Stratosphere–Troposphere Coupling during Spring Onset

ROBERT X. BLACK AND BRENT A. McDaniel
School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia

WALTER A. ROBINSON
Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

(Manuscript received 25 March 2005, in final form 21 December 2005)

ABSTRACT

The authors perform an observational study of the relation between stratospheric final warmings (SFWs) and the boreal extratropical circulation. SFW events are found to provide a strong organizing influence upon the large-scale circulation of the stratosphere and troposphere during the period of spring onset. In contrast to the climatological seasonal cycle, SFW events noticeably sharpen the annual weakening of high-latitude circumpolar westerlies in both the stratosphere and troposphere. A coherent pattern of significant westerly (easterly) zonal wind anomalies is observed to extend from the stratosphere to the earth’s surface at high latitudes prior to (after) SFW events, coinciding with the polar vortex breakdown. This evolution is associated with a bidirectional dynamical coupling of the stratosphere–troposphere system in which tropospheric low-frequency waves induce annular stratospheric circulation anomalies, which in turn, are followed by annular tropospheric circulation anomalies.

The regional tropospheric manifestation of SFW events consists of a North Atlantic Oscillation (NAO)-like phase transition in the near-surface geopotential height field, with height rises over polar latitudes and height falls over the northeast North Atlantic. This lower-tropospheric change pattern is distinct from the climatological seasonal cycle, which closely follows seasonal trends in thermal forcing at the lower boundary. Although broadly similar, the tropospheric anomaly patterns identified in the study do not precisely correspond to the canonical northern annular mode (NAM) and NAO patterns as the primary anomaly centers are retracted northward toward the pole. The results here imply that (i) high-latitude climate may be particularly sensitive to long-term trends in the annual cycle of the stratospheric polar vortex and (ii) improvements in the understanding and simulation of SFW events may benefit medium-range forecasts of spring onset in the extratropics.

1. Introduction

The annual transition from winter to spring (spring onset) and its interannual variability are important elements of extratropical Northern Hemisphere climate. Spring onset affects the hydrological cycle, vegetative growing season, and ecosystem productivity (Cayan et al. 2001; D’Odorico et al. 2002). Interannual variability in spring onset has been linked to variability in the Arctic Oscillation (AO) or closely related North Atlantic Oscillation (NAO; D’Odorico et al. 2002; Overland et al. 2002) and is associated with regional variations in sea ice, tropospheric ozone, cloudiness, and air temperature (Wang and Key 2003; Belchansky et al. 2004; Lamarque and Hess 2004). It is clearly of general interest to understand better the nature and physics of the large-scale extratropical circulation changes that occur during spring onset.

Climatologically, spring onset occurs during the same time of year as the annual collapse of the stratospheric polar vortex. Polar vortex weakenings are known as sudden stratospheric warmings (SSWs), and each winter concludes with the so-called stratospheric final warming (SFW) marking the final transition from westerlies to easterlies in the extratropical stratosphere. The timing of SFWs is controlled by the preexisting stratospheric flow structure and variations in the upward propagation of tropospheric planetary waves. Thus, it is highly variable from year to year (Waugh and Rong
In addition to interannual variability, the stratospheric circulation is also distinguished by long-term trends. For example, between the mid-1980s and late 1990s the polar vortex became stronger, colder, and more persistent, particularly during spring (Waugh et al. 1999; Zhou et al. 2000). These trends were linked to concurrent decreases in planetary wave activity, SSW frequency, and stratospheric ozone levels (Labitzke and Naujokat 2000; Hu and Tung 2003; Rex et al. 2004). The sources of such stratospheric trends are unresolved and the subject of considerable debate in the recent literature (e.g., Manzini et al. 2003).

A robust bidirectional dynamical coupling between the stratosphere and troposphere has been observed in the boreal extratropics during winter (Thompson and Wallace 1998; Baldwin et al. 2003; McDaniel and Black 2005) in association with intraseasonal variability in the northern annular mode (NAM). The NAM is the primary mode of circulation variability in the Northern Hemisphere extratropics and its lower-tropospheric manifestation (or footprint) is known as the Arctic Oscillation (e.g., Baldwin et al. 2003). During winter NAM events are characterized by a deep and coherent extratropical circulation anomaly pattern that extends from the earth’s surface upward into the middle stratosphere. This pattern acts to connect the strength of the stratospheric polar vortex to the sign and magnitude of the near-surface AO pattern (Thompson and Wallace 1998). Interestingly, recent statistical analyses illustrate that stratospheric NAM signatures often precede tropospheric NAM events (Baldwin and Dunkerton 2001; Sigmond et al. 2003; Black and McDaniel 2004). In fact, it has further been demonstrated that the lower-stratospheric NAM is a useful predictor of subsequent tropospheric NAM behavior (Baldwin et al. 2003). On the other hand, the diagnostic study of Polvani and Waugh (2004) also shows that stratospheric NAM variations are systematically preceded by anomalous upward fluxes of planetary wave activity emanating from the troposphere. Although this brings into question the proximate physical source for a presumed downward stratospheric influence, it remains evident that important dynamical interactions between the extratropical stratosphere and troposphere exist in association with winter NAM events.

Both observational and modelling studies have revealed stratosphere–troposphere coupling to also occur in association with midwinter SSW episodes (Taguchi 2003; Limpasuvan et al. 2004). The latter study finds strong parallels between SSW events and the intraseasonal time evolution of negative NAM events. SSW events are triggered by anomalous planetary wave driving (as in Polvani and Waugh 2004) and then followed by the negative phase of the Arctic Oscillation (as in Baldwin and Dunkerton 2001). We note, however, that while SSWs occur about every second or third year, SFW events are observed to occur every year. Further, SFW events happen during a time period when the Northern Hemisphere extratropical atmosphere is transitioning from a winter dynamical regime to a summertime state. As such, it is of interest to study the extent to which the above characteristics carry over to a consideration of SFW events.

Motivated by a combined consideration of the above research, we perform an exploratory observational analysis of the impact of SFWs upon the large-scale circulation of the stratosphere and troposphere. This new research problem is approached by performing a composite evolution analysis of SFW events in which the composite circulation time evolution is contrasted with the climatological trend (i.e., the mean seasonal cycle) values. Our approach is outlined in section 2, the primary results are presented in section 3, and section 4 provides our concluding remarks.

2. Methods

The basic input data for our study are the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) daily average reanalyses (Kalnay et al. 1996) archived on 17 pressure levels extending from 1000 to 10 hPa. We consider both total and anomaly fields, where the latter are defined in terms of deviations from a smoothed climatological trend (seasonal cycle). The statistical significance of the composite anomalies is assessed using a Student’s t test (in which each annual SFW event is considered as an independent sample). We further restrict our attention to those anomaly features that are reproducible in the first and second halves of the data record. SFW events are identified as the final time that the zonal-mean zonal wind at 70°N (the core latitude of the stratospheric polar vortex) drops below zero without returning to a specified positive threshold value until the subsequent autumn. We apply this criterion to running 5-day averages at 10 and 50 hPa (with thresh-
olds of 10 and 5 m s\(^{-1}\), respectively) and find the mean SFW dates to be 4 and 14 April, respectively. Thus, it typically takes a week or so for SFW events to progress from the mid- to lower stratosphere, where a tropospheric impact is expected to be greater (Baldwin et al. 2003). Our 50-hPa SFW events occur, on average, about 17 days later than the SFW dates identified in Waugh and Rong (2002) using the Nash et al. (1996) criterion. Also, all our SFW events occur after 12 March while five of Waugh and Rong’s cases occur during February. Thus, we effectively isolate a later stage in the polar vortex breakdown characterized by the onset of easterlies within the vortex core (noting that the criterion used by Waugh and Rong employs a critical wind speed of \(\sim 15\) m s\(^{-1}\) along the outer edge of the polar vortex).

The SFW dates identified are then used to construct composite time evolutions based on 47 years (1958–2004) of reanalysis data. For the 50-hPa cases, in addition to compositing 47 SFW events together, we also construct separate composites of the 22 earliest and 22 latest events (separated by three median events) to study potential sensitivities to SFW timing. This is partly motivated by the study of Waugh and Rong (2002) who also contrasted early and late events. As will be discussed, the basic large-scale circulation characteristics are not very sensitive to this stratification. The primary difference is that the later cases tend to proceed more gradually than early cases, which interestingly is in opposition to what Waugh and Rong (2002) found in their study. (This is shown explicitly within the context of Fig. 2. Besides this distinction, the main features discussed in Figs. 3 and 4 are well reproduced in both the early and late composites that, for the sake of brevity, are not shown.)

3. Results

Our general approach is illustrated in Fig. 1, which presents composite analyses based on the 10-hPa SFW dates. Figure 1a is derived from (unfiltered) daily averaged data and contrasts the long-term climatological trend in high-latitude 10-hPa zonal-mean zonal wind to a parallel SFW composite evolution. The SFW composite is associated with a much more rapid decline in the midstratospheric westerlies than observed in the climatological trend, with anomalous westerlies (easterlies) occurring prior to (after) SFW onset. This suggests that the climatological trend does not provide an adequate depiction of the typical breakdown rate for the polar vortex. This is likely due to the interannual variability in the timing of SFW events (\(\sigma \sim 18\) days), which acts to spread out the sharp decline observed during individual years. To study this further we performed a parallel composite analysis for stratospheric fall cooling (SFC) events (plotted as a black line in Fig. 1a), which have an average onset day of 29 August. Unlike for SFW, the SFC composite does not contain an analogous increase in slope relative to the climatological trend. This is because of the relatively small interannual variability in the timing of SFC events (\(\sigma \sim 4\) days). In any case, in comparing SFW and SFC composite time evolutions a clear difference in their relative slope is evident. This indicates a fundamental asymmetry in the respective behavior of spring and fall onsets in the stratosphere, with the latter typically proceeding more gradually.

One of the primary goals of the remaining analyses is to examine the extent to which the signature evident for SFW in Fig. 1a extends down to tropospheric levels. To explore this, composite evolutions of National Oceanic and Atmospheric Administration Center for Climate Prediction (NOAA CPC) daily NAO and AO index anomalies are displayed in Fig. 1b. This figure provides modest initial evidence that the lower-tropospheric circulation is usually characterized by persistent positive episodes of the NAO in the weeks prior to SFW events with a rapid shift toward the negative NAO phase thereafter. We note that the SFW precursor signal observed here is less evident in studies of midwinter SSW events (Limpasuvan et al. 2004). This may indicate a difference in the dynamical preconditioning of the troposphere prior to SFW events, which have not been studied in this manner before.

Composite analyses based on 50-hPa SFW dates are shown in Figs. 2–4. The high-latitude climatological zonal wind evolution during the time of spring onset is contrasted with parallel SFW composite evolutions (centered on the onset date) in Fig. 2. The climatological picture portrays a gradual transition from the winter state (strong westerlies in the stratosphere and upper troposphere) toward a quasi-steady summer state (typified by stratospheric easterlies and a weak upper-tropospheric jet). There is little perceptible change in the lower tropospheric wind field. The SFW composite, in contrast, shows a more abrupt transition in both the stratosphere and troposphere. The middle stratosphere experiences two periods of rapid deceleration: between days −20 and −15 and between days −5 and 0. During the latter period, strong decelerations are also observed in the lower stratosphere and through the depth of the troposphere. Thereafter, the stratosphere and troposphere both attain quasi-steady states with some relaxation back toward winter conditions occurring around day +20. Separate composites derived from the 22
Fig. 1. (top) Daily values of the 10-hPa zonal mean zonal wind averaged from 60° to 80°N for 40 yr. Pink curve: Long-term seasonal trend. Blue curve: Composite of SFW events (centered on mean SFW date). Black curve: Analogous composite of SFC events (centered on mean SFC date). (bottom) A composite of the daily AO and NAO indices with respect to SFW dates. The analysis is performed for 54 yr (1950–2003) after first removing a remnant annual cycle (taken as the long-term daily average seasonal cycle smoothed with a 31-day running average operator).
earliest and 22 latest SFW events (bottom two frames of Fig. 2) reveal qualitatively similar features. The primary differences are the (i) more gradual evolution of the late composite and (ii) enhanced relaxation toward the initial state in the early composite. The former feature is opposite of what Waugh and Rong (2002) found (noting that their classification procedure isolated an earlier part of the SFW life cycle; see the discussion in section 2).

SFW composite analyses of anomaly fields are shown in Fig. 2. The daily time evolution of zonal-mean zonal wind (m s$^{-1}$) averaged from 60° to 80°N. (top left) The climatological-mean time evolution centered on 14 April (denoted lag 0). (top right) The parallel time evolution for a composite constructed with respect to the annual timing of SFW events at 50 hPa (lag 0). (bottom left) earliest and (bottom right) Composite of 22 latest SFW events.
in Figs. 3 and 4. The composite evolution of zonal wind and eddy forcing anomalies are shown in the top panels of Fig. 3. These figures present anomalies that are averaged over the latitude band encompassing the largest zonal wind anomaly changes (70°–80°N; see the bottom panel of Fig. 3). Consistent with Fig. 1 we find a pattern of statistically significant westerly (easterly) anomalies prior to (after) SFW onset extending from the stratosphere to the earth’s surface. The westerly anomalies prior to day −10 are largest in magnitude and are considered most robust. Notably, the strongest precursor occurs around day −30 and consists of a vertically contiguous pattern of westerly anomalies that attains maximum amplitude in the troposphere prior to peaking in

Fig. 3. Anomalies composited with respect to SFW events (lag 0). (top left) Time evolution of composite zonal-mean zonal winds averaged from 70° to 80°N (shading: m s⁻¹). Colored contours indicate the 90% and 95% confidence levels for a two-sided Student’s t test. (top right) Time evolution of local wave driving (shading: m s⁻¹ day⁻¹) and red contours that indicate regions of upward Eliassen–Palm flux anomalies (units: 10⁵ m² s⁻²) averaged from 70° to 80°N for low-pass anomalies. (bottom) The composite change in the zonal-mean zonal wind anomaly (UP) field between lags −10 and +10 (units: m s⁻¹). Blue and yellow contours indicate the 90% and 95% confidence levels for a two-sided Student’s t test. The purple contour indicates the climatological mean tropopause location.
Fig. 4. The 1000-hPa geopotential height anomalies (shaded: m) composited with respect to SFW events (lag 0). Colored contours indicate the 90% and 95% confidence levels for a two-sided Student’s t test. (top left) The time average for lags -20 to -15. (top right) The time average for lags +5 to +10. (bottom left) The difference between the two previous fields. (bottom right) A parallel analysis using climatological data.
the stratosphere. Accounting for the 10-day mean progression of SFW events from 10 to 50 hPa, the tropospheric feature found at day −30 precisely corresponds to the positive NAO signal observed at day −20 in Fig. 1. After day −30, the tropospheric feature disappears while the stratospheric westerly anomalies gradually progress downward toward tropospheric altitudes.

The circulation quickly transitions to easterly anomalies after SFW onset. The largest tropospheric easterly anomalies are found to occur after the largest mid-stratospheric anomalies. Interestingly, the tropospheric response after day 0 is composed of two distinct features: a brief and relatively weak easterly anomaly pattern at day +1 and a stronger response maximized at day +9. The former feature occurs in tandem with maximum easterly anomalies at stratospheric altitudes while the latter feature emerges while the stratospheric easterly anomalies weaken in amplitude. The synoptic behavior of the first and second features is consistent with the respective direct and indirect tropospheric responses to stratospheric forcing discussed by McDaniel and Black (2005). This delineation in the tropospheric response is not evident in parallel studies of SSW events (Limpasuvan et al. 2004).

The two stratospheric deceleration periods discussed in Fig. 2 are associated with distinct bursts of upward Eliassen–Palm flux and stratospheric wave driving anomalies by low-frequency eddies (top right of Fig. 3). The second burst begins (day −7) with an anomalous trough in the upper troposphere that extends from the North Pole to Florida and ends (day −3) with a wave-1 disturbance in the stratosphere (not shown). The instigation of SFW events by low-frequency anomalies is consistent with the diagnosed behavior of SSW events (Limpasuvan et al. 2004) and NAM events (Polvani and Waugh 2004). The latitudinal structure of the composite zonal wind change that occurs during the 20-day period encompassing SFW events is displayed in the bottom frame of Fig. 3. This plot shows that there are not only significant high-latitude zonal decelerations during SFW events but also opposing accelerations in midlatitudes. The high-latitude zonal wind changes are substantial and are structurally distinct from the canonical NAM paradigm in which the tropospheric anomaly pattern is displaced −10° south of the stratospheric pattern (e.g., Black and McDaniel 2004).

The near-surface manifestation of SFW events is displayed in Fig. 4. As suggested by our preliminary analyses (Fig. 1), the 1000-hPa height anomaly evolution depicts a transition between broadly similar but oppositely signed anomaly patterns, primarily distinguished by a significant anomaly dipole between polar latitudes and the northwest coast of Europe. Although the observed anomaly patterns partly project on the canonical AO/NAO pattern, there are notable distinctions such as the (i) northward and eastward shift of the Atlantic center and (ii) relative prominence of the polar center (e.g., Fig. 1 of Thompson and Wallace 1998). This represents another difference with parallel SSW analyses as a clear negative NAO signature emerges after SSW events (Fig. 9 of Limpasuvan et al. 2004). The above distinctions are consistent with the relatively modest NAO signals observed in Fig. 1b.

The resulting 1000-hPa height change pattern (lower left frame of Fig. 4) illustrates that SFWs are associated with local 1000-hPa height increases (decreases) exceeding 60 m (50 m) at the polar (Atlantic) center. Again, although substantial circulation changes are clearly occurring over the NAO region, the change pattern does not project well upon the canonical NAO structure (spatial pattern correlation ≤0.6). It is also of interest to compare the structure and magnitude of the SFW change pattern to the parallel climatological trend (lower right frame of Fig. 4). This field is calculated in the same way as the SFW change except considering the time evolution of climatological daily averages centered on 14 April (lag 0). The climatological trend pattern exhibits height increases (decreases) over the extratropical oceanic (continental) regions, leading to a weakening of the semipermanent surface features of the boreal winter circulation (the Aleutian and Icelandic low pressure systems; the Siberian high). This trend pattern is precisely what one would expect as the high-latitude continental regions preferentially warm and lose atmospheric mass to the still-cool oceans. Although the main features of the SFW change pattern are of the same order of magnitude as the climatological trend pattern, the two fields are, if anything, in regional quadrature with one another. Thus, the organizing influence of SFW events upon the regional tropospheric circulation is not simply an amplification of the climatological trend. Our results suggest that spring onset in the troposphere may be composed of two distinct parts: one that is predominately thermally forced by the lower boundary and a second part that is linked to the annual breakdown of the stratospheric polar vortex. In particular, it would appear that the large-scale circulation changes occurring at polar latitudes during spring onset are largely determined by the stratospheric polar vortex evolution.

---

3 Intra-annual periods greater than 10 days are isolated using a 151-point Lanczos filter (prior to the calculation of the eddy flux field).
4. Concluding remarks

We have performed an exploratory analysis of the impact of stratospheric final warmings upon the extratropical large-scale circulation in the Northern Hemisphere. Using a composite observational approach, we find that SFW events provide a strong organizing influence upon the large-scale circulation of both the stratosphere and troposphere during the period of spring onset. A coherent pattern of significant westerly (easterly) zonal wind anomalies is observed to extend from the stratosphere down to Earth’s surface at high latitudes prior to (after) SFW events, coinciding with the annual breakdown of the stratospheric polar vortex. At negative time lags the largest tropospheric westerly anomalies slightly precede peak westerly anomalies in the middle stratosphere. The midstratospheric westerly signal then gradually descends and is followed by weaker and less robust tropospheric westerlies just prior to SFW onset. At positive time lags the largest tropospheric easterly anomalies follow the largest stratospheric anomalies. High-latitude decelerations are accompanied by zonal accelerations at lower latitudes in both the stratosphere and troposphere. The zonal wind change pattern is distinct from the canonical NAM structure as the high-latitude tropospheric anomaly feature is shifted north compared to its NAM counterpart.

At stratospheric altitudes, SFW events are characterized by a transition from westerlies to easterlies that is much more rapid than suggested by climatological trend values. We further find that the stratospheric polar vortex typically breaks down much more quickly during spring than it develops during fall, suggesting a fundamental asymmetry in the respective behavior of seasonal transitions in the stratosphere. This asymmetry is consistent with spring (fall) onset being driven primarily by dynamical (radiative) processes within the stratosphere. The stratospheric zonal wind decelerations observed during SFW events arise from anomalous wave driving associated with low-frequency eddies propagating upward from tropospheric altitudes. Therefore, the troposphere is implicated as a likely root source of the SFW modulation of tropospheric climate (suggesting a feedback process between the troposphere and stratosphere).

At tropospheric levels SFW events act to dramatically sharpen the springtime weakening of the high-latitude westerlies compared to climatological trend values. More specifically, the high-latitude troposphere appears to switch to a quasi-steady summerlike state after SFW events. The regional manifestation of SFW events consists of an NAO-like phase transition in the near-surface height field, with a pattern of coherent height rises (falls) over polar latitudes (northeast North Atlantic). This change pattern is distinct from the parallel climatological trend, which itself consists of height rises (falls) over the extratropical oceanic (continental) regions of the Northern Hemisphere. We suggest that the large-scale circulation changes that occur in the lower troposphere during spring onset can be decomposed into two parts: one due to changes in the lower boundary thermal forcing and a second part (isolated in this study) related to SFW events.

There are intrinsic difficulties in associating dynamical behavior with the SFW, because these events are embedded in a nonstationary climate, and the occurrence of these events is a major contributor to that nonstationarity. Although one goal of the current study is to determine that contribution, it should be kept in mind that it is not possible to determine, from observational data alone, what the circulation would have been on a given day if the final warming had not, say, taken place a few days earlier. Specifically, composite anomalies for days prior to the SFW (negative lags) exclude contributions from years in which the SFW had already occurred at that date, so it is expected, and indeed we find, that lower-stratospheric zonal winds anomalies are westerly for days before the SFW and easterly for days after the SFW. Stratospheric zonal wind anomalies (Fig. 3) immediately preceding and following the SFW date are, thus, to some extent, built into our analysis. We also find, however, a prominent stratospheric westerly anomaly signature around 30 days before the SFW. Dates this early lie nearly outside the range of SFW onset, so this feature is unlikely an artifact. Moreover, we find statistically significant and robust precursor anomalies in dynamical fields besides the stratospheric zonal winds used to construct our composites: tropospheric zonal winds, tropospheric geopotential heights, and wave driving. It is likely that these features are dynamically, not just statistically, linked to SFW events. Determining whether they are causes or consequences of the SFW will require a combination of further analysis and modeling.

There are important similarities and differences between the current results and previous studies of midwinter sudden stratospheric warming (SSW) events or more general intraseasonal NAM variability. As in previous studies (Baldwin and Dunkerton 2001; Limpasuvan et al. 2004; Black and McDaniel 2004), we find evidence that the largest zonal decelerations occur first at stratospheric altitudes. Conversely, we also find important structural differences between the tropospheric anomaly patterns identified here and patterns identified elsewhere. The primary difference is that the key extratropical anomaly features in our study are re-
tracted and/or shifted northward toward the pole in comparison to the results of other studies (Limpasuvan et al. 2004). Thus the near-surface anomaly patterns identified here do not have a one-to-one correspondence with the NAO anomaly pattern. This has important consequences for selecting a suitable basin field for projecting the large-scale tropospheric response to SFW events. As in Polvani and Waugh (2004) and Limpasuvan et al. (2004) we find that SFW events are initiated by anomalous wave driving associated with upward propagating tropospheric waves. Finally, a stratification of SFW events into separate composites of the 22 earliest and 22 latest cases reveals that the later events tend to proceed more gradually than early events, contrary to the results of Waugh and Rong (2002) who focused on an earlier stage in the polar vortex breakdown.

We conclude that, in contrast to the climatological trend, SFW events noticeably sharpen the annual weakening of the circumpolar westerlies in both the stratosphere and troposphere during spring onset. This evolution is associated with a robust large-scale dynamical coupling of the stratosphere and troposphere and results in a distinct regional circulation change in the lower troposphere. An important implication of the current results is that high-latitude climate may be particularly sensitive to decadal trends in the persistence and late-winter variability of the stratospheric polar vortex (potentially altering the nature of spring onset at polar latitudes). It is clearly of practical interest to examine the representation and prediction of spring onset by numerical climate and weather prediction models. We suggest that improvements in the physical understanding and numerical simulation of the time evolution of SFW events will likely lead to enhancements in medium-range forecasts of spring onset.

Acknowledgments. This research is supported by the NSF Climate and Large-Scale Dynamics Program under Grants ATM-0237304, ATM-0456157, and ATM-0456188 and by the NASA Living with a Star Targeted Research and Technology Program under Grant NAG5-13492. We thank the three anonymous reviewers for their helpful comments and guidance. The NCEP–NCAR reanalyses come from the NOAA Climate Diagnostics Center from their Web site at http://www.cdc.noaa.gov. The NAO and AO time series come from NOAA-CPC at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/history.shtml.

REFERENCES

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscil-