The ENSO Signal in Tropical Tropospheric Temperature

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ABSTRACT

Interannual anomalies in tropical tropospheric temperature have been shown to be related to interannual anomalies in tropical mean sea surface temperature (SST) by a simple moist adiabatic relationship. On physical grounds, it is less obvious than it might at first seem that this should be the case. It is expected that the free-tropospheric temperature should be sensitive primarily to SST anomalies in regions in which the mean SST is high and deep convection is frequent, rather than to the tropical mean SST. The tropical mean also includes nonconvecting regions in which the SST has no direct way of influencing the free troposphere. However, interannual anomalies of SST averaged over regions of high monthly mean precipitation are very similar to interannual anomalies of tropical mean SST. Empirical orthogonal function analysis of the monthly SST histograms for the period of 1982–98 reveals a leading mode, well separated from the others, whose structure is very similar to a simple shift of the annual and climatological mean histogram, without change of shape. As a consequence, many different ways of sampling the histogram will yield similar anomaly time series, and the adequacy of the mean SST for predicting the tropospheric temperature appears coincidental from the point of view of the uncoupled atmospheric problem with given SST. There is a suggestion in the results that changes in the histogram shape may be significant for the tropospheric temperature anomalies associated with some large El Niño events and that in those events it is indeed the SST anomalies in the convective regions that are most important in controlling the tropospheric temperature.

1. Introduction

There is a clear interannual signal, associated with the El Niño–Southern Oscillation (ENSO) phenomenon, in the temperature of the tropical free troposphere (Yulaeva and Wallace 1994). Interannual tropical mean tropospheric temperature anomalies associated with ENSO appear to be related to tropical mean SST anomalies by a simple moist-adiabatic relationship (Hurrell and Trenberth 1998; Wentz and Schabel 2000). Soden (2000) showed that a variety of atmospheric general circulation models (GCMs) were able to simulate the ENSO signal in tropospheric temperature fairly accurately, given the observed sea surface temperature (SST) distribution as a boundary condition.

The moist-adiabatic relationship between tropical mean SST and tropical mean tropospheric temperature appears at first glance to be consistent with the simplest possible physical model, in which convective adjustment renders the tropical tropospheric temperature profile moist adiabatic (Stone and Carlson 1979), the surface air temperature is close to the SST, and the surface relative humidity has some approximately fixed value. We argue that, in fact, because the SST is spatially variable while the free-tropospheric temperature is much less so, the relationship between the tropical mean SST and tropospheric temperature is not as simple as it appears, but results from a special feature of the time-varying SST distribution.

Convective adjustment can act directly only in regions of frequent precipitation, which also tend to be regions of high SST. However, the atmospheric temperature is constrained by dynamical adjustment to be nearly horizontally uniform throughout the Tropics (e.g., Charney 1963; Schneider 1977; Held and Hou 1980; Bretherton and Smolarkiewicz 1989; Sobel and Bretherton 2000). It

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follows that, to a first approximation, the entire tropical atmosphere, including dry regions, should lie on a single moist adiabat determined by the SST in the regions in which it is highest (Wallace 1992). In regions of low SST, the surface has no direct means of influencing the free troposphere, and SST anomalies in such regions should not induce free-tropospheric temperature anomalies unless the SST anomalies are both positive and large enough to induce deep convection.

Based on this picture, there is no simple reason to have expected the close correspondence between interannual anomalies in tropospheric temperature and tropical mean SST that is observed. The tropical mean SST includes a significant contribution from regions of low SST and infrequent deep convection, and thus the tropical mean SST anomalies can in principle differ significantly from the SST anomalies in regions of high SST and frequent deep convection, the latter of which should determine the tropospheric temperature, in our view. The observations need to be reconciled with our physical arguments if the idea of moist convective adjustment is to be preserved.

We show that, at least for the two decades studied here, our physical picture is consistent with observations because the dominant mode of interannual variation in the SST histogram is essentially a simple shift of the entire histogram with no change in shape. The tropical mean SST thus has nearly the same interannual anomalies as the SST averaged over the strongly precipitating regions only (''rainy-region SST''). Our interpretation is that the correspondence of the tropical mean SST with tropical tropospheric temperature anomalies is essentially a coincidence resulting from the approximate invariance of the SST histogram's shape, though there may be an underlying dynamical reason for that approximate invariance. In strong El Niño events, the rainy-region SST does seem to be a slightly better predictor of tropospheric temperature than the tropical mean SST is.

Su et al. (2002, manuscript submitted to *J. Climate*) use numerical simulations to infer an influence function that describes to what extent SST anomalies in a given region control tropospheric temperature anomalies. They do find somewhat larger influence, though not greatly larger (as our argument supposes), in regions of high mean SST than elsewhere, and they provide arguments to explain this result. We leave the moderate discrepancy between their view and ours for future resolution.

2. Results

We use monthly mean anomalies in tropospheric temperature, as measured by channel 2 of the microwave sounding unit (MSU) instrument (Spencer and Christy 1992); the precipitation as analyzed by Xie and Arkin (1997), which includes information from rain gauges, satellite measurements, and model output; and the sea surface temperature according to the Integrated Global Ocean Services System (IGOSS) dataset (Reynolds and Smith 1994).

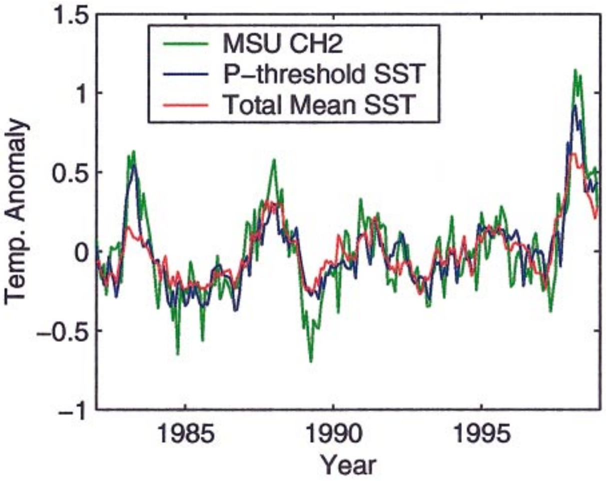

FIG. 1. MSU channel-2 temperature (°C) anomaly (green), precipitation-weighted SST anomaly (blue), and total mean SST anomaly (red) for 1982–98. Note that the mean SST anomaly is below the other two in the 1982/83 and 1997/98 El Niños, the first and last of the three largest positive peaks in all three curves.

Figure 1 shows the time series of monthly mean anomalies in three quantities: the MSU channel-2 tropospheric temperature, averaged from 30°S to 30°N and over all longitudes; the mean SST averaged over all ocean regions from 30°S to 30°N; and a rainy-region SST, computed as

$$\mathrm{SST}_P = \frac{\sum_i H(P_i - P_0)\mathrm{SST}_i}{\sum_i H(P_i - P_0)}, \qquad (1)$$

where i represents a spatial location on the grid, P_i is the (total) Xie–Arkin precipitation at that location, and SST_i is the SST anomaly at that location.[1] The sum is again taken over all ocean points between 30°S and 30°N. Here H is the Heaviside step function, and P_0 is a threshold, which we have chosen to be 6 mm day^{-1}; the results are not sensitive to modest changes in P_0. Scatterplots of monthly mean P versus SST for individual space–time points (not shown) show, with considerable scatter, mostly low values of P for SST < 27°C or so and a rapid increase of P at higher SST, as expected based on earlier studies that examined relationships between convective indices, such as outgoing longwave radiation, and SST (Graham and Barnett 1987; Fu et al. 1990, 1994; Zhang 1993). Thus, SST_P mainly samples the upper portion of the tropical SST distribution.

The three curves in Fig. 1 are nearly coincident. There is a hint in Fig. 1 that SST_P is better than the tropical mean SST for capturing the atmospheric temperature

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[1] In doing this, the IGOSS data (at 1° grid spacing) were regridded to the 2.5° grid spacing of the Xie–Arkin data.

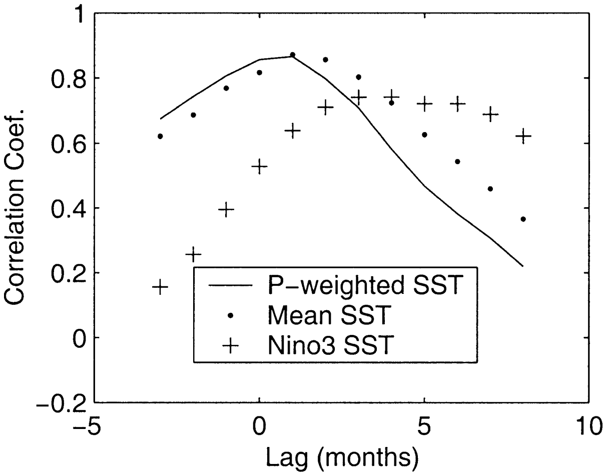

FIG. 2. Lag correlations of MSU channel-2 temperature anomaly against precipitation-weighted SST anomaly (solid curve), total mean SST anomaly (dotted curve), and Niño-3 SST anomaly (plus signs), for 1982–98. A positive lag means the atmospheric temperature measured by MSU lags the SST.

signal of the largest El Niño events; this is true for the 1982/83 and 1997/98 El Ninõs, the first and third of the three largest positive peaks in the time series. However, it is not true for the second, so with such a small sample the generality of this result is in doubt. In terms of overall correlation with the MSU data, Fig. 2 shows that SST_P is not superior to SST.

In Fig. 2 we show lag correlations between the two different SST time series shown above and the MSU channel-2 time series. Also shown, for reference and because ENSO is considered to be the primary dynamical driver of the interannual variations, is the lag correlation between the Niño-3 (5°S–5°N, 90°–150°W) SST and the MSU data. A positive lag means the SST leads the atmospheric temperature. The SST_P and the mean SST have nearly identical instantaneous (lag 0) correlation, but the mean has somewhat greater correlation at lags of 1 month and longer. The Niño-3 curve has a smaller maximum correlation than any of the others and a larger lag of maximum correlation, around 3–6 months, as has been noticed previously (Pan and Oort 1983; Yulaeva and Wallace 1994). The Niño-3 correlation is also much greater than the others at lags of 4–5 months or more.

The short lag of maximum correlation for all but the Niño-3 time series can be explained by the fact that local convective adjustment to SST anomalies is very rapid in regions in which deep convection is common and that the timescale for this adjustment to be communicated to the whole global Tropics is roughly the timescale for a fast equatorial Kelvin wave to circumnavigate the equator, or less than 1 month. The fact that the Niño-3 region maximizes at considerably longer lags than the others is consistent with the notion that the Niño-3 region drives the warming of SST in other regions through the atmosphere (Yulaeva and Wallace 1994; Klein et al. 1999; Chiang and Sobel 2002). The longer lag is consistent with the larger heat capacity associated with the ocean mixed layer (in regions other than Niño-3), which must also be warmed in order for convective heating anomalies directly associated with Niño-3 anomalies to warm the atmosphere, inducing a delay. The SST_P and mean SST curves already have this delay built in. They are nearly synchronous with the atmospheric temperature, presumably because both are being simultaneously driven by the central and east Pacific SSTs, as represented by Niño-3. The smaller maximum correlation of the Niño-3 time series as compared with the others is consistent with the fact that, despite its being the locus of the strongest interannual variability, the Niño-3 region constitutes only a small portion of the tropical oceans and cannot single-handedly determine the atmospheric temperature.

To understand in more detail why the tropical mean SST is nearly as good a predictor of the tropospheric temperature anomaly as the rainy region is, we performed an empirical orthogonal function (EOF) analysis on the histogram of tropical SST. For each month in the record, we computed a tropical SST histogram with a bin size of 0.2°C. The mean histogram over the entire record is shown in Fig. 3a and has the expected negative skewness with a cutoff near 30°C (Wallace 1992). We then computed a seasonal climatology by computing a mean histogram for each month of the year and computed anomalous histograms with reference to these climatological means. We then computed the EOFs of these anomalous histograms (the EOFs computed when the seasonal cycle is included are very similar). The dotted curve in Fig. 3b shows the first EOF, which explains 31.8% of the variance and is well separated from the next two at 16.0% and 12.9%, respectively. The principal component time series of the first EOF has a correlation coefficient of 0.81 with the tropical mean SST. The solid curve in Fig. 3b was computed by taking the mean histogram shown in Fig. 3a, shifting it by 0.2°C, subtracting the original from the shifted histogram (in essence, a differentiation of the histogram), and normalizing so that the curve thus produced and the first EOF have the same maximum value. Apart from some small noise-induced oscillations in the differentiated histogram and the fact that it has somewhat larger amplitude than the EOF at the lowest SSTs, the two curves are very similar, indicating that the dominant mode of SST variability corresponds approximately to a shift in the entire histogram without change of shape. Given this condition, there are many different ways of sampling the SST histogram that would yield anomaly time series similar to the mean (and to each other); the rainy-region SST is just one example.

3. Discussion

The near invariance of the shape of the SST histogram emerges as an interesting feature of our analysis, and one that requires explanation. The simplest explanation

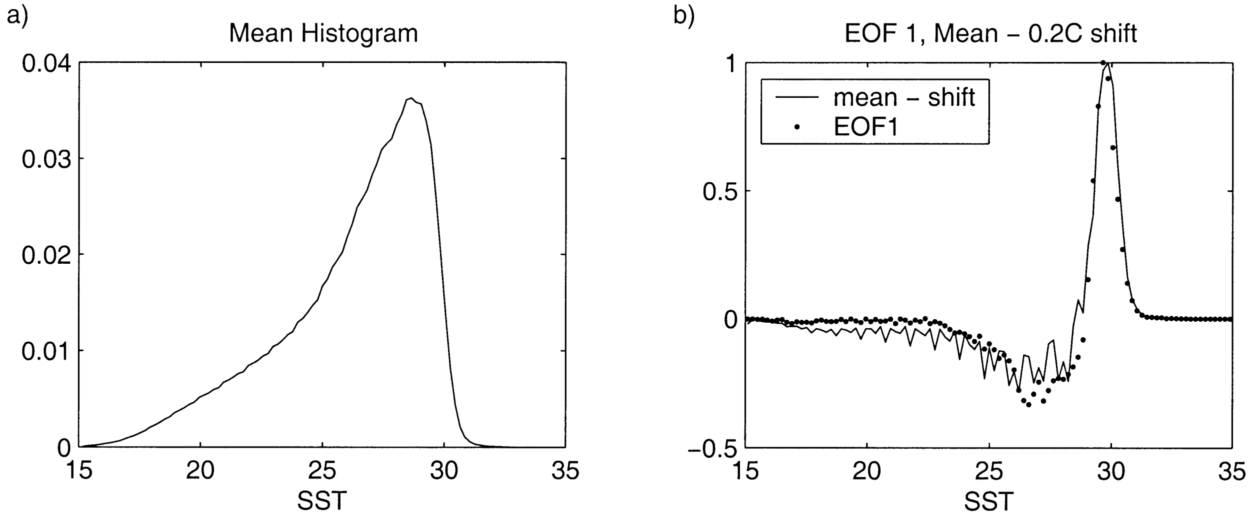

FIG. 3. (a) Mean histogram of 30°S–30°N SST over the 1982–98 record. (b) First EOF of the interannual anomaly in the SST histogram (dotted curve) and curve obtained by differentiating the mean shown in (a) (solid curve). See text for details.

seems to us to be the tendency for SST anomalies in convective regions to broaden in spatial scale until they reach the *atmospheric* deformation radius (Emanuel et al. 1994). SST anomalies influence the tropical free troposphere by inducing anomalous deep convection and heating. The dynamical adjustment of the atmosphere spreads the temperature anomaly over an atmospheric deformation radius, which for SST anomalies located within an equatorial deformation radius of the equator, is effectively the entire Tropics, as is observed for the ENSO signal (Yulaeva and Wallace 1994). Atmospheric temperature anomalies are eventually communicated to the sea surface in tropical ocean (or land) regions remote from the initial SST anomaly. Surface atmospheric temperature and humidity are connected to the free-tropospheric temperature to some degree by convective adjustment, at least in regions of deep convection. The sea surface temperature is then influenced by the surface atmospheric temperature and humidity through surface fluxes. A warmer overlying atmosphere will tend to warm the SST and vice versa. The dynamical adjustment of the atmosphere, the scale of which is the atmospheric deformation radius, is thus communicated back to the ocean. Brown and Bretherton (1997) pointed out that this mechanism might be the one by which ENSO induces SST anomalies in the tropical Indian and Atlantic Oceans, and Chiang and Sobel (2002) use a single-column model to simulate this process. Klein et al. (1999) found that the communication to the ocean is accomplished ultimately by anomalies in cloudiness and surface evaporation, both of which are influenced by the atmospheric temperature, though evaporation is also influenced strongly by the surface wind speed.

4. Conclusions

Simple physical arguments lead us to expect that the tropical mean free-tropospheric temperature will be determined predominantly by the SST where it is highest and convection is most frequent, rather than by the tropical mean SST. The data are at least consistent with this picture. It is difficult to show conclusively that the rainy regions' SST is controlling the tropospheric temperature, because the histogram tends to shift under interannual variability without changing shape very much. As a consequence, the time series of tropical mean and rainy-region SST anomalies are very similar and are equally well correlated instantaneously with tropical mean tropospheric temperature anomalies.

Nonetheless, our physical arguments suggest that this apparent adequacy of the mean SST for explaining the tropical mean tropospheric temperature is coincidental from the point of view of the uncoupled atmospheric problem, although the tendency of the SST histogram to shift quasi-uniformly may be a natural dynamical consequence of atmosphere–ocean coupling.

There is a suggestion in the results that the rainy-region SST is a better predictor for some of the largest El Niño events.

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