Influencia de ENSO en los modos de variabilidad de la estratosfera boreal en invierno

ENSO influence on the variability modes of the boreal winter stratosphere

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RESUMEN

Se ha propuesto recientemente que la circulación estratosférica puede estar jugando un papel importante en la transmisión de la señal de ENSO al sector Euro-Atlántico. En este contexto, en el presente estudio se analiza la influencia de ENSO en los modos de variabilidad de la estratosfera del Hemisferio Norte en invierno. Se ha llevado a cabo un Análisis de Componentes Principales del geopotencial en 20 hPa separando los datos en inviernos El Niño y La Niña (periodo 1957/58-2001/02). El modo anular en la estratosfera retiene un 10% más de la variancia total del geopotencial durante inviernos La Niña. Este primer modo estratosférico es el único con el que, con significación estadística, el ozono en 20 hPa correlaciona linealmente, siendo esta relación más alta en los inviernos El Niño. Por otra parte, los modos con estructura de onda zonal uno acumulan más variabilidad durante inviernos El Niño. En nuestros resultados se muestra una mayor presencia de anomalías de carácter ondulatorio en la estratosfera durante condiciones El Niño.

Palabras clave: El Niño-Oscilación del Sur, modos de variabilidad, circulación estratosférica.

ABSTRACT

The stratospheric circulation has been recently proposed to play an important role in transmitting the ENSO signal to the Euro-Atlantic region. In this context, the influence of ENSO on the boreal stratospheric modes of variability in winter is studied. A Principal Component Analysis of the geopotential height at 20 hPa is performed partitioning the data into El Niño and La Niña winters (1957/58-2001/02 period). It is found that the stratospheric annular mode retains almost a 10% more variance of the field for cold-La Niña than for warm-El Niño winters. On the other hand, zonal-wave-number-one modes accumulate more variability for warm-El Niño winters. Our results support the presence of more stratospheric wave-like anomalies coming from the troposphere during warm-El Niño conditions. Statistical linear correlation between ozone and stratospheric variability is restricted to the annular mode, being the signal stronger for warm-ENSO winters.

Key words: El Niño-Southern Oscillation, variability modes, stratospheric circulation.

SUMMARY: 1. Introduction. 2. Data and method. 3. Results and discussion. 4. Conclusions. 5. Acknowledgements. 6. References.

1. INTRODUCTION

The El Niño-Southern Oscillation (ENSO) phenomenon is the major source of interannual variability in the climate system (Hsiung and Newell 1983). Its effects are not restricted to the tropical Pacific, but extend to extratropical regions altering the atmospheric circulation of both the troposphere and stratosphere; and significant climate anomalies are also found worldwide (Trenberth et al., 1998 and references therein).

ENSO-induced changes in the tropospheric North Pacific-American sector are marked and well understood (see Trenberth et al. 1998 for a review). However, the influence of ENSO on Euro-Atlantic sector is weak and more controversial, and proposed mechanisms have been elusive up to date (see Brönnimann 2007 for a review). A separate remark deserves the studies of Ineson and Scaife (2008) and Cagnazzo and Manzini (2009), who show a dynamically active role of the high-latitude stratosphere in successful simulations of the teleconnection between ENSO and North Atlantic-European climate. Such a feature corresponds to situations in which stratospheric sudden warmings occur. The stratospheric teleconnection pathway proposed in both studies implies El Niño-forced enhanced upward propagation of ultra-long planetary waves from the troposphere, subsequent upper-zonal flow deceleration, downward propagation of the signal to the lower stratosphere, and its final reach at surface.

Besides the mentioned recent finding of the active role of the polar stratosphere in spreading ENSO anomalies, the influence of ENSO on the stratosphere has been extensively studied in the last decades. Early observational studies based on the SO index already show an association between warm-El Niño (cold-La Niña) events and weakening (strengthening) and warming (cooling) of the polar vortex (van Loon and Labitzke, 1987; Hamilton, 1993). However, the limited number of ENSO events and the superposition of different signals in the observations, such as the Quasi-Biennial Oscillation (QBO), yield to a poor statistical significance of the results (Baldwin and O'Sullivan, 1995). In contrast, several modelling studies have successfully captured the ENSO signal on the stratosphere. There is good agreement in establishing the influence of warm-El Niño as an enhancement of vertically propagating planetary waves that disturb and weaken the stratospheric polar vortex, which favour higher temperatures over the polar cap (Sassi et al., 2004; García-Herrera et al., 2006; Manzini et al., 2006). On the other hand, no consistent signal during cold-La Niña conditions is found (Manzini et al., 2006).

Another seminal work, based on observations, has been published by Quadrelli and Wallace (2002). These authors describe significant changes in the Northern Hemisphere Annular Mode (hereafter NAM) at surface in terms of the ENSO phase, i.e. the sea surface temperature (SST) related to ENSO. They compose data sub-sets for each ENSO phase from reanalysed records and separately compute the leading sea-level pressure mode. Close fractions of explained variance of sea-level pressure yield structural differences between warm and cold episodes (32% and 25% , respectively): the former appears related to regional oscillation with a more prominent Arctic centre of action; and the latter is associated with a more hemispheric oscillation.

Even so, the soundness of the NAM defined at surface remains under debate (Deser, 2000; Ambaum et al., 2001; Wallace and Thompson, 2002; García-Serrano et al., 2009); but so does not the annular mode at upper-levels, concretely in the lower stratosphere (Thompson and Wallace, 1998, 2000; Deser, 2000). Other works have shown how long-lived anomalies in the stratospheric NAM frequently precede persistent anomalies in the tropospheric NAM (Thompson et al., 2002, 2003), which points out the potential predictability of the wintertime climate at intraseasonal and seasonal time-scales on the basis of lower stratospheric polar vortex.

An attempt is made in this work to link two main sources of predictability up to seasonal-to-interannual scales, namely ENSO and lower-stratosphere. We present evidence for the sensitivity of the stratospheric variability modes to ENSO-SST polarity. As far as we are aware, this is the first study doing this exercise and establishing these conclusions. However, our starting point and results are supported by a number of works that discuss that troposphere-stratosphere coupling may be helpful to better understand the observed ENSO teleconnection to North Atlantic-European climate variability.

2. DATA AND METHOD

The following datasets are used in this study:

a) 12-hourly atmospheric fields from ERA40 Re-analysis on a 2.5ºlon x 2.5ºlat grid (Uppala et al., 2005), retrieved from the European Centre for Middle-Range Weather Forecast (ECMWF) website. The fields used are geopotential height (GPH), horizontal wind velocity, temperature and ozone mass mixing ratio. The vertical domain is from mid-troposphere up to 10 hPa.
b) Monthly fields of sea surface temperature (SST) from Reynolds Extended Reconstructed SST (Smith and Reynolds, 2003) dataset, retrieved from the Climate Diagnostic Center (CDC) website. These data are gridded on a 2ºlon x 2ºlat mesh.

The study focuses on winter months extending from December to March (DJFM) for the 45-year period 1957/58-2001/02. As mentioned in the previous section, the analysis technique is similar to that in Quadrelli and Wallace (2002), and is next summarized. The atmospheric fields are partitioned into warm and cold ENSO winters as defined by the Niño3.4 index (hereafter, warm and cold winters), each containing 10 winters (Fig.1). Specifically, warm and cold ENSO winters are defined as those seasons when the absolute value of the monthly anomalies of the Niño3.4 index exceeds 0.5 standard deviations during consecutive December to

February months. Note that these two subsets are not the same as in Quadrelli and Wallace (2002). It is noticeable the anomalous warm (cold) tongue over the central-eastern Pacific surrounded by negative (positive) SST anomalies in Fig.1A (B), which strongly resembles El Niño (La Niña) fingerprint.

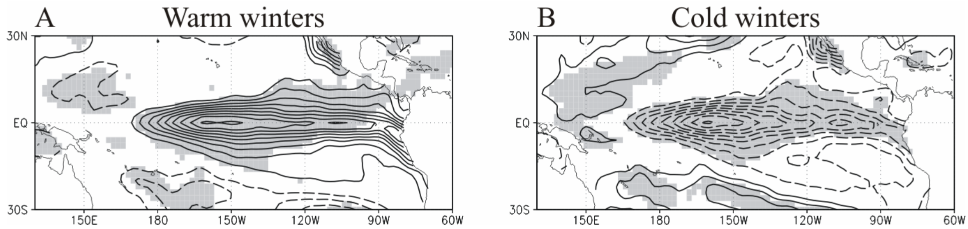

Figure 1. Composite of SST anomalies in the tropical Pacific in DJFM months for the selected warm winters: A) 1958, 1964, 1966, 1969, 1973, 1983, 1987, 1992, 1995 and 1998; and cold winters: B) 1963, 1971, 1974, 1976, 1985, 1989, 1996, 1999, 2000 and 2001. The year corresponds to January of the DJF sequence. Positive (negative) anomalies in solid (dashed) lines. Zero line is omitted. Contour interval is 0.2 K. Shading denotes statistical significant anomalies with α=0.01 (two-tailed t-test).

A Principal Component Analysis (PCA; von Storch and Zwiers, 2001) of the GPH at 20 hPa (GPH20) north of 20ºN is performed for warm and cold winters. To gain in statistical significance from the available data, we make use of a 10-day running 30-day means for the PCA calculations.

3. RESULTS AND DISCUSSION

The spatial structures of the leading PCA mode of GPH20 for warm, cold and all winters are shown in Fig.2. Large anomalies of one sign dominate the polar latitudes for the three cases, and anomalies of the other sign extend along mid-latitudes. This is a well-known pattern: the NAM (Thompson and Wallace, 1998). As mentioned in the Introduction, the NAM pattern in the stratosphere is well-established unlike its tropospheric counterpart, and represents variations in the intensity of the cyclonic stratospheric polar vortex.

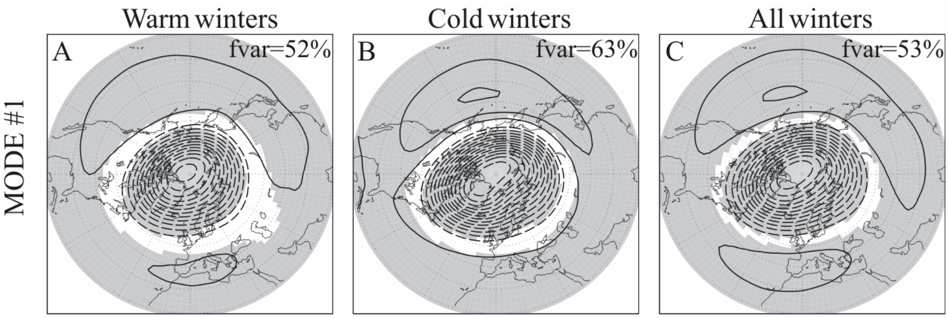

Figure 2. Spatial structure of the leading PCA mode of GPH20 for warm, cold and all winters, obtained by projecting interannual anomalies of GPH20 in DJFM onto the respective leading standardized PC time series. Positive (negative) anomalies in solid (dashed) lines. Zero line is omitted. Contour interval is 40 m per standard deviation of the PC time series. Shading indicates statistical significant results with α=0.01 (as in Fig.1).

Concerning the Fig.2, note that positive (negative) values of the standardized leading PC time series are associated with a relatively strong (weak) polar vortex. The differences between warm-NAM and cold-NAM structures are the somewhat broader extension and slightly larger values of the anomalies over the polar cap and the more pronounced anomalies in midlatitudes for the latter. Nevertheless, the main difference is not structural but statistical: the warm-NAM accumulates 52% of the total variance – very close to the fraction of the variance (denoted "fvar" in Fig.2) represented by the NAM for all winters (53%) – whereas the cold-NAM explains 63%. This is to say that the annular mode becomes significantly more important during cold winters since it represents more variability, which causes the stratospheric circulation anomalies to be more zonally symmetric. Since an unperturbed vortex is related to annular-structured anomalies, our result is consistent with previous findings that state that the vortex is less disturbed during cold-La Niña conditions (van Loon and Labitzke, 1987).

The vertical structures of the zonally symmetric zonal wind anomalies observed in association with the annular mode for warm, cold and all winters are shown in Fig.3. The structure of the three panels is consistent with results of Thompson and Wallace (2000). The NAM is dominated by meridional dipoles with nodes centred at about 40ºN. In the mid-troposphere (~ 500 hPa) the maximum of zonal-mean zonal wind is located at 60ºN, which slightly tilts northward in the lower stratosphere. For cold winters (Fig.3B), the overall layout looks like an amplification of the signal for all the winters (Fig.3C). Besides the difference in the strength of the anomalies in midlatitudes, another discrepancy between warm and cold winters is identified in the tropical stratosphere. Whereas the anomalies are of the same sign for the former, they change sign at 30 hPa for the latter. 30-hPa level is precisely the altitude at which the zonal wind maximum is located for warm winters. A QBO modulation in these low-latitudes could be acting (Garfinkel and Hartmann, 2007). In particular, in the case of warm winters, a tendency to the easterly phase is associated with the positive phase of the leading PCA mode. This is consistent with studies that have linked the east phase of the QBO to a weaker polar vortex (e.g., Calvo et al., 2007).

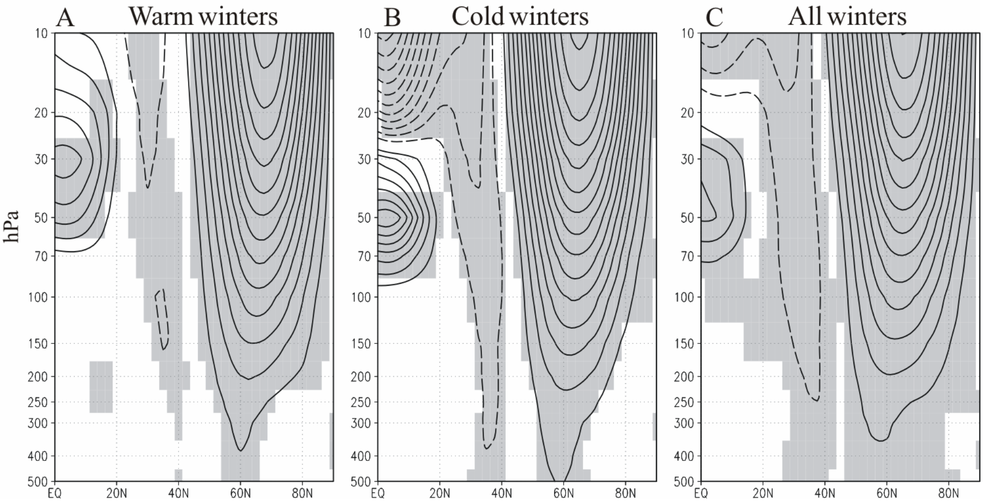

Figure 3. Vertical structure of the zonal-mean zonal wind anomalies associated with the leading variability mode of GPH20 for warm, cold and all winters, obtained by projecting the wind anomalies onto the respective standardized PC time series. Contour interval is $1 m \cdot s^{-1}$ per standard deviation of the PC time series. Positive (negative) values in solid (dashed) lines. Zero line is omitted. Shading indicates statistical significant results (as in Fig.1).

Fig.4 shows the spatial structures of the second and third PCA modes of GPH20 for warm, cold and all winters. Both modes present a zonal-wavenumber-1 configuration, the ultra-long planetary wave most likely to propagate into the stratosphere (Charney and Drazin, 1961). For the second mode (Fig.4 top row), anomalies of one sign are centred over Scandinavia and northern Eurasia and anomalies of the opposite sign are situated over North America. There are clear structural differences between warm and cold winters, namely the extension of the antinodes. The Eurasian centre of action is spatially confined to the European sector for warm winters, whereas it extends along the entire Eurasian continent and North Atlantic and presents two maxima for cold winters, which is suggestive of an additional contribution to the perturbation (quasi-wavenumber-2). Besides, the two antinodes have the same amplitude for warm winters unlike for cold and all winters, which reinforces the concept of a pure wavenumber-1 mode.

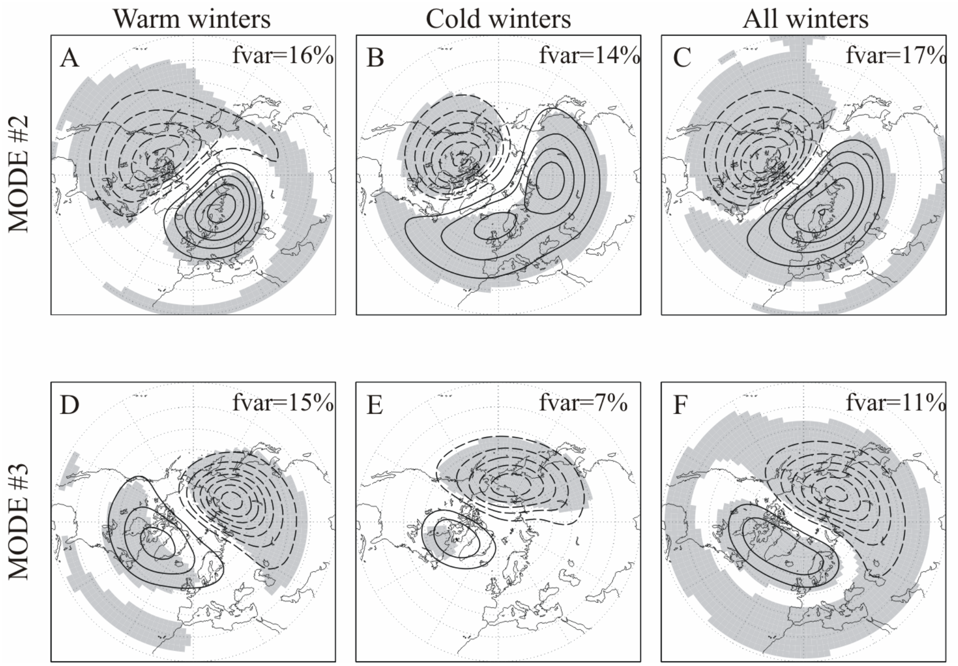

Figure 4. As Fig. 2, but for the second and third PCA modes of GPH20.

The third PCA mode of GPH20 (Fig.4 bottom row) shows a strong antinode over eastern Eurasia, which is shifted to Kamchatka for cold winters. The other antinode is weaker and centred over Greenland for warm and all winters, and barely presents statistical significance for cold winters.

The variance fraction combining PCA modes 2 and 3 is 31% for warm, 21% for cold and 28% for all winters. Thus, the variance of the GPH20 represented by the wavenumber-1 modes is 10% greater for warm than for cold winters, which is in agreement with previous findings that associate enhanced planetary wave activity in the stratosphere with warm-El Niño conditions (i.e. García-Herrera et al., 2006). To sum up, we find that the annular mode accumulates more variance of GPH20 for cold winters, whereas wave-number-1 modes represent more variance for warm winters.

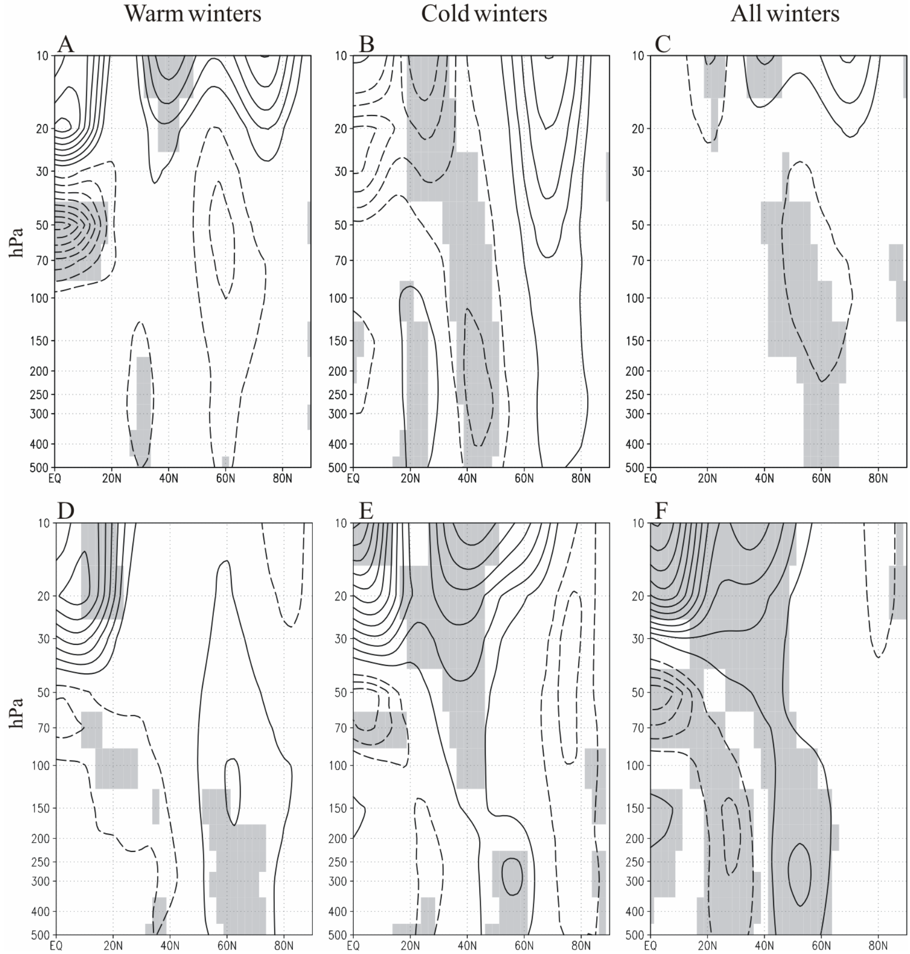

Figure 5. As Fig. 3, but for the second (top) and third (bottom) PCA modes of GPH20. Contour interval is 0.5 $m \cdot s^{-1}$ per standard deviation of the PC time series.

Let us next focus on the vertical structure of zonal-mean zonal wind anomalies associated to modes 2 and 3 of GPH20 (Fig.5). For the second mode, the configuration of the anomalies is very similar in extratropical latitudes for warm and all winters, but the statistical significance is poor. This is somehow expected since the structure of the mode is wave-like. Relevant differences appear again in the tropics at the stratosphere, where the anomalies change sign above 30 hPa for warm winters. A barotropic structure appears in the troposphere for cold winters, and midlatitude anomalies seem to be linked to subtropical middle-stratosphere (Fig. 5B). This pattern of anomalous zonal-mean zonal wind is remarkably different from the other two cases, making evident that the second PCA mode of GPH is not exactly the same as the one for warm and all the winters as mentioned before. For the third mode, a dipole structure with node at 40ºN is displayed for cold and all winters, which dramatically tilts southward at stratospheric levels reaching the equator near 30 hPa (Figs. 5E, F).

We next investigate the relation of the stratospheric variability modes to upward planetary-wave propagation, making use of the northward heat flux at 100 hPa averaged over 45ºN-75ºN ($[v*T*]_{45°N-75°N}^{100hPa}$, where brackets indicate zonal mean and asterisks denote zonal deviation). This quantity is an indicator of the planetary wave activity penetrating the stratosphere from the troposphere (Hu and Tung, 2003). The linear correlations are statistically significant for the second mode of GPH20 for the three sets examined (warm, cold and all winters, Table 1). This result supports the hypothesis of the wave-like mode forced by tropospheric planetary waves, mentioned earlier in this paper. The highest correlation coefficient with the second mode is found for warm winters (-0.681), which highlights the relatively higher importance of tropospheric planetary waves for the second mode of GPH20 during warm-El Niño conditions. Here, it is noticeable the distinct behaviour of warm and cold winters, with the correlation for all winters in between. For the third mode, associated to a wave-number-1 mode as well, the highest linear correlation with $[v*T*]_{45°N-75°N}^{100hPa}$ is found for cold-La Niña winters (-0.369), although with a value very similar to that with the second mode.

	Warm winters	Cold winters	All winters
PC#1	-0.257	-0.136	-0.272
PC#2	-0.681	-0.351	-0.549
PC#3	0.091	-0.369	-0.194

Table 1. Linear correlation coefficients between $[v*T*]_{45°N-75°N}^{100hPa}$ and the first three PCA modes of GPH20. Shading indicates statistical significant values with α=0.01 (two tailed t-test).

Finally, we explore a possible influence of ENSO phases on the relationship between stratospheric variability modes and ozone concentration. Firstly, to identify roughly any signal of this dependence we compute a linear correlation between the 20-hPa ozone mixing ratio and each of the main three PC of GPH20. The only statistically significant linear relationship is obtained with the annular mode independently of the polarity of ENSO (Table 2), whose positive correlation coefficient reflects that a strong polar vortex ($PC_{NAM}<0$) hinders the meridional transport of ozone from the tropics to high latitudes, and consequently correlates with low ozone content (and vice versa). However, the most relevant result is that the highest correlation coefficient corresponds to warm ENSO winters, close to that for the all-winters set but higher than for cold ENSO winters.

This result is consistent with a recent and more complex study by Cagnazzo et al. (2009) who, after analyzing the ENSO response in chemistry climate models, obtained negligible response on the Northern polar stratosphere temperature and ozone for the cold ENSO events occurred in the 1980-1999 period. On the other hand, the mean of all model simulations reported a warming of the polar vortex during strong warm ENSO events associated with an anomalous increase of total ozone north of 70ºN.

Another result obtained in this work is that the cases with the weakest polar vortex and highest ozone mixing ratio at 20 hPa (i.e., zonal wind $u_{20} < 5$ m·s^{-1} and $[O_3]_{20} > 9.50 \times 10^{-6}$, both 65ºN-85ºN average) correspond to warm-El Niño winters in which the contribution of the first GPH20 mode is the most relevant. Concretely, these cases occurred around on February of 1958, 1973 and 1987. Three cases out of 10 warm ENSO winters is not a negligible number taking into account that other three winters of this set were perturbed by volcanic eruptions (1963/64, 1982/83 and 1991/92). Despite the non-linearity in the stratospheric behaviour for both ENSO phases, two opposite examples have been identified among cold-La Niña winters (1996 and 2000), that is, cases with the strongest polar vortex and lowest ozone content (i.e., $u_{20} > 10$ m·s^{-1} and $[O_3]_{20} < 6.75 \times 10^{-6}$, averaged over the polar band).

	Warm winters	Cold winters	All winters
PC#1	0.364	0.286	0.356
PC#2	0.161	0.109	0.007
PC#3	0.049	-0.106	-0.026

Table 2. As in Table 1 but with the 20-hPa ozone mixing ratio.

The results presented in this work encourage further studies that investigate the dynamical variability of the annular mode in the lower stratosphere associated to the ENSO phases.

4. CONCLUSIONS

The polarity of ENSO is found to have an impact on the main modes of variability in the winter boreal stratosphere. The main conclusions of this study are as follows:

1. The annular mode accumulates more variance of stratospheric geopotential height for cold than for warm ENSO winters (i.e., 63% against 52%, respectively).
2. Wave-number 1 modes appear to be more important in the stratospheric variability during warm than for cold-ENSO winters (i.e., 31% against 21%, respectively).
3. The highest linear correlation is obtained between the second wave-like mode of 20-hPa geopotential and the planetary wave activity penetrating the stratosphere from the troposphere for warm-ENSO winters.
4. The relation between ozone content and geopotential variability at lower stratosphere appears restricted to the annular mode, being the signal stronger for warm-ENSO winters: strong polar vortex correlates with low ozone mixing ratio at 20 hPa (and vice versa).

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