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Report #8

EGS Vening Meinesz Conference #1

GLOBAL AND REGIONAL SEA-LEVEL CHANGES AND THE HYDROLOGICAL CYCLE

Loiri-Porto San Paolo
Sardinia, Italy
4-6 October, 1999

by
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with contributions by the conference participants:
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I G B P

G A I M

"Global and Regional Sea-Level Changes and the Hydrological Cycle" October 4-6, 1999 - Loiri-Porto San Paolo, Sardinia, Italy

The Conference on "global and regional sea-level changes and the hydrological cycle" addressed the measurement, causes and consequences of recent and projected near-future sea level changes. This bears on the scientific issues facing IGBP/GAIM, BAHC, and LOICZ as well as WCRP and IHDP*. The Conference was sponsored by the EGS* as the first in the new Vening-Meinesz topical conference series.

Climate models currently predict that the global mean surface temperature will increase in the coming decades in response to increasing greenhouse gases in the atmosphere. As one of the serious consequences of this climate change, a substantial rise of the global mean sea level is expected. Knowledge of the rate of sea-level rise to be expected on regional to global scale is most significant because of the potentially devastating impact on human society and coastal ecosystems. In fact, a large proportion of the world's population (currently about 2.5 billion), live within 60 km of the coast, and these areas often have a well developed infrastructure that could be severely disrupted by further sea level rise. Therefore, observations and scientific research are needed which can give guidance in the proper development of coastal zones in order to mitigate the social and ecological impact of future climate change in an effective and economically affordable way. The specific future research priorities for addressing these issues were formulated at the conference and are included below.

Conference Objective

The objective of the conference was to provide a forum for critical discussion of the present state of knowledge of sea-level variability in relation to the hydrological cycle both at global and regional scales. The main focus was on the identification of problem areas which need to be investigated and key parameters which need to be monitored in order to improve our understanding of the physical phenomena and their interactions governing the spatial and temporal variations of sea level. The key areas were identified as measurement & monitoring, quantification of global hydrologic balance, and evaluation of impacts as they pertain to policy issues and the IPCC process.

Key Issues

The issues confronting investigations of modern sea level rise can be grouped into three categories:

- **Measurement**
- **Mechanisms**
- **Impacts.**

Measurement of sea level change in the 20th century has traditionally been based on tide gauge records, corrected for coastal epeirogeny in response to glacial re-equilibration. The relatively long tide gauge records make it possible to extract a secular signal from highly variable short-term observations. For almost two centuries, sea-level observations have been provided from a network of tide gauges with sites along the coasts all around the world (but mostly in the northern

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* International Geosphere Biosphere Programme (IGBP)
Global Analysis, Interpretation and Modelling (GAIM)
Biospheric Aspects of the Hydrological Cycle (BAHC)
Land-Ocean Interactions in the Coast Zone (LOICZ)
World Climate Research Programme (WCRP)
International Human Dimensions Programme on Global Environmental Change (IHDP)
European Geophysical Society (EGS)
Intergovernmental Panel on Climate Change (IPCC)

hemisphere). Tide gauges measure sea-level relative to the land surface at the local coast. Therefore, vertical crustal movements originating, for example, from local subsidence, tectonics and post-glacial rebound influence such measurements. In order to decouple global sea-level changes from local effects, epeirogenic motion needs to be monitored and better understood on the basis of models of the Earth's mantle and lithosphere. In this way, the relative sea level recorded by tide gauges can be converted to the more globally relevant eustatic sea level which depends on the relative volumes of the global ocean water and the global ocean basin.

More recently, satellite radar altimeter observations of sea level have made it possible to record variations in the open ocean as well as along the coastline, but these records exist only for the last decade or so mkaing it difficult to extract secular sea level trends. They will, however, become increasingly important in the 21st century. Because these measurements are based on the satellite height relative to the center of mass of the Earth in a well-defined terrestrial reference system, rather than to the local land surface, global and regional absolute sea-level changes can now be determined. However, radar altimeter instruments experience drifts on the order of 1-2 mm/yr and must be calibrated or modeled, causing the use of these instruments to measure sea level change very challenging.

Available space and in situ techniques must be used routinely and combined for the monitoring of absolute and relative sea level changes at various spatio-temporal scales, i.e., from local or regional to global scales and from seasonal to inter-decadal time scales. Such observations are of fundamental importance for the understanding of how the volume and mass of the oceans change in response to global change as well as of the physical interactions between the cryosphere, hydrosphere and atmosphere involved in sea level changes.

In addition to measurements of global sea level change, satellite altimetry makes it possible to measure the spatial variability of sea level. This will enable the assessment of ocean circulation model and coupled model performance. For projections of the magnitude of future sea level rise, it is necessary to understand the mechanisms by which water is transferred between the ocean and other storage reservoirs. As such, measurement is closely coupled to mechanisms.

The ***mechanisms*** of sea level change can be grouped into two types–those that change the volume of the Earth's ocean basin, and those that change the volume of the Earth's ocean water. On the time scales of concern in modern global change (decade to century), only water volume changes are important globally, as the tectonic influences on basin geometry act slowly relative to the time scale of interest. (However, locally, "tectonic" processes such as glacial rebound and subsidence due to ground water withdrawal can significantly affect local relative sea level.) Global ocean water volume is increased by adding water to the ocean by melting grounded ice, by adding water by a variety of human activities, or by decreasing the density of the existing water mass through warming of the marine mixed layer.

A climate signal in sea-level can be expected for two reasons: firstly, the ocean volume changes whenever a change in the heat content of ocean water takes place, and secondly, ocean mass changes due to a change in the mass flow between the ocean and other reservoirs of the hydrological cycle. Monitoring ocean temperature and ice volume is not a simple matter, however. While sea surface temperatures are relatively well measured, deep ocean thermal structure remains unconstrained. Even the thermal structure of the mixed layer is not well monitored, although some efforts are being made toward that end. Ice volume can be measured by direct observation, but accuracy has been a problem to date. Satellite radar altimeters are now capable of measuring large-scale (300 km or longer) ice sheet elevation changes over relatively smooth and level ice surfaces. Problems with radar penetration, and scattering in marginal and sloped ice surfaces have limited the accuracy of such measurement to date. However, during the beginning of the next decade, a spaceborne laser altimeter (Icesat) will be launched that is capable of measuring ice thickness (elevation) change with much higher accuracy and smaller spatial scale than radar altimeters. The time series data from the existing radar altimeters together with those of Icesat, should provide critical insights regarding the measurement and causes of changes in contemporary (decadal) ice sheet mass.

The ocean is the largest reservoir in the global hydrological cycle, and, moreover, the flows between the ocean and the other reservoirs are generally larger than the flows between any pair of the other reservoirs. Water vapor, fluid water and/or ice are involved in most of the important natural processes on the Earth's surface. The energy available for the hydrological cycle thus crucially determines the state and the processes in the system. Sea level and its spatial and temporal variability, therefore, may not only be important for understanding the potential impacts of climate change but also prove to be a key parameter of the Earth system.

Predicting future sea level changes in both important and difficult. Model projections for future global and regional sea level changes are still highly uncertain due to uncertainties in the heat and mass balance of the ocean as well as in the near-term effect of climate change on Antarctic ice budgets. Although there is no doubt that a global warming will cause ocean thermal expansion, present results based on Atmosphere-Ocean General Circulation models are not yet reliable enough because of the difficulty in modelling the complex thermodynamic interactions between ocean and atmosphere (in addition to difficulties modelling the ocean and atmosphere individually). On climatological time scale, the cryosphere has the largest potential to contribute to ocean mass and sea-level changes. Unfortunately, the present mass balance of polar ice sheets is not precisely known. Model predictions do not agree on the amount of warming expected at high latitudes rendering it difficult to understand how the equilibrium of polar ice masses will be altered by the changing relationships between increases in precipitation and increases in ablation. While there is some consensus that mountain glaciers and Greenland ice sheet will lose mass in the future and contribute to sea level rise, the role of Antarctica, the largest potential contributor is very poorly constrained. While there is general consensus that in the short-term, atmospheric warming will lead to southern ocean surface warming and will increase precipitation on the Antarctic ice sheet, the counteracting effects (and time scale) of warming on ice rheology, ice streams, and the West Antarctic grounding line in the long-term are less clearly defined, and remain unquantified. Moreover, contributions from other reservoirs such as ground water or terrestrial surface waters are difficult to estimate and more difficult to predict. Considering this present situation, a detailed monitoring of the sea-level variability is essential.

The ***impacts*** of sea level rise are of greatest concern to the general population, particularly in and near coastal communities. Direct hydrologic consequences include flooding of coastal wetlands, salinization of coastal aquifers, alterations of estuarine steam flow, and exacerbation of storm damage to both ecosystems and human-built structures (e.g. houses, roads, bridges, etc.). The present natural coastal defenses are, in most cases, insufficient because they rely on a dynamic interaction between sea level, wave energy, and sediment transport that is corrupted by the presence of artificial structures. Existing man-made coastal defenses will be unable to accommodate an increase in storm activity super-imposed on a significant rise in mean sea-level. A better documentation of the rate of sea level rise (measurement) and understanding of the causes (mechanisms) will lead to better prediction of the consequences of future sea level rise. It is hoped that this will place policy-makers and others in coastal communities in a better position for rational decision-making regarding local responses.

The most serious impacts of sea level rise were identified at the meeting as:

Shoreline erosion- Shoreline systems, most notably beaches, are subject to increased erosion as sea level rises. The loss of material is not necessarily limited to the shoreline, however. There is an equilibrium profile to be maintained in the coastal zone that will respond to sea level rise by eroding as much as a kilometer inland from the present shoreface, thus extending the region of impact. Nearshore topography and land use need to be documented at the local level in order to be able to predict the impacts of sea level rise on local shorelines.

Exacerbation of storm wave damage- Given the historical frequency and severity of coastal storms such as hurricanes and typhoons, any rise in sea level will greatly increase the extent of damage within the coastal zone, particularly during high tide. If there is an increase in storm frequency or severity as a part of other aspects of global change, then sea level rise will further exacerbate the risk of severe storm damage due to high waves.

Storm surges- In addition to damage caused by waves and erosion, flooding due to storm surges will increase under conditions of higher sea level. As is true at present, damage due to flooding will be most severe when the surges strike during high tide.

Coastal ecosystem loss- As sea level rises, coastal ecosystems are subject to flooding, and in many cases cannot keep pace with rapidly rising sea level so are drowned. Because the existing equilibrium profile is often artificially maintained with levees, seawalls, and other means of "protection", the low-level ecosystems cannot migrate landward and can be lost completely in these cases. The resulting loss of hatcheries for coastal fisheries also had serious consequences regarding marine ecosystems.

Aquifer salinization- A significant fraction of world population relies on groundwater drawn from coastal aquifers for their fresh water supply. As sea level rises, the depth of the freshwater lens in the coastal zone is greatly reduced, leading to salinization of water supplies. In extreme cases exacerbated by overpumping, the aquifer may rapidly become unsuitable for drinking and even for irrigation.

Research Recommendations

It became clear at the conference that IPCC projections are limited by the lack of both observational data and quantitative understanding of the global hydrologic balance. It would appear that the uncertainties in sea level projections for the next 100 years have not greatly improved since the second IPCC assessment because the necessary observational and conceptual gaps have not been filled in the intervening years. Consequently, attention was paid at the conference to the identification of the few most critical areas in which focused research will provide the necessary insights to enhance the reliability of sea level projections.

After a number of presentations of research results pertaining to measurement, analysis and modelling of ice and other hydrologic budgets, and impacts & policy, the conference concluded with a session aimed at identifying the research priorities appropriate for addressing the key outstanding issues. Although we separate measurement, causes and impacts in the discussion below, the three are intimately related, and conference participants recognized the need for the research community to forge stronger links between these research areas.

• ***Measurement***

Tide Gauges- The tide gauge record is invaluable because of its longevity, despite the difference between records caused by local tectonics and postglacial rebound. With tide gauge stations tied to the Terrestrial Reference Frame using space geodetic techniques such as GPS, these records will provide an increasingly reliable means to monitor future sea level variations globally. Toward that end, it was determined that additional state-of-the-art tide gauges in the record-poor, but globally important southern ocean, will be critical to the coming years. While century-long records will not be available from new tide gauges for another century, geocentrically-referenced gauges will be of value immediately, as they will record not only relative sea level, but coastline epeirogeny as well.

Satellites- Global ocean surface height records from TOPEX-POSEIDON and other radar altimeters with greater high-latitude coverage (Geosat, ERS-1, and ERS-2) have provided a quantum leap in our ability to measure the topography of the global ocean, and even in the short time satellite altimetry has been operational and despite of the uncertainty of its accuracy at the level of less than 1 mm/yr (due primarily to instrument drift), a clear signal of sea level change has been recorded. This change is not globally uniform, but varies spatially depending on climate, ocean circulation patterns, and non-homogeneities in the changes in mixed layer thermal structure. Additional satellite altimeters with greater high-latitude coverage are operational or planned for the near future by NASA, the US Navy, CNES and ESA (e.g. GFO-1, JASON-1, ENVISAT), making the future bright for a global satellite observational network, *provided the satellites are indeed launched*, and the data become available. Radar altimeters can also measure large-scale elevation change for interiors of ice sheets. Spaceborne laser altimeter, IceSat, to be launched in 2001, is anticipated to enable the definitive determination of mass balance of the ice sheets, and thus their impact on sea level change. Advanced satellite gravity mapping missions, CHAMP, GRACE, and GOCE, to be launched by the middle of the next decade, will enable five-fold improvement of the mean gravity field (geoid) of the Earth, and will allow accurate measurements of mass redistribution of the Earth system components with a spatial scale of 300 km. GRACE is anticipated to be able to measure large-scale mass balance of the ice sheet, mass change of the hydrosphere and the ocean, to provide insights to the cause of the sea level change. The most critical need identified at the conference pertaining to satellite records was the need to continuous operation and thus records. Gaps in records can lead to uncertainties and errors in the time series of these critical observations. The high-latitude coverage is obtained by merging the ERS and GFO altimetry with the TOPEX/POSEIDON altimetry. It is recommended that these altimeter systems be calibrated and monitored for their respective instrument and geophysical and media correction drifts as well as their links to each other, using permanent calibration sites and island tide gauges, toward a consistent and long-term observation system for the long-term monitoring of global sea level change.

•Causes

Continental hydrologic budget- In what seemed at first as a surprising conclusion from a primarily oceanographic research community, the most critical need (highest priority) was identified as better quantification of the hydrologic budget of the continents. This need arises from the large and variable water flux between oceans and continental interiors, as well as the knowledge that these fluxes are being altered by land use and water resource utilization. A comprehensive data set is necessary for global information regarding river hydrographs, ground water levels, lake and reservoir levels, soil moisture, and land cover for at least the present time, and if possible for the last century as well. A few of these issues are beginning to be addressed through international research programs such as WCRP, IGBP and IHDP, but it is not clear that they have the necessary resources available for this major international task. Much of the necessary data already exist in a multitude of local, regional, and national archives, but the task of organizing and assembling these data into an integrated global data set is a major undertaking in itself, even before it is used to identify data gaps for future observational programs. As such, it is imperative that activities be initiated as soon as possible toward the end of a global hydrologic data base.

Ice budgets- The balance between increased melting as a result of atmospheric warming, and increased precipitation (as snow) in Antarctica plays a critical role in the global hydrologic budget. As such, research is needed in observation of ice accumulation rates on the basis of surface elevations, monitoring of meteorology in and around the southern ocean and coastal Antarctica, and modeling of the relationship of sea surface temperatures to Antarctic atmospheric circulation and precipitation patterns.

Ocean temperature- Because a major factor in modern sea level rise is the thermal expansion of the mixed layer, better monitoring of ocean temperature will increase our ability to assess the present and future contribution to sea level rise. While sea surface temperatures are monitored adequately, the thermal structure of the mixed layer over which we must integrate to determine its contribution to sea level rise, is very poorly known. As a result, IPCC projects must include broad scenarios with great uncertainty regarding this term. However, detailed gravity data may provide the necessary constraints to determine the density profile of the mixed layer. It was concluded at the conference that these should be collected and applied to the problem of shallow ocean density. On longer time scales, thermal structure of the deep ocean plays an increasingly imoprtant role.

Anthropogenic influences- With numerous mechanisms by which human activity directly transfers water between continental interiors and the ocean, it will not be possible to accurately account for past (20th century) sea level changes, nor to project future changes without some simple analysis of human intervention in the hydrologic cycle. Activities such as ground water mining, deforestation, and draining of wetlands contribute to sea level rise, while construction of new dams ameliorates sea level rise caused by other factors. In particular, the volume of water stored behind dams both as surface and ground water is poorly constrained, but may be significant. The latter half of the 20th century is the time period of the greatest rate of dam-building and water impoundment. It is also the time over which most tide gauge data is derived. Consequently, by impounding water at a significant rate globally, we be masking the sea level rise being caused by other factors. If the rate of new dam construction slows or stops, then we should expect the observed rate of sea level rise to increase accordingly in the 21st century, even if other factors remain unchanged from the 20th century. The magnitudes of the various anthropogenic effects is not reliably known, but can be readily assessed through simple observational and data compilation programs.

• ***Impacts***

The assessment of the impacts of sea level rise over the next century is hindered by a lack of knowledge of the detailed topography of the near shore. New global elevation maps based on detailed surveys at cm resolution will make it possible to accurately determine the areas which will be inundated by storm surges under conditions of rising sea level. This will require a concerted effort by the satellite altimetry community as well as local ground-based geodetic surveyors in all coastal areas world-wide.

The policy sector is most concerned with the impacts of sea level rise because they could have significant economic, social, and therefore political consequences. While environmentally logical and scientifically expedient solutions to sea level rise may include policies directed at "rolling easements", and other land use regulations, these might be considered Draconian measures by those landowners involved, and would thus be exceedingly difficult to enact locally. It was agreed at the conference, however, that the scientific commuity can contribute to teh porcess most effectively by placing assessments of flooding and storm damage risk into the context of the framework convention on climate change and should be an integral part of the IPCC process.

The issue of how involved the scientific community should become in the political process of national and international decision-making is complex and can lead to awkward situations for individual scientists as well as research organizations. Nevertheless, the application of scientific results to pressing current problems is a critical aspect of global change research that should not be skirted for fear of misinterpretation by the lay public and popular press. It was agreed at the conference that the sea level research community should make every reasonable effort to make research results available to the public and to the decision-makers within the policy sector. This must involve both publication in the popular press as well as involvement in IPCC and additional regional and local processes.

Summary of Research Recommendations

Measurement	**Causes**	**Impacts** Assessment	**Policy**
Satellites- continuity, high latitude coverage, GPS buoys, **Linked GPS-Tide Gauge system**	***Continental Hydrologic Budget***	***Coastal Zone Elevation*** (cm-scale resolution)	Scientific input into **IPCC** process
Tide Gauges- addition of new gauges in southern ocean (while mantaining existing gauges)	Ice Budgets		Community Position Statement on Sea Level
	Ocean Temperature Anthopogenic influences		

Agenda

3 October, 1999
Sunday

18:00 - 19:00 *Registration*

4 October, 1999
Monday a.m.

09:00 - 09:30 *Opening*

The hydrological cycle: What can we learn from sea level?
Chairperson: S. Zerbini

09:30 - 10:00 J.L. Chen, C.R. Wilson and B.D. Tapley
Hydrological contribution to global mean sea level change.

10:00 - 10:30 V. Klemes
Can the dynamics of global water balance cause sea-level anomalies?

10:30 - 11:00 *Break*

11:00 - 11:30 Mercier, F.
Interannual lake level changes and regional hydrology.

11:30 – 12:00 M. V. Bolgov
Climate change and water level fluctuations in inland water bodies

12:00- 14:00 *Lunch*

Mass balance of the ocean: Where are the largest uncertainties and how can they be reduced?
Chairperson: A. Cazenave

14:00 - 14:30 F. Remy, B. Legresy
Ice sheet mass balance from space techniques.

14:30-15:00 J. H. Zwally
Determination of interannual to decadal changes in ice sheet mass balance from satellite altimetry.

15:00-15:30 H.-P. Plag
What can we learn from sea level about changes in ice sheets?

15:30 – 16:00 M. Kuhn
The contribution of glaciers and small ice caps to sea level change

16:00 – 16:30 *Break*

Chairperson: H.P. Plag

16:30 – 17:00 R. Hohmann, P. Schlosser, A. Ludin, R. Weppernig
Excess Helium-4 in the Southern Ocean: a tracer for glacial melt water

17:00 – 17:30 W. R. Peltier
Global models of post-glacial sea level history: the role of ”implicit ice”.

17.30 – 18:00 D. Sahagian
Anthropogenic alterations of global hydrology and sea level.

18:00- 18:30 S. Cloetingh
Vertical motions of the lithospheric models and constraints.

20:30 *Dinner*

5 October, 1999
Tuesday a.m.

Sea-level observations: What are our present and future capabilities to observe changes and variability?
Chairperson: J. Zwally

09:00 – 09:30 A. Cazenave
Sea level change from satellite altimetry.

09:30 – 10:00 C. K. Shum, C. Y. Zhao, P. Woodworth
Determination and characterization of global mean sea level change.

10:00 - 10:30 A. Braun, A. Helm, M. Rentsch, T. Schoene
Calibration of ERS altimetric data in the Western Spitsbergen shelf through tide gauge data.

10:30 – 11:00 *Break*

Sea-level observations: What are our present and future capabilities to observe changes and variability?
Chairperson: W.R. Peltier

11:00 – 11:30 Richter B., S. Zerbini, M. Negusini, W. Schwahn, C. Romagnoli
Mean sea level and vertical crustal motions: an experiment in the Adriatic area.

11:30 – 12:00 R. Bingley, N. T. Penna, A. H. Dodson, V. Ashkenazi, T.F. Baker, S. J. Waugh, F. N. Teferle
GPS Monitoring vertical land movements at tide Gauges in the UK.

12:00 – 12.30 E. V. Stanev, E.L. Peneva. P.-Y. Le Traon
The recent changes of Black Sea level. Estimates from mariograph, altimeter and hydrological data.

12:30 – 14:30 *Lunch*

5 October, 1999
Tuesday p.m.

Sea-level observations: What are our present and future capabilities to observe changes and variability? (cont.)
Chairperson: C.K. Shum

14:30 – 15:00	W. Bosch The 1997 North Atlantic sea level anomaly.
15:00 – 15:30	P. Knudsen, O. B. Andersen Changes in sea level, sea surface temperature and atmospheric pressure from satellites.
15:30-16:00	K. van Onselen Detectability of sea level height variation patterns.
16:00 - 16:30	*Break*

Past Sea Levels
Chairperson: S. Cloetingh

16:30 – 17:00	O.K. Mason, W. Dupré Early Medieval (AD 700-1100) avulsion of the Yukon river delta: climatological control due to increased precipitation?
17:30 – 18:00	G. Di Donato, R. Sabadini, L.L.A. Vermeersen, A.M. Negredo, E. Carminati Multi-disciplinary approach to sea-level change in the Adriatic Sea and in the Po delta: insights from modeling and stratigraphic analysis.
18:00 – 18:30	N. Harvey, T. Belperio, B. Bourman Regional Variations in the Paleo sea-level record from Australia
18:30 – 19:00	A.O. Selivanov Spatial-temporal variability of sea-level changes on the coasts of Russia during the Late Pleistocene and Holocene: eustasy, tectonics or geoidal changes?
20:30	*Dinner*

October 6, 1999
Wednesday a. m.

Impacts of Sea Level Rise
Chairperson: D. Sahagian

9:30- 10:00	J. A. Lowe, J. M. Gregory Predicted changes in storm surge activity around the United Kingdom coastline in a future climate with increased greenhouse forcing.

10:00 - 10:30	D. Thomson Relative sea-level change and modelling the altered hydrology of a rapidly subsiding wetland.
10:30-11:00	*Break*
11:00 – 11:30	N.B. Bernier, K.R. Thompson, J. Bobanovic, H. Ritchie Modeling storm surges on the East coast of Canada: case studies and projected changes in flooding risk.
11:30 - 12:00	J. Titus The impacts, responses, and legal implications of rising sea level along the U.S. Atlantic and Gulf Coast: new maps and policies
12:00 – 14:00	*Lunch*

October 6, 1999
Wednesday p. m.

Predicting future relative sea-level variations: How do we proceed from global to regional scales?
Chairperson: J. Titus

14:00 – 14:30	S. F. Singer Will global warming raise sea levels?
14:30 – 15:00	J. A. Lowe, J. M. Gregory Natural inter-annual variability of sea surface height evaluated using a multi-century AOGCM simulation.
15:00– 15:30	J.M. Gregory, J.A. Lowe Global and regional sea-level rise predictions from the HADCM3 AOGCM.
15:30 – 16:00	J. M. Gregory, J.A. Church IPCC third assessment report on sea-level change 1900-2100.
16:00 - 16:30	*Break*
16:30 - 17:30	Chairs & The scientific organizing Committee *PANEL Discussion-* Where do we go from here? Future research priorities for the Sea Level community
17:30- 17:45	D. Sahagian Summary
17:45 - 18:00	Discussion and concluding remarks
20:30	*Cocktail and Gala Dinner*

Abstracts

MODELLING STORM SURGES ON THE EAST COAST OF CANADA: CASE STUDIES AND PROJECTED CHANGES IN FLOODING RISK

N.B. Bernier (1), K.R. Thompson(1), J. Bobanovic (1) and H. Ritchie (2)
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Concern over the serious economic consequences of increased coastal erosion and flooding under future climate scenarios has motivated our study of sea-level variations along the east coast of Canada. A particular focus is the damage associated with severe winter storms. Here we report on results from a 2-D barotropic ocean model driven by wind and pressure fields provided by the Atmospheric Environment Services of Canada. First, we verify that sea-level observations in the region agree with our model predictions. The numerical model is computationally expensive and so we also explore the use of a much simpler statistical model, for use in predictions. In this statistical model, we assumed that the sea-level variability is a linear combination of past and present meteorological fields, so that the sea-level variation could be expressed as a combination of those fields. This allows us to calculate site specific transfer functions between the meteorological forcing and sea-level response. The transfer functions can be used to predict efficiently variations in future sea-level variability based on predictions of future climate.

GPS MONITORING OF VERTICAL LAND MOVEMENTS AT TIDE GAUGES IN THE UK

R M Bingley (1), N T Penna (1), A H Dodson (1), V Ashkenazi (1), T F Baker (2), S J Waugh (1) and F N Teferle (1)
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Changes in mean sea level recorded by tide gauges are corrupted by land movements at the tide gauge sites, which can be of a similar order of magnitude. Since 1990, the IESSG and POL have carried out a series of projects related to the development of techniques for the application of GPS to monitoring vertical land movements at selected sites of the UK National Tide Gauge Network.
The initial projects were based on the use of episodic GPS campaigns. During the period from 1991 to 1996, sub-sets of a network of sixteen tide gauges were observed in a series of nine episodic GPS campaigns. In the latest project, a combination of continuous and episodic GPS measurements are being used. During 1997 and 1998, continuously operating GPS receivers were established at five of the tide gauges, and in 1999, a further set of episodic GPS measurements were made at the other tide gauges in the network. This paper will present the results and experiences from all of the episodic and continuous GPS observations that have been made at tide gauges in the UK.

CLIMATE CHANGE AND WATER LEVEL FLUCTUATIONS IN INLAND WATER BODIES.

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The regime of the water level of inland seas and lakes is a basic problem of hydrology. The anomalies of these processes have been insufficiently investigated. Predicting variations in the level of inland water bodies is importance for ecological forecasts and for validating measures associated with development of water resources. The hydrological regime of these water bodies depends both on natural processes (river runoff) and on the human impact. Abnormal level variations in inland water bodies have adverse effects on both the environment and on the economy of coastal and shore zones. For example, in the 1970s the significant drop in the level of the Caspian Sea greatly endangered biological productivity; at the present time, an increase in the water level is resulting in huge economic losses due to the submersion of settlements and industrial areas. The causes of abnormal variation in the hydrological regime of inland seas and lakes (Caspian etc.) during the last decades are investigated.

THE 1997 SEA SURFACE HEIGHT ANOMALY OF THE NORTH ATLANTIC SUBPOLAR GYRE

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For the period 1992-1998 Topex/Poseidon altimeter data is used to study the evolution of North Atlantic sea level anomalies relative to a long term mean sea level. Comparing the mean sea level with annual and seasonal mean fields an anomalous sea surface height feature can be significantly identified for the year 1997. The anomalous evolution becomes in particular clear when mean periodic oscillations of the sea surface are identified and removed. Variations in sea surface temperature (taken from AVHRR) and sea level pressure (from NCAR/NCEP) were analysed in parallel in order to investigate correlations between these data sets and to study the impact of the inverted barometer correction to the altimeter data. The observed anomaly was preceded by a drastic decrease of the NAO index in late 1996 and coincides with a salinity anomaly in the northern North Atlantic. The evolution of sea surface temperature anomalies is similar to that of the sea level anomalies. The temperature anomalies, however, appear as a precursor with a phase, about one months in advance.

CALIBRATION OF ERS ALTIMETRIC DATA IN THE WESTERN SPITSBERGEN SHELF THROUGH TIDE GAUGE DATA

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A sea level analysis using satellite altimetry requires very accurate data and up-to-date models of ionospheric, tropospheric and tidal effects. Beside this, other error sources like inaccurate orbit recovery and insufficient retracking algorithms for extreme conditions, e.g. strong winds or high waves, lead to the fact, that large errors still remain in the computed sea level. A comparison with in-situ data, e.g. from sea level analysis of tide gauges, is one possibility to improve our understanding of sea level change as seen by satellite altimetry. A comparison of tide gauge data in Ny- Alesund, Svalbard, with the ERS altimeter mission data over the last seven years was performed to calibrate the altimetry data. Although globally a sea level rise of about 2 mm/year is expected, a relative sea level fall of about 10 mm/year occurs in Svalbard, which is mainly a consequence of post-glacial rebound in Fennoscandia. The vertical motions in this region are obtained from GPS and VLBI measurements. The tide gauge data is available in hourly values, a wavelet analysis was performed to identify the main tidal periods. Trends of daily, weekly monthly and yearly means were evaluated to investigate the temporal evolution of the tide gauge values. The remaining differences between the altimetric data and the tide gauge data will be presented and future requirements for processing altimetric data for sea level studies will be discussed.

SEA LEVEL CHANGE FROM SATELLITE ALTIMETRY

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Satellite altimetry, operational since the begining of the 90s, appears as a new tool for monitoring the ëtrueí volume and mass change of the oceans in response to climate changes. Satellite altimetry provides indeed precise sea level measurements in a terrestrial reference frame tied to the Earthís center of mass, with a high spatio-temporal coverage. Analysis of altimetry data from the Topex-Poseidon mission indicates a global mean sea level rise of 2 mm/yr since early 1993. Geographical distributions, and global averages as well, of sea level and sea surface temperature trends over 1993-1998 are highly correlated, which suggests that at least part of the observed interannual sea level change has a steric (thermal) origin. At the level of 1 mm/yr however, several factors due to instrumental drifts or non-modeled effects in the altimetric system may still affect sea level trend estimates. Comparisons performed between Topex-Poseidon-based and tide gauge-based sea level change, have allowed the detection of instrumental drifts onboard the Topex-Poseidon satellite, demonstrating the interest of tide gauge measurements for the calibration of current altimetry missions. However tide gauge-based sea level measurements are made relative to the land, hence are contaminated by vertical crustal movements. It is thus of primary importance to monitor vertical crustal motions at tide gauge sites with space geodesy positioning systems.
At the annual frequency, Topex-Poseidon has detected a mean sea level variation of 4 mm amplitude, maximum in autumn. This oscillation results from the combined effects of the thermal expansion of the sea waters and exchange of water with the atmosphere and continents. The steric contribution has an amplitude of 5 mm and is maximum in spring, i.e., in out of phase with the observed mean sea level. Removing the steric contribution thus produces an annual sea level fluctuation of 9 mm amplitude, maximum in autumn, which may result from changes in the mass content of the oceans. Estimate of the annual changes of the atmospheric water vapor content, snow depth and coverage, and continental soil moisture leads to an equivalent sea level change of 8 mm amplitude, almost in phase with the Topex-Poseidon minus steric sea level. This result shows that it is possible to nearly close the total seasonal water budget and confirms that at this time scale, the Greenland and Antarctica mass balances are nearly in equilibrium .

HYDROLOGICAL CONTRIBUTION TO GLOBAL MEAN SEA LEVEL CHANGE

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Analysis of TOPEX/Poseidon satellite altimeter data indicates that the global mean sea level variation has a clear seasonal signal with an amplitude of about 2 to 3 mm, along with a long term drift. This seasonal variation is associated with mass redistribution within the global hydrological cycle plus steric thermal contributions. We investigate seasonal variations of water vapor in the atmosphere and water storage on land using both assimilated atmospheric models and climatological data, and to estimate the corresponding global mean sea level changes. The predicted seasonal global mean sea level changes are then compared with the seasonal variabilities observed by TOPEX/Poseidon altimetry data, after the latter are corrected for the steric effect using a simplified thermal model derived from the NOAA World Ocean Atlas 1994 and space-measured sea surface temperature data. The good agreement in both amplitude and phase between TOPEX/Poseidon observation and hydrological model prediction indicates that the TOPEX/Poseidon altimeter may provide key information for the global water mass budget by placing observational constraints on the mass budget variations predicted by global atmospheric and hydrological models.

MULTI-DISCIPLINARY APPROACH TO SEA-LEVEL CHANGE IN THE ADRIATIC SEA AND IN THE PO DELTA: INSIGHTS FROM MODELLING AND STRATIGRAPHIC ANALYSIS

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Present day sea-level changes in the Adriatic sea are the result of the superposition of natural and anthropogenic vertical movements. Geophysical modelling of the tectonic mechanisms active in the central Mediterranean and of post-glacial rebound allows us to establish the contributions of such processes to sea-level changes. Along the eastern part of the Italian peninsula, the comparable effects of tectonic subsidence and post-glacial rebound sum up to a total sea-level increase as high as 1 mm/yr. Inferences on the effects of sediment load and sediment compaction on the vertical motions are obtained from stratigraphic data (commercial wells and seismic lines). The sum of all of these terms constitutes the natural component of sea-level change. The obtained values are quite consistent with the sea-level changes inferred from archeological data which, being averaged over the last 2000 years, can be considered negligibly influenced by anthropogenic factors. The anthropogenic component of sea-level change can be inferred by comparison between the total natural vertical velocities we calculate and vertical velocities obtained from other data sets. An application is proposed using tide gauge records from Venice and Ravenna.

IPCC THIRD ASSESSMENT REPORT ON SEA-LEVEL CHANGE 1900--2100

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Coupled atmosphere--ocean general circulation models (AOGCMs) are the main tools used for prediction of time-dependent climate change during the 21st century. Results for sea-level change derived from several AOGCMs have been made available for the IPCC Third Assessment Report, enabling comparisons to be made between models and with observations. The current rate of global average sea-level rise can be accounted for, when allowance is made for the large uncertainties. Thermal expansion is probably a larger contributor to eustatic change than loss of mass from mountain glaciers. Over the next hundred years, the predictions indicate that thermal expansion will be the dominant term; estimates of the global average change have a central value of about 0.5 m, as in the Second Assessment Report. All AOGCMs indicate substantial geographical variation in sea-level change, principally because of the non-uniformity of heat uptake and thermal expansivity; changes in salinity, wind-stress, ocean circulation and atmospheric pressure also have an influence. Local eustatic change can be at least 50% greater than the global average. The models do not agree well on the detail of geographical patterns, but do show some similarities on large scales.

GLOBAL AND REGIONAL SEA LEVEL RISE PREDICTIONS FROM THE HADCM3 AOGCM

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The recent availability of high-quality sea surface altimeter data offers an opportunity for a new kind of evaluation of coupled atmosphere--ocean general circulation models (AOGCMs). Comparison with TOPEX/POSEIDON data shows that the geographical distribution of mean sea surface height relative to the geoid, which reflects the density and current structures of the ocean, is well simulated by the HadCM2 and HadCM3 AOGCMs. HadCM2 has a spatial resolution of 2.5° X 3.75°, and has been widely used as a basis for global and regional climate change prediction. HadCM3 is a newly developed model having a higher spatial resolution of 1.25° X 1.25°, which permits an improved simulation of ocean currents and heat transports. The annual cycle of sea surface height shows maxima in northern and southern mid-latitudes in autumn; the geographical distribution of the phase of the cycle is in excellent agreement with observations, and the amplitude is reasonable. This gives confidence in the simulation of surface flux variations in seasonal time scales. The annual cycle of both the steric and the hydrological components of global average sea level is also consistent with observationally based estimates.

REGIONAL VARIATIONS IN THE PALEO SEA-LEVEL RECORD FROM AUSTRALIA

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Geological data from Australia provide evidence of Late Quaternary climatic and associated sea-level fluctuations from a number of different regions. Studies in South Australia provide evidence of Late Quaternary high sea-level stands associated with Oxygen Isotope stages 1 to 19, with the most comprehensive data for the last interglacial high sea-level stand. Well defined geological data also exist for interstadial events during the last glacial (Oxygen Isotope stages 3, 5a and 5c) and for the Holocene postglacial sea-level rise, primarily from the marine and inter-tidal sediments of the South Australian gulfs. Against this backdrop, investigations have been conducted to determine regional variations in the Holocene sea-level curve. This paper describes paleo sea-level studies from prograding coastal sediments adjacent to historic tide-gauge sites in South Australia. These sites are of interest given significant differences in mean sea-level trends between the sites which suggest geological influences on the tide-gauge data. Geological investigations using vibrocoring and backhoe excavation techniques identified paleo-sea-level indicators within the sediments. All sites were accurately levelled to determine the position of the paleo sea-level indicators relative to their modern counterparts. The dominant indicators were the boundaries between the sub-tidal seagrass (Posidonia) facies and the inter-tidal sand flat facies; between the sand flat facies and the mangrove (Avicennia marina) facies; and between the mangrove facies and the samphire (Halosarcia-Sarcocornia andSclerostegia-Halosarcia) marsh facies. Sediments from these boundaries were sampled and radiocarbon dated to produce sea-level curves. Results indicate a variation in the

dominance of paleo-sea level indicators at different sites. The data also reveal the influence of both postglacial hydroisostatic warping of the shelf and anthropogenic influences. The paper draws conclusions on the implications of this regional study within the broader context of both Australian mean sea-level trends, as derived from historic tide-gauge data, and the emerging pattern of coastal response to the Holocene sea-level transgression in Australia.

EXCESS HELIUM-4 IN THE SOUTHERN OCEAN: A TRACER FOR GLACIAL MELT WATER

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The ice shelves surrounding Antarctica contain about 10% air by volume. During the melting of the glacial ice a significant fraction of this trapped air is dissolved in the sea water. Helium has the lowest solubility among the gases contained in air and, therefore, the meltwater is highly supersaturated in helium. The He signal imprinted by addition of glacial meltwater can be detected in large portions of the shelf region of the Southern Ocean and can be correlated to the volume of melted glacial ice. Excess 4He data were collected from transects in the shelf region extending from the eastern Ross Sea to the southwest coast of the Antarctic peninsula. Due to the prevailing wind direction, this region is covered with sea ice most of the year and, therefore, gas exchange between the ocean and the atmosphere is to a large extent suppressed. Particularly large 4He concentrations are observed in the upper 500 m on the shelf. The inventory of 4He with local meltwater origin south of 70∞S is approximately 1012 ccSTP. With an assumed air content of ice of 0.12 ccSTP/g, this inventory represents a total amount of glacial meltwater of 1500 Gt. With an average residence time of the shelfwater of 2.5 years, the 4He data suggest an annual melting rate of approximately 600 Gt/yr (0.02 Sv).

CAN THE DYNAMICS OF GLOBAL WATER BALANCE CAUSE SEA-LEVEL ANOMALIES?

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The time change in the ocean mass, $z(t)$, is the result of the integration over a time period $(t\text{-}t_0)$ of the difference between the water inputs, $x(t)$, and outputs, $y(t)$, so that

$$z(t) = z\,t_0 + \int_{t_0}^{t} [x(\tau) - y(\tau)]\, d\tau$$

and the sea level, $h(t)=f[z(t)]$, is a cumulative process in t.
One of the peculiar properties of cumulative processes (studied by Slutzky, Yule, Feller and others) is that their traces may display quasi-periodic and cyclic properties even when their forcing functions $x(t)$ or $y(t)$ are random. It has been shown (Klemes and Klemes, Water Resources Research, 24, 1, 93-104, 1988) that the periodic pattern becomes more regular as the order of the cumulative process increases and, in certain circumstances, it fast (in orders 3 to 4) converges to a pure sine wave over the sample size. The above reference shows examples of this effect on the mass of glaciers, lake levels and streamflow. The purpose of this presentation is to explore the question whether it might play a role in some quasi-regular patterns in sea-level fluctuations, either directly through the water balance of the ocean reservoir or indirectly through higher order effects of the dynamics of the polar ice mass balance or of the ocean heat balance.

CHANGES IN SEA LEVEL, SEA SURFACE TEMPERATURE AND ATMOSPHERIC PRESSURE FROM SATELLITES

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In studies of Global Change, sea surface temperature data may provide valuable information. Global sea surface temperature data may indicate changes in the heat budget of the oceans. Five years of sea surface temperature data and sea level height for the same period is analysed. Altimetry from the TOPEX/POSEIDON satellite will be used along pressure observations provided in the T/P records and low resolution averaged sea surface temperature data from the ATSR 1 and 2 sensor onboard the ERS satellites and AVHRR data from the NOAA satellites.
The global and regional characteristics of the sea level trends and the trends in the sea surface temperature as well as trends in the atmospheric pressure during 1992-1997 are investigated. The changes in the sea level are compared with changes in sea surface temperature to decide whether the changes in sea level are related to changes in the heat content of the ocean. Spatial and temporal correlation between the signals are investigated, and a bivariate coherency analysis of the sea level together with the sea surface temperature is carried out at different spatial scales.

THE CONTRIBUTION OF GLACIERS AND SMALL ICE CAPS TO SEA LEVEL CHANGE

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Although glaciers and small ice caps have a total area of less than 5 percent of the Antarctic and Greenland ice sheets they are believed to have contributed about one third of the sea level rise of the past 100 years. This paper summarizes the advances that have been made in calculating the meltwater of glaciers and small ice caps since the Second Assessment Report of the IPCC. Latest estimates of global glacier mass balance are based on individual treatment of up to 100 regions and use local precipitation or GCM-produced energy and accumulation values. They indicate a present contribution of glaciers of 0.2 to 0.4 mm per year to global sea level rise.

NATURAL INTER-ANNUAL VARIABILITY OF SEA SURFACE HEIGHT EVALUATED USING A MULTI-CENTURY AOGCM SIMULATION

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Sea surface height varies on a wide range of temporal and spatial scales. A quantitative understanding of the patterns of natural (internally generated) sea surface height variability is necessary in order to assess the significance of potential anthropogenic changes in sea-level.
In this study, sea surface height variability on time scales longer than 1 year has been calculated from multi-century simulations of the pre-industrial climate system made using the Hadley Centre Atmosphere-Ocean general circulation models (AOGCM). Results from two versions of this model are presented. The versions differ in the resolution of their ocean components, their use of flux corrections, and their parameterisation of the transport of heat within the ocean. Spectral decomposition has been used to discern the frequencies of the dominant modes of oscillation.
The variance of the modelled sea surface height is found to be spatially inhomogeneous; the magnitude of the variance at some locations is an order of magnitude greater than the global mean value. The patterns of sea surface height variance will be compared with results from the TOPEX/Poseidon altimeter and the implications of the results for the detection of a sea-level change signal on global and region scales will be discussed.

PREDICTED CHANGES IN STORM SURGE ACTIVITY AROUND THE UNITED KINGDOM COASTLINE IN A FUTURE CLIMATE WITH INCREASED GREENHOUSE FORCING

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A potential consequence of climate change is an alteration of the frequency of extreme coastal storm surge events. It is these extreme events which, from an impacts point of view, may be of more concern than the slow inundation of coastal areas by century scale changes in mean sea level.
In this study, a 35 km resolution storm surge model of the North Sea shelf region has been driven by winds and pressures predicted by the Hadley Centre nested regional climate model. Simulations of both present day and future climate (the end of the 21st century) have been performed; the effects of predicted changes in weather and mean sea-level have been investigated.
Results suggest that the return periods of extreme storm surge events around the United Kingdom coastline decrease with increases in mean sea-level. At most locations, changes in local meteorology lead to further changes in the return periods. The statistical significance of the predicted changes in storm surge occurrence will be discussed.

EARLY MEDIEVAL (AD 700-1100) AVULSION OF THE YUKON RIVER DELTA: CLIMATOLOGICAL CONTROL DUE TO INCREASED PRECIPITATION?

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Hydrological input into the Yukon River is predominantly nival, consisting of both seasonal snow melt and melting glacial ice. Although meteorological floods can simultaneously affect extensive areas of the river, localized ice-jam floods during break-up introduce anomalies that may preclude the reconstruction of basin-wide flood history. Yukon Delta cutbanks record flood history and the river's interaction with sea and storm level changes; its chenier plain witnessed storm ridge addition before 1500 BC associated with eustatic sea level in the adjacent Bering Sea at –1.5 m below present. The Yukon-Kuskokwim (YK) delta consists of several sub-lobes, formed as deposition shifted northeastward, from the Black River lobe active 2500 BC-500 BC, to the present lobe formed since 2000 BP. Limiting ages indicate that a major avulsion in the Yukon Delta occurred in the late 1st millennium AD and led to the formation of a new lobe. This avulsion was contemporaneous with erosional truncation within beach ridge complexes throughout west and northwest Alaska. Limited sea level data indicate a 50 cm drop in eustatic sea level as well. Correlations with regional (alluvial, tree ring, glacial advances), as well as global records from Greenland ice cores, and the Nile and East Asian rivers favor a climatic cause.

INTERANNUAL LAKE LEVEL CHANGES AND REGIONAL HYDROLOGY

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Topex/Poseidon and ERS-1 altimeters were primarily designed to measure height of the sea surface. Nevertheless, we can also use satellite altimetry to investigate level changes of continental lakes. We use 6 years of Topex/Poseidon altimetry data to study level changes of African Lakes. We also analyse the ERS-1 Waveform Altimeter Product raw data set to produce lake level time series. Due to its shorter intertrack spacing, ERS-1 provides a much denser coverage of lakes than Topex/Poseidon. When avalaible, in situ lake level measurements are compared with altimetric time series.

In this analysis, we focus on the seasonal and interannual fluctuations of lake levels. Using available regional hydrometeorological data, we further study the water balance over each lake catchment basin. On the annual time-scale, we show a clear correlation between lake level and precipitation fluctuations while on the interannual time-scale, regional as well as global climatic changes are invoked.

GLOBAL MODELS OF POSTGLACIAL SEA LEVEL HISTORY: THE ROLE OF "IMPLICIT ICE"

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The gravitationally self-consistent global theory of postglacial relative sea level history, which includes the impact upon rsl of both the viscoelastic deformation of the solid earth and the variations of both the surface ice and water loads that induce this deformation, involves the solution of an integral equation that I have previously referred to as the Sea Level Equation. The inputs required to enable rsl predictions to be made with this theory include a space-time model of ice thickness variations (i.e. a model of the glaciation-deglaciation process) and a model of the internal viscoelasticity of the earth. Recently published analyses (Peltier, 1998, GRL, 25, 3057-3960) based upon the topographically self consistent form of this theory (Peltier, 1994, Science, 265,195-201) demonstrate that the requirement of surface mass balance serves to define an "implicit" component of the ice load that arises due to a nonperturbative effect in the linear theory based integral sea level equation. This concept fully resolves a previously revealed mass balance discrepancy and has important implications concerning the action of the cryosphere in the hydrological cycle. A very preliminary discussion of these ideas was provided in a recent review (Peltier, 1998, Rev. Geophys., 6, 603-689) but will be much more fully developed in this presentation.

WHAT CAN WE LEARN FROM SEA LEVEL ABOUT CHANGES IN ICE SHEETS?

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Global ocean volume (GOV) and mass (GOM) characterize the ocean as a reservoir in the global hydrological cycle. These two quantities are absolute numbers, which have a rather complex relationship with local relative sea level (RSL) measured by tide gauges. On climatological time scales, the cryosphere has the greatest potential to contribute to changes in GOM, with the relation between these GOM changes and RSL being described by the sea-level equation. Thermal expansion is generally considered as a major contributor to GOV changes, with the resulting RSL changes depending on where heat is being absorbed in ocean water or released. Despite the complex relationship between RSL and GOM/GOV, observations of coastal RSL have been used repeatedly to obtain estimates of a global sea-level rise (GSLR) in a simple arithmetic way, correcting the local RSL trends only for effects of post-glacial rebound. The GSLR estimates have then been taken as constraints for GOV and/or GOM changes. In a different approach, here the physical relationship between mass changes in the cryosphere and resulting sea-level changes is used to invert the RSL trends for changes in the Antarctic and Greenland ice sheets. In a first step, the finger-prints of these two large ice sheets in sea level are fitted to the trends for all available tide gauges to determine average rates of the present-day mass changes in the Greenland and Antarctic ice sheets. A basic uncertainty in this inversion is found to be due to deficiencies in the post-glacial rebound models used to correct for the contribution of past mass changes. However, the results indicate a significant difference in the mass changes of the Antarctic and Greenland ice sheets.

ICE SHEET MASS BALANCE FROM SPACE TECHNICS

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Each year, the equivalent of 6 mm of sea level falls in Antarctica or Greenland. About the same quantity is rejected either via icebergs or via melting. The exact mass balance is unknown: we do not know even if it is positive or negative. Any space sensors is able to look for long term evolution of the ice sheet surface, but only the radar altimetrer is able to estimate volume change and thus the contribution of ice sheet to sea level change. We will show results from the comparison between Seasat and ERS altimeters above Antarctica and from 6 years of Topex above Greenland. The comparison between Seasat and ERS suggests that the Antarctica ice sheet is not in balance: the signature of topographic changes seems to be due to a dynamic answer associated with sea-level rise at the end of the last glaciation. The 6 years of
dual-frequency altimeter Topex above Greenland also suggest an imbalance mostly due to atmospheric changes.

MEAN SEA LEVEL AND VERTICAL CRUSTAL MOTIONS: AN EXPERIMENT IN THE ADRIATIC AREA

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To properly determine and understand sea-level fluctuations, it is necessary to measure vertical crustal motions at tide gauge stations. Within the many research activities of the EU SELF II project, an experiment was designed and initiated in order to optimize the GPS and gravity observation strategies for a cost-effective determination of height changes and to assess the time variability of gravity related to environmental effects.
In this experiment two GPS receivers have been installed at the Medicina and Port Corsini stations. Medicina is a fiducial reference site near Bologna, while at Port Corsini, located on the Adriatic coast near the city of Ravenna, a tide gauge of the Italian national network is operational. At both stations continuous GPS observations are being performed since three years and relevant meteorological parameters such as air pressure, temperature, relative humidity and precipitation data are also collected on a continuous basis. In addition, at Medicina continuous observations of water table are being recorded. At Medicina, a superconducting gravimeter has been installed since two and half years to monitor variations of the gravity field continuously. This ensemble of different observational capacities establishes a powerful example of an integrated multipurpose network for global change research.
The analysis and interpretation of both the GPS and gravity data collected so far at Medicina made it possible to identify clear common signals. In the period June-November 1997 the gravity data show a remarkable increase of about 6 (Gal in correspondence to a significantly increased scatter in the GPS height time series (6 mm rms compared to 4 mm rms prior and after the mentioned period). Starting September 1997, both time series exhibit a marked annual signal with a phase difference of about 45 days, where gravity anticipates the surface effects recorded by GPS. A non-tidal semiannual signal is present as well in both time series with a similar phase difference. Episodic gravity and GPS height fluctuations seem to correlate as well. Both gravity and GPS data series indicate the presence of subsidence in the order of 2-to-3 mm/yr which is confirmed by the latest VLBI solutions referring to 10 years of data. These findings will be interpreted on the basis of the present knowledge of the geology, geophysics, atmosphere and hydrology of the area, not withstanding the possible response of the site to climate change forcing and variability. In particular, thermoelastic effects

should be investigated in conjunction with the observed periodic signals, and potential tectonic influences connected with active crustal deformations and seismic sequences of both distant (Umbria region, September-October 1997) and more local (Reggio-Emilia area, second half of 1997) earthquakes as regards the observed anomalous behavior during the second half of 1997.
The analysis of the Port Corsini GPS data identifies a subsidence rate of 7.7 mm/yr which is in excellent agreement with the results provided by high-precision leveling measurements performed in the period 1992-1999. If this subsidence rate is accounted for when estimating the sea-level variation from the Port Corsini tide gauge data for the 1993-1997 time interval, a good agreement is found with the sea-level rate estimated by Cazenave et al. (1999) from the Topex data for the northern Adriatic.

ANTHROPOGENIC ALTERATIONS OF GLOBAL HYDROLOGY AND SEA LEVEL

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The influence of human activity on the hydrologic cycle has reached the point where it affects the hydrologic balance between ocean and continental storage reservoirs. Land use changes associated with expanding agriculture to support an increasing human population have already had a profound influence on basin-scale hydrology, and in extreme cases, on regional climate. Major human activities which lead to hydrologic alterations include irrigation (from ground water mining and surface water diversion), deforestation, wetland filling or drainage, and new dam construction. With the exception of the latter, these all contribute to the transfer of water from the continents to the ocean and a reduction of continental water resources. However, water impoundment behind dams may partially or completely counteract the cumulative effect of the others. Present compilations of reservoirs impounded by dams include only the results of major engineering projects. Smaller impoundments have largely been ignored. The cumulative volume of the literally millions of small reservoirs such as farm ponds and rice paddies may approach that of the larger documented reservoirs. Unfortunately it is not practical to make a global inventory of millions of small and unregistered reservoirs, so their volume may never be known precisely. The quantity of water stored in artifically raised water tables behind dams has also not yet been addressed. The issue of water impoundment or release from continental drainage basins affects global sea level. Recent estimates based solely on major dammed reservoirs suggest that if new dam construction is not maintained at the rates of the 1960s through 1980s, the rate of sea level rise could increase by about half a millimeter per year. If the water stored in small impoundments and ground water is taken into account, this figure could be much greater.

SPATIAL-TEMPORAL VARIBILITY OF SEA-LEVEL CHANGES ON THE COASTS OF RUSSIA DURING THE LATE PLEISTOCENE AND HOLOCENE: EUSTASY, TECTONICS OR GEOIDAL CHANGES?

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During the Late Pleistocene and Holocene (the last 120-130 Kyrs) drastic sea-level changes of over 100 m in an amplitude changes occurred. The primary factor of these large-scale sea-level changes was glacioeustatic one. However, sea-level changes indicated by ancient coastlines in various coastal areas differed much from each other. In many cases these differences are apparent and resulted from the subsequent tectonic deformations. However, our analysis demonstrated obviously a close correlation between ancient coastlines elevations/depths and recent geoidal anomalies. It appeared that the gravitational field of the Earth expressed in anomalies of geoidal surface relatively to the hydrostatic spheroid was similar to the present one during the early Late Pleistocene interglacial (130-80 Kyrs B.P.), whereas in the middle of the Late Pleistocene, 40-30 Kyrs B.P., positive and negative anomalies of the geoidal surface were 30-40% less expressed than now and the general shape of the Earth's surface was approximately half closer to the hydrostatically equilibrium one. The range of geoidal changes in the relative sea level during the last 100 Kyrs could be as high as 50-100 m thus comparable to the direct glacioeustatic changes. Geoidal-induced sea-level changes were clearly pronounced on the coasts of Russia in the Lateglacial and Postglacial time.

DETERMINATION AND CHARACTERIZATION OF GLOBAL MEAN SEA LEVEL CHANGE

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Recent studies of global sea level change have concluded that the global eustatic rate of sea level rise during the last century has been 1-2 mm/yr [Warrick et al., 1993]. Although there is no firm evidence of an acceleration in the rate of sea level rise over this time period [Woodworth, 1990], the projected future sea level rise is 13 +/- 4 cm during the next 40 years (1987-2027), and 61 cm over the next 100 years (1987-2087) [Woodworth, 1995]. Sea level change represents consequences of complicated interactions of the solid Earth-atmosphere-hydrosphere-ocean-cryosphere system and in part forced by human-originated greenhouse effect. Current long-term (40-100 years) sea level change estimates (e.g., IPCC studies) are primarily provided by long-term tide gauges located near coastal regions and continental margins. The estimate has deficiencies from vertical land movements (e.g., due to postglacial rebound and local land motion) and the associated vertical datum knowledge, and the fact that the data only covers less than 5% of the global ocean. Satellite radar altimetry missions, both historic and current (Geos-3, Seasat, Geosat, ERS-1, TOPEX/POSEIDON, ERS-2, GFO-1, and future (Envisat, Jason-1, NPOESS), would provide global coverage but has much shorter data span (less than 10 years of continuous data), and lack of adequate knowledge of the respective instrument biases. In this study, we will provide an analysis of the present-day global mean sea level change using multiple mission altimeter measurements and tide gauge data. Second part of the study is intended to provide a characterization of the sea level change by using modern observations, including global sea surface temperature (spaceborne and in situ), ice extents, postglacial rebound models, glacier and ice sheet mass balance data, and the potential use of future gravity change mapping mission, such as GRACE.

WILL GLOBAL WARMING RAISE SEA LEVELS?

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Global sea level (SL) has undergone a rising trend, averaging about 1.8 mm per year for at least a century (Figure 1) [1], and probably much longer. Its cause appears to be unrelated to decadalscale climate fluctuations; it may be a consequence of the millennial-scale warming that began about 15,000 years ago. This argument is strengthened when we note that all climate-related factors together can account only for about 20 percent of the observed rise since 1990 (Figure 2). We observe, furthermore, that departures (anomalies) from a linear SL rise during 1905-1975 show a pronounced inverse correlation with global average temperature (GAT) -- and even more so with tropical average sea surface temperature (TASST) (Figure 3). These findings suggest that --

under current conditions -- evaporation from the sea surface with subsequent deposition on the polar ice caps, principally in the Antarctic, produces negative changes in SL that outweigh increases from the melting of mountain glaciers and the thermal expansion of ocean water. It is likely, therefore, that any future moderate warming -- from whatever cause -- will also slow down the ongoing SL rise of 18 cm per century, rather than speed it up. Theoretical studies of precipitation increases in the Polar Regions [2] and results from General Circulation Models (GCMs) [3, 4, 5] support this conclusion. Further support comes from the (albeit limited) record of annual ice accumulation in polar ice caps [6, 7].

THE RECENT CHANGES OF THE BLACK SEA LEVEL. ESTIMATES FROM MARIOGRAPH, ALTIMETER AND HYDROLOGICAL DATA

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The sensitivity of Black Sea level variations to hydrological cycle is extremely strong since the ratio between fresh water flux and the volume of the sea is relatively large value in comparison to other semi-enclosed seas. The well-constrained water balance of this sea makes possible to produce accurate estimates of the fluxes. In the present paper we analyze TOPEX/POSEIDON altimeter data in the Black Sea in parallel with available hydrological and meteorological data with the aim to study the water balance and the dependency of sea level oscillations on meteorological and hydrological forcing. The consistency between satellite and pegel data is also analyzed. It is proved that using altimeter data can contribute to improving water balance estimates at seasonal and inter-annual time scales. The main focus is on the observed variability in the last 70 years. The relationship between the amplitude of seasonal oscillations of mean sea level (about 10 cm) and fresh water fluxes is quantified. This is very important to understanding the mechanisms of circulation and water mass formation in the interconnected system Black Sea-Mediterranean Sea.

RELATIVE SEA-LEVEL CHANGE AND MODELING THE ALTERED HYDROLOGY OF A RAPIDLY SUBSIDING WETLAND

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Alluvial floodplains are some of the most productive regions in the world. Rivers feeding these systems collect and concentrate nutrients from their watersheds which drives increased production in associated systems. Their productivity is attractive, however the dynamics of these systems are not conducive to human settlement and were subsequently altered to make them more habitable. Alteration has removed the source of their long-term productivity and in some cases jeopardized their existence. Both the nature and importance of these systems makes them a focal point for studying the land-sea interface. By nature, alluvial floodplains are transient structures that interact strongly with sea-level changes. For millennia, the Mississippi River and the Gulf of Mexico restructured this region (Mississippi River Deltaic Plain). Now control structures alter the riverís load and force most of what is left off the continental shelf. Restoration seems unlikely, sea-level changes and natural subsidence are no longer offset by riverine sediment deposition, and it is believed that there will be 50% less land in Louisianaís coastal zone by the year 2050. Implications for the Pontchartrain Estuary (Southeastern Louisiana) are similar in the long term but currently the estuary seems more influenced by runoff than by the Gulf of Mexico. Drought years have led to increased salinity throughout the estuary and alterations to community structure in primary producers that are the major contributors to vertical accretion in areas isolated from sediment deposition.

THE IMPACTS, RESPONSES, AND LEGAL IMPLICATIONS OF RISING SEA LEVEL ALONG THE U.S. ATLANTIC AND GULF COAST: NEW MAPS AND NEW POLICIES

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Along most of the U.S. coast, sea level is rising and shores are retreating. Increasing concentrations of carbon dioxide and other greenhouse gases are expected to accelerate the rate at which the sea rises, with a two-foot rise likely in the next century and a much larger rise possible. Given current land use and shore protection policies, a large-scale loss of sandy estuarine beaches, wetland shores, and very shallow water habitats is likely. Fortunately, environmental policies could be developed to enable these ecosystems to survive rising sea level. Unfortunately, those policies are not currently being implemented outside of a few states, and society is missing an opportunity to inexpensively safeguard the coastal environment.

Ocean beaches are more likely to survive sea level rise than the bay shores. There is a strong constituency to protect public uses of ocean beaches. The common technology for holding back the sea along ocean shores (beach nourishment) does not destroy the beach. Private seawalls along the ocean are much more expensive than the bulkheads necessary to hold back a bay. Finally, existing policies to protect natural shores such as setbacks and bulkhead prohibitions generally only apply to ocean shores.

This paper focuses on land use measures for ensuring the survival of bay shores in the face of coastal erosion and rising sea level. Unlike coastal engineering projects which often can only be implemented at a scale of tens of millions of dollars, these measures can be implemented by counties, borough, towns, and private property owners interested in protecting natural shores in perpetuity. We also present maps based on the use of USGS digital elevation model data.

Causes of Sea Level Rise. Tidal gauge measurements show that sea level is rising about 2.5-3 mm/yr along most of the Atlantic and Gulf Coast. About 50% of this rise can be explained by land subsidence in these areas, 10% from a retreat of alpine glaciers, and 5-15% from the warming and resulting expansion of the ocean; th remaining 25-35% is unexplained. EPA projects that global warming could raise sea level 50-60 cm along most of the U.S. coast in the next century, with a 5% chance that the rise could be greater than 100 cm.

For purposed of this conference, one issue worth flagging is the distinction between global and relative sea level rise projections. Many impact studies of global warming either assume that relative sea level rise will equal IPCC-projected global sea level rise, or calculate relative sea level rise as equal to IPCC-projections plus a local subsidence component estimated as historic relative sea level rise minus an estimate of global sea level rise. The problem with that approach is that it fails to deal with the fact that IPCC (and other) model runs estimate that climate change only added 5-10 cm to sea level in the last century, whereas the data suggests that the rise was closer to 20 cm. The IPCC low scenario projects that greenhouse gases will contribute1.8 mm/yr to sea level, an acceleration compared with the 0.5 mm/yr historic contribution–but a deceleration compared with the measured contribution. Therefore, we are left with the absurd situation in which people analyzing the impacts of the low scenario would assume that sea level will decelerate in the next century, even though the model on which they are relying assumes acceleration! (Of course, if one genuinely believes that the historic discrepancy between models and data resulted from unusual random fluctuations that had nothing to do with global warming and that will not be repeated in the next century, then this approach is reasonable.) The EPA reports on the Probability of Sea Level Rise employ an alternative procedure: use the models to estimate the projected acceleration of sea level due to climate change, and then add that to the current trend in relative sea level. This approach avoids the forgoing inconsistency problem.

Inundation of Low Lands. Rising seas tend to inundate low land, erode wetlands and beaches, increase coastal flooding, and increase the salinity of aquifers and estuaries. Previous assessments have estimated that a 50-100 cm rise would inundate 9000-18000 square miles of land, and that it would cost $100-500 billion to hold back the sea and protect developed areas. Only recently, however, has EPA developed maps illustrating the vulnerable land. Using digital elevation model output and NOAA shoreline data, we have prepared a map of the US Atlantic and Gulf Coasts illustrating the 1.5-meter contour, which is about 1.3 meters above sea level. That map is being published at scales in which a single U.S. state appears on a sheet of paper, as well as a map showing the entire eastern half of the nation. The map does not purport to project the future shoreline, but rather that area most vulnerable to inundation.

EPA is also proceeding, slowly, on a second mapping effort that will project changes in shorelines. That efforts requires one to make an assumption regarding which areas will be protected and which areas will be inundated; EPA is developing those scenarios through a collaboration with local government planners in New Jersey and North Carolina, and effort that will be expanded to include other states. We are also developing maps that can be presented at thbe 1:100.000 scale, and thereby illustrate impacts of sea level rise on the county scale.

Loss of Estuarine Shores. If our coastal zones were not developed, natural systems could migrate inland and rising sea level would not cause a major reduction in estuarine beaches or shallow habitats. There would be a net loss of coastal wetlands, because the area of wetland is far greater than the area of land just above the wetlands. But the overall integrity of coastal ecosystems would remain intact.

Most of the coast is or will become developed, however, and homeowners rarely choose to give up their land to the sea. Along ocean shores, beach nourishment is the preferred strategy, which enables property to be protected without the loss of the beach. The estuarine shore, however, is being replaced with walls or concrete, rock, steel, and wood. In Maryland alone, 300 miles of shoreline have been armored in the last 15-20 years. These structures eliminate beaches, narrow strip of tidal wetlands, and eventually, shallow waters as well.

Federal Programs Fail to Protect Estuarine Shores Even Today. Federal programs have two fundamental limitations. First, wetland programs generally focus on marshes, swamps, and other vegetated wetlands, but ignore the estuarine beaches. Second, they tend to focus on the total area of habitat being protected, to the exclusion of other measures such as the length of shoreline or land/water interface being threatened. As a result, the value of estuarine beaches, adjacent shallow waters, and narrow riparian strips of wetlands are automatically devalued; a mile of beach, for example, may represent only one acre of land. Nevertheless where the loss of natural shores has an important cumulative environmental impact, the law may require federal agencies to address the direct destruction of estuarine shores.

The law does not, however, require the federal government to address the indirect destruction resulting from the beaches and wetlands being squeezed between the rising sea and development. Our institutions assume that sea level and shorelines are stable. Federal jurisdiction to regulate wetlands is based on where the high water mark is today. Federal programs can prevent filling and armoring of wetlands and beaches; but they generally lack the authority to prevent the filling, development, and armoring of land that is dry today but would become a beach or wetland in the future as the sea rises. State and local governments may have to take the lead.

Current and Possible Future Efforts to Protect Natural Wetlands and Beaches as Shores Erode. State efforts to recognize shoreline migration have been mixed. Several states have policies to allow ocean beaches to survive rising sea level; but those policies do not apply to protect estuarine shores. Nevertheless, they probably serve as a good model for bay beaches and wetland shores. Several states have enacted setbacks based on current erosion rates, as a means of preventing ocean shores from being armored. Even this approach is only a temporary solution, because the shore will eventually erode up to the setback.

Texas, Maine, Rhode Island, Oregon, and (to a limited extent) South Carolina have adopted an alternative approach: the “rolling easement.” The term “rolling easement” refers to a broad collection of institutional mechanisms which guarantee that naturally migrating shorelines have the right of way over the desires of private property owners to hold back the sea. To the private property owner, this approach is less draconian than a setback, because one is allowed to develop one’s land--but only on the condition that he or she will not eliminate the intertidal beaches which are, for the most part, owned by the public. If the sea does not rise, then the environmental policy does not impose a major cost on the property owner; if the sea does rise, however, the environment is not sacrificed In addition to setbacks and rolling easements, density restrictions, cluster development, land purchases and nondevelopment easements may be the effective

The Takings Question. Allowing wetlands and beaches to migrate inland requires people to abandon their land to the sea which, at first glance, would appear to run afoul of the U.S. Constitution’s admonition that “nor shall private property be taken for public use without just compensation.” Setbacks that prevent any beneficial use of a given property are likely to be takings (See Lucas v. South Carolina Coastal Council). Rolling easements, by contrast, will not be a taking, because (a) they allow property owners to use their property until the sea threatens it; and (b) under the public trust doctrine, the public owns (or has an easement along) all intertidal wetlands. Even though these policies need not be takings, simple fairness may suggest that stringent policies should not be implemented without some compensation. In the case of a rolling easement, the fair compensation would be small, because the required abandonment of the property would be many decades hence.

Why Local Entities May Be Best Suited for Protecting Natural Shores. The first step should probably not be statewide implementation of controversial land use measures. Such an approach may have been warranted along ocean coasts, where many states had a strong consensus on the need to keep recreational beaches. There is no such consensus along estuaries, however. A more realistic step is for states to decide whether they want to keep any significant fraction of their natural shores, and if so, which ones.

Is the state the appropriate level of government to undertake such an assessment? As the owner of the intertidal lands in most cases, the state ultimately must decide how to deal with these issues. But at the first instance, local government is the more appropriate level of government in many states. Local governments have generally enacted land-use plans and zoning regulations that determine which private lands are likely to remain open space and which will become urbanized. The same type of thinking could be applied to determine which shores should be armored and which should remain in their natural conditions. Especially in the case of land that has not yet been developed, the local government is in the position to ensure that future subdivisions are designed in a fashion consistent with the plan. For example, if the shore is going to retreat, a local government can make sure that all homes are accessible by shore-perpendicular roads.

Private parties can also play an important role. Conservation groups that find themselves selling coastal lands to raise funds for other purposes, can reserve a rolling easement on any property they sell, thereby ensuring that the shore is not armored. Developers can propose to reserve rolling easements and donate it to a public or private conservation entity, as part of environmental mitigation or enhancement programs needed to secure permits. Finally, individual owners of coastal property can donate rolling easements on their property to conservancies or public conservation entities–and claim a tax deduction.

DETECTABILITY OF SEA LEVEL HEIGHT VARIATION PATTERNS

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In order to distinguish anthropogenic influences (e.g., those due to greenhouse-gas induced warming) from ìnaturalî variations in sea level height, long data series are required. Sea level height time series containing in the

order of 100 years of data are available from a number of tide gauges. From these individual time series, local patterns in relative sea level can be determined.
If data sets for tide gauges in a region are combined, a better estimate of sea level variation patterns common to this region could be obtained. However, in order to combine the various time series, heights of the tide gauge bench marks have to be related to a common reference system. This height connection introduces measuring and systematic errors into the data sets.
The purpose of this work is to examine how the detectability of a common pattern in sea level data is influenced by the limited accuracy of the geodetic measuring techniques used to connect the tide gauges in height. Time series used are a combination of simulated patterns with periodic variations obtained from tide gauges (with more than 100 years of observations) situated along the Dutch coast. Sea level variation patterns under consideration are linear patterns possibly in combination with a sea level rise acceleration at the beginning or towards the end of the time series.

DETERMINATION OF INTERANNUAL TO DECADAL CHANGES IN ICE SHEET MASS BALANCE FROM SATELLITE ALTIMETRY

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A major uncertainty in predicting sea level rise is the sensitivity of ice sheet mass balance to climate change, as well as the uncertainty in present mass balance. Since the annual water exchange is about 8 mm of global sea level equivalent, the ± 25% uncertainty in current mass balance corresponds to ± 2 mm/yr in sea level change. Furthermore, estimates of the sensitivity of the mass balance to temperature change range from perhaps as much as - 10% to + 10% per K. Although the overall ice mass balance and seasonal and inter-annual variations can be derived from time-series of ice surface elevations from satellite altimetry, satellite radar altimeters have been limited in spatial coverage and elevation accuracy. Nevertheless, new data analysis shows mixed patterns of ice elevation increases and decreases that are significant in terms of regional-scale mass balances. In addition, observed seasonal and interannual variations in elevation demonstrate the potential for relating the variability in mass balance to changes in precipitation, temperature, and melting. From 2001, NASA's ICESat laser altimeter mission will provide significantly better elevation accuracy and spatial coverage to 86˚ latitude and to the margins of the ice sheets. During 3 to 5 years of ICESat-1 operation, an estimate of the overall ice sheet mass balance and sea level contribution will be obtained. The importance of continued ice monitoring after the first ICESat is illustrated by the variability in the area of Greenland surface melt observed over 17-years and its correlation with temperature. In addition, measurement of ice sheet changes, along with measurements of sea level change by a series of ocean altimeters, should enable direct detection of ice level and global sea level correlations.

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