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Edited by Henry F. Diaz and Vera Markgraf
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Introduction

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Significant progress has been made over the last decade in understanding the mechanisms and global manifestations of the weather and climate anomalies referred to as El Niño/Southern Oscillation (ENSO). The ENSO phenomenon constitutes the largest single source of interannual climatic variability on a global scale, and because its effects are wide-ranging and often severe, it has attracted the attention of many scientists worldwide.

In broad outline, the large-scale sea-level pressure 'seesaw' across the tropical Pacific Ocean which defines the Southern Oscillation, and the anomalous oceanographic and atmospheric conditions which occur periodically along the upwelling zone of the eastern equatorial Pacific and along the coast of southern Ecuador and Peru, known as 'El Niño,' are manifestations of slowly evolving, coupled ocean-atmosphere processes that give rise to characteristic responses in the atmosphere and the ocean.

A concerted effort to monitor the principal atmospheric and oceanographic variables that make up the ENSO has led to an improved understanding of the phenomenon and an emergent ability to predict the development of recent ENSO events with a few months lead time. Because the global climatic patterns associated with the extreme modes of the ENSO cycle are quite different, there has been some concern that one or the other pattern (either the warm 'El Niño' phase, or its opposite, cold 'La Niña' phase) could become much more frequent in the future as a result of changes in the Earth's climate brought about by increases in atmospheric concentrations of so-called greenhouse gases. Such a possibility has spurred interest in determining whether the ENSO system has undergone low-frequency variations in the past. This has led to efforts to extend the modern ENSO record by making use of historical records of climatic

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anomalies known to be associated with the ENSO, such as failure of the Indian monsoon and unusually heavy rainfall and flooding in the normally arid coastal region of northern Peru. These studies have resulted in the extension of the chronology of the warm or El Niño phase of the Southern Oscillation by several centuries. More recently, the annual record of Nile River floods which extends back in time to the 7th century AD has been used to develop a chronology of ENSO variability in the western portion of the core ENSO region. That work is documented in Section B of this book, which deals with the use of historical records in ENSO reconstruction.

Analyses of high-resolution proxy records (tree-rings, ice cores, sea corals, varved sediments) have made it possible to extend the ENSO chronology farther back in time, thereby providing a longer temporal basis to evaluate ENSO changes in the time domain. They also furnish additional geographical 'anchors' that are useful in evaluating the spatial consistency of ENSO patterns through time. The results of this work, which are detailed in Section C of this volume help us to learn more about the century to millennial-scale characteristics of the ENSO phenomenon. Finally, lower resolution proxy records such as flood deposits and time series derived from paleoecological changes recorded in the sedimentary record from terrestrial and coastal marine environments provide information that may help us understand changes in the long-term behavior of ENSO, and perhaps provide clues regarding possible forcing mechanisms.

This book is an outgrowth of a workshop that was held in Boulder, Colorado, in May 1990 to examine some of the proxy evidence of ENSO-related climatic variability. Although the strongest manifestations of the ENSO are found in the tropical Pacific and Indian oceans and some of the adjacent coastal regions, atmospheric and oceanic teleconnections outside the tropics have also been well documented. It was felt that a comprehensive review of worldwide ENSO-sensitive paleoclimate indices was needed. It was also felt that the spatial and temporal resolution of many of the proxy records was such that it would be profitable to have paleoclimatologists present their findings to an audience that included not only people within their own general discipline, but also to oceanographers and atmospheric scientists involved in ENSO research. The stated goals of the workshop were to facilitate the exchange of information among different workers in the different paleoclimate fields and to promote greater interaction among those researchers working with the field observations (palynologists, dendroclimatologists, geomorphologists, etc.) and atmospheric scientists and oceanographers doing ENSO research. Our goal with this book is to bring together a variety of related topics under the common theme of ENSO variability. The techniques discussed in the separate chapters range from the use of written historical records which document the climatic effects known to be modulated by the different phases of the ENSO phenomenon, to analysis of tree-ring records, ice cores, tropical coral records, sedimentary and pollen records from lacustrine and near-coastal marine environments.

The book is divided thematically as well as by the temporal resolution of the ENSO records themselves. In Section A, *ENSO in the modern record*, which immediately follows this introduction, the observational basis for describing the phenomenon and some of the modeling work applicable to understanding the physical mechanisms of the ENSO are presented. Section B, *Use of historical records in ENSO reconstruction*, presents the results of studies aimed at reconstructing past ENSO occurrences from the historical record. Several chapters in this section examine the evidence for changes in the frequency and intensity of ENSO events (mostly with regard to its warm El Niño phase) and one describes some plausible linkages between the ENSO-modulated climate, which is manifested in the form of enhanced climatic variability and the vegetation and fauna in the Australasian region. The period of time covered here extends over roughly the last one-and-a-half millennia. In Section C, *Paleoclimate reconstructions of ENSO from tree-ring records*, we examine how tree-ring records are used to 'predict' the occurrence of ENSO events prior to available instrumental records from the statistical relationships between climatic anomalies forced by the ENSO phenomenon, and its effect on tree growth. Section D, *Records from ice cores and corals*, describes the use of other types of paleoindicators. Coral atolls along the equatorial Pacific provide several geochemical measures that can be related to environmental changes associated with changes in the ENSO cycle. The use of ice cores retrieved from mountain glaciers in areas affected by atmospheric circulation changes induced by ENSO are described here, and its utility to reconstruct ENSO events (signals) at annual resolution for the last several centuries is evaluated by comparison with ENSO-sensitive tree ring records from the southwestern United States and with ENSO reconstructions based on historical records.

The last section, titled *Low-resolution paleoclimate reconstruction of ENSO: marine and terrestrial proxy indicators* (Section E), examines the basis for interpreting lower resolution proxy records in the context of high frequency phenomena such as ENSO. The studies describe how low frequency variations in the vegetation assemblages, fire histories, bioproductivity, sedimentary records of fisheries abundances, etc. that can be inferred from such records can be used to interpret the possible state of the ENSO system during those times. In this and previous chapters, the possible connection between solar forcing variations and changes in the expression of the ENSO signal is also explored. The last chapter, *Synthesis and future prospects*, attempts to bring together the key findings and ideas presented in the book and discusses future prospects for interdisciplinary research aimed at reconstructing climatic variability at year to century and longer time scales.

It is hoped that this book will serve to stimulate further work both in the area of constructing additional reliable proxy chronologies from these and other ENSO-sensitive regions, as well as to stimulate the development of new, innovative ways to analyse existing proxy and instrumental records. A conviction that was shared by many people at the workshop was that improved reliability of individual ENSO indices might be achieved by pooling together as many of the proxy series as is feasible. This should also lead to increased confidence in the interpretation of specific features in the reconstructed record. If this were possible, one might also be able to ascertain with some degree of confidence whether there have been any significant changes in the spatial structure of ENSO during the past several hundred years, and whether ENSO has undergone changes in its frequency characteristics during the late Holocene.

We feel that the ample talent and multidisciplinary expertise that has been brought to bear on this important scientific question will have a broad audience, and that it will be useful to people involved not only on scientific research issues related to ENSO, but also to those working on the socioeconomic impacts associated with ENSO variability.

SECTION A

ENSO in the modern record

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Atmospheric teleconnections associated with the extreme phases of the Southern Oscillation

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Abstract

An overview is presented of the principal climatic characteristics associated with the development of warm and cold phases of the ocean-atmospheric phenomenon known as El Niño/Southern Oscillation (ENSO), and of the most salient large-scale teleconnection features related to those extremes. Besides giving the reader some appreciation of the typical climatic patterns in different parts of the globe during the extreme ENSO phases, we have made an effort to illustrate some of the event-to-event variability inherent in various climatic indices associated with this phenomenon.

ENSO is not a stationary system; there are substantial differences between events that are reflected in a variety of ENSO indices. It is shown that even for a particular set of ENSO measures, the association among such indices may vary with time. It is important to keep this mind when analysing long-term associations with individual proxy variables of ENSO activity, such as tropical corals or glacier varves.

Introduction

Elements of the global-scale climate phenomenon now referred to as the El Niño/Southern Oscillation (ENSO) began to be noted (though not by that name) toward the end of the 19th century (see Nicholls 1992, this volume). Starting with the observations of Sir Charles Todd, the South Australian Government Observer, published in Australia in the late 1880s, and culminating in a series of papers by Sir Gilbert Walker and collaborators (Walker 1923; Walker and Bliss

1932), knowledge of these large-scale atmospheric pressure changes and related fluctuations in rainfall in the tropics gradually accumulated. It was Walker who gave the name 'Southern Oscillation' (SO) to the sea-level pressure 'seesaw' that he documented in the tropical Pacific and Indian oceans.

Associated with this large-scale fluctuation of atmospheric mass (see Trenberth 1976; van Loon and Madden 1981; Trenberth and Shea 1987) are marked changes in tropical Pacific sea surface temperature (SST), particularly along the eastern equatorial Pacific upwelling zone and off the coast of Peru (see Philander 1990). One of the primary effects of the evolution of tropical Pacific SSTs and related changes in air-sea interaction is found in the strong interannual variation of rainfall throughout the global tropics. In fact, Nicholls (1988) found that the interannual variance of mean annual precipitation in the core region of the El Niño/Southern Oscillation is larger than in areas less affected by the phenomenon.

After the work of Walker in the 1920s and 1930s, studies on the general characteristics and mechanisms of remote atmospheric and oceanic responses (teleconnections) associated with sea-level pressure (SLP) and SST fluctuations in the equatorial Pacific waned. Interest in the Southern Oscillation and the El Niño was re-established in the late 1950s, beginning with the work by Berlage (1957) and following the 1972 El Niño, which brought about considerable economic hardship to Peru and other countries around the world (see overviews by Julian and Chervin 1978; Rasmusson and Carpenter 1982; Enfield 1989).

Beginning with the work of J. Bjerknes (1966, 1969), our understanding of the physical mechanisms responsible for the observed large-scale associations of seasonal and longer time scale climatic variations linked to the ENSO has grown manyfold. Modern refinements to our knowledge of the workings of ENSO, starting with Troup (1965), have added considerably to our understanding of this dominant mode of atmospheric and upper ocean variability. In particular, the synthesis provided by Rasmusson and Carpenter (1982) of the composite structure of ENSO in the tropics and the analysis of the planetary scale associations provided by Horel and Wallace (1981) and van Loon and Madden (1981), van Loon and Shea (1987), and Rasmusson and Wallace (1983), among others, have underscored the pervasive influence of this dynamical system. More recently, Ropelewski and Halpert (1987, 1989) and Kiladis and Diaz (1989) have detailed the spatial and temporal variability of surface temperature and precipitation throughout the globe associated with ENSO.

The reader is also referred to the recently published book by Glantz et al. (1991), which addresses the subject of ENSO-induced teleconnections linking climate anomalies throughout the globe, for a review of the societal impacts associated with this phenomenon, as well as a review of the physical mechanisms operating during ENSO.

In the following pages, we will first describe the typical evolution of atmospheric features associated with ENSO during its life cycle. We will then focus on an important issue that bears on the reliability of paleo-ENSO reconstructions, namely, how consistent from one event to another the remote atmospheric and oceanic responses are to ENSO. In this regard, our emphasis will be on those regions where analysis of ENSO-sensitive proxy records are discussed in other sections of this book. We note that various other observational aspects of ENSO are also examined in the chapters in this book by Enfield (1992), Nicholls (1992), and Quinn (1992).

Typical evolution and climatic features of ENSO

In this section, we review the general climatic characteristics of the 'typical' ENSO event. Here, we use 'ENSO' to refer to the general system that comprises both warm (the 'El Niño' phase) and cold (so-called 'La Niña' episodes) sea surface temperature extremes of Walker's Southern Oscillation. The signals discussed here are based primarily on studies using a composite of several events (Rasmusson and Carpenter 1982; Ropelewski and Halpert 1986, 1987, 1989; Kiladis and van Loon 1988; Kiladis and Diaz 1989). However, we wish to emphasize that individual events may differ markedly from the mean pattern; the next section discusses some of these differences among ENSO events and gives some examples of the range of variability to be expected from one event to another.

By far the best-defined ENSO teleconnection is associated with sea-level pressure (SLP), and it was this signal that led Hildebrandson (1897), Lockyer (1906), and Walker (1923) to detect and define the SO. Essentially, the pressure signal of the SO is observed as a 'seesaw' between the southeastern tropical Pacific and the Australian-Indonesian region, such that when pressure is below normal in one region it tends to be above normal in the other on time scales ranging from monthly to annual (see Fig. 2.1). A measure of the state of the SO is nowadays defined by the Southern Oscillation Index (SOI), which is based on the standardized SLP difference between Tahiti and Darwin, Australia. Located near the core regions of the SO, these stations have relatively long periods of record, so that the SOI can be calculated back to the year 1882 (see Ropelewski and Jones 1987).

Early workers on the SO were aware that extremes in the pressure seesaw were associated with marked climatic anomalies in both the tropics and the subtropics. For example, Walker (1923) established that high pressure over the Australasian region was accompanied by drought over India and Australia, and cool, wet winters over the southeastern United States.

While the pressure oscillation associated with the SO has been known for about a century, it was not until the late 1950s and the 1960s that the connection between the SO and SST was demonstrated (Berlage 1957; Ichiye and Petersen 1963; Bjerknes 1966, 1969). Generally, SST along the western coast of South America and along the equator in the central and eastern Pacific is anomalously cold for its latitude. This is due to strong oceanic upwelling associated with trade winds along the equatorial regions and equatorward flow along the South

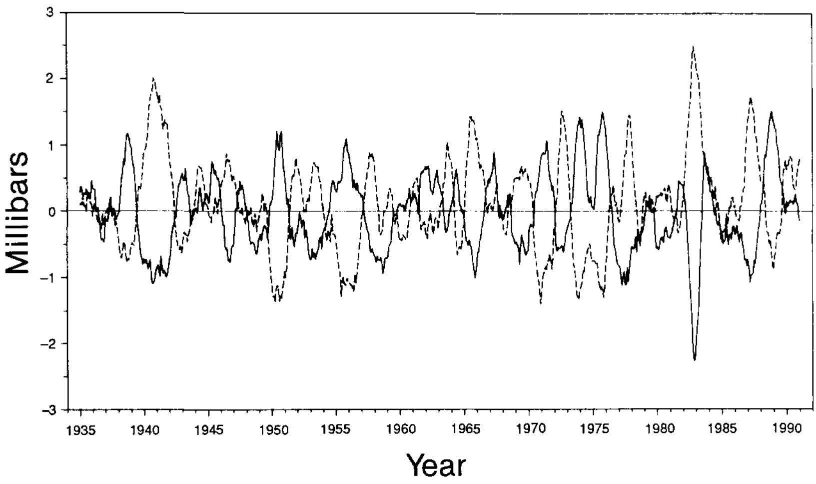

Fig. 2.1 Nine-month running mean of monthly sea-level pressure anomalies at Darwin, Australia (dashed line) and at Tahiti (solid line). Period of record is January 1935–May 1991. Correlation = −0.75.

American coast (see Enfield 1989). These cool SSTs stabilize the lower atmosphere, inhibiting precipitation and giving rise to the hyperarid climate of coastal Peru. This aridity extends well into the central Pacific, occupying a wedge-shaped region that extends as far west as the dateline and southeastward from this general vicinity to about the latitude of Santiago, Chile, along the South American coast. This region is referred to as the Pacific 'dry zone.'

Every few years this aridity is broken by periodic heavy rainfall episodes lasting several months, associated with a dramatic increase of equatorial Pacific SST. Along the Peruvian coast this phenomenon has been known as El Niño because of its general occurrence near Christmas time (see Wyrtki 1975; Enfield 1989). The coastal plains of Ecuador and northern Peru are particularly susceptible to flooding during El Niño, although regions farther south and the islands along the equatorial upwelling zone can also see spectacular rainfall increases. In essence, the weakening of the South Pacific High is accompanied by a decrease in the strength of the trade winds, weakening the oceanic upwelling and causing SSTs to rise. This warming of the ocean surface causes increased evaporation and heating of the troposphere, and decreased atmospheric stability, creating conditions favorable for convection and rainfall. The process tends to be self-sustaining because the development of organized areas of convection near the equator will tend to further weaken the trade winds within and to the west of the convective area, thereby causing SSTs in that area to remain anomalously warm. Thus, forcing mechanisms of these so-called warm ENSO events are due to a complex ocean-atmosphere instability dependent on the coupling of the two media (see Rasmusson and Wallace 1983; Philander 1990).