LETTERS

Indices of El Niño Evolution

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ABSTRACT

To characterize the nature of El Niño–Southern Oscillation (ENSO), sea surface temperature (SST) anomalies in different regions of the Pacific have been used. An optimal characterization of both the distinct character and the evolution of each El Niño or La Niña event is suggested that requires at least two indices: (i) SST anomalies in the Niño-3.4 region (referred to as N3.4), and (ii) a new index termed here the Trans-Niño Index (TNI), which is given by the difference in normalized anomalies of SST between Niño-1+2 and Niño-4 regions. The first index can be thought of as the mean SST throughout the equatorial Pacific east of the date line and the second index is the gradient in SST across the same region. Consequently, they are approximately orthogonal. TNI leads N3.4 by 3 to 12 months prior to the climate shift in 1976/77 and also follows N3.4 but with opposite sign 3 to 12 months later. However, after 1976/77, the sign of the TNI leads and lags are reversed.

1. Introduction

The El Niño–Southern Oscillation (ENSO) phenomenon is the dominant mode of coupled atmosphere–ocean variability on interannual timescales. El Niño, as the warm phase of ENSO, comes in many different "flavors." Every event has a somewhat different and distinct character. El Niño has been quantified in terms of simple indices as corresponding to times when sea surface temperature (SST) anomalies in the Niño-3 region (5°N–5°S, 150°–90°W) exceed 0.5°C or when SST anomalies in the Niño-3.4 region (5°N–5°S, 170°–120°W) exceed 0.4°C, which are evidently enough to produce perceptible impacts in Pacific rim countries (Trenberth 1997). However, such a definition does not discriminate between major, moderate, and minor El Niño events. Nor does it determine the character of individual events in terms of different SST patterns throughout the rest of the tropical Pacific. Because precipitation patterns depend on the total SST field, including gradients of SST, and the associated sea level pressure, and thus on the winds and the atmospheric convergence at low levels, these differences in patterns of SST in the Tropics matter a great deal in determining the flavor of each El Niño. This is the case not only throughout the Tropics but, through teleconnections, in the extratropics as well. Hence, an index of average SST in one region cannot adequately characterize the nature of the event.

A further key ingredient in determining the flavor is the rather different evolution of each El Niño. Although ENSO tends to be phase locked to the annual cycle and peaks in amplitude in the northern winter (Rasmusson and Carpenter 1982; Trenberth 1997), the evolution of El Niño events has changed substantially. In particular, before about 1976/77, when there was an abrupt climate shift in the Pacific circulation centered in the Tropics (Trenberth 1990; Trenberth and Hoar 1996; Zhang et al. 1997; Guilderson and Schrag 1998; Urban et al. 2000), El Niño events tended to develop first along the coast of South America and then spread westward, as was found in the composites of Rasmusson and Carpenter (1982) based on six warm ENSO events from 1951 to 1972. More recent events developed first in the central Pacific and then spread eastward (e.g., Wang 1995). There are also decadal changes in climate throughout the Pacific basin (Trenberth and Hurrell 1994).

Simply characterizing the different flavors, as seen in the different structure of individual events and their evolution, has been done mainly through the indices in different parts of the tropical Pacific. In addition to those noted above, use is made of SSTs averaged over the Niño-1+2 region (0°–10°S, 90°–80°W), which is the traditional Niño region along the South American coast,

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and Niño-4 (5°N–5°S, 160°E–150°W). However, the SSTs in all four Niño regions are highly correlated and so a simple description has not been easy to accomplish. In this letter we describe two indices that characterize much of ENSO and its evolution. A key point is that at least two indices are required.

2. Indices of ENSO

In a study, to be reported elsewhere, of coupled variability between the atmosphere and ocean as seen through SSTs and the divergent component of vertically integrated atmospheric energy transports, using singular value decomposition analysis, we found that the two dominant modes were closely related to ENSO and its evolution. The first mode was well described by time series corresponding to SST anomalies in the Niño-3.4 region (which we refer to as N3.4), while the second mode helped capture the evolution of ENSO in the months leading up to the event and, with opposite sign, the subsequent evolution after the event. The latter highlighted the differences between the SSTs near the date line and those along the coast of the Americas in the Tropics. Accordingly, it appears that ENSO can be characterized, to some extent, by the combination of two indices. The first, N3.4, can be thought of as representing the average equatorial SST across the Pacific from about the date line to the American coast. The second is the gradient across the same region. Therefore, the second index, which we call the Trans-Niño index (TNI), can be given by the difference between the normalized SST anomalies averaged in the Niño-1+2 and Niño-4 regions. Because N3.4 can be approximately thought as the sum of these two indices, N3.4 and TNI are approximately orthogonal at zero lag.

The smaller areal extent of Niño-1+2 and the larger variance of the SSTs in the region compared with Niño-4 means that normalization is desirable before the difference is taken. The SSTs are first standardized in each region by removing the monthly mean to get the anomalies and dividing by the standard deviation of the anomaly time series. We define $\mathrm{TNI} = \mathrm{SST}_{1+2_N} - \mathrm{SST}_{4_N}$, where the subscript N refers to normalization of the anomalies, and then we further normalize the resulting series to have unit standard deviation.

a. Data

We have explored the indices using a combination of two datasets. The first is the optimum interpolation SST analysis of the National Centers for Environmental Prediction (NCEP) Climate Prediction Center, described by Reynolds and Smith (1994), which begins November 1981. To extend the record we take advantage of the new HADISST dataset, from the Hadley Center, in which SSTs have been reanalyzed in a consistent manner to address problems found with the earlier Global Sea-Ice and SST (GISST) data series of SST analyses (see Hurrell and Trenberth 1999). Hence, we use this dataset from January 1871 to October 1981 and the NCEP SST analyses from November 1981 to September 2000. Both grids are 1° × 1° and all area averages and computations are at full resolution.

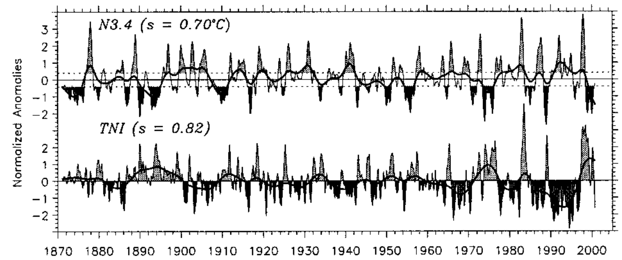

FIG. 1. Time series of SSTs from Niño-3.4 (top), and TNI (bottom) from 1871 to 2000. Both time series are normalized by the standard deviation *s*, as given. (top) Shading is included to show where thresholds of ±0.4°C are exceeded, indicating ENSO events. A low-pass spline fit highlights interdecadal variations.

The analyses after late 1981 make use of satellite data to improve coverage and better define the patterns of SST. Prior to 1981, observational coverage has varied. Because the number of observations in the tropical Pacific drops greatly prior to about 1950, the quality of the analyses is not as good as in recent years and structures of SST anomalies are partially imposed by the method of analysis, which used empirical orthogonal functions as a means of spatial interpolation. Data are very sparse in the Pacific prior to the opening of the Panama Canal in 1914, and many months do not contain any observations in the Niño-3.4 or Niño-4 regions.

The base period of 1950–79 is used to define the monthly means and standard deviations. For 1950–79 the SST standard deviations are 0.917°C for Niño-1+2, 0.745°C for Niño-3.4, and 0.567°C for Niño-4. A raw TNI is computed using the monthly anomalies. As has been traditionally done for the N3.4 time series in the NCEP monthly *Climate Diagnostics Bulletin* a 5-month running mean of TNI is computed, and the result is normalized using the standard deviation for 1950–79 (0.818). (The monthly time series of the indices are available online at www.cgd.ucar.edu/cas/indices/.)

b. Time series

Figure 1 presents the time series of the two indices. For N3.4 the shading shows where the index exceeds 0.4°C in magnitude and therefore, as long as these persist for six months or more (Trenberth 1997), they indicate ENSO events. Of note in these plots are the major El Niño events of 1878, 1982/83, and 1997/98 in N3.4. The magnitude of the TNI fluctuations drops noticeably prior to about 1960, and its overall character changes prior to about 1900. While the 1982/83 and 1997/98 events have strong signatures in TNI, there is no such signal in 1878. We suspect this is more a commentary on the quality of the analyses and the absence of data

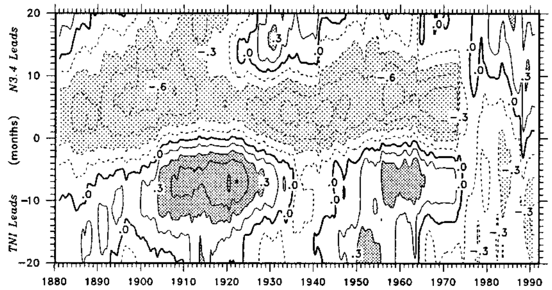

FIG. 2. Moving cross correlations of TNI with N3.4 as 241-month running means (about 20 yr). Negative lag means TNI leads, and positive lag means N3.4 leads. Values exceeding 0.3 in magnitude are shaded.

than a reflection of the true variability. Consequently, we focus on the post-1900 period in subsequent results.

Because we have suggested that the two indices should be orthogonal but related at leads and lags through the evolution of ENSO, we compute cross correlations over about 20-yr periods, to cover several ENSO events, as a function of lead and lag up to ± 20 months. We use N3.4 as the reference series and negative lag refers to a lead by TNI, while a positive lag refers to a lead by N3.4. To center the results, we use 241 months to compute the running correlations (Fig. 2). The 5% two-tailed significance level is 0.28 and we have shaded values exceeding 0.3 in magnitude. This reveals how the two indices have varied in their relation to each other throughout the twentieth century.

Correlations overall are close to zero at zero lag (Fig. 2). There is a strong tendency prior to 1976 for values of TNI of opposite sign (negative correlations) to occur 3 to 12 months after N3.4 and also values of the TNI of the same sign occur 3 to 12 months before N3.4. The positive correlations are not as strong as the negative ones, and they break down from 1935 to 1945 because of the prolonged 1939–42 El Niño event. Figure 2 spectacularly reveals an abrupt transition about 1976/77 of the change in evolution of ENSO as the effects of the 1982/83 El Niño enter into the running correlation. After the late 1980s, when the period after 1977 is encompassed in the 20-yr moving correlation, values of TNI of opposite sign occur about 12 months before N3.4, with correlations exceeding -0.5, to be followed after the peak in N3.4 by TNI of the same sign about 10 months later and correlations of 0.3.

c. SST patterns

To show what these indices mean in terms of SST patterns, we present correlations for 1900– 1976 and 1977–2000 to show differences and similarities across the climate shift. Throughout the record, for N3.4 (Fig. 3) there is a strong connection in the central and eastern tropical Pacific, with a ''boomerang'' shape of opposite signed anomalies at 20°–40° latitude in both hemispheres linked in the far western equatorial Pacific. Pos-

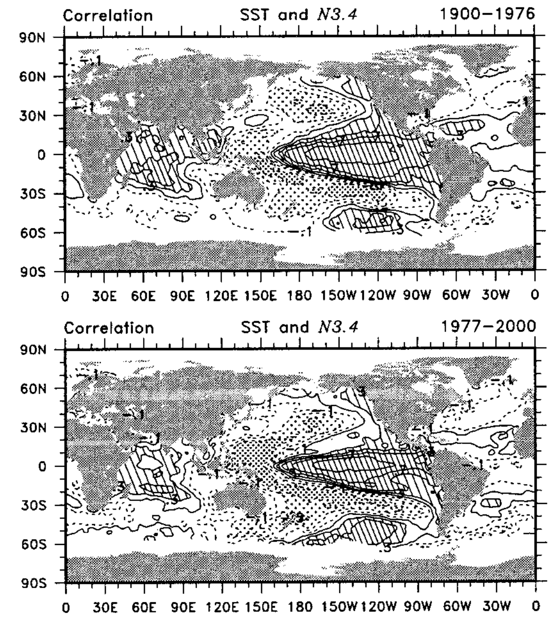

FIG. 3. Correlations of SST anomalies with N3.4 for 1900–76 and 1977–2000. Values exceeding 0.3 are hatched and less than -0.3 are stippled. The contour interval is 0.2.

itive values in the Indian Ocean, a weak dipole structure in the tropical Atlantic, negative values in the North Pacific and around New Zealand, and positive values in the southeast Pacific are all features known to be associated with ENSO (Trenberth and Caron 2000).

For TNI (Fig. 4), however, there are differences between the two subperiods. For 1900–76 the boomerang-

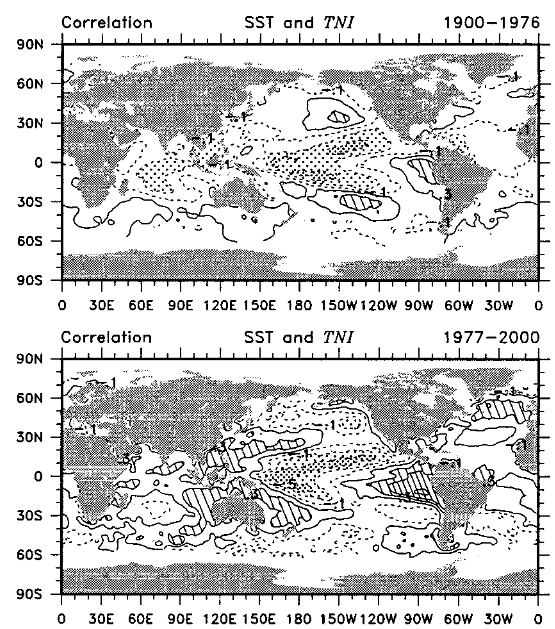

FIG. 4. Correlations of SST anomalies with TNI for 1900–76 and 1977–2000. Values exceeding 0.3 are hatched and less than -0.3 are stippled. The contour interval is 0.2.

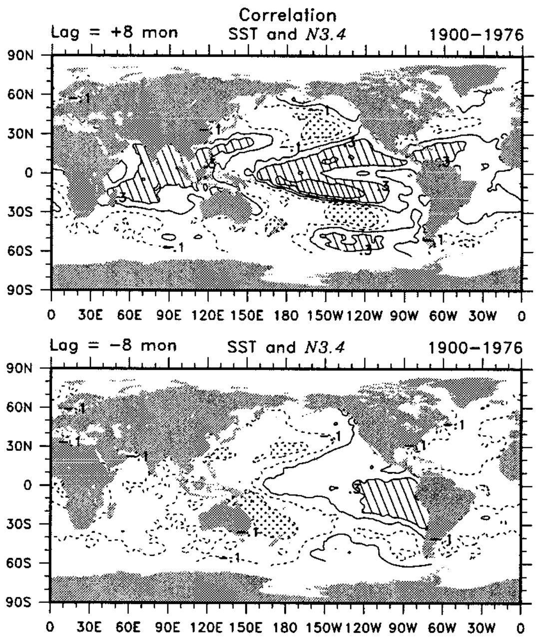

FIG. 5. Correlations of SST anomalies with N3.4 at ±8 months lag for 1900–76. Values exceeding 0.3 are hatched and less than −0.3 are stippled. The contour interval is 0.2.

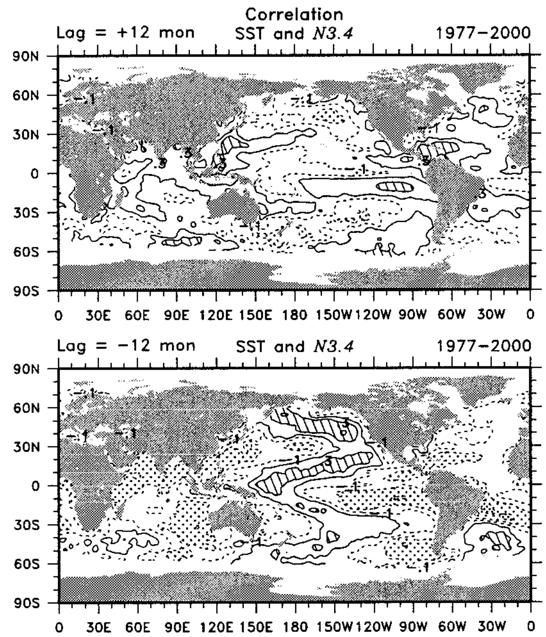

FIG. 6. Correlations of SST anomalies with N3.4 at ±12 months lag for 1977–2000. Values exceeding 0.3 are hatched and less than −0.3 are stippled. The contour interval is 0.2.

shaped negative correlations have moved eastward relative to Fig. 3 and become dominant, while the positive correlations have shrunk. Positive correlations emerge in the Pacific near 45°N and 35°S, and negative values are evident in the Indian Ocean. For 1977–2000, the dipole across the tropical Pacific remains, although the patterns have changed substantially nearly everywhere else.

The corresponding regression patterns (not shown) are quite similar. For N3.4, the SST anomalies corresponding to a unit standard deviation are 1°C in the equatorial Pacific and −0.5°C in the boomerang structure. For TNI, representative anomalies are ±0.5°C in the two main centers, but are as large as 1°C just off Ecuador in the post-1977 interval.

To demonstrate the relevance of TNI to the evolution of ENSO, Fig. 5 shows the correlations with N3.4 at ±8 months lag for 1900–76 while Fig. 6 shows the same but for 1977–2000 at ±12 months lag. The discussion focuses on the El Niño phase of ENSO.

At −8 months lag (i.e., before the El Niño peak) for 1900–76 (Fig. 5), warming occurs along the coast of South America, as found by Rasmusson and Carpenter (1982), and the TNI pattern is somewhat evident. At +8 months lag, however, there is a strong TNI pattern present with negative sign. For the post-1977 period, the maximum warming at −12 months lag in the central equatorial Pacific appears to develop from the boomerang-shaped off-equatorial and western equatorial regions, with a strong negative TNI presence obvious. The positive anomalies develop and progress eastward. By +12 months lag the importance of the TNI with positive sign is somewhat evident, as the positive SST anomalies are now south of the equator in the Pacific and cooling has spread from the west along the equator.

3. Conclusions

To even approximately describe the character and evolution of ENSO events it is essential to have at least two indices, and perhaps more. Climate models have great difficulty in realistically simulating ENSO (Latif et al. 2001) and a primary measure of success has been the magnitude of SST anomalies in Niño-3.4 region. However, TNI should also be examined in evaluating models to determine the extent to which the different flavors of ENSO are captured. Several studies (e.g., Jones 1989; Christy and McNider 1994; Zhang et al. 1996) have attempted to linearly ''remove'' the influence of ENSO using a single index. We suggest that much of the ENSO-related variance probably remains from such a process because of the different flavors of El Niño and the slow and varying evolution of each event. While adding TNI may help, the change in TNI patterns outside of the Tropics is a limitation. Also, the leads and lags of TNI relative to N3.4 suggest that the index may be important for predictive purposes.

We have suggested that two indices of ENSO are necessary to enable the flavors of ENSO to be captured. Essentially these consist of the equatorial average SST anomalies east of the date line, which is well represented by N3.4, and the contrast in SSTs across the equatorial Pacific, given by TNI. The former has a pattern that is fairly stable with time throughout the twentieth century, while the latter appears to have changed at the time of the climate shift in 1976/77 outside of the tropical Pacific. Of considerable interest is the dramatic switch in the evolution of ENSO at the time of the 1976/77 shift that is well captured by the relationship between these two indices (Fig. 2). The reasons why the change in evolution with the 1976/77 climate shift occurred are quite uncertain but appear to relate to changes in the thermocline (Guilderson and Schrag 1998) that could be linked to climate change and global warming (Trenberth and Hoar 1996; Timmermann et al. 1999).

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