The Role of the Stratosphere in Tropospheric Climate Variability and Climate Change

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Review of Recent Developments

The stratosphere contains less than 15% of the total mass of the atmosphere. Thus the traditional view has been that weather and climate in the stratosphere are controlled strongly by processes in the troposphere and that stratospheric influences on the troposphere are minor. In recent years, however, scientists have become increasingly interested in the possible effects of changes in the stratospheric circulation on the troposphere (e.g., Robock, 2001; Wallace and Thompson, 2002). One reason for this interest is the recognition that some of the strongest radiative perturbations that have affected climate in the recent past have occurred in the stratosphere. In particular, the rapid change in stratospheric ozone concentrations over about the last 20 years associated with anthropogenic input of chlorine compounds has greatly influenced the climate system. Moreover, the sulfate aerosols injected into the stratosphere by large explosive volcanic eruptions (such as those of El Chichon in 1982 and Mt. Pinatubo in 1991) persist for at least two years and have strong effects on both the shortwave and longwave components of the radiative balance. Given the relatively large stratospheric perturbations caused by such phenomena, even a fairly modest interaction with tropospheric circulation could affect surface climate in interesting ways (e.g., Robock, 2001).

A second reason for this new interest comes from a recent spate of studies claiming to find a tendency for stratospheric perturbations in the Northern Hemisphere winter circulation to propagate downward to the troposphere (e.g. Baldwin and Dunkerton, 2001). This means that knowledge of the stratospheric circulation could be used as the basis for seasonal forecasts of tropospheric circulation, at least in Northern Hemisphere winter.

A similar tendency for perturbations to propagate downward has been noted in some comprehensive atmospheric general circulation models (GCMs). Figure 6 illustrates results obtained using a "troposphere-stratosphere-mesosphere" GCM as part of a collaborative project between the author and **Mark Baldwin** (Northwest Research Associates). The calculation begins by deseasonalizing and low-passing daily time series of the Northern Hemisphere three-dimensional geopotential height field over 34 years of a control model simulation. An empirical orthogonal function (EOF) analysis is applied independently to the time series of anomalies at each height. Figure 6 shows the time series of the coefficient of the first EOF, contoured in the height-time plane. The blue and yellow-red areas correspond to opposite phases of this EOF—the blue colors indicate times when the polar vortex is more westerly than normal, with correspondingly cold high-latitude temperatures, and the yellow-red areas indicate heights and times with a more easterly (or less westerly) vortex and anomalously warm high-latitude temperatures.

Figure 6 displays interesting anomalies in each winter (anomalies are much smaller in other seasons). The tendency for the anomalies to propagate downward is evident within the stratosphere, but is less consistent between the stratosphere and troposphere—sometimes anomalies appear first in the troposphere and then in the stratosphere, sometimes the other way around. Overall, however, the mean tendency is for the tropospheric perturbations to follow those in the stratosphere, in basic agreement with the recent observational studies. This statistical tendency is the basis for suggesting that skillful seasonal tropospheric forecasts can be made based on knowledge of the state of the large-scale stratospheric circulation.

The interest in stratospheric influence on tropospheric seasonal weather patterns has even reached the major governmental agencies with practical forecasting responsibilities. Several recent issues of the *Monthly Report on the Climate System*, published by the Japan Meteorological Agency, have featured cover figures showing aspects of stratospheric circulation. Seasonal forecasts at the US National Center for Environmental Prediction use aspects of the stratospheric circulation as inputs.

There is no guarantee, however, that the tendency for downward propagation of anomalies across the tropopause reflects an actual physical effect of the stratospheric flow on tropospheric flow. Geophysics has many examples of phenomena showing a phase progression actually opposite to the physical propagation of disturbances (for example, the opposite vertical components of the phase and group velocities for internal gravity waves). It could, thus, even be that the causality is entirely from troposphere to stratosphere and that the development of anomalies in the troposphere, on average, happens to follow a predictable course with a passive (and incidental) effect on the stratospheric flow.

If, however, the causality is really downward, the implications for modeling climate change are great. The strong radiative effects of changes in ozone and other greenhouse gasses should change the stratospheric circulation, which would lead to a mean trend in tropospheric circulation. Wallace and Thompson have argued that this sequence may be needed to explain the observed pattern in surface temperature increase over the last few decades. The warming has been enhanced particularly over northern Europe and northern Asia (NENA). While there are straightforward reasons for expecting greater surface warming at high latitudes (stronger mean atmospheric stratification

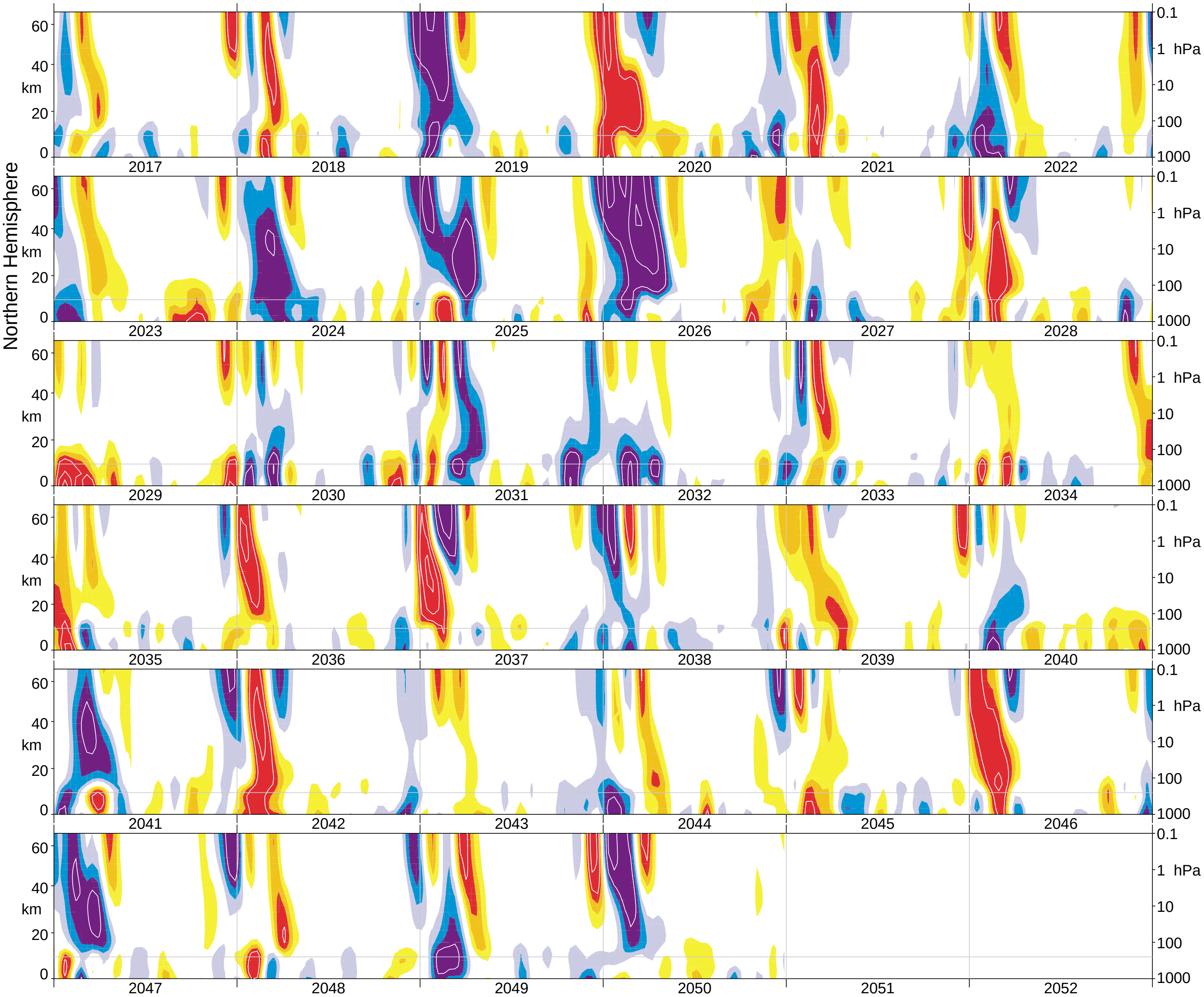

Figure 6. *Height-time section of anomalies in the coefficient of the first EOF of Northern Hemisphere geopotential variation from 34 years of control integration with the SKYHI general circulation model. The EOF analysis is performed independently at each level. The blue areas correspond to cases with anomalously westerly polar vortex and cold polar conditions and the red/yellow areas to opposite anomalies. The values at each level are normalized by the standard deviation at that level and the contour interval is unity. Only anomalies greater than one standard deviation are shaded. The thin vertical lines show the beginning of each calendar year. The years are labeled arbitrarily starting in "2017." The thin horizontal lines show the approximate height of the extratropical tropopause.*

which confines the warming near the surface, and snow-albedo feedback), and over land (less surface heat storage than over the ocean), the actual observed warming in NENA regions seems higher than would be expected from these effects alone. Wallace and Thompson (2002) suggest that the changes in the winter-mean near-surface circulation associated with changes in the stratospheric circulation could account for the strength of the NENA-region warming. Interestingly, the long-term trend in the geographical warming pattern is similar to the patterns of anomalous surface temperature generally seen after major volcanic eruptions, which produce their most direct radiative effects in the stratosphere.

Other investigators have found that the surface warming predicted by global GCMs in response to increasing greenhouse gas concentration can differ depending on whether the model includes adequate resolution in the stratosphere. Shindell et al. (1999) found that they could get their model to simulate a realistically enhanced warming over NENA regions when their model included several levels extending through the entire stratosphere, but not when it had a more typical configuration for climate models (i.e., a model top near 30 km).

Several investigators have taken these indications of significant stratospheric influence in the troposphere to speculate about solar influence on surface climate. There has been a long and controversial history of investigations into a possible correlation between the 11-year cycle in solar activity and surface climate. While various claims of empirical correlations have been made, it has generally seemed implausible that the very small (~0.1%) modulation of the total solar flux over the solar cycle could have much influence on climate. However, the solar minimum versus solar maximum contrast is much larger at the very shortwave end of the solar spectrum. These very short wavelength photons are almost completely absorbed before they reach the troposphere, and their modulation can be expected to directly produce significant solar cycle temperature changes in the upper atmosphere (perhaps of the order of 2ºC near the stratopause, even more at higher levels). If the large-scale dynamics couples the tropospheric circulation to the stratospheric circulation, the physical link from the solar variations to surface climate variations is plausible.

Work Underway at IPRC

All these new developments are certainly provocative and may, in fact, point to features that are of great importance in understanding and modeling climate changes. However, despite the many papers published on this subject in the last few years, some very basic questions remain. One difficulty, even in GCM studies, lies in unambiguously detecting the effects of stratospheric climate forcing. The winter stratosphere is a region with strong internal variability on interannual timescales, and in some GCMs at least, stratospheric circulation varies spontaneously on decadal or even longer timescales (Hamilton, 1995, 2000; Butchart et al., 2000).

A second problem is understanding the mechanisms that can exert a quantitatively significant effect at the surface. To date, the record among GCMs that have actually produced significant tropospheric effects of stratospheric volcanic aerosol or stratospheric ozone changes is mixed.

As part of the work on global change at IPRC, the author is involved in several related modeling efforts to clarify the role of the stratosphere in tropospheric weather and climate. This work, which is conducted in collaboration with colleagues at the NOAA Geophysical Fluid Dynamics Lab (GFDL), Rutgers University, Northwest Research Associates, and Laboratoire Meteorologie Dynamique in France, uses the SKYHI model, a troposphere-stratosphere-mesosphere model developed over the last quarter century at GFDL. This model is a full climate GCM with a serious treatment of the atmospheric circulation to heights near 80 km. The model has been tested extensively and many features of the simulated stratospheric circulation have been shown to be realistic. In particular, the overall level of interannual variability in the extratropical Northern Hemisphere circulation and the response of the extratropical circulation to ocean temperature variations and to tropical circulation variations are all reproduced fairly well (Hamilton, 1995, 1998).

One test with the current SKYHI looks at how realistic the unforced variability is (e.g., the present Figure 6) and how the model responds to the well-observed stratospheric aerosol input following the 1991 Mt. Pinatubo eruption (see the 2001/Fall issue of *IPRC Climate*). This research has many aspects, including (a) understanding how the model simulation depends on numerical resolution (Hamilton et al., 1999, 2001; Koshyk and Hamilton, 2001), (b) how the tropical stratosphere interacts with the extratropical stratosphere (Hamilton, 1998), and (c) the nature of long period of unforced variability in the stratospheric circulation. The model is also being applied to some very direct studies of the dynamical effects of stratospheric circulation on the underlying troposphere. In these experiments, the control version of the SKYHI model is applied in a series of winter seasonal integrations. The initial conditions for each run are taken from the early winter in one year of a long control run, but with a strong zonally symmetric perturbation arbitrarily added to the stratospheric polar vortex. This amounts to suddenly adding a blue or red perturbation in Figure 6 to the simulation, but only in the stratosphere. The subsequent evolution of the tropospheric circulation will then be compared to that in the control run. If the stratosphere does dynamically affect the troposphere, the imposed stratospheric perturbation should show a systematic effect in the troposphere. Such an outcome would establish, in the simplest context, the significance of downward dynamical interactions.

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