Observed Tropospheric Temperature Response to 11-yr Solar Cycle and What It Reveals about Mechanisms

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ABSTRACT

Using 54 yr of NCEP reanalysis global data from 1000 to 10 hPa, this study establishes the existence and the statistical significance of the zonal-mean temperature response to the 11-yr solar cycle throughout the troposphere and parts of the lower stratosphere. Two types of statistical analysis are used: the composite-mean difference projection method, which tests the existence of the solar cycle signal level by level, and the adaptive AR(p)-t test, which tells if a particular local feature is statistically significant at the 95% confidence level. A larger area of statistical significance than that in previous published work is obtained, due to the longer record and a better trend removal process. It reveals a spatial pattern consistent with a ''bottom up'' mechanism, involving evaporative feedback near the tropical ocean surface and tropical vertical convection, latent heating of the tropical upper troposphere, and poleward large-scale heat transport to the polar regions. It provides an alternative to the currently favored ''top down'' mechanism involving stratospheric ozone heating.

1. Introduction

There is, as yet, no accepted mechanism for producing the temperature response in the lower terrestrial atmosphere to the 11-yr solar cycle forcing, although the candidates are numerous and perhaps too many [see the reviews by Gray et al. (2005); Gray et al. (2010); Haigh (2007)]. Since the response is expected to be small given the small radiative forcing of 0.1% from solar minimum (min) to solar maximum (max), which is imbedded in a larger climate noise, many of the features ''observed'' may not be real (i.e., statistically significant). We therefore pay particular attention not only to establishing the existence of the 11-yr solar signal in the response but also to the statistical significance of the features to which we will point.

So far, we have established the existence of the solar cycle signal at the Earth's surface using various datasets, some 150 yr long (Camp and Tung 2007a; Tung and Camp 2008; Tung et al. 2008; Zhou and Tung 2010; Tung and Zhou 2010). To get some hints on the mechanism, we need to examine the latitude–height patterns of the response. The availability of the upper-air data restricts the earliest global data record we can examine to 1958, the International Geophysical Year, when a coordinated effort in upper-air measurements began (Jenne 1999).

Previously, Labitzke et al. (2002) obtained the annual-mean latitude–height pattern of zonal-mean temperature from 1000 to 10 hPa, in a composite-mean difference (CMD) between solar max years and solar min years, using National Centers for Environmental Prediction (NCEP) reanalysis (1968–99). The correlation of the response to the forcing is low, and no statistical test was attempted. Haigh (2003) used multiple regression analysis and obtained a latitude–height pattern as the regression coefficient of the total solar irradiance (TSI). A statistical test was performed using the Student's t test after prewhitening the data. Most of the signal in the latitude–height plane was found not to be statistically significant, with the exception of a horizontal region of warming near the tropical tropopause, and two vertical strips of warming at midlatitudes, forming a ''horseshoe'' pattern of warming. The cause for this pattern has been attributed to a shift in the Hadley circulation, which supposedly weakens and broadens during solar max (Haigh 1999). Haigh et al. (2005) further suggested that such shifts in the tropical circulation can be brought about by an increase in tropical temperature in the lower stratosphere caused by enhanced ozone absorption of solar ultraviolet radiation. This is often termed the ''top down'' mechanism.

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On the other hand, numerous model studies of the greenhouse gas warming problem show that a robust response to radiative heating near the surface also takes the form of an expanded Hadley circulation, resulting in a poleward shift of the tropospheric jets and the accompanying storm tracks [see Held and Soden (2006) for a summary]. It is also known that such patterns can be produced with a spectrally uniform change in solar irradiance (Manabe and Wetherald 1975; Manabe 1983; Hansen et al. 1984) without needing the enhanced UV change required in the top down mechanism. In fact, a 2% change in TSI (20 times the observed variation from solar min to solar max) produces a similar amplitude and spatial pattern in the troposphere as a $2 \times CO_2$ radiative forcing would produce. The amplitude of both is amplified by the climate feedbacks by a factor of 2, which are model dependent. Recently, Cai and Tung (2012) explained how a ''bottom up'' mechanism, involving only the troposphere, can lead to the response mentioned above: The bulk of the solar forcing, in absolute terms, is in the visible/near-infrared range, which penetrates to the surface of the Earth, and has the largest amplitude in the tropics. Here, most of the absorbed energy goes into evaporating water. The ''evaporative feedback'' reduces the surface warming, and reduces heat loss to the underlying ocean. Vertical convection in the tropics deposits this energy in the form of latent heat in the upper troposphere, below the tropopause. The negative meridional temperature gradient in the upper troposphere, further strengthened by water vapor feedback, leads to a large-scale downgradient poleward heat transport. The latter produces a poleward shift of the tropospheric jet. A warmed pole aloft then radiatively warms the statically stable polar surface via downward thermal radiation. The resulting pattern at the surface is one with polar amplification of warming, with the largest surface warming found at high latitudes, where the solar forcing is actually the smallest, and the minimum warming over the ocean in the tropics—just the opposite of what one would expect from the meridional shape of the solar forcing.

It therefore appears that either a top-down or a bottom-up mechanism can produce the same observed horseshoe pattern of solar cycle warming in the latitude–height plane. The mechanism of Cai and Tung (2012) yields additional predicted patterns that can be tested using observation. It is hoped that, with the longer observational record that is now available, we will be able to find more features that are statistically significant, helping to deduce which of the mechanisms proposed is dominant in producing the observed response.

2. Data and methodology

We analyze the monthly-mean air temperature data from the NCEP reanalysis (Kalnay et al. 1996) over the period 1958–2011. The method of locally weighted scatterplot smoothing (LOWESS) (Cleveland 1979; Cleveland and Devlin 1988) is applied to 20-yr subsets of data to obtain the nonuniform trend, which is removed before analysis. The second reanalysis dataset, the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim; Dee et al. 2011), which revises and corrects the 40-yr ECMWF Re-Analysis (ERA-40), is currently too short (only since 1979) to average out the quasi-biennial oscillation (QBO) and El Niño–Southern Oscillation (ENSO) contamination in the lower stratosphere and upper troposphere.

First, we establish the existence of an 11-yr solar cycle signal using the composite-mean difference projection method (Camp and Tung 2007a). The null hypothesis is that there does not exist a solar cycle signal, so that the observed correlation coefficient ρ is obtainable with randomly generated data. In the second statistical test, we ask if specific features of the solar cycle response are distinguishable from random noise at various latitudinal and vertical locations. The null hypothesis is that the magnitude of the response at that location is not high enough to distinguish it from randomly generated noise.

3. Results

Figure 1 shows the CMD spatial pattern at several pressure levels (left column) along with the time series obtained by projecting the annual-mean temperature data onto this pattern (middle column). At 1000 hPa, the result here is consistent with the surface warming obtained previously by Camp and Tung (2007a), showing polar amplification of warming and tropical minimum of warming to the south of the equator, where there is more ocean. The response in time generally follows the TSI index.

Figure 2 shows the latitude–height distribution of the CMD pattern. A second type of statistical test, the adaptive AR(p)-t test is performed and the result expressed in contour form. The regions that pass the statistical test at the 95% confidence level are larger than in previous work.

a. Troposphere

The existence of the solar cycle signal is established for the entire troposphere for the first time at the 95% confidence level in the annual mean (see confidence level on the right axis of Fig. 2).

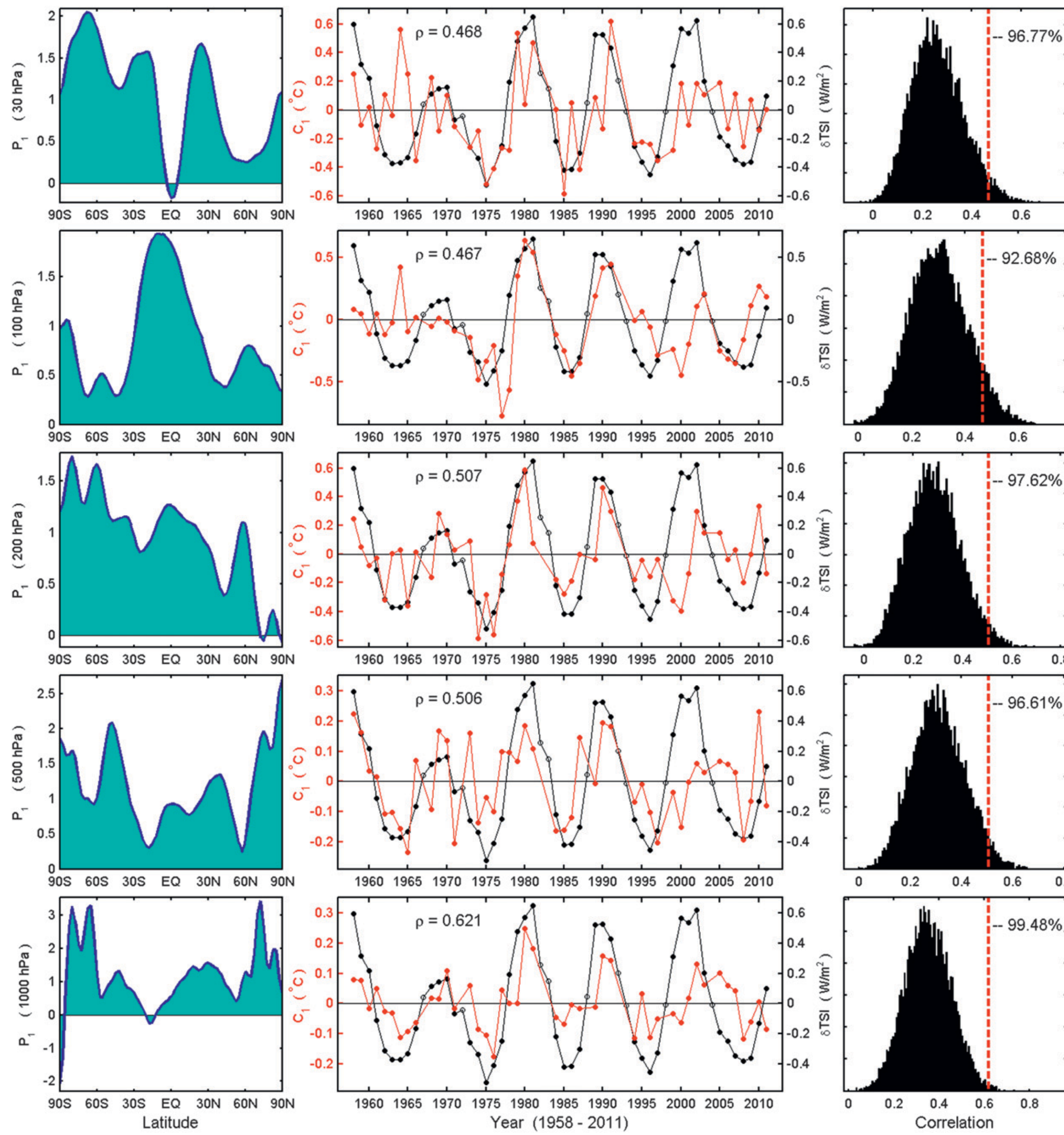

FIG. 1. (left) CMD patterns as a function of latitude of the annual-mean zonal-mean NCEP temperature, and (middle) the time series obtained by projecting the temperature data onto this pattern with the TSI index superimposed. The correlation coefficient ρ between these two time series is indicated in (middle). (right) The statistical confidence level using the Monte Carlo–generated synthetic data and their correlation coefficients with the TSI (the null distribution) are shown at each pressure level. Autocorrelations in the real temperature data are simulated in the synthetic data using the moving-block bootstrap method (Efron and Tibshirani 1993; Lahiri 2003; Leger et al. 1992; Wilks 1997; Zhou and Tung 2010), which resamples blocks (each 7 yr long) of consecutive data points with replacement from the observed time series.

There is a warming region below the tropopause over the tropics, with the statistically significant part centered at 200 hPa. This feature is present for all four seasons. If it were due to ozone heating, then the warming center would have occurred in the stratosphere. This same warming center at 200 hPa is found in the model result of Cai and Tung (2012), caused by latent heating brought up from the surface by vertical convection. At the surface, evaporative feedback should reduce the warming there, and indeed we find minimum warming

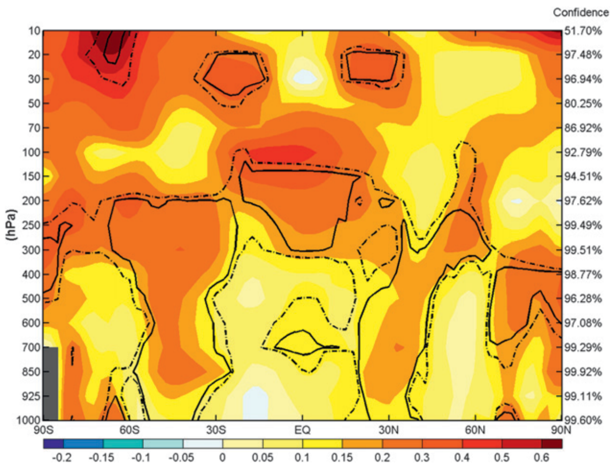

FIG. 2. CMD pattern between the solar max and solar min groups in annual-mean zonal-mean NCEP temperature (°C). Dot–dashed and solid contours are for the 90% and 95% confidence levels, respectively, based on a two-sided test: a modified Student's t test with a model in the form of $x(t) = \beta \cdot \mathrm{TSI}(t) + \varepsilon(t)$, where $x(t)$ represents the temperature data and $\varepsilon(t)$ is assumed to be an autoregressive Gaussian red noise of order p [AR(p)]. We then fit an AR(p) model to the residual $\hat{\varepsilon}(t) = x(t) - \hat{\beta} \cdot \mathrm{TSI}(t)$ and assume that $\varepsilon(t)$ obeys the same AR(p) process as $\hat{\varepsilon}(t)$. The Yule–Walker estimation is used for the autoregressive coefficients, and p is determined by minimizing the Akaike information criterion with a correction (Brockwell and Davis 2002). The existence of the 11-yr solar cycle signal is established level by level, with the confidence level listed on the right axis.

over the tropical surface south of the equator, where there is more ocean. At the 200-hPa level, there is a negative poleward temperature gradient and so poleward and downward heat transport is possible, and the spatial patterns appear to show a poleward and downward pattern of warming. Two vertical strips of warming outside the edge of the tropics are a robust feature for all seasons, and statistically significant. Haigh (2003) first showed this in the annual mean. We interpret them as a consequence of the large-scale heat transport in the troposphere leading to the poleward shift of the Hadley circulation. This is the same interpretation as originally advanced by Haigh et al. (2005), except that we will argue that they may not be due to stratospheric influence.

Similar patterns but of much smaller areas of statistical significance are shown in Fig. 11 of Gray et al. (2010) using ERA-40 temperature, consisting of the tropical tropospheric warming that occurs below 100 hPa (well separated from the lower-stratospheric heating located around 50 hPa) and two broken strips of warming near the midlatitudes.

There is no indication of a solar peak–cold (La Niña) event association at the equatorial Pacific, as proposed by Van Loon et al. (2007) and Meehl et al. (2009). For recent reexaminations, see Haam and Tung (2012), Tung and Zhou (2010), and Roy and Haigh (2010, 2012).

b. Stratosphere

The statistical significance of the solar cycle signal in the stratosphere is notoriously difficult to establish. The largest warming occurs over the polar stratosphere in the polar night. Since both solar max and easterly QBO can trigger a stratospheric sudden warming (Naito and Hirota 1997), the solar signal is statistically significant only during the quiet, westerly phase of the QBO. The small difference between solar max and solar min during the more perturbed easterly phase of the QBO can be of either sign and not statistically significant (Camp and Tung 2007b). We are able to obtain a statistically significant solar cycle polar stratospheric warming during boreal winter [December–February (DJF)] using the CMD projection method without having to segregate the data into QBO phases (Fig. 3a). The amplitude of the warming is, however, smaller than if the data were segregated, due to the QBO contamination. This result is consistent with the conclusion of Camp and Tung (2007b), that solar max warms the polar stratosphere during late winter and that there is generally no reversal of the solar max warming regardless of the phase of the QBO. The pattern of polar warming and cooling south of 60°N is suggestive of the meridional pattern of the sudden warming phenomenon (Matsuno 1971). The polar stratospheric signal in the dynamically active season of austral late winter–early spring [September–November (SON)] in the stratosphere (Fig. 3b) is consistent with its northern counterpart, but it is not statistically significant possibly because of poorer data quality. In the tropics, the direct solar ozone heating occurs near the stratopause, at 1 hPa (Gray et al. 2010). In the lower stratosphere, the warming is thought to be indirect and affected by ENSO and variable sea surface temperature; therefore, it is sensitive to the subperiod analyzed. The two warming centers near 30 hPa on both sides of the equator are statistically significant in the annual mean (Fig. 2), but they are not present in winter and summer. Nor are they occurring in the same region in other seasons. They show up most clearly in July–August (Fig. 3c) as the downward legs of heating centered at the equator with a maximum at 10 hPa or higher. However, because the heating is located so high above the tropopause and because it does not occur in all seasons—it is actually a cooling in the lower stratosphere in the 2 months shown in Fig. 3d—it is not likely that they are the cause of the two tropospheric vertical strips of warming, which are seen in all seasons in approximately the same locations.

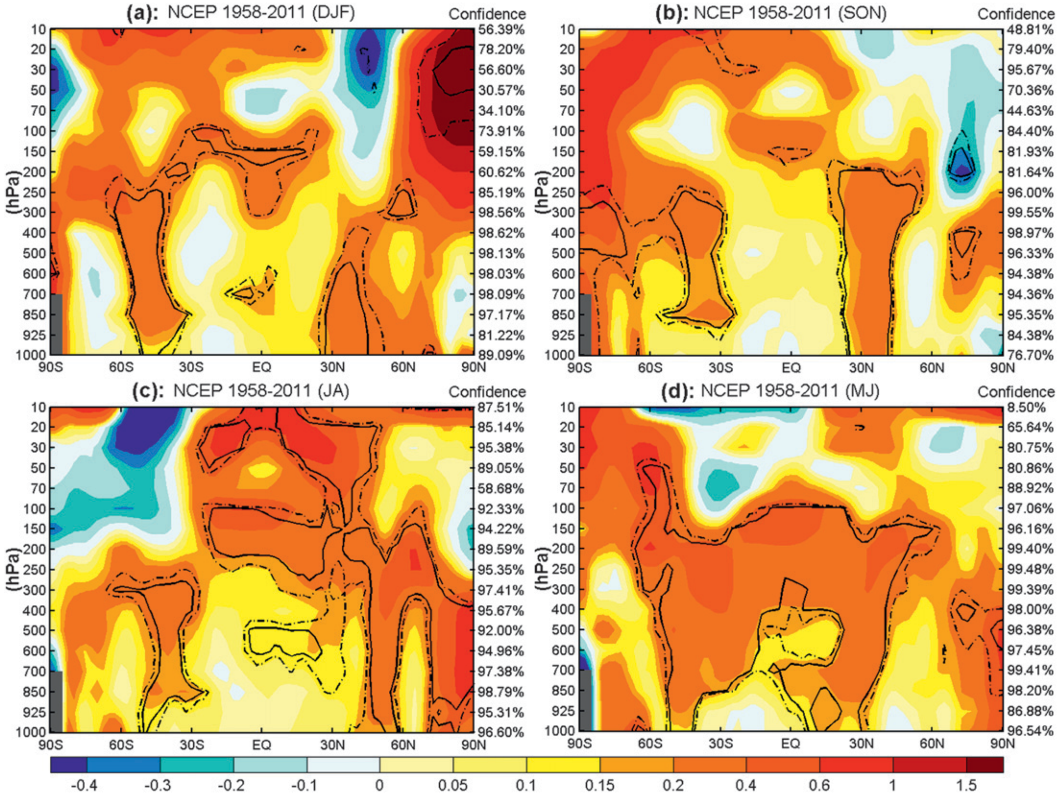

FIG. 3. As in Fig. 2, but for (a) boreal winter (DJF), (b) late austral winter and early spring (SON), (c) July–August average, and (d) May–June average.

4. Conclusions

We have established statistically the existence of the 11-yr solar cycle signal in temperature throughout the troposphere. There is a robust heating center located over the tropics below the tropopause in all seasons, which is statistically significant. It cannot be interpreted as heating due to ozone absorption of solar UV radiation, since tropospheric ozone concentration is extremely small. This heating is situated above a minimum in warming over the tropical ocean surface, suggestive of vertical convection caused by surface heating and evaporative feedback (which reduces surface warming). There are two vertical strips of warming outside the edge of the tropics in the troposphere that could be a result of a poleward shift of an expanded Hadley circulation. The evidence we present here is suggestive of a ''bottom up'' mechanism for the tropospheric and surface response similar to that for greenhouse warming, as discussed in Cai and Tung (2012): Most of the solar forcing reaching the surface in the tropics does not go directly into warming the ocean but into evaporating water and heating the upper troposphere through convection and latent heating. From there large-scale transport carries the heat poleward, resulting in a global warming pattern. Because the tropical ocean is not warmed appreciably, only a small fraction of the heat is transferred into the ocean mixed layer. This may explain why the lag in the surface and tropospheric response is almost nonexistent, smaller than expected based on the thermal inertia of the entire mixed layer, and why the amplitude of the response is close to that estimated at equilibrium.

Previously, there have been several general circulation modeling studies with fixed sea surface temperature (SST) (Shindell et al. 1999; Haigh 1996, 1999; Larkin et al. 2000; Matthes et al. 2004; Balachandran et al. 1999) to isolate the ''top down'' effect. However, given that the visible/near-infrared solar heating in these experiments still penetrates to the surface, evaporates water, and causes vertical convection, the calculated circulation change could still be, at least partly, from the bottom-up mechanism that we proposed. Since the change in the tropical SST is small in both the observation shown here and in the model of Cai and Tung (2012) where the SST was allowed to vary, fixing the SST in the important tropics in these experiments does not present a condition so different as to prevent the bottom-up mechanism from acting. Therefore, the results from these fixed SST experiments cannot be interpreted as arising only from the top-down mechanism.

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