

Sea level rise and coastal flooding – understanding the risk

NTSLF-Challenger Symposium 2-3 November 2009

Abstracts

Day 1 Monday 2 November 2009

Session 1 – Impacts of sea level rise

Defra/EA strategy for flood risk to the UK

Alison Baptiste

Environment Agency

The Environment Agency has new responsibilities on the coast that require us to balance the needs of people, the economy and the natural environment in the long term. The decisions we take have significant consequences for individuals and communities living and working on the coast and to be effective we need dedicated engagement with the public.

This presentation will outline the approach that Defra and the Environment Agency are taking to understand and respond to how sea level rise affects both coastal flooding and erosion risk. It will describe what's at risk, the current climate trends and the impact of those on the coast. Coastal flooding and erosion is not just about people and properties but also habitats and the wider environment too and Shoreline Management Plans are the tools that enable us to set the strategic direction for future management of the coast. We can never eliminate the risk or stop the coast from changing, so we need to learn to live with it and the presentation will conclude with practical examples of where Defra and the Environment Agency are working with communities to understand and respond to the risk.

Sea level, storm surges and the insurance industry

Rowan Douglas

Willis Research Network

Global consequences of sea level change

Professor Robert Nicholls

University of Southampton

Relative sea-level rise can have a range of impacts on coastal areas including (1) increased storm damage, flooding and submergence, (2) increased erosion, (3) ecosystem changes such as coastal wetland loss and change, and (4) surface and groundwater salinisation. To date, most global assessments have only considered subsets of these impacts and also failed to consider the benefits (and costs) of adaptation.

This paper will explore these potential impacts of sea-level rise at a global scale across a range of impacts, a range of sea-level rise scenarios, and a range of adaptation options. The sea-level rise scenarios will include consideration of the AR4 IPCC Report range as well as the high impact low probability tail to the distribution of sea-level rise above these scenarios. This has been considered in the Thames Estuary 2100 Project by the H++ scenario, which explores this range of possible change using the limited information that is available. It is concluded that a 2-m rise by 2100 is not implausible and hence this considered as an upper change by 2100.

The potential impacts are large with one estimate being that 146 million people and about US \$ 1 trillion dollars of GDP are within 1 m of sea-level rise, based on current exposure and sea level. This exposure is often translated into impacts without any consideration of the potential for adaptation. However, the economic analysis of impacts and adaptation suggests that protection will be economic in many cases and the actual impacts may be much lower than the potential impacts. The evidence from low-lying cities that have subsided up to several metres during the 20th Century supports this conclusion, as all these cities have been protected and continue to grow.

Issues concerning the possible limits to protection and the benefits of mitigation which will reduce the likelihood that these high end rises in sea level will occur will be considered.

Session 2 – Sea level variability and observations of sea and ice (I)

Recent changes in UK sea levels and comparisons to elsewhere

Professor Philip Woodworth

Proudman Oceanographic Laboratory

This presentation will contrast the UK-average sea level record obtained from tide gauges and altimetry with the quasi-global curves provided by several sets of authors. The UK-average record compares closely to sea level time series from the neighbouring European coastline, and even has many similarities to the global curves. These similarities include an acceleration in the rate of rise between the 19th and 20th centuries, with a particularly high rate of rise after 1920, a deceleration after 1960, and a relatively recent high rate since the 1990s. Sea level around the UK rose during the 20th century at an average rate of 1.4 mm/year, slightly lower than the global value. However, at a local level, the sea level trends observed at particular locations vary depending upon the rate of vertical land movement, such as can be obtained from geological measurements (e.g. a new map for the British Isles from Durham University) and, more recently, from GPS and Absolute Gravity information.

Accelerations and decadal variability in sea levels observed at the eastern boundary of the North Atlantic were investigated a couple of years ago by Miller and Douglas (GRL, 2007). They inferred a relationship between eastern-boundary sea level and the strength of the gyre-scale circulation of the North Atlantic, represented by air pressure near to the centre of the sub-tropical gyre (i.e. gyre spin-up/down). Their analysis was limited to the use of sea level and air pressure data from approximately 1880 onwards. However, in a recent investigation (Woodworth, Pouvreau and Wöppelmann, *Ocean Science*, 2009), we have been able to use records commencing in the middle of the 18th century, or twice as long as those used before. This has been made possible by a huge amount of data archaeology of tide gauge data from Brest, which has the longest continuous sea level record on the European Atlantic coastline, and of air pressure fields for the eastern North Atlantic derived from terrestrial instrumental pressure records and ship logbook

information. We have confirmed that the relationship between eastern-boundary sea level and gyre strength suggested by Miller and Douglas holds over much longer timescales, and that gyre strength can explain a large part of the decadal and century timescale accelerations in European (including UK) sea level records. These findings have important implications, suggesting that redistribution of water could have played an important role in the observed sea level rise, instead of (or as well as) changes in ocean volume.

The character of sea level variability: Spatial variations in spectra and statistics

Professor Christopher Hughes
Proudman Oceanographic Laboratory

Sea level varies as a result of a range of different processes, associated with wind-driven dynamics, Rossby waves, eddies, meandering fronts and other features. Some processes may dominate in one part of the ocean, while others dominate elsewhere. In this presentation I will discuss, based on satellite altimetry and ocean model diagnostics, how the spectrum of sea level variability varies from place to place, and which processes are reflected in the different spectra. As a result of these processes, spectra can change not only in power, but also in colour, sometimes over rather short distances. I will also discuss the complementary quantities, skewness and kurtosis of sea level variability, which depend critically on the phases rather than just the power of the spectrum. These quantities are closely linked to the propagation of isolated eddies and the meandering of sharp fronts in the deep ocean.

Long term variability in the Greenland ice sheet

Professor Anthony Long
University of Durham

There is considerable scientific and public interest in the potential contribution of the Greenland Ice Sheet (GIS) to future global and regional sea level rise. Much of this concern stems from recent observations of rapid mass loss, especially from the 1990s onwards, which suggest that the ice sheet is presently contributing ~ 0.5 mm yr sea-level rise. Palaeoenvironmental data provide interesting long-term perspectives on these short-term observations. In this paper I review the evidence for long-term variability of the GIS during warmer than present conditions, considering the hypothesised evolution of the ice sheet during the Eemian and the Holocene thermal optimum, two intervals of time when temperatures were several degrees warmer than present and the ice sheet is thought to have been smaller than its present dimensions. I argue that there is significant uncertainty regarding the Eemian ice extent, reflecting limitations to ice sheet / climate models and disagreement on the timing and magnitude of the Eemian sea-level highstand. Reconstructions that infer significant collapse of the Eemian GIS and several meters of equivalent sea-level rise need to be considered with these uncertainties in mind. During the Holocene thermal optimum, models and observations agree that the ice sheet retreated inland of its present margin but that it did not collapse catastrophically; indeed reconstructions constrained by recently collected sea level data suggest margin retreat in west Greenland of not more than ~60-80 km. This retreat was replaced, during the late Holocene, by several thousand years of ice sheet expansion which means that in many areas the ice sheet today is close to its maximum size since c. 5000-9000 years ago. Long-term perspectives may lack the precision of current geodetic

observations, but they do provide crucial information on trends as opposed to short-term fluctuations in ice sheet behaviour.

Sea level variability in continuous records of the past 500,000 years and implications for the future

Professor Eelco Rohling

National Oceanography Centre Southampton

Over the last decade, we have developed a new sea-level quantification tool. Results agree with those from existing methods (notably fossil corals), but new method for the first time allows continuous resolution in 100-200 year time-steps. This allows comparison of the history of sea level, and hence global ice volume, with variability in other key climate parameters, notably temperature and greenhouse-gas concentrations measured in ice-cores. Comparison between temperature and sea-level changes over the past half million years (= 5 full glacial cycles) reveals an exponential relationship. Used with the ice-core-derived temperature:CO₂ relationship, this relationship implies that natural processes would drive sea level to a long-term (millennial-scale) equilibrium position at around 25±5 m above the present, for the current 387 ppmv CO₂ concentration. This portrays the disequilibrium state in the climate system, or the total potential ice-volume adjustment that might be expected if the current CO₂ concentrations were maintained over several millennia. Other results reveal that rises above the present sea level (during the Last Interglacial) progressed at rates up to 1.6±1.0 m per century.

The total magnitude and rates of sea-level adjustment found from these natural data significantly exceed model-based IPCC projections, even when considering their scenarios with 'high climate sensitivity'. Our most recent work begins to provide an explanation: using the new sea-level/ice-volume records as the final essential piece in the jigsaw puzzle of climate sensitivity, it appears that climate sensitivity and/or the amplification of polar temperature response to climate forcing are not at constant values. The nature of the combined non-linearity, however, appears to have been systematic throughout the last 5 glacial cycles. If that systematic nature applies also to future responses, then the observed high magnitude and rates of sea-level adjustment become increasingly realistic for the next few centuries.

Session 3 – Modelling future sea levels

Keynote talk: Processes contributing to future sea level change

Professor Detlef Stammer

University of Hamburg

Climate Scenario Simulations and other estimates suggest a substantial increase in global sea level over the next century. Estimates range from about 40 cm to more than 100 cm, which reflects the substantial uncertainty in existing projections. The increase will be caused primarily by heat uptake by the ocean and by freshwater added to the ocean due to polar ice melting. However, other processes will contribute as well, including regional and local dynamics of the adjusted circulation. Moreover, the adjustment of the global ocean to those forcing functions is complex and substantial regional changes can be expected before a global equilibrium is being reached. The talk will summarize processes

contributing to regional and global sea level change on climate time scales and will provide some examples, especially with respect to Greenland ice melting.

Modelling sea level change using AOGCMs

Professor Jonathan Gregory

University of Reading

AOGCMs are the main tools used to make projections of climate change during the 21st century. There are large uncertainties in the projections they give for sea-level change. For a given emissions scenario, the systematic uncertainty in projections of global-mean thermal expansion arises from uncertainties in climate sensitivity and ocean heat uptake efficiency. The geographical distribution of sea-level change due to ocean processes results from the patterns of changes in temperature and salinity, on which models show limited agreement. Observational constraints on model projections should be investigated in order to reduce uncertainty.

Semi-empirical modelling of the sea level-temperature relationship

Professor Martin Vermeer

Helsinki University of Technology

Modelling phenomena in nature can be done in two principally different ways:

- 1) physical modelling, by embodying known physics into working code; or
- 2) statistical / parametric modelling, by conjecturing simple relationships between quantities and empirically deriving the unknown parameters in them.

Semi-empirical modelling of the sea level - temperature relationship is an example of the second approach, pioneered in Rahmstorf (2007). It is called "semi"-empirical, as the relationship conjectured is based in physics. The relationship found based on tide gauge and global mean temperature data for the instrumental period can then be extrapolated into the 21st Century; studies using general circulation model output provide further insight.

In Vermeer & Rahmstorf (in review) the relationship between sea level rise dH/dt and temperature T is refined by including a dependence on dT/dt . The new relationship provides a significantly better fit for the instrumental period as testified by the Akaike criterion. It requires, however, taking into account the storage on land of water in artificial reservoirs as compiled by Chao et al. (2006).

Grinsted et al (2008) report semi-empirical work for the past two millennia using a combination of instrumental and proxy data, showing that the long-term response of sea level must contain a time period of several centuries. Ongoing work by us, based on salt-marsh sea level proxy work from the Eastern USA by Horton and Kemp, robustly replicates this, though it is clear that there must also be a millennium-plus response associated with glaciation and deglaciation.

Sea level rise for 2100AD as projected by these modelling efforts for the common IPCC AR4 scenarios is substantially higher than in that report, being compatible with the 80cm - 2m range also found by Pfeffer et al. (2008) from physical considerations.

Anthropogenic forcing dominates sea level rise since the 1800s

Dr Svetlana Jevrejeva

Proudman Oceanographic Laboratory

We use a delayed response statistical model to attribute the past 1000 years of sea level variability to various natural (volcanic and solar radiative) and anthropogenic (greenhouse gases and aerosols) forcings. We find that until 1800 the main drivers of sea level change are volcanic and solar forcings. However, for the past 200 years sea level rise is mostly associated with anthropogenic factors. For the first time we show that only 4 cm (25% of total sea level rise) during the 20th century is attributed to natural forcings, the remaining 14 cm are due to a rapid increase in CO₂ and other greenhouse gases. This is much larger than the impact of the volcanic eruptions which have produced a net lowering of about 7cm compared with levels expected if there had been no eruptions in the 20th century.

Session 4 – Vertical land movement

Measuring vertical land movement at global tide gauges using GPS

Dr Matt King

Newcastle University

A long-standing complexity in the interpretation of tide gauge (TG) records for sea level change has been obtaining suitably accurate and precise estimates of vertical tide gauge motion. These motions have geophysical origins at various scales, such as glacial isostatic adjustment (GIA) or local subsidence, as well as local monumentation origins, such as due to pier movement. At present, corrections are typically made based on models of GIA only. Since the early 1990s, GPS coordinate time series have been considered a possible source of such corrections, but it is only recently that GPS has been demonstrated to be useful for this long-intended purpose. Here, we present results of a global reprocessing of GPS data from the mid-1990s through to the present-day, including data at, or near to, dozens of long-running TG sites. We pay particular attention to systematic errors, applying consistent state-of-the-art observation models when producing the GPS coordinate time series, and further mitigating them during the reference frame realisation stage. Rigorous uncertainty estimates, considering temporal noise correlations, are also produced for each vertical velocity. These new estimates of vertical tide gauge motions are then applied to long-running TG sea level trends and we will report on the subsequent geocentric rates of sea level change and make comparison to other recent estimates.

Monitoring the vertical motion of the UK using GPS and absolute gravity

Dr Richard Bingley

University of Nottingham

Here we present a new map of current vertical land movements of the UK and investigate changes in sea level (decoupled from changes in land level) around the UK, using the latest results from monitoring using continuous Global Positioning System (CGPS) and absolute gravity (AG) measurements. Our latest results are based on a recent re-processing that included data for the period from 1997 to 2008 from two AG stations and more than 100 CGPS stations in this region. In our CGPS processing strategy we applied a combination of re-analysed satellite orbit and Earth rotation

products together with updated models for absolute satellite and receiver antenna phase centres and for the computation of atmospheric delays. Our reference frame implementation used a semi-global network of approximately 50 IGS stations located in North America, Greenland and Eurasia, to align our daily position estimates, using a minimal constraints approach, to ITRF2005. We then assessed the accuracy of our CGPS estimates of vertical land movements along with their associated uncertainties, which were computed from a detailed stochastic model of the position time series, using the independent estimates of vertical land movements from the two AG stations. In this presentation we show how the resulting geodetic (AG-aligned CGPS) estimates have been used to produce a map of vertical land movements over the last decade, and we compare this to geological maps of Holocene land level changes; all of these maps being useful for the assessment of future changes in relative sea level in the planning of flood and coastal risk management in the UK. We also show how the geodetic estimates for tide gauges can be used to investigate changes in sea level (decoupled from changes in land level) around the UK. This work was funded by a NERC SOFI small research grant (NE/F012179/1), by the Environment Agency (contract 22869), and as part of the development of products to be made available through NERC BIGF (R8/H10/59).

The November 9 Storm Surge: a geodetic perspective

Dr Simon Williams

Proudman Oceanographic Laboratory

Mass movements in the atmosphere, the ocean, the terrestrial hydrosphere and the cryosphere continually load the Earth surface and cause the solid Earth to deform. Crustal deformation caused by the ocean tides have been observed by a number of geodetic techniques (for instance GPS and Absolute Gravity) and are now routinely corrected for at the observation level. Global datasets such as NCEP and ECMWF have allowed the routine estimation of atmospheric loading at any site around the world. However, the detection and/or separation of the mm to cm-level deformation caused by non-tidal ocean loading using GPS measurements are not routine.

Storm surges on the north-west European shelf are reasonably common ocean events that affect many coastal areas and pose a serious flood hazard to countries bordering the North Sea. The 9 November 2007 event (storm Tilo) was the worst storm surge experienced in almost two decades. Using the POLSSM high resolution model that provides non-tidal hourly sea levels covering the North Sea region with approximately 12 km grid cells, we demonstrate that such non-tidal ocean loading height displacements can reach up to 30 mm at the time of a storm surge. By correcting for this displacement at the observation level, we show that GIPSY precise point positioning daily height estimates (using reprocessed JPL orbital products) for continuous GPS sites around the North Sea are sensitive to non-tidal ocean loading both during and outside of times of storm surges. For example, for a 30 day window centred around the November 2007 surge arising from storm Tilo, we obtain improvements in height precision of nearly 50% at some sites.

Vertical motion in the SE of England from SLR, GPS and AG

Vicki Smith

NERC Space Geodesy Facility

Efforts to realise and maintain a high-accuracy global Terrestrial reference frame are driving an increase in demand for geodetic sites offering multi-technique capabilities. An important contributory site in this effort is the Space Geodesy Facility (SGF) at

Herstmonceux, East Sussex, which operates a highly precise satellite laser ranging station, two GNSS receivers (GPS and GLONASS), an absolute gravimeter and a borehole from which the local water table is logged.

In this presentation we will look at the long time-series of vertical height results from both the SLR (25 years) and GPS (15 years) techniques at Herstmonceux, as well as nearly three years of absolute gravimeter data, which is recognised to be an independent technique which is critical for the measurement of vertical height motion.

Day 2 Tuesday 3 November 2009

Session 5 – Sea level variability and observations of sea and ice (II)

Keynote talk: Contemporary sea level change at global and regional scales

Professor Anny Cazenave

LEGOS

Measuring sea level change and understanding its causes has considerably improved in the recent years, essentially because new in situ and remote sensing observations have become available. In this presentation, I summarize recent results on contemporary sea level rise. I first present sea level observations from satellite altimetry since the early 1990s. Then I discuss most recent progress made in quantifying the processes causing sea level change on time scales ranging from years to decades, i.e., thermal expansion of the oceans, land ice mass loss and land water storage change. For the 1993-2008 time span, the sum of climate-related contributions (2.85 ± 0.35 mm/yr) is only slightly less than altimetry-based sea level rise (of 3.3 ± 0.4 mm/yr) : ~ 30% of the observed rate of rise is due to ocean thermal expansion and ~ 55% results from land ice melt. Recent acceleration in glacier melting and ice mass loss from the ice sheets increases the latter contribution up to 80% over the past five years. Finally, I briefly discuss the spatial patterns in sea level trends and the main causes of regional variability.

What drives sea level variability around Europe?

Dr Simon Holgate

Proudman Oceanographic Laboratory

In our attempts to understand global sea level change, it has become obvious that tide gauge records display variability over all sorts of timescales. This variability is often not coherent between different locations and in general we remove it by filtering or fitting a linear trend, with the aim of extracting a globally coherent signal. However we also find that the long term trends aren't necessarily spatially coherent either.

With the advent of satellite altimetry, the spatial variability of sea level trends has become something that we can no longer ignore. The data have therefore made us re-think what we mean by "global mean sea level change" and consider the policy implications of regional sea level variability.

While some of the difference in long term trends can be attributed to the effects of vertical land movement and in particular, glacio-isostatic adjustment, there is still considerable variability which we do not explicitly model.

Recent work by Hill et al has used the MIT climate model to globally reduce variance in tide gauge records. Building on this idea, I will here discuss a more detailed study of long tide gauge records at Brest, France and Newlyn, UK, and the reduction in variance made possible using a regional model and multiple regression techniques. It is shown that the reduction in variance enables us to gain more insight into the long standing question of why Newlyn and Brest have differing rates of sea level change, despite being only 200km apart.

Contributions from Antarctic ice sheets: is a marine ice-sheet collapse beginning in West Antarctica?

Professor David Vaughan

British Antarctic Survey

The loss of ice from ice sheets in Antarctica and Greenland is a major source of current sea-level rise, and one that is accelerating rapidly. The most recent report from the Intergovernmental Panel on Climate Change highlighted that the greatest uncertainty in projections of future sea-level rise is due to a lack of knowledge about these two ice sheets and, in particular, uncertainty as to the potential for rapid collapse of marine ice sheets that rest on beds substantially below sea level. The largest remaining marine ice sheet is the portion of the West Antarctic ice sheet draining into the Amundsen Sea. In this talk, I will show that losses from this ice sheet have accelerated in recent decades, and show no signs of achieving a new equilibrium. Current rates of change arguably allow us to bracket maximum likely contributions to sea-level rise that could arise from this area in the next 50 – 100 years, but prediction is extremely difficult beyond that timeframe. So while it is increasingly plausible that we are seeing the early stages of a collapse of this part of the WAIS, there is still no consensus on the maximum rates of sea-level rise such a collapse might eventually cause. To achieve progress in this area will require a much clearer understanding of the processes that limit the rate of collapse that can be sustained in a realistic marine ice sheet. A discussion of these rate-limiting processes may drive a new emphasis in ice sheet research and, perhaps perversely, justify glacier-dynamic research in Greenland. It may be only there that we can observe glaciers exhibiting some of the behaviour that will be critical during a collapse of the West Antarctic ice sheet. I will thus issue a call for greater synthesis between, researchers working at the opposite ends of the Earth, and those working in ocean and glacial environments, and discuss ice2sea, a new EU Framework 7 Programme, which could offer a framework through which to achieve some of these goals.

Past and future contributions from glaciers and ice sheets to sea level rise

Professor Tavi Murray

University of Wales Swansea

The cryospheric contribution of sea level rise results from changes in the mass balance of glaciers and ice sheets. I review a number of methods of mass balance measurement for both mountain glaciers and the ice sheets, concentrating on the relative strengths and weaknesses of these methods. I will concentrate on examples from small glaciers and the Greenland Ice Sheet. The techniques include measurement of volume changes using airborne or satellite altimeters and photogrammetry, direct measurement of mass changes using the GRACE satellites, and mass flux methods. I will summarise recent findings on the rates of mass loss from different regions. The most variable component of Greenland's mass balance is the flow dynamics of tidewater outlet glaciers, which have dominated recent changes in the cryospheric contribution to sea level rise. Recent

predictions of sea level rise, for example those in the IPCC 2007 report, do not include these dynamic changes. Before predictive models can be further developed, far greater process understanding of the forcings is required. I will provide examples of the complexity and non-linear response of these systems, which clearly demonstrate the importance of changes in tidewater glacier dynamics to sea level rise.

The impacts of self-attraction and loading on sea level change and bottom pressure

Dr Mark Tamisiea

Proudman Oceanographic Laboratory

While sea-level trends and annual amplitudes are frequently reported as global averages, these single values obscure the large regional variations that go into the averages. One mechanism contributing to this geographic variability is self-attraction and loading (SAL); water flux between the continents and the oceans causes both crustal motion and changes to the equipotential surface of the oceans. In previous studies, the patterns resulting from the SAL effects have been used to infer the mass balance of the large ice sheets using long tide gauge (TG) records. However, SAL also operates on shorter time scales and can thus be used to understand part of the geographic variability of the annual and interannual signals in sea level. This study focuses particularly on the annual cycle. While the mass flux from the global water cycle contributes significantly to the global mean sea-level annual amplitude, at any given location the dynamic ocean signals are generally much larger than those due to mass flux. In contrast, bottom pressure typically has smaller amplitude variations than those of sea level, and the SAL effects in bottom pressure can be as large as those due to dynamic ocean signals. In this talk, we model the impact of SAL due to the annual water cycle on TG and bottom pressure recorder (BPR) observations. We find a positive variance reduction when we remove the modelled time series from the TG records. In some regions, the SAL effect is large enough (nearly 2 cm annual amplitude) to warrant its removal from the observations prior to assimilation of the data into dynamic ocean models that include no SAL physics. When considering BPR records, removing the SAL effects in addition to the dynamic ocean estimates from ECCO significantly improves the variance explained compared to that from removing only ECCO. Thus, we conclude that understanding the SAL effects is vital for interpreting data from BPRs.

Aspects of sea level variability in marginal seas

Professor Mikis Tsimplis

National Oceanography Centre Southampton

Assessing the risk sea level rise poses to coastal regions requires an understanding of global, regional and local processes as well as some skill in forecasting how these can evolve in the future. Sea level changes in marginal seas in particular can be very different from the global mean. The causes of such discrepancies are not well understood. A review of work done on sea level change around some of the European marginal seas will be given with open issues on the interpretation of the observed trends discussed. Then results on sea level change at the north-west Pacific marginal seas will be presented and compared with those derived from the European seas.

Clues to future sea level rise: linking geological and instrumental records of change

Dr Robin Edwards
Trinity College Dublin

Recently inferred accelerations in the rate of sea level rise have focussed attention on the need to increase the number and distribution of sea level records covering the last few hundred years. One way to achieve this is to develop high resolution sea level reconstructions that can bridge the gap between short-term instrumental data and longer-term geological records. Microfossil-based transfer functions for tide level are becoming increasingly popular tools for producing decimetre and multi-decadal scale records of change from saltmarsh sediments. The success of this approach depends upon precisely and accurately quantifying the vertical relationships between individual microfossil species and elevation with respect to a tidal datum. These relationships, which are determined by studying the modern distributions of intertidal taxa, are then used to infer past saltmarsh surface elevation change from fossil assemblages recovered from sediment cores. The resulting reconstructions, which can attain quoted precisions of ± 5 cm, permit small scale fluctuations in relative sea-level (RSL) to be examined and have led to several publications examining the timing of past changes in the rate of RSL rise.

This paper presents a brief overview of the transfer function methodology and its application to the reconstruction of recent RSL change. It reviews recently published research and comments on the current state of the art with regard to record resolution. It concludes by highlighting some ongoing research that illustrates some of the current issues and developments in the field.

Session 6 – Risk management and operational forecasting

Best practice for extreme sea level estimations

Dr Kevin Horsburgh
Proudman Oceanographic Laboratory

Insured losses due to coastal flooding in the UK cost approximately £1 billion each year, and thousands of properties are at risk. Any increase in flood frequency or severity, due to sea level rise or changes in storminess, would impact on economic and social systems, as well as fragile ecosystems. Extreme sea levels result from a number of components including global mean sea level, regional trends, land movements, plus any alteration to the tidal regime or storm surge characteristics due to these changes. It is essential that statistical information on coastal extremes is both up to date and accessible by decision makers and coastal engineers. Previous work has shown that a Revised Joint Probability Method (RJPM), that exploits knowledge of the interaction between tide and storm surge, offers considerable improvements over annual maximum methods that then fit a generalised extreme value distribution (GEV) to observed sea level maxima. Here we update and extend the RJPM techniques to include improved physical and statistical assumptions. We adopt three different techniques to estimating the return levels of extreme sea level from quality-controlled tide gauge data. Firstly, we employ functions of the tide to perform a location-scale normalisation of non-tidal residuals and then obtain the distribution parameters using a point-process method; secondly, we construct the joint probability functions of tide and surge directly within a number of discrete tidal bands; finally, we calculate joint probability of the skew surge (the time-independent difference between peak prediction and observations) with the tide. We use an

ensemble of these three sets of local estimates to calibrate the corresponding return levels at all coastal locations around the UK as provided by a suite of hydrodynamic models, all forced by the ERA40 1° dataset. The estimates at the sites themselves are more reliable than any previous calculations because of improved methodology and the increased length of tide gauge data. The high-resolution models create a means of dynamical interpolation and thus deliver a consistent spatial method for estimating extreme sea levels around the entire UK coastline, including complex topographic regions. It is intended that this work should provide the most reliable basis for estimating extreme water levels around the UK coast, and the method can be extended elsewhere with ease. The results are directly applicable to flood and coastal defence policy.

Operational ensemble forecasting of coastal storm surges

Dr Jonathan Flowerdew
UK Meteorological Office

The overtopping of flood defences by coastal storm surges is a significant threat to life and property. A traditional single weather forecast can miss the particular combination of factors that lead to a severe event. Ensemble forecasting addresses this problem by producing multiple alternative forecasts, which aim to represent the distribution of possible outcomes by sampling the uncertainty in the initial state and model formulation. This provides an explicit estimate of the probability of an extreme event, which can be combined with information about potential costs and losses to improve the risk management process.

This talk will describe the development and evaluation of an ensemble forecasting system for coastal storm surges, based on the Met Office atmospheric ensemble and the currently operational deterministic storm surge forecasting system. The storm surge ensemble has now been running for almost three years in trial mode, with positive feedback from both Met Office and Environment Agency forecasters. For the surge on 9 November 2007, which received significant media coverage, it produced a clear signal of an abnormal event at the full 54 hour lead time, with a useful indication of the range of possible water levels. Statistical verification covering two winters demonstrates that the ensemble spread is indeed a reliable indicator of the significantly increased uncertainty associated with large surge events, although the error in more normal situations is dominated by inaccuracies in the separate harmonic tide prediction which is used to convert surge to water level. Probabilistic verification shows some advantage over climatological error distributions, particularly for larger thresholds and longer lead times. Following this successful trial, the system is scheduled to become Operational by the end of 2009, with a further trial to explore the potential value of longer range forecasts.

Storm surge climatology for European seas in 2100

Dr Jason Lowe
UK Meteorological Office

Waves in an ensemble future climate

Dr Judith Wolf

Proudman Oceanographic Laboratory

We examine the projections of future wave climate around the UK driven by winds from a subset of the Met Office/Hadley Centre climate model ensemble members. The wave model which is used is based on the well-tested 3rd-generation spectral model WAM implemented on two grids: a coarse 1° grid for the whole Atlantic to provide boundary conditions, and a 12km model of the NW European continental shelf. The model was run using three sets of atmospheric model wind forcing covering the period 1960-2100. The cases comprised an unperturbed run with medium climate sensitivity and two other members of a climate sensitivity ensemble, based on a medium emissions scenario. The WAM model has been well-validated previously and here it is shown to be statistically in reasonable agreement with the ERA-40 reanalysis (which is a comprehensive global hind-cast of the last 40 years of waves and wind, combining model fields with a wide range of observations) for the NE Atlantic. Seasonal mean and extreme waves are generally expected to increase to the SW of UK, reduce to the north of the UK and experience little change in the southern North Sea. There are large uncertainties especially with the projected extreme values. Changes in the winter mean wave height are projected to be between -35cm and + 5cm. Changes in the annual maxima are projected to be between -1.5m and +1m. Projections of longer return period wave reflect the same pattern but with larger error bars. The implications of coastal impacts of climate change for various parts of the UK coast are examined. The SW is expected to see higher wave heights, with lower waves to the north. In the southern North Sea little change is anticipated.

Managing the risk for the Thames Estuary: the TE2100 project

Sarah Lavery

Environment Agency

Posters

Modelling Storm Surges in the Irish and Celtic Seas using a Finite Element Model (TELEMAC)

John Maskell

Proudman Oceanographic Laboratory

Finite difference models have traditionally been used operationally for storm surge forecasting. In comparison to finite element models they were often easier to implement and did not contain spurious modes of sea level elevation and velocity that were often present in finite element solutions. However, these spurious modes have been removed from finite element solutions by using simple elements and modified forms of the governing equations. Finite element models have many potential advantages for storm surge modelling in particular their ability to have a graded mesh with spatially varying grid resolution providing high resolution in shallow water areas where accuracy of the wind stress input is most important and the tide and surge show greatest spatial variability. A finite element model (TELEMAC) of the tide in the Irish and Celtic Seas is used to hind cast a significant storm surge event that occurred in January 2005 using atmospheric forcing from the Met Office's 'mesoscale' weather forecast model. The predicted surge residuals are compared to those of the finite difference operational surge model (CS3), a higher resolution finite difference model (NISE10) and to the residuals observed at tide gauges. The meteorological forcing is constant in all three simulations

so any improvements in the predicted residuals compared to tide gauge measurements can be attributed to resolution enhancement. The results show that TELEMAC performs as well as the operational model and a higher resolution finite difference model at east Irish Sea port locations based on RMS errors. While there is a significant improvement in the RMSE at Port Erin probably due to better representation of the North Channel, there is no significant improvement at other east Irish Sea port locations. It is apparent that any benefits of resolution increase eventually become limited by the resolution of the forcing met data and/or the bathymetry.

Late Holocene relative sea-level change in southwest England

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Geological observations of late Holocene sea-level changes can be used to extract rates of vertical land movement in the UK (Shennan and Horton, 2002; Gehrels, in press). The accuracy of estimates in the southwest of England has been questioned, however, as they are based on observations from limited, and poorly constrained, data (Gehrels, 2006; Massey et. al. 2008; Gehrels, in press). Current geophysical models show that the southwest is affected by post-glacial land subsidence which is the combined effect of the melting of the British/Irish and Scandinavian ice sheets (Bradley et al. 2009), yet there are still misfits between observations and model outputs. More high-quality late Holocene sea-level index points are required to quantify vertical land movement as accurately as possible in order to (1) test the hypothesis that the southwest is the fastest subsiding region in the UK, (2) validate geophysical models, (3) and improve regional sea-level projections (Gehrels, in press). This study presents 10 new late Holocene sea-level index points from Thurlestone, south Devon. In contrast to previous studies in the region (e.g. Morey, 1983; Healey, 1995), these samples are overlying an incompactable substrate and are therefore not affected by sediment consolidation. The new sea-level data from the late Holocene suggest a rise in relative sea-level of ~0.5 mm/yr between 4600 and 450 BP. New rates of relative sea-level changes, calculated in this study, show a reasonable fit to Lambeck's (1995) model. Model predictions by Bradley et al. (2009) for Thurlestone also match the data, which is reassuring because they are used in the latest UK sea-level predictions (Jenkins et. al, 2008).

Google Flood

Alison Nock

University of Plymouth

With climate change seemingly inevitable, the delivery of timely information to predict coastal floods at a range of temporal and spatial scales is vital. Coastal flooding due to extreme weather events will continue to threaten towns, cities and seaports. The problem may be exacerbated in the future by global sea level rise and by an increase in the frequency and magnitude of severe storm events. This PhD research has been designed in response to this threat. It is being funded by several government agencies in the United Kingdom (UK), such as the Natural Environment Research Council (NERC), the Environment Agency (EA) and the Department for Environment, Food and Rural Affairs (DEFRA). This research aims to provide the scientific expertise to address key environmental science themes including global climate change and natural hazards. It is being undertaken in the Coastal Flooding by Extreme Events (CoFEE) project which is a component part of the Flood Risk from Extreme Events (FREE) Programme. An integrated approach to flood modelling using Geographic Information Systems (GIS)

technologies will assess how flood risk will change in the future due to predicted scenarios of sea level rise and the increased frequency of extreme storm events. The research aims to improve prediction on the speed and extent of coastal flooding caused by a range of storm conditions through the development of a science-based process flood model and a Google Flood Internet web mapping application. Research deliverables will assist flood forecasting and mitigation. The insurance market, flood risk and emergency management sectors stand to benefit from the novel tools and techniques.

The National Tidal and Sea Level Facility

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The Permanent Service for Mean Sea Level

Sveta Jevrejeva

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A Simple Linear Refinement for the Prediction of Extreme Water Levels

Alan Hisscott

IoM Met Office

Performance of harmonic tidal predictions when compared to measured tide levels around the Isle of Man has been found to vary throughout the annual cycle. A simple method has been developed for refining predictions of extreme sea water levels using surge model data to monitor and modify tidal predictions over a short time span. Results suggest that significant improvements can be obtained irrespective of the varying accuracy of harmonic predictions at any time.

Model assessment of the sea level changes in the North Atlantic between 1950-1970 and 1980-2000

Vassil Roussenov

University of Liverpool

An Initial Investigation of PSI around the Tide Gauge Sites in the UK

Ligia Adamska

University of Nottingham

Tide Gauge (TG) records of mean sea level are an important data set for the computation of long-term estimates of changes in sea level both for regional and global analyses. To fully understand long-term sea level changes, there is a need to identify the component of the change in mean sea level measured by a TG that is due to changes in land level. Information on vertical land motions obtained from continuous Global Positioning System (CGPS) measurements at or close to TGs are used to correct the TG records for these motions. However, this technique is only capable of providing a point-wise estimate for these motions, i.e. at the CGPS antenna installation.

Persistent Scatterer Interferometry (PSI) is a powerful technique for identifying long-term changes in vertical land motions. The PSI technique uses a stack of multi date imaging

radar data to identify and analyse dense arrays of naturally occurring, consistently bright or coherent points in the images. It provides millimetre accuracy and is fast becoming a standard technique for the measurement of vertical land motions over wide spatial extents and in many application areas.

This poster presents the initial results from NERC SOFI-funded research carried out at IESSG, University of Nottingham, in collaboration with BGS and POL, on the use of PSI around TG sites in the UK. In this research the PSI techniques is being applied to complement existing CGPS measurements in order to investigate the suitability of applying PSI to coastal areas and assess the extent of any localised vertical motions around the TGs.

The Global Sea Level Observing System (GLOSS)

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GLIMPSE

Tavi Murray

Swansea University

The Role of Space Geodesy in Underpinning Space-based Earth Observation

Graham Appleby

NERC Space Geodesy Facility

Port City Exposure to Flooding and Sea-Level Rise

Robert Nicholls

University of Southampton

The Tyndall Coastal Simulator

Robert Nicholls

University of Southampton

Sea-Level Rise Impacts as a Function of Temperature Rise

Robert Nicholls

University of Southampton

UK extreme storm surges, 1960-2001: a comparison between observations and the UK operational model forced by ERA-40

Chris Wilson

Proudman Oceanographic Laboratory

Impact of a Lisbon-type tsunami on the UK coastline and the implications for tsunami propagation over broad continental shelves

Chris Wilson

Proudman Oceanographic Laboratory

Work done by the Wind on the Geostrophic Ocean Circulation: The Effect of Small Scales in the QuikSCAT Wind Stress Data

Chris Wilson

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Modelling the influence of sea level rise on tides and storm surges on the European continental shelf

Mark Pickering

National Oceanography Centre