The Many Faces of ENSO

(A Quantitative Evaluation of ENSO Indices)

by

Deborah E. Hanley, Mark A.Bourassa,
James J. O'Brien, Shawn R. Smith, and Elizabeth R. Spade

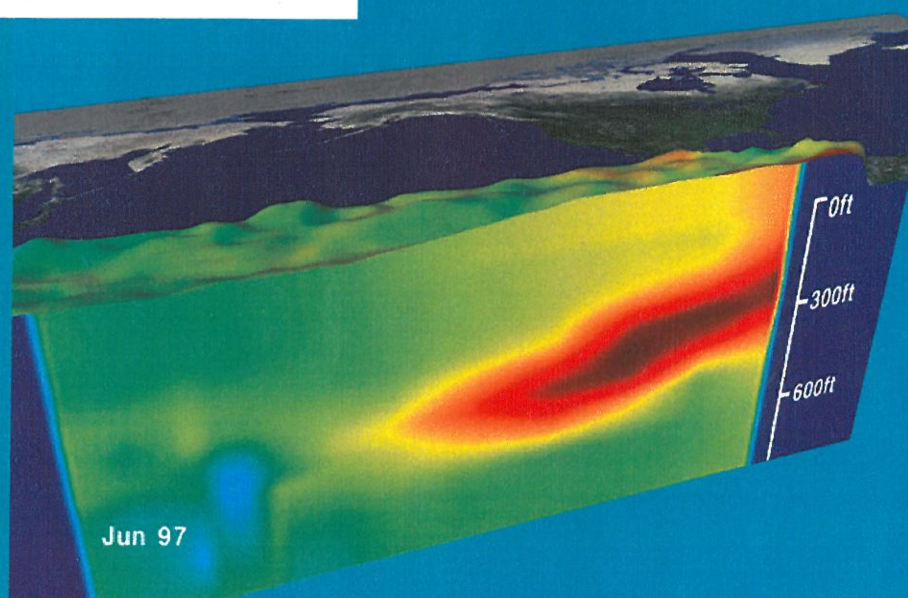
The Center
for
Ocean-Atmospheric
Prediction Studies

Florida State University
Tallahassee, Florida, USA
32306-2840

Dr. James J. O'Brien

Director

Technical Report
2001-01
December 2001



Cover figure obtained from http://nsipp.gsfc.nasa.gov/enso/visualizations/index.html. Colors in the figure represent the temperature anomalies beneath the ocean surface during June 1997. Red (blue) color indicates temperatures 10°C above (below) normal. Surface topography indicates sea surface height variations.

CENTER FOR OCEAN-ATMOSPHERIC PREDICTION STUDIES
THE FLORIDA STATE UNIVERSITY
TALLAHASSEE, FL 32306-2840
DR. JAMES J. O'BRIEN, DIRECTOR

THE MANY FACES OF ENSO
(EL NIÑO–SOUTHERN OSCILLATION)

By
DEBORAH E. HANLEY, MARK A. BOURASSA,
JAMES J. O'BRIEN, SHAWN R. SMITH, AND ELIZABETH R. SPADE

Technical Report
2001-01

December 2001

FOREWARD

This report is adapted from the Master's Thesis of Elizabeth Spade. As the reader is aware, there are many indicators of ENSO phase. Indices based on regional mean sea surface temperatures (Niño 1, 2, 3, and 4) were created by the Climate Analysis Center (1982), based on a study by Rasmussen and Carpenter (1982). Barnston and Chelliah (1997) gave us Niño 3.4, which combines parts of the Niño 3 and Niño 4 regions. At COAPS, we have used the JMA temperature index. This study also includes the pressure-based SOI index and the multivariate index (MEI).

In this report we compare these indices over a 100-year period using a reconstructed sea-surface temperature data set. We also compare these indices to many empirical studies. There are inconsistencies in each pair of ENSO indices. Analysis of these ENSO indices suggests that the JMA index is most sensitive to La Niña events while the SOI, Niño 3.4, and Niño 4 are equivalently sensitive to El Niño events. After reading this report, I would appreciate any comments you may have on our conclusions.

Jim O'Brien
Director, COAPS
Florida State University

TABLE OF CONTENTS

ABSTRACT

El Niño-Southern Oscillation (ENSO) is a natural, coupled atmospheric-oceanic cycle that occurs in the tropical Pacific Ocean on an approximate time scale of 2-7 years. ENSO events have been shown in previous studies to be related to extremes in weather (e.g. hurricane occurrences, frequency and severity of tornadoes, droughts, floods). Because of the teleconnections of ENSO events to extreme weather events, the ability to classify an event as El Niño or La Niña is of interest to the scientific community.

ENSO is most often classified using indices that indicate the warmth and coolness of equatorial tropical Pacific Ocean sea-surface temperatures (SSTs). Another index commonly used 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 capturing 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 determine if there is indeed an index that is superior in defining ENSO events; or alternatively, to determine which indices are best for various applications.

Sea surface temperature indices are calculated from a 100-year dataset of reconstructed monthly SSTs. Running sums are created from the indices to reveal trends in SST evolution and identify periods with more or less frequent ENSO extreme phases. The magnitude of ENSO events and sensitivity of the SST-based indices are compared to the atmospheric pressure-based Southern Oscillation Index.

Results show that the Niño 4 and Niño 1+2 indices do not have a strong response to El Niño and La Niña events, respectively. The Niño 3.4, Niño 3, and JMA indices are closely correlated to the SOI index. During the Modern Era (1958-1992), the Niño 3 and Niño 3.4 are superior to the JMA when compared to the SOI; however, the JMA and Niño 3 are in better agreement with past empirical studies during this period.

Analysis of the sensitivity of the indices 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 JMA index is found to be more sensitive to La Niña events than all other indices. The SOI, Niño 3.4,

and Niño 4 are almost equally sensitive to El Niño events and are more sensitive than the JMA, Niño 1+2, and Niño 3.

1. Introduction

ENSO is a natural coupled-cycle in the ocean-atmospheric system over the tropical Pacific that operates on a time scale of 2-7 years. Observations of El Niño-related weather impacts near Peru can be traced to 1525 (Ortlieb 2000), and these impacts were first noted by scientists in the 1890s (Glantz 1996). Warm (El Niño) and cold (La Niña) ENSO phases have been associated with regional extremes in precipitation. Severe droughts occur in some places while torrential rains with flooding occur in others. During a warm ENSO event, the eastern coastal tropical Pacific fish population may decrease due to nutrient-poor water replacing the nutrient-rich water as a result of reduced upwelling in the coastal areas (Ahrens 1994).

The phase and strength of El Niño-Southern Oscillation (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 used to classify ENSO events include regional sea-surface temperature (SST) indices (e.g., Niño 1+2, Niño 3, Niño 4, Niño 3.4, Japanese Meteorological Agency-JMA), the surface atmospheric pressure-based Southern Oscillation Index (SOI), and the Multi-Variate 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-year SST anomaly data set from 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 SST index are then compared to each other as well as to the SOI. This study focuses on defining ENSO years as warm (El Niño), cold (La Niña), or neutral; it does not consider the timing or duration of the ENSO events.

A detailed background including the history and cycle of ENSO, the descriptions of the indices used, and a discussion of duration, strength, and timing of an ENSO event is 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-year record. The Niño 3.4, Niño 3, and the JMA indices faired similarly when compared to the SOI, while the Niño 1+2, Niño 4, and TNI indices had substantially poorer matches to the SOI. The Niño 1+2 index shows a poor response to La Niña events, whereas the Niño 4 index responds poorly to El Niño events. The TNI is good at showing patterns of formation of ENSO events but was not designed to capture the occurrence of ENSO events. Comparison of ENSO indices to modern (1958-1992) subjective analyses confirms these findings and shows that the Multivariate ENSO index (MEI) has shortcomings akin to the TNI. The Niño3 and JMA are the best matches with these subjective analyses. Sensitivity studies 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 (1996) 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 1996). 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.

When neutral conditions exist, the normal trade winds blow westward across the tropical Pacific Ocean. The atmospheric pressure is high in the east and low in the west while ocean temperatures are warm (~30°C) in the west and cold (~21°C) in the east. The ocean's mixed-layer is thick in the west and thin in the east, and downwelling (upwelling) occurs in the western Pacific (near the South American coast). Most convective activity takes place in the western part of the Pacific Ocean over the warm SST pool, primarily over and east of Indonesia. Modifications to the neutral pattern (i.e., El Niño or La Niña) shift the boundary of the warm pool, modifying the tropical convection and wind patterns, and these in turn affect the weather at many locations over North and South America, and other parts of the globe.

The exact initiation of a warm ENSO phase is unknown; however, anomalous westerly wind events (known as westerly wind bursts) appear to be a key component. Westerly wind bursts typically occur over the equatorial warm pool (north of New Guinea). Downwelling Kelvin waves develop in the ocean if the wind bursts become prolonged or there are several strong bursts in succession. The Kelvin waves propagate eastward reaching the coast of South America in roughly two months.

Equatorial downwelling Kelvin waves raise the thermocline the western Pacific Ocean, transporting some of the relatively warm water eastward, resulting in a locally thinner mixed layer. As Kelvin waves reach the eastern Pacific Ocean, they lower the thermocline in the eastern Pacific Ocean, resulting in a locally thicker mixed layer (Glantz 1996). There is strong upwelling along the eastern Pacific coast. In neutral ENSO years, this upwelling causes the thermocline to outcrop (reach the surface), bringing the cold nutrient-rich waters to the surface. During El Niño years, the eastern Pacific mixed layer is sufficiently thick that outcropping does not occur, resulting in much warmer SSTs. Thus, near an El Niño onset, anomalously warm SSTs appear east of the warm pool near the South American coast.

The modification of the SST pattern starts a positive feedback process in the equatorial atmospheric circulation. The westward motion of the warm pool's strong equatorial SST gradient results in a westward motion of the area of maximum convective activity, which is associated with the maxima in cloud cover, downwelling long-wave radiation, and rainfall. There are also changes in the convective regions over Central and South America, which are coupled to changes in the Walker circulation, and hence changes in the trade winds. The trades become anomalously eastward, with stronger winds to the west of the area of maximum convection, which can be associated with additional wind bursts and equatorial downwelling Kelvin waves.

At the peak of a warm ENSO phase, there are often droughts in Indonesia and increased rainfall along the Peruvian Coast. The main convective activity is located in the central Pacific. In the western and central Pacific, the trades may reverse and blow towards the east. This pattern is now known to affect weather in North America (Ahrens 1994; Glantz 1996; Richards et al. 1996; Bove et al. 1998; Legler et al. 1998) and over much of the globe (Glantz 1996; Philander 1990; Rasmusson and Carpenter 1982).

When equatorial Kelvin waves reach the South American coast, they propagate poleward along the coast as coastal Kelvin waves. These coastal waves generate Rossby waves, which travel westward across the ocean basin. The speed of the Rossby wave is a function of latitude. It takes approximately nine months to cross the equatorial Pacific, and roughly a decade in the North pacific.

ENSO cold phases are characterized by stronger than normal trade winds across the tropical Pacific basin, which thins the mixed layer and increases the area of outcropping off the Peruvian coast. Higher atmospheric pressure in the east and lower pressure in the west will accompany the stronger than normal trades. Western Pacific equatorial convection moves accompany the stronger than normal trades. Western Pacific equatorial convection moves further west in a cold event, with more rain in Indonesia and Australia.

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. Trenberth (1997) suggests the definition of El Niño given by Glantz (1996) is the best qualitative definition that exists at this point in time.

a. ENSO indices

Many different indices have been used to designate when an El Niño or a La Niña event has occurred. Eight indices are examined in this study: Niño 1+2, Niño 3, Niño 4, Niño 3.4, Japanese Meteorological Agency (JMA), SOI, Trans-Niño Index (TNI), and the Multivariate ENSO Index (MEI). The SOI is a pressure index, the MEI is a multivariate index, and the rest are SST-based indices.

The Niño 1+2, Niño 3, and Niño 4 indices are defined using mean SSTs within different regions of the Equatorial Pacific (Fig. 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 (Fig. 1). The Niño 1+2 region is the combination of the Niño 1 and Niño 2 regions and is sensitive to seasonal and El Niño-induced changes. The Niño 3 region is located in the central equatorial Pacific and is much less sensitive to continental influences than the Niño 1 and Niño 2 regions (Fig. 1). The Niño 4 region encompasses part of the western equatorial Pacific where the sea surface temperatures are high (Fig. 1). Changes in SSTs in the Niño 4 region are related to longitudinal shifts of the strong east-west temperature gradients along the equator.

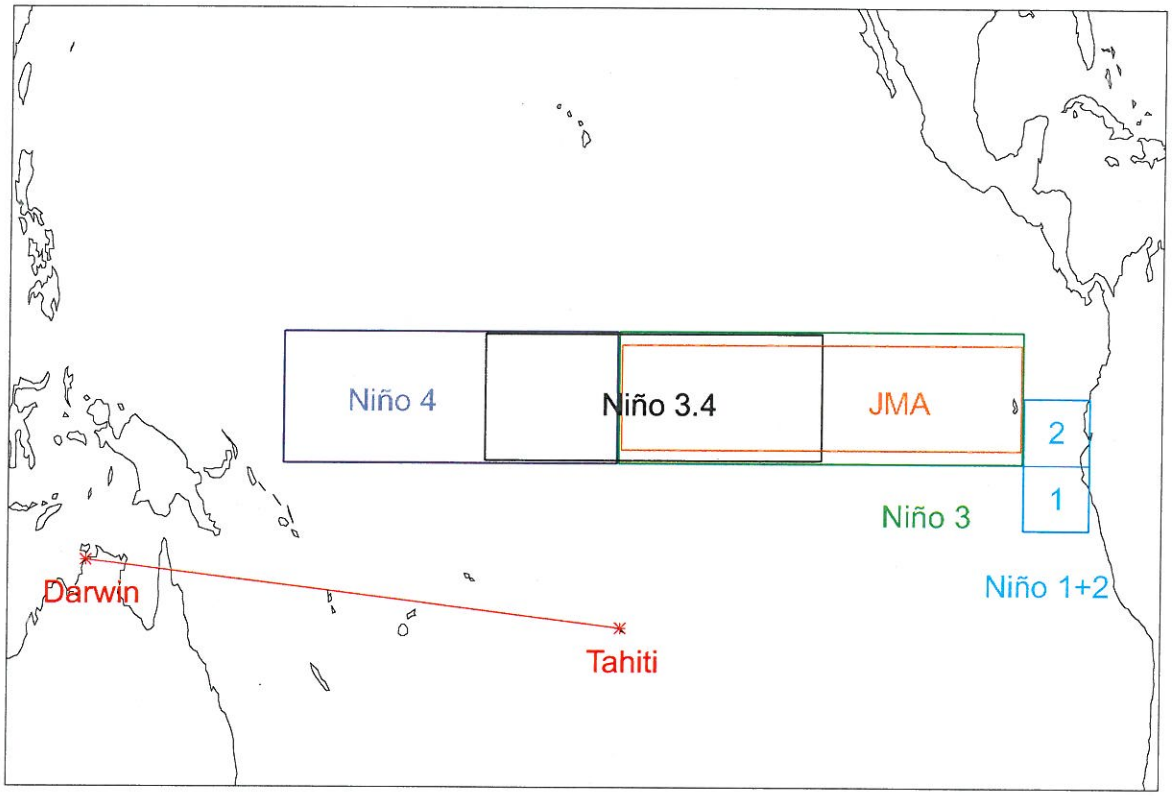


Figure 1. Locations of SST index regions. Regions in the tropical Pacific used to define average SST anomalies for the Niño 1+2 (blue), Niño 3 (green), JMA (orange), Niño 3.4 (black), and Niño 4 (purple) ENSO indices. Also plotted are the locations of Tahiti and Darwin, which are used to create the SOI (red).

The Niño 3.4 region overlaps portions of the Niño 3 and Niño 4 regions covering an area from 5°N-5°S and 170°W-120°W (Fig. 1). Barnston and Chelliah (1997) defined the Niño 3.4 region; they found better correlation with ENSO events than the Niño 3 region, where ENSO events were defined by the SOI. The JMA index was produced by the Japanese Meteorological Agency (JMA, 1991) and is located within the Niño 3 region (Fig. 1). The JMA region extends from 4°N-4°S and 150°E-90°E.

Horel and Wallace (1981) compared several SO parameters in the tropical Pacific including a sea-surface temperature index, a sea-level pressure (SLP) index, 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 this study is based on the difference between the Tahiti (French Polynesia) and Darwin (Australia) SLP (i.e. Tahiti minus Darwin; Fig. 1). Chen (1982) found the Tahiti-Darwin combination contained the largest variance 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. Trenberth (1984) noted significant noise unrelated to the SO. The dataset also has missing data early in the time series. Ropelewski and Jones (1987) proposed three possible reasons for this missing data:

1) There was no data taken in Tahiti during the years with missing data (e.g. 1894, 1907, 1915, etc.)
2) The data were possibly lost when the manuscript was being transferred to France
3) France had to ship replacement pieces for the non-working barometers.

The Trans-Niño index (TNI) is loosely related to the east-west temperature gradient in the eastern tropical Pacific (Trenberth and Stepania 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 to west versus west to east). 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 based on six different variables: SLP, zonal component of surface wind, meridional component of surface wind, SST, surface air temperature and total cloudiness fraction of the sky. The MEI is computed separately for twelve sliding bi-monthly (DJ, FM, etc.) seasons and is produced real-time by Klaus Wolter at the Climate Diagnostic Center (CDC) (http://www.cdc.noaa.gov/~kew/MEI/).

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 AD, 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 sea surface temperatures around 7°-12°C above normal, and are associated with above-normal rainfall and massive destruction. Strong events included those with sea surface temperatures 3°-5° C above normal, and are associated with large amounts of rainfall and major damage. A moderate event was one with sea surface temperatures 2°-3°C above normal, and causes above-normal rainfall and minor damage. A weak event had hardly any damage, normal rainfall, and sea surface temperatures 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 and 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 1980's (V. Kousky, personal communication, 2001) and provides the commonly used Tahiti minus Darwin SOI. The JMA defines a warm (cold) ENSO event as a consecutive six-month period (including October, November, and December), where the SST anomalies in the JMA region (Fig. 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 this study, the JMA definition 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 time scale for an El Niño event must be greater than two years due to the time needed for the evolution of the event. Timing plays a role in which indices best capture the ENSO events. 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 1996). 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 SST data (Meyers et al. 1999) over the regions of the Pacific Ocean corresponding to each index (Fig. 1, Table 1) for each month from 1894-1993. The reconstructed SST data are created on a 2° latitude by 2° longitude grid extending from 29°N to 29°S and 121°E to 75°W, covering a period from 1894 to 1993.

Table 1: Latitude and longitude ranges defining area averages for SST indices. SOI is calculated using pressure differences between Tahiti (17.5S, 149.6W) and Darwin (12.4S, 130.9W).

Index	Latitude range	Longitude range
Nino 1+2	0 - 10S	90 - 80W
Nino 3	5N - 5S	150 - 90E
Nino 3.4	5N - 5S	170 - 120W
Nino 4	5N - 5S	160E - 160W
JMA	4N - 4S	150 - 90E
TNI	Nino 1+2 & Nino 4	Nino 1+2 & Nino 4

Missing data often exist in SST datasets from the mid 1800s until the mid 1900s. Meyers et al. (1999) reconstructed the SST anomalies in order to have a temporally and spatially complete data set 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; Slutz et al. 1985), 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° x 2° grid) SST anomaly fields.

The ENSO indices recalculated herein are based on the spatially averaged SSTs in the applicable ENSO regions (Fig. 1, Table 1). The indices used in this study are the JMA (ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/), the Niño 1+2, Niño 3.0, and Niño 4.0 (Climate Analysis Center 1982), the Niño 3.4 (Barnston and Chelliah 1997), and the TNI (Trenberth and Stepania 2001). Long-term monthly climatologies for each ENSO region are calculated by averaging over each 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 five-month running mean (Fig. 2). The five-month running mean of the SST anomalies represent the time series of each ENSO SST index (other than the TNI). 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), as well as several qualitative analyses (van Loon and Madden 1981; Rasmusson and Carpenter 1982; Quinn et al. 1987). For the SOI Index, a thirteen-month mean of the Tahiti-Darwin SLP anomalies (Fig. 2) is used instead of a five-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
2) ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi.

In addition, a multivariate index created by Klaus Wolter is also used for comparison. Details of this index are available at http://www.cdc.noaa.gov/~kew/MEI/.

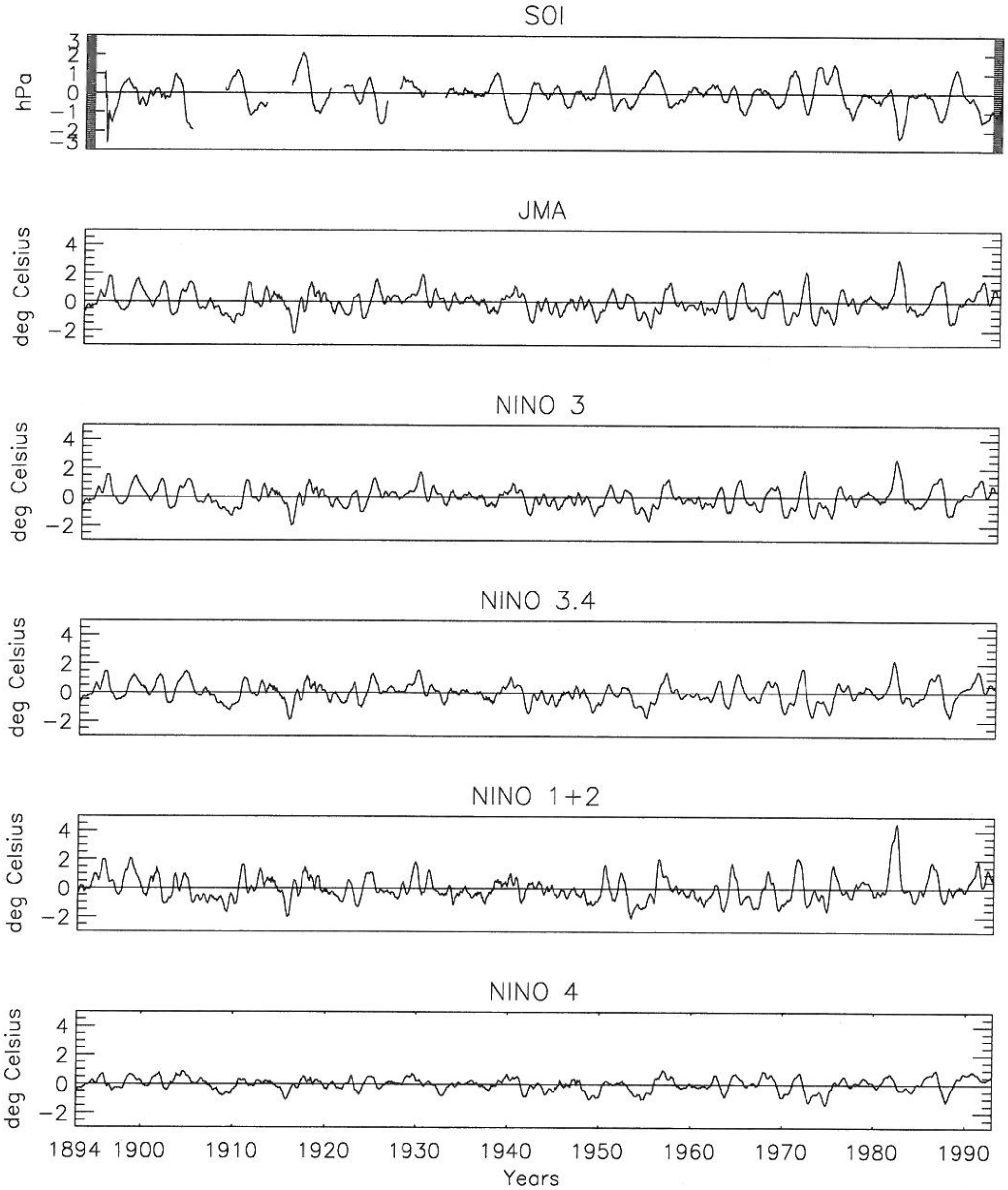


Figure 2. Time-series of the 13-month running mean of the SOI and five-month running means of various SST-based ENSO indices.

4. Analysis and discussion

The relative strength/weakness 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 well-known empirical studies, the SOI, and the JMA. Finally, the sensitivity of the SST indices to identification of the strength of the ENSO extreme events is assessed and the sensitivity of indices to one another is calculated.

a. SST Index Trends

A running sum filter is applied to each reconstructed index to reveal multi-year trends in the SST anomalies (Fig. 3). The running sums have upwards 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 to 1925, 1930 to 1941, and 1976 to 1981). These slowly changing periods may be the result of periods of alternating El Niño and La Niña events of equal 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 inter-decadal 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. 3).

There appears to be high correlation between trends in the running sums of the ENSO SST indices (Fig. 3); however, the Niño 1+2 (Niño 4) amplitude is higher (lower) than the other indices. This implies differences in response to ENSO events in the Niño 1+2 and Niño 4) regions. The upwelling occurring in the Niño 1+2 region is strong. Increased area of upwelling during La Niña events has little impact on SST anomalies because the water is already cold in the Niño 1+2 region. This reduces the sensitivity of Niño 1+2 to La Niña events. The Niño 4 region is located in the western Pacific warm pool, and extends into the central Pacific: the dynamical range for El Niño anomalies is relatively small. The Niño 1+2 and Niño 4 indices will underemphasize or overemphasize different phases of ENSO events. Therefore, the Niño 3, Niño 3.4, and JMA are better correlated with each other.

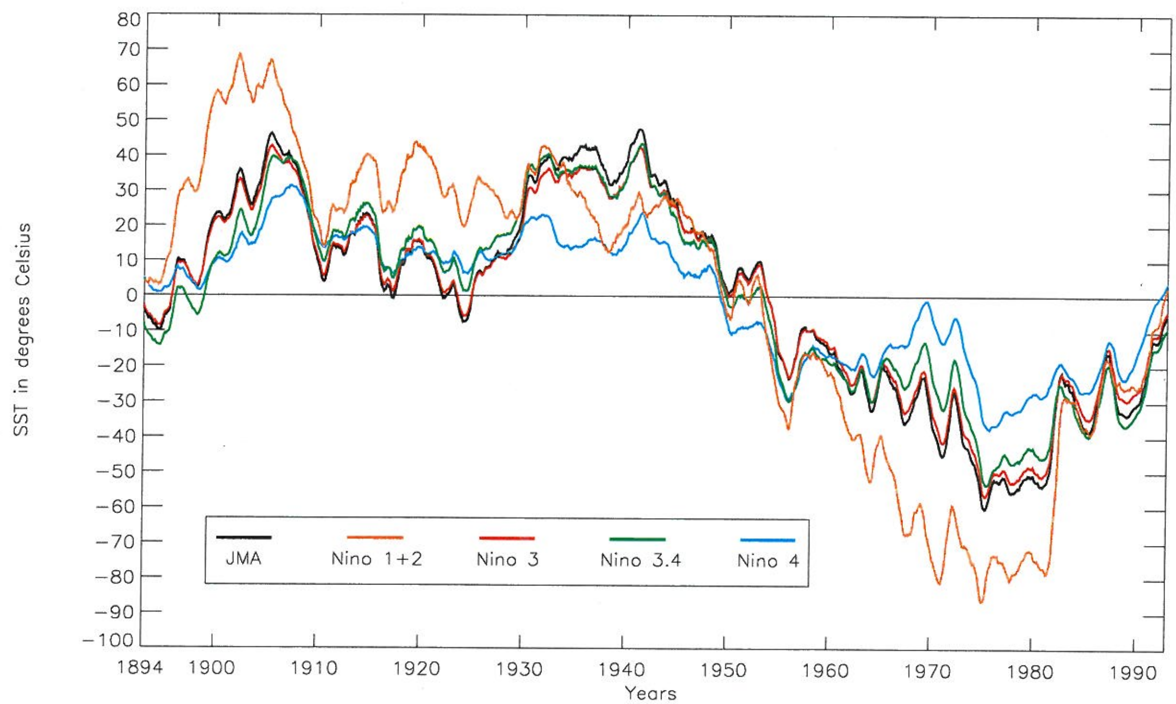


Figure 3. Time-series of the SST index running sums with each mean removed. The running sums are plotted for the JMA (black), Niño 1+2 (orange), Niño 3 (red), Niño 3.4 (green), and Niño 4 (blue) reconstructed SST ENSO indices.

b. Classifying the El Niño and La Niña years

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 (Fig. 1) to be greater than 0.5°C (less than –0.5°C) for six consecutive months and the months must include October, November, and December. In this study, the thresholds are determined from the reconstructed data anomalies. The anomaly series are sorted into three categories: values ≤ 25th percentile, values ≥ 75th percentile, and the value in between these two percentiles. The value that defines the upper quartile (75th percentile) is identified and used as a threshold (T_w) for El Niño occurrences. Likewise, the value that defines the lower quartile (25th percentile) is identified and 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. 4). To satisfy the JMA criteria for a warm (cold) ENSO event, six consecutive months including October, November, and December, have to be above (below) the thresholds defined for each reconstructed index. The advantage of using quartiles is that they are determined from the data, and they need not be symmetric around zero. Any year not meeting the ENSO warm (El Niño) or cold (La Niña) phase criteria is defined as a neutral year.

1) COMPARISON TO EMPIRICAL STUDIES

Empirical studies that classify ENSO years are compared to the reconstructed JMA index ENSO years (Table 2). The first study under consideration is van Loon and Madden (1981). ENSO events were classified by examining the pressure distribution of opposing phases of the Southern Oscillation at five different locations. Extreme phases of the oscillation were identified for the northern hemisphere winters (December, January, and February means) from 1899/1900 through 1978/1979 using sea-level pressures from Darwin, Cocos Island, Samoa, Tahiti and Santiago, and Djakarta. Extremes were classified as LOW/WET (L/W) and HIGH/DRY (H/D). LOW and HIGH refer to the pressure over the eastern and central tropical Pacific Ocean while WET and DRY refers to the rainfall in the equatorial Pacific. The combination of L/W (El Niño) was chosen when a peak in the rainfall, high-pressure anomalies in the tropical Indian Ocean, and a trough of pressure in the tropical Pacific occurred at the same time. The opposite conditions defined a H/D (La Niña) year. Of the L/W phases classified by van Loon and Madden (1981), six years are not classified as El Niño by the reconstructed JMA index. Of the H/D phases classified by van Loon and Madden (1981), six years are not classified as La Niña by the JMA index. Van Loon and Madden (1981) missed three El Niño events and five La Niña events identified by the JMA index. Van Loon and Madden (1981) note that their list may not contain all the SOI extreme events during the 80-years because a year had to satisfy both the pressure and precipitation criteria. Although they believe their study does not include any events that were not extreme, weaker events may have been eliminated and may correspond to some of the JMA defined events.

Rasmusson and Carpenter (1982) defined El Niño events (1953-1976) based on those previously classified by other studies and then used surface marine observations, satellite data and station observations to describe the evolution of major warm events in the eastern and central tropical Pacific. Over the period of comparison, the JMA El Niño years are identical to those of Rasmusson and Carpenter.

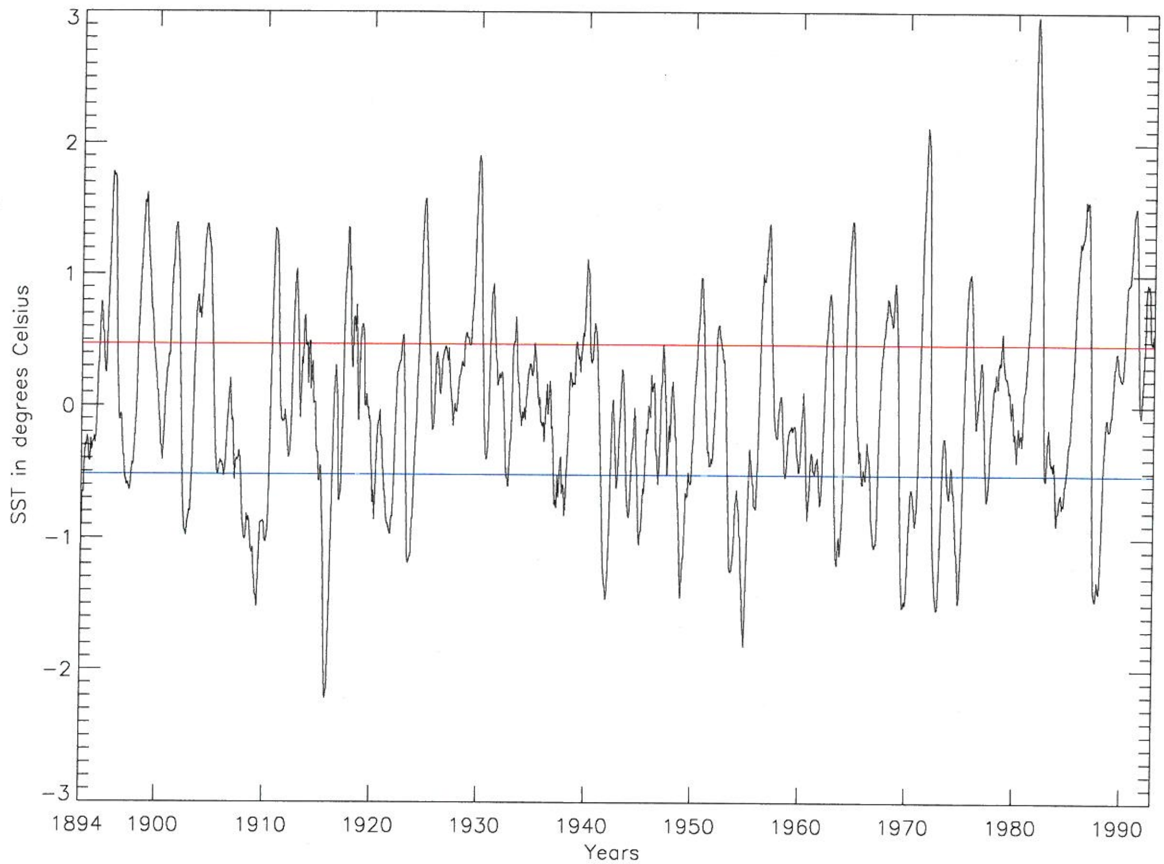
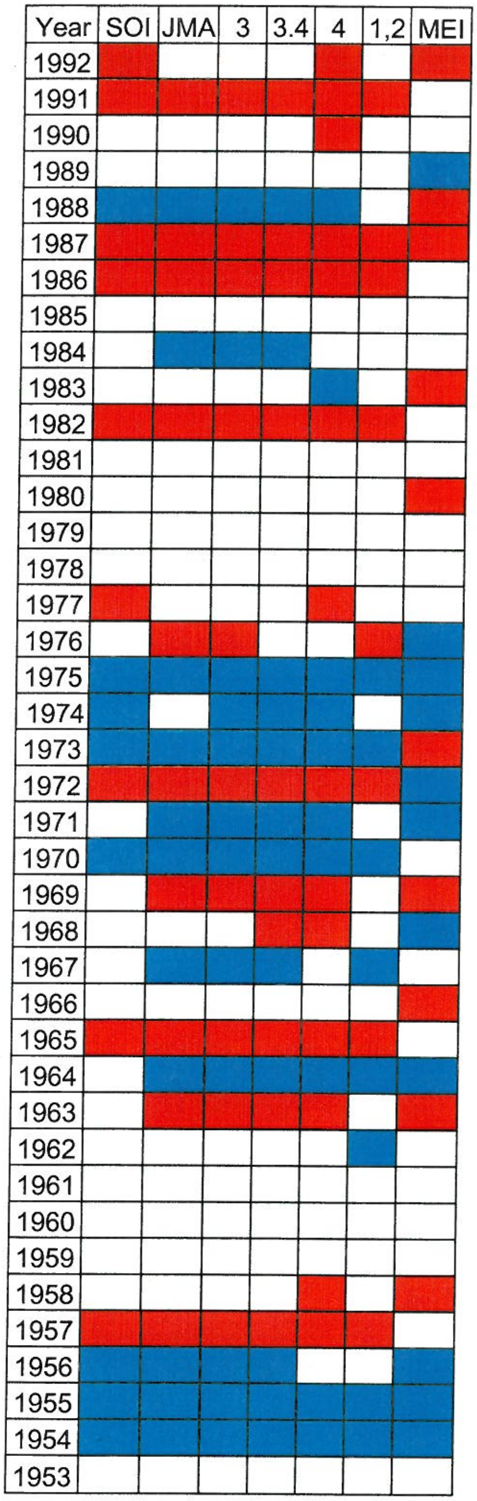


Figure 4. Time-series of the five-month running means of the reconstructed JMA SST anomalies. The red and blue solid lines mark the upper and lower quartile values, which are the thresholds for defining an El Niño event or La Niña event, respectively.

Quinn et al. (1987) created a comprehensive list of strong, warm (El Niño) events derived from historical references over the past four and a half centuries. After 1800, when observations became more available, they determined the strength of events by using the SCOR definition (see section 2c). Prior to 1800, event strength was determined subjectively from written descriptions of weather conditions, ship logs, etc. Weak events were not considered in this study. For the period of comparison (1894-1987), Quinn et al. (1987) misses six warm events classified by the JMA, and the JMA misses seven warm events classified by Quinn et al. (1987). However, these misses occurred in the early part of the record, where the SSTs used to calculate the indices are expected to have greater uncertainty. There is close correlation between Quinn et al. (1987) and Rasmusson and Carpenter (1982) during the period 1953-1976. This is not unexpected and is due to the fact Rasmusson and Carpenter (1982) defined ENSO years based on the results of Quinn et al. (1987). The two years that differ between the two studies correspond to weak events, which Quinn et al. (1987) did not consider.

While the agreement between the JMA index and the study by Rasmusson and Carpenter (1982) appears to be closer than between the other studies, Rasmusson and Carpenter (1982) only considered warm events over a 22-year period. Van Loon and Madden (1981) considered both warm and cold events during an 80-year period while Quinn et al. (1987) spanned the full 99 years of this study but did not consider cold events or weak warm events. Conclusions concerning the accuracy of the JMA index when compared to previous studies are difficult to make considering the different characteristics of the studies and their varying study periods. If we compare only warm events during the period 1954-1976 when all three studies overlap, we can conclude that there is better agreement between the JMA and Rasmusson and Carpenter (1982) than other studies. Quinn et al. (1987) miss two JMA warm events. Van Loon and Madden (1981) miss no JMA warm events and four JMA cold events while the JMA miss one van Loon and Madden (1981) warm event and two cold events.

An alternative assessment of the best of the three most widely used SST indices (Niño 3, Niño 3.4, and JMA) can be based on the Modern Era (since 1958; Table 3). There are three events that the JMA, Niño 3, and Niño 3.4 do not agree on. The JMA and Niño 3 classify 1976 as a warm event while the Niño 3.4 classifies it as a neutral event. The JMA classifies 1974 as a neutral event while the Niño 3 and Niño 3.4 classify it as a cold event. The year 1968 is defined



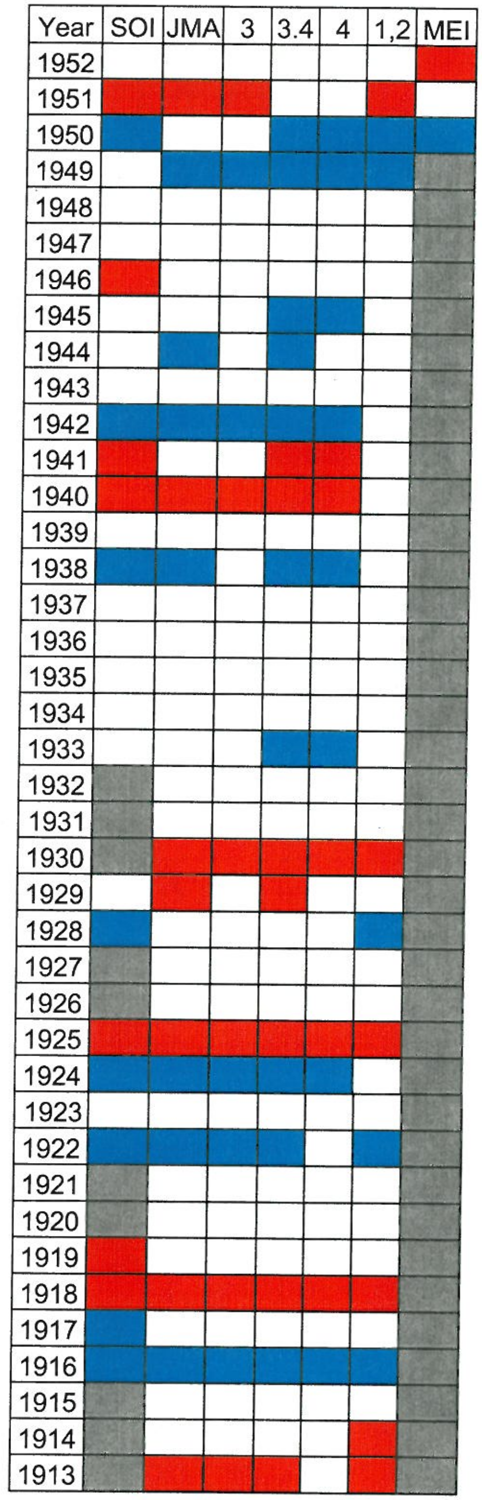


Table 3: Comparison between reconstructed SST indices and the SOI. Colors are the same as in Table 2.

Year	SOI	JMA	3	3.4	4	1,2	MEI
1912							gray
1911	red	red	red	red		red	gray
1910	blue	blue	blue	blue	blue		gray
1909	blue	blue	blue	blue	blue	blue	gray
1908	gray					blue	gray
1907	gray						gray
1906	gray						gray
1905	gray	red	red	red	red	red	gray
1904	red	red	red	red	red		gray
1903	blue	blue	blue	blue	blue	blue	gray
1902		red	red	red	red	red	gray
1901							gray
1900							gray
1899		red	red	red	red	red	gray
1898	blue				blue		gray
1897							gray
1896	red	red	red	red	red	red	gray
1895	gray					red	gray
1894	gray						gray

Table 3 continued.

as a warm event for the Niño 3.4 index but a neutral event for the Niño 3 and JMA indices. When the three indices are compared to the SOI, the JMA misses two SOI warm events and one SOI cold event. The Niño 3 and Niño 3.4 also miss two SOI warm events, but capture all of the SOI's cold events. When compared to the SOI for the Modern Era period of time, the Niño 3 and Niño 3.4 indices perform better than the JMA index. In each of these three cases (1968, 1974, and 1976), the JMA agrees with papers from van Loon and Madden (1981), Rasmusson and Carpenter (1982), and Quinn et al. (1987), whereas the Niño 3 and Niño 3.4 do not agree with these past studies. The JMA, Niño 3, and Niño 3.4 indices each miss two cold and two warm events from van Loon and Madden (1981). The JMA and Niño 3 capture all of the warm events from both Rasmusson and Carpenter (1982) and Quinn et al. (1987), whereas the Niño 3.4 misses one warm event from Rasmusson and Carpenter (1982) and one warm event from Quinn et al. (1987). When compared to historical studies, the JMA and Niño 3 perform slightly better than the Niño 3.4.

2. COMPARISON TO OBJECTIVE INDICES

The ENSO years defined by each reconstructed index as well as the MEI are compared to those defined by the SOI index (Table 3). These comparisons are summarized in a matrix format (Table 4). 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 4a). The off-diagonal values represent 'false-alarms' (upper right) or 'misses' (upper left). The TNI (not shown) and the MEI (Table 4f) are the only indices in which there was extreme disagreement in the sense that the SOI indicated a warm (cold) event and the MEI defined a cold (warm) event. Relative to the SOI, the Niño 1+2 index misses the most total number of events, while the Niño 3 index has the fewest combined false alarms and misses. The MEI is not a good predictor of ENSO events since it misses more SOI events than it correctly identified (~52% missed). 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 El Niño events (15), with the fewest misses (4); however, it has the greatest number of false alarms (3). In contrast, the Nino 1+2 index has the smallest number of correct El Niño events (12) and false alarms (3); however, it has the greatest number of misses (7). It is quite clear that the Nino 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.

Table 4: Matrices of the comparison of reconstructed SST indices (a-e) and MEI (f) with the SOI. There are a total of 83 years available for comparison of the SST indices to the SOI due to missing SOI data, while 42 years are included in the MEI comparison (MEI is only available from 1951 onwards).

(a) JMA Index

	SOI Index: El Nino	Neutral	La Nina	Total SST ENSO Events
El Nino	14	6	0	20
Neutral	5	32	5	42
La Nina	0	6	15	21

(b) NINO 3 Index

	El Nino	Neutral	La Nina	Total SST ENSO Events
El Nino	14	5	0	19
Neutral	5	34	5	44
La Nina	0	5	15	20

(c) NINO 3.4 Index

	El Nino	Neutral	La Nina	Total SST ENSO Events
El Nino	14	6	0	20
Neutral	5	30	3	38
La Nina	0	8	17	25

(d) NINO 4 Index

	El Nino	Neutral	La Nina	Total SST ENSO Events
El Nino	15	7	0	22
Neutral	4	31	4	39
La Nina	0	6	16	22

(e) NINO 1+2 Index

	El Nino	Neutral	La Nina	Total SST ENSO Events
El Nino	12	3	0	15
Neutral	7	37	9	53
La Nina	0	4	11	15
Total SOI Events	19	44	20	

(f) MEI Index

	SOI Index: El Nino	Neutral	La Nina	Total MEI ENSO Events
El Nino	2	7	2	11
Neutral	7	11	1	19
La Nina	1	5	6	12
Total SOI Events	10	23	9	

c. 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°C and T_c=-0.52°C (Fig. 5). For the sensitivity study, El Niño years are classified as strong when the mean of months (*MOM*) that meet the ENSO definition are greater than or equal to three times the warm phase threshold ($MOM \geq 3T_w$) (e.g. $MOM \geq 1.41$°C for the JMA). Moderate and weak El Niños are defined when $2T_w \leq MOM < 3T_w$ (e.g. 0.94°C to 1.41°C for the JMA) and $T_w \leq MOM < 2T_w$ (e.g. 0.47°C to 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. 5).

Scatter plots of the indices (SST versus SOI) show the different strengths of the events and the sensitivity of the indices to the ENSO events (Figs. 5 and 6). Neutral events (black x's) located outside the neutral boundaries indicate that the events exceeded the mean anomaly magnitude criteria set forth by the thresholds; however, they fail the criteria for six or more consecutive months with sufficiently large anomalies.

The JMA, Niño 3 and Niño 3.4 indices classify the strongest El Niño event (circle) as 1982. The Niño 1+2 region classifies the 1982 event as a strong event but the 1972 El Niño event appears to be stronger (Fig. 6a). The Niño 4 index downgrades the 1982 event to a moderate event (Fig. 6d). 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 that can occur 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 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).

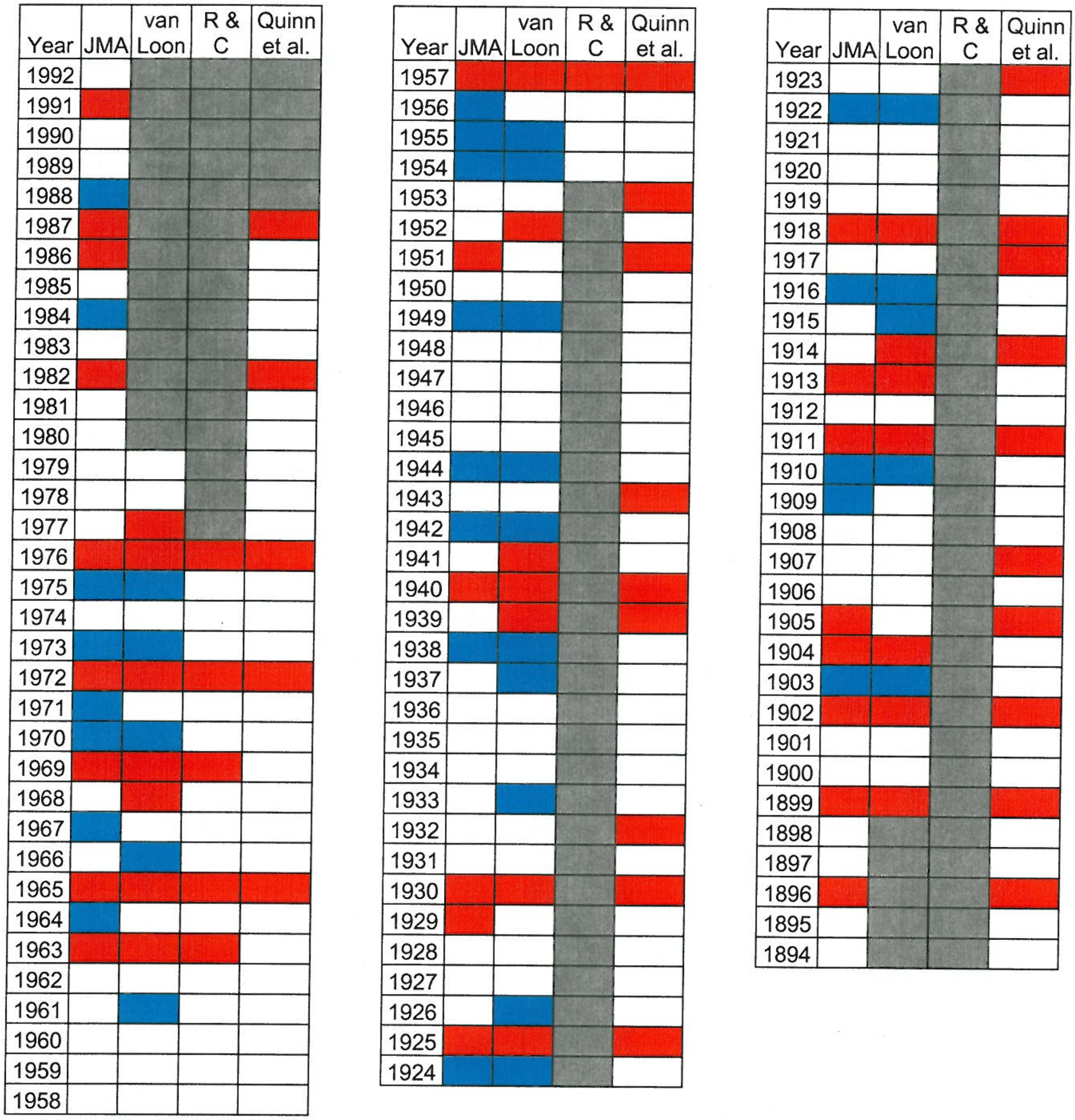


Table 2: ENSO years defined within several empirical studies (van Loon and Madden 1981, Rasmusson and Carpenter 1982, and Quinn et al. 1987) versus reconstructed JMA indices. Red boxes indicate El Niño years, blue boxes indicate La Niña years, and gray boxes indicate missing years.

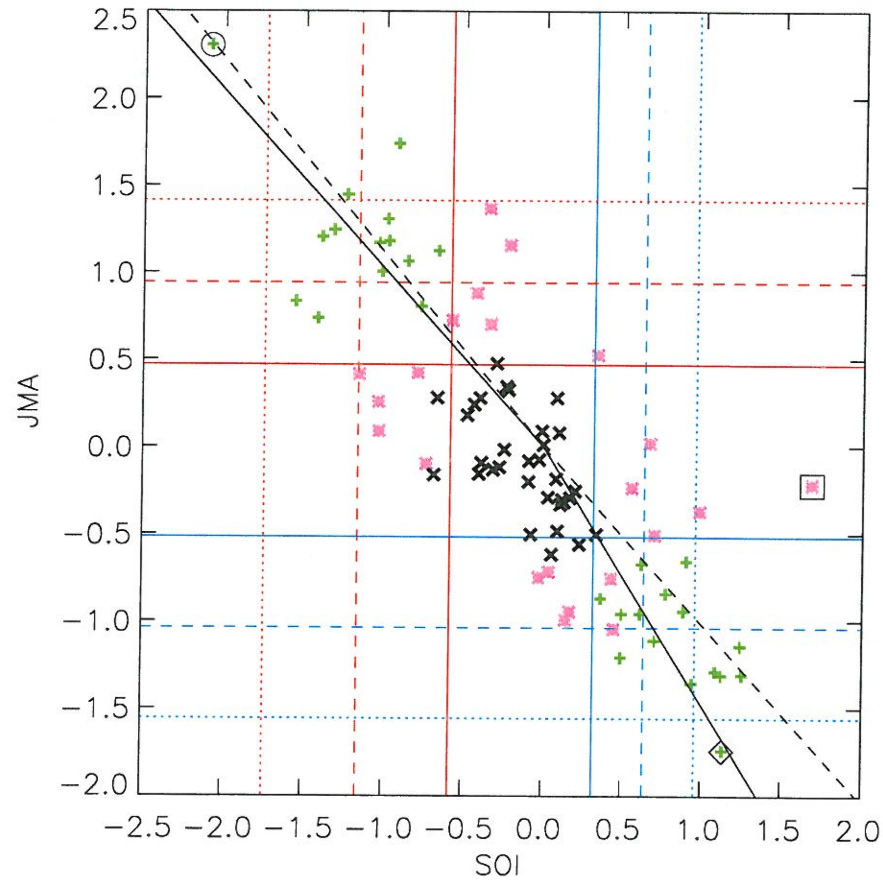


Figure 5: Scatter-plot of the JMA index versus the SOI. The green symbols (+) indicate matching ENSO extreme phases, black symbols (x) indicate matching neutral events, and pink symbols (*) indicate mismatches. A black square indicates suspect data, a black diamond indicates the strongest La Nina event, and a black circle indicates the strongest El Nino event. The lines indicate the thresholds for defining the strength of ENSO events. The solid red (blue) line is the threshold for defining and El Nino (La Nina) 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.

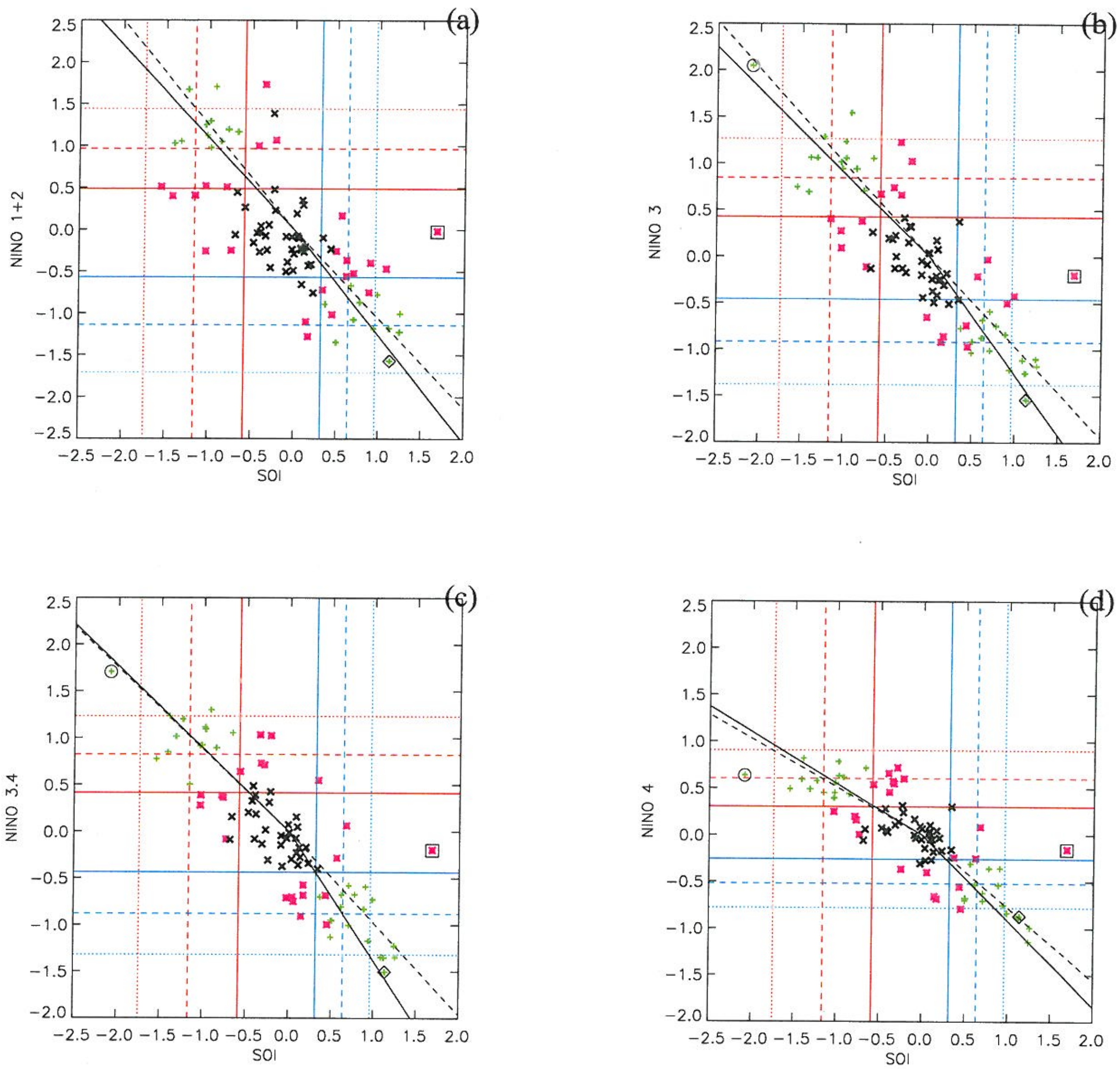


Figure 6: Same as Fig. 8 except for temperature indices versus the SOI: (a) Niño 1+2; (b) Niño 3; (c) Niño 3.4; and (d) Niño 4.

The Niño 1+2 region appears to be less responsive to La Niña events than other indices, identifying only 6 strong or moderate events. All of the indices identify the 1916 (diamond) La Niña as the strongest event, but the Niño 1+2 region downgrades it to a moderate event (Fig. 6a). It is suggested that the reason for the downgrading of this event is that the Niño 1+2 region upwelling is strong, but increased upwelling during La Niña has little impact on SST anomalies.

The Niño 4 index matches the most moderate and strong La Niña events compared to the SOI (13 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 poor showing of the TNI index (Trenberth and Stepania 2001) at identifying ENSO phases associated with each year indicates that a linear addition of the two indices is insufficient for the creation of an improved index.

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 La Niña event. During World War I (1914-1918), shipboard data became sparse in all regions of the Pacific Ocean. Therefore, less data were available in the regions of the SST indices; consequently, the confidence in the reconstructed SSTs is lower. Complete SLP records on Tahiti and Darwin allow the 1917 event to be captured by the SOI.

The response of one index relative to another can easily be seen in scatterplots (Figs. 5-7). 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 to the SOI is defined as

$$RS = \frac{\partial\, JMA}{\partial\, SOI} \frac{s_{SOI}}{s_{JMA}} \qquad (1)$$

where the derivative is the best-fit slope, and the s's are standard deviations estimated from the available sample. The relative sensitivity can also be demonstrated with scatterplots (Figs. 5-7). The diagonal dashed black line indicates the best-fit slope that would be found if the two indices have identical sensitivity. The slope of this line is equal to the standard deviation of the variable on 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.

The uncertainty (Taylor 1982) in the relative sensitivity (σ_{RS}) is

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

where m is the best-fit slope, and sigma 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 though generalized cross validation (Wahba and Wendelberger 1980). For comparisons of temperature indices to the SOI, the first term on the right hand side of (2) 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. 5), the JMA index is clearly more responsive to El Niño events than the SOI, and it is also substantially more sensitive to La Niña events. Looking at the other temperature indices (Fig. 7, Table 5), the SOI is more sensitive to El Niño that 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.

Table 5. Sensitivity of Temperature Indices relative to SOI, for El Niño and La Niña ENSO phases. Uncertainties indicate one standard deviation.

	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

Temperature indices can be compared in the same manner (Table 6, Fig. 7). Due to the relatively good performance with respect to the modern qualitative studies, and the good La Niña sensitivity relative to the SOI, the JMA index is used as the standard of comparison. The Niño 1+2 index has a greater response to El Niño; however, there is a great deal of uncertainty in that assessment, resulting in a poor relative sensitivity. 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.

Table 6. Sensitivity of Temperature Indices relative to JMA, for El Niño and La Niña ENSO phases. Uncertainties indicate one standard deviation.

	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

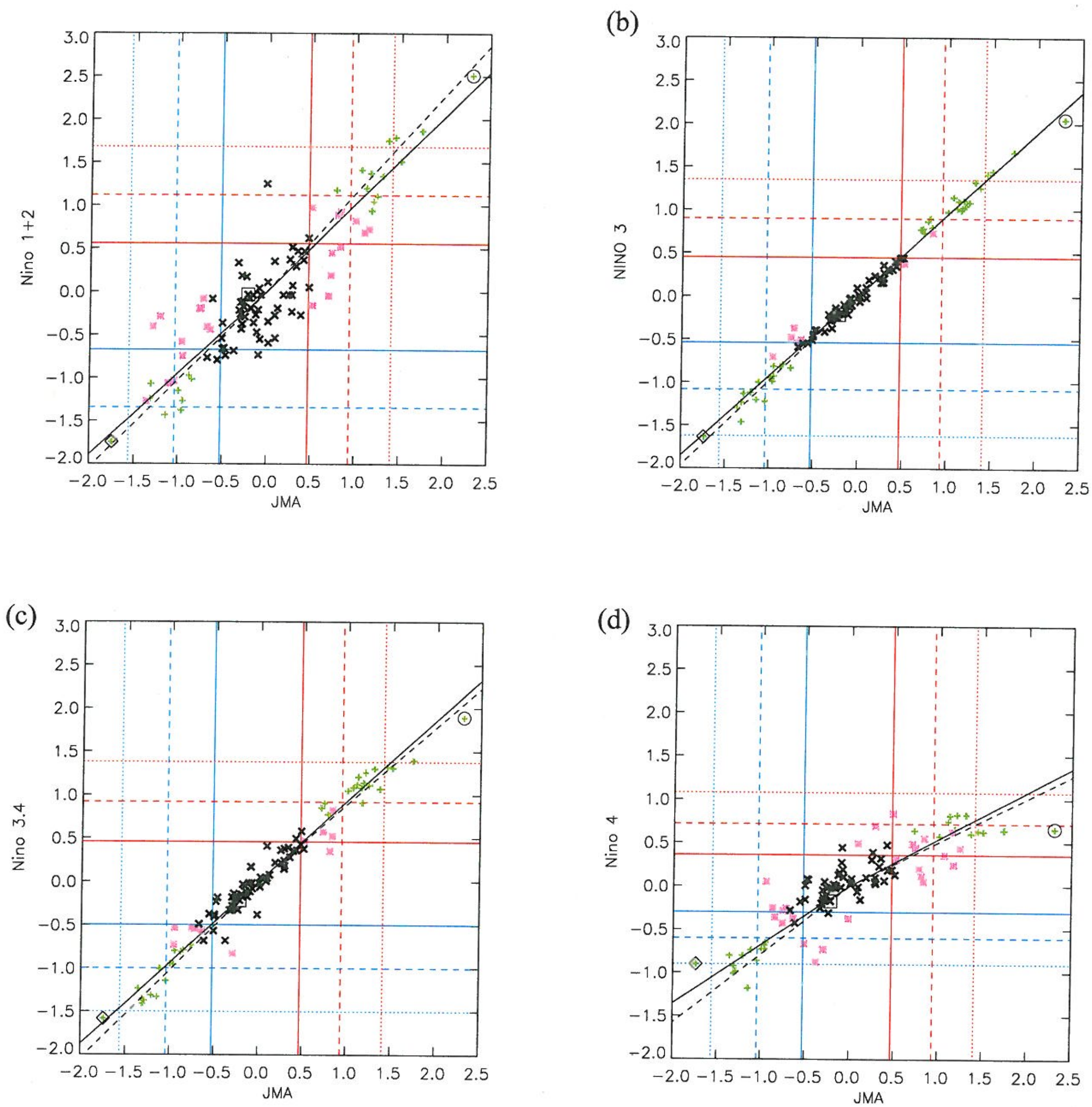


Figure 7: Scatter-plot of ENSO temperature indices versus the JMA index. The green symbols indicate matching ENSO extreme phases, black symbols indicate matching neutral events, and pink symbols indicate mismatches. The lines indicate the thresholds for defining the strength of ENSO events. The solid red (blue) line is the threshold for defining and El Nino (La Nina) events, the dashed lines are the thresholds for a moderate ENSO event, and the dotted lines are the thresholds for a strong ENSO event.

5. Conclusions

Seven ENSO indices are reconstructed from monthly SST anomalies to examine and compare characteristics of the different indices. A running sum filter applied to time series of index 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. The Niño 1+2 is higher in amplitude, suggesting higher response to warm events while the Niño 4 index was the opposite, exhibiting higher response to cold events.

The SST indices are compared to the past empirical studies of van Loon and Madden (1981), Rasmusson and Carpenter (1982), and Quinn et al. (1987). Results from this comparison are difficult to interpret due to the varying lengths of the empirical studies and the considerable overlap that exists between the studies. If we consider only the time period covered by all three studies (1954-1986), the study by Rasmusson and Carpenter (1982) is best correlated with the years defined by the reconstructed JMA index.

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) than any other index and the highest number of ENSO phase matches (63). The Niño 1+2 index is the worst, missing the highest number of events (23) and matching the lowest number (60). The MEI proved to be a poor predictor of ENSO events, missing more events in a 42-year period than it captured. The TNI also proved to be a poor predictor of events.

The ENSO years are categorized into four different strength categories: weak, moderate, strong, and neutral. Scatter plots are created to show the different strengths of the events and the sensitivity of the indices to the ENSO events. The Niño 4 index is shown to be a good measure of La Niñas, but a poor indicator of El Niños. The Niño 1+2 index has the opposite characteristics. These results are consistent with those derived from examining the running sums of the indices. 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; however, the poor showing of the TNI index in identifying ENSO phases associated with each year indicates that a linear addition of the two indices is insufficient for the creation of an improved index.

The Niño 3, Niño 3.4, and JMA indices are compared to the SOI and the empirical studies for a shorter period (Modern Era; 1958-1992). During this shorter period of record, the Niño 3 and Niño 3.4 indices perform better than the JMA when compared to the SOI. Nevertheless, the JMA and Niño 3 have better agreement with past studies when the Modern Era is considered.

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 are equally sensitive to El Niño events and are more sensitive than the JMA, Niño 1+2, and Niño 3.

ACKNOWLEDGEMENTS

This work was funded by the National Oceanic Atmospheric Administration Office of Global Programs, which supports an Applied Research Center at COAPS. The principal investigator at COAPS is Dr. James J. O'Brien. The National Aeronautical Space Administration (NASA) also contributed to this research.

REFERENCES

Aceituno, P., 1992: El Niño, the Southern Oscillation, and ENSO: Confusing names for a complex ocean-atmosphere interaction. *Bull. Amer. Meteor. Soc.*, **73**, 483-485.

Ahrens, C. D., 1994: *Meteorology Today: An Introduction to Weather, Climate, and the Environment*. West Publishing Company, 5th ed, 591.

Barnston, A.G. and M. Chelliah, 1997: Documentation of a highly ENSO-related SST region in the Equatorial Pacific. *Atmos.-Ocean*, **35**, 367-383.

Bjerknes, J., 1966: A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, **18**, 820-829.

Bove, M. C., 2000: PDO modification of U.S. ENSO climate impacts. M. S. thesis, Department of Meteorology, The Florida State University, 104 pp.

Bove, M. C., J. B. Elsner, C. W. Landsea, X. Niu, and J. J. O'Brien, 1998: Effect of El Niño on U.S. landfalling hurricanes, Revisited. *Bull. Amer. Meteor. Soc.*, **79**, 2477-2482.

Chen, W. Y., 1982: Assessment of Southern Oscillation sea-level pressure indices. *Mon. Wea. Rev.*, **110**, 800-807.

Climate Analysis Center, 1982: Special Climate Diagnostics Bulletin: The Global Climate Fluctuation of June-August 1982.

Glantz, M. H., 1996: *Currents of Change: El Niño's Impact on climate and Society*. Cambridge University Press, 194 pp.

Horel, J.D., and J. M. Wallace, 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813-829.

JMA, 1991: Climate charts of sea-surface temperature of the western North Pacific and the global ocean. Marine Department, JMA, 51 pp.

Legler, D. M., K. J. Bryant, and J. J. O'Brien, 1998: Impact of ENSO-related climate anomalies on crop yields in the U.S. *Climatic Change,* **42**, 351-375.

Mantua, N., cited in 2001: The Pacific Decadal Oscillation. [Available on-line from http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_egec.htm.]

Meyers, S. D., J. J. O'Brien, and E. Thelin, 1998: Reconstruction of monthly SST in the Tropical Pacific Ocean during 1868-1993 using adaptive climate basis functions. *Mon. Wea. Rev.*, **127**, 1599-1612.

Ortlieb, L., 2000: The documented historical record of El Niño events in Peru: An update of the Quinn record (sixteenth through nineteenth Centuries). *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts,* H. F. Diaz and V. Markgraf, Eds., Cambridge University Press, 207-295.

Philander, S.G., 1990: *El Niño, La Niña, and the Southern Oscillation.* Academic Press, 293 pp.

Quinn, W. H., V. T. Neal, and S. E. Antunez De Mayolo, 1987: El Niño occurrences over the past four and a half centuries. *J. Geophys. Res.*, **92**, 14,449-14,461.

Quiroz, R. S., 1983: Seasonal Climate Summary: The climate of the "El Niño" winter of 1982-1983—A season of extraordinary climatic anomalies. *Mon. Wea. Rev.*, **111**, 1685-1706.

Rasmusson, E. M. and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354-384.

Richards, T. S., J. J. O'Brien, and A. C. Davis, 1996: The effect of El Niño on U.S. landfalling hurricanes. *Bull. Amer. Meteor. Soc.*, **77**, 773-774.

Ropelewski, C. F. and P. D. Jones, 1987: An extension of the Tahiti-Darwin Southern Oscillation Index. *Mon. Wea. Rev.*, **115**, 2161-2165.

Slutz, R., S. Lubker, J. Hiscox, S. Woodruff, R. Jenne, D. Joseph, P. Steurer, and J. Elms, 1985: COADS, Comprehensive Ocean-Atmosphere Data Set. Tech. Rep., University of Colorado.

Taylor, J. R., 1982: Least-squares fitting, An introduction to error analysis. University Science Books, 153-172.

Trenberth, K.E, 1984: Signal versus noise in the Southern Oscillation. *Mon. Wea. Rev.*, **112**, 326-332.

___, 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.*, **78**, 2771-2777.

___, and D. J. Shea, 1987: On the evolution of the Southern Oscillation. *Mon. Wea. Rev.*, **115**, 3078-3096.

___, and D. P. Stepania, 2001: Indices of El Niño evolution. *J. Climate*, **14**, 1697-1701.

van Loon, H. and R. A. Madden, 1981: The Southern Oscillation. Part 1: Global associations with pressure and temperature in northern winter. *Mon. Wea. Rev.*, **109**, 1150-1162.

Wahba, G., and J. Wendelberger, 1980: Some new mathematical methods for variational objective analysis using splines and cross-validation. *Mon. Wea. Rev.*, **108,** 1122-1143.