WCRP REPORT
World Climate Research Programme

Report

WCRP/IOC Workshop on Regional Sea-Level Change

(UNESCO/IOC, Paris, 7-9 February 2011)

Organizing Committee: T. Aarup (local contact), A. Cazenave (France), J. Church (Australia, co-chair of WCRP/IOC Task Group on Sea-Level Variability and Change), J. Gregory (co-chair, UK), R. Ponte (USA), D. Stammer (co-chair, Germany), M. Tamisiea (UK), S. Wijffels (Australia), and P. Woodworth (UK).

(Workshop called for by WCRP/IOC Task Group on Sea-Level Variability and Change, organized by CLIVAR/GSOP, and sponsored by WCRP)

April 2011

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Table of Contents

1) Background

Past discussions of sea level have been mostly focused on global averages. However, sea level is changing on a regional scale more prominently than it is changing globally. Accurate predictions of regional sea-level change on decadal to centennial time scales are therefore required for coastal impact and adaptation assessments. Moreover, existing climate models largely disagree about patterns and magnitudes of sea-level variability and change on regional scales, and it is entirely unclear whether they have any skill in predicting regional sea level. Understanding these changes in terms of underlying physical and dynamical processes is essential for giving practically useful advice regarding the impact of future sea level rise on society. For that purpose a workshop was held by the WCRP/IOC Task Group on sea level.

The workshop discussed regional changes of sea level in comparison to global changes, underlying time and space scales, mechanisms and their representations in climate models. It discussed observed regional sea level changes, confronted them with those inferred from numerical simulations, and compared future predictions and their analysis in terms of processes.

The workshop was attended by about 40 experts from all over the world who are concerned with understanding past and ongoing sea level observations and with predicting sea level into the future. It was structured around the following four sessions:

Session 1: Observed regional sea level variability and change: The session discussed observations (paleo/proxy tide gauges, altimeters and GRACE) of regional variability and long-term changes in sea level and the interpretation of its regional patterns.

Session 2: Dynamics and kinematics of regional sea level variability: This session discussed the natural variability of sea level and the processes responsible, on all time scales. The discussion did draw heavily on models (ocean-only and coupled) and ocean syntheses, but also used observations to define modes of variability, like ENSO, PDO, SAM, or NAO.

Session 3: Causes and mechanisms for recent and future regional sea level changes: This session discussed the hindcasting of past and the projection of future regional sea level changes by climate, ocean, ice-sheet and solid-Earth models, including attribution of changes to radiative forcing agents.

Session 4: Initiation of studies for AR5: The final section of summary talks addressed current challenges and possible ways forward in observing, modeling and predicting regional sea level. The session picked up issues raised during the previous sessions that will be built upon in more detail in future studies.

In the following two sections we will summarize the main findings from the workshop and list the issues that were raised in the discussions. Workshop participants are listed in Annex 1. Annex 2 contains the Workshop program. Abbreviations are explained in Annex 3.

April 2, 2011

D. Stammer and J. Gregory

2) Workshop Summary

Altimetry has fundamentally transformed our knowledge of interannual and decadal sea level variability during the last two decades. Altimetric observations and numerical simulations of the recent past reveal regional changes in sea level that deviate widely from the global mean and often show the opposite sign. Many processes contribute, being associated with changes in the ocean, changes in the atmosphere and changes in the solid Earth. While changes in the solid Earth are partly reflecting longer term changes, especially the former two are oscillatory in nature and primarily reflect variability rather than secular trends. Accordingly, much of the observed regional changes in sea level are associated with modes of climate variability, and one should not confuse changes observed during the altimeter period with primarily long term trends. On the interannual to decadal time scale, there is a reasonable correspondence between decadal sea level variability and changes in upper-ocean heat and salt content, which can be explained in terms of a redistribution by natural modes of variability in the coupled system. To what extent terrestrial hydrology provides an important contribution on decadal and on the long time scales has to be investigated.

Emerging evidence exists that most of the observed regional changes are steric in nature, to a large degree being caused by redistribution in temperature and salinity in response to changing winds. More comprehensive data coverage and correction of observational errors have greatly refined our picture of T and S changes. Local effects (e.g., shelf dynamics, tectonics) may complicate or obscure the relationship between coastal and offshore sea level change. Improvement in knowledge of variability and trends on multi-decadal timescales depends on continuing work on tide-gauge and proxy evidence.

Given the newly available data sets it is now possible to decipher the steric changes in thermosteric and halosteric sea levels, revealing that salt changes do matter for regional sea level changes – information that was lacking in the past in most parts of the world. But we do have preferred regions where barotropic mass-related changes are important. Since those latter regions are located in regions of high-latitude water mass formation they might be quite important as source regions for longer term sea level changes, and might coincide with regions of long-term heat and freshwater uptake (e.g., subpolar North Atlantic).

Nevertheless, coherence in emerging results suggests that changing winds and associated changes in the flow field and transports are a very important cause for observed changes in regional (steric) sea level changes. This mechanism will hold on the decadal time scale, associated there mostly with climate modes. It might also be one of the important drivers for regional sea level changes on decadal to millennial time scales. Other changes in transports in the ocean and atmosphere are also regionally important, such as changes in the Atlantic meridional overturning and gyre circulations. However, changes in surface fluxes of heat and freshwater into the ocean will become more important with increasing time scales.

To be more complete and quantitative we need a more extended data base, and this includes deep temperature and salinity information as well as pressure information. Those data are required to decipher, (i) where bottom pressure changes are important contributions to sea level variability and change, which needs to be investigated as a function of time scale; (ii) where regions of heat and freshwater uptake (through surface fluxes) are located in detail, which is not obvious from the data base and needs more attention.

While it is obvious that wind stress impacts regional sea level on all time scales (decadal to millennial time scales), it is not obvious why the wind is changing during the last one or two decades as it does. Nevertheless, observed changes seem to be responsible for a large amount of observed sea level changes in the Pacific and Indian Ocean. Understanding modes of atmospheric forcing changes (including atmospheric teleconnections), their causes and their relation to regional sea level changes is important and needs more attention.

Climate model simulations of future regional sea-level changes due to anthropogenic climate change on multi-decadal timescales likewise show geographical variability, which is substantial compared with the global-mean rise. Again, the pattern can mostly be explained by local temperature and salinity changes, i.e., they are steric in nature, but are likely to be caused by a combination of changes in surface heat and freshwater forcing, changed redistribution by interior mixing, and trends in the wind-driven and thermohaline circulation.

In addition to forced and natural dynamical variability and trends, patterns of regional sea level changes are affected by the influence on the geoid and the solid Earth of the redistribution of ocean mass and changes in ice and water mass on land. First syntheses of contributions to regional sea level changes are now available providing information about regional long-term (secular) trends in sea level on a global basis. Corresponding information is available based on climate models, but also from statistical up-scaling approaches. The consistency or inconsistency between them has to be tested and discussed. Moreover, similar information is required for decadal time scales.

3) Open Issues and Outlook

Several open issues were identified during the discussion of the workshop. Among them is the question of errors in observations and models, as well as model-data synthesis methodologies. It is unclear at the time of writing if climate models can properly account for variability and trends and can be used for regional predictions and projections. Along those lines, the workshop discussed approaches to test and improve models and to reduce systematic uncertainties in predictions. Finally, the workshop identified studies of regional sea level variations and changes that would be valuable as input to the upcoming AR5 IPCC report.

In the following we give a more detailed account of the open issues.

1. *Uncertainties in solid-Earth and gravity models used for predictions/projections.*

   Such models are required during many stages of analyzing sea level variability and changes. Yet uncertainties remain in existing models, which need to be improved for quantitative regional sea level predictions. With respect to the more immediate elastic deformation, the largest uncertainty resides in the distribution of mass loss that goes into the predictions.

2. *Estimates of relative contribution of climate modes to sea level variability.*

   While consensus exists that a major fraction of the observed sea level changes during the last decade are caused by internal climate variability, it is not known what the relative contribution of specific climate modes (ENSO, PDO, NAO, …) is to sea level variability.

3. *Intercomparison of climate modes in climate models and observations (amplitudes, periods, phases, internal structures).*

   It is not obvious how realistically climate modes are being simulated by climate models. This calls for a comparison of climate modes in observations and climate models.

4. *Change of climate modes as function of CO_2 forcing.*

   We have indications that climate modes will change in a warming climate. Given the clear role of climate modes for regional sea level, it is important to know how climate modes will change in the future.

5. *Separation of climate modes and long-term trends (in observations and in models).*

   Regional sea level observed during the last 1-2 decades is strongly influenced by climate modes. It is important to better understand how to separate long-term trends from natural climate variability in observations and models.

6. *Encourage further analysis of proxy and tide gauge data.*

   For that purpose it is encouraged to make more use of paleo-data to expand the observational data base backward and thereby obtain an enhanced data base to understand long-term trends.

7. *We need to understand the degree of decadal variability in sea surface height observations and in forecasts.*

   Similar to long-term trends we also need to better understand and quantify the amount of decadal internal variability in existing observations and in forecasts and projections. Even projections of regional sea level changes over 100 years will be influenced by internal decadal variability.

8. *We need to allow for deep ocean-only sampling from GRACE thereby omitting the shallow water mass contributions to large-scale bottom pressure variations.*

   To separate out contributions of mass changes on the shallow shelf from regional sea level variability observed over the deep ocean it is recommended to produce GRACE fields that omit data from shallow areas in the processing of bottom pressure fields.

9. *Investigation of contributions of wind forcing changes relative to other forcing components on regional sea level variability and secular changes.*

   While it is obvious that changes in wind forcing are a primary driver for sea level changes observed during the last decades, it is not obvious what the relative contribution of changes in wind forcing and buoyancy forcing is in long-term climate projections.

10. *Impact of changes in the wave field on sea level need to be investigated.*

    The wave field impacts the observations of sea level. Moreover, the underlying electromagnetic (em)-bias correction in altimetry has a large uncertainty. It should be investigated how a changing wave field might impact the observations of regional sea level patterns.

11. *Encourage deep ocean observations; better data sets are fundamental.*

    It is recommended to enhance our data base of deep hydrographic observations (below 2000m depth).

12. *Inconsistency in atmospheric forcing – needs to be looked at more critically.*

    The workshop participants acknowledge large remaining uncertainties in surface forcing fields. It is recommended to use ocean (sea level) information to decipher those uncertainties by comparing

resulting sea level changes against observations and thereby learn more about the accuracy of the forcing, a strategy that is being pursued in ocean syntheses efforts.

13. *Encourage investigation of whether sea level changes can be attributed to particular radiative forcings and the use of such relationships to constrain projections*.

    It is encouraged to further quantify the relationship between patterns of observed sea level trends and changes in the various radiative forcings, and use these relationships to better constrain projections of sea level trends in climate models.

14. *Improve studies of fingerprinting ice melting, also by using paleo-data*.

    Melting polar ice sheets produce a clear pattern in regional sea level. It is encouraged to further investigate those patterns and use them to identify potential contributions of ongoing ice sheet melting in existing sea level observations by also using paleo-data (e.g., salt marshes).

15. *Encourage intercomparison of climate modes in CMIP5 Models and comparison with observations in order to understand model deficiencies and uncertainties, especially structural uncertainty*.

    Upcoming CMIP5 results need to be compared against observations in terms of climate modes and variability to better understand the role of model deficiencies and uncertainties in simulating corresponding regional sea level variability and change. Respective results are required as input to the AR5 report.

16. *Encourage use of CMIP5 predictions for regional studies of sea surface height on interannual to decadal time scale*.

    Upcoming CMIP5 projections need to be evaluated with respect to regional sea level variability on interannual and decadal time scales and longer-term trends in regional sea level patterns. Relevant results should be made available as input to the AR5 report.

17. *Encourage further investigations of static responses and impact on ice sheet dynamics*.

    Sea level will decline in the vicinity of melting polar ice sheets as a static adjustment to an underlying mass redistribution in the Earth system. We need to further investigate the static response and its impact on ice sheet dynamics.

18. *Improve understanding of dynamical response of sea level to climate forcing, including high-latitude freshwater forcing*.

Enhanced freshwater input will lead to a dynamical adjustment of the ocean. We need to better understand the dynamical response of sea level to polar ice sheet melting and analyze this adjustment in coupled climate models.

Remaining modeling and data issues that need attention can be summarized as follows.

1) **Model issues**

•*Resolution in shallow and deep ocean domains*

What is the impact of model resolution on the simulated regional pattern of sea level variability and change, especially near the coast?

•*Eddies and their role on sea level statistics*

Eddies have a substantial impact on observations of the regional sea level. The degree of aliasing of the regional sea level by the mesoscale in observations is not clear; likewise not clear is the impact of lack of eddies in the climate model on the simulated regional sea level pattern.

•*Consideration of different physics (diffusion coefficients, topography representation, equation of state, overflows, deep convection and other subgrid-scale parameterizations)*

Numerical details have a strong influence on model solutions, including the sea level, the degree of which has to be quantified.

•*Atmospheric forcing fluxes (wind fields important)*

What is the influence of uncertainties in surface forcing fields on a simulated regional sea level regional?

•*Treatment of freshwater flux conditions*

Details of the freshwater forcing implementation might have a strong impact on sea level simulations.

2) **Data issues**

•*More accurate measures of deep ocean variability with sufficient space/time resolution*

•*Monitoring salinity changes could be important in extensive regions*

•*Accurate gravity missions to help to quantify mass and deep steric ocean contributions to regional sea level changes*

•*Improve understanding of sea level statistics and frequency-wave number spectral characters*.

Annex 1

Workshop Participants

Rory Bingham
Department of Civil Engineering and Geomatics
Newcastle University
Newcastle Upon Tyne, NE1 7RU, UK
Tel: +44 222 8203
Email r.j.bingham@newcastle.ac.uk

Nathaelle Bouttes
Meteorology Building
University of Reading
P O Box 243
Reading RG6 6BB, UK
Tel: +44 118 378 6016
Email n.bouttes@reading.ac.uk

Mark Carson
KlimaCampus Hamburg
Grindelberg 5
University of Hamburg, Germany
Tel: +49 (0)40 42838 6104
Fax: +49 (0)40 42838 7471
Email: mark.carson@zmaw.de

Anny Cazenave
Laboratoire d'Etudes en Géophysique et Océanographie Spatiales LEGOS-CNES, Observatoire Midi-Pyrénées
18 Av. E. Belin, 31400 Toulouse, FRANCE
Tel: +33 (0) 5 61 33 29 22,
Fax: +33 (0) 5 61 25 32 05
Email: anny.cazenave@cnes.fr

Don P. Chambers
College of Marine Science
University of South Florida
140 Seventh Avenue
St. Petersburg, FL 33701
United States
Tel: +1 (727) 553-3351
Email: dchambers@marine.usf.edu

John Church
CSIRO Marine and Atmospheric Research
GPO Box 1538
Hobart
Tasmania 7001
Australia
Ph +61 3 6232 5207
Email: John.Church@csiro.au

Catia Domingues
CSIRO Marine and Atmospheric Research
GPO Box 1538
Hobart
Tasmania 7001
Australia
Email: Catia.Domingues@csiro.au

Paul Durack
CSIRO Marine and Atmospheric Research
GPO Box 1538
Hobart
Tasmania 7001
Australia
Email: Paul.Durack@csiro.au

Ichiro Fukumori
JPL Mail Stop 300-323
4800 Oak Grove Drive
Pasadena, CA 91109
USA
Tel: +1 818.354.6965
Fax: +1 818.393.6720
Email: if@pacific.jpl.nasa.gov

Peter J. Gleckler
Program for Climate Model Diagnosis and Intercomparison
Lawrence Livermore National Laboratory
Mail Code L-103
7000 East Avenue
Livermore, CA 94550
Tel: +1 (925) 422-7631
Fax: +1 (925) 422-7675
Email: gleckler1@llnl.gov

Natalya Gomez
Department of Earth and Planetary Sciences
Harvard University
20 Oxford Street,
Cambridge, MA 02138, USA
Email: ngomez@fas.harvard.edu

Jonathan Gregory
Meteorology Building,
University of Reading,
P O Box 243,
Reading RG6 6BB, UK
Tel: +44 118 378 5602
Email j.m.gregory@reading.ac.uk

Weiqing Han
Department of Atmospheric and Oceanic Sciences
University of Colorado at Boulder
Phone: +1 303-735-3079
Fax: +1 303-492-3524
Email weiqinghan99@gmail.com

Carling Hay
Department of Physics,
University of Toronto,
Toronto, ON M5S 1A7, Canada
Email:
chay@atmosp.physics.utoronto.ca

Simon Holgate
National Oceanography Centre
Joseph Proudman Building
6 Brownlow St.
Liverpool L3 5DA, UK
Tel: +44 151 7954900
Fax: +44 151 7954912
Email: simonh@pol.ac.uk

Chris Hughes
National Oceanography Centre
Joseph Proudman Building
6 Brownlow Street
Liverpool L3 5DA, UK
Tel: + 44 0151 795 4854
Fax: +44 0151 795 4801
Email: cwh@pol.ac.uk

Caroline Katsman
KNMI
P.O. Box 201, 3730 AE De Bilt, The Netherlands
Telephone: +31 30 2206715 (direct)
Fax: +31 30 2210407
Email: katsman@knmi.nl

Till Kuhlbrodt
Meteorology Building
University of Reading
P O Box 243
Reading RG6 6BB, UK
Telephone: +44 (0) 118 378 6014
Fax: +44 (0) 118 378 8316
Email: t.kuhlbrodt@reading.ac.uk

Kurt Lambeck
Research School of Earth Sciences
The Australian National University
Canberra , ACT 0200, Australia
Tel: +61 2 6125 5161
Fax: +61 2 6125 5443
Email: Kurt.Lambeck@anu.edu.au

Felix W. Landerer
NASA
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena
California 91109 - USA
Email: Felix.W.Landerer@jpl.nasa.gov

Eric W. Leuliette
NOAA Lab for Satellite Altimetry
1335 East-West Hwy, E/RA31
Silver Spring, MD 20910-3226, USA
Tel: +1 301 713 2857
Fax: +1 301 713 3136
Email: Eric.Leuliette@noaa.gov

Eric J. Lindstrom
NASA Headquarters
Science Mission Directorate
Earth Science Division
Mail Suite 3B74
Washington, DC 20546
USA
Tel: +1 202-358-4540
Fax: +1 202-358-2770
Email: eric.j.lindstrom@nasa.gov

Jason Lowe
Meteorology Building,
University of Reading,
P O Box 243,
Reading RG6 6BB, UK
Tel: +44 118 378 5612
Email jason.lowe@metoffice.gov.uk

Parluhutan Manurung
National Coordinating Agency for Surveys and Mapping (BAKOSURTANAL)
Jl. Raya Jakarta-Bogor Km 46
Cibinong 16911
Indonesia
Tel: +62 21 8790 7730
Fax: +62 21 8790 7730
Email: parluhutan@bakosurtanal.go.id

Shayne McGregor
School of Ocean and Earth Science and Technology
University of Hawaii
Honolulu, Hawaii 96822, USA
Tel: +1 (808) 956-8396
Fax: +1 (808) 956-9425
Email: shaynemc@hawaii.edu

Mark Merrifield
Chairman, GLOSS Group of Experts
University of Hawaii Sea Level Center
Department of Oceanography
1000 Pope Road, MSB 317
Honolulu HI 96822
United States
Tel: +1 808 956 6161
Fax: +1 808 956 2352
Email: markm@soest.hawaii.edu

Laury Miller
NOAA Laboratory for Satellite Altimetry,
E/RA31, 1335 East-West Hwy,
Silver Spring, MD 20910, USA
Email: laury.miller@noaa.gov

Krishna Mirle Achutarao
CAS, IIT Delhi, Hauz Khas
New Delhi
110016, India
Tel: 011-26596278
Email akrishna@cas.iitd.ac.in

Gary Mitchum
College of Marine Science
University of South Florida
140 Seventh Avenue
St. Petersburg FL 33701
United States
Tel: +1 727 553 3941
Fax: +1 729 553 1189
Email: mitchum@marine.usf.edu

Anne Pardaens
Met Office Hadley Centre
FitzRoy Road
EXETER EX1 3PB
UK
Tel: +44 1392 886142
Email: anne.pardaens@metoffice.gov.uk

Rui M. Ponte
Atmospheric and Environmental Research, Inc.
131 Hartwell Avenue
Lexington, MA 02421-3126 USA
Tel: +1 781-761-2288,
Fax: +1 781-761-2299,
Email: rponte@aer.com

Bo Qiu
Department of Oceanography
School of Ocean & Earth Science & Technology
University of Hawaii at Manoa
1000 Pope Road
Honolulu, HI 96822, USA
Tel: +1 (808) 956-4098
Fax: +1 (808) 956-9225
Email: bo@soest.hawaii.edu

Dean Roemmich
Scripps Institution of Oceanography
Mail Code: 0230
UCSD
9500 Gilman Drive
La Jolla, CA 92093, USA
Email: droemmich@ucsd.edu

Jens Schroeter
Alfred Wegener Institute
Bussestr. 24
27515 Bremerhaven
Germany
Phone +49-(0)471-48311762
Fax: +49-(0)471-48311797
Email: jens.schroeter@awi.de

C.K. Shum
Division of Geodetic Science,
School of Earth Sciences,
Ohio State University
125 S Oval Mall,
Columbus, Ohio 43210-1398,
U.S.A.
Tel: +1 614-292-7118,
Fax: +1 614-292-7688;
Email: ckshum@osu.edu

Detlef Stammer
Oceanography and Remote Sensing of
the Earth System, KlimaCampus
Universität Hamburg
Bundesstr. 53, 20146 Hamburg
Germany
Tel. +49 40 428385052
Fax: +49 40 428387063
Email: detlef.stammer@zmaw.de

Tatsuo Suzuki
Japan Agency for Marine - Earth
Science and Technology
3173-25, Showa-machi,
Kanazawa-ku, Yokohama City,
Kanagawa, 236-0001
Japan
Email: tsuzuki@jamstec.go.jp

Mark Tamisiea
National Oceanography Centre
Joseph Proudman Building
6 Brownlow Street
Liverpool L3 5DA, UK
Tel: + 44 (0) 151 795 4821
Fax: + 44 (0) 151 795 4801
Email: mtam@pol.ac.uk

Josh Willis
Jet Propulsion Laboratory
M/S 300-323
4800 Oak Grove Drive
Pasadena, CA 91109
Tel: +1 818.354.0881
Fax: +1 818.393.6270
Email: joshua.k.willis@jpl.nasa.gov

Ralph Weisse
Helmholz-Zentrum Geesthacht
Center for Marine & Coastal Research
Institute for Coastal Research
Max-Planck Str. 1
D-21502 Geesthacht
Germany
Tel: +49 4152-87-2819
Fax: +49-4152-87-42819
Email ralf.weisse@hzg.de

Philip L. Woodworth
National Oceanography Centre
Joseph Proudman Building
6 Brownlow Street
Liverpool L3 5DA, UK
Tel: + 44 (0) 151 795 4860
Fax: + 44 (0) 151 795 4801
Email: plw@pol.ac.uk

Jianjun Yin
Department of Geosciences
University of Arizona
Tucson, AZ
USA
Fax: +1 (520) 621-2672
Email: yin@email.arizona.edu

Annex 2

Program

WCRP/IOC Workshop on Regional Sea Level Change

(UNESCO/IOC, Paris)

Start: 9:00 Monday February 7 2011; End: 16:00 Wednesday February 9 2011

Each speaker should prepare for a 15 min. talk, to leave 10 min for discussion.

Agenda:

7-8 February 2011: Session 1-3
9 February 2011: Session 3 and 4
Coffee Breaks: 10:30 – 11:00; 15:30 – 16:00
Lunch breaks: 12:30 – 14:00

Monday February 7 2011:

Registration: 8:00 – 8:45

Opening: 9:00: Charge to meeting, logistics, etc.: (15 min.)

Opening of Meeting: J. Gregory and D. Stammer

Welcome from IOC and WCRP, Wendy Watson-Wright, Executive Secretary of IOC
Logistics: Thorkild Aarup

Begin of Sessions: 9:15

Session 1 and Session 2

Adjourn for the day 6pm and reception

Day 2:

Re-adjourn: 9:00.
Group photo during Morning Coffee Break

Session 2 and Session 3
Adjourn for the day 18:00 and dinner

Day 3:

Re-adjourn: 9:00.

Session 3 and Session 4
Closing of the workshop: 16:00

Session 1: Observed regional sea level variability and change (6h)

The session will discuss observations (paleo/proxy tide gauges, altimeters and GRACE) of regional variability and changes in sea level and the interpretation of its pattern.

Chair/Rapporteur: Josh Willis, Don Chambers

Speakers (in order):

1. K. Lambeck: The certainties and uncertainties of regional variations in sea level due to glacio-hydro isostatic processes
2. Mark Tamisiea: Contribution of glacial isostatic adjustment to GRACE estimates of sea level change
3. J. Schroeter: Reconstruction of global and regional sea level from tide gauge records since 1900

   (Approximate morning break)

4. Dean Roemmich: A global view of regional steric sea level variability, 2004 – 2010, from the Argo Program
5. Catia Domingues: Observed and simulated regional patterns of thermosteric sea-level rise
6. Paul Durack: Revisiting halosteric and thermosteric sea level rise, 1950-2000
7. Leuliette: Regional sea level budgets and ocean mass transport estimates from GRACE, altimetry, and Argo

   (Approximate lunch)

8. Josh Willis: Explaining regional sea level variations during the satellite altimeter era
9. Phil Woodworth: Identifying and understanding changes in sea level around the North Atlantic
10. R. Weisse: Regional mean sea level changes in the German Bight in the 20th century
11. Mark Merrifield: Recent regional sea-level trends in the Pacific

    (Approximate afternoon break)

12. Don Chambers: Decadal-scale non-steric sea level changes in the North Pacific
13. Weiqing Han: Indian Ocean sea level change in a warm climate
14. Parluhutan Manurung: Web-based real time monitoring, improving long-term sea level data time Series in Indonesia

Session 2: Dynamics and kinematics of regional sea level variability (4 1/2h)

This session will discuss the natural variability of sea level varieties?? and the processes responsible, on all time scales. The discussion will draw heavily on models (ocean-only and coupled) and ocean syntheses, but also use observations to define modes of variability, like ENSO, PDO, SAM, or NAO.

Chair/Rapporteur: D. Stammer, J. Church

Speakers (in order):

1. Anny Cazenave: Spatial trend patterns in sea level from altimetry, past sea level reconstructions and CNRM-CMIP3 coupled climate model
2. Rory Bingham: The impact of interannual ocean density variations on regional and global mean sea level as revealed by Argo
3. Fukumori: Distinguishing sea level change due to heating and freshwater input from redistribution by ocean circulation
4. Chris Hughes: Towards a separation of the physical processes behind sea level change
5. Laury Miller: Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise
6. R. Ponte: Some challenges in the study of regional sea level variability
7. Gary Mitchum: Low frequency sea level variations on the boundaries of the North Atlantic
8. Shayne McGregor: Wind effects on past and future regional sea-level trends in the southern Indo-Pacific
9. Bo Qiu: Regional sea level and circulation variability in the tropical western Pacific Ocean
10. Mark Carson: Low-frequency variability of regional sea level in millennium climate model simulations

Session 3: Causes and mechanisms for recent and future regional sea level changes (6h)

This session will discuss the hindcasting of past and the projection of future regional sea level changes by climate, ocean, ice-sheet and solid-Earth models, including attribution of changes to radiative forcing agents.

Chair/Rapporteur: Jonathan Gregory, Rui Ponte

Speakers (in order):

1. Birgit Klein: Requirements on regional sea level analysis from the perspective of an operational marine service provider

2. Krishna Mirle Achutarao: Testing the skill of (CMIP3) models in simulating observed Northern Indian Ocean sea-level changes

3. Jianjun Yin: Regional sea level rise projections on the northeast coast of the United States

4. Tatsuo Suzuki: Regional distribution of sea level changes resulting from enhanced greenhouse warming in the Model for Interdisciplinary Research on Climate version 3.2 (MIROC 3.2)

5. Caroline Katsman: Regional projections of twenty-first century sea-level change

6. Felix Landerer: Probabilistic projections of regional sea-level rise

7. Till Kuhlbrodt: The regional structure of ocean heat uptake and its causes

8. Anne Pardaens: A model study of factors influencing projected changes in regional sea level over the twenty-first century

9. John Church: Regional fingerprints of radiative forcing of sea-level rise

10. P.J. Gleckler: Exploring the impact of model and data uncertainties in the detection and attribution of upper-ocean warming

11. Detlef Stammer: Response of the coupled ocean-atmosphere system to Greenland ice melting

12. Carling Hay: Detecting the sea-level fingerprint of polar ice mass changes

13. Natalya Gomez: Sea level as a stabilizing factor for marine ice sheets

14. CK Shum: On the geophysical causes of present-day sea-level rise

Session 4: Initiation of studies for AR5

Final section of summary talks addressing current challenges and possible ways forward in observing, modeling and predicting regional sea level. Possibly these could include:
- observed variability and trends and whether models can account for them
- uncertainties in making predictions and projections and perhaps there are other orthogonal angles as well.

The session would pick up issues raised during the previous sessions that will be built upon in more detail. Especially addressing particular areas and identifying issues raised, which imply what science would be useful for AR5.

Chair/Rapporteur: D. Stammer, J. Gregory

D. Stammer: Opening summary of all issues raised during the workshop and presentation of strawman for AR5 studies.

Subsequently: Discussion of all open issues and initiation of research activities.

Annex 3

List of abbreviations

AR5	IPCC Fifth Assessment Report
CLIVAR	WCRP Climate Variability and Predictability Project
CMIP5	Coupled Model Intercomparison Project Phase 5
ENSO	El-Niño – Southern Oscillation
GRACE	Gravity Recovery and Climate Experiment
GSOP	CLIVAR Global Synthesis and Observations Panel
IOC	Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change (of WMO and UNEP)
NAM	Northern Annular Mode
PDO	Pacific Decadal Oscillation
SAM	Southern Annular Mode
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WMO	World Meteorological Organization
WCRP	World Climate Research Programme