International Sea Level Workshop

10-11 June, 1997
Honolulu, Hawaii, USA

Conducted under the auspices of
The GCOS/GOOS/WCRP Ocean Observations Panel for Climate
and
The CLIVAR Upper Ocean Panel

Sponsored by
The United States Department of Commerce
National Oceanic and Atmospheric Administration

Workshop Report

April, 1998

GCOS No. 43
GOOS No. 55
ICPO No. 16

EXECUTIVE SUMMARY

The GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC) and the CLIVAR Upper Ocean Panel, through their respective Chairs, convened a Workshop on the international *in situ* sea level network for climate applications and research, with the sponsorship and support of the US National Oceanic and Atmospheric Administration (NOAA). The aim of the workshop was to more explicitly link the scientific requirements of the Ocean Climate Observing System plan of GCOS/GOOS, and the scientific research areas of the CLIVAR Science Plan, to the implementation of the *in situ* sea level network, as represented by GLOSS and its Implementation Plan.

In preparation for the Workshop, NOAA engaged a consultant, Dr. V. Gornitz, to prepare a draft report on the design for a global sea level network for monitoring climate variability on seasonal to centennial time scales. This draft report provided a substantial basis for the Workshop discussions. The final report is presented here as a foundation for the future scientific development of the sea level observing system, in conjunction with GLOSS and its Implementation Plan.

The Workshop framed several statements and conclusions for consideration by its principal sponsors (the GCOS/GOOS/WCRP OOPC and CLIVAR UOP), NOAA, and the organizations with prime oversight responsibility (GCOS/GOOS and CLIVAR).

Scientific and technical oversight

The Workshop recommends that a scientific Working Group for climate aspects of sea level be established. This group would provide scientific advice on climate related aspects of sea level to the GLOSS Group of Experts and to the research and operational programs via the UOP and the OOPC. A proposal has been forwarded to IOC.

In situ sea level network and altimetry

The Workshop emphasized that *in situ* and high-accuracy altimetric measurements provide powerful complementary information on the climate scale variations of sea level. Altimetry is very important due to its open ocean spatial coverage, but it is not yet an "operational" system, and it cannot be considered a replacement for *in situ* sea level observations for scientific and technical reasons. It is critical that altimetric data are made more readily available.

Estimation of Long-term Trends in Sea Level

The Workshop endorsed a dual strategy. The *preferred observing system* comprises:

- altimetry for global sampling, at approximately 10 day intervals;
- approximately 30 *in situ* gauges for removing temporal drift;
- additional gauges at the margins of the altimeter (e.g., continental coasts and high latitudes);
- a program of geodetic positioning; and
- a program of data archaeology and development.

An *alternative observing system*, proposed due to the lack of guaranteed availability of altimetric data and due to the lack of experience and confidence in the application of altimetry to measuring long-term trends, would comprise a globally distributed network of *in situ* measurements, with similar effect to the GLOSS Long-Term Trends set:

- a program of geodetic positioning; and
- a program of data archaeology and development.

Report on the in situ sea level network

The Workshop commended Dr. Gornitz on the draft report "Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales". Several modifications arose as a result of the Workshop discussions.

Priority for Geodetic Positioning

The Workshop recommended the following priorities for geodetic positioning:

- sites used for referencing altimetric measurement;
- sites used for long-term trend estimation; and
- sites used for ocean circulation studies.

Data Archaeology

The Workshop wished to explicitly acknowledge the valuable contributions to the sea level data base from data rescue and data rehabilitation efforts and recommended further effort be devoted to this area.

Sea Level for ENSO Prediction

The Workshop concluded that sea level data were important for studies of predictability and for experimental and practical prediction. This conclusion reversed a tendency to downgrade sea level data relative to other data. The Workshop also noted that western Pacific sites were relatively more influential in validation and prediction problems.

The WOCE Fast-Delivery Center

The Workshop recommended that the WOCE Fast-delivery Center be continued but with a broader mandate, effectively servicing all the climate sea level near-real-time delivery requirements.

Development of the in situ sea level network

In consideration of the Gornitz report, the Workshop recommended:

- enhancement of the network in the tropical western Pacific and in the region of the Indonesian Throughflow;
- support for those Southern Ocean stations and for stations implemented or planned in the vicinity of the Antarctic continent, and adjacent to Drake Passage; and
- encouragement for improved accessibility to data from Brazil (e.g., Recife) and other stations presently not included in the Fast-Delivery service.

Mean Sea Level Pressure data and other ancillary data

The Workshop recommended that atmospheric pressure be designated a required variable for all non-tropical sites, particularly at high latitudes, and a desirable variable at tropical sites.

CONTENTS

MEETING REPORT

Welcome and Introduction

Wolfgang Scherer opened the Workshop in the Asia Room of the Hawaii Imin International Conference Centre. He welcomed the Workshop participants and noted the importance of this meeting for the future of the *in situ* sea level network. He thanked the members of the Joint Institute for Marine and Atmospheric Research for providing the Workshop facilities and for acting as local hosts. After noting logistical arrangements, Scherer introduced the Chairman for the meeting, Neville Smith.

Smith added his welcome and thanked NOAA for organising and sponsoring the Workshop. The letter of invitation and background are included in Appendix B. He noted that Ants Leetmaa, the Chair of the CLIVAR Upper Ocean Panel and his nominal co-Chair for this meeting could not be present. He also noted that the Workshop would only consider sea level data for climate research and applications. While the GLOSS Implementation Plan would provide a substantial basis upon which this workshop could build, he noted that the scientific rationale needed to be considered more thoroughly. In particular, the published and emerging plans of GCOS/GOOS and CLIVAR needed to be discussed, and the impact of remote sensing (in addition to altimetry), other direct observations, and improved modelling capabilities needed to be factored in. This Workshop should consider the advantages and weaknesses of the existing *in situ* sea level network and seek synergy with other elements of the observing system.

Smith introduced the Agenda for the meeting (Appendix C). He noted that there would not be a lead speaker for the session on Atlantic gyres and circulation. He also noted that Whitworth was unable to attend the Workshop at the last moment. Woodworth volunteered to provide some background on Antarctic research. The original Agenda was substantially modified on day 2 to accommodate some of the major issues that emerged on the first day. Smith noted that the Workshop wished to promote discussion and debate and so invited informal contributions against the various agenda items.

Smith noted that one of the main outcomes of the Workshop would be a report on the climate *in situ* sea level network. Vivien Gornitz was engaged by NOAA to assist with formulating this report, the initial draft of which was included with the Workshop background material. The aims of the Workshop, which largely addressed a review of this report, included:

- An explanation of the scientific requirements for *in situ* sea level observations and their combination with satellite altimeter measurements as they relate to climate problems.
- A world map depicting the subset of tide gauge stations to be included in the global "climate" network. The network design will utilize stations already in existence to the maximum extent possible, and recommend establishment of any new stations required for adequate spacial distribution. The task will be to specify the most efficient network to be maintained over the long term.
- The scientific rationale for including each particular station in the network.
- The measurement and data reporting capabilities required for each station within the network.

- A station list establishing the priority for implementing geodetic referencing measurements.
- A recommended mechanism for ongoing evaluation of the network design and for international implementation of future network modifications should they become warranted as the state of scientific understanding advances.

Smith noted that the Workshop was not looking for "sea level solutions" but rather the contribution made by sea level data to the solution of climate problems. The sea level observing system is part of a bigger, complex system, so the Workshop should take account of synergies, uniqueness and possible proxies. The Gornitz report is the initial template. The aim is to endorse its conclusions or, if the Workshop so decides, draw different conclusions. Smith stressed that recommendations should be focussed on the role of sea level data for climate research and monitoring. The Workshop should base the science on CLIVAR, and avoid making recommendations/drawing conclusions in areas which are not relevant to those implementing and maintaining the SL network.

The Programmatic Context

CLIVAR and the OOPC - N. Smith

Smith began this session by describing some of the history behind the interest of GCOS/GOOS and CLIVAR in this Workshop. Planning for the GCOS/GOOS Ocean Observing System for Climate began with the Ocean Observing System Development Panel (OOSDP) who published a Report on the conceptual design for an ocean observing system for climate in 1995 (copies were available at the Workshop). The OOSDP Report is regarded as the primary scientific design reference for GOOS/GCOS, and is being adopted as the basis for the observing system design in CLIVAR. In the OOSDP Report sea level for monitoring long-term change was a primary goal. However details were left open-ended. Sea level for ENSO prediction, though ranked lower than SST, wind stress and subsurface temperature, was still considered an important variable.

The CLIVAR Science Plan identified as priorities the examination of interannual, decadal, and longer term variability relating to ENSO events, monsoons, and ocean wide fluctuations, and the determination of accelerated sea level rise. The importance of sea level observations for constraining model initialization, for validating models, and for mapping of sea level variability through altimetry supplemented by selected in situ measurements was stressed. The Science Plan called for efforts to determine the number of stations that should be maintained to meet CLIVAR's scientific objectives. The CLIVAR Upper Ocean Panel (chaired by Ants Leetmaa) is responsible for the design of the ocean observing network.

The Ocean Observations Panel for Climate (which Smith chairs) was created as a follow-on panel by GCOS, GOOS and WCRP. The OOPC places greater emphasis on implementation, and is committed to close cooperation with the Upper Ocean Panel of CLIVAR. At its first meeting, the OOPC reconsidered the strategy for long-term sea level monitoring, particularly the impact of altimeters. They also noted changing circumstances for ENSO prediction. In response they initiated a project to examine blended *in situ* - altimeter products for long-term change (Le Provost), and subsequently joined with NOAA (and the CLIVAR UOP) in convening this Workshop. Substantial consultations with the GLOSS GE were also initiated. The OOPC took the view that:

(1) GLOSS is the prime system for implementation and maintenance of sea level gauge networks;

(2) The CLIVAR Upper Ocean Panel is the prime source of scientific advice on observational requirements for climate research: the sustained and focussed ocean climate observing systems; and

(3) The OOPC is the prime source of scientific advice on requirements for, and integration of sea level measurements into, operational (baseline) ocean observing systems.

Smith noted that the CLIVAR Implementation Plan is presently being drafted and that the outcomes of this Workshop would be timely and important for the details of implementation. (Lukas added some further remarks on CLIVAR under item 3.2.) Smith noted that, from the point of view of both CLIVAR and GCOS/GOOS, it was important that the scientific rationale for sea level observations was clear. It is also important that the recommended network is sufficient and necessary, which might mean some rationalisation but not necessarily reduction. While the principal interest was in sites for climate, this does not rule out other valid justifications for maintaining networks. Smith also noted that it was important to recognize the multi-variate, multi-platform and multi-faceted character of the global observing system.

GLOSS - P. Woodworth

Philip Woodworth, the Chair of the GLOSS Group of Experts, provided an overview of recent developments in GLOSS. He showed the present sampling of GLOSS and noted that around 90% of the sites were "operational" (that is, providing regular measurements of sea level and/or water pressure at a fixed level). He noted that the "age of altimetry" had had a profound impact on the work of GLOSS, in one extreme questioning the need for gauges at all, and at the other providing a complementary data stream which added value to *in situ* information.

The GLOSS Implementation Plan (GIP), which was ratified at the recent meeting of GLOSS, provides a core network of around 287 gauges, all of which have some measure of support. The GIP identifies 3 subsets: sites for long-term trends (LTT), sites for calibration of altimeters (ALT), and sites supporting ocean circulation studies OC). The ALT set (based on the work of Mitchum) required around 30 sites, some of which needed geodetic (GPS) instrumentation. Woodworth noted that there had been considerable discussion of GPS prior to the GLOSS meeting and that substantial actions had been recommended in order that the geophysical community could provide the geodetic information required by GLOSS.

The GIP was made available to all Workshop participants. There was debate about the appropriate strategy for addressing weaknesses in the LTT design (taken up later under the discussion of long-term trends, item 4.2), and about setting priorities for GPS. Woodworth noted that it is often appropriate, in cases where there are several equally plausible approaches, to leave these decisions to regional groups.

Scientific Issues

Pacific Ocean seasonal-to-interannual variability - C. Koblinsky

Koblinsky presented model and data analyses based on 27 tropical Pacific Ocean sites from the WOCE Fast-Delivery data archive (from Yan Xue, Ants Leetmaa et al, NMC; more detail can be found in the report of the 2nd meeting of the CLIVAR Upper Ocean Panel). Based on these analyses it was concluded that:

- the highest priority sites for ENSO were those located between 15S and 15N;
- Kapingamarangi and Nauru were of doubtful impact, but important;
- the quality of data from Rabaul needed improvement;
- Nuku Hiva has a broken record and low signal-to-noise ratio; and
- sites north of 15N had low S/N.

From these studies (and other results presented by Mark Merrifield) it was clear that *in situ* sea level data were very useful for studying and predicting ENSO-related variability. The length of several of the records (compared with, e.g., XBT and TAO records) made such data extremely important for predictability studies.

Koblinsky also showed several intercomparisons between direct and remote estimates of sea level anomalies, and with model data assimilation estimates. Using daily values of measured sea level at Baltra, the rms altimetry minus *in situ* data difference was around 4 cm. Some of the larger differences in the Western Pacific could be attributed to salinity effects. Monthly differences were around 2 cm. Koblinsky noted that care needed to be taken when subsampling the altimeter data. The results suggested that local effects were important at Honiara, Rabaul, Suva and Noumea (the satellite was sampling different fields). In some cases the effect were oceanographic, in other due to volcanic activity (e.g., Rabaul). Koblinsky concluded that it would be useful to do a site-by-site intercomparison. Spatial resolution was also a factor, e.g., the Honolulu correlation drops off very quickly away from the island. Koblinsky noted the absence of data from Clipperton, a potentially very useful site.

The discussion noted the importance of good local models for extrapolating local signals to the location of the satellite overpass. Mitchum and Le Provost noted that such models may be more effective than resiting gauges. The discussion also highlighted the issue of having adequate metadata available. Koblinsky also noted that the S/N for GeoSat data seemed to be around 50% of that for T/P, which made it less useful but certainly not useless.

Asian-Australian monsoon - R. Lukas

Roger Lukas began by discussing the general issues being tackled by CLIVAR and the approach of CLIVAR. He noted that CLIVAR interests spread across many space and time scales, and that while the Scientific Plan and Implementation Plan were broken into convenient themes, in reality there were strong and complex interactions. The Australian-Asian Monsoon, for example, was clearly influenced by ENSO and, in turn, there was strong evidence that the Monsoon systems impacted ENSO. Many of these issues are discussed in the CLIVAR

Implementation Plan (Draft: http://www.clivar.ucar.edu/iplan/contents.html) section G2: Interannual variability of the Asian/Australian Monsoon. Lukas focused on several key scientific knowledge gaps:

(1) the influence of the Indonesian Throughflow,

(2) the effect of low-latitude western boundary currents,

(3) the bifurcations of the South and North Equatorial Currents in the western Pacific Ocean, and

(4) the effect of upwelling regions.

There is strong evidence for the forcing of the monsoon on the circulation but no evidence as yet for a significant feedback. Some research suggested a resonance, while others pointed to the links between the North Equatorial Current (NEC) and the Kuroshio Current. Lukas noted the paucity of thermal data in the Western Pacific Ocean, as well as the importance of detailed knowledge of bathymetry and geometry.

Sea level data were by implication very critical for the study of ocean circulation processes linked to the A-A Monsoon system and to the circulation in the western and Northwest Pacific. Lukas noted the importance of sea level data for studying Indian Ocean variability. For example, differences in sea level between Palau-Davao or Davao-Darwin have been used as a measure of the throughflow between the Pacific and Indian Oceans

Tropical Atlantic variability - M. Vianna

Marcio Vianna noted the strong motivation for tropical Atlantic Ocean studies arising from the observed connections between ocean variations and continental and regional rainfall variability (e.g., SST and Nordeste rainfall). Vianna discussed the dipole located about the Atlantic Intertropical Convergence Zone (ITCZ) (the Atlantic Dipole), whereby warm South Atlantic SST and relatively cool SST north of the ITCZ were correlated with rainfall changes. The dominant period of the dipole is around 12 years. Several studies have postulated a positive feedback via latent heat. Vianna concluded that there was no longer any doubt that the Atlantic Dipole exists as a genuine mode of variability. He noted the presence of a local ENSO-like mode, and of remote effects associated with ENSO. The dipole oscillation was modulated by heat transport of the western boundary currents. The 2nd EOF of Atlantic sea level shows a peak in 1973-74 corresponding with a minimum in the dipole mode, consistent with a significant role for western boundary currents.

Vianna noted that Recife is an important site for studying such variability. He also noted the proposed PIRATA project which is presently getting underway through French and Brazilian support. Sea level data and PIRATA were complementary. Proper interpretation of the data required improved boundary current models and observations. He recommended inclusion of the following stations into the proposed network: Fortaleze, Temisa, Tamandare, Fort Noronha, San Pedro, San Paulo, Cayenne, Sao Tome, Ascension Island and St. Helena.

Straits, choke-points and constricted passages - K. Ridgeway

Ken Ridgeway began by discussing the Indonesian Throughflow and the variety of methods used thus far to estimate its transport. The estimates ranged from zero through to 20 Sv. He noted the critical dependence on knowledge of bathymetry. He also presented some preliminary results from Nan Bray from a shallow water array of pressure gauges in the Indonesian Archipelago. The data return and quality is extremely encouraging. Estimates based on XBT sampling suggest a maximum throughflow during warm events. Sea level data are an important source of ancillary information.

Ridgeway also discussed research based on western Pacific gauges located around New Guinea and the adjacent islands. The gauge data were effective for closing volume transport budgets and, by implication, would be extremely useful for studies of western boundary current interactions and variability. Roger Lukas reinforced this point by showing results based on sub-samples from the POCM model. Sea level information from Java, Darwin, Davao and the western Pacific Warm Pool could effectively monitor the strength of the throughflow, as well as provide critical information for process studies. He noted that altimetry was limited in this region, thus placing greater importance on *in situ* monitoring.

Ridgeway concluded by showing some results for the ACC along SR3, the repeat section south of Australia (see also Item 3.7). The discussion noted the tendency for the sea level signal to be concentrated to the south, and that floats were being used in conjunction with sea level data.

Circulation of the North Pacific - M. Kawabe, R. Lukas, H. Mojfeld.

Masaki Kawabe led off the discussion on the circulation of the Pacific Ocean. He showed results from a monitoring study of the Kuroshio using sea level data. He noted that the presence of large meanders in the Kuroshio Current could be well monitored by sea level at Kushimoto, Uragami, Hachijojima and Miyakejima. Data from Naze, Nakanoshima and Nishinoomote can be used to follow latitudinal variations. He also noted sea level data can be used to monitor the velocity and transport of the Kuroshio (see Appendix F). Results were also presented for the Tsushima Current and for the North Pacific gyre. Kawabe's presentation provided convincing evidence of the utility of sea level data for monitoring studies and for studying the predictability of, e.g., the path of the Kuroshio. For example, Oshoro, Hosojima, Hamada and Hachinohe (or Miyako).

Kawabe noted several amendments that were required for the Japanese sites included in the long-term trends section. He also noted that sites like Miyakejima, Hachijojima and Nakanoshima were of limited value for studying variability associated with the Pacific North American oscillation.

Kawabe urged the Workshop to recommend geodetic fixing (by GPS or other means) for several of the Japanese sites.

Roger Lukas introduced the proposed CLIVAR project, the Basin Extended Climate Study (BECS), presently a joint initiative between Japanese and US scientists. He noted the tendency for currents to advect high-salinity water into the Western Pacific and the importance of the ocean circulation for decadal climate variations. BECS will study the dominant variability on seasonal, interannual and decadal time scales and develop the observing and modelling systems needed to understand the key processes and to identify predictable signals. Sea level data would be important for this goal.

Harold Mojfeld provided a brief report on the recent development of the North Pacific tsunami warning system. He noted that new real-time reporting bottom pressure recorders were now being deployed and that these data might be useful for climate studies. He also noted that recent data suggests the N. Pacific is switching back to conditions like those prior to 1977.

Atlantic gyres and circulation

As noted above, no expertise was available at the meeting in this area. The participants agreed that the Workshop report, including the sea level network report of Gornitz should be circulated to appropriate experts for comment. Several participants did note the importance of sites around the Labrador Sea and of sites in the western boundary current regions of the North and South Atlantic.

High-latitude circulation - P. Woodworth

T. Whitworth was unable to attend, so Phil Woodworth agreed to provide some of the results from joint US-UK projects.

Woodworth noted that the presence of ice limits the utility of altimetry at high southern latitudes. Studies using FRAM results suggests that Drake Passage throughflow is strongly correlated with sea level along the southern perimeter of the ACC. This result makes a strong case for gauges located on the Antarctic continent. Bottom pressure recorders have been deployed at several locations around Antarctica (e.g. South Drake Passage, offshore of Sanae, offshore of Dumont d'Urville) while coastal gauges have provided complementary data (e.g. Faraday, Syowa, Mawson). Preliminary results suggest a highly coherent signal from low frequencies down to a period of around 10 days, over large scales. The strong message coming out of these studies is that sea level and bottom pressure data remain a very effective information source for studying ocean variability.

Long-term sea level trends - P. Woodworth

Phil Woodworth presented a summary of the rationale for the LTT sites in the GLOSS IP. Based on Douglas's (1991) study, it was concluded that at least 60 years of data were needed before a trend could be detected. This limited the number of useful sites. In order to address some of the large gaps which then emerge, somewhat shorter records were also included. However significant gaps still remain, particularly at mid- to high southern latitudes.

For the future detection of trends and possible accelerations in the rate of sea level rise, it was critical that LTT sites have proper geodetic fixing. The GLOSS LTT plan makes specific recommendations. Woodworth showed some results from the Hadley Centre coupled climate model which showed heightened sensitivity in the NE Atlantic and in the region north of the Ross Sea. The LTT plan puts great focus on GPS, not only for the accuracy of future measurements, but also as a method for estimating past land movement. The use of data archeology to extend records and to fill some of the critical gaps was noted as an important strategy.

This topic was pursued in more detail under Item 4.2

Altimeter drift correction - G. Mitchum

Gary Mitchum discussed the study which forms the basis of the GLOSS ALT network. The aim of the method is to remove the inevitable drift in altimeter measurements using a select set of *in situ* gauges. Mitchum noted that there were three principal sources of error in trend estimates: random errors (order 0.6 mm/year), land motion (order 0.3) and errors that have large scale spatial structure; e.g., atmospheric water vapour errors. The aim is to produces estimates with accuracy order 0.2 mm/year over 10 years.

The criteria for selecting sites included a) small rms alt-*in situ* data differences, b) the availability of geodetic positioning, and c) the length of record. An analysis of errors suggested that around 30 sites were needed to reduce the drift error down to the desired level. Taking note of the latitudinal error variations introduced by water vapour, Mitchum selected the sites so that they were evenly spread with latitude.

A copy of the paper was made available at the Workshop. Details can be found in the GLOSS IP and in the GLOSS V meeting report.

Sea level data and climate modelling - C. Le Provost.

Le Provost presented two typical examples related, on one side, to the use of *in situ* data to validate conclusions on climate change numerical modelling studies (Ezer et al, 1995) and on the other side on the use of coupled ocean atmosphere model experiments to investigate the problem of sea level rise in the context of greenhouse global warming scenarios (Gregory, 1993). Initializing their model with the Levitus climatologies of the North Atlantic Ocean over the periods 1955-1959 and 1970-1974, Ezer, Mellor and Greatbatch used POM (the Princeton Ocean Model) to perform short term prognostic calculations to infer the dynamically adjusted fields corresponding to the observed hydrographic and wind stress climatology of each pentad. One result of their study is that the Gulf Stream transport was considerably weaker (by about 30 Sv) during the 1970's compared to the 1950's. This approach is quite unusual, but the authors used sea level data to sustain their finding: as the gyre spins down, sea level along the Western North Atlantic coasts must rise, while going down in the middle of the gyre at Bermuda. This is exactly what the available in situ data indicate, validating the Ezer et al results.

Le Provost also showed results from the Hadley Centre coupled model (Gregory, 1993). The 2*CO_2 predictions for thermal expansion induced sea level change indicate significant spatial variability in potential future sea level rise/fall as the ocean circulation adjusts to the warmer world. This contrasts with reported long term sea level changes for the past century (e.g. Douglas) which suggest roughly uniform rises of order 18 cm. However, the possibility that spatial variations can occur is shown by the simulations of Hsieh and Bryan, which suggest different coastal and deep sea responses in case studies of injection of water to the northern or southern hemispheres, as the ocean responds transiently via Kelvin and Rossby waves.

Le Provost also noted the need for sea level data for data assimilation studies. (See, for example, the Abstract of Kobinsky, Appendix F.)

Main points

The Chair noted that the discussions in this session emphasised the importance of detecting long-term trends, in the existing record and in the future. The discussion also stressed the importance of a complementary altimetric and *in situ* measurement network. The Chair noted the strong scientific emphasis attached to western boundary currents and so suggested that this area should be singled out for special attention in Session 3 (as reflected in the Agenda, Appendix C). The discussion also suggested that the Workshop agenda and Gornitz' report should alter the focus from the Monsoon alone to Indian Ocean Variability and the A-A Monsoon system, and that the Pacific circulation section focus on the North Pacific. The Agenda for the following session was altered accordingly.

The discussion also noted the importance of atmospheric pressure measurements and so an item was added to the agenda for later discussion. Roger Lukas also noted that little attention had been given to applications and impacts, so some time would be found to discuss these issues.

Network Design

The sea level network report: Criteria and Station Evaluation - V. Gornitz

Vivien Gornitz introduced the draft report, entitled "Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales" (version dated May 5 1997). The Final Version is included as Appendix A of this report.

Gornitz discussed the background and rationale behind the study, noting both the positive and negative attributes of *in situ* sea level/pressure measurements. Six key science goals were identified, in which *in situ* sea level data play an important role. A systematic approach was presented for the selection of quality tide gauges. Gornitz noted the strong interest in interannual variability in the tropical Pacific and interest in longer period modes such as the North Atlantic Oscillation (NAO). Periods of low NAO index could be identified on composite sea level curves from the northwest Atlantic basin.

In relation to the criteria used to rate stations, several discussion points were raised. Several participants wondered how such a system could be used to recommend *future* sea level networks. Mitchum and Luther pointed out that the criteria and Tables were able to assess the importance of individual gauges based on experience till now, but were not well suited to extrapolating into the future. They pointed out that it was unclear how the Workshop would progress from the information in the report, which is based on the criteria, to a set of recommendations. Mitchum, Vianna and Le Provost noted that the unique location of particular sites, (i.e., those not surrounded by nearby stations) was not adequately represented in the criteria. Smith and Koblinsky further noted that the scientific importance of certain sites was not appropriately reflected in the present draft.

Wyrtki noted that stations existed for a variety of purposes and that the Workshop Report and Gornitz' report should avoid giving the impression that station information was worthless if it was not relevant to climate. In many cases, climate was a secondary consideration. The Workshop should be sensitive to these issues. He also noted that scientific discovery often stems from the uncorrelated (noise) part of the records and so the network should allow for these possibilities.

Mitchell noted that the gauges used by the National Tidal Facility have resolution superior to that demanded for the applications discussed in this report, which means that quality judgements may also be different. Mitchum noted that it is the island stations which are most important. John Hannah noted that it was critical to get the scientific goals right, then decide on the appropriate sea level requirements.

Lukas noted that it was important to find an effective method for mapping national efforts onto the sea level climate monitoring matrix. It was also noted that GLOSS technical standards might not always be appropriate for specific scientific tasks (Woodworth later noted that the technical standards recommended in the GLOSS IP should be appropriate for all the scientific issues under discussion at this Workshop). Wyrtki noted the importance of permanence: the availability of a guardian for the site and the probability of sustained support.

On the basis of these discussions it was concluded that the station criteria should be modified. Specifically, the criterion of "location" should also include a factor for "uniqueness" of data and scientific impact. Allowance should be made for the availability of ancillary data. It was also agreed that an additional column should be set up in the selection matrix (but not counted in the final score) for "practicality"; i.e., a logistical consideration, encompassing the prospect of data continuity, ease of maintenance, and costs.

The Chair suggested that the best approach for moving from the draft report of Gornitz to recommendations for the future would be to state that the report represents the present situation. The report would not include a "recommendations" section. Instead, the Workshop would identify the key cross-cutting issues for the global network (either on a regional basis, or for particular sites), and frame recommendations which draw on the information ensconced in the report. The Workshop agreed that this was a workable strategy.

Gornitz would collate comments and suggest modifications to the network report.

Long-term trends

The Chair once more drew the attention of the Workshop to the existing plan in the GLOSS IP (GLOSS-LTT, Annex 4 of the GIP), as well the sites included in the Gornitz draft report. He noted the suggested additions by Kawabe and asked the Workshop to consider whether the Gornitz and GLOSS-LTT sets were consistent and adequate.

Several participants addressed the obvious (spatial) gaps in both plans and suggested that, in cases where glaring gaps existed, a strategy should be given for addressing this weakness. Two extra sites in the Labrador Sea region were suggested. The newly established Southern Ocean island stations (Kerguelen, Crozet, Amsterdam, ...) should be included. While these stations would be of little use in the short term for assessing trends, they would provide information on spatial variability, particularly in view of the postulated extra sensitivity of the Southern Ocean region. John Hannah suggested that, with a strong recommendation from the Workshop, it may be possible to maintain a site at Cape Roberts in the vicinity of the Ross Sea. Other sites that could be considered are Fortaleza, Dakar, Diego Garcia, several sites on the Indian Sub-Continent, Martinique, Ascension Is. and Prudo Bay. Woodworth suggested that the GLOSS Core Network would be a good place to start with these considerations.

Scherer noted that it was important that the recommended lists do demonstrate a degree of rationalisation and scientific selection. Woodworth had previously noted that, in the cases where several possible sites were available, decisions on the most effective site should rest with regional bodies. It was resolved that the Gornitz report (then Table 9) would group close stations (e.g., Scandinavia, or Washington D.C., New York and Baltimore on the US east coast) so that the final recommended list would reflect a more evenly spread distribution of sites. The "clusters" were on the east and west coasts of the US, Europe, Japan and Australasia, with the obvious regional responsibilities. A recommendation would be included to this effect.

There was also a consensus that emphasis and support should be given to data archaeology projects which provide one of the means for extending the record temporally, and effective strategy for alleviating some of the spatial sampling problems. A recommendation would be included to this effect.

All participants agreed that altimetry should now be considered a fundamental requirement for monitoring long-term trends. Proper geodetic positioning for sites was also considered extremely important (see Item 4.10). For the "clusters" it was agreed that regional groups assign priority for geodetic fixing.

Elimination of trends in altimeter data

There were no major comments or changes in the station selection of the Mitchum strategy. Of the 30 stations listed (the then Table 10) 10 stations were in need of geodetic systems. Mitchum emphasised that the recommended set should not be considered as fixed and that it was important to evolve the selection as technology improved. While emphasis was given to GPS, DORIS was also an important alternative. It was also important that local geoid models be included and improved since these permitted better connection (correlation) between the *in situ* site and nearby altimeter paths.

Tropical Pacific

It was agreed that Chichijima, Honolulu and Midway would be more appropriate for the North Pacific selection. Miramitorishima (Marcus Is.) should be added.

The participants agreed that the selection criteria should enable differentiation between western Pacific sites (which were identified by Koblinsky as being of greater importance) and central and eastern Pacific sites. Clipperton might also be added for possible upgrading (logistics are difficult though). Manus Is. should be added for multidecadal studies. The western Pacific sites referred to by Ridgeway (and by Mitchell) would also be reconsidered.

The most important message was that *in situ* sea level data had regained prominence in recent studies, and that an explicit statement should be included from the workshop noting this change.

Boundary current monitoring

The discussions of the previous day suggested that boundary current sites were of particular scientific significance and warranted specific attention in the Gornitz report and Workshop Report. M. Vianna would provide some background material. R. Lukas and K. Ridgeway could be consulted for information on the W. Pacific region.

No specific selections were discussed other than those arising from discussion of the W. Pacific and throughflow, and from discussion of the N. and S. Atlantic. The primary areas for consideration were the West Pacific, the Gulf Stream, the Kuroshio Current, the east and west coasts of South America, the east and west coasts of Australia, the Agulhus Currrent, and the Californian Current system. Mojfeld noted that consideration should be given to coastal-off shelf relationships. Geodetic fixing was extremely important if data in the boundary current are to be used for inferring the strength of currents.

Atlantic modes

Fiúza and Vianna suggested some changes in the selections for the Atlantic Dipole. No major issues arose.

Straits and choke points

Marion Is should be added for the throughflow region. There was interest in the sites currently being occupied in the Throughflow region but the results were considered too preliminary for any strong conclusions to be drawn.

High latitudes

Dumont D'Urville has now been established and should be included, as should Crozet and Amsterdam Is. (St Paulo). Heard Island and Cape Roberts should also be added.

The importance of sites on or adjacent to the Antarctic continent would be highlighted.

North Pacific

No major modifications were suggested though Gornitz would undertake a review in the light of the change in criteria and the focus on the North Pacific but not including boundary current regions. The stations recommended by Kawabe were accepted.

Priority for geodetic positioning

It was agreed that first priority should go to the sites identified by Mitchum's study. The second level of priority would go to the long-term trends' locations on the "perimeter" of altimeter coverage. Consistent with GLOSS, support was also given to sites supporting ocean circulation studies since, for example, monitoring of boundary current strength depended on knowledge of the absolute position.

Atmospheric pressure measurements and other ancillary data

Luther noted that at mid-latitudes mean sea level pressure (MSLP) data are critical. A major proportion of the "signal" in uncorrected data derives from atmospheric variability. Le Provost showed results from Kerguelen which demonstrated that atmospheric "noise" dominated at mid-frequencies; for the data to be useful for ocean circulation studies, this noise must be eliminated. Luther noted that at Sweeper Cove the atmospheric influence goes out to low frequencies.

At least 2 years of MSLP, sea level and subsurface water pressure are needed to correctly interpret signals. MSLP is a required ancilliary data set for mid- and high-latitude measurements, and desirable for low latitudes.

It was noted that other ancillary data (e.g., SST, sea surface salinity) are useful for interpreting sea level data. As a rule, ancillary data increase the value of sea level data sets.

Data management issues

The principal discussion item was the future of the WOCE Fast-Delivery Center. Clearly the Center provides an important function which will be required for the foreseeable future.

The Workshop agreed that the Center should assume a "new life" as a fast-delivery service for climate sea level data. Its functions would complement those of PSMSL. The data acceptance policy should be open - it would emphasise that all sites are potentially useful if the data are made available in a timely and useful manner.

The value of data archaeology was discussed again, including the importance of finding and/or rescuing co-located MSLP data. The main point was that data archaeology is an extremely effective strategy for improving knowledge of variability, and hence of predictability. The regions adjacent to the Indian Sub-Continent, the Indonesian Throughflow, and the east coast of South America were considered potentially fruitful areas in this regard.

Impacts and applications

Lukas noted that it was extremely important to identify a few direct applications of sea level data since several funding agencies attached great importance to these connections.

It was decided to add a section on applications and impacts of sea level variability and long-term changes to the Gornitz report. Mitchum (N. Pacific lobster), Mitchell (w. Australian lobster), Vianna (Brazil) and Hannah would provide appropriate text on fisheries. Gornitz would also consider impacts in the coastal region, including examples of episodic and permanent flooding, and beach erosion.

The Workshop concluded that, at some future gathering of this nature, time should be specifically dedicated to discussion of impacts and applications of sea level data.

Mechanisms for on-going evaluation and oversight

Time did not permit discussion of these issues in the workshop but the Scientific Steering Group did debate it at some length later.

There was agreement that a more effective mechanism to interface between the scientific oversight groups, such as the OOPC and CLIVAR UOP, and the IOC/GLOSS group should be instituted. The present Workshop had demonstrated the general interest in, and need for, such interfacing. The Chair noted that, in his opinion, the GLOSS Group of Experts was too remote from activities of the scientific panels and was not given its proper accreditation when issues at the interface of scientific planning and implementation arose. In principle this should not happen, as pointed out by the Chairman of the GGE, as the GLOSS Group, the SSG of this Workshop and the OOPC contain several de facto members in common. Nevertheless, several participants, including the Chairman GGE, noted that the approximately biennial meetings of the GLOSS GE were too infrequent for future needs; limited IOC resources were noted as having been the prime reason for this situation in the past.

After some discussion, three layers of scientific organisation were identified. The first aligns with scientific oversight, and includes panels like OOPC and CLIVAR UOP. It would also include the GOOS Coastal Panel and LOICZ.

The second aligns with coordination and implementation activities of nations, in effect GLOSS. The GLOSS Chairman and Technical Secretary and the Group of Experts are the foci of this activity.

The discussions suggested a third, intervening level should be considered. It might be called a Scientific Working Group for Climate Aspects of Sea Level (with a possible further sub-committee on Coastal Aspects established at a later date), and would include scientists familiar with the broad thrust of scientific programs and sea level measurements, and of course practitioners familiar with the technical and practical details of sea level measurement. Members of the sub-committee would represent CLIVAR UOP, LOICZ, GCOS/GOOS etc. This Group would play a lead role in the development of future GLOSS "scientific plans" (in effect, some possible combination of the Gornitz report and the Chapter 3 of the GLOSS IP) and would translate scientific requirements into ongoing plans for practical and effective networks for sea level measurements.

Details of this arrangement would be worked out between the Chair of this Workshop, the Chair of the GLOSS GE, P. Woodworth, and the GLOSS Secretariat and Director of the GOOS Project Office[1].

Workshop Conclusions and Recommendations

General outcomes and summary

The Proceedings of the Workshop and the publication of the Gornitz Report "Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales" (together with the GLOSS IP and GLOSS GE meeting report) will provide a substantial foundation upon which future operational and research activities can build. The coordination across these different levels of activity is healthier now than it has been at any other time in the past.

This Workshop provided the opportunity to close the loop between implementation activities within GLOSS and the published and emerging plans of GCOS/GOOS and CLIVAR.

Circumstances dictated that this Workshop could not be held at the optimal time, which would have been prior to the GLOSS IP meeting, and subsequent to the publication of the CLIVAR Implementation Plan. This resulted in some confusion as to the exact purpose of the Workshop. The initial motivation was to provide convincing scientific arguments in order that

---

1 A proposal has been submitted to the Secretariat of IOC.

the essential functionality of the existing *in situ* sea level network could be preserved. There was, and remains, considerable pressure to trim the resources dedicated to sea level measurements and the only effective buttress is a strong scientific rationale; this has been provided by this Workshop. Second, the OOPC (representing "operational" climate activities) needed to have better definition of the requirements for monitoring sea level trend. What mix of altimetry and *in situ* measurements was most appropriate? Through the activities of GLOSS and this Workshop the answer to this question is now far clearer. Finally, the scientific agenda emerging from CLIVAR highlighted the need for sea level data for a variety of problems. This Workshop has made a first attempt at articulating those needs and matching the available sites against the requirements. So the primary audience consists of the sea level resource managers, GCOS/GOOS (represented by the OOPC) and CLIVAR. However, because of the extra attention to scientific "drivers", GLOSS itself has become a significant member of the audience (in addition to its significant role as a provider of data). The results from the study and Workshop will provide important texture and detail for the GLOSS IP and for the future activities of GLOSS.

Another uncertainty concerned the path that would be taken from the detail of the network report of Gornitz (in effect a representation of the current status of the *in situ* sea level network) toward future plans and recommendations (what is needed). Through discussions at the Workshop and between SSG members, it became clear that this could only be achieved by treating the report as background for a set of actions and recommendations for the future which would constitute the principal findings of the Workshop. It was also concluded that this was an ongoing process, and therefore it was proposed to establish a Scientific Working Group, which would promote development of the network (not merely preservation) consistent with evolving scientific objectives and priorities. One of the first actions of the Scientific Working Group should be to convene further discussion on the details of the network report. It will also function in terms of on-going evaluation and evolution of the network.

The central importance of altimetry was an obvious recurring theme. The "age of altimetry" has forever changed the way the height and shape of the sea surface are measured. In this new era, *in situ* sea level does not become redundant, but constitutes an important information base upon which improved altimetry can be developed. The synergy between remote and direct measurements is the new operating paradigm. Gauges can provide continuity, relatively low maintenance costs, sampling in areas poorly represented by altimeters, and coastal impact applications.

The conclusions of the Workshop reflected consolidation and rationalisation (e.g., combined remote and direct data for sea level trends, but with specific requirements), but also revised and new scientific requirements (e.g., ENSO and monitoring of Sothern Ocean variability).

Workshop statements, conclusions and recommendations:

- ### Scientific and technical oversight

The Workshop recommends that a Scientific Working Group for Climate Aspects of Sea Level be established to facilitate implementation according to the scientific requirements specified by various operational and research programs associated with sea level aspects of climate change.[2] This group would provide scientific advice on climate related aspects of sea level to the GLOSS GE and thereby interface to the national sea level activities and interests of IOC Member States.

The sub-committee would include representation from the major research and operational programs, including CLIVAR (via the Upper Ocean Panel), GCOS/GOOS (via the OOPC and the Coastal Panel), and LOICZ. The Group would be responsible for the development of a scientific strategy for climate-related sea level measurements, as input to future Science Plans, and would advise the wider GLOSS GE on all scientific issues which might impact GLOSS Implementation. At a later date, further scientific sub-committees may be established concerned with Coastal Aspects of sea level, as considered appropriate by IOC/GOOS, GGE etc.

The Workshop requests the present Chair of GLOSS and the Chair of the Workshop to liaise with the GLOSS Secretariat and the Director of the GOOS Office to a) consult with the potential sponsors to endorse the creation of the Climate Sea Level Group and to assess possible resource implications, b) create suitable terms-of-reference if necessary, and c) suggest possible membership.

- **In situ network and altimetry**

The Workshop wishes to reiterate and emphasise the importance of altimetry for all aspects of sea level measurements and its various applications. The Workshop notes that altimetry is not a replacement for *in situ* methods, but constitutes a powerful complementary source of information which adds further value to both the direct and remote data streams. However, altimetric missions do not yet have "operational" status in the same sense as, for example, remote sensing of SST, so the forward-looking strategy must be based on the premise that the availability of altimetric measurements may be interrupted without warning and for indefinite periods. It is critical that altimetric data are made more readily available, where possible with decreased delays but with appropriate attention to quality.

- **Estimation of long-term trends in sea level**

The Workshop acknowledged the continuing high level of interest in the estimation of sea level trends and possible accelerations in the rate of sea level change. Accordingly, it endorsed a dual strategy.

The *preferred observing system* comprises:

- altimetry for global sampling, at approximately 10 day intervals, for spatial patterns and estimation of spatial and temporal variability;
- approximately 30 *in situ* gauges for removing temporal drift in the altimetric measurements;
- those gauges of the GLOSS-LTT set which sample the margins of the altimeter, for example coastal regions and high latitudes;

---

2 The proposal put forward to IOC seeks the establishment of a Working Group with GLOSS/IOC as its lead sponsor, and the OOPC and UOP as secondary sponsors.

- a program of geodetic positioning (see below); and
- a program of data archaeology and development, targeting the sampling gaps and areas where referencing of the altimetric measurements is weak.

In view of the lack of guarantee attached to altimetric measurements, and the lack of experience and confidence in the application of altimetry to measuring long-term trends, the Workshop further recommended the maintenance of an *alternative observing system* comprising:

- a globally distributed network of *in situ* measurements, with similar effect to the GLOSS-LTT set, and listed under long-term trends in the network report;
- a program of geodetic positioning (see below); and
- a program of data archaeology and development, targeting the sampling gaps and areas where referencing of the altimetric measurements is weak.

For regions where there exists several alternative, but potentially equally effective *in situ* sites, the strategy requests regional groups to designate the preferred site and a backup, and to implement geodetic positioning accordingly. The Workshop endorsed the strategies of GLOSS for its GLOSS-LTT and GLOSS-ALT networks and noted that the strategy recommended above is broadly consistent with the GLOSS Implementation Plan.

- **Report on the Sea Level Network**

The Workshop commended Dr Gornitz on the draft report "Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales" and requested that it be developed according to the general and specific comments from the Workshop participants. Specifically, the Workshop requested:

1) a broader definition of "location" be adopted whereby the scientific relevance and uniqueness of specific sites would be represented in the selection matrix,

2) that the logistical considerations (continuity of support, permanence, costs of maintenance) be documented, but not included in the final score of the selection matrix,

3) that due account be taken of the availability of ancillary data, such as air pressure,

4) that the titles of various science goals be altered to better reflect the principal focus,

5) that a scientific goal on boundary currents be added, and

6) a section be included which discusses impacts and applications.

For 2) Scherer, Woodworth, Merrifield and Mitchum offered to provide advice. Vianna, Ridgeway, Lukas and Sturges (Gulf Stream) would be contacted for input on 5). Mitchum, Mitchell, Vianna, Hannah and Gornitz would provide contributions for 6).
This report represents a detailed consolidation of what we now know about the existing network. The revised draft would be circulated to the Workshop participants for further comment, and to selected individuals where expertise was not available (e.g., A. Clarke for Atlantic circulation).

- **Priority for geodetic positioning**

In accordance with the strategy for long-term trend estimation, the Workshop recommended the following priorities for geodetic positioning:

  - sites used for referencing altimetric measurement (see "Preferred" system above GLOSS-ALT and the report calibration sites);

  - sites used for long-term trend estimation, with preference to sites at the margins of altimeter coverage, and noting the request for regional and/or national groups to assign priority where several alternatives exist; and

  - sites used for ocean circulation studies, with preference to sites used in current and/or volume transport estimation.

- **Data archaeology**

The Workshop wished to explicitly acknowledge the valuable contributions to the sea level data base from data rescue and data rehabilitation efforts. It was noted that well targeted efforts can extend predictability studies and reduce uncertainty in the spatial patterns of variability, as well as improving the overall value of the data base. The Workshop therefore recommends further effort to be devoted to this area, with the Indian sub-continent, south-east Asia and the South Atlantic being identified as prime areas for such activity.

- **Sea level for ENSO prediction**

The Workshop concluded that sea level data (both remote and direct) were now very important for studies of predictability and for experimental and practical prediction. This conclusion reversed a tendency to downgrade sea level data relative to subsurface temperature data and surface wind and temperature data. The Workshop commended the various studies which examined the impact and quality of sea level information and broadly endorsed the recommendations of the CLIVAR Upper Ocean Panel with regard to the importance of sea level information. The Workshop noted western Pacific were relatively more influential in validation and prediction problems.

- **The WOCE Fast-Delivery Center**

The WOCE Fast-Delivery Centre has provided an important service across a broad range of applications of sea level data. This importance is explicitly recognised in the station selection criteria.

The Workshop therefore recommended that the Center be transformed into a Center with a broader mandate, effectively servicing all the climate sea level near-real-time delivery of data. Its functions would be complementary to that of PSMSL. The data acceptance policy would be open, emphasising that all sites have information which is potentially useful for climate studies. It was suggested that the centre might be called the Climate (Sea Level) Fast-Delivery Center, explicitly acknowledging the broader climate mandate rather than attachment to any particular operational or research program.

- **Development of the in situ sea level network**

The Workshop recognised that the draft report and the GLOSS Implementation Plan were sound representations of the existing capabilities and that, after suitable revision, would constitute a valuable assessment of the importance and impact of particular sites. However, the Workshop also concluded that it was important to initiate actions and development which would enhance the information gathered, preserve the existing capabilities, and prepare the network for future demands. Specifically, it should begin the process of evaluating prospective sites for inclusion into the planned network and modify the existing criteria and designate new ones for consideration of future stations.

It therefore recommended specific action in several key locations, the details of which are included in the body of this Workshop Report and in the network report. Specifically, the Workshop recommended:

  - enhancement of the network in the tropical western Pacific and in the region of the Indonesian Throughflow;
  - support for those Southern Ocean stations presently being implemented, for stations implemented or planned in the vicinity of the Antarctic continent, and stations adjacent to Drake Passage; and
  - encouragement for improved accessibility to data from Brazil (e.g., Recife) and other stations presently not included in the Fast-Delivery service.

- **MSLP data and other ancillary data**

The Workshop concluded that ancillary data provide important added-value to sea level data sets. In particular the Workshop recommended that atmospheric pressure be designated a required variable for all non-tropical sites, particularly at high latitudes, and a desirable variable at tropical sites.

- **Publication and circulation of workshop results**

The Scientific Steering Group recommended that the Workshop Report, including a revised "Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales", be published under the auspices of OOPC and CLIVAR, with due acknowledgment of the sponsorship of NOAA. Furthermore, it requested that the key results be circulated via appropriate newsletters and bulletins, including those of GLOSS, CLIVAR, GCOS and GOOS.

- **Follow-up actions**

The Workshop envisages that the proposed Scientific Working Group will effectively assume leadership for the issues and actions raised in this Workshop. In the event that this proposal is not accepted, the Workshop recommends that regular Workshops be convened to discuss these and similar issues and to provide for evolution of the scientific plans.

LIST OF ACRONYMS

CLIVAR	WCRP Climate Variability and Predictability Experiment
ENSO	El Niño-Southern Oscillation
GCOS	Global Climate Observing System
GLOSS	IOC Global Sea Level Observing System
(GLOSS-)ALT	GLOSS Altimeter calibration sites
(GLOSS-)LTT	GLOSS Long-Term Trends sites
GLOSS GE	GLOSS Group of Experts
GLOSS IP (GIP)	GLOSS Implementation Plan
GOALS	Global Ocean-Atmosphere-Land System
GOOS	Global Ocean Observing System
IGBP	International Geosphre Biosphere Program
IOC	Intergovernmental Oceanographic Commission
ITCZ	InterTropical Convergence Zone
LOICZ	IBGP's Land Ocean Interactions in the Coastal Zone Experiment
NOAA	U.S. National Oceanic and Atmospheric Administration
OOPC	Ocean Observations Panel for Climate
PSMSL	Permanent Service for Mean Sea Level
SST	Sea surface temperature
TAO	Tropical Atmosphere-Ocean Array
TOGA	Tropical Ocean Global Atmosphere Experiment (WCRP)
UOP	CLIVAR Upper Ocean Panel
XBT	Expendable BathyThermograph
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment

APPENDIX A:

DESIGN OF A GLOBAL SEA LEVEL NETWORK FOR MONITORING CLIMATE VARIABILITY ON SEASONAL TO CENTENNIAL TIME SCALES

DESIGN OF A GLOBAL SEA LEVEL NETWORK FOR MONITORING CLIMATE VARIABILITY ON SEASONAL TO CENTENNIAL TIME SCALES

Vivien Gornitz

with contributions from the International Sea Level Workshop

Sept. 5, 1997

Abstract

Sea level is a fundamental element of the climate system and it represents the integration of complex coupled ocean-atmosphere processes. This report outlines the design of a sea level observing system, which will combine an operational network of tide-gauge stations with satellite altimetry and geodesy, in support of monitoring and predicting climate variability and change on seasonal to centennial time-scales. A systematic rationale is presented for the selection of high-quality tide-gauge stations to monitor sea level or sea surface height. Building upon the goals and recommendations of the Ocean Observing System Development Panel (OOSDP, 1995), the Ocean Observations Panel for Climate (OOPC, 1996), and the CLIVAR Science Plan (1995; 1997), this study identifies a number of key science issues in which in-situ sea level data play an important role. These include monitoring of: 1) tropical ocean variability and predictability (e.g., ENSO, Indian Ocean and Asian-Australian monsoons, tropical Atlantic variability), 2) extratropical gyres and circulation (e.g., NAO, north Pacific variability), 3) high latitude circulation, 4) straits, narrows, and "chokepoints", 5) western boundary currents, 6) long-term sea-level rise, 7) satellite altimeter calibration, 8) model validation, and 9) sea level impacts and applications. A set of criteria have been developed to evaluate tide gauge stations: scientific relevance and uniqueness of site, record length and completeness, temporal resolution, overall data quality, timeliness of data distribution, and GPS linkages. The results are summarized in a series of tables and maps. Proposed upgrades and additions to the network are discussed.

INTRODUCTION

The climate system varies over a broad range of space and time scales. Sea level is a fundamental component of the climate system and it represents the integration of complex coupled ocean-atmosphere processes. The ocean surface responds to diurnal, seasonal, and interannual fluctuations in atmospheric pressure, winds, coastal upwelling, geostrophic currents, and heat fluxes. On longer time scales, variations reflect changes in freshwater and heat flux, also eustatic and steric changes associated with climate change, and slow deformation of the earth's crust. However, the critical climate signals resulting from these diverse physical processes are often obscured by the natural variability occurring at shorter time scales, making interpretation difficult without more fundamental knowledge of the variability on different space and time scales. Sea level data, however, have several natural advantages that should be exploited in the design of a sea level measurement network which will operate synergistically with other complementary measurement networks and other elements of the global climate observing system.

This report outlines a design for an operational global network of tide-gauge stations, integrated with satellite altimetry and geodesy, in support of monitoring and predicting climate variability and change on seasonal to centennial time scales. The sea level observing system design, proposed here, builds upon the science goals and recommendations of the Ocean Observing System Development Panel (OOSDP, 1995), the Ocean Observations Panel for Climate (OOPC) (IOC, 1996), and the CLIVAR (Climate Variability and Predictability) Science Plan (1995; 1997). This study builds a systematic rationale for the selection of high quality tide-gauge stations that will monitor sea level or sea surface height. The geographic distribution of stations is intended to address a number of specific science questions relating to climate variability and change over a range of time-scales. Furthermore, the in-situ network will be linked to satellite altimeters for ocean-wide coverage and with space geodetic techniques for determination of absolute sea level, and to the extent that they are available, other remote and direct observing system elements. While the objectives of this study are complementary to those of the GLOSS Implementation Plan (1997), they are more specifically focused on the scientific issues outlined in the OOSDP, OOPC, and CLIVAR reports. The results of this study will also further assist in the refinement and evolution of the sea level network recommended in the GLOSS Implementation Plan.

Sea level data represent an important integrative physical property and are one of the few sources of information on variations over long (multidecadal to centennial) periods. Sea level observations, some going back over 100 years, come from tide-gauge records (e.g., the Permanent Service for Mean Sea Level [PSMSL], Bidston Observatory, U.K.; the University of Hawaii Joint Archive for Sea Level [JASL]; Appendix A.1). Global means estimated from the longer tide-gauge records indicate a sea level rise of 1-2.5 mm/yr over the last 100 years (IPCC, 1996a). Tide-gauge data have made an important contribution to our understanding of the El Nino/Southern Oscillation (ENSO) phenomenon (e.g., Mitchum and Wyrtki, 1988; Komar and Enfield, 1987), ocean circulation (e.g., Thompson, 1990), the Kuroshio current (e.g., Yamashiro and Kawabe, 1996), and the throughflow between the Pacific and Indian Oceans (e.g., Arief and Murray, 1996; Bray et al., 1996; Wyrtki, 1987).

Despite their great value in studying ocean dynamics and detecting climate change signals, tide gauges have several limitations (Gornitz, 1995a; Groger and Plag, 1993; Pirazzoli, 1993; Woodworth, 1991). These include sampling errors due to short and broken time series and a strong geographical bias towards the Northern Hemisphere (Fig. 1). A major source of variability in sea level comes from terrigenous crustal motions, which are only partially resolved by existing geological or geophysical models (Gornitz, 1995a; Peltier, 1996; Davis and Mitrovica, 1996). Linkage of tide-gauges to permanent GPS (and/or SLR or VLBI) receivers is required to separate changes in ocean level from land motions (Carter, 1994).

Satellite altimetry, of the accuracy of TOPEX/POSEIDON (Fu and Cheney, 1995), provides the first global observations of sea surface height variability on a dense sampling grid, and enables the testing and verification of global ocean circulation models. Studies of global ocean dynamics have demonstrated the utility of satellite altimeters, although they still have relatively short records. The longer records provided by tide-gauge data complement these altimeter measurements and provide a context for interpretation of trends derived from altimetry (e.g., Nerem, 1995). On the other hand, the large-scale spatial coverage of altimeters enables a more effective separation of interannual effects (e.g., ENSO) from secular trends due to anthropogenic change. Although a number of satellite altimetry missions exist and are planned (Fig. 2), only the current TOPEX/POSEIDON and the JASON (TOPEX/POSEIDON follow-on) are designed to perform at an accuracy of better than 5 cm (CLIVAR, 1996). However, approaches are being developed to cross-calibrate these satellite altimeters, which enables improved utilization of data from other platforms (e.g., ERS 1/2, ENVISAT).

A need, therefore, exists for continuity of in-situ data across satellite missions, as well as continuity over tide-gauge technologies in order to make most effective use of the historical record. Long records must be maintained to determine the secular trend and acceleration of sea level, for input to assessments of global climate change, such as the Intergovernmental Panel on Climate Change (IPCC). Relative sea level data are required for assessment of coastal hazards, manangement and development of coastal resources. A tide-gauge network is essential as a backup in the event of failure of altimeters and to bridge gaps between altimeter missions. Tide gauges will continue to play an important role in calibrating altimetry measurements, checking for instrument drift, verifying ocean model experiments, and providing higher freqency sampling at high latitudes poorly covered by altimeters. The pronounced differences in temporal and spatial resolution between in-situ and satellite instruments means that they resolve different portions of the space-time variability spectrum. Therefore, a joint system of tide gauge and satellite altimetry measurements provides a more comprehensive overview of the ocean component of climate variability and secular change (Fig. 3).

BACKGROUND

The Final Report of the OOSDP (1995) recommended several subsets of tide-gauge stations: 1) to support ENSO predictions, taken from the TOGA network; 2) to detect decadal and longer changes in sea level, from the GLOSS network, using stations which are geocentrically located with GPS or VLBI; and 3) to calibrate and validate altimeter measurements. The OOPC (IOC, 1996) reexamined these priorities. They concluded that the joint use of altimetry with tide gauges will generate a product that will retain the advantages of the historic in-situ record but with the global coverage of the altimeter.

The CLIVAR Science Plan (WMO, WCRP, 1995) similarly identified as priorities the examination of interannual, decadal, and longer-term variability relating to ENSO events, monsoons, and ocean-wide fluctuations, and the determination of rates of anthropogenically-induced sea-level change, and for intercomparison of altimetry with in-situ data.

The U.S. Ocean CLIVAR Implementation Planning Report (Oct., 1996) also viewed satellite altimetry and tide-gauges as two complementary systems for sea level monitoring. Additional recommendations were to maintain and upgrade a subset of the existing tide gauges as key elements of the CLIVAR programs for: 1) calibration of altimeters, 2) backup in case of altimeter failure, 3) coverage at high latitudes, and 4) study of long-term sea level trends. These various programs view sea level as one component of a multi-variate climate observing system, albeit a significant one.

The GLOSS Implementation Plan (GLOSS, 1997) focuses on a variety of sea level issues. General guidelines for the selection of appropriate stations are outlined. The Implementation Plan calls for a global core network of around 200-250 tide-gauge stations worldwide, including a subset of stations for long-term sea-level trends (GLOSS-LTT), an island-based subset of gauges equipped with GPS geodetic control for calibration of altimeters (GLOSS-ALT), and a network of gauges to provide ongoing monitoring of ocean circulation (GLOSS-OC). The GLOSS-OC sites will supplement altimeter measurements. Key applications of the latter include sampling of narrow straits, wider straits, and "choke points" (e.g., Indonesian archipelago, Florida Straits), the Antarctic coast, and other areas poorly sampled by altimeters.

DESIGN OF A GLOBAL SEA LEVEL NETWORK FOR CLIMATE MONITORING

Science issues

This section describes important scientific issues relating to sea-level variability and change over seasonal and longer time-scales. Nine major goals, and a number of subgoals have been identified. The primary objective is to select an optimal set of tide-gauge stations, to be integrated with satellite altimetry, space geodesy, and other complementary observations, in order to monitor and predict sea-level variability over seasonal to decadal and centennial time-scales. The major science issues are: 1) tropical ocean variability, 2) extratropical gyres and circulation, 3) straits and "chokepoints", 4) high latitude circulation, 5) western boundary currents, 6) long-term sea-level rise, 7) satellite altimeter calibration, 8) validation of ocean models, and 9) impacts and applications.

The tide-gauge network, in conjunction with satellite altimetry (e.g., Fig. 3), will provide the necessary data to establish the climatology of sea surface height, over the world's oceans, including the statistics of its variability, ranging from the seasonal cycle to decades. In-situ measurements provide very high temporal-resolution data (minutes, hourly) for a number of point sources, whereas satellite altimeters provide broader areal coverage, at low temporal sampling rates (e.g., the 10-day repeat cycle of TOPEX/POSEIDON). This difference in spatial and temporal sampling rates between the two types of instruments indicates that they are not observing the same thing, and thus need to be used jointly in order to maximize their information capacity. Stations selected for the network can be used to help establish the large-scale spatial and temporal patterns of sea-level variability over seasonal to decadal periods and longer. In addition, stations filling important geographical data gaps should be recommended for inclusion in the network.

The complementary nature of the tide-gauge data and altimetric observations become especially evident over longer time-scales. Multidecadal to centennial sea level time-series from a limited number of tide-gauge stations can be compared with the shorter, but more spatially-extensive, satellite coverage. Longer time-scales are needed to detect changes in the frequency and intensity of climatic phenomena such as the El-Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), the Pacific-North American pattern (PNA), and the tropical Atlantic dipole. Thus, the same regions examined for seasonal to decadal variability should continue to be monitored, selecting those stations with sufficiently long records (i.e., preferably >40 years, but at least ≥20 years). Major science goals and subgoals are listed below. Given the concern over coastal hazards, a section has also been included on impacts of sea level variability and long-term change.

Science goals:

1. **Tropical ocean variability and predictability**
   a. ENSO events
   b. Indian Ocean and Asian-Australian monsoons
   c. Tropical Atlantic variability
2. **Extratropical gyres and circulation--variability and predictability**
   a. North Atlantic currents and the NAO
   b. North Pacific variability
3. **High latitude circulation--Arctic regions and Antarctica**
4. **Straits and chokepoints**
5. **Western Boundary Currents**
6. **Long-term sea level trend**
7. **Satellite altimeter calibration**
8. **Model validation**
9. **Impacts and applications**

Each of these science goals and subgoals is now discussed in turn.

1. Tropical variability and predictability

1a. ENSO. ENSO is a large-scale, low frequency atmospheric and oceanic oscillation in the tropical Pacific Ocean. El Ninos recur roughly every 3-4 years. During the El Nino phase, large-scale warm sea surface temperature (SST) anomalies appear throughout the central and eastern tropical Pacific, the easterly trade winds slacken, and atmospheric convection moves from the western to the central Pacific, following the warm SSTs. The thermocline shoals in the western Pacific and deepens in the central and eastern Pacific. Upwelling along the South American coast weakens considerably. These phenomena lead to positive sea level anomalies along the west coast of the Americas (see Fig. 4). The reverse conditions occur during the opposite phase (La Nina).

In the tropics, the spatial and temporal coherence of the patterns related to interannual climate fluctuations (i.e., the ENSO cycle) offers a greater degree of predictability than at higher latitudes. The unique history in sea level records can help establish the significance of predictions: simulations and experimental forecasts can be performed over longer periods than possible with subsurface data or altimetry alone. Tide gauges provide an important control for altimetry and subsurface temparture data in the Pacific (Koblinsky, this Workshop). Assimilation of sea level data with other ocean data sets can further improve ENSO predictions (Zebiak and Cane, 1987; Cane et al., 1996).

Highest ratings for ENSO predictions are assigned to island stations in the western Pacific Ocean within 15° N and S. Medium ratings are given to stations up to 20° N or S, and lower ratings up to 25° N or S. Although the ENSO signal is largest in the western and central Pacific (e.g., Mitchum and Wyrtki, 1988), ENSO-related positive sea level anomalies are registered on tide-gauge records all along the west coast of South and North America, as far north as Alaska (Figure 4; Chelton and Enfield, 1986; Komar and Enfield, 1987). Therefore, coastal stations from the eastern Pacific margin should also be included. Appropriate stations can be selected from the TOGA and WOCE "fast-delivery" data bases.

1b. Monsoons. Monsoons, especially in the Indian Ocean and southeast Asia-Australia, contribute substantially to annual-interannual climate variability. Sea-surface temperature anomalies may affect monsoonal behavior. Key ocean areas identified by CLIVAR (1997) include: Indonesia, the South China sea, the western Pacific, and the Indian Ocean. Variations in the Asian-Australian monsoon may be strongly influenced by ENSO, and vice-versa (CLIVAR, 1997; R. Lukas, this Workshop). The Asian-Australian monsoon also closely influences western Pacific boundary currents and the Indonesian throughflow (see below).

Suitable tide-gauge stations in the Indian Ocean and western Pacific can be taken from the TOGA and WOCE networks. As for 1a, timeliness of data receipt is important. However, since many of the island sites have very short records, they should be supplemented by coastal stations, particularly from the Indian sub-continent (e.g., see Clarke and Liu, 1994).

1c. Tropical Atlantic Variability. M. Vianna (this Workshop) has identified two regional modes of variability that affect the tropical Atlantic. The first is a dipole mode (Atlantic Dipole) linked to variability in the trade wind field and the position of the Atlantic Intertropical Convergence Zone (ITCZ), which results in a see-saw-like variation in SST between the northern and southern Atlantic over decadal time-scales (see also Carton, 1997). These fluctuations in SST have been linked to periods of floods and droughts in Brazil and west Africa. A second, faster, ENSO-like mode may be modulated by the Pacific ENSO and the NAO (see below).

Unpublished data by Vianna and Domingues (1994) from EOF analysis of detrended and deseasonalized monthly North Atlantic sea levels show strong variability on QB-triennial, 4-5 and 12-15-year periods. EOF 2 had maximum values along the U.S. east coast, between Miami and New York. A close correpondence is found between east coast sea levels and the Atlantic Dipole, thus suggesting that coastal sea level data from Brazil may also be useful in studying dipole processes. Two stations with records longer than 40 years are recommended: Recife and Fortaleza, which correpond to the south and north sides of the Dipole, respectively.

The Pilot Research Moored Array in the Tropical Atlantic (PIRATA 1997-2000) is a planned observational program designed to monitor and study atmospheric and upper oceanic variability in the tropical Atlantic on seasonal to interannual time-scales (M. Vianna, this Workshop). The array consists of atlas moorings, island sea level and meteorological stations, and coastal tide gauges. Atmospheric and oceanographic data will be collected and transmitted via satellite in real-time, in a manner similar to the TOGA-TAO systems. Existing tide-gauge stations, such as those located along the northern coast of Brazil, on equatorial Atlantic islands, and West Africa will provide useful data on ocean heights. Coastal tide gauges can also provide a historic record of the variability of western boundary currents in the Atlantic (such as the Northern Brazil Current and the Gulf Stream).

2. Extratropical gyres and circulation--variability and predictability.

2a. North Atlantic Current and North Atlantic Oscillation (NAO). The North Atlantic is a major locus of climate variability on interannual to decadal time scales, affecting much of the North Atlantic (Rogers and Van Loon, 1979). The NAO Index is defined as the normalized sea surface pressure difference between Stykkisholmur, Iceland and Ponta Delgada, Azores (IPCC, 1996), or Lisbon, Portugal (Hurrell, 1995). The see-saw in atmospheric pressure between the Azores and Iceland affects the strength of the mid-latitude westerlies and hence, the trajectory of storm tracks. Therefore, NAO fluctuations strongly modulate weather patterns over western Europe and the Middle East. A negative NAO index is associated with bitter cold and dry winters in northwest Europe, and relatively warm temperatures in Greenland and the Labrador Sea, as well as warmer, wetter conditions in southern Europe and the eastern Mediterranean (e.g., 1965, 1966, 1969, 1970, 1977, 1979). The reverse conditions hold true for positive NAO index years (e.g., 1973, 1975, 1981, 1983, 1989).

While the NAO is primarily an atmospheric phenomenon, recent research suggests possible links to North Atlantic ocean circulation (Dickson, 1997; McCartney, 1997). The NAO also appears to have a role in the large anomalous pole tide around the North Sea (Tsimplis et al., 1994).

North Atlantic climate variability on multidecadal time-scales, is reflected in fluctuations of dynamic topography, or sea surface height, and is potentially predictable (Griffies and Bryan, 1997). Based on their model results, Griffies and Bryan recommend satellite altimetry measurements as "the foundation for a climate monitoring and prediction system".

Sea levels are closely correlated with the NAO Index (Figure 5). Tide-gauge stations in Scandinavia and southeastern United States show positive correlations with the NAO Index, whereas stations from southern Europe, the Mediterranean, and southern Quebec are negatively correlated (V. Gornitz, unpubl. data). Therefore the proposed sea level network should include stations from both sides of the North Atlantic basin.

Sea level variability on multidecadal time-scales also expresses longer-term variations in the intensity of the North Atlantic thermohaline circulation (e.g., the "Great Salinity Anomaly" of the 1960s and 1970s; Dickson et al., 1988). Mysak et al. (1990) have linked this salinity anomaly to interdecadal North Atlantic sea ice anomalies and to the NAO. During this episode, sea levels along the European coastline were far below normal (Woodworth, 1987).

Modeling studies suggest that minor changes in ocean salinity or temperature, such as may result from global warming, could disrupt the thermohaline "conveyor belt", with important climate consequences. The Denmark Strait-Davis Strait-Labrador Sea regions show particularly high temporal variability on multidecadal time-scales, but anomalies extend as far south as Newfoundland and Nova Scotia (Delworth et al., 1997; 1993). Thus stations from these areas should be selected.

2b. North Pacific Variability. Sea-surface temperature (SST) variability in the North Pacific is closely related to the winter Pacific-North American (PNA) atmospheric pattern of variability. The PNA consists of four centers of action in mid-tropospheric pressure, including Hawaii, the west coast of North America, the North Pacific, and even the southeast U.S. Of these, the north Pacific center is dominant (Trenberth and Hurrell, 1994). They therefore define the North Pacific (NP) index as the area-weighted mean sea level pressure over the region 30-65°N, 160°E-140°W. The NP time series also closely tracks changes in the intensity of the Aleutian low in winter. To help map the broader patterns of north Pacific variability, tide-gauge stations should include those from Japan, the Kuril Islands, British Columbia, and the U.S. West Coast. Hawaiian island stations (e.g., Honolulu) are also relevant.

3. High-latitude circulation.

The orbital inclination of satellites such as TOPEX/POSEIDON precludes sea surface observations at polar latitudes. The Arctic region is important because many climate change simulations show an amplified response at higher latitudes, mainly due to the highly non-linear ocean-ice-atmosphere interactions. Conversely, in regions of deep convection, the ocean effectively distributes the enhanced thermal forcing over the entire column and into the deep water, thus favoring a subdued response in SST. The sea level responses, however, tend to follow the heat content and so may not correspond exactly with those of the SSTs. Sea level measurements will reflect variability in both the thermally-related (baroclinic) and barotropic components. Areas such as the Baffin Bay-Davis Straits, or the Greenland Sea-Norwegian Sea play key roles in deepwater formation and thermohaline circulation (Dickson, 1997).

Monitoring of the Antarctic Circumpolar Current (ACC) is of particular interest for its role in oceanic circulation and deepwater formation in the Southern Hemisphere. Anomalies in surface atmospheric pressure, wind stress, sea-surface temperature, and sea-ice extent have recently been found to be part of an "Antarctic circumpolar wave", coupled to the ACC and possibly to ENSO activity in the South Pacific (White and Peterson, 1996). Sea levels along the Antarctic coast may be a potential index of ACC transport (Woodworth et al., 1996) and may, furthermore, be linked to these other variables. Tide gauges can also provide improved tidal data, needed to reduce tide model uncertainties in this region. Such data are not readily available from present altimeters.

In-situ coverage of the Antarctic coast is therefore fundamental. However, because of sea-ice extent along the Antarctic coast for most of the year, which will interfere with sea level measurements, nearby ice-free sites should be considered, as well.

4. Narrow straits and "choke points".

Narrow straits and constricted passages may affect the transport of water mass, and ultimately the thermohaline circulation. Pairs of gauges across straits provide another form of integrated measurement and may thus be a superior monitor of climate variations. Specific examples include the Lombok Strait, Indonesian archipelago (Arief and Murray, 1996; Bray et al., 1996; Lukas et al., 1996), the Florida Straits (Komar and Enfield, 1987); Straits of Gibraltar; the Drake Passage. Particularly important for the last case are stations located on the southern side (Woodworth et al., 1996).

The Indonesian throughflow has been monitored using sea level differences between Davao and Darwin (Wyrtki, 1987). Arief et al. (1996) have correlated Lombok Strait current variations with sea level at Cilicap. More recently, direct measurements have been made using pressure gauges and XBT measurements on both sides of the Lombok and Sumba Straits, Timor Passage, and Ombai Straits. Throughflow indices have been calculated using sea level and tranport between Davao, Philippines and Darwin, Australia, and also south Java (Cilicap) and New Guinea. Other tide gauges have recently been set up on Manus Is. and Kavieng to study circulation within the Papua New Guinea archipelago (K. Ridgeway, this Workshop).

5. Western Boundary Currents.

Western boundary currents are directly connected to strong wind-driven circulation. They contribute a significant fraction of the transport of mass, heat, and salt across the oceans, and thus form an important element of the global climate system. The western boundary of the North Atlantic is dominated by the Gulf Stream, which extends northeastward into the North Atlantic Current. The North Brazil Current flows north across the equator and turns clockwise into the North Equatorial Countercurrent. The situation along the Western Pacific Boundary is more complicated, owing to the irregular distribution of island groups and the convoluted flow through the Indonesian archipelago.

In the western Pacific, the Kuroshio Current in southern Japan regularly takes one of three typical paths: 1) the large meander (tLM) path, 2) the nearshore (nNLM) and 3) offshore non-large-meander paths (oNLM) (Fig. 6a; Kawabe, this Workshop). The LM and NLM paths vary on decadal time-scales, with a primary period of around 20 years. Sea level variations caused by these current meanders can be monitored by tide gauges at Kushimoto (or Uragami) and Miyakejima to monitor the nNML, and Kushimoto vs Hachijojima to monitor the oNLM (Kawabe, 1995). Variations in the LM and NLM paths across the Tokara Strait can be observed by sea level stations at Naze, Nakanoshima and Nishinoomote (Fig. 6a; Kawabe, 1995; Yamashiro and Kawabe, 1996). Surface velocity of the Kuroshio is monitored by measuring the difference in sea level between Ishigakijima and Keelung (northern Taiwan) and between Naze and Nishinoomote (Tokara Strait).

Velocity of the Tsushima Current is obtained by differencing the sea levels of Izuhara-Pusan (western channel) and Hakata-Izuhara (eastern channel) (Fig. 6a; Kawabe, 1982).

Sea levels of the interior area of the subtropical gyre can be monitored at Chichijima, Ishigakijima, Naha, Okinawa, Naze, and Minamitorishima (Fig. 6b).

The tropical western Pacific boundary currents (Lukas et al., 1996) are affected by the strong annual monsoon and the pronounced interannual variability associated with the ENSO. Sea level stations are essentially those used for monitoring the Indonesian throughflow and several from the Philippines.

Gulf Stream. Coastal ocean modeling of the North Atlantic (Ezer et al., 1995), in accord with earlier studies, shows a weakening of the Gulf Stream in the 1970s as compared to the 1950s. Associated with this change in the Gulf Stream, model sea levels along the east coast of North America rise by 5-10 cm over this time period, in good agreement with observed sea level at 15 tide-gauge stations.

North Brazil Current. Variability of the North Brazil Current and the relationship between coastal and open ocean sea level, circulation and transport can be studied by a combination of TOPEX/POSEIDON satellite data, good hydrography and modeling, current meter moorings, supplemented by selected tide gauge stations (M. Vianna, this Workshop).

6. Long-term sea-level rise.

The consensus view is that global sea level has risen about 18 cm over the last 100 years, with a range of 10-25 cm (IPCC, 1996a). Around half of the observed rise is attributed to thermal expansion and melting of mountain glaciers, presumably caused by the global warming of ~0.5°C over this period. However, there is no evidence of acceleration of sea level over the last 100 years (Douglas, 1992; Gornitz and Solow, 1991; Woodworth, 1990). Nonetheless, current sea level trends are 1.0-1.8 mm/yr higher than the corresponding late Holocene sea level trends from the same areas (Gornitz, 1995b). The timing of onset of this present period of sea level rise remains uncertain.

Because of the presence of low-frequency sea level fluctuations (Sturges, 1987; see below), Douglas (1991) recommends selection of stations with records of at least 60 years, that are more than 80% complete. However, in order to insure equitable geographic representation, the record length requirements for data-sparse regions can be reduced to >30 years. The possibility that low-frequency waves may be embedded in the longest sea-level records (Sturges, 1987; Douglas, 1992) makes it important to identify these signals and their forcing possibility is quite strong, as the assumptions made in deriving the error bar are rather conservative, especially where the determination of land motion by GPS is concerned.

In Table 11, SIG = an estimate of tide gauge quality, equal to the standard deviation of the difference between the altimeter and tide gauge, if only one pass is available, but which also takes into account the number of passes available. IGS/CORS = GPS receiver locations in both networks were examined. X means neither has one within 100 km of the tide gauge; the number is the distance in km to the nearest GPS receiver. The five latitude ranges are chosen such that the surface area between 60°S and 60°N is divided equally; then 6 sites are chosen within each latitude range.

The rationale for choosing the gauges has been presented at the GPS Workshop at JPL. A final report has been submitted to NASA at the end of March, and will also be included in the GPS Workshop proceedings.

Of the 30 sites chosen, 17 have a receiver within 100 km. Several others (e.g., Honolulu) should be easy to instrument, leaving approximately 10 stations that will require special attention in placement of GPS receivers. Alternate stations can be substituted, but they need to fulfill these conditions: show a sufficiently small SIG and be located on ocean islands within the same latitude band.

8. Model Validation.

One application of tide-gauge data is for validation of sea-level fluctuations in ocean circulation models and coupled ocean-atmosphere general circulation models (O-AGCMs; e.g., Tokmakian, 1996; Enfield and Harris, 1995; Gregory, 1993). For example, Gregory (1993) finds areas of major SL change off Newfoundland, the Cape of Good Hope, and Arabia for scenarios of 1%/yr CO_2 increase. Mikolajewicz et al. (1990) report strongest SL increases in the eastern North Atlantic, and a decrease in the Ross Sea, for doubled CO_2. In the GISS coupled ocean-GCM, the largest SLR, due to thermal expansion alone, occurs throughout much of the Arctic Ocean and mid-latitude North Atlantic, with areas of negative SLR surrounding the Antarctic, for a 1%/yr CO_2 increase (G. Russell, priv. comm., 1997). In a simpler, shallow ocean water model, Hsieh and Bryan (1996) find that coastal sea level rise is more sensitive to changes in the northern North Atlantic than to the Southern Ocean, especially during the earlier stages of global warming.

Tide gauge data can be used to verify or constrain model results. For example, Ezer et al. (1995) compare changes in sea level between the 1970s and 1950s from coastal ocean model results with 15 eastern North American tide gauge stations. For most stations, differences between calculated and observed sea level rise are less than 2 cm.

Because the spatial patterns of projected sea-level change differ among models, tide gauges used for model validation should be geographically well-distributed and favor non-altimetric regions, such as continental margins and high latitudes. On the other hand, to validate gyre circulation, oceanic islands are preferred. Also, since these types of models may be used for studies of interannual variability as well as long-term climate change, temporal resolutions should cover a range of time-steps, going from days to years, and longer time series are therefore preferred. Satellite geodetic connections are also important, in order to place the in-situ data in the same reference frame as satellite altimetry data, which may be used in conjuntion with the models.

9. Sea level Impacts and Applications.

Changes in frequency and intensity of extreme events (i.e., cyclones and storm surges), superimposed on long-term sea-level rise, represent the components of climate change of greatest concern to coastal zones and small islands. Accelerated sea-level rise, over multidecadal periods, will cause permanent land inundation, more frequent storm flooding, increased beach erosion, and salt water incursion into estuaries and aquifers (IPCC, 1996b; Nicholls and Leatherman, 1995; Gornitz, 1991). Most global impact assessments, such as that of the IPCC (1996b), are based on an assumption of uniform sea-level rise. Not only do model studies project spatially varying increases in sea level (e.g., Gregory, 1993; Hsieh and Bryan, 1996), and in ocean loading following future ice melt (Conrad and Hager, 1997), but physical characteristics of the coastline (such as lithology, landform, wave climate, longshore currents, and storm frequencies), and also relative sea-level trends differ geographically (Gornitz, 1991). Thus, potential impacts are likely to range widely.

Tide gauges record the relative sea level trend, which contains a component of vertical land motion, in addition to change in real ocean level, including that due to global climate change. Crustal movements can be estimated from geological data or geophysical models (Gornitz, 1995b; Peltier, 1996), or, preferably, by linkage of the tide gauge to GPS (and/or SLR, DORIS, VLBI) receivers. Therefore, any global sea level rise scenario should be adjusted for local land movements, in order to derive a more accurate assessment of land loss or flood zones.

As an example of coastal planning policy, New Zealand now incorporates impacts of long-term sea-level change (J. Hannah, priv. comm., 1997). Along with other physical variables which influence the rate of coastal erosion, the IPCC (1995) sea level projections are used to calculate the extent of coastal hazard zones. Within these zones, development activities are either restricted or are subject to specific constraints to avoid unacceptable levels of long-term risk to either lives or assets. In conjunction with determination of hazard zones, the IPCC projections are also a key factor in calculation of acceptable minimum floor levels for new coastal housing developments. In such cases, developers are prohibited from building homes for which the ground floor levels are less than a specified height above mean sea level.

On interannual to decadal time-scales, changes in ocean temperature and circulation will affect marine productivity. An example from the Hawaiian Islands is now discussed.

Sea level measurements are relevant in evaluating and predicting environmental and ecological variability. For example, sea level has been used to monitor variations in spiny lobster recruitment, and hence to predict lobster catch, in the northwestern Hawaiian Islands (Polovina and Mitchum, 1992, 1994). Sea levels at French Frigate Shoals and Midway Island were found to be correlated with lobster catch. The spatial structure of sea level variations during the 1986-87 ENSO event was determined from sea surface height measured by the GEOSAT satellite altimeter. The correlation resulted from the close association between the sea levels and the strength of the subtropical countercurrent, which crosses the Hawaiian islands. The sea level records, which contained a much longer time series than the altimeter data, revealed major variations during other, earlier ENSO events in the Pacific. A possible biological mechanism for the observed correlation is that the flow variations affect the ability of planktonic lobster larvae to resettle the ridge. Since lobsters are approximately 4 years old when harvested, this suggests that the sea level difference 4 years earlier could act as a predictor of lobster catch (Polvina and Mitchum, 1994).

This study demonstrates the synergistic value of longer sea level time series coupled with the more spatially dense satellite observations. Another important finding of this study is that the sea level difference between French Frigate Shoals and Midway Island provides a better index than either sea level record alone.

Methodology for evaluation of tide-gauge stations

This section presents a set of objective criteria to evaluate existing tide-gauge stations recommended for inclusion in the global sea-level network, in terms of the science goals outlined above (except for impacts and applications). The stations have been initially screened by stratifying them geographically and by setting minimum thresholds for record length and completeness (criteria 1 and 2). Stations not fulfilling these basic requirements have been omitted, except as needed to fill significant geographic gaps. A selection matrix is set up as follows. Each criterion is assigned a weight factor ranging from 1 to 5, in order of increasing importance (Tables 1a and b). These weight factors vary from one goal to another. Each station is then rated on a scale of 1-3 (low, medium, high priority) for each goal and criterion. The final score becomes the weighted average of the weight factors and ratings for all the applicable criteria. For continental margins, a spacing rule of 500 to 1000 km was applied, by selecting the highest quality station within each region. Stations < 500 km apart were eliminated. Such stations are marked with an asterisk in the rating matrices (Appendix A.2). The stations are then reclassified into two groups for each science goal, based on their overall scores: Group 1) High quality stations, in terms of current data; Group 2) Other important stations, needing upgrading (Tables 2-12).

Datasets examined in the screening process include the University of Hawaii Joint Archive for Sea level (JASL), the WOCE Fast Delivery network, GLOSS, and the Permanent Service for Mean Sea Level (PSMSL) RLR data sets (Appendix A.1).

Criteria:

1. Location. The maximum score is based on relevance of location to the science goal (as defined above) and uniqueness of location (absence of other nearby stations). In addition, priority is given to small oceanic islands, because they are more representative of open ocean conditions. Since many oceans either lack small islands (e.g., the North Atlantic, North Pacific, polar regions; goals 2-5) or island record lengths are currently too short for multidecadal analysis, (goals 1b,c; 3, 4), larger islands or mainland coastal sites must also be utilized. In such cases, exposed coasts are preferable to embayments, fiords, estuaries, or river deltas. The latter are affected by subsidence, sedimentation, and interannual fluctuations in river runoff. (On the other hand, deltaic and estuarine regions are especially vulnerable to coastal flooding and inundation due to sea level rise, thus of prime interest for impact studies). Sampling scales: select major islands/island groups for tasks 1, (2), 7, 8; coastal stations (~500-1000 km spacings) to insure completeness of geographic coverage and wherever longer records are required (e.g., 6).

2. Record length and completeness. Record lengths of at least 20 years are needed to monitor seasonal to decadal variability for ENSO, Indian Ocean monsoon, the North Pacific, North Atlantic, and the Atlantic dipole (goals 1-2). Three points are accorded records > 20 years, 2 points for 10-19 years, and 1 point for < 10 years. For studies of multidecadal to centennial variability, 3 points are given for records > 40 years, 2 points for 30-39 years, and 1 point for 20-29 years. Because narrow straits (goal 4) currently have very short records, 3 points are assigned to records > 15 years, 2 points for 8-15 years, and 1 point < 8 years. Detection of acceleration in trends of sea-level rise (goal 5) requires 60 years or more of data (e.g., Douglas [1991]) for better-sampled regions, such as western Europe or North America. To insure geographical representativeness, however, this requirement can be eased to as little as 30 years from data-poor regions. The longest records, i.e. >80 years, can be used to detect low-frequency waves (Sturges, 1987). Altimeter calibration and model validation probably need records at least 10 years (goal 7). All records should be at least >80% complete.

*3. **Temporal resolution.*** Studies of seasonal-interannual-decadal variability require data sampled at hourly, daily, to monthly intervals (goals 1-5). Analyses of multidecadal variability and sea-level rise need monthly to annual data (goals 1-5, 6). However, calibration of altimetry needs at least hourly data, and possibly even higher temporal resolution (goal 7).

4. Data quality. (a) Platform and land stability. Exclude or avoid stations with extreme RSLR trends (>±10mm/yr), known recent seismicity, high rates of local land subsidence, major changes of gauge location, level shifts, or absence of a reference datum. (b) Noise. Exclude or avoid stations with excessive noise due to wind or wave setup. (c) Instrumental problems. Major discontinuities in the record, breaks, level shifts (see above).

5. Satellite geodesy linkages. Tide gauges record relative sea level, which includes a component caused by land motions. In order to obtain the trend of absolute sea level rise, the land motion component must be determined, using GPS or equivalent geodetic techiques. High latitude regions are experiencing higher than average rates of land uplift, due to ongoing glacial rebound. Satellite altimeters are not as precise at high latitudes. Furthermore, there may be a latitude-related calibration problem (see 7a). For these reasons, GPS linkages to tide gauges, particularly at high latitudes and for long term trends, are important.

Proximity to existing permanent GPS sites (Fig. 7) should be taken advantage of, wherever feasible, for all science tasks, and especially for goals 3, 6, 7, and 8. ("Proximity" is defined here as location of the tide gauge within 20 km of a permanent GPS site and within the same tectonic setting. A total of 3 points go to stations within 20 km; 2 points, 20-50 km; 1 point, 50-100 km). Additional GPS receivers should be deployed at selected key stations flagged with an asterisk in Tables 10, 12.

6. Data distribution timeliness. Inclusion of the tide-gauge within a network that provides timely distribution of data (such as the WOCE Fast Delivery system; Fig. 8) is particularly important for predictability of ENSO, monsoons, and for satellite calibration (subgoals 1a-b, 7). It is lower priority for other tasks (subgoals 1c-5) not only because too few of these stations are in the WOCE Fast Delivery network, but because models for prediction are still in the developmental stages. It is not an issue for multidecadal studies, nor for detection of long-term sea-level trends.

7. Logistics. Stations in remote locations are to be assessed in terms of the permanence of the installation, the practicality of maintainance, and associated operating and logistics costs.

Evaluation of tide-gauge stations

Tables 2-12 and Figures 9a, b summarize the results of the evaluation for science goals 1-8 (Goal 9--impacts and applications--is not rated here). (See Appendix A.2 for further details on individual stations, and Appendix A.3 for an overall summary). The top group of stations in each table lists high quality gauges. The lower group represents other important stations which require upgrading, for one reason or another. While such stations have shortcomings, based on

current data holdings, their key location with respect to prime science missions makes them appropriate for the **planned** climate monitoring network (Tables 2-12, bottom). Table 11 lists priority stations for altimeter calibration, based on G. Mitchum's report (see above).

Coverage of the Pacific and Atlantic Oceans is reasonably adequate for examining ENSO, North Pacific variability, and North Atlantic gyres over a range of time scales. However, in-situ data suitable for seasonal to interannual analyses are still far too short for multidecadal observations of the Indian Ocean, tropical Atlantic Ocean islands, narrow straits and chokepoints, or high latitudes.

ENSO. Highly-rated stations for seasonal to decadal time ranges generally include tropical Pacific islands in the WOCE Fast Delivery data network, with > 20 years of continuous, high quality data (Table 2a, top). Other important stations include Easter Island in the eastern Pacific, Balboa and stations along the west coast of South America (Table 2a, bottom). Other than Balboa, the latter stations have data problems (e.g., multiple level shifts or short and broken records).

Priority stations for multidecadal analysis have over 40 years of continuous data (Table 2b, top). Record lengths for most of the remaining stations are less than 30 years (Table 2b, bottom).

Monsoons. Indian Ocean islands have very short time series--barely sufficient for interannual observations. Furthermore, fewer of these islands are in the WOCE Fast Delivery network. Thus, scores are generally lower than for Pacific islands (Table 3a). Higher-rated stations are in the WOCE Fast Delivery network, with good overall data quality, in spite of short record lengths.

A few stations from the Indian subcontinent, the Philippines, and Thailand have sufficiently long records for multidecadal to centennial observations (Table 3b, top). Other stations (Table 3b, bottom) have noisy data which need upgrading.

Tropical Atlantic Variability. Most tropical Atlantic Ocean islands have extremely short and gappy records (mostly <10 years) and are not in the WOCE Fast Delivery network (Table 4). Many of the better stations lie north of the equator, thus leaving the South Equatorial Current, the North Brazil Current and the North Equatorial Countercurrent regions undersampled. Important tropical Atlantic island stations, although having very short time-series, include Sao Tome, St. Peter and Paul, Fernando de Noronha, Cape Verde, Ascension Is., and St. Helena.

Other than Bermuda, only Recife and Fortaleza have multidecadal records. Digitization of data from Recife has recently been completed; that for Fortaleza is in progress (M. Vianna, this Workshop).

North Atlantic Oscillation. High priority stations for seasonal to decadal NAO observations surround the North Atlantic basin rim (Table 5a, top). Other strategically-located stations that should be included in any future network are: Reykjavik, Ny Alesund, Ponta Delgada (Azores), and Nain (Labrador). These stations presently display either low temporal resolution, absence from the WOCE Fast delivery system, short/gappy records, or data quality problems.

For multidecadal observation periods, some otherwise important stations (e.g. Godthab, Greenland and Torshavn; Table 5b, bottom) presently have too short records. Key West, while ranking high due to its excellent data quality and long record, lies on the southwestern boundary of the area of interest.

North Pacific Variability. Relevant stations include those from northern Japan and northwest North America (Table 6a, top). Some Alaskan and Aleutian Island stations, although located near the center of action of the PNA, are less suitable, because of stability problems or absence from the WOCE Fast Delivery data network. Pacific Northwest stations (e.g. Sitka, Ketchikan, Victoria, Tofino, Adak) have good long-term observations, as do Mera and Midway (Table 6b). Stations from California and the Hawaiian islands, Wake, Guam, and Johnston Island (see *ENSO*) can also be included here, to round out coverage of North Pacific variability.

High-latitude circulation. a. Arctic. Suitable stations include Ny Alesund, Barentsburg, Godthab, Torshavn, Russkaya Gavan, and Murmansk (Table 7a). Among the few Arctic stations in North America are Prudhoe Bay, Alaska and Tuktoyaktuk, Northwest Terr., which should continue to be maintained.

b. Antarctic. Only Faraday (now called Vernadsky) and perhaps Syowa (although a broken series) have records long enough for studies requiring more than a few years of data (Table 7b). Other good stations for monitoring the Antarctic Circumpolar Current along the Antarctic coast include Bahia Esperanza and Casey, which should continue to be maintained. Stations on the southern tip of South America (Diego Ramirez and Ushuaia) are less effective in detecting current variations (Woodworth et al., 1996). Kerguelen and Macquarie Islands are ice-free and have permanent GPS receivers, but are presently data-sparse.

Narrow straits and chokepoints. Key stations for monitoring the Florida Straits include Settlement Point (Bahamas), Key West, and also Miami Beach (moved to nearby Virginia Key, since 1994; Table 8).

The Drake Passage between South America and Antarctica is important for monitoring the Antarctic Circumpolar Current (see above). Woodworth et al. (1996) find that most of the sea level changes associated with the transport change takes place on the south side of this strait (i.e., the northern end of the Palmer Peninsula or the South Orkney Islands). Thus, relevant stations include Bahia Esperanza or Signy. These stations, however, are data-poor, and therefore, Faraday, although located further from the strait, would be a better choice, based on present data holdings.

Ceuta and Gibraltar, which presently have rather short records, should be maintained to monitor the strategic Gibraltar Straits.

The Indonesian gauges presently lack sufficiently long records for more than seasonal to interannual observations. However, given the importance of monitoring the Indonesian throughflow, stations such as Benoa (Lombok), Cilicap, Surabaya or Bitung should continue to be maintained.

Western Boundary Currents. A number of Japanese stations are well-placed to measure the meanders of the Kuroshio Current (e.g. Kushimoto, Aburatsu, Naha, Maisaka, Miyakejima; Table 9a, top). Data from several other stations need upgrading (e.g., Naze, Izuhara, Hakata; Table 9b, bottom).

The Gulf Stream can be monitored at Bermuda and long-term southern U.S. stations, such as Key West, Fernandina, Charleston, and Wilmington (Table 9). For observing the North Brazil Current, useful stations include Recife and Fortaleza (both records being digitized;

M. Vianna, this Workshop).

Long-term sea level rise. Stations with long term records are listed in Table 10. Scores represent a compromise between record length and completeness, data quality, and proximity to existing space geodetic sites. Many otherwise excellent stations rank lower due to the present lack of nearby GPS ties, although this situation is rapidly changing. Examples include Brest, Aberdeen II, Newlyn, Esbjerg, Bergen, Cascais, Genova, Bombay, Sydney, Balboa, and Cristobal.

Some regions are geographically over-represented (e.g., Scandinavia, North America, and Japan). Thus, in addition to those listed in Table 10, other quality stations that could also be selected include: Stavangar (Norway), Smogen, Varberg, Ystad, Kungsholmsfort (Sweden), Warnemunde (Germany), Copenhagen, Aarhus, Fredrickshavn, Hirtshals (Denmark), Hilo (Hawaii), Prince Rupert, Tofino (British Columbia), Seattle, Los Angeles, La Jolla, Mayport, Savannah, Eastport (U.S.A.). Baltimore, Washington, D.C. and Annapolis all lie within Chesapeake Bay, which reduces their priority. Philadelphia, in spite of its 95-year record, is omitted, because of its inland location, up the Delaware River, subject to strong influence of streamflow variations. Similarly, the Astoria sea level record is also affected by river fluctuations. Stations from Sweden and Finland, along the northern Gulf of Bothnia, are omitted, in spite of very long records, because they are isolated from an open ocean environment and their relative sea level curves are dominated by glacial rebound. Calcutta is dropped, because of strong local land subsidence in the Ganges-Brahmaputra Delta region.

Geographically under-represented regions include Africa and South America. The only long-term station in Africa, Takoradi, Ghana (record length 64 years) shows an anomalous sea level record after 1966, following a ship's collision with the pier (P. Woodworth, 1997, priv. comm.). The stations from the west coast of South America are relatively short, and show signs of instability, both instrumental and tectonic--this being an active plate boundary.

Model Validation. Stations that are well-suited for model validation (Table 12) generally have long records with close GPS ties, and are also highly rated for other science goals. These include Pacific island stations such as Guam, Kwajalein, Pago Pago, and Chichijima, Honolulu, and also coastal stations such as San Diego, Victoria, Neah Bay. Other appropriate stations, although presently lacking close GPS ties, are New York City, Tofino, Cascais, Midway, or Port Victoria in the Indian Ocean (which however presently has a very short record).

PROPOSED CHANGES AND ADDITIONS TO THE SEA LEVEL NETWORK

The previous section described a set of in-situ stations considered important for monitoring climate variability, prediction, and long-term change. However, many of these potentially useful stations need to be upgraded (e.g., Tables 2-12, bottom). Suggested improvements to the planned sea level network consist of:

1. deployment of GPS receivers at additional stations (e.g., those flagged with asterisks in Tables 10 and 12).
2. addition of more stations to a high temporal resolution, rapid-delivery system, such as the WOCE Fast Delivery Center.
3. accumulation of continous time-series over longer periods.
4. installation of improved gauge instrumentation.

Geographically relevant tropical islands with very short records should continue to acquire more data. Such islands include Diego Garcia, Port Victoria (Indian Ocean), St. Peter and Paul, Fernando de Noronha, Ascension Is., St. Helena, Cape Verde, and Sao Tome (Atlantic Ocean). Other stations for which even less data presently exist are nonetheless needed to fill major gaps in spatial coverage. These include: Clipperton (eastern Pacific), Crozet Is., Amsterdam Is., Heard Is., Cape Roberts (Southern Ocean), Dumont d'Urville (Antarctica), Miramitorishima--Marcus Is. (Pacific Ocean), and Manus Is., Kavieng, Wewak, Madang, Lae, and/or Alotau (Papua New Guinea)--for western Pacific boundary currents.

Important high latitude stations that should be maintained include Nain (Labrador), and Prudhoe Bay, in the Arctic, and Rothera, O'Higgins, Signy, Forster, Mawson, and Davis, on the Antarctic coast. A higher degree of redundancy here is vital, inasmuch as data dropouts are more common than at more accessible latitudes (P. Woodworth, 1997, priv. comm.). Data collected from Indonesian gauges (e.g., Benoa, Padang, Surabaya, Bitung, Meneng) should be updated and added to international sea level data bases.

The distribution of tide gauges with long records (Table 10) provides good coverage of western Europe, North America, Japan, and moderately good coverage of Australia and the Pacific Islands, but very sparse coverage of Africa and South America. A number of stations in these latter two continents should be maintained and improved. While present-day records from these stations are still too short for long-term observations, they could become useful in the future, if data continue to be collected. Such stations include Port Nolloth, Simon's Bay, (South Africa), and Walvis Bay, (Namibia).

The Pacific coast of South America may present problems because of ongoing tectonic activity (this problem applies to the entire circum-Pacific "belt of fire" as well), thus the need for more GPS receivers in this region, to filter out the tectonic signal. The Atlantic coast of South America is a relatively-stable passive margin. Stations from this region with currently short records that could eventually be considered for long-term observations include Mar del Plata, Cananeia, and Recife. (Palermo and Montevideo are other possible candidates, but are lower in priority because of their proximity to Buenos Aires, which is already on the list--see Table 10).

Because of its good historical record in an otherwise data-poor region, the Aden tide-gauge should continue to be maintained and its record updated. The last year of record in the PSMSL RLR dataset is 1969. Similarly, the gauge at Santa Cruz de Tenerife, which was out of order since 1990, should be repaired and maintained. Figure 10 shows the location of additional stations recommended to fill major gaps in data coverage for the proposed sea level network.

SUMMARY AND CONCLUSIONS

This report outlines the elements of the in-situ component of a sea level network, as part of an integrated system for monitoring and predicting climate variability and change on seasonal to centennial time-scales. Drawing upon the findings of the OOSDP, OOPC, and CLIVAR, this study has defined a suite of key science issues in which in-situ sea level observations play an important role. These include monitoring of: 1) tropical ocean variability and predictability (e.g., ENSO, Indian Ocean and Asian-Australian monsoons, tropical Atlantic variability), 2) extratropical gyres and circulation (e.g., NAO, north Pacific variability), 3) high latitude circulation, 4) narros straits and "chokepoints", 5) western boundary currents, 6) long-term sea-level rise, 7) satellite altimeter calibration, 8) model validation, and 8) sea level impacts and applications.

A systematic rationale has been developed to evaluate high-quality tide-gauge stations. Candidate stations are rated on the basis of a set of criteria which include scientific relevance and uniqueness of site, record length and completeness, temporal resolution, overall data quality, timeliness of data distribution, and GPS connections. Logistics and ancillary data are also considered but not rated. The results are summarized in Tables 2-12, Appendix A.2, A.3, and Figs. 9, 10. Stations are grouped into two major categories: 1) Current high quality gauges for each science task; 2) other important stations which need upgrading. Figure 9 shows the distribution of current high quality gauges. Suggested upgrades include accumulation of further data from currently data-poor tropical islands (Tables 3, 4, bottom), stations at high latitudes (Table 7, bottom), and from narrow straits (Table 8, bottom), also addition of more stations into a timely-response system, improvements in gauge instrumentation, and deployment of GPS instruments at additional sites with long records (e.g., Table 10). These sites are shown in Figure 10. Additional recommended coastal stations from data-poor regions in Africa and South America are also shown in Fig. 10.

Further discussion is needed on a number of topics. These should be taken up by the proposed Sea Level Scientific Working Group (This Workshop--Recommendations). Suggested topics include the following:

* Development and implementation of the operational network.

* Assessment of logistical considerations for remote locations.

* Determination of the optimal number and location of stations for each science goal.

* Prioritization of stations to be equipped with GPS receivers.

* Provision of a mechanism for integrating the in-situ sea level network with satellite altimetry and geodetic installations.

* Provision of a mechanism for ongoing review of the network design and implementation of future modifications to the network in light of scientific advances.

* Provision of a mechanism for continual monitoring and periodic updating of global and regional sea level trends.

REFERENCES

Arief, D., and Murray, S.P., 1996. Low-frequency fluctuations in the Indonesian throughflow through Lombok Strait. J. Geophys. Res., 101, 12,455-12,464.

Bray, N.A., Hautala, S., Chong, J., and Pariwono, J., 1996. Large-scale sea level, thermocline, and wind variations in the Indonesian throughflow region. J. Geophys. Res., 101, 12,239-12,254.

Cane, M. A., Kaplan, A., Miller, R.N., Tang., B., Hackert, E.C., and Busalacchi, A.J., 1996. Mapping tropical Pacific sea level: Data assimilation via a reduced state space Kalman filter. J. Geophys. Res., 101, 22,599-22,617.

Carter, W.E., ed., 1994. Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee. NOAA Tech. Report NOSOES0006, 81p.

Carton, J.A., 1997. See-saw sea. Nature, 385, 487-489.

Chelton, D,B, and Enfield, D.B., 1986. Ocean signals in tide gauge records. J. Geophys. Res., 91, 9081-9098.

Clarke, A.J. and Liu, X., 1994. Interannual sea level in the northern and eastern Indian Ocean, J. Phys. Ocean., 24, 1224-1235.

CLIVAR Scientific Steering Group, 1995. CLIVAR--A study of climate variability and predictability. Science Plan. WCRP-89; WMO/TD No. 690, 157p.

CLIVAR, 1996. U.S. Ocean CLIVAR Implementation Planning Report, San Antonio, TX, June 10-12, 1996. Draft version 3, Oct. 11, 1996.

CLIVAR Initial Implementation Plan. Ed.: CLIVAR Scientific Steering Group, WCRP No. 103, WMO/TD No. 869, ICPO No. 14, in press. (http://www.clivar.ucar.edu/climp.html).

Conrad, C.P. and Hager, B.H., 1997. Spatial variations in the rate of sea level rise caused by the present-day melting of glaciers and ice sheets. Geophys. Res. Lett., 24, 1503-1506.

Davis, J.L. and Mitrovica, J.X., 1996. Glacial isostatic adjustment and the anomalous tide gauge record of eastern North America, Nature, 379, 331-333.

Delworth, T., Manabe, S., and Stouffer, R.J., 1993. Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. J. Clim., 6, 1993-2011.

Delworth, T., Manabe, S., and Stouffer, R.J., 1997. Multidecadal climate variability in the Greenland Sea and surrounding regions: a coupled model simulation. Geophys. Res. Lett., 24, 257-260.

Dickson, R., 1997. From the Labrador Sea to global change. Nature, 386, 649-650.

Dickson, R.R., Meincke, J., Malmberg, S.A., and Lee, A.J., 1988. The "Great Salinity Anomaly" in the northern North Atlantic, 1968-82. Prog. Oceanogr. 20, 103-151.

Douglas, B., 1991. Global sea level rise. J. Geophys. Res., 96, 6981-6992.

Douglas, B., 1992. Global sea level acceleration. J. Geophys. Res., 97, 12,699-12,706.

Enfield, D.B. and Harris, J.E., 1995. A comparative study of tropical Pacific sea surface height variability: tide gauges versus the National Meteorological Center data-assimilating ocean general circulation model, 1982-1992. J. Geophys. Res., 100, 8661-8675.

Ezer, T., Mellor, G.L., and Greatbatch, R.J., 1995. On the interpentadal variability of the North Atlantic Ocean: Model simulated changes in transport, meridional heat flux and coastal sea level between 1955-1959 and 1970-1974. J. Geophys. Res., 100, 10,559-10,566.

Fu, L. L. and Cheney, R.E., 1995. Applications of satellite altimetry to ocean circulation studies: 1987-1994. Rev. Geophys., 32, Suppl., 213-223.

GLOSS, 1997. Gloss Implementation Plan 1997, presented at the Fifth Session of the IOC Group of Experts on the Global Sea-Level Observing System (GLOSS), Pasadena, California, Mar. 19-21, 1997.

Gornitz, 1991. Global coastal hazards from future sea level rise. Glob. Planet. Change, 89, 379-398.

Gornitz, V., 1995a. Monitoring sea level changes. Clim. Change 31, 515-544.
Gornitz, V., 1995b. A comparison of differences between recent and late Holocene sea level trends from eastern North America and other selected regions. J. Coast. Res. Spec. Issue 17, p. 287-297.
Gornitz, V. and Solow, A., 1991. Observations of long-term tide-gauge records for indications of accelerated sea-level rise. In: Greenhouse-gas-induced Climatic Change: A Critical Appraisal of Simulations and Observations, M.E. Schlesinger (ed.), Elsevier Science Publ., Amsterdam, pp. 347-367.
Gregory, J.M., 1993. Sea level changes under increasing atmospheric CO_2 in a transient coupled ocean-atmosphere GCM experiment. J. Climate, 6, 2247-2262.
Griffies, S.M. and Bryan, K., 1997. Predictability of North Atlantic multidecadal climate variability. Science, 275, 181-184.
Groger, M. and Plag, H.-P., 1993. Estimations of a global sea level trend: limitations from the structure of the PSMSL global sea level data set. Glob. and Planet. Change. 8, 161-179.
Hsieh, W.W. and Bryan, K., Redistribution of sea level rise associated with enhanced greenhouse warming: a simple model study. Clim. Dyn., 12, 535-544.
Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science, 269, 676-677.
IGS/PSMSL, 1997. Proc. of IGS/PSMSL Workshop on "Methods for Monitoring Sea Level: GPS and Tide-Gauge Benchmark Monitoring, GPS Altimeter Calibration", Jet Propulsion Laboratory, Pasadena, CA, Mar. 17-18, 1997 (in press).
IOC, 1996. Joint GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC). First session, Miami, Florida, USA, Mar. 25-27, 1996. Intergovernmental Oceanographic Commission Reports of Meetings with Experts and Equivalent Bodies. GCOS Report No. 24.
IPCC, 1996a. Climate Change 1995: the Science of Climate Change. Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., eds., Cambridge University Press, Cambridge, 572p.
IPPC, 1996b. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis. Watson, R.T., Zinyowera, M.C., and Moss, R.H., eds., Cambridge University Press, Cambridge, 878p.
Kawabe, M., 1982. Branching of the Tsushima Current in the Japan Sea. Part I. Data Analysis. J. Oceanogr. Soc. Japan, 38, 95-107.
Kawabe, M. 1995. Variations of current path, velocity, and volume transport of the Kuroshio in relation with the large meander. J. Phys. Oceanogr., 25, 3103-3117.
Komar, P.D. and Enfield, D. B., 1987. Short-term sea-level changes and coastal erosion. SEPM Spec. Publ. 41, 17-27.
Lukas, R., Yamagata, T., and McCreary, J.P., 1996. Pacific low-latitude western boundary currents and the Indonesian throughflow. J. Geophys. Res., 101, 12,209-12,216.
McCartney, M., 1997. Is the ocean at the helm? Nature, 388, 521-522.
Mikolajewicz, U., Santer, B.D., and Maier-Reimer, E., 1990. Ocean response to greenhouse warming. Nature, 345, 589-593.
Mitchum, G.T., 1996. Monitoring the stability of satellite altimeters with tide gauges. J. Atm. Ocean. Tech (submitted).
Mitchum, G.T. and Wyrtki, K., 1988. Overview of Pacific sea level variability. Mar. Geol., 12, 235-245.
Mysak, L.A., Manak, D.K., and Marsden, R.F., 1990. Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an interdecadal Arctic climate cycle. Clim. Dyn., 5, 111-133.
Nicholls, R.J. and Leatherman, S.P., eds., 1995. Potential Impacts of Accelerated Sea-Level Rise on Developing Countries. J.Coast. Res. Spec. Issue No. 14, 323p.

Nerem, R.S., 1995. Measuring global mean sea level variations using TOPEX/POSEIDON altimeter data. J. Geophys. Res., 100, 25,135-25,151.
OOSDP, 1995. Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System: An Ocean Observing System for Climate. Final Report of the Ocean Observing System Development Panel, 265p.
Peltier, W.R., 1996. Global sea level rise and glacial isostatic adjustment: An analysis of data from the east coast of North America. Geophys. Res. Lett., 23, 717-720.
Pirazzoli, P.A., 1993. Global sea-level changes and their measurement. Glob. and Planet. Change, 8, 135-148.
Polovina, J.J. and Mitchum, G.T., 1992. Variability in spiny lobster Panulirus marginatus recruitment and sea level in the northwestern Hawaiian Islands. Fishery Bull., 90, 483-493.
Polovina, J.J. and Mitchum, G.T., 1994. Spiny lobster recruitment and sea level: results of a 1990 forecast. Fishery Bull., 92, 203-205.
Roach, D., Mitchum G.T., and Wyrtki, K., 1989. Length scales of interannual sea level variations along the Pacific Margin. J. Phys. Ocean., 19, 122-128.
Rogers, J.C. and Van Loon, H., 1979. The seesaw in winter temperatures between Greenland and northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. Mon. Weath. Rev., 107, 509-519.
Scherer, W. D., 1990. In-situ Absolute Global Sea Level Monitoring: A 5-Year Implementation Plan. NOAA National Ocean Service, unpubl. manuscript.
Sturges, W., 1987. Large-scale coherence of sea level at very low frequencies. J. Phys. Ocean., 17, 2084-2094.
Thompson, 1990. North Atlantic sea level and circulation, in *Sea-Level Change*, NRC, Nat'l Acad. Press, Washington, D.C., pp. 52-62.
Tokmakian, R., 1996. Comparisons of time series from two global models with tide-gauge data. Geophys. Res. Lett., 23, 3759-3762.
Trenberth, K. E. and Hurrell, J.W., 1994. Decadal atmosphere-ocean variations in the Pacific. Clim. Dyn., 9, 303-319.
Tsimplis, M.N., Flather, R.A., and Vassie, J.M., 1994. The North Sea pole tide described through a tide-surge numerical model. Geophys. Res. Lett., 21, 449-452.
White, W.B. and Peterson, R.G., 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. Nature, 380, 699-702.
Woodworth, P.L., 1987. Trends in U.K. mean sea level. Mar. Geodesy, 11, 58-87.
Woodworth, P.L., 1990. A search for accelerations in records of European mean sea level. Intl. J. Clim., 10, 129-143.
Woodworth, P.L., 1991. The Permanent Service for Mean Sea Level and the Global Sea Level Observing System. J. Coast. Res., 7, 699-710.
Woodworth, P.L., Vassie, J.M., and Hughes, C.W., 1996. A test of the ability of TOPEX/POSEIDON to monitor flows through the Drake Passage. J. Geophys. Res., 101, 11,935-11,947.
Wyrtki, K., 1987. Indonesian through flow and the associated pressure gradient. J. Geophys. Res., 92, 12,941-12,946.
Yamashiro, T. and Kawabe, M., 1996. Monitoring of position of the Kuroshio axis in the Tokara Strait using sea level data. J. Oceanog., 52, 675-687.
Zebiak, S.E. and Cane, M., 1987. A model ENSO. Mon. Wea. Rev., 115, 2262-2278.

Table 1a. Selection matrix with weight factors for science goals 1-8. Seasonal to decadal time-scales.

Goals:	1a1	1b1	1c	2a1	2b1	3	4a1	5a1	8
Criteria:									
1. Location	5	5	5	5	5	5	5	5	2
2. Record length & completeness	4	3	3	4	4	3	3	3	3
3. Temporal resolution	5	5	4	4	4	4	4	4	4
4. Data quality	4	4	4	4	4	4	4	4	4
5. Satellite geodesy	0	0	0	0	0	4	0	0	4
6. Data timeliness	4	4	3	3	3	3	3	3	3

Key:

0=Not relevant
1=Low importance
2
3=Medium importance
4
5=High importance

Table 1b. Selection matrix with weight factors for science goals 1-6. Multidecadal to centennial time-scales.

Goals:	1a2	1b2	2a2	2b2	4a2	5a2	6
Criteria:							
1. Location	5	5	5	5	5	5	2
2. Record length & completeness	4	3	4	4	3	3	5
3. Temporal resolution	2	2	2	2	2	2	0
4. Data quality	4	4	4	4	4	4	4
5. Satellite geodesy	0	0	0	0	0	0	4
6. Data timeliness	0	0	0	0	0	0	0

Key:

0=Not relevant
1=Low importance
2
3=Medium importance
4
5=High importance

Table 2a. Stations for ENSO--seasonal to decadal variability.

Existing high quality stations

Majuro	Kwajalein	Pago Pago
Malakal	Pohnpei	Wake
Honiara	Papeete	Honolulu
Kanton	Rarotonga	San Diego
Christmas	Penrhyn	Suva
Rikitea	Funafuti	Nauru
Noumea	Saipan	Hilo
Guam	Santa Cruz	Cabo San Lucas
Johnston Is.		

Other important stations which need upgrading

Kapingamarangi	Balboa	Caldera
Easter Island	Arica	Callao
Truk	Quepos	

Table 2b. Stations for ENSO--multidecadal to centenntial variability.

Existing high quality stations

Guam	Wake	Legaspi
Kwajalein	Honolulu	Davao
Johnston Is.	Balboa	
Pago Pago	San Diego	

Other important stations which need upgrading

Majuro	Kanton	Truk
Malakal	Papeete	Hilo
Honiara	Rikitea	Antofagasta
Christmas Is.	Noumea	

Table 3a. Stations for Indian Ocean and Asian-Australian Monsoons--seasonal to decadal variability

Existing high quality stations

Mombasa	Diego Garcia	Darwin
Cocos Is.	Rodrigues	Male-B, Hulule
Gan (Maldives)	Port Louis	
Zanzibar	Salalah	

Other important stations which need upgrading

Bombay	Vishakhapatnam	Legaspi
Aden	Ko Lak	Davao
Cochin	Ko Sichang	Port Victoria (Seychelles)

Table 3b. Stations for Indian Ocean and Asian-Australian monsoons--multidecadal-centennial variability.

Existing high quality stations

Bombay	Legaspi	Ko Sichang
Aden	Davao	Karachi
Cochin	Ko Lak	
Vishakhapatnam		

Other important stations

Saugor	Diamond Harbor	Jolo
Kandla	Calcutta	

Table 5a. Stations for the North Atlantic Oscillation--seasonal to decadal variability.

Existing high quality stations

Lerwick	Cascais	Aberdeen II
Bermuda	Montauk	Funchal
Key West	Portland	New York City
Newlyn	Brest	Wilmington
Halifax	Barentsburg	Boston
St. John's, NFLD	Torshavn	Charlottetown
Fernandina	Esbjerg	Godthab/Nuuk
Charleston		

Other important stations which need upgrading

Reykjavik	Heimsjo	Marseille
Ny Alesund	Bergen	Genoa
Santa Cruz-Tenerife	Stavanger	Trieste
Ponta Delgada	Narvik	Tuapse

Table 5b. Stations for North Atlantic Oscillation--multidecadal to centennial variability.

Existing high quality stations

Barentsburg	Halifax	New York City
Bermuda	Lerwick	Boston
Key West	Santa Cruz-Tenerife	Charleston
Bergen	Montauk	Wilmington
Newlyn	St. John's, NFLD	Charlottetown
Esbjerg	Heimsjo	Marseille
Brest	Aberdeen II	Genoa
Fernandina	Cascais	Trieste
Portland		Tuapse

Other important stations

Reykjavik	Narvik	Torshavn
	Godthab/Nuuk	

Table 6a. Stations for North Pacific variability--seasonal to decadal variability.

Existing high quality stations

Chichijima	Adak	Crescent City
Neah Bay	Ofunato	San Diego
Honolulu	Mera	Sitka
Midway	Ketchikan	Tofino

Other important stations which need upgrading

Attu Is.	Victoria	Seward
Kodiak	San Francisco	(Minamitorishima)

Table 6b. Stations for North Pacific variability--multidecadal to centennial variability.

Existing high quality stations

Tofino	Midway	Victoria
Neah Bay	Adak	Crescent City
Sitka	Mera	San Francisco
Honolulu	Ketchikan	San Diego

Other important stations which need upgrading

Chichijima	Seward	Ofunato
Yuzhnokurilsk	Attu Is.	Kamchatskiy

Table 7. Stations for high latitude circulation

A. Arctic

Existing high quality stations

Ny Alesund	Godthab/Nuuk	Narvik
Reykjavik	Barentsburg	

Other important stations

Prudhoe Bay	Tuktoyaktuk	Russkaya Gavan
Nain	Torshavn	Murmansk

B. Antarctic

Existing high quality stations

Faraday		

Other important stations

Kerguelen Is.	Diego Ramirez	Syowa
Macquarie Is.	Bahia Esperanza	Ushuaia
	Casey	

Table 8a. Stations for narrow straits and chokepoints--seasonal to decadal variability.

Existing high quality stations

Key West	Miami Beach	Ceuta
Faraday	Diego Ramirez	Fernandina
Settlement Point	Darwin	

Other important stations which need upgrading

Benoa (Lombok Str.)	Gibraltar	Meneng
Ushuaia	Bitung	Padang
Bahia Esperanza	Surabaya	Port Hedland
	Cilicap	

Table 8b. Stations for narrow straits and chokepoints--multidecadal to centennial variability.

Key West	Faraday	Settlement Point
Miami Beach	Fernandina	

Table 9a. Stations for western boundary currents--seasonal to deacadal variability.

Existing high quality stations

Kushimoto	Settlement Point	Nishinoomote
Aburatsu	Naha	Pusan
Key West	Charleston	Legaspi
Bermuda	Maisaka	Davao
Fernandina	Miyakejima	Recife
	Wilmington	

Other important stations needing upgrading

Naze	Jolo	(Cayenne)
Hakata	Izuhara	(Uragami)
Odomari	(Fortaleza)	(Hachijojima)
	(Manus Is.)	

Table 9b. Stations for western boundary currents--multidecadal to centennial variability.

Existing high quality stations

Key West	Kushimoto	Wilmington
Bermuda	Aburatsu	Maisaka
Fernandina	Pusan	Nishinoomote
Legaspi	Recife	Jolo
Davao	Charleston	

Other important stations

Miyakejima	Odomari	Naze
Naha	Hakata	Izuhara
	(Fortaleza)	

Table 10. Stations for long-term sea level rise.

High quality stations

Goteborg	Hampton Roads	Charleston
Stockholm	Fremantle	Buenos Aires
Auckland	Helsinki	Daugavgriva
Honolulu	Guam	Neah Bay
Victoria	Kwajalein	Marseille*
Key West	Trieste	Santa Cruz de Tenerife
Bermuda	San Francisco*	Mera*
San Diego	New York City*	Reykjavik

Other important stations

Sydney*	Brest*	Aburatsubo
Manila	Cascais*	Ketchikan
Narvik	Genova*	Quequen
Vancouver*	Bombay*	Pensacola
Boston*	Tonoura*	Fernandina*
Portland*	Wajima	Halifax*
Liepaja	Lyttleton II	Aden*
Wismar*	Crescent City	Vishkhapatnam
Esbjerg*	Balboa	Ko Lak
Cuxhaven	Cristobal	Takoradi*
Aberdeen II*	Atlantic City	Xiamen
N. Shields	Bergen*	Cartagena
Newlyn*	Tuapse*	

* Additional GPS receivers should be deployed at selected key stations. Reference page 36, discussion of satellite geodesy linkages.

Table 11. Rating of stations for altimeter calibration (after G. Mitchum).

STATION	LAT.	LONG.	SIG	IGS	CORS
	Latitude Range 60°S to 30°S				
Hobart	-42.88	147.3	102	12.3	x
Diego Ramirez	-56.51	291.3	85	x	x
Valparaiso	-33.03	288.4	78	90.8	x
Kerguelen	-49.35	70.2	67	2.7	x
Chatham Island	-43.95	183.4	63	1.1	x
Juan Fernandez	-33.62	281.2	46	x	x
	Latitude Range 30°S to 10°S				
Easter Island	-27.15	250.6	65	6.5	x
Port Louis	-20.16	57.5	57	x	x
Pago Pago	-14.28	189.3	42	x	x
Nuku'alofa	-21.13	184.8	39	x	x
Papeete	-17.52	210.4	30	4.7	x
St. Helena	-15.97	354.3	21	x	x
	Latitude Range 10°S to 10°N				
Christmas Island	1.99	202.5	45	x	x
Santa Cruz	-0.75	269.7	40	1.5	x
Point la Rue	-4.67	55.5	37	5.5	x
Diego Garcia	-7.29	72.4	31	3.5	x
Kwajalein	8.73	167.7	29	1.3	x
Ascension Island	-7.90	345.6	25	6.5	x
	Latitude Range 10°N to 30°N				
Las Palmas	28.15	344.6	68	48.2	x
Key West	24.55	278.2	59	x	x
Guam	13.43	144.6	52	29.3	x
Johnston Island	16.75	190.5	50	x	x
Cabo San Lucas	22.88	250.1	47	x	x
Honolulu	21.31	202.1	35	x	x
	Latitude Range 30°N to 60°N				
Neah Bay	48.37	235.4	107	83.5	x
Kodiak Island	57.73	207.5	95	x	22.8
Kushiro	42.97	144.4	63	x	x
Flores, Azores	39.45	328.9	62	x	x
Bermuda	32.37	295.3	58	0.1	x
San Diego	32.72	242.8	54	18.1	8.4

Table 12. Stations for model validation

Existing high quality stations		
Guam	Chichijima	Mera
Kwajalein	Hilo	Victoria
Honolulu	Pago Pago	Neah Bay
Key West	Diego Garcia	Montauk
Bermuda	Cocos Is.	Newlyn*
San Diego	Charleston	Halifax*
	St. John's, NFLD	

Other important stations		
New York City*	Midway	Tofino
Lerwick*	Johnston Is.	Boston*
Port Victoria (Seychelles)	Adak	Reykjavik
		Casais*

* Additional GPS receivers should be deployed at selected key stations. Reference page 36, discussion of satellite geodesy linkages.

Figure Captions

Figure 1.	Distribution of tide-gauge stations from the PSMSL Revised Local Reference (RLR) dataset with record lengths: (a) > 20 years; (b) > 40 years; (c) > 60 years.
Figure 2.	Present and planned satellite altimetry missions (after GLOSS, 1997).
Figure 3a.	TOPEX/Poseidon annual anomaly for sea surface topography for each of four years.
Figure 3b.	Comparison of time series of monthly mean sea level from Christmas Is. (top) and Baltra (bottom) with sea surface heights from TOPEX/Poseidon. (cc=0.94, rms+17mm, Christmas Is-T/P; cc=0.91, rms=20mm, Baltra-T/P; after C. Koblinsky, NASA GSFC).
Figure 4.	ENSO events recorded in annual mean detrended sea level data, eastern Pacific Basin (1935-1995); south (top) to north (bottom). Major ENSO years: 1941, 1958, 1969, 1972, 1983, 1987-88, 1992. (Sea level data from PSMSL).
Figure 5.	Map of North Atlantic basin, showing correlation coefficients of annual mean detrended sea level data with standardized NAO_{SST} Index (index from DeMenocal and Cullen, 1997, Lamont-Doherty Earth Observatory, priv. comm.).
Figure 6.	(Top) Tide-gauge stations potentially useful for monitoring north Pacific boundary currents, particularly the Kuroshio and Tsushima Current (M. Kawabe, 1997). (Bottom) Tide-gauge stations in Japan and environs. Those underlined are considered for inclusion in the proposed global sea level network (after M.Kawabe, 1997).
Figure 7.	Location of fixed GPS sites in the International GPS and Geophysical Service (IGS).
Figure 8.	Tide-gauge stations in the WOCE "Fast Delivery" dataset (U. Hawaii Sea Level Center).
Figure 9a.	Location of existing high-quality tide-gauge stations for science goals 1-5 seasonal to decadal time-scales.
Figure 9b.	Location of existing high-quality tide-gauge stations for science goals 1-6; multidecadal to centennial.
Figure 10.	Additional stations recommended for inclusion into the proposed sea level network.

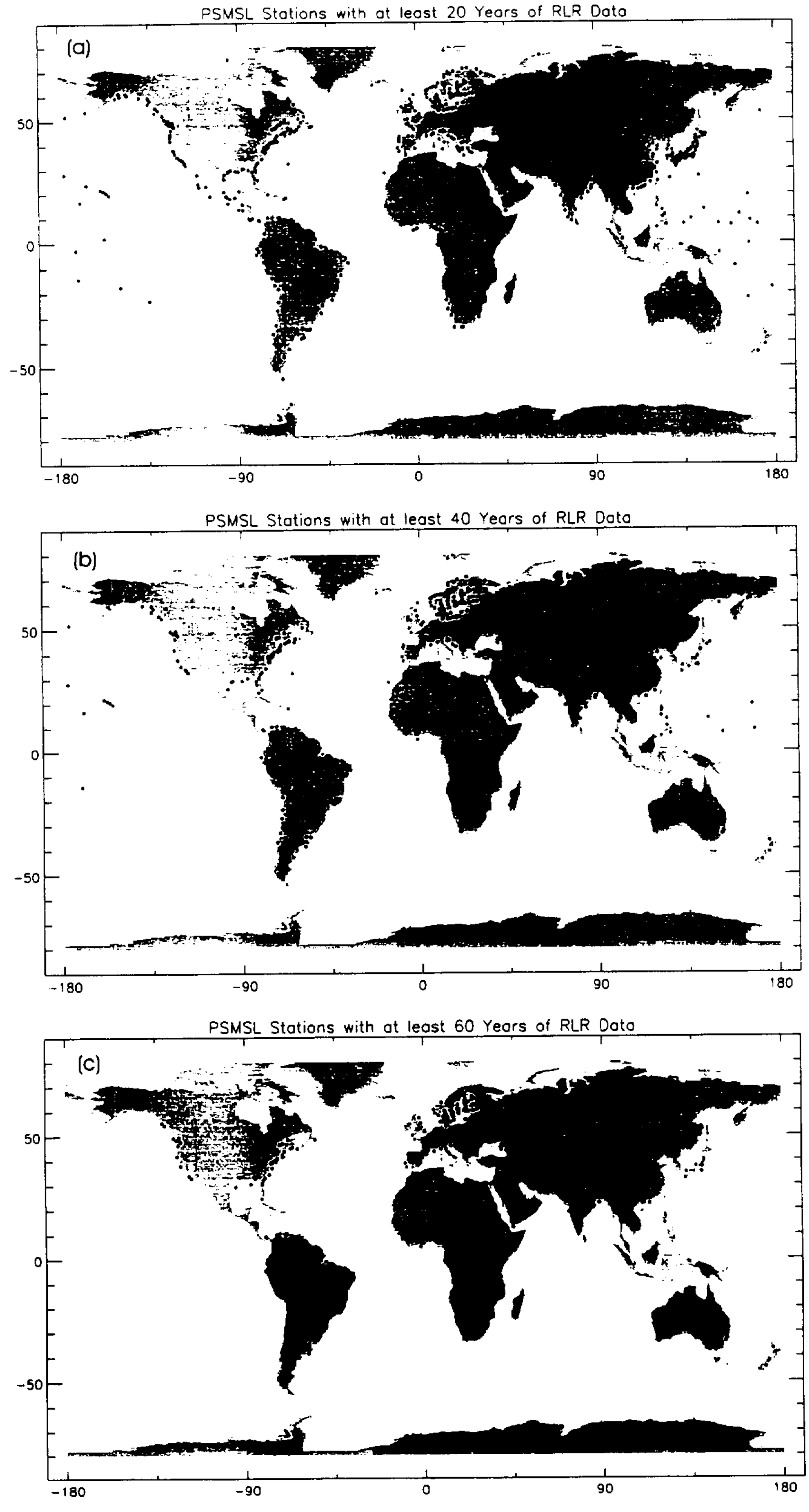


Figure 1. Distribution of tide-gauge stations from the PSMSL RLR dataset with record lengths: a) >20 years; b) > 40 years; c) >60 years.

```
          Altimeter Spacecraft: Next Decade

1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005

 ESA ERS-1
 -------------------------------->

      U.S./France TOPEX/POSEIDON
      ---------------------------------------------->

                    ESA ERS-2
                    --------------------------->

                             U.S. Navy Geosat Follow-On 1
                             ------------------------->

                                 ESA ENVISAT
                                 ------------------------------>

                                      France/U.S. TPFO-1
                                      ------------------------------>

                                                   France/U.S.   TPFO-2
                                                   ------------------>
```

Figure 2. Present and planned satellite altimetry missions (after GLOSS, 1997).

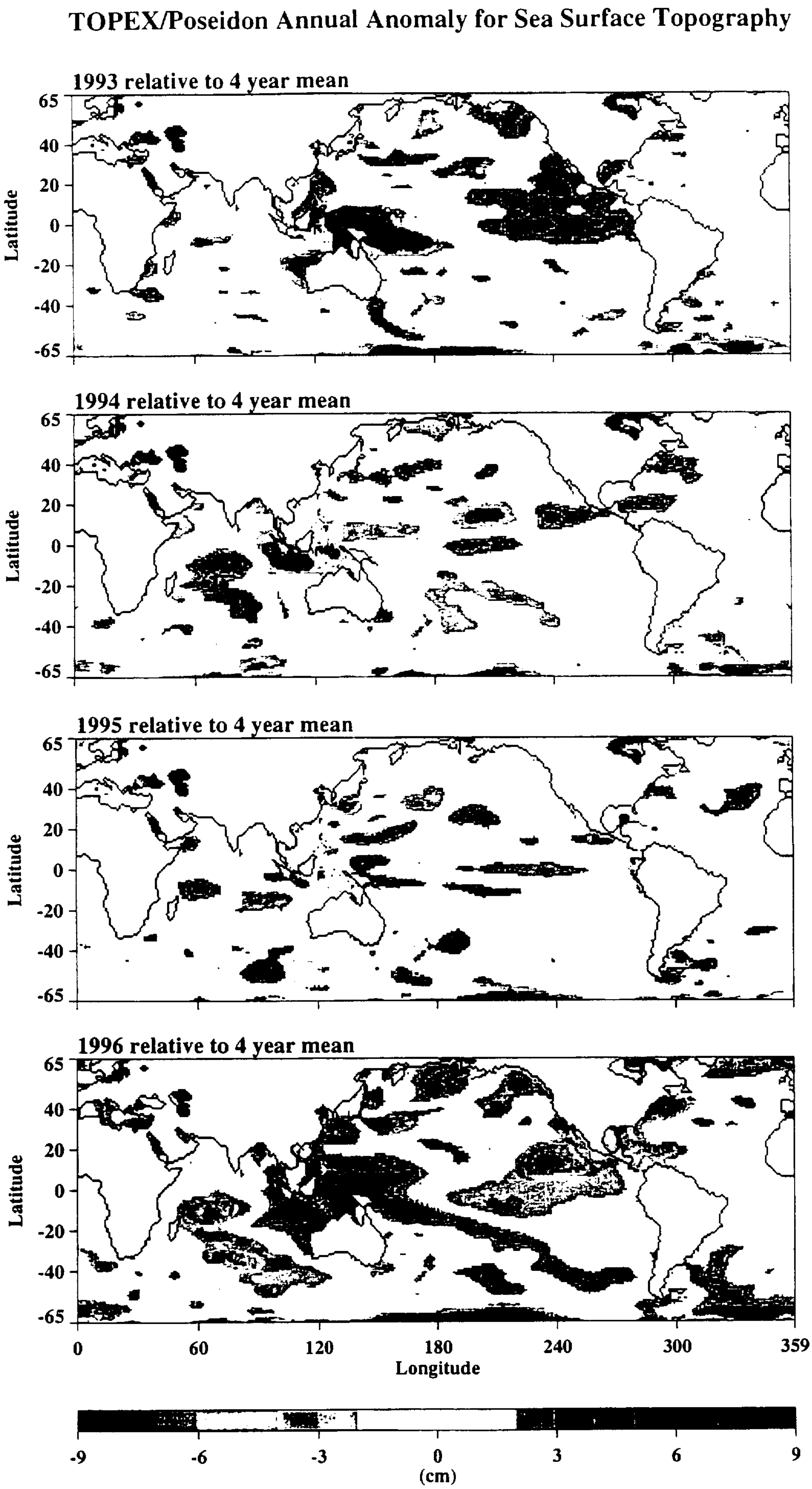


Figure 3a. TOPEX/Poseidon annual anomaly for sea surface topography for each of four years.

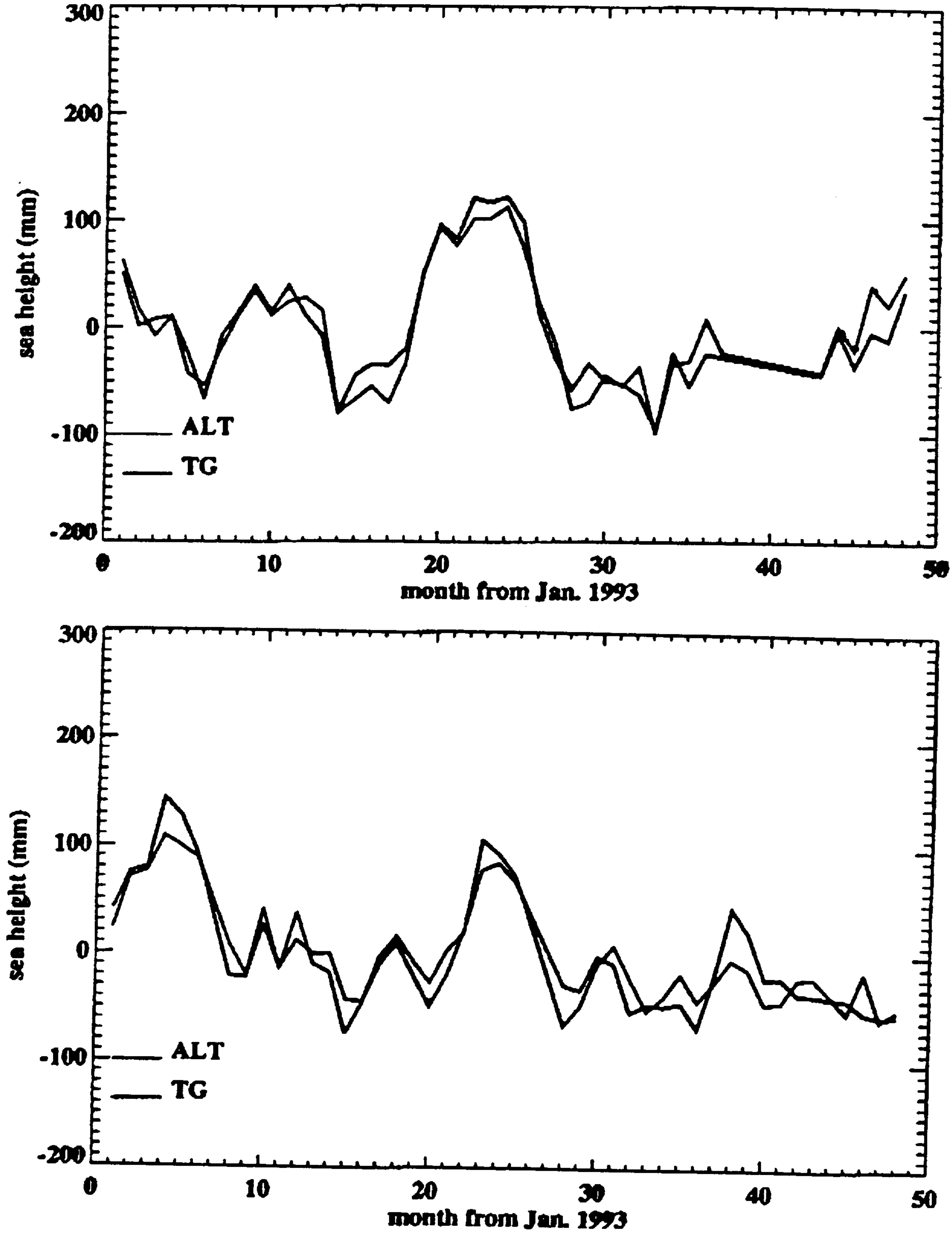


Figure 3b. Comparison of time series of monthly mean sea level from Christmas Is. (top) and Baltra (bottom) with sea surface heights from TOPEX/Poseidon. (cc=0.94, rms+17mm, Christmas Is-T/P; cc=0.91, rms=20mm, Baltra-T/P; after C. Koblinsky, NASA GSFC).

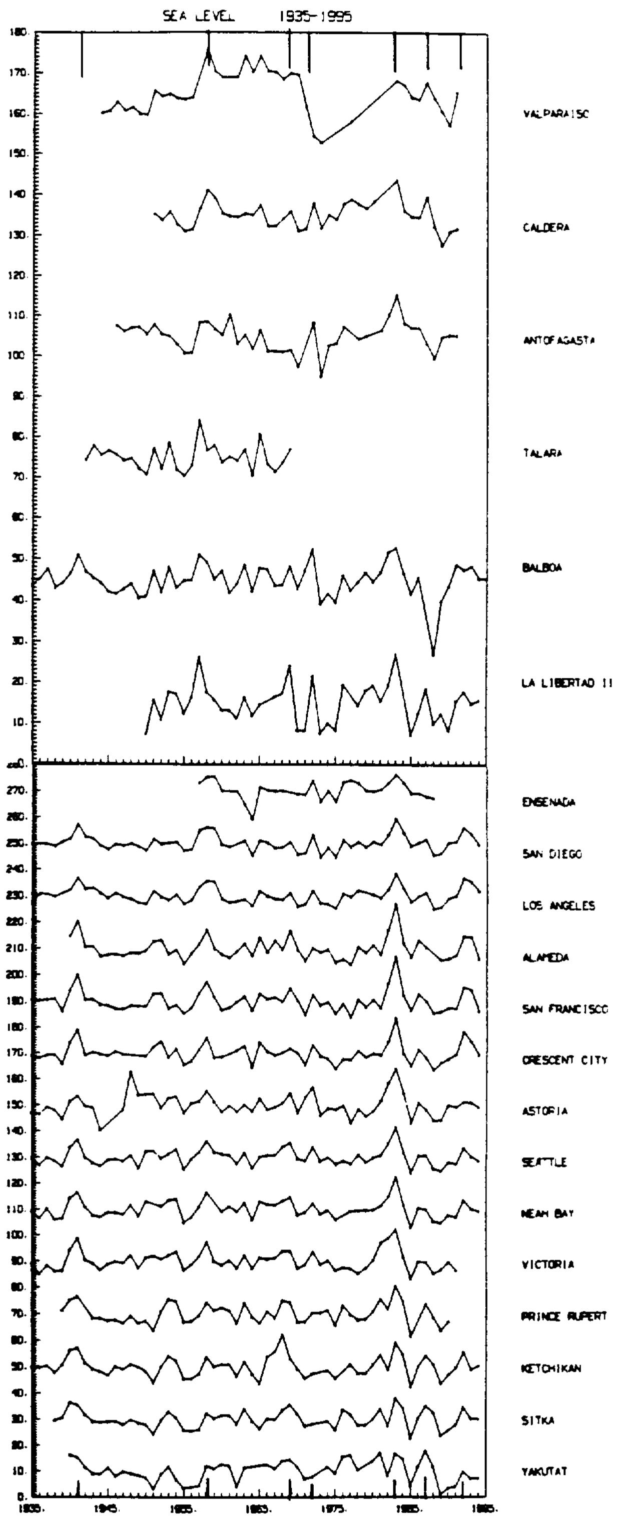


Figure 4. ENSO events recorded in annual mean detrended sea level data, eastern Pacific Basin (1935-1995); south (top) to north (bottom). Major ENSO events: 1941, 1958, 1969, 1972, 1983,1987-1988, 1992.

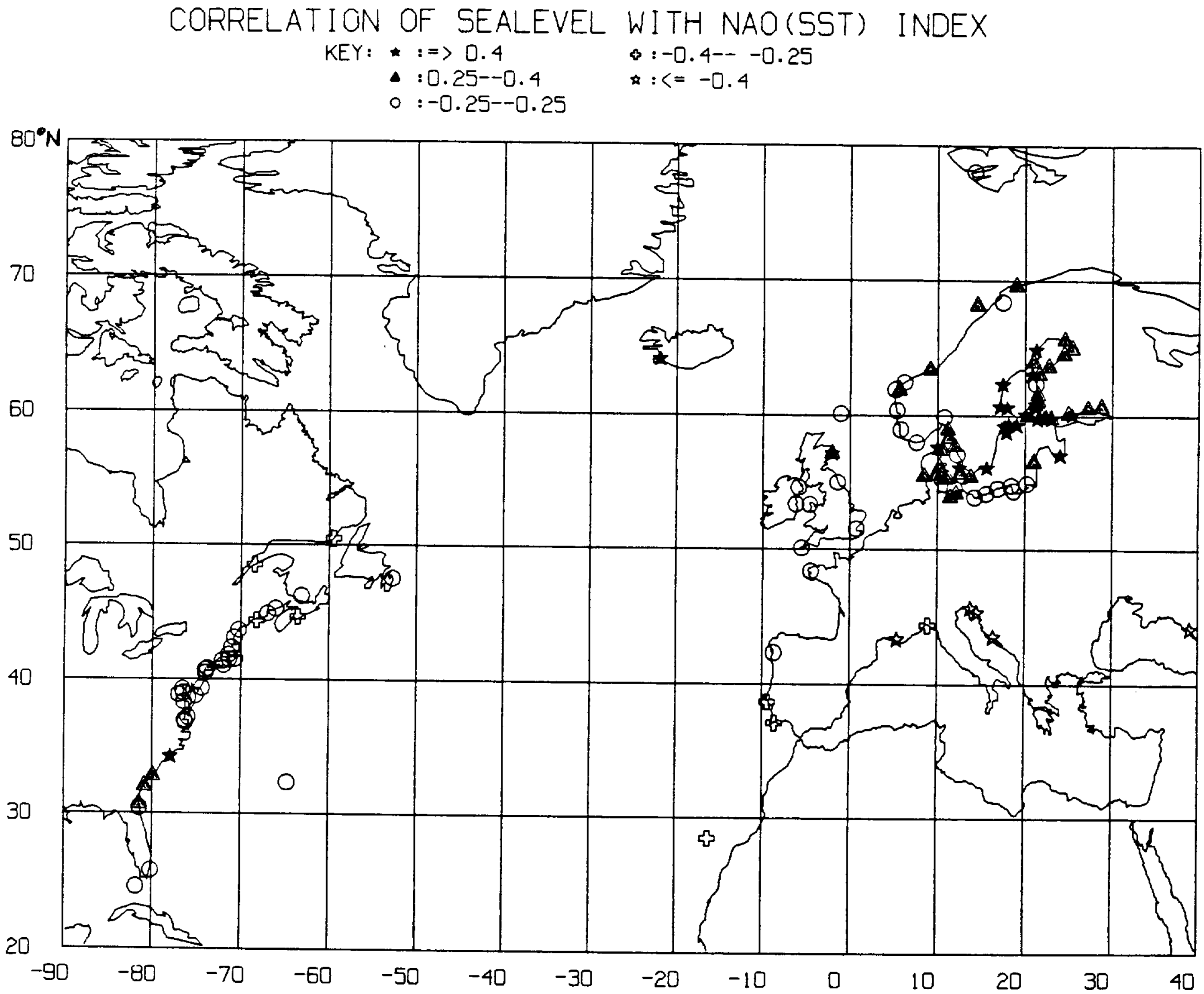


Figure 5. Map of North Atlantic basin, showing correlation coefficients of annual mean detrended sea level data with standardized NAO_{SST} Index (index from DeMenocal and Cullen, 1997, Lamont-Doherty Earth Observatory, priv. comm.).

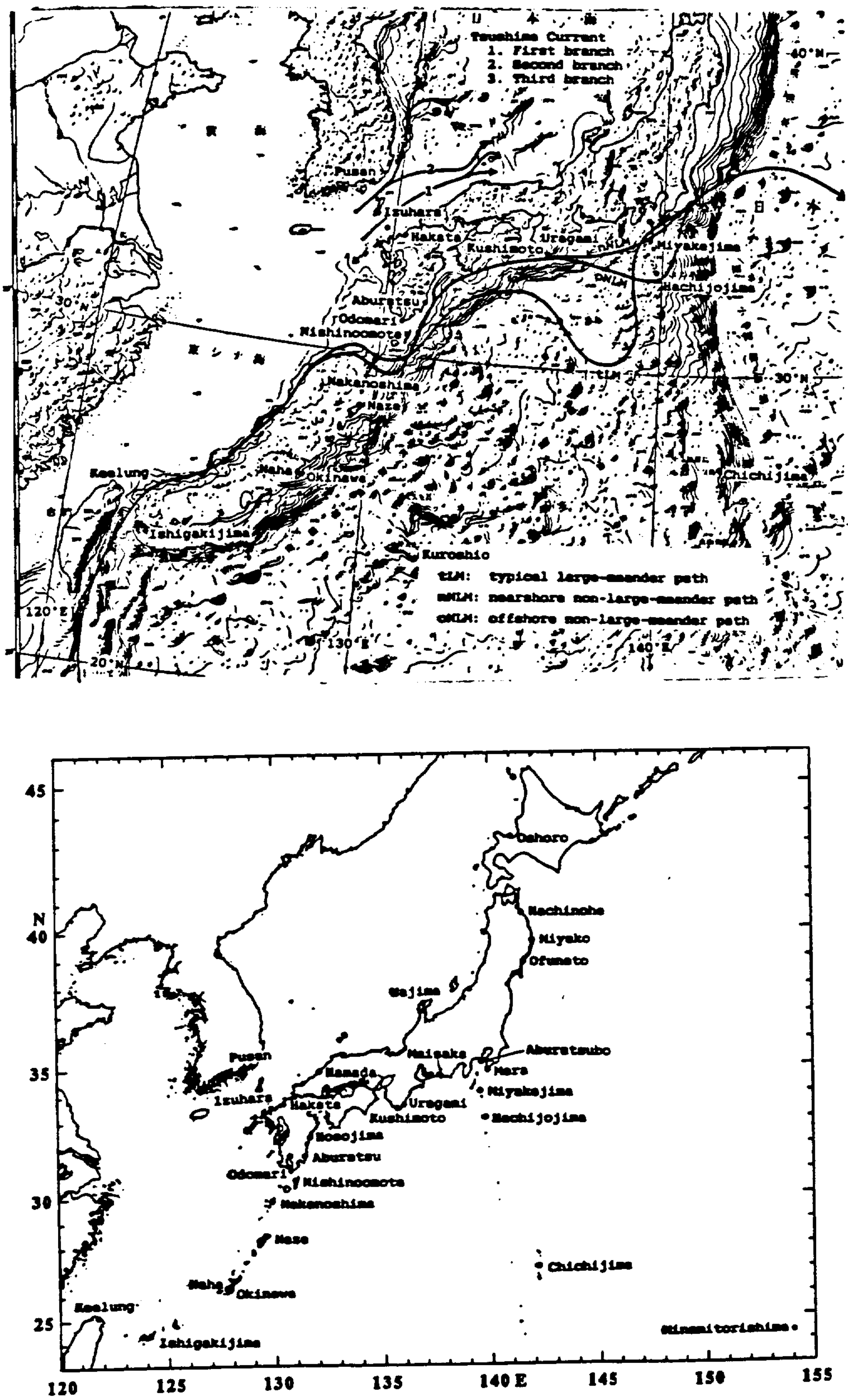


Figure 6. (Top) Tide-gauge stations potentially useful for monitoring north Pacific boundary currents, particularly the Kuroshio and Tsushima Current (M. Kawabe, 1997). (Bottom) Tide-gauge stations in Japan and environs. Those underlined are considered for inclusion in the proposed global sea level network (after M.Kawabe, 1997).

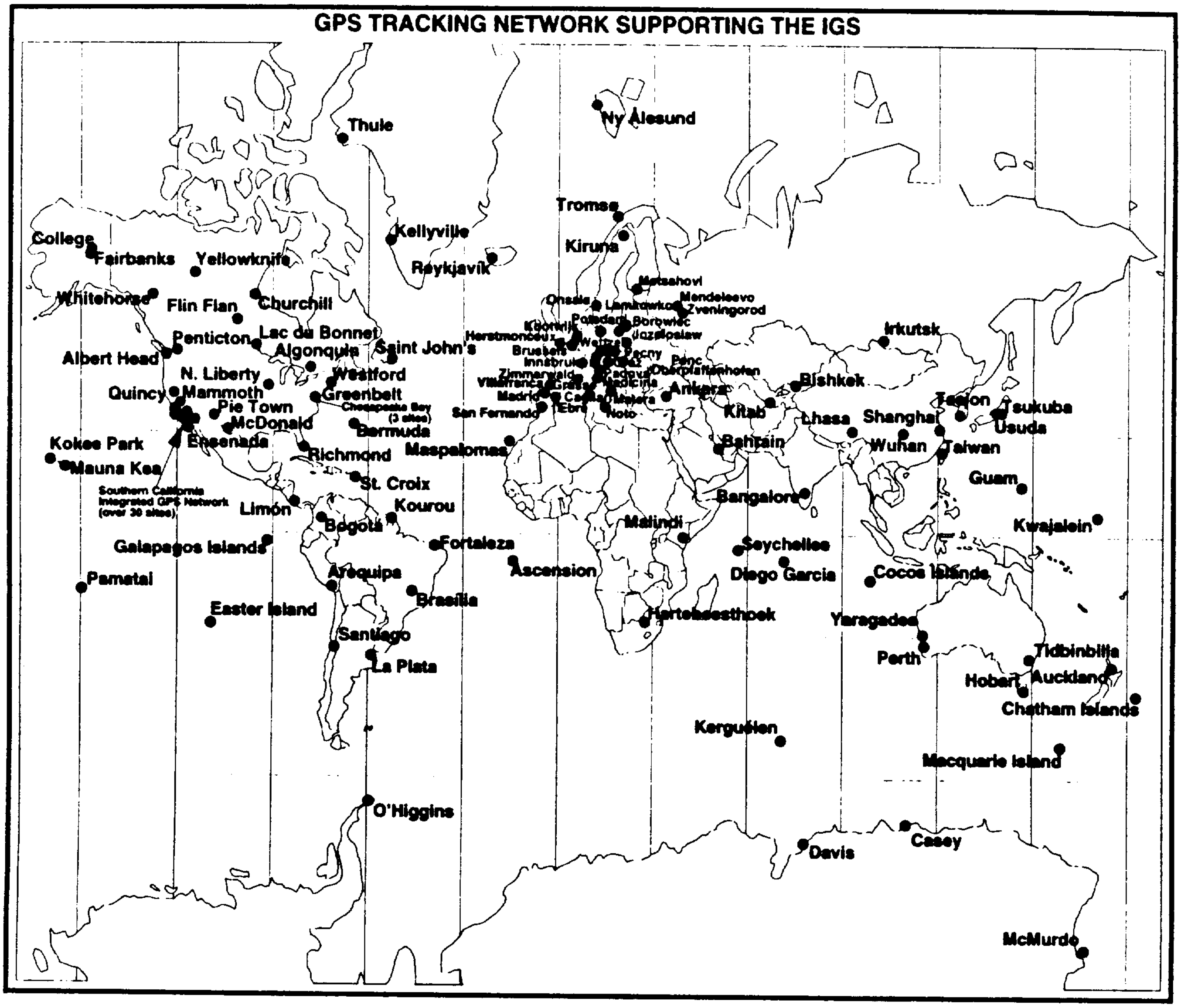


Figure 7. Location of fixed GPS sites in the International GPS and Geophysical Service (IGS).

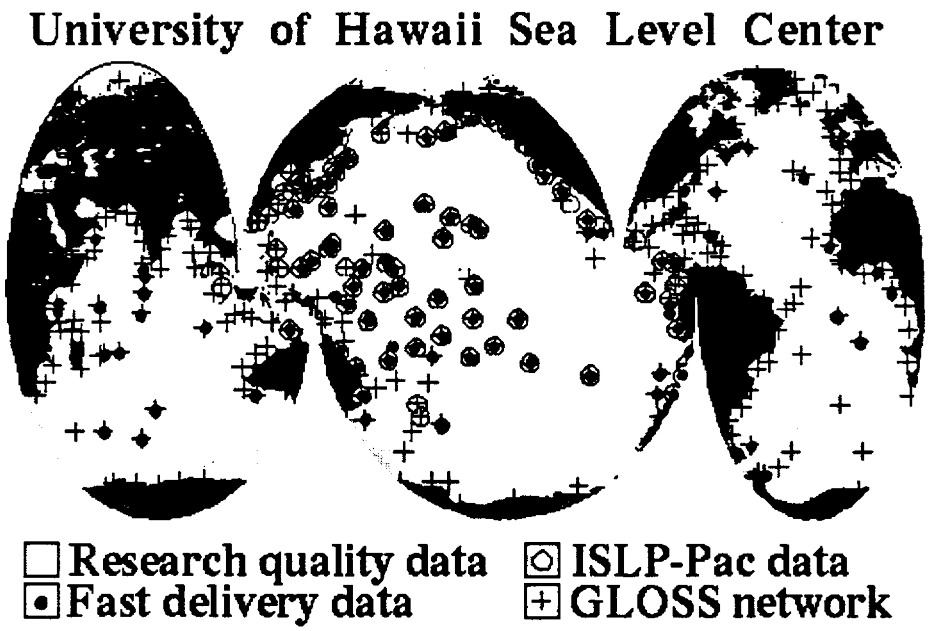


Figure 8. Tide-gauge stations in the WOCE "Fast-Delivery" dataset (black circles).

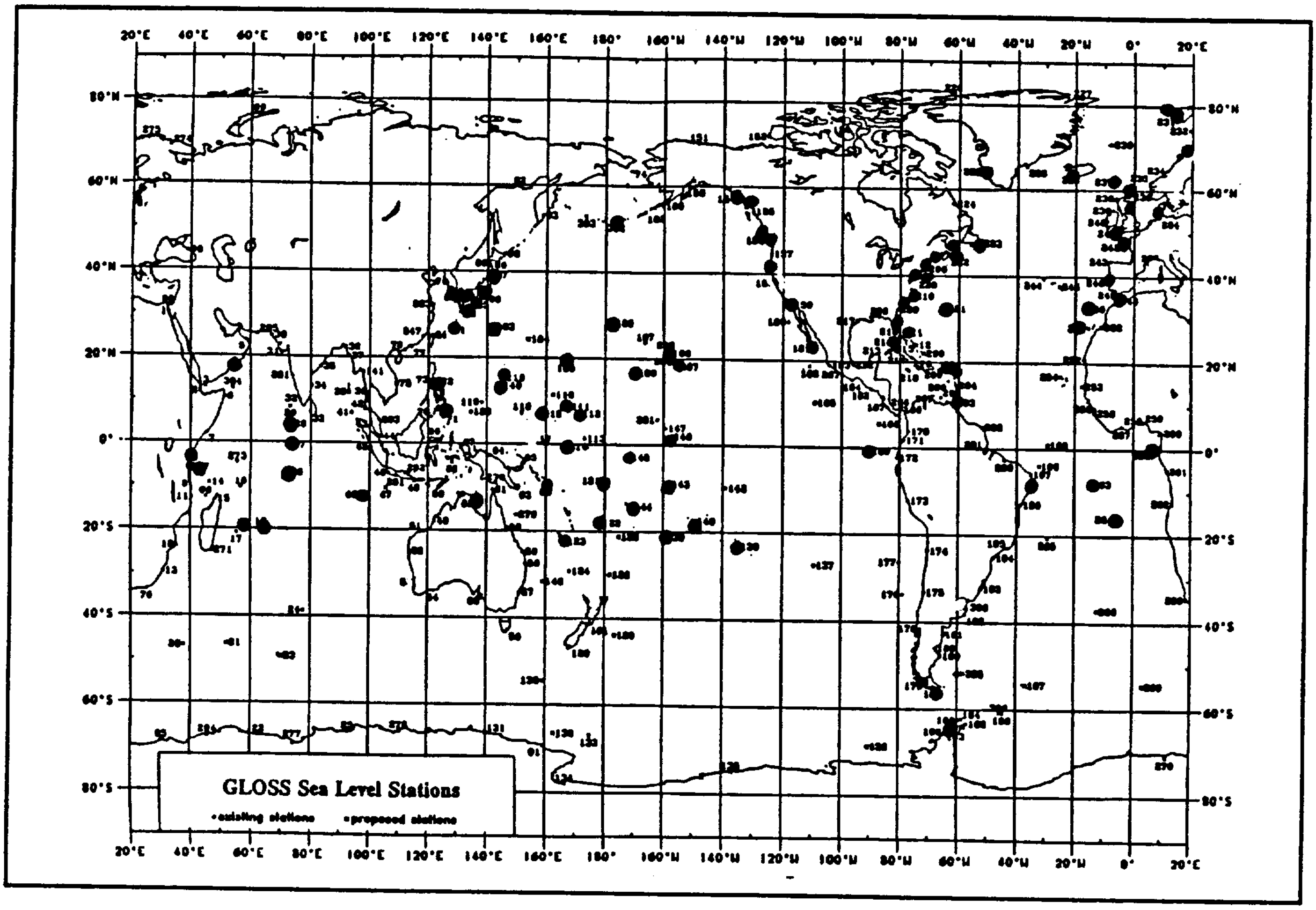


Figure 9a. Location of tide-gauge stations for science goals 1-5; seasonal to decadal time-scales.

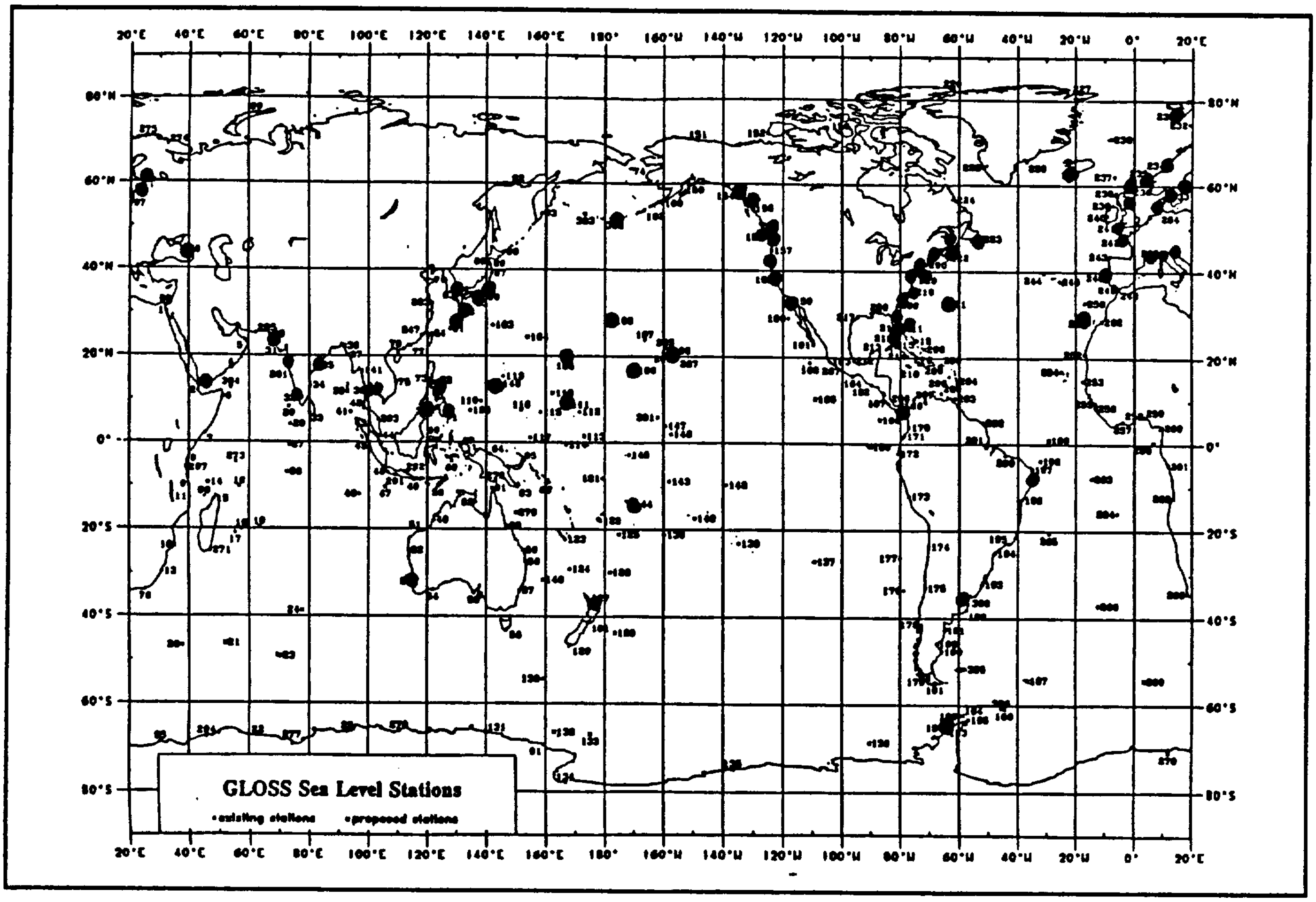


Figure 9b. Location of existing high-quality tide-gauge stations for science goals 1-6; multidecadal to centennial time-scales.

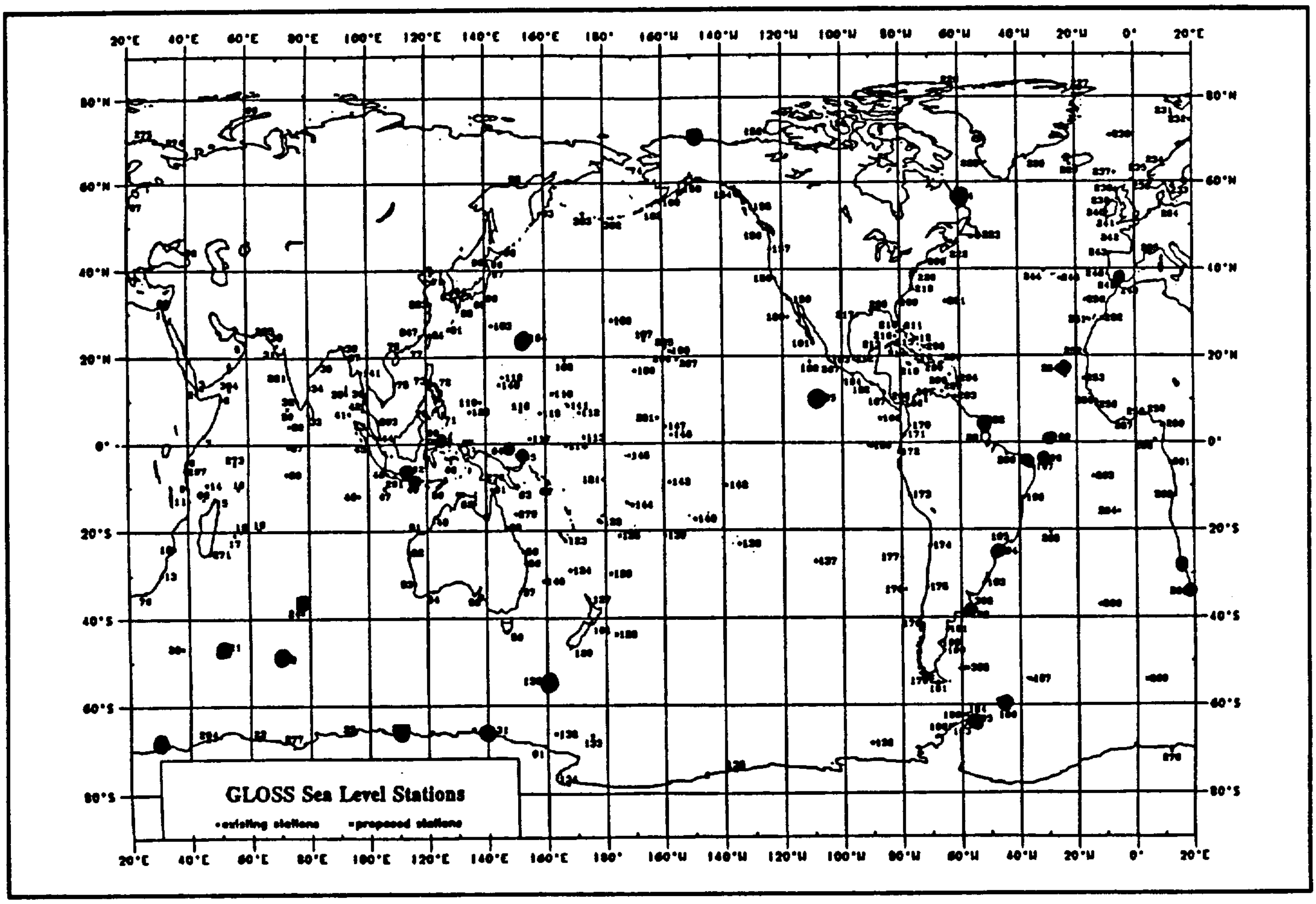


Figure 10. Additional stations recommended for inclusion into the proposed sea level network.

Appendix A.1

Sea Level Data Sets

1. Permanent Service for Mean Sea Level

The Permanent Service for Mean Sea Level (PSMSL), Bidston Observatory, U.K., collects, analyzes, interprets, and publishes sea level data from a global network of over 1700 tide gauges from more than 170 national authorities. It is supported by the Intergovernmental Oceanographic Commission (IOC), the U.K. Natural Environment Research Council, and the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

The PSMSL receives monthly and annual mean values of sea level from the worldwide network and enters the raw data directly into a "Metric" file for each station. In order to use the sea level data in a time series, the monthly and annual averages for each station are reduced to a common datum (i.e., common to all years at each station, but not among stations), by using the tide-gauge benchmark datum history supplied by the national authority (Spencer and Woodworth, 1993). The data adjusted in this manner constitute the "Revised Local Reference" or RLR dataset. The RLR dataset is the one preferred for sea level studies involving time series analysis or computation of secular trends. The distribution of tide gauges in the PSMSL RLR network is shown in Figure 1.

Data holdings from the PSMSL are available through anonymous FTP (node bisag.nbi.ac.uk; directory /pub/psmsl).

2. Global Sea Level Observing System

The Global Sea Level Observing System (GLOSS), established by the IOC in 1985, is a network of approximately 300 tide-gauge stations around the world, intended to monitor global sea level, as well as other practical applications on national to regional levels (GLOSS, 1997). Data from the GLOSS network are collected and archived at the PSMSL in the form of monthly mean values.

As of October 1996, there are a total of 308 stations in GLOSS. Of these, 186 are Category 1 ("Operational" stations, for which the latest data are 1992 or later), 46 are Category 2 ("Probably operational" stations, for which the latest data fall between 1982-1991, 21 are Category 3 ("Historical" stations, for which the latest data are older than 1982, and finally, 55 are Category 4 (for which no PSMSL data exist, but which have other data). Figure 2 shows the distribution of tide-gauge stations in the GLOSS network, by category. Some, but not all, of the GLOSS stations are in the PSMSL RLR and JASL (see below) datasets, as well.

Information about the GLOSS data holdings is given in the GLOSS Station Handbook CD-ROM (version 3.0, July, 1996), which may be obtained from the British Oceanographic Data Centre (BODC), Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA, U.K.

3. Joint Archive for Sea Level

The University of Hawaii Sea Level Center (UHSLS), Honolulu, Hawaii, supported by the National Oceanographic and Atmospheric Administration (NOAA), acquires, processes, and archives sea level data from the Tropical Ocean Global Atmosphere (TOGA) project, the Indo-Pacific Sea Level Network, the IGOSS Sea Level Program in the Pacific, and the "Fast Delivery" Data Center for the World Ocean Circulation Experiment (WOCE). Data from the TOGA program and other sea level data are stored in the Joint Archive for Sea level (JASL) at the UHSLC (Caldwell and Merrifield, 1996). As of August 1996, data from 335 stations with 4426 station-years of quality-assured data have been made available to the World Data Center-A (WDCA) for Oceanography, Washington, D.C., and to the PSMSL. A listing of stations in JASL and supporting documentation may be obtained via the Web: http://www.soest.hawaii.edu/UHSLC/. There is a significant degree of overlap between the stations in JASL and in GLOSS.

4. The World Ocean Circulation Experiment

The World Ocean Circulation Experiment (WOCE) data, consists of hourly, daily, and monthly values of sea level, mostly from GLOSS island sites, and pairs of gauges across straits, designed primarily for comparison with and validation of satellite altimetry data of sea surface heights. WOCE "fast delivery" data are available from the University of Hawaii Sea Level Center (Fig. 8). Lower frequency WOCE data are archived at the BODC next to the PSMSL, Bidston Observatory. A listing of WOCE fast delivery stations and supporting documentation may be obtained via the Web: http://www.soest.hawaii.edu/UHSLC/, fast delivery data, readme.

The WOCE "delayed mode" delivery center is operated by the British Oceanographic Data Centre (BODC, Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA, U.K.), which assembles, quality controls, and distributes the comprehensive WOCE sea level data set. As of October, 1996, 125 sites were represented, of which 117 are "operational", with data from 109 of these in the data set. Data are available via the Internet: http://www.pol.ac.uk/bodc/woce/dmsldac.html.

5. Other Sea Level Centers

The Southern Ocean Sea Level Centre, National Tidal Facility, Flinders University of South Australia, Adelaide, Australia. Web address: http://www.ntf.flinders.edu.au.

Ocean and Lake Levels Division of NOS/NOAA, Silver Spring, Maryland, U.S.A. Web address: http://www.olld.nos.noaa.gov.

References:

Caldwell, P. and Merrifield, M., 1996. Research Quality Data Holdings of the University of Hawaii Sea Level Cenerter: August 1996. SOEST-96-07; JIMAR Contrib. No. 96-307, Data Report No. 14, 41p.

GLOSS, 1997. Gloss Implementation Plan 1997, to be presented at the Fifth Session of the IOC Group of Experts on the Global Sea-Level Observing System (GLOSS), Pasadena, California, Mar. 19-21, 1997.

Spencer, N.E. and Woodworth, P.L., 1993. Data Holdings of the Permanent Service for Mean Sea Level (November 1993). PSMSL, Bidston Observatory, U.K., 81p.

Appendix A.2

Station Rating Matrices

The following matrices detail the station ratings presented in Tables 1.a - 12 of APPENDIX A: *Design of a Global Sea Level Network for Monitoring Climate Variability on Seasonal to Centennial Time Scales*. The rating rationale is explained in the section of APPENDIX A titled "Methodology for evaluation of tide-gauge stations."

SCIENCE GOAL: 1a1. ENSO Seasonal-Decadal Variability

REQUIREMENTS: **Pacific Islands +-15°N,S; West Coast America**
>=20 years = 3 pts., 19-10 years = 2 pts., < 10 years = 1 pt., 80% complete; Hr+; WOCE Fast

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**23**	**18**	**23**	**18**	**0**	**18**	
Pohnpei	1B	115	3	3	3	2	0	3	94
Nauru	4A	114	3	3	3	1	0	3	88
Majuro	5A	112	3	3	3	3	0	3	100
Malakal	7A	120	3	3	3	3	0	3	100
Honiara	9A	66	3	3	3	3	0	3	100
Christmas	11B	146	3	3	3	3	0	3	100
Kanton	13B	145	3	3	3	3	0	3	100
*Fr. Frig. Shoals	14A	107	1	3	3	3	0	3	85
Papeete	15A	140	3	2	3	3	0	3	94
Rikitea	16A	138	3	3	3	3	0	3	100
Suva, Fiji	18A	122	3	3	3	1	0	3	88
Noumea	19A	123	3	3	3	3	3	3	100
Easter	22E	137	3	1	3	2	3	3	82
Rarotonga	23A	139	3	2	3	3	0	3	94
Penrhyn	24A	143	3	2	3	3	0	3	94
Funafuti	25A	121	3	2	3	3	0	3	94
Saipan	28A	118	3	2	3	3	0	3	94
Kapingamarangi	29A	117	3	2	3	1	0	3	82
Santa Cruz (Galapagos)	30A		3	2	3	3	0	3	94
Cabo San Lucas	34A	161	2	3	3	2	0	3	86
Wake	51A	105	2	3	3	3	0	3	92
Johnston Island	52A	109	3	3	3	2	0	3	94
Guam	53A	149	3	3	3	3	0	3	100
Truk	54A	116	3	3	3	3	0	0	82
Kwajalein	55A	111	3	3	3	3	0	3	100

SCIENCE GOAL: 1a1. ENSO Seasonal-Decadal Variability

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**23**	**18**	**23**	**18**	**0**	**18**	
Pago Pago	56A	144	3	3	3	2	0	3	94
Honolulu	57A	108	2	3	3	3	0	3	92
Hilo	60A	287	2	3	3	2	0	3	86
Antofagasta	80A	174	2	3	3	2	0	0	68
Arica	83A		2	2	3	2	0	3	80
Lobos de Afuera	84A		2	2	3	1	0	3	74
Quepos	87A	167	2	3	3	1	0	3	80
Caldera	88A		2	2	3	2	0	3	80
Callao	93B	173	2	3	3	1	0	3	80
Balboa	302A	168	2	3	3	3	0	0	74
San Diego	569A	159	2	3	3	3	0	3	92

* Not Included in Summary

SCIENCE GOAL: 1a2. ENSO Multi-Decadal Centennial

REQUIREMENTS: Pacific Islands +-15°N,S; South America
>=40 years = 3 pts., 39-30 years = 2 pts., 29-20 years = 1 pt., 80% complete

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**33**	**27**	**13**	**27**	**0**	**0**	
Pohnpei	1B	115	3	1	3	2	0	0	73
Nauru	4A	114	3	1	3	1	0	0	64
Majuro	5A	112	3	1	3	3	0	0	82
Malakal	7A	120	3	1	3	3	0	0	82
Honiara	9A	66	3	1	3	3	0	0	82
Christmas	11B	146	3	1	3	3	0	0	82
Kanton	13B	145	3	1	3	3	0	0	82
*Fr. Frig. Shoals	14A	107	1	1	3	3	0	0	60
Papeete	15B	140	3	1	3	3	0	0	82
Rikitea	16A	138	3	1	3	3	0	0	82
Noumea	19A	123	3	1	3	3	0	0	82
Cabo San Lucas	33A	69	2	1	3	2	0	0	62
Chichijima	47A	103	3	1	3	3	0	0	82
Wake	51A	105	2	3	3	3	0	0	89
Johnston Island	52A	109	3	3	3	2	0	0	91
Guam	53A	149	3	3	3	3	0	0	100
Truk	54A	116	3	1	3	3	0	0	82
Kwajalein	55A	111	3	3	3	3	0	0	100
Pago Pago	56A	144	3	3	3	2	0	0	91
Honolulu	57A	108	2	3	3	3	0	0	89
Hilo	60A	287	2	3	3	2	0	0	80
Antofagasta	80A	174	2	3	3	2	0	0	80
Balboa	302A	168	2	3	3	3	0	0	89
Tumaco	303A	171	2	3	3	2	0	0	80
San Diego	569A	159	2	3	3	3	0	0	89

SCIENCE GOAL: 1a2. ENSO Multi-Decadal Centennial

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**33**	**27**	**13**	**27**	**0**	**0**	
Legaspi	371A	72	2	3	3	3	0	0	89
Davao	372A	71	2	3	3	3	0	0	89
Jolo	373A	70	2	2	3	2	0	0	71

* Not Included in Summary

SCIENCE GOAL: 1b1. Indian Asian-Australian Monsoon Seasonal-Decadal

REQUIREMENTS: **Indian Ocean and SW Pacific**
>=20 years = 3 pts., 19-10 years = 2 pts., < 10 years = 1 pt., 80% complete; Hr+; WOCE Fast

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**24**	**14**	**24**	**19**	**0**	**19**	
Mombasa	101A	8	3	1	3	3	0	3	91
Port Louis	103C	18	3	1	3	2	0	3	84
Diego Garcia	104C	26	3	0	3	3	0	3	86
Rodrigues	105A	19	3	1	3	2	0	3	84
Male-B, Hulule	108B	28	3	1	3	1	0	3	78
Gan	109A	27	3	1	3	3	0	3	91
Muscat-Oman	110A	5	3	1	3	2	0	0	65
Port Victoria	111B	273	3	1	3	3	0	0	72
Salalah	114A	4	2	1	3	3	0	3	83
Hiron Pt., Bangladesh	134A		3	2	3	2	0	0	70
Charchanga	138A	36	3	2	3	2	0	0	70
Karachi	147A	30	2	3	2	3	0	0	65
Nose-Be	150A	15	3	1	3	2	0	0	65
Zanzibar	151A	297	3	2	3	2	0	3	89
Darwin	168A	62	2	2	3	2	0	3	81
Cocos Island	171A	46	3	1	3	3	0	3	91
Durban	181A	13	2	2	3	2	0	0	62
Cochin		32	3	3	2	3	0	0	73
Madras		34	3	2	2	1	0	0	56
Vishakhapatnam		35	3	3	2	3	0	0	73
Kandla			3	3	2	2	0	0	67
Mangalore			3	3	2	2	0	0	67
Saugor			3	3	2	2	0	0	67
Diamond Hb			3	3	2	1	0	0	60
Calcutta			3	3	2	1	0	0	60

SCIENCE GOAL: 1b1. Indian Asian-Australian Monsoon Seasonal-Decadal

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			24	14	24	19	0	19	
Kidderpore			3	1	2	1	0	0	51
Aden		3	3	3	2	3	0	0	73
Bombay			3	3	2	3	0	0	73
Legaspi	PSMSL	72	3	3	2	3	0	0	73
Davao	PSMSL	71	3	3	2	3	0	0	73
Jolo	PSMSL	70	3	2	2	2	0	0	62
Macao	PSMSL		2	3	2	2	0	0	59
Ko Lak	PSMSL	39	3	3	2	3	0	0	73
Ko Sichang	PSMSL		3	3	2	3	0	0	73

SCIENCE GOAL: 1b2. Indian Monsoon Multi-Decadal - Centennial

REQUIREMENTS: **Indian Ocean**
>40 years = 3 pts., 40-30 years = 2 pts., 29-20 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**36**	**21**	**14**	**29**	**0**	**0**	
Karachi	147A	30	3	2	3	3	0	0	93
Cochin	PSMSL	32	3	3	3	3	0	0	100
Madras	PSMSL	34	3	2	3	1	0	0	74
Vishakhapatnam	PSMSL	35	3	3	3	3	0	0	100
Kandla	PSMSL		3	2	3	2	0	0	83
Mangalore	PSMSL		3	1	3	2	0	0	76
Saugor	PSMSL		3	3	3	2	0	0	90
Diamond Hb	PSMSL		3	3	3	1	0	0	81
Calcutta	PSMSL		3	3	3	1	0	0	81
Kidderpore	PSMSL		3	1	3	1	0	0	67
Bombay	PSMSL		3	3	3	3	0	0	100
Aden	PSMSL	3	3	3	3	3	0	0	100
Legaspi	PSMSL	72	3	3	3	3	0	0	100
Davao	PSMSL	71	3	3	3	3	0	0	100
Jolo	PSMSL	70	3	2	3	2	0	0	83
Macao	PSMSL		2	3	3	2	0	0	78
Ko Lak	PSMSL	39	3	3	3	3	0	0	100
Ko Sichang	PSMSL		3	3	3	3	0	0	100

SCIENCE GOAL: 1c1. Tropical Atlantic Variability - Seasonal-Decadal

REQUIREMENTS: Brazil, Atlantic Islands, West Africa (Azores, Caribbean)
>= 20 years = 3 pts., 19-10 years = 2 pts., < 10 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			26	16	21	21	0	16	
St. Peters and Paul	201A	199	3	1	3	1	0	0	59
*Ponta Delgada	211A	245	1	2	3	3	0	0	61
Las Palmas	217D	251	2	1	3	3	0	0	65
Funchal	218B	250	2	2	3	3	0	0	70
Sao Tome	225A	260	3	1	3	1	0	3	75
Pt. Noire-Congo	234A	261	3	1	3	1	0	0	59
San Juan, PR	245A	206	3	2	3	3	0	3	95
Trinidad-Tobago	248A	203	3	1	3	3	0	0	73
Charlotte Amelie	255A		3	2	3	3	0	0	79
*Bermuda	259A	221	1	3	3	3	0	3	83
Ascension Is.	291A	263	3	0	3	3	0	3	84
Recife			3	3	2	3	0	0	77
Tenerife			2	3	2	2	0	0	61
Fernando de Noronha	203B	198	3	1	3	2	0	0	66
St. Helena	292A	264	3	0	3	3	0	3	84
Dakar	223D	253	3	1	3	2	0	0	66

* Not Included in Summary

SCIENCE GOAL: 2a1. NAO Seasonal-Decadal

REQUIREMENTS: **North Atlantic**
> 20 years = 3 pts., 20-10 years = 2 pts., < 10 years = 1 pt.;
Hr+; WOCE Fast

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**25**	**20**	**20**	**20**	**0**	**15**	
Barentsburg		231	3	3	2	3	0	0	78
Ny Alesund			3	2	2	3	0	0	72
Reykjavik		229	3	3	2	2	0	0	72
Torshavn		237	3	3	2	3	0	0	78
Narvik			2	3	2	2	0	0	63
Heimsjo			2	3	2	3	0	0	70
Bergen			2	3	2	3	0	0	70
*Stavanger			2	3	2	3	0	0	70
Lerwick		236	3	3	3	3	0	3	100
Aberdeen II			2	3	3	3	0	0	77
Newlyn	294	241	3	3	3	3	0	3	100
Esbjerg			3	3	2	3	0	0	78
Brest		242	3	3	2	3	0	0	78
Cascais	209A	246	3	3	3	3	0	0	85
Tenerife			3	3	2	2	0	0	72
Ponta Delgado	211A	245	3	1	3	3	0	0	72
Funchal	218A	250	3	2	3	3	0	0	78
Bermuda	259A	221	3	3	3	3	0	3	100
Key West	242A	216	3	3	3	3	0	3	100
Fernandina	240A		3	3	3	3	0	0	85
Charleston	261A		2	3	3	2	0	3	85
Wilmington			2	3	3	3	0	0	77
New York City			2	3	3	3	0	0	77
Montauk			3	3	3	3	0	0	85
Boston			2	3	3	3	0	0	77

SCIENCE GOAL: 2a1. NAO Seasonal-Decadal

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**25**	**20**	**20**	**20**	**0**	**15**	
Portland			3	3	3	3	0	0	85
Halifax		222	3	3	3	3	0	3	100
Charlottetown			2	3	3	3	0	0	77
St. John's NFLD		223	3	3	3	3	0	0	85
Godthab/Nuuk		225	2	3	3	3	0	0	77

* Not Included in Summary

SCIENCE GOAL: 2a2. NAO Multi-Decadal Centennial

REQUIREMENTS: **North Atlantic**
>=45 years = 3 pts., 44-35 years = 2 pts., 34-25 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**33**	**27**	**13**	**27**	**0**	**0**	
Barentsburg		231	3	3	3	3	0	0	100
Reykjavik		229	3	2	3	2	0	0	82
Torshavn		237	3	2	3	2	0	0	82
Narvik			2	2	3	3	0	0	80
Heimsjo			2	3	3	3	0	0	89
Bergen			3	3	3	3	0	0	100
Lerwick			3	2	3	3	0	0	91
Aberdeen II		236	2	3	3	3	0	0	89
Newlyn	294	241	3	3	3	3	0	0	100
Esbjerg			3	3	3	3	0	0	100
Brest		242	3	3	3	3	0	0	100
Cascais	209A	246	2	3	3	3	0	0	89
Tenerife			3	3	3	2	0	0	91
Bermuda	259A	221	3	3	3	3	0	0	100
Key West	242A	216	3	3	3	3	0	0	100
Fernandina	240A		3	3	3	3	0	0	100
Charleston	261A		2	3	3	3	0	0	89
Wilmington			2	3	3	3	0	0	89
New York City			2	3	3	3	0	0	89
Montauk			3	2	3	3	0	0	91
Boston			2	3	3	3	0	0	89
Portland			3	3	3	3	0	0	100
Halifax		222	3	3	3	3	0	0	100
Charlottetown			2	3	3	3	0	0	89
St. John's NFLD		223	3	2	3	3	0	0	91
Godthab/Nuuk		225	2	2	3	3	0	0	80

SCIENCE GOAL: 2b1. North Pacific Variability Seasonal-Decadal

REQUIREMENTS: 30°N - 65°N; 140°E - 130°W
>=20 years = 3 pts., 19-10 years = 2 pts., < 10 years = 1 pt.;
Hr+; WOCE Fast

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			25	20	20	20	0	15	
Midway	50A	106	3	3	3	2	0	3	93
Chichijima	47A	103	3	3	3	3	0	3	100
Ofunato	351A	87	2	3	3	3	0	3	92
Mera	352A	86	2	3	3	3	0	3	92
Yuzhnokurilsk		90	3	3	2	1	0	0	65
Kamchatskiy		93	3	3	2	1	0	0	65
Adak	40A	302	3	3	3	2	0	3	93
Attu Island		303	3	3	3	2	0	0	78
Kodiak	39A		3	2	3	3	0	0	78
Seward		150	2	3	3	3	0	0	77
Sitka		154	3	3	3	3	0	0	85
*Ketchikan			2	3	3	3	0	3	92
Tofino		156	3	3	3	3	0	0	85
Victoria			2	3	3	3	0	0	77
Neah Bay			3	3	3	3	0	3	100
Crescent City			2	3	3	3	0	3	92
Honolulu	57A	108	3	3	3	3	0	3	100
+Minamitorishima		104							
San Francisco		158	2	3	3	3	3	0	77
San Diego	569A	159	2	3	3	3	3	3	92

* Not Included in Summary

\+ No Data Available

SCIENCE GOAL: 2b2. North Pacific Variability Multi-Decadal Centennial

REQUIREMENTS: >40 years = 3 pts., 40-30 years = 2 pts., 29-20 years = 1 pt.; 30°N - 65°; 140°E - 130°W

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**33**	**27**	**13**	**27**	**0**	**0**	
Midway	50A	106	3	3	3	2	0	0	91
Chichijima	47A	103	3	1	3	3	0	0	82
Ofunato	351A	87	2	2	3	3	0	0	80
Mera	352A	86	2	3	3	3	0	0	89
Yuzhnokurilsk		90	3	3	3	1	0	0	82
Kamchatskiy		93	3	2	3	1	0	0	73
Adak	40A	302	3	3	3	2	0	0	91
Attu Island		303	3	1	3	2	0	0	73
Seward		150	2	2	3	3	0	0	80
Sitka		154	3	3	3	3	0	0	100
Ketchikan			2	3	3	3	0	0	89
Tofino		156	3	3	3	3	0	0	100
Victoria			2	3	3	3	0	0	89
Neah Bay			3	3	3	3	0	0	100
Crescent City			2	3	3	3	0	0	89
+Minamitorishima		104							
Honolulu	57A	108	3	3	3	3	0	0	100
San Francisco		158	2	3	3	3	0	0	89
San Diego	569A	159	2	3	3	3	0	0	89

+ No Data Available

SCIENCE GOAL: 3.1. High Latitudes - Seasonal-Decadal

REQUIREMENTS: >20 years = 3 pts., 20-10 years = 2 pts., <10 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			22	13	17	17	17	13	
Kerguelen Island		23	3	1	3	2	3	0	72
Macquarie Island		130	3	1	3	2	3	0	72
Diego Ramirez		180	3	1	3	2	0	3	68
Faraday		188	3	3	3	3	0	3	82
Syowa		95	2	1	3	3	0	0	53
Ushuaia		181	1	1	3	3	0	0	46
Bahia Esperanza		185	3	1	3	3	1	0	66
Russkaya Gavan		99	3	3	2	2	0	0	58
Murmansk		274	2	3	3	2	0	0	56
Barentsburg		231	3	3	2	3	0	0	63
Ny Alesund			3	2	2	3	3	0	76
Narvik			2	3	2	3	1	0	62
Torshavn		237	3	3	2	2	0	0	58
Reykjavik		229	2	3	2	2	3	0	67
Godthab/Nuuk		225	2	3	3	3	0	0	62
Tuktoyaktuk			3	2	2	3	0	0	59
Prudhoe Bay		151	3	1	3	3	0	0	60
Nain		224	3	1	3	3	0	0	60
Signy		306	3	1	3	2	0	0	55

SCIENCE GOAL: 4.1. Narrow Straits, Choke Points - Seasonal-Decadal

REQUIREMENTS: >15 years = 3 pts., 15-8 years = 2 pts., <8 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			26	16	21	21	0	16	
Key West	242A	216	3	3	3	3	3	3	100
*Miami Beach	241A	218	3	3	3	3	3	0	84
Settlement Point	257A	211	3	2	3	3	0	3	95
Fernandina	240A		2	3	3	3	0	0	75
Ceuta	207D	249	3	2	3	3	0	0	79
Gibraltar		248	3	2	3	2	0	0	72
Ushuaia		181	3	1	3	3	0	0	73
Bahia Esperanza		185	3	1	3	3	2	0	73
Faraday		188	3	3	3	3	0	3	100
Diego Ramirez		180	3	1	3	2	0	3	82
Benoa (Lombok)	163A	49	3	1	3	3	0	0	73
Cilicap		291	2	1	3	2	0	0	58
Padang		45	2	1	3	3	0	0	65
Surabaya	160A	292	3	1	3	2	0	0	66
Bitung	33A	69	3	2	3	2	0	0	72
Meneng	158A		3	1	3	2	0	0	66
Darwin	168A	62	2	2	3	2	0	3	79
Port Hedland	169A	51	2	2	3	2	0	0	63

* Not Included in Summary

SCIENCE GOAL: 4.2. Narrow Straits, Choke Points - Multi-Decadal Centennial

REQUIREMENTS: >40 years = 3 pts., 40-30 years = 2 pts., 29-20 years = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**36**	**21**	**14**	**29**	**0**	**0**	
Key West	242A	216	3	3	3	3	3	0	100
*Miami Beach	241A	218	3	3	3	3	3	0	100
Settlement Point	257A	211	3	0	3	3	0	0	79
Fernandina	240A		2	3	3	3	0	0	88
Faraday		188	3	2	3	3	0	0	93

* Not Included in Summary

SCIENCE GOAL: 5.1. Western Boundary Currents - Seasonal-Decadal

REQUIREMENTS: >20 years = 3 pts., 19-10 years = 2 pts., <10 years = 1 pt.;
Hr+, WOCE Fast

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			26	16	21	21	0	16	
Miyakejima	357A		3	3	3	2	0	0	77
Kushimoto	353A	85	3	3	3	3	0	3	100
Aburatsu	354A	82	3	3	3	3	0	3	100
Naha	355A	81	3	3	3	2	0	3	93
Maisaka	356A		3	3	3	3	0	0	84
Naze	359A		3	3	3	1	0	0	70
+Uragami									
+Hachijojima									
Nishinoomote	PSMSL		3	3	2	3	0	0	77
Odomari	PSMSL		3	3	2	2	0	0	70
Pusan	PSMSL	84	3	3	2	3	0	0	77
Izuhara	PSMSL		3	3	2	1	0	0	63
Hakata	PSMSL		3	3	2	2	0	0	70
Legaspi	371A	72	3	3	2	3	0	0	77
Davao	372A	71	3	3	2	3	0	0	77
Jolo	373A	70	3	2	2	2	0	0	65
Recife	PSMSL		3	3	2	3	0	0	77
Key West	242A		3	3	3	3	0	3	100
Settlement Point	257A	211	3	2	3	3	0	3	95
Fernandina	240A		3	3	3	3	0	3	100
Charleston	261A		3	3	3	2	0	3	93
Wilmington	PSMSL		2	3	3	3	0	0	75
Bermuda	259A	221	3	3	3	3	0	3	100

+ No Data Available

SCIENCE GOAL: 5.2. Western Boundary Currents - Multidecadal-Centennial

REQUIREMENTS: >40 years = 3 pts., 39-30 yrs. = 2 pts., 29-20 yrs. = 1 pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**36**	**21**	**14**	**29**	**0**	**0**	
Miyakejima	357A		3	1	3	2	0	0	76
Kushimoto	353A	85	3	2	3	3	0	0	93
Aburatsu	354A	82	3	2	3	3	0	0	93
Naha	355A	81	3	1	3	2	0	0	76
Maisaka	356A		3	1	3	3	0	0	86
Naze	359A		3	1	3	1	0	0	67
+Uragami									
+Hachijojima									
Nishinoomote	PSMSL		3	1	3	3	0	0	86
Odomari	PSMSL		3	1	3	2	0	0	76
Pusan	PSMSL		3	2	3	3	0	0	93
Izuhara	PSMSL		3	1	3	1	0	0	67
Hakata	PSMSL		3	1	3	2	0	0	76
Legaspi	371A	72	3	3	3	3	0	0	100
Davao	372A	71	3	3	3	3	0	0	100
Jolo	373A	70	3	2	3	2	0	0	83
Recife	PSMSL		3	2	3	3	0	0	93
Key West	242A		3	3	3	3	0	0	100
Fernandina	240A		3	3	3	3	0	0	100
Charleston	261A		3	3	3	2	0	0	90
Wilmington	PSMSL		2	3	3	3	0	0	88
Bermuda	259A	221	3	3	3	3	0	0	100

+ No Data Available

SCIENCE GOAL: 6. Long-Term SLR

REQUIREMENTS: >60 years = 3 pts., 59-40 years = 2 pts., 39-30 years = 1pt.

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**13**	**33**	**0**	**27**	**27**	**0**	
Reykjavik		229	3	2	3	2	3	0	80
Narvik			2	3	3	3	1	0	78
Bergen			2	3	3	3	0	0	69
*Stavanger			2	3	3	3	0	0	69
*Smogen			3	3	3	3	1	0	82
Goteborg		233	3	3	3	3	3	0	100
*Varberg			3	3	3	3	1	0	82
*Ystad			3	3	3	3	2	0	91
*Kungsholmsfort			2	3	3	2	1	0	69
Stockholm			3	3	3	3	3	0	100
Helsinki			3	3	3	3	2	0	91
Daugavgriva			2	3	3	2	3	0	87
Liepaja			3	3	3	3	0	0	73
*Warnemunde			3	3	3	3	0	0	73
Wismar			3	3	3	3	0	0	73
*Kopenhagen			3	3	3	3	0	0	73
*Fredericia			3	3	3	3	0	0	73
*Aarhus			3	3	3	3	0	0	73
*Frederikshavn			3	3	3	3	0	0	73
*Hirtshals			3	3	3	3	0	0	73
Esbjerg			3	3	3	3	0	0	73
Cuxhaven		284	3	3	3	3	0	0	73
Aberdeen II			3	3	3	3	0	0	73
*N. Shields			3	3	3	3	0	0	73
Newlyn	294	241	3	3	3	3	0	0	73

SCIENCE GOAL: 6. Long-Term SLR

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**13**	**33**	**0**	**27**	**27**	**0**	
Brest		242	3	3	3	3	0	0	73
Cascais	209A	246	3	3	3	3	0	0	73
Marseille		205	3	3	3	3	1	0	82
Genova			3	3	3	3	0	0	73
Trieste			2	3	3	3	2	0	87
Tuapse		98	2	3	3	3	0	0	69
Tenerife			3	3	3	2	2	0	82
Takoradi	231A		3	3	3	1	0	0	55
Aden		3	3	2	3	3	0	0	62
Karachi	147A	30	2	2	3	3	0	0	58
Bombay			3	3	3	3	0	0	73
Cochin		32	3	2	3	3	0	0	62
Vishakhapatnam		35	3	2	3	3	0	0	62
Ko Lak		39	3	2	3	3	0	0	62
Ko Sichang			3	2	3	3	0	0	62
Macao	338A		3	2	3	2	0	0	53
Xiamen	376A	247	3	2	3	2	0	0	53
Yuzhnokurilsk		90	3	2	3	1	0	0	44
Mera	352A	86	3	3	3	3	1	0	82
Aburatsubo			2	3	3	3	0	0	69
Kushimoto	353A	85	3	3	3	2	0	0	64
Hosojima			3	3	3	2	0	0	64
Tonoura			3	3	3	3	0	0	73
Wajima			3	3	3	3	0	0	73
Manila	370A	73	2	3	3	1	3	0	78
Sydney		57	2	3	3	3	1	0	78
Fremantle	175A	53	3	3	3	3	2	0	91
Auckland II	70A	127	3	3	3	3	3	0	100
Lyttleton II			3	3	3	3	0	0	73
Guam	53A	149	3	2	3	3	3	0	89
Truk	54A	116	3	2	3	3	0	0	62

SCIENCE GOAL: 6. Long-Term SLR

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**13**	**33**	**0**	**27**	**27**	**0**	
Kwajalein	55A	111	3	2	3	3	3	0	89
Midway	50A	144	3	2	3	2	0	0	53
Honolulu	57A	108	3	3	3	3	3	0	100
*Hilo	60A	287	3	2	3	3	2	0	80
Ketchikan			2	3	3	3	0	0	69
*Vancouver			2	3	3	3	1	0	78
Victoria			3	3	3	3	3	0	100
Neah Bay			3	3	3	3	1	0	82
Seattle			2	3	3	3	2	0	87
Crescent City			3	3	3	3	0	0	73
San Francisco		158	2	3	3	3	2	0	87
*Los Angeles			2	3	3	3	3	0	96
San Diego	596A	159	2	3	3	3	3	0	96
Balboa	302A	168	3	3	3	3	0	0	73
Tumaco	303A	171	3	2	3	1	0	0	44
La Libertad II	91A	172	3	2	3	1	0	0	44
Antofagasta	80A	174	2	2	3	2	0	0	49
Valparaiso	81A,B	175	2	2	3	1	1	0	49
Quequen			2	3	3	3	0	0	69
Buenos Aires			2	3	3	3	2	0	87
Cartagena	265A	207	3	2	3	2	0	0	53
Cristobal	266A	208	3	3	3	3	0	0	73
Pensacola		288	2	3	3	3	0	0	69
Key West	242A	216	3	3	3	3	3	0	100
*Mayport			2	3	3	3	0	0	69
Fernandina	240A		2	3	3	3	0	0	69
*Savannah		289	2	3	3	3	0	0	69
Charleston	261A		2	3	3	2	3	0	87
*Wilmington			2	2	3	3	0	0	58
Hampton Roads			2	3	3	3	3	0	96
Atlantic City		220	2	3	3	3	0	0	69

SCIENCE GOAL: 6. Long-Term SLR

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			**13**	**33**	**0**	**27**	**27**	**0**	
New York City			2	3	3	3	2	0	87
Boston			2	3	3	3	1	0	78
Portland			2	3	3	3	1	0	78
*Eastport			2	3	3	3	0	0	69
Halifax		222	2	3	3	3	0	0	69
Bermuda	259A	221	3	3	3	3	3	0	100
Wake	51A	105	3	2	3	3	0	0	62

* Not Included in Summary

SCIENCE GOAL: 8.1. Model Validation - Seasonal - Decadal

REQUIREMENTS: **Ocean Islands**
>= 40 years = 3 pts., 39-20 years = 2 pts., < 20 years = 1 pt.;
Hr+; GPS

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			10	15	20	20	20	15	
Chichijima	47A	103	3	2	3	3	3	3	95
Midway	50A	106	3	3	3	2	0	3	73
Wake	51A	105	3	3	3	3	0	0	65
Johnston Island	52A	109	3	3	3	2	0	3	73
Guam	53A	149	3	3	3	3	3	3	100
Kwajalein	55A	111	3	3	3	3	3	3	100
Pago Pago	56A	144	3	3	3	2	3	3	93
Honolulu	57A	108	3	3	3	3	3	3	100
Hilo	60A	287	3	3	3	3	2	3	93
San Diego	569A	159	2	3	3	3	3	3	97
Mera	352A	86	3	3	3	3	1	3	87
Adak	40A	302	3	3	3	2	0	3	73
Sitka		154	3	3	3	3	0	0	65
Victoria			3	3	3	3	3	0	85
Neah Bay			3	3	3	3	1	3	87
Tofino		156	3	3	3	3	1	0	72
Diego Garcia	104C	26	3	1	3	3	3	3	90
*Port Victoria	111B	273	3	1	3	3	3	0	75
Cocos Island	171A	46	3	1	3	3	3	3	90
Cochin			2	3	2	3	0	0	55
Karachi	147A	30	2	3	2	3	0	0	55
Vishakhapatnam		35	2	3	2	3	0	0	55
Bombay			2	3	2	3	0	0	55
Reykjavik		229	3	2	2	2	3	0	67
Torshavn		237	3	2	2	2	0	0	47

SCIENCE GOAL: 8.1. Model Validation - Seasonal - Decadal

Station Name	JASL Number	GLOSS Number	Location Setting	Rec Length Complete	Temp Resolution	Data Quality	Satellite Geodesy	Timeliness WOCE Fast	Total Score
weights:			10	15	20	20	20	15	
Bergen			2	3	2	3	0	0	55
Lerwick		236	3	2	3	3	0	3	75
Aberdeen II			3	3	2	3	0	0	58
Newlyn	294	241	3	3	3	3	0	3	80
Cascais	209A	246	3	3	3	3	0	0	65
Tenerife			3	3	2	2	2	0	65
Bermuda	259A	221	3	3	3	3	3	3	100
Key West	242A	216	3	3	3	3	3	3	100
Fernandina	240A		3	3	3	3	0	0	65
Charleston	261A		2	3	3	2	3	3	90
New York City			2	3	3	3	2	0	75
Montauk			3	3	3	3	3	0	85
Boston			2	3	3	3	1	0	68
Portland			2	3	3	3	1	0	68
Halifax		222	3	3	3	3	0	3	80
St. John's NFLD		223	3	2	3	3	3	0	80

* Not Included in Summary

Appendix A.3

Station Rating Summary

This appendix summarizes the station ratings detailed in Appendix A.2.

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
Aberdeen II						77	89								73	58
Aburatsu													100	93		
Aburatsubo															69	
Adak								93	91							73
Aden			73	100											62	
Antofagasta	68	80													49	
Arica	80															
Ascension Is.					84											
Atlantic City															69	
Attu Island								78	73							
Auckland II															100	
Bahia Esperanza										66	73					
Balboa	74	89													73	
Barentsburg						78	100			63						
Benoa (Lombok)											73					
Bergen						70	100								69	55
Bermuda						100	100						100	100	100	100
Bitung											72					
Bombay			73	100											73	55
Boston						77	89								78	68
Brest						78	100								73	
Buenos Aires															87	
Cabo San Lucas	86	62														
Calcutta			60	81												
Caldera	80															
Callao	80															
Cartagena															53	
Cascais						85	89								73	65
Ceuta											79					
Charchanga			70													
Charleston						85	89						93	90	87	90

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
Charlotte Amelie					79											
Charlottetown						77	89									
Chichijima		82						100	82							95
Christmas	100	82														
Cilicap											58					
Cochin			73	100											62	55
Cocos Island			91													90
Crescent City								92	89						73	
Cristobal															73	
Cuxhaven															73	
Dakar					66											
Darwin			81								79					
Daugavgriva															87	
Davao		89	73	100									77	100		
Diamond Hb			60	81												
Diego Garcia			86													90
Diego Ramirez										68	82					
Durban			62													
Easter	82															
Esbjerg						78	100								73	
Faraday										82	100	93				
Fernandina						85	100				75	88	100	100	69	65
Fernando de Noronha					66											
Fremantle															91	
Funafuti	94															
Funchal					70	78										
Gan			91													
Genova															73	
Gibraltar											72					
Godthab/Nuuk						77	80			62						
Goteborg															100	
Guam	100	100													89	100
Hachijojima																
Hakata													70	76		

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
Halifax						100	100								69	80
Hampton Roads															96	
Heimsjo						70	89									
Helsinki															91	
Hilo	86	80														93
Hiron Pt., Bangladesh			70													
Honiara	100	82														
Honolulu	92	89						100	100						100	100
Hosojima															64	
Izuhara													63	67		
Johnston Island	94	91														73
Jolo		71	62	83									65	83		
Kamchatskiy								65	73							
Kandla			67	83												
Kanton	100	82														
Kapingamarangi	82															
Karachi			65	93											58	55
Kerguelen Island										72						
Ketchikan									89						69	
Key West						100	100				100	100	100	100	100	100
Kidderpore			51	67												
Ko Lak			73	100											62	
Ko Sichang			73	100											62	
Kodiak								78								
Kushimoto													100	93	64	
Kwajalein	100	100													89	100
La Libertad II															44	
Las Palmas					65											
Legaspi		89	73	100									77	100		
Lerwick						100	91									75
Liepaja															73	
Lobos de Afuera	74															
Lyttleton II															73	
Macao			59	78											53	

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
Macquarie Island										72						
Madras			56	74												
Maisaka													84	86		
Majuro	100	82														
Malakal	100	82														
Male-B, Hulule			78													
Mangalore			67	76												
Manila															78	
Marseille															82	
Meneng											66					
Mera								92	89						82	87
Midway								93	91						53	73
Minamitorishima																
Miyakejima													77	76		
Mombasa			91													
Montauk						85	91									85
Murmansk										56						
Muscat-Oman			65													
Naha													93	76		
Nain										60						
Narvik						63	80			62					78	
Nauru	88	64														
Naze													70	67		
Neah Bay								100	100						82	87
New York City						77	89								87	75
Newlyn						100	100								73	80
Nishinoomote													77	86		
Nose-Be			65													
Noumea	100	82														
Ny Alesund						72				76						
Odomari													70	76		
Ofunato								92	80							
Padang											65					
Pago Pago	94	91														93

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
Papeete	94	82														
Penrhyn	94															
Pensacola															69	
Pohnpei	94	73														
Ponta Delgado						72										
Port Hedland											63					
Port Louis			84													
Port Victoria			72													
Portland						85	100								78	68
Prudhoe Bay										60						
Pt. Noire-Congo					59											
Pusan													77	93		
Quepos	80															
Quequen															69	
Rarotonga	94															
Recife					77								77	93		
Reykjavik						72	82			67					80	67
Rikitea	100	82														
Rodrigues			84													
Russkaya Gavan										58						
Saipan	94															
Salalah			83													
San Diego	92	89						92	89						96	97
San Francisco								77	89						87	
San Juan, PR					95											
Santa Cruz (Galapagos)	94															
Sao Tome					75											
Saugor			67	90												
Seattle															87	
Settlement Point											95	79	95			
Seward								77	80							
Signy										55						
Sitka								85	100							65
St. Helena					84											

SCIENCE GOAL SUMMARY

Station Name	1a1	1a2	1b1	1b2	1c1	2a1	2a2	2b1	2b2	3.1	4.1	4.2	5.1	5.2	6	8.1
St. John's NFLD						85	91									80
St. Peters and Paul					59											
Stockholm															100	
Surabaya											66					
Suva, Fiji	88															
Sydney															78	
Syowa										53						
Takoradi															55	
Tenerife					61	72	91								82	65
Tofino								85	100							72
Tonoura															73	
Torshavn						78	82			58						47
Trieste															87	
Trinidad-Tobago					73											
Truk	82	82													62	
Tuapse															69	
Tuktoyaktuk										59						
Tumaco		80													44	
Uragami																
Ushuaia										46	73					
Valparaiso															49	
Victoria								77	89						100	85
Vishakhapatnam			73	100											62	55
Wajima															73	
Wake	92	89													62	65
Wilmington						77	89						75	88		
Wismar															73	
Xiamen															53	
Yuzhnokurilsk								65	82						44	
Zanzibar			89													

APPENDIX B

LETTER OF INVITATION AND BACKGROUND

April 11, 1997

Dear ________________

You are invited to join a group of your colleagues to participate in an International Workshop for the design of an in-situ global sea level monitoring network to support prediction of climate variability at all time scales and for the detection of long term sea level change. The Workshop will be held in Honolulu, Hawaii, USA, 10-11 June 1997.

The Final Report of the OOSDP, the *Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System*, outlined the elements of the ocean observing system for climate. The report called for definition of two overlapping subsets of tide gauging stations: 1) a subset of the TOGA network in support of ENSO prediction; and 2) a subset of the GLOSS network for detection of decadal and longer changes in sea level. A number of these stations would provide calibration and validation of altimeter measurements.

Subsequent to the OOSDP's Final Report, the OOPC concluded that the combination of altimeter and in situ data appeared to offer a product that retained the benefits of both the long in situ record and global coverage of the altimeter. This conclusion implied a critical role for a subset of fast response, referenced tide gauge stations. Long term sea level change was identified by the OOPC as a top priority to be developed as an integrated global observation strategy--including determination of a network of in situ gauges to be combined with altimeter measurements.

The *CLIVAR Science Plan* identified as priorities the examination of interannual, decadal, and longer term variability relating to ENSO events, monsoons, and ocean wide fluctuations, and the determination of accelerated sea level rise. The importance of sea level observations was expressed for constraining model initialization, for validating models, and for mapping of sea level variability through altimetry supplemented by selected in situ measurements. The Plan called for efforts to determine the number of stations that should be maintained to meet CLIVAR's scientific objectives.

The GLOSS Group of Experts recently conducted a re-assessment of their requirements for global observations of sea level. The *GLOSS Implementation Plan 1997* defined three overlapping subsets of the GLOSS tide gauge network as being of special interest with regard to ongoing studies of 1) long term sea level trends, 2) altimeter calibration, and 3) ocean circulation.

The purpose of the Honolulu Workshop is to bring together the efforts of these activities, in light of the scientific objectives of CLIVAR, and to synthesize the "subset" of gauging stations that will best serve the requirements of climate research and prediction. The product of the Workshop will be a *Workshop Report* that will advise the operating agencies of the global sea level community on the most effective and efficient implementation of the "climate network" of tide gauge stations. This documented advice will include:

1. Explanation of the scientific requirements for in situ sea level observations and their combination with satellite altimeter measurements as they relate to the climate problem.

2. A world map depicting the subset of tide gauge stations to be included in the global "climate" network. The network design will utilize stations already in existence to the maximum extent possible, and recommend establishment of any new stations required for adequate spacial distribution. The task will be to specify the most efficient network to be maintained over the long term.

3. Scientific rationale for including each particular station in the network.

4. Measurement and data reporting capabilities required for each station within the network.

5. A station list establishing the priority for implementing GPS measurements.

6. A recommended mechanism for ongoing evaluation of the network design and for international implementation of future network modifications should they become warranted as the state of scientific understanding advances.

Although this is an ambitious scope of work, there should be a minimum of actual writing required of the Workshop participants. We have asked Dr. Vivien Gornitz at Columbia University to draft a preliminary document that will serve as the starting point for the Workshop deliberations. This draft document has been reviewed by an ad-hoc Scientific Steering Group, and a revised draft will be sent to Workshop participants within the next few weeks. We will also invite critical review of the draft document by the international climate and sea level communities (OOPC, CLIVAR SSG and UOP, WOCE SSG, IOC/GE-GLOSS, lead authors of IPCC Chapter 7).

The Workshop is intended to provide an international forum to consider the draft document and reviewer comments, and then to define the in-situ sea level network for climate. The Scientific Steering Group will follow up the meeting by incorporating the Workshop's findings into the final *Workshop Report*.

This project is organized and sponsored by the United States National Oceanic and Atmospheric Administration (NOAA). We have worked though the Scientific Steering Group to provide initial liaison with the CLIVAR Upper Ocean Panel and the OOPC.

Mike Johnson is serving as point of contact for the Workshop. Please let him know at your earliest convenience if you will be able to participate (telephone 1-301-427-2089 x 62; fax 1-301-427-2073; e-mail johnson@ogp.noaa.gov).

Thank you very much, and we look forward to working with you on this project.

Sincerely,

Mike Johnson and Wolfgang Scherer
Organizing Committee

APPENDIX C

AGENDA

International Sea Level Workshop
10-11 June, 1997
Honolulu, Hawaii, U.S.A.
Hawaii Imin International Conference Center
Asia Room

AGENDA

Tuesday, 10 June 1997

0830 Welcome & Introduction - Wolfgang Scherer

0900 **Session 1: International Programs** - Chair: Neville Smith

1. CLIVAR - Roger Lukas
2. OOPC - Neville Smith
3. GLOSS - Phil Woodworth

1000 Break

1030 **Session 2: Science Issues** - Chair: Neville Smith

1. Pacific seasonal to interannual variability - Chet Koblinsky
2. Austral/Asian monsoon - Roger Lukas
3. Tropical Atlantic variability - Marcio Vianna
4. Straits, chokepoints, and constricted passages - Ken Ridgway

1230 Lunch

1330 **Session 2 (continued)**

5. Pacific gyres and circulation - Masaki Kawabe
6. Atlantic gyres and circulation
7. High latitude circulation--Antarctica - Phil Woodworth

1500 Break

1530 **Session 2 (continued)**

8. Long-term sea level trend and low-frequency waves - Phil Woodworth

9. Altimeter calibration - Gary Mitchum

10. Applications of sea level data in climate modeling - Christian Le Provost

1700 Reception

Wednesday, 11 June 1997

0830 **Session 3: Network design** - Chair: Neville Smith

1. Station evaluation and criteria - Vivien Gornitz
2. Station selection: Long term trends
3. Station selection: Altimeter calibration

1000 Break

1030 **Session 3 (continued)**

4. Station selection: Tropical Pacific
5. Station selection: Western boundary currents
6. Station selection: Atlantic modes
7. Station selection: Straits and chokepoints
8. Station selection: High latitudes
9. Station selection: North Pacific circulation

1230 Lunch

1330 **Session 3 (continued)**

10. Priority for GPS instrumentation
11. Measurement and data reporting requirements
12. Mechanisms for ongoing evaluation, implementation, and modification

1500 Break

1530 **Session 4: Workshop recommendations** - Chair: Neville Smith

1700 Adjourn

APPENDIX D

PARTICIPANTS

Prof. Armando F.G. Fiúza
Instituto de Oceanografia
Universidade de Lisboa
Rua Ernesto Vasconcelos (Campo Grande)
1700 Lisboa
PORTUGAL
Ph.: (351) 1-757-3141, x 2910/2913
Fax: (351) 1-750-0009
fiuza@fc.ul.pt

Dr. Vivien Gornitz
NASA / GISS
2880 Broadway
New York, NY 10025
USA
Ph.: (1) 212-678-5566
Fax: (1) 212-678-5552
vgornitz@giss.nasa.gov

Dr. John Hannah
Dept. of Surveying
University of Otago
P.O. Box 56
Dunedin
NEW ZEALAND
Ph.: (64) 3-479-9010
Fax: (64) 3-479-7586
john@albers.otago.ac.nz

CDR Michael Johnson, NOAA
NOAA / OGP
1100 Wayne Ave.
Suite 1210
Silver Spring, MD 20910
USA
Ph.: (1) 301-427-2089, x 62
Fax: (1) 301-427-2073
johnson@ogp.noaa.gov

Mr. Yuji Kashino
Dept. of Oceanography (until 2/98)
MSB 420
University of Hawaii
1000 Pope Road
Honolulu, HI 96822
USA
Ph.: (1) 808-956-4107
Fax: (1) 808-956-9222
kashinoy@iniki.soest.hawaii.edu

Ocean Research Dept. (3/98)
Japan Marine Science and
Technology Center
2-15 Natsushima Yokosuka
237 JAPAN
Ph.: (81) 468-66-3811
Fax: (81) 468-65-3202
kashinoy@jamstec.go.jp

Dr. Masaki Kawabe
Ocean Research Institute
University of Tokyo
1-15-1, Minamidai
Nakano-Ku
Tokyo 164
JAPAN

Ph.:
Fax: (81) 3-5351-6418
kawabe@ori.u-tokyo.ac.jp

Dr. Bernard Kilonsky
JIMAR
University of Hawaii
1000 Pope Road
Honolulu, HI 96822
USA

Ph.: (1) 808-956-6574
Fax: (1) 808-956-2352
kilonsky@hawaii.edu

Dr. Chet Koblinsky
NASA / GSFC
Code 971
Greenbelt, MD 20771
USA

Ph.: (1) 301-286-4718
Fax: (1) 301-286-0240
koblinski@gsfc.nasa.gov

Dr. Christian Le Provost
Laboratoire d'Océanographie
et de Géophysique Spatiale
observatoire de Midi-Pyrénées
18 Avenue Edouard
Belin, 31055, Toulouse
FRANCE

Ph.: (33) 5-6133-2923
Fax: (33) 5-6125-3205
leprovos@pontos.est.cnes.fr

Dr. Roger Lukas
Dept. of Oceanography, MSB 312
JIMAR
University of Hawaii
1000 Pope Road
Honolulu, HI 96822
USA

Ph.: (1) 808-956-7896
Fax: (1) 808-956-9222
rlukas@iniki.soest.hawaii.edu

Dr. Doug Luther
Dept. of Oceanography
MSB 307
University of Hawaii
1000 Pope Road
Honolulu, HI 96822
USA

Ph.: (1) 808-956-5875
Fax: (1) 808-956-9165
dluther@soest.hawaii.edu

Dr. Mark Merrifield
Dept. of Oceanography
MSB 317
University of Hawaii
1000 Pope Road
Honolulu, HI 96822
USA
Ph.: (1) 808-956-6161
Fax: (1) 808-956-2352
markm@iniki.soest.hawaii.edu

Mr. Bill Mitchell
National Tidal Facility
The Flinders University of South Australia
GPO Box 2100
Adelaide, S.A. 5001
AUSTRALIA
Ph.: (618) 8-201-7525
Fax: (618) 8-201-7523
bill@pacific.ntf.flinders.edu.au

Dr. Gary T. Mitchum
Dept. of Marine Science
University of South Florida
140 Seventh Ave. South
St. Petersburg, FL 33701
USA
Ph.: (1) 813-553-3941
Fax: (1) 813-553-1189
mitchum@marine.usf.edu

Dr. Harold Mofjeld
NOAA / PMEL
7600 Sand Point Way NE
Seattle, WA 98115
USA
Ph.: (1) 206-526-6800
Fax: (1) 206-526-6744
mofjeld@pmel.noaa.gov

Dr. Ken Ridgway
CSIRO, Division of Marine Research
GPO Box 1538
Hobart, Tasmania 7001
AUSTRALIA
Ph.: (61) 3-6232-5226
Fax: (61) 3-6232-5123
ridgway@marine.csiro.au

Dr. Wolfgang Scherer
NOAA, National Ocean Service
1305 East-West Highway
Silver Spring, MD 20910
USA
Ph.: (1) 301-713-2981, ext. 119
Fax: (1) 301-713-4392
wscherer@nos.noaa.gov

Dr. Neville Smith
Research Centre
Bureau of Meteorology
GPO Box 1289K
150 Londsdale Street
Melbourne, VIC 3001
AUSTRALIA

Ph.: (61) 3-9669-4434
Fax: (61) 3-9669-4660
N.smith@bom.gov.au

Dr. Marcio Luiz Vianna
Programa Oceanografia
Instituto Nacional de Pesquisas Espacials
Av. Astronautas, 1758-12227-010
Cx. Postal 515
Sao Jose dos Campos-SP
BRAZIL

Ph.: (55) 12-345-6477
Fax: (55) 12-345-6460 / 322-9325
mvianna@ltid.inpe.br

Dr. Philip Woodworth
Director, PSMSL
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead MERSEYSIDE L43 7RA
UNITED KINGDOM

Ph.: (44) 151-653-8633
Fax: (44) 151-653-6269
plw@pol.ac.uk

Dr. Klaus Wyrtki
Dept. of Oceanography
MSB 317
University of Hawaii
1000 Pope Road
HSB 430
Honolulu, HI 96822
USA

Ph.: (1) 808-956-7729
Fax: (1) 808-956-4104
markm@iniki.soest.hawaii.edu

APPENDIX E

SCIENTIFIC STEERING GROUP

Vivien Gornitz
Mike Johnson
Chet Koblinsky
Ants Leetmaa
Christian Le Provost
Syukuro Manabe
Gary Mitchum
Wolfgang Scherer
Neville Smith
Philip Woodworth

APPENDIX F

COLLECTED ABSTRACTS

Tide gauges in Japan to be listed for global monitoring

Masaki Kawabe
Ocean Research Institute, University of Tokyo
Japan

A. Ocean Circulation [Science goal 2] (Fig. 1)

1. Kuroshio

a. Current path

The Kuroshio in the southern region of Japan shows relatively regular variations of current path; it takes three typical paths alternately: the large-meander (LM) path and the nearshore and offshore non-large-meander (NLM) paths (Kawabe 1985, 1986). The variation between the LM and NLM paths is more than decadal with primary periods of about 20 years (Kawabe 1987).

The variations are perfectly monitored by sea level at Kushimoto, Uragami (to detect LM or NLM) and Miyakejima, Hachijojima (location over the Izu Ridge) (Kawabe 1985, 1995). The north-south move in the Tokara Strait related to the variation between the LM and NLM paths is monitored by sea level at Naze, Nakanoshima and Nishinoomote (Kawabe 1995; Yamashiro and Kawabe 1996).

b. Current velocity and volume transport

Surface velocity of the Kuroshio is monitored by the difference in sea level of Ishigakijima minus Keelung (east of Taiwan) and Naze minus Nishinoomote (Tokara Strait). Volume transport of the Kuroshio is monitored by the linear combination of sea level at Naze, Nishinoomote, and Odomari, $Tr(Sv) = 0.250\ Nz + 0.158\ Ni - 0.277\ Od + 24.4$ (Kawabe 1995).

2. Tsushima Current

Velocity of the Tsushima Current is monitored by sea level at Pusan (Korea), Izuhara and Hakata; by the difference in sea level of Izuhara minus Pusan (western channel of the Tsushima Strait) and Hakata minus Izuhara (eastern channel) (Kawabe 1982).

3. Interior area of the subtropical gyre

Sea levels at Chichijima, Ishigakijima, Naha, Okinawa, Naze, and Minamitorishima are useful for monitoring the sea level in the subtropical gyre of the North Pacific.

B. Long Term Trend [Science goal 5]

Long-term measurement of sea level is made at Oshoro, Hosojima, Hamada and Hachinohe (or Miyako), except Wajima, Aburatsubo, and Mera nominated in Table 9 of the draft.

C. PNA pattern [Science goal 2]

Miyakejima is not good for this purpose, because the sea level there is highly contaminated by the Kuroshio path variation.

The stations nominated in Table 6 of the draft and this report except Miyakejima, Hachijojima, and Nakanoshima may be good.

Some stations in Korea and China should be included?

Recommendation

(1) I finally recommend to list up the tide stations in Fig. 2.

(2) The report of this workshop should strongly urge the Japanese agencies to establish the GPS systems at the tide gauges as soon as possible to measure the vertical movement of the bench marks.

References

Kawabe, M. (1982): Branching of the Tsushima Current in the Japan Sea. Part I. Data analysis. J. Oceanogr. Soc. Japan, 38, 95-107.

Kawabe, M. (1985): Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. J. Oceanogr. Soc. Japan, 41, 307-326.

Kawabe, M. (1986): Transition processes between the three typical paths of the Kuroshio. J. Oceanogr. Soc. Japan, 42, 174-191.

Kawabe, M. (1987): Spectral properties of sea level and time scales of Kuroshio path variations. J. Oceanogr. Soc. Japan, 43, 111-123.

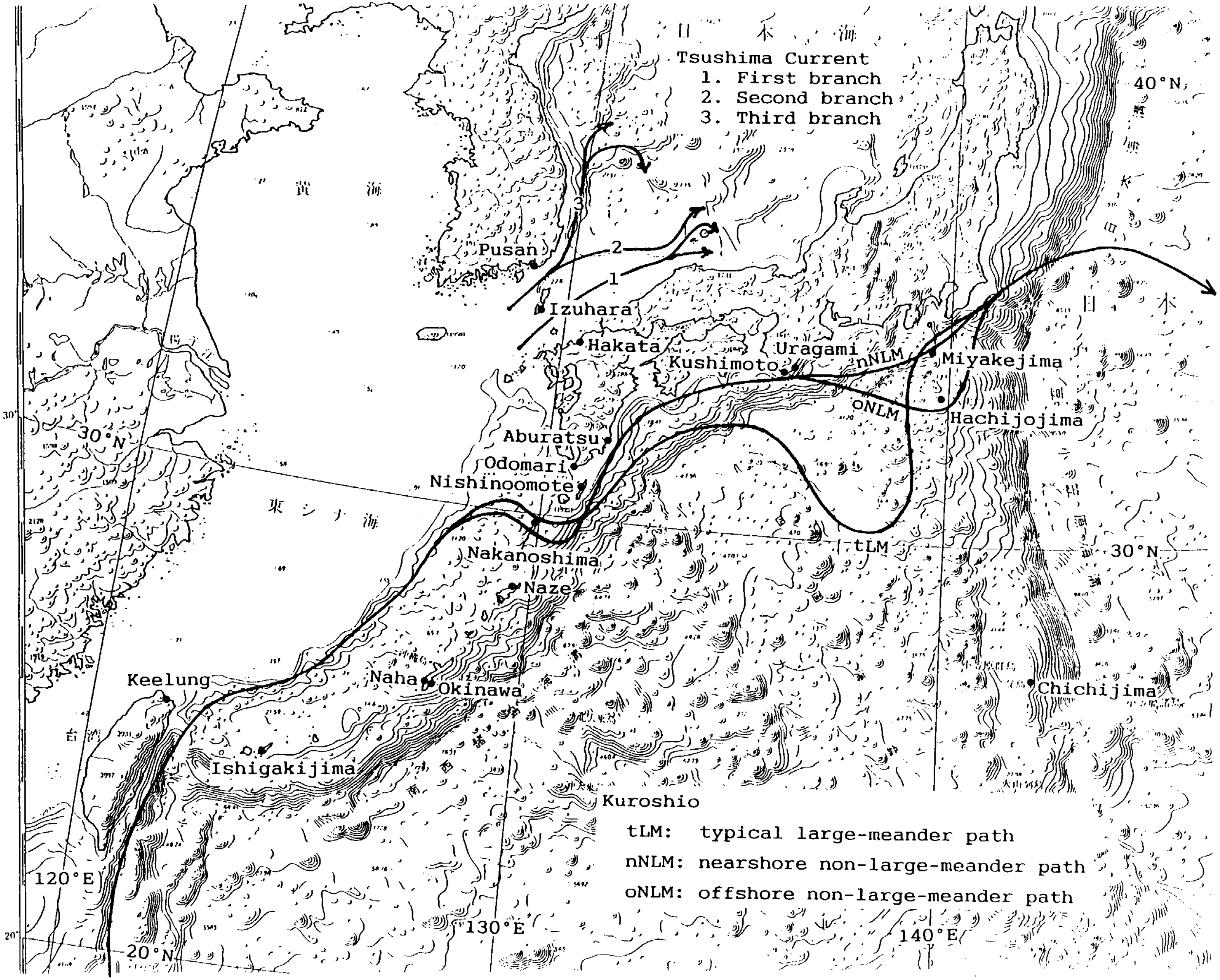
Kawabe, M. (1995): Variations of current path, velocity, and volume transport of the Kuroshio in relation with the large meander. J. Phys. Oceanogr., 25, 3103-3117.

Yamashiro, T., and M. Kawabe (1996): Monitoring of position of the Kuroshio axis in the Tokara Strait using sea level data. J. Oceanogr., 52, 675-687.

Figure caption

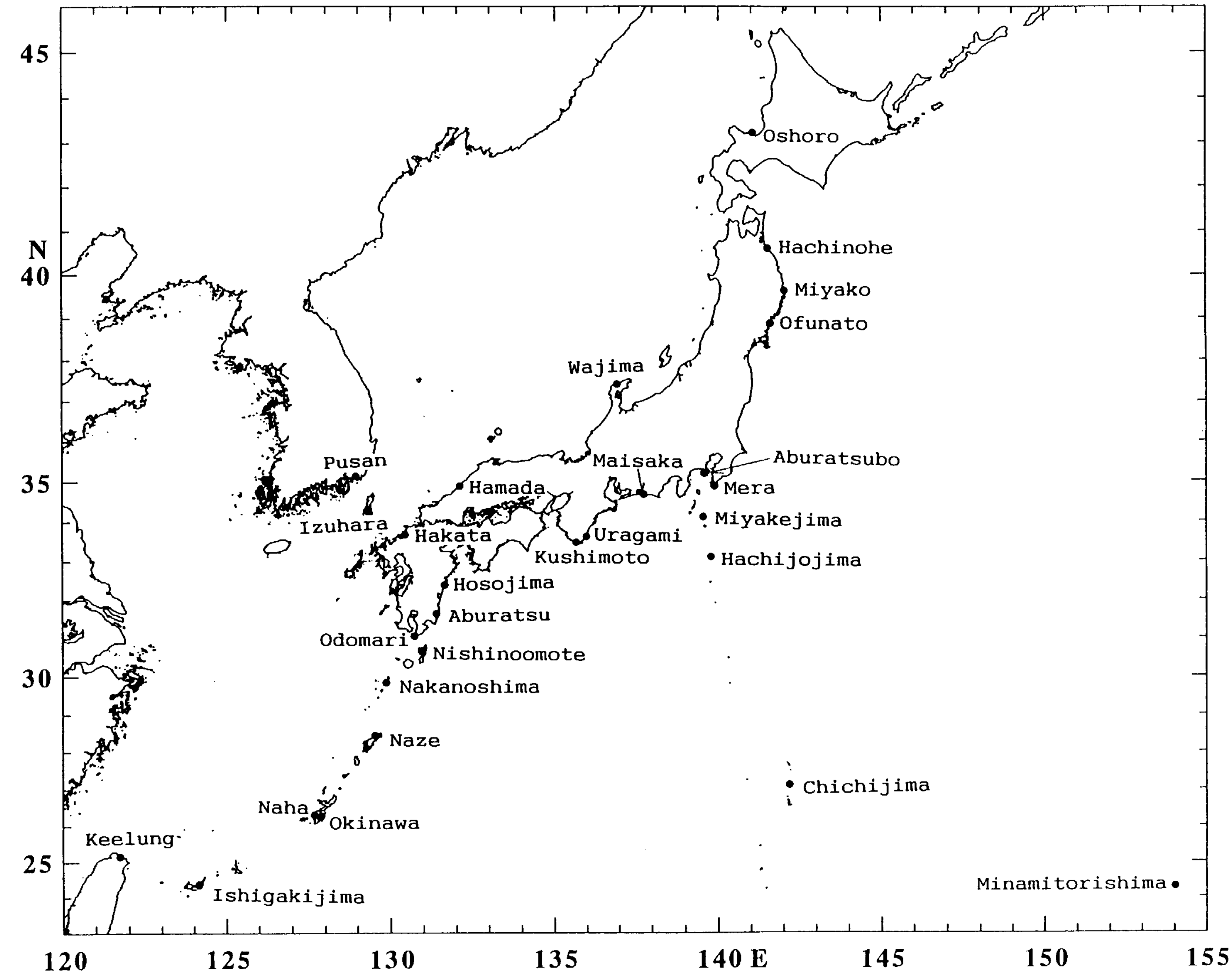
Figure 1. Tide stations for monitoring of the ocean circulation in the subtropical North Pacific, particularly for the Kuroshio and the Tsushima Current.

Figure 2. Tide stations in Japan to be listed for global monitoring, including Pusan (Korea) and Keelung (Taiwan).



Tsushima Current
1. First branch
2. Second branch
3. Third branch
40°N
Pusan
Izuhara
Hakata
Uragami
Kushimoto
nNLM
Miyakejima
oNLM
Hachijojima
Aburatsu
Odomari
Nishinoomote
Nakanoshima
tLM
30°N
Naze
Naha
Okinawa
Keelung
Ishigakijima
Chichijima
Kuroshio
tLM: typical large-meander path
nNLM: nearshore non-large-meander path
oNLM: offshore non-large-meander path
120°E
130°E
140°E
20°N

Figure 1



45
N
40
35
30
25
120
125
130
135
140 E
145
150
155
Oshoro
Hachinohe
Miyako
Ofunato
Wajima
Aburatsubo
Mera
Maisaka
Pusan
Hamada
Miyakejima
Izuhara
Hakata
Uragami
Kushimoto
Hachijojima
Hosojima
Aburatsu
Odomari
Nishinoomote
Nakanoshima
Naze
Chichijima
Naha
Okinawa
Keelung
Ishigakijima
Minamitorishima

Figure 2

Pacific seasonal to interannual variability

C. Koblinsky
NASA Goddard Space Flight Center
USA

In the Pacific, a well distributed grid of sea level gauges have been available for studies of seasonal-to-interannual change for more than two decades thanks in large part to the insight and efforts of Professor Klaus Wyrtki. Following several years when these observations provided arguably the best observations of large scale processes in the Pacific, they are now found to be most useful in validation, data assimilation, and to a lesser extent, forecasting, because of the impact of satellite altimetry and Tropical Ocean Atmosphere Array in this decade.

Recently, attempts have been made to test the utility of sea level gauges in model assimilation systems for ocean circulation. A study by Busalacchi (personal communication, 1997) using a simple linear model suggests that the available tropical Pacific gauges would have the same impact on model solutions as the present network of eXpendable BathyThermograph measurements from Volunteer Observing Ships. Both of these systems are found to complement the denser observations from the TOGA TOA array or TOPEX/POSEIDON. Consequently, the tide gauge data are usually held out of assimilation solutions to provide an independent validation of the result.

Xue has evaluated the impact of tide gauge observations on tropical Pacific climate prediction by using a Markov model (Xue et al, 1994) assuming the lack of other in situ or satellite observations. After "training" the model with data from the 1980 to 1995 period, she is able to demonstrate for the 1970s tide gauges, alone, could permit useful forecast information about tropical Pacific sea surface temperature for about 6 months into the future, after which the prediction skill drops precipitously. For this work, gauges in the western tropical Pacific between +/- 15 degrees latitude are most important in the initialization of the prediction. Followed in importance by gauges in the eastern tropical Pacific and the sub-tropical gauges

As mentioned above, sea level gauges are currently being held out of most ocean assimilations and predictions of Pacific seasonal to interannual variablity to provide validation. This is a very important role because the gauge measurement reflects the integrated sum of the internal temperature and salinity fields which the model systems are trying to simulate. Already this validation work has been extremely valuable to detect model problems in the western tropical Pacific apparently the result of a changing upper ocean salinity field. Secondly, comparisons of monthly anomalies between sea level gauges and either altimetry or tropical Pacific ocean models are showing differences typically of only a few cm rms, so that measurement precision at the gauge must be at a sub-centimeter level.

These model and altimetry validation exercises with tide gauge data have highlighted a few specific issues for the current set of gauges in the Pacific. First, the sites in the Bismarck Islands of the western tropical Pacific, specifically Rabaul, may not be the best position to provide open ocean validation in that region. Drift between the site at Rabaul and altimetry show the known problems of tectonic movement at that gauge. The new site at Manus Island may address this problem. Second, Nauru continues to be an important site because of its location, but it is sometimes not representative of the ocean because of local wind setup. A local model should be developed to filter the problem at the site. Third, discrepancies between altimetry and observations at Kapingamarangi suggest possible rain contamination in the altimetry measurement and this should be examined. Fourth, large islands, such as Fiji and New

Caladonia have local effects that influence the gauge measurement and need to be addressed by local dynamical models that can extend the gauge measurement offshore. Finally, in the North and South equatorial currents the local space and time scales are found to be short around the gauge sites (e.g. Honolulu, Raratonga, Wake) and this needs to be taken account of in the altimetry or model analyses.

In closing, it should be noted that many gauges in the Pacific compare with altimetry to a precision of better than 2 cm rms for monthly averages over more than 4 years. This is a tribute to both observation systems. The combination of these data with in situ temperature and salinity profile data within ocean model assimilation and validation should provide valuable insight into Pacific seasonal-to-interannual variability and benefit future forecasts of climate change.

Application of sea level data in climate modeling

Christian Le Provost
Laboratoire d'Oceanographie et de Geophysique Spatiale
Observatoire de Midi-Pyrenees
France

As noted in the GLOSS implementation plan (section 5.1-3) and in Gornitz's report (section 6b), one very valuable application of sea level tide gauge data is their use for validation of ocean model simulations related to climate variability and climate change studies. Examples of such applications are more numerous now that ocean numerical models are more realistic, and that ocean modelers consider sea level fluctuations as one physical quantity of interest for their studies. Gornitz's report refer to Tokmakian (1996) for global ocean model experiments and Enfield and Harris (1995) for tropical Pacific simulations including data assimilation. Another major example has been given by Koblinsky in his presentation, for ENSO modeling and prediction.

In the present talk, reference is made to a different example related to climate change investigations at mid latitude in the Atlantic ocean, by Ezer Mellor and Greatbatch (1995). In this paper dedicated to an investigation of the interpentadal variability of the North Atlantic Ocean, the authors developed an unusual approach, based on short term simulations but with high resolution, to reproduce the state of the Atlantic Ocean over the periods 1955-1959 and 1970-1974, with model initializations based on Levitus climatological temperature and salinity data of each pentad, and forced by surface wind stress of these pentads derived from the COADS data sets. While the results agree with earlier studies indicating that the Gulf Stream was considerably weaker (by about 30 Sverdrup) during the 1970's, they indicate also some changes in the poleward heat transport. And the sea level along the North American coast is used as an independent indicator to confirm, by comparison with observed sea level at 15 gauge stations, that these climate changes are real.

Models can also be used for the design and for improvements of the sea level gauge network, in climate change perspectives. Although the few available CO2 doubling numerical experiment issued from global AGCM's are not in full agreement between each others, they all seem to indicate that sea level changes will not be the same everywhere over the global ocean, and that enhanced signals will occur in some areas such as the Northern part of the North Atlantic Ocean, or around Antarctica (Gregory,1993). Then the necessity to include in the new sea level gauge implementation plan actions for the settlement of new stations in these remote areas.

Reference has also been made in this talk to a recent paper of Hsie and Bryan, who suggest some ideas on why AGCM results on sea level variation differ from one model to the other : it could be partly due to insufficient resolution along the coastlines, where sea level anomalies propagate as Kelvin waves, and then spread over the ocean as Rossby waves. This study suggest, as a consequence of these mechanisms, that sea level rise estimated from tide gauges distributed along the coastlines will over-estimate by almost a factor of 2, the sea level rise induced by climate change in the Northern North Atlantic, and under estimate the one taking place around the Antarctic Circumpolar Current.

The main messages of this talk are thus:

1) historical sea level gauge records represent a valuable potential for climate change

tests and validation of numerical model studies,

2) outputs from numerical models must help the design of the global sea level gauge network in order to be able to detect possible future sea level rise due to anthropogenic CO2 increase, i.e. including sea level gauge stations over the Northern North Atlantic, and around Antarctica and the ACC,

3) some modeling studies suggest that possible sea level rise estimates resulting from global warming effects, if computed as usually from coastal sea level gauge only, could over-estimate the effects associated with sea level increase occuring in the Northern part of the North Atlantic, and under-estimate the one isuued from the Southern Ocean: a full monitoring of the possible sea level rise need to rely on a global coverage, which is now available from satellite altimetric measurements. Hence the interest of blending the new altimeter datasets with the long term sea level gauge datasets, which offer the potential for combining the synoptic scale informations recently supplied by the satellite data with the historical records of the in situ tide gauge network.

Reference:

Tokmakian,R, 1996. Comparisons of time series from two global models with tide gauge data. Geophys.Res.lett.,23,3759-3762.

Enfield, D.B., and Harris J.E., 1995. A comparative study of tropical Pacific sea surface height variability : tide gauges versus the National Meteorological Center data-assimilating ocean general circulation model, 1982-1992. J.Geophys.Res., 100, 8661-8675.

Ezer,T., Mellor, G.L. and Greatbatch, R.J., 1995. On the interpentadal variability of the North Atlantic Ocean : model simulated changes in transport, meridional heat flux and coastal sea level between 1955-1959 and 1970-1974. J. Geophys. Res., 100, C6, 10559-10566.

Gregory, J.M., 1993. Sea level changes under increasing atmospheric CO2 in a transient coupled ocean-atmosphere GCM experiment, J. Climate, 6, 2247-2262.

A Subset of the Global Tide Gauge Network to Monitor the Drift of Altimetric Satellites

Gary T. Mitchum
Department of Marine Science
University of South Florida
USA

It has recently been shown that the global tide gauge network can be exploited to provide estimates of the drift rate of the sea surface heights from the TOPEX/Poseidon altimeter mission. This work, which has been submitted to the Journal of Atmospheric and Oceanic Technology and is available from the author, concluded that it is presently possible to determine the drift rate with an error bar (1 sigma) of approximately 2 mm/yr. A relatively small part of this error is due to random errors, with most of it coming from possible systematic errors arising from the meridional distribution of the tide gauges used in the earlier study, and from the possibility of land motion contaminating the vertical rates inferred from the tide gauges.

Following a suggestion by Bruce Douglas, I undertook a study to determine an optimum set of tide gauge locations that, when coupled with GPS measurements of the land motion, would allow calculations of drift rates of altimeters in the future to this accuracy or better. Ideally such a set would be relatively small in order to avoid significant costs in maintaining the network while simultaneously determining the drift rate accurately enough to make an impact on the most demanding applications of the altimetric sea surface heights; e.g., the determination of the rate of change of global mean sea level.

A set of 30 stations has been selected that should allow the estimation of drift rates to an uncertainty of better than 1 mm/yr when using 3 years of data. Over 5 years this uncertainty would be of order 0.4 mm/yr; over 10 years it drops to less than 0.2 mm/yr, which brings us to the range where accelerations of the sea level rise rate might be observable. This possibility is quite strong, as the assumptions made in deriving the error bar are rather conservative, especially where the determination of land motion by GPS is concerned.

Narrow Straits, Chokepoints and Constricted Passages

Ken Ridgway
CSIRO, Division of Marine Research
Australia

It has been recognized elsewhere that placing sea level stations in particularly advantageous locations may provide us with extra information. This is particularly true in the case of flow through narrow straits where large-scale phenomena may be compressed into a limited geographical extent. This presents the possibility of monitoring such phenomena with relatively limited resources.

In such circumstances we are exploiting the fact that flow through such straits may be geostrophic whereby the surface currents may be measured and also barotropic which enables the transport to be determined. In practice we find that real situations turn out to be much more complex than the simple theory inherent in these ideas, but they still provide a useful starting point.

Possibly the most important such chokepoint is the Pacific/Indian Ocean Throughflow region. This represents a much more complicated geometry than a simple ocean strait, however the opportunity exists for suitably sited instruments to provide valuable time series of throughflow transport. Many observation programs have been performed over the past 20 years but no clear consensus exists regarding the magnitude of the throughflow transport (Godfrey, 1996).

In broad terms Wyrtki (1987) has shown that the seasonal changes in throughflow transport may be monitored by the sea level difference between the Pacific and Indian Ocean endpoints of the Indonesian archipelago. With our contemporary knowledge this would perhaps best be represented by stations at Manus (PNG) and Darwin (Fig. 1). However, on interannual timescales this station pair is not appropriate as Clarke et al. (1994) demonstrate that Darwin sea level is more typical of the Pacific than the Indian Ocean. Instead at the Indian Ocean end using the sea level record from Cilicap (southern Java coast) would provide a better result. Unfortunately this station has only relatively short duration record and would need to be upgraded.

A very recent experiment has been conducted to determine explicitly the magnitude of the transport through individual deep passages within the archipelago. This has involved the deployment of pressure gauges at either side of the deep channels. Preliminary results from the first 18 months deployment are encouraging (Fig 2). Inferred transports form these pressure differences show fluctuations of order +- 5 Sv with strong correlation between the flow through Lombok and Sumba Straits (Fig. 3). If these results do provide realistic measurements of the throughflow transport then a strong case would be made to maintain these deployments for an extended period. In addition any relationship between the permanent coastal gauges and the pressure gauge results needs to be determined. Arief et al (1996) has shown that 16-100 day band-passed records of currents in Strait and sea level at Cilicap are highly correlated (Fig. 4).

An associated aspect of the throughflow problem is the circulation within the PNG archipelago (the South-western Pacific). A network of gauges installed with high spatial resolution (Fig. 5) has shown that the flow through the individual straits may be monitored (Fig. 6). Of particular interest is the anomalous northward flow (~ 15 Sv) associated with

ENSO which was observed in both the sea level records and XBT derived steric heights (Fig. 7).

The other major chokepoints of widespread interest allow the ACC to be conveniently monitored (Fig. 8). Major monitoring programs beginning in 1979 at Drake Passage and continuing within WOCE have involved deployments of pressure gauges, full depth CTD transects and XBT high density repeat sections. Results indicate that transport fluctuations are mainly barotropic and maybe monitored by sea level or pressure observations (Whitworth et al., 1985, Meredith et al., 1996). In fact the southern side of the passage appears to be most useful for observing transport variations (Woodworth et al., 1996). The most recent results from the WOCE observations indicate that the transport signal is highly correlated on the southern side of the ACC all around.

Finally, sea level measurements have been shown to be very useful in other regions including the Florida Straits, where a high degree of skill is exhibited if sea level results are combined with currents inferred from ocean cables Mayer & Maul, 1991), and the Strait of Gibraltar (Bormans et al., 1986).

References

Arief D. and S. P. Murray (1996) JGR, 101, 12,455-12,464.
Bormans et al (1986) Oceanologica Acta, 9, 403-414.
Clarke A and X. Lui (1994) JPO, 24, 1224-1235.
Godfrey J. S (1996) JGR, 101, 12,217-12,237.
Mayer D.a. and G. A. Maul (1991) JGR, 96, 4971-4972.
Meredith P. et al (1996) JGR, 101, 22,485-22,494.
Ridgway K.R. et al (1993) JGR, 98, 16,387-16,395.
Whitworth T and R. G. Peterson (1985) JPO, 15, 810-816.
Woodworth P. L. et al (1996) JGR, 11,935-11,947.
Wyrtki (1987) JGR, 92, 12,941-12,946.

Coastal Sea Level Data: Can it be important for Tropical Atlantic Variability and Predictability Studies at Interannual and Interdecadal Scales?

Marcio L. Vianna
Instituto Nacional de Pespuisas Espacials
Brazil

The purpose of this talk is to review in a conceptual way the current knowledge about the importance of known Tropical Atlantic Ocean processes to global climate variability, indicating where and how long series of coastal sea-level data can help understanding of these processes and enhance predictability in the regional climate.

It is now well known from both numerical modeling and empirical -statistical studies that at least two regional processes in the Tropical Atlantic Ocean/Atmosphere climate system should be taken into account if predictability of climate at interannual to interdecadal scales is to be achieved:

1. The so-called Tropical Atlantic SST Dipole mode.
2. The El NiÒo-like equatorial mode.

The El Niño-like mode will not be discussed here due to the fact that its physics is somewhat better understood, and it may be considered as the Atlantic counterpart to the well-known Pacific ENSO. On the other hand, variability in the trade wind field and the position of the ITCZ in the region, which depends on the interhemispheric gradient of SST, and presents most of its variance around 12-13 years, has no counterpart in the other oceans, and is the subject of this review.

Basic facts:

(i) EOF and rotated EOF studies of the SST field, both global (i.e., Kawamura, 1994) or regional (Houghton&Tourre, 1992; Mehta & Delworth, 1995, among others), suggest coherent variability at interdecadal scales within the Atlantic basin. A quasi-meridional phase change from equatorial to subpolar latitudes includes a "tropical dipole-TD", but with a slight phase difference between the north and south sides, apparent if one uses rotated EOF's. This difference in detail have caused some debate as to the reality of the TD. Extra-tropical variability is also coherent at these scales, especially on the western side, up to subpolar latitudes.

(ii) However, very recent work has shown that the TD can be simulated by a postulated thermodynamic feedback process between the ocean surface and the overlying atmosphere, where wind-dependent surface heat flux is the basic mechanism through which oscillations in the system are possible at interdecadal scales. The two free paramenters of a simplified Hybrid Atmosphere-Ocean GCM can be calibrated to reproduce oscillations at the 12-13 year period for a true ocean thermal dipole that resembles what is known from observed data (Chang et al, 1997); different calibrations furnish the El NiÒo-like behaviour.This elegant work establishes the concept of variability as due to mixing of two pure modes, as mentioned above.

(iii) One of the important "missing links" among the processes responsible for the evolution of the dipole refers to the ocean dynamics part, whereby the ocean may be the actor in a transition from a present "dipole state" to the next, possibly involving advective heat trans-equatorial fluxes, possibly by western boundary currents and thermohaline shallow meridional cells.

(iv) Recent work (Ezer et al, 1995) has shown, by use of the Princeton Ocean (sigma) Model with coastal-following horizontal coordinates, that coastal sea level is sensitive to variability of the thermohaline structure of the North Atlantic and its circulation. Their study was aimed at, among other things, deriving the thermohaline circulation from the observed hydrography and winds, and used it to find the interpentadal changes (1955-1959 x 1970-1974) in circulation. It also showed a 5-10cm rise in sea level, which could be correlated to a weakening of the Gulf Stream in about 30 sv between the two pentads.

(v) Our own studies (Vianna & Domingues, 1994, unpublished) of detrended and deseasonalized monthly sea level data from the North Atlantic through EOF's indicated that between 1956 and 1987 variability was dominated by the QB-triennial, 4-5 and 12-15 year scale oscillations. EOF no.2 has its maximum loadings over the N.American coast, between Miami and New York, and its Principal Component time series seems to be consistent with dipole index time series (Servain, 1971; Chang et al, 1997), reflecting here, albeit indirectly, that good correlations should be expected between these indices and sea level data from the western Tropical Atlantic. This seems to imply that at least two coastal sea level stations in Brazil, with existing long series (40 y plus), may be useful for dipole process studies: Recife (digitalization of data recently completed) and Fortaleza (digitalization to be done), which correspond to the South and the North sides of the dipole. Both can conceptually contribute to the understanding of the variability of the structure of the North Brazil Current area, which effects the oceanic trans-equatorial advective heat flux.

(vi) The relationship between coastal sea level and open ocean sea level, circulation and heat transport can now be done through use of Topex/Poseidon data, calibrated with good hydrography and modeling, and by current meter moorings in the North Brazil Current area.

(vii) The Pilot Research Moored Array in the Tropical Atlantic (PIRATA-1997-2000) was conceived as a necessary project to implement an ocean-atmosphere observing system for the region, which can obtain data in the monitoring mode which is adequate to address some of these challenges. Its consists of ATLAS moorings, island sea level and met stations, and coastal sea level stations. The scientific teams involved will not only maintain the systems, but distribute the data through the web, in the same manner as the TOGA-TAO systems (by PMEL).The teams will conduct both empirical and numerical model assisted analysis of the present and past data necessary to get some understanding of the complete nature of the processes involved in the dynamics of the regional climate. Expected benefits for Brazil, Africa and the Americas seem to be clearly perceived by local governments, and that is the reason why implementation is starting already in 1997 (PIRATA Document-1997), with the first 5 moorings already funded by the three countries. Projects which go in parallel to PIRATA are also commented upon (VAMOS, ACCE, etc).

The Global Sea Level Observing System (GLOSS)

P.L.Woodworth
Permanent Service for Mean Sea Level
Proudman Oceanographic Laboratory, Bidston Observatory
U.K.

The Global Sea Level Observing System (GLOSS) is an Intergovernmental Oceanographic Commission (IOC) coordinated programme for the establishment of a global network of tide gauges for application to climate, oceanographic and coastal sea level research. GLOSS can be considered a component of the Global Ocean Observing System (GOOS), and particularly as a major contributor to its Climate and Coastal Modules.

Since 1990, when the first GLOSS Implementation Plan was published, progress in GLOSS has been significant, and has been a major stimulus to the improvement in quality and quantity of data delivered to the Permanent Service for Mean Sea Level (PSMSL). GLOSS activities now also include a large number of regional projects and products, and a range of international training courses and materials.

During 1996-97, GLOSS objectives were extensively re-assessed by the GLOSS Group of Experts, resulting in a new Implementation Plan for the programme submitted for approval by the IOC Assembly in July 1997. This re-assessment was necessary in view of the rapid developments in new techniques capable of providing information on sea level changes, such as the Global Positioning System (GPS), absolute gravity and satellite radar altimetry.

The new Plan defines a GLOSS Core Network (GCN) of around 280 gauges distributed worldwide, designed to provide an approximately evenly-distributed sampling of global coastal sea level variations; a GLOSS Long Term Trends (LTT) set of gauge sites (some, but not all, of which are in the GCN) for monitoring long term trends and accelerations in global sea level, these will be priority sites for GPS receiver installations to monitor vertical land movements; a GLOSS altimeter calibration (ALT) set, mostly islands, to provide an ongoing facility for mission intercalibrations; and a GLOSS ocean circulation (OC) set, including in particular gauge pairs at straits and in polar area, complementing altimetric coverage of the open deep ocean. The Plan outlines updated mechanisms for global tide gauge data flow.

A major challenge for the future will be to merge information from the various data sources, old and new, regional and global, within one overall system. Special emphasis needs to be placed on GLOSS developments in certain regions with regard to technical training and science exploitation, to complement the GLOSS global activities.

Coherence of Bottom Pressures around Antarctica

P.L.Woodworth
Proudman Oceanographic Laboratory, Bidston Observatory
U.K.

Since the late 1980s, the Proudman Oceanographic Laboratory (POL) has deployed bottom pressure recorders (BPRs) either side of, and in the middle of, the Drake Passage (DP), as part of the World Ocean Circulation Experiment (WOCE). The object has been to provide information on Antarctic Circumpolar Current (ACC) transports at the DP 'choke point' for comparison to those at the African and Australian choke points. BPR instruments at those locations have been deployed by Dr.Tom Whitworth and colleagues from Texas A&M University.

Meanwhile, numerical model information (e.g. from the Fine Resolution Antarctic Model, FRAM) has indicated:

(i) the relative importance of 'south side' BPRs and of Antarctic coastal gauges for ACC monitoring, and

(ii) the fact that there might be circum-continental coherent signals in BP (or sub-surface pressure
or sea level) data at the few mbar (or cm) level which can be related to transports.

This presentation discusses some of the recent findings from the BP deployments and from tide gauges around the Antarctic coastline provided by several countries. The main feature observed is that large-scale coherence does appear to exist between BPR sites and gauges many 1000s of kilometres apart from low frequencies (e.g. annual) to timescales of order 10 days. The data analysis is continuing, but so far the signals appear to be approximately 2-3 times larger than those suggested by FRAM. While BP techniques are constantly improving (e.g. via the use of air-launched 'expendable' BPRs), the availability and suitability of data from the coastal sites (e.g. Faraday, Syowa, Mawson, Dumont d'Urville and several other GLOSS sites) suggest that they might be the appropriate data sources to concentrate effort upon in future, although perhaps containing a greater degree of near-coastal local 'noise'.

Long Term Trends in Global Sea Level

P.L.Woodworth
Permanent Service for Mean Sea Level
Proudman Oceanographic Laboratory, Bidston Observatory
U.K.

Analysis of data from the Permanent Service for Mean Sea Level by several authors has shown that global sea level may have risen by approximately 10-25 cm during the past century, possibly partly as a result of the general rise in air and ocean temperatures during that time. (See the Second Scientific Assessment of the Intergovernmental Panel on Climate Change, IPCC). This presentation discusses some of the long tide gauge records and the main limitations of the PSMSL data set in providing 'global' estimates. These include the inadequate geographical distribution of the historical data set, and the fact that records of sea level obtained from tide gauges are relative to the level of the local land upon which the gauges are situated. Estimates of rates of vertical land movement at gauge sites, either from geodynamic models of the Earth, or from direct measurements obtained from Global Positioning System (GPS) and other new geodetic techniques, are therefore required (as discussed in detail at a joint PSMSL and IGS Workshop at the Jet Propulsion Laboratory in March 1997).

The presentation discusses some of the issues for monitoring global sea level change in the future, including the need for good spatial coverage of gauges (e.g. through GLOSS), the need to monitor possible 'accelerations' in the longer records, and a 'medium term strategy' for investment in GPS at gauge sites. Some conclusions are:

(1) The PSMSL data set has been used by all authors of long term sea level changes. The likelihood of obtaining extra very long records ('data archaeology') is small (e.g. the Maul et al. study of Key West data) but still very important.

(2) The IPCC review concludes that a 10-25 cm rise has occurred over the past century but that there has been no compelling evidence for acceleration of that trend in that time.

(3) The 10-25 cm is anomalous compared to the average trend over the past few millennia. A filling in of the 'data gap' over the past 2000 years is almost as important as planning for the future.

(4) GLOSS-LTT and altimetry are feasible measurement strategies for the future, together with continued GCM developments in order to understand the climate forcings better and to be able to make better model predictions.