Summary Statement from the
World Climate Research Programme Workshop

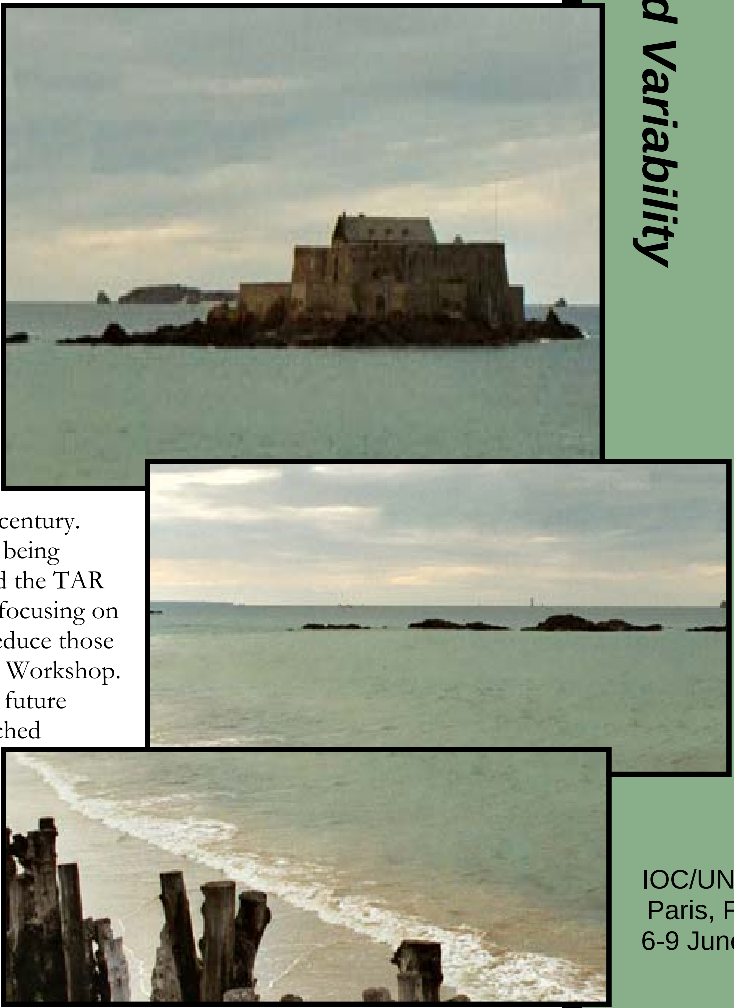
Understanding Sea-level Rise and Variability

IOC/UNESCO
Paris, France
6-9 June 2006

THE WORKSHOP. 163 scientists from 29 countries attended the Workshop on Understanding Sea-level Rise and Variability,[1] hosted by the Intergovernmental Oceanographic Commission of UNESCO in Paris June 6-9, 2006. The Workshop was organized by the World Climate Research Programme (WCRP)[2] to bring together all relevant scientific expertise with a view towards identifying the uncertainties associated with past and future sea-level rise and variability, as well as the research and observational activities needed for narrowing these uncertainties. The Workshop was also conducted in support of the Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan;[3] as such, it helped develop international and interdisciplinary scientific consensus for those observational requirements needed to address sea-level rise and its variability.

The Issue – Since the beginning of high-accuracy satellite altimetry in the early 1990s, global mean sea-level has been observed by both tide gauges and altimeters to be rising at a rate of just above 3 mm/year, compared to a rate of less than 2 mm/year from tide gauges over the previous century. The extent to which this increase reflects natural variability versus anthropogenic climate change is unknown. About half of the sea-level rise during the first decade of the altimeter record can be attributed to thermal expansion due to a warming of the oceans; the other major contributions include the combined effects of melting glaciers and ice sheets. Changes in the storage of water on land (such as the depletion of aquifers and increases in dams and reservoirs) remain very uncertain.

The Motivation – The coastal zone has changed profoundly during the 20th century, primarily due to growing populations and increasing urbanization. In 1990, 23 percent of the world's population (or 1.2 billion people) lived both within a 100 km distance and 100 m elevation of the coast at densities about three times higher than the global average. By 2010, 20 out of 30 mega-cities will be on the coast, with many low-lying locations threatened by sea-level rise. With coastal development continuing at a rapid pace, society is becoming increasingly vulnerable to sea-level rise and variability—as Hurricane Katrina recently demonstrated in New Orleans. Rising sea levels will contribute to increased storm surges and flooding, even if hurricane intensities do not increase in response to the warming of the oceans. Rising sea levels will also contribute to the erosion of the world's sandy beaches, 70 percent of which have been retreating over the past century. Low-lying islands are also vulnerable to sea-level rise.



An improved understanding of sea-level rise and variability will help reduce the uncertainties associated with sea-level rise projections, thus contributing to more effective coastal planning and management. Adaptation measures, including enhanced building codes, restrictions on where to build, and developing infrastructures better able to cope with flooding, should help to minimize the potential losses.

Relation to the IPCC Assessments – The Third Assessment Report (TAR)[4] of the Intergovernmental Panel on Climate Change (IPCC) estimated that sea level will rise between 9 and 88 cm by the end of the 21st century. The Fourth Assessment Report (due in 2007) is currently being reviewed by governments. The Workshop complemented the TAR by starting with the set of uncertainties it identified, then focusing on the scientific and observational requirements needed to reduce those uncertainties, as well as uncertainties identified during the Workshop. The Workshop did not attempt to develop projections of future changes as the TAR did. The Workshop participants reached consensus that the increase in the rate of global mean sea-level rise towards the end of the 20th century, to just above 3 mm per year from less than 2 mm per year on average over the previous century, is a robust finding. The Extended Workshop Report[5] will address how the many uncertainties in understanding the causes of 20th century sea-level change and its recent acceleration could be reduced for input to future IPCC Assessment Reports.

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RESEARCH RECOMMENDATIONS. Workshop participants reviewed current knowledge concerning all aspects of sea-level rise, determined uncertainties in knowledge of the contributing factors, and generated a summary set of recommendations focused on reducing those uncertainties. Most of the recommendations seek to guide ongoing research that should be nurtured; others encourage open data sharing, data archaeology, and better use of data already in hand. Finally, there are new needs based on emerging science and technology development. An overview of those recommendations, organized according to the Workshop plenary themes (not in priority order), is below:

Paleo Sea-level Changes – Information on relative sea-level rise over the past ~8,000 years obtained from a variety of geological indicators can be used to estimate and model vertical land movement at tide gauges resulting from glacial isostatic adjustment and other factors. To what extent can modern observations of sea level based on tide gauges and altimetry be extended back in time, using complementary techniques to constrain estimates of the contribution of ice sheets to sea-level rise since the Last Glacial Maximum?

- Enhance the spatial coverage of information on relative sea-level variability and change over the past ~8,000 years in order to estimate the extent to which such changes may have been global, regional, or local.
- Assess changes in relative sea levels from a geographically well-distributed set of salt marshes and relatively isolated basins, coral reefs and other biological markers, and archaeological sites as an aid to extending the historical record back several hundred years.

Figure 1: An 8,000-year-old well off the coast of Israel now submerged by rising sea level.

Historical and Present Sea-level Change – Beginning in 1992, global mean sea-level has been observed by both tide gauges and altimeters to be rising at a rate of 3.2 ± 0.4 mm/year, compared to a rate of 1.7 ± 0.3 mm/year from tide gauges over the previous century. To what extent does this increase in the global mean represent an acceleration?

- Pursue data archaeology by retrieving and making accessible historical, paper-based sea-level records, especially those extending over long periods and in the Southern Hemisphere.
- Extend the Jason series of satellite altimeters for a second decade in order to resolve the spatial and temporal variability, as well as acceleration, in the rate of global sea-level rise.
- Complete the Global Sea Level Observing System (GLOSS) network of approximately 300 gauges, each with high-frequency sampling and real-time data availability. Gauges should be linked to absolute positioning where possible (either directly at the gauge or leveling to nearby absolute networks) to enable an assessment of the coastal signatures of the open-ocean patterns of sea-level variability and the incidence of extreme events, as well as the calibration of satellite altimeters.

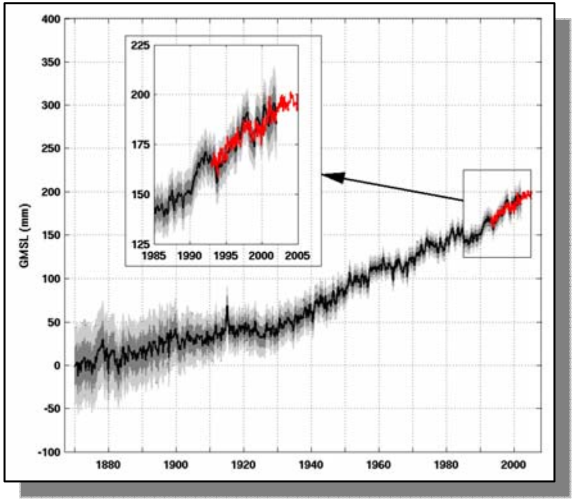

Figure 2: Monthly averages of global mean sea level reconstructed from tide gauges (black, 1870-2001) and altimeters (red, 1993-2004) show an increase in the rate of sea-level rise; the seasonal cycle has been removed.

Thermal Expansion – Current estimates of thermal expansion account for approximately half of the change observed in global mean sea-level rise over the first decade of the satellite altimeter record, but only about a quarter of the change during the previous half century. To what extent does this reflect under-sampling of ocean temperature data versus a manifestation of enhanced climate change in the last decade? While progress has been made in modeling sea-level rise, the current generation of climate models does not adequately reproduce the estimated thermal expansion. Are the discrepancies the result of inadequate observations or models?

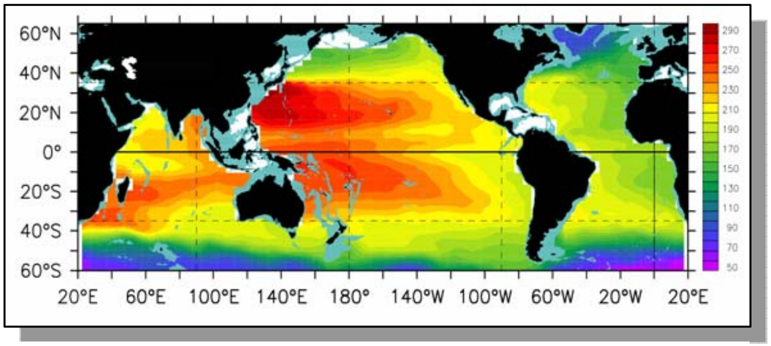

Figure 3: Argo has provided a means to estimate changes in upper-ocean heat content.

- Complete and sustain the Argo array of profiling floats to obtain broad-scale, upper-ocean (from surface to 2000 m depth) observations of the temperature and salinity fields.
- Extend the Argo-type capability to enable the collection of similar observations under the sea ice.
- Design and implement an effort to obtain routine temperature and salinity fields from the deeper ocean (below 2000 m) complementary to those for the upper ocean sampled by Argo.
- Compare and contrast different observational analysis and ocean data assimilation techniques (including the ongoing development of new techniques) using the same observations to estimate the contribution of thermal expansion to global mean sea-level rise.
- Reconcile differences between observations of sea-level variability and trends and the ability of different ocean and climate models to realistically depict these.

Cryosphere – Terrestrial glaciers and the Greenland and Antarctic ice sheets have the potential to raise global sea level many meters. Terrestrial glaciers are shrinking all over the world. During the last decade, they have been melting at about twice the rate of the past several decades. On the polar ice sheets, there is observational evidence of accelerating flow from outlet glaciers both in southern Greenland and in critical locations in Antarctica. Both inland snow accumulation and marginal ice melting have increased over the Greenland ice sheet, but there is little evidence for any significant accumulation trend over the Antarctic ice sheet. What are the changes occurring in glaciers and ice sheets and how are they impacting sea level?

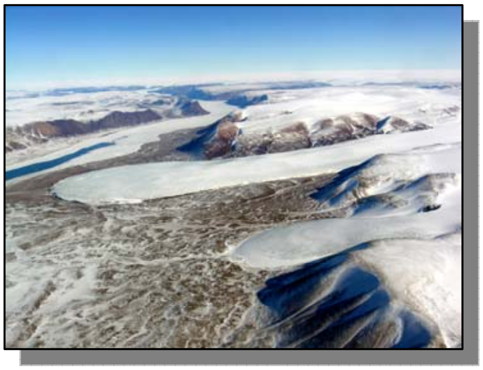

Figure 4: An outlet glacier in Greenland draining ice from the ice sheet onto a large outwash plain.

- Reconcile estimates of ice sheet mass balance derived using different approaches, and determine whether recent increases in mass losses are anomalous or reflect improvements in observational techniques.
- Identify causes for the apparent recent increases in mass loss to enable development of improved glacier models.
- Extend ongoing measurements of ice-thickness transects to cross each major outlet glacier in Greenland and Antarctica.
- Complete the World Glacier Inventory through sustained support for the Global Land Ice Measurements from Space (GLIMS) program.
- Extend observational coverage of terrestrial glaciers beyond traditional areas (e.g., the Alps and Alaska) to include all representative regions, thereby enabling improvements in monitoring and modeling.
- Utilize the Ice, Cloud, and land Elevation Satellite (ICESat) laser and, once launched, CryoSat-2 radar altimeter satellites—complemented by aircraft altimetry—to survey changes in the surface topography of the ice sheets; and based on experience gained, develop a suitable follow-on satellite.
- Utilize the Gravity Recovery and Climate Experiment Satellite (GRACE) and appropriate follow-on missions to infer changes in the mass of the glaciers and ice sheets.
- Seek continued access to satellite Interferometric Synthetic Aperture Radar (InSAR) data in order to measure flow rates in glaciers and ice sheets; this will require suitable satellite missions—both existing and new—and ready access to resulting data, particularly over near-coastal regions of Greenland and Antarctica.
- Improve models to identify causes for the apparent increased mass losses from the polar ice sheets and use that as the basis for better simulations of future scenarios; particular effort is needed with respect to ocean/ice shelf interactions, surface mass balance from climate models, and the inclusion of higher-order stress components in high-resolution ice-dynamic models.

Terrestrial Water Storage – The Third Assessment Report (TAR) notes that the largest uncertainties in contributions to sea-level rise are associated with terrestrial water storage. What is the potential for a combination of satellite observations—with finer resolution, broader coverage, and longer duration—and appropriate *in situ* data to significantly reduce these uncertainties, as well as lay the basis for improvements in associated models?

- Explore means to extrapolate the latest estimates of large-reservoir storage from the International Commission on Large Dams to include the contributions from progressively smaller reservoirs.
- Compile data for representative sites concerning changes in subsurface storage resulting from activities such as groundwater use, aquifer mining, irrigation recharge, and surface storage leakage.

Figure 5: Increases in dam and reservoir storage can reduce the rate of sea-level rise.

- Utilize GRACE to observe changes in land water storage, the Soil Moisture and Ocean Salinity spacecraft (SMOS) – when launched in 2007 – to observe changes in soil moisture, and available satellite altimeters (Jason, Envisat, and GFO) to observe river, lake, and reservoir levels along the satellite ground-tracks.
- Develop and implement a mission with an advanced *wide-swath* altimeter to observe the two-dimensional surface-water levels on land—rivers, lakes, and reservoirs—and their changes in space and time.
- Utilize improvements in satellite and *in situ* observations to facilitate the development of improved global land surface models and their application to reducing associated uncertainties.

Geodetic Observing Systems – The development and implementation of geodetic techniques has enabled a revolution in the Earth sciences, providing the fundamental reference frame critical for the collection of all satellite and many *in situ* observations addressing sea-level rise and variability. However, to take advantage of those capabilities, they must be reliable and consistent over the long term (i.e., decades). While these techniques collectively define the International Terrestrial Reference Frame (ITRF) being brought together through the efforts of the Global Geodetic Observing System, they are at the same time losing support and degrading in capability. How can we enhance and sustain support for the ITRF so that it can be made robust and stable?

- Update and integrate complementary geodetic capabilities (SLR, VLBI, DORIS, and GPS)—co-locating them where possible—into a reliable and consistent global geodetic ground and space network.
- Install GPS positioning at all appropriate GLOSS tide gauge stations to determine changes in global and regional sea level.
- Develop an integrated geodetic modeling capability that can be combined with those for the Earth sciences.
- Utilize observations of the time-invariant gravity field from the Gravity Field and Steady-State Ocean Circulate Explorer (GOCE), once launched, to determine the precise geoid, thereby enabling an estimation of the absolute ocean circulation for constraining climate models, as well as an improvement in understanding of geophysical processes related to sea level.

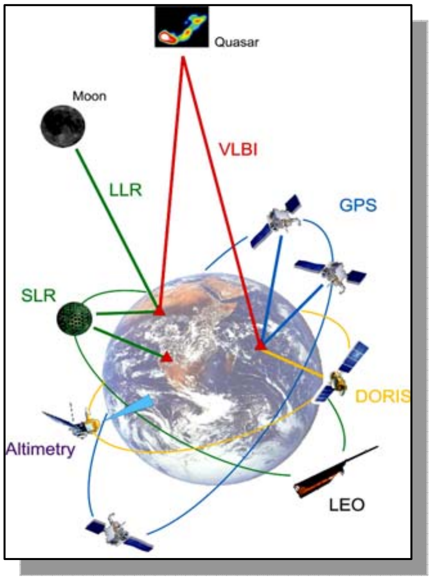

Figure 6: Integrating existing geodetic capabilities can provide an improved reference frame.

Surface Mass Loading – The main mass loads considered here are the great ice sheets, which covered large areas during the Last Glacial Maximum; the Earth is still visco-elastically responding to the removal of those loads. In addition, changes in the present ice sheets, glaciers and ice caps, and terrestrial storage result in ongoing changes in surface loading. Uncertainties in models of Glacial Isostatic Adjustment (GIA) affect sea-level measurements from tide gauges via uncertainties in modelled vertical land movements; these uncertainties also impact altimeter measurements of sea level and measurements of changes in surface loads (including sea level and ice-sheet mass balance) made by temporal gravity missions such as GRACE. Other changes in mass loads include those associated with tectonic activity such as earthquakes, as well as local extraction of water and hydrocarbons.

Figure 7: Boathouses in Scandinavia now considerably farther from the water's edge where they were built, demonstrating uplift due to GIA.

- Utilize sea level from tide gauges equipped with a capability for absolute positioning, together with observations from satellite altimetry, gravity, GPS, and other datasets, to improve models of past ice sheet loading and glacial isostatic adjustment used to estimate sea-level change.
- Use improved *fingerprint* analysis to help identify contributions from the ice sheets, glaciers, and terrestrial storage to present-day sea-level change.

Extremes – Global sea-level rise will have a pervasive impact by raising the mean water level on top of which must be added the combined effect of high tides, surface waves, storm surge, and flooding rivers—making the incidence of flooding to a given level more frequent, i.e., a *100-year* coastal flooding event can become a *10-year* event at some locations. Unless such change is taken into account, design criteria for existing coastal structures can become out-of-date and lead to catastrophic flooding such as experienced in New Orleans with Hurricane Katrina. Moreover, the possibility that severe weather events may become more frequent and/or intense with our changing climate will only make matters worse. How can we translate what has been learned from the Workshop into easily understood information that can be used by coastal planners and engineers, emergency managers, insurers, and the public at large?


Figure 8: A warmer ocean can contribute to more intense hurricanes.

- Pursue data archaeology and complete the GLOSS network of tide gauges, each with high-frequency sampling and real-time data availability, to enable an assessment of the incidence of extreme flooding events.
- Extend tide gauge and storm surge risk estimation to include waves, river flows, and their interactions; apply statistical methods for proper estimation of the joint probability of extreme flooding events.
- Extend and reanalyse the historical hurricane data sets to assess the extent to which the frequency and intensity of hurricanes and mid-latitude storms may have changed in response to anthropogenic forces.
- Estimate the uncertainty in how storminess may change in the future at a variety of locations (tropical and mid latitudes) using a combination of ensembles of climate model simulations and observational constraints.
- Develop coastal storm surge models (and/or high-resolution global models) capable of application to all areas of storm surge risk worldwide.
- Engage with the impacts and engineering communities to link storm surge and wave models to inundation and erosion models at more locations.

OBSERVING SYSTEM RECOMMENDATIONS. A number of the research recommendations relate specifically to observing system requirements. An open data policy is needed, together with timely, unrestricted access for all. Using the Argo and Jason policies as a guide, this access would include real-time, high-frequency sea-level data from the GLOSS tide gauges and co-located GPS stations, as well as data from satellite missions and *in situ* observing systems. Data archaeology—retrieving and making accessible historical, paper-based sea-level records, especially those extending over long periods and in the Southern Hemisphere—is needed. Satellite observations need to be as continuous as possible, with overlap between successive missions and coincident with the collection of appropriate *in situ* observations. In general, ongoing satellite and *in situ* observing systems should adhere to the Global Climate Observing System (GCOS) observing principles.

Sustained, Systematic Observing Systems (Existing Capabilities)

- Sea level.
  - Extend the Jason series of satellite altimeters for a second decade and beyond through implementation of a Jason-3.
  - Complete the GLOSS network of approximately 300 gauges, each with high-frequency sampling and real-time data availability. Gauges should be linked to absolute positioning where possible (either directly at the gauge or leveling to nearby absolute networks) to enable an assessment of the coastal signatures of the open-ocean patterns of sea-level variability and the incidence of extreme events, as well as the calibration of satellite altimeters.
- Ocean volume.
  - Complete and sustain the Argo array of profiling floats to obtain broad-scale, upper-ocean observations of the temperature and salinity fields.
- Ocean, terrestrial water, and ice mass.
  - Sustain observations of the time-varying gravity field from GRACE and plan for an appropriate follow-on mission with finer spatial resolution to contribute to estimating changes in:
    - Ocean mass.
    - Terrestrial water storage.
    - Ice sheet mass.

- Ice sheet and glacier topography and thickness.
  - Sustain satellite observations utilizing radar (GFO, ENVISAT and future missions like Cryosat-2 and Sentinel-3) and laser (ICESat) altimeters, complemented by aircraft and in situ observations, to survey changes in the surface topography of the ice sheets.
- Reference frame.
  - Strengthen and sustain support for the International Terrestrial Reference Frame (ITRF), integrating the geodetic components – SDR, VLBI, DORIS, and GNSS (GPS, together with GLONASS & Galileo once launched) – to make them more robust and stable.
  - Utilize observations of the time-invariant gravity field from GOCE, once launched, and other stand-alone missions to determine the precise geoid.

Development of Improved Observing Systems (New Capabilities)

- Ocean volume.
  - Extend the Argo-type capability to enable the collection of similar observations under the sea ice.
  - Design and implement an effort to obtain observations for the deep ocean complementary to those from Argo for the upper ocean.
- Ice sheet and glacier topography.
  - Based on experience gained with radar and laser satellite altimeters, develop and implement a suitable follow-on capability.
- Ice velocity.
  - Develop and implement an InSAR mission to observe flow rates in glaciers and ice sheets.
- Sea and terrestrial water levels; ice sheet and glacier topography.
  - Develop and implement a mission with an advanced *wide-swath* altimeter to observe the:
    - Sea level associated with the oceanic mesoscale field, coastal variability, and marine geoid/bathymetry.
    - Surface water levels on land and their changes in space and time.
    - Surface topography of glaciers and ice sheets.

References

[1] http://copes.ipsl.jussieu.fr/Workshops/SeaLevel/index.html

[2] http://wcrp.wmo.int/

[3] http://www.earthobservations.org/doc_library/geoss_docs.html

[4] http://www.ipcc.ch/activity/tar.htm

[5] An extended workshop report in book form is planned for 2007.

Selected Bibliography

The Workshop built on and derived benefit from these broad references, as well as numerous detailed reports and papers that are not listed here.

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Abbreviations and Acronyms

ACE CRC	Antarctic Climate and Ecosystems Cooperative Research Centre
CliC	Climate and Cryosphere Project
CLIVAR	Climate Variability and Predictability Study
CryoSat-2	Second Cryospheric Satellite
CSIRO	Commonwealth Scientific and Industrial Research Organization
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ESSP	Earth System Science Partnership
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GFO	GeoSat Follow-on Satellite
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 Satellite
GPS	Global Positioning System
GWSP	Global Water System Project
GRACE	Gravity Recovery and Climate Experiment Satellite
ICESat	Ice, Cloud, and Land Elevation Satellite
IGBP	International Geosphere Biosphere Programme
InSAR	Interferometric Synthetic Aperture Radar
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
JSC	Joint Scientific Committee
NOAA	National Oceanic and Atmospheric Administration
POL	Proudman Oceanographic Laboratory
PSMSL	Permanent Service for Mean Sea Level
SLR	Satellite Laser Ranging
SMOS	Soil Moisture and Ocean Salinity Satellite
TAR	Third Assessment Report (of the IPCC)
UNESCO	United Nations Educational, Scientific, and Cultural Organization
VLBI	Very Long Baseline Interferometry
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modeling

About the Sea-level Rise and Variability Workshop

The Workshop was approved at the XXVIth session of the Joint Scientific Committee for the World Climate Research Programme (WCRP), Guayaquil, Ecuador, March 2005. In accordance with the WCRP Strategic Framework 2005-2015, the Workshop brought together all relevant WCRP science to identify uncertainties in sea-level rise and variability and the associated research and observational activities for narrowing those uncertainties. This required contributions from a range of WCRP projects and activities (CLIVAR, ocean thermal expansion; CliC, glacier and ice sheet contributions; GEWEX, terrestrial water storage; WGCM, coupled climate modeling). In addition, expert contributions from IGBP, the ESSP GWSP, and other relevant groups were valuable.

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