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Effect of volcanoes on the vertical temperature profile in radiosonde data

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[1] Comparison of the responses of radiosonde temperatures to aerosol forcing from the Agung, El Chichon, and Pinatubo volcanic eruptions shows the expected stratospheric warming, with a maximum at 50 mbar in the tropics, and a predominantly cooling effect in the troposphere with a maximum in the middle or upper troposphere. The tropospheric cooling is greater after the Pinatubo eruption, with a significant effect on the temperature difference between the upper and lower tropical troposphere. The tropospheric coolings after El Chichon and Agung are more vertically uniform. The size of the difference between the Pinatubo and El Chichon responses is somewhat sensitive to the choice of data subset and the index used to account for the effects of El Niño-Southern Oscillation. Differential effects of volcanic eruptions on the upper and lower tropical troposphere should be considered as possible causes of differential temperature trends at those levels. *INDEX TERMS:* 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 8409 Volcanology: Atmospheric effects (0370); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS:* volcanic eruptions, El Chichon, Pinatubo, vertical temperature profile, stratospheric temperature, tropospheric temperature

1. Introduction

[2] Changes in the vertical temperature profile of the atmosphere may be important for detection of anthropogenic temperature change [*Vinnikov et al.*, 1996; *Santer et al.*, 1996; *Tett et al.*, 1996]. It is therefore interesting to ask how volcanic eruptions affect upper air temperatures and to what extent their effects differ at different atmospheric levels.

[3] Some evidence suggests relative cooling in upper versus lower tropospheric temperatures [*Santer et al.*, 1996; *Tett et al.*, 1996; *Parker et al.*, 1997] and in tropospheric versus surface temperatures [*Gaffen et al.*, 2000; *Brown et al.*, 2000; *Santer et al.*, 2000] over the past few decades. That relative cooling has not yet been satisfactorily explained. Effects of volcanic eruptions may contribute to these differences in trends [e.g., *Bengtsson et al.*, 1999; *Santer et al.*, 2000, 2001]. Observations of the effects of volcanoes on the vertical temperature structure may help to resolve this issue. Observations are also useful for comparison to modeled responses to volcanic forcings.

[4] Agung, Bali (8°S, 115°E) in March 1963, El Chichon, Mexico (17°N, 93°W) in April 1982, and Pinatubo, Philippines (15°N, 120°E) in June 1991 are the most climatically significant eruptions of the past 50 years [*Andronova et al.*, 1999]. Numerous observational studies of the surface and stratospheric temperature effects of these three volcanoes exist [see *Angell*, 1997; *Robock*, 1991, 2000, and references cited therein]. Analyses of Microwave Sounding Unit (MSU) satellite data show peak stratospheric warming of 0.75°C after El Chichon and 1.1°C after Pinatubo [*Christy and McNider*, 1994; *Parker et al.*, 1996]. After accounting for El Niño-Southern Oscillation (ENSO) by regression against equatorial sea surface temperature (SST), *Angell* [1988, 1990] showed tropical tropospheric cooling of up to 0.5°C after Agung and El Chichon. *Parker* [1985], in contrast, regressed tropospheric temperatures against the Southern Oscillation Index (SOI) and found inconclusive results for the same eruptions. *Kodera* [1994] showed the change in vertical-latitudinal profile, in both the troposphere and stratosphere in the first winter after Pinatubo, from operational analyses, revealing tropical and high-latitude cooling but midlatitude winter warming in the troposphere. *Oehlert* [1986] found that Agung increased tropospheric warming trends for 1957–1979 and 1964–1979, with the relative effect at different levels varying between the two time periods. *Michaels and Knappenberger* [2000] found the effect of Pinatubo and El Chichon on MSU lower tropospheric temperature trends from 1979 to 1998 was only −0.009°C/decade, but *Santer et al.* [2001] found an effect on lower tropospheric temperatures between −0.05 and −0.14°C/decade for 1979–1999, with a smaller effect at the surface.

[5] *Angell* [1988, 1997, 1999] used a selected set of 63 stations for the troposphere, 300–100 and 100–50 mbar layers and 15 stations for 50 mbar and above. This work uses a much larger data set, allowing analysis of a total of nine levels in the troposphere and stratosphere combined, for all latitudes. *Parker* [1985] used a similar data set but did not analyze the detailed variation of volcanic effects with atmospheric level. Existing satellite data for the past 2 decades give fuller spatial coverage but do not resolve the vertical structure with the detail that is available from radiosonde data.

2. Data and Methods

[6] The Hadley Centre gridded radiosonde temperature data set (HadRT) [*Parker et al.*, 1997], kindly provided by David Parker of the Hadley Centre Met Office in the United Kingdom, is derived from data transmitted by reporting countries in the form of monthly means (CLIMAT TEMP data). The data set contains anomalies from the 1970–1990 mean, interpolated onto a 5° (latitude) by 10° (longitude) horizontal grid for 850, 700, 500, 300, 200, 150, 100, 50, and 30 mbar levels. We used the versions designated HadRT2.1 and HadRT2.0, with and without the adjustments based on MSU data described by *Parker et al.* [1997] and *Free et al.* [2002]. The data include many more stations than are represented in the Angell analyses but do not contain any constraint insuring continuity of station data over time. Like other radiosonde data, HadRT2.0 also contains inhomogeneities produced by changes in instruments and

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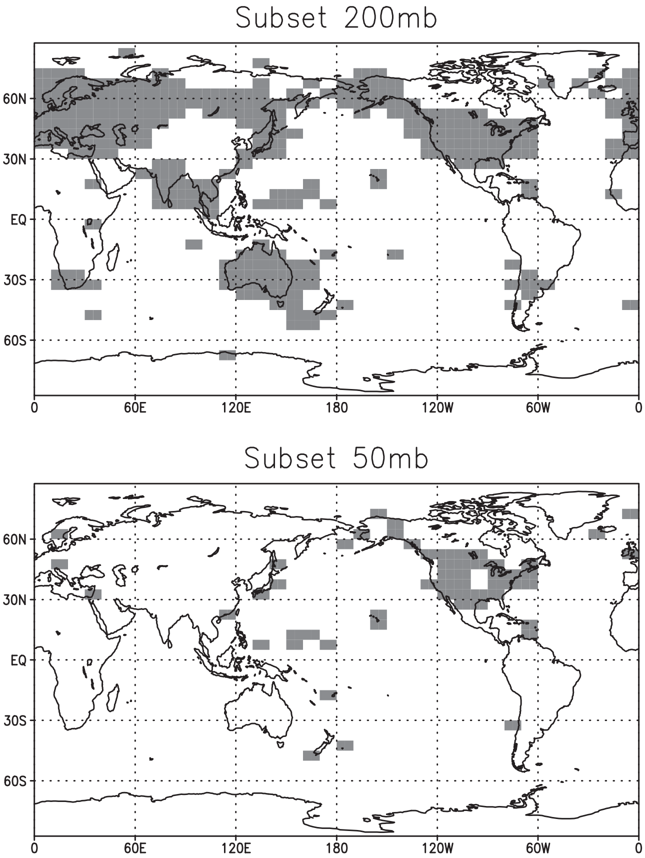

Figure 1. Grid boxes included in (top) 200 and (bottom) 50 mbar data subsets.

procedures [*Gaffen*, 1994]. HadRT2.1 values since 1979 have been adjusted by comparison with collocated MSU data (version "c"), but retain any inhomogeneities occurring before 1979. The HadRT adjustments are also subject to any uncertainties and errors present in the MSU data used as a reference.

[7] To test the sensitivity of our results to inhomogeneities in the radiosonde data, we compared results from the HadRT2.0 and HadRT2.1 data sets and found that the differences between tropical mean volcanic temperature effects (as defined below) were less than 0.06 degrees for all three eruptions at all levels. We conclude that inhomogeneities and their adjustment, although potentially important for trend analysis, are probably not an important source of error in our analysis of the short-term effects of Pinatubo or El Chichon. Since Agung occurred before the period in which the data were adjusted, results for that eruption may be less reliable. In the results shown in the rest of this paper we used the adjusted data.

[8] We removed the effects of the $\sim$27-month quasi-biennial oscillation (QBO) by regression against monthly 50 mbar winds at Singapore using data from 1958 through 1999, excluding the three years after major volcanic eruptions. Lags were chosen for each latitude and altitude so as to maximize the correlation between the QBO index and temperature at that location. The lags varied between 15 months at 30 and 50 mbar in the Northern Hemisphere midlatitudes to -3 months at 50 mbar in the Southern Hemisphere, with maximum correlation of -0.6 at 30 mbar at the equator for a lag of 5 months. Averaging the residual data over 24 months eliminates virtually all QBO variability remaining after the regression.

[9] After removing the QBO signal, we calculated the ENSO signal by linear regression against the Southern Oscillation Index using the lag between 0 and 6 months that gave the best correlation for each level and latitude band. (Lags were typically 4 to 6 months.) Correlations ranged from -0.23 to -0.53 in the tropical troposphere. At locations where the correlation was significant at the 95% level we subtracted the resulting ENSO signal from the data. We also performed the same procedure using the Nino3.4 SST index for comparison. The difference between results for these two indices gives some indication of the uncertainties involved in removing the effects of ENSO. To minimize the influence of the eruptions on the ENSO signal, we performed the regressions without the 3 years following each of the three eruptions. (Results excluding the 5 years after each eruption were not noticeably different.)

[10] Our work differs from previous research that attempts to separate ENSO and volcanic signals in that we are working with nine vertical levels and nine latitude zones. This may allow a better separation of ENSO and volcanic signals than analysis using global mean data alone, but the increased noise levels in the unaveraged sonde data can also increase uncertainty in the estimated ENSO signal. Separation of volcanic and ENSO signals may be complicated by possible effects of eruptions on the commonly used ENSO indices and by possible nonlinearities or changes over time in the relation between ENSO indices and atmospheric temperatures [*Kelly and Jones*, 1996; *Hoerling et al.*, 2001; *Trenberth and Stepaniak*, 2001; *Wigley*, 2000; *Santer et al.*, 2001; T. M. L. Wigley and B. D. Santer, Differential ENSO and volcanic effects on surface and tropospheric temperatures, submitted to *Journal of Climate*, 2002, hereinafter referred to as Wigley and Santer, submitted manuscript, 2002]. Our analysis could be affected by uncertainties in ENSO signals arising from these or other sources.

[11] We calculated zonal mean temperatures for nine 20° latitude bands, for each of the nine pressure levels. To compare the temperature responses to Pinatubo, El Chichon, and Agung, we subtracted the mean of the residual temperature series for the 24 months before each eruption from the mean for the 24 months afterward, to give the 2-year mean change. Results using a 36-month averaging period lead to generally similar conclusions. We also calculated the difference between the layer mean temperatures in the upper (300–200 mbar) and lower (850–500 mbar) troposphere in the tropics.

[12] Many changes in the spatial coverage of the radiosonde data have occurred in the past, and these changes could distort our results in several ways. First, if the coverage differs between the 24 months before and after the eruption, and the volcanic signal is not uniform within the zonal bands being averaged, the computed temperature change may be affected. Second, if the coverage during the time period used for ENSO or QBO regression differs from that in the time period around the eruption, the reconstructed ENSO signal may not be accurate. To test these possibilities, we compared several subsets of the gridded data having greater consistency of reporting over time. The subsets initially considered were 200mb, 50mb, and without India (WI), in addition to the entire adjusted data set ("full"). To be included in the 200mb (50mb) subset, grid boxes must have data at 200mb (50mb) for at least 67% of all months outside of the 3 years following the major eruptions and also must have data for at least 18 of the 24 months before and after each eruption. The first criterion is intended to provide an adequate time period for ENSO and QBO regressions, and the second criterion to insure comparable coverage before and after each eruption, and among the three eruptions. Because the quality of data from the region over and near India may be particularly bad [*Parker et al.*, 1997], we also used the WI subset, which includes all grid boxes except those between 60° and 100°E longitude and 5° and 30°N latitude. Figure 1 shows the coverage of the 200mb and 50mb subsets. (Note that the subsets will differ at all atmospheric levels, not just the levels used to define the subsets.) The

200mb data are close to the full coverage of the HadRT data set, with the most noticable difference being absence of data for China and the northern part of South America. In contrast, the 50mb set is drastically reduced, with only one grid box between 5°N and 30°S, and no data south of 50°S latitude. Because of this lack of Southern Hemisphere coverage, and the sparseness of coverage in Europe and Asia, we do not show plots of results limited to the 50mb subset in the remainder of the paper.

3. Changes in Temperature after Pinatubo, El Chichon, and Agung

3.1. Gridded Temperature Responses

[13] Figure 2 shows maps of the 24-month mean change in temperature after Pinatubo, El Chichon, and Agung for 50, 300, and 700 mbar in the full data set (after removal of QBO and ENSO effects using the SOI). The maps show stratospheric warming and tropospheric cooling in most areas of the tropics, as found in earlier work [e.g., *Newell*, 1970; *Angell*, 1988, 1990, 1997; *Christy and McNider*, 1994; *Labitzke and McCormick*, 1992]. In all cases, northern mid and high latitudes show strong longitudinal variability, with warming over North America and cooling over Europe at 50 mbar after both Pinatubo and El Chichon. For winter (not shown) the responses show the tropospheric "winter warming" pattern described by *Robock and Mao* [1995, Figure 10].

[14] In the tropical troposphere the region centered on India shows unusually strong cooling after Pinatubo and warming after El Chichon in comparison with the rest of the tropics. Although the regional pattern of temperature response in the National Centers for Environmental Prediction (NCEP) reanalysis [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] (not shown) is generally similar to that in the radiosonde data after these two eruptions, the reanalysis data does not show this large response over India. Several previous analyses of radiosonde data have omitted Indian data because it was found to be temporally and spatially incoherent [*Parker et al.*, 1997; *Hurrell et al.*, 2000]. Because of these issues, we have used the data subset excluding India (WI) for most of the subsequent analysis.

3.2. Zonal Mean Responses

[15] Figure 3 shows the latitude-altitude patterns of temperature response for the three eruptions after removal of the SOI and QBO signals, using the WI data subset, and the regions in which the signal is statistically significant at the 95% confidence level (shaded). Statistical significance was assessed using a two-sample *t* test with adjustment for serial correlation in the data [*Zwiers and von Storch*, 1995]. All three eruptions show the expected stratospheric warming in the tropics, with a maximum near 50 mbar. This warming is relatively hemispherically symmetrical and centered at the equator for El Chichon, but for Pinatubo and Agung is stronger in the Southern Hemisphere than in the North, as observed by *Angell* [1993]. The Southern Hemisphere high-latitude stratospheric warming after Pinatubo (at a similar altitude as in the tropics) may be at least partly due to the smaller eruption of Cerro Hudson in Chile (46°S) in August 1991. As found in the works of *Angell* [1993, 1997], the 50 mbar stratospheric warming maxima in the tropics are similar in magnitude (roughly 1.2 to 1.8°C) for all three eruptions when averaged over the first two posteruption years.

[16] In the troposphere the patterns of cooling are different for the three eruptions. After Pinatubo, there was a maximum cooling of ~1°C in the tropical upper troposphere, with cooling extending up to nearly 100 mbar. In contrast, the El Chichon and Agung tropospheric responses in the tropics are small and more nearly the same in the vertical, with the shift from tropospheric cooling to stratospheric warming occurring around 200 mbar for Chichon and 300 mbar for Agung. Although the tropics show very little tropospheric response after Agung, the response at Southern midlatitudes is similar in vertical profile to that of Pinatubo but with a maximum cooling of 0.9°C at 500 mbar (Figure 3) and warming of 1.5°C extending as low as 200 mbar around 60°S. (However, since data was very sparse south of 40°S and above 200 mbar at the time of the Agung eruption, our results for stratospheric and southern midlatitude responses in 1963–1965 must be viewed with caution.)

[17] In the full data set including India (not shown) the Pinatubo response has a larger maximum tropospheric cooling centered at 20°N. The El Chichon response using the full data set shows slightly greater warming in the stratosphere and cooling in the troposphere than shown in Figure 3. The Agung response is essentially the same with or without the Indian data. As might be expected given its inadequate data sampling, the 50 mbar subset shows much noisier results which vary strongly from those in the larger data sets. Results using the Nino3.4 index are similar in overall pattern to those in Figure 3 (using SOI) but show reduced tropospheric cooling for Pinatubo and increased cooling for El Chichon. We explore these differences further in the form of tropical mean temperature profiles in the next section.

3.3. Tropical and Global Mean Response

[18] Figures 4a and 4b compare the effect on the tropical mean temperature profiles due to the Pinatubo and El Chichon eruptions using four combinations of data subsets and ENSO indices (full data set/SOI index, WI subset/SOI index, 200 mbar subset/SOI index, and WI subset/Nino3.4 index). The size of the response is affected noticeably by the choice of subset and index, but in all cases the tropospheric response to Pinatubo (Figure 4a) is largest at 200 to 300 mbar, with a noticable difference between lower tropospheric and upper tropospheric effects. For El Chichon (Figure 4b), the tropospheric cooling is smaller and more uniform in the vertical. Figure 5 shows the difference between the Pinatubo and El Chichon responses for the same four cases. The difference depends strongly on the data subset and ENSO index used, but in all cases shown, the response after Pinatubo is larger than after El Chichon and the difference is largest in the upper troposphere.

[19] Figure 6 shows the tropical mean and global mean responses to the three eruptions in the WI data set (which excludes India), using the SOI for ENSO removal. For Pinatubo the response is statistically significant at the 95% level at 50 mbar and below 100 mbar, but the responses to Agung and El Chichon are not significant in the troposphere. Note the difference in mean temperature change at 150 mbar for the three eruptions in the tropics: large cooling for Pinatubo but minimal change or warming for the others. At 100 mbar the two earlier eruptions produce warming of more than 0.5°C, but Pinatubo's effect is much less. This result is consistent with the lack of an obvious Pinatubo signal in both radiosonde and reanalysis tropical tropopause temperature data found by *Randel et al.* [2000] and *Seidel et al.* [2001]. Using a 36-month averaging period rather than 24 months, we find smaller temperature effects, but the differences between the Pinatubo and Chichon temperature effect profiles remain. In the global mean the difference between Pinatubo and the other two eruptions is less pronounced, and the amplification of cooling in the upper troposphere after Pinatubo is much less in the global mean than in the tropics.

3.4. Differential Effect on Upper Versus Lower Troposphere

[20] We show in Figure 7a the time series of the layer-mean temperature anomalies in the upper troposphere (300–200 mbar, UT) and the lower troposphere (850–500 mbar, LT) between 30°S and 30°N, after removal of the ENSO and QBO signals by linear

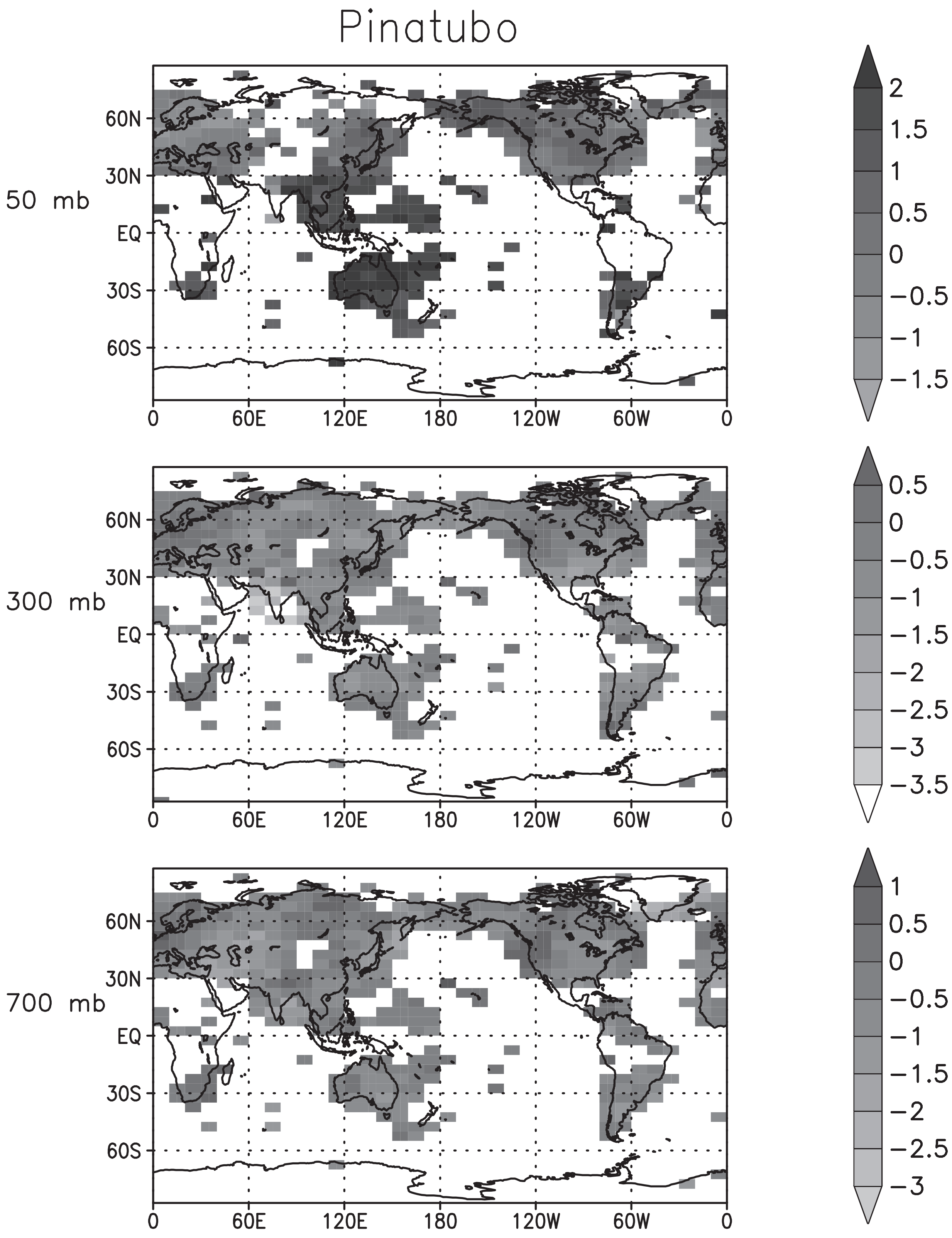

Figure 2a. Mean of temperature anomalies (°C) for the 24 months after the eruption minus the 24 months before the eruption in the full data set, after removal of quasi-biennial oscillation (QBO) and El Niño-Southern Oscillation (ENSO) (Southern Oscillation Index (SOI)) signals as described in the text, for Pinatubo (1991) and at 50, 300, and 700 mbar. See color version of this figure at back of this issue.

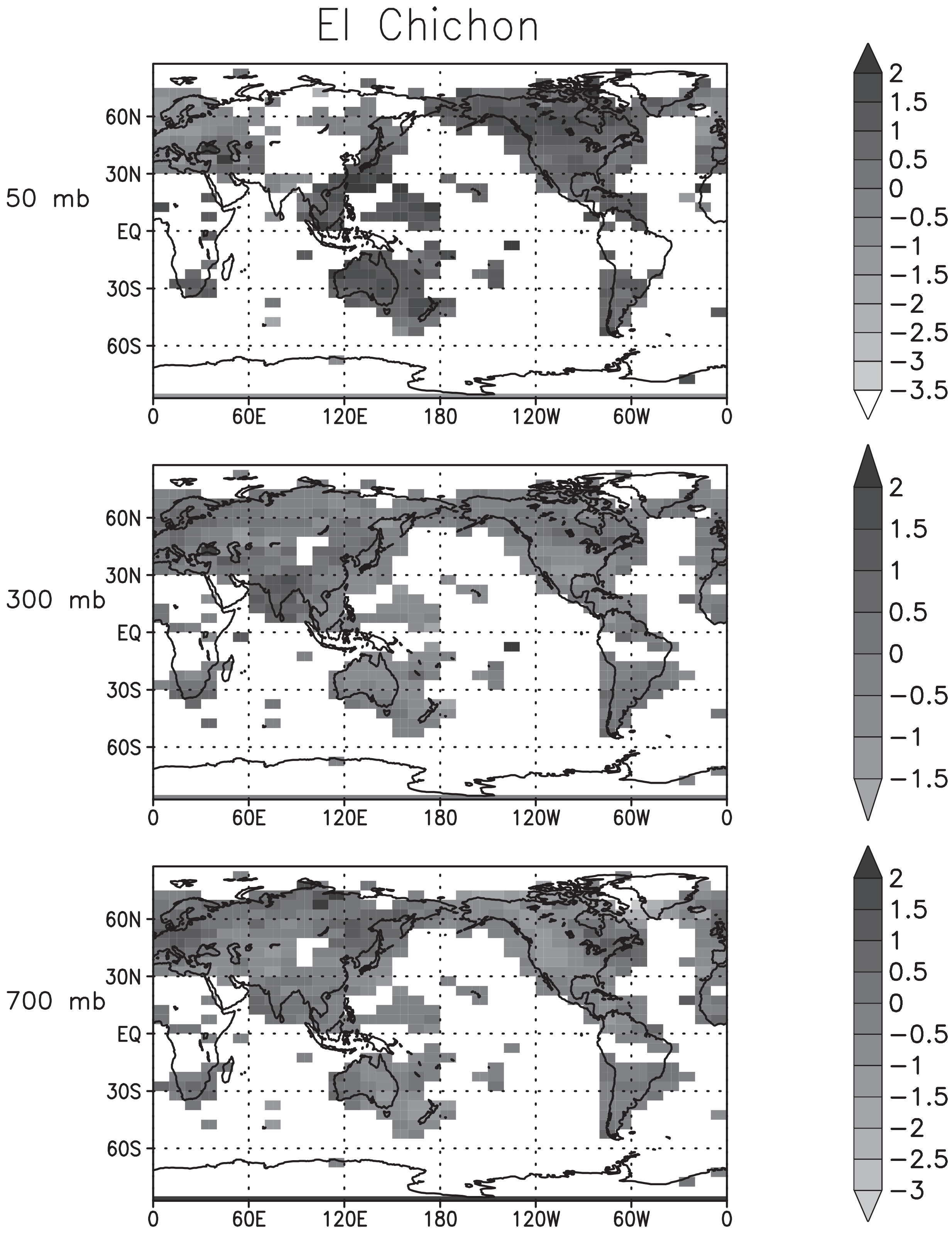

Figure 2b. Same as Figure 2a, except for El Chichon (1982). See color version of this figure at back of this issue.

regression, for the WI data subset, and in Figure 7b the difference between these two time series (UT minus LT). The temperature difference shows large decreases after El Chichon and Pinatubo (i.e., the upper troposphere cools more than the lower troposphere), but not after Agung. While the decrease in the UT-LT difference occurs rapidly after Pinatubo, there is little change in the UT-LT difference for the first year following El Chichon. After El Chichon the LT cools initially at a similar rate as the UT, but then appears to

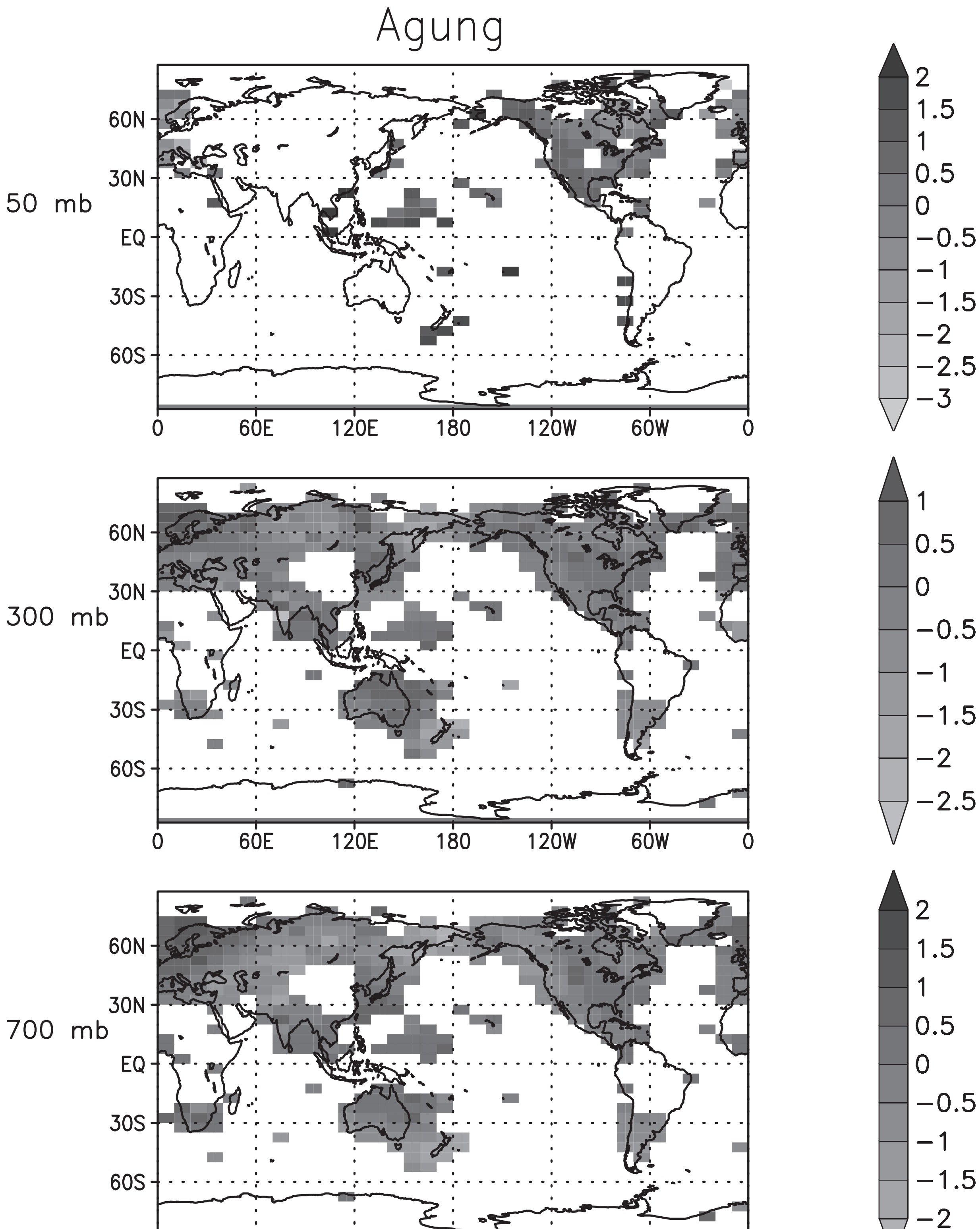

Figure 2c. Same as Figure 2a, except for Agung (1963). See color version of this figure at back of this issue.

recover much more rapidly, so that the UT-LT difference has its minimum almost 3 years after the eruption.

[21] The mean change in the tropical UT-LT temperature difference for the 2 years before and after Pinatubo is −0.33°C in the WI data set, which is significantly different from zero, and from the changes after Agung and El Chichon, at the 95% confidence level. The UT minus LT time series are similar for the 200 mbar and full data sets and for both ENSO indices. The distinct posteruption

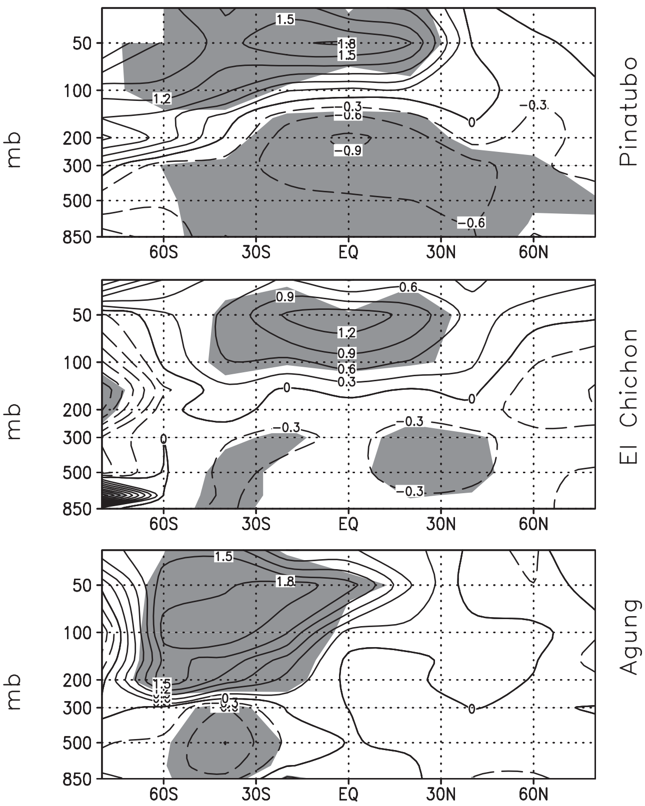

Figure 3. Zonal mean temperature anomalies (°C) for the 24 months after the eruption minus the 24 months before the eruption, after removal of QBO and ENSO signals, for Pinatubo, El Chichon, and Agung. Shading denotes differences significant at the 95% confidence level.

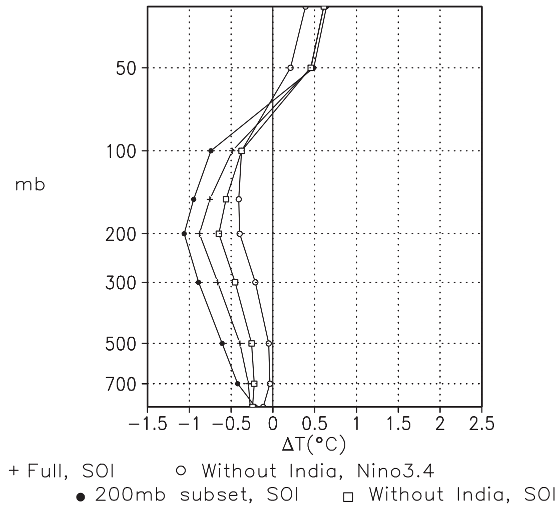

Figure 5. Differences between the Pinatubo results in Figure 4a and the El Chichon results in Figure 4b.

changes in the UT-LT differences are not apparent in global mean or extratropical results.

4. Comparison With Previous Results

[22] Most previous studies of upper air effects of volcanoes have examined the maximum temperature response rather than the 2-year mean temperature effects, so direct comparison of our results with previous studies is difficult. Analyses of the global mean MSU satellite temperature data show maximum stratospheric warming of 1.10°C for Pinatubo and 0.75°C for Chichon. [*Christy and McNider*, 1994; *Parker et al.*, 1996]. We find 2-year

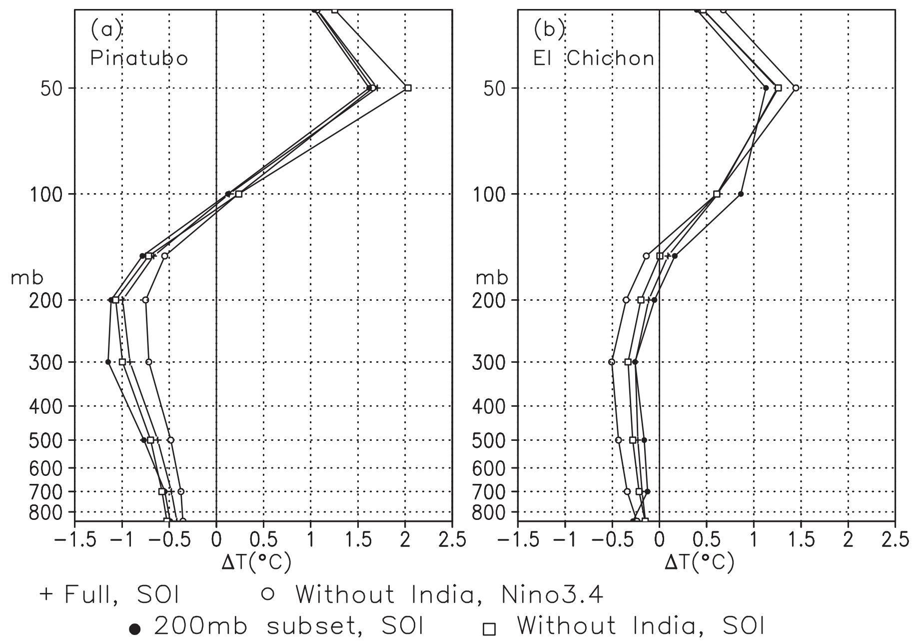

Figure 4. Difference in mean temperatures (°C) for the 24 months before and after the Pinatubo (a) and El Chichon (b) eruptions, after removal of QBO and ENSO signals, averaged from 30 S to 30 N for the full data set using SOI index (crosses), WI (without India) subset using SOI index (open circles), 200mb subset (grid boxes with relatively complete data at 200 mb) using SOI index (filled circles), and WI subset using Nino3.4 index (open squares).

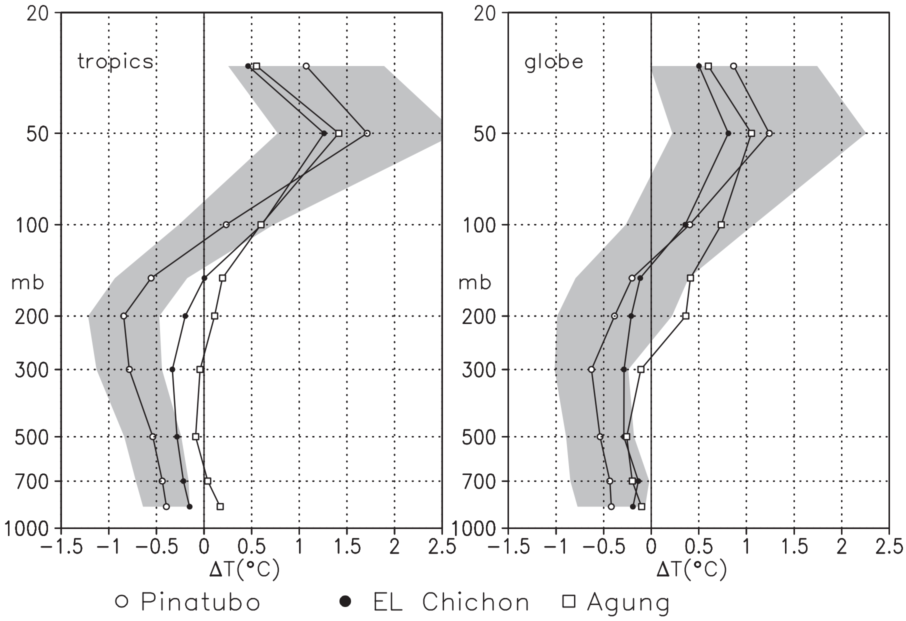

Figure 6. Mean of temperature anomalies (°C) for the 24 months after the eruption minus the 24 months before the eruption, for Pinatubo, El Chichon, and Agung, after removal of QBO and ENSO (SOI) signals, averaged from 30°S to 30°N and over the globe, from the WI data subset. Shading indicates 95% confidence intervals for Pinatubo.

mean changes at 50 mbar of ~1.2°C for Pinatubo and 0.7°–0.9°C (depending on data subset and ENSO index) for El Chichon. The range of ratios of the Chichon to Pinatubo responses for 50 mbar is 0.61–0.74 globally, compared to a ratio of 0.68 in the MSU data. For the tropics, our ratios are larger (0.70–0.87).

[23] *Christy and McNider* [1994] estimated the tropospheric (MSU2R) responses from the stratospheric response, giving a

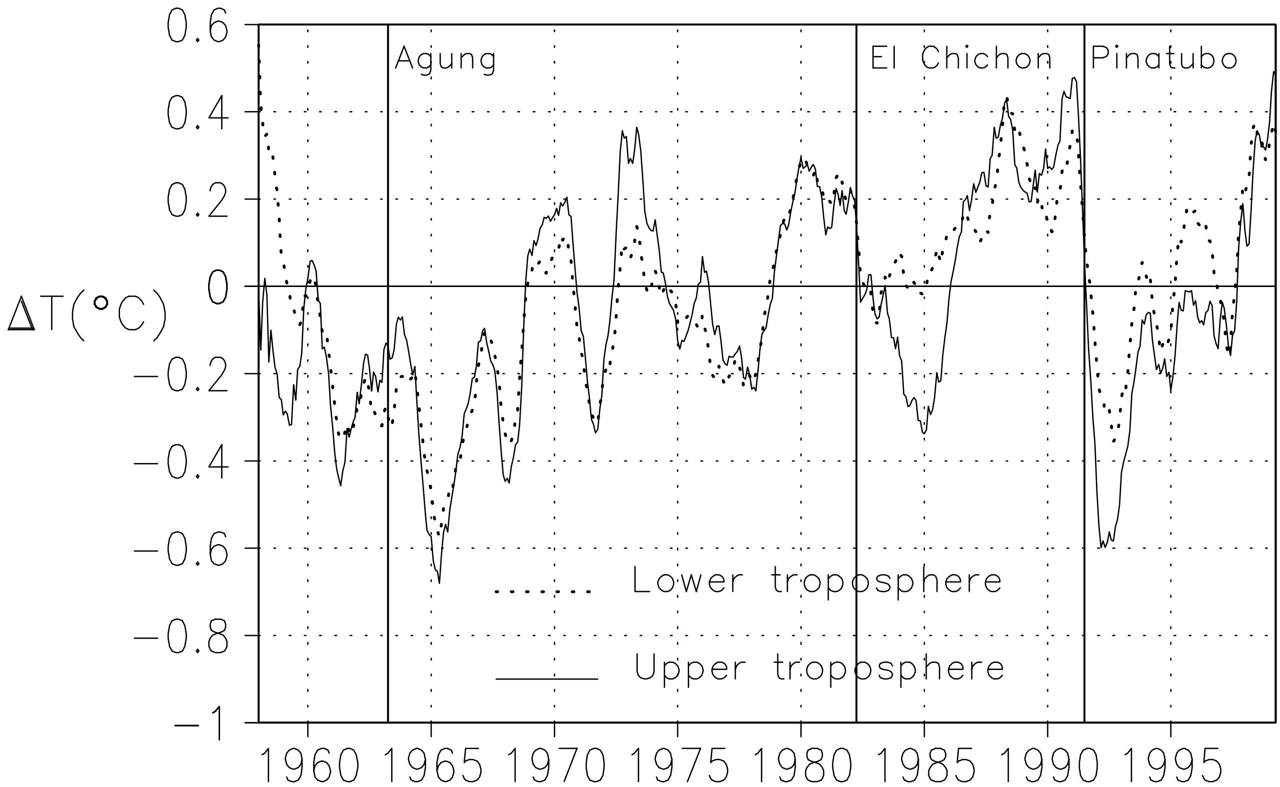

Figure 7a. Twelve-month running means of monthly mean temperature anomalies (°C) in the 300–200 mbar upper tropospheric layer (solid line) and in the 850–500 mbar lower tropospheric layer (dotted line) between 30°S and 30°N. Vertical lines indicate times of the three eruptions.

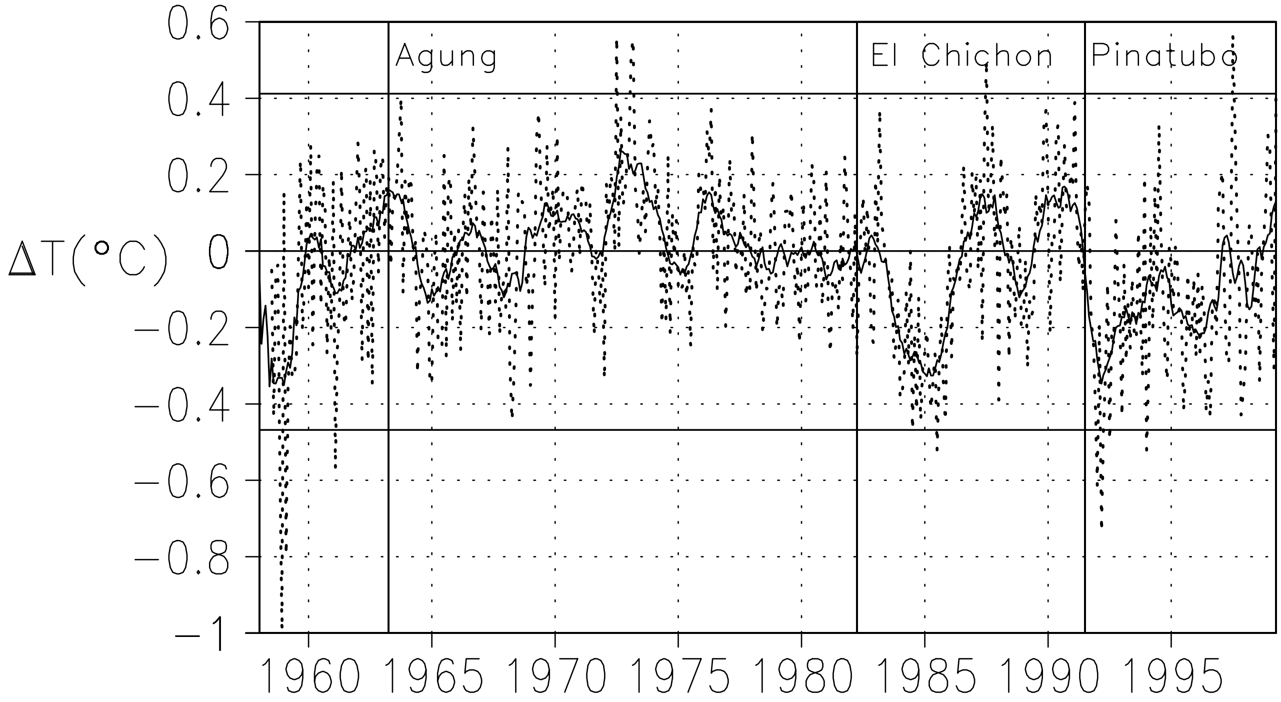

Figure 7b. Monthly zonal mean temperature anomalies (°C) in the 300–200 mbar upper tropospheric layer minus zonal mean temperature anomalies in the 850–500 mbar lower tropospheric layer, after removal of the QBO and ENSO signals, between 30°S and 30°N. Dotted line is raw data. Heavy solid line is smoothed with a 12-month running mean. Horizontal lines indicate two times the standard deviation of monthly mean differences for the whole unsmoothed record. Vertical lines indicate times of the three eruptions.

global mean lower tropospheric cooling with a peak of ~0.4°C for Chichon and 0.6°C for Pinatubo. Our 700 mbar responses generally show lower relative response for Chichon versus Pinatubo than found by Christy and McNider, with ratios of 0.28–0.54 globally and 0.23–0.89 in the tropics, compared to 0.67 for MSU. Using an iterative procedure to remove ENSO effects, Wigley and Santer (submitted manuscript, 2002) found maximum global MSU lower tropospheric (MSU2LT) cooling of 0.3°C after Chichon and 0.7°C after Pinatubo, giving a ratio of 0.43. *Santer et al.* [2001] gives a range of 0.39 to 0.75 using three ENSO indices and 0.39 to 0.52 using the two indices we used. Our results are closer to those of Wigley and Santer (submitted manuscript, 2002) and *Santer et al.* [2001] than to *Christy and McNider* [1994].

5. Discussion

[24] The Pinatubo effect in the tropics, greater cooling in the upper troposphere than in the lower troposphere, is similar (but of reverse sign) to model predictions for the tropics for greenhouse warming, that is, amplification of surface effects in the upper troposphere due to changes in convective heat transport [e.g., *Manabe and Stouffer*, 1994]. Under this interpretation the surface response to El Chichon and Agung may simply have been too small to give a noticeable upper tropospheric amplification in the tropics. The increased chlorine levels, changes in stratospheric dynamics, and resulting increased ozone depletion after Pinatubo versus earlier eruptions [*Brasseur and Granier*, 1992] may have decreased the stratospheric warming and increased the upper tropospheric cooling after Pinatubo [*Kirchner et al.*, 1999; *Bengtsson et al.*, 1999]. In addition, the relative lack of aerosol in the Northern Hemisphere after the Agung eruption [*Dyer and Hicks*, 1968] could have decreased the tropical-mean tropospheric cooling for that event. It should be noted that since the radiosonde data do not sample all areas of the globe evenly, the zonal mean responses shown here may not accurately represent the zonal mean for the entire atmosphere. On the basis of the comparisons of results from different data subsets discussed above, however, we believe that the differences between the responses to Pinatubo and El Chichon are not due to changes in data coverage.

[25] The effect of volcanic eruptions on long-term temperature trends depends on the rate at which the atmosphere returns to its normal state after the volcanic eruption (Wigley and Santer, submitted manuscript, 2002). While demonstrated volcanic effects in surface observational data have generally been limited to a maximum of 2 or 3 years after the eruption due to the high levels of noise in the data [e.g., *Robock and Mao*, 1995], model results suggest that the heat storage effects of the ocean may cause extended cooling for five or more years [e.g., *Bengtsson et al.*, 1999; Wigley and Santer, submitted manuscript, 2002]. Figure 7 also suggests a recovery period longer than 2 to 3 years for the troposphere. Although this study is limited to the more easily detected short-term effects of eruptions, our results support findings by others that volcanoes may have different effects on trends at different levels in the atmosphere [see *Santer et al.*, 2001]. Since the data we use do not include surface temperatures, our findings do not directly address observed differences between surface and tropospheric temperatures.

6. Conclusions

[26] The responses to Agung, El Chichon, and Pinatubo all show stratospheric warming with a maximum at 50 mbar in the tropics, and a predominantly cooling response in the troposphere with a maximum in the mid to upper troposphere, but the details of the responses differ noticeably among the three eruptions, particularly in the troposphere. Different subsets of the radiosonde data give somewhat different results. The responses are also somewhat sensitive to the index used to reduce the influence of ENSO. The

response to Pinatubo shows significant amplification of cooling in the upper versus lower tropical troposphere, whereas results for El Chichon and Agung show a smaller tropospheric response that is more evenly distributed vertically. In the 2 years after the eruption of Pinatubo the difference between temperatures in the upper and lower tropical troposphere changed significantly. These differential volcanic effects should be considered as possible contributing factors to observed differences in temperature trends at different levels in the atmosphere, especially for relatively short time periods such as the last 20 years.

[27] **Acknowledgments.** We thank David Parker for providing the Hadley gridded radiosonde data. Dian Seidel, Becky Ross, and Ben Santer provided helpful comments. This work was performed while M. Free held a National Research Council Associateship at NOAA.

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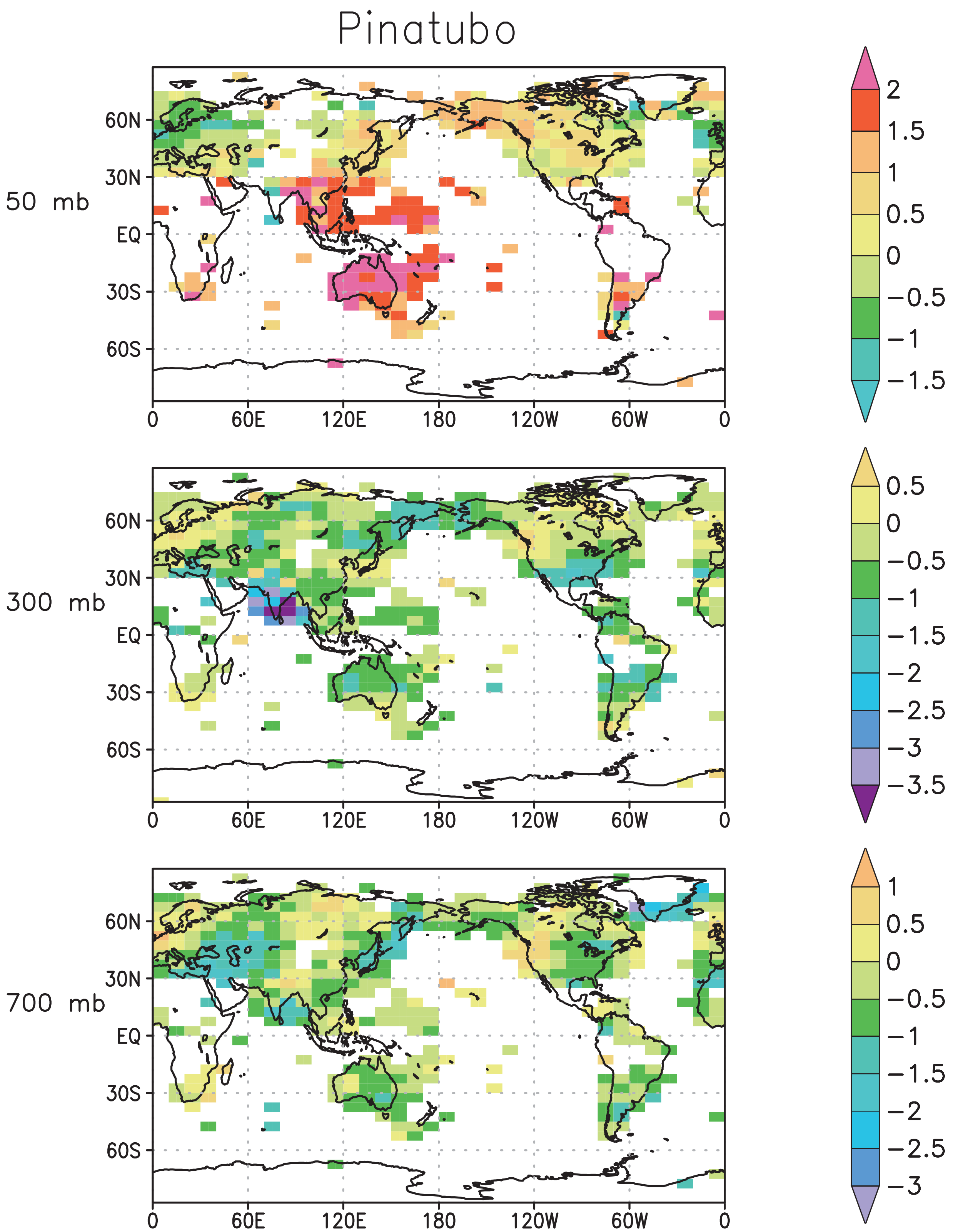

Figure 2a. Mean of temperature anomalies (°C) for the 24 months after the eruption minus the 24 months before the eruption in the full data set, after removal of quasi-biennial oscillation (QBO) and El Niño-Southern Oscillation (ENSO) (Southern Oscillation Index (SOI)) signals as described in the text, for Pinatubo (1991) and at 50, 300, and 700 mbar.

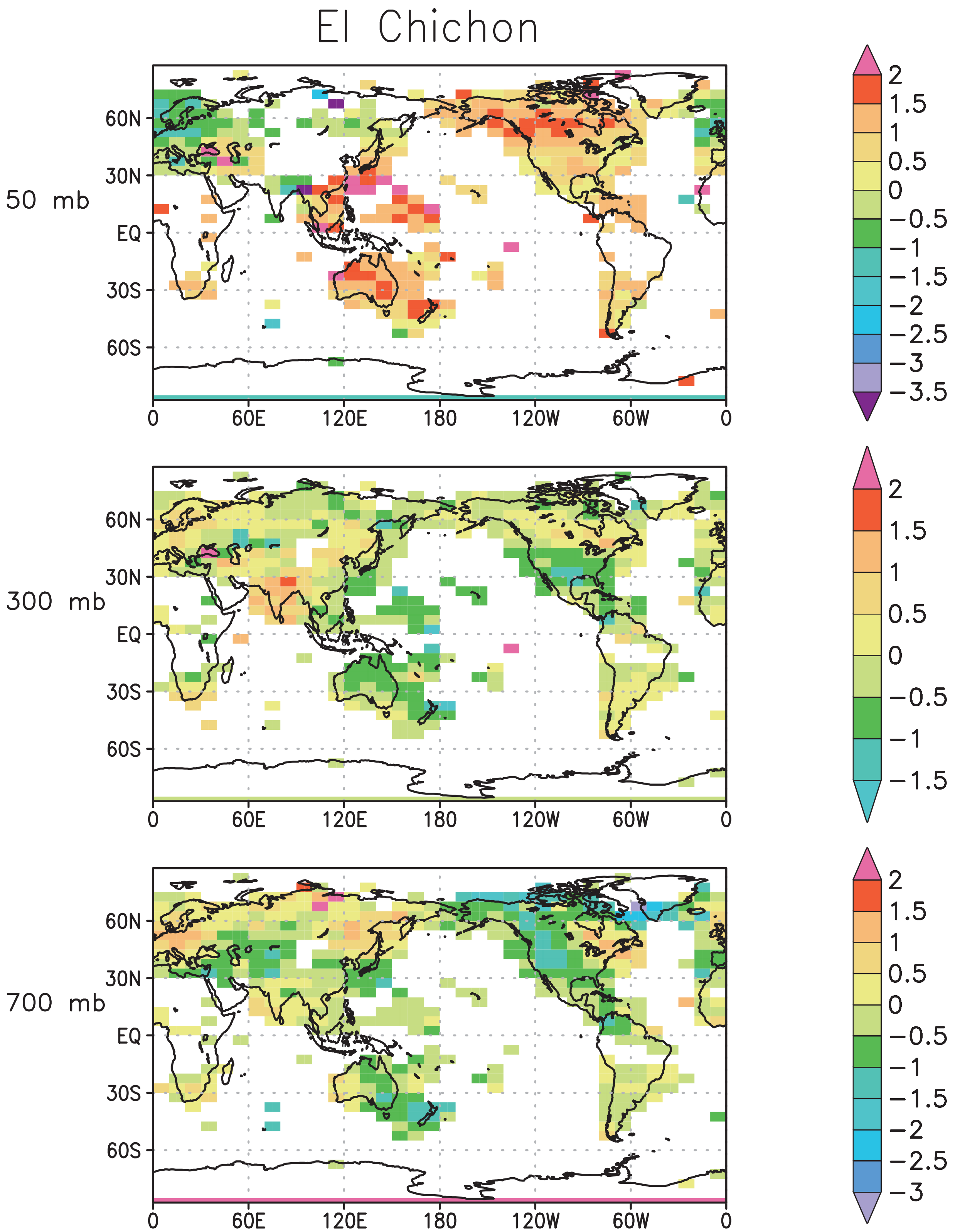

Figure 2b. Same as Figure 2a, except for El Chichon (1982).

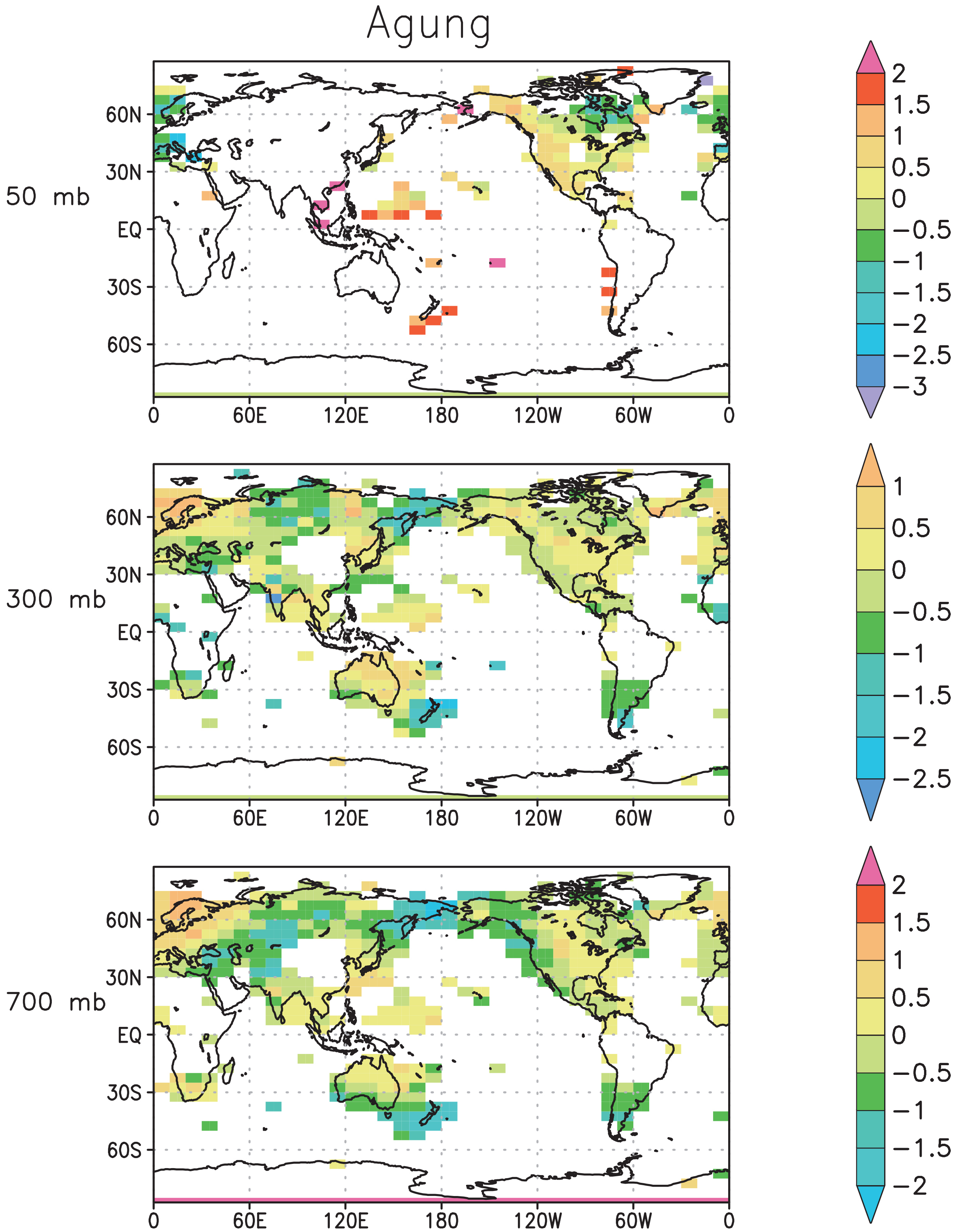

Figure 2c. Same as Figure 2a, except for Agung (1963).