Climate Change and Small Pelagic Fish

This book details the effects of climate variability on small pelagic fish and their ecosystems and fisheries. These fish (for example, anchovy, sardine, sprat, and herring) comprise about one-quarter of the global fish catch and are particularly abundant in coastal upwelling regions off the west coasts of the Americas and Africa, off Japan, and in the NE Atlantic. Their stocks fluctuate greatly over the time scale of decades, with large ecological and economic effects. This book describes the nature and cause of these fluctuations, and their effects. It outlines results from paleo-oceanographic studies, showing that fluctuations similar to those at present have also occurred over the past two millennia. The potential effects of future climate change, both natural and anthropogenic, on stocks and fisheries, are considered. It concludes by recommending the continued international study and assessment of small pelagic fish in order to best inform management and policy under a changing climate.

No other book addresses climate change effects on fish in such an extensive manner. The book is also distinctive in being the product of a collaboration of academic and fisheries scientists from each of the regions with major stocks of small pelagic fish. It is written for research scientists, academics, and policy makers in fisheries, oceanography, and climate change.

Dave Checkley is a biological oceanographer with expertise in the ecology of marine zooplankton and fish and fisheries oceanography. He is a Professor at the Scripps Institution of Oceanography, University of California, San Diego. He has been a NATO Postdoctoral Fellow at DAFS in Aberdeen, Scotland, a member of the faculties of the University of Alaska, the University of Texas, and North Carolina State University, and a Tech Awards Laureate of the Tech Museum, San José, California. He led the development of CUFES, SOLOPC, and REFLICS. He is the co-chair of Small Pelagic Fish and Climate Change (SPACC) and Editor-in-Chief of *Fisheries Oceanography*.

Jürgen Alheit is a fisheries biologist. His main interest is the impact of climate variability on marine ecosystems. While working at the Intergovernmental Oceanographic Commission at UNESCO in Paris, he was responsible for the Ocean Sciences in Relation to Living Resources Programme of IOC and FAO, which focused on small pelagics. He is the co-founder and former co-chair of SPACC, chair of the GLOBEC Focus 1 Working group on Retrospective Analysis, and chair of the German GLOBEC Project. He serves on the Scientific Steering Committee of the GLOBEC International Programme.

Yoshioki Oozeki is the Chief Scientist of the Fish Ecology Section, National Research Institute of Fisheries Science, Fisheries Research Agency, Japan, and Professor of Marine Life Science at the Tokyo University of Marine Science and Technology. He is a fisheries biologist with expertise in the larval biology and ecology of small pelagic fish, and has led the egg and larval survey project in waters around Japan for 12 years. He has also investigated larva physiology, database management, stock assessment, sampling gear technology, and variation of fish in relation to climate. He received the Uda Award from the Japanese Society of Fisheries Oceanography in 2007.

Claude Roy is a physical oceanographer with expertise in fisheries oceanography and upwelling systems dynamics. As a scientist of the French Research Institute for Development (IRD), he spent extended periods of time in countries bordering upwelling systems during which he contributed to the implementation of several regional "climate and fisheries" research and training projects. He has been involved in SPACC since the late 1990s and served as its co-chair from 2003 to 2008.

Climate Change and Small Pelagic Fish

EDITED BY

DAVID M. CHECKLEY, Jr.
Scripps Institution of Oceanography, University of California, San Diego, USA

JÜRGEN ALHEIT
Baltic Sea Research Institute, Warnemünde, Germany

YOSHIOKI OOZEKI
National Research Institute of Fisheries Science, Kanagawa, Japan

CLAUDE ROY
L'Institut de Recherche pour le Développement (IRD), Plouzané, France

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To Reuben Lasker

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Dave Checkley
Jurgen Alheit
Yoshi Oozeki, and
Claude Roy

Abbreviations

AAIW	Antarctic Intermediate Water
ABC	Allowable Biological Catch
AC	Azores Current
ACMRR	Advisory Committee of Experts on Marine Resources Research
AEP	Annual Egg Production
ALP	Aleutian Low Pressure
AMCI	Assessment Model Combining Information
AMO	Atlantic Multidecadal Oscillation
ASAP	Age-Structured Assessment Program
BP	Before Present
BAC	Biological Action Centers
BC	Benguela Current
BITS	Baltic International Trawl Survey
BMSY	Biomass of Maximal Sustainable Yield
CACom	California Commercial Fish Landing Records
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CanCE	Canary Current Ecosystem
CANSAR	Catch-at-Age Analysis for Sardine
CC	California Current
CC	Climate Change (Chapter 14)
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCE	California Current Ecosystem
CCO	Central California Offshore subpopulation of sardine
CCSR	Center for Climate System Research
CCW	Cold Coastal Water
CEOS	Climate and Eastern Ocean Systems
CHRS	Constant Harvest Rate Strategy
CPR	Continuous Plankton Recorder
CPUE	Catch per Unit Effort
CS	Catalan Sea
CSA	Catch-Survey Analysis
CUFES	Continuous Underway Fish Egg Sampler
CV	Coefficient of Variation
DEPM	Daily Egg Production Method
DFR	Daily Fecundity Reduction
DIN	Dissolved Inorganic Nitrogen
EAF	Ecosystem Approach to Fisheries
EBUS	Eastern Boundary Upwelling Systems
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
EOF	Empirical Orthogonal Function
ERS	European Remote-Sensing Satellite
ESSW	Equatorial Subsurface Water
EU	European Union
EURO-SARP	European Sardine–Anchovy Recruitment Program
EwE	EcoPath with EcoSim
FAO	Food and Agriculture Organization
FiB	Fishing-in-Balance
FL	Fork Length
GAM	Generalized Additive Model
GCM	Global Ocean Circulation Models
GFCM	General Fisheries Council for the Mediterranean
GL	Gulf of Lions
GLM	General Linear Model
GLOBEC	Global Ocean Ecosystem Dynamics
GOOS	Global Ocean Observing System
HAMSOM	Hamburg Shelf Ocean Model
HC	Humboldt Current
HCE	Humboldt Current Ecosystem
HCR	Harvest Control Rule
HSI	Habitat Suitability Index
IBM	Individual-Based Model
IBTS	International Bottom Trawl Survey of the North Sea
ICA	Integrated Catch-at-Age
ICLARM	International Center for Living Aquatic Resources Management
IFOP	Instituto de Fomento Pesquero
IGBP	International Geosphere Biosphere Programme
IGP	Intraguild Predation
IMARPE	Instituto del Mar del Perú
IMECOCAL	Investigaciones Mexicanas de la Corriente de California
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IRD	Institute for Research and Development
IREP	International Recruitment Project
ISPR	Instantaneous Surplus Production Rate
ITQ	Individual Transferable Quota
IUCN	International Union for the Conservation of Nature and Natural Resources
KC	Kuroshio Extension
KCE	Kuroshio Current Ecosystem
KESA	Kuroshio Extension South Area
KO	Kuroshio–Oyashio
KOTZ	Kuroshio–Oyashio Transition Zone
LME	Large Marine Ecosystem
MIN	Minimum Number of Individuals
MLD	Mixed Layer Depth
MLE	Maximum Likelihood Estimator
MSC	Marine Stewardship Council
MSVPA	Multispecies Virtual Population Analysis
MSY	Maximum Sustained Yield
MTI	Mixed Trophic Impact

NA	Northeast Atlantic
NAC	North Atlantic Current
NACW	North Atlantic Central Water
NAO	North Atlantic Oscillation
NEA	Northeast Atlantic
NEMURO	North Pacific Ecosystem Model for Understanding Regional Oceanography
NIES	National Institute for Environmental Studies
NISP	Number of Identified Specimens
NMFS	National Marine Fisheries Service
NOAA	National Oceanographic and Atmospheric Administration
NPZ	Nutrient–Phytoplankton–Zooplankton
OMP	Operational Management Procedure
ORSTOM	Office de la Recherche Scientifique et Technique Outre Mer
OSLR	Ocean Science in Relation to Living Resources Programme
P/B	Production/Biomass
P2P	Prey-to-Predator
PC	Peru Current
PCC	Peru Coastal Current
PDO	Pacific Decadal Oscillation
POM	Princeton Ocean Model
PROCOPA	Peruvian–German Cooperative Program for Fisheries Investigations
REX	Recruitment Experiment
ROMS	Regional Ocean Model System
RPS	Recruit Per Spawner
RQ	Respiratory Quotient
RSHR	Regime-Specific Harvest Rate
SACW	South Atlantic Central Water
SAfE	South Africa Experiment
SARDYN	Sardine Dynamics and Stock Structure in the Northeast Atlantic
SARP	Sardine–Anchovy Recruitment Program
SATW	Sub-Antarctic Temperate Water
SAW	Sub-Antarctic Water
SBB	Santa Barbara Basin
SCOR	Scientific Committee on Oceanic Research
SDR	Scale Deposition Rate
SECC	Southern Extension of the Cromwell Current
SEW	Surface Equatorial Water
SL	Standard Length
SLP	Sea Level Pressure
SPACC	Small Pelagic Fish and Climate Change
SPF	Small Pelagic Fish
SSB	Spawning Stock Biomass
SSB/R	Spawning Stock Biomass/Recruit
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SSW	Subtropical Surface Water
STECF	Scientific, Technical and Economic Committee for Fisheries (EU)
STSW	Subtropical Surface Water
SURBA	Survey Based
TAB	Total Allowable Bycatch
TAC	Total Allowable Catch
TL	Trophic Level
TNA	Tropical North Atlantic Index
VMS	Vessel Monitoring System
VPA	Virtual Population Analysis
WA	Western Australia (but also Washington state)
WCRP	World Climate Research Program
WSSD	World Summit for Sustainable Development
XSA	Extended Survival Analysis

Contributors

Mahfuzuddin Ahmed
The WorldFish Center, Jalan Batu Maung, Batu Maung, 11960 Bayan Lepas, Penang, Malaysia

Jürgen Alheit
Baltic Sea Research Institute, Seestr. 15, 18119 Warnemünde, Germany

Patricia Ayon
Instituto del Mar del Perú, Apartado 22 Callao, Perú

Andrew Bakun
Pew Institute for Ocean Science, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, 33149–1098, USA

Manuel Barange
Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH, UK

Tim R. Baumgartner
Centro de Investigación Científica y de Educación Superior de Ensenada, Km 107 Carretera Tijuana-Ensenada, Ensenada, Baja California, C.P. 22860, Mexico

Miguel Bernal
Instituto Español de Oceanografía, C/ República Saharaui, s/n, 11510 Puerto Real

Arnaud Bertrand
Institut de Recherche pour le Développement, CRH, Avenue Jean Monnet, Sète, France c/o Instituto del Mar del Perú, Lima, Perú

Antonio Bode
Instituto Español de Oceanografía, Centro Oceanográfico de A Coruña, Spain

Richard Brodeur
Northwest Fisheries Science Center, NOAA, Newport,Oregon, USA

Leonardo R. Castro
Laboratorio de Oceanografía Pesquera y Ecología Larval, Departamento de Oceanografía, Universidad de Concepción, PO Box 160-C, Concepción, Chile

Maria Cristina Cergole
Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Alameda Tietê 637, CEP 01417–020, São Paulo, SP, Brasil

Francisco P. Chavez
Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, California, 95039 USA

David M. Checkley, Jr.
Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093–0218, USA

Kevern Cochrane
FAO, Via delle Terme di Caracalla, 00100 Roma, Italy

Janet C. Coetzee
Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, South Africa

Marta Coll
Dalhousie University, Department of Biology, 1355 Oxford Street, Halifax, Nova Scotia, Canada, B3H4J1 and Institute of Marine Science (CMIMA-CSIC), Passeig Marítim de la Barceloneta, 37–49, 08002, Barcelona, Spain

Luis A. Cubillos
Instituto Español de Oceanografía, Centro Oceanográfico de A Coruña, Spain

Carryn L. de Moor (formerly Cunningham)
MARAM (Marine Resource Assessment and Management), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, South Africa

Philippe Cury
Centre de Recherche Halieutique Méditerranéenne et Tropicale, IRD – IFREMER & Université Montpellier II Avenue Jean Monnet, BP 171 34203 Sète, Cedex, France

Georgi M. Daskalov
CEFAS, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK

José A. A. De Oliveira
CEFAS, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK

Mark Dickey-Collas
IMARES, PO Box 68, 1970 AB Ijmuiden, The Netherlands

Robert Emmett
NOAA Fisheries, 2030 South Marine Science Drive, Newport, Oregon, 97391, USA

Pepe Espinoza
Instituto del Mar del Perú, Lima, Perú

Vicente Ferreira
Centro de Investigación Científica y de Educación Superior de Ensenada, Km 107 Carretera Tijuana-Ensenada, Ensenada, Baja California, C.P. 22860, Mexico

David B. Field
Monterey Bay Aquarium Research Institute, Moss Landing, CA & University of California, Santa Cruz, Santa Cruz, California, USA

Pierre Fréon
ECO-UP Unit, Centre de Recherche Halieutique, IRD, BP 171, 34203 Sète, Cedex, France

Kevin Friedland
National Marine Fisheries Service, Narragansett , Rhode Island, USA

Susana Garrido
Instituto Nacional de Investigação Agráia e das Pescas, Lisboa, Portugal

Daniel J. Gaughan
WA Fisheries and Marine Research Laboratory, Department of Fisheries, PO Box 20, North Beach WA 6920, Australia

Renato Guevara-Carrasco
Instituto del Mar del Perú, Apartado 22 Callao, Perú

Dimitri Gutierrez
Instituto del Mar del Perú, Callao, Perú

Rognvaldur Hannesson
Norwegian School of Economics and Business Administration, Helleveien 30, NO-5045, Bergen, Norway

Samuel F. Herrick Jr.
NOAA, NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California, 92037, USA

Kevin Hill
NOAA-NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California, 92037, USA

Larry Hutching
Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, South Africa

Leire Ibaibarriaga
AZTI-Tecnalia, Marine Research Unit, Herrera Kaia Portualdea z/g, 20110 Pasaia, Spain

Xabier Irigoien
Arantza eta Elikaigintzarako Institutu Teknologikoa, Pasaia, Spain

Larry Jacobson
NOAA-NMFS, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, Massachusetts, 02543–1026, USA

Astrid C. Jarre
Danish Institute for Fisheries Research, The North Sea Centre, P.O. Box 101, 9850 Hirtshals, Denmark

Souad Kifani
Institut National de Recherche Halieutique, Casablanca, Morocco

Fritz W. Köster
Danish Institute for Fisheries Research, Jaegersborgvej 64–66, Lyngby DK-2800, Denmark

Christophe Lett
Institut de Recherche pour le Développement, UR ECO-UP, University of Cape Town, Oceanography Department, Rondebosch, 7701, South Africa

Hector Lozano-Montes
CSIRO Marine and Atmospheric Research, Underwood Avenue, Floreat, WA, Australia, 6014

Alec D. MacCall
National Marine Fisheries Service, Southwest Fisheries Science Center, 110 Shaffer Rd., Santa Cruz, California, 95060, USA

Jacques Massé
IFREMER, Rue de l'Ile d'Yeu, B.P. 21105, 44311 Nantes, France

Bernard A. Megrey
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle, Washington, 98115, USA

Todd Miller
Center for Marine Environmental Studies, Ehime University, Ehime, Japan

Christian Möllmann
Institute for Hydrobiology and Fisheries Science, University of Hamburg, Hamburg, Germany

Coleen Moloney
Zoology Department and Marine Research Institute, University of Cape Town, Rondebosch 7701, South Africa

Hideaki Nakata
Faculty of Fisheries, Nagasaki University, 1–14 Bunkyo-cho, Nagasaki, 852–8521, Japan

Sergio Neira
Marine Biology Research Centre, University of Cape Town, Rondebosch 7702 Cape Town, South Africa

Miguel Ñiquen
IMARPE, Esquina Gamarra y General Valle S/N, Chucuito, Callao, Perú

Hiroshi Nishida
National Research Institute of Fisheries Science, Fuku-ura 2–12, Kanazawa-ku, Yokohama, 236–8648, Japan

Jerrold G. Norton
NOAA, NMFS, Southwest Fisheries Science Center, 1352 Lighthouse Avenue, Pacific Grove, California, 93950, USA

Rosemary E. Ommer
University of Victoria, CEOR, Victoria, British Columbia, V8W 2Y2, Canada

Yoshioki Oozeki
National Research Institute of Fisheries Science, Fisheries Research Agency, 2–12–4 Fuku-ura, Kanazawa, Yokohama, Kanagawa, 236–8648, Japan

Isabel Palomera
Institut de Ciencias del Mar (CSIC), Passeig Marítim de la Barceloneta 37–49, 08003 Barcelona, Spain

Julio Pena-Torres
Universidad Alberto Hurtado, Erasmo Escala 1835, Santiago, Chile

R. Ian Perry
Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, British Columbia, V9T 6N7, Canada

Benjamin Planque
Institute of Marine Research – Tromsø, Postboks 6404, 9294 Tromsø, Norway

Ruben Rodriguez-Sanchez
Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Kenneth A. Rose
Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana, 70803, USA

Jean-Paul Roux
Ministry of Fisheries and Marine Resources, Lüderitz, Namibia

Claude Roy
L'Institut de Recherche pour le Développement (IRD), Plouzané, France

Suzana A. Saccardo
CNR-ISMAR, Largo Fiera della Pesca, 60125 Ancona, Italy

Renato Salvatteci
Centro de Investigación Científica y de Educación Superior de Ensenada, Km 107 Carretera Tijuana-Ensenada, Ensenada, Baja California, C.P. 22860, Mexico

Alberto Santojanni
CNR-ISMAR, Largo Fiera della Pesca, 60125 Ancona, Italy

Jake Schweigert
Fisheries & Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, British Columbia, V9T 6N7, Canada

Rodolfo Serra
Instituto de Fomento Pesquero, Blanco 839, Valparaiso, Chile

Lynne Shannon
Marine Research (MA-RE) Institute, University of Cape Town, Private Bag X3, Rondebosch 7702, Cape Town, South Africa

Stylianos Somarakis
University of Patras, Department of Biology, 26500 Patra, Greece

Andy Soutar
Drumlins Farm, Massena, New York, USA

Yorgos Stratoudakis
Instituto Nacional de Investigação Agrária e das Pescas (INIAP/IPIMAR), Avenida de Brasilia s/n, 1449–006 Lisboa, Portugal

U. Rashid Sumaila
Fisheries Economics Research Unit, Fisheries Centre, University of British Columbia, Vancouver, British Columbia, V6T 1Z4, Canada

Hiroshige Tanaka
Seikai National Research Institute, Fisheries Research Agency, Nagasaki, Japan

Axel Temming
Institute for Hydrobiology and Fisheries Science, University of Hamburg, Hamburg, Germany

Andres Uriarte
AZTI, Herrera Kaia Portualde z/g, 20110 Pasaia (Guipuzkoa), Basque country, Spain

Carl D. van der Lingen
Marine and Coastal Management, Private Bag X2, Rogge Bay 8012, South Africa

Francisco Werner
Marine Sciences Department, University of North Carolina, Chapel Hill, North Carolina, 27599–3300, USA

Akihiko Yatsu
Hokkaido National Fisheries Research Institute, Katsurakoi 116, Kushiro 085–0802, Japan

Foreword

The effects of large-scale, environmentally driven changes on the distribution and abundance of fish populations have been a major source of concern for fishery scientists and managers for decades, particularly those dealing with the assessment and management of small pelagic fisheries. While much still needs to be investigated and elucidated, significant progress has been made in describing and understanding the primary aspects of observed large-scale changes in small pelagic fish production and the most likely causal mechanisms, climate–fish abundance interactions, patterns of change, species interactions, and many other important issues. A newer and additional difficulty is that global climate change is altering the structure and functioning of marine ecosystems, which in turn affects availability of ecological resources and benefits, changes the magnitude of some feedbacks between ecosystems and the climate system, and will affect economic systems that depend on marine ecosystems. Newer questions and uncertainties have to be faced. For instance, will there be an increase in variability from season to season and year to year? Predictions of such changes in the future are likely to be less reliable than they may have been in the past, given that the past will become less useful as a guide to the future.

There is, therefore, a pressing need to assess progress made in knowledge development and emerging challenges regarding the variability of and changes in marine ecosystems, including the dynamics of populations of small pelagic fish, which collectively occupy a central role in the food web. This book makes an important and timely contribution to this overall need. It covers the major trends, findings and results of various international research efforts aimed at improving our understanding of climate-induced changes in the production and abundance of small pelagic fish populations, as well as progress made in assessing the predictability of future changes.

The book builds mostly on the results achieved through the collaborative research work undertaken under the auspices of the Small Pelagic Fish and Climate Change regional programme (SPACC) of the Global Ocean Ecosystem Dynamics international project (GLOBEC). Indeed, this publication represents one of the major achievements of SPACC/GLOBEC. Over the subsequent 15 chapters, a well-selected group of international experts has summarized working hypotheses, results and findings in their own fields of expertise. The end result is a successful and comprehensive technical summary and assessment of the current state of knowledge and future research prospects of small pelagics–climate interactions, their fisheries and related ecosystems.

Science is an iterative learning process where current researchers build on challenge as well as modify the findings of their predecessors. To make progress in science, one needs to look at and analyze the past. The historical perspective provided in Chapters 1 and 2 fulfills this purpose by including a brief but thorough review of the main international research initiatives, working hypotheses, mathematical models, research results and findings, and meetings and events where these were publicized and discussed, some of which are now considered major benchmarks in the development of our current understanding of the variability of small pelagic fish populations. These two chapters highlight the progress made in the last three decades towards understanding the effects of climate on the life history and population dynamics of small pelagics and on the use of this knowledge for, first, challenging traditional fisheries management approaches typical of the 1950s, 1960s and 1970s where the aim was maximizing long-term production under steady-state assumptions, and, second, moving towards fully recognizing the importance of climate-induced fluctuations and changes in these fish populations and the various spatial and temporal scales on which they vary. Reference is also made to more recent efforts towards trying to elucidate the role of small pelagics in regulating the ecosystems and to the steps being taken to move towards a fisheries management that takes more into account the ecosystem as a whole, in line with the principles of the Ecosystem Approach to Fisheries (EAF) promoted by the FAO.[1]

The habitat characteristics of the main marine systems hosting particularly large populations of small pelagic fish are described and discussed in Chapter 3. This chapter highlights both the uniqueness and similarities of these habitats, as well as the possible effects of future climate change on them. The natural variability of small pelagics is well covered in Chapter 4, while Chapter 5 describes decadal-scale fluctuations of small pelagics. Analyses of scales in marine sediments, archeological remains and historical records confirm that small pelagics did vary considerably prior to the development of current industrial

[1] Food and Agriculture Organization.

fishing, but also show important differences in the variability patterns of small pelagic populations during the nineteenth and the twentieth centuries, with some extremes in variability occurring on shorter time scales under intensive fishing. This suggests that ecosystem paradigms based on industrial catch records and modern observations may only capture a small part of the range of intrinsic variability of small pelagics, thus limiting our understanding of the possible responses to climate change. Nevertheless, observations of catch records and other usually higher-resolution twentieth and twenty-first century records confirm that populations of small pelagics are characterized by large and relatively long-lasting changes in their abundance and in other population parameters, which are often associated with regime shifts in the dynamics of their marine ecosystems. There is also growing evidence that these ecosystem shifts could be associated with large-scale changes in subsurface processes and basin-scale circulation in the oceans.

Chapters 6, 7 and 8 cover the several biophysical and trophic dynamics models that have been developed and/or are applied to small pelagics to synthesize current understanding, test hypotheses and examine potential consequences of changes in environmental conditions and species interactions. Chapter 6 provides a thorough overview of models that include the physical environment and the population dynamics of either early life stages of fish or juveniles and adults. While referring to the various models, their input requirements, computing challenges and forecasting capabilities, the point is made that much effort is still necessary to get to the stage of having usable "physics-to-fish full life-cycle models" capable of addressing the long-term consequences of climate change on fish and fisheries. Chapter 7 provides an updated review of the trophic dynamics of small pelagics, using seven selected regional case studies and information on feeding-apparatus morphology, diet composition, foraging behavior, and other observations used for the parameterization of bioenergetic and other trophic dynamic models. In discussing the interactions and disparities in the trophic dynamics of coexisting small pelagic species, and between anchovy and sardine in particular, it is suggested that the observed abundance alternations between the two could be trophically mediated. The use of trophic models to examine the trophic dynamic role of small pelagics in five selected marine ecosystems is described in Chapter 8, where it is reported that the models analyzed show how a decrease in small pelagic fish abundance will have detrimental effects on both higher and lower trophic levels of the food web and that, for instance, trophic model simulations consistently suggest that gelatinous zooplankton may increase when small pelagic fish stocks decline. Conversely, a decrease in jellyfish abundance may be expected if pelagic fisheries were allowed to rebuild, which is in agreement with circumstantial evidence for some systems.

The assessment and management of small pelagic fisheries, including the social and economic dimensions, are well examined in Chapters 9, 10 and 11. The assessment and management approaches, methods, models, harvesting strategies, and controls and regulatory measures used in selected major small pelagic fisheries are analyzed in Chapter 9. The point is made that the speed of response and the flexibility of management that these highly variable fisheries demand can only be provided though properly tailored scientific assessment and management programs, while noting that improved management of fisheries and related ecosystems is essential in adapting to the impacts of climate change in fisheries. Chapter 10 examines a full range of economic benefits small pelagics can provide, including their direct commercial value as well as their value as prey of predators of higher commercial value and for recreational and non-commercial predators, including international and domestic considerations when looking at different management and conservation options. Social and economic aspects are further dealt with in Chapter 11, where important issues such as social and economic power, institutional frameworks, resource access rights, equity, property rights, differences in temporal and spatial scales, market globalization, ethics, technology, and interactive political agendas between developed and developing countries are examined and discussed.

Future challenges and ways forward are summarized and highlighted in the last four chapters. Chapter 12 examines potential mechanisms for the low-frequency variability in sardine and anchovy populations discussed in other sections. A working theory is proposed in which sardine productivity is linked to low-frequency variability in boundary current flows, with weaker flow periods being favorable for extended sardine reproductive success and stronger flow periods restricting reproduction success to coastal areas. On the other hand, anchovies are always restricted to coastal waters and are more influenced by upwelling and coastal productivity (which tend to be correlated with boundary current fluctuations), giving rise to a tendency of sardine and anchovy alternations. A number of unresolved issues key for improved management and understanding of small pelagics and their related ecosystems are examined in Chapter 13. In particular, this chapter explores further the wasp-waist concept, according to which a dominant highly variable small pelagic fish population, largely responding to its own internal dynamics, may significantly drive the operation of its entire ecosystem. Several types of non-linear feedback mechanisms, breakout thresholds, distributional dynamics, density dependent growth, niche replacement and mechanisms of species alternations are discussed,

in support of proposals, worth noting, for research in the years to come. Chapter 14 points out that there is already evidence of sensitivity of small pelagic species and related ecosystems to climate change and of decreased resilience of natural ecosystems caused by overexploitation. Possible scenarios of climate and ecosystem change are then discussed to identify significant gaps in the knowledge of processes and interactions between changes in climate and other ecosystem stressors. Lastly, the book concludes with a thorough synthesis in Chapter 15 of SPACC, its reasons to exist and its major work and findings. Much of it is distilled from the ideas and findings reported in the first fourteen chapters while emphasizing that, for instance, observations from both paleontological and historical records are consistent with a conceptual model in which populations fluctuate due to extrinsic rather than intrinsic factors, which in turn is consistent with the observed out-of-phase variations of sardines and anchovies. Also emphasized is that humans must be considered an important part of the ecosystem and that overexploitation decreases resilience of systems to climate change as well as to more " normal" climate conditions, while reference is made to the wasp-waist concept and the pivotal role small pelagics play in the ecosystems in which they are found. Main gaps in current knowledge and understanding of small pelagic fish dynamics are further discussed, concluding that: the synthetic approach so far focused on small pelagics in highly productive upwelling regions shall be extended to multiple systems at a global scale, including, for example, western boundary currents; future research work be undertaken under the aegis of an international program like SPACC, using the comparative approach and involving scientists from a broad spectrum of disciplines, including climate, fisheries, oceanography, and the social sciences; and that a periodic international assessment of the state of science and climate effects on small pelagic fish be undertaken, as in other fields of science. A key point brought out by the book as a whole is the importance of a more ecosystem-oriented approach to research and fisheries management. Regarding the latter, one may stress that global climate change requires even more precautionary and adaptive approaches on behalf of all stakeholders.

Jorge Csirke (FAO)
Michael H. Glantz (NCAR)[2]
James Hurrell (NCAR)

Addresses and Affiliations:

Jorge Csirke
Director
Fisheries and Aquaculture Management Division
Fisheries and Aquaculture Department
Food and Agriculture Organization of the United Nations (FAO)
Viale delle Terme di Caracalla
00153 Rome, Italy

Michael H. Glantz[3]
Director
Center for Capacity Building (CCB)
National Center for Atmospheric Research
Box 3000
Boulder, Colorado 80307
USA

James Hurrell
Senior Scientist
National Center for Atmospheric Research
Climate and Global Division
PO Box 3000
Boulder, Colorado 80307-3000, USA

[2] National Center for Atmospheric Research.

[3] Address as of January 1, 2009:
Michael H. Glantz, Director
Consortium for Capacity Building
Institute for Arctic and Alpine Research
University of Colorado
Boulder, Colorado 80309–0450
USA.

Preface

Small pelagic fish include anchovy, sardine, herring, and sprat. They comprise approximately one-quarter of the world's fish catch. The abundance and catch of the small pelagic fish fluctuate greatly on the scale of decades, notably anchovy and sardine off Peru, Japan, Southern Africa, and California. Climate varies on the same scale. How does climate affect small pelagic fish? Can our understanding of this relationship be used to inform management and policy?

Small pelagic fish occupy a key position in marine ecosystems. They respond to change from below (climate, bottom-up) and above (fishing, top-down). In turn, variation of stocks of small pelagic fish affect their prey (plankton) and predators (e.g. fish, marine birds and mammals, and human). Capture fisheries are now maximal and, as the human population increases, aquaculture will thus continue to grow, exacerbating the demand for small pelagic fish as food for cultured fish. The complex ecosystem and economic roles of small pelagic fish necessitate a holistic view of their dynamics.

The Small Pelagic Fish and Climate Change (SPACC) program is a part of Global Ocean Ecosystem Dynamics (GLOBEC). SPACC was formed to understand and predict climate-induced changes in the production of small pelagic fish. It is unusual in being composed of scientists from both academia and management. This book, a product of SPACC, presents the status of our understanding in 2008. It has 82 authors from 22 countries in Africa, Asia, Australia, Europe, and North and South America. Our hope is that it will form a basis and hence point of departure for future research.

The book consists of 15 chapters. Each, save the first, contains a summary and boxes, the latter connecting the chapters to the overarching theme of climate change and small pelagic fish. Chapters 1 and 2 provide a historical context. Chapter 3 describes habitats of the major stocks. Chapters 4 and 5 concern past variability of small pelagic fish, inferred from sediments and historical records. Chapters 6, 8, and 12 address models, and Chapter 7 trophic dynamics. Chapters 9, 10, and 11 concern the fisheries for small, pelagic fish, stock-by-stock and globally, and the human dimensions of climate change and small pelagic fish. Chapters 13 and 14 address the future. Chapter 15 provides a synthesis and recommendations.

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David M. Checkley, Jr.
Jürgen Alheit
Yoshioki Oozeki
Claude Roy