The Solar Cycle and Stratosphere-Troposphere Dynamical Coupling

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Submitted to J.A.S.-T.P. Special Issue (Prague Workshop), 30 December, 2003.

Abstract. Observations and modeling studies support the hypothesis that solar cycle/ozone interactions create temperature and wind anomalies in the tropical upper stratosphere near 1 hPa. During extended winter, interactions with planetary-scale Rossby waves draw low-latitude stratospheric wind anomalies poleward and downward through the stratosphere. Although the details of how the solar cycle affects stratospheric winds are not well understood, solar influence on surface climate would likely involve interactions with stratospheric Rossby waves and the coupling of the lower stratospheric circulation to near Earth's surface. Here we provide an overview of stratosphere-troposphere dynamical coupling. We also discuss dynamical mechanisms that might communicate stratospheric circulation anomalies downward from the stratosphere to the troposphere and surface.

1. Introduction

Nearly all of the energy that drives the climate system comes from the sun, and variations in solar radiation on several timescales are linked with substantial variations of Earth's climate. Records of surface, upper ocean, and lower tropospheric temperatures, together with the sun's irradiance, suggest that climate changes are associated with relatively small changes in energy that Earth receives from the sun. These fluctuations occur on timescales from centuries [e.g., the little ice age: *Eddy*, 1976] to thousands of years [e.g., Milankovich orbital cycles: *Hayes et al*, 1976].

Solar irradiance also varies slightly over an 11-year cycle as the sun's magnetic activity alters its energy output. Although the total energy output of the sun varies by only ~0.1% over the solar cycle [*Fröhlich and Lean*, 1998], radiation at longer UV wavelengths increases by several percent. Still larger changes—a factor of two or more—are found in extremely short UV and X-ray wavelengths. For the past 200 years this fairly regular cycle has inspired researchers to link solar-cycle variations to variations in weather and climate. Ultimately, most of the proposed links came to naught because the relationships were specious. Some lacked field significance [solar-cycle correlations were at isolated locations, *Barnston and Livezey*, 1989], some were non-stationary (correlations that decrease or disappear as newer data are obtained) and others suffered large gaps in temporal coverage.

Early attempts to associate the solar cycle with weather and climate variations involved surface or tropospheric observations. More recently, *Labitzke* [1987] examined stratospheric data and found a relationship involving the solar cycle, North Pole temperatures at 50 hPa, and the phase of the Quasi-biennial Oscillation (QBO) in equatorial stratospheric winds. These results were met with some skepticism for two reasons: 1) the short data record meant that the results were marginally significant, and 2) there was no mechanism to explain the relationship.

Since 1987 there have been four developments which provide evidence in favor of a solar influence on the atmosphere:

- **Strong statistical relationship in the data record**. *Labitzke*'s [1987] discovery was followed by several papers which expanded on the original result [*van Loon and Labitzke* 2000; *Labitzke*, 2004, this issue]. Strong correlations are seen year-round between the solar cycle and stratospheric geopotential heights and temperatures in both hemispheres, irrespective of the phase of the QBO. Only during northern late winter does the QBO appear to modulate the direct correlation with the solar cycle [*Dunkerton and Baldwin*, 1992]. Variations approximately in phase with the solar cycle are also seen in satellite records of global temperature in the lower troposphere, the North Atlantic Oscillation, surface temperature, and upper ocean temperature.
- **Solar-ozone mechanism.** As noted above, the UV spectrum varies by several percent over a solar cycle. Since UV radiation is absorbed by ozone in the stratosphere, the concentration of ozone varies with the intensity of UV radiation. This radiative-photochemical mechanism effectively amplifies the solar cycle through a positive feedback with the ozone concentration, apart from dynamical feedbacks. Ozone

variations have a direct radiative impact on the stratosphere and troposphere, and observations of temperatures are broadly consistent with the expected radiative forcing.

- **Model simulations consistent with observations**. Mechanistic models and general circulation models (GCMs) with interactive ozone and solar-cycle variations in UV show effects broadly similar to the observations [e.g., *Matthes et al*., 2003]. Model simulations demonstrate that "small perturbations are reinforced over long periods of time, resulting in systematic changes to the stratospheric circulation" [*Arnold and Robinson*, 1998]. A cumulative influence of external forcings over the course of a winter season was seen in the stratosphere's response to equatorial QBO [*O'Sullivan and Dunkerton*, 1994].
- **Dynamical mechanism to amplify solar effects.** Observations [*Kodera et al.,* 1990] and models show that circulation anomalies in the upper stratosphere move poleward and downward through wave-induced momentum transport. Anomalously weak winds in the polar vortex during stratospheric warmings are seen to move downward through the stratosphere, often penetrating the troposphere and reaching Earth's surface. The same is true of anomalously strong winds. This dynamical mechanism—which is really a combination of mechanisms involving planetary-wave forcing, induced circulation and possible feedback between planetary and synoptic-scale waves—could maintain and energetically amplify the stratospheric solar signal (or another signal such as the QBO or volcanic eruption) and communicate this signal to the troposphere.

These four developments provide evidence that the 11-year solar cycle has an effect on the lower atmosphere, and merit further study in this area. Indeed, our current understanding of the processes involved is qualitative at best, and there remain many quantitative, as well as qualitative, issues to address. (The Third IPCC Assessment [*Houghton et al*., 2001], for example, states that the level of scientific understanding of solar radiative forcing is "very low.") We echo that sentiment and add that the level of understanding of dynamical feedbacks is also low. A conceptual framework for understanding of downward influence would be helpful, and may be developed along the following lines. There seem to be two mechanisms, or pathways, involved by which the direct solar/ozone heating in the low-latitude upper stratosphere can be communicated to the global lower stratosphere and troposphere. One mechanism or pathway is direct; the other is indirect. The *direct* mechanism, effective year-round, works by modulating the Hadley circulation. Ozone changes have a direct radiative impact on the stratosphere and troposphere [*Shindell et al.*, 1999a; *Larkin et al.*, 2000; *Lean and Rind*, 2001]. It is plausible that changes in tropical ozone, though small, have a subtle but statistically significant effect on the extratropical circulation of the troposphere [*Hou and Molod*, 1995; *Haigh*, 2001].

The *indirect* mechanism works through modulation of upward-propagating planetary-scale Rossby waves, and would be effective only during the extended winter season (October-April) when the stratospheric polar vortex is westerly [*Charney and Drazin*, 1961] and planetary-scale Rossby waves propagate into the stratosphere. The stratospheric zonal flow is changed where the Rossby waves break, and the altered winds affect subsequent planetary wave propagation from the troposphere. Observations show that changes in the strength of the polar vortex move downward through the stratosphere, and the surface pattern looks like the leading mode of variability, called the Arctic Oscillation [*Thompson and Wallace*, 1998]. The total effect on the atmosphere may be a superposition of direct and indirect effects [*Lean and Rind*, 2001].

In this overview paper, we are not concerned with the details of solar influence on the upper stratosphere nor if the solar cycle and QBO interact. Rather, we take the view that any such solar effect that alters stratospheric winds could be communicated to the troposphere by the direct and indirect pathways described above. In this paper we focus on the indirect pathway via the extratropical stratosphere, and on mechanisms by which stratospheric circulation anomalies are communicated poleward and downward to the lower stratosphere, and how the tropospheric circulation is subsequently affected. It is the *communication* and possible *amplification* of stratospheric signals downward to Earth's surface that is crucial to any solar-climate mechanism.

2. Stratospheric response to solar forcing

Observations support the hypothesis that the 11-year solar cycle modulates ozone concentrations and ozone heating in the tropical upper stratosphere and lower mesosphere [*Hood*, 1997; *Hood and Soukharev*, 2000], with approximately a 1K temperature change with the solar cycle. Further support comes from GCMs [e.g., *Matthes et al.*, 2003].

Some effect on subtropical winds is also expected, although the observed strengthening of subtropical mesospheric jet at solar maximum [*Kodera and Yamazaki*, 1994] is larger than what would be expected from radiative forcing alone.

Changes of mean zonal wind in the middle atmosphere are usually associated with changes in wave forcing, and feedbacks between the two provide a mechanism for coupling between widely separated atmospheric regions. *Gray et al.* [2001a,b] and *Gray* [2003] found that zonal wind anomalies during early winter in the tropical stratopause region are important in modulating the strength of the northern polar vortex through the rest of the winter. The mechanism, though imperfectly understood, may be similar to that associated with the extratropical QBO [*Holton and Tan*, 1980]: namely, the QBO modulates the waveguide for planetary waves and the ability of these waves, when they break, to draw low-vorticity air from the tropics into midlatitudes. The waves are confined to higher latitudes when the QBO is easterly and are thereby amplified and able to enlarge the Aleutian anticyclone, which tends to erode, weaken and possibly disrupt the main vortex. The key QBO level for maximum extratropical correlation in the Holton-Tan oscillation is near 40-50 hPa, whereas Gray's key level is in the upper stratosphere, near 1 hPa. Perhaps wave reflection and breaking in the subtropical upper stratosphere and lower mesosphere are important to the coupling mechanism [*Dunkerton,* 1987; *Perlwitz and Harnik*, 2003].

Observations provide evidence that the strength of the northern polar vortex is affected by solar-induced circulation changes near the tropical stratopause. *Labitzke* [2001] found that the strength of the polar vortex at 30 hPa during November-December differs significantly between high solar flux and low solar flux years. *Kodera and Kuroda* [2002] found that the stratospheric response originates in the tropical stratopause region, and propagates poleward and downward through the winter. This propagation mechanism involves the interaction of planetary-scale waves with the zonal mean flow, so that the net effect is to draw wind anomalies poleward and downward through the stratosphere [*Dunkerton*, 2000].

An analogy is sometimes made with the QBO itself, in which equatorial waves systematically create and draw mean-flow anomalies downward [*Lindzen and Holton*, 1968; *Holton and Lindzen*, 1972; *Plumb*, 1977; *Dunkerton*, 1997]. Notwithstanding the differences between the tropical QBO and extratropical case described above—such as the role of planetary Rossby waves, and back reflection of these waves to the troposphere—both phenomena share a key ingredient in that wave, mean-flow interaction acts to maintain the anomaly during the course of its downward propagation over several density scale heights.

Our understanding of the interaction between tropical wind anomalies and the circulation at higher latitudes is incomplete. A major impediment is the lack of observational data for the tropical and subtropical upper stratosphere. Operational rawinsonde observations typically extend only to near 10 hPa. Some idea of their latitudinal coverage can be obtained from *Dunkerton and Delisi* [1985]. Rocketsonde observations extend into the mesosphere, but ended more that ten years ago, and were acquired at stations 8 degrees or more off the equator. Balanced winds derived from satellite temperatures, beginning in the late 1970s, are problematic but reasonable results can be obtained for the zonal mean flow [*Delisi and Dunkerton*, 1988; *Dunkerton and Delisi*, 1991]. Today, data assimilation is widely used for creation of global gridded datasets, but the coverage and quality of input data remain critical issues. The most comprehensive of its kind, the ECMWF ERA-40 reanalysis[1] covers the time period 1958-2001 up to 1 hPa, but it is difficult to verify the accuracy of the analysis owing to the general lack of ground-based data, particularly in the tropics and southern hemisphere. Preliminary validation against rocketsondes (which were not assimilated in the reanalysis) indicates that the ERA-40 data provide a good representation of tropical stratospheric winds after 1978 [A. Untch, personal communication, 2003]

Whatever the details of solar influences on the upper stratosphere, if the solar cycle modulates winds in the subtropical stratopause region, then these anomalies could, in principle, be drawn poleward and downward (via wave, mean-flow interaction) to the lowermost stratosphere. From the discussion thus far, it is not clear that the troposphere should be affected. The circulation of the troposphere is more complicated, with many other external forcings, and internal feedbacks with synoptic-scale baroclinic waves. It seems unlikely that a purely stratospheric forcing should have much effect on the denser troposphere. In the next section we review observational evidence that a signal associated with poleward and downward propagation of stratospheric anomalies does indeed reach the surface. The apparent coupling between stratosphere and troposphere has been quanti-

[1] www.ecmwf.int

fied in terms of annular-mode signals in the two regions. Included in our discussion is a description of how the surface response is created.

3. Stratosphere-troposphere dynamical coupling

The troposphere influences the stratosphere mainly through a variety of atmospheric waves that propagate upward and interact with the stratospheric flow. In the tropics, the quasi-biennial oscillation (QBO) is driven by a combination of gravity, Kelvin, and mixed Rossby-gravity waves [*Dunkerton*, 1997]. In the extratropics, the *Charney and Drazin* [1961] criterion guarantees trapping of all large-scale waves when the stratospheric flow is easterly, and all but the longest waves during winter when the flow is westerly. During northern winter air flowing over mountain ranges and continental landmasses creates planetary-scale Rossby waves that propagate upward, refract, and reflect in the stratosphere. It is the circulation of the lowermost stratosphere that determines where wave activity propagates, and the degree to which large-scale waves affect the troposphere.

Rossby waves that enter the stratosphere break within the stratosphere or mesosphere, creating long-lived fluctuations in the strength of the winds that form the stratospheric polar vortex. The stratosphere organizes chaotic wave forcing from below to create variations in the strength of the polar vortex, which can last a month or two. Changes in the strength of the polar vortex then feed back to affect weather and climate in the troposphere.

The Southern Hemisphere has fewer mountain ranges and less land surface. Hence, the planetary-scale waves there are smaller and influence the stratosphere less than in the Northern Hemisphere. Consequently, the south polar vortex is relatively quiescent, until late spring, when the vortex breaks down [*Thompson et al*., 2004].

Fluctuations in the strength of the stratospheric polar vortices in both hemispheres are observed to couple downward to surface climate [*Baldwin and Dunkerton*, 1999, *Thompson et al*., 2004]. This relationship can be described in terms of annular modes, the leading patterns of geopotential variability at levels through the troposphere and stratosphere[2]. Figure 1 illustrates that the Northern Annular Mode (NAM) patterns at 10 hPa and at 1000 hPa are similar, and to first order, zonally symmetric. In the stratosphere the NAM is a measure of the strength of the polar vortex. At the surface the NAM is also know as the Arctic Oscillation, which is very similar to the North Atlantic Oscillation (NAO) [*Wallace*, 2000]. The surface NAM corresponds to substantial large-scale changes in weather and climate. When the surface NAM is positive, pressures are lower than normal over the polar cap but higher at low latitudes, with stronger westerlies at mid-latitudes, especially across the Atlantic. Northern Europe and much of the United States are warmer and wetter than average, and Southern Europe is drier than average. Although the coupling between the stratospheric and tropospheric NAM is robust in both observations and models, the reasons for this coupling are not well understood.

The relationship between NAM anomalies in the stratosphere and troposphere is emphasized if averages are taken of the weakest and strongest observed stratospheric anomalies. The NAM index at 10 hPa can be used to define events during which the stratospheric polar vortex was either extremely weak or strong. Figure 2a is a composite of 18 weak vortex events (which correspond to stratospheric warmings). On average, weak vortex conditions tend to descend through the lower stratosphere and are followed by negative NAM anomalies at the surface for ~two months. The opposite is true for anomalously strong vortex conditions (Figure 2b). The long tropospheric anomalies suggest that coupling to the stratosphere should tend to increase the timescale of the NAM during winter. Figure 3 illustrates that the surface NAM timescale is considerably longer during winter, but this observation alone is not sufficient to conclude that the stratosphere induces these changes—the long winter NAM timescale could presumably be caused by the annual cycle. Further evidence that the timescale of the surface NAM is affected by stratospheric conditions comes from the Southern Hemisphere. If the long winter timescale of the NAM is a reflection of the annual cycle, then one would expect that the timescale of the Southern Annular Mode (SAM) would be longest in southern winter. Figures

[2] The NAM is defined as the leading empirical orthogonal function (EOF) of slowly varying (e.g., month-to-month) wintertime hemispheric geopotential at each isobaric level, and is the spatial pattern that accounts for the greatest fraction of geopotential variance. Daily indices of the annular modes are calculated for each level by projecting daily geopotential anomalies onto the leading EOF patterns. For details of the calculation see *Baldwin and Dunkerton* [2001].

3b shows that this is not the case. The longest surface SAM timescale is found during November-December, at the time of the maximum SAM variance in the lowermost stratosphere (Figure 3c). Taken together, these observations are strong evidence that large, long-lived circulation anomalies in the lower stratosphere can lengthen the time-scale of the annular modes in the troposphere.

The long timescale of stratospheric effects has practical implications for extended-range weather forecasts [*Baldwin et al*., 2003a,b]. The stratosphere can be used as a statistical predictor of the surface NAM on timescales of up to two months. Figure 4 illustrates the predictability of the monthly-mean 1000-hPa NAM after a 10-day lead, as a function of season and NAM pressure level used to predict the 1000-hPa NAM. The contours are the percent variance of the surface NAM, with darker shading indicating better predictability of the surface NAM. The key result illustrated is that the monthly-mean surface NAM is better predicted by the lower stratospheric NAM than any tropospheric level. The stratosphere provides predictability earlier in the winter, more predictability during midwinter, and extends predictability into the Spring. The practical application of this relationship may be through numerical extended-range forecast models that include a realistic stratosphere, or through a combined statistical-dynamical technique [W. Norton, personal communication, 2003].

There is now strong observational and modeling evidence that human-induced changes to the stratospheric ozone layer in the Southern Hemisphere have affected surface climate. *Thompson and Solomon* [2002] provided the observational evidence, while *Gillett and Thompson* [2003] used a GCM forced only by the observed ozone anomalies since 1979 (Figure 5). Both the observations and model results show that surface temperatures, pressures, and winds are affected for up to three months following the stratospheric ozone anomalies. These results also bear a similarity to the Northern Hemisphere results shown in Figure 2., suggesting that the same mechanism is at work. The stratospheric ozone anomaly cools and strengthens the vortex. On average, the subsequent long-lasting tropospheric effects are similar to the stratospheric changes.

Research on stratosphere-troposphere coupling has the potential to benefit society in two major ways. First, extended-range weather forecasts and seasonal forecasts may be improved by including stratospheric information either statistically or dynamically. The stratospheric information could include not only changes to the strength of the polar vortex, but also the phase of the QBO. As first noted by *Holton and Tan* [1980], the polar vortex is, on average, weaker when the QBO is easterly. Changes in the strength of the polar vortex couple downward, so that QBO effects are seen at the surface during northern winter [*Thompson et al*., 2002]. Knowledge of the state of the QBO, solar cycle and stratospheric NAM is potentially valuable for extended-range and seasonal prediction. Although the external forcings themselves vary on a wide range of timescales, from days to ~10 years, their instantaneous values (as measured by an appropriate index) can be incorporated as statistical predictors or as initial perturbations in a dynamical model.

The second benefit to society is on decadal and longer timescales, and again involves the connection between the stratospheric polar vortex and the surface annular modes. If the stratospheric circulation changes with the solar cycle, ozone depletion, or increasing greenhouse gases, those changes will likely be reflected in changes to surface climate. In climate prediction, unlike extended-range forecasting, we are not concerned with the instantaneous state of a particular forcing, but with the probability distribution function of forcings and atmospheric response: subtle but statistically significant changes in the centroid, shape and extreme values that portend climate change.

Modeling studies of solar effects on climate are not in close agreement [e.g., *Rind and Balachandran, 1995; Haigh, 1996; Matthes et al., 2004*]. The disagreement is not surprising because model predictions of future climate (with increasing greenhouse gases) do not agree as to whether the stratospheric polar vortex will strengthen or weaken. The timing of such external influences within the seasonal cycle is also important (e.g., whether in early or late winter) and may eventually help to explain some of the disagreement between models [*O'Sullivan and Dunkerton*, 1994]. Even for models with a "proper" representation of stratosphere, results can be opposite. *Shindell et al.,* [1999b], for example, predicted a stronger, colder stratospheric polar vortex and increasing surface NAM index. In contrast, J. Kettleborough [personal communication, 2003] found that the stratospheric polar vortex would become warmer and weaker (with 4X CO2), with a more negative NAM index and a region of surface cooling at high latitudes. It is not yet possible to determine which scenario is more correct, but the answer has critical implications for climate and how society anticipates, and acts pro-actively towards, future climate change.

A fundamental scientific problem is that we do not have a quantitative understanding of stratosphere-troposphere coupling. In particular, there is no comprehensive theory for how stratospheric circulation anomalies affect tropospheric climate. Without that understanding, we do not know what to expect as climate changes or how solar-induced anomalies should affect climate. Predictive capability is derived largely from comprehensive GCMs, but as noted above, the models' ability to simulate accurately the magnitude and timing of circulation anomalies embedded in the seasonal cycle is critical when assessing the climate impact of external forcings.

There is substantial observational and modeling evidence that stratospheric processes affect tropospheric climate on many timescales. But there is still no established theory to explain the observed and simulated downward linkages. What are the mechanisms by which wind anomalies in the lowermost stratosphere induce changes to surface weather patterns? Perhaps the simplest explanation is that surface is pressure anomalies (at a fixed height in the lower stratosphere) should be seen throughout the tropospheric column. This appears to be at least a partial explanation—surface pressure anomalies are similar to those in the lowermost stratosphere [D. Thompson, personal communication, 2003]. This result is consistent with results of a mechanistic model of stratospheric vacillation [*Ortland and Dunkerton,* 2004] indicating that wave forcing and induced mean meridional circulation in the lower stratosphere are responsible for perhaps half of the surface pressure signal. Another mechanism that could contribute to surface effects is wave reflection in the upper stratosphere [*Perlwitz and Harnik*, 2003; *Ortland and Dunkerton*, 2004].

Based on current understanding and the rather limited number of studies performed, we are inclined to speculate that in situ stratospheric forcings alone cannot account for all of the observed signal in the troposphere. Whatever the dominant mechanism, it is likely that an amplifier is needed. Near the tropopause there is a region of overlap between stratospheric zonal wind anomalies and both planetary and synoptic-scale waves. Weak changes to the winds could be amplified by interactions with waves that extend several kilometers into the stratosphere [*Baldwin et al*., 2003a]. The altered waves would be expected affect tropospheric circulation and induce surface pressure changes corresponding to the NAM. If the stratospheric anomalies can affect momentum fluxes in the upper troposphere, then one would expect an immediate affect on surface pressure [*Haynes and Shepherd*, 1989]. One possibility is that this type of interaction occurs primarily over the

Atlantic sector, and affects the Atlantic storm track [B. Hoskins, personal communication, 2003].

4. Conclusions

One way that the 11-year solar cycle could influence tropospheric climate is through an indirect pathway: tropical stratospheric ozone heating creates off-equatorial circulation anomalies, and subsequent interactions with planetary-scale Rossby waves bring the anomalies poleward and downward in the winter hemisphere. Such a mechanism is understood to communicate the QBO to the high-latitude stratosphere, and there is evidence that high-latitude stratospheric winds are sensitive to wind anomalies in the equatorial upper stratosphere—precisely where solar cycle/ozone heating anomalies are observed. If solar-induced tropical circulation anomalies are communicated to high latitudes, they would likely be seen as changes to the strength of the stratospheric polar vortex during extended winter, which are observed to affect the tropospheric circulation. On average, when the polar vortex is stronger than average in the lower stratosphere, the tropospheric NAM index is positive. This pathway for solar influence could involve interactions with the QBO, but the details are not yet understood.

An understanding of the dynamics of solar effects in the tropical stratosphere is made difficult by the paucity of wind observations in the equatorial upper stratosphere. Without knowing the solar signal in wind, and the latitudinal profiles of wind anomalies in the upper stratosphere, it is difficult to develop a quantitative understanding of the processes involved. Modeling studies also point toward sensitivity to tropical wind anomalies in the upper stratosphere. Once wind anomalies are created (whether by solar variations, the QBO, or other causes), they alter the propagation of planetary-scale Rossby waves and their mean-flow forcing. It is the interaction with Rossby waves that draws the wind anomalies poleward and downward, effectively amplifying the (density weighted) energy of anomalies as they descend. This interaction allows relatively small perturbations in the upper stratosphere to affect the circulation of the lower stratosphere.

Although we do not have a detailed understanding of the dynamics of stratosphere/troposphere coupling, downward communication of stratospheric anomalies to the troposphere is robust in observations and models. If solar effects change the strength of the stratospheric polar vortex, then (as with the QBO) then there should be an effect on the tropospheric NAM. Such effects could be seasonal, or cumulative over a season: more likely to occur, for example, in the late winter when solar modulation of the polar vortex appears to be largest. Because the data record is short, verification of solar effects in the troposphere may be difficult. Further progress in our understanding will likely require carefully designed numerical experiments to test hypotheses.

5. References

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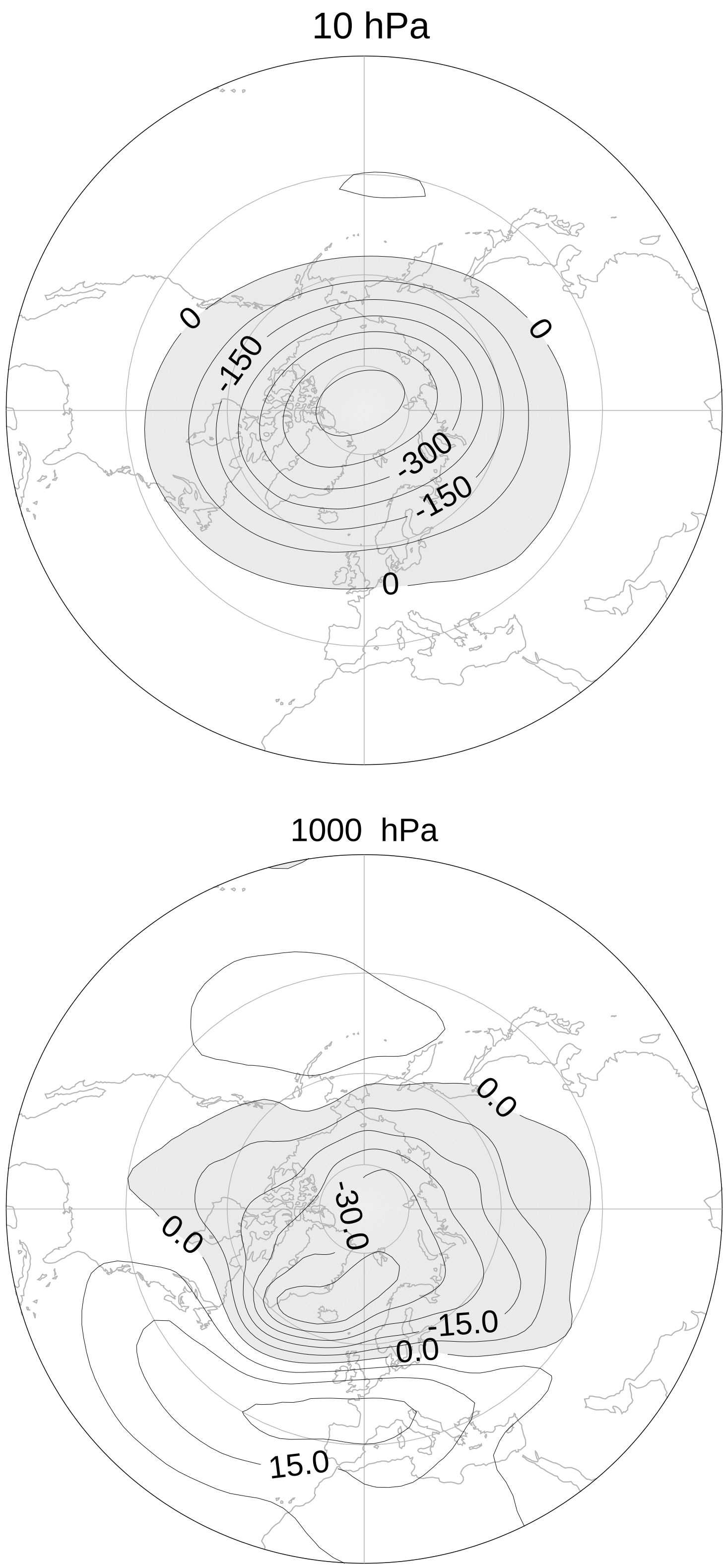


Figure 1. Northern Annular Mode (NAM) patterns at 10 and 1000 hPa. The patterns are calculated as the leading empirical orthogonal function of November–April (90-day lowpass filtered) geopotential for 1958–2000.

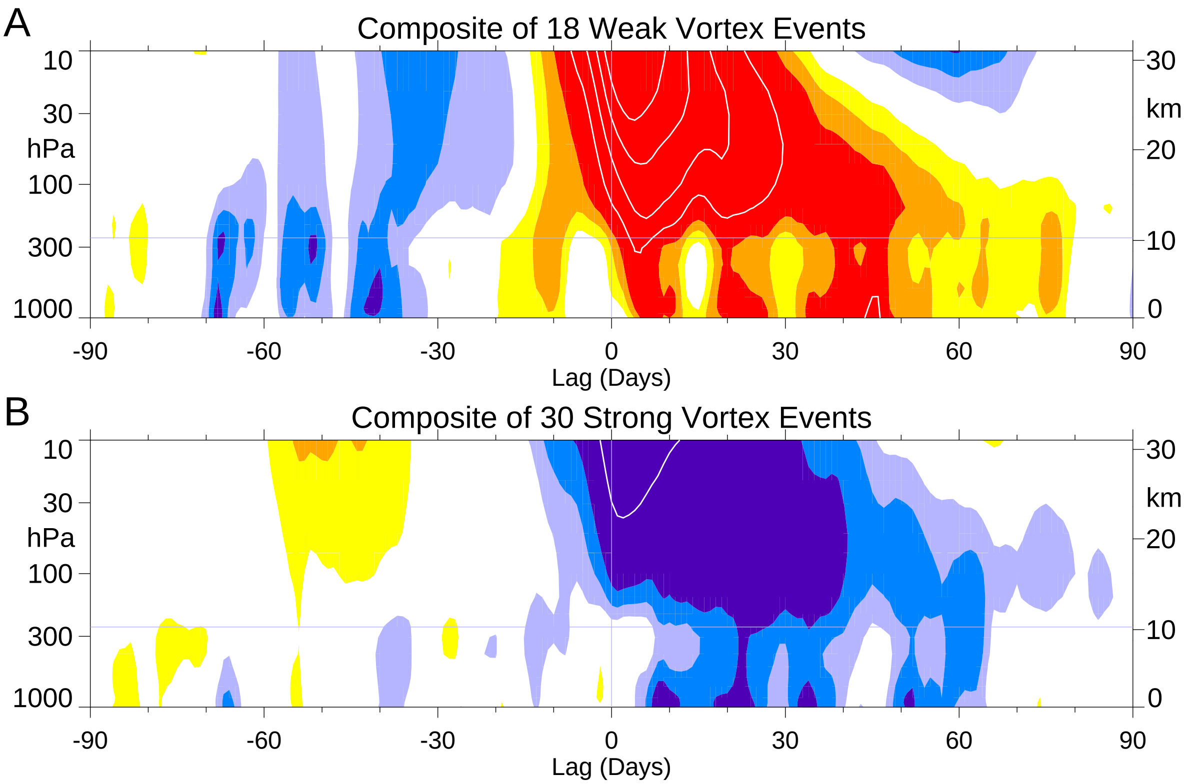


Figure 2. Composites of time-height development of the NAM for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa NAM values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between -0.25 and 0.25 are unshaded. The thin horizontal lines indicates the approximate tropopause. From *Baldwin and Dunkerton* [2001].

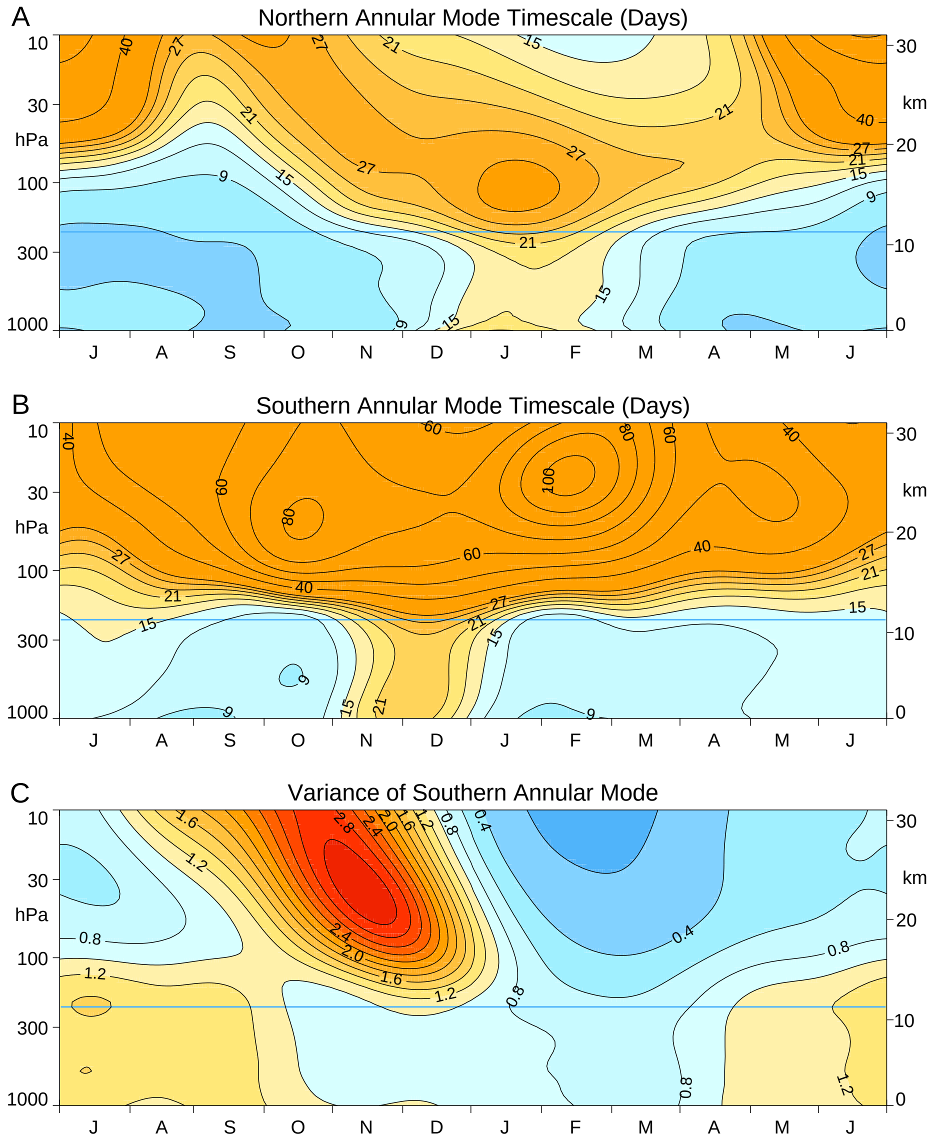


Figure 3. **(A)** Timescale of the NAM as measured by the time (days) for the NAM autocorrelation function to drop to 1/*e* (~0.378). The horizontal line in each panel represents the approximate tropopause. The timescale is estimated with a least-squares fit of an exponential curve to the autocorrelation function. The contour interval is three days up to 30 days, and 10 days at higher values. **(B)** As in **(A)**, except SAM. **(C)** Variance or the SAM. SAM time series at each level are normalized to unit standard deviation. From *Baldwin et al*., [2003b].

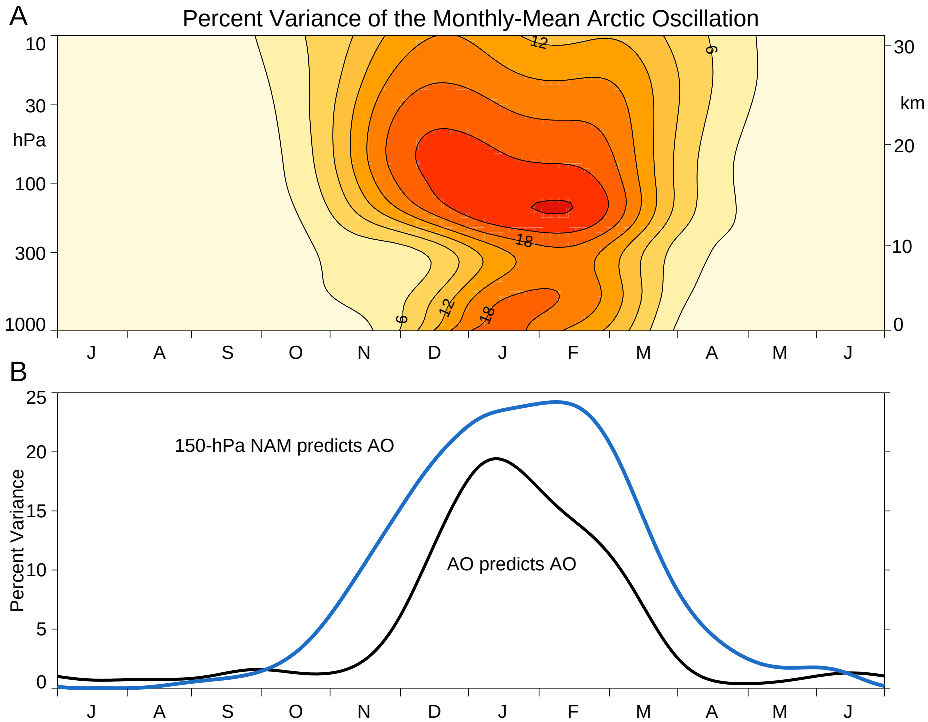
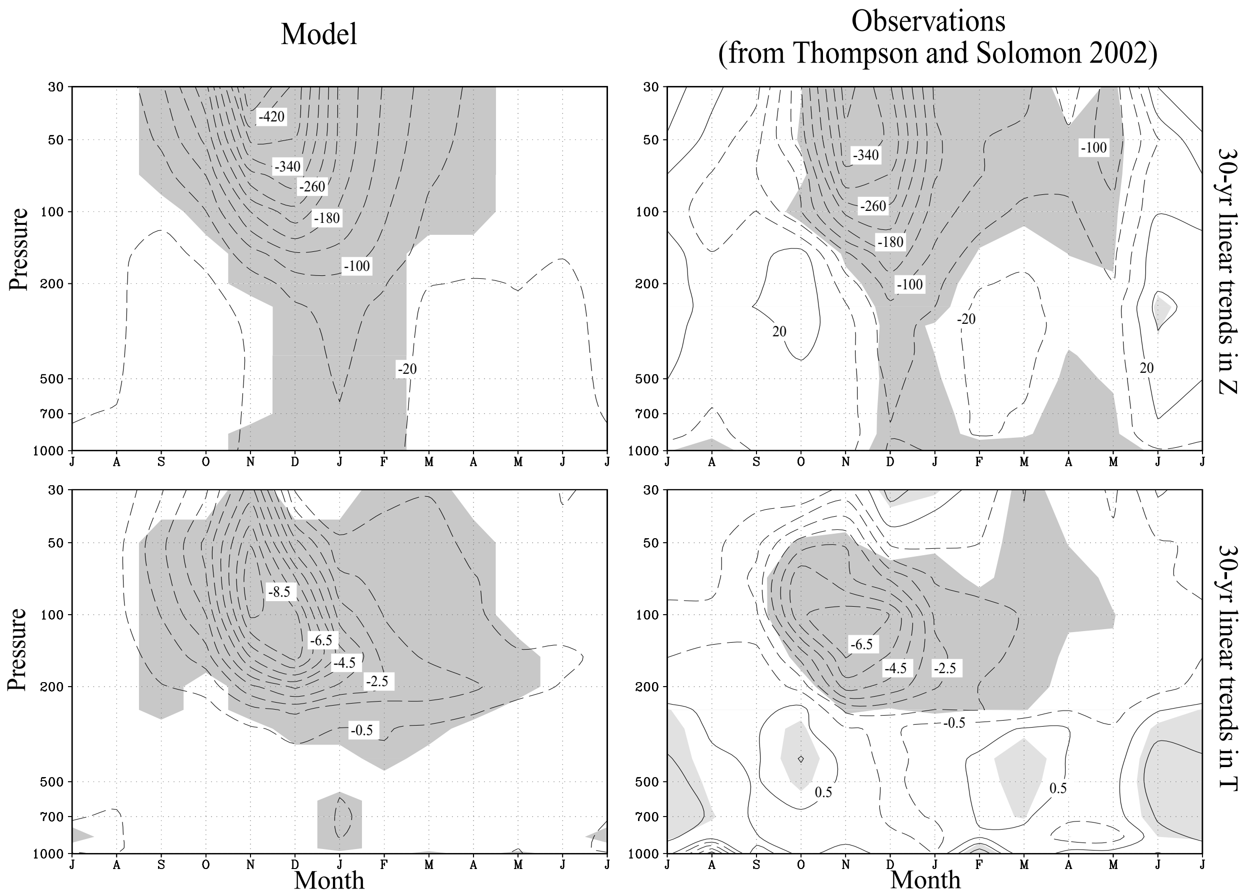


Figure 4. **(A)** Predictability of the monthly-mean Arctic Oscillation (1000-hPA NAM) after a 10-day lead. Values are obtained by linear regression between the daily NAM time series and the monthly-mean Arctic Oscillation beginning after 10 days, and are displayed as percent variance of the monthly-mean Arctic Oscillation. **(B)** Cross sections through **(A)** at 1000 and 150 hPa. Blue curve: 150-hPa NAM predicts the monthly-mean AO; black curve: AO predicts the monthly-mean AO. From *Baldwin et al*. [2003b].



Model
Observations
(from Thompson and Solomon 2002)
30-yr linear trends in Z
30-yr linear trends in T
Pressure
Month
30
50
100
200
500
700
1000
J
A
S
O
N
D
J
F
M
A
M
J
J
-420
-340
-260
-180
-100
-20
20
-8.5
-6.5
-4.5
-2.5
-0.5
0.5

Figure 5. Simulated (left column) and observed (right column) changes in (upper row) geopotential height (m) and (lower row) temperature (K) poleward of 65°S. Observed changes are 30-year linear trends (1969–98) averaged over seven radiosonde stations, and shading indicates changes which exceed one standard deviation of the monthly time series. Simulated changes are differences between the model integration with depleted stratospheric ozone and the control, sampled at the locations of the radiosonde stations used in Thompson and Solomon [2002], and shading indicates regions of significant change at the 95% level. From *Gillett and Thompson* [2003].