Downward coupling between the stratosphere and troposphere: The relative roles of wave and zonal mean processes

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Abstract

Wave and zonal mean features of the downward dynamic coupling between the stratosphere and troposphere are compared by applying a time-lagged singular value decomposition analysis to Northern Hemisphere height fields decomposed into zonal mean and its deviations. It is found that both zonal and wave components contribute to the downward interaction, with zonal wave 1 (due to reflection) dominating on the short time scale (up to 12 days) and the zonal mean (due to wave-mean flow interaction) dominating on the longer time scale. It is further shown that the two processes dominate during different years, depending on the state of the stratosphere. Winters characterized by a basic state that is reflective for wave 1 show strong correlations (and covariance) for wave 1 components when the stratosphere is leading and no relationship in the zonal mean. On the other hand, winters characterized by a stratospheric state that does not reflect waves show a strong correlation only in the zonal mean fields. This study suggests that downward reflection of waves (primarily of zonal wavenumber 1) is a significant component of troposphere/stratosphere dynamics.

1 Introduction

There is increasing evidence that stratospheric dynamic processes play a significant role in tropospheric climate variability across a wide range of times scales. However, the dynamic mechanisms by which the stratosphere can influence the tropospheric circulation are not well understood. Many recent studies of the downward dynamic coupling between the stratosphere and troposphere have emphasized zonal mean dynamics, in relation to the Annular Modes (Baldwin and Dunkerton, 1999, 2001; Kuroda and Kodera, 1999; Kodera et al., 2000; Christiansen, 2001; Ambaum and Hoskins, 2002; Black, 2002; Polvani and Kushner, 2002; Plumb and Semeniuk, 2003). In particular, observations show that large anomalies in the strength of the stratospheric polar vortex descend to the lower-most stratosphere and are followed by anomalous tropospheric weather regimes that closely resemble the features of the Northern Hemisphere Annular Mode (NAM) (Baldwin and Dunkerton, 1999, 2001; Thompson et al., 2002).

The downward progression of observed zonal mean anomalies is thought to result from the dynamics of wave-mean flow interaction (Christiansen, 2001; Baldwin and Dunkerton, 2001; Plumb and Semeniuk, 2003; Polvani and Waugh, 2003). Planetary Rossby waves generated in the troposphere propagate upward and change the stratospheric flow when they grow enough to break and be absorbed. The region of strongest interaction of the waves with the mean flow shifts slightly due to these changes in the basic state, resulting in a downward and poleward progression of the mean flow perturbations. Clearly, the strength of this interaction depends both on the strength of the tropospheric wave forcing and on the stratospheric mean flow itself.

A different mechanism – downward reflection of wave energy by the stratosphere back into

the troposphere – has been suggested as a mechanism by which the stratosphere can effect the troposphere (Hines, 1974; Geller and Alpert, 1980; Schmitz and Grieger, 1980). Recently, an observational study using new dynamical and statistical diagnostics found evidence for reflection in the Northern Hemisphere upper stratosphere, with an impact on the structure of tropospheric waves of zonal wavenumber 1 (Perlwitz and Harnik, 2003; PH hereafter). The main basic state configuration under which reflection of wave 1 occurs is when the stratospheric jet peaks in the mid-stratosphere (Harnik and Lindzen, 2001; PH). Reflection in this case occurs because the meridional gradients in the potential vorticity become negative above the jet maximum (Matsuno, 1970, for theoretical considerations), as a result of the decrease of the zonal mean winds with height above the jet peak.

Recent studies have stressed the implication of the zonal mean downward coupling between the stratosphere and troposphere for the prediction of winter weather on the intraseasonal and interannual time scale (Baldwin and Dunkerton, 2001; Thompson et al., 2002; Baldwin et al., 2003). Observations also indicate, however, that stratospheric NAM-like anomalies do not always propagate down into the troposphere (Baldwin and Dunkerton, 1999; Kodera and Kuroda, 2000; Zhou et al., 2002). Tropospheric and stratospheric NAM-like anomalies are only coupled during late winter/spring but not during fall/early winter (Kodera and Kuroda, 2000). In addition, during the active season, downward propagation is found mostly during times when the polar vortex is weak, in conjunction with major stratospheric warmings (Baldwin and Dunkerton, 1999; Kodera et al., 2000; Zhou et al., 2002). A statistical signal of downward reflection of wave 1, on the other hand, is found during seasons with a strong polar vortex (Perlwitz and Graf, 2001; PH). This suggests there are two kinds of downward coupling between the stratosphere and troposphere, depending on the stratospheric dynamical state. In one state, most of the wave energy gets deposited in the

stratosphere, resulting in strong wave-mean flow interaction, while in the other state, wave energy is reflected back down to the troposphere primarily affecting the structure of tropospheric planetary waves. While this makes sense, it remains to be determined whether this could lead to two distinct dynamical states in the stratosphere and what processes determine which one of these will dominate at any given time.

In this paper we do not attempt to answer these questions, rather, we determine whether these two types of dynamical coupling exist in observations, at different times. We examine the relative roles of wave and zonal mean processes in the downward coupling, by analyzing the covariance between observed height fields at stratospheric and tropospheric pressure levels, for different stratospheric mean basic states. In section 2, the data and analysis approach are introduced. The results are described in section 3. Discussion and conclusion are given in section 4.

2 Data and Approach

a. Data

This study is based on the 4×daily reanalysis of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996). We use daily-mean geopotential height data for the period from December 1979 to April 2003. The data are available on 17 pressure levels from 1000 hPa to 10 hPa, on a $2.5° \times 2.5°$ grid. For our calculations, we interpolate the data to a $5° \times 5°$ grid. This interpolation does not influence the results. We use data north of 30°N.

The geopotential height data of NCEP/NCAR reanalysis are also the basis for the NAM signature time series at 17 pressure levels between 1000 and 10 hPa (Baldwin and Dunkerton,

1999), used in this paper. The NAM is defined as the leading empirical orthogonal function (EOF) of 90-day low pass filtered wintertime hemispheric geopotential at tropospheric and stratospheric pressure levels. Daily indices of the NAM are calculated for each level by projecting daily geopotential height anomalies onto the leading EOF patterns. A detailed description of the approach and the maps of the NAM signature can be found in Baldwin and Dunkerton (1999). The stratospheric time series describe the strength of the stratospheric polar vortex. The spatial structure of the related tropospheric patterns is less zonally symmetric than the stratospheric ones with the Arctic center of action shifted toward Greenland. The NAM-signature time series are provided by Mark Baldwin (data from 1958 to 2001 are available on the following web page: http://www.nwra.com/resumes/baldwin/nam.html, the update to 2003 were kindly provided upon personal request).

For the calculations of the reflection index, we use the zonal wind at 2 and 10 hPa from the stratospheric analysis product compiled and distributed by NASA Goddard Space Flight Center (GSFC) Atmospheric Chemistry and Dynamics Branch. This data is based on an objective analysis of satellite data.

b. Time-lagged SVD analysis

The downward progression of zonal mean circulation anomalies from the stratosphere to the surface has been illustrated on the basis of both time-lagged correlations of the NAM signature time series (Baldwin and Dunkerton, 1999) and the zonal wind at 60°N (Christiansen, 2001). The relationship between tropospheric and stratospheric wave 1 height fields was investigated using a time-lagged singular value decomposition (SVD) analysis (see PH).

In the present paper, we use the time-lagged SVD analysis (Czaja and Frankignoul, 2002) to isolate the leading coupled modes, which explain the maximum covariance between the

daily geopotential height fields at two pressure levels. To account for the possibility that different dynamical mechanisms can dominate the relationship between two fields at positive and negative time lags, we analyze the covariance for each time lag separately.

We expand the two height fields, Z_1 and Z_2, at times t and $t+\tau$, respectively, into K orthogonal signals plus noise, as follows:

$$Z_1(x,t) = \sum_{k=1}^{K} \mathbf{u}_k(x)\mathbf{a}_k(t) \tag{1}$$

$$Z_2(x,t+\tau) = \sum_{k=1}^{K} \mathbf{v}_k(x)\mathbf{b}_k(t+\tau) \tag{2}$$

The covariance between $\mathbf{a}(t)$ and $\mathbf{b}(t+\tau)$ is the kth singular value s_k of the covariance matrix between Z_1 and Z_2, and the coupled modes are ordered with decreasing covariance for increasing k (Bretherton et al., 1992). The total squared covariance SC between the two fields is $SC = \sum_{k=1}^{K} s_k^2$.

We use the 10 hPa level as the reference level, and carry out the corresponding SVD analyses with all observational pressure levels between 10 and 1000 hPa, and various time lags τ ranging from -30 to +30 days (61 time lags in total). We keep the 90-days of the reference level (10 hPa) fixed from 1 January to 31 March while the time series of the second height field is shifted by -30 to 30 days. A positive time lag indicates the 10 hPa field is leading.

We use temporal unfiltered height fields but apply a strong spatial filtering in order to separate zonal-mean and wave processes. More explicitly, we apply the time-lagged SVD analysis to the zonal mean, the deviations from the zonal mean, and the zonal wavenumber 1 and 2 fields. We use the total squared covariance SC as measure of the relationship between the two fields. In addition, we calculate the correlation coefficients between the

expansion coefficients of the leading coupled modes $\mathbf{a}_1$ and $\mathbf{b}_1$. Note that in contrast to cross correlations, the covariance does not have to show the maximum at lag 0 and 10 hPa.

We remove the mean seasonal cycle and apply a square root of cosine latitude weighting prior to the SVD analysis. In order to concentrate on the intra-annual variability and exclude the influence of a trend on the covariance and correlations, the annual mean averages of the geopotential height fields are removed. To be able to compare the covariance between height fields at various pressure levels, the data were weighted with the square root of the density.

c. The reflective index U2-10 and 30 hPa NAM index

We composite the data based on two indices – the wave 1 *reflective index* U2-10 as in PH and the *30 hPa NAM index*. PH showed that the high-latitude zonal mean wind difference between 2 and 10 hPa is a good index for separating reflective and non-reflective basic states for wave 1 vertical propagation. This index is defined as $U(2-10) \equiv \langle U \rangle (2hPa) - \langle U \rangle (10hPa)$, where $\langle U \rangle$ is the zonal mean wind averaged over 58°– 74°N and over time. We composite the 8 years[1] with largest and smallest Jan-Mar U2-10 averages (for years, see Table 1a).

The 30 hPa NAM index which represents the strength of the stratospheric polar vortex is determined from the daily NAM signature time series at 30 hPa level, averaged over January to March. Composites are again based on the 8 smallest (weak polar vortex) and largest index years (strong polar vortex) as indicated in Table 1b.

[1] A sample of 8 years represents one third of the period investigated (24 years).

3 Results

First, we compare our analyses for the zonal mean and wave fields, for all high winters (Jan-Mar[2]), 1980 to 2003. Figure 1 shows the squared covariance between the 10 hPa and various pressure levels p and time lags ($SC_{10}(\tau, p)$), for the zonal mean, the deviation from zonal mean, and zonal waves 1 and 2. The $SC_{10}(\tau, p)$ of the zonal mean fields (Figure 1a) is consistent with previous calculations of the time-lagged correlations between the stratospheric and tropospheric NAM signature time series as well as the zonal winds at 60°N (Baldwin and Dunkerton, 1999; Christiansen, 2001). The covariance is strongest when the stratosphere leads, with the longest time lags and persistence near the surface (1000 hPa), and a weaker and less persistent relation for the mid troposphere (300-700 hPa). Our approach also reveals that this covariability is mainly due to the first coupled mode, especially near 1000 hPa, where it explains more than 98% of the total squared covariance (the first mode explains more than 70% of the covariance in mid troposphere). The dominance of the coupling at the surface is found in other studies, but the reason for it is not entirely clear.

The covariability of the zonal deviation fields (Figures 1b), on the other hand, is strongest when the troposphere leads. We note that, unlike the zonal mean, a few coupled modes are needed to explain the total squared covariance for the zonal deviations. This is mostly due to the fact that the zonal deviations include a whole variety of wave processes, especially in the troposphere. In addition, at a given latitude, two parameters (amplitude and phase) are needed to describe each zonal wavenumber (unlike the zonal mean which is only one parameter).

[2]Thompson and Wallace (2000) showed that January to March represents the active season of coupling between the tropospheric and stratospheric annular modes.

A comparison of the zonal deviation fields with the zonal wave 1 covariances (Figure 1c) further suggests that the dominant process is upward propagation of planetary wave 1, with some contribution of upward propagation of wave 2 for short time scales (Figure 1d). In addition, we see a peak when the stratosphere leads. This peak was shown by PH to be associated with downward reflection. We also note that downward wave coupling due to wave 1 is most pronounced for mid-tropospheric pressure levels, with the peak covariance occurring at around 400 hPa and a lag of 6 to 7 days.

To further compare the zonal mean and wave coupling, we combine $SC_{10}(\tau, p)$ of both processes in one plot (Figure 2a), using the level of maximum covariance for each (1000 and 400 hPa for the zonal mean and wave 1, respectively). Again, we see that the covariance is strongest for negative time lags, and is due almost entirely to upward propagation of waves. At positive time lags, both zonal mean and wave processes contribute, with wave coupling dominating on short time scales (less than 12 days) and zonal mean processes dominating on longer time scales. Since most past studies have looked at correlations rather than covariances (Baldwin and Dunkerton, 1999; Christiansen, 2001, PH), we also calculate the correlation coefficient between the expansion coefficients of the leading coupled modes at these levels (Figure 2b). Comparing with Figure 2a, we see that the correlations in the leading coupled mode give essentially the same results as the covariances.

These results suggest there are two different processes that lead to a downward coupling between the troposphere and stratosphere. One is associated with wave-mean flow dynamics leading to a significant signal in the zonal mean field, especially near the surface. The second one is related to wave reflection with significant effect on the tropospheric wave 1 field. Furthermore, PH showed that the wave-wave coupling occurs only during certain years, when the stratospheric basic state is reflective. We therefore expect the relative importance

of these two processes to also depend on the reflective state of the stratosphere. To test this we use the reflection index U2-10 (see PH and section 2c), and repeat the time lagged SVD analysis only using data for the 8 Jan-Mar periods with the most positive (non reflective) or most negative (reflective) U2-10 values. Figure 3 shows the corresponding $SC_{10}(\tau, p)$ for the key levels (zonal mean: 1000 hPa; wave 1: 400 hPa). As in PH, we find that downward wave coupling (dashed lines) only occurs during reflective years[3]. The main new finding is a strong dependence of the zonal mean coupling (solid lines) on the reflective state of the stratosphere. During non-reflective years (when downward wave coupling is weak) there is a strong zonal mean covariance at positive time lags, while during reflective years (when downward wave coupling is strong) there is essentially no zonal mean covariance for positive time lags.

To relate these results to the correlations in NAM signature time series, which have been used in the majority of recent studies of stratosphere-troposphere downward coupling, we calculate NAM-based correlations, and compare to our results. This is motivated by the fact that NAM patterns are not strictly zonally symmetric, thus they differ somewhat from the zonal mean patterns used here. We use the daily unfiltered NAM signature time series (section 2a) to calculate the time-lagged correlation coefficients between the time series at 10 hPa and other pressure levels for all Jan-Mar periods during 1980-2003, as well as for the reflective and non reflective years used above (Figure 4). During non-reflective winters, we clearly see a downward progression of the NAM anomalies to the lowermost stratosphere, followed by a significant NAM signal at the surface. During reflective years, on the other

[3]Note that the wave-wave covariances (compare dashed lines in plots a and b) are similar to the calculations done by PH, but here we composite the data based on seasonal, rather than monthly U2-10 values.

hand, the anomalies do not propagate downward within the stratosphere and no relationship to the NAM anomalies at the surface is found (the correlations peak at zero time lag, and diminish below 200 hPa). The correlation plot for all years shows main features of both reflective and non-reflective years. Note that the correlations for all years are more significant, because they are based on three times as many years than the composites.

4 Discussion and conclusions

We have compared the stratosphere-troposphere time lagged-covariances of the zonal mean and wave components of the Northern Hemisphere circulation. We have shown that during winter (Jan-Mar) while the upward interaction is dominated by wave processes, both the zonal mean and wave components contribute to the downward interaction, with zonal wave 1 dominating the short (up to 12 days) time scale coupling and the zonal mean dominating on longer time scales. Furthermore, we find that for the downward interaction, the two processes dominate during different years, depending on the state of the stratosphere. Winters characterized by a stratospheric basic state that is reflective for wave 1 show strong correlations (and covariance) for wave 1 components when the stratosphere is leading, but do not show any significant correlations in the zonal mean components (and NAM signature). On the other hand, winters characterized by a stratospheric state that does not reflect waves show a strong correlation only in the zonal mean fields (and NAM signature), when the stratosphere leads. This suggests the downward progression of zonal mean wind anomalies, found in many previous studies (e.g., Baldwin and Dunkerton, 1999; Christiansen, 2001) is only a characteristic feature of those winters which are non-reflective. PH found a reflective state during about half of the winters in the period 1980 to 2002.

The results above were obtained by separating the data based on a reflective index (the zonal mean wind shear in the upper stratosphere, see PH). PH also found that a reflective configuration of the zonal mean wind is characterized by an anomalously strong vortex lower down (around 30 hPa), while a non reflective configuration is characterized by an anomalously weak vortex lower down. More reflection is consistent with a stronger vortex (and a strong NAM) in the lower stratosphere, since it implies weaker wave absorption (a substantial portion of the wave energy returns down to the troposphere).

This would imply that the positive and negative phases of the NAM will exhibit inherently different time evolution in the stratosphere, which will manifest itself in the downward interaction with the troposphere. Essentially we expect downward coupling for the zonal mean component to be much stronger during weak NAM. To further test this, we repeat the composite analysis but separate the data based on the stratospheric NAM index (see section 2c for details). Figure 5 shows the results for a NAM index at 30 hPa (but we get the same results based on other stratospheric levels). We see a similar separation into zonal mean and wave type downward couplings, with the zonal mean interaction characterizing weak NAM years, and wave processes characterizing strong NAM years.

We expect downward reflection to directly modify the planetary scale wave field in the troposphere, by modifying its longitudinal orientation, as part of the vertical phase structure changes that accompany the change in direction of vertical wave propagation (these changes in the planetary wave structure may then modify other tropospheric fields). Our results also suggest that wave reflection indirectly affects the troposphere by not allowing the NAM-associated processes to affect it. For example, some of the differences in the probability of extreme weather events in the few months following strong positive and negative anomalies of the stratospheric vortex (Baldwin and Dunkerton, 2001; Thompson et al., 2002), may be

due to the differences in the coupling process itself (NAM-related versus reflection).

To summarize, while numerous previous studies have stressed the importance of zonal mean processes, our study suggests that downward reflection of waves is a significant component of troposphere/stratosphere dynamics and cannot be ignored in the discussion of a possible downward effect of the stratosphere on the troposphere. Besides a possible direct effect on the tropospheric planetary scale waves during reflective years, the formation of reflecting surfaces during some winters also halts the downward NAM-like influence, and any of its possible effects. Having two coupling regimes may have important implications for weather prediction, if either one of these coupling mechanisms does eventually show potential predictability.

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Table 1: The 8 years with the most positive and negative Jan-Mar average values used for compostive analysis. a) The reflective index U2-10 and b) the 30 hPa NAM index.

a) reflective index	
reflective	non-reflective
1982, 1986, 1990, 1992, 1993, 1996, 2000, 2003	1981, 1985, 1987, 1988, 1991, 1999, 2001, 2002

b) 30 hPa NAM index	
strong vortex	weak vortex
1986, 1988, 1990, 1993, 1994, 1996, 1997, 2000	1985, 1987, 1991, 1998, 1999, 2001, 2002, 2003

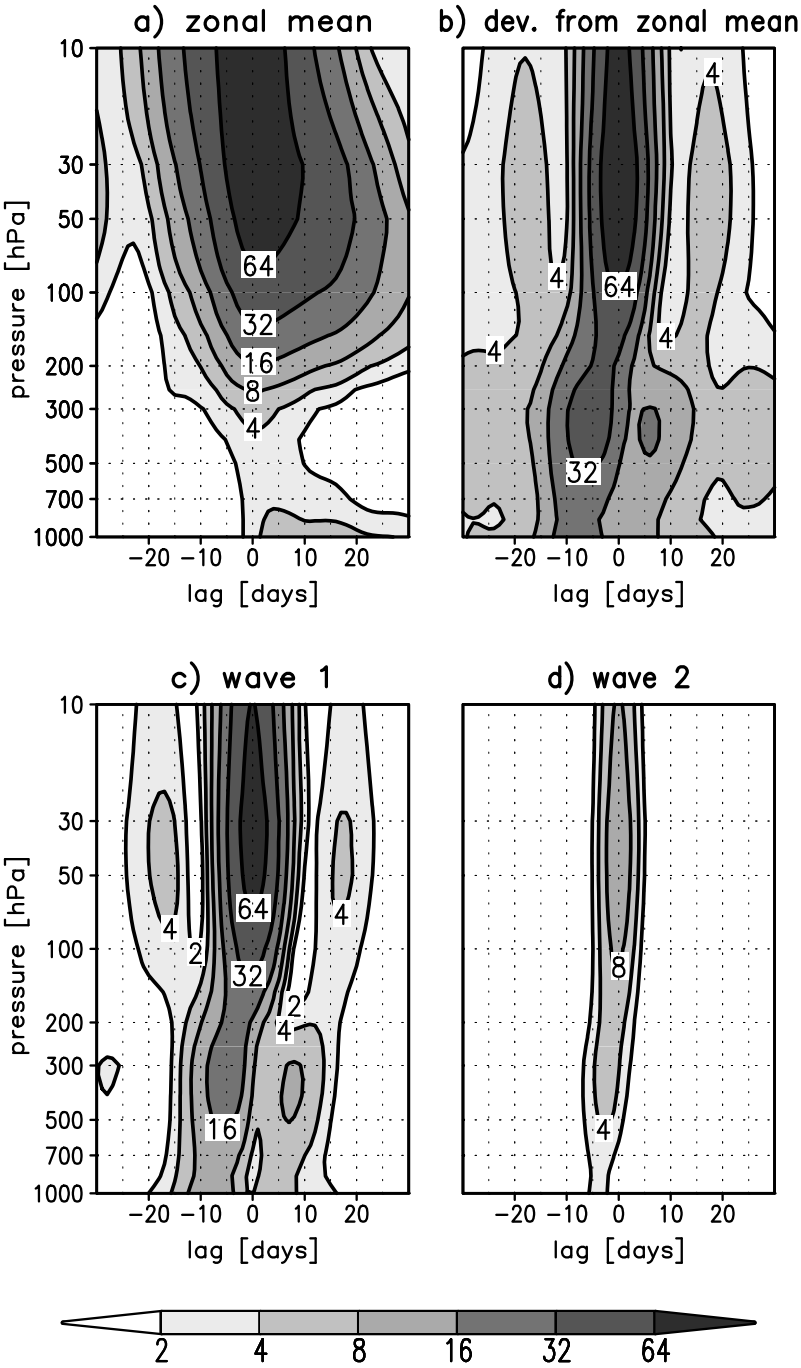

Figure 1: Total squared covariance [10^9gpm^2] between geopotential height fields at 10 hPa all pressure levels between 1000 and 10 hPa, for time lags ranging from -30 to 30 days. a) zonal mean, b) deviations from zonal mean, c) wave 1 and d) wave 2. A positive time lag indicates that the stratospheric field is leading.

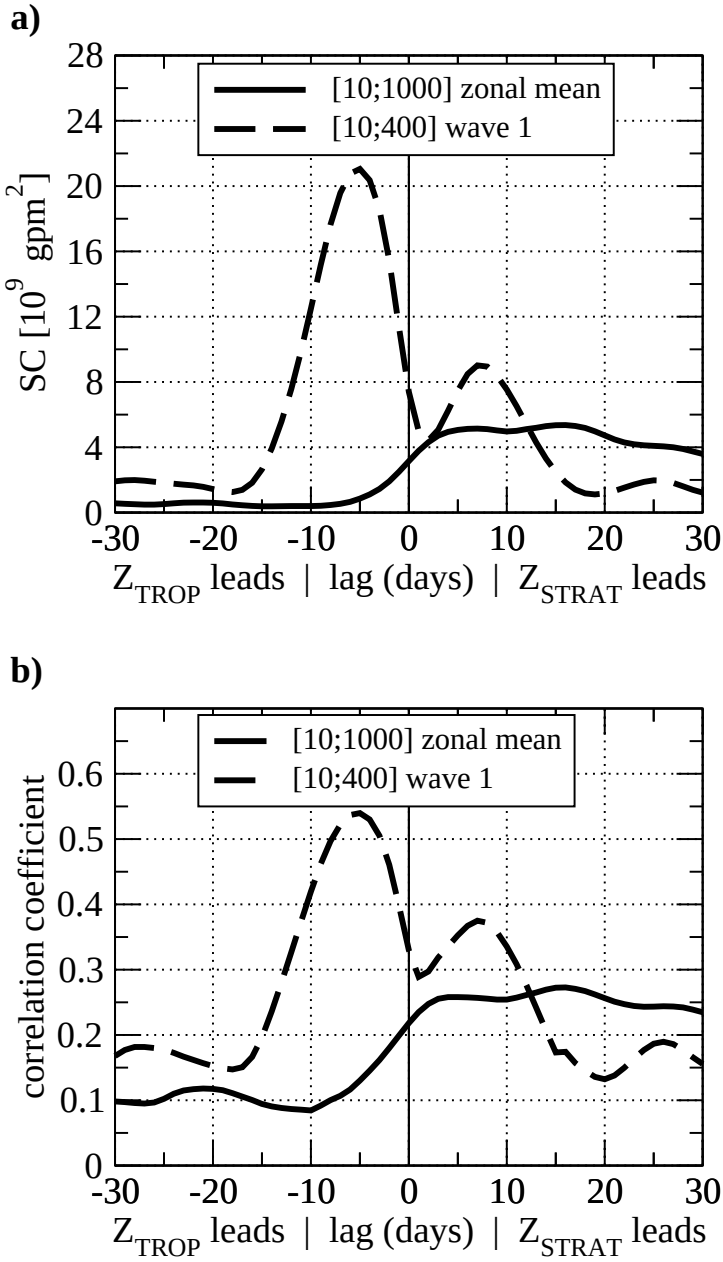

Figure 2: a) Total squared covariance between tropospheric and stratospheric height fields [10^9gpm^2] north of 30°N for time lags between -30 and 30 days. b) Correlation coefficients between the leading coupled mode. Solid line: 10 and 1000 hPa zonal mean fields, dashed line: 10 and 400 hPa wave 1 fields. A positive time lag indicates that the stratospheric field is leading.

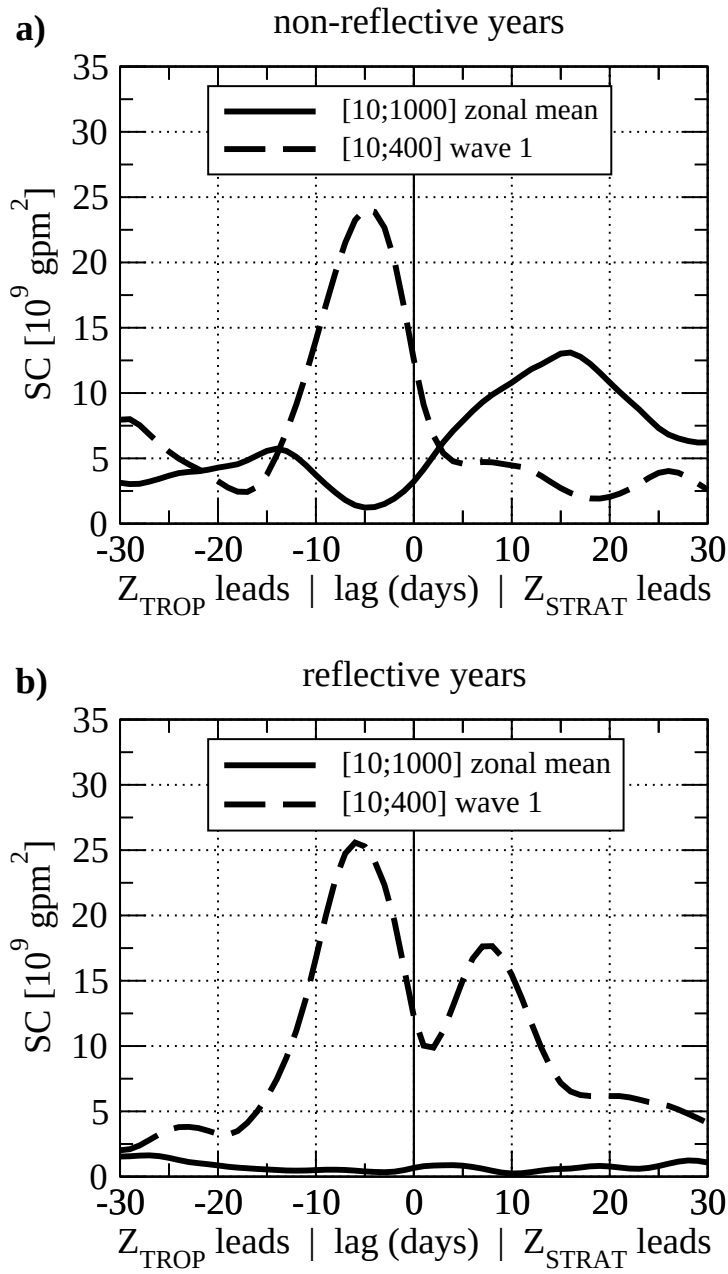

Figure 3: Same as Figure 2a but for the composites based on a) non-reflective years and b) reflective years.

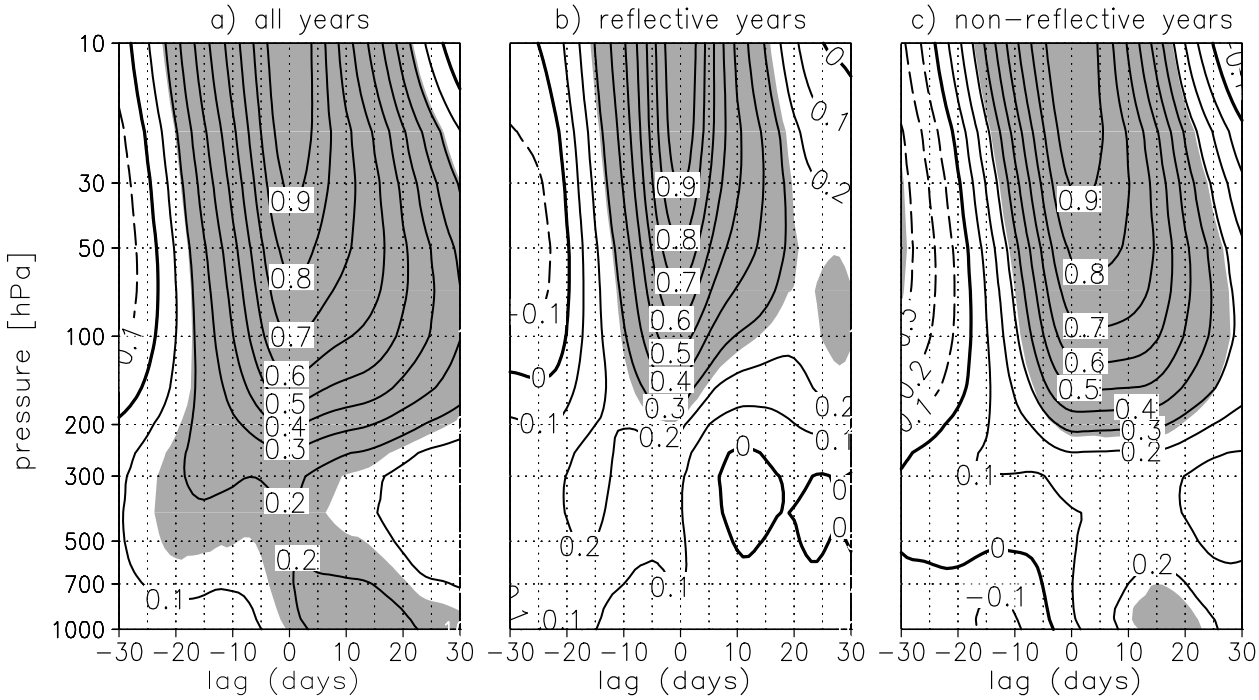

Figure 4: Correlation coefficients between the NAM signature time series at 10 hPa and at the levels between 1000 and 10 hPa for time lags between -30 and 30 days a) all winters 1980 - 2003, b) reflective years and c) non-reflective years. Negative values are dashed. The shading indicates where the correlations are significant at least at the 95% level taking into account the autocorrelation in the time series. A positive time lag indicates that the 10 hPa time series is leading.

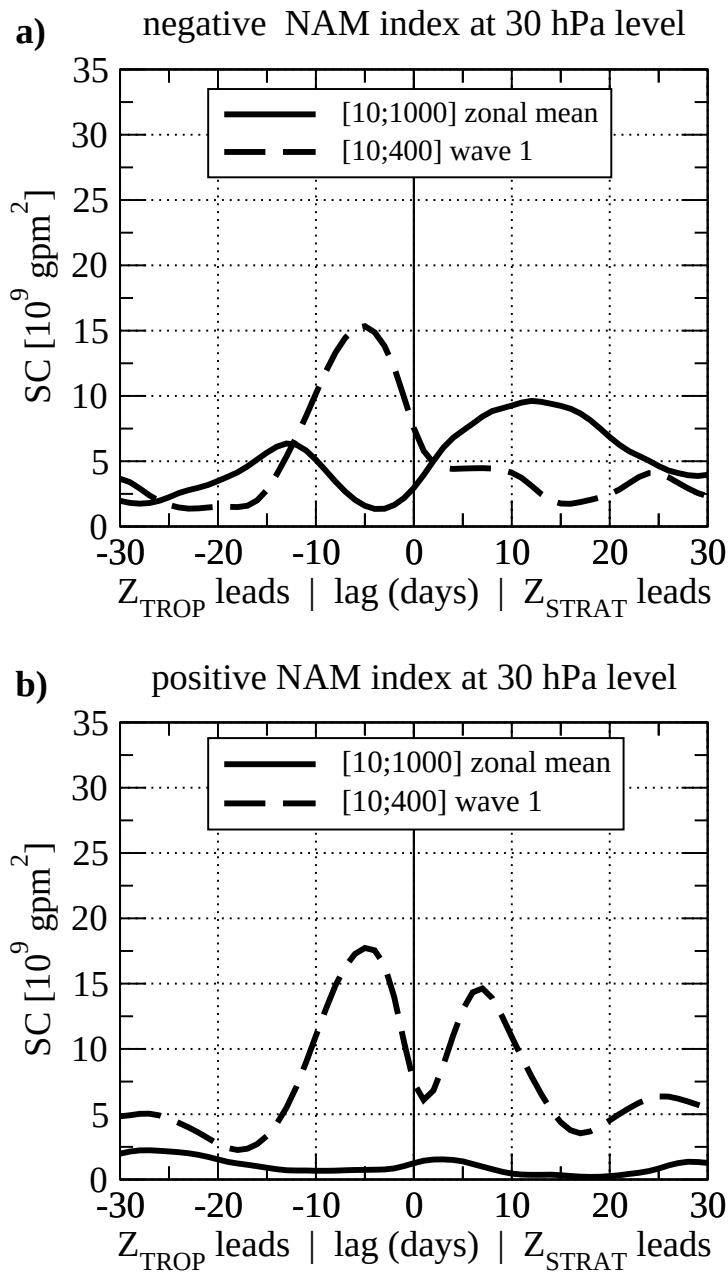

Figure 5: Same as Figure 2a but for the composites based on a) negative and b) positive 30 hPa NAM index.