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Stratospheric polar warming by ENSO in winter: A statistical study

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[1] Applying Linear Discriminant Analysis on 47 years of NCEP stratospheric temperature data from 1959 to 2005, we find that the warm-ENSO ("El Niño") years are significantly warmer also in the stratosphere at the Northern Hemisphere polar and midlatitudes than the cold-ENSO ("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 two ENSO groups, classified according to the equatorial Pacific-ocean Cold Tongue Index, is 4°K warmer in the polar stratosphere in the warm-ENSO mean than in the cold-ENSO mean. The difference is statistically significant at above the 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. **Citation:** Camp, C. D., and K.-K. Tung (2007), Stratospheric polar warming by ENSO in winter: A statistical study, *Geophys. Res. Lett.*, *34*, L04809, doi:10.1029/2006GL028521.

1. Introduction

[2] It has been claimed that the Northern stratospheric polar vortex is more perturbed and warmer during El Niño winters than during 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 found that the statistical significance of the suspected relationship between ENSO and the zonally averaged flow could not be established anywhere north of 20°N at any level from 100 to 10 hPa. He attributed the negative result to the difficulty in disentangling the ENSO effect from the quasi-biennial oscillation (QBO) effects; the latter was thought to be larger than the former. Not helping matters is the fact that El Niño 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 is statistically significant and that Stratospheric Sudden Warmings (SSW) are twice as likely to occur in El Niño winters than in La Niña winters, thus providing a mechanism for the possible influence of ENSO on the polar stratosphere.

[3] *Camp and Tung* [2007] (hereinafter referred to as CT07), 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 occur 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 eight groupings, and they estimated that even their 47 years of data was not long enough to establish a statistical separation. Consequently, CT07 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 by the easterly QBO and by the solar max from the least-perturbed state are quite similar, both taking the familiar form expected from SSWs. The suggestion is then that both external perturbations somehow precondition the mean state of the stratosphere to trigger polar SSW by upward propagating planetary waves, and therefore there are more frequent SSW events during easterly QBO and also during solar max, as originally suggested by *Labitzke* [1982]. The finding that the spatial patterns of the two phenomena are so similar also explains why the solar cycle and QBO signals have a history of being entangled in data and the effect of each was discovered only when the data was grouped according to a single phase of the other [*Labitzke and van Loon*, 1988; *Naito and Hirota*, 1997].

[4] It is intriguing to note that CT07 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 was possible either because the ENSO effect on the polar vortex is small or because the perturbation from ENSO takes a spatial form that is almost orthogonal to the spatial form of both QBO and solar cycle perturbations. The former possibility – that the ENSO signal is smaller than the QBO signal – was mentioned by some previous authors, as reviewed above. We will show instead that the latter is the case. This possibility then allows

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us to establish the statistical significance of the ENSO perturbation without having to stratify the data according to the phase of either QBO or the solar cycle. Previous analyses 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, at least as large if not larger than that from QBO.

2. Data and Methods

[5] We use the same methodology as described in detail by CT07. This LDA-based method has previously been used by *Schneider and Held* [2001] to identify the spatial patterns associated with inter-decadal variations of surface temperature. Traditional LDA, as described by *Wilks* [1995], uses the known classification of a training set of data to classify new data; our technique inverts this and uses all of the data to isolate the classification rule which, for these analyses, is a set of spatial weights. As in the work by CT07, 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 Chichón 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), which measures the eastern Pacific sea-surface temperature anomaly and is maintained and updated by University of Washington's Joint Institute for the Study of Atmosphere and Ocean (http://jisao.washington.edu/enso/). Warm-ENSO (or sometimes called El Niño) years are defined when the CTI is greater than 0.25°K. Similarly, a year when the CTI is less than −0.25°K, is classified as a cold-ENSO (or La Niña) year. With these two exclusion criteria, 34 of the original 47 years of data remain. If we were to fail to obtain a statistically significant separation 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 the other perturbations of the stratosphere. A three-month average over December–January–February is used here, consistent with previous observational analysis.

[6] 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 to 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 the ratio 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 claim that they are "almost orthogonal" to each other is instead demonstrated by a large value of R. How large is large enough is quantified by a Monte-Carlo test. Given a set of observed data $X(t, x)$, which in our case is the stratospheric temperature anomaly at time t and location x, the LDA optimization algorithm obtains the maximum separation R by varying the weights to be given to the data at each spatial location, denoted by $u(x)$. The elements of $u(x)$ represent the relative importance of a given location to R. When the original centered data $X(t, x)$, is projected onto $u(x)$, we get the first canonical variate, $C(t) = Xu(x)$, a time series representing the amplitude of the difference between the two groups as thus spatially filtered. The associated spatial pattern, $P(x)$, is then recovered by regressing the data onto $C(t)$, i.e., $X(t, x) = C(t)P(x) + \epsilon(t, x)$. 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. This procedure is somewhat different from the usual EOF projection, in that the spatial pattern, $P(x)$, is not produced first with the index $C(t)$ produced subsequently by projecting the data onto that spatial pattern. Instead the time series, $C(t)$, which yields the best separation between the warm- and cold-ENSO years (in the time domain) is produced first. The spatial pattern is then obtained by regressing the data onto the time series. The spatial information contained in the data is taken into account when determining $C(t)$ via the spatial weights. This procedure has the advantage that the residual $\epsilon(t, x)$ in our decomposition is minimized in its ENSO temporal signals.

3. Results

[7] The spatial pattern $P(x)$ that best distinguishes the ENSO warm years from the ENSO cold years is given in Figure 1a. 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. This and the absence of cooling in the structure are what distinguish the ENSO pattern from the QBO pattern. The projected time series as a function of years is plotted in Figure 1b. It shows that despite the presence of other variability, the time index $C(t)$ nicely separates the El Niño years as having positive values (warming over the pole and midlatitudes in the stratosphere) from the La Niña years as having mostly negative values (cooling over the pole and the midlatitudes). 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 the mean of one group to the mean of the other group, and that measure yields a group mean difference of 4°K (see Figure 1c). 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 CT07. Note that, as in the work by CT07, the values shown are the temperature averaged between the lower stratosphere, between 10 to 50 hPa. Indications from model simulation [e.g., *Sassi et al.*, 2004] are that the maximum warming occurs higher up, at 40 km. That the polar warming by ENSO is actually comparable to that by QBO is unexpected, as previous authors have thought that ENSO signal is much smaller than QBO's. (At least that

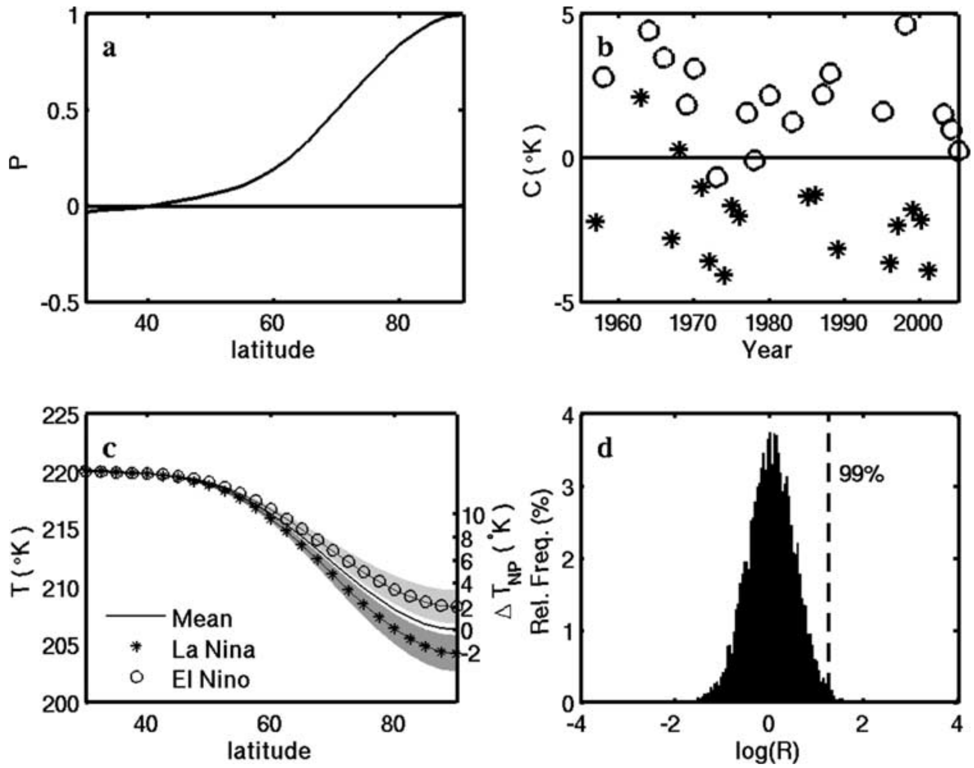

Figure 1. LDA analysis of 10–50 hPa mean zonal mean temperature in December-January-February. (a) The spatial pattern $P(x)$ that best distinguishes the warm-ENSO years from the cold-ENSO years, normalized so that the polar warming is one. (b) The time series $C(t)$, which represents the index for $P(x)$. The vertical scale is in °K at the pole. (c) The mean of temperature during all warm-(cold-) ENSO years, denoted by circles (asterisks). The shading denote ±1 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 data sets constructed by randomly choosing 17 data points, with replacement, in the original data set 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.

was the reason given as to why the QBO effect was seen while the ENSO effect was indeterminate statistically.) In Figure 1c, the solid line is the mean temperature of all years. The circles denote the mean anomaly of all El Niño years, while asterisks that of the La Niña years, with the climatology superimposed. The mean anomaly is obtained by multiplying $P(x)$ by the mean of $C(t)$ for each group. Shaded regions denote the one-standard deviation projections within each group. Figure 1c shows that when projected onto the 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 1d, 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 by CT07).

4. Discussion and Conclusions

[8] 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 by the QBO and by the solar cycle is more confined to the polar region.

[9] 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). *Sassi et al.* [2004] further showed 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 quadrupole signature characteristic of Sudden Warmings (cooling over the tropics and 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 CT07, once an SSW is triggered by say, the easterly QBO, the presence of another trigger, such as El Niño, does not double the magnitude of the warming.

[10] 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. SSW events are the extreme form of these breaking wave occurrences. At the current stage of our understanding, SSWs can be triggered 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]. CT07 suggests that (2) and (3) operate probably by preconditioning the mean state of the stratosphere to facilitate the vertical and poleward propagation of planetary waves. ENSO influence may take a slightly different route for (4), although warm ENSO also increases the frequency of Sudden Warming as in (2) and (3). *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. *Sassi et al.* [2004] also emphasized the very significant zonally asymmetric differences between the two phases of ENSO.

[11] A puzzling feature of the observed spatial pattern presented here is the lack of tropical cooling associated with the larger warming occurring over the polar region during the warm-ENSO years. This appears to be at variance with the SSW interpretation as the cause of the warm-ENSO-induced stratospheric anomaly, which should have a compensating cooling at low latitudes associated with the large SSW over the polar latitudes. This feature is also present in the model results of *Sassi et al.* [2004] for the altitude region of 10–50 hPa considered in this paper. Higher up however, at the altitude of maximum polar warming at 40 km, the typical latitudinal structure of an SSW is found with compensating cooling of 1°K in the subtropical region. It therefore appears that for some reason the ENSO-induced SSW tends to occur slightly higher up than the QBO- or solar-induced SSW. The available NCEP data below 10 hPa yields only part of the picture, but fortunately the apparent altitude difference of the stratospheric ENSO effect, as compared to the QBO or solar effect, leads to a latitudinal difference that is sufficient to allow a LDA separation of these phenomena and enable us to establish the statistical significance of the ENSO effect.

[12] Unlike the case of QBO and solar cycle phenomena, which involve very little change in the planetary wave source in the troposphere, ENSO represents a major source of forcing for planetary waves of different wave numbers [*Blackmon et al.*, 1983; *Horel and Wallace*, 1981]. How this change in the source of forcing affects the stratospheric response, in particular the latitudinal and vertical extent of where planetary waves break, needs to be further studied.

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