

NOTES AND CORRESPONDENCE

A Quantitative Evaluation of ENSO Indices

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ABSTRACT

El Niño–Southern Oscillation (ENSO) is a natural, coupled atmospheric–oceanic cycle that occurs in the tropical Pacific Ocean on an approximate timescale of 2–7 yr. ENSO events have been shown in previous studies to be related to regional extremes in weather (e.g., hurricane occurrences, frequency and severity of tornadoes, droughts, and floods). The teleconnection of ENSO events to extreme weather events means that the ability to classify an event as El Niño or La Niña is of interest in scientific and other applications.

ENSO is most often classified using indices that indicate the warmth and coolness of equatorial tropical Pacific Ocean sea surface temperatures (SSTs). Another commonly used index is based on sea level pressure differences measured across the tropical Pacific Ocean. More recently, other indices have been proposed and have been shown to be effective in describing ENSO events. There is currently no consensus within the scientific community as to which of many indices best captures ENSO phases. The goal of this study is to compare several commonly used ENSO indices and to determine whether or not one index is superior in defining ENSO events; or alternatively, to determine which indices are best for various applications.

The response and sensitivity of the SST-based indices and pressure-based indices are compared. The Niño-4 index has a relatively weak response to El Niño; the Niño-1+2 index has a relatively strong response to La Niña. Analysis of the sensitivity of the indices relative to one another suggests that the choice of index to use in ENSO studies is dependent upon the phase of ENSO that is to be studied. The Japan Meteorological Agency (JMA) index is found to be more sensitive to La Niña events than all other indices. The Southern Oscillation, Niño-3.4, and Niño-4 indices are almost equally sensitive to El Niño events and are more sensitive than the JMA, Niño-1+2, and Niño-3 indices.

1. Introduction

El Niño–Southern Oscillation (ENSO) is a natural coupled cycle in the ocean–atmospheric system over the tropical Pacific that operates on a timescale of 2–7 yr. Observations of El Niño–related weather impacts near Peru can be traced back to 1525 (Ortlieb 2000); and these impacts were first noted by scientists in the 1890s (Glantz 2001). Warm (El Niño) and cold (La Niña) ENSO phases have been associated with regional extremes in precipitation (e.g., Ropelewski and Halpert 1996). During a warm ENSO event, the eastern coastal tropical Pacific fish population may decrease due to reduced nutrient content in the coastal waters (Ahrens 1994).

The phase and strength of ENSO events are typically defined by an index; however, there are many such indices. There is no consensus within the scientific community as to which index best defines ENSO years or

the strength, timing, and duration of events. Indices that are commonly used to classify ENSO events include regional sea surface temperature (SST) indices [e.g., Niño-1+2, Niño-3, Niño-4, Niño-3.4, and Japan Meteorological Agency (JMA); see Table 1 for definitions] and the surface atmospheric pressure–based Southern Oscillation index (SOI). In addition to the aforementioned indices, several other indices have been proposed for the study of ENSO events. Two of these indices include the trans-Niño index (TNI) and the multivariate ENSO index (MEI). The effectiveness of these indices for indicating the phase and strength of the ENSO cycle is examined.

The SST indices are calculated using a reconstructed 100-yr SST anomaly dataset (Meyers et al. 1999). This approach allows the SST indices to be reconstructed without any gaps in the time series. The ENSO years and strengths defined for each index are then intercompared. This study focuses specifically on defining ENSO years as warm (El Niño), cold (La Niña), or neutral; and the strength of the events.

The descriptions of the indices used, as well as a discussion of duration, strength, and timing of an ENSO

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event are contained in section 2. The data are discussed in section 3. The methodology and results are found in section 4. Results suggest there is no single index that best captures ENSO phases when looking at the full 100-yr record. The Niño-3.4, Niño-3, and JMA indices fared similarly when compared to the SOI, while the Niño-1+2 and Niño-4 indices had substantially poorer matches to the SOI; however, we will show that the SOI is not an ideal standard of comparison. The Niño-1+2 index shows a weak response to La Niña events, whereas the Niño-4 index responds weakly to El Niño events. The TNI has been suggested to be good at showing patterns of formation of ENSO events, but it was not designed to capture the occurrence of ENSO events. The MEI correlates well with the SOI and SST-based indices in terms of identifying ENSO phases, but the response and sensitivity of this index is not evaluated in this study due to data limitations with the MEI. Sensitivity studies, which consider noise as well as response, suggest different indices are recommended depending upon the phase of ENSO to be studied. These and other results are summarized in section 5.

2. Background

El Niño is defined by Glantz (2001) to be the “name given to the occasional return of unusually warm water in the normally cold water [upwelling] region along the Peruvian coast.” It is also “a Pacific basin-wide increase in sea surface temperatures in the central and/or eastern equatorial Pacific Ocean” (Glantz 2001). The Southern Oscillation (SO) refers to “the global-scale phenomenon characterized by a change in the atmospheric pressure-field difference between the eastern and western tropical Pacific” (Aceituno 1992). El Niño and the Southern Oscillation are now known to be part of a coupled atmosphere–ocean system commonly known as ENSO. ENSO has three phases: warm tropical Pacific SSTs (El Niño), cold tropical Pacific SSTs (La Niña), and near-neutral conditions. ENSO is a complex system and many aspects of its development are still not well understood (especially cold phases). The lack of understanding further complicates efforts to define the morphology of ENSO events.

a. ENSO indices

Many different indices have been used to designate when El Niño or La Niña events have occurred. Six indices are examined in this study: Niño-1+2, Niño-3, Niño-3.4, Niño-4, the JMA index, and the SOI. The SOI is a pressure index and the rest are SST-based indices. The TNI and MEI will also be discussed.

The temperature-based indices are defined using mean SSTs within different regions of the equatorial Pacific (Table 1). The Niño-1 region is located off the coast of Peru and Ecuador, while the Niño-2 region is located near the Galapagos Island (Table 1). The com-

TABLE 1. The lat and lon ranges defining area averages for SST indices. SOI is calculated using pressure differences between Tahiti (17.5°S, 149.6°W) and Darwin (12.4°S, 130.9°E).

Index	Lat range	Lon range
Niño-1+2	0°–10°S	90°–80°W
Niño-3	5°N–5°S	150°–90°W
Niño-3.4	5°N–5°S	170°–120°W
Niño-4	5°N–5°S	160°E–150°W
JMA	4°N–4°S	150°–90°W
TNI	Niño-1+2 and Niño-4	Niño-1+2 and Niño-4

bined Niño-1+2 region is highly responsive to seasonal and El Niño–induced changes (Glantz 2001). The Niño-3 region is located in the central equatorial Pacific and is much less responsive to continental influences than the Niño-1 and Niño-2 regions. The Niño-4 region encompasses part of the western equatorial Pacific where the sea surface temperatures are typically warmest. Changes in SSTs in the Niño-4 region are related to longitudinal shifts of the strong east–west temperature gradients along the equator (Glantz 2001).

The Niño-3.4 region overlaps portions of the Niño-3 and Niño-4 regions covering an area from 5°N–5°S to 170°–120°W (Table 1). Barnston and Chelliah (1997) defined the Niño-3.4 region based on the correlation between the SOI-defined ENSO events being stronger with the Niño-3.4 index than with the Niño-3 index. The JMA index was defined by the Japan Meteorological Agency and is located within the Niño-3 region (Table 1), extending from 4°N–4°S to 150°–90°W.

The TNI is loosely related to the east–west temperature gradient in the eastern tropical Pacific (Trenberth and Stepaniak 2001). The TNI is a scaled difference between scaled SST anomalies averaged in the Niño-1+2 and Niño-4 regions. It has been suggested that the TNI indicates the evolution of the SST warming (i.e., east–west versus west–east). Trenberth and Stepaniak (2001) found that the TNI leads the ENSO signal in the Niño-3.4 region by 3–12 months prior to the climate shift of 1976/77 and lags thereafter. Because of this variable lag correlation, the TNI is not a good index for identification of individual ENSO events so it will not be included in our comparison of ENSO years.

The MEI is calculated based on six observed variables over the tropical Pacific (Wolter and Timlin 1993). These variables are sea level pressure, zonal and meridional components of the surface wind, SST, surface air temperature, and total cloudiness fraction of the sky. Values of the MEI from 1950 to the present are available online from the Climate Diagnostics Center (<http://www.cdc.noaa.gov/~kew/MEI>).

Horel and Wallace (1981) compared several SO parameters in the tropical Pacific including a sea surface temperature index, a sea level pressure (SLP) index, a 200-hPa index, as well as several rainfall indices. They found the SST and SLP indices to be best correlated with each other, although the correlation was not perfect.

This result suggests that the definition of the SOI in terms of SST will differ from the definition of SOI in terms of SLP. The SOI used in the present study is based on the commonly used difference between the Tahiti (French Polynesia) and Darwin (Australia) SLP (i.e., Tahiti minus Darwin; Table 1). Chen (1982) found the Tahiti–Darwin combination contained the largest variance (compared to differences at other locations) in the SO period range. The pressure difference is a measure of the strength of the trade winds, which flow from regions of high pressure in the eastern Pacific to regions of lower pressure in the western Pacific. There have been a few problems documented with the SOI dataset: the dataset has missing data early in the time series, as well as significant variability in the dataset (Trenberth 1984) that is unrelated to the SO.

b. Classifying El Niño and La Niña years

ENSO events can be classified by year of occurrence, strength, duration, or timing. Quinn et al. (1987) categorized El Niño events over the past four and a half centuries by the strength of the event. They used the Scientific Committee on Oceanic Research (SCOR) definition for identifying ENSO events after 1800 A.D., when atmospheric and sea surface data became available. Prior to 1800, other factors had to be considered and the strength of events was decided subjectively. The SCOR definition is as follows: the presence of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12°S) where the SST anomaly exceeds one standard deviation for at least four consecutive months at three or more of five coastal stations (Talara, Puerto Chicama, Chimbote, Isla Don Martin, and Callao). Very strong events were classified with SSTs around 7°–12°C above normal, and are associated with above-normal rainfall and massive destruction. Strong events (quite strong events) included those with SSTs 3°–5°C (5°–7°C) above normal, and are associated with large amounts of rainfall and major damage. A moderate event was one with SSTs 2°–3°C above normal, above-normal rainfall, and minor damage. A weak event had hardly any damage, normal rainfall, and SSTs 1°–2°C above normal.

Several other authors and agencies have provided methods for identifying the occurrence of an ENSO warm or cold phase. The methods vary greatly and each index identifies some common ENSO events. For example, van Loon and Madden (1981) defined ENSO events using sea level pressure data at multiple stations. The method of van Loon and Madden (1981) resulted in the identification of an equal number of warm and cold phases for the period 1899–1979. The Climate Prediction Center has produced the Niño-1, -2, -3, and -4 SST indices of ENSO occurrence since the early 1980s (V. Kousky 2001, personal communication) and provides the commonly used Tahiti minus Darwin SOI. The JMA defines a warm (cold) ENSO event as a consec-

utive 6-month period, including October, November, and December, where the SST anomalies in the JMA region (Table 1) are greater than 0.5°C (less than –0.5°C). The JMA identifies two more ENSO warm phases than cold phases during the period 1894–1992. In the present study, the JMA criterion for duration is used to define the ENSO extremes; however, the SST thresholds for occurrence are determined using a quartile method (see section 4b).

The duration of ENSO events and timing of ENSO events are also important. Trenberth and Shea (1987) suggest the timescale for an El Niño event must be greater than 2 yr due to the time needed for the evolution of the event. Timing plays a role in which ENSO characteristics are best captured by the ENSO indices. The Niño-3.4 captures the ENSO event near its onset in the late summer. Other indices (e.g., Niño-1+2, Niño-4, JMA) best capture the events in the winter when ENSO events usually peak (Glantz 2001). This study does not focus on changes in duration or timing of the events but rather the strength of the events and the years of the events.

3. Data

The SST-based ENSO indices are most fairly compared when the indices are determined from a common SST dataset. The SST indices are reconstructed by averaging reconstructed SST data (Meyers et al. 1999) over the regions of the Pacific Ocean corresponding to each index (Table 1) for each month from 1894 to 1993. The reconstructed SST data are available on a 2° latitude × 2° longitude grid extending from 29°N to 29°S and 121°E to 75°W, covering a period from 1894 to 1993.

Missing data often exist in SST datasets from the mid-1800s until the mid-1900s. Meyers et al. (1999) reconstructed the SST anomalies to provide a temporally and spatially complete dataset for the equatorial Pacific Ocean. Monthly Reynolds optimal interpolation SST fields from November 1981 to 1993 were used to determine the empirical orthogonal functions (EOFs) of monthly anomalies. These functions were projected on available in situ observations to create spatially complete fields. The in situ data used were SSTs from the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987), with the biases related to instrument errors removed. The applicable number of modes of EOFs was determined using the 1970s COADS SSTs. The variance of the misfits to large-scale features was minimized using large-scale error analysis to choose the number of modes. The COADS SST anomalies of the months under consideration were least squares fit to the number of EOF modes chosen. This procedure resulted in spatially complete (2° × 2° grid) SST anomaly fields.

The ENSO indices recalculated herein are based on the spatially averaged SSTs in the applicable ENSO regions (Table 1). Long-term monthly climatologies for each ENSO region are calculated by averaging over each

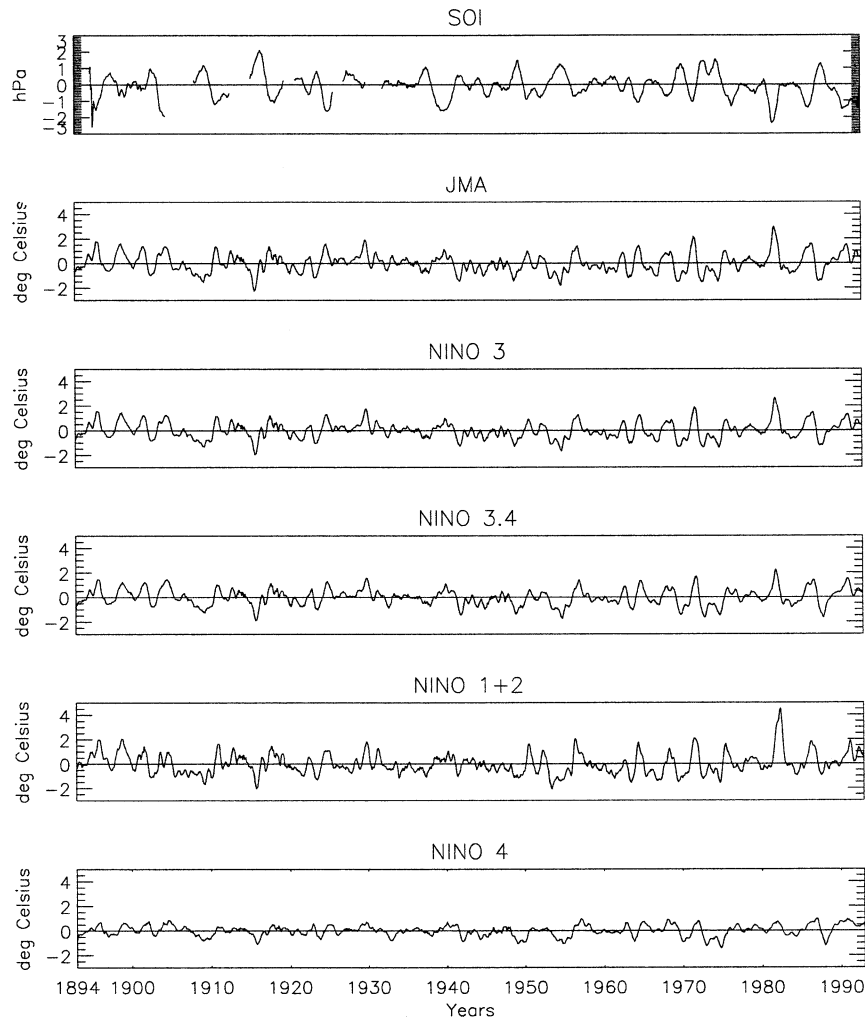


FIG. 1. Time series of the 13-month running mean of the SOI and 5-month running means of various SST-based ENSO indices.

calendar month in the time series. The long-term mean is subtracted from each time series to create series of anomalies, which are then smoothed with a 5-month running mean (Fig. 1). The 5-month running mean of the SST anomalies represent the time series of each ENSO SST index. For the SST indices, a positive value that exceeds an upper threshold (section 4b) is defined as an El Niño event and a negative value less than a lower threshold is defined as a La Niña event.

The SST-based ENSO indices are compared to the SOI (which has an opposite sign convention for ENSO events). For the SOI, a 13-month mean of the Tahiti–Darwin SLP anomalies (Fig. 1) is used instead of a 5-month mean due to the relatively poor signal-to-noise ratio. The SOI values are obtained from the Climate Prediction Center (CPC) and are available from the following CPC ftp sites: 1) <ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi.his>, and 2) <ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi>.

4. Analysis and discussion

The relative strengths/weaknesses of each index in identifying ENSO phases are analyzed through several methods. First, trends in the reconstructed indices are evaluated using a running sum filter. Next, ENSO years are classified and compared to the SOI and the JMA. Finally, the response of the SST indices to the strength of the ENSO extreme events is assessed, and the sensitivity of indices relative to one another is calculated.

a. SST index trends

A running sum filter, applied to each reconstructed index to reveal multiyear trends in the SST anomalies (Fig. 2), can be defined using the following relationship:

$$R(t) = \sum_{i=1}^{i=t} X(i), \quad (1)$$

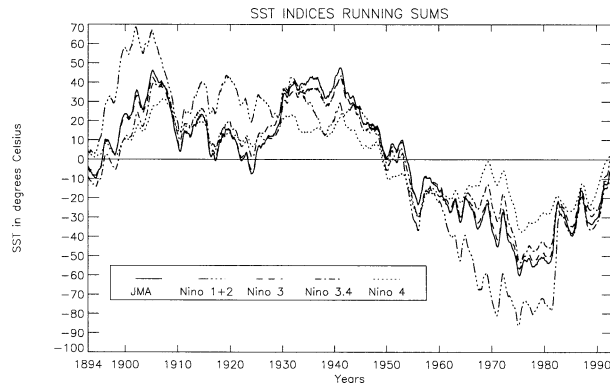


FIG. 2. Time series of the SST index running sums with each mean removed. The running sums are plotted for the JMA (black), Niño-1+2 (alternating long dash then three short dashes), Niño-3 (long dash), Niño-3.4 (alternating long dash and short dash), and Niño-4 (short dash) reconstructed SST ENSO indices.

where $R(t)$ is the running sum filter, X is time series, and t and i are indices for the time series. The running sums have upward trends from 1894 to 1906, 1925 to 1930, and 1982 to 1993. A rise in the running sum shows a period of positive SST anomalies that is associated with stronger and/or more frequent El Niño events. The downward trends in the running sums occur from 1906 to 1910 and a longer period from 1942 to 1976. A decrease indicates a period that may be associated with strong and/or more frequent La Niña events. There are slowly changing periods (near-zero slopes) in the running sums (e.g., 1910–25, 1930–41, and 1976–81). These slowly changing periods may be the result of periods of alternating El Niño and La Niña events of similar magnitude, consequently, one would expect little to no change in the slope of the running sums. These running sums appear to be negatively correlated to the Pacific decadal oscillation (PDO); an interdecadal pattern of climate variability located in the North Pacific Ocean (Mantua 2001). The running sums show mostly zero to positive slope prior to 1940. During this same period, the PDO was generally in a negative phase. The phase of the PDO shifted to positive values around 1942 (Bove 2000) and stayed in this phase until the mid-1970s. This period corresponds with the prolonged negative slope observed in the SST index running sums (Fig. 2). There appears to be high correlation between trends in the running sums of the ENSO SST indices (Fig. 2); however, the Niño-1+2 (Niño-4) amplitude is greater (less) than the other indices. This implies differences in response to ENSO events in the Niño-1+2 and Niño-4 regions.

b. Classifying the El Niño and La Niña years

For each index, the years corresponding to El Niño or La Niña are determined through a modified JMA definition. The JMA definition for a warm (cold) ENSO event requires SST in the JMA region (Table 1) to be

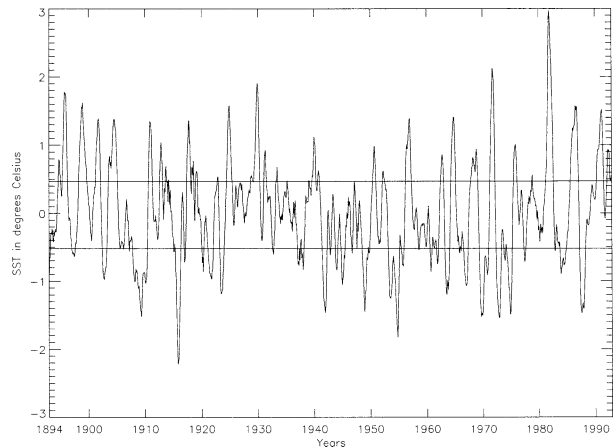


FIG. 3. Time series of the 5-month running means of the reconstructed JMA SST anomalies. The solid black lines mark the upper and lower quartile values, which are the thresholds for defining an El Niño or La Niña event, respectively.

greater than 0.5°C (less than -0.5°C) for six consecutive months and the months must include October–November–December (OND). In this study, the thresholds are determined from the reconstructed data anomalies. The monthly anomalies are sorted, and values for the 25th and 75th percentiles are determined. The value that defines the upper quartile (75th percentile) is used as a threshold (T_w) for El Niño occurrences, and the 25th percentile is used as a threshold (T_c) for La Niña occurrences. For example, the reconstructed JMA index has a T_w of 0.47°C and a T_c of -0.52°C (Fig. 3). Any year not meeting the ENSO warm (El Niño) or cold (La Niña) phase criteria is defined as a neutral year. The advantages of using quartiles are that they are determined from the data, and they need not be symmetric around zero.

c. Comparison to objective indices

The ENSO years defined by each reconstructed index are compared to those defined by the SOI index. These comparisons are summarized in a matrix format (Table 2). Matching events are shown in the diagonals of the matrices (e.g., JMA and the SOI agreed on 14 El Niño events, 32 neutral events, and 15 La Niña events; Table 2a). The off-diagonal values represent “false-alarms” (false positives) or “misses” (false negatives). Relative to SOI-based events, the Niño-1+2 index misses the most events, while the Niño-3 index has the fewest combined false alarms and misses. When the SOI is used as the standard of comparison, the differences between the various temperature indices are small. The Niño-4 index correctly identifies the most SOI-based El Niño events (15), with the fewest misses (4); however, it has the greatest number of false alarms (7). In contrast, the Niño-1+2 index has the smallest number of correct SOI-based El Niño events (12) and false alarms (3); however,

TABLE 2. Matrices of the comparison of reconstructed SST indices (a)–(e) with the SOI. There are a total of 83 yr available for comparison of the SST indices to the SOI due to missing SOI data.

		SOI			Total SST ENSO events
		El Niño	Neutral	La Niña	
(a) JMA index	El Niño	14	6	0	20
	Neutral	5	32	5	42
	La Niña	0	6	15	21
(b) Niño-3 index	El Niño	14	5	0	19
	Neutral	5	34	5	44
	La Niña	0	5	15	20
(c) Niño-3.4 index	El Niño	14	6	0	20
	Neutral	5	30	3	38
	La Niña	0	8	17	25
(d) Niño-4 index	El Niño	15	7	0	22
	Neutral	4	31	4	39
	La Niña	0	6	16	22
(e) Niño-1+2 index	El Niño	12	3	0	15
	Neutral	7	37	9	53
	La Niña	0	4	11	15
Total SOI events		19	44	20	

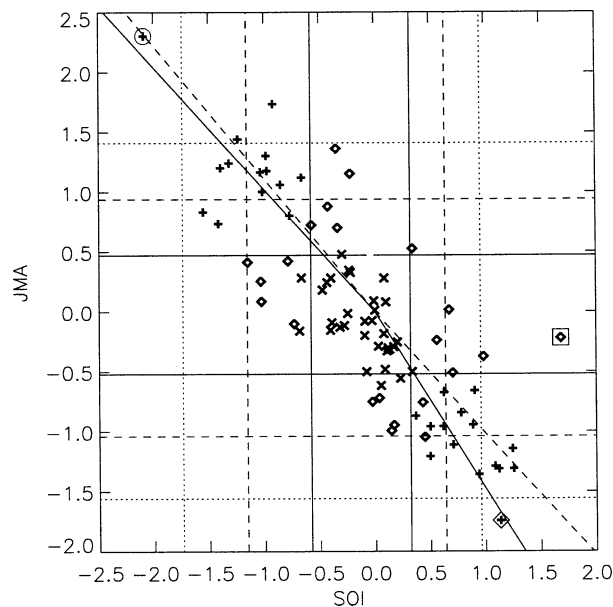


FIG. 4. Scatterplot of the JMA index vs the SOI. The + symbols indicate matching ENSO extreme phases, × symbols indicate matching neutral events, and ◊ symbols indicate mismatches. The lines indicate the thresholds for defining the strength of ENSO events. The solid lines are the thresholds for defining ENSO events, the dashed lines are the thresholds for a moderate ENSO event, and the dotted lines are the thresholds for a strong ENSO event. The circled event is the 1982 El Niño event, the diamond event is the 1916 La Niña event, and the squared event is the 1917 neutral extreme event. The solid black line is the best-fit slope to the data and represents the relative sensitivities of the two indices. The black dashed line represents the best-fit slope that would be found if the two indices had identical sensitivities.

it has the greatest number of misses (7). It is quite clear that the Niño-1+2 index is not well suited for identifying La Niña years; however, differences between the other indices appear to be small. Contingency tables can be used to determine unsuitable indices, but are inadequate to distinguish among the better temperature indices.

The MEI cannot be recomputed based on the methodology contained in this study; however, values are available for the period 1950–present and a comparison of the MEI can be made to the SOI and other SST indices from these values. When considering quartiles of the MEI, there is good agreement between SOI-based ENSO year, reconstructed SST indices, and the MEI (not shown). The agreement between the MEI and the SST indices is slightly better than that between the MEI and the SOI. This is consistent with the results of Wolter and Timlin (1998), who showed the MEI had a higher correlation to the Niño-3 index than the SOI or other SST indices. Nevertheless, the MEI identifies several ENSO events that are not identified by any other index, suggesting that the differences are significant.

d. Response and sensitivity of ENSO indices

Weak, moderate, and strong El Niño and La Niña events are defined using multiples of the quartile thresholds (T_w and T_c) previously defined. For example, in the case of the JMA, $T_w = 0.47^\circ\text{C}$ and $T_c = -0.52^\circ\text{C}$ (Fig. 4). These thresholds are compared to the mean of the months (MOM) of the 6–9 months around OND that exceed ENSO thresholds (section 4b). For neutral years, the MOM is based on all 9 months (July–March). For the response study, El Niño years are classified as strong when the MOM is greater than or equal to 3 times the warm phase threshold ($\text{MOM} \geq 3T_w$; (e.g., $\text{MOM} \geq$

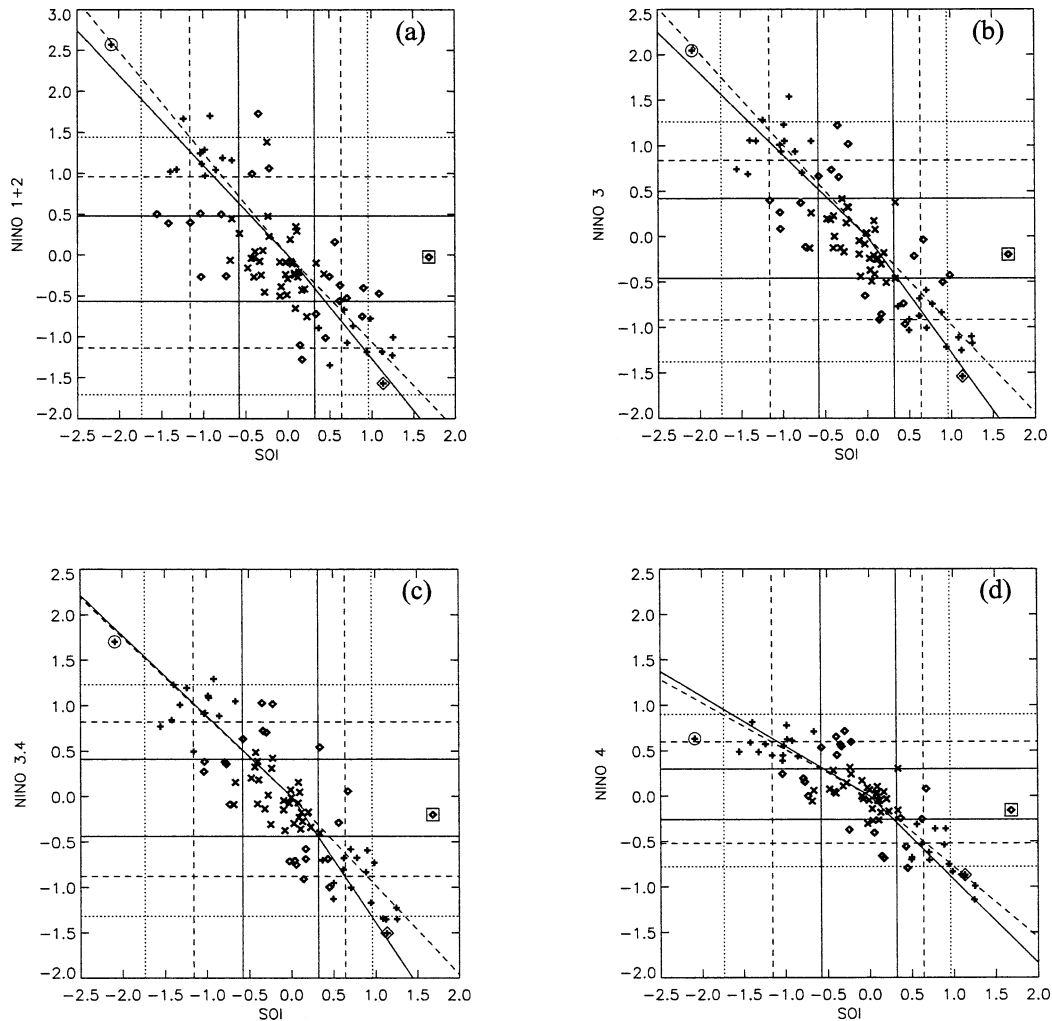


FIG. 5. Same as Fig. 4 except for ENSO temperature indices vs the SOI: (a) Niño-1+2; (b) Niño-3; (c) Niño-3.4; and (d) Niño-4.

1.41°C for the JMA). Moderate and weak El Niños are defined when $2T_w \leq \text{MOM} < 3T_w$ (e.g., 0.94°–1.41°C for the JMA) and $T_w \leq \text{MOM} < 2T_w$ (e.g., 0.47°–0.97°C for the JMA), respectively. Cold phases are classified for strength in a similar manner. This method classifies three strong El Niños and one strong La Niña for the JMA index (Fig. 4).

Scatterplots of the indices (SST versus SOI) show the different strengths of the events and the response of the indices to the ENSO events (Figs. 4 and 5). Neutral events (× symbols) located outside the neutral boundaries indicate that the events exceeded the mean anomaly magnitude criteria set forth by the thresholds; however, they fail the criterion for six or more consecutive months with sufficiently large anomalies.

The 1917 neutral event (square) seems to be out of place in all of the comparisons. The temperature indices define the 1917 event as a neutral event while the SOI classifies it as a strong La Niña event. At the present time, we are unable to explain this anomaly. There does

not appear to be any satisfactory explanation of this event in past or current literature.

The JMA, Niño-1+2, Niño-3, and Niño-3.4 indices classify the strongest El Niño event (circle) as 1982. The Niño-4 index downgrades the 1982 event to a moderate event (Fig. 5d). The Niño-4 region has a deeper mixed layer compared to the other ENSO regions, which suppresses the amount of warming that can occur in the sea surface temperatures. Consequently, the magnitude of SST warming observed in the Niño-4 region is less than that observed in other ENSO regions.

The JMA, Niño-1+2, Niño-3, and Niño-3.4 indices all show El Niño events reasonably well. The Niño-1+2 and Niño-3.4 have the most moderate and strong El Niño events matched with the SOI (12 events) while the Niño-4 has the least number of strong and moderate El Niño event matches compared to the SOI (6).

The Niño-1+2 region appears to be less responsive to La Niña events than other indices, identifying only six strong or moderate events. All of the indices except

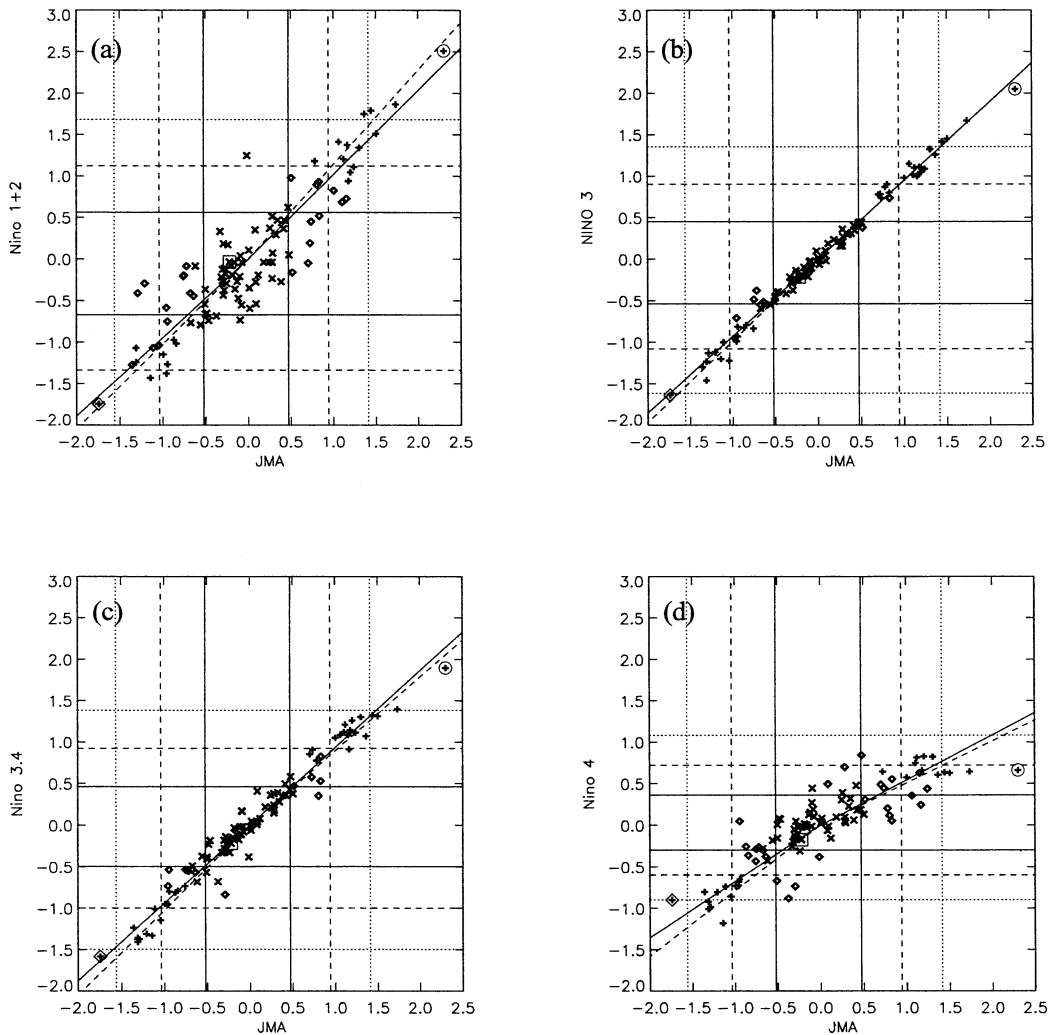


FIG. 6. Same as Fig. 5 except for ENSO temperature indices vs the JMA index.

Niño-4 identify the 1916 (diamond) La Niña as the strongest event, but the Niño-1+2 region downgrades it to a moderate event (Fig. 5a). It is suggested that the reason for downgrading this event is that upwelling is strong in the Niño-1+2 region, but increased upwelling during La Niña has little impact on SST anomalies. The Niño-4 index has the most moderate and strong La Niña events compared to the SOI (13 events), but downgrades the 1916 La Niña event and identifies two La Niña events that are stronger than the 1916 events.

These findings suggest that combining Niño-4 information on La Niñas and Niño-1+2 information on El Niños could result in a superior index. The TNI index (Trenberth and Stepaniak 2001) proved to be inappropriate for identification of ENSO phases associated with each year, indicating that a linear addition of the two indices is insufficient for the creation of an improved index. It also suggests that an index based solely on a strong response is flawed.

The response of one index relative to another can easily be seen in scatterplots (Figs. 4–6). For example, we have already shown that the Niño-4 index appears to have a relatively weak response to El Niño, and the Niño-1+2 index has a relatively weak response to La Niña. However, sensitivity is a better indicator of the effectiveness of an index: it considers both the signal and the noise, and it can be used to compare indices with differing units. For example, the relative sensitivity (RS) of the JMA index and SOI to ENSO is defined as

$$RS = \frac{\partial JMA}{\partial SOI} \frac{s_{SOI}}{s_{JMA}}, \quad (2)$$

where the derivative is the best-fit slope, and s is the standard deviation estimated from the available sample. The relative sensitivity can also be demonstrated with scatterplots (Figs. 4–6). The diagonal dashed black line indicates the best-fit slope that would be found if the

TABLE 3. Sensitivity of temperature indices relative to SOI, for El Niño and La Niña ENSO phases. Uncertainties indicate one std dev.

	Niño-1+2	Niño-3	JMA	Niño-3.4	Niño-4
El Niño	-0.881 ± 0.063	-0.892 ± 0.026	-0.919 ± 0.030	-1.012 ± 0.029	-1.070 ± 0.098
La Niña	-1.191 ± 0.050	-1.314 ± 0.050	-1.45 ± 0.11	-1.416 ± 0.073	-1.179 ± 0.026

two indices have identical sensitivity ($RS = 1$) and the observed standard deviations. The slope of this line is equal to the standard deviation of the variable plotted on the abscissa (restricted to positive values for El Niño, and negative values for La Niña), divided by the standard deviation of the variable plotted on the ordinate axis. A steeper best-fit slope (solid black line) than the dashed black line indicates that variable plotted on the abscissa is more sensitive than the variable plotted on the ordinate axis, while more gentle slopes indicate the opposite. Note that the anomalous La Niña of 1917 is excluded from calculations of uncertainty and sensitivity slopes.

The uncertainty (σ_y) of a calculated variable (y) can be determined (Taylor 1982) in terms of the uncertainties $\{\sigma_x\}$ in the input variables $\{x\}$ and the functional dependence, $y = f(\{x\})$:

$$\sigma_y = \left[\sum_i \left(\frac{\sigma_{x_i} \partial f}{\partial x_i} \right)^2 \right]^{0.5}. \quad (3)$$

This calculation applies to independent input variables; therefore, it is only an approximation in this application. The uncertainty in relative sensitivity (σ_{RS}) is

$$\sigma_{RS} = \left[\left(\frac{s_{JMA}}{s_{SOI}} \sigma_m \right)^2 + \left(\frac{m}{s_{SOI}} \sigma_{s_{JMA}} \right)^2 + \left(\frac{m s_{JMA}}{s_{SOI}^2} \sigma_{s_{SOI}} \right)^2 \right]^{0.5}, \quad (4)$$

where m is the best-fit slope (e.g., $\partial JMA / \partial SOI$), and σ indicates uncertainty in the subscripted variable. The values of m and σ_m can easily be calculated through standard statistical techniques (Taylor 1982). In this case we have simplified the problem by specifying that the best-fit line must pass through the origin. The uncertainties in the estimated standard deviations are determined through generalized cross validation (Wahba and Wendelberger 1980). For comparisons of temperature indices to the SOI, the first term on the right-hand side of (4) dominates the uncertainty, typically accounting for >80% of the variance. However, when temperature indices are compared to each other, the contributions from each term are usually similar.

Indices can have differing sensitivities to various ENSO phases, so slopes should be considered separately

for El Niño and La Niña events. For example (Fig. 4), the JMA index is somewhat less responsive to El Niño events than the SOI, and it is also substantially more sensitive to La Niña events (Table 3). Looking at the other temperature indices (Table 3; Fig. 5), the SOI is more sensitive to El Niño than the Niño-1+2, Niño-3, and JMA indices; and has similar sensitivity to the Niño-3.4 and Niño-4 indices. In contrast, all the temperature indices are more sensitive to La Niña than the SOI, with the JMA, Niño-3, and Niño-3.4 indices being clearly superior to the others.

Temperature indices can be intercompared in the same manner (Table 4; Fig. 6). Due to the good La Niña sensitivity, the JMA index is used as the standard of comparison. The Niño-1+2 index has a greater response to El Niño (Fig. 6); however, there is a great deal of uncertainty in that assessment, resulting in a poor relative sensitivity (Table 4). The JMA, Niño-3, Niño-3.4, and Niño-4 indices are almost identically effective as indicators of El Niño. As La Niña indicators, the other temperature indices clearly have less sensitivity than the JMA index.

5. Conclusions

Many indices have been defined by which ENSO events can be described. There is currently no consensus in the scientific community as to which of these indices best captures ENSO phases. Five ENSO indices are reconstructed from monthly SST anomalies to examine and compare characteristics of the different indices. The indices are compared using several methods.

A running sum filter applied to time series of indices of SST anomalies reveals strong similarities in the Niño-3, -3.4, and JMA indices. The Niño-1+2 and Niño-4 running sums are found to be significantly different from the other indices. Positive changes in the Niño-1+2 index are higher in amplitude, suggesting stronger responses to warm events while the negative changes in the Niño-4 index were the opposite, suggesting stronger response to cold events.

When the reconstructed SST indices are compared to the SOI, results show the Niño-3 index has the fewest number of false alarms and misses (20) and the highest

TABLE 4. Sensitivity of temperature indices relative to JMA, for El Niño and La Niña ENSO phases. Uncertainties indicate one std dev.

	Niño-1+2	Niño-3	Niño-3.4	Niño-4
El Niño	0.892 ± 0.010	1.001 ± 0.004	1.043 ± 0.005	1.071 ± 0.087
La Niña	0.924 ± 0.009	0.941 ± 0.003	0.916 ± 0.004	0.859 ± 0.043

number of ENSO phase matches (63) relative to SOI-based ENSO phases. The Niño-1+2 index has one of the worst responses, missing the highest number of events (23) and matching the lowest number (60). Comparison of the MEI to the SOI and reconstructed SST indices over a relatively short time period (43 yr) suggests that the MEI performs reasonably well during this period, although it may be too sensitive, resulting in an overprediction of ENSO events.

The La Niña and El Niño ENSO years are categorized into three different strength categories: weak, moderate, and strong. Scatterplots show the different strengths of the events and the sensitivity of the indices to the ENSO events. The Niño-4 index is shown to have a strong response to La Niña, but a poor response to El Niño. The Niño-1+2 index has the opposite characteristics. The Niño-4 index downgrades the strongest ENSO events relative to all other SST indices. This is consistent with the running means, where the Niño-4 running mean is shown to have lower amplitude than all other SST indices.

Analysis of the sensitivity of the indices to one another suggests that the choice of which index to use in ENSO studies is dependent upon the phase of ENSO that is to be studied. The JMA index is found to be more sensitive to La Niña events than all other indices. The SOI, Niño-3.4, and Niño-4 indices are equally sensitive to El Niño events and are more sensitive than the JMA, Niño-1+2, and Niño-3 indices.

The TNI is the result of a combination of two indices: Niño-1+2 and Niño-4. The resulting index has been shown to be effective in describing the evolution of ENSO events that are defined using the Niño-3.4 index (Trenberth and Stepaniak 2001). The TNI is found to have a 3–12-month lead (lag) when compared to the signal in the Niño-3.4 region prior to 1976/77 (after 1977) and thus is ineffective in defining ENSO events on its own. These results and the results from the current study suggest that if a new index is developed based on a combination of two existing indices, the JMA index (La Niña sensitive) should be combined with one of the SOI, Niño-3.4, or Niño-4 indices (El Niño sensitive). Furthermore, the combination should be nonlinear, with weights that depend upon the likely ENSO phase.

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