Stratospheric Polar Warming by ENSO in Winter, a Statistical Study

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Abstract

Applying Linear Discriminant Analysis on 47 years of NCEP stratospheric temperature data from 1959 to 2005, we find that the El Niño years are significantly warmer at the Northern Hemisphere polar and midlatitudes than the La Niña years, during winter. Specifically, the zonal mean, December-February mean, 10-50 hPa mean temperature, when projected onto the coherent spatial structure that best distinguishes the El Niño years from the La Niña years, is 4° K warmer in the El Niño mean than the La Niña mean. The difference is statistically significant at above 95% confidence level. This is the first time statistical significance has been established for ENSO's influence on the polar stratosphere. A surprising result is that the ENSO perturbation to the polar stratosphere is comparable in magnitude to the better-known QBO perturbation, which is 3.8° K between easterly QBO mean and the westerly QBO mean.

1. Introduction

It has been claimed that the northern stratospheric polar vortex is more perturbed and warmer during El Niño winters than for La Niña winters ([*Labitzke and Van Loon*, 1989; *Van Loon and Labitzke*, 1987]). However, [*Van Loon and Labitzke*, 1987] found no statistically significant relationship between ENSO (El Niño-Southern Oscillation) and the polar stratosphere using 28 years of December-January-February data. [*Hamilton*, 1993] examined 34 years of December-February mean circulation in the Northern Hemisphere stratosphere, and could not establish the statistical significance of the suspected relationship between ENSO and the zonally averaged flow anywhere north of 20° N at any level from 100 to 10 hPa. He attributed the difficulty in disentangling the ENSO effect from the quasi-biennial oscillation (QBO) effects, which appeared stronger. Not helping matters is the fact that El Nino winters tended to coincide with the easterly phase of the QBO. [*Baldwin and O'Sullivan*, 1995] also found that the effect of QBO on the stratospheric climate to be considerably larger than those from the tropospheric modes of variability associated with ENSO. Using the WACCM GCM, [*Sassi, et al.*, 2004] and [*Taguchi and Hartmann*, 2006] generated a long enough time series for them to deduce, at least in the model generated data, that the warming difference between El Niño and la Niña years are statistically significant and that Stratospheric Sudden Warmings are twice as likely to occur in El Nino winters than in La Nina winters, thus providing a mechanism for the possible influence of ENSO on the polar stratosphere.

[*Camp and Tung*, 2006] suggested that there are at least three external perturbations to the polar stratosphere during late winter: easterly QBO, solar max and El Niño. The "least-perturbed state", as they called it, with a cold pole, should be during years when all three perturbations happen to be in their opposite phases, *i.e*. westerly QBO, solar min and La Niña. However, to discriminate one state from another would require 8 grouping, and they estimated that even their 47 years of data record was not sufficiently long to establish a statistical separation. Consequently, Camp and Tung ignored the ENSO effect and established the statistical significance of the perturbations by the easterly QBO, by the solar max and by a combination of easterly QBO and solar max, from the "least-perturbed state" of westerly QBO and solar min. Their method used Linear Discriminant Analysis (LDA), which depends on the unique features of the spatial patterns to discriminate easterly QBO years from westerly QBO years, and solar max years from solar min years. One significant result obtained is that the latitudinal shapes of the perturbation from easterly QBO and from solar max are quite similar, both taking the familiar form expected from Stratospheric Sudden Warmings. The suggestion is then that both external perturbations somehow precondition the stratosphere for Sudden Warming, and therefore there are more frequent Sudden Warming events during easterly QBO and during solar max, as originally suggested by [*Labitzke*, 1982].

It is intriguing to note that Camp and Tung established the statistical significance of the perturbations from QBO and solar cycle without having to stratify the data according to the phase of ENSO. This is possible either because the ENSO effect on the polar vortex is small or that the perturbation from ENSO takes a spatial form which is almost orthogonal to the spatial form of both QBO and solar cycle perturbations. We will show that the latter is the case. This possibility then allows us to establish the statistical significance of the ENSO perturbation without having to stratifying the data according to the phase of either QBO or the solar cycle. Previous analysis did not take advantage of the spatial information of the ENSO influence on the stratosphere. The ENSO perturbation we obtained this way turns out to be quite large, larger than even that from QBO. This is contrary to previous expectations.

2. Data and methods

We use the same methodology as described in detail in [*Camp and Tung*, 2006]. The LDA method has previously been used by [*Schneider and Held*, 2001]to identify the spatial patterns associated with interdecadal variations of surface temperature. As in Camp and Tung, we consider the mean temperature in the 10-50 hPa layer, zonally averaged, and detrended using a cubic polynomial. The effects of volcanoes are minimized by removing the year following El Chichon and following Pinatubo. Instead of dividing the data according to many possible groups, such as easterly and westerly QBO, solar max and solar min, cold ENSO and warm ENSO, we attempt to see if a statistical significant discrimination can be obtained even if we have only two groups: cold and warm ENSO. The two phases of ENSO are defined here using the contemporaneous Cold Tongue Index (CTI). Warm ENSO (or sometimes called El Niño) years are defined when the CTI is greater than 0.25 K. Similarly, the year when the CTI is less than -0.25 K, it is classified as a cold ENSO (or La Niña) year. If we were to fail to obtain statistically significance this way, then we would conclude that we may need to wait for the data record to get long enough for us to take into account of the other perturbations of the stratosphere. Three month average over December-January-February is used here, consistent with previous observational analysis.

We attempt to find, objectively, the coherent spatial pattern that best distinguishes the warm ENSO years from the cold ENSO years, in the presence of other variability such as QBO and solar cycle. This is done by maximizing the separation between these two groups as measured by the separation measure R. The quantity R is defined as the ratio of the variance between the two groups and the variance within each group. Other variability, such as QBO and solar cycle, contributes to the within-group variance, and this appears in the denominator of the ratio. Thus by maximizing R, we are also minimizing the QBO and solar cycle variance within each group, with the result that the spatial pattern we obtain this way also serves to in some sense “filter out” QBO and solar cycle. The ratio R becomes infinite if the within group variance, such as those due to QBO and solar cycle, is truly orthogonal to the ENSO variance. With a data record of sufficient length, this does not happen.

The optimization algorithm does not actually yield the spatial pattern but the weights at each spatial location, denoted by $u(\mathbf{x})$. The elements of $u(\mathbf{x})$ represent the relative importance of a given location to R . When the original centered data $X(t, \mathbf{x})$ is projected onto $u(\mathbf{x})$, we get the first canonical variate, $C(t)=Xu(\mathbf{x})$, a time series whose elements are “scores” for each observation. The associated spatial pattern, $P(\mathbf{x})$, is then recovered by regressing the data onto $C(t)$, i.e. $X(t, \mathbf{x})=C(t)P^T(\mathbf{x}) + \varepsilon(t, \mathbf{x})$. In other words, $P(x)$ is the spatial pattern which best distinguishes between the two groups of observations while the time series *C(t)* represents an "index" for that spatial pattern.

3. Results

The spatial pattern $P_1(\boldsymbol{x})$ that best distinguishes the ENSO warm years from the ENSO cold years is given in Figure 1(a). With only two predefined groups there is only one such spatial pattern. Unlike the QBO or the solar cycle warming patterns, which have large warming over the pole and smaller and more widespread cooling over the midlatitudes and the tropics, the ENSO warming of the pole is wider in latitude and extends into the midlatitudes. Absence of cooling in the structure is probably what distinguishes the ENSO pattern from the QBO pattern. The projected time series as a function of years is plotted in Figure 1(b). It shows that despite the presence of other variabilities, the time index $C_1(t)$ nicely separates the El Niño years as having positive values (warming over the pole and midlatitudes in the stratosphere) and La Niña years as having mostly negative values (cooling over the pole and the midlatitudes). The values shown are the temperature averaged between the lower stratosphere, between 10 to 50 hPa. At the pole the warming from peak La Niña to peak El Niño is quite large, about 9° K. A more conservative measure is from mean of one group to the mean of the other group, and that measure yields a group mean difference of 4° K (see Figure 1(c)). This value is to be compared with the polar warming by QBO of 3.8° K and by solar cycle of 4.6° K, obtained previously by Camp and Tung. That the polar warming by ENSO is actually larger than that by QBO is unexpected, as previous authors have thought that ENSO signal is much smaller than QBO's. In Figure 1(c), the solid line is the mean temperature of all years. The circles (asterisks) denote the mean anomaly of all El Niño (La Niña) years, with the climatology superimposed. The mean anomaly is obtained by multiplying $P_1(\mathbf{x})$ by the mean of C_1 for each group. Shaded regions denote the one-standard deviation projections within each group. Figure 1(c) shows that when projected onto derived weights of this spatial pattern, the warm ENSO years are well separated from the cold ENSO years; their shaded regions do not overlap. A Monte-Carlo test (bootstrap with replacement) shows that the observed separation measure R, denoted by the vertical dashed line in Figure 1 (d), is not likely to be obtained by chance. Although this particular test yields a confidence level of 99% at the particular truncation level of $r=12$ used, we claim only that our result is statistically significant at 95% confidence level. At this level and above there is a range of r all yielding statistically significant results (see discussion in Camp and Tung).

4. Discussion and Conclusion

The polar stratosphere during winter in the Northern Hemisphere is perturbed by the momentum and energy deposited there by the planetary waves propagated from the troposphere. Sudden Warming events are the extreme form of these breaking wave occurrences. At the current stage of our understanding, Sudden Warmings can be initiated by (1) unforced variability, *i.e*. chaos ([*Yoden, et al.*, 2002]); (2) easterly QBO ([*Holton and Tan*, 1982]);(3) solar max ([*Labitzke*, 1982]) and (4) warm ENSO ([*Van Loon and Labitzke*, 1987]). [*Taguchi and Hartmann*, 2006] found that, based on model runs, warm ENSO strengthened the forcing of wave number 1 planetary wave at midlatitudes in the troposphere and, since wave-1 propagates more freely to the polar stratosphere than wave-2, the wave heat flux from the troposphere to the polar stratosphere is enhanced, leading to more frequent occurrence of wave-1 type Sudden Warming.

In this work, we established that the polar stratosphere in winter is about 4° K warmer in the mean during warm ENSO years as compared to the cold ENSO years. We furthermore established for the first time that such a difference is statistically significant at above the 95% confidence level. The different spatial pattern of the ENSO perturbation is used to "filter out" other variability, such as the QBO and the solar cycle, which warm the polar stratosphere by approximately the same magnitude, but the spatial pattern of the warming is more confined to the polar region.

Our spatial pattern deduced from observation is consistent with that generated in a GCM by [*Sassi*, *et al.*, 2004], who showed a wide latitude of warming (from midlatitudes to the pole) in the warm-cold ENSO difference, of a comparable magnitude of 4° K in the lower stratosphere (10-50 hPa). What [*Sassi, et al.*, 2004] further showed is that in February the warming extended further up in the stratosphere, reaching a peak value of 7° K at 40 km over the pole, switching sign at 50 km into cooling. There is a distinct quadruple pole signature characteristic of Sudden Warmings (cooling over the tropics-warming over the pole in the lower stratosphere, but warming over tropics and cooling over the pole in the mesosphere), which reinforces the interpretation of [*Taguchi and Hartmann*, 2006] that the El Niño warming of the polar stratosphere is caused by Sudden Warming.
A corollary of the Sudden Warming interpretation of the El Niño induced perturbation of the polar stratosphere is that its warming is not additive to that of the easterly QBO. This

is because, as was pointed out by Camp and Tung, once a sudden warming is triggered by say, the easterly QBO, the presence of another trigger, such as El Niño, does not double the magnitude of the warming.

Acknowledgment

The research was supported by the National Science Foundation, Climate Dynamics Program, under grant ATM-3 32364

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Figure Legend

Figure 1. LDA analysis of 10-50 hPa mean zonal mean temperature in December-January-February. (a) The spatial pattern $P_1(x)$ that best distinguishes the warm ENSO years from the cold ENSO years, normalized so that the polar warming is one; (b) the time series $C_1(t)$, which represents the index for $P_1(x)$. The vertical scale is in degrees C at the pole; (c) the mean of temperature during all warm (cold) ENSO years, denoted by circles (asterisks). The shading denote +-one standard deviation from the mean; (d) Bootstrap Monte-Carlo test with replacement, showing the frequency of occurrence of the separation measure *R* in 10,000 synthetic datasets constructed by randomly choosing 17 data points, with replacement, in the original dataset to assign to the El Niño group and another 17 years to assign to the La Niña group regardless of their original classifications, while preserving the group structure and truncation parameter of the original analysis. The *R* of the original dataset is denoted by a vertical dashed line.

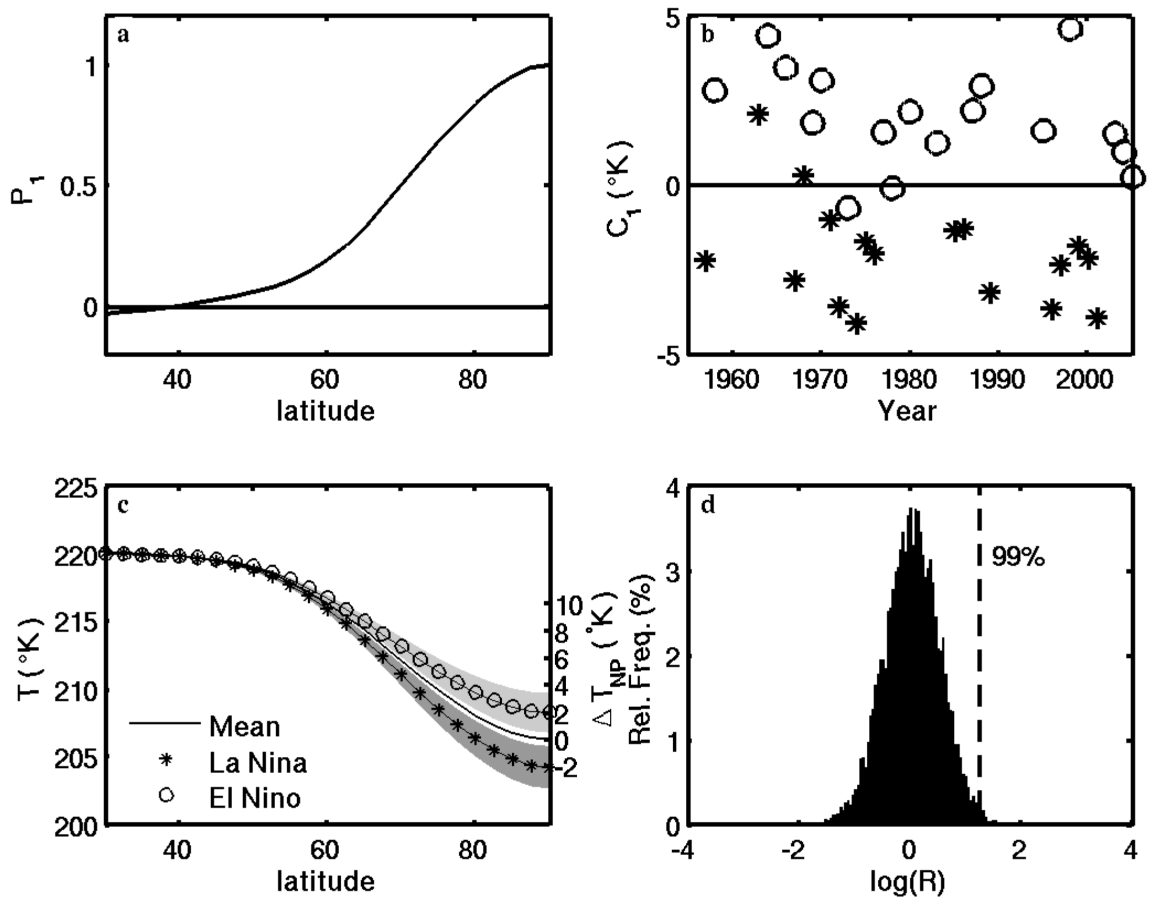
a
P_1
latitude
b
C_1 (°K)
Year
c
T (°K)
ΔT_{NP} (°K)
Mean
La Nina
El Nino
latitude
d
Rel. Freq. (%)
99%
log(R)

Figure 1