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Observed El Niño–Southern Oscillation temperature signal in the stratosphere

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[1] Studies of stratospheric temperature variability typically include seasonal, quasi-biennial oscillation, solar, and volcanic effects, but the response to El Niño–Southern Oscillation (ENSO) is less well recognized. Modeling work suggests that ENSO may produce effects on surface climate at high latitudes by interaction with the polar stratosphere, yet until recently, past work has often failed to find a statistically significant ENSO response in polar stratospheric temperature observations. Using zonal mean temperatures from several improved radiosonde data sets beginning in 1958, we show a significant El Niño cooling signal in the tropical stratosphere and warming signal in the Arctic stratosphere in winter. In the tropical stratosphere the difference of more than 1 K between El Niño and La Niña temperatures is similar in magnitude to the tropospheric warming signal. The significant signal, derived from regression analysis, of more than 4 K in the winter Arctic stratosphere is generally largest in the lower stratosphere and extends into the upper troposphere. The signal, with a maximum in late winter, accounts for 14% to 25% of stratospheric temperature variability at 100 mbar in Arctic winter in radiosonde and reanalysis data. Satellite-derived temperatures show significant El Niño cooling in the tropical stratosphere in boreal winter, but the warming signal in the Arctic stratosphere is not statistically significant in that data set.

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1. Introduction

[2] A growing body of research suggests that interaction between the high-latitude stratosphere and troposphere may be important for improved seasonal and interannual climate prediction [e.g., *Baldwin et al.*, 2003]. In particular, the El Niño–Southern Oscillation (ENSO) signal in the polar stratosphere is of practical interest because of its possible effects on surface weather and climate through the North Atlantic oscillation. A weakened polar vortex and warming in the Arctic stratosphere is often followed by cold surface temperatures in areas of Europe and eastern North America affected by the North Atlantic oscillation [*Thompson et al.*, 2002], and ENSO is one of the factors that may influence this pattern. Evidence suggests that major El Niños may produce unusually cold winters in Europe and that the stratosphere may play a role in this effect [*Brönnimann*, 2007; *Ineson and Scaife*, 2009; *Cagnazzo and Manzini*, 2009]. ENSO effects outside of the northern high latitudes may also be important.

[3] While the warming effects of El Niño on tropospheric temperatures are well documented, the response in the stratosphere is less well understood. We first review results for the tropical stratosphere. *Reid* [1994] showed stratospheric cooling above the tropical tropospheric warming during El Niños, using data from a few radiosonde stations for 1965–1981. *Lau et al.* [1998] using satellite data for 1985–1993 found that El Niño warming in the tropical troposphere produces an equivalent-sized cooling in the tropical stratosphere. *Crooks and Gray* [2005] used multiple linear regression to isolate the solar signal in the stratosphere in the European Centre for Medium-Range Weather Forecasts 40 Year Reanalysis (ERA-40) and, in the course of this analysis, showed tropical cooling as well as statistically significant warming around 35 km near the North Pole for the El Niño signal. However, *Calvo Fernández et al.* [2004] found very little zonal mean ENSO response anywhere in the stratosphere in satellite temperature data. *Weare* [2008] showed the spatial patterns of stratospheric temperature response to El Niño in outgoing longwave radiation in the tropics, with cooling at 50 mbar for a lag of 5 months. More recently, *Randel et al.* [2009] show a significant ENSO temperature signal in the tropical stratosphere. Some modeling studies also show cooling in the tropical stratosphere in response to El Niño [e.g., *Garcia-Herrera et al.*, 2006].

[4] Turning to the Arctic stratosphere, the majority of earlier ENSO studies in that region looked at effects on circulation (e.g., the polar vortex) rather than temperature. Although some early work [e.g., *van Loon and Labitzke*, 1987] found suggestions of a connection, *Hamilton* [1993, p. 3468] found "no evidence for a significant relation between the Southern Oscillation ... and the zonally averaged [stratospheric] flow ...for any region poleward

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of 20 degrees N." While *Kryjov and Park* [2007] reported that the relationship was significant only during solar minima, *Brönnimann* [2007] showed a highly significant correlation of 0.42 between the strength of the polar vortex (as measured by the difference in 100 mbar heights for 75–90°N minus those for 40–55°N) and Niño3.4 sea surface temperatures (SSTs), using data reconstructed back to 1922. *Garfinkel and Hartmann* [2008] conclude that warm ENSO events weaken the polar vortex significantly only when they produce a "Pacific–North American" response in the troposphere.

[5] Studies of the relation of ENSO to stratospheric temperatures have found significant connections in the Arctic in models. Middle-atmosphere models forced with observed tropical sea surface temperatures show an Arctic warming signal in El Niño winters that begins in the upper stratosphere and propagates downward, with a maximum signal in February [*Garcia-Herrera et al.*, 2006; *Sassi et al.*, 2004; *Manzini et al.*, 2006]. The model studies differ on the level at which the maximum signal occurs (from ~10 mbar in some to ~30 mbar in others). These papers also differ on the lower altitude limit of the significant effect, with *Manzini et al.* [2006] finding an effect down to 300 mbar but *Sassi et al.* [2004] finding no significance below ~20 mbar. *Manzini et al.* [2006] find the effect is significant for El Niño but not La Niña. *Garcia-Herrera et al.* [2006] conclude that the cooling in the tropical stratosphere and warming in the Arctic are produced by Rossby waves propagating ENSO anomalies vertically into the middle atmosphere, accelerating the meridional circulation in the stratosphere during El Niños.

[6] Recently several papers have found statistically significant El Niño–related Arctic stratospheric warming in reanalysis data. *Camp and Tung* [2007], using spatial patterns to separate quasi-biennial oscillation (QBO) and solar signals from ENSO signals, found significant Arctic warming in National Centers for Environmental Prediction (NCEP) reanalysis temperatures at 10–50 mbar during El Niño winters. *Garcia-Herrera et al.* [2006] found a significant ENSO warming in ERA-40 data around 30–40 km for 60–90°N. *Garfinkel and Hartmann* [2007] found that the composite of El Niño winter temperatures at 10 mbar north of 65°N was significantly warmer than climatology but did not examine lower levels.

[7] These recent papers on ENSO effects in the Arctic stratosphere use reanalysis data and examine primarily levels of 50 mbar and above. Since reanalyses can be subject to problems, especially near the poles and in the stratosphere [*Randel et al.*, 2004; *Thorne*, 2008], the present work tests these results using in situ data from radiosondes. It also examines all atmospheric levels for which such data are available, revealing significant effects in the lower stratosphere and upper troposphere in the Arctic not shown in previous observational work.

2. Data

[8] This paper uses monthly mean temperature data from three adjusted radiosonde data sets and one that has not been adjusted. Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) [*Free et al.*, 2005] includes data from 85 stations at 13 atmospheric levels. The Hadley Center Atmospheric Temperature (HadAT2) [*Thorne et al.*, 2005] data set uses over 600 stations and contains just 9 levels of data. The Iterative Universal Kriging (IUK) [*Sherwood et al.*, 2008] data set uses over 500 stations and has 10 levels. Each of these data sets has been adjusted by differing methods to reduce temporal inhomogeneities. To extend coverage to 20 and 10 mbar, which are not included in the three adjusted data sets, we also use the Integrated Global Radiosonde Archive (IGRA) database [*Durre et al.*, 2006], which has not been adjusted. All are available from 1958 to at least 2005. All data sets have large gaps in spatial coverage, particularly in the tropics and at high latitudes. The number of stations with long records in the Arctic is relatively small, with only five north of 70°N and one north of 80°N in RATPAC; the most northerly RATPAC station is at 82.5°N. IGRA contains only 3 stations north of 80°N.

[9] We supplement this analysis with data from the microwave sounding unit (MSU) for the stratosphere [*Christy et al.*, 2003] and NCEP–National Center for Atmospheric Research (NCAR) reanalysis [*Kistler et al.*, 2001] temperatures for comparison. (The MSU data are not ideal for our purposes because they combine temperatures from a broad layer including some tropospheric levels.)

[10] To account for the effects of the QBO we use the 50 and 30 mbar winds at Singapore from the Free University of Berlin (available at http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo), with the seasonal cycle removed. We use Niño3.4 SSTs (available at http://www.cpc.noaa.gov/data/indices) to represent ENSO.

3. Methods

[11] We have processed the station data by calculating monthly anomalies (for data sets not already in anomaly form) as differences from the mean for the time period 1970–1990 and averaging the anomalies into 10° zonal means. The calculations described in this section are applied to these monthly, zonal means.

[12] Analysis of ENSO effects in the stratosphere can be complicated by the presence of the QBO, which dominates variability in the tropical stratosphere and also affects the extratropical stratosphere via the mechanism first described by *Holton and Tan* [1980]. Specifically, westerly stratospheric winds at the equator are associated with warmer stratospheric temperatures in the deep tropics and colder temperatures in the Arctic stratosphere. Although *Garfinkel and Hartmann* [2007] found no correlation between 50 mbar equatorial winds and ENSO, we find correlations for 2–3 month lags of 0.2–0.3 (significant at the 90% level) for January and February, excluding the 3 years after major volcanic eruptions. The sense of the correlations for 1958–2004 is to favor westerly QBO winds during warm ENSO events, which would tend to decrease the perceived temperature effect of ENSO in the stratosphere. We therefore try to minimize the QBO signal in our data before assessing the ENSO response.

[13] We use two approaches to identify the ENSO signal and distinguish it from that of the QBO: linear regression and compositing. In the first approach, we regress the temperatures from 1958 to 2005 against a QBO index consisting of the deseasonalized 50 mbar wind at Singapore

and subtract the resulting signal from the full temperature series. We then perform a second regression using the Niño 3.4 SSTs and the residual temperatures. For both regressions, we exclude 3 years after major volcanic eruptions to minimize their confounding effects. We perform the ENSO regression on all monthly temperatures together, on mean winter temperatures (using the average of December, January and February) and on temperatures for individual months separately. The temperature and ENSO time series are detrended, and the ENSO index is smoothed with a 7 month running mean before the regressions. Because surface and tropospheric temperatures typically show their maximum relation to El Niño SSTs for lags of 3–4 months [*Trenberth et al.*, 2002], we lagged the temperatures by 4 months behind the ENSO index. (Most results are not sensitive to the choice of lag between 1 and 4 months.) To assess the significance of the results, we use the standard error of the regression coefficient. The results are considered significant if the regression coefficient is significantly different from 0 at the 95% level. To present the results in a way that can be compared meaningfully with the results from compositing (discussed immediately below), we reconstruct the ENSO temperature signal time series by multiplying the regression coefficient by the ENSO index series, then subtract the mean of this signal for the six largest negative events from the mean of the signal for the eight largest positive events. In addition, to evaluate the robustness of our results, we repeat our calculations using multiple linear regression with both 30 mbar and 50 mbar winds plus a solar proxy term. For the multiple linear regression, we test statistical significance using a bootstrap procedure with block resampling.

[14] In the second (compositing) approach we examine the mean of radiosonde temperatures for the larger El Niño and La Niña events for both phases of the QBO, as well as for westerly and easterly phases separately. The QBO phase is identified from the time series of deseasonalized 50 mbar Singapore winds. The warm SST (El Niño) events used are the winters (identified by the year in which January falls) of 1969, 1970, 1973, 1987, 1988, 1995, 1998, and 2003, all with Niño3.4 anomalies greater than 1 K. The cold events are 1971, 1974, 1976, 1989, 1999, and 2000, all with Niño3.4 less than −1 K. We again exclude the 3 years after major volcanic eruptions. Since the seasonal regression analysis shows that the ENSO signal is present primarily in January and February, we use only those months to create the composites.

[15] If serial correlations were high in our time series, the regression significance could be deceptively high unless we account for that autocorrelation. Lag-1 temperature autocorrelations for consecutive years of RATPAC data for January and February are generally less than 0.2 in the Arctic stratosphere but can be as high as 0.6 elsewhere, so we reduce the degrees of freedom for our significance testing by multiplying the number of years by the factor $(1 - r)/(1 + r)$, where r is the lag-1 autocorrelation.

[16] In addition to the regression and composite analyses we present Pearson correlation coefficients between the ENSO signal and stratospheric temperatures for selected levels and regions to further test the strength of the relations found here. For these calculations we use the ENSO signal obtained from the multiple regression analysis, minus the QBO and solar signals found from that analysis, again using a fixed lag of 4 months between the SSTs and the stratospheric temperatures. These correlation calculations are made for all months, for winter means and for individual winter months for the MSU data sets and for winter means for the reanalysis and the four radiosonde sets. In addition, we have subsampled the MSU data to match the locations of the RATPAC radiosonde stations and calculated MSU equivalent stratospheric time series from the RATPAC data. The correlation analysis is then applied to those time series for comparison to the MSU results.

4. Results

4.1. ENSO Signal From Linear Regression

[17] Figure 1 shows the mean of the ENSO signal derived from linear regression using all months, for the eight largest El Niño events minus the signal for the six largest La Niña events. Only regions and levels at which the signal is statistically significant at the 95% level are colored. Although the details of the signals vary among the data sets, all show widespread tropospheric warming along with cooling at most tropical latitudes in the stratosphere, centered near 70–50 mbar, with a stronger stratospheric signal in the Northern Hemisphere (NH) tropics than in the Southern Hemisphere (SH) tropics. Some data sets show moderate warming around 100 mbar in the Arctic, but the signal is not consistent and not present above 150 mbar for 80–90°N. There is no signal in the Antarctic stratosphere, but RATPAC and HadAT2 show stratospheric warming around 60°S. NCEP reanalysis data (not shown) show less significant cooling in the tropics than the sonde data, but greater warming for the Arctic from 100 to 20 mbar.

[18] Figure 2 shows the boreal winter (December–February (DJF)) ENSO signal derived from linear regression, plotted as in Figure 1. All radiosonde data sets show cooling in the tropical stratosphere centered near 50 mbar with a maximum of more than 2 K for most data sets, stronger than that for all months shown in Figure 1. There is also cooling in the NH midlatitudes around 200 mbar and in the midtroposphere at 50–60°S (where DJF is summer) and warming in the stratosphere around 50–60°S.

[19] In the Arctic, all data sets show a winter warming of at least 4 K around 100 mbar, extending in most data sets up to 10–30 mbar. Surprisingly, they also show significant warming extending into the Arctic troposphere, as far down as 500 mbar for two data sets. In all data sets the warming is stronger closer to the pole. Despite these common elements, the details of the Arctic signal differ among the four data sources, with RATPAC showing no significant effect above 50 mbar while IGRA shows a signal up to 10 mbar. Results are qualitatively similar if the regression is done without first subtracting the QBO signal. The NCEP reanalysis (not shown) shows a stronger Arctic signal than the radiosondes, extending from 300 to 20 mbar.

[20] Figure 3 shows results for radiosonde data sets for winter from the alternative, multiple regression procedure. The responses are generally similar to those from the simpler regression, with somewhat stronger Arctic warming in most cases. The similarity in results using the two methods suggests that the signal is not affected dramatically by QBO or solar influences.

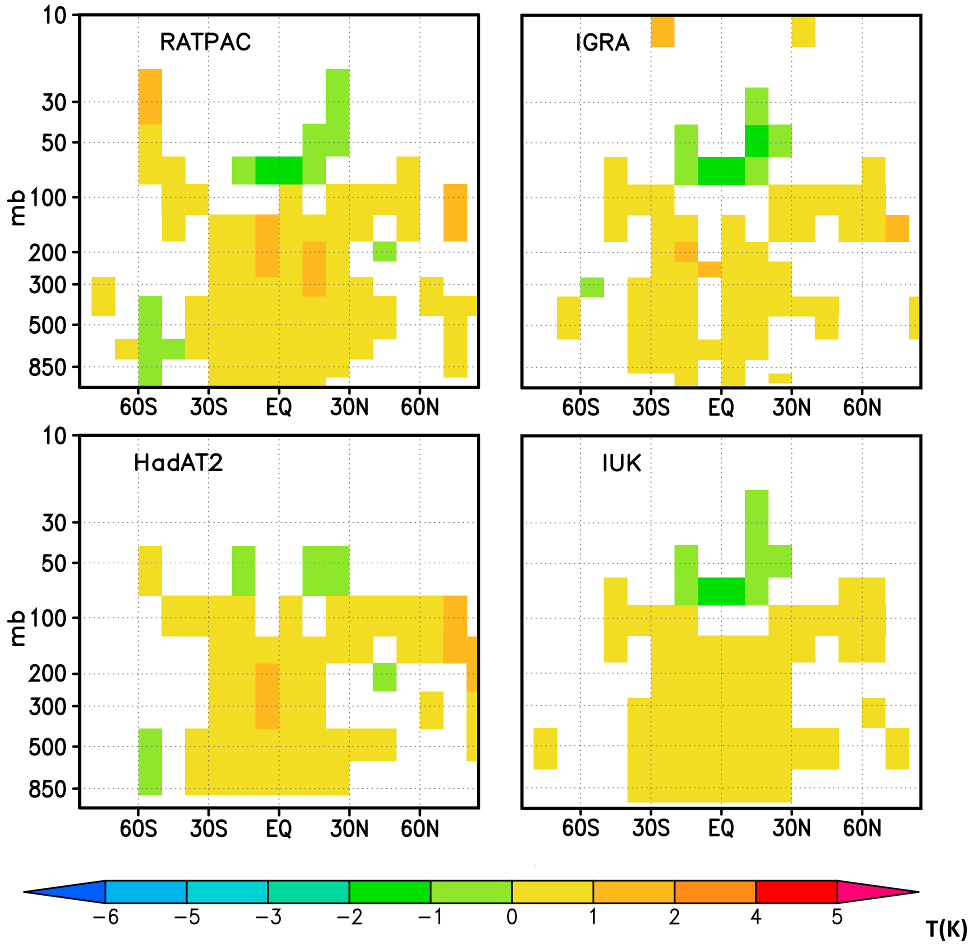

Figure 1. ENSO temperature signal (K) from linear regression using all months in radiosonde data sets, shown for areas where the signal is statistically significant at the 95% level. At 80–90°S data are missing for the lower troposphere in all data sets and at all levels in HadAT2.

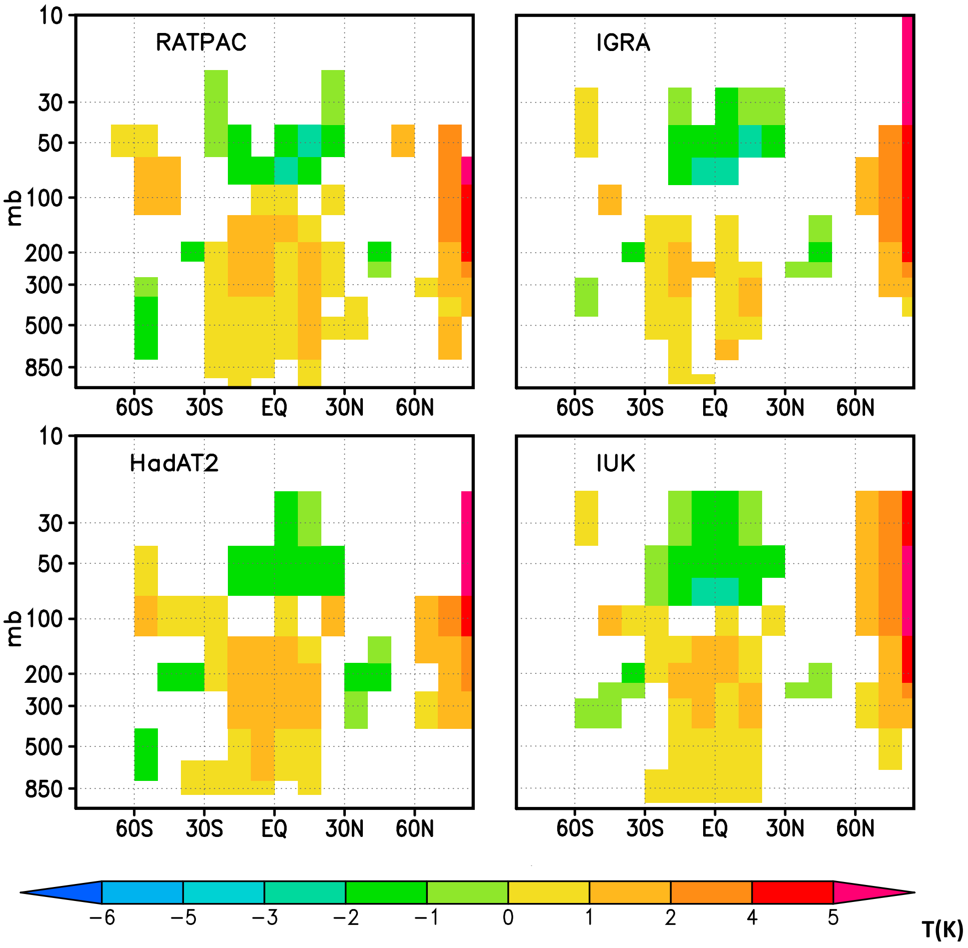

Figure 2. As in Figure 1, but showing signal from linear regression using the mean of December, January, and February temperatures.

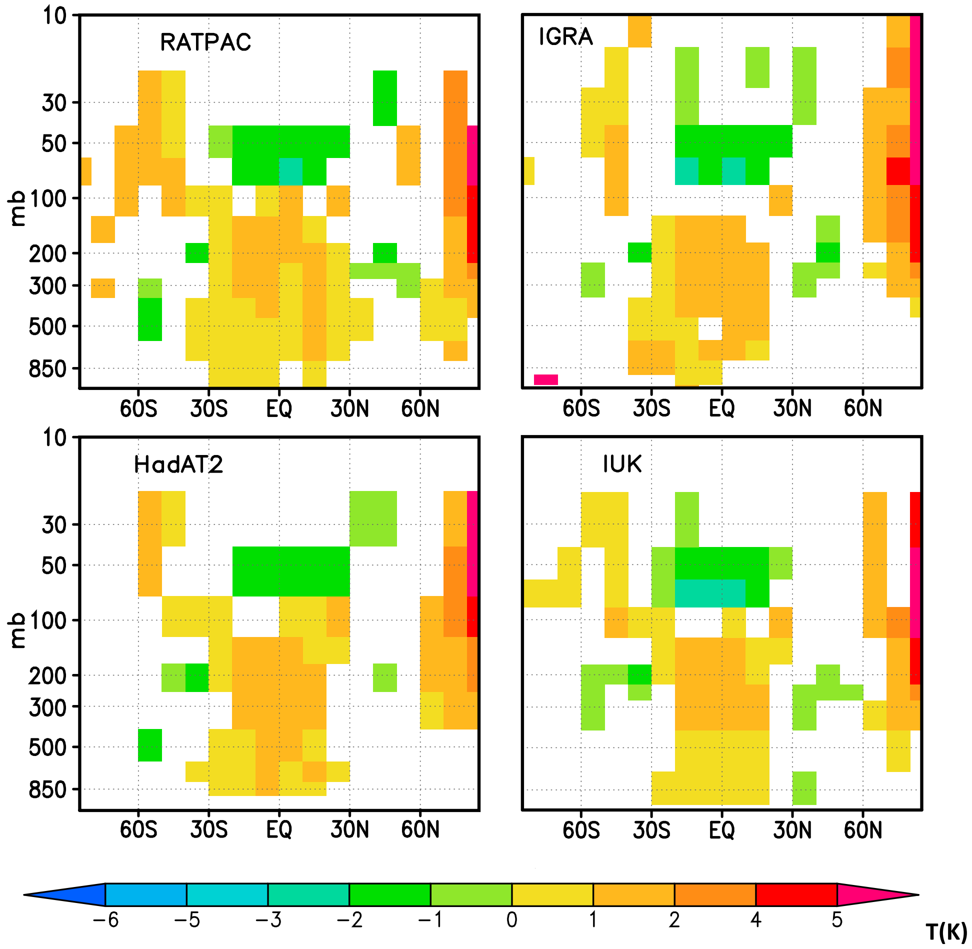

Figure 3. As in Figure 1, but showing signal from multiple regression rather than simple linear regression, using the mean of December, January, and February temperatures.

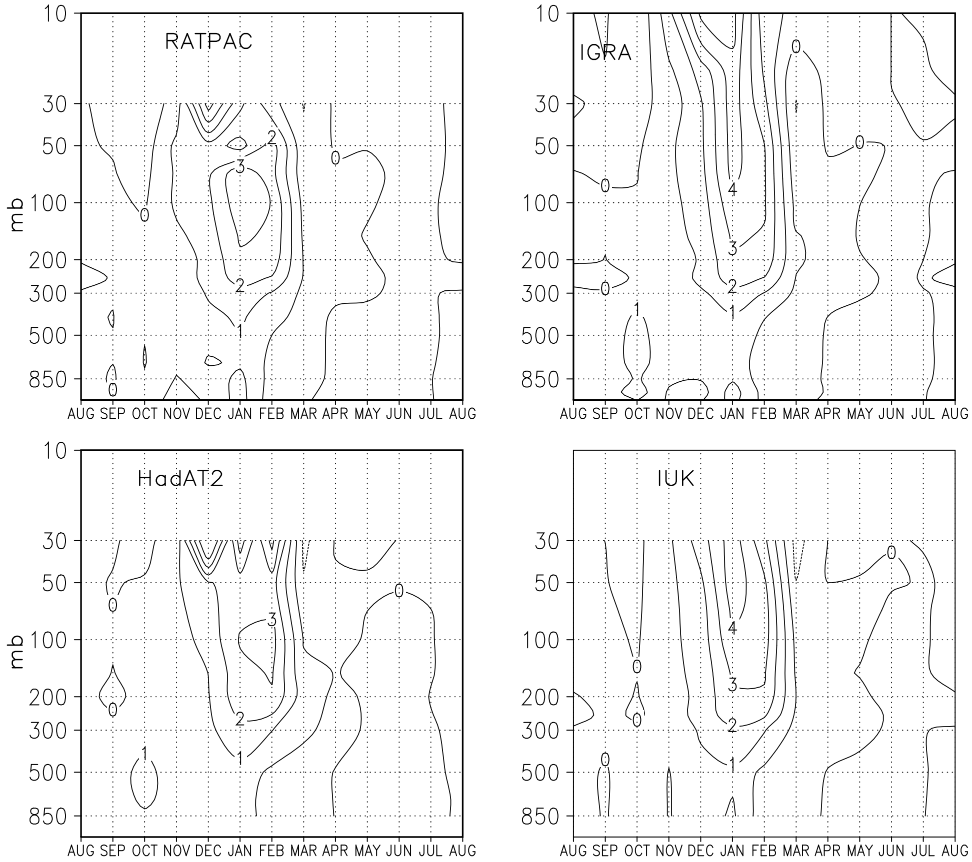

Figure 4. Seasonal evolution of the El Niño temperature signal (K) derived from linear regression using 4 radiosonde data sets as a function of atmospheric pressure level for 1987–1988 at 70–90°N.

[21] Figure 4 shows the signals from regression in the Arctic using data separated by month. The warming ENSO effect is strongest for January–February at 100 mbar. All data sets show some degree of warming in the troposphere in January for warm ENSO events. Models suggest that the Arctic ENSO signal should start in the upper stratosphere and propagate down [*Manzini et al.*, 2006; *Garcia-Herrera et al.*, 2006]. Evidence of such progression can be seen in most of the plots. Our use of monthly mean rather than daily or weekly data and the data limitations above 30 mbar may tend to obscure this aspect of the time evolution.

4.2. ENSO Signal From Composites

[22] Figure 5 shows composites of observed winter temperatures for El Niños minus La Niñas for areas where the differences are statistically significant. The results are similar to the regression response shown in Figure 2 for the Arctic stratosphere but show greater cooling in the tropical stratosphere. These plots also show warming in the SH lower stratosphere at 40–60°S, as seen in the winter regression results. This signal is actually the result of a cooling in the La Niña years rather than a warming from El Niños. The Arctic signal is primarily an El Niño response, with the composite of La Niñas showing only a weak response at high northern latitudes (not shown). La Niñas do, however, show a significant cooling response around 50–60°S, like that seen in the regression results in Figures 2 and 3. The differences between El Niño or La Niña and neutral years are mostly not statistically significant in the stratosphere.

[23] When we composite only those El Niño and La Niña years that do not coincide with easterly QBO winds, we find a stronger Arctic and tropical ENSO signal (Figure 6) than seen in the regression analysis (Figure 2) or in the composite for both QBO phases (Figure 5). The significant Arctic signal is centered around 100 mbar, although IGRA shows a signal up to 10 mbar for 80–90°N. In years in which the QBO is in the easterly phase, Arctic temperatures are similar in El Niño and La Niña years (not shown). This absence of effect when the QBO is in the easterly phase was also seen in earlier work [e.g., *Garfinkel and Hartmann*, 2007]. However, if postvolcanic years are ignored, there are only two El Niño and two La Niña years in which the QBO was in its easterly phase, so it is difficult to draw a meaningful conclusion from this limited record.

4.3. Correlations

[24] Figure 7 shows the time series of winter (DJF) temperature from 70 to 90°N at 100 mbar from RATPAC along with the ENSO index for the fall (multiplied by 2 to aid visual comparison). It is evident from this plot that the ENSO index accounts for only a small part of the total variability of Arctic stratospheric temperatures. It also appears that the two time series are in phase during ~1965–1977 and ~1987–2000 and out of phase at other times. To clarify the strength of the relations shown in the regression and composite analysis from sections 4.1 and 4.2 for Arctic temperatures, Table 1 shows correlation coefficients between the ENSO index and observed winter temper-

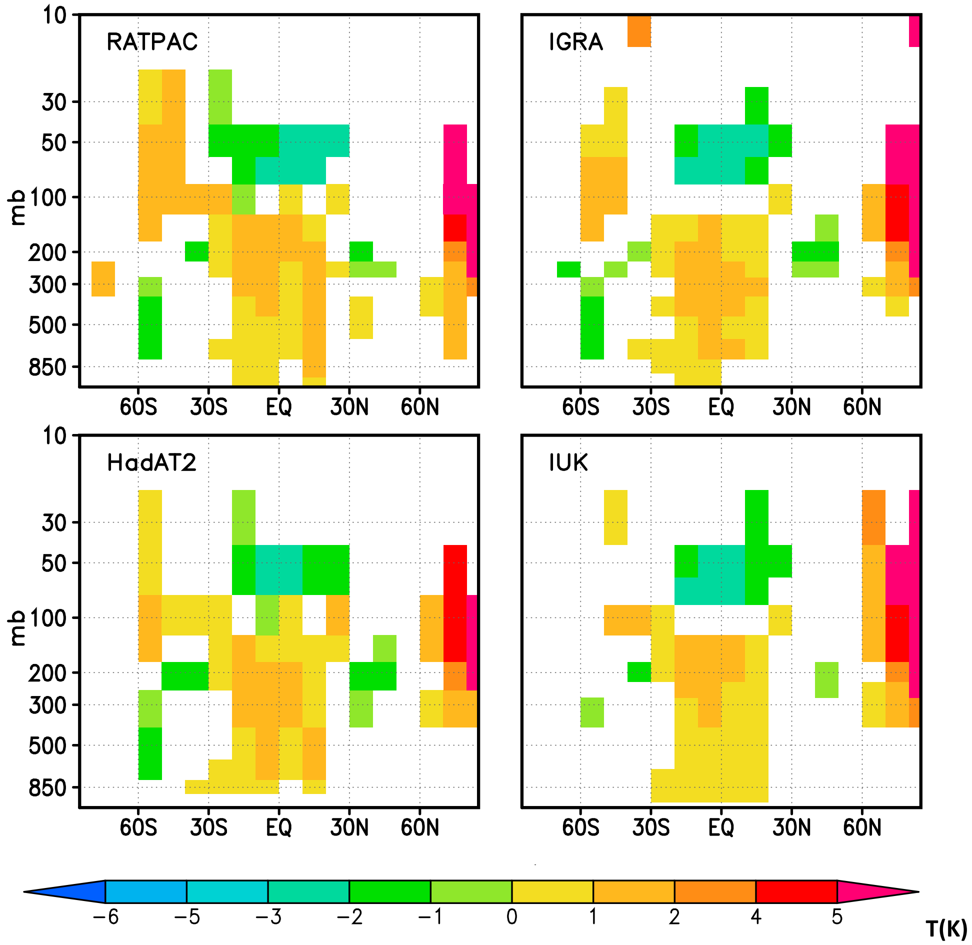

Figure 5. Mean of January and February temperatures (K) for eight El Niño events minus mean for six La Niñas, plotted as a function of latitude and pressure (mbar). Only areas with results statistically significant at the 95% level are plotted.

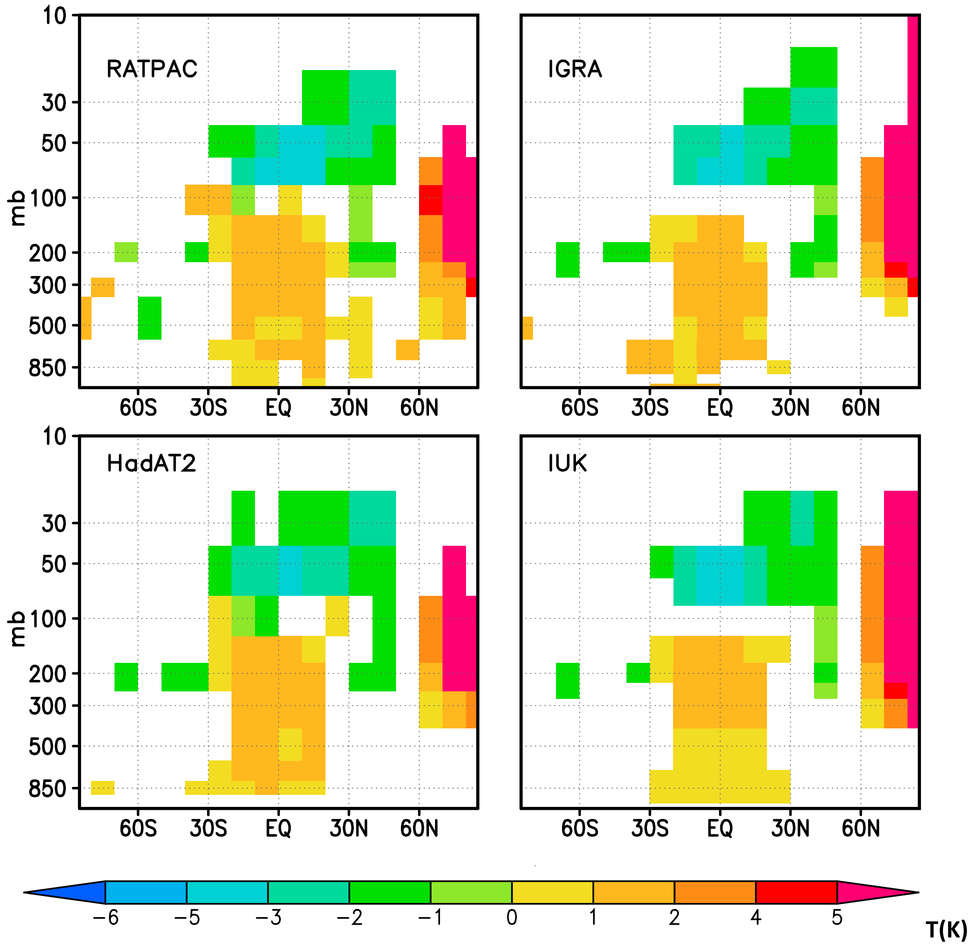

Figure 6. As in Figure 5, but using only winters in which the QBO is in the westerly phase.

atures after removal of the QBO and solar signals for this and certain other levels. The level of greatest correlation varies widely among the four data sets, but the correlations at 100 mbar are all close to 0.4. Reanalysis shows even larger correlations for the Arctic in winter.

[25] Winter mean MSU satellite data show significant negative correlations with ENSO SSTs in the tropical winter stratosphere (Table 2). When the satellite data are subsampled to match the locations of the sonde stations, the relation improves. The relation is not significant if all months rather than just winter are considered. Winter El Niño warming in the Arctic stratosphere is present but is not significant for either the full or subsampled satellite data, with correlation coefficients around 0.3. This is true for individual months as well as for the winter mean. In both regions the correlation is greater for the subsampled than for the full data set. When RATPAC sonde data are converted to MSU lower stratosphere equivalents, they show significant correlations for the Arctic, unlike the subsampled or full MSU satellite data. The results suggest that the sonde data in the Arctic may exhibit a

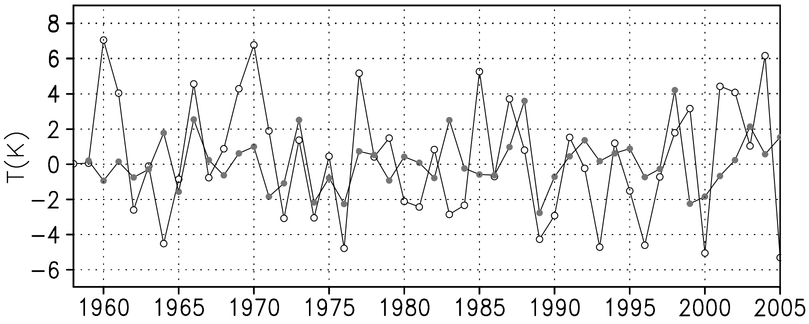

Figure 7. Time series of DJF temperature (K) from RATPAC at 100 mbar for 70–90°N (open circles) with mean Niño3.4 ENSO index for August, September, and October (closed circles), the latter multiplied by 2 to facilitate comparison.

stronger signal than the satellite data regardless of spatial sampling.

5. Discussion

[26] Our results differ from other recent work in finding a significant ENSO effect using ordinary linear regression and, in the Arctic, also differ with regard to the level at which it occurs. Previous work [*Camp and Tung*, 2007; *Garfinkel and Hartmann*, 2007] finds Arctic winter effects at 10–50 mbar, but our regression analysis reveals a strong signal at lower altitudes, in some cases extending into the troposphere. This is consistent with the model results of *Manzini et al.* [2006] but not with those of *Sassi et al.* [2004]. The tropical warming signal is consistent with previous work using other data sets.

[27] *Manzini et al.* [2006] found no Arctic cooling response for La Niñas in composites of model output or reanalysis data. Our results from compositing are similar in the sense that the cooling in La Niña years is not significant at most altitudes and latitudes. The lack of cooling response in the Arctic in La Niña years arises because the Arctic winter stratosphere was warm during 2 of the 6 La Niña years and cool during the others. The 2 warm years occurred when the QBO winds were from the east; the reverse was true for the cool years. Given the small number of La Niña years available for compositing since 1958 and the confounding influence of the QBO, it is hard to reach a convincing conclusion on this question using the compositing method.

[28] Our results from compositing showing clearer ENSO effects in the westerly QBO phase than in easterly years are consistent with other results regarding the interaction of the QBO and ENSO effects in the Arctic [*Garfinkel and Hartmann*, 2007]. Some authors [e.g., *Brönnimann*, 2007] suggest a possible saturation effect, such that when the easterly QBO switches the polar stratosphere into a warm mode, the effects of ENSO are overwhelmed by this preexisting QBO effect. *Garfinkel and Hartmann* [2008] present evidence that the saturation explanation is not valid and suggest that the relation may be an artifact of the relatively short record. *Calvo et al.* [2009] find El Niño effects in a model study for both QBO phases, with the QBO affecting the timing of the warming effect.

[29] The pattern of temperature anomalies descending from the upper to the lower polar stratosphere in Figure 4 resembles that of sudden stratospheric warmings (SSWs). Indeed almost all the warmest years shown in Figure 7, including 5 of the 8 El Niño years considered here, are listed as having SSWs in Figure 3 of *Taguchi* [2008]. However, according to that work, SSWs occur for 24 of the 40 nonvolcanic winters, including many with neutral ENSO SSTs and some La Niña years. *Taguchi and Hartmann* [2006] showed increased likelihood of SSWs in El Niño winters in a model and in daily NCEP reanalysis data but were unable to demonstrate statistical significance of this effect. Other model studies also support a connection between ENSO effects and SSWs [*Ineson and Scaife*, 2009; *Cagnazzo and Manzini*, 2009]. Further investigation of the linkages between SSWs and ENSO effects on polar temperatures in data is clearly warranted.

Table 1. Pearson Correlation Coefficients Between Niño3.4 SSTs and Stratospheric Temperature for Winter Months From 70 to 90°N[a]

	RATPAC	HadAT2	IUK	IGRA	NCEP Reanalysis
Level of max r[b] (mbar)	30	50	200	20	70
ENSO max r[c]	0.45	0.46	0.40	0.41	0.52
r at 100 mbar[d]	0.38	0.43	0.36	0.38	0.51

[a] Winter months are DJF.

[b] Pressure level at which correlation of ENSO index and temperature is largest, after subtraction of the QBO and solar signals.

[c] Correlation coefficient at that level in residual time series after removal of QBO and solar signals.

[d] Correlation for ENSO index at 100 mbar.

Table 2. Means of Pearson Correlation Coefficients Between Niño3.4 SSTs and Winter Temperatures in MSU Data[a]

Data Set	20°N–20°S	70–90°N
Full MSU lower stratosphere[b]	**−0.42**	0.28
Subsampled MSU[c]	**−0.51**	0.30
RATPAC MSU equivalent[d]	**−0.38**	**0.42**

[a] Correlations in bold face are significant at the 95% confidence level.

[b] MSU data for the lower stratosphere.

[c] MSU data subsampled as for RATPAC radiosonde locations.

[d] RATPAC radiosonde data weighted to approximate the MSU lower stratosphere product.

6. Conclusions

[30] 1. We find a statistically significant ENSO signal in radiosonde temperatures for the tropical stratosphere with a maximum at 70–50 mbar. This signal, consisting of an anomalously cool (warm) stratosphere during El Niño (La Niña), is weaker in NCEP reanalysis data and not significant in MSU data for the lower tropical stratosphere except in winter.

[31] 2. A significant El Niño warming signal consisting of a more than 4 K difference between El Niño and La Niña temperatures is present in the winter Arctic stratosphere in radiosonde data, primarily in January and February, and extends into the troposphere. This signal is not statistically significant in MSU data for the stratosphere.

[32] 3. Although compositing suggests that this Arctic winter signal is absent for the easterly QBO phase, the small number of ENSO events during QBO east years makes analysis difficult.

[33] 4. Compositing shows significant Arctic and tropical ENSO signals only for warm (El Niño) events.

[34] 5. The vertical extent and level of maximum Arctic warming depend on the data set and method of analysis, but most results indicate warming extending down to the tropopause and in some cases the midtroposphere.

[35] 6. ENSO explains 14–25% of the variance in Arctic winter temperature in the stratosphere after QBO and volcanic effects have been removed.

[36] **Acknowledgments.** We thank the anonymous reviewers for helpful comments and the originators of the data sets for providing those products.

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