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 a strong relationship between stratospheric and tropospheric wave-1 fields when the stratosphere is leading and show no significant correlations in the zonal mean fields. On the other hand, winters characterized by a stratospheric state that does not reflect waves show a strong relationship only between stratospheric and tropospheric zonal mean fields. This study suggests that there are two types of stratospheric winter states, characterized by different downward dynamic interaction. In one state, most of the wave activity gets deposited in the stratosphere, resulting in strong wave–mean-flow interaction, while in the other state, wave activity is reflected back down to the troposphere, primarily affecting the structure of tropospheric planetary waves.

1. Introduction

There is increasing evidence that stratospheric dynamic processes play a significant role in tropospheric climate variability across a wide range of time 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 lowermost 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, at least to the lower-most stratosphere, 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 2004). 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 (e.g., Holton and Mass 1976; Kodera et al. 2000; Kodera and Kuroda 2000a). Clearly, the strength of this interaction depends both on the strength of the tropospheric wave forcing and on the stratospheric mean flow itself.

The mechanisms by which the zonal mean signal is transmitted to the troposphere are not well understood thus far. In addition to a downward progression of the regions of strong wave–mean-flow interaction, a direct adjustment of the flow to potential vorticity (PV) anom-

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alies (diagnosed by PV inversions; Hartley et al. 1998; Ambaum and Hoskins 2002; Black 2002) and downward control (Haynes et al. 1991) may also play a role. Recent model and observational studies emphasize the role of transients for maintaining the zonal mean response in the troposphere (Limpasuvan et al. 2004; Song and Robinson 2004).

A different mechanism of a downward dynamic influence—reflection of wave activity by the stratosphere back into the troposphere—has also been suggested in the past (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, hereafter PH). The main basic-state configuration under which reflection of wave 1 occurs is when the stratospheric jet peaks in the midstratosphere (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 2000b; Zhou et al. 2002). Tropospheric and stratospheric NAM-like anomalies are coupled during late winter/spring but not during fall/early winter (Kodera and Kuroda 2000b). 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; Limpasuvan et al. 2004). 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 2001a; PH). This suggests that 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 activity gets deposited in the stratosphere, resulting in strong wave–mean-flow interaction, while in the other state, wave activity 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.

As a first step to answer these dynamics questions, 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 the analysis approach are introduced. The results are described in section 3. Discussion and conclusions are given in section 4.

2. Data and approach

a. Data

This study is based on the 4-times-daily reanalysis of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–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 to 10 hPa, on a 2.5° × 2.5° grid. For our calculations, we interpolate the data to a 5° × 5° grid. This interpolation does not influence the results. We use data between 30° and 85°N.

The NCEP–NCAR reanalysis geopotential heights are also the basis for the NAM signature time series (Baldwin and Dunkerton 2001). The NAM is defined as the leading empirical orthogonal function (EOF) of 90-day low-pass-filtered wintertime hemispheric geopotential heights (north of 20°N). A separate EOF calculation is made for each of the 17 pressure levels from 1000 to 10 hPa. Daily indices of the NAM are calculated by projecting daily (unfiltered) geopotential height anomalies onto the leading EOF patterns (for details, see note 10 in Baldwin and Dunkerton 2001). The stratospheric time series describe variations in the strength of the stratospheric polar vortex. The spatial structure of the related tropospheric patterns is less zonally symmetric with the Arctic center of action shifted toward Greenland (Baldwin and Dunkerton 1999; Perlwitz and Graf 2001b).

The NAM signature time series are provided by M. Baldwin (2003, personal communication). The data from 1958 to 2001 are available on his Web page (http://www.nwra.com/resumes/baldwin/nam.html).

For the calculations of the reflection index [January–February–March (JFM) 1980–2003], we use the zonal wind at 2 and 10 hPa from the stratospheric analysis product compiled and distributed by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Atmospheric Chemistry and Dynamics Branch. These data are based on an objective analysis of satellite data. For more details about data quality, see the NASA GSFC Web site (http://hyperion.gsfc.nasa.gov/Data_services/met/about_nmc_data.html). We also note that Harnik and Lindzen (2001) used this dataset to investigate reflection in the Southern Hemisphere and found a consistency between the zonal mean basic-state and corresponding wave geometry, and the geopotential height wave field evolution, suggesting that the reflection index based on this data is meaningful.

b. Time-lagged singular value decomposition 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, as follows:

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

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

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 $\mathrm{SC} = \sum_{k=1}^{K} s_k^2$.

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 that the 10-hPa field is leading. No temporal filtering is applied to the data.

To separate zonal mean and wave processes, we apply a strong spatial filtering to the data. With the help of the time-lagged SVD analysis, we determine the statistical relationship between zonal mean fields, the deviations from the zonal mean fields, and the zonal wavenumber-1 and -2 fields, separately. That means the same kind of spatial filtering is applied to both Z_1 and Z_2. In the first case, both Z_1 and Z_2 are zonal mean fields; in the second case, both Z_1 and Z_2 are deviations from the zonal mean and so on.

The total SC is a measure of the total relationship between the grid points of the two fields and, thus, depends on the number of grid points. A grid-size independent measure C can be defined as follows:

$$C = \sqrt{\mathrm{SC}/(n_1 n_2)}, \tag{3}$$

where C is the mean covariance between any two grid points of two fields Z_1 and Z_2, with n_1 and n_2 being the number of grid points of these fields. In the present study, $n_1 = n_2 = 864$ (corresponding to a 5° × 5° grid between 30° and 85°N). In addition to C, 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 maximum covariance does not have to be 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.

TABLE 1. The eight years with the most positive and negative JFM average values of the reflective index U(2–10) used for composite analysis.

Reflective	Nonreflective
1982, 1986, 1990, 1992, 1993, 1996, 2000, 2003	1981, 1985, 1987, 1988, 1991, 1999, 2001, 2002

c. The reflective index U2–10

PH showed that the high-latitude zonal mean wind difference between 2 and 10 hPa is a good index for separating reflective and nonreflective basic states for wave-1 vertical propagation. This index is defined as $U(2\text{–}10) \equiv \langle U\rangle(2\ \mathrm{hPa}) - \langle U\rangle(10\ \mathrm{hPa})$, where $\langle U\rangle$ is the zonal mean wind averaged over 58°–74°N and over time. The reflective basic state corresponds to a negative index U(2–10) with the polar night jet peaking in the midstratosphere. In the case of the nonreflective state (positive index), the zonal wind at mid- to high latitudes increases with increasing height. For the SVD and correlation analyses, we composite the 8 yr with the largest and smallest January–March U(2–10) averages (for years, see Table 1). A sample of 8 yr represents one-third of the period investigated (24 yr).

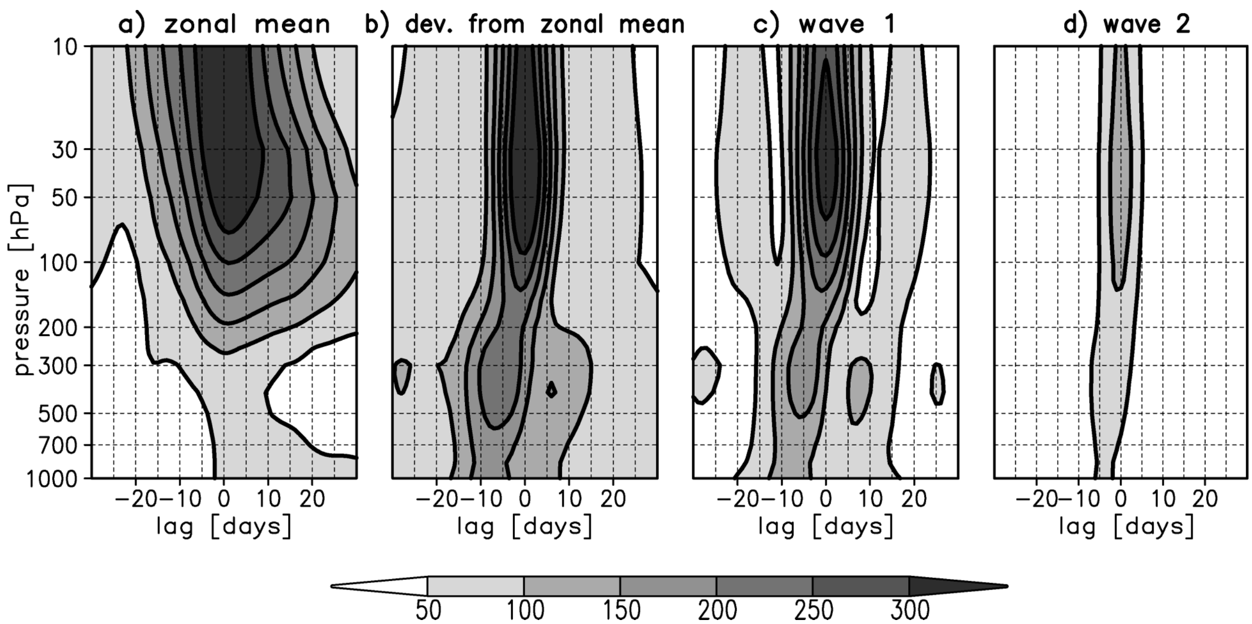

FIG. 1. The C [gpm^2] between geopotential height fields at 10 hPa and all pressure levels between 1000 and 10 hPa, for time lags ranging from −30 to 30 days. (a) Zonal mean, (b) deviations from zonal mean, (c) wave 1, and (d) wave 2. A positive time lag indicates that the stratospheric field is leading.

3. Results

First, we compare our analyses for the zonal mean and wave fields, for all high winters (JFM[1]), 1980 to 2003. Figure 1 shows the covariance between the 10-hPa and various pressure levels p and time lags [$C_{10}(\tau, p)$], for the zonal mean, the deviation from zonal mean, and zonal waves 1 and 2. The $C_{10}(\tau, p)$ of the zonal mean fields (Fig. 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 at the midtropospheric pressure levels (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 SC in the midtroposphere). The dominance of the zonal mean coupling of the stratospheric circulation to the surface is found in other studies, but the reason for it is not entirely clear.

The covariability of the zonal deviation fields (Fig. 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 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).

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

To further compare the zonal mean and wave coupling, we combine $C_{10}(\tau, p)$ of both processes in one plot (Fig. 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 stud-

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

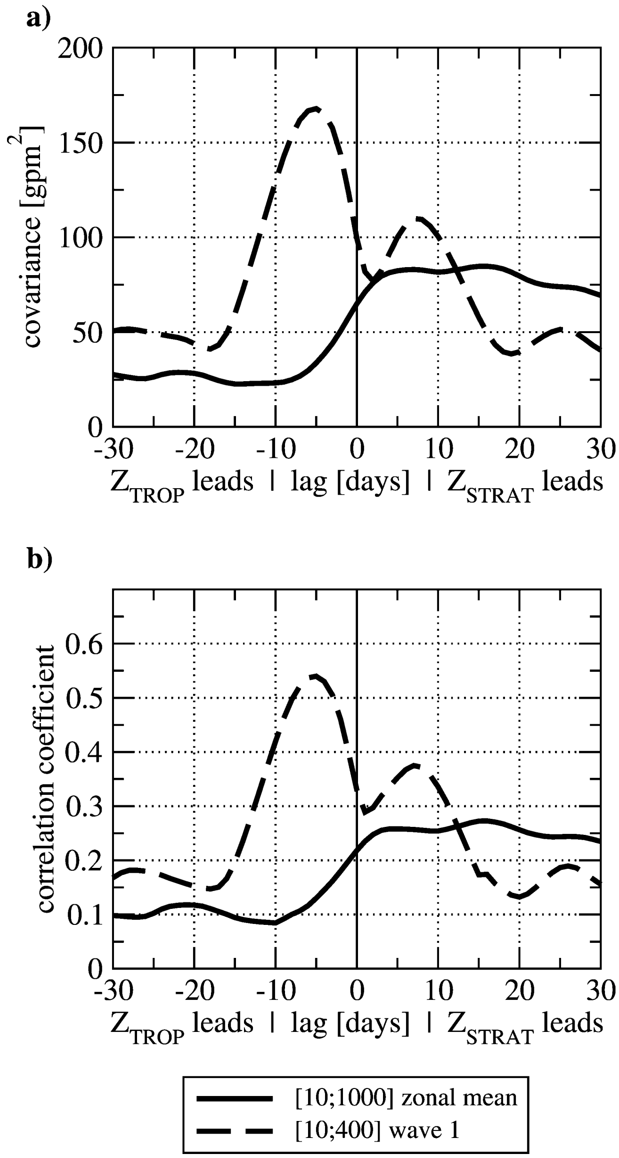

FIG. 2. (a) The C [gpm^2] between tropospheric and stratospheric height fields north of 30°N for time lags between −30 and 30 days. (b) Correlation coefficients between the leading coupled mode. Solid line: 10- and 1000-hPa zonal mean fields; dashed line: 10 and 400 hPa wave-1 fields. A positive time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

ies 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 (Fig. 2b). Comparing with Fig. 2a, we see that the correlations in the leading coupled mode give essentially the same results as the covariances.

These results based on all years suggest that 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

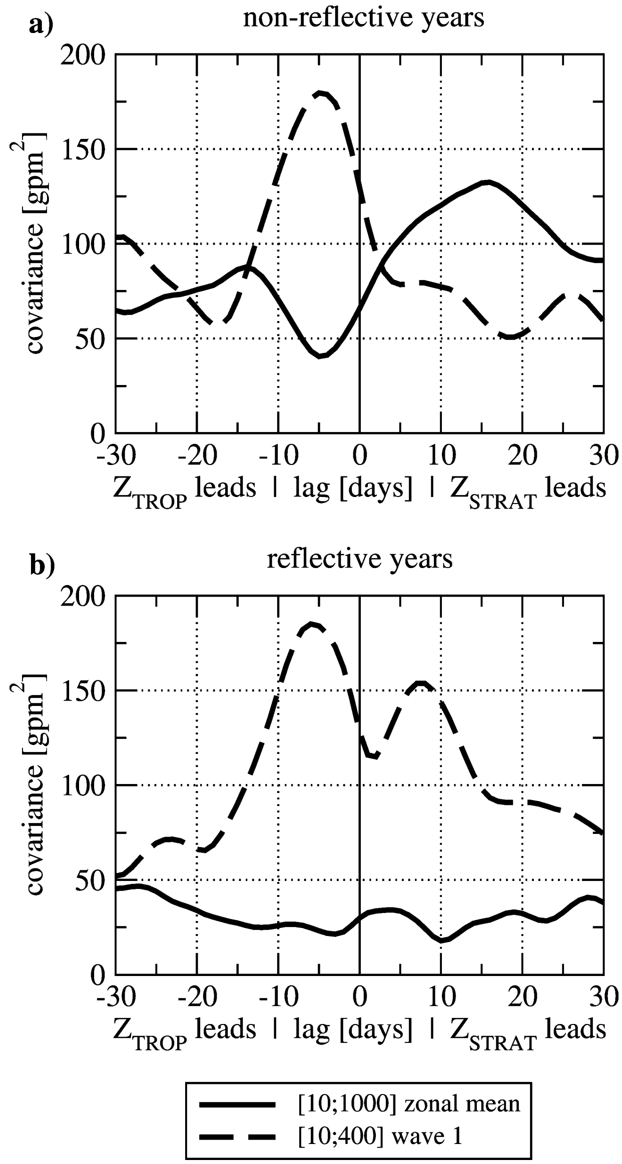

FIG. 3. Same as in Fig. 2a, but for composites based on (a) nonreflective years and (b) reflective years.

significant signal in the zonal mean field. The second one is related to wave reflection with a 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 U(2–10) (see PH and section 2c), and repeat the time-lagged SVD analysis only using data for the eight JFM periods with the most positive (nonreflective) or most negative (reflective) U(2–10) values. Figure 3 shows the corresponding $C_{10}(\tau, p)$ for the key levels (zonal mean: 1000 hPa; wave 1: 400 hPa). As in PH,

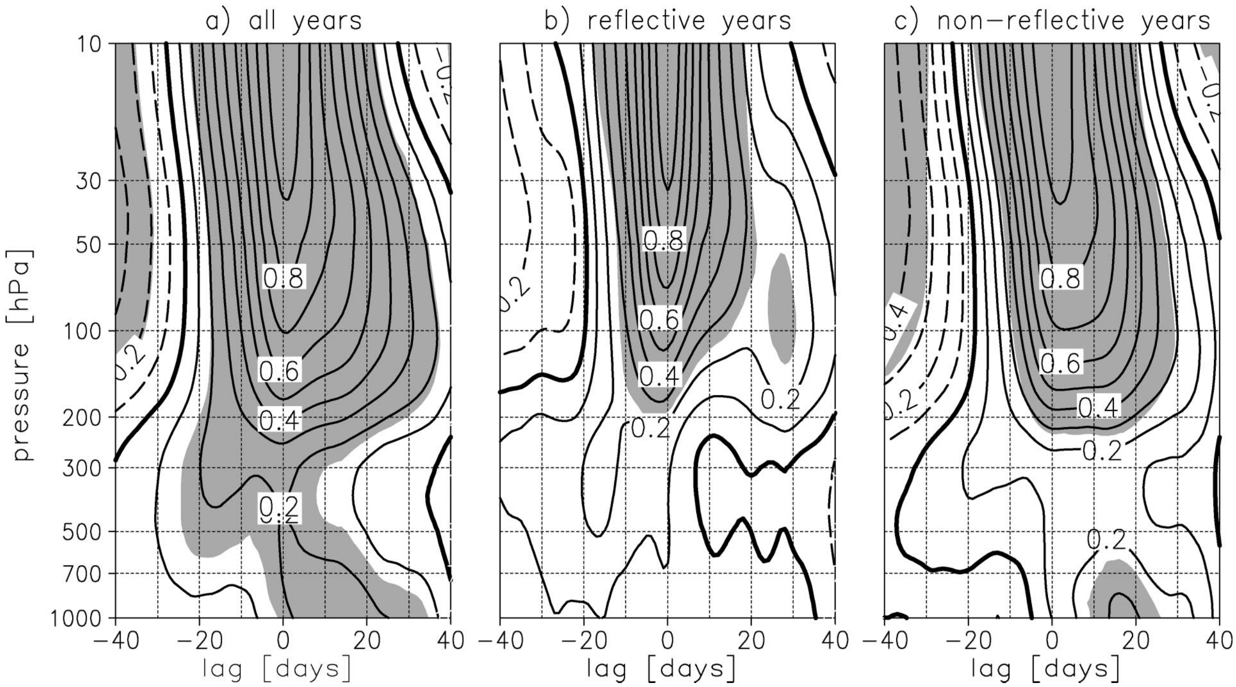

FIG. 4. Correlation coefficients between the NAM signature time series at 10 hPa and at the levels between 1000 and 10 hPa for time lags between −40 and 40 days for (a) all winters 1980–2003, (b) reflective years, and (c) nonreflective years. The thick line represents a value of 0; negative values are dashed. The shading indicates where the correlations coefficients 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.

we find that downward wave coupling (dashed lines) only occurs during reflective years.[2]

The main new finding is a strong dependence of the zonal mean downward coupling (solid lines) on the reflective state of the stratosphere. During nonreflective years (when downward wave coupling is weak), the $C_{10}(\tau, p)$ for the zonal mean fields show a pronounced maximum at a time lag of 16 days. Clearly, zonal mean related processes dominate the downward dynamic coupling. During reflective years, however, $C_{10}(\tau, p)$ for the zonal mean fields is small, and a persistent significant relationship at positive time lags, as found when using all years (Fig. 2a), does not exist. During these reflective winters, downward coupling between the stratosphere and troposphere is dominated by the process of wave reflection.

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 them 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 JFM periods during 1980–2003, as well as for the reflective and nonreflective years (Fig. 4).

The results strongly agree with the previous findings of this paper. During nonreflective 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 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). By extending the analysis to time lags between ±40 days, we see negative (positive) descending NAM-like anomalies followed by positive (negative) descending anomalies. This phase change is consistent with low-frequency vacillations found in observational and model studies of wave–mean-flow interaction (e.g., Holton and Mass 1976; Kodera et al. 2000; Kodera and Kuroda 2000a).

The correlation plot for all years (Fig. 4a) shows main features of both reflective and nonreflective years. Note that the correlations for all years are more significant because they are based on 3 times as many years as the composites. Note also that significant correlations in the NAM index at negative time lags in the midtroposphere

[2] Note that the wave–wave covariances (compare dashed lines in Figs. 3a and 3b) are similar to the calculations done by PH, but here we composite the data based on seasonal rather than monthly U(2–10) values.

are due to the wave component included in the NAM features.

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 (JFM) 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 a strong relationship 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 raises the question of how our results relate to those of Baldwin and Dunkerton (2001) who composited time–height sections of the 1000 to 10 hPa NAM signature anomalies (from long-term mean) for extreme positive and negative 10-hPa NAM events. They found a general tendency of these extreme anomalies to migrate down. Our results suggest that most of the extreme NAM events that constitute the composites of Baldwin and Dunkerton occurred during nonreflective winters. If this is the case, we expect to find a larger NAM variability in the stratosphere during nonreflective years, and, indeed, we find that the standard deviation of the the stratospheric NAM-signature time series is about 40% larger during nonreflective years compared to reflective years (not shown). An important implication is that 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).

The relation of reflection to the strength of the vortex in the mid- to lower stratosphere is still not understood well enough. PH found that a reflective configuration of the zonal mean wind is characterized by an anomalously strong vortex lower down (around 30 hPa), while a nonreflective configuration is characterized by an anomalously weak vortex lower down. Assuming that the 30-hPa zonal wind index of PH is a good indication of the NAM state, this would suggest that a zonal mean coupling will dominate the downward interaction during negative NAM years. We note, in this regard, that more reflection is consistent with a stronger and more persistent vortex (positive NAM) in the lower stratosphere, since it implies weaker wave absorption (a substantial portion of the wave momentum returns down to the troposphere).

In addition to indirectly affecting the troposphere by not allowing the NAM-associated processes to affect it, we expect downward reflection to directly modify the planetary-scale wave field in the troposphere by changing the longitudinal orientation of the waves. This is expected as part of the vertical phase structure changes that accompany the change in direction of vertical wave propagation. The changes in the planetary-wave structure may then modify other tropospheric fields.

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. 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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