THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

THE MANY FACES OF ENSO

(EL NIÑO–SOUTHERN OSCILLATION)

By

ELIZABETH REBECCA SPADE

A thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:
Fall Semester, 2001

Degree Awarded:
Fall Semester, 2001

The members of the Committee approve the dissertation of Elizabeth R. Spade defended on September 13, 2001.

James J. O'Brien
Professor Directing Dissertation

Peter S. Ray
Committee Member

Paul H. Ruscher
Committee Member

This thesis is dedicated to my parents, William R. Spade and Rebecca W. Spade, and most importantly, to my Lord and Savior, Jesus Christ…

ACKNOWLEDGMENTS

I would like to thank Dr. James O'Brien, my major professor, with his guidance during my thesis. I would also like to thank Shawn Smith for his guidance and help throughout my thesis. I want to thank my other committee members, Dr's. Peter Ray and Paul Ruscher, for helping me to finalize my thesis. Thanks to Dr. Mark Bourassa and Dr. Deborah Hanley for their help in editing and reviewing my paper. Thanks Jiraporn Whalley for all of her help with my computer programming. I would like to thank Mike Halpert and Diane Stokes from the Climate Prediction Center (CPC) for answering all of my e-mail questions. The financial support for this research was provided by the National Aeronautical Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). Finally, I want to thank all of my family and friends for all of their prayers and support throughout the duration of my research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

El Niño-Southern Oscillation (ENSO) can be identified using different types of indices (e.g., sea level pressure or temperature) that measure the warmth and coolness of sea surface temperatures (SSTs). There is no consensus within the scientific community on which index is the best at capturing ENSO phases.

Seven different indices are calculated with monthly reconstructed SSTs. Running sums are created from the indices to reveal trends within the SSTs and to identify the periods with more or less ENSO extreme phases. ENSO warm and cold phase years are defined by the Japanese Meteorological Agency (JMA) definition but a quartile method is used to obtain thresholds of occurrence. The strengths of ENSO events, sensitivity of the indices, and magnitudes of ENSO events are compared to other SST indices (e.g., SOI, TNI, MEI).

Each reconstructed SST index classifies the 1916 La Niña year and the 1982 El Niño year as the strongest ENSO event years. Results show that the Niño 4 and Niño 1+2 indices are not sensitive to capturing El Niño and La Niña events, respectively. When considering at the Modern Era (since 1958), the JMA and Niño 3 indices are the best indices to use in defining ENSO phases.

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1. INTRODUCTION

El Niño-Southern Oscillation (ENSO) has a large impact on world climate through air-sea interaction. Warm (El Niño) and cold (La Niña) ENSO phases have been associated with extremes in precipitation. Severe droughts occur in some places while torrential rains with flooding occur in others. During a warm ENSO event, the fish population may decrease due to nutrient-poor water replacing the cold, nutrient-rich water in the eastern coastal tropical Pacific Ocean through the process of reduced upwelling (Ahrens 1994). The phase and strength of ENSO events are typically defined by an index. However, there are many such indices, and it is not clear which is best for defining ENSO years, strength, timing, or duration of ENSO events. There is currently no consensus within the scientific community as to which index is the best at defining ENSO years.

El Niño events have been shown to be associated with suppressed hurricane activity. Hurricane Andrew hit Florida on August 24, 1992. Many people say that 1992 was an El Niño year and we still had Andrew. However, there was only a very weak El Niño in 1992. It is the hurricane season before an El Niño winter that reduces hurricanes in the Atlantic (Bove et al. 1998). This is some justification for this study.

Indices that are used to classify ENSO events include sea surface temperature (SST) indices (e.g., Niño 1+2, Niño 3, Niño 4, Niño 3.4, Japanese Meteorological Agency-JMA), the atmospheric surface pressure-based Southern Oscillation Index (SOI), and the Multi-Variate Index (MEI). The latter is based on six different meteorological parameters. The effectiveness of these indices for indicating the phase and strength of the ENSO cycle is examined.

The SST indices are calculated using the reconstructed one hundred year SST anomalies from Meyers et al. (1998) to determine which index is the best at capturing ENSO phases. The SST indices were reconstructed to have complete indices over the Pacific Ocean without any missing data within the indices. The ENSO years and strengths defined for each SST index are then compared. Finally, the identified ENSO years are compared to other indices (e.g. MEI, TNI, etc.) to determine which index is the best for defining ENSO event years. The current study focuses on defining ENSO years as warm (El Niño), cold (La Niña) or neutral and 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 the 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. All SST indices faired the same when compared to the SOI except for the Niño 1+2, Niño 4, and TNI indices. The Niño 1+2 and Niño 4 indices downgraded very strong ENSO events to moderate events. The TNI is good at showing

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patterns of formation of ENSO events but was not designed to capture the occurrence of ENSO events. The final conclusions are within Section 5.

2. BACKGROUND

ENSO is a natural coupled oscillation in the ocean-atmospheric system over the tropical Pacific that operates on a time scale of 2-7 years. El Niño can be traced to around 1525 off Peru (Ortlieb 1999) and was first noted by scientists in the 1890s (Glantz 1996). There are many different indices that can be used to identify warm (El Niño) and cold (La Niña) phases of ENSO. ENSO events can be classified by year occurrence, when they peak, duration and strength of an ENSO event.

a. Definitions and History

El Niño is defined by Glantz (1996) as a "name given to the occasional return of unusually warm water in the normally cold water [upwelling] region along the Peruvian coast, disrupting local fish and bird populations". It is also "a Pacific basin-wide increase in both 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

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known as ENSO (El Niño – Southern Oscillation). ENSO has three phases: warm ocean (El Niño), cold ocean (La Niña), and near neutral conditions.

When neutral conditions exist in the tropical Pacific, the normal trade winds are blowing towards the west across the Pacific Ocean. There is an atmospheric high pressure in the east and low pressure in the west. The ocean temperatures are warm (~30°C) in the west and cold (~21°C) in the east. The ocean thermocline is thick in the west and thin in the east, resulting in upwelling 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 in the neutral pattern (i.e., El Niño or La Niña) shifts the boundary of the warm pool, east and west, and affects the weather downstream at many locations over North and South America.

The exact initiation of a warm ENSO phase is still hard to define, however, anomalous westerly wind events (known as westerly wind bursts) are a key component. Westerly wind bursts typically form over the equatorial warm pool (north of New Guinea). Oceanic downwelling Kelvin waves will develop if the wind bursts become prolonged or there are several strong bursts in succession. The Kelvin waves propagate eastward towards the coast of South America in roughly two months as a down-welling internal wave.

As the Kelvin wave is moving, it suppresses the thermocline in the eastern Pacific and reduces the slope of the thermocline across the equatorial Pacific. The Kelvin waves suppress the upwelling off the Peruvian Coast, leading to warmer, less-nutrient water along the Peruvian Coast. The reduction of equatorial upwelling in the eastern Pacific is

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due to the weakening of the equatorial easterlies that occurs across the eastern Pacific Ocean along with negative swings of the SO, which helped to increase sea surface temperatures (SSTs) (Bjerknes 1966). The SO is shifting the low pressure towards the east, which results in lower sea level pressure in the eastern Pacific Ocean. The sun will start to warm the water in the central Pacific and more convection will be observed. At this point the atmosphere conditions feed back into the ocean to perpetuate the ENSO warm phase. The weaker PGF along the equator, slackened trade winds, and westerlies in the western Pacific can initiate additional Kelvin waves. These waves will help to depress the thermocline and further warming in the central Pacific will result in increased convective activity.

At the peak of a warm ENSO phase, there are droughts in Indonesia and rainfall along the Peruvian Coast. The main convective activity is in the central Pacific, the trades may reverse and blow towards the east, and the thermocline is thicker in the east, which results in warmer SSTs due to decreased vertical mixing in the ocean. This pattern is now known to affect weather downstream in North America (Ahrens 1994; Glantz 1996; Richards et al. 1996; Bove 1997; Legler et al. 1998) and over much of the globe (Glantz 1996; Philander1990; Rasmusson and Carpenter 1982).

The end of an El Niño is caused by an oceanic Rossby wave (Glantz 1996). The Rossby wave is a westward-moving internal wave, generated from the reflection of the Kelvin wave off the eastern Pacific Coast, which will depress the thermocline in the west and raise the thermocline in the east. It is a slower moving wave compared to the Kelvin wave and it will take nine and a half months for a Rossby wave to make it from the coast

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of South America to the coast of Indonesia. Initially the Rossby wave will enhance current El Niño conditions. The peak of the Rossby wave will help in amplifying these conditions in the central part of the Pacific Ocean. This occurs near the peak of an El Niño event. As the peak of the wave moves to the eastern Pacific, the trough of the Rossby wave will be in the central Pacific. The thermocline will rise in the eastern Pacific. The rising thermocline reinitiates upwelling in the eastern Pacific.

Cold phases are also ENSO events. During a cold phase, the trade winds will blow stronger than normal across the tropical Pacific basin. These anomalously strong trade winds will enhance upwelling off the Peruvian coast. Enhanced high pressure in the east and reduced pressure in the west will accompany the stronger than normal trades. Convection will move further west in a cold event with more rain in Indonesia and Australia. The thermocline will become shallower than normal in the east. The stronger trades, shallower thermocline in the east and the enhanced upwelling will reduce the SSTs in the eastern and central equatorial Pacific Ocean lower than normal (Philander 1990).

ENSO is a complex system and its phases can be hard to define. Trenberth (1997) suggests the definition of El Niño given by Glantz (1996) is the best qualitative definition that exists at this point in time. El Niño has always been hard to define since each scientist has their own definition of El Niño and different criteria for identifying ENSO events. More importantly, some aspects of ENSO development (especially cold phases) are still not well understood. The lack of understanding further complicates efforts to define the morphology of ENSO events.

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b. ENSO Indices

Many different indices are used to designate when an El Niño or a La Niña has occurred. Eight indices are used to complete 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 refer to mean SST within different regions of the Equatorial Pacific (Fig. 1; Rasmussen and Carpenter 1992). The Niño 1+2 index is sensitive to seasonal and ENSO-induced changes. The Niño 1 region is located off the Coast of Peru and Ecuador, while the Niño 2 region is near the Galapagos Island, a transition zone between the central and eastern equatorial Pacific (Fig. 1). The Niño 3 region is in the central equatorial Pacific and is much less sensitive to the continental influences than the Nino 1 and Nino 2 regions (Fig. 1). The Niño 4 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.

The Niño 3.4 overlaps portions of the Niño 3 and Niño 4 regions (Fig. 1). The Niño 3.4 region is located from 5°N-5°S and expands from 170°W-120°W. Niño 3.4 was defined in Barnston et al. (1997) where they found that the Niño 3.4 was better correlated with ENSO events than Niño 3. A sample correlation with the SOI proved to be stronger for Niño 3.4 than Niño 3. The JMA index is produced by the Japanese Meteorological

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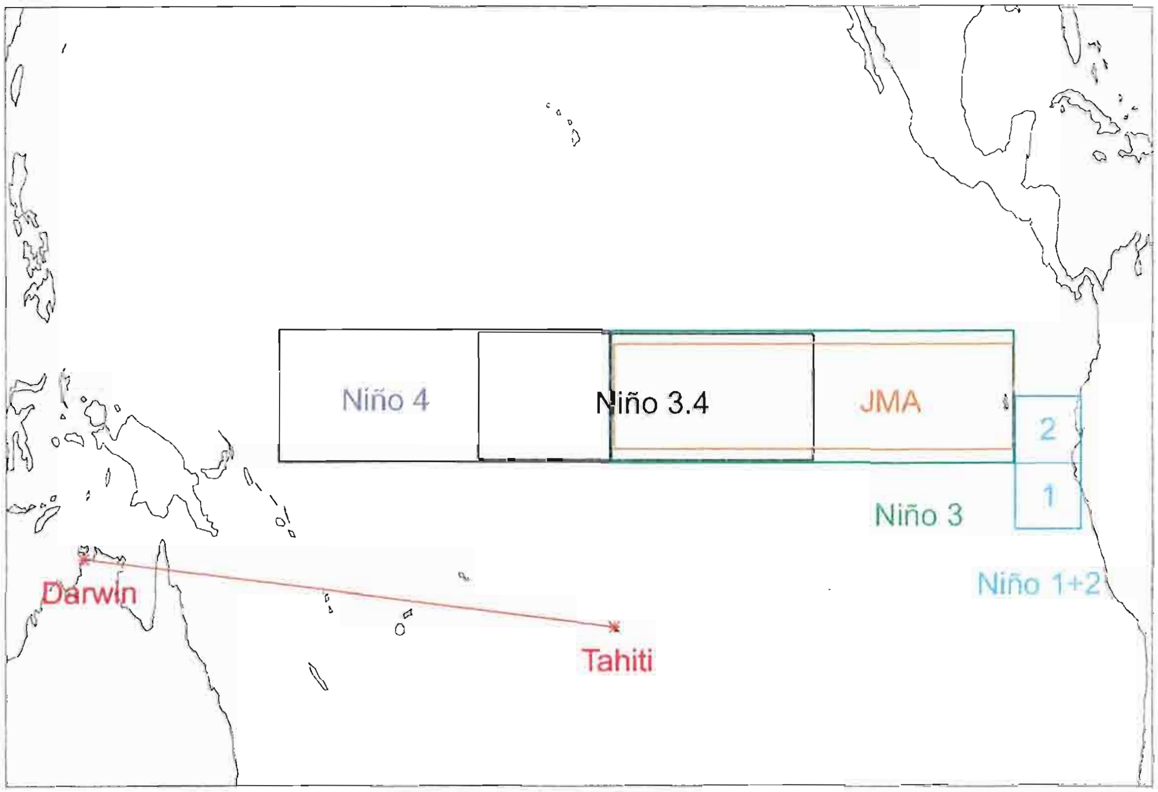

Figure 1. Locations of Regions. Regions in the tropical Pacific used to define average SST anomalies for the Niño 1+2 (blue), Niño 3 (green), JMA (orange), Niño 3.4 (black), and Niño 4 (purple) SST-based ENSO indices. Also plotted are the locations of Tahiti and Darwin, used to create the SOI (red).

Agency and is located in the middle of the Niño 3 region (Fig. 1). The JMA region extends from 4°N-4°S while the Niño 3 region is two degrees of latitude larger (5°N-5°S).

The SOI is an air pressure index based on the difference between the Tahiti (French Polynesian) and Darwin (Australia) sea level pressure (SLP) (i.e. Tahiti minus Darwin) (Fig. 1). The pressure difference is a measure of the strength of the trade winds, which flow from regions of high pressure to regions of lower pressure. There are a few problems documented with the SOI: Trenberth (1984) notes significant noise throughout the monthly data due to either transient features of the circulation not related to the SO or other small scale features. Another problem with the SOI is the missing data within the index. Ropelewski et al. (1987) propose 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.

Trenberth (2001) suggested that more than one index might be needed to show the evolution and intensity of ENSO events. As a result, he created the Trans-Niño index (TNI) that is the east-west temperature gradient in the eastern tropical Pacific. The TNI is a difference between scaled SST anomalies averaged in the Niño 1+2 and Niño 4 regions. It represents a difference of scaled SSTs across the Pacific from the date line to the American coast. It indicates the pattern 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 but it works well for patterns of formation of ENSO events.

The MEI an index that 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/).

c. Classifying ENSO Events

ENSO events can be classified by year of occurrence, strength, duration, and 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 their ENSO events. 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, above-normal rainfall and massive destruction. Strong events included those with sea surface temperatures 3°-5° C above normal with large amounts of rainfall and still major damage. A moderate event was one with sea surface temperatures 2°-3°C above normal with above-normal rainfall
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and minor damage. A weak event had hardly any damage, normal rainfall, and sea surface temperatures 1°-2°C above normal.

Methods of defining ENSO events and years are also important when studying ENSO. Different indices (e.g. JMA, Nino 3.4, SOI, etc.) are used in different ways to identify ENSO events. The JMA definition for a warm (cold) ENSO event requires SST in the JMA region 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. Van Loon et al. (1981) defined their ENSO events by averaging the pressures for December, January, and February, over the Northern Hemisphere north of 20°N and examining patterns. Each index and past study has different years defined as ENSO events. Van Loon et al. had the exact same number of El Niño and La Niña events. However, they neglect the neutral events and focus only on the extreme events. The JMA has more La Niña events than El Niño events. Ropelewski et al. (1987) used some of the El Niño events from Rasmussen and Carpenter (1982) and some La Niña events from van Loon et al. (1981) to define their ENSO years. In this study, the JMA index definition for duration is used but the SST thresholds are determined from the data. The thresholds for this study are the values at the upper and lower quartiles of each index.

Duration of ENSO events and timing of ENSO events are also important. Trenberth et al. (1987) found 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 for indices to 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, etc.) best capture

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the events in the winter when ENSO events usually peak. This study does not focus on the duration of the event or the timing of the event but rather the strength of the events and the years of the events.

There is currently no consensus within the scientific community as to which index is the best to use. In this study, we reconstruct the SST indices with the goal of identifying which index best captures El Niño and La Niña events. We anticipate that the results of this study will serve as a guideline identifying events in future ENSO research.

3. DATA

Reconstructed monthly sea surface temperature (SST) data (Meyers et al. 1998) are used to calculate SST based ENSO indices. The reconstructed SST data were created in 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. The subset of gridded temperature data used for this study covers the entire time period and a portion of the Pacific Ocean ranging from 15°N to 15°S and from 121°E to 75°W.

Missing data are often absent in SST data sets from the mid 1800s until the mid 1900s. Meyers et al. (1998) reconstructed the SST anomalies in order to have a temporally and spatially complete data set over the Equatorial Pacific Ocean. Monthly Reynolds Optimal Interpolation (OI) SST fields from November 1981 to 1993 were used to determine the Empirical Orthogonal Functions (EOFs) of monthly anomalies. The EOF basis functions were derived from a fourteen-year period starting in 1981 and continuing until the early 1990s. These functions are projected on available in-situ observations to create spatially complete fields. The in-situ data are SSTs from the Comprehensive Ocean-Atmosphere Data Set (COADS; Slutz et al. 1985), and had biases related to instrument errors removed. The applicable number of modes of EOFs was determined using the 1970s COADS SSTs: variance of the misfits to large-scale features

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of was minimized using large-scale error analysis (LSEA) 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 and the climatology and running mean were added. Monthly tropical SST anomaly fields were reconstructed to create spatially complete (2° x 2° grid) data from the early 1860s to the early 1990s.

The ENSO indices recalculated herein are based on the spatially averaged SSTs in the applicable ENSO regions. 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 (Rasmussen and Carpenter 1982), the Niño 3.4 (Barnston et al. 1997) and the TNI (Trenberth et al. 2001). A multivariate index created by Klaus Wolter (http://www.cdc.noaa.gov/~kew/MEI/) was also used for qualitative purposes only.

The above ENSO indices will be compared to the SOI. The SOI values were 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

4. METHOD AND ANALYSIS

The ENSO indices are calculated from reconstructed SST fields (Meyers et al. 1998). Running sums of the reconstructed SST indices are examined to evaluate trends in the SST time series. This is a seldom used but simple idea that is very useful. Warm and cold ENSO years are identified (for each index) using the upper and lower quartile values as thresholds of occurrence. The ENSO years and strengths defined for each SST index were then compared.

a. Calculating the SST Indices

The merits of the 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. 1998) over the regions of the Pacific Ocean corresponding to each index (Fig. 1, Table 1) for each month from 1894-1993. Long-term monthly climatologies for each region were calculated by averaging over each calendar month in the time series. The long-term monthly climatology was subtracted from each time series to create series of anomalies, which is smoothed with a five-month running mean (Fig. 2). Missing data are avoided by appending the anomalies for January

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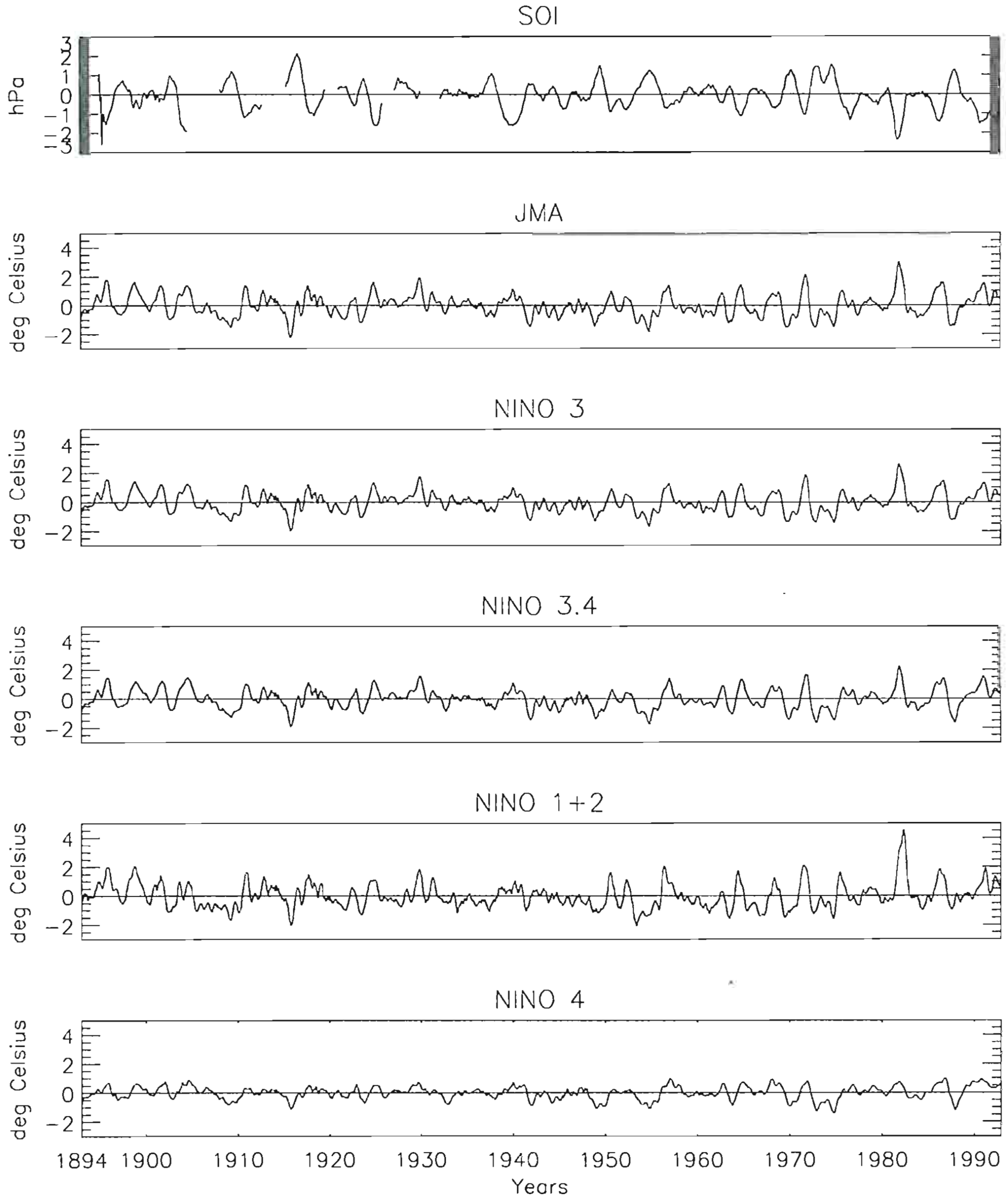

Figure 2. SOI 13 Month Running Mean and SST Indices 5 Month Running Means.

Table 1: ENSO Index Regions. Latitude and Longitude ranges defining area averages for SST indices. TNI regions and SOI station locations provided for completeness.

Index	Longitude maximum and minimum	Latitude maximum and minimum
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
SOI		
Tahiti	17.5S	149.6W
minus		
Darwin	12.4S	130.9E

and February 1894 and November and December of 1993 to the five-month running mean time series, which helps maintain the length of the time series. 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 that exceeds a lower threshold is defined as a La Niña event. The SOI has an opposite sign convention for ENSO events.

The SOI is the primary comparison index for this study. A thirteen-month mean of the Tahiti-Darwin SLP standardized anomalies is used instead of a five-month mean due to the relatively poor signal to noise ratio in the SOI Index.

A running sum of each reconstructed index is created to reveal multi-year trends in SST anomalies (Fig. 3). 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. A decrease indicates a period that may be associated with strong and/or more frequent La

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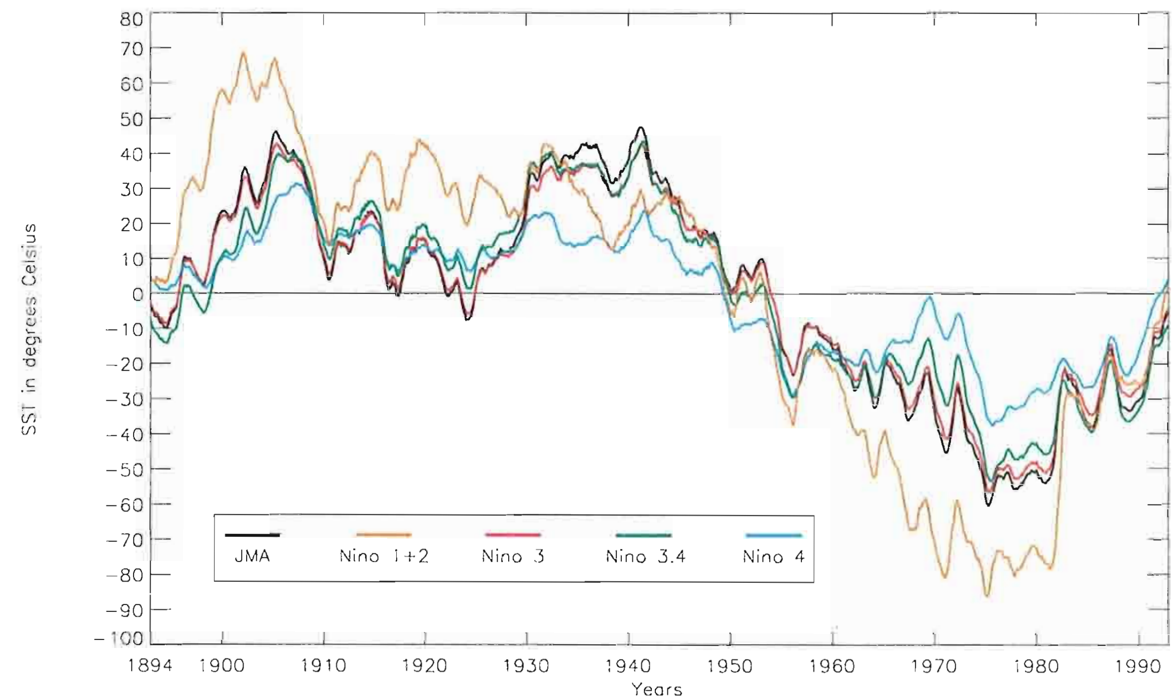

Figure 3. SST Index Running Sums with means removed. The running sums show the multi-years trends within the SST anomalies. The running sums are plotted for the JMA (black), Niño 1+2 (orange), Niño 3 (red), Niño 3.4 (green), and Niño 4 (blue) reconstructed SST ENSO indices.

Niña events. Several explanations are possible to describe slowly changing periods (near zero slopes) in the running sums. During a period of alternating El Niño and La Niña events of equal magnitude, one would expect little to change in the slope of the running sums. These running sums show trends on several time scales.

There are differences between these indices. The Niño 1+2 and Niño 4 indices are much different from the other SST indices. This implies differences in sensitivity to ENSO events. The upwelling occurring in the Niño 1+2 region is strong. Increased upwelling during La Niña has little impact on SST anomalies. The water is already cold in the Niño 1+2 region and with increased upwelling, the water is unable to get colder than its present state. The Niño 4 region is located in the western Pacific Ocean. Even though part of the Niño 4 regions lies within the central Pacific, the dynamical range for La Niña anomalies is relatively small. The Niño 1+2 and Niño 4 indices will either underemphasize or overemphasize ENSO events. Therefore, the Niño 3, Niño 3.4, and JMA indices have better correlations with one another and are able to capture ENSO phases.

The running sums have upwards trends in 1894 to 1906, 1925 to 1930, and 1982 to 1993. The downward trends in the running sums are 1906 to 1910 and a long period from 1942 to 1976. There are zero trends during 1910 to 1925, 1930 to 1941, and 1976 to 1981. These running sums appear to show a well-defined Pacific Decadal Oscillation (PDO) signal. The PDO is an interdecadal pattern of climate variability located in the North Pacific Ocean (Mantua 2001).

b. Classifying the El Niño and La Niña Years

Definition of years corresponding to El Niño or La Niña is determined through a quartile method and the JMA definitions for ENSO events. The anomaly series were sorted into three categories: values below the 25th percentile, values above the 75th percentile, and the value in between these two percentiles. The value that defines the upper quartile (75th percentile) was identified and used as a threshold for El Niño occurrence (T_w). Likewise, the value that defines the lower quartile (25th percentile) was identified and used as a threshold for La Niña occurrence (T_c). As an example, the JMA has a T_w=0.47°C and a T_c=-0.52°C (Fig. 4). The JMA index definition for the duration of an ENSO event, six consecutive months including October, November, and December, above (below) a threshold, was used to define the ENSO warm (cold) years (Fig. 5). A threshold of +0.5°C is used in the JMA definition, but these are replaced by T_w and T_c in our quartile method. Advantages of quartiles are that they are determined by 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.

Past empirical studies that classify ENSO years are compared to the JMA index ENSO years defined in this study to show how a temperature based index compares to past empirical studies (Fig. 5). The first comparison made was with van Loon et al. (1981). They define an ENSO event by looking at the pressure distribution of the opposing phases of the SO in five different places. They defined the northern winters (southern summers) from 1899/1900 to 1978/1979 when the oscillation was at an extreme

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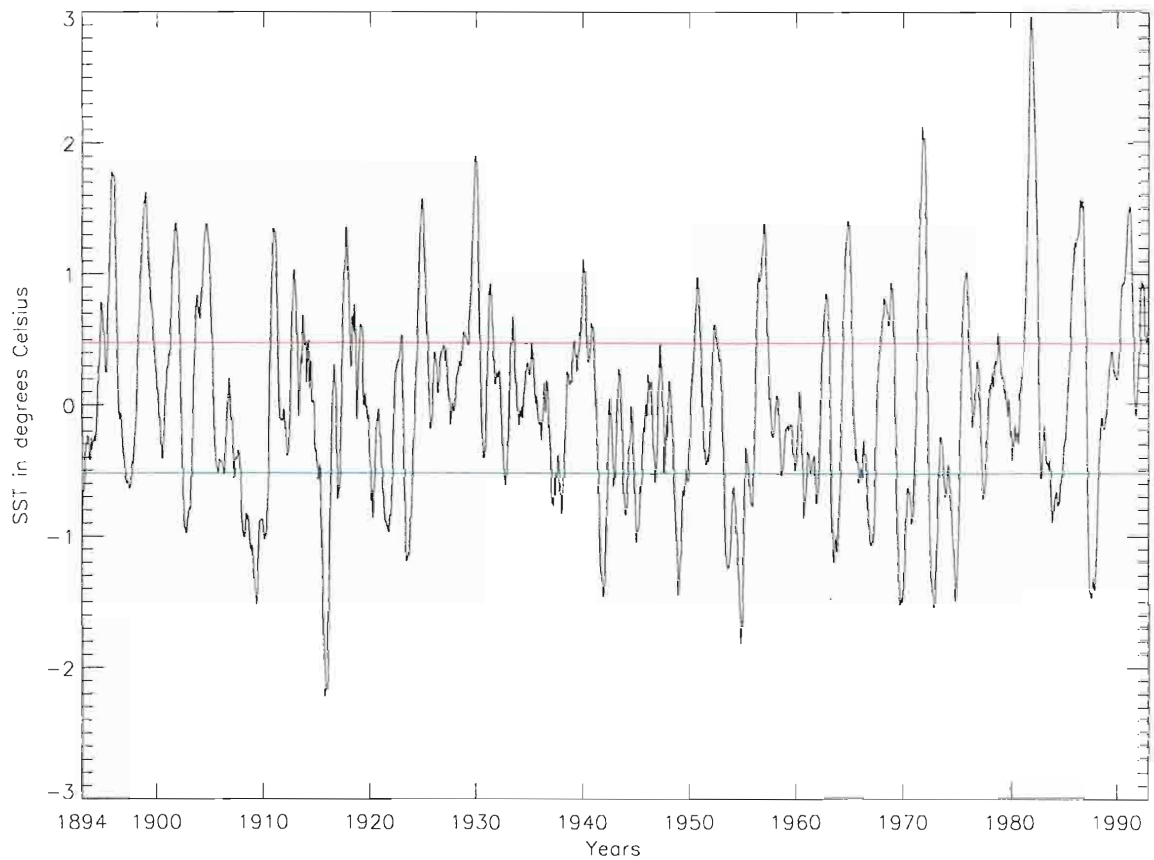

Figure 4. Quartiles. Five month running mean of the JMA SST anomalies. The red and blue solid lines mark the upper and lower quartile value respectively, and are the thresholds for defining an El Niño event or La Niña event.

and used SLPs from Darwin, Cocos Island, Samoa, Tahiti and Santiago, and Djakarta. They used these regions to obtain the pressure distributions of the opposing ENSO phases. 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. WET and DRY refer to the rainfall in the Pacific long the equator. They chose the combination of L/W when a peak in the rainfall occurred at the same time as high-pressure anomalies occurred in the tropical Indian Ocean and a trough of pressure in the tropical Pacific. The opposite defined a H/D year. They used three months for the definition of their year: December, January, and February.

Comparison of Van Loon et al. (1981) to JMA ENSO years defined here show that there are differences in the indices. Of the number of El Niños (warm events) classified by Van Loon et al. (1981), six years are not classified as El Niños by the JMA index. Of the number of La Niñas (cold events) classified by Van Loon et al. (1981), six years are not classified by the JMA index. Van Loon et al. (1981) missed three El Niño events and five La Niña events defined by the JMA index.

The next comparison is made with Rasmusson and Carpenter (1982). They based their study on the warm events after 1953 since data earlier than that time were sparse and no real conclusions could be drawn. They used the average SST anomalies from the upper Peru Coast, close to the Niño 1+2 region, for their discussion. Long-term means and standard deviations were computed from mean-monthly values for a one-degree latitude and five-degree longitude box along six shipping lanes between the South

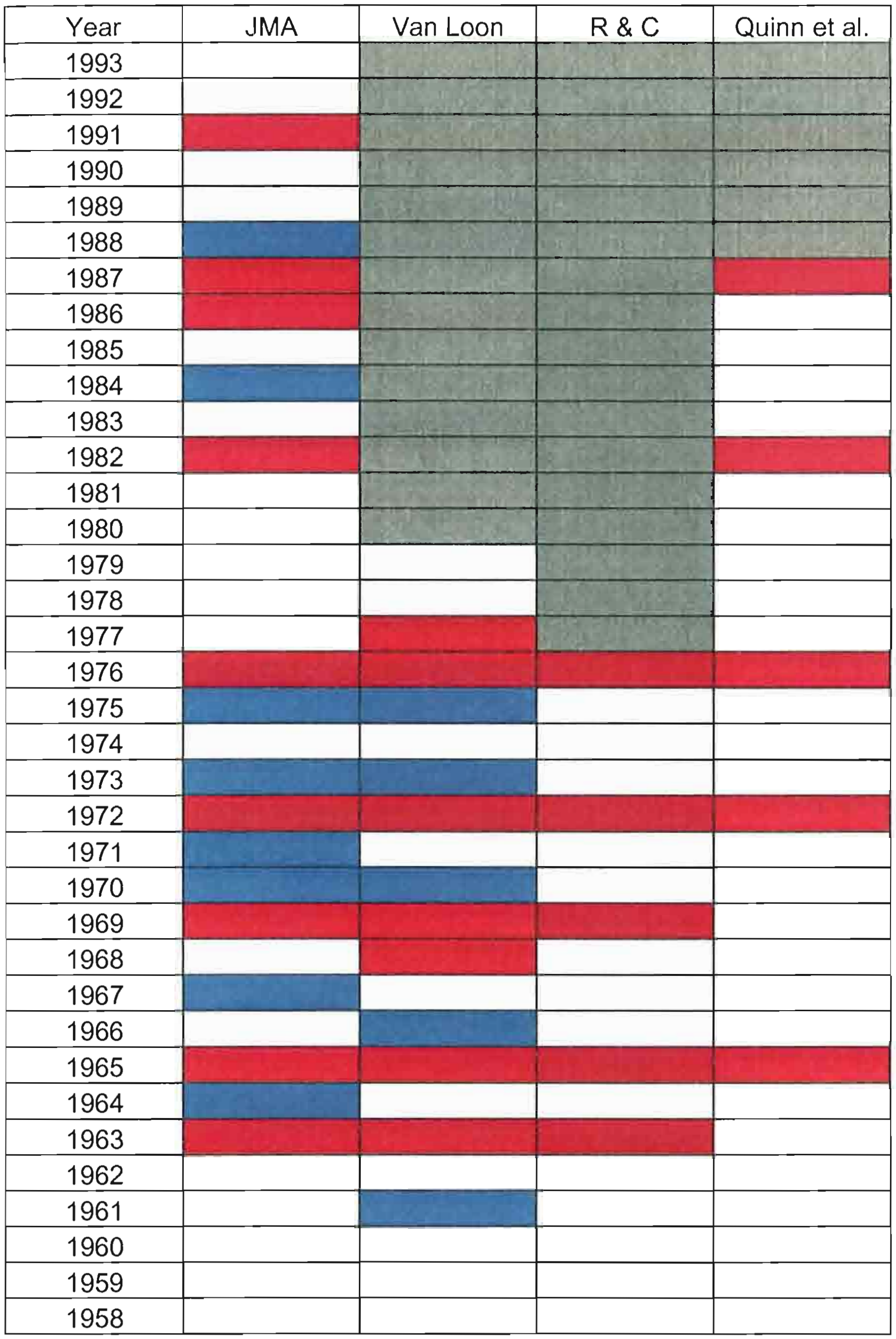

Figure 5: JMA ENSO year definitions versus Van Loon et al. (1981), Rasmusson and Carpenter (1982), and Quinn et al. (1987). El Niño year (red) and La Niña (blue) are rarely uniform across all indices. The ENSO year is defined as starting in October and extending to September of the following year. Gray indicates missing years.

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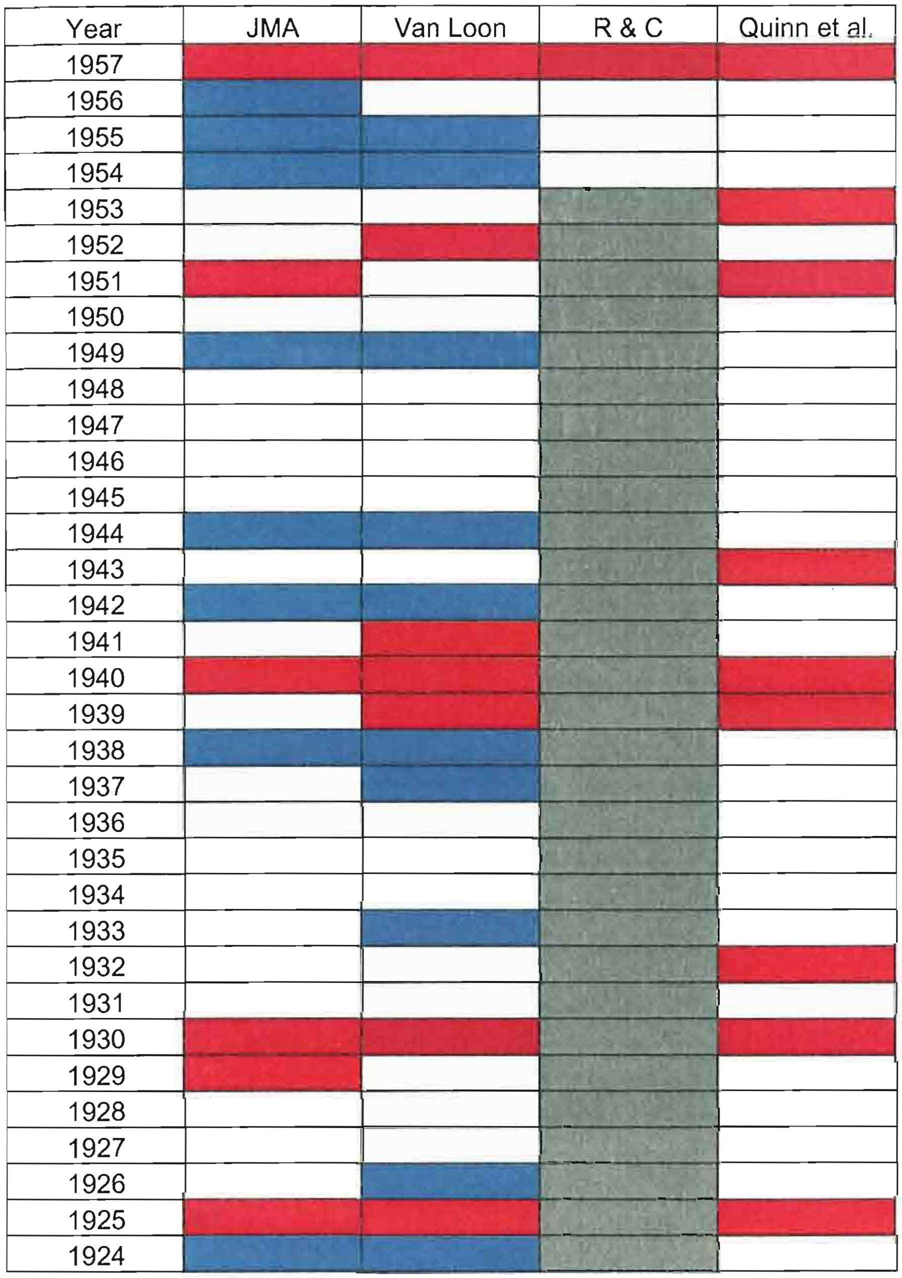

Fig. 5 continued.

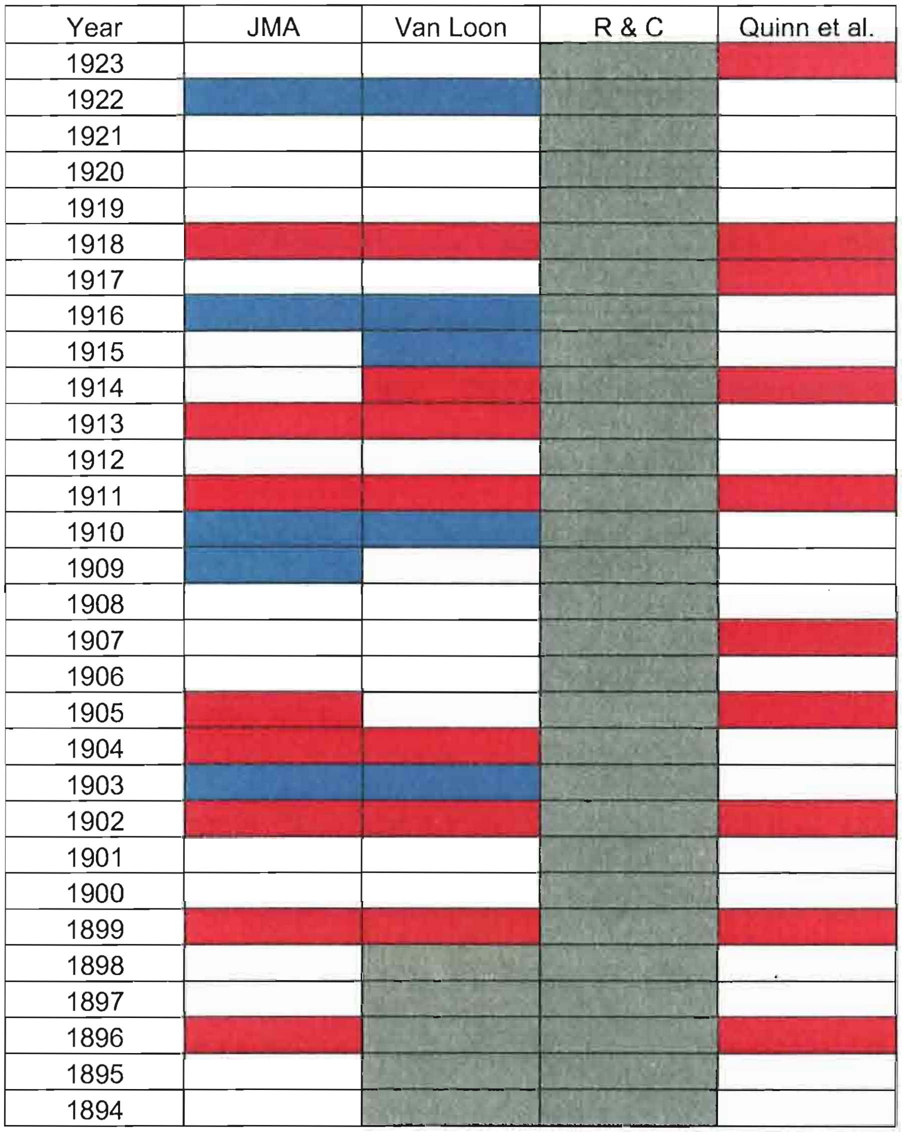

Fig. 5 continued.

American coast and the equator. Wind components were also calculated. A four-pass editing procedure was applied to the derived data. Any value of SST that was outside ±3.65σ for a particular calendar month was removed and a new monthly mean and standard deviation was calculated. In comparing their ENSO years to the JMA index, the JMA captures all of Rasmusson and Carpenter's (1982) El Niño events.

Quinn et al. (1987) is used as another comparison index. They also only focused only on warm (El Niño) events. They used historical references to investigate El Niño events that have occurred over the past four and a half centuries. They divided up these events into weak, moderate, strong, and very strong by using the SCOR definition (section 2c). Weak events were not used in defining El Niño years. Compared with the JMA index, Quinn et al. (1987) misses six warm events classified by the JMA. However, the JMA misses seven warm events classified by Quinn et al. (1987).

The ENSO years defined for each index were then compared against those defined by the SOI index to determine when the indices either agreed or disagreed on the SOI classification of events (Fig. 6). There are nine ENSO events (five warm and four cold) that the JMA does not capture in comparison to the SOI and there are fifteen ENSO events (six cold and nine warm) that the SOI does not capture in comparison to the JMA. The Niño 3 misses ten SOI ENSO events (five warm and five cold) and the SOI misses thirteen Niño 3 ENSO events (five cold and eight warm). Eight SOI ENSO events (five warm and three cold) are missed by the Niño 3.4 index while fifteen Niño 3.4 ENSO events (eight cold and seven warm) are missed by the SOI index. The Niño 4 misses eight SOI ENSO events (four warm and four cold) while the SOI misses fifteen Niño 4

eight SOI ENSO events (four warm and four cold) while the SOI misses fifteen Niño 4

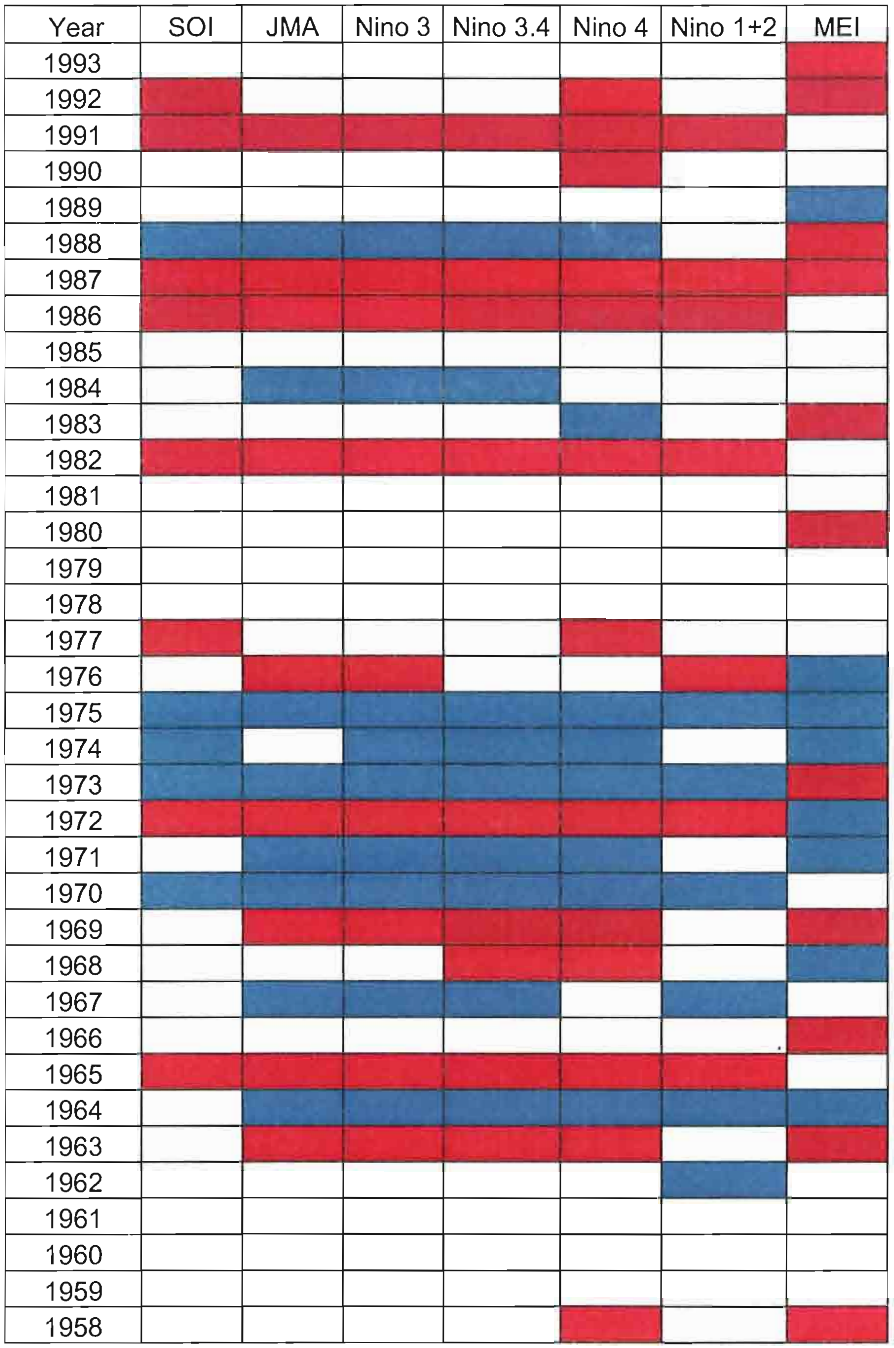

Figure 6: Same as Fig. 5 but ENSO year definitions for each reconstructed index and the MEI.

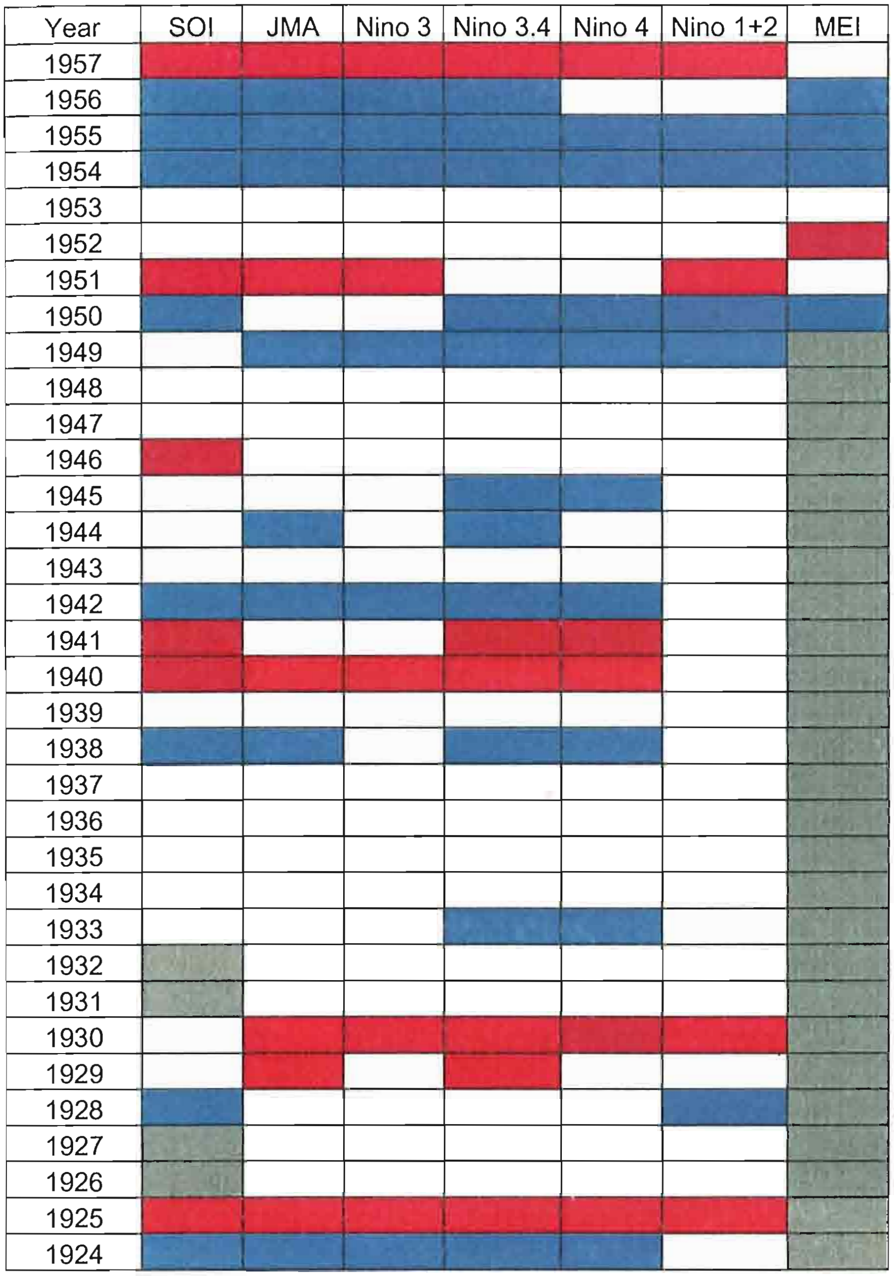

Fig. 6 continued.

Year	SOI	JMA	Nino 3	Nino 3.4	Nino 4	Nino 1+2	MEI
1923							
1922							
1921							
1920							
1919							
1918							
1917							
1916							
1915							
1914							
1913							
1912							
1911							
1910							
1909							
1908							
1907							
1906							
1905							
1904							
1903							
1902							
1901							
1900							
1899							
1898							
1897							
1896							
1895							
1894							

Fig. 6 continued.

ENSO events (six cold and nine warm). The SOI misses thirteen ENSO events (six cold and seven warm) defined by the Niño 1+2 and Niño 1+2 misses fifteen events (seven warm and eight cold) defined by the SOI. In comparison to the MEI, the SOI missed ten warm events and six cold events. However, the MEI missed eight warm events and three cold events when compared to the SOI.

The TNI (Trenberth 2001) is also compared to the SOI. It is reconstructed from the Meyers et al. (1996) SSTs. The TNI is designed only to indicate the pattern of the SST warming (i.e. East to West versus West to East), and it is good for identifying patterns of formation of ENSO events. It represents a difference of scaled SSTs across the Pacific from the date line to the American coast. Therefore, the TNI ENSO years will not match well with either the SOI or the other SST indices.

When comparing the past studies with the JMA index, we see that the past study that has the best comparison to the JMA is Rasmussen and Carpenter (1982). The TNI is a very impractical indicator for predicting ENSO years.

The ENSO year classifications were compared to the SOI to see how many times the SOI and the SST indices agreed (Table 2). For example, there are six occurrences when the JMA classified ENSO years as El Niño while the SOI classifies those years as neutral. The tallies in a box for different SST versus SOI matrices may include different ENSO years. As an example, the Niño 4 matches three different SOI El Niño years than Niño 3. Each matrix has boxes for matching ENSO events, ones for opposite events, and those for neutral extreme events. Most indices do well, but one must look at the false alarms to determine the better index for the ENSO event. For the JMA versus SOI there

alarms to determine the better index for the ENSO event. For the JMA versus SOI there

Table 2: ENSO Matrices. Comparison of temperature ENSO index years (defined for the reconstructed SST) versus the SOI years. Each matrix indicates how well the ENSO events of the temperature index matches those of the SOI. The totals of the SST ENSO events are the total of ENSO events within temperature indices.

			SOI Index: El Nino	SOI Index: Neutral	SOI Index: La Nina	Total SST ENSO Events
a)	JMA Index	El Nino	14	6	0	20
		Neutral	5	32	5	42
		La Nina	0	6	15	21
b)	NINO 3 Index	El Nino	14	5	0	19
		Neutral	5	34	5	44
		La Nina	0	5	15	20
c)	NINO 3.4 Index	El Nino	14	6	0	20
		Neutral	5	30	3	38
		La Nina	0	8	17	25
d)	NINO 4 Index	El Nino	15	7	0	22
		Neutral	4	31	4	39
		La Nina	0	6	16	22
e)	NINO 1+2 Index	El Nino	12	3	0	15
		Neutral	7	37	9	53
		La Nina	0	4	11	15
	Total SOI Events		19	44	20	

are fourteen El Niño matches and six false alarms, whereas for the Niño 4 versus SOI where there are fifteen matches and seven false alarms. The Niño 1+2 captures thirty-seven neutral events but has twenty-three false alarms while the Niño 3 index captures thirty- four neutral events with twenty false alarms. The Niño 3.4 captures the most La Niña events (17), but it has eleven misses. Contingency tables were created but they showed no useful information. Looking at the matrices and based on false alarms, it seems the Niño 3 and Niño 4 indices capture El Niño events the best. The best indices for capturing La Niña events are the Niño 3.4 and Niño 4 indices. The Niño 1+2 index seems to be the best at capturing neutral events.

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). As an example, in the case of the JMA, T_w=0.47°C and T_c=-0.52°C (Fig. 7). Each defined strong El Niño year is classified when the mean of months (MOM) that meet the ENSO definition is greater than three times the warm phase threshold (MOM > $3T_w$) (i.e. anything greater than 1.41°C for the JMA). Moderate and weak El Niños are defined when $2T_w \leq$MOM < $3T_w$ (i.e. 0.94°C to 1.41°C for the JMA) and $T_w \leq$MOM < $2T_w$ (i.e. 0.47°C to 0.97°C for the JMA), respectively. Cold phases are classified for strength in a similar manner. Weak and moderate La Niñas are defined when $T_c \geq$ MOM > $2T_c$ (i.e. –0.52°C to –1.04°C for the JMA) and $2T_c \geq$ MOM > $3T_c$ (i.e. –1.04°C to -1.56°C for the JMA), respectively. Strong La Niñas are

are defined when $T_c \geq$ MOM > $2T_c$ (i.e. –0.52°C to –1.04°C for the JMA) and $2T_c \geq$
MOM > $3T_c$ (i.e. –1.04°C to -1.56°C for the JMA), respectively. Strong La Niñas are

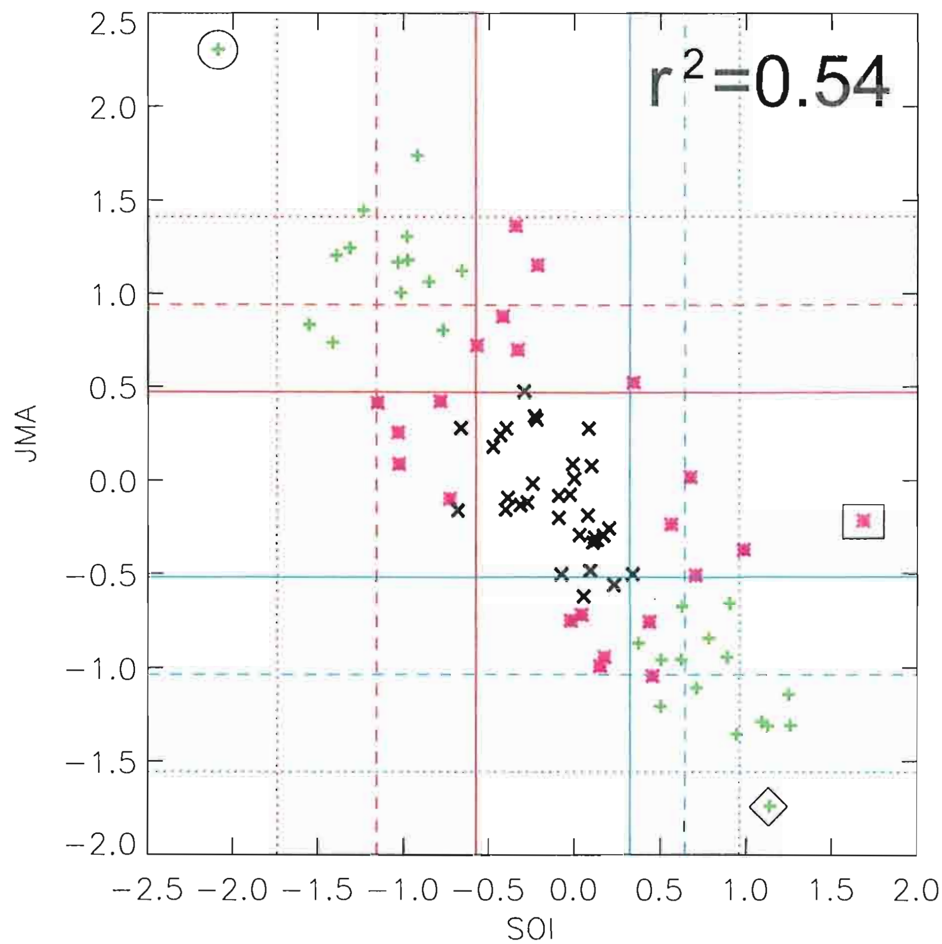

Figure 7: JMA Index vs. SOI Index. The green cross symbols indicate matching ENSO extreme phases, black x symbols indicate matching neutral events, pink asterisks indicate neutral vs. extreme mismatches. A black square indicates suspect data, a black diamond indicates the strongest La Nina event, and 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.

defined when $3T_c \geq MOM$ (i.e. anything less than –1.56°C for the JMA). For example, this method classifies three strong El Niños and one strong La Niña for the JMA index (Fig. 7).

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. 7 and 8). The neutral events (black x's) are 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. Correlation coefficients were calculated along with these scatter plots. The values are as follows: 0.54 for the JMA; 0.38 for the Niño 1+2; 0.56 for the Niño 3; 0.61 for the Niño 3.4; and 0.58 for the Niño 4.

Each index classifies the strongest El Niño event (circle) as 1982. The Niño 1+2 also classifies the 1972 El Niño event as one of the strongest as well. However, the Niño 4 does not (Fig. 8d). The 1982 ENSO event, which is identified as a strong event within the other indices, is identified as a moderate event within the Nino 4 region. The conjecture for the shift is that the water is already warm. As the ocean warms, the atmosphere evaporates the warm water forming clouds. When rain falls from these clouds, the ocean water is cooled. Therefore, the water temperature is unable to reach values higher than ~31°C. Furthermore, the Niño 4 region has a deeper mixed layer than the other ENSO regions. It is easier for the SST to rise in shallow areas than in deep areas. Therefore, due to the warm water already in existence, the Niño 4 region will be less sensitive to the ENSO signal for an El Niño event.

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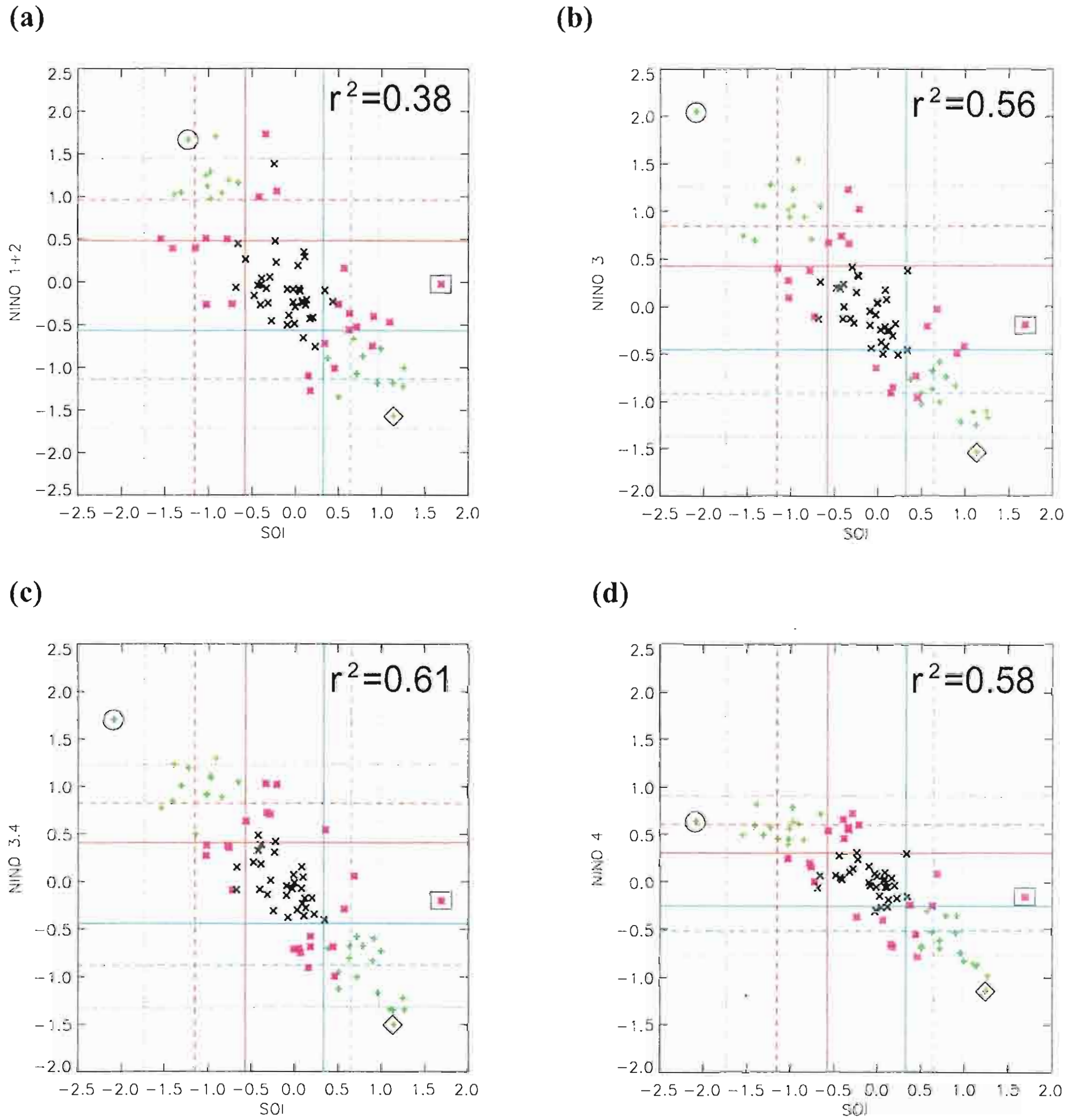

Figure 8: Same as Fig. 7 except for the following temperature indices versus the SOI: a) Niño 1+2; b) Niño 3; c) Niño 3.4; and d) Niño 4.

The Niño 1+2 region shows less La Niña events due to sensitivity. All of the indices identify the 1916 (diamond) La Niña as the strongest event, but the Niño 1+2 region classifies it as a moderate event (Fig. 8a). The conjecture of the downgrading of this event is the Niño 1+2 region upwelling is strong, but increased upwelling during La Niña has little impact on SST anomalies.

The 1917 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, the shipboard data becomes 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 downgrading of a peak cold event in the Niño 1+2 region and a warm event in the Niño 4 region show that these regions are less reliable at capturing the magnitude of ENSO events. The JMA, Niño 3 and Niño 3.4 all show El Niño events well. The Niño 3.4 has the most moderate and strong El Niño events compared with the SOI with 12 total events. The Niño 4 has the least strong and moderate El Niño event matches compared to the SOI; however, it has most moderate and strong La Niña events matches compared to the SOI with 12 events total. The Niño 1+2 has the least moderate and strong La Niña events.

The JMA was compared to SST indices (Fig. 9). It is clear that the Niño 3 index (Fig. 9b) is closely related the JMA with a correlation coefficient of 0.99. This occurs because the JMA is in the same region as Niño 3. The Niño 3.4 index (Fig. 9c) is also

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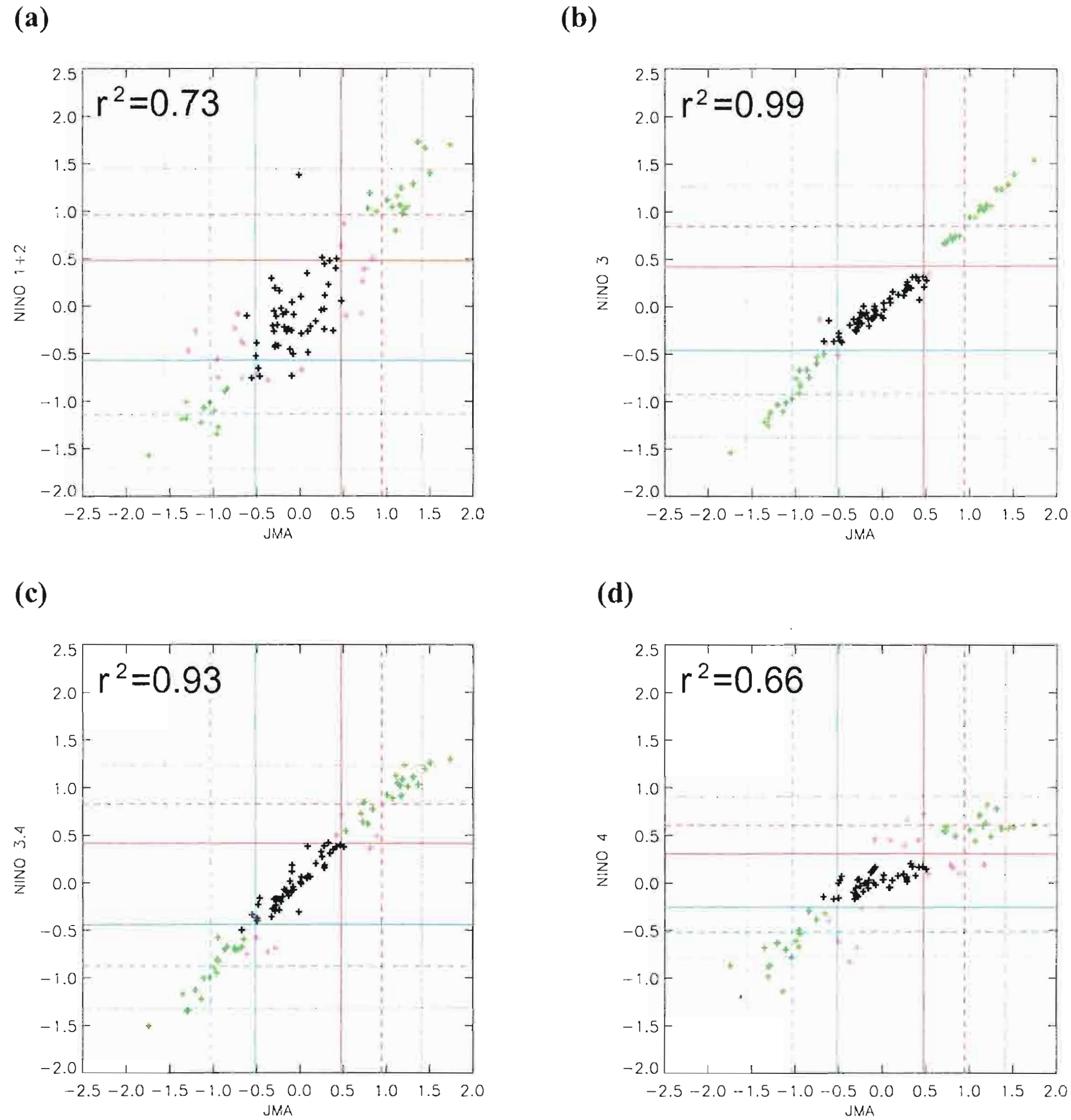

Figure 9: JMA Index vs. ENSO temperature indices. The green cross symbols indicate matching ENSO extreme phases, black x symbols indicate matching neutral events, pink asterisks indicate neutral vs. extreme mismatches. The lines indicate the thresholds for defining the strength of ENSO events. The solid 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.

well correlated with the JMA with a correlation coefficient of 0.93. However, it is apparent the Niño 1+2 and Niño 4 indices (Figs. 9a, d) are not correlated as well with the JMA (0.73 and 0.66, respectively) since they are not in the same region as the JMA.

When comparing the three most widely used ENSO indices, Niño 3, Niño 3.4, and JMA, we look at the Modern Era (since 1958). 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 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. In each of these three cases, the JMA agrees with papers from Van Loon et al. (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 et al. (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). With respect to the Modern Era, the JMA and Niño 3 indices are the best indices to use when determining ENSO phases, since there is a very high correlation between the two indices.

5. CONCLUSIONS

Seven ENSO indices are reconstructed from monthly SST anomalies to examine the indices' strengths, weaknesses, and sensitivity. A running sum is applied to the indices to show multi-year trends and periods of ENSO extremes. The SST indices are compared to the SOI. Matrices are formed to look at the concurrences of SOI and SST ENSO year matches, mismatches, and opposite event matches. Scatter plots are created to show the strengths of the ENSO events, sensitivity of the indices, and the magnitudes of different SST indices ENSO events compared to other SST index events.

For the reconstructed indices, the same type of smoother is used on all of the indices. However, the actual calculation of the indices by the other organizations may not include the same smoother as the one used in this study.

The JMA index is compared to the past empirical studies of Van Loon et al. (1981), Rasmusson and Carpenter (1982) and Quinn et al. (1987). The JMA misses six El Niño and six La Niña ENSO events classified by Van Loon et al. (1981), seven El Niño ENSO events defined by Quinn et al. (1987) and none of the Rasmusson and Carpenter El Niño ENSO events (Fig. 5). When the reconstructed SST indices are compared to the SOI, results show the Niño 3.4 and JMA are the best two indices for capturing ENSO phases (Fig. 6). The Niño 3.4 missed eight ENSO events and the JMA

compared to the SOI, results show the Niño 3.4 and JMA are the best two indices for
capturing ENSO phases (Fig. 6). The Niño 3.4 missed eight ENSO events and the JMA

missed nine ENSO events. The Niño 4, MEI, and Niño 3 faired well also. However, the Niño 1+2 was the worst by missing thirteen ENSO events.

Reconstructed ENSO year definitions are compared to the SOI to see how many times the SOI and the SST indices agree (Table 2). One must look at the false alarms to determine the better index for capturing ENSO phases. Based on the false alarms, the Niño 3 and Niño 4 indices best capture El Niño events, Niño 3.4 and Niño 4 best capture La Niña events, and Niño 1+2 best captures the neutral 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 (Fig. 8). Each index shows 1917 as an outlying neutral year. The Niño 1+2 downgrades the 1916 La Niña event from strong to moderate while the Niño 4 downgrades the 1982 El Niño event from strong to moderate. The JMA index is compared to the reconstructed SST indices (Fig. 9). The Niño 3 index has the best correlation to the JMA than the other SST indices due to its Equatorial Pacific Ocean location.

The JMA, Niño 3, and Niño 3.4 indices were then compared against each other, against the SOI, and finally against the past empirical studies in the Modern Era (since 1958). Since the JMA and Niño 3 indices are highly correlated to one another, these comparisons help show that the JMA and Niño 3 indices are better indices at capturing ENSO phases rather than the Niño 3.4, especially when compared to the past empirical studies.

studies.

The Niño 3, Niño 3.4, and JMA all capture ENSO phases well for all one hundred years. The Niño 1+2 and Niño 4 seem to under-emphasize ENSO events by downgrading two events. If the Modern Era (since 1958) is the main emphasis, then the JMA, Niño 3, and Niño 3.4 are the better indices to use. However, the best indices at capturing ENSO phases are the Niño 3 and JMA indices.

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BIOGRAPHICAL SKETCH

Elizabeth Rebecca Spade
586 Longwood Drive
Fayetteville, North Carolina 28314
(Home): 910-485-1254

Degrees

B.S. in Meteorology, 1999, North Carolina State University
M.S. in Meteorology, 2001 (expected), The Florida State University

Experience

1998: Researched the re-intensification of Hurricane Danny with Dr. Alan Riordan for the summer

1998: Worked as a Meteorological Intern under Gregory Fishel at WRAL-TV in Raleigh, N.C. for the summer. Also, helped cover Hurricane Bonnie in the fall.

1999-2001: This thesis

Honors

National Honor Society

Memberships

American Meteorological Society (AMS)

National Weather Association (NWA)

Phi Beta Psi

Mu Beta Psi- National Honorary Musical Fraternity

Personal Information

Born July 5, 1977 in Fayetteville, North Carolina

Resided in Fayetteville, North Carolina (located next to Fort Bragg-the largest military base in the US) until attending North Carolina State University in the Fall of 1995

Resided in Raleigh, North Carolina until attending The Florida State University in the Fall of 1999