THE FUTURE OF SEA SURFACE HEIGHT OBSERVATIONS

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ABSTRACT *- A brief review of the use of sea surface height (SSH) data for climate-related research is given that serves to identify key constraints on a strategy for obtaining SSH observations in the future. The present status of the SSH observing system is reviewed, and a plan for the future observing system that builds on the present system is developed. We conclude that the technology for maintaining an effective SSH observing system is available now, and given resources, this system can make a significant contribution to CLIVAR.*

1 - INTRODUCTION

There are two primary goals that we wish to accomplish in this paper. First, we want to establish the scientific utility of sea surface height measurements for the study of low frequency variations in the oceans within CLIVAR, and thus to provide a rationale for an ongoing program of observing sea surface height from satellite altimeters and from tide gauges. Obviously, any significant observational effort, and particularly efforts that include large remote sensing components, must be based on solid evidence that the data obtained will be useful, even essential, for the science questions at hand. Second, we also want to use these justifications to provide a sensible set of requirements for how the sea surface height measurements need to be made. That is, we will attempt to answer questions such as : What mix of satellite and in situ measurements is most desirable? Is more than one altimeter required at any given time? What orbit or orbits for the satellite altimeters are most desirable? What improvements need to be made to the in situ tide gauge network? This list of questions is not exhaustive, but is given to provide an idea of the types of questions for which we would hope to provide some input.

We will first review the scientific applications that have been made to date using the existing sea surface height observing system, with emphasis on the results that have become possible in recent years with the addition of precise satellite altimetry to the overall sea surface height observational system. We will focus on the results that are most relevant to low frequency variations in the ocean-atmosphere system, but would like to remind the reader of the wide range of studies made possible with the advent of precise altimetry, including studies in many areas of geophysics and in near real-time monitoring of ocean conditions. We will then briefly review the development of the present observing system, both in situ and altimetric components, and describe the present situation in a bit more detail. This portion of the discussion will conclude with our best assessment of the prospects for continuing and improving the existing system. Finally, based on the science requirements that we will develop in the first section, and based on the capabilities that we now know are obtainable in sea surface height measurement, we will outline a set of requirements for the future observing system that we believe will continue and expand the present successes into CLIVAR and beyond.

2 - SCIENTIFIC JUSTIFICATION AND RATIONALE

We will begin by making some basic definitions. Sea surface height (hereinafter SSH) is strictly speaking only measured by the satellite altimeters. The SSH is the deviation of the vertical position of the sea surface relative to a known reference surface. Ideally, this reference surface is the oceanic geoid, but in practice it is commonly the mean of the SSH variations relative to an arbitrary reference ellipsoid computed during a specified time period. In this case the reference surface includes the geoidal height and the mean topography associated primarily with the geostrophically balanced portion of the steady ocean currents, as discussed, for example, by Wunsch and Stammer (1998) and Fu (1999). The reason that the geoid is not used as the reference surface is simply that the errors in the present geoid are of order 10 cm at scales (half wavelength) longer than 1000 km, which are too large to allow high quality estimates of the mean oceanic dynamic topography. This should change in the future, however, with the launch of several missions concerned with the oceanic geoid, such as GRACE (Wahr et al., 1998), GOCE (see http://saturn.srzn.ruu.nl), and CHAMP (see http://www.gfz.potsdam.de/pb1/CHAMP). These missions promise to reduce the geoid errors to order 1 cm on scales longer than 100 km, which is sufficient to allow direct determination of the absolute topography associated with western boundary currents, for example. The ability to directly observe absolute geostrophic currents should have a large impact on mass and heat balance studies as well.

Sea level, on the other hand, is measured by tide gauges, and it is generally useful to think of these measurements as simply the value of SSH at the ocean/land boundaries. This is not quite appropriate, however, as the reference surface for the sea level variations is not the same as that for the altimetric SSH observations. The reference level for the sea level data is the height of the adjacent land, and these levels are not easily transferred into any global reference frame. Also, if the land is not vertically stable, the reference level is changing in a way that is not known precisely. This situation is changing, however, with the advent of satellite geodesy techniques, as will be discussed briefly below. While we want to remain aware of these differences, for our present purposes we will consider sea level and SSH to be measurements of the same physical quantity, and will refer to both as SSH measurements.

What does SSH respond to? If we specify what physical processes have a signature in the SSH variations, then we can in principle invert the SSH data to obtain information about these same physical processes. The richness of phenomena that SSH responds to is simultaneously the blessing and curse of these data. An excellent discussion along these lines was given a number of years ago for sea level data by Chelton and Enfield (1986), and that discussion applies equally well to SSH observations from altimeters. A more recent review that gives an idea of the breadth of phenomena affecting SSH, but which focuses more on SSH from altimetry, is given by Fu (1999). For the moment we note that low frequency SSH changes are associated with variations in surface geostrophic velocities via the geostrophic balance, with changes in the heat content of the upper ocean, and with changes in the total ocean volume that might accompany increases or decreases of grounded ice mass, for example. All of these types of variations are of direct interest to CLIVAR studies on time scales of interannual to decadal to centennial and beyond.

Most readers will know that tide gauge sea levels have long been used for these purposes. For example, Mitchum and Wyrtki (1988) provide a review of studies in the Pacific, and additional information is also available (e.g., IOC, 1997). Some readers may not know, however, that despite the fact that the T/P time series are still less than 10 years in length, an impressive set of studies has already been done that contribute significantly to climate-related research questions. While we do not have space to do an exhaustive review of these studies, other reviews do exist for the reader interested in a more complete set of references. A good starting point for a review of the science questions addressed with the T/P data might be the second special issue of the Journal of Geophysical Research - Oceans (December, 1995) that was dedicated to the initial science results from T/P, or the special issue of the AVISO Newsletter (No. 6 in 1998) that described ongoing studies using the T/P data. Since that time much progress has been made, and useful reviews that focus on circulation results and issues relevant to climate variability have already been given (i.e., Fu, 1999; Wunsch and Stammer, 1998). A glance at any of these sources will immediately reveal the broad range of science questions that have already been addressed using these data, including tidal studies, geodetic studies, problems concerning the Earth's gravity field, and studies of surface gravity waves from the significant wave height data obtained from T/P. Recently, an emphasis on making operational uses of the altimetric data has developed and a major conference on this topic was held in Biarritz, France in October 1997. For a summary of some of these efforts to make the altimetric data available in near real-time, and to make operational use of these data, additional information is available on the World Wide Web at http://ibis.grdl.noaa.gov/SAT/near_rt and at http://www.cls.fr/duacs.

Focusing now on research that is most directly relevant to climate variability, we will discuss three particular areas of inquiry that should illustrate the desirability of having a precise sea surface observation system in place in the future. These three areas are studies of the ocean mesoscale variability, studies of the interannual variability associated with the ENSO phenomenon, and attempts to make estimates of the very low frequency changes in global mean sea level, that is, to measure the global sea level rise rate from the combination of altimetric and sea level data. We realize that these choices are somewhat arbitrary, and we could instead focus on variations of the Antarctic Circumpolar Current or the North Atlantic Oscillation for example, but in the interest of space we will address only these three. While the latter two questions concerning ENSO and volume change are obviously climate questions, the inclusion of the ocean mesoscale variability is somewhat more subtle. The reason for including it, though, is simply that the energy exchanges between the oceanic eddy field and the mean circulation of the ocean are of significant importance, and until these exchanges are either observed directly and assimilated into ocean models, or understood well enough to make appropriate parameterizations, it is unlikely that climate models will simulate the mean circulation well enough that we could trust the predictions the models make concerning decadal or longer variations in the ocean circulation. There is another reason for considering the mesoscale as well. Recently, Tierney et al. (1999) and Stammer et al. (1999) have demonstrated that this small scale energy can be aliased in the T/P data in certain parts of the ocean, and this possibility must be addressed in order that the analyses of low frequency variability from altimeters can be trusted.

The description of the mesoscale energy distribution with satellite altimetric heights has a long history, dating back to an early estimate from Seasat (Cheney et al., 1983). For readers not familiar with these types of descriptions, a map of the temporal variance of the T/P SSH field, which is often used as a proxy for mesoscale energy, is shown in Fig. 1. Of course, similar maps can be made from other altimeters, such as ERS-2, and a product making use of multiple altimeters would have definite advantages. More recently, seasonal modulations of the eddy energy distribution have been made (e.g., McLean et al., 1997; Stammer and Wunsch, 1998), and increasingly, studies of the eddy field variability have more directly attacked the problem of how these variations affect mean flows, as is the case with the study of Qiu (1995), for example, who investigated the dynamics of the Kuroshio Extension in the North Pacific using the T/P data. There has also been progress in studying mesoscale motions near continental margins, for example, along the U.S. west coast by Strub et al. (1997). As a final example, the wavenumber spectrum inferred from the nearly continuous alongtrack data from T/P was used by Stammer (1997) to make an evaluation of geostrophic turbulence ideas, among other things. Again, these examples are not a complete survey of the studies that have been done, but are only intended to give an idea of the progress that has come in the general area of mesoscale variability because of the unique data resource provided by satellite altimetry in the past decade. Further discussion of these issues can be found in Le Traon and Morrow (1999).

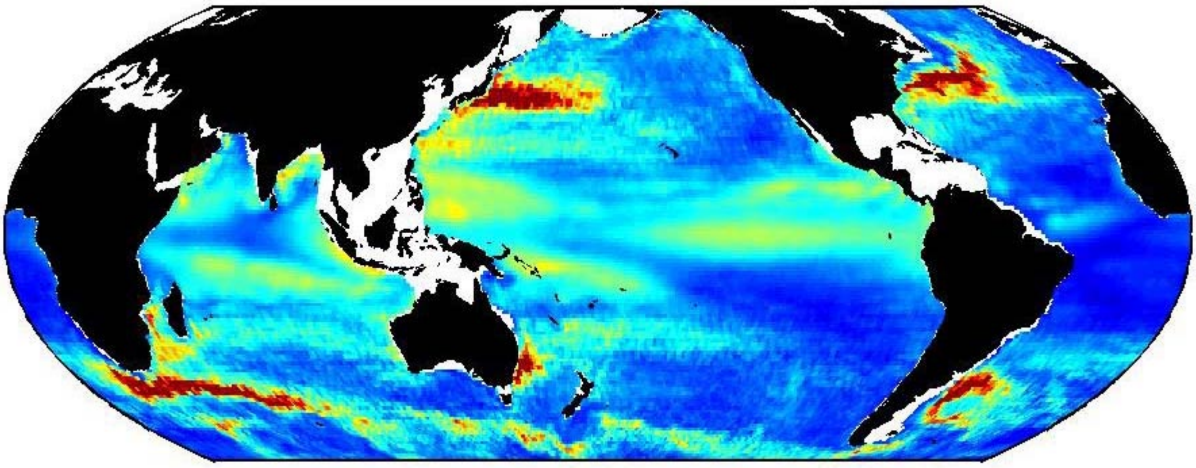

Figure 1 : SSH variance from T/P. The T/P data are first gridded to regular maps at 10-day intervals. The root mean square values of the SSH variations at each spatial grid point are then computed over the period September, 1992 to May, 1999, and these are shown on the figure. The color scale starts at 0 (blue) and saturates at a value of 20 cm (red).

The study of ENSO has a similarly rich history despite the relative brevity of the altimetric time series. The first two years of the Geosat exact repeat mission happened to fall during an almost ideal time period for such studies. The first year of this period spanned the 1986-1987 warm event, while the second year captured a very distinct cold event during 1987-1988. Descriptions of the sea surface height field associated with the ENSO event were made (e.g., Miller et al. 1988; Cheney and Miller, 1988), and more importantly, the spatial coverage of the altimetric data was exploited to quantitatively examine a hypothesis by Wyrtki (1985) that the ENSO events resulted in a net transport of mass from the tropics to higher latitudes in addition to the well-known flux of mass from west to east across the Pacific (Miller and Cheney, 1990). Such a poleward transport was not observed in the Geosat data, and this result was supported by an independent analysis of the TOGA-TAO data by Springer et al. (1990). More recently, using the T/P data, studies have addressed the persistently anomalous conditions during the early 1990's as well as the very strong ENSO event of 1997-1998 (e.g., Boulanger and Menkes, 1999), and much more work is ongoing. The advantage of the complete spatial coverage afforded by the altimeters for observing and describing ENSO is illustrated in Fig. 2, which shows a snapshot of the SSH anomalies during the height of the 1997-1998 event, and this advantage will doubtlessly result in further improvements in our understanding of this climatically important phenomenon.

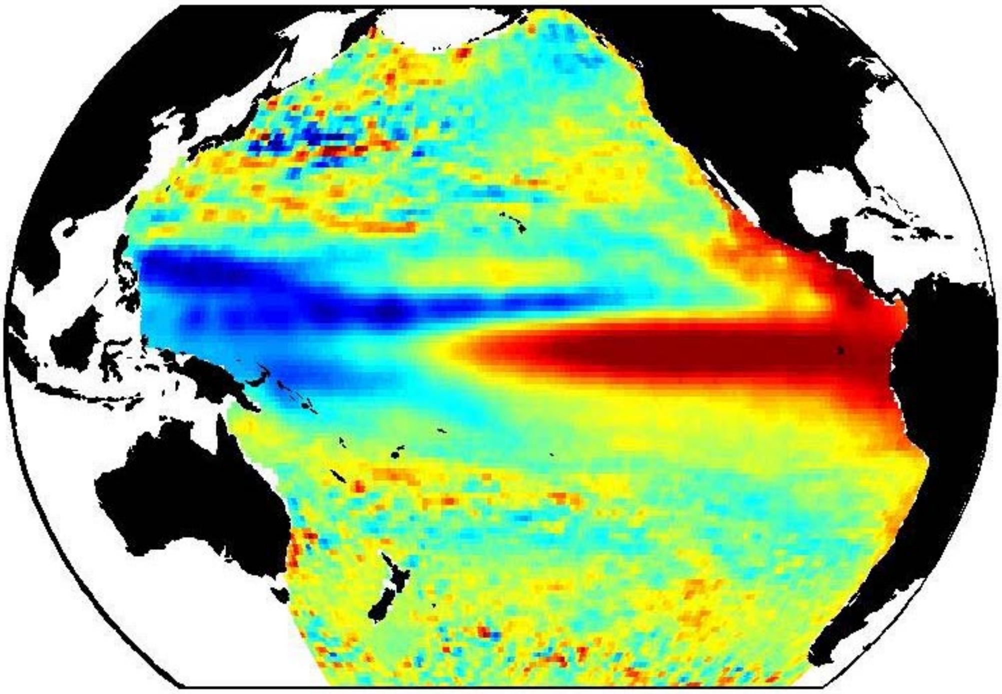

Figure 2 : The SSH height anomaly field in the tropical Pacific during the height of the 1997-98 ENSO event. SSH deviations are computed relative to the mean conditions, including the mean seasonal cycle, during 1993-1996, inclusive. The map shows the mean of the deviations from July through December of 1997. High sea level is shown as red; low sea level is blue. The color scale saturates for SSH anomalies of 25 cm magnitude.

The final climate signal that we will briefly review concerns efforts to measure global sea level rise rates from altimetry. Although it may seem obvious that altimetric time series are too short to address this problem, and that the global tide gauge network determinations (e.g., Douglas, 1991 and 1995; Warrick et al., 1996) of the rise rate cannot be improved upon, this is not necessarily the case. The reason is that the altimetric data, again because of the nearly complete spatial coverage, can make a sensible estimate of the global average SSH at a point in time, thus allowing signals that correspond to simple redistributions of ocean mass to largely cancel out, leaving only the signals that correspond to the ocean volume fluctuations that are of more direct interest for some climate change studies. Calculations of this type have been done by various groups (e.g., Nerem, 1995; Minster et al., 1995; Cazenave et al., 1998; Nerem et al., 1999), and a recent summary of these calculations has been given by Nerem and Mitchum (1999). A somewhat surprising result from the T/P calculations of the globally averaged SSH trend is that the globally averaged SSH time series contains a significant signal associated with the 1997-1998 ENSO event that is consistent with a net warming of the ocean during the event (Nerem et al., 1999). This is illustrated in Fig. 3, and we note that the reasons for this warming are not well understood at present.

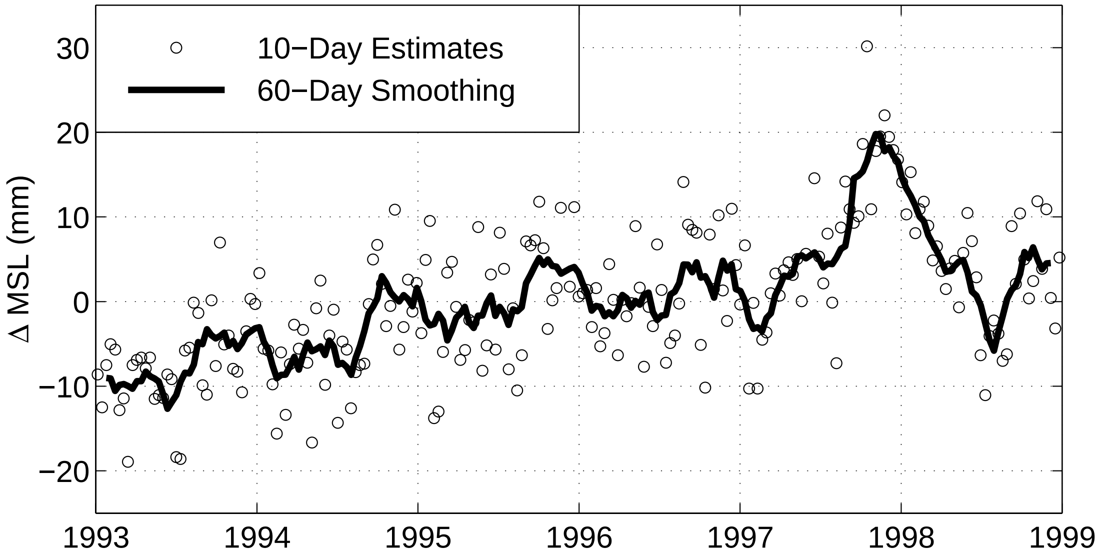

Figure 3 : Time series of the global mean sea level computed from T/P (after Nerem and Mitchum, 1999). The mean sea level estimate is computed for each 10-day T/P cycle, and these points are shown by open circles. The solid curve is a 60-day running mean of the 10-day points that emphasizes the low frequency variability in the curve.

Another reason for mentioning these volume change studies is that the altimetric time series must be very stable in time in order for altimetric estimates of SSH to be useful in this context. That is, the bias, or drift, errors must be controlled very carefully, or in tide gauge terminology, we must have very high quality datum control. The necessity of monitoring errors such as these has led to the development of altimetric drift estimates from the global tide gauge network (Mitchum, 1998; IOC, 1997), and provides an excellent example of the synergistic use of the two components of the overall sea surface height observing system. If the altimetric series can be maintained to a standard that allows these ocean volume calculations to be done, then the SSH series will almost certainly be stable enough for studies of variability at interannual to decadal scales. In this sense, the global sea level rise rate applications set the standard for the altimetric error budget, while the mesoscale energetics applications set the standard for the spatial and temporal resolution required of the SSH observing system.

The above brief consideration of the signals that can be addressed with precise altimetric heights supported by in situ sea level observations allows us to identify the critical factors that will result in data of maximum utility for climate studies. First, based on the signals that we have discussed, we conclude that we require data of T/P quality in terms of precision and accuracy, and we assume that the altimetric data will be supported by appropriate in situ sea level data. The in situ data are necessary to monitor the precision and accuracy of the altimetric heights, with accuracy being defined here in terms of freedom from low frequency drift errors, and are also required to place the relatively short altimetric series into a longer term context. This latter application is what was referred to in the World Ocean Circulation Experiment (WOCE) as determining the "representativeness" of the WOCE data that were collected during a similarly brief time period. Also, tide gauge data can usefully supplement the altimetric data in some critical places, such as ice covered regions and across straits and narrow western boundary currents. Second, based on the need to resolve the mesoscale variations and to study the effect of these fluctuations on the energetics of the mean circulation, we also conclude that the spatial and temporal resolution required is set by the need to directly observe the mesoscale variability to a degree that allows, probably in conjunction with assimilative numerical models, a proper description of the oceanic eddy field and the interactions of this field with the mean field.

This latter constraint, which concerns the spatial and temporal resolution of the SSH system, means that we must be able to resolve signals that occur at spatial scales on the order of several oceanic Rossby radii, and on time scales of days to weeks, which cannot presently be done with a single altimeter. The important question is how many altimeters must be available at any given time, and what orbits should these satellites occupy? The answers to these questions are not known at this time, but various simulations are being done. For example, Jacobs et al. (1999) have estimated that three altimeters are needed to directly observe the mesoscale variations without additional statistical or dynamical model input. If assimilative models are used, however, two satellites are adequate. In a different set of simulations, Le Traon and Dibarboure (1999) conclude that most of the improvement in reproducing the mesoscale variability is obtained in going from a single altimeter to two flying simultaneously. Adding additional altimeters improves the results, but to a lesser degree. It is clear that at least two altimeters are required, and that three coordinated missions would almost certainly suffice, but the optimal number is still under study, and likely depends on economics to a large degree. We should note, however, that these studies assume nadir altimeters, and the conclusions could change significantly if a swath altimeter (see below) becomes available.

3 - MEASURING SSH : HISTORY, STATUS, AND FUTURE PLANS

The development of satellite altimetry as a tool for studying ocean circulation began in the 1970's with the Skylab and GEOS-3 instruments in the early part of the decade, and the potential was clearly illustrated by the Seasat mission in 1978. Following these "proof of concept" missions, Geosat was launched in 1985 by the U.S. Navy in order to better specify the oceanic geoid. Fortunately for oceanographers, after this geodetic mission was completed, the satellite was manuevered into an exact repeat orbit with a 17-day repeat period and the data were made available to the oceanographic community. The timing was especially fortuitious, since the repeat track portion of the mission came in time to clearly observe the ENSO event of 1986-1987 and the subsequent La Nina event in 1987-1988. After the failure of the Geosat time series, which came several years past the planned lifetime of the satellite, there was a short gap until the European Space Agency launched an altimeter on ERS-1, which also carried a suite of other sensors. ERS-1 spent a significant portion of time in a 35-day repeat orbit, and these are the ERS-1 altimetric data most often used by oceanographers. Building on the successes of Geosat and ERS-1, there were subsequent launches of ERS-2 in 1995, which has been maintained in the ERS-1 35-day repeat orbit, and the Geosat Follow-On in 1998, which continues the 17-day repeat orbit occupied by Geosat during the oceanographic phase of its observations.

The TOPEX/Poseidon (T/P) mission, which was launched in 1992 as a joint U.S./French project and continues at present in a 10-day repeat orbit, was the first mission specifically dedicated to making precise altimetric measurements of SSH for the purpose of studying the global circulation and its variations. T/P was designed with a dual frequency altimeter and a water vapor radiometer for making the best estimates of the effective index of refraction along the satellite to ocean path. The orbit for T/P was carefully chosen in order to insure that the largest tidal constituents would be aliased to relatively high frequencies, thus enabling much improved tidal analyses after launch (see for example the special issue on Tidal Science that appeared in Progress in Oceanography in 1997). The precision orbit determination effort was unprecedented, with significant effort prior to launch aimed at improving knowledge of the Earth's gravity field and at developing models for the drag forces acting on the satellite, and with the postlaunch addition of global tracking data from the DORIS and GPS systems. These efforts resulted in a dataset that significantly exceeded the prelaunch error budget, as summarized by Fu et al. (1994), and improvements continue to be made. For those readers interested in more detail about the T/P mission, and in the precision estimates in particular, the first T/P special issue in the Journal of Geophysical Research - Oceans in December, 1994 is an excellent starting point.

The situation at present regarding ongoing altimetric measurements is as follows. T/P continues to return high quality data and the time series is approaching 7 years in length at the time of this writing. ERS-2 is also continuing to produce data that is nearly of T/P quality. Having these two altimeters in orbit simultaneously has proven to be a unique advantage. The spatial-temporal sampling is improved using both datasets, and the quality of the T/P dataset has proven useful in improving the orbit estimates for ERS-2 (LeTraon and Ogor, 1998) and in evaluating the basic precision and accuracy of these data. In turn, the measurements from ERS-2 have been used to evaluate potential problems with the T/P instruments. It is clear that multiple altimetric instruments are complementary rather than redundant, as discussed in the previous section. For example, higher resolution versions of Fig. 1 can be produced.

So what does the future hold? After the success of the present missions, it might seem obvious that precision altimetry would continue, but that may be overly optimistic. Continuation of the T/P time series seems fairly certain, with JASON-1, again a French and U.S. collaboration, scheduled to launch in 2000 and to occupy the T/P groundtrack. JASON-2, scheduled for 2004, could pave the way for a series of JASON satellites that is the most promising proposal for continuing the high accuracy of the T/P data. The European Space Agency's ENVISAT is scheduled to launch in early 2001 and will be in the same orbit as the ERS series. These missions, if all go forward, could carry the T/P and ERS time series through to 2005, and possibly to 2010, although that is probably overly optimistic as it assumes approval of JASON-2. Starting around 2010, the U.S. plans to include an altimeter as part of the National Polar-orbiting Operational Satellite Series (NPOESS), although it is not yet clear exactly how this would best be accomplished. The possibility of a free-flying altimeter has been raised, but it is more likely that the altimeter would be carried on one of the main NPOESS satellites because of cost issues. There are valid concerns about the quality of the data that could be obtained by such a configuration, however, and thus these issues are still the subject of continuing study. Finally, for completeness we note that there may be a satellite altimeter onboard the Indian satellite OCEANSAT-2 in 2003 or 2004, although this has not been confirmed and we do not know any details about this instrument at this time.

In addition to these continuations of the present time series there are also technological developments on the horizon that are potentially very exciting. First, as part of the NASA Instrument Incubator Program, a project has been funded at the Johns Hopkins University's Applied Physics Laboratory (Raney, 1998) to develop a low-power altimeter that is light enough to enable multiple altimeters to be placed into orbit from a single launch vehicle. Second, CNES in France is also investigating low cost altimeter missions on microsatellites as part of their ALTIKA project, which has proposed a Ka band (35.75 GHz) altimeter with a radiometer and possibly with DORIS tracking. Finally, an alternative to multiple satellites may be possible with the development at the JPL in the U.S. of a wide swath altimeter that obtains SSH measurements not only at nadir, which is the situation with all present altimeters, but along a swath of order 200 km total width. Preliminary estimates, which are probably conservative, indicate that the errors should be comparable to T/P at nadir and increase by roughly a factor of two at the ends of the swath (Rodriguez et al., 1999). It is possible that an experimental version of this swath altimeter might be flown as part of the JASON-2 mission.

We also need to consider the status of the tide gauge component of the SSH observing system. A major advantage of the sea surface height observing system is that the remote sensing component, satellite altimetry, is complemented by one of the most comprehensive set of time series of analogous in situ data available for any physical parameter. These are the tide gauge sea levels, of course, which are taken to be measurements of the SSH at ocean boundaries and islands, as discussed earlier. Instrumental sea level records from tide gauges exist back to the 19th century, and records exceeding 50 years in length are not uncommon (Fig. 4), although the spatial distribution of these long records is less than optimal for global climate studies, with most of the long time series found in Europe and along the coasts of North America. But having these long in situ records allows us to do things in climate studies that would not otherwise be possible, such as examining the longer temporal context for any signals observed in the altimetric record of SSH. One example of this is the work by Johnston and Merrifield (1999), who used a combination of the spatial information from altimetry and the temporal strength of the tide gauge series to describe interannual variability in the strong zonal circulation in the tropical Pacific. In addition to providing this link to the past, the tide gauges also bolster the altimetric data in ice covered areas, and across narrow straits and currents (IOC, 1997).

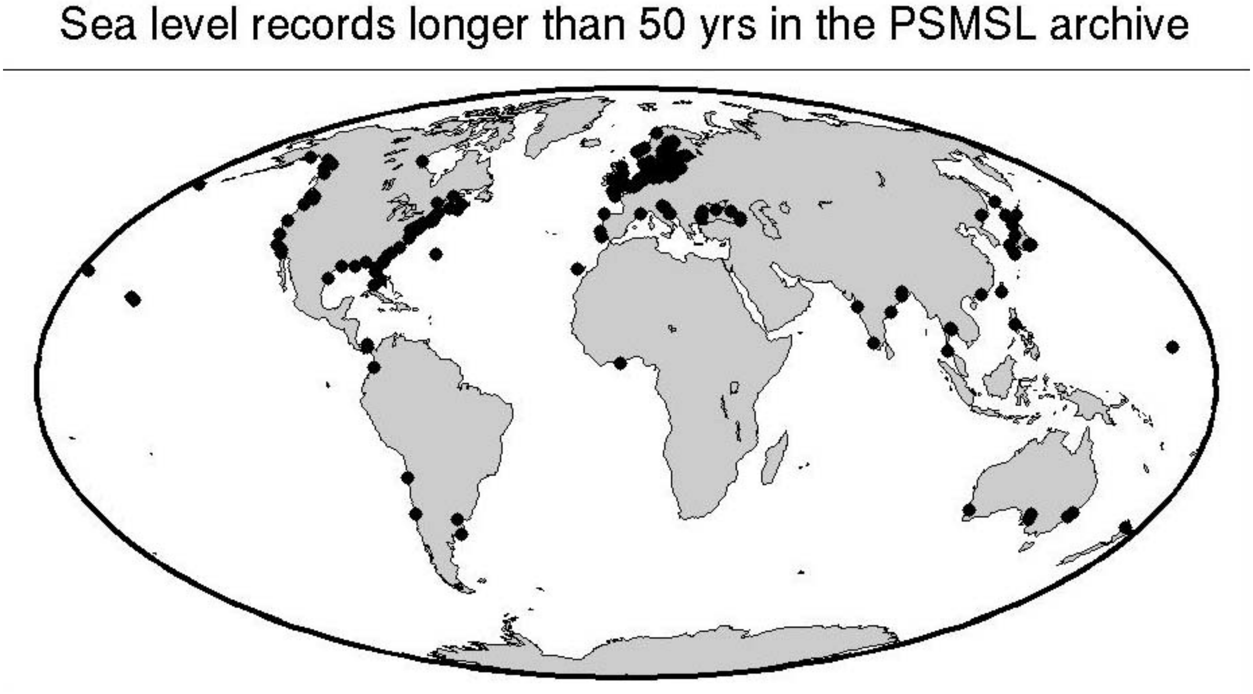

Figure 4 : Sea level stations from the PSMSL dataset that have at least 50 years of monthly mean data available.

Historically, the sea level data used by most researchers have been the monthly mean sea level values collected at the Permanent Service for Mean Sea Level (PSMSL) of the International Council of Scientific Unions. Contributors from many countries compute the monthly means from high frequency observations and send these data to the PSMSL. These activities are complemented by an international program of the International Oceanographic Commission called the Global Sea Level Observing System (GLOSS) that exists to monitor the development of the global sea level system and dataset. At the time the PSMSL was established, simply collecting monthly means was the only manageable system, and consequently the high frequency data were generally not archived at any international center, and are often difficult to obtain. Even worse, in some cases the high frequency data exist only in paper form and are in danger of being lost. This situation is changing, however, and in recent years many of the high frequency records have been collected and made available thanks to contributions to GLOSS by the Tropical Ocean Global Atmosphere (TOGA) and WOCE projects. For example, at present over 100 stations are available in near real-time from the University of Hawaii Sea Level Center (Fig. 5). GLOSS has expanded to encompass these activities, and now includes the GLOSS Core Network of approximately 300 stations, the GLOSS Long-Term Trends network, and the GLOSS-ALT network that focuses on issues related to altimetry. IOC (1999) gives a complete overview of GLOSS and of all of these activities.

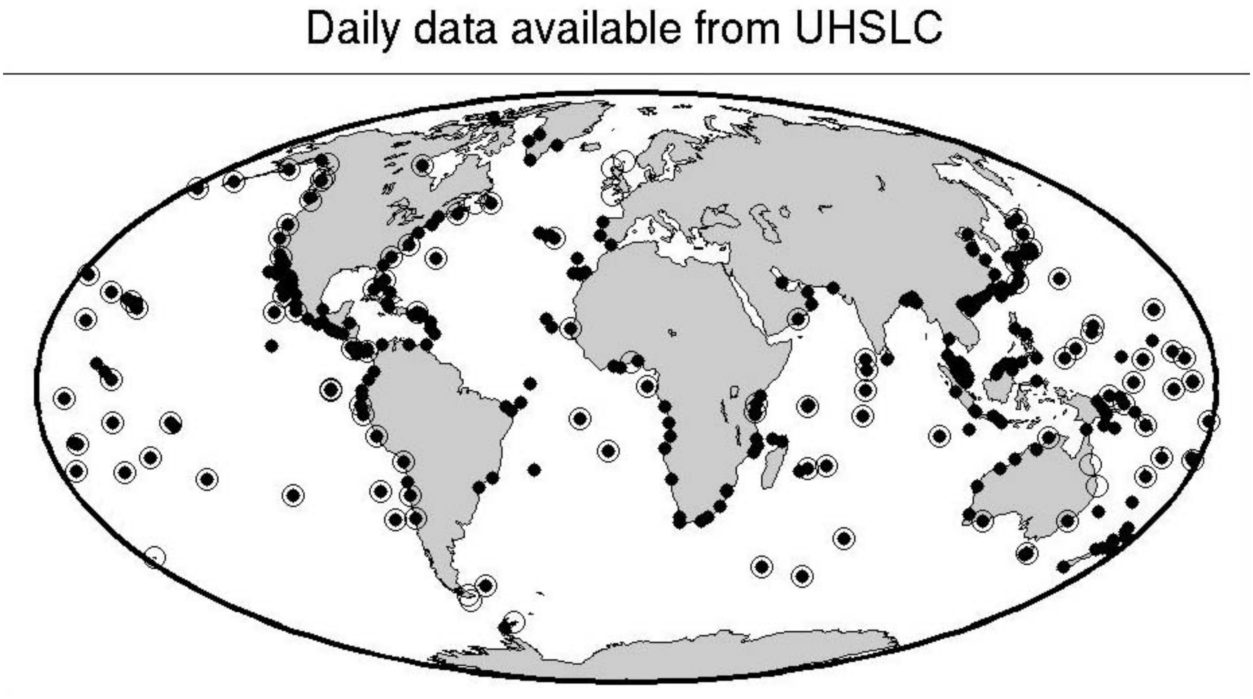

Figure 5 : Sea level stations where daily data is available from the University of Hawaii Sea Level Center. Note that all stations are shown regardless of the record length available, and few of these records approach the 50-year lengths shown in the previous figure. The stations shown with open circles report daily data in near real-time (i.e., after 1-2 months).

The future plans for the tide gauge network are focused on maintaining and improving the quality of the present network, which is largely complete in the sense that most of the GLOSS gauges are presently operational. It must be noted, however, that there are significant needs for modernization and upgrading at many sites, and finding resources for maintenance is an ongoing concern. There are specific ways in which the dataset can be upgraded to better serve the overall SSH observing system. First, easy and quick access to the available high frequency data is essential for the joint use of these data with the altimetric data. A plan exists for doing this (IOC, 1997), and implementing that system is important. Second, recovering and archiving the high frequency data from which the monthly means were computed is important because it enables significant improvements in the quality assurance of the monthly mean data. In some cases this simply means archiving the data in international centers as called for in the GLOSS plan (IOC, 1997); in other cases it may involve data archaeology efforts to recover and digitize the original paper recordings of the sea level. Third, and most important, we need better geodetic controls on the tide gauges, as discussed at length elsewhere (e.g., Neilan et al., 1998). As we examine lower frequency signals, which are often of smaller amplitude than the signals studied in the past, uncertainties due to land motion are of greater importance. This is especially true for the use of the tide gauges to monitor altimeter drift, as we will discuss more fully in the next section.

4 - SETTING REQUIREMENTS FOR THE FUTURE SSH OBSERVING SYSTEM

Based on the foregoing discussion, we argue that in order for the future SSH observing system to be able to address climate issues we need to require data of a comparable precision to the T/P data in at least one groundtrack, and we additionally argue that this should be the T/P groundtrack. Additional coverage is necessary to properly describe the energetic variations associated with the oceanic mesoscale motions, which will require either more than one altimeter to be available at any given time, or the development of the swath altimeter. Also, in order to address the relatively small amplitude signals associated with decadal variations, and to address very low frequency sea level change as the time series lengthen, it is necessary that these time series be very stable. That is, the data must also be accurate in addition to being very precise. This requirement strongly suggests that the T/P time series be maintained into the foreseeable future. Thus, in this section we will review the precision of the T/P data, which we propose as a benchmark for the future missions. We will then review the accuracy requirements, in the sense of what is required in order to detect and possibly correct small amplitude drift errors in the altimetric series. This naturally leads to a consideration of some future requirements for the tide gauge portion of the SSH observing system.

For the discussion of the T/P precision, we start by noting that based on the papers describing the results of the T/P geophysical evaluation period following launch, Fu et al. (1994) prepared a postlaunch estimate of the precision of the T/P measurements. These results indicated an error estimate for TOPEX, excluding tide model errors for the moment, of 4.7 cm, while the analogous precision estimate for Poseidon was 5.1 cm. These error estimates apply to the 1 Hz T/P data, which in turn correspond to a 6-7 km alongtrack separation. T/P data that have been averaged spatially and/or temporally will of course have smaller errors. Significant improvement has come in the time since launch, especially in the orbit determinations (Tapley et al., 1996), and the present error estimates are 4.3 cm and 4.6 cm for TOPEX and Poseidon, respectively, again for the 1 Hz data. To put these precision estimates into perspective, Fig. 6 shows the errors estimated for various altimeters from GEOS-3 to T/P, which shows especially well the large reduction in the orbit errors over time.

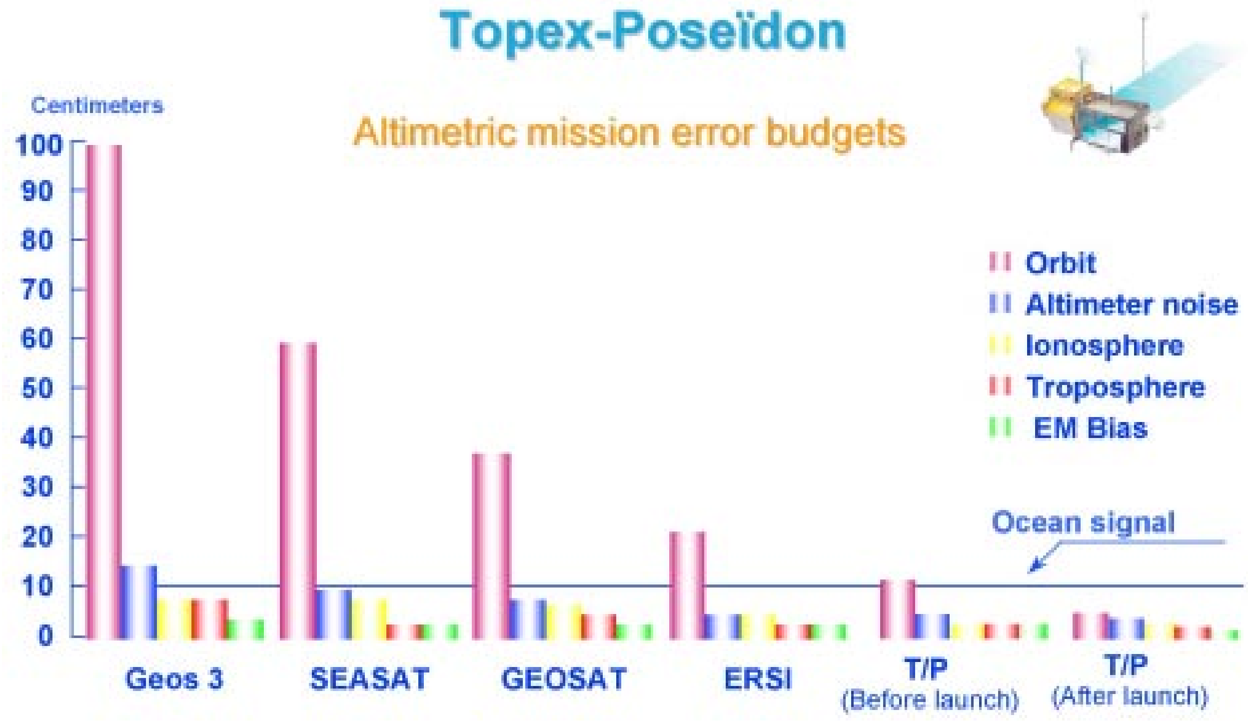

Figure 6 : Error estimates for various satellite altimetry missions from GEOS-3 to T/P. Note especially the large decrease in the orbit errors, from nearly a meter for GEOS-3 to order 3 cm for T/P. These error estimates correspond to the high frequency data from the altimeters (typically 1 Hz), and errors are smaller for spatially and temporally averaged data.

These precision estimates do not, however, include errors due to the models used to remove tides from the SSH data. These tide model errors have similarly decreased during the T/P mission, mainly due to the use the T/P data to make direct estimates of the tidal parameters along the groundtrack. At the time of the Fu et al. (1994) summary, typical tide model errors were estimated to be of order 3-5 cm, with much larger errors in some locations, but these errors have since been reduced to 2-3 cm (Shum et al., 1997). Hydrodynamic modelling efforts have also progressed significantly, and assimilation of the T/P into these models is being explored as well (e.g., Egbert, 1997; Le Provost et al., 1998; Tierney et al., 1999). It is important to note that the reduction of the tide and orbit errors is largely due to having a long time series on a single, well-designed groundtrack. If the T/P groundtrack is abandoned, there is no guarantee that we will be able to do nearly so well until another long time series is assembled, which is one of the primary arguments for maintaining the T/P series, of course.

An obvious way to make an overall assessment of the precision of the T/P system for producing sea surface heights is to compare these heights to sea level measurements from tide gauges. One comparison of this type (Mitchum, 1994) was carried out shortly after the launch of the T/P satellite, for example. Those results were obtained without any temporal averaging, and thus apply to the highest frequency data that T/P returns. This comparison indicated that the overall precision of the T/P data was typically 3-4 cm. Cheney et al. (1994) did a similar analysis, but averaged the data to monthly time scales. These results led to error estimates of order 2 cm, indicating that much of the error in the T/P system is uncorrelated temporally and therefore averages down nearly as fast as white noise. Even more encouraging is that the fact that in the time since these studies were done, the T/P data have improved, and similar calculations now show errors of less than 3 cm for the highest frequency data, which is almost a factor of two reduction in the error variance. An example of a recent T/P and tide gauge comparison is shown in Fig. 7, which shows the tide gauge record at Christmas Island in the central tropical Pacific and the analogous T/P sea surface height series in the vicinity of the island. This comparison uses data from 8 T/P passes near the island, and an effort is made to account for spatial and temporal lags between the sea level data and the T/P data, due to propagating signals for example, and the T/P data from the different passes are also weighted appropriately in forming the best T/P SSH series to use at the gauge location. This comparison is somewhat better than the globally averaged result, giving an rms difference between the series of 1.9 cm for the 10-day cycle data and 1.3 cm for monthly averaged data (not shown), but it is not particularly unusual for island stations in the tropical parts of the oceans.

So what do we conclude from this discussion of the precision of T/P? Since we require that this precision is necessary in the future, we need to note the factors that lead to this precision. First, the altimeter is dual frequency, allowing a direct estimate of the ionosphere. Second, an onboard radiometer provides a direct estimate of the large and highly variable wet tropospheric correction to the range. Third, and probably most important, to repeat this success with another mission there must be an effort toward precision orbit determination that is comparable to what was done for T/P. Remaining in the T/P groundtrack is an advantage, placing the altimeters on small free flyers allows better modeling of body forces on the satellite, and tracking by multiple systems (e.g., SLR, DORIS, GPS, TDRSS) is also a significant advantage. Fourth, in order to make proper interpretations of the SSH, the aliased tidal signals must be accurately modeled and removed, including the contributions from the internal tides (e.g., Ray and Mitchum, 1997). Again, remaining in the T/P groundtrack makes this more straightforward than would be the case in a new configuration.

Obviously there are good reasons for keeping an instrument in the T/P groundtrack, but this needs to be considered in a wider context, of course. At this point, therefore, we will expand on the issue of which orbits the future altimeters should occupy in order to obtain data that is precise enough to satisfy the science applications that we intend to make. The two critical constraints that were developed in the previous section were an ability to resolve mesoscale variations, and an ability to monitor small amplitude trends in the global mean of the SSH. These two contraints lead to possibly conflicting conclusions about what orbits might be best. For the best observations of the mesoscale, the orbits need to be selected in such a way as to provide the best spatial and temporal resolution from the array of altimeters available at any given time. From the point of view of the studies of low frequency variability, including the volume change studies, the precision and accuracy of the SSH data is of primary importance. The best way to insure the latter is to continue to occupy the same groundtracks for long periods of time. This allows us to build the best possible tide models. It allows us to determine the best estimate of the mean SSH reference field. And it allows us to examine the longest and most homogenous time series possible, which is critical for low frequency studies where ideal data are sometimes not as important as data that are known to have been measured consistently throughout the time series. Note for example the problems inherent in estimating global temperature trends due to changes in measurement techniques over time (e.g., Houghton et al., 1996).

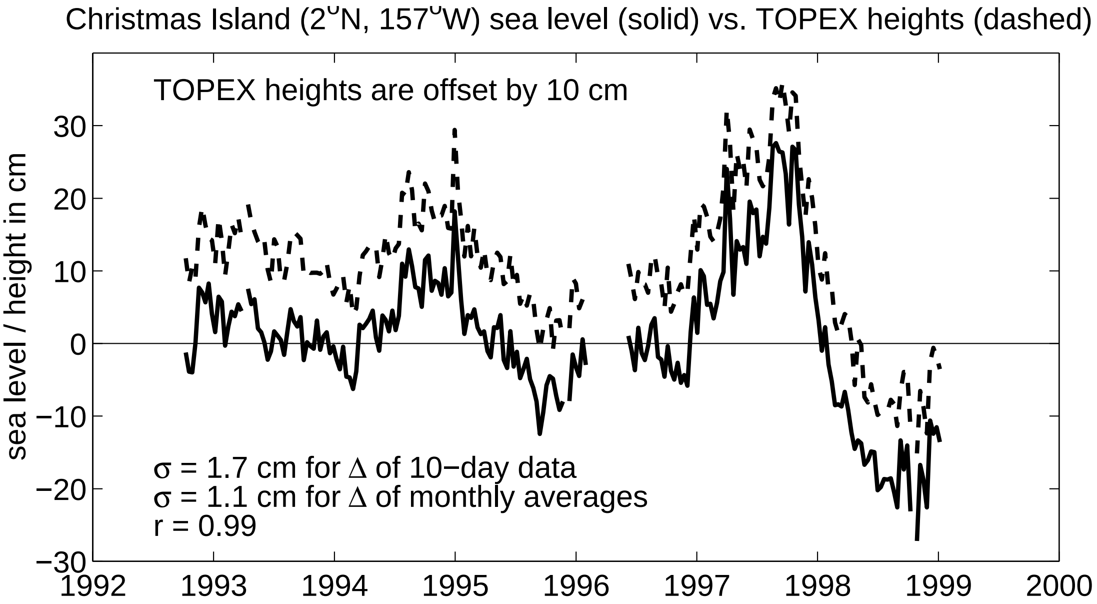

Figure 7 : Comparison of the T/P data with the tide gauge data at Christmas Island in the equatorial central Pacific. Data from 8 nearby T/P passes are combined to make an estimate of the 10-day averaged sea level at the tide gauge.

So how are these requirements on the orbits to be balanced? If we were to conclude that it would take 50 years in a single groundtrack to reach the precision and accuracy required for low frequency studies at decadal and longer series, then one might argue that there would not be a great loss in starting over in new orbits at this point since we would be sacrificing less than a decade of data. It appears, however, that even the most stringent low frequency studies, those aimed at measuring global sea level rise rates and accelerations, likely could produce important results, such as a quantitative check on the IPCC projections (Houghton et al., 1996), with as little as 10-15 years of data in the T/P groundtrack (Nerem and Mitchum, 1999). So the sacrifice of the nearly 10 years of data that we have already collected would be disastrous. Consequently, we conclude that the long-term strategy should be to continously occupy the groundtracks where the longest time series already exist, and we have seen in the previous section that these groundtracks are the ones followed by T/P and the ERS satellites. Given that T/P is the standard for altimetric precision, maintaining this time series should be a high priority. This requires placing a high emphasis on JASON-2 and possibly making additional JASON missions beyond that. The resolution requirement would be satisfied by supplementing these observations with an additional altimeter or altimeters, perhaps in the ERS or Geosat orbit, in a way that best improves the overall spatial and temporal resolution of the complete array of measurements. And we should also recall that a JASON series in the T/P groundtrack that carried a swath altimeter, or was supported by multiple, inexpensive altimeters in others orbits (e.g., ALTIKA, the JHU/APL proposal, NPOESS) would also serve both needs.

As discussed earlier, though, excellent precision is not sufficient; the SSH data must also be stable in time. That is, we are particularly concerned with identifying low frequency errors, or drifts, in the T/P data when using these data for estimating sea level change. Techniques to do this have been developed using the tide gauge measurements, as well as by using other satellite altimeters and other types of in situ data, and a summary of all of these methods is given by Mitchum (1998). We will focus on the use of the global tide gauge network, which works by computing a difference of the T/P heights with the in situ estimates of sea level. Computing differences is done in order that the ocean signals that are common to both the T/P and in situ data will cancel, isolating the errors for further analysis. After this global tide gauge approach successfully identified an algorithm error in the early T/P data and also gave the first indication of a possible drift in the wet correction (Mitchum, 1998), confidence in these calculations increased and these drift estimates are now routinely considered in the ongoing T/P calibration and validation activity. An independent effort at the Harvest platform, on the other hand, is the best technique at present that can detect mean, or time independent, biases, which is extremely valuable for determining offsets between different satellite missions. Alternatives for obtaining the mean bias using tide gauges and independent geodetic measurements are possible (e.g., Murphy et al., 1996; Cazenave et al., 1999), though, and should be investigated fully in the future. The GLOSS program, through its GLOSS-ALT component, is taking an active role in monitoring and supporting all of these applications of the tide gauge data.

The idea of using tide gauges to provide a ground truth for the altimetric variations does have a very serious limitation, which is that it is necessary to either assume that the tide gauges are all vertically stable over long periods of time, or to independently estimate the vertical land motion in the vicinity of each gauge used in the analysis. A striking demonstration of the effect of land motion has been given by Cazenave et al. (1999) at the island of Socorro off the west coast of Mexico using independent estimates of the land motion at the site from DORIS measurements. The only ultimate solution to the land motion problem is to have space geodetic measurements, such as DORIS or GPS, at any tide gauge used in the drift estimation (Neilan et al., 1998). But at present very few gauges are so equipped and alternative methods for estimating land motion and assessing the uncertainty due to land motion have been devised. Discussing these methods is beyond the scope of the present paper, however, and for the present purpose we simply note that preliminary estimates of the T/P drift using the land motion estimates have been made, and these are shown in Fig. 8 (Mitchum; 1998; Nerem and Mitchum, 1999). A sensitivity analysis indicates that the uncertainty in these drift rate estimates due to the uncertainty in the land motion is of order 0.4 mm/yr, which is still the dominant error in the estimate of the drift rate. It is a significant improvement, however, over the 1 mm/yr error estimate made by Mitchum (1998) in the earlier calculations.

What do we conclude from this analysis in terms of what the future tide gauge system should be in order to insure the stability of the final SSH product? First, we must continue to have the high frequency in near real-time data from a globally distributed set of carefully maintained tide gauges. Second, although we have not discussed this in detail, to make the best internal estimates of the land motion we also need as long a historical record of sea level at each gauge as possible, which will require data archaeology efforts in some cases. Third, it is very important that the land motion estimates be as accurate as possible, as this is still the largest source of error in the drift estimates. This requires making space geodetic measurements (e.g., GPS or DORIS) of the land motion rates at as many tide gauges as possible. Plans to do this are progressing (IOC, 1997), and the prospects are promising. To conclude this discussion of tide gauge requirements, we should emphasize that these requirements are specific to the application of the tide gauge data to maintaining the stability of the altimetric heights. In order to place altimetric analyses into a longer temporal context, as discussed earlier, it is also required that we maintain and improve the long sea level records and the global sea level observing system of the GLOSS program.

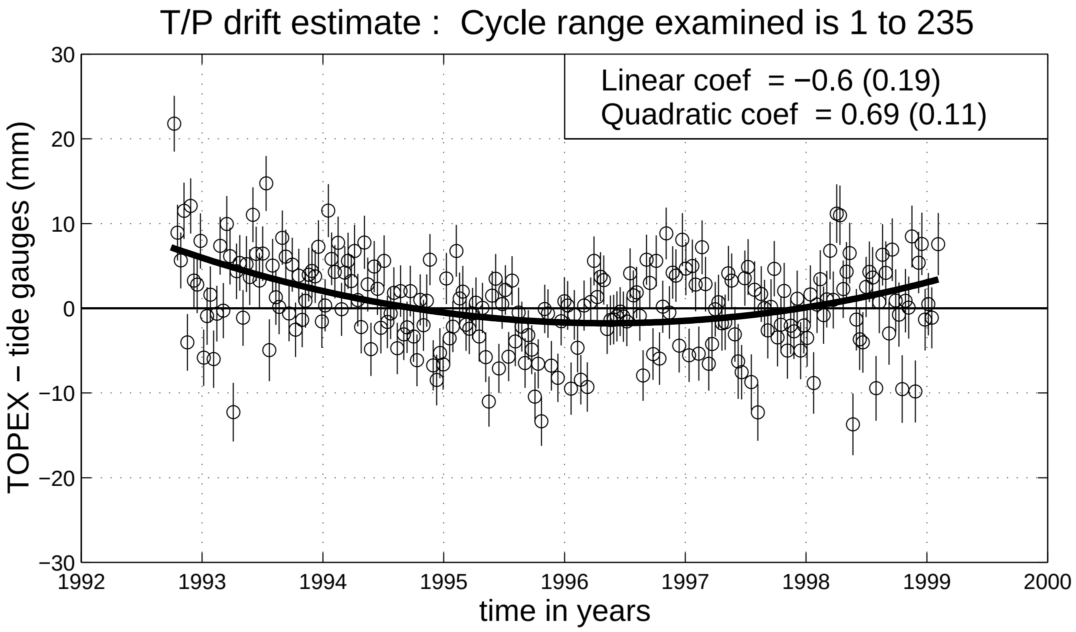

Figure 8 : The present estimate of the estimate of the T/P drift error based on the global tide gauge network. All of the tide gauges shown as open circles in Fig. 3 were used in this analysis, although some did not prove useful. Additional details on the method used to derive this estimate are given by Mitchum (1998) and in Nerem and Mitchum (1999). The solid curve is from a weighted least squares fit of a quadratic curve to the 10-day estimates given by the open circles.

The altimetric component of the SSH system can be fairly simply described. The system should consist of observations on the same T/P groundtrack in order to assure the continuation of these high quality time series, which will provide the backbone for the overall altimetric system. These observations should be complemented by 1-2 additional missions in different groundtracks (e.g., in the ERS or Geosat orbits) to improve the spatial and temporal resolution. As an alternative, a swath altimeter in the T/P orbit might provide the necessary resolution, but that will take time to evaluate. In summary, though, we now know how to maintain an effective SSH observing system, and given resources this system can be maintained through CLIVAR and beyond, resulting in a uniquely valuable contribution to the overall observing system.

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