Understanding Sea-level Rise and Variability

Poster Abstracts

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Poster Abstracts

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TOPIC 1:

What have we learned from the paleo/historical records?

P1 The Holocene sea-level of the coast of Israel

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Our interdisciplinary study evaluates the relative contribution of the glacio-hydro-isostatic and the eustatic factors to the Holocene sea-level curve of the Mediterranean coast of Israel. Superimposed upon this are the relative changes resulting from any vertical tectonic movement of the land. We use mainly land and underwater archaeological data as constraints on palaeo sea-levels, and then compare the observational limits with isostatic models for sea-level change across the region. Significant differences between the observed and predicted change are interpreted as being of tectonic origin. For the Holocene curve up to the last 2,000 years, we obtained data from submerged archaeological sites, land observations of water-front man-made structures and wells located up to 100 m from the coastline, and shipwrecks. For the last 2,000 years, we used data from 64 coastal domestic wells that had been excavated in ancient Caesarea. These were dated from the early Roman period (the oldest from the 1st century AD), up to the end of the Crusader period (mid- 13th century AD). The depths of these coastal water wells establish the position of the ancient water table, and therefore the position of sea-level for the first 1,300 years AD. The connection between the coastal water table and changes in sea-level has been established from modern observations and this was used to reconstruct sea-level during historical time.

The comparison indicates that at about 9,500 to 9,000 years BP sea-level was not higher than –16.5 m, and probably about –20 m, or even lower. By 8,000 years BP, sea-level had risen, but still was not higher than about –7 m, and was probably about –10 m, or even lower. According to the model predictions sea-level was still lower than –3 to –4.5 m 6,000 years BP, and remained below its present level until about 3,000 to 2,000 years BP. The Caesarea results indicate that at about 2,000 years BP sea-level was at its present elevation, while during the Byzantine period it was at or above present level (about 30 cm ± 15 cm). During the Crusader period sea-level may have been lower than today by about 40 cm ± 15 cm. For the last 1,000 years we used bio-constructions, mainly the Dendropoma petraeum reefs along the abrasion platform, as a tool for reconstructing palaeo-sea-levels. Unfortunately, both the elevation accuracy (±10 to 20 cm) and the range of the corrected and calibrated radiocarbon dates obtained from the Dendropoma do not provide high-resolution data for the rising sea, but it seems that sea-level rose slowly from the relatively low levels during the Crusader period up to the 19th century. These results are strengthened by global tide-gauge data indicating sea-level rise at a rate of approximately 1.0-1.5 mm/year during most of the 20th century (a total of 10-15 cm).

The comparison between the Israeli Holocene model for sea level rise and the archaeological observations lead to the conclusion that the average rate of vertical tectonic movement for the last 9,500 years, at least along the Carmel coast, has been less than 0.2 mm/y. The Caesarea well data are also consistent with an absence of significant vertical tectonic movement of the coast over the last 2,000 years, and therefore indicates that ocean volumes have been constant for much of this period.

P2 Comparison between long term (geological) and short term (instrumental) relative sea level data in Italy

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Sea-level change along the Italian coast is the sum of eustatic, glacio-hydro-isostatic, and tectonic factors. The glacio-hydro-isostatic component has been recently predicted and compared with field data at sites not affected by significant tectonic processes.

With the aims of estimating the coastal tectonic movements along the Italian coastline, we combine published and new radiometric radiocarbon dates from materials that can be well connected with the Holocene relative sea level using geomorphological and archaeological markers. Rates of tectonic uplifts were calculated comparing the observed data with the predicted sea level curves from Lambeck model. Results show that many sites in central Italy, Sardinia and NW Sicily are stable; on the contrary, many places in southern Italy are uplifting at rates larger that 2 mm/yr or are subsiding (NE Italy) at rates of about 1 mm/yr. Southern Italy Holocene uplift rates are increasing when compared with the long-term uplift rates calculated from the MIS 5.5 highstand. On the contrary in NE Italy, tectonic subsidence (subtracting the anthropic component) shows a slow-down when compared with long-term data.

It is our aim to compare the late Holocene tectonic rates with instrumental values retrieved from a number of different sources. We select two different coastal areas, which is Trieste (subsidence) and the Messina Straits (uplift). Our working hypothesis is that the geologically determined movement rates should be observed also presently, as the geologic rates represent average persistent values. In the case that the rates do not correspond to the instrumental values, the differences must be explained by instrumental direct or indirect (environmental noise) effects, anthropogenic effects, short-term tectonic effects (seismic cycle). The Trieste area is considered to be aseismic, the seismic band being located some tens of km to the East, bordering the Adria plate. The Messina Straits is one of the most active seismic areas of Italy, and here discrepancies are liable to be found due to fault movements. For the greater Trieste area, we consider up to 100 years of tide gauge measurements (PSMSL), 40 years of tilt measurements, 50 years of repeated leveling measurements, and 13 years of satellite altimeter data (Topex/Poseidon), three years of GPS data. For the Messina Straits we use satellite altimeter data and tide gauge observations (PSMSL and APAT), the only data at our hands presently. For the Trieste area we find a partial agreement with the results predicted from the geology. The longest-term observations (tide gauge, tilt, levelling) reveal that there are considerable changes in the calculated rates in the time interval considered, which makes it questionable to define one single rate value. There is though a general agreement with the subsidence and its northerly decrease in magnitude. The results on crustal vertical movement which stem from the comparison of satellite altimetric observations and the tide gauge measurements are controversial. For the Messina Straits the tide gauge data show the pre-co-and post-seismic crustal movement tied to the 1908 Messina seismic event. Furthermore the tide-gauges confirm an uplift rate of the coast of the order of 2 mm/yr. Joint analysis of tide gauge and satellite altimetric data agree to the fact that the coast is uplifting.

P3 Mean high waters and extreme sea levels at Liverpool since 1768

P. Woodworth

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William Hutchinson was a former privateer (pirate) captain who became Dockmaster at Liverpool in 1759. His measurements of the heights and times of high water spanned 1764-1793 (the 1764-1767 data are now lost) and provided the first extended set of UK tidal information (other than those in the 17th century also at Liverpool by Jeremiah Horrocks which are also lost). The data have been used in studies of changes in mean high water (a proxy for mean sea level) and extreme sea levels at Liverpool over the past two and a half centuries, some of the longest records in Europe. Hutchinson also compiled a complete set of meteorological measurements including air pressures, and his data set was (arguably) the first in which the 'inverse barometer effect' was identified (the Swede Nils Gissler sometimes gets the credit as does, incorrectly, James Clark Ross). This poster will show some of Hutchinson's data and provide information on a great man who should be mentioned in all sea level text books. The use of his data is continuing in a comparison of 18th century sea level measurements at Liverpool with those taken at almost the same time at Brest in France, presently being 'data rescued' by Guy Woppelmann and colleagues.

P4 Coral microatolls and a low-resolution record of sea-level changes

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Corals have been used to provide an indication of sea-level changes over the Quaternary. Individual colonies of massive coral can grow up to a level close to mean low tide and then continue to grow outwards, forming flat-topped discoid corals, termed microatolls. Microatolls are living on their outer margin but are predominantly dead on their upper surface. Microatolls in their growth position are fixed biological sea-level indicators and can be used to indicate previous limits to coral growth. Fossil microatolls have been used extensively to reconstruct Holocene sea-level variations on reef tops; for example, on the Great Barrier Reef, microatolls indicate a higher stand of the sea and its gradual fall over the past 6000 years. Much of the Indo-Pacific reef province has experienced relative sea levels in the mid- and late Holocene that have been slightly above present and microatolls may be preserved at a height presently above that of their living counterparts on reef flats in the eastern Indian Ocean, Southeast Asia, northern Australia, and across much of the equatorial Pacific Ocean. It has also been shown that living microatolls can be used to track the pattern of sea-level variation over past decades. Larger specimens can reach several metres across and contain a growth record of tens to hundreds of years. Typically, microatolls comprise a single colony of massive Porites up to several metres in diameter. Microatolls grow upward until constrained by a water level close to mean low tide level, after which they continue lateral growth and become disc-shaped corals. Where a microatoll, previously limited by water level, experiences an increase in water level it can resume vertical growth and begin to overgrow the formerly dead upper surface. Successive falls in water level result in exposure of the living rim, and a series of terracettes develop, recording the water level falls. Fluctuations of water level with a periodicity of several years are recorded on the upper surface of a microatoll as a series of concentric annuli, and such undulations occur on Pacific microatolls tracking, but lagging behind, sea-level fluctuations that are linked to El Niño. Sclerochronology provides insight into the life-history of the coral and can reveal times at which growth has been lowered by changes in the water surface. In areas where storms are experienced, over-turning of the colony can occur during individual storms, or microatolls may have responded to the moating of water behind boulder ramparts formed as a result of storms. In these cases their upper surface may record elevation of water level within impounded moats above that of regional sea level. However, in open-water situations microatolls enable centimetre-scale reconstructions of former sea level. This poster outlines the potential for using these corals to monitor sea-level changes over decadal to millennial time scales.

P5 Reconstructions of salt-marsh accumulation rates and relative sea-level changes during the past 1500 years for three sites along the east coast of North America

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We present and discuss detailed reconstructions of relative sea-level (RSL) variation during the past 1500 yr from cores of salt-marsh peat collected in North Carolina (NC), Connecticut (CT) and Newfoundland (NFd). The ultimate aim is to analyze similarities and differences in RSL variability in terms of (known) changes in the climate-ocean-ice system, and to place into perspective the significance of instrumental records of RSL rise.

We 14C dated, at closely spaced (4-6 cm) intervals, in-core macrofloral palaeomarsh-surface (PMS) indicators, and applied 210Pb/137Cs bulk sediment dating to every cm of the upper 60 cm of the core. This step yields an age-depth error envelope representing the temporal change in PMS elevation. The second step quantifies, for every (other) cm (= PMS) of the core, the vertical distance between PMS and local palaeo-mean high water (PMHW) using fossil marsh foraminifera assemblages and a transfer function.

Compaction-free RSL data for CT and NC document a gradually decreasing rate of RSL rise over the past several thousand years, with average rates of 0.9 mm/yr and 0.4 mm/yr, respectively since 500 AD. Nearest tide-gauge records show average rates of RSL rise of 2.2 mm/yr (New London, CT) and 2.1 mm/yr (Wilmington, NC) for the past ca. 70 yr. PMS and PMHW reconstructions for the past 150 yr for NC and CT, suggest these higher rates of RSL rise commenced between the late 1700's and early/late 1800's, respectively.

For the period 500-1700/1900 AD, core-based PMHW reconstructions for CT and NFd are characterized by small-amplitude (5-20 cm, ignoring statistical error), low-frequency (25-100 yr) fluctuations superimposed on a long-term linear trend of ~1 mm/yr. Autocompaction appears to be small; age control is insufficient to resolve (a)synchroneity of the PMHW fluctuations. An unrealistic PMHW reconstruction for NC may reflect overriding influence of other ecological factors (*e.g.* salinity). The PMS record for NC describes a ~0.4 mm/yr linear trend for the period 500-1700/1800 AD. The accommodation of linear trends through the pre-1700/1800 AD data implies that the method is unable to resolve western Atlantic sea-level variations, if any, associated with the Medieval Warm Period and Little Ice Age.

P6 Reviewing historical sea level records in France over 300 years

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In 2000, the unexpected discovery of a set of sea level measurements carried out in Brest between 1778 and 1792 led us to undertake the search for ancient unpublished data in the archiving centres all around France. Our search has revealed historical sea level records that are worth analysing in the context of recent climate sea level changes due to global warming. Long sea level records turn out to be more numerous than the two already well-known examples of Brest and Marseille records. This is not surprising since France was pioneer in the surveying of sea level: observations have been made in Brest since 1679. This poster first presents the historical data sets which have been discovered so far. We then focus on the Brest station to illustrate the most relevant issues that must be addressed when dealing with historical sea level records: What is the quality of the 'archaeological' data? Can the past records be related to the present-day ones?

A set of sea level records dating from 1756 to present and including high waters and low waters observations as well as tide gauge data has been analysed for the Brest station. Careful editing was undertaken by examining the residuals between tidal predictions and observations. The method proved useful to find and correct timing errors, changes in the time-reference system, changes in the tide-gauge zero and errors in the transcriptions of observations. After this process we have managed to construct a coherent time series of high waters and low waters spanning from 1807-2004 and we have used them to study the evolution of the mean sea level (MSL). We have proved that we can use the mean tide level (MTL) trend as a proxy to study the evolution of MSL. Three linear trend periods can be distinguished in the Brest MTL time series over the period 1807-2004 with an inflexion point around 1890. We obtain a sea level acceleration of 0.0071+/-0.0008mm/yr2 over the whole period using a simple quadratic least squares adjustment. Our results support the recent findings of an enhanced coastal sea level rise during the last decade compared to the global estimations of about 1.8mm/yr over longer periods.

P7 What we have learned from the archaeological and biological data Holocene relative sea-level changes along the mediterranean coasts

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Recent sea-level variations: results from the superposition of eustatic and crustal mobility. Tectonic and isostatic movements have prevailed since 6000 BP. Using multi-disciplinary indicators (biological, geomorphological and archaeological) we are building a high-resolution RSL databank along the Mediterranean. We have developed a new methdology using different proxies: mid-littoral bioconstructions, marine molluscs fixed upon archaeological remains and mid-littoral notches. In this poster we present precise results from two case studies: Marseilles, in a so-called stable tectonic context, and Pozzuoli located in the Phlaegrean Fields volcanic complex, Italy.

In the ancient harbor of Marseille (Southern France), marine fauna fixed upon archaeological structures in addition to biosedimentary units document a 1.5 m steady rise in relative sea level during the past 5000 years, followed by a near stable level at present datum from about 1500 years AD to the last century. This trend is similar to the one previously documented along the rocky coasts of the same region. Field observations inside and outside the harbour confirm that no sea level stand higher than present ever occurred during the studied period.

TOPIC 2:

20^{th} century sea-level rise and variability estimates from tide gauges and altimeters

P8 Sea level variability in Sri Lankan waters

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Sea level variations in Sri Lanka coastal waters on time scale daily and seasonal are investigated using past and recent tide gauge records. The sea level data from few stations in the Northern Indian Ocean are also analysed for comparison.

Sea level variations in Sri Lankan coastal waters feature both tidal and non-tidal fluctuations superimposed on relatively large seasonal oscillations. The oceanic tides are mixed semidiurnal with a spring tidal range of 0.40 - 0.60 m. Smaller ranges appear in northeastern part of Sri Lanka possibly due to a wider continental shelf in that region. The main semi-diurnal (M2 and S2) tidal phases on the east coast are nearly opposite phase from the west coast, with a rapid phase change along the southeast coast. The phase difference between Point Pedro and Jaffna is also in opposite phase on the northern most part of Sri Lanka.

High frequency coastal tide gauge records around the island exhibits short-period oscillations with periodicity of 0.4–2.0 h, which are attributed due to shelf oscillation seiches. The coastal tide gauges observations during 26 December 2004 and 28 March 2005 Indian Ocean Tsunamis reveals that the energy at existing high frequency shelf oscillations are particularly enhanced and continued for several days with larger amplitudes.

Low pass filtered residual sea level shows that the oscillation is mainly annual in character, but significant variations takes place also over a period of about 05 days and interseasonal time scales which are possibly due to the variation of air pressure and wind.

In the inner Bay of Bengal, the seasonal sea level range is about 0.9 m with highest levels during August and lowest in January. The range decreases towards south and its less than 0.1 m at Diego Garcia. The seasonal sea level ranges around Sri Lanka waters amounts to 0.25-0.30 m with maximum height in December-January and minimum in July-August. Approximately, half of this difference (15 cm) in Sri Lanka Waters is explained by the steric height variations, assuming a well-mixed surface layer of 100 m and seasonal salinity variations of 2 psu around Island. On the other hand, the seasonal range of sea level pressure is 5mb with maximum in January and minimum in June-July, hence mean sea level is 5 cm lower in January compared to July, due to the inverse barometric effect. Anyhow, it is obvious that shifting winds and current systems off the coast (Schott *et al*., 1994) may contribute to the seasonal variability as well.

Interannual sea level variability and sea level trend are also examined in the northern Indian Region, particularly data from sea level stations near to Sri Lanka.

P9 Coupling instrumental and proxy records of recent sea-level change

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Long instrumental records of sea-level change are scarce and very few date back to pre-industrial times. Geological records of sea-level change, on the other hand, are often imprecise and lack sufficient temporal resolution in recent centuries. To bridge the gap between the geological and observational records of sea-level change, this paper presents high-resolution proxy sea-level reconstructions from recent salt-marsh sediments that offer useful supplements to the small data base of long-tide gauge records.

Reconstructions of sea-level change derived from salt-marsh sediments use microfossils (commonly foraminifera or diatoms) in cores to constrain the former position of sea level. This is achieved by surveying the height at which populations of modern counterparts are found in the modern environment and by assigning this height to the fossil populations. The height of the fossil assemblages is surveyed to the same (tidal) datum as the modern populations which allows the difference between modern and former sea level to be calculated. Dating methods that are used to assign an age to the former sea-level positions include radiometric techniques (AMS14C, 210Pb, 137Cs, 241Am) and specific stratigraphic markers (*e.g.*, pollen, tephra, Pb concentrations, Pb isotopic ratios).

Records presented in this paper were obtained from salt marshes in Atlantic Canada, Iceland, the British Isles, and New Zealand. In each location the proxy record for the 20th century can be directly compared with tide-gauge records to validate the method of reconstruction. The salt-marsh records generally provide one sea-level data point for every 5 or 10 years, depending on vertical accretion rates. Short-term (multi-) annual variability is not resolved. The vertical precision of sea-level reconstructions ranges from ±5 to ±20 cm and depends on site characteristics, especially tidal range. The dating precision of sediments deposited during the 19th century is ±10 years, improving to ±5 years or better in the 20th century.

The emerging picture is that the recent acceleration of sea-level rise is global in character and started between the middle 19th and the early 20th century, coincident with global temperature rise. Differences in the timing of the onset of rapid sea-level rise across the North Atlantic Ocean may reflect spatial non-uniformity of steric sea-level change. It is concluded that proxy records from salt-marsh sediments are of great value for documenting the spatial and temporal patterns of sea-level rise in the past 200 years and, ultimately, for determining the causes of this rise.

P10 Decadal rates of sea level change during the 20th century.

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Decadal rates of sea level change over the 20^{th} century were explored using nine long and nearly continuous sea level records. These records were found to capture the variability found in a larger number of records over the last half century.

The mean rate of sea level rise over the 1904-2003 period was 1.67+/-0.04 mm/yr. The rate of sea level rise during the second part of the last century was 1.42+/-0.14 mm/yr, less than the rate during the first half of the century (1.91+/-0.14 mm/yr). The two highest decadal rates of rise occurred in the decades centred on 1938 (4.54 mm/yr) and 1979 (5.37 mm/yr).

P11 Causes of sea level changes during the TOPEX period

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The ECCO adjoint model framework is being used to estimate possible causes that lead to observed changes in sea level over the last decade. For that purpose the ECCO global state estimation was used as background information and an optimization run was set up that minimizes the sea level trend. Model parameters that were adjusted, include the initial conditions of temperature and salinity, net surface heat and freshwater fluxes as well as wind stress. With each of the parameters specific physical processes are associated that account for different relative contributions to changes in the sea level trend. We suggest physical mechanisms involved in the presently observed changes in sea level and try to assess their relative importance.

P12 Comparing global sea level rise estimates from satellite altimetry and a global ocean reanalysis: 1993-2001

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Satellite altimeter observations show that global sea level has been rising over the past decade at a rate of about 3 mm/yr, well above the centennial rate of 1.8 mm/yr. This has been occurring despite the presence of large geographical variations, including large areas of falling sea level. Here we investigate the global and regional nature of this signal by comparing satellite altimeter measurements of sea level change between 1993 and 2001 with estimates of the steric component of sea level change for the same period based on the SODA 1.2 reanalysis of global ***in situ*** temperature and salinity (Carton ***et al.***, 2005). A map comparison of the two trend data sets shows broad geographical similarities, including high positive rates (>10 mm/yr) throughout much of the western Pacific and eastern Indian Oceans, negatives in the eastern tropical Pacific, and positives in the North Atlantic. Surprisingly, the reanalysis rates tend to have higher absolute values than the altimeter rates, particularly in the tropical Pacific. Analyzing the data sets in three zonal bands (66N to 30N, 30N to 30S, 30S to 66S) reveals distinct latitudinal differences. The northern and equatorial bands exhibit roughly similar average altimeter rates of sea level rise, at 2.5 and 2.3 mm/yr, respectively, and similar levels of correlation (~0.7) between altimeter trends and reanalysis trends on a local (grid point) basis. The southern band shows the highest average altimeter rate, at 3.9 mm/yr, suggesting that much of the increase between the centennial global rate determined from tide gauges and the 1993-2001 global altimeter-derived rate is due to rapid changes in the Southern Ocean. However, a local comparison shows that the reanalysis trends are poorly correlated with the altimeter trends in this band, making it difficult to distinguish between steric and eustatic contributions in the one band of greatest sea level rise. The poor correlation between the two data sets is probably due the lack of ***in situ*** hydrographic observations in the Southern Ocean, a situation which no longer exists because of the advent of the Argo program, coincidentally in 2001.

P13 Forcing of sea level variability around Europe.

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Developments in understanding long and short-term processes in sea level variability in the Mediterranean Sea on the basis of tide gauge data, temperature and salinity data and two dimensional models are presented. Different parameters dominate decadal sea level variability over the last four decades. The North Sea is dominated by wind, while the Mediterranean appears dominated by atmospheric pressure and the Black Sea by changes in the evaporation. Deep water formation

changes in the Eastern Mediterranean during the 1990s are linked with sudden sea level changes there. We reconfirm the close correlation of the NAO with sea level variability and we reconstruct NAO related sea level variability backwards in time for the past 4 centuries. From this reconstruction error bars for sea level trends related to the NAO variability are suggested.

P14 Nonlinear trends in global and regional sea level

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(2) Arctic Centre

We analyze the Permanent Service for Mean Sea Level (PSMSL) database of sea level time series using a method based on Monte Carlo Singular Spectrum Analysis (MC-SSA). We remove 2-30 year quasi-periodic oscillations and determine the non-linear long-term trends for 12 large ocean regions. In contrast with linear trends, where the rate of mean sea level rise is constant, our results reveal the evolution of sea level rise during the 20th century and show that the highest regional rates of up to 3-5 mm/yr occurred between 1920-1950 (with some regional variations). The major contributions to the global sea level rise during 1920-1940 are from the North Atlantic (4.2 mm/yr), Indian (3.5 mm/yr), and Mediterranean (3.1mm/yr) regions. Our global sea level trend estimate of 2.4 mm/yr for the period from 1993 to 2000 is comparable with the 2.6 mm/yr sea level rise calculated from TOPEX/Poseidon altimeter measurements. However, we show that over the last 100 years the rate of 2.5 mm/yr occurred between 1920 and 1945 and resulted in a sea level rise of 48 mm, is likely to be as large as today's. We evaluate errors in sea level using two independent approaches, the robust bi-weight mean and variance, and a novel "virtual station" approach that utilizes geographic location of stations.

P15 The Permanent Service for Mean Sea Level (PSMSL)

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Since 1933, the Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. It is based at the Proudman Oceanographic Laboratory (POL). The PSMSL is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) established by the International Council of Scientific Unions (ICSU). The mission of the PSMSL is to provide the community with a full Service for the acquisition, analysis and interpretation of sea level data. Aside from its central role of operation of the global sea level data bank, the PSMSL provides advice to tide gauge operators and analysts. It plays an important role in the development of the Global Sea Level Observing System (GLOSS), especially most recently in the provision of tide gauges to Africa (ODINAFRICA project). The database of the PSMSL contains almost 54000 station-years of monthly and annual mean values of sea level from over 2000 tide gauge stations around the world received from almost 200 national authorities. On average, approximately 1500 station-years of data are entered into the database each year. This data set is used in all analyses of recent regional and global sea level changes, including those which inform the Intergovernmental Panel on Climate Change.

P16 Coherency of sea level across oceanic basins derived from tide gauge records

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Sea level monitoring is important as sea level rise is an indicator of global change and one of the most important parameters for coastal protection. Sea level variability is determined by several factors including large scale atmospheric forcing, changes in the thermohaline circulation as well as thermosteric effect.

In this analysis, forty-two regional sea level indices were used, these were derived from tide gauges records representing three oceanic basins (Pacific, Atlantic and Indian Oceans) and the European Seas (Baltic and Mediterranean Sea). The sea level indices were determined by extracting the first Empirical Orthogonal Function (EOF) from regions where tide gauges that had a coherent sea level signal. Here, we explore the existence of teleconnections by cross-correlating these regional sea level indices with the aim of identifying possible teleconnections across ocean basins. In addition we explore the relationship between the sea level indices and five regional climatic indices, which include, the North Atlantic Oscillation (NAO), Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), Mediterranean Oscillation Index (MOI) and the Trans-Polar Index (TPI). The analysis was performed, both with and without atmospheric pressure correction. This work reveals teleconnections in sea level both within and between oceanic basins.

P17 Ocean mass and heat changes recovery from GRACE and altimetry data

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Sea level variability consists of two components, *i.e.* changes due to mass redistribution (eustatic) and due to variations in ocean heat content (steric). Altimetry observes the total variation in sea level height and cannot distinguish between the two components. The GRACE monthly solutions of the time-variable gravity field allow direct estimates of changes in the ocean water mass budget. Combined with satellite altimetry observations, this can be used to estimate changes in the ocean heat content as well. Since the amplitudes of these signals are relatively small (compared to the hydrological signal over land), it is important that both the GRACE and altimetry data are corrected and combined in a consistent manner. By definition, GRACE is insensitive to variations in the degree 1 terms of the potential. Chambers *et al.* (2004) first noted that the inclusion of these geocenter variations in the GRACE monthly solutions leads to an improved estimations of global ocean mass variations when compared with altimetry corrected for steric effects. The influence of this effect on both the altimetry and GRACE observations is further explored in this presentation. Additionally, we discuss the other corrections that should be applied to correctly reconcile the two data sets.

P18 Communicating indices and key indicators for sea level

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The availability of almost 14 years of high-quality satellite altimetry and a renewed focus on analysis of historical sea-level data means that we are now in a much better position to understand what has and is happening to sea level. Sea-level rise is no longer characterised by one global average number for the 20th century. Instead there is recognition that the rate of global averaged sea-level rise varies and that there are regional variations of sea level on all time scales. There is also a greater focus on extreme sea-level events, how the frequency and intensity of these events are changing and of their very significant impacts on coastal regions and society. While our understanding of the causes for sea-level variability and rise and our ability to project future rise has increased, there remain significant gaps in our knowledge. There is also increasing public and policy-maker interest in sea-level rise and its implications for coastal planning, disaster management and the potential need for housing of environmental refugees. One of the challenges facing the scientific community is how to communicate knowledge and uncertainties of current and projected sea levels and their likely impacts. We argue now is the appropriate time to define indices and key indicators of sea level and to communicate more effectively information on sea level to the public, industry and policy makers. These indices and key indicators could be part of the annual WMO Statement on the Status of the Global Climate. Indices and key indicators to be reported could include global averaged sea level, a map of regional sea level, occurrences of extreme events during the year, estimates of the various contributions to observed sea-level change, including ocean thermal expansion, maps of the ice sheet changes and major events such as observations of accelerations of glaciers.

P19 Sea level rise in the Bay of Bengal: Its impacts and adaptations in Bangladesh

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Bangladesh is one of the most densely populated countries in the world where 35.1 million people (25% of total population) live in the coastal zone within a land area of 47,201 km^2. A substantial part of the coastal zone has already been suffered from destruction and degradation of land, saltwater intrusion, and water logging, as well as natural disasters such as cyclone, storm surge and flood. It is very likely that sea level rise (SLR) will further aggravate those coastal problems. The low-lying topography, settlement of deltaic plain, highly variable hydrological regimes, widespread poverty, large population density, poor institutional development etc. have particularly made Bangladesh vulnerable to SLR. Globally, sea-level is rising and it is expected to continue rising with an accelerating rate. That is a great concern for Bangladesh where rate of SLR is comparatively large. Efforts have been made to quantify the SLR in particular to Bangladesh. From an analysis of 26 years data, it is observed that sea level in the Bay of Bengal is rising by 4.0 to 7.8 mm/year. These rates are much higher in comparison with that of global rate. An increasing tendency of sea level from west to east along the coast has also been identified. It implies the influence of local factors such as uneven land subsidence, meteorological conditions and hydrological regimes.

The impacts of SLR in the coastal regions of Bangladesh are enormous and of great concern for the whole country. There will be likely migration of people from the coastal area to further inland thus creating socio-economic problems in other areas. The SLR would cause recession of flat sandy beaches in the south-eastern part of the country while it may create significant back water effect in the west and central coastal zones. The SLR would contribute substantially in coastal flooding and saltwater intrusion. The forest ecosystems of the country would suffer due to floods in monsoon and moisture stress in winter.

The ecological security of the largest patch of productive mangroves in the world, the Sundarbans, would be at risk due to a combination of low-flow and saltwater intrusion in winter. Ironically, Bangladesh has already experienced some of the impacts of SLR such as salinisation, land erosion, frequent cyclones and tidal surges etc.

As the country has been experiencing natural disasters for many decades, it has well developed its adaptation strategies in associations with international communities since then. Under the increasing threat of potential SLR and associated impacts, the country is further strengthening its adaptations practices. Some of the national level adaptation measures include the rehabilitation of coastal embankment with increased height, construction of new refugee shelters, and plantation of new mangroves along the coastal belt. Other important aspects of adaptation are enhancing communities' knowledge by training and public awareness, development of community based flood proof measures, and improvement of accuracy and timing of cyclone warning system. The authors have investigated the possible impacts of climate change and SLR on coastal flooding in terms of extent and depth of flooding. Present and future adaptation measures are being assessed to cope with the expected SLR.

P20 A study on water level variations in the estuary and gulf of St. Lawrence

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Extreme value analysis (EVA) are carried out for three sites with century-long water level observations, Lauzon (near Quebec City) at the head of the Estuary, Rimouski in the middle of the Estuary and Charlottetown in the lower reach of the Estuary-Gulf system. The EVA analyses at Lauzon and Charlottetown both show a significant shortening of the return periods of storm surge events of the same size in the latter part of the 20st century compared to the first part. An event that used to occur once in 20 years on average now only takes about 4 years to return, and the bigger the events are, the shorter their return periods become. This may indicate that the surge forcing environment has changed in the last half century. However, the EVA at Rimouski does not reveal such a significant shift before and after 1957. Further investigation is required for this inconsistency.

Long-term annual mean sea level variations are examined throughout the Estuary, Gulf and its vicinities. Two types of long-term trends are identified by regression analysis. In the eastern and southern parts of Gulf and its vicinities, the annual sea levels exhibit a steady rising trend with rates ranging from 22 to 33 cm/century. In the Estuary, the annual sea levels show an opposite trend, falling steadily at rates of 3.4 to 6.4 cm/century. This result seems to indicate that both crustal rising and subsidence are taking place respectively in the Estuary and in the Gulf to either offset or enhance the effect of global sea level rising. The annual mean sea level variations also show inter-annual/decadal oscillations which become progressively stronger from the Gulf to the head of the Estuary, with amplitudes less than 5 cm at Charlottetown to more than 10 cm at Lauzon. This suggests that the causing agents might be some climate factors that are of the same period of variations.

The century-record storm surge event at Lauzon was identified and examined. This surge lasted from March 4 to 6, 1971 with its peak value of 2.81 m at 1:00 (UTC) on March 5. The peak did not occur at high tide fortunately. Had it occurred 8 hours earlier or 4 hours later, Quebec City would have been flooded heavily. This surge was caused by a low pressure system passing over Lauzon and moving eastward. The associated strong winds blowing along the channel of the Estuary towards Lauzon may also have played its role.

P21 Progress in altimeter calibration using the global tide gauge network

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In the past decade, the use of tide gauges in calibrating satellite altimeters has become widely accepted. Because tide gauge sea levels are referenced to a datum on land, an estimation of land motion at each tide gauge must be made in order to compare tide gauge sea levels with altimeter heights. The errors due to land motion at the tide gauges are the largest remaining source of uncertainty in this method of altimeter calibration. Since the last calibration method was described (Mitchum, 2000) more GPS and DORIS stations have become available, many near to the tide gauges presently used for altimeter calibration. Not all tide gauges, however, have a GPS or DORIS receiver nearby, so a method of making the best possible land motion estimates and putting reasonable error bars on these estimates is challenging. We have tested a variety of methods for doing this, by including tectonic information, for example, and our preliminary results will be presented.

P22 Sea level rise at Kerguelen over the last 50 years

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(1) LEGOS - Toulouse, France
(2) CLDG, La Rochelle - France
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Relative sea level rise at Kerguelen Island over the last 55 years has been investigated using a combination of historical and recent tide gauge data. The best estimate of the relative sea level trend from data sets spanning 38 years is estimated to be 1.1 +/- 0.7 mm yr-1. We have tried to quantify the error budget due to some of the possible sources of uncertainty. As expected, the main source of uncertainty comes from oceanic interannual variability, preventing an accurate estimate of the sea level trend over short record lengths. However, our values are reasonably consistent with other reported Southern Hemisphere sea level trends for similar time periods.

P23 The Global Sea Level Observing System (GLOSS)

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(2) Proudman Oceanography Laboratory - Liverpool, UK

The Global Sea Level Observing System (GLOSS) is an international programme coordinated by the Intergovernmental Oceanographic Commission (IOC) for the establishment of high quality global and regional sea level networks for application to climate, oceanographic and coastal sea level research. The main component of GLOSS is the 'Global Core Network' of 300 sea level stations around the world for long term climate change and oceanographic sea level monitoring. The Core Network is designed to provide an approximately evenly-distributed sampling of global coastal sea level variations. Another component is the GLOSS long term trends set of gauge sites for monitoring long term trends and accelerations in global sea level. These is priority sites for Global Positioning System receiver installations to monitor vertical land movements, and their data contribute to long term climate change studies such as those of the WMO-UNEP Intergovernmental Panel on Climate Change. The GLOSS altimeter calibration set consists mostly of island stations, and will provide an ongoing facility for mission intercalibrations. A GLOSS ocean circulation set, including in particular gauge pairs at straits and in polar area, complements altimetric coverage of the open deep ocean within programmes such as WOCE and CLIVAR.

P24 Increase in high frequency (2-14 years) variability in sea level records

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(2) Arctic Centre

We analyze 1000 sea level records from the Permanent Service for Mean Sea Level (PSMSL) database. Using advanced statistical methods we separate nonlinear trends and statistically significance oscillations for 12 large ocean basins. We demonstrate that signals in the 2.2-13.9 year band contribute from 5 to 20 % of variability in time series. We also show that variability in sea level records over periods 2-14 years has increased during the past 50 years in most ocean basins. We provide evidence that this increase in 2-13.9 year variability is associated with the greater influence of the large scale atmospheric circulation represented by the Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation and Pacific Decadal Oscillation indices.

P25 An exercise of combining tide gauge and GPS results to derive trends in sea level

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The observational information provided by a tide gauge may appear as the most adequate and useful quantity for the coastal management: a relative sea level height with respect to the underlying land upon which the gauge is settled. However, to devise any appropriate plan to manage the coastline it is preferable to understand which is the relative magnitude of the mechanisms that potentially underlay a relative sea-level rise. Is the relative sea-level rise due to eustatic changes or due to the local land subsidence? Monitoring vertical land motion at tide gauges becomes even more mandatory if absolute or climate related signals in mean sea level are to be derived from the coastal tide gauge records. The approaches to measure the rates of vertical land motion of the tide gauges, whether isostatic, tectonic or more local, have been discussed at several major international meeting since 1988. However, the use of space geodesy, and GPS in particular, to monitor vertical land motions

at tide gauges has proven to be not as straightforward as supposed 15 years ago. Determining rates of vertical land motion with an accuracy better than 1 mm/yr is still a very challenging problem in Geodesy. Many issues must be taken into account: we are aiming at a level of performance where serious consideration of the reference frame and its long term stability need to be addressed. A terrestrial reference frame, accurate and stable at the millimetre level must be maintained over decades. A complete reanalysis of the GPS data is currently being carried out at our analysis centre ULR, which is dedicated to routinely process a global set of GPS stations that are co-located with tide gauges. The absolute antenna phase centre corrections for both satellites and receivers have been implemented, as well as new models to take into account the troposphere refraction. Four years of daily and weekly GPS solutions have been produced so far using the same models and analysis strategy leading to a homogeneous data set of station positions. They cover the period 2002-2005, which allows to draw individual time series of positions of more than 2.5 years for most of the stations, the minimum length to derive trends without seasonal effect biases. A careful inspection both of the GPS time series of vertical positions and the co-located tide gauge records is conducted to derive a comprehensive picture of what is going on at the various sites included in our processing scheme.

Which are the station where we can estimate reliable trends from the GPS data? From the tide gauge data? What about their synergy? What is the present state of knowledge of absolute sea level rise that can be inferred from our analysis? Which is the impact of the terrestrial reference frame implementation on the estimation of vertical velocities? These are the questions that we would like to address in this poster.

P26 Sea level raise differences on Colombian Pacific ocean between tide gauges and altimetry data.

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Long-term mean sea level change is a variable of considerable interest in the studies of global climate change. There are many components contributing to sea-level rise but some times local trends plays a very large role. Colombian Pacific Ocean is a very good example of that situation, where the land level beneath the tide gauges (coastal zone) is rising in some places and sinking in others according to geology studies.

Using the Tumaco and Buenaventura tide gauges located on Colombian Pacific coast (1°50 N, 78°44 W; 3°54 N 77°06 W) with record between 1953 to 2000, and altimetry sea level (Topex-Jason) data near to the tide gauges, we are showing the differences in sea level rise between the tide gauge and altimetry. Tumaco tide gauge showing relative fall of sea level round -1.14 mm/yr whereas altimetry round -1.67 mm/yr in other hand Buenaventura tide gauge showing rise of sea level round 2.3 mm/yr whereas altimetry fall -2,39 mm/yr. The differences could be related to the isostatic adjustment and tectonism associated with movement of the land surface.

P27 20th century sea level rise: Its determination and causes

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Sea level rise has been widely recognized as a measurable signal as one of the consequences of possible anthropogenic effect of global climate change. The current and post-IPCC Third Assessment Report (TAR, 2001) determination of the 20th century sea level rise is estimated to be around 1.7–1.8 mm/yr. This paper describes the determination and the causes of the 20th century global sea level rise, estimated to be 1.73 ±0.42 mm/yr, using tide gauges (1900–2004) and multiple satellite altimetry (1984–2005). Our adjustment technique assumes known sea level trend geographical patterns from thermosteric sea level measurements, from glacial isostatic adjustment, and the ice melt sources including mountain glaciers, Greenland and Antarctic ice sheets. We estimated that the ice sheets and glaciers contribute an estimated ~90% (1.56 mm/yr) of the sea level budget, the steric contribution is about 10%, while ignoring the global hydrologic contribution. The adjustment implies a preferred scale to ICE-4G of 1.27, which best fits the sea level measurements.

TOPIC 3:

Ocean thermal expansion

P28 Global ocean thermal expansion deduced from a combination of satellite and *in situ* data

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Satellite data (altimeter and SST) and ***in situ*** temperature and salinity measurements are the two major complementary components of the global ocean observing system. ***In situ*** profiles provide precise but sparse measurements of the ocean vertical structure whereas altimeter and SST data provide high temporal and spatial synoptic observations. These two data sets have been combined to produce global 3-D thermohaline observed fields from the surface down to 700 m depth.

The merging approach uses first, a multiple linear regression method to derive synthetic T and S profiles from the satellite measurements. These synthetic profiles are then combined with the ***in situ*** T and S profiles using an optimal interpolation method that takes into account analyzed error on the different observations.

Twelve years (1993-2005) of 3-D thermohaline fields have been produced with this method as part of the “Observed Ocean” system developed in the frame of the French Operational Oceanography Mercator project. The “Observed” fields have been first validated and compared with independent ***in situ*** data sets in order to provide an estimation of the performances of the system over the whole ocean.

The quality of the estimated fields allows us to study the seasonal and interannual variability of the thermal expansion of the global ocean.

P29 Decadal sea level changes in the 50-year GECCO ocean synthesis

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The global synthesis obtained by the German ECCO effort (GECCO) over the 50-year period 1952 through 2002 on a 1 degree global grid is being analyzed with respect to its decadal and longer term changes in sea level. The synthesis combines most of the data set available during this period with the MIT/ECCO ocean circulation model using its adjoint over the entire period. Regional changes in sea level over the last decade are described and compared with results obtained from TOPEX and from an earlier shorter optimization. The trends over the last decade are compared with those obtained over the pre-Topex period. Relative contributions from thermo- and halo-steric changes are discussed and compared with estimates of thermo-steric changes obtained from ***in situ*** data. We also discuss limitations of ocean syntheses in estimating globally averaged sea level changes.

P30 Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses

M. Ishii

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A historical objective analysis of subsurface temperature and salinity was carried out on a monthly basis from 1945 to 2005 using the latest observational databases and a sea surface temperature analysis. The objective analysis is a revised version of Ishii ***et al.*** and is available at 16 levels in the upper 700 m depth.

The new analysis is suitable for the discussion of global warming. A validation study against the tide gauge shows that the amplitude of thermosteric sea level becomes larger and the agreement became better in comparison with the previous analysis. A substantial part of local sea level rise along the Japanese coast appears to be explained by the thermosteric effect. The thermal expansion averaged in all longitudes from 60S to 60N explains at most half of recent sea level rise detected by satellite observation during the last decade. Considerable uncertainties remain in steric sea level, particularly over the southern oceans (15S -60S). Temperature changes within mixed layer depth make no effective contribution to steric sea level changes along the Antarctic Circumpolar Current. According to statistics using only reliable profiles of the temperature and salinity analyses, salinity variations are intrinsically important to steric sea level changes in high latitudes and in the Atlantic Ocean. Although data sparseness is severe even in the latest decade, linear trends of global mean thermosteric and halosteric sea level for 1955 to 2003 are estimated to be 0.31 +/- 0.07 mm/yr and 0.04 +/- 0.01 mm/yr, respectively. These estimates are comparable to those of the former studies.

Seeking for reasons for a large difference of thermosteric sea level in the southern oceans, a cross validation study was done, in which it is evaluated how the observation distribution affects on the analysis results by comparing the most well-defined SST analysis in the oceanography. This study revealed that the accuracy of temperature analysis in the southern oceans are much less even in the recent decades than that in the northern oceans. Fresh water input to the oceans might be an important factor in the there as well as in the global oceans, as Antonov ***et al.*** (2002) pointed out. However, there are no reliable observational evidences of fresh water input which explain the discrepancy. If the discrepancy is due mainly to data sparseness of oceanographical observation, our estimation would be underestimated severely. Remark also that the contribution from density changes below the 700 m depth to the steric sea level was not considered here.

P31 Constructing estimates of ocean steric sea-level rise from sparse ocean data sets

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Ocean thermal expansion is an important component of sea-level rise. Estimates of ocean thermal expansion for the last five decades have been produced from the comparison of individual sections, objective mapping of historical data sets and ocean reanalysis experiments. However, the combination of the available estimates of ocean thermal expansion and other contributions to sea-level rise has not adequately explained the observed sea-level rise estimated from tide-gauge and satellite-altimeter data. One potential explanation is that current ocean thermal expansion estimates are biased because of sparse data coverage, particularly in the Southern Hemisphere. Reduced space optimal interpolation techniques have been used for reconstructing historical sea surface temperature, atmospheric pressure and sea-level time series. We are developing procedures for applying this technique to sparse oceanographic data sets. Initial results focus on the seasonal variability of steric heights for the post 1993 period and for the annual variations over several decades. This sentence reads a bit funny – should be either “variability” or “variation of”?

P32 Variability and projections in sea level calculated in control, 20th century and 21st century simulations with the CSIRO Mk3.5 model

S. O'Farrell

CSIRO Marine and Atmospheric Research - Victoria, Australia

There is considerable interest in how well climate model can represent the patterns of sea level rise seen at the end of the 20th century in order to increase confidence in projections in the 21st century. One aspect examined in this study is how well the natural modes of variability are represented in the sea level pattern.

For this study we have used a new set of simulations with the CSIRO Mk3.5 (a model generation after the one used for the IPCC 4AR). This model had minimal drift in the temperature at the atmosphere ocean interface and improved stratification and circulation particularly in the Southern Ocean. A set of simulations out to 2100 has just been completed. The analysis up to now has focused on the natural modes of variability in the model control simulations using an EOF analysis; this will be extended to the 20th century and early 21st century to see if the model reproduces correct modes for the current observed satellite altimeter era and the reconstructed sea level patterns of Church and White.

P33 Dynamic sea level changes linked to a changing thermohaline circulation: does vertical mixing matter?

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The present-day thermohaline circulation (THC) is associated with a gradient in sea level between the North Atlantic Ocean (low) and South Atlantic Ocean (high) of about 60 cm. Climate models suggest a reduction of the THC in the course of this century, in response to a reduction of the meridional density contrast due to ocean warming, and hence a rise in local sea level in the North Atlantic Ocean.

However, climate models all parameterize vertical mixing in the ocean interior simply as being (nearly) constant. Recently, more sophisticated parameterizations have been proposed that do better justice to our current understanding of these processes.

It has already been shown that the application of such parameterizations in ocean models affects the response of the THC to changes in the meridional density contrast in the Atlantic Ocean. In this study, the implications for projections for dynamic sea level changes are shown to be considerable as well.

P34 Regional decadal trends in sealevel and implications for determining global mean sealevel change and its causes

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(2) Atmospheric and Environmental Research- Lexington, MA, USA

Estimates of regional patterns of sealevel change are obtained by combining a general circulation model extending to 80 degrees latitude and several hundred million ocean observations in a constrained optimization procedure for the period 1993-2004. The data include not only the available altimetry, but most of the modern hydrography, ARGO float profiles, sea-surface temperature and other observations. Regional variations greatly exceed existing estimates of the mean rise in sealevel, including some regions with sealevel fall. Although thermal effects are largest, the contributions from salinity changes and mass redistribution within the oceans are both significant. Contributions below 1000m are also important, but not dominant. The inferred global sealevel change is similar to other estimates derived strictly from data analyses, but there are quantitative differences. Given the complexity of the regional trends and the sparsity of the ***in situ*** hydrographic database, considerable uncertainty remains in the attribution of global mean sealevel change to thermal expansion or other effects. A major obstacle is the absence of atmospheric estimates that are consistent in their conservation of freshwater and heat.

P35 Steric and eustatic effects: Understanding measured sea level rise by data assimilation

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Sea surface elevations as measured by the altimeter (1993-2003) together with hydrographic measurements are assimilated into a global OGCM that has a free surface, ***i.e.*** that conserves mass rather than volume.

The combination of both types of measurements appeared to be necessary to get a reasonable estimate of the oceanic circulation. Furthermore referencing the altimeter data to the GRACE geoid improves the modelling of anomalies. Further improvement in estimating sea level change was achieved by including the steric effects (thermosteric and halosteric) into the modelled sea surface elevation, because local sea level trends vary substatial in space and time. They are closely associated to heat and salt anomalies in the ocean. This finally allowed to estimate the temporally variing oceanic mass budget from sea surface elevations.

P36 Dynamic and steric sea level changes in an IPCC-A1B scenario simulation

F. Landerer, J. Jungclaus, J. Marotzke

Max Planck Institute for Meteorology - Hamburg, Germany

This poster analyzes regional sea level changes in a climate change simulation using the Max Planck Institute for Meteorology coupled Atmosphere Ocean General Circulation Model ECHAM5/MPI-OM. The climate change scenario builds on observed atmospheric greenhouse gas (GHG) concentrations from 1860 to 2000, followed by the International Panel on Climate Change (IPCC) A1B climate change scenario until 2100; from 2100 to 2199, GHG concentrations are fixed at the 2100 level. Compared to the unperturbed control climate, global sea level rises 0.26 m by 2100, and 0.56 m by 2199 through steric expansion; eustatic changes are not included in this simulation. The model's sea level evolves substantially different between ocean basins, with variations in the range of +/-100% of the global mean sea level change. Sea level rise is strongest in the Arctic Ocean due to enhanced fresh water input from precipitation and continental run-off, and weakest in the Southern Ocean due to compensation of steric changes through dynamic sea surface height (SSH) adjustments. In the North Atlantic (NA), a complex tripole SSH pattern across the subtropical to subpolar gyre front evolves, which is consistent with a northward shift of the NA current. On interannual to decadal timescales, the SSH difference between Bermuda and the Labrador Sea correlates highly with the combined baroclinic gyre transport in the NA, but only weakly with the meridional overturning circulation (MOC), and thus does not allow for estimates of the MOC on these timescales.

The spatial distribution of density changes is influenced generally as much by salinity variations as by changes in temperature, but the two often partly cancel each other. Thermosteric sea level change is positive in almost all ocean regions, but varies considerably by region. Maximum thermosteric expansion occurs in the subtropical North Atlantic, while negative halosteric anomalies in this region partly compensate the thermosteric sea level rise. Freshening in the Arctic Ocean, however, leads to an additional halosteric sea level rise. This contrast between lower and higher latitudes can be partly explained by the increased atmospheric moisture transport from low to high latitudes. Steric anomalies in the Pacific Ocean are largely positive, but of smaller magnitude.

The vertical distribution of thermosteric and halosteric anomalies that contribute to sea level change is very different between ocean basins. In the North Atlantic, the steric anomalies reach to depths of the North Atlantic Deep Water (2000 m), whereas steric anomalies in the entire Pacific Ocean occur mainly in the upper 500 m. In the Southern Ocean, steric anomalies occur throughout the entire water column (more than 3000 m), reflecting the strong vertical exchange of buoyancy in this region.

P37 How accurate is the historical hydrographic database for the purpose of the estimation of the global ocean temperature trends?

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(1) AWI - Bremerhaven, Germany
(2) BSH -

Yearly globally averaged temperature anomalies were calculated in 22 layers by comparing historical data against the WOCE time period. There are six data types in the composite hydrographic data set used for these calculations: Nansen bottles, CTD, expendable bathythermographs (XBT), mechanical bathythermographs (MBT) and profiling floats. The global anomalies were calculated separately for each data type. The XBT and MBT data were found to be positively biased (typically 0.2-0.5°C) relative to the more accurate CTD and Nansen bottle data. Since the XBT and the MBT data largely dominate in number the CTD and Nansen bottle data they essentially determine the overall temperature anomaly in the upper 1500 meter layer. Year mean corrections of both MBT and XBT data result in about 50-percent reduction of the overall temperature increase between 1950s and 1990s for the layer 0-3000m. Global yearly temperature anomalies were also calculated for the countries with the largest contributions to the composite dataset. Similarly to different data types, large systematic differences have been found between the country specific subsets of data. We argue, that a proper quality assessment of the composite historical hydrographic dataset is crucial for the assessment of the long-term temperature changes in the Global Ocean.

P38 Combining altimetry and GRACE to study steric sea level

D. Chambers

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Previously, we have demonstrated that one can obtain a reasonable estimate of steric sea level (SSL) by combining total sea level (SL) maps from Jason-1 altimetry and equivalent water level maps from GRACE. However, this has been limited to spatial resolutions (half-wavelength) of 1000 km or more because of systematic errors in the GRACE gravity coefficients. Recently, a new set of GRACE coefficients has been released by the processing centers. A new method of filtering the coefficients has also recently been demonstrated to be effective in reducing the systematic errors.

Here, we re-examine 21-months of the GRACE data produced by the University of Texas Center for Space Research from February 2003 to March 2005. After applying the new filter to the coefficients, we find that we can obtain significant ocean mass variations at a half-wavelength of 500 km. This is impossible to do without the filter. At a resolution of 500 km resolution, the error variance is reduced by nearly 60%. With the previous GRACE data, we estimated the error to be about 2 cm RMS at 1000 km smoothing. Using the new data and filtering, we now estimate the error in the GRACE equivalent water level to be 2 cm RMS or less at 750 km, and 2.5 cm RMS or less at 500 km.

Using these new GRACE maps, we compute SSL at 500 km and 750 km resolution and study the variations using Empirical Orthogonal Functions (EOFs). The seasonal modes are compared to the SSL derived from World Ocean Atlas 2001, and show improvements over previous comparisons. In addition, some intriguing interannual variations are observed and discussed.

P39 Determination of steric sea level variations from combined Topex/Poseidon altimetry and GRACE gravimetry data

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By combining sea level observations from satellite altimetry with averaged gravity variations over the oceans from the GRACE satellite, it is possible to separate the steric (mainly thermal expansion) and ocean mass contributions to global mean sea level variations.

We have analysed GRACE geoid data computed by Biancale *et al.* (2005). These geoid data are provided at 10-day interval from July 2002 to March 2005. The geoids are given up to degree and order 50, which correspond to a spatial resolution of 400 km. These 10-day geoids have been expressed in terms of land water storage over the continents and ocean mass change over the oceans. We checked that the land water storage averaged over the continental domain is exactly the negative ocean mass averaged over the ocean domain. We also analysed the global mean sea level using Topex/Poseidon altimetry data over the same period. Then removing the GRACE-based mean ocean mass time series to the Topex/Poseidon mean sea level allows us to estimate the steric component. Comparison with thermal expansion estimates based on *in situ* hydrographic data is performed over the overlapping time span.

P40 Recent decrease in thermosteric sea level

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Recently updated estimates based on *in situ* profile data show a decrease in globally averaged, 0/750 m thermosteric sea level between 2003 and 2005 of approximately 5 mm. The decrease in thermosteric sea level is due to a loss of approximately 3.2 x 1022 J of heat from the upper-ocean during this period. A complex spatial pattern is associated with this signal. Large-scale decreases in thermosteric sea level occurred in both the tropical N. Atlantic and a broad band in the S. Pacific centered on 20°S. Without additional information, however, it is difficult attribute these large-scale features to actual oceanic heat loss as opposed to changes in ocean circulation. Nevertheless, the global integral appears to be well sampled and the decrease in thermosteric sea level is unlikely to be the result of poor *in situ* sampling. The recent decrease has surprising implications for the components of sea-level rise, given that total sea level has continued to go up during this period. If the difference between globally averaged thermosteric sea level and total sea level can be considered an inferred estimate of ocean mass, this would imply a rapid increase in the rate of freshwater flux into the ocean. Between 1995 and 2000, the inferred ocean mass estimate increases at a rate of approximately 1 mm/yr, while the rate of increase between 2000 and 2005 is 3.8 mm/yr.

P41 Ocean thernal expansion, 1955-2005

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We quantify thermal expansion of the World Ocean for 1955-2005. Thermal expansion reached a relative maximum in 2003 and has decreased in the following two years.

P42 Sea level change: What have we learned from satellite altimetry, satellite gravity, and ocean temperature measurements?

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The launch of TOPEX/Poseidon (T/P) in 1992 initiated a new era in sea level change studies. The continuation of the altimeter sea level time series by Jason, the initiation of precise satellite gravity measurements with the launch of GRACE in 2002, and the densification of *in situ* ocean temperature measurements (Argo, etc.) have all contributed to an improved understanding of the magnitude and causes of sea level change. We review the recent results from these datasets and use them to develop a budget for present-day sea level change. The results show that these datasets provide good estimates of the total amount of sea level change, the contribution of thermal expansion, and the contribution of water from the continents (ice melt, etc.). However, a number of critical questions remain to be answered, particularly with regard to predicting the amount of sea level rise we will see in the next century.

TOPIC 4:

Contributions from the cryosphere to sea-level change

P43 Glacier changes and their impact on rising global sea level in China and Central Asia

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Mountain glaciers and ice caps other than polar ice sheets (referred to as small glaciers) have been suffering from wide-spread wastage under an increase in average air temperature at the Earth's surface during the 20th century. The melting of these small glaciers has caused global sea level rise at a rate of 0.2-0.4 mm•a-1, and more contribution from small glaciers was projected during the 21st century as a result of global warming. However, a recent result for Alaskan glaciers indicated that the contribution of small glaciers to sea level rise might be lowly estimated. Such a discrepancy could be the limitation of observations of glacier lengths and mass balance series for those regions (like Alaska, Central Asia) where there were less or without monitored glacier datasets. Considering the results from Alaskan glaciers, we are interested in whether the contribution from glaciers in Central Asia, the largest glacierized area in the mid-low latitudes has been underestimated. Here we present the results of glacier changes in China since the Little Ice Age maximum (over 3000 glaciers) and during the past decades (over 5000 glaciers) by using aerial photos (1950s-1980s), topographical maps and remotely sensed digital imageries (1999-2001), then extrapolate these data to glaciers of other parts in Central Asia. Our results indicate that the sea level contribution from Central Asian glaciers may be overestimated for the recent decades.

P44 Greenland ice sheet contributions to sea level, recent past and future

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Meteorological station records, ice cores, and atmospheric data assimilation models were used to develop reconstructions of Greenland ice sheet surface and total mass budget parameters reaching back from the present to the late 1800s. Variability information contained in the overlapping data present the ability to develop empirical functions to predict future ice sheet mass balance changes in different future climate scenarios. Results suggest significant past and future ice sheet contributions to rising global sea level and also inter-annual and inter-decadal variability of varying levels of coherence.

P45 Contribution of glaciers in Northwestern North America to rising sea level

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We have used airborne altimetry to measure surface elevations along the central flowline of nearly 100 glaciers in Alaska, Yukon Territory and northwestern British Columbia (northwestern North America). Comparison of these elevations with contours on maps derived from 1950s to 1970s aerial photography yields elevation and volume changes over a 30 to 45 year period. Approximately one-third of glaciers have been re-profiled 3 to 5 years after the earlier profile, providing a measure of short-timescale elevation and volume changes for comparison with the earlier period. We found that glaciers in northwestern North America have contributed to about 10% of the rate of global sea level rise during the last half-century and that the rate of mass loss has approximately doubled during the past decade. Glaciers in northwestern North America therefore comprise a significant portion of the global cryospheric contribution to rising sea level.

We present several methods for quantifying errors and reducing uncertainties in regional estimate of glacier contribution to rising sea level. Tidewater glaciers, which have a cycle of slow advance and rapid retreat, can introduce substantial errors in regional estimates of glacier volume change. The tidewater glacier cycle is regionally asynchronous and, in the case of retreat, can result in catastrophic mass losses over short time periods. For example, nearly half of the regional volume change in the Western Chugach Mountains was caused by Columbia Glacier, which has been in a state of rapid thinning and retreat from 1980 to the present. In contrast, the Taku Glacier in the Coast Mountains has been thickening and advancing during most of the past 50 years. Therefore tidewater glaciers need to be treated independently in regional extrapolations and should not be included in averaging schemes used to represent entire regions.

In the Coast Mountains, we calculated regional volume changes by differencing topographic map (1950 or 1970s) and Shuttle Radar Topography Mission (2000) Digital Elevation Models. The resulting geodetic mass balances were used to assess errors in regional extrapolation of airborne altimetry data. We found that airborne altimetry underestimated the regional volume changes by about one half because dynamic tidewater and lake-terminating glacier systems were undersampled. On average, lake-terminating glaciers in this region are as significant contributors to rising sea level as are tidewater glaciers.

We show that accurate glacier outlines are essential when calculating regional glacier volume changes. In the Western Chugach Mountains, regional volume losses using a high resolution glacier outline were 10% less than those determined using older, low resolution outlines.

An analysis of glacier area-altitude distributions in each region is used to estimate the sensitivity of glaciers to possible future changes in climate. We show that the Kenai and St. Elias mountains are particularly sensitive to future climate warming because these regions have large amounts of area at or below the elevation of the long-term average equilibrium line elevation.

P46 A Statistical approach to estimating the contribution of glaciers to future sea-level rise

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Valley glaciers and small ice caps are expected to provide the bulk of the cryosphere's contribution to sea-level rise over the next century (~ 0.23 m, IPCC, 2001). A lack of quantitative data for the vast majority of glaciers worldwide (only 100 glaciers out of a total population of 160,000 have mass balance records for longer than 5 years) makes this estimation difficult. Therefore, a different approach to modelling individual glaciers and applying to a region is proposed. A generic valley-glacier system model that predicts variations in width, depth, accumulation and ablation along the glacier has been developed. The model will be calibrated on a small number of glaciers for which data is available and the phase space of free parameters within the model will be constrained. Using the calibrated model and synthetic input, a response surface of sea-level contribution as a function of glacier climatology and topography will be constructed with an assessment of the associated uncertainty. The final stage of the project will be to sample the response function in accordance with estimates of the global distribution of glaciers in the climate-topography phase space to estimate overall sea-level rise. The work presented here details the first two stages of this project.

The 1-d flow model uses an energy balance scheme which drives a melt model that includes refreezing within the snowpack and the development of a superimposed ice layer to buffer the loss of mass. The model uses ERA 40 data that is interpolated to the glacier as climatic input for the long wave radiation, turbulent fluxes and precipitation calculations. Glacier geometry is either given explicitly or derived from characteristics that can be remotely sensed (glacier length, width, area).

The model has been applied to two glaciers, South Cascade glacier, USA, and Midre Lovenbreen, Svalbard. These were chosen to represent two different regimes; one where superimposed ice is an important component of mass balance and one where it is not. South Cascade is a small (~ 2.5 km), north facing maritime valley glacier, with an altitudinal range of 1630 – 2150 m a.s.l. (Rasmussen and Krimmel, 1999). The summer temperatures are usually 5 – 20°C, with small (< 0.05 m averaged over the glacier) or no superimposed ice forming in a season (Krimmel, 1999) and winter temperatures are usually warm (above -10 °C). Midre Lovenbreen is a north- facing polythermal Arctic glacier (~ 4.5 km), with an altitudinal range of 50 -550 m a.s.l. (Wright, 2005). Summer temperatures reach a maximum in July, with an average of ~ 5 °C, while winter temperatures are cold with the mean temperature between December to March below -10 °C (Wright, 2005). Superimposed ice on this glacier can account for up to 37 % of the average annual total accumulation (Wright, 2005).

P47 Potential sea level rise estimates from the glacierisation of an entire mountain range as exemplified with observations from the European Alps

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Total ice volume of glaciers and ice caps (excluding Greenland and Antarctica) corresponds to a sea level rise (SLR) equivalent of about 0.5 m. The ice cover of the European Alps thereby only contributes by about 0.3 mm. However, the extensive amount of available information on glacier distribution and fluctuations, dating back to 1850, allows to apply and validate common scaling approaches for the estimation of glacier area and volume changes and its projection into the 22nd century.

Complete Alpine ice cover can be compiled for the 1970s, when the about 5,150 glaciers covered a total area of 2,909 km^2. This Alpine inventory is used together with digital outlines from the Swiss Glacier Inventory and in consideration of relative changes of different glacier size classes to extrapolate total Alpine glacier covers in 1850 and 2000 which amount to 4,475 km^2 and 2,270 km^2, respectively. This corresponds to an overall loss from 1850 up until the 1970s of 35%, and almost 50% by 2000. Thereby, the relative loss of area decreases with glacier size. It is, hence, essential that the glacier sample, used for the extrapolation, covers all size classes and is representative for the entire mountain range.

Changes in glacier volume can be calculated by multiplying representative mass balance values with the average surface area of a given time period. The cumulative balance of -12 m w.e. over a mean glacier area of 2,590 km^2 during the time interval 1975–2000 indicates a volume loss of 30 km^3. As average slope and equilibrium line altitude have increased, but glacier size, altitude extent, mass flux and driving stress decreased, the percentage of volume loss must be even greater than the calculated area loss of 22%. On this basis, the total Alpine ice volume can be roughly estimated as 200 km^3 in 1850, 105 km^3 in the 1970s, and 75 km^3 in 2000. For the 1970s, straightforward volume-area scaling indicates a total ice volume of 140 km^3, whereas a more process-oriented approach based on mean glacier thickness along the central flowline results in a volume of 130 km^3. The range of the different approaches corresponds to about 0.1 mm SLR equivalent, or to one third of the potential contribution.

A numerical model experiment, based on an empirical relationship between annual precipitation and summer temperature at the glacier steady-state equilibrium line altitude, shows that the possibility of Alpine glaciers to disappear within decades is far from slight.

Modern strategies of glacier monitoring combine *in situ* measurements, remote sensing techniques and numerical modelling.

These approach allows to assess past as well as potential

evolutions of area and volume of a glacier ensemble within an entire mountain range. The main uncertainty of these estimations comes from the representativity of the available measurements for the entire glacierisation of the mountain region, and from the large range of the different volume estimations.

P48 Reassessing the input-output mass budget of East Antarctica between 50°E and 140°E

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Accurate assessments of the past and future mass budgets of polar ice sheets are essential to resolving contributions to past sea-level rise and projecting responses to climate change respectively. Both tasks require that ice accumulation and ice flow are each accurately described, and that differing changes in interior and coastal margins are integrated. This is usually described as the mass budget method (*e.g.* Rignot and Thomas 2002).

Current ice sheet mass imbalances and corresponding contributions to sea level change can also be estimated by directly observing changes in mass (*e.g.* GRACE mission) or elevation (*e.g.* satellite altimetry).

Initial results from GRACE (Velicogna and Wahr 2006) suggest that East Antarctica is in balance, while satellite altimeter measurements of surface elevation changes over a slightly longer time-frame [Zwally *et al* (2005), Davis *et al*. (2005)] indicate that the interior of the East Antarctic ice sheet is thickening slightly, although there is not quantitative agreement about the magnitude.

Direct estimates of ice sheet change appear capable of considerable accuracy and are useful in establishing the present state, but they only constrain the difference between the physical ingredients - current rates of net ice deposition and export by ice dynamics from the region surveyed.

As a step towards testing how well current ice accumulation estimates correlate with the presently observed pattern of ice flow and how the East Antarctic interior might be presently contributing to sea-level change, historical field measurements of ice flow from Enderby Land to Wilkes Land (50°E to 140°E) are compared with estimates of ice accumulation to estimate the state of balance using computed "balance" ice fluxes (Budd and Warner 1996). This enables local estimates of the regional state of balance to be made, even for sparsely surveyed regions.

The measured ice fluxes are drawn from ANARE field surveys of ice motion and ice sheet thickness, while the balance fluxes are computed using ice accumulation datasets and a satellite derived digital elevation model.

The comparisons enable some inferences about differing regional states of imbalance of the ice sheet, about uncertainties involved in the component flux approach to the budget, and about the fidelity with which the available accumulation datasets reflect the long-term ice input.

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P49 Modelling future volume changes of glaciers using ERA40-reanalysis and climate models – A sensitivity study on Storglaciären, Sweden

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The overall goal of our project is to model the contribution of melt from glaciers outside the ice sheets to future sea-level rise on a century time-scale. As a first step we computed until the year 2100 the mass balance and volume evolution of Storglaciären, a small valley glacier in Sweden, using a temperature-index mass balance model. We focus on the sensitivity of results to the choice of climate model and variants of adjusting ERA-40 temperatures to local conditions. ERA-40 temperature and precipitation series from 1961-2001 are validated and used both as input to the mass balance model and for statistical downscaling of one regional and six Global Climate Models (GCMs). Future volume projections are computed using area-volume scaling and constant glacier area. ERA-40 data correlates well with observations and captures observed inter-annual variability of temperature and precipitation. The mass balance model driven by several variants of ERA-40 input performs similarly well regardless of temporal resolution of the input series (daily or monthly). The model explains ~70% of variance of measured mass balance when the input temperatures are reduced by the lapse rate that maximizes model performance. Fitting ERA-40 temperatures to observations close to the glacier does not improve the performance of the model, leading us to conclude that ERA-40 can be used for mass balance modeling independent of meteorological observations. Projected future volume series show a loss of 50-90% of the initial volume by 2100. The differences in volume projections vary by 40% of the initial volume for six different GCMs input to mass balance model, while each volume projection varies by 20% depending on whether volume-area scaling or constant area is used and by 10% depending on details in the mass balance model used. The correction of biases in the seasonal temperature cycle of the GCMs with respect to the ERA-40 data is crucial for deriving realistic volume evolution. A possible way of using our results to predict a total contribution of glaciers to sea level rise in the 21st century is direct application of the model to other glaciated regions taking advantage of the model's simple data requirements available from ERA-40 reanalysis. However, further study is needed to evaluate how far the calibrated mass balance model for one glacier is transferable to other glaciers, and whether representative sets of model parameters can be found for glaciers in similar environmental settings.

P50 Numerical modeling of ocean circulation over the continental shelf and beneath the ice shelves in the Amundsen Sea, Antarctica

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Using a 3-D numerical model, we investigate the hydrography and circulation of ocean waters overlying the continental shelf in the Amundsen Sea. The goal of this study is to better understand processes which govern the temporal and spatial distribution of 'warm' circumpolar deep water (CDW) on the continental shelf, and its derivatives. That deep water, abundant offshelf, migrates onto the continental shelf and subsequently beneath the floating ice shelves that drape most of the coastline in this sector. This leads to extensive basal melting, which may be negatively impacting the mass balance of the West Antarctic Ice Sheet. We employ a coupled isopycnic ocean, dynamic-thermodynamic sea ice, and thermodynamic ice-shelf model, along with daily varying atmospheric forcing and available bathymetry, to simulate the pathways and properties of waters on the continental shelf. We compare model simulations to ocean observations taken in the area since 1993.

TOPIC 5:

Terrestrial water storage

P51 Comparison of snow and liquid water mass variability over North America from GRACE and hydrological model data

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The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides monthly solutions for the Earth's gravity field in terms of spherical harmonic coefficients (L2 products) complete to degree and order 120. It is expected that GRACE will provide reliable constraints on water storage variability and dynamical processes in the Earth's interior. In North America, in particular, a good knowledge of short term mass variations is important in order to have a good representation of the secular changes in the gravitational potential due to postglacial rebound.

In this study, time series of monthly geopotential fields (February 2003 to January 2005) are constructed and analyzed subsequently in order to study short term (annual and inter-annual) mass redistributions over North America. To study the spatial patterns of the time varying mass effects, principal component analysis (PCA) is applied on the series of the residual (with respect to the two-year mean) geopotential field. Then, singular spectrum analysis (SSA) is applied on the leading principle components in order to reveal their temporal structure. A strong annual signal is extracted in Western Canada and the USA, Alaska, and Quebec, which matches the location of maximum seasonal snow change in North America shown by the models. Furthermore, the GRACE annual signal is compared with continental water storage outputs from the LaD, CPC, and GLDAS models in order to draw conclusions about the agreement with each particular model. The models' surface mass anomalies for the same two-year interval are converted into geoid changes and are compared to the estimated annual GRACE signal. Our results agree, in general, with results from previously published studies based on least-squares inversion of the GRACE time series, which confirms the ability of the PCA procedure to estimate annual mass variability from the noisy GRACE data.

P52 Seasonal terrestrial water storage change and global mean sea level variation

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We examine estimates of seasonal terrestrial water storage change, and its contribution to global mean sea level variation using different data resources, including time-variable gravity observations from the Gravity Recovery and Climate Experiment (GRACE) mission, and terrestrial water storage and atmospheric water vapor changes from the NASA global land data assimilation system (GLDAS) and National Centers for Environmental Prediction (NCEP) reanalysis atmospheric model. The results are compared with satellite altimeter observations. At seasonal time scales, the results from all estimates are consistent in amplitude and phase, in some cases with remarkably good agreement. The results provide a good measure of average annual variation of water stored within atmospheric, land, and ocean reservoirs. We examine how varied treatments of degree-2 and 1 spherical harmonics from GRACE, laser ranging, and Earth rotation variations affect GRACE mean sea level change estimates. We also show that correcting the standard equilibrium ocean pole tide effect for mass conservation is needed when using satellite altimeter data in global mean sea level studies. These encouraging results suggest that it is reasonable to consider estimating longer-term time series and rates of water storage in these reservoirs, as a way of tracking climate change. However, other long-term mass change signals, such as postglacial rebound, must be correctly modeled and removed, in order to correctly interpret long-term water mass change signals over either ocean or land.

P53 Continental freshwater discharge from GRACE

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Freshwater discharge from the continents is a key water cycle component with important implications for Earth system interactions and global environmental change. However, no comprehensive global streamflow observing network for the world's major continental watersheds currently exists. Here we propose a method for estimating monthly discharge for the continents and their large drainage regions based on the use of GRACE estimates of terrestrial water storage changes in a coupled land-atmosphere water balance. The method has been previously tested on the Amazon, Mississippi and Mackenzie river basins. Here we apply the approach at the continental scale. Results and comparisons to observations indicate that the method has important potential for global-scale discharge monitoring of combined surface water and submarine groundwater discharge.

P54 Vertical Motion Observed by Satellite Altimetry and Tide Gauges

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In principle, the difference between the sea surface height changes measured by tide gauge and altimeter is the vertical motion at the tide gauge. Combining long-term tide gauge and decadal altimetry observations to infer vertical motion of the solid Earth has been proposed by prior studies. An attempt to use this technique resulted in vertical motion solutions with uncertainties >>2 mm/yr, rendering the technique not as viable. Here we describe a novel technique, which is an improved algorithm used by Kuo *et al.* (2004) which used long-term tide gauge records (>30 years) and decadal TOPEX altimeter and a stochastic network adjustment approach in the semi-enclosed Baltic Sea and in the Great Lakes to determine vertical motion at tide gauge sites at an accuracy <0.5 mm/yr. This extended algorithm could potentially apply to worldwide tide gauges for improved determination of vertical motions, which the primary purpose to improve sea level determination to also potentially include more sites which previously are not used because of unknown vertical motions, including tectonic activities

TOPIC 6:

Context of sea-level observations

P55 CAGENET: A proposal for a Canadian Geodetic Network for Earth Systems Monitoring

M.G. Sideris, and the CAGENET team

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Currently, Canada has a very sparse, and thus highly insufficient, network of permanent GPS stations and GPS-collocated tide gauge stations (49 and 12, respectively, in total) for monitoring various Earth processes such as postglacial rebound, sea level and climate changes, surface water and arctic ice dynamics, storm surges and tsunamis, earthquake strain buildup, and regional and local tectonic stress fields and land deformations. This sparse coverage of monitoring sites severely compromises the ability (i) of Earth scientists and engineers to monitor, understand, model and predict complex Earth systems in Canada and world-wide, (ii) of government and industry to develop hazard mitigation, early warning and response strategies, and (iii) of Canada to play a key role in the various international Earth observation programmes.

In order to improve this situation, a consortium of scientists from 11 universities and 5 governmental institutions across Canada have proposed the development and realization of a Canadian Geodetic Network for Earth Systems Monitoring (CAGENET). 50 new permanent Global Navigation Satellite System (GNSS) receiver stations are being proposed to be added nationwide, with upgrades to 10 existing permanent GPS receivers to GNSS receivers, and an addition of 8 new tide gauge stations co-located with GNSS stations. It is also proposed to increase dramatically the number of absolute gravity stations with the acquisition of an absolute gravimeter.

The diverse research team will assimilate data sets collected by the network's sensors to study, among other things, sea level, surface water and arctic ice changes, as well as earthquake, flood and surface deformation hazards. Better understanding of these Earth processes will yield immediate benefits to the fields of sea level and climate change impact and adaptation, hazard monitoring and mitigation, water resources management, and mapping, positioning and navigation. CAGENET will, therefore, not only bring Canada to the forefront of Earth systems research but it will also contribute significantly to the numerous current and future global efforts for monitoring our planet.

P56 Mean sea level, satellite altimetry and global vertical datum realization

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Over the past several decades, the definition of a global vertical datum and the realization of such a system has been a topic of great research and debate. Many different methods for defining a vertical reference system to be implemented all over the globe have been presented. The definition of such a global vertical reference system is further complicated by accuracy and spatial coverage limitations of the traditional techniques, and the sea level variations affecting tide gauge and satellite altimetry measurements.

This poster provides a very brief account of the various definitions and realizations of a vertical datum, and highlights the role of mean sea level and altimetric satellite measurements to the vertical datum definition issue. Since one of the major problems with the definition and subsequent acceptance or adoption of a globally defined datum is dealing with existing regional datums, the Canadian and North American (NA) situation are briefly presented first to illustrate some of the issues, and future plans, involved in vertical datum realizations. Then the most common approaches to vertical datum definition and realization are presented. Finally, details are given on the important role that mean sea level and satellite altimetry play in the realization of (i) regional vertical datums and (ii) the global vertical datum or World Height System.

P57 Development of Indonesian sea level monitoring network supporting for precise applications

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Lesson learned from the Indian Ocean Tsunami, Indonesia have been improving the existing national sea level monitoring network not only for serving mapping but also dedicated to applications required more precise observations such as weather and climate research, and multi hazard assessment and tsunami warning system. The improvements are mainly focused on three parts namely (i) to densify the station distribution with real (or near real) time data communication, (ii) to set up precise datum and (iii) to up grade the tide staffs with high quality material. First, based on the grand design of Indonesia Tsunami Warning System, in addition to the existing 60 stations, it is planned to set up a number of 60 real time stations situated adjacent to the tsunamigenic plate boundaries. Most of the stations would be part of Indian Ocean Tsunami Warning System (IOTWS) with the establishment coordinated by IOC/UNESCO. At present there are 7 of 60 planned real time stations in place of which 4 stations were set up under cooperation with the University of Hawaii Sea Level Centre (UHSLC), 2 stations funded by the Indonesia Government and one stations donated by the OTT Company of Germany. It is expected by the end of 2006, there would be 20 stations installed. Second, efforts on providing precise datum have been carried out annually with precise geodetic leveling from the tide gauge staff to Tide Gauge Bench Mark (TGBM) and precise GPS measurements at TGBM, referenced to the latest International Terrestrial Frame (ITRF). Lastly, improvement of the tide gauge staff from sheet steel to that of fiber glass bar is expected to provide high quality, and long life stable staff meter. We identified that using the vertical staff gauges of sheet steel or aluminum is one of the error sources such as discontinuity in the sea level reading time series and improper join between the sheet steels of a tide staff. Errors caused by discontinuity in sea level readings may occur when the station operators are mistakenly archived the data record of tide staff change. At least every one or two year replacement of sheet steels should be carried out since the scale readings are becoming deteriorated resulting from regular cleaning of the staff from coral and sea creatures. Improper joins between sheet steel of a tide staff are not perfectly made during the replacement. Therefore, we designed new type of tide gauge staffs made of fiber glass bar with the reading scale covered by strong and transparent resin layer. This staff bar with size of 5 cm x 8.5 cm x 3 meters, consecutively for thickness, width and length, it could provide high stable reading scale for more than ten years. It expected that the high resolution observations with real time data communication, precise datum and high stable tide staffs, this will contribute significant improvements in the sea level monitoring in the Indonesian Archipelago.

P58 Managing sea level rise: A regional coastal simulator to support decision making

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Coastal regions are particularly vulnerable to the increases in sea level and storminess, and significant impacts are inevitable through the 21st century and beyond without adaptation. Successful adaptation demands a scientific understanding of coastal dynamics at broad scale including the interaction with ecological and human systems; in addition, it requires defining appropriate goals and developing suitable systems of coastal governance. This research builds on the considerable progress made during the Tyndall phase1 that included process based modelling of the effect of climate change on wave climates, coastal erosion, flood analysis, ecosystem responses and local socio-economic scenarios. In Tyndall Phase 2, a fully integrated tools for coastal simulation and analysis will be developed within a regional coastal simulator that can be used to identify how the future coastline may evolve; to determine what constitutes a sustainable coastline by quantifying ecosystem, flood and erosion risks; and to explore how best to deliver sustainable natural and social capital in the coastal zone in the face of climate change.

The development of regional coastal simulator requires linking the existing models to the Hadley Centre's coupled global climate model via a downscaled regional model, including wave and surge simulations. As nearshore sandbanks control the coastal wave climate, a new sandbank morphological model will be developed derived from: (i) direct process models (applying calibration techniques used for long-term nearshore wave climate), (ii) conceptual models, and (iii) cellular methods. The Scroby Sands offshore turbine site will be used for calibration and validation of this model. The coastal simulator will be applied at sub-cell scale to explore coastal evolution and risk.

The implications on coastal resources will be assessed by investigating the consequences of geomorphological change for biodiversity and ecosystem elements using fuzzy set approach. Socio-economic impacts will be assessed using downscaled socio-economic scenarios and urban landuse model developed using Agent Based Modelling that enables feedbacks and provides dynamic modelling. A wide range of adaptation options will also be explored, including both conventional and novel flood risk management systems to identify robust portfolios of hard and soft measures which could deliver a sustainable coastal zone. These will include wave energy extraction and large-scale managed realignment. Links to relevant stakeholders will be maintained using an existing network developed in phase 1 and further enhanced with those involved in shoreline management and coastal biodiversity. This network will be used to explore stakeholder participation and for improving coastal governance to respond to the challenge of climate change.

P59 Efforts to understand sea level variability in the Southeastern Brazilian coast

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The Tropical and Mid-latitudes South Atlantic is one of the worst sampled oceans of the world for the sea level (Woodworth & Player, 2003). This problem increases the global uncertainties of the estimates for sea level variability and trends. On the other hand, this oceanic region does not present severe tropical storms and has geologically stable coastal boundaries thus a good signal to noise ratio may be achieved for estimating sea level climatic variability. Also, the region connects the two main areas of deep water formation - Weddel Sea and the Norwegian Sea - through the "conveyor belt" (Broecker, 1994). So, it is a particularly suitable region for understanding the global sea level variability.

In Brazil, only two sea level records have data long enough to allow climatic estimates: Cananeia, just over 50 years record, and Rio de Janeiro, over 40 years, in the Southeastern coast, both indicating sea level rise (3.2 +- 0.4 and 3.6 +- 1.1 mm/yr respectively) at rates twice as fast as the global upper bounds estimates (Mesquita *et al.*, 1995; Church *et al.*, 2001). To understand this variability, efforts are being made to instrument the Cananeia station with real time tide gauge and permanent GPS records alongside with gravity measurements.

Efforts also have been made towards obtaining a long sea level record from Santos port - the largest port in the South America -

where beach erosion, increasing number of extreme events and salinization of the estuary have been reported (Harari & Camargo, 1995), although the 2004 Sumatra tsunami recorded with local 1m amplitudes during high tides was almost unnoticed. In this port, dredging operations have been performed periodically, so real time tide gauges observations are also necessary to increase navigation security.

Data from oceanographic stations in the Southeastern Brazilian coast are not enough to estimate trends in the dynamic heights, eventhough it is the most sampled oceanic region along the Brazilian coast. Systematic yearly observations of the entire water column in an oceanographic section through the Brazil deep basin have been proposed (Mesquita, 1989); these observations would give the dynamical thickness of different water masses in the region and their varibilities, allowing to compare them to the sea level records in the coast.

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P60 A global database of sea-level indicators

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In order to analyse large sets of sea-level indicators (SLIs) as presented at the poster 'Fuzzy logic as an alternative tool for the interpretation of sea-level indicators with respect to glacial-isostatic adjustment' we suggest the storage of SLI data in an SQL database system. This allows the extraction of subsets by given conditions in an automatised way and also the development of maps, sea-level curves, histograms and other representations of the data set. Using the open source database system PostgreSQL, such a database was build up during the strategy fund program SEAL, Sea Level Change: an Integrated Approach to its Quantification, of the Helmholz Community of German Research Centers (HGF) and covers at present 14,000 SLIs. The dataset is based on compilations by Art Dyke (North America), Ian Shennan (Britain), Kevin Fleming (equatorial regions) and own compilations of Fennoscandia, Barents Sea, Patagonia and Antarctica. The poster presents the current state of the database, the stored attributes as examples for its use. The motivation of this presentation is to refresh the idea to build up a unique global database of SLIs as already formulated and started during the IGCP project 61, invite collegues of similar compilations to contribute to this database or merge the different existing compilations to one unique system.

P61 The concepts in sea level studies: a detailed analysis of errors

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In the context of climate change and global warming, sea level has gained a central role for two reasons, namely (1) as a quantity potentially constraining the mass balance in the global water cycle, and (2) as a quantity associated with one of the main impacts of a global warming potentially threatening a large part of the human population. The impact related quantity is Local Sea Level (LSL), while for the mass balance the global ocean mass is a key indicator. Estimates of a global sea level rise over the last 100 years have been utilized in the climate change discussion as an indication of changes in the ocean volume and mass. Scenarios of future global and regional sea level changes are increasingly used to plan mitigation in order to protect the densely populated coastal areas. However, the discussion of sea level rise and the mass balance of the global water cycle, as well as the impact of sea level changes is hampered by the absence of a well defined terminology that is based on a commonly accepted basic concept reflecting the underlying physics properly.

Here we define LSL as the local distance from ocean bottom to sea surface. LSL is an absolute quantity, *i.e.* reference frame independent. LSL is directly related to the volume of the ocean and, for known density distributions, the mass of the ocean. At coastal locations, appropriately established and operated tide gauges measure directly. Correcting tide gauge measurements of LSL for vertical land motion leads to a reference frame dependent quantity, which is no longer directly related to ocean volume changes. LSL is different from the geocentric position of the sea surface, which is determined by satellite altimetry. The latter is reference frame dependent and not directly related to ocean volume and mass changes.

At any location, LSL is the output of Earth system processes acting on a wide range of spatial and temporal scales. For low frequencies, this leads to a complex equation of LSL as a function of the heat and salinity distribution in the ocean, ocean currents and atmospheric circulation, the mass distribution in the large ice sheets, continental glaciers, and the terrestrial hydrosphere, postglacial rebound, endogenic and anthropogenic vertical land motion and geoid changes, as well as changes in shape and extent of the ocean basins. The fingerprint of all mass-related contributions are described by the so-called 'sea level equation', which links mass movements to sea level changes.

The LSL equation is used as a tool to set up a detailed quantitative error budget of local, regional and global estimates of sea level changes obtained from tide gauge and satellite altimetry measurements. Moreover, it is demonstrated that the LSL equation provides a basis for setting up local scenarios of plausible future LSL variations needed for the planning of mitigation and adaptation. The LSL equation emphasizes the need to establish such local scenarios in a global geodetic reference frame, putting high demands on the accuracy of this frame.

P62 Tide gauges contribution to altimeter calibration experiences in the western Mediterranean

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Three Begur Cape experiences on radar altimeter calibration and marine geoid mapping made on 1999, 2000 and 2002 are overviewed. One campaign has also been made in June 2003 at the Ibiza island area. The marine geoid has been used to relate the coastal tide gauge data from Ibiza and San Antonio harbours to off-shore altimetric data. A technical Spanish contribution to the calibration experience has been the design of GPS buoys and GPS catamaran taking in account the University of Colorado at Boulder and Senetosa/Capraia designs.

L'Estartit tide gauge is a classical floating tide gauge set up in l'Estartit harbour. Data are taken in graphics registers, from which a data each two hours is recorded in electronic support. This two hour data are interpolated to one hour data to do a good harmonic analysis of the astronomical tide. Tide gauge is controlled each week to get correct and accuracy data and the tide gauge maintenance has the same periodicity. A quality control to ensure the self-consistency of the records has been made. The tide gauge heights are geo-referenced to a benchmark in the adjacent jetty identified as number 314 094 002 in the Cartographic Institute of Catalonia (ICC) classification (UTM coordinates X=517199.76m, Y=4655985.52m and Z=+1.72m from the zero reference height of the tide gauge). The coordinates of this geodetic mark have been calculated in 1999 by a precise leveling survey in order to connect the benchmark to the local EUREF sub-network that includes the permanent GPS IGS-ITRF station at Cap de Creus,

It is expected to have installed at l'Estartit harbour the radar tide gauge Datamar 3000C and the Thales Navigation Internet-Enabled GPS Continuous Geodetic Reference Station (iCGRS) System with a choke ring antenna, by end of the year 2006. The overall system will constitute a CGPS Station.

Puertos del Estado (Spanish Harbours) installed the tide gauge station at Ibiza harbour in January 2003. The station belongs to the REDMAR network (http://www.puertos.es). The tide gauge also belongs to the ESEAS (European Sea Level) network. In this case an Aanderaa water level/temperature sensor (3796 A) with compensating unit for atmospheric pressure has been installed at the Golondrinas pier (Ibiza harbour). In 2004 a permanent GPS station, funded by the ESEAS – RI EU project, was collocated with the tide gauge in a building in front of the tide gauge peer. The station coordinates are: 38º54'40.56" N, 1º26'59.46"E. The San Antonio tide gauge, deployed by IMEDEA Institute, was funded by the European Space Agency (ESA) in the framework of the calibration and validation activities of the ENVISAT radar altimeter RA-2. The instrument is an Aanderaa WLR 7 complemented with an Aanderaa Air Pressure Sensor 2810 installed on the dock of San Antonio harbour. In the framework of the campaign, the levelling of the Ibiza and San Antonio tide gauges to the respective GPS markers was performed. The role of the tide gauges measurements had three main components: Calibration of the GPS buoys, MSS mapping during GPS catamaran campaigns and to do Indirect Altimeter Calibration.

We present a synthesis of the results obtained from Topex/Poseidon and the first results on Jason-1 altimeter calibration using the direct measurements from GPS buoys and the derived marine geoid. The Ibiza results, related to Jason-1, agree relatively well with results obtained at Corsica, Harvest and Bass Strait calibration permanent sites. Moreover, the geodetic activities (e.g., GPS, levelling) has permitted to build a very accurate (few mm) local network linked to the European one, with a reference frame compatible with the satellite altimetry missions (ITRF2000). A perspective of a new Jason-1, including Envisat, Ibiza campaigns to be made around 2007 will be presented with inclusion of complementary technology as LIDAR airborne systems.

These campaigns were supported by the Spanish Ministery of Science and Technology under projects of the National Space Program ref: ESP1997-1816-CO4-03 and ESP2001-4534-PE.

TOPIC 7:

Responses to changes in surface mass loading

P63 Contribution of the 2004 Sumatra-Andaman earthquake to sea-level change

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GPS-observations have demonstrated that the 2004 Sumatra-Andaman earthquake resulted in very large horizontal co-seismic displacements, still up to 27 cm at a distance of 400 km from the epicenter (Vigny ***et al.***, 2005). Three months later, the Nias earthquake occurred just to the south. During this event GPS measured horizontal displacements up to 20 cm. Earthquakes with such magnitudes are expected to have a significant effect on the co-seismic vertical and gravitational displacement fields as well. Therefore, earthquakes will change both the relative sea level (RSL), defined as the radial distance between the sea floor and the geoid level, and the absolute sea level, which is assumed to be consistent with the geoid.

Both the seismic deformations and the resulting sea level changes have been simulated by means of a spherical, self-gravitating, radially stratified Earth model with linear viscoelastic rheology. The sea level equation has been implemented to ensure water mass conservation.

The results show that the RSL change has a maximum value of 3.5 meters over the fault plane, decreasing fast with distance. At the coast of Sumatra values of several decimeters are found and even at the coast of Thailand a rise of approximately 20 mm is predicted. The absolute sea level changes are maximally 15 mm, close to the epicenter. In the far-field the influence of the earthquake on the sea level does not exceed +/- 0.5 mm.

P64 Sea-level change due to the coupling between variations in the Earth's rotation and glacial-isostatic adjustment

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Climatic fluctuations dominate changes in the distribution of ice and water over the Earth's surface, which in turn affects climate itself. Ice accumulation or ablation and the accompanying changes in sea level result in the deformation of the solid Earth, termed glacial-isostatic adjustment (GIA). The resulting changes in surface topography and bathymetry in turn affects the spatial pattern of sea-level change, again influencing the deformations. The redistribution of ice and water, and mass distribution changes in the Earth's interior also induce perturbations in the Earth's gravitational field and rotational characteristics. The wander of the rotation axis, in turn, induces variations in the centrifugal force and, subsequently, additional variations in sea level and surface deformations. All of these factors therefore mean that the determining sea-level change coupled with polar wander due to changes in ice-water mass loading is a complex geophysical and mathematical problem. Assuming that the deformation in the Earth is small, the movement of the rotation vector can be described by the linearized Liouville equation. The numerical integration of this requires us to specify the temporal perturbations in the inertia tensor. The new approach presented here, which is based on the MacCullagh formulae, derives this from the time-dependent variations in the second-degree spherical harmonics of the induced changes in the gravitational potential.

Once the Liouville equation is solved, the temporal variability in the centrifugal force is established. This driving force is then considered in the linear-momentum and Poisson equations for GIA to compute the subsequent surface-deformation and gravitational potential changes. This rotational feedback, called the rotational deformation, is mathematically described by various terms in the field equations governing GIA. We will present the separate effects of individual terms on sea-level variations. The rotational deformations are treated in the time domain, which eliminates the need to apply the traditional Laplace-transform method, and in addition allows the conventional approach based on load Love numbers to be extended to the case of a 3-D viscoelastic earth model.

P65 Relative sea-level changes due to recent mountain deglaciation

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Sea-level changes are caused by several different processes, including ocean-water warming and freshening, changes in surface and groundwater storage and the loss of glacier ice mass. According to the IPCC report 2001 melting of mountain glaciers contributes 0.2-0.4mm per year to sea-level rise. Direct observational constraints are unavailable and the different estimates are based on different model assumptions and parameters.

Numerical calculations are based on indirect measures of ice-volume changes. In particular these are the area of glaciated regions, temperature time series and parameters for mass balance sensitivities. The postulated retreat of the model for 100 glaciated regions calculated for the period 1865-1990 is in agreement with the IPCC results, although closer to the lower limit. Results indicate that melt-water from Patagonia, the Himalayas, Alaska and Canada, and the Arctic Sea constitute more than 90% of the global total, and that the glaciers in these regions have the greatest impact on eustatic and isostatic sea level change.

Dyurgerov ***et al.*** (2005) has independently estimated the eustatic sea-level rise and obtained a value of 0.51mm per year. This compilation of glacier volume changes is based on available mass balance observations. However, since observational data is not complete it is necessary to extrapolate from individual sites to larger areas, which again is based on model assumptions and consequently results in uncertainties in the total values. In particular a volume/area scaling algorithm has been applied, that results in a considerably higher value for total glacier volume than reported by some other authors. Furthermore, this data set represents the change in glacier-volume of a more recent period (1961-2003).

The mass redistribution between the ice load and the ocean results in a spatial variability of relative sea-level changes and vertical displacements of the Earth's surface. The regional pattern, and also the geodetic signal, is determined by the location of the largest changes in glacier volume and to a lesser degree by the ocean-land geometry. Results from numerical modelling at the Yakutat tide gauge station in Alaska shows 1.1mm per year relative sea-level fall. For the Ny Ålesund station in Spitsbergen relative sea-level fall at a rate of 0.7mm per year can occur due to mountain deglaciation. Similar estimates for vertical land uplift at GPS sites can reach 0.6mm per year in Alaska and Spitsbergen.

It is necessary to improve the reliability of the model of glacier volume changes in order to be able to model the rebound and the change in gravitational attraction due to mass redistribution. On the contrary, a dense and highly accurate network for monitoring relative sea-level changes and vertical deformation of the Earth's surface may provide the possibility to extract the contribution of the geodetic signal caused by nearby mountain deglaciation. However, this is subject to tectonic deformation in that area being known or negligible.

P66 Sensitivity of GIA models with shallow low-viscosity earth layers to the ice-load history in relation to the resolving power of GOCE

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The GOCE satellite mission, which is planned by ESA for launch in 2006, is designed to map the static global gravity field with centimeter accuracy in geoid height at hundred km resolution. Such a global high resolution gravity field might be able to constrain properties of shallow low-viscosity zones using glacial isostatic adjustment (GIA) models. In van der Wal, Schotman and Vermeersen (2004) it is shown that a crustal low-viscosity zone (CLVZ) can introduce variations in geoid height up to several decimeters with spatial scales of hundred kilometers, and that this response is sensitive to changes in the properties of the CLVZ. In this study we show, using spherical harmonic degree amplitudes, that GOCE is sensitive to differences in the ice-load history up to degree 130 for a CLVZ. This means that GOCE could provide information on the ice-load history in the presence of a CLVZ, provided that our knowledge of the earth is sufficient. To extract information about the CLVZ from the degree amplitudes, we show that it is possible to largely remove the influence of the ice-load history and thus compute spectral signatures for different properties of the LVZ. We focus on the continental shelf-areas of western Europe to show the sensitivity of present-day sea level rise to the inclusion of a CLVZ. In future work we will introduce lateral heterogeneities in our earth model using the finite element method (see Wu, Wang and Schotman 2004) to obtain realistic estimates of the effect of a CLVZ.

P67 Fuzzy logic as an alternative tool for the interpretation of sea-level indicators with respect to glacial-isostatic adjustment

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An important constraint for the inference of mantle viscosity and loading history of the last glaciation is the variation of the Holocene relative sea level (RSL) height following the last Pleistocene deglaciation. As a measure of this variation, sea-level indicators (SLIs) like peat, shells or driftwood which are related to the former RSL height are used. Usually, a nominal RSL height and age is derived from the particular SLI where the uncertainty due to the type of the SLI is expressed by a standard deviation and, so, interpreted in terms of probabilities. In contrast, we express the depositional conditions of the SLI by fuzzy sets which defines a more realistic relation between the observed height of the SLI and the former sea-level height in terms of possibilities. Fuzzy logic then allows a systematic classification of the SLIs available, the validation of Holocene RSL height change and the inversion of the viscosity structure of the earth's mantle as for glacial changes. We show the properties and advantages of this method by application to different regions of the earth.

P68 Recovering lateral variations in lithospheric strength from bedrock motions with a coupled ice sheet-lithosphere model

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Sea level is generally studied with glacial isostatic adjustment models consisting of a prescribed ice history (such as ICE-3G) and a visco-elastic earth model governing deformation to surface loading. Most of these ice histories result from optimization procedures given a collection of sea level data and a specific earth model. The earth model is in general laterally homogeneous. We coupled a vertically integrated two-dimensional ice flow model to an elastic lithosphere earth model to study the effects of lateral variations in lithospheric strength on both ice sheet evolution and local bedrock adjustment. This approach of using a dynamical ice flow model is completely independent from existing methods since the ice model is based on ice rheology and paleoclimatic data instead of sea level data. Moreover, we used a lithospheric model which incorporates lateral variations in lithospheric strength.

We constructed synthetic bedrock motion time series to assess their potential in resolving lithospheric structure. These inverse experiments show that the model can resolve lateral variations in lithospheric strength from bedrock data, provided that we have data from both sides of a lateral transition in lithospheric strength.

The inversion which solves for a lateral transition is able to find a solution which is consistent with all data, even if they are noisy. In the presence of lateral variations in lithospheric strength, there is no solution to the inverse problem for which all data are modeled correctly for a uniform lithospheric model. The synthetic data show no sensitivity to the location of the transition. As a result we require information from independent sources about the locations of possible transitions in lithospheric strength.

P69 Ocean thermal expansion: Simulated oceanic mass load changes and their implications

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Ocean thermal (or thermosteric) expansion occurs due to heat uptake by the ocean under global warming conditions and is frequently simulated in climate change scenarios with coupled atmosphere ocean general circulation models. Although steric sea level changes do not alter the constant global ocean water mass, a mass redistribution within the global ocean does occur. Here, we present a simple conceptual model that explains why these mass redistributions must ensue due to ocean thermal expansion: the reason of the described effect can be explained with the decreasing ocean area with increasing depth, and ocean warming occurring at deeper layers. Thus, shallow shelf areas experience relatively strong positive mass load changes, while the deep ocean areas show a consistent small negative mass load anomaly.

Mass load changes are equivalent to ocean bottom pressure changes. We diagnose these bottom pressure changes in a global warming simulation performed with the Max Planck Institute for Meteorology coupled Atmosphere Ocean General Circulation Model ECHAM5/MPI-OM. The climate change scenario builds on observed atmospheric greenhouse gas (GHG) concentrations from 1860 to 2000, followed by the International Panel on Climate Change (IPCC) A1B climate change scenario until 2100; from 2100 to 2199, GHG concentrations are fixed at the 2100 level. Compared to the unperturbed control climate, global sea level rises 0.26 m by 2100, and 0.56 m by 2199 through steric expansion; eustatic changes are not included in this simulation.

We estimate that bottom pressure can increase up to 0.45 m with a global mean sea level rise of 0.26 m and simultaneous ocean circulation changes. Furthermore, bottom pressure changes as a function of bottom depth can be quite different locally. Since the shallow ocean areas are not distributed evenly across the world ocean, the additional mass loading from mass redistribution at constant global ocean mass results in anomalies in the spherical harmonic components of Earth's gravity field. For length-of-day changes, derived from anomalies of the oceanic Stokes coefficient C_20, the estimated effect is of the order of 0.1 ms length-of-day change with a global mean steric sea level rise of 0.56 m.

The effects of ocean mass redistribution or bottom pressure changes at constant global ocean mass have not received much attention in climate change simulations, but it may have important implications for applications such as GRACE.

P70 Antartic glacial history, glacial isostatic adjustment, and consequences for global sea-level change

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GRACE satellite measurements of time-variable gravity over ice sheets have the potential to determine the mass balance over interannual time scales. Recent work by several groups using GRACE data (Velicogna and Wahr, 2006; Ramillien *et al.*, 2006; Luthcke *et al.*, 2006) indicate that Antarctica is in negative mass balance. Although this is a preliminary result due to the poorly constrained atmospheric component of the signal and spatial error distribution at high latitudes (Horwath and Dietrich, 2006), if it is confirmed, it is one of the most important scientific results from space geodesy over the past several decades. An additional source of uncertainty associated with gravity measurements is caused by the uncertain level of ongoing glacial isostatic adjustment (GIA). Crustal uplift generates a gravity increase in space that is opposite to the observed gravity decrease arising from present-day ice mass decrease.

We have developed an Antarctic ice-sheet history model (IJ05) which is based on a synthesis of the current constraints on past ice history and present-day mass imbalance. It provides about 10 m of equivalent eustatic sea-level rise since Last Glacial Maximum (LGM). Although the initial retreat of the grounding line begins at about 21,000 yr BP, the retreat is prolonged and features a substantial drawdown of ice that continues up to about 2000 years ago. The IJ05 model is tuned to ice core stratigraphy, glacier moraine and rock surface exposure dates, and offshore grounding-line retreat chronology. The largest potential uncertainty that remains is the possibility of a large ice dome centered in the Weddell Sea, an area for which we have little field data. The predicted present-day glacial isostatic adjustment (GIA) uplift rates peak at 14-18 mm/yr and geoid rates peak at 4-5 mm/yr for two contrasting viscosity models. If the asthenosphere underlying West Antarctica has a low viscosity then the predictions could change substantially due to the extreme sensitivity to recent (past two millennia) ice mass variability. We treat the uncertainty in both the ice history and viscosity structure as a source of error for present-day GRACE measurements and provide a quantitative mapping of that error into the 21st century secular mass budget of Antarctica.

P71 Surface gravity and geoid rates to constrain postglacial rebound models in North-America

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Postglacial rebound models can be used for prediction of uplift rates, or they can be used to constrain Earth parameters and ice history using observations of the rebound process. The latter path is taken here, making use of gravity data available from the readjustment of the Canadian Gravity Standardization Network (Pagiatakis and Salib 2003). In this presentation, simulations of postglacial rebound are compared with these data and with a geoid rate constructed from a combination of GPS and gravity data.

The postglacial rebound model used is a simple radially symmetric 6-layer Earth with Maxwell rheology. Marine base ice is accounted for in the solution of the sea level equation, but without rotational feedback (even though this significantly alters the C21-coefficient, Tamisea ***et al***., 2002). We demonstrate that shifting ice from one dome to another does not affect the geoid rate much. The main uncertainty in postglacial rebound models results from lack of knowledge of mantle viscosity. Using different values as approximation for viscosity profiles found in the literature, we find that increasing the lower mantle viscosity increases the magnitude of the geoid rate. Increasing the upper mantle viscosity increases details in the geoid rate pattern.

The geoid rate is derived from rates of absolute gravity and absolute vertical velocities from GPS which are combined in a generalized least-squares collocation approach. Error propagation yields standard deviations up to 0.1 mm/year. Although the simulations are too simple to infer a definitive viscosity profile, we note that comparison with the derived geoid rate shows that an Earth model with slightly higher upper and lower mantle viscosity than the one by Peltier (2004) is preferred.

P72 A revised theory of polar wander during glacial isostatic adjustment and its consequences for the "sea level enigma"

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Changes in glacial loading, sea levels and the shape of the solid Earth perturb the Earth's inertia tensor and consequently its rotation vector. Observations of true polar wander (TPW) therefore provide important constraints on glacial isostatic adjustment (GIA) and sea level change. Previous studies of TPW, however, have failed to include a nonhydrostatic component in the "background" (unperturbed) oblateness of the Earth, and have therefore underestimated the rotational stability of the Earth system in response to GIA forcing. We present a revised theory for the equations governing load-induced rotation perturbations on viscoelastic earth models, in which the background form of the planet combines a hydrostatic component and an observationally- inferred excess ellipticity. The new treatment significantly reduces the rotational response to GIA processes, and therefore alters some conclusions based on TPW observations. An important example is the "sea level enigma" (Munk, 2002), in which GIA models appear to completely predict rotation data (in the form of secular changes in J2 and TPW as well as ancient eclipse data), but in doing so rule out significant contemporary melting from global ice reservoirs. The "enigma" lies in 1.2 mm/yr of 20th century sea level rise that remains unaccounted for. We demonstrate that when the revised rotational theory is applied, the enigma disappears. It is shown that present day TPW and changes in J2 are consistent with ongoing ice melting equivalent to 1 mm/yr eustatic sea level rise.

P73 Post-glacial rebound and sea-levels: Constraints on the thickness of Holocene ice-sheets from models involving lateral viscosity variations and transient creep

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In order to bring constraints on both the mantle rheology and the thickness of the main ice-sheets, we study the variations of sea-level in relation with the ice history during the last 20Kyr. In this global study of post-glacial rebound, we consider viscoelastic rheologies involving transient creep, phase transitions and also lateral variations of the mechanical properties of the mantle associated with cratonic roots.

Little differences in the predicted sea-levels over Scandinavia and Canada or in the far field are found between, on one hand, models with cratonic roots below cratons and an asthenosphere below oceans and young continents and, on the other hand, models with cratonic roots everywhere.

Using the models without lateral viscosity variations, we attempted to invert simultaneously for both the mantle mechanical properties and the ice thicknesses over Scandinavia, Canada and Antarctica. The fitted data consist in a large database of sea-levels during the last 15000yrs plus some recent values of uplift rate deduced from GPS. Starting from previously published ice models (for example ICE5G) the variations of ice thicknesses are simply introduced through proportionality coefficients independent of time multiplying the ice thicknesses over respectively Scandinavia, Canada and Antarctica. The thickness of the elastic lithosphere, the viscosities of the sub-lithosphere (top 250 km), of the upper mantle and of the lower mantle are also inverted for. Models with various amounts of transient creep or phase transitions are considered.

The values of the inverted parameters for the solutions close to the best fitting value (within 10% of this best fitting solution) are rather dispersed. Only the viscosity of the upper mantle is well defined (around 10 20.7 Pa s). However, many of the well fitting models share similar characteristics: Viscosities in the sub-lithosphere and in the lower mantle around 10 22 Pas, thick ice over Canada (up to 1.3 x Ice5g) and limited melting of ice over Antarctica (0.25 x Ice5g for some models). This last quantity is particularly important as it affects considerably the present-day estimate of ice melting over Antarctica deduced from Grace gravity variations.

TOPIC 8:

Past and future changes in extreme sea levels and waves

P74 Extreme sea level variability along the east coast of India: Present scenario and future projections

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The east coast of India is characterised by the occurrence of storm surges resulting from tropical cyclones generated in the Bay of Bengal. Most of these cyclones occur during post-monsoon period (October to November), while some occur during the southwest monsoon period (June to September). Previous studies (Shenoi *et al.*, 2002) have shown that conditions in the Bay during post-monsoon season, such as higher SST, weaker near-surface winds, increased stratification in the upper ocean due to high river discharges etc. are favourable for convective activities in the atmosphere, which cause formation and intensification of low pressure systems. These low pressure systems travel northward and northwestward and strike the east coast of India and the coast of Bangladesh.

Earlier studies on storm surges along the east coast of India mostly concentrated on development of numerical models to simulate and predict individual storm surge events. A recent study (Unnikrishnan *et al.*, 2004) consisted of analysing hourly tide gauge data for identifying extreme sea level events in the past and for estimating their return periods. Selected stations, namely, Paradip, Vishakhapatnam and Chennai were considered for the analysis. Return period curves were used to assess the flood risks associated with a projected future sea level rise.

Future projections of regional climate were made (Unnikrishnan *et al.*, 2006) by analysing the regional climate model (HadRM2) results for the northern Indian Ocean. HadRM2 simulations (2041-2060) for a control run, in which the concentrations of CO_2 is kept constant at the level of year 1990 and a run with a 1 % increase of concentrations of CO_2 every year (GHG run) since 1990 in an IS92a scenario were analysed for the frequency distribution of cyclones in the Bay. No significant change in the frequency of tropical disturbances between the two runs is found; however, the frequency of intense cyclones is found to be more in the increased GHG simulations than in the control run.

A storm surge model, developed for the Bay of Bengal, forced by daily winds from HadRM2, was run for the 20 year period. Tides along the open boundary were prescribed from a global tidal model. The simulations showed increase in frequency of high surges in the increased GHG run than in the control run.

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P75 Waves and climate change in the North-East Atlantic

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Wave height in the North Atlantic has been observed to increase over the last quarter-century, based on monthly-mean data derived from observations. Empirical models have linked a large part of this increase in wave height with the North Atlantic Oscillation. Wave models provide a tool to study impacts of various climate change scenarios and investigate physical explanations of statistical results. In this case we use a wave model of the NE Atlantic. Model tests were carried out, using synthetic wind fields, varying the strength of the prevailing westerly winds and the frequency and intensity of storms, the location of storm tracks and the storm propagation speed. The strength of the westerly winds is most effective at increasing mean and maximum monthly wave height. The frequency, intensity, track and speed of storms have little effect on these mean wave height but intensity, track and speed significantly affect maximum wave height.

P76 GFDL sea level rise experiments

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GFDL has recently developed two new AOGCMs. These two models are very different from the earlier GFDL models. An important new feature is the use of an explicit free surface scheme in the ocean component of the model. This allows true water fluxes when water moves across the atmosphere-ocean interface. In the past, a virtual salt flux scheme needed to be used which could distort the impact of these fluxes.

In addition to a long 1860 control integration, the new AOGCMs have been used to study climate changes over the past 140 years and into the future. The future integrations used the SRES B1, A1B and A2 scenarios. Present day and year 2100 stabilization integrations were also performed.

Analysis of these integrations indicates that volcanic eruptions can have remarkably long lasting impacts on sea level rise, as long as 1 century. For example, the large Krakatau eruption in 1883 impacts sea level rise well into the 20th century in the model integrations (Delworth *et al.* 2005).

As noted by early authors, sea level changes have very long response time scales to changes in radiative forcing. Evidence for this statement is indicated by the fact that sea level continues to rise long after the radiative forcing is held constant in the various stabilization integrations.

There are large differences in the amount of sea level rise between the two AOGCMs. This difference is due to large differences in the CONTROL simulations of these models in the Southern Ocean (Russell *et al.* 2006). In one, the Southern Hemisphere jet and associated surface wind stress maximum is located much too far north, as is the case in most other AR4 models. The poorly located winds, leads to a poor Southern Ocean simulation with too little mixing when compared to observations. In the second model, the winds and Southern Ocean simulation are much more realistic. The more realistic mixing in this model allows the ocean to take up much more heat when the radiative forcing increases due to the increasing greenhouse gases. The increased heat uptake results in a much larger sea level rise.

The pattern of sea surface height changes due to internal ocean dynamics due to changes in the surface fluxes indicate that the pattern of change is very similar among the various forcing scenarios. Only the magnitude of the change varies from scenario to scenario. One change that is evident is the increase in sea surface height between 40 and 60S. This is due to the southward shift in the ACC associated with the southward shift of the atmospheric wind maximum. Another pattern seen is that associated with the weakening of the thermohaline circulation in the North Atlantic.

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P77 Effects of climate change on extreme coastal sea levels

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Contributions to changes in extreme sea level result from a number of components that have been extensively studied over recent years. In assessing the hazards to coastal communities it is important to understand those interactions between the different sea level contributions and their capacity for co-occurrence. Accurate estimates of extreme coastal sea level rise require knowledge of global mean sea level changes, observed regional trends, regional land movements and changes to storm surge characteristics due to modified climatic winds. We use a series of numerical models to show these coupled changes in storm surge characteristics, tidal propagation, waves and consequently extreme water levels. These changes have an impact on the environmental and socio-economic infrastructure at the coast. In the numerical experiments presented here, two long (30 year) timeslices are simulated: a control run representing present day conditions and a future run for an increased CO_2 scenario. Extreme value statistical methods are used to compare the results from the two simulations. Based on a median IPCC sea level rise we estimate an extreme level distribution relative to the land for the year 2070. The uncertainty associated with each component is discussed. The work demonstrates that because the integrated effects of climate change are regional, one can use regional climate models coupled to ocean models both to increase scientific understanding and to assist policy makers.

P78 Extreme wind waves worldwide from the VOS Data, their changes over the last 100 years and their potential impact on the occurrence of extreme sea levels

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Wind wave observations from Voluntary Observing Ships (VOS) are available for more than 150 years and represent the longest record of wave characteristics in comparison to the satellite data and numerical model hindcasts. Although before the WW-II the data are sparse, for the last 50 years, especially in the Northern Hemisphere Oceans VOS data are characterized by quite dense sampling and may successfully compete with the model and satellite data. In contrast to the other data sources, VOS data initially provide separate estimates of wind sea and swell (from which significant wave height (SWH) can be further computed) and, thus, allow for a separate analysis of wave statistics in extreme wind seas and swells. We used in our analysis visual wave observations from the ICOADS archive of marine meteorological variables, covering the period form 1784 to 2004. After the initial data quality control and multiply consistency checks the visual data were used to estimate changes in mean wave parameters during the last 120 years and characteristics of extreme waves over the World Ocean north of 20S for the last 50 years. The two methods of the estimation of extreme wave statistics were applied. First, the initial values distribution method (IVDM) was used. In this method extreme wave statistics were estimated form the tails of distribution functions fitted to all wave observations for different sizes of the grid cells from 4-degree to 20-degree. The results reported considerably smaller estimates of extreme wave heights in comparison to those reported by altimeter data and WAM model hindcasts. Thus, the highest 100-year return value in the North Atlantic was about 17 meters. In the next step, extreme wind waves were estimated from the peak-over-threshold (POT) method. For the application of POT to the irregularly sampled VOS data we developed a statistical methodology of the determination of storm durations and storm wave peaks. The methodology was validated using 6-hourly WAM data. Application of the POT method to the North Atlantic and North Pacific has shown 100-year return values in significant wave height higher than 22 meters, that is already comparable to the estimates derived from the model simulations. Separate estimates of extreme wind seas and extreme swells, derived from the VOS data demonstrated that extreme values of SWH are largely dominated by seas. Finally, interdecadal variability of statistical characteristics of extreme waves was considered. Interdecadal changes in extreme waves may amount to several meters and demonstrate out-of-phase behaviour in the North Pacific and North Atlantic. The reasons for this phenomenon are discussed in terms of modes of atmospheric circulation variability over the Northern Hemisphere. Finally we discuss potential impact of the extreme wind waves on the occurrence of the local extremes of sea level estimated at the coastal and island tide gauges.

P79 RegIS2: Integrated Metamodel tool for regional climate change assessment

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RegIS2 enables stakeholders to assess the impacts of future climate change on fluvial and coastal flooding, hydrology, biodiversity and agriculture in East Anglia and the North West. Metamodels, accessed via a GIS interface, produce coupled simulations of possible impacts under different climate scenarios for the 2020s and 2050s. The interface also allows users to analyse a range of possible adaptive responses and the influence of future policy and socio-economic scenarios upon this response

Although climate change is a global issue, there is an appreciation of the sensitivity of the coastal zone, biodiversity, agriculture and hydrology at the local to regional scale. As well as impacts on individual sectors, there is a need to consider interactions between sectors. Within the interface, interactions between systems are explored by linking the metamodels to one another, using the data from one model to drive the others.

One of the main components of the integrated tool is the flooding metamodel, based on predictions of sea level rise and increase in storm surges. Specific outputs of this metamodel include the changes in areas of saltmarsh and both coastal and fluvial floodplain grazing marsh, as well as areas at risk of flooding and numbers of people affected by flooding.

The RegIS2 project was funded by the UK Government's Department of Environment, Food and Rural Affairs (Defra) and by UKCIP.

P80 Future changes in Northern Hemisphere extra-tropical cyclones

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Extra-tropical cyclones strongly influence weather and climate in mid-latitudes and any future changes in the frequency, distribution or intensity of these cyclones may have large impacts on the local scale. In this study extra-tropical cyclones are located and tracked in mean sea level pressure data at 6 hourly intervals from experiments carried out with the HadGEM1 coupled ocean-atmosphere model. The atmosphere component of HadGEM1 has a horizontal resolution of N96 (1.25° latitude x 1.875° longitude) and 38 vertical levels. The experiments include a pre-industrial control, a fixed 2xCO_2 experiment and an IPCC SRES A1B experiment. The simulated cyclone track densities in the control experiment compare fairly well with observations in all seasons. In the future simulations there are fewer storms in winter in both hemispheres and the magnitude of the changes generally increases as the temperature rises. There is no shift to deeper storms in the Northern Hemisphere. The tracks shift pole-wards in the Southern Hemisphere. The future changes in storms simulated by HadGEM1 show some similarities to those of earlier Hadley Centre models, *e.g.* fewer Northern Hemisphere winter storms, but the regional changes vary between the models, showing that large uncertainties remain.

P81 Rising Sea Level and New York City: A Case Study

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Global sea level has been rising ~1.7 to 1.8 mm/yr over the past half century, in part due to ocean warming (0.4 mm/yr), and also due retreat of mountain glaciers, as well as thinning of the coastal Greenland ice sheet and parts of the West Antarctic ice sheet.

With nearly 2400 km of shoreline, New York City will be especially vulnerable to the consequences of sea level rise and can anticipate an increased frequency of coastal flooding, affecting significant sections of the financial district, lower Manhattan, Coney Island, the Rockaways, and low-lying Staten Island neighborhoods. Severe storms have historically disrupted and shut down the metropolitan transportation system. Portions of the three major airports - JFK, LaGuardia, and Newark Airports - a number of highways, most area rail and tunnel entrances, and other important infrastructure lie at elevations of 3 meters or less. The storm surge from a category 3 hurricane on a track slightly west of the city could easily surpass this height in many places, even at present without additional sea level rise. This region has experienced several category 3 hurricanes during the 20th century. The duration and number of intense tropical cyclones has already begun to increase.

What of the future? A recent Columbia University-GISS study for the U.S. National Assessment of Potential Consequences of Climate Variability and Change has shown that by the 2080s, sea level could rise by 30-95.5 cm in New York City and 24-108 cm, regionally. As a consequence, the return period of the 100-year flood for combined extra-tropical and tropical cyclones would decrease to 4-36 years in New York City, and 4-60 years, regionally. New GISS E GCM simulations of sea level rise for the New York City metropolitan area for a range of IPCC SRES scenarios suggest increases of 0.25 to ~1 m by the end of this century. Additional studies using several other GCM simulations are in progress. The implications of these findings and possible adaptation strategies will be discussed further.

P82 Assessing the impact of climate change on storm surges in southeast Australia

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A study has been undertaken into the impact of climate change on extreme sea levels along the eastern Victorian coast in southeast Australia and at higher resolution over the Gippsland Lakes and Corner Inlet under specific wind speed change and sea level rise scenarios. Extreme sea levels along this coastline are driven primarily by the passage of cold fronts with their accompanying pressure trough and westerly to southwesterly or southerly winds. Typically, the storm surge component of these events does not exceed 1 m in height. The events can occur year round, but they tend to be most common during the winter half year. The fronts generate a coherent sea level response along the southeast coastline. The methodology devised for this study involves modelling with a hydrodynamic model several hundred actual storm surge events selected on the basis of sea level residuals, derived from tide gauge data, exceeding a defined threshold. Extreme value theory is applied to the modelled sea levels to determine return periods of storm surge at longer return periods than can be estimated directly from the data. Scenarios of average and 95th percentile wind speed changes were determined from 13 climate models yielding low to high wind speed change projections. Results for the annual wind speed changes ranged from -5 to +10 % while 95th percentile wind speed changes ranged from -6 to +11 % by 2070 compared with respective values estimated over 1961 to 1990. Winds during winter indicated a stronger potential increase with the worst case scenario yielding increases in average winds of 14% and in 95th percentile winds of 19% by 2070. Under the annual and winter worst case scenarios, one in 100 year storm surges increased in magnitude along the coastline in the range of 0.10 to 0.13 m and 0.16 to 0.22 m respectively, indicating that in this region, sea level rise scenarios which are in the range of 0.07 to 0.49 m by 2070 will have the dominant effect on increasing the severity of storm surges in this region in the future. Under the low wind scenario, the reduction in storm surge height due to decreasing wind speeds was found to be cancelled out by the low sea level rise scenario. The total sea level return periods were calculated by combining tides and surge using a Monte-Carlo approach. On the high resolution grids, the impact of storm surge change and sea level rise on inundation of low lying land is also investigated.

P83 The effect of climate change on the frequency of extreme sea-level events

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It is probable that the most important impact of climate change on sea level is the way in which it affects the extremes. The frequency of extreme (high) sea-level events may be increased by a raising of mean sea level or by an increase in variability relative to mean sea level. Observations from Australia and the USA are used to indicate changes of the frequency of extreme events due to both causes during the 20th century. It is shown that events that happened on an annual to decadal time scale happened up to 15 times more often after 1950 than before 1950.

Observations from the 20th century are then used to indicate how much the frequency of extreme events is expected to increase as a result of projected sea level rise during the 21st century. Results for Australia and the USA suggest that the frequency of extremes will increase by up to a factor of six for every 10 cm of mean sea level rise, indicating a complete change in the regime of extremes if sea levels rises by as much as 50 cm during this century.

P84 COASTDAT at IfK of GKSS, I: Detailed description and assessment of coastal climate change since 1958 in N Europe

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In a concerted effort of a series of quasi-realistic models of the regional atmosphere, the hydrodynamics of the North Sea and of the wave conditions, the global re-analyses of NCEP are downscaled to a high-resolution grid presentation of storminess, currents, water levels and wave heights in Northern Europe and particularly the North Sea area. In this way, the past development is estimated with an hourly time increment. Even if not all events are reproduced in detail, the statistics as conditioned by the large scale atmospheric state compare favourably with the limited instrumental evidence, in particular with respect to all aspects related to marine windiness.

The analysis of the changing conditions indicates that for most parts of Northern Europe, storminess was on the rise until the early 1990s, after which a decline took place with the notable exception of the southern North Sea. The characteristics of storm surge heights and wave heights followed this trend in marine windiness, with an increase of only a few centimeters in terms of storm surge heights but up to 80 cm in high waves during the past four decades in the German Bight.

The resulting hourly, high-resolution data set forms one of two major components of the data set COASTDAT, which is provided by the Institute for Coastal Research at GKSS to a variety of clients dealing with changing ecological conditions, coastal defense and offshore activity.

P85 COASTDAT at IfK of GKSS, II: Detailed projections of coastal climate change until 2100 in N Europe

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In a concerted effort of a series of quasi-realistic models of the regional atmosphere, the hydrodynamics of the North Sea and of the wave conditions, global climate change scenarios prepared for IPCC are downscaled to a high-resolution grid presentation of storminess, currents, water levels and wave heights in Northern Europe and particularly in the North Sea area. In this way, possible and plausible future developments are derived with an hourly time increment.

The analysis of the changing conditions indicates that for most parts of Northern Europe, storminess will increase at least in the domain of the North Sea. Maximum wind speeds may increase by about 10% accordingly, storm surge heights may rise by some 20 cm in the German Bight. Adding these increases to the expected mean sea level rise, higher storm water levels in Hamburg of 60 and more cm are plausible for the end of the 21st century. In this scenario, high waves in the German Bight may grow by another 20 cm. With such expectations for the end of the century, it appears unlikely that any man-made changes in the wind conidtions and related effects in coastal zones can be detected within the next couple of decades.

The resulting hourly, high-resolution data set forms another of two major components of the data set COASTDAT, which is provided by the Institute for Coastal Research at GKSS to a variety of clients dealing mainly with coastal defense.

P86 Annual and seasonal extreme sea levels in the Northwest Atlantic: Hindcasts over the last 40 years and projections for the next century

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Over the next century, sea level rise and plausible climate change scenarios point to increased flooding risk for many low lying coastal regions. Unfortunately, many regions at risk have insufficient data for standard extremal analysis which requires long time series of annual maxima of hourly sea level observations. It is therefore difficult to evaluate the distribution of extremes under the current conditions and even more problematic to assess the effect of climate change on the return period of extremes. In this study, a dynamical surge model is used to reconstruct multi-decadal sea level records and evaluate how climate change may modify flooding risk for coastal communities.

The approach is to perform a 40 year hindcast of storm surges in the Northwest Atlantic using a 2-D nonlinear barotropic ocean model forced by realistic 6 hourly winds and air pressures. Total sea levels are reconstructed by combining (i) the 40 year hindcast of storm surges, (ii) tidal predictions, and (iii) a statistical parameterization that represents baroclinic and seiche effects. An extremal analysis of the reconstructed total sea levels shows that the 40 year return levels are in good agreement (within 10 cm) with the levels calculated from multi-decadal sea level records. The approach therefore allows the calculation of flooding risk at locations for which there are few or even no data. The approach has also been tailored to focus on a season of interest such as the breeding season of an endangered bird species. The effects of sea level rise and changes in the frequency and intensity of atmospheric storms are also evaluated.

A Digital Elevation Model is used to downscale the results of the annual and seasonal extremal analyses to the community/urban level. Spatial maps of the return period of extreme sea levels, under current conditions and following plausible climate change scenarios, are presented.

The observation records were also used to identify areas where tide-surge interaction contributes to sea level variability. The Northumberland Strait sea levels are the most affected (about 10 cm) by tide-surge interaction. Numerical simulations performed with a tidally forced storm surge model were used to identify the cause of tide-surge interaction. Bottom friction was found to be the principal contributor.

Baroclinicity was also found to play a role in the sea level variability of the Northwest Atlantic. The Northumberland Strait sea levels were found to be the most affected (about 15 cm) by the seasonal variations in the density structure and thus stratification. These seasonal density variations lead to the displacement of the M2 amphidromic point and are associated with a seasonal cycle in the phase and amplitude of the tides.

P87 Rapid determination of earthquake magnitude using GPS for tsunami warning systems

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The 26 December 2004 Sumatra earthquake (Mw 9.2-9.3) generated the most deadly tsunami in history. Yet within the first hour, the true danger of a major oceanwide tsunami was not indicated by seismic magnitude estimates, which were far too low (Mw 8.0-8.5). This problem relates to the inherent saturation of early seismic-wave methods. Here we show that the earthquake's true size and tsunami potential can be determined using Global Positioning System (GPS) data up to only 15 minutes after earthquake initiation, by tracking the mean displacement of the Earth's surface associated with the arrival of seismic waves. Within minutes, displacements of >10 mm are detectable as far away as India, consistent with results using weeks of data after the event. These displacements imply Mw 9.0 ± 0.1, indicating a high tsunami potential.

Our results show greatly enhanced sensitivity to the magnitude of great earthquakes where the global IGS network is augmented by GPS stations in the near field, indicating the advantage of having real-time GPS networks near oceanic subduction zones. Fortunately many such networks exist, or are being planned, and so could be upgraded with real-time communications and incorporated into tsunami warning systems.

A key question we pose to this workshop is how such near-real time inversions from GPS for the earthquake source, hence the predicted vertical displacements of the ocean bottom, can be best implemented in future tsunami warning systems. Sensor networks for tsunami warning systems currently include seismometers and deep ocean pressure recorders that provide real-time data on earthquakes and resulting tsunamis to warning centers, which assess the possible threat and alert emergency managers who advise the public. The seismic data are important for the rapid detection and location of potentially significant events. GPS data could then be used to rapidly model the earthquake and thus initialize parameters for real-time modeling of tsunami generation. The tsunami models could then be validated and further constrained using ocean sensor data. Thus seismic, geodetic, and oceanic data could be truly integrated in tsunami warning systems.

P88 Extreme water level decompositions

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Hourly and daily averaged tide gauge time series are used to determine the primary contributors to high water levels on a station-by-station basis. The water level records are decomposed into tidal, high frequency (*e.g.,* storms, eddies), seasonal, and low frequency (*e.g.*, ENSO, NAO) variability and secular trends. The superposition of these components provides visual representations of extreme event climatologies, which in turn help identify the primary causes of extremes at each location. The tide gauge-derived water level product can be combined with wave set-up models to provide a more complete picture of coastal water level extremes. A case study is presented for the Hawaiian Islands.

P89 Impacts of sea-level rise in Tuvalu

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The low-lying Tuvalu islands are under imminent threat from sea level rise. Sea level rise is already exacerbating the problem of eroding and retreating coastlines. Also, there has been persistent and increasing severity of sea flooding from higher tides, increasing salinity of ground water and land is increasingly below sea level. Ground salinity increases from seawater intrusion and sea flooding have resulted in some seaweed species now establishing themselves on land. Poor septic tank drainage, and reduced subsurface drainage generally, is now causing major problems in the Tuvalu atolls. In addition to sea level rise effects, global warming may also impact as increased sea flooding associated with future increases in tropical cyclone frequency. Despite the impacts being currently experiences at Tuvalu, it is unfortunate that quantifiable local trends in sea level rise tend to be masked by other factors. In particular as the ocean responds to various physical driving forces, El Nino-Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) effects cause sea level variability which tend to mask the rising trend. Nonetheless sea-level rise effects are already a Tuvalu reality with physical changes in island ecology and environment. In fact, rising sea levels will continue to cause many impacts to precious and unique coastal areas, including loss of marine and terrestrial habitat, and will eventually lead to permanent inundation of Tuvalu and other low-lying small island states.

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IAPSO: International Association for the Physical Sciences of the Oceans
IACMST: Interagency Committee on Marine Science and Technology (UK)
ICSU: International Council for Science
IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer (France)
IGN: Institut Geographique National (France)
IOC of UNESCO: Intergovernmental Oceanographic Commission
IPY: International Polar Year
IRD: Institut de Recherche pour le Développement (France)
NASA: National Aeronautics and Space Administration (USA)
NSF: National Science Foundation (USA)
NOAA: National Oceanic and Atmospheric Administration (USA)
NERC: Natural Environment Research Council (UK)
Rijkswaterstaat (The Netherlands)
SCAR: Scientific Committee for Antarctic Research
TU Delft: Delft University of Technology (The Netherlands)
UKMO: Meteorological Office (UK)
UNESCO: United Nations Educational, Scientific and Cultural Organization
WCRP: World Climate Research Programme
WMO: World Meteorological Organization

Participating Programs

Argo: International Argo Project
CryoSat: ESA's Ice Mission (ESA)
ENVISAT: Environmental Satellite (ESA)
ERS: European Remote Sensing satellite (ESA)
ESEAS: European Sea Level Service
GCOS: Global Climate Observing System
GGOS: Global Geodetic Observing System
GLOSS: Global Sea Level Observing System
GOCE: Gravity Field and Steady-State Ocean Circulation Explorer (ESA)
GOOS: Global Ocean Observing System
GRACE: Gravity Recovery and Climate Experiment (NASA)
ICESat: Ice, Cloud, and Land Elevation Satellite (NASA)
IGS: International GNSS Service
Jason: Ocean Surface Topography from Space (NASA/CNES)
SMOS: Soil Moisture and Ocean Salinity (ESA)

Co-Sponsors

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