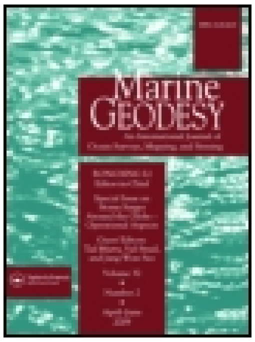

Marine Geodesy

ISSN: 0149-0419 (Print) 1521-060X (Online) Journal homepage: www.tandfonline.com/journals/umgd20

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To cite this article: Gary T. Mitchum & Klaus Wyrtki (1988) Overview of Pacific sea level variability, Marine Geodesy, 12:4, 235-245, DOI: 10.1080/15210608809379595

To link to this article: https://doi.org/10.1080/15210608809379595

Published online: 10 Jan 2009.

Marine Geodesy, Volume 12, pp. 235-245
Printed in the UK.
0149-0419/88 $3.00 + .00

Overview of Pacific Sea Level Variability

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Abstract *Sea level measurements have proven to be extremely valuable for investigations of the dynamics of the world's oceans. Although a comprehensive review of studies using sea level is beyond the scope of this article, it can give an idea of the impact that these data have had on the development of our understanding of ocean and ocean-atmosphere dynamics. The discussion is restricted geographically and temporally to the variability of the Pacific Ocean on time scales longer than several days and is organized into two broad categories. The main section is concerned with the description of a few selected phenomena that are conveniently divided according to their time scale. For example, research studies concerned with the dynamics of the seasonal cycle of the Pacific Ocean are covered. This category also contains a description of the important work on interannual sea level fluctuations and their relationship to global climate disturbances, followed by a short discussion of the use of sea level variability as a tool for monitoring other interesting quantities that are difficult to observe directly. For example, the use of the geostrophic approximation allows sea level differences to be interpreted as an index for surface currents. The article concludes with a brief discussion of several developing technologies that promise further advances in our understanding of Pacific sea level variability.*

Introduction

The purpose of this article is to give an overview of the development of our understanding of sea level variability in the Pacific Ocean. The topic of sea level variability obviously covers a wide range of studies and we do not attempt to fully cover this area. The intention is rather to give an idea of the impact that sea level data has had on studies of ocean and ocean-atmosphere dynamics. A number of interesting topics have to be excluded from consideration at the outset. First, we concentrate on sea level measured at tide gauges and do not discuss in detail the valuable contributions made by studies of dynamic height variability. Second, high frequency phenomena such as the energetic diurnal and semidiurnal tides are neglected in favor of variability on time scales longer than a few days. We also do not discuss boundary phenomena such as shelf waves, but restrict our attention to the large-scale fluctuations. Finally, we concentrate on tropical sea level studies. This emphasis is motivated by the special value of sea level data in the tropics.

To motivate this discussion of Pacific sea level variability, it is useful to consider the impact that sea level data has had on our understanding of the El Nino/Southern Oscillation (ENSO) problem. The recognition of the ENSO phenomenon as a dominant signal in the earth's short-term climate fluctuations has come hand in hand with the analysis of sea level data and the development of the Pacific Sea Level Network at the University of Hawaii. An important early step was taken when Wyrtki (1973) noted a connection between the transport of the North Equatorial Counter Current as measured by sea level differences and the occurrence of El Nino conditions in the eastern Pacific. Shortly after, he noted that tropical ocean current fluctuations were related to the trade wind fluctuations (Wyrtki 1974b) and that this provided a mechanism for forcing the ENSO events (Wyrtki 1975). The increasing interest in these climatic events motivated the establishment of the Pacific Sea Level Network (Wyrtki 1979a) in the mid-1970s. As a consequence, the event in 1976 was analyzed with data from 28 stations (Wyrtki 1979b) as compared to only 13 island stations for the 1972 event (Wyrtki 1977). A map showing the present status of the Pacific sea level network is shown in Figure 1.

The next section discusses a selection of studies that describe the Pacific sea level variability on several time scales. These brief descriptions address the annual cycle, the interannual events, and the intraseasonal scale, which is a particularly active area of research at present. This is followed by a section describing a number of more indirect uses of the sea level data for monitoring quantities such as mass and heat transports. The article ends with a brief look at where we stand and where we will be going in the near future in our studies of the Pacific sea level variability.

Descriptions of Sea Level Variability

Some early descriptions of the low frequency Pacific sea level variability were given by Roden (1960, 1963a,b). A number of interesting and relatively general results were obtained. First, the seasonal and nonseasonal portions of the variance were found to be of the same order. Second, outside the tropics, atmospheric pressure fluctuations accounted for a significant part of the total sea level variability. Also, coherence lengths were found to be several hundred kilometers and varied according to the wind and current regimes. Roach et al. (1988) have since expanded the study of the coherence lengths around the entire Pacific margin. Since Roden's work, direct descriptions of the Pacific sea level field have generally focused on a portion of the frequency spectrum or, equivalently, on fluctuations characterized by a specific time scale. This separation provides a natural way to organize our discussion into consideration of the annual period variability, of the interannual fluctuations, and of intraseasonal signals that have periods of a few days to a few months. We look first at the annual fluctuations.

One of the first treatments of the annual variability was a global description given by Pattullo et al. (1955). These authors found signals that were out of phase across the equator, lagged the solar heating cycle by several months, and resulted in high sea level in the fall and low sea level in the spring. This signal was attributed to temperature-related density changes in the upper 100 m of the ocean and was particularly clear at low and temperate latitudes. A more recent description of the annual variability in the Pacific was given by Wyrtki and Leslie (1980). This study used tide gauge data from islands as well as along the ocean margins.

Many recent studies have focused not on the temperature-induced signals, but on the annual period variability that is due to the ocean's dynamic response to wind and atmospheric forcing at the annual period. As one example, Bigg and Gill (1986) explored such local forcing effects using sea level data from along the eastern Pacific boundary. These authors found that annual period fluctuations in the wind stress explained a large

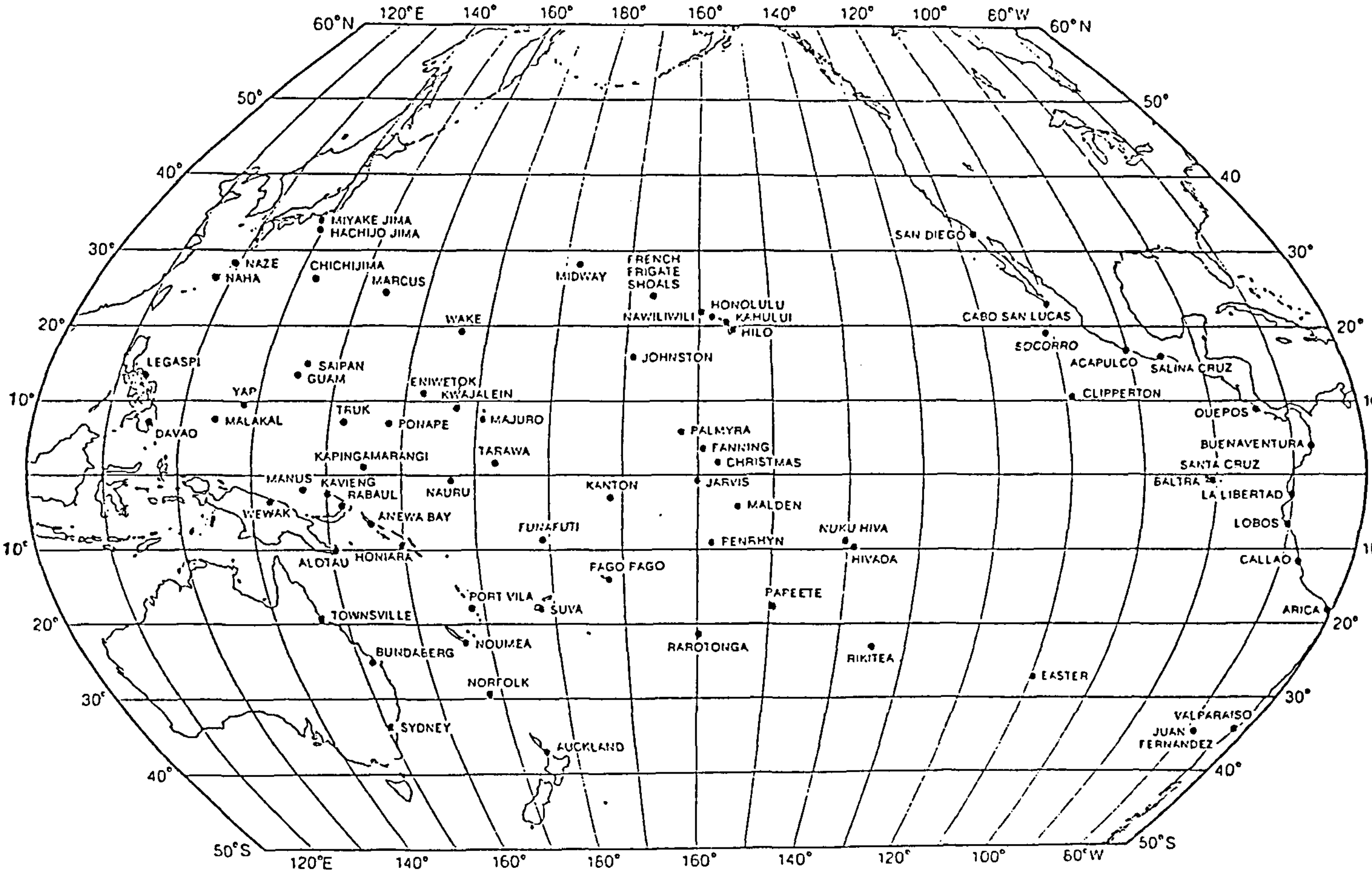

Figure 1. The present status of the sea level network in the Pacific. Most of the instruments are standard tide gauges. However, pressure gauges are used at some locations such as Jarvis and Clipperton.

portion of the annual sea level variations. It must also be realized that the wind variations can excite annual period oceanic waves that can affect annual sea level signals at locations far from the forcing region. For example, using dynamic height measurements, Meyers (1979a,b), Lukas and Firing (1985), and others have described the generation and propagation of annual period oceanic signals in relation to the annual wind variability.

One particularly interesting study of the annual sea level variability was done using the tide gauge data at Truk Island in the western Pacific. Meyers (1982) reported what he termed a bimodal annual cycle. The annual amplitude of the sea level signal was found to be large during ENSO events and small otherwise, and thus reflected the presence of interannual events that are dynamically linked to the annual cycle. This "phase-locking" of the ENSO events to the annual signal was noted earlier by Meyers et al. (1982) and is presently an active area of research. We now consider these interannual events in more detail.

The most significant year-to-year changes in the Pacific sea level field are related to the occurrence of the ENSO events. It is important to note the eventlike nature of this phenomenon. Typically, conditions are abnormal for a period of about a year, with events occurring on average about once every 4 or 5 years (Quinn et al. 1978, 1987). In addition to the descriptions of the 1972 and 1976 events mentioned in the introduction, the sea level data in the Pacific provided an excellent description of the very strong but somewhat atypical event in 1982/1983 (Wyrtki 1984, 1985a) and, as result, the features common to the various events are now known rather well. The sea level field drops over a large area of the western tropical Pacific and signals are observed to propagate across to the eastern boundary along the equatorial waveguide. These signals then propagate poleward along the boundary as coastal Kelvin waves (Enfield and Allen 1980; Chelton and Davis 1982). The sea level anomaly field during March 1987 (Figure 2) illustrates the drop of sea level in the western Pacific and the rise along the eastern boundary. There is also some evidence for interhemispheric oscillations in the Indian and western Pacific oceans (Bye and Gordon 1982) that have periods similar to the time between ENSO events. These signals appear to involve coupled oscillations of the subtropical gyres (Wyrtki and Wenzel 1984).

We conclude this section with a discussion of the relatively high frequency signals that can be referred to as intraseasonal fluctuations. These signals have time scales of a few days to a few months and have only recently received a great deal of attention. Of course, these fluctuations do not appear in data that have been averaged to obtain monthly means; the widespread use in the past of monthly mean data explains the relative lack of attention paid to these signals. To avoid confusion, we must point out that the term "intraseasonal" is often associated with fluctuations in a period band of about 40 to 60 days. These signals are probably related to equatorial Kelvin waves excited by atmospheric variability at similar periods. However, we use the term "intraseasonal fluctuations" in the literal sense of fluctuations within a season. These signals may or may not be related to atmospheric forcing or involve Kelvin wave dynamics.

Many of the observations in this frequency band are connected with the waveguides at the equator and along the eastern boundary. In the equatorial waveguide Knox and Halpern (1982) documented a Kelvin wave in the equatorial Pacific, and Lukas et al. (1984) subsequently demonstrated that short period Kelvin waves were important in the onset phase of the 1982/1983 El Nino event. McPhaden et al. (1988) have recently documented such a Kelvin pulse as the response to westerly wind bursts in the western Pacific. An important early paper by Wunsch and Gill (1976) identified 3- to 5-day

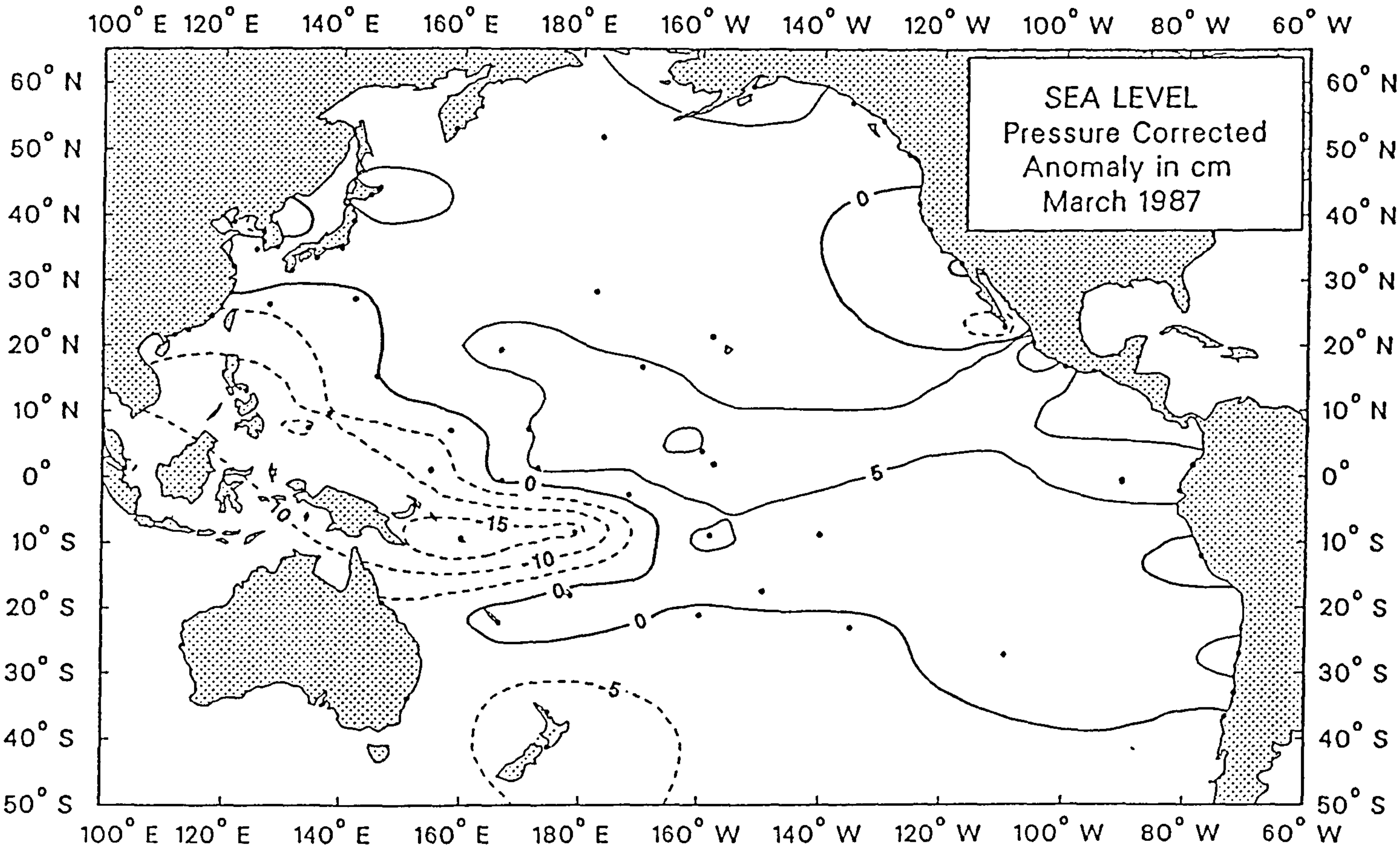

Figure 2. March 1987 sea level anomalies. Station locations are marked by dots. The sea level anomalies are relative to the mean annual cycle computed over 1975–86, and are corrected for atmospheric pressure.

oscillations as equatorial inertia-gravity waves and discussed the forcing of these waves by the wind field. Recently, Spillane et al. (1987) and Enfield (1987) have done a comprehensive description of 40- to 60-day oscillations along the eastern boundary and have related them to remote forcing along the equator to the west.

Not all of the observations of intraseasonal fluctuations are restricted to the waveguides, however. For example, Luther (1982) described barotropic, basin-scale fluctuations at periods less than a week. Such rapid modes of oscillation have also been discussed theoretically (e.g., Christensen 1973). More recently, Mitchum and Lukas (1987) presented a frequency spectrum of the sea level in the western and central Pacific as a function of latitude from 25 °N to 25 °S. A rich variety of phenomena is exposed; signals are found that are due to equatorial waves, zonal current instabilities, long period tides, and mesoscale eddies, among others.

These various descriptions of the Pacific sea level variability at the annual, interannual, and intraseasonal time scales are but a small subset of the work that has been done. However, these studies do give an idea of the variety of signals revealed by the sea level data. Furthermore, it must be realized that the value of the sea level data is enhanced by our ability to make indirect measurements of other physical quantities that may be difficult to measure directly. The next section briefly discusses a few of these indirect uses of sea level.

Indirect Uses of Sea Level

An early discussion of the use of sea level data to infer other interesting dynamical quantities was given by Wyrtki (1961, see Chapter 7). Because the height of the sea surface is determined by the integration of effects such as ocean density, currents, and large-scale mass redistribution, the sea level data can be used to infer other dynamically interesting quantities. This information can often be extracted with the use of judicious assumptions about the dynamics controlling the sea level field. The simplest example is the use of sea level differences to infer ocean currents by assuming that there is a geostrophic balance. This balance has been shown to be useful for monitoring the zonal currents in the tropical Pacific, and time series of various current indices (such as those shown in Figure 3) are routinely produced. The details of this procedure are given by Wyrtki (1974a). As another example, Blaha and Reed (1982) have shown that sea level differences can be used to index the transport in the Kuroshio.

Even more exciting results have been obtained in the tropics with the realization that the vertical density structure can be approximated as a two-layer system. Density is assumed constant within each layer and the upper layer is allowed to move, whereas the lower layer is taken to be motionless. This idealization is often referred to as a one-and-a-half-layer model and yields the very useful result that sea level is directly proportional to the thickness of the upper layer of the ocean. Numerical models using this formulation have demonstrated an impressive ability to hindcast sea level variations when forced by the observed wind field (Busalacchi and O'Brien, 1980, 1981). This approximation was examined for monitoring purposes by Wyrtki (1978) and, more recently, Rebert et al. (1985) have shown the approximation to be useful out to about 15° latitude in the tropical Pacific. Thus the tropical sea level fluctuations can be integrated in the horizontal to monitor upper layer volume changes (Wyrtki 1985b) and mass flux. If the sea level data are combined with an estimate of the temperature of the upper layer, then it also becomes possible to monitor heat content (Delcroix and Gautier 1987) and heat flux.

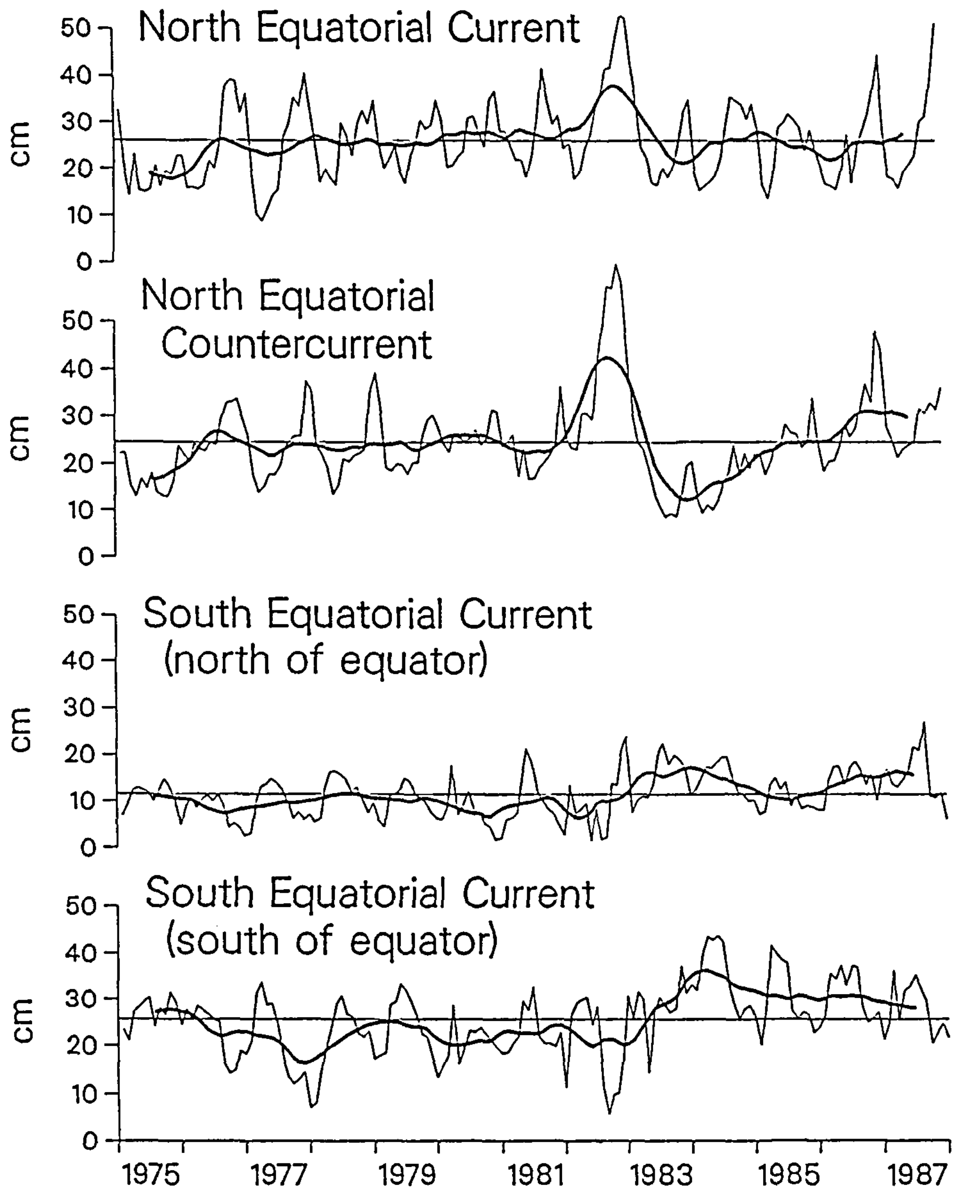

Figure 3. Time series of equatorial current indices. The indices are computed by perturbing the meridional profile of mean surface dynamic height with the monthly mean time series of the sea level variations and calculating the appropriate ridge to trough difference for each current for each month. The signs of the indices are such that larger values mean stronger currents. The mean value of each index is at the horizontal line.

It has also been suggested that long-term rises in global sea level could be used to monitor a hypothesized global warming due to increased levels of atmospheric carbon dioxide. Unfortunately, this signal is quite small compared to the natural variability of the sea level and definitive results are difficult to obtain (Barnett 1984; Sturges 1987). It is important to note that this oceanic variability of the sea level extends even to very low frequencies and therefore greatly complicates the use of mean sea level for geodetic purposes. Chelton and Enfield (1986) discuss the problems involved in assuming that secular sea level changes are nonoceanic in nature and give an excellent summary of various ocean signals that can be found in tide gauge records.

Where Are We and Where Are We Going?

Over the past several decades, many studies of the sea level variability of the Pacific have been done and have led to a greatly improved description of the sea level field and also to improved understanding of a number of derived quantities such as the volume of the tropical warm water sphere. Only a few of these results are presented here, but it should be apparent that much progress has been made. Much of the advance has been possible because of the development and maturation of the island observing network. This network is presently a central focus of the Tropical Ocean-Global Atmosphere (TOGA) program and is also gearing up to meet the needs of the World Ocean Circulation Experiment (WOCE). In addition, contributions are being made to an international program to establish a permanent global sea level observing system (GLOSS).

Where are we going in the near future? Two of the most promising developments are the emergence of satellite altimetry as an additional source of sea level information and the possibility of forming a globally leveled tide gauge network. The GEOSAT altimeter has clearly demonstrated the potential of the satellite method (Cheney et al., 1986; Miller et al. 1986, 1988), although there are still questions about this method of remotely sensing sea level (Wyrtki 1987). The altimeter to be flown on the TOPEX/POSEIDON mission (Born et al. 1985) promises even more accurate data. Satellite technology is also responsible for the possibility of eventually leveling the global tide gauge network. At present the mean sea level at the tide gauge is unknown in any absolute coordinate system and the determination of the absolute sea level surface requires ancillary data that is difficult to obtain. Now, however, the technique of Very Long Baseline Interferometry in conjunction with portable GPS receivers makes it possible to place at least a subset of the tide gauge network into an absolute reference frame (Carter et al. 1987). This global leveling will allow determination of a mean sea level surface and will aid in long-term monitoring efforts.

The traditional tide gauge networks will also benefit from more modern technologies. Satellites allow data to be telemetered from remote sites in order to provide more timely information. This also reduces the number of gaps in the final datasets due to the use of redundant sensors and the availability of immediate information on the status of the installation. Along another line, a new approach to tide gauges is currently being implemented by NOAA. The Next Generation Water Level Measurement System (Carter et al. 1987) measures the water level acoustically, supports a suite of ancillary sensors, and provides data telemetry. In summary, these upgrades to the existing tide gauge networks and the application of new satellite-based measurement techniques promise exciting new opportunities to build upon the progress already made in understanding the variability of sea level.

Acknowledgments

Support for this work was provided by the TOGA Sea Level Center through NOAA Cooperative Agreement NA85ABH00032 to the Joint Institute for Marine and Atmospheric Research (JIMAR), University of Hawaii, and by National Science Foundation grant OCE 85-15404. JIMAR contribution 88-0156.

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