonal flow weakens, the stratospheric circulation becomes highly asymmetric and the stratospheric polar vortex is displaced off the pole. In the most dramatic cases, stratospheric temperatures can rise by ~50 K and the stratospheric circumpolar flow can reverse direction in the span of just a few days.

Sudden stratospheric warmings involve interactions between the zonal flow of the polar stratosphere and the anomalous growth of upward propagating planetary waves, consisting primarily of zonal wavenumbers one and two (e.g., Matsuno, 1970; Andrews et al., 1987). When a vertically propagating wave enters the polar stratosphere, it imparts a westward acceleration there through wave dissipation or wave transience. The decelerated westerly zonal flow is brought back toward balance by a poleward mean meridional flow anomaly, which accelerates the zonal flow through the Coriolis force, and induces temperature changes that also bring the flow toward balance. By continuity, the poleward mean meridional flow across the axis of the eddy forcing requires sinking (rising) motion below and poleward (equatorward) of the forcing region. The adiabatic temperature changes associated with these induced meridional motions act to weaken the meridional temperature gradient, as required by thermal wind balance, and give rise to the rapid warming observed in the polar stratosphere during a SSW.

The presence of vertically propagating waves is a necessary, but not sufficient condition for a SSW to occur: the stratospheric zonal flow must also be “pre-conditioned” such that wave activity is focused towards the polar vortex (e.g. Labitzke, 1981; Butchart et al., 1982; McIntyre, 1982). The polar vortex is
generally preconditioned when it is poleward of its climatological location, such that it appears “tighter” about the pole. In this case, the relatively small mass and moment of inertia of the vortex allow upward propagating waves to exert tremendous influence on the circulation through wave forcing (McIntyre, 1981). The preconditioning of the vortex is typically initiated by a precursor planetary wave that breaks along the periphery of the vortex (Dunkerton et al., 1981). However, the preconditioning of the vortex may also be a function of low frequency vacillations in the stratospheric circulation, in which anomalies in the stratospheric zonal flow are drawn poleward and downward on timescales of several months (e.g., Holton and Mass, 1976; Kodera et al., 2000; Kodera and Kuroda, 2002; Kuroda, 2002).

Sudden stratospheric warmings have been historically viewed as a stratospheric phenomenon, but increasing evidence suggests that they may also have a marked influence on the circulation of the troposphere. Anecdotal evidence of the impact of SSWs on the circulation of the troposphere was first presented in Quiroz (1977), who observed large temperature changes in the troposphere in association with the stratospheric sudden warming event of 1976-77. Recently, Baldwin and Dunkerton (1999) examined 40-years of daily data and found that large amplitude anomalies in the lower stratospheric zonal flow typically descend throughout the depth of the stratosphere on a timescale of weeks, and that the largest amplitude anomalies in the stratosphere frequently appear to descend to tropospheric levels. Baldwin and Dunkerton (2001) subsequently found that the surface signature of these downward propagating anomalies strongly resembles the surface signature of the Northern Hemisphere Annular Mode (NAM), a large-scale pattern of climate variability associated with out-of-phase fluctuations in the strength in the zonal flow between centers of action located ~35°N and ~55°N (e.g., Hurrell, 1995; Thompson and Wallace, 1998, 2000). Similar downward propagation of temperature anomalies is also recently observed by Zhou et al. (2002) when large stratospheric circulation changes persist as a result of strong initial wave forcing.

Numerous modeling experiments have demonstrated a distinct tropospheric response to circulation anomalies imposed at stratospheric levels (e.g., Boville 1984; Polvani and Kushner, 2002; Norton, 2003), and several theories have been proposed in an effort to explain how variability in the stratosphere can impact the circulation of the troposphere. One theory involves the impact of the stratospheric circulation on the index of refraction of vertically propagating waves (e.g., Chen and Robinson, 1992; Hartmann et al., 2000; and Shindell et al., 2001). At a given level, the index of refraction for vertically propagating planetary waves is a function of the strength of the zonal flow (e.g., Chen and Robinson 1992; Hu and Tung, 2002; Lorenz and Hartmann, 2003). When the zonal flow is very strong in the lower stratosphere, vertically propagating waves tend to be deflected equatorward, and vice versa. Since the eddy flux of westerly momentum is in the opposite direction of the wave propagation, it follows that regions below levels of strong zonal flow (and hence anomalous vertical shear) will be marked by anomalous convergence of zonal momentum by waves, and vice versa. Hence, while wave energy ultimately originates at tropospheric levels, the above mechanism will tend to draw large amplitude anomalies in the zonal flow of the stratosphere downward with time. It also provides a possible mechanism whereby large amplitude zonal wind anomalies at lower stratospheric levels can impact the circulation of the upper troposphere.

Another mechanism whereby the stratosphere can impact the troposphere can be interpreted as a variant on the dynamics of “downward control” (Haynes et al., 1991). In the context of downward control, momentum forcing at stratospheric levels is transported to the surface via an induced meridional circulation. Since the stratosphere contains at most ~25% of the total mass of the extratropical atmosphere during the winter season, this mechanism is generally dismissed as incapable of driving anomalies in the tropospheric circulation. Nevertheless, recent evidence suggests that downward control can drive comparatively large anomalies in the troposphere, if the stratospheric anomalies project onto the preferred modes of variability of the tropospheric circulation (Black, 2002; Robinson, 2003). Another variant of the so-called downward control principal was proposed by Ambaum and Hoskins (2002). In this case, potential vorticity (PV) anomalies in the lower stratosphere lead to deformations in the height of the polar tropopause which, in turn, give rise to similarly signed PV anomalies at tropospheric levels.

The purpose of this study is to provide a comprehensive analysis of the climatological life cycle of a SSW at levels throughout the depth of the troposphere and stratosphere. In contrast to Baldwin and Dunkerton (1999, 2001), we analyze results not only for the zonal flow, but also for the fluxes of momentum and heat by eddies of varying spatial scales, and for the meridional circulation. By fully documenting the evolution of various dynamical quantities during an observed SSW, the results provide a benchmark for assessing numerical simulations of the influence of SSW on the circulation of the troposphere, and pro-
vide a physical reference for theories that seek to explain the observed linkages between stratospheric and tropospheric variability. The rest of the study is divided into three sections; the methodology and data are discussed in Section 2; the results are presented in Section 3; and Section 4 offers a synthesis of the principal findings of the study.

2. Data and Analysis

The study uses 44 years of data (1958-2001) from the National Center for the Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis project (Kalnay et al., 1996). The data set contains daily averages of geopotential height, winds, and temperature fields on a 2.5° x 2.5° grid at 17 vertical pressure levels extending from 1000 to 10 hPa. Before the analysis was performed, the zonal resolution of the data was degraded to 7.5° longitude resolution such that only waves of length scales larger than zonal wavenumber 15 are retained in the calculations. All anomalies are computed as departures from the daily climatological annual cycle determined from the entire 44-year record.

Variability in the strength of the extratropical stratospheric polar vortex is defined on the basis of the leading Principal Component (PC) time series of daily zonal mean zonal wind anomalies at 50 hPa during the October-April season. When forming the temporal covariance matrix for the calculation of the PC, the grid points in the horizontal data domain were weighted by the square root of the cosine of latitude. The resulting PC time series explains ~54% of the variance in the 50 hPa zonal-mean wind field, and is therefore referred to as the Stratospheric Zonal Index (SZI). The pattern found by regressing zonal-mean zonal wind anomalies at 50-hPa onto the standardized SZI describes out-of-phase fluctuations in the stratospheric zonal flow with a node centered ~45°N (Figure 1a). By definition, positive values of the SZI correspond to stronger than normal westerlies poleward of 45°N.

The temporal evolution of a typical sudden stratospheric warming is analyzed using lagged composite analysis based on the amplitude of the SZI. Weakening of the vortex is included in the analysis when the SZI drops below one standard deviation below its long term mean (i.e., below -1.0 standard deviations). The composites are centered about the date (referred to as day 0) that is the midpoint between the day that the SZI drops below -1.0 standard deviations and when it rises again above -1.0 standard deviations. The central dates correspond closely to the time when the polar westerlies are at their weakest.

Overall, 39 events were selected based on the above criteria. The central dates associated with these events occur between early December and early April, and exhibit a weak bias towards more events during late winter (Figure 1b). From these 39 events, we constructed a 75-day composite life cycle, which was divided into five 15-day increments that reflect the onset (days -37 to -23), growth (days -22 to -8), maturation (days -7 to +7), decline (days +8 to +22), and decay (days +24 to +37) of a typical sudden stratospheric warming. Note that historically, minor and major stratospheric warmings are defined on the basis of strict, but ultimately subjective criteria (e.g. Andrews et al., 1987). We prefer the criteria outlined above since it is derived in an objective manner. The methodology outlined above does not distinguish a priori between major and minor warmings.

3. The Life Cycle of a Sudden Stratospheric Warming

Figure 2 shows the composite of the anomalous zonal mean zonal wind, zonal mean temperature, and the EP-flux during the life cycle of a stratospheric sudden warming. During the onset of the SSW, the zonal flow in the extratropical stratosphere is anomalously weak equatorward of 60°N, but westerly wind anomalies appear poleward of ~70°N. Hence, the vortex is anomalously constricted about the pole and appears preconditioned for effective wave forcing (McIntyre, 1982; Andrews et al., 1987). At this time, the stratosphere is disturbed by marked heat flux anomalies above 100-hPa, which correspond to vertically propagating waves along the node of the anomalous wind anomalies (around 60°N). The convergence of the EP-flux in the stratosphere gives rise to anomalous easterly forcing poleward of 50°N above 100-hPa. Weak warm temperature anomalies are found over the pole above 30-hPa. The relatively weak easterly anomalies centered 50-hPa at the Equator, which are also found throughout the composite life cycle, are the hallmark of the easterly phase of the equatorial Quasi-Biennial Oscillation (QBO), which favors an increased frequency of occurrence of SSOs (Holton and Tan 1980).

During the growth and mature stages of the SSW, the easterly forcing due to the convergence of the anomalous EP-flux gives rise to the dramatic weakening of the zonal flow and warming of the polar stratosphere that characterizes all SSWs (Andrews et al., 1987). The convergence of the EP-flux descends with time throughout the onset, growth, and mature stages of the SSW, along with the associated wind and temperature anomalies. At the mature stage, the easterly

anomalies in the stratospheric flow have reached largest amplitude and extend from the surface to the top of the analysis. At this time, the largest warming of the polar stratosphere is centered near 50-hPa. The wave flux below 100-hPa is markedly increased. The anomalous EP-flux is directed poleward near 300-hPa and downward in the troposphere.

In the decline stage of the SSW, both the wind and temperature anomalies in the stratosphere weaken and descend in altitude. Beginning in the mature phase, the anomalous EP-fluxes are downward throughout the stratosphere, which implies anomalously low tropospheric planetary wave sources as the SSW diminishes. During the decay stage, the easterly wind anomalies have nearly disappeared, and the warm temperature anomalies have descended to 200-hPa.

The poleward and downward movement of the anomalous zonal-mean wind and temperature from the upper stratosphere to the lower stratosphere throughout the life cycle of the SSW is reminiscent of the stratospheric oscillation cycles observed by Kodera et al. (2000), Kodera and Kuroda (2002), and Kuroda (2002). The coincidence of downward propagation in the zonal flow with downward propagation in the convergence of the EP-flux suggests wave-mean flow interaction in the stratosphere as the mechanism. The cold temperature anomalies in the polar stratosphere above 30-hPa in the decay stage suggest the onset of a oscillation cycle of opposite sign, although the time scale of these warmings is generally a substantial fraction of the winter season.

The temporal evolutions of SSWs in the stratospheric circulation has been extensively documented in the literature, but the results in Figure 2 also demonstrate that the typical SSW is associated with marked anomalies in the tropospheric circulation.
Fig. 2. Composites of anomalous zonal-mean zonal wind (left), zonal-mean temperature (middle), and EP flux with their divergence (right) during warming events life-cycle. Negative contours are given as dashes. Zero contour is given as bold solid line. The wind contour interval is 1 m s\(^{-1}\). Dark (light) shading indicates values less (greater) than -2 (+2) m s\(^{-1}\). The temperature contour interval is 1 K. Dark (light) shading indicates values less (greater) than -2 (+2) K. The EP flux divergence (divided by \(\rho_o a \cos \theta\), where \(\rho_o\) is basic density, \(a\) is the Earth’s radius, and \(\theta\) is latitude) is contoured in the right column at every 0.25 m s\(^{-1}\) day\(^{-1}\) with deceleration in dark shading. The vector lengths in the right column are referenced with respect to the top figure in column.
Consistent with results presented in Baldwin and Dunkertton (1999, 2001), weakening of the stratospheric zonal flow descends not only throughout the stratosphere, but into the troposphere as well. The most striking tropospheric features in Figure 2 are the pronounced EP-fluxes in the troposphere during the mature phase of the SSW. At this time, the upper tropospheric circulation is marked by both anomalous equatorward momentum fluxes above 500-hPa, and by anomalously weak poleward heat fluxes in the lower troposphere.

The vertically varying temporal evolution of the SSW is explored further in Figure 3. As noted above, the onset and growth period of the SSW is associated with poleward eddy heat flux anomalies (positive vertical component of EP-flux, $F_z$) in the extratropical stratosphere while the decline and decay phases are associated with equatorward eddy heat flux anomalies (negative $F_z$; see Figure 3b). The heat fluxes are almost entirely associated with wavenumber one disturbances (Figure 4). During the growth stage, the largest poleward heat fluxes tend to descend in time in conjunction with the descending easterly anomalies in the extratropical zonal flow.

When the largest easterly anomalies reach the tropopause level, pronounced equatorward momentum flux anomalies (positive meridional component of EP-flux, $F_y$) appear at upper tropospheric levels (see Figure 3a), and pronounced heat flux anomalies appear at lower tropospheric levels. The tropospheric momentum flux anomalies are associated primarily with waves smaller than wavenumber three (Figure 4), and thus presumably reflect a decrease in the poleward momentum fluxes by mostly baroclinic waves following sudden stratospheric warmings. This is consistent with recent evidence that transient eddy feedbacks are important for annular mode maintenance in the Northern Hemisphere (Lorenz and Hartmann, 2003). That the anomalous momentum fluxes are largest over the North Atlantic half of the hemisphere suggests that SSWs project particularly strongly onto variations in the North Atlantic storm track and jet stream (Figure 5). Zhou et al. (2002) report similar North Atlantic variations in their observations of upper tropospheric circulation changes related to downward propagating temperature anomalies from the polar stratosphere.

In addition, the anomalous upper tropospheric momentum fluxes are nearly concurrent with anomalous mean meridional circulation in the troposphere. Strong poleward wind anomalies exist between days -10 and +10 around 300-hPa, which do not exhibit a descending pattern (see Figure 3d). Though difficult to see, strong equatorward meridional wind anomalies...
Fig. 4. Vertical and horizontal component of EP-flux integrated poleward of 50°N for various wavenumbers. Contribution from wavenumbers greater than or equal to 4 is shown in bottom row. Contours of the vertical component and horizontal component are given every $10 \times 10^6$ kg s$^{-2}$ and $20 \times 10^6$ kg s$^{-2}$, respectively. Negative contours are given as dashes. Zero contour is given as bold solid line. For the vertical component, dark (light) shading denotes values less (greater) than or equal to $-20$ ($+20$) $\times 10^6$ kg s$^{-2}$. For the horizontal component, dark (light) shading denotes values less (greater) than or equal to $-40$ ($+40$) $\times 10^6$ kg s$^{-2}$ (as in top two figures of Figure 3).

(dark shadings) are present near the surface during the mature stage and beyond (see also Figure 7). By continuity, anomalous sinking motion appears nearly the same time as meridional wind anomalies (see Figure 3; note that the NCEP/NCAR data has no vertical winds observations above 18 km). Thus, an anomalous meridional circulation develops in the troposphere during the mature stage after the poleward heat flux, temperature, and wind anomalies descend down to the upper troposphere where the strong anomalous equatorward momentum persists.

Figure 6 shows the life cycle of a SSW in the zonal varying, anomalous geopotential height field at the surface, 250-hPa, and 50-hPa. In the stratosphere, the wavenumber one disturbance that is evident during the onset of the SSW in Figure 2 is associated with an anomalous anticyclone over the Aleutian Islands and anomalous cyclone over Russia (Figure 6,
Fig. 5. Time-averaged distribution of $u^*v^*$ anomalies during the MATURE phase (time average between day -7 to day +7). Here, the star denotes departure from zonal symmetry. The variables $u$ and $v$ are zonal wind and meridional wind, respectively. Hatched areas show values lesser or equal to -30 m$^2$ s$^{-2}$, representing regions of strong anomalous equatorward momentum fluxes.

At this time, significant anomalies that resemble wavenumber one are also evident near the surface, but with anomalously low heights over the North American half of the hemisphere and anomalously high heights over the Eurasian half of the hemisphere.

As the SSW intensifies, the anomalies become dominated by a high degree of zonal symmetry, with anomalously high geopotential heights over the polar region and anomalously low geopotential heights throughout middle latitudes in both the stratosphere and troposphere. Consistent with Baldwin and Dunkerton (2001), the tropospheric anomalies during the mature phase bear a striking resemblance to the surface signature of the NAM. As the warming decays, the anomalous high stratospheric heights are displaced off the pole while the NAM-like anomalies persist at the surface.

### 4. Summary

This study presents a “climatological” view of the life cycle of a stratospheric sudden warming in both the atmospheric flow and in eddy heat and momentum fluxes. The analysis makes no a priori distinction between types of warming (major or minor) or between the differing ways in which the vortex is initially perturbed (i.e., Schoeberl, 1978 notes that weaker warmings are generally associated with zonal wavenumber two disturbances; Yoden et al., 1999). The key results associated with the composite life cycle are summarized in Figure 7.

Strong heat flux anomalies (large, positive $F_z$) are observed in the preconditioned upper stratosphere several weeks before the maturation of the sudden warming (Figure 7a). These fluxes are associated mainly with wavenumber one disturbances that are evident at both tropospheric and stratospheric levels. The intensification of anomalous poleward heat fluxes is followed by substantial easterly anomalies in the stratosphere and strong polar stratospheric warming that descend through the stratosphere as wave activity breaks at increasingly lower stratospheric levels (Figure 7c). When the zonal wind anomalies reach the lower stratosphere (~150-hPa, strong equatorward momentum fluxes (large, positive $F_y$) appear near 300-hPa (Figure 7b) and strong equatorward heat flux anomalies appear in the lower troposphere (Figure 2 and 4). The upper tropospheric momentum flux anomalies are comprised of mostly smaller scale disturbances (less than zonal wavenumber 3) and are largest over the North Atlantic sector (Figure 5). Also at this time, an anomalous over-turning cell develops in the troposphere as large northward zonal mean wind anomalies develop near 300-hPa and large southward wind anomalies develop in the surface circulation (Figure 8d) with downward wind anomalies in between (Figure 3e).

The Coriolis force associated with the upper tropospheric meridional wind anomalies in Figure 7d act to oppose the anomalous convergence of momentum flux in middle latitudes implied by Figure 7b. Hence, the anomalous tropospheric circulation anomalies during the mature phase of a SSW must be driven by the anomalous fluxes of eddy momentum at upper tropospheric levels. The wave forcing gives rise to predominantly poleward circulation anomalies from 40°N to the pole, descent over the polar region, and equatorward return flow near the surface. The Coriolis torque acting on the induced meridional circulation anomalies acts to drive the near-surface easterly wind anomalies along ~55-60°N. The corresponding meridional circulation anomalies equatorward of 40°N (not shown) give rise to near-surface westerly wind anomalies along ~30°N. As such, the out-of-phase tropospheric wind anomalies revealed during the mature phase of the SSW (see Figure 3), and subsequently the negative bias in the NAM during the mature phase of the SSW (Figure 7e; see also Baldwin and Dunker-
Fig. 6. Composites of geopotential height (in decameters, dam) anomalies at various levels. The contour interval is 3 dam, 1 dam, and 0.5 dam for 50 hPa, 250 hPa, and 1000 hPa, respectively. Negative (positive) anomalies are shown as blue (red) contours. Zero contours are omitted for clarity. Yellow shading indicates areas with 95% confidence level (based on t-statistics).
ton 2001) is consistent with the anomalous momentum fluxes in the upper troposphere. Note that while the momentum flux anomalies becomes large during the mature phase, the momentum flux and meridional circulation anomalies in Figure 7 do persist to the end of the life cycle, just as the NAM anomalies (or index) do. Since the NAM anomalies are the time integral of the momentum forcing, they do not show the peak near the mature phase as strongly as the momentum forcing. These basic dynamical mechanisms are similar to those driving NAM variability not associated with SSWs.

The key results in this study are thus the following:

1. The downward propagating events in the stratospheric zonal flow associated with SSWs (and as outlined in Baldwin and Dunkerton, 1999, 2001) are preceded by preconditioning of the stratospheric circulation, and by anomalous wavenumber one forcing in both the stratosphere and troposphere;

2. The downward propagating anomalies in the stratospheric zonal flow are accompanied by downward propagating anomalies in the convergence of the EP-flux, which indicates that downward propagation reflects wave-mean flow interactions in the stratospheric circulation (e.g. Kodera and Kuroda, 2002, and Kuroda, 2002);

3. When the downward propagating wind anomalies reach the tropopause level, the tropospheric circulation is marked by large anomalies in the flux of momentum by waves of smaller than wavenumber three. The results suggest that the key dynamical pro-
cesses that underlie the observed coupling between the stratospheric and tropospheric circulations involve the linkage between variability in the zonal flow of the lower stratosphere and baroclinic wave activity in the troposphere.

References


