THE EL NIÑO–SOUTHERN OSCILLATION PHENOMENON

Many widely dispersed climatic extremes around the globe, such as severe droughts and floods and the failure of the Indian monsoon, can be attributed to the periodic warming of the sea surface in the central and eastern equatorial Pacific Ocean, termed the El Niño or Southern Oscillation (ENSO). In the past few decades many advances have been made in our understanding of ENSO. These have led to marked improvements in our ability to forecast its development months or seasons in advance, allowing practical prediction and adaptation to global impacts.

Edward Sarachik and Mark Cane have been key participants in advancing our understanding of ENSO from the modern beginning of its study. The book begins by introducing the basic concepts before moving on to more detailed theoretical treatments. Chapters on the structure and dynamics of the tropical ocean and tropical atmosphere ground the treatment of ENSO in a broader observational and theoretical context. The atmosphere and the oceans are given equal attention. Chapters on ENSO prediction, ENSO past and future, and ENSO impacts introduce the reader to the broader implications of the phenomenon.

This book provides an introduction to all aspects of this most important mode of global climate variability. It will be of great interest to research workers and students in climate science, oceanography and related fields, at all levels of technical sophistication.

EDWARD S. SARACHIK is Emeritus Professor of Atmospheric Sciences at the University of Washington. He has been an active contributor to research on tropical meteorology, tropical oceanography and coupled interactions in the tropics. He has also worked on other problems of oceanography, in particular the global thermohaline circulation. Dr. Sarachik has served on nineteen National Research Council committees, chairing two, in particular the Tropical Ocean Global Atmosphere (TOGA) Panel. He worked to found the International Research Institute for Climate and Society and has chaired IRI advisory committees since its inception. Until his retirement, he co-directed the Center for Science in the Earth System at the University of Washington, a center devoted to the dynamics of climate variability and change and the impacts of such variability and change on the ecology, built environment and people of the Pacific Northwest of the USA. He is a fellow of the American Meteorological Society, the American Geophysical Union, and the American Association for the Advancement of Science.

MARK A. CANE is G. Unger Vetlesen Professor of Earth and Climate Sciences and Director of the Master of Arts Program in Climate and Society at the Lamont Doherty Earth Observatory, Columbia University. With Lamont colleague Steven Zebiak, he devised the first numerical model able to simulate ENSO, and in 1985 this model was used to make the first physically based forecasts of ENSO. Since then the Zebiak–Cane model has been the primary tool used by many investigators to enhance understanding of ENSO. Dr. Cane continues to work on El Niño prediction and its impact on human activity, especially agriculture and health. His efforts over many years were instrumental in the creation of the International Research Institute for Climate and Society at Columbia. His current research interests include paleoclimate problems and the light they shed on future climate change. Dr. Cane has been honoured with the Sverdrup Gold Medal of the American Meteorological Society (1992), the Cody Award in Ocean Sciences from the Scripps Institution of Oceanography (2003), and the Norbert Gerbier–MUMM International Award from the World Meteorological Organization (2009). He is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, the American Geophysical Union and the American Academy of Arts and Sciences.

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Preface

This is a book about the set of coupled atmosphere–ocean phenomena known collectively as ENSO (El Niño–Southern Oscillation). While it will concentrate on what is known about ENSO, its mechanism, its effects, and how predictable it is, it will also touch on what is known about the paleohistory of ENSO and what we might expect in the future as mankind puts CO_2 and other radiatively active constituents into the atmosphere. The approach, while theoretical and sometimes necessarily mathematical, will concentrate on observations and on physical principles. Rigor will be acknowledged and appreciated but rarely practiced. When something in the text is stated to be known, but is not explained, the symbol ☼ (usually accompanied by a reference or footnote) will be used. This will be true of all chapters except the Preview (Chapter 1), where much will be arbitrarily stated, subsequently to be explained in the rest of the book.

Because ENSO is an intrinsically coupled ocean–atmosphere process, we will introduce the essentials of both the tropical atmosphere and ocean and explain the unique properties of each medium. Because ENSO is an intrinsically Pacific phenomenon, we will explain the unique aspects of the tropical Pacific and which of its features makes it particularly congenial for the existence of ENSO. We will describe those tropical atmospheric and oceanic mechanisms that ultimately help to explain the mechanism of ENSO. While there is no general agreement about what the ENSO mechanism is, we would expect that a similar book written a decade or so henceforth would contain much of the same material. In pursuit of the ENSO mechanism throughout this book, these themes will recur: the ability of warm sea-surface temperature to anchor regions of persistent precipitation; the ability of regions of persistent precipitation to induce surface westerly wind anomalies to the west of these regions; the tendency of anomalously warm sea-surface temperature anomalies in the Pacific to become warmer by local processes; and the tendency of cold sea-surface temperature anomalies to be associated with shallower thermoclines.

In order to draw the reader into the subject, the book will begin with a Preview which will touch lightly on all the subject matter in the remainder of the book. We recommend that all readers, regardless of sophistication, read the Preview in order to gain a feel for the method and content of the book and to devise a personal plan for reading the subsequent chapters. While not everything in the Preview is explained, the important topics are introduced and, where explanation is complex or requires the kind of mathematical treatment that will be established in a later chapter, a warning will be given that the matter cannot be understood without some additional work.

Each chapter will begin with a short precis which will indicate the broad outlines of the chapter. The book will conclude with a recap which will mirror, but not repeat, the content of the book. It is hoped that, in this way, the reader will be able to read the book in a manner suitable for his or her ability and needs. Essential mathematics will be relegated to the appendices. Some exercises will be interspersed in the chapters in order to give the reader some useful practice in deriving some basic results.

The aim of the authors is to produce a book that can be read on many levels by many audiences, depending on their interests and capabilities. Anyone reading the Preview, the chapter headings, and the final Postview chapter will get a very complete idea of what this book is about. We view our audience as scientists who are at least familiar with the nature of scientific explanation while perhaps not being familiar with the nitty-gritty of fluid mechanics, meteorology or oceanography. We expect that a second-year graduate student in meteorology or oceanography would have enough basic background to work through the entire book.

This book has two authors but many ancestors. Both authors owe a permanent debt to the prime inspiration for our careers in the geosciences, Jule Charney, and it is to his memory that this book is dedicated.

This book, and our approach to the material, arose from a series of lectures addressed to people of diverse backgrounds and abilities. The lecture series was given three times in Fortaleza, Brazil (thanks to the good offices of Antonio Divino Moura and Carlos Nobre, with the cooperation of the Centro de Previsão de Tempo e Estudas Climáticos [CPTEC] and Fundação Cearense de Meteorologiae Recursos Hídricos [FUNCEME]) and twice at the International Centre for Theoretical Physics in Trieste, Italy, with many thanks to J. Shukla and A. D. Moura for setting up the lectures and to Lisa Ianitti for the loving care with which she treated the students, the lecturers and the manuscript. Virginia DiBlasi typed an early version of the draft and provided essential technical support throughout, as well as much-appreciated moral support. Finally, we would like to thank the numerous colleagues and students who did so much to shape our ideas over the years in conversations, seminars and correspondence. Many of their names are scattered throughout this book. We do not educate easily, so we are especially grateful for their perseverance.

We are grateful to Tony Barnston, Mike Halpert, Emilia Jin, Alexey Kaplan, Billy Kessler, Todd Mitchell, Jenny Nakamura and Daiwei Wang for special efforts in providing figures for our use in the book.

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Abbreviations

AR4	Fourth Assessment Report of the IPCC
CGCM	coupled general-circulation model
CMZ	Cane–Münnich–Zebiak
CISK	conditional instability of the second kind
COADS	comprehensive ocean–atmosphere data set
CPTEC	Centro de Previsão de Tempo e Estudos Climáticos
ECHAM	European Centre–Hamburg
ECMWF	European Centre for Medium-Range Weather Forecasts
EEP	eastern equatorial Pacific
ENSO	El Niño–Southern Oscillation
EUC	equatorial undercurrent
FUNCEME	Fundação Cearense de Meteorologia e Recursos Hídricos
GCM	general-circulation model
GCOS	global climate observing system
GR	global residual
GTS	global telecommunication system
HadCM3	Hadley Centre coupled climate model
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
ITCZ	intertropical convergence zone
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
KE	kinetic energy
KPP	K profile parameterization
LCL	lifting condensation level
LGM	last glacial maximum
MJO	Madden–Julian oscillation
MME	multi-model ensemble
MSU	microwave sounding unit

NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP (USA)	National Centers for Environmental Prediction
NEC	north equatorial current
NECC	north equatorial counter current
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
OLR	outgoing long-wave radiation
pdf	probability distribution function
PDO	Pacific Decadal Oscillation
PE	potential energy
Q-G	quasi-geostrophic
rms	root-mean-square
SEC	south equatorial current
SLE	St. Louis encephalitis
SLP	sea-level pressure
SO	Southern Oscillation
SODA	simple ocean data analysis
SOI	Southern Oscillation index
SPCZ	South Pacific convergence zone
SS	Schopf and Suarez (and vice versa)
SST	sea-surface temperature
SSTA	sea-surface temperature anomaly
SVD	singular value decomposition
SWE	shallow-water equation
TAO	tropical atmosphere–ocean
TI	trade inversion
TKE	turbulent kinetic energy
TOGA	Tropical Ocean Global Atmosphere
ZC	Zebiak–Cane