Sea Level Changes: Measurements and Analysis

Sixtieth Anniversary Meeting of The Permanent Service for Mean Sea Level 9-10 December 1993

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Abstract

The Permanent Service for Mean Sea Level (PSMSL) is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) established by the International Council of Scientific Unions.

This report is a record of a scientific meeting on recent developments in the measurement and analysis of sea level changes held on 9-10 December 1993 at the Linnean Society, Burlington House in London. The meeting, which coincided with the sixtieth anniversary of the PSMSL, was held under the auspices of FAGS and the Royal Astronomical Society. The two days included twenty oral, fourteen poster and two video presentations of different aspects of the field by distinguished scientists.

The three main themes of the meeting were:

(1) the development of the new technologies which are revolutionising the study of sea level changes. These include the Global Positioning System (GPS), absolute gravity, satellite altimetry and advanced tide gauges;

(2) the development of geological and climatological models of long term sea level changes;

and (3) the linkage of the work of the other FAGS Services, including the International Earth Rotation Service and the World Glacier Monitoring Service, to sea level research on the occasion of the PSMSL's sixtieth anniversary.

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Background to the Meeting: Welcoming Speech by P.L.Woodworth, PSMSL

Ladies and Gentlemen, my name is Philip Woodworth. On behalf of my co-organisers David Pugh and Trevor Baker I would like to welcome you to the Linnean Society[1] for what I am sure will be an excellent two day meeting on the subject of sea level changes. We are very pleased to see so many people from abroad, and we hope that you enjoy your visit and the meeting in spite of the stormy London weather and the hard seats in this room.

Some of you may have travelled here from more than one other sea level meeting in the last week. I know that there were important conferences both in France last week and yesterday at the Royal Society. Moreover, some people I believe will have yet another week of meetings next week on sea level and new geodetic techniques. One can maybe have too much of a good thing. However, you will see that the agenda of this meeting is very varied, with something of interest for everyone, and I am sure that it will be very rewarding.

There are three reasons why it was decided to hold such a scientific meeting here and at this time. First of all, there is usually a meeting in Burlington House about this time of year on some branch of geodesy or geophysics. A meeting on sea level falls naturally into that series and the Proudman Oceanographic Laboratory (POL), principally my colleague Trevor Baker, was asked by the Royal Astronomical Society (RAS) to organise it.

Research into present day sea level changes is no longer just about installing a tide gauge. A researcher needs to have some familiarity with techniques such as satellite radar altimetry, the Global Positioning System (GPS) and absolute gravity, as well as being conversant with developments in understanding sea level changes on geological timescales, modelling possible changes in the future with the use of climate models, and modelling the geoid or gravity field via surface gravity, satellite altimetry and satellite perturbation data.

This is, therefore, a very wide field, and technical developments are coming along thick and fast. Consequently, it was decided to have a meeting such as this to review some of the recent research.

The second reason for the meeting was that this year 1993 could be said to be the sixtieth anniversary of the Permanent Service for Mean Sea Level (PSMSL), which is based at POL at Bidston Observatory on Merseyside, and which is responsible for one of the main sea level research datasets. I say "could be said to be the sixtieth anniversary" but that is not entirely the case. The PSMSL, so named, was in fact established as a "Permanent Service" of the International Council of Scientific Unions (ICSU) in 1958, around the time of the International Geophysical Year. However, in practice it was a continuation of the Mean Sea Level Committee which had been set up at the Lisbon International Union of Geodesy and Geophysics (IUGG) conference in 1933 at the initiative of Professor Witting from Finland. Most of the work of data compilation for the Committee fell to its Secretary, Professor Joseph Proudman, of what was then the Liverpool University Tidal Institute at Bidston, and that work was continued by Drs.Corkan, Doodson and Rossiter also from Bidston. So it is not stretching the facts too much to claim that in practice the PSMSL started at that earlier date, and it is anyway nicer to have a meeting celebrating a sixtieth anniversary than a thirty-fifth one! A paper by Jack Rossiter, published in 1963 in the International Hydrographic Review[2], provides more details of the PSMSL's history for anyone interested. The format of the present day PSMSL databank is very much Rossiter's invention, and sea level analysts will be familiar with jargon such as "Revised Local Reference" which he invented.

Rossiter died in 1972 but we are very pleased to have here today so many surviving people who have been involved with the PSMSL in recent years. Former PSMSL Directors Geof Lennon and David Pugh are both here, as is the present Director of POL, Brian McCartney. Geof Lennon was in charge of the PSMSL during the 1970s before emigrating to Australia where he developed the Flinders sea level databank into what is now the Australian National Tidal Facility. David Pugh oversaw the PSMSL throughout most of the 1980s before joining the higher ranks of the Natural Environment Research Council (NERC), becoming Global Sea Level Observing System (GLOSS)[3] Chairman and writing a best selling book on sea level changes[4]. He maintains his connection with the PSMSL as President of the International Association for the Physical Sciences of the Ocean (IAPSO) Commission on Mean Sea Level and Tides which acts as the PSMSL's Directing Board. Also here today are Carole Pugh and Elaine Spencer who have each performed the PSMSL Secretary job at various times. Elaine has been Secretary for the last 15 years and, in practice, *is* the PSMSL.

There are many other friends here today who have been associated with the PSMSL through GLOSS activities. These include Albert Tolkachev who is GLOSS and Global Ocean Observing System (GOOS)[3] Technical Secretary at the Intergovernmental Oceanographic Commission (IOC) which (together with ICSU/FAGS) provides a small amount of international funding each year to the PSMSL. Also we have Gary Mitchum (Hawaii Sea Level Center), George Maul (AOML, Miami) and several other colleagues. All of these have worked tirelessly to see GLOSS established over the last decade. If one returns to Rossiter's 1963 paper, one reads "One common factor can be distinguished throughout all (sea level research). It is the need for more permanent gauges efficiently maintained, producing records which are accurately processed to give mean levels. As a personal ambition for the Permanent Service I shall be more than pleased, if during the next 25 years, we build up an adequate network of such stations so that our successors will have the data to work with which we at present are denied". Well, 30 years after Rossiter wrote those words, perhaps GLOSS is now getting somewhere as several presentations and posters at this meeting will show.

So, on behalf of the PSMSL, may I welcome those people I have mentioned and others here today from many corners of the world who have been connected with the PSMSL for many years either as data contributors or analysts?

This brings me to the final reason for the meeting. The PSMSL is a member of a family of geophysical databanks coordinated under the auspices of ICSU into the Federation of Astronomical and Geophysical Data Analysis Services (FAGS)[5]. Each databank within FAGS does an excellent job. However, in these days when earth science is becoming increasingly multi-disciplinary, it is important that communication between the FAGS Services be as effective as possible, and a meeting such as this is one way of stimulating such communication. We are very pleased, therefore, that Claude Boucher (representing the International Earth Rotation Service, IERS) and Wilfried Haeberli (Director of the World Glacier Monitoring Service, WGMS) have been able to attend. The IERS and WGMS are the two FAGS Services which are closest to the PSMSL in terms of overlap of fields of research. The definition and control of a global geodetic network by the IERS will be seen at this meeting to be vital to a proper understanding of vertical ocean and land level movements, while the monitoring of ice sheet changes by the WGMS obviously parallels sea level research.

It is unfortunate that Professor Paul Melchior, Director of the International Centre for Earth Tides in Brussels, another FAGS Service, cannot attend as he is yet another victim of the current influenza epidemic. He would have spoken on the overlap between ocean and earth tide research. However, he would have been welcome on a personal level also as for many years he has supported the work of the PSMSL at the IUGG and within FAGS Council as well as, of course, having an interest in Bidston's earth tide research.

So that is some of the background behind this meeting. You will see from the agenda that the four sessions are roughly divided into oceanography this morning; geodesy and modelling long term sea level changes this afternoon; geology, geodynamics, tides and gravity tomorrow morning; and altimetry and ice and sea level monitoring tomorrow afternoon[6]. Also, although our original intention was to have just a small meeting without posters, the demand for additional topics to be presented resulted in the RAS agreeing that we could show a dozen or so posters. These are displayed upstairs in the Linnean Society library and please use the coffee and lunch breaks to stretch your legs away from these hard seats and to take a look at them. We assume that their authors will be present for some of the time to explain them in detail. In addition, two videos will be shown in the Lecture Room at these times. This evening we hope that you can attend a small reception given by IAPSO to mark the PSMSL's sixtieth anniversary and organised by the RAS.

So on with the meeting, and although this is the PSMSL's sixtieth (or thirty-fifth) anniversary, we did not want a purely tide gauge meeting. However, we did want someone to start the meeting who has been associated with the PSMSL in the past, and we were very pleased that David Aubrey from Woods Hole Oceanographic Institution was able to come. David and Professor K.O.Emery have probably been the analysts who have made the most use of PSMSL data in their research. Many of you will be familiar with their papers and recent book on sea levels, land levels and tide gauges[7]. However, David is a versatile fellow with wide interests in oceanography and coastal engineering, and his talk to start this meeting has the modest title "Relative Sea Levels and Civilization".

Notes:

(1) The Linnean Society, founded in 1788, is the oldest scientific society in the world devoted to natural history. The Society Lecture Room used for the meeting was the same room in which at a meeting of the Society on 1st July 1858 Charles Darwin and Alfred Russell Wallace made the first communications of their views of *The Origin of Species by Natural Selection.* An original portrait of Darwin dominates the room. With regard to sea level research, Charles Darwin is, of course, famous for his observations of tsunamis, Andean land uplift and the evolution of fringing reefs, barrier reefs and atolls atop sinking volcanic islands in *The Voyage of the Beagle*. One of his sons, George Darwin, conducted extensive tidal research, and with Lord Kelvin was one of the early developers of harmonic tidal analysis. The Society Lecture Room was, therefore, an entirely appropriate location for a sea level meeting.

(2) Rossiter, J.R. 1963. The work of the Permanent Service for Mean Sea Level. International Hydrographic Review, 40(1), 85-89.

(3) See Appendix 1 of this report.

(4) Pugh, D.T. 1987. Tides, surges and mean sea-level: a handbook for engineers and scientists. Wiley, Chichester, 472pp.

(5) See Appendix 2 of this report.

(6) The Chairmen of the sessions were Roger Flather, Trevor Baker, David Pugh and Graham Alcock respectively. The presentations of Cartwright and of Melchior were not given owing to influenza. However, their abstracts have been included in this report as they are of great interest.

(7) Emery, K.O. and Aubrey, D.G. 1991. Sea levels, land levels, and tide gauges. Springer-Verlag, New York, 237pp.

Scientific Abstracts

Relative Sea Levels and Civilization

David G.Aubrey, Woods Hole Oceanographic Institution, USA

Relative sea levels and civilization are closely intertwined, with sea levels affecting the course of civilization and civilization, in turn, affecting sea levels. This symbiotic relationship has provided for interesting case studies throughout the world. Examples of the influence of relative sea levels on civilization include the drowning of civilizations as relative sea level has risen; the migration of civilizations as harbors have dried due to rising land levels; and the economically and socially expensive loss of human infrastructure as relative sea levels have fluctuated. Influence of civilization on relative sea levels are equally important: the hypothesized greenhouse effect would increase sea levels in some regions, due to trace gas emissions by civilization; groundwater and oil and gas withdrawals from sediments have caused localized subsidence, increasing economic costs to combat the "rising" seas; and water consumption and river controls have altered local basin hydrologies, increasing magnitudes and rates of fluctuations of relative sea levels, particularly in semi-enclosed or enclosed seas. The interaction of civilization with relative sea levels is but a single, small example of the relationship between mankind and nature, but it is an example relevant to demonstrate the often unanticipated linkages and feedbacks between the two.

Mean Sea Level and Climate Variability in Australasia

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Mean sea levels and their relationship to changes in the climate for Australasia have been examined. There exists a large anomaly in the annual signal along the south coast of Australia, facing the Southern Ocean, with sea levels and barometric pressures both attaining their maxima during austral winter. There are also large interannual fluctuations due to El Niño in the north-west and in the south. These fluctuations precede El Niño by some months, enabling a seasonal forecast for weather conditions based on mean sea levels. These are derived from the high resolution sea level gauges installed under the national Greenhouse programme. A possible mechanism for this link and the latest survey of mean sea level trends will be presented.

Sea Level Fluctuations at Periods Longer Than a Few Years; How Much of it is Wind Forced?

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In an attempt to make better estimates of the long-term rise of sea level, and particularly to allow detection of changes in the rate of rise, we have been trying to understand the large sea-level fluctuations at periods of roughly 50 - 200 months observed on the east coast of the United States. In an effort to begin in the simplest way, we have tried to understand the similar variations observed at

Bermuda.

The Bermuda tide gauge record extends back into the late '30s. Sea level fluctuations there are highly coherent with dynamic height from hydrographic data. It would seem, therefore, that the observed low frequency variability in sea level might possibly contain clues about climate, on the limited time scales accessible in the record, because dynamic height contains information on heat storage.

Using the COADS data, we have made a simple model of wind forcing of the Atlantic from the African coast to Bermuda; we use the Levitus data to estimate the long Rossby wave speed as a function of longitude. We find that sea level estimated this way is remarkably similar to observed sea level at periods longer than a few years. The computed r.m.s. variability agrees in magnitude with the variability observed at the depth of roughly the 15-degree isotherm. Merely using the mean curl across the Atlantic, however, is not a good way to estimate the signal; we find that there is a significant amount of power at the lowest frequencies on the eastern side of the ocean as well as near Bermuda. We might wonder if the wind data are reliable at these very long periods were it not for the high coherence between our results and observed sea level.

It is likely that significant changes in buoyancy forcing by the atmosphere could be highly coherent with changes in wind; nevertheless these results suggest that the variability in sea level -- and hence in temperature -- can perhaps be accounted for without invoking changes in stored heat of the deep ocean.

The Need for Tide Gauge Data in the Age of Altimetry

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I think it likely that 20 years from now we will look back to the Geosat altimetry mission as the beginning of a new era in the measurement of the height of the sea surface. This "age of altimetry" will be marked by continuous altimetric measurements at the Geosat level of accuracy or better and by simultaneous missions that increase the temporal and spatial sampling rates. The new age will also see the routine production of sea surface height datasets that are useful to a broad range of scientists. If these predictions come true, as I think they will, then a question naturally arises. Do we still need to operate tide gauges along the coastlines of the continents and on open ocean islands?

I will consider this question from several viewpoints. First, from the point of view of "local" interests in the height of the sea, which include phenomena from tidal variations to sea level rise. Second, I will consider the needs of analyses at time scales of interannual and shorter. These time scales define a region where scientific and operational interests are presently intersecting heavily. Finally, I will consider the need for information at global change time scales, which I define as interdecadal and longer and that I will argue is primarily scientific.

The Contribution of IERS to Sea Level Change Studies

C.Boucher, IERS Central Bureau (IGN), Paris, France

The International Earth Rotation Service (IERS), is a FAGS service like the PSMSL established in

1988, succeeding to BIH and IPMS. It is in charge to determine Earth orientation parameters - polar motion and angular rotation or Earth Rotation Parameters (ERP) and precession-nutation - in conventional celestial and terrestrial reference systems for which IERS also determines realizations as accurately as possible.

The IERS products can play a significant role in the studies of sea level changes. Three topics are discussed in this paper:

- use of the geophysical transfer function between polar motion/LOD and global sea level rise, together with ERP series

- use of the IERS Terrestrial Reference Frames (ITRF) to determine geocentric sea levels at tide gauges, and their time variations

- use of ITRF to obtain global sea surface models at various epochs from satellite radar altimetry missions (SEASAT, GEOSAT, ERS-1, TOPEX-POSEIDON.. .)

In all these applications, the improvements and assessment of the quality of IERS products (ERP and ITRF) is a key factor to a more reliable estimate of sea level changes.

Monitoring Vertical Displacements of Tide Gauges by GPS: Datum Problems

V.Ashkenazi, R.M.Bingley, G.M.Whitmore, G.A.Beamson (Institute of Engineering Surveying and Space Geodesy, University of Nottingham, UK) and T.F.Baker (POL, Bidston Observatory, UK)

Monitoring of the vertical movements of tide gauges requires high accuracy heights which can be achieved by fiducial GPS. The choice of datum, or reference framework, for fiducial GPS is of critical importance, since it defines the scale, orientation and origin of the whole network. Furthermore, for long-term monitoring of displacements over several decades, one must also make provision for modelling the movement of the reference framework, or the fiducial stations themselves, in order to correctly time-tag the observed heights.

Using data from the UK Tide Gauge GPS Project, tests have been carried out to assess the quality of several alternative global reference frameworks. These frameworks were based on pure SLR, VLBI, or GPS measurements, or a combination of these techniques. The results demonstrate that fiducial GPS can indeed achieve internal consistency and very high accuracies, and that this high accuracy is mainly limited by the quality of the datum, as defined by the adopted coordinates of the fiducial stations. The tests indicated that, in the particular context of Northern Europe, a pure GPS defined datum was the best.

Tide Gauge Benchmarks: Prospects for Removing Changes in Absolute Elevation using GPS

G. Blewitt, M. B. Heflin, and L. J. Romans (Jet Propulsion Laboratory, California Institute of Technology, USA), T. M. VanDam (NVI, NASA Goddard Space Flight Center, USA), J. L. Davis and P. Rongshi (Harvard Smithsonian Institute, Center for Astrophysics, USA), T. H. Dixon and C. Harrison (Rosenstiel School of Marine Sciences, University of Miami, USA), J. M. Johansson (Onsala

Space Observatory, Chalmers University, Sweden), B. Engen and O. Kristiansen (Statens Kartverk, Norway), G. Maul (NOAA Atlantic Oceanographic and Meteorological Laboratory, USA), A. E. Niell (Haystack Observatory, Massachussetts Institute of Technology, USA)

We stress the importance of removing changes in absolute elevation from tide-gauge measurements in the monitoring of global sea-level, and the ways in which the Global Positioning System (GPS) can help in this regard. First, we discuss the theory and practice of using GPS to establish a stable geocentric terrestrial reference within which absolute geodetic height can be monitored. Second, we discuss estimation of station height, error sources, and expected geodetic signals, including the role of crustal loading effects ranging from present day changes in atmospheric and oceanic pressure to prehistoric deglaciation. Third, we show (i) detection of correlations in recent independent GPS and VLBI solutions that may be caused by variations in elevation, and (ii) evidence of real geophysical signals in GPS height solutions due to atmospheric pressure loading and ocean tidal loading. We conclude with a summary of the status of the International GPS Geodynamics Service (IGS), examples of plans for GPS regional networks collocated with tide-gauges (e.g., in Scandinavia and Florida), and prospects for how IGS and regional networks might work together to produce calibrations for the variation in absolute geodetic height of tide gauge benchmarks.

Long Term and Current Sea Level Changes and Land Movements in the UK

Ian Shennan, Department of Geography, Durham University, UK

Crustal downwarping has occurred throughout southern and south-eastern England and most of Wales for at least the last 4000 years. Highest estimated rates of subsidence are for the Thames estuary and Norfolk. Glacio- and hydro-isostatic processes have resulted in uplift in northern England and mainland Scotland. The rates of uplift have decreased since deglaciation; estimates for the present range from approximately zero in south Lancashire and the Tees estuary, to over 1mm a-1 in central Scotland. A comparison has been made of the secular trends in sea-level from the late Holocene period (determined from geological data) and the twentieth century (from the tide gauge data). In most cases the two data sets of trends are well correlated. The tide gauge trends are systematically larger than the long-term trends inferred from the geological data by c.1.0+/-0.15 mm a-1 which can be interpreted as an estimate of the regional eustatic rate of sea-level change for the twentieth century.

Modelling Past and Future Sea Level Changes on the Century Time Scale

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Uncertainties in future sea level rise derive from uncertainties in future climate as well as the contributing factors; oceanic thermal expansion, Greenland ice sheet, Antarctic ice sheet and small glaciers. The work of an ongoing multi-institutional CEC project to make improved estimates of future global-mean sea-level change due to greenhouse-gas-induced climate change is described (Raper *et al.*, 1993). One of the products will be an updated, integrated model for climate and sea level prediction. The results of field work and detailed modelling carried out during the project will be encapsulated into simple contributing models. So far, research on small glaciers and recent changes to the carbon cycle model imply that our projections may be revised downwards.

A further source of uncertainty arises from possible regional changes in sea level caused by dynamic changes in the ocean circulation. Initial experiments, using an ocean general circulation model, indicate that region-specific differences in sea level can be quite marked (Mikolajewicz *et al.*, 1990). For the CEC project, the Max Planck Institute are undertaking to determine the possible regional sea level changes in the North Sea using their models.

Raper, S.C.B. and contributors, 1993: *Climate and Sea Level Changes and the Implications for Europe.* In press.

Mikolajewicz, U., B.D. Santer and E. Maier-Reimer, 1990: *Ocean response to greenhouse warming.* Nature, 345, 589-593.

Sea-Level Change and Shoreline Evolution around Great Britain and the North Sea for the Past 20000 Years

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The occurrence of raised and submerged shorelines of Scotland, England and Wales is well documented and has been qualitatively understood in terms of two components: the crustal rebound in response to the melting of the late Pleistocene ice sheet over the British Isles and the rise in sea level resulting from the quasi-simultaneous melting of the more voluminous ice sheets over North America and Europe. To this have to be added smaller but still significant contributions from the rebound of nearby Fennoscandia and from the loading of the sea floor by the melt-water load. Models of this glacio-hydro-isostatic rebound require a knowledge of both the history of glaciation and deglaciation and of the Earth's physical response to changes in surface loading. The application of the models has often been limited by the difficulty of separating the uncertainties introduced by an inadequate knowledge of the ice history and of the Earth rheology but by matching model predictions with observations, it becomes possible in some circumstances to separate these two sources of unknowns and to develop consistent rebound models. This is the case for the British Isles where there is a reasonable distribution of Holocene sea-level observations from sites around and within the limits of glaciation, including sites quite close to the former centre of glaciation, and rebound models can be established that are consistent with sea level data and with glaciological evidence. Such models provide a basis for reconstructing palaeo-shorelines in the offshore region and for constraining models of Holocene and Late Devensian coastal evolution. In previous attempts to map the palaeo-shorelines in the North Sea it has been usual to assume that sea level change is everywhere equal to the eustatic change. But this can produce misleading results, particularly in areas such as the entrances to the Firth of Forth where the eustatic approximation would lead to the emergence of this area in contrast to the submergence predicted by the correct theory.

Because of the delayed response of the earth to the glacial growth part of the load cycle, the evolution of the North Sea and Irish Sea at the time of maximum glaciation is controlled by the rheology of the mantle and the area of emergence increases during the early phase of deglaciation. Thus the Irish Sea, for example, is separated from the Atlantic in the south by about 19 ka BP. For a while the crustal adjustment of the sea floor to the changing loads keeps up with the eustatic change such that the shoreline is nearly stationary from about 16 to 12 ka BP, and the major period of formation of the now submerged North Sea shoreline would date from the Lateglacial time rather than from the time of maximum glaciation. Also a land bridge between Ireland and Britain is predicted to survive until about 13 ka BP. After about 12 ka BP the eustatic influence becomes important and the transgression of the offshore region is rapid. Separation of Britain from the continent of Europe occurs by about 7 ka BP. Between about 18 and 10 ka BP the predicted water depths in the North Sea, other than in the Norwegian Trough, are generally shallow, and frequently less than 20 m.

On Two Different Aspects of the Ocean's Role in Geodynamics

H.-P.Plag, M.Gröger and W.Pomrehn, Institute of Geophysics, University of Kiel, Germany

Two subsets of the PSMSL monthly mean sea level data are used to elaborate on different aspects of the ocean's role in the dynamics of the global Earth system:

(1) The densest regional subset of long records covers the Baltic Sea and North Sea area. In this region, the most protruding interannual signal is a quasi-periodic oscillation with a mean period of roughly 14 months, which is commonly associated with the pole tide. The data set evidences sudden temporal changes in the frequency of this 'apparent' pole tide, and the temporal variations in both frequency and relative power are spatially highly coherent. A similar signal with the same temporal pattern is found in the air pressure in parts of this region. The sudden leaps in frequency are related to distinct features of the Northern Hemispheric temperature variations during the last hundred years. The leaps are thought to be due to rapid changes in the circulations of the coupled atmosphere-ocean system resulting from or leading to step-like changes of the mean temperature of the Northern Hemisphere.

(2) The temporal subset with the best global coverage, namely that of the interval between 1950 and 1979 reveals a global East-West fluctuation of decadal time scales with coastal amplitudes of several cm. This large-scale phenomenon indicates that the global oceans may significantly contribute to the excitation of the decadal fluctuations in the length of day.

Some Miscellaneous Thoughts on the Collection and Use of Sea-Level Data

David E.Cartwright, F.R.S., Petersfield, UK

A retrospective glance at the treasure trove of scientifically useful data provided without cost by the corpus of historical tide-gauge records is followed by a reminder of the shortcomings of the 'monthly mean' convention, and its possible replacement by proper digital filters, evenly spaced in time.

The basic *raison d'etre* of the PSMSL from its earliest days has been to provide the means to detect global secular rise in 'geocentric' - as distinct from 'relative' - sea level. However, despite on-going efforts to monitor vertical earth movement, the spatial density of observing sites is too sparse to achieve global averages. We require a *spatially integrated* empirical measure of geocentric sea level whose interannual variance is less than the expected secular change in, say, 10-20 years. Most promising seems to be a continued programme of nearly global satellite altimetry in conjunction with ocean-wide acoustic thermometry.

Climate models are also necessary as essential aids to understanding spatial and interannual variability, but they must be anchored to the empirical data. Ultimately, not only the models but also all remotely sensed data relative to sea level depend on *in situ* recordings for calibration. We count on the PSMSL to continue to provide such dependability.

Oceanic Tides in Relation with Earth Tides

P.Melchior, International Centre for Earth Tides (FAGS), Observatoire Royal de Belgique, Avenue Circulaire 3, B-1180 Bruxelles, Belgium

Recent developments in earth tide research (superconducting gravimeters precise to a few nanogals) make necessary an extended development of the luni-solar gravitational potential (up to 2000 terms or more).

Besides the problem of calibrations of the instruments, uncertainties in the interpretation of the earth tide measurements are essentially due to a correct evaluation of oceanic tides (attraction and loading effects) based upon corange-cotidal maps and of the periodic atmospheric loading.

Diurnal earth tides contain the signature of a resonance in the liquid core of the Earth and are associated with the astronomical nutations.

Tidal tilts and strains are perturbing measurements in other fields of work, such as particle orbits in accelerators.

Absolute and Relative Gravity and Sea Level

K.Charles and R.G.Hipkin (Department of Geology and Geophysics, University of Edinburgh, UK), R.J.Edge, T.F.Baker and G.Jeffries (POL, Bidston Observatory, UK)

A fixed point on land is usually taken as the reference for sea level. It is important to determine the absolute rate of uplift of the land. The acceleration due to gravity decreases with increasing distance from the centre of the Earth. A height change of 1 cm corresponds to a change in gravity of about 2 parts in 10^9 (2 μgal). Geocentric height changes due to active tectonics or post glacial rebound can occur with rates in the order of 1 cm year^{-1}. The estimated rate in Britain is about 5 mm per year vertical displacement over a baseline of 1000 km, so the value of gravity must be observed with a precision of 3-4 parts in 10^9 in order to measure the effect within a decade.

The FG5 absolute gravity meter is claimed to have an absolute accuracy of 1-2 parts in 10^9 and an internal precision of 0.2 - 0.4 parts in 10^9. Experience with POL's FG5 meter (FG5-103) in Britain has not yet achieved this level of repeatability, but absolute measurements have been made at a small number of sites and these values will be transferred to the rest of the country via the British Precise Gravity Network 1993 (BPGN93).

The BPGN93 consists of about 70 sites in Scotland, England and Wales about 100 km apart. All the sites were newly established for this network and have been selected for their long term stability with respect to subsidence and minimum likelihood of modifications to the local environment in the next decades.

The accuracy of relative gravity observations relies on the calibration of the instruments used. The shape of the calibration curve is determined by laboratory procedures, and the overall scale will be determined by absolute measurements. The internal precision from a free adjustment is 3-6 µgal for gravity differences of up to 600 mgal.

Satellite Altimetry : A Precise Measurement System for Truly Global Sea-level Monitoring

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Satellite altimetry has the proven capability for precise monitoring of the sea-surface at spatial and temporal resolutions unsurpassed by other techniques. Global studies lead to improved knowledge of the mean-sea level and its variability. Separation of the ocean topography from the Earth's geoid, an equipotential surface of the gravity field, is feasible at long-wavelengths for which the uncertainty in the geoid is less than the topographic signal. However full utilisation of altimetry is limited by deficiencies in the geoid which are unlikely to be resolved until a dedicated gravity field mission is launched.

Long-term analysis of altimeter datasets yields the mean altimetric sea-surface, a combination of the geoid and the quasi-stationary topography. Variability studies can be performed by differencing sea-surface anomalies determined over short time spans with respect to the mean surface. Details will be presented of the latest results with particular reference to the two currently operational satellites ERS-1 and TOPEX/POSEIDON.

Secular Glacier Melt Rates

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Melt rates of mountain glaciers can be determined using mass balance measurements and by applying a simple continuity model to glacier length changes over time intervals which correspond to the dynamic response time (typically about 50 to 100 years). The most complete information exists in the Alps where precision mapping and regular surveying of selected glaciers already started at the end of the 19th century.

Average rates of glacier mass loss in the Alps during 20th-century warming were a few decimetres water equivalent per year. During the last decade (1980-1990), they further increased by more than 50% with respect to the secular average. With due consideration to the feedback mechanisms affecting glacier mass balance, the observed melt rates are comparable with estimated rates of anthropogenic greenhouse forcing (2 to 3 W/m^2). The recent emergence of a stone-age man from cold ice/permafrost on a high-altitude ridge of the Oetztal Alps confirms results of earlier moraine investigations: the extent of Alpine ice is probably more reduced today than ever before during the past 5,000 years and now seems to pass beyond the "warm" limit of the range known for natural fluctuations during the Upper Holocene.

At least qualitatively, the secular trend observed in the Alps appears to be representative for glacierized mountain ranges all over the world. More detailed assessments on a global scale should be obtained by combining direct mass balance measurements at selected sites with remotely sensed information on length changes of suitable glaciers. Small mountain glaciers give the clearest "climate" signal but could disappear within decades if atmospheric warming indeed accelerates. On the other hand, large valley glaciers in humid coastal regions such as the Gulf of Alaska or Patagonia have the potential for contributing to sea level rise far into the coming centuries.

Recent Fluctuations in the Volume of the Antarctic Peninsula Ice Sheet

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A series of over snow level lines have been set up over the period 1972-86 in Palmer Land and on Alexander Island. The height of the snow surface with respect to fixed points on local nunataks at each end of the level line has been measured, and in some cases remeasured, using traditional surveying techniques. Further data has been collected during the 1992/3 Antarctic summer when GPS satellite surveying techniques were used to remeasure the level lines. Accumulation changes at each site will be determined from ice cores. The data so far suggest that for cold sites with mean annual temperatures less than -11°C the ice sheet is thickening in response to the increased accumulation associated with warmer temperatures. On the other hand at warmer valley glacier sites where ablation occurs in the summer the ice volume is shrinking in response to the warmer climate. A theoretical analysis of the dynamic response of the Antarctic Peninsula Ice Sheet to changes in surface mass balance has been used to evaluate these results and predict (tentatively) how the volume of the Antarctic Peninsula Ice Sheet may change in the future.

An Analysis of Sea Level Changes Along the Dutch Coast

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It is of great political importance that an expected acceleration of mean sea level rise will be detected as early as possible. Time series of annual mean sea level, measured at tide gauges, show a lot of noise, which makes this early detection more difficult. Classical methods are not very appropriate for this purpose.

A relatively new method, SSA (Singular Spectrum Analysis), was applied to time series of mean sea level and also to mean high water and mean low water. Very good and smooth trend lines were obtained.

These trend lines show an acceleration of the relative mean sea level since about 1975. In order to investigate the significance of this acceleration it was tried to reduce the noise of the time series. It turned out that about 40 % of the noise could be explained by meteorological phenomena, represented by time series of air pressure (yearly averages) of six stations, three around the North Sea and three around the North Atlantic Ocean. The influence was determined by multiple linear regression techniques. Application of the SSA method to the noise reduced time series yielded the remarkable result that the acceleration shown by the trend lines of the original data became very small or even disappeared.

Data Archaeology: Sea Level Rise at Key West, Florida, 1846-1992, America's Longest Record?

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From the geological record we know that global sea level has been rising since the Holocene glacial maximum (18,000 ybp) with rates ranging from approximately 10 mm/yr ca. 10,000 years ago to less than 0.5 mm/yr during the last 3,000 years. The instrumental record is typically only 50 years long except in a few cases, and the rate of global relative sea level rise from such direct observations is in the range 1-2 mm/yr. The instrumental record from Key West, Florida is continuous only since 1913, but sporadic data have been found dating to 1846 for which a summary datum can be recovered. Linear trend of annual mean sea level at Key West is 1.9 mm/yr during the last 147 years, and there is no statistically significant evidence of acceleration in the rise as might be hypothesized from global warming. The approximately 30 cm rise in water level since the mid 1840's has had little socioeconomic effect on Key West Island, which has grown in area due to bulkhead construction and sea bottom reclamation; ecological effects however have been significant. For the epoch 1951-1987, Key West sea level rise is best explained as the sum of steric expansion of the upper 1000 meters in the adjacent water column (1.4 mm/yr) plus vertical land motion due to modeled post-glacial rebound (0.9 mm/yr). Geodetic techniques allow direct measurement of the land motion, and centimeter accuracies are now being obtained at a single GPS site in Florida and millimeter precision is obtainable with differential GPS. Comparison of monthly Key West sea level (1981-1989) with the Naval Research Laboratory numerical circulation model explains only 16% of the variance, and for the annual means, the records are essentially uncorrelated. Using models to improve signal-to-noise in order to detect anthropogenic effects in sea level will probably require improved wind fields, realistic thermohaline variability, and finer spatial resolution.

Monitoring Vertical Displacements of Tide Gauges by GPS: Ocean Tide Loading Effects

V.Ashkenazi (Institute of Engineering Surveying and Space Geodesy, University of Nottingham, UK), T.F.Baker (POL, Bidston Observatory, UK), R.M.Bingley, G.A.Beamson, D.J.Curtis and A.H.Dodson (IESSG, University of Nottingham, UK)

For a rigorous determination of heights at coastal tide gauge sites, the effects of ocean tide loading must be modelled during fiducial GPS processing. This modelling is particularly important if periodic fiducial GPS campaigns are being used as opposed to a permanent tracking GPS network.

A GPS observation campaign was carried out over three days in February 1993, to investigate the effects of ocean tide loading on heights. Three stations were occupied at sites where the ocean tide loading effects in the UK are markedly different; Newlyn, Herstmonceux and Nottingham.

The observations provided 50 hours continual monitoring of land movement at the three sites, and the data were processed in three-hourly sessions, using the IGS precise ephemeris. Changes in the height differences from session to session showed a high correlation with the theoretical M2 ocean tide loading, and through the incorporation of a tide model in the GPS software, the precision of these height differences was significantly improved. The results illustrate that a certain level of accuracy can be obtained by using 24 hour GPS observations to effectively 'average' over the duration of the tidal wavelength of the main M2 ocean tide, but that without modelling, shorter observation periods can lead to significantly reduced accuracy.

The Space-Time Structure of African Mean Sea Level

G.B.Brundrit (Department of Oceanography, University of Cape Town, South Africa) and D.Chemane (Department of Oceanography, University of Southampton, UK and INAHINA, Mocambique)

Records of monthly mean sea level for all African sites bordering the Atlantic and Indian Oceans (and on Madagascar and other nearby Indian Ocean islands) have been selected from the global archive maintained by the Permanent Service for Mean Sea Level. Whilst these records are somewhat sparse and intermittent, they have responded to exploratory statistical analysis in both time and space to reveal the essential character of their large scale variability. The possibility of equatorially forced interannual variations travelling polewards is noticeable along the Atlantic coast, whilst a dominating seasonal signal is apparent in the Indian Ocean.

Sea Level, Mainland Rise or Fall and its Trend in Shanghai

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According to the records of tidal gauge, the relative sea level (RSL) change can be determined. Considering the tidal gauges vertical deformation relative to the Earth mass centre, the absolute sea level (ASL) change will be detected. In order to determine the vertical movement of the crust in Shanghai region the geodesy reference system has been established for two years since 1991. This system contains two satellite laser range (SLR) stations (Sheshan and Wuchang), a global position system (GPS) net connected with Wushong and Sheshan, and precise gravimetry between Wuchang, Sheshan and Wushong. The latter's precision is 7 microgals, GPS's 0.7 ppm, and SLR's 3 mm in one year.

In this paper, the RSL change and mainland rise or fall have been calculated and analysed in terms of long records (1945-1991) of Wushong tidal gauge and data of crust deformations in the past. Their results are +1.8mm/a. and -2.5mm/a. respectively. The RSL rise is correlated with the temperature variation of Shanghai in the past 100 years. The temperature has risen 0.44°C which is close to that of global temperature, because there are some greenhouse gas effects. This paper presents that the RSL in Shanghai will rise about 28-61cm by 2050. Undoubtedly this will have a large effect on Shanghai, but the influence is not so serious as some scientists have predicted.

Generating Revised Local Reference of Historical Tide Gauge Readings in the Southern Baltic Sea

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A reinvestigation of the tide gauge recordings of the German stations Warnemünde and Wismar was performed. This includes intensive research in archive materials and collection of additional informations from different sources. In the poster the following results of this investigation will be shown:

- a discovery of monthly mean values for the years 1848 - 1881 (Wismar) and 1855 - 1881 (Warnemünde), for which only yearly means were known (that means an extension of the monthly data series into the past for about 30 years)

- the history of the connection of the tide gauge zeros to levelling benchmarks was compiled

- the relations of different height systems which were in use are described

- the problems of correcting monthly means computed from less than 4 readings per day will be discussed

- the resulting revised time series of monthly mean values will be displayed.

Both stations are connected to the ITRF by GPS measurements.

Monitoring Vertical Displacements of Tide Gauges by GPS: Atmospheric Modelling

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The atmosphere exhibits both short-term, ie weather fronts, and long-term, ie seasonal (temporal) fluctuations in space. It is the inability, at present, to accurately parameterise these variations for the calculation of propagation delays which is one of the major limiting factors in the determination of high accuracy heights by fiducial GPS, for such applications as the monitoring of the vertical displacements of tide gauges.

A series of fiducial GPS observation campaigns have been carried out during four different seasons of the temperate climate of South-West Sweden, in conjunction with Water Vapour Radiometer (WVR) measurements at Onsala. The main aims of the project are to assess the effect of the wet path delay on the ability of fiducial GPS to provide high accuracy height determination, and to attempt to model this effect.

Results from these campaigns show a significant correlation between the wet path delay time gradient, estimated from the WVR data at Onsala, and the height determination of a baseline from Onsala to Jönköping, 134 km to the East. Furthermore, the application of a WVR derived gradient model significantly improves the height determination, by a factor of two under high gradient conditions.

GSI's Tactics Towards Detecting Sea Level Change

Shigeru Matsuzaka and Yoshiro Nakahori, Geographical Survey Institute, Kitasato 1, Tsukuba, Ibaraki 3056 Japan

The Geographical Survey Institute (GSI) in Japan has embarked on a program to detect sea level rise using latest geodetic techniques. A transportable Very Long Baseline Interferometer (VLBI) will be used to establish fiducial points with respect to a geocentric global reference frame. With several of these points as absolute reference, GPS and levelling determine the height of tidal stations. Gravity

measurements (absolute or relative) will also be utilized to obtain accurate vertical information.

The Paramount Role of Meteorological Variables on MSL

Antonino Palumbo, Dipartimento di Geofisica e Vulcanologia, Universita Degli Studi di Napoli, Italy

Atmospheric pressure "P" exhibits a bistable mode of oscillation caused by the Mn (nodal) external tidal excitation with a sudden 180 degree phase switch at the end of the last century inducing in turn a coherent behaviour in the following climatic and oceanic parameters, physically well related among themselves, as follows:

Air temperature "Ta" adiabatically related to P
Rainfall "R" related to Ta and P
Sea surface temperature "SST" related to Ta
Evaporation "E" related to Ta and to SST
Mean sea level "MSL" related to water expansion (SST) and to R

Both the above evidenced phase switch and the physical MSL-climatic relationships are found responsible for the failure of previous significant determinations of the Mn term in long series of climatic and in turn in MSL data over the last two centuries.

The large induced 18.6 year signal in MSL is responsible for the large discrepancy between the Mn term computed according to the tidal forcing and the observed one which includes also the large and variable contribution of the 18.6 year term induced by the climatic components.

GLOSS and WOCE Sea Levels

L.J.Rickards, S.L.Dowell (British Oceanographic Data Centre, Bidston Observatory, UK) and A.Tolkachev (Intergovernmental Oceanographic Commission, Paris)

The Global Sea Level Observing System (GLOSS) is based on an international network of sea level measuring stations, coordinated by the Intergovernmental Oceanographic Commission (IOC). The network comprises some 300 stations spaced at approximately 1000km intervals around the continental coastlines and with a gauge in each main oceanic island group. This poster reviews the progress of GLOSS and briefly considers further developments in the light of ocean monitoring programmes like the IOC Global Ocean Observing System (GOOS).

The GLOSS network has provided the framework for the World Ocean Circulation Experiment (WOCE) sea level network. The WOCE programme is establishing two sea level Data Assembly Centres (DACs), responsibility for which has been vested jointly in the University of Hawaii and the British Oceanographic Data Centre (BODC). This poster illustrates the work of the 'delayed mode' DAC at BODC, which began its activities early in 1991. It is responsible for the assembly, distribution and supply of sea level data to the full extent of quality control possible covering all of the 100 or so gauges in the WOCE sea level network.

The ACCLAIM Programme in the South Atlantic and Southern Oceans

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The ACCLAIM (Antarctic Circumpolar Current Levels from Altimetry and Island Measurements) programme is designed to study variations in the flow of the ACC on large time and space scales. The ACC is one of the important ocean current systems since it links all three meridional oceans and is responsible for inter-ocean transfer of mass, heat and salt. The dynamics of the system are not well understood and measurements of the flux of various parameters are required. ACCLAIM consists of a network of island tide gauges and bottom pressure recorders in the South Atlantic and Southern Oceans which are arranged to span the ACC to provide measurements of pressure difference and hence variability in transport. Since 1985 an extensive dataset of measurements has been collected and these are being used in a number of analyses. The ACCLAIM network is also part of GLOSS and of the ERS-1 and TOPEX/POSEIDON sea level network providing data for the validation of satellite altimetry.

Reference

Spencer, R., Foden, P.R., McGarry, C., Harrison, A.J., Vassie, J.M., Baker, T.F., Smithson, M.J., Harangozo, S.A. and Woodworth, P.L. 1993. *The ACCLAIM programme in the South Atlantic and Southern Oceans*. International Hydrographic Review, 70, 7-21.

New Australian Antarctic Tide-Gauges

R.Summerson (Australian Antarctic Division), R.Handsworth (Platypus Engineering) and G.W.Lennon (NTF, Flinders, Australia)

In 1991, following representations to the Australian Antarctic Division by the National Tidal Facility, Flinders University of South Australia, a new program of sea level measurements in the Australian Antarctic Territory was embarked upon. Platypus Engineering, a specialist instrumentation manufacturer in Hobart, Tasmania, was contracted to build a system for sea level measurement designed for Antarctic waters. In 1992 and 1993, three tide gauges were deployed at Australian Antarctic stations.

The system incorporates three components:

1) a 750 kg concrete mooring to provide a semi-stable datum;

2) a sea level recorder which incorporates a Parascientific Digiquartz pressure transducer, a temperature sensor, a battery with a five year life, the facility for storing two years of 10 minute continuously averaged data and the means to communicate the data;

and 3) a communication system, deployed from the surface to retrieve data.

To date, a six months record has been retrieved from Mawson and Davis stations during the winter, demonstrating the success of the system.

The Anomalous North Sea "Pole Tide"

M.N.Tsimplis, Proudman Oceanographic Laboratory, Bidston Observatory, UK

Monthly mean sea level values from tide gauges at the coasts of the North Sea are compared with the monthly means from an operational storm-surge and tidal model. The time series cover the period 1955-1984. The model describes most of the variability in all frequencies except the annual. Most of the energy around the pole tide frequency is also reproduced by the model. Since the model includes only eight main diurnal and semi-diurnal tidal constituents it is concluded that the deviations from the equilibrium pole tide are of meteorological origin. The annual cycle due to steric effects is also estimated. The meteorology introduces errors in the apparent MSL trends of up to 0.8 mm/yr for the 30 year period in the eastern North Sea.

Reference

Tsimplis, M.N., Flather, R.A. and Vassie, J.M. 1993. *The North Sea pole tide described through a tide-surge numerical model.* To be published in Geophysical Research Letters.

The Inverse Barometer and Five Day Waves in the Central Atlantic

P.L.Woodworth, S.A.Windle and J.M.Vassie, Proudman Oceanographic Laboratory, Bidston Observatory, UK

The local inverse barometer (LIB) model, whereby deep ocean levels respond isostatically (i.e. by about 1 cm/mbar) to air pressure changes on timescales of approximately 2 days or more, is routinely applied in oceanographic analysis of altimeter data. However, there has been considerable recent discussion in the literature on just how accurate the simple LIB model is.

We have used tide gauge data from POL's ACCLAIM network in the South Atlantic to study departures (D) from the LIB as a function of latitude in the frequency band 0.05 - 0.5 cycles/day. Outside of this band, one would certainly not expect the LIB to apply, owing to complex dynamics at high frequency and seasonal and interannual processes (e.g. steric changes) at low frequencies. We define:

$$D = (\zeta/\zeta_B) - 1 = -(\zeta/AP) - 1 = -SSP/AP$$

where ζ is sea level change, $\zeta_B = -AP$ is expected change in sea level from the LIB and AP is air pressure change, and $SSP = \zeta + AP$ is change in sub-surface pressure as measured by the ACCLAIM pressure transducers. If the LIB were a perfect model, a coherence analysis between AP and SSP would yield low coherence and zero transfer function (T) from AP to SSP, and zero values of D.

The Central Atlantic has also been shown to be of interest *vis à vis* the LIB in numerical models. For example, that of Ponte (1993) shows significantly non-zero and negative D at five day timescales in the region, whereas it is nearer zero almost everywhere else in the world.

The ACCLAIM data indeed qualitatively support Ponte's model, although the observed values in the Central Atlantic for D are larger than even he suggests. The tide gauge data from Port Stanley show only moderate violation of the LIB, as do data from Tristan da Cunha. However, at St.Helena there is significant coherence around periods of 5 days, small phase lag, and T of order 1, suggesting D values of about -1. Ascension's data show similar behaviour.

So, our first conclusion is that, from the point of view of altimetrists, the simple LIB is not a good model in the Central Atlantic in the frequency band 0.05 - 0.5 cycles day (and particularly around periods of 5 days), for which the total r.m.s. variability in SSP at St.Helena is of the order of 4 cm. At one time this might have been thought to be a small amount in altimetric terms. However, it is the sort of signal to which TOPEX/Poseidon data are now being applied.

In 1987, Cartwright, Spencer and Vassie (CSV) demonstrated that changes in SSP in this frequency band were coherent and in phase across the Tropical Atlantic equator, and were coherent with those at Ascension, with some evidence for slightly increasing phase lag with increasing frequency. These data suggested large scale coherent barotropic variability, T approximately 1 throughout, radiating from the equator. Our newer data show the SSP changes to be coherent even further south at St.Helena, with a coherence analysis between SSP at Ascension and St.Helena giving T about 1 and phase lag around zero across the band.

The large scale barotropic variability certainly exists. However, how is it forced? The regional wind field, which is known to also contain energy at these frequencies, must play a part. However, that might be expected to produce baroclinic variability also. (See discussion in CSV, 1987). More intriguingly, in view of the "narrow band" coupling between air pressure and SSP around 5 day periods, and in view of Luther's (1982) suggestion from Pacific data of a barotropic, planetary wave(s) possibly forced by the well-known (Madden and Julian, 1972) global variability in air pressure at this period, is this further evidence for such barotropic modal structure of the ocean?

It seems to us that, while altimetry will provide a valuable dataset for studying processes such as the LIB, its spatial-temporal sampling is not ideal, and that it is still vital to study (primarily island) tide gauge data for comparison to numerical models such as that of Ponte.

References

Cartwright, D.E., Spencer, R. and Vassie, J.M. 1987. *Pressure variations on the Atlantic equator.* Journal of Geophysical Research, 92(C1), 725-741.

Luther, D.S. 1982. *Evidence of a 4-6 day barotropic, planetary oscillation of the Pacific Ocean.* Journal of Physical Oceanography, 12, 644-657.

Madden, R.A. and Julian, P.R. 1972. *Further evidence of global scale, 5-day pressure waves.* Journal of the Atmospheric Sciences, 29, 1464-1469.

Ponte, R.M. 1993. *Variability in a homogeneous global ocean forced by barometric pressure.* Dynamics of Atmospheres and Oceans, 18, 209-234.

Sea Level Fluctuations: Geophysical Interpretation and Environmental Impact (SELF)

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Measurements of sea level variations are affected by several factors acting on different spatial and temporal scales. Relative sea level is being determined at many tide gauges around the world. Tide gauge readings are influenced, for example, by tectonic activity, by motion due to post-glacial rebound, by variations in the ground water content, by surface loading and other causes. Tide gauges have not yet been connected to a common datum. The SELF Project, being developed within the CEC ENVIRONMENT programme, aims at bringing a selected ensemble of tide gauges in the Mediterranean basin and Black Sea area into the well-defined global reference system established through the Satellite Laser Ranging and/or Very Long Baseline Interferometry techniques. Absolute gravity measurements contribute to achieving a vertical reference accurate to centimetre level and to provide an independent check on the occurrence of vertical crustal movements. Analyses of the monthly sea-level data derived from tide gauge recordings in the Mediterranean area are being performed and they reveal an unexpectedly large variability of the coastal annual (Sa) and semiannual (Ssa) tidal constituents which is spatially highly coherent. This variability on decadal time scales most likely is associated with changes in the regional atmospheric circulation. Observations of geological sea level markers of the past provide a valuable framework for the assessment of present trends and in predicting the future sea level pattern in response to climatic fluctuations. In this paper the results of the first year of research activity undertaken within the SELF project are presented.

Closing Remarks
by Meeting Organisers P.L.Woodworth, T.F.Baker and D.T.Pugh

We would like to thank all who made this meeting possible. At the Royal Astronomical Society, John Lane (Executive Secretary) provided advice on its planning for over a year, while Jean and Jack Kirk supplied the lunches and the evening reception. At the Linnean Society, Marquita Baird (Meetings Officer) and her staff provided Lecture Room facilities and the use of the Linnean Library. Sally Dowell (POL) and Mike Meredith (University of East Anglia) helped with registrations and poster displays. Finally, we would like to thank once again all the speakers and the poster and video providers for their excellent presentations, and the Chairmen of the sessions for keeping the meeting to time.

Perhaps the most memorable feature of the two days was in meeting so many people whom we knew previously only by name. We hope very much to keep in touch in future and we can be contacted via:

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Appendix 1:

GLOSS and GOOS by A.Tolkachev (IOC, Paris)

The Global Sea Level Observing System (GLOSS)

The Global Sea Level Observing System is an international system initiated in 1985 and coordinated by IOC, to provide high-quality standardised sea level data from a global network of sea level stations. The measuring system has become known as GLOSS because it provides data for deriving the Global Level of the Sea Surface, a smooth level after averaging out waves, tides and short-period meteorological events. The GLOSS network has been designed to observe large-scale sea level variations of global implications, and stations were identified at intervals of approximately 1000 km along the continental coasts and on islands, but generally not closer than 500 km. In selecting individual sites, priority is given to gauges which have been functioning for a long period. All gauges are required to aim for an accuracy of 10 mm in level, and 1 minute in time. All must be linked to bench marks against which their datum is checked regularly.

This network monitors sea level changes which could be indicative of global warming, ocean circulation patterns, climate variability, etc., and contributes data to international research programmes such as TOGA and WOCE. It also provides high quality data for practical applications of national importance. The measurements by GLOSS gauges complement satellite altimetry measurements.

The Implementation Plan for GLOSS (IOC Technical series No. 35, 1990) provides details regarding the GLOSS structure and implementation. The elements of GLOSS are:

* A global network of permanent sea level stations to obtain standardised sea level observations; this forms the primary network to which regional and national sea level networks can be related;
* Data collection for international exchange with unified formats and standard procedures which includes both near-real-time as well as delayed mode data collection;
* Data analysis and product preparation for scientific and/or practical applications;
* Assistance and training for establishing and maintaining sea level stations as part of GLOSS and improving national sea level networks;
* A selected set of GLOSS tide-gauge bench marks accurately connected to a global geodetic reference system (i.e., the conventional terrestrial frame established by the International Earth Rotation Service).

Permanent Service for Mean Sea Level (PSMSL) collects and archives data from GLOSS stations in the form of monthly mean values, but hourly and daily values are also expected to be made available from all stations by the originators. The development of GLOSS is seen as a dynamic activity, supervised by a group of experts, who are guiding the development in a manner most useful to ocean science and for the analysis of global change. At present (June 1993) 204 stations provide sea level data to PSMSL and specialised sea-level centres established within IGOSS, TOGA and WOCE. GLOSS is recognised as an existing activity of the Global Ocean Observing System. The proposed GLOSS network consists of 306 sea level stations which will be operated and maintained by 85 countries. The GLOSS Handbook, a PC-based data set describing the current status of each tide gauge in the GLOSS network, is being maintained by PSMSL. The Manual on Sea Level Measurement and Interpretation (IOC Manual and Guides No. 14) provides recommended procedural guides for sea-level measurements, their analysis and for assisting those Member States who wish to install or reactivate their sea-level stations.

Many countries participating in GLOSS have already received support and assistance in the form of training of their specialists and the provision of equipment either through IOC and/or through bilateral and multilateral cooperation.

Member States participating in GLOSS have designated national GLOSS contracts. Regional GLOSS coordinators have been designated for some IOC regional bodies, in particular for IOCARIBE, IOCEA, IOCINCWIO. The IOC Group of Experts on GLOSS provides advice to IOC on the implementation of GLOSS.

The Global Ocean Observing System

The Global Ocean Observing System (GOOS) has been initiated by the Intergovernmental Oceanographic Commission (IOC). The International Council of Scientific Unions (ICSU), the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) have agreed to cooperate in this endeavour. GOOS will be developed on a sound scientific basis using the findings of existing, ongoing research programmes, including WOCE, TOGA and JGOFS. Operational programmes including IGOSS, IODE and GLOSS form a foundation. GOOS will utilise operational observing methods, both remote sensing and *in-situ* measurements obtained from ships, towed and anchored systems, drifting buoys and sub-surface floats.

It is essential that we start developing GOOS now as a global framework for systematic ocean observations to meet needs for detecting and forecasting climate variability and change; for assessing the health or state of the marine environment and its resources, including the coastal zone; and for supporting an improved decision-making and management process..... one which takes into account potential natural and man-made changes in the environment and their effects on human health and resources. The planning presently encompasses five modules: (i) Climate Monitoring, Assessment and Prediction; this module is common with the ocean component of GCOS - the Global Climate Observing System; (ii) Monitoring and Assessment of Marine Living Resources; (iii) Monitoring of the Coastal Zone Environment and its Changes; (iv) Assessment and Prediction of the Health of the Ocean; and (v) Marine Meteorological and Oceanographic Operational Services. The major elements of GOOS are operational, oceanographic observations and analyses, timely distribution of data and products, data assimilation into numerical models leading to predictions, and capacity building within participating Member States, especially in developing countries, to develop analysis and application capability. GOOS will be developed in a phased approach: (i) a planning phase including conceptualisation, design and technical definition; (ii) operational demonstrations for each of the five modules; (iii) implementation of permanent aspects of the Global Ocean Observing System; and (iv) continued assessment and improvement in the individual aspects of the entire system.

Today we are experiencing unprecedented pressures on our natural resources. Sustainable development of these resources is hindered by our inability to detect emerging environmental problems at an early stage when remedial measures are still possible. Nowhere is this inadequacy so pronounced as in the marine area. Global energy cycles and the biological processes upon which all life depends are critically influenced by the ocean. Governments collectively are only now beginning to recognise the complexity and interdependence of all aspects of the system. Systematic global observations of the world oceans are required to improve our knowledge and predictive capabilities which will be the basis for more effective and sustained use of the marine environment, with the associated economic benefits.

Appendix 2:

The ICSU Federation of Astronomical and Geophysical Data Analysis Services by D.T.Pugh (Secretary, FAGS)

The earliest scientific measurements were probably of the movements of the sun through the heavens. When wise men among the ancients developed scientific theories to fit the observed facts, they did so to satisfy the practical human demands of adjusting to the seasons. Like today's scientists, they must have understood the basic experimental requirement: good science needs good data. Studies of the Earth, the solar system, and the universe, demand data of the highest quality, measured systematically over as long a period as possible.

Although observations have been made since time immemorial, few records were kept in a systematic way to allow detailed analyses and the identification of trends and changes. Today's scientists have developed a solution to this problem. The Federation of Astronomical and Geophysical Data Analysis Services (FAGS), formed in 1956, is an Interdisciplinary ICSU Body. FAGS includes ten individual Services each operating under the authority of one or more of the sponsoring ICSU Unions: IAU, IUGG and URSI. Each Service Director is an acknowledged international authority on the phenomena for which the Service is responsible. The Directors are charged not only with receiving data from a world wide network of co-operating agencies, but also for quality control, dissemination of data and advice to interested scientists, and above all for applying their expertise to the scientific analysis and interpretation of the integrated sets of observations.

Scientific interest in these analyses continues to grow. For example, recent studies of the variations in the rate of rotation of the earth are important in relation to meteorological changes, glacier distribution in polar regions, geomagnetic activity and space navigation. The long-term changes are of special interest, for example in anticipating the effects of climate trends on the global economy, the possibility that slow tectonic movements and tides may play a role in triggering earthquakes, and the coastal impacts of secular changes in sea levels.

FAGS Services give special attention to questions of instrument calibration, resolution and stability. Reliable scientific analyses of small but important long-term geophysical trends is only possible if the methods of making the measurements over decades and centuries have been carefully controlled. No new measuring procedure can be introduced without careful comparison, and checks for compatibility with the older methods. Here the advice and experience of the Service Directors is invaluable as guidance for the network of individual measuring systems which operate at a national level.

Each Service works independently, under the general auspices of FAGS, towards the common goal of long-term scientific excellence in data analysis and interpretation of astronomical and geophysical variability. The sponsoring Unions appoint Advisory Boards with strong international membership to guide and assist each Director to achieve these goals.

Although the central co-ordination of FAGS began under ICSU as recently as 1956, many of the individual Services have a much longer history. Most maintain data which has been collected over decades, and in some cases, centuries. We are sometimes asked what is a typical FAGS Service. Before venturing an answer, it is appropriate to consider the special activities of each Service in turn.

International Earth Rotation Service. (established in 1895) Paris

maintains the terrestrial reference system for both positions and velocities; it also maintains an extragalactic celestial reference system and determines the earth orientation parameters which connect these systems; it organises the observational activities necessary to collect the appropriate data. The advent of satellite geodetic measurements such as Very Long Baseline radio Interferometry, Lunar Laser Ranging, the Global Positioning System, and Satellite Laser Ranging, has revolutionised the accuracy of the studies: crustal movements as small as 2 to 5 mm per year are detectable, and changes in the length of the day are monitored to within 0.0002 seconds. The various IERS results contribute in many ways to space research, astronomy and geophysics. For example, data on the earth's rotation are interpreted in terms of mantle elasticity, structure and properties of the core-mantle boundary, rheology of the core, underground waters, ocean circulation, atmospheric winds and mass distribution.

Quarterly Bulletin on Solar Activity (1928) Japan

publishes a record of solar activity, which is as final and complete as possible, for studying short- and long-term activities of the sun. These activities include sunspots, synoptic charts of solar magnetic fields, chromospheric eruptions, intensity of the solar wind, and solar radio emissions. More than 70 observatories and institutes contribute observations to these syntheses.

International Service for Geomagnetic Indices (1932) St Maur, France

collects and publishes data disturbance variations of the geomagnetic field. Disturbances include sudden commencement of magnetic storms, solar flare effects, and pulsation disturbances. Variations in the intensity of the earth's magnetic field are related to the level of solar activity, and the amount of energy coming from the sun into the earth's environment.

Permanent Service for Mean Sea Level (1933) Merseyside, UK

collects and analyses monthly mean sea level data from a global network of tide gauges. These gauges are operated by a wide range of national authorities: hydrographers, surveyors, oceanographic institutions, and individual university departments. PSMSL works to improve the quality of the measurements, and the range of global coverage. There is a shortage of reliable long-term sea level observations in the Antarctic, and from ocean islands. The latter are important to get an even coverage of the measurements. To increase the data flow, PSMSL has worked with the Intergovernmental Oceanographic Commission of UNESCO to develop GLOSS, an Intergovernmental system for measuring sea levels to common high standards. Altimetry has given a new momentum to these analyses, and in future the emphasis will be on developing integrated products for sea level based on both coastal and satellite measurements. In recent years the prospects of global warming, and possible enhanced rates of sea level rise, have made the demands for PSMSL analyses more urgent. Present rates of sea level rise of 0.15 m per century may increase, but there is no evidence for this yet.

Bureau Gravimetrique International (1951) Toulouse, France

collects on a world wide basis, all gravity measurements and pertinent information about the gravity field of the earth; it compiles and stores the information on a computerised data base in order to redistribute them to a large variety of scientific users. Other data such as mean values of gravity anomalies, geoid heights, topographic heights, and satellite altimetry derived geoid heights are also collected and distributes to scientists world-wide. The BGI also records absolute measurements of gravitational acceleration. One of the application in which BGI assists is the preparation of geoids, for cartographic and hydrographic applications.

International Centre for Earth Tides (1960) Brussels

Ocean tides are easily observed by the casual coastal visitor, but the gravitational attractions of the moon and sun are also felt by the solid earth. The tidal forces and the earth's responses to these can be calculated and measured to great accuracy. These earth responses relate to the elasticity of the mantle and to the properties of the liquid core. Movement of water due to ocean tides also affects the crustal deformations observed by sensitive gravity meters, tilt meters and strain gauges. When known, global effects are removed from the records, and the residuals are analysed in terms of local phenomena and tectonic features.

International Ursigram and World Day Service (1962) Chatswood, Australia

describes itself as "The World Space Weather Warning Service". It operates through a network of ten Regional Warning Centres, which have responsibility for collecting data in their geographic area and distributing it to users through the other centres. The wide distribution of these centres is typical of many of the FAGS Services: Paris, Prague, Warsaw, Moscow, New Delhi, China, Tokyo, Sydney Australia, Boulder USA and Ottawa. Warnings of disturbances in the solar terrestrial environment are used by radio communicators, surveyors using geophysical techniques, power line and pipe line authorities, operators of satellites, and a host of scientific users. IUWDS also encourages co-ordinated observations by preparing the International Geophysical Calendar each year; this lists a series of 'world days' which scientists may use to carry out synchronised experiments.

World Glacier Monitoring Service (1967) Zurich

Increased interest in possible global warming has focused on trends in the extent of glaciers; maps of fluctuations are published at 5-year intervals. A century of systematic observations clearly reveals a general shrinkage of mountain glaciers on a global scale, which provides one of the most reliable pieces of evidence for a secular warming trend. Glacier inventory information provides the basis for identifying global trends, and for isolating locally anomalous behaviour; but interpretation is not straightforward, and standard procedures for monitoring glacier length and volume must be applied.

Sunspot Index Data Centre (1985) Brussels

Since 1981 the SIDC has collected data from some 40 co-operating centres to calculate a provisional sunspot number, but the records go back as far as 1700. Recently the Service has begun separate analyses of activity in the two solar hemispheres. On top of the well known 11 year periodicity in sunspot activity, there are many shorter and longer-term fluctuations. Apart from strong scientific interest, users include space-centres and telecommunication systems. SIDC issues 12-month forecasts, with necessary cautions. The level of sun spot activity will generally decrease through the 11-year cycle until 1997.

Centre de Données Stellaires (1985) Strasbourg

is the world reference data base for the identification of astronomical objects. It collects all of the useful data concerning these objects from observatories around the world, upgrades this information by critical evaluation and comparisons, and distributes the results for further research. CDS has also had a major part to play in most of the major astronomical space missions, by identifying observed sources, and by helping to solve problems of data archiving and access.

Clearly, there is no typical FAGS Service, but as the above summary shows, there is a general theme: of attention to co-ordinated global observing systems of the highest quality; data assimilation; analysis and interpretation of this data using the best scientific expertise; and a commitment to make these results available for other scientists, and for a wide range of other practical applications.

ICSU and the Scientific Unions provide a small sum of money to assist the Services in their central activities, but the main support comes in each case from the national authorities which undertake these responsibilities for the benefits of international science. The Council of FAGS ensures that standards are maintained, and that where possible links among the Services are developed. Joint meetings of the Services Directors and the FAGS Council are held every four years, to exchange ideas and experience, and occasional cross-Service scientific meetings are organised. Contact between Services is also achieved by means of inviting Directors to gatherings such as this PSMSL sixtieth anniversary meeting.

The driving force and vision which established a co-ordinated system of astronomical and geophysical observations and analysis within ICSU came from scientists. They demanded, and now receive, data of the highest quality to enhance our understanding of the earth on which we live, and of the solar and stellar systems which surround us. The foresight of ICSU and its Unions in setting up the FAGS system has been widely commended. Nevertheless the final acknowledgement must go to the generations of anonymous observers without whose patient and exact application of their measuring skills, none of this would have been possible.

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