

UNDERSTANDING
SEA-LEVEL RISE
AND VARIABILITY

Understanding Sea-Level Rise and Variability

Edited by John A. Church, Philip L. Woodworth, Thorkild Aarup and W. Stanley Wilson

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In Memoriam: M.B. Dyurgerov

The Editors and Authors of this volume wish to honor the memory of Dr Mark B. Dyurgerov and acknowledge his valuable contributions to it. He will be missed by the glaciological and sea-level communities as an honest broker and an excellent scientist.

UNDERSTANDING SEA-LEVEL RISE AND VARIABILITY

EDITED BY

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Foreword

Sea-level variability and change are manifestations of climate variability and change. The 20th-century rise and the recently observed increase in the rate of rise were important results highlighted in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report completed in 2007.

In the last few years, there have been a number of major coastal flooding events in association with major storms such as Hurricane Katrina in 2005 and the Cyclones Sidr and Nargis in 2007 and 2008 respectively. The loss of life has been measured in hundreds of thousands and the damage to coastal infrastructure in billions of dollars. Such major coastal flooding events are likely to continue as sea level rises and have a greater impact as the population of the coastal zone increases.

The rate of coastal sea-level rise in the 21st century and its impacts on coasts and islands as expressed in the 2007 IPCC report contained major uncertainties. Incomplete understanding of the ocean thermal expansion, especially that of the deeper parts of the ocean, and uncertainties in the estimates of glacier mass balance and the stability of ice sheets are among the many factors which limit our ability to narrow projections of future sea-level rise. In particular, the instability of ice sheets requires special attention because it could lead potentially to a significant increase in the rate of sea-level rise over and above that of the 2007 IPCC report.

The World Climate Research Programme has led the development of the physical scientific basis that underpins the IPCC Assessments. On 6–9 June 2006 it organized a workshop in Paris, France, that brought together the world's specialists on the many aspects of the science of sea-level change to provide a robust assessment of our current understanding as well as the requirements for narrowing projections of future sea-level rise. The present book is based on the deliberations at the workshop and provides a comprehensive overview of present knowledge on the science of sea-level change.

The findings in this book will help set priorities for research and for observational activities over the next decade that will contribute to future assessments of the IPCC. In turn, the improvements in these assessments will better inform governments, industry, and society in their efforts to formulate sound mitigation and adaptation responses to rising greenhouse gas concentrations and sea level, and their economic and social consequences. In that respect, information on

global and regional sea-level comprises an important product of a climate service. Its generation cuts across many disciplines and observation systems and requires effective coordination among many organizations.

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Cosponsors

ACE CRC: Antarctic Climate and Ecosystems Cooperative Research Centre
(Australia)

AGO: Australian Greenhouse Office (Australia)

BoM: Bureau of Meteorology (Australia)

CNES: Centre National d'Etudes Spatiales (France)

CNRS: Centre National de la Recherche Scientifique (France)

CSIRO: Commonwealth Scientific and Industrial Research Organization (Australia)
DFO: Department of Fisheries & Oceans (Canada)
EEA: European Environment Agency
ESA: European Space Agency
ESF-Marine Board: Marine Board of the European Science Foundation
EUMETSAT: European Organization for the Exploitation of Meteorological Satellites
EU: European Union
GEO: Group on Earth Observations
GKSS: GKSS Forschungszentrum (Germany)
IASC: International Arctic Science Committee
IAG: International Association of Geodesy
IAPSO: International Association for the Physical Sciences of the Oceans
IACMST: Interagency Committee on Marine Science and Technology (UK)
ICSU: International Council for Science
IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer (France)
IGN: Institut Geographique National (France)
IOC of UNESCO: Intergovernmental Oceanographic Commission
IPY: International Polar Year
IRD: Institut de Recherche pour le Développement (France)
NASA: National Aeronautics and Space Administration (USA)
NSF: National Science Foundation (USA)
NOAA: National Oceanic and Atmospheric Administration (USA)
NERC: Natural Environment Research Council (UK)
Rijkswaterstaat (The Netherlands)
SCAR: Scientific Committee for Antarctic Research
TU Delft: Delft University of Technology (The Netherlands)
UKMO: The Met Office (UK)
UNESCO: United Nations Educational, Scientific and Cultural Organization
WCRP: World Climate Research Programme
WMO: World Meteorological Organization

Participating Organizations and Programs

Argo: International Argo Project
CryoSat: ESA's Ice Mission (ESA)
ENVISAT: Environmental Satellite (ESA)
ERS: European Remote Sensing satellite (ESA)
GCOS: Global Climate Observing System
GGOS: Global Geodetic Observing System
GLOSS: Global Sea-Level Observing System
GOCE: Gravity Field and Steady-State Ocean Circulation Explorer (ESA)

GOOS: Global Ocean Observing System

GRACE: Gravity Recovery and Climate Experiment (NASA)

ICESat: Ice, Cloud, and Land Elevation Satellite (NASA)

IGS: International GNSS Service

Jason: Ocean Surface Topography from Space (NASA/CNES)

SMOS: Soil Moisture and Ocean Salinity (ESA)

Abbreviations and Acronyms

AES40	North Atlantic wind and wave climatology developed at Oceanweather with support from Climate Research Branch of Environment Canada
ANU	Australian National University
AOGCM	atmosphere–ocean general circulation model
AR4	IPCC Fourth Assessment Report
BP	before present
CCM2	NCAR Community Climate Model version 2
cGPS	continuous GPS
CLASIC	Climate and Sea Level in parts of the Indian Subcontinent
CLIMBER	Climate and Biosphere model (of the Potsdam Institute for Climate)
CLIVAR	Climate Variability and Predictability project
CLM	Climate Version of the Local Model developed from the LM by the CLM Community (clm.gkss.de)
CNES	Centre National d’Etudes Spatiales (France)
CRF	celestial reference frame
CS3	POL barotropic model for the European Continental Shelf ($1/9^{\circ} \times 1/6^{\circ}$ latitude by longitude or approximately 12 km resolution)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (CSIRO); also to refer to the climate model developed by CSIRO
CSX	POL barotropic model for the European Continental Shelf ($1/3^{\circ} \times 1/2^{\circ}$ latitude by longitude or approximately 35 km resolution)
CZMS	Coastal Zone Management Subgroup
DIVA model	Dynamic Interactive Vulnerability Assessment model

DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ECHAM3, ECHAM4, ECHAM5	atmosphere-only versions of the European Centre Hamburg climate model
ECHAM5-OM, ECHAM4/OPYC3, ECHAM5/MPI-OM1	alternative coupled models (atmosphere and ocean) versions of the European Centre Hamburg climate model
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite (ESA)
EOF	empirical orthogonal function
EOP	Earth Orientation Parameters
ERA-40	reanalysis product provided by ECMWF (http://www.ecmwf.int/research/era/)
ERS-1, -2	European Remote Sensing satellites 1 and 2
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GCM	general circulation model
GCN	GLOSS Core Network
GCOM2D	Global Coastal Ocean Model, depth-average version
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GFDL	Geophysical Fluid Dynamics Laboratory (of the National Oceanic and Atmospheric Administration)
GFO	GeoSat Follow-on Satellite
GGOS	Global Geodetic Observing System
GIA	glacial isostatic adjustment
GLIMS	Global Land Ice Measurements from Space
GLONASS	Global Orbiting Navigation Satellite System
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
HadAM3, HadAM3P, HadAM3H	variants of the Hadley Centre atmospheric climate model, version 3

HadCM2, HadCM3	versions of the Hadley Centre coupled climate model
HadRM2, HadRM3	versions of the Hadley Centre regional atmospheric climate model
IAG	International Association of Geodesy
ICESat	Ice, Cloud, and Land Elevation Satellite
IDS	International DORIS Service
IERS	International Earth Rotation and Reference Systems Service
IGFS	International Gravity Field Service
IGOS-P	Integrated Global Observing Strategy-Partnership
IGS	International GNSS Service
ILRS	International Laser Ranging Service
InSAR	interferometric synthetic aperture radar
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
ISMASS	Ice Sheet Mass Balance and Sea Level project
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IVS	International VLBI Service
JCOMM	WMO/IOC Joint Technical Commission for Oceanography and Marine Meteorology
JMA	Japan Meteorological Agency
JMA T106	JMA GCM with T106 spatial resolution (1.1°×1.1°)
ka	thousand years ago
KNMI	Royal Netherlands Meteorological Institute
LGM	Last Glacial Maximum
LSM	land-surface model
MEO	Medium Earth Orbit(er)
MIROC	Model for Interdisciplinary Research on Climate series of models
MIS	marine oxygen isotope stage
MLWS	mean low water springs
MWP	melt water pulse
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Center for Atmospheric Research (USA)
NCEP	National Centers for Environmental Prediction (NOAA)

NOAA	National Oceanic and Atmospheric Administration (USA)
ODINAfrica	Ocean Data and Information Network for Africa
ORCHIDEE	French global land surface model
OSTM	Ocean Surface Topography Mission (radar altimeter mission)
PDI	power dissipation index
POL	Proudman Oceanographic Laboratory (UK)
POLCOMS	POL Coastal-Ocean Modelling System (a three-dimensional model for shelf regions)
POM	Princeton Ocean Model
PRUDENCE	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (European Union-funded project)
PSMSL	Permanent Service for Mean Sea Level
RACMO	Regional Atmospheric Climate Model (KNMI)
RCAO	Rosby Centre Regional Atmosphere-Ocean model
REMO	Hamburg regional climate model
RLR	Revised Local Reference data set of the PSMSL
RSLR	relative sea-level rise
SAR	synthetic aperture radar
SLR	satellite laser ranging
SRALT	satellite radar altimetry
SRES	Special Report on Emissions Scenarios, and the scenarios therein
SST	sea-surface temperature
STOWASUS	Regional Storm, Wave and Surge Scenarios for the 2100 century
SWH	significant wave height
SWOT	Surface Water Ocean Topography (NASA)
TAR	IPCC Third Assessment Report
TE2100	Thames Estuary in 2100 project (of the UK Environment Agency)
TIGA-PP	Tide Gauge Benchmark Monitoring Pilot Project of the IGS
T/P	TOPEX/Poseidon radar altimeter satellite
TPW	true polar wander
TRF	terrestrial reference frame
TRIMGEO	Tidal Residual and Intertidal Mudflat Model

TRS	Terrestrial Reference System
UNESCO	United Nations Educational, Scientific and Cultural Organization
VLBI	very-long-baseline interferometry
WASA	Waves and Storms in the North Atlantic (European Union-funded project)
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
XBT	expendable bathythermograph