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REVIEW ARTICLE

Sea Level Rise: The Facts and the Future[1]

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ABSTRACT: Sea level records from the Pacific are analyzed to determine the rate of long-term sea level rise and its relation to climate change. The trend is largely dependent on vertical movements of the land on which the sea level gauges are located and varies from place to place. Other obvious contributions to sea level rise come from melting of glaciers, from global warming, and from sea floor spreading. Present rate of sea level rise is about 1 mm per year and is subject to a large uncertainty. Assumptions about global warming in conjunction with the greenhouse effect are critically reviewed to project possible rise of sea level in the next 50 yr. It is concluded that effects of a doubling world population within the next 40 yr will have much more disastrous consequences for our environment than potential rise of sea level.

IT IS FASHIONABLE these days to talk about the greenhouse effect, about global warming, and about global sea level rise, but often enough very little attention is given to the observational evidence on which these discussions and speculations are based. In this article I evaluate the data and information that form the basis for arguments related to sea level rise and emphasize their very large uncertainties.

The Observed Sea Level Rise

Geologists have known for a long time that the earth is not static. Continental drift, seafloor spreading, mountain formation, and other processes slowly and steadily change the face of the earth and the shape of the ocean basins. Tectonic changes of the earth's crust involve both horizontal and vertical movements. The vertical movements can be measured along the coasts by means of sea level observations. Among the best-documented vertical movements is the rise of Scandinavia at a rate of about 1 m per century (Sauramo 1958). Portions of southern Alaska near Glacier Bay rise even faster, at a rate of 30 mm per year (Hicks and Shofnos 1965). Sea level measurements have shown that parts of Japan sink as fast as 24 mm per year, while others rise at 6 mm per year (Aubrey and Emery 1986), indicating a tilting of the island (Figure 1). Sea level measurements in the Caribbean show rates of sea level rise to vary between 8 mm per year and zero. Pirazzoli (1986) has analyzed sea level data worldwide and found large regional variations. Most of the stations indicate an apparent rise of sea level, but the signal is confused by the vertical movements of the land.

Sea level measurements by means of tide gauges determine the relative position of land and sea at the coast line. The tides are the most prominent signal in these records, but the measurements allow us to relate the mean sea level averaged over a selected period to fixed points on land, called bench marks. On the basis of these measurements it is not possible

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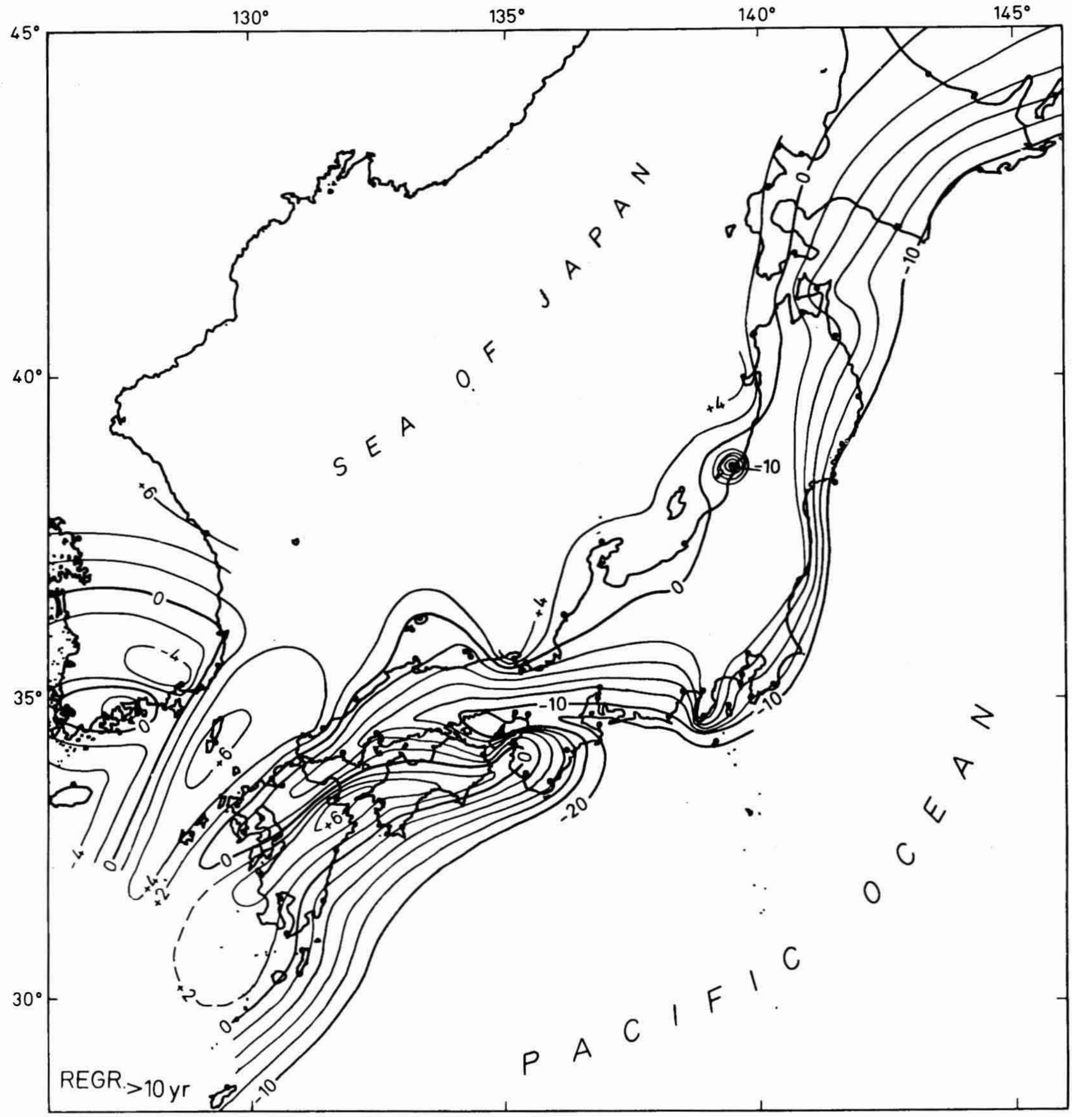


FIGURE 1. Average annual vertical movement of land relative to sea level for the duration of 86 tide-gauge records in Japan having records longer than 10 yr, plus 8 stations for Korea to establish boundary positions. Rates are based upon least-squares linear regressions, and they range from + 6 to − 24 mm per year. Contours are at intervals of 2 mm per year. Stations are shown as solid dots. (From Aubrey and Emery 1986: used by permission)

to differentiate between vertical movements of the land and of the sea.

Times series of annual mean sea level at selected stations in the Pacific Ocean with long records are shown in Figure 2. The linear trend of sea level at Honolulu or Balboa is 1.5 mm per year, but at other stations like Sydney and Hosojima the trend is smaller or not at all apparent. Year-to-year fluctuations of sea level are large and are due to fluctuations of atmospheric pressure, of the winds, of ocean circulation, and of ocean heat content (Chelton and Enfield 1986). A trend in records of yearly mean sea level can only be established with

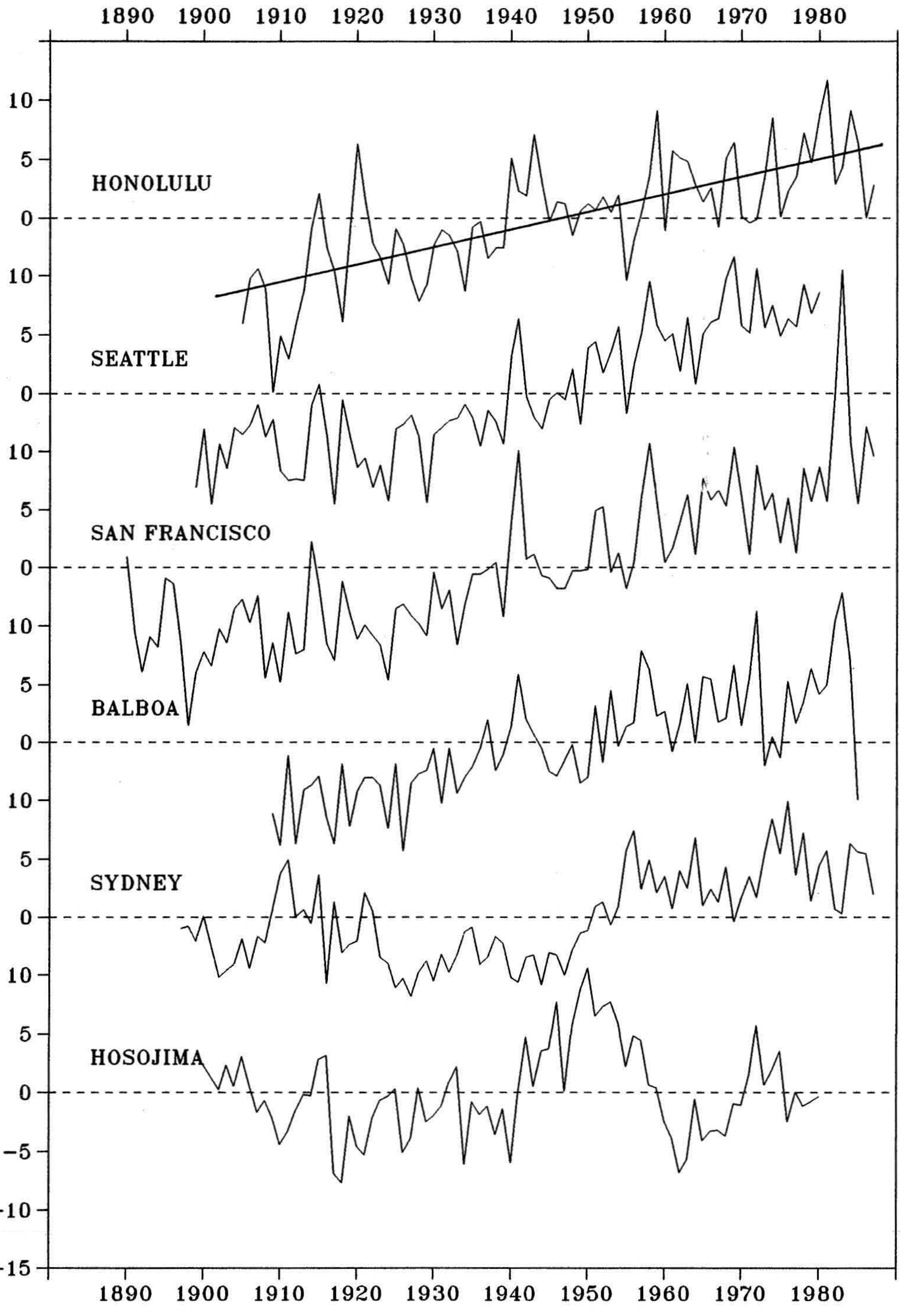


FIGURE 2. Annual mean sea level (in centimeters) at six stations on the Pacific Ocean with long records. The linear trend of sea level rise at Honolulu is 1.5 mm per year or 15 cm per century.

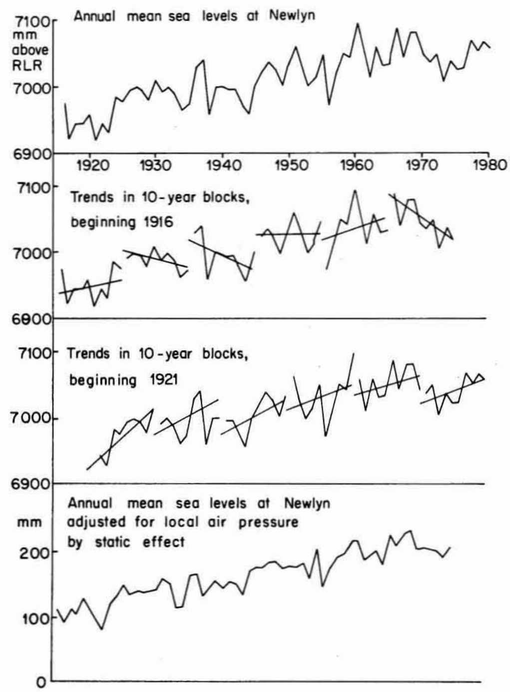


FIGURE 3. Comparison of trends in annual mean sea level at Newlyn, England, taking successive 10-yr blocks from 1916 and from 1921. The figure at bottom shows the reduction in noise that results after correcting for the mean annual air pressure. (From Pugh 1987: used by permission)

confidence if such records are for longer than about 20 yr (Pugh 1987) (Figure 3). Consequently, no conclusive information about sea level rise can be expected from newly installed tide gauges for many years.

Sea level at Honolulu rises at a rate of 1.5 mm per year, but at nearby Hilo on the island of Hawaii sea level rises more than twice as fast, 3.8 mm per year (Figure 4), which indicates that the island of Hawaii is sinking relative to Oahu because of the loading with lava. The difference of the rates of sea level rise at the two stations also demonstrates the large uncertainties of estimates of sea level rise from observations of relative sea level.

Several attempts have been made to estimate the global rise of sea level during the past century on the basis of sea level measurements. Gornitz et al. (1982) arrived at a value of 1.2 mm per year. Barnett (1984) estimated an increase of mean global sea level of 1.4 mm per year for the last century and 2.3 mm per year for the period 1930 to 1980, indicating an acceleration in recent decades. These values are not coherent around the globe and may be subject to large errors because of the uneven distribution of observing stations, which are chiefly in the northern hemisphere. The study by Barnett (1984) showed that relative sea level rises fastest along the east coast of North America, where the continental shelf is loaded down by masses of recent sediments (Figure 5). The east coast of Asia shows no definite trend, and in the Indo-Pacific a trend is apparent only in recent years. These and other estimates are summarized in a report by the IAPSO (International Association of the Physical Sciences of the Ocean) Advisory Committee on Tides and Mean Sea Level (1985). A generally accepted value for the rise of mean sea level during the past century is 1 mm per year, with an uncertainty of the same magnitude.

It should be noted that during the last ice age, about 18,000 yr ago, sea level was more than 100 m below the present level. At that time large quantities of water were deposited on the continents in the form of ice. The most rapid melting occurred over a period of about 10,000 yr, resulting in an average rise of sea level at a rate of 1 m per century, much larger than the rate estimated for the last century.

Causes of Sea Level Rise

There are four major causes that contribute to sea level rise: (1) sinking of the land; (2) warming of the water in the oceans; (3) addition of water to the oceans from the melting of glaciers; and (4) deformation of the ocean basins. Minor contributions to a change of mean sea level may come from changing wind systems and changes of ocean circulation.

The sinking or rising of land due to tectonic movements is particularly strong along the continental coasts, where most sea level stations are located. These vertical movements are also often of small horizontal scale and vary greatly from place to place. It is anticipated that new geophysical measuring tech-

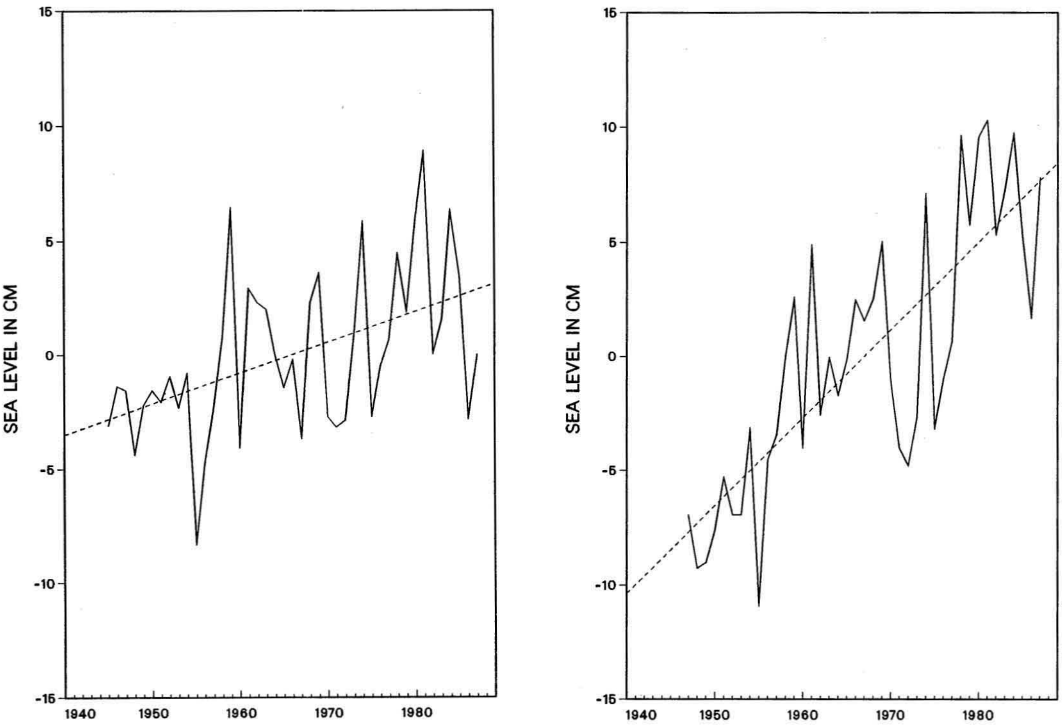


FIGURE 4. Annual mean sea level (in centimeters) at Honolulu (left) and Hilo (right) in the Hawaiian Islands from 1947 to 1987, and linear trend.

niques (Diamante et al. 1987) will allow the determination of vertical movements of the land over periods of a decade or longer with an accuracy of a few centimeters. Such measurements will only be made at a few selected sites because of their cost. It will consequently be a long time until the effects of vertical land movements can be adequately determined. These measurements will eventually allow us to correct the observed change of relative sea level at tide gauges for the vertical land movements to determine the absolute change of sea level.

The effect of volume changes of seawater due to an increase in its temperature, which has received considerable attention recently, is discussed below at some length.

Sea level may rise because of the addition of water from the melting of glaciers and ice fields and possibly of the polar ice caps. Meier (1984) has estimated that melting of glaciers has contributed about 28 mm of water to the level of the oceans during the period 1900 to 1960. The error of this estimate is about 16 mm. This estimate does not include the contribution of the melting of glaciers in Greenland and Antarctica, which is unknown. Meier (1984) claimed that melting of glaciers may have contributed as much as one-third to one-half of the observed global sea level rise. A melting of all the ice in Antarctica and Greenland would add about 65 m of water to the oceans, but this melting would require many thousands of years.

The volume of the ocean basins also varies with time because of tectonic movements. Changes in this volume may cause changes in sea level even if the total water volume remains constant. These changes escape our ability to measure them, because it would require the mapping of the topography of the ocean bottom to an accuracy of less than 1 cm, repeated

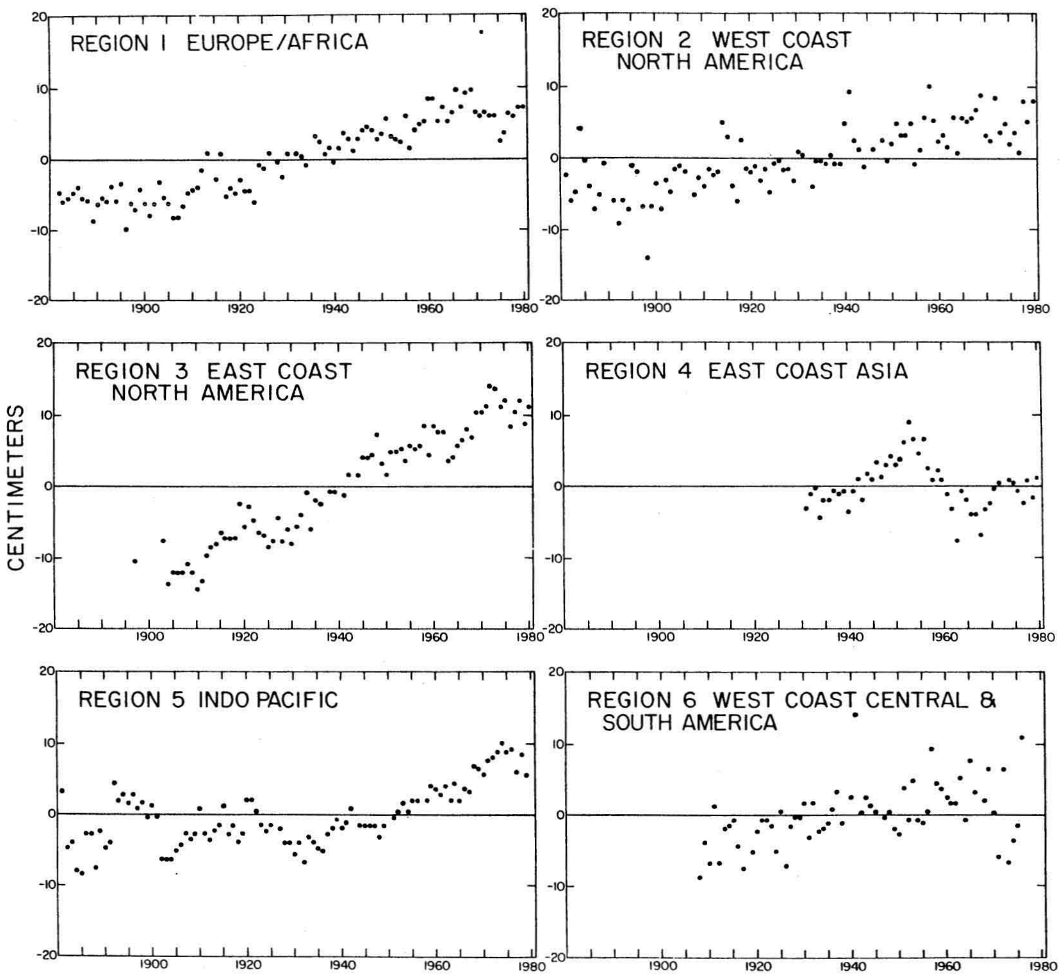


FIGURE 5. Annual averages of sea level (in centimeters) in six different regions of the world, showing trends in sea level. (From Barnett 1984: used by permission)

after many years. On the contrary, observations of sea level change may ultimately allow conclusions about the changing volume of the oceans, after other effects can be accounted for.

In summary, one can point to the great uncertainties of our knowledge about sea level rise. Observations at tide gauges allow an estimate of relative sea level rise on the order of 10 to 15 cm per century. The contribution of melting of continental glaciers and ice fields has been estimated as about 4 cm in the last century, but the rate of melting in Antarctica and Greenland is unknown. Of great uncertainty is the rate of sinking or rising of the continental margins, where sea level monitoring stations are located, but it is of the same order of magnitude as the observed sea level rise. Totally unknown is the contribution to sea level change of a change in volume of the ocean basins. Although our knowledge of the magnitude of the contributions of different causes to global sea level rise is very uncertain, the actual change of sea level at a given location

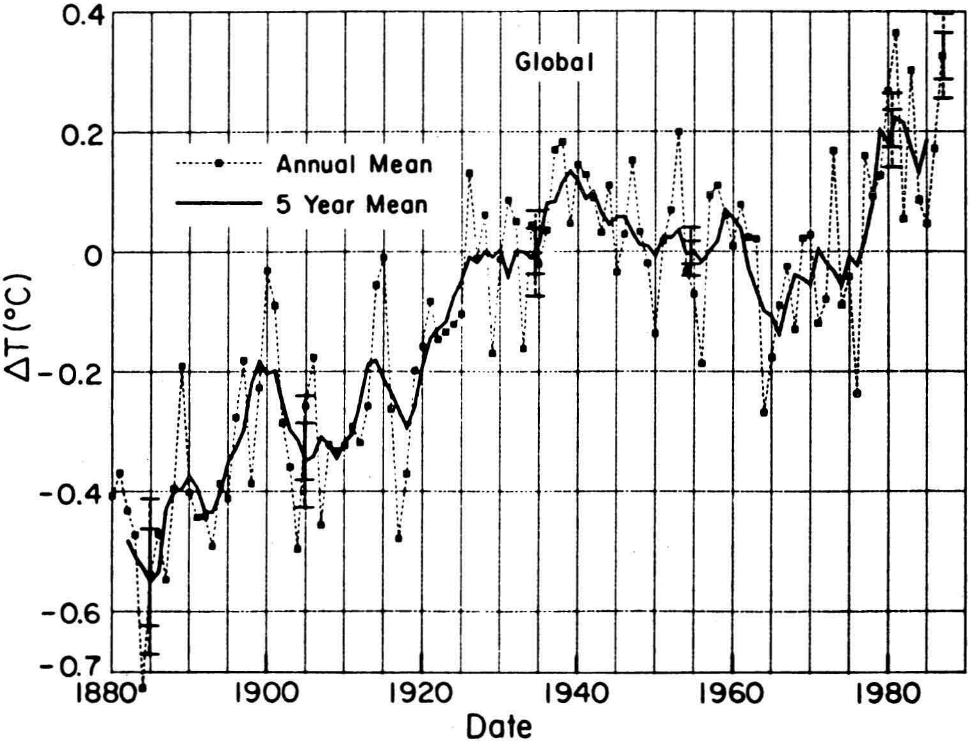


FIGURE 6. Global temperature trend (°C) between 1880 and 1987. (From Hansen and Lebedeff 1988: used by permission)

can be rather well determined by sea level measurements.

Global Warming

A large portion of the observed rise in sea level may be due to global warming. If atmospheric and ocean temperatures increase, the upper layers of the ocean would expand, leading to a slow rise of sea level. The question is again: Has such a temperature increase been observed and how large is it?

It is most difficult to observe global warming, because one needs long, continuous, and highly precise time series of temperature measurements. Moreover, most observing stations are located on land and in the northern hemisphere, and the natural variability from year to year and decade to decade needs to be accounted for to avoid aliasing of the time series. Nonetheless, scientists have attempted to extract a trend from the data; the well-known analysis by Hansen and Lebedeff (1988) is shown in Figure 6. There was definitely an increase in temperature from 1880 to 1940 by about 0.5°C. After 1940 temperatures decrease slightly until 1970, only to increase rapidly from then on. It is unclear if this recent increase is an effect of short-term climatic variability or a sign of the greenhouse effect, which should appear as a much more gradual and steady increase of temperature. A similar increase of global sea surface temperature has also been documented by Jones et al. (1986) using data observed from ships all over the world's oceans.

There seems to be general agreement among scientists that global temperatures at the boundary of ocean and atmosphere have increased by about 0.6°C during the last century.

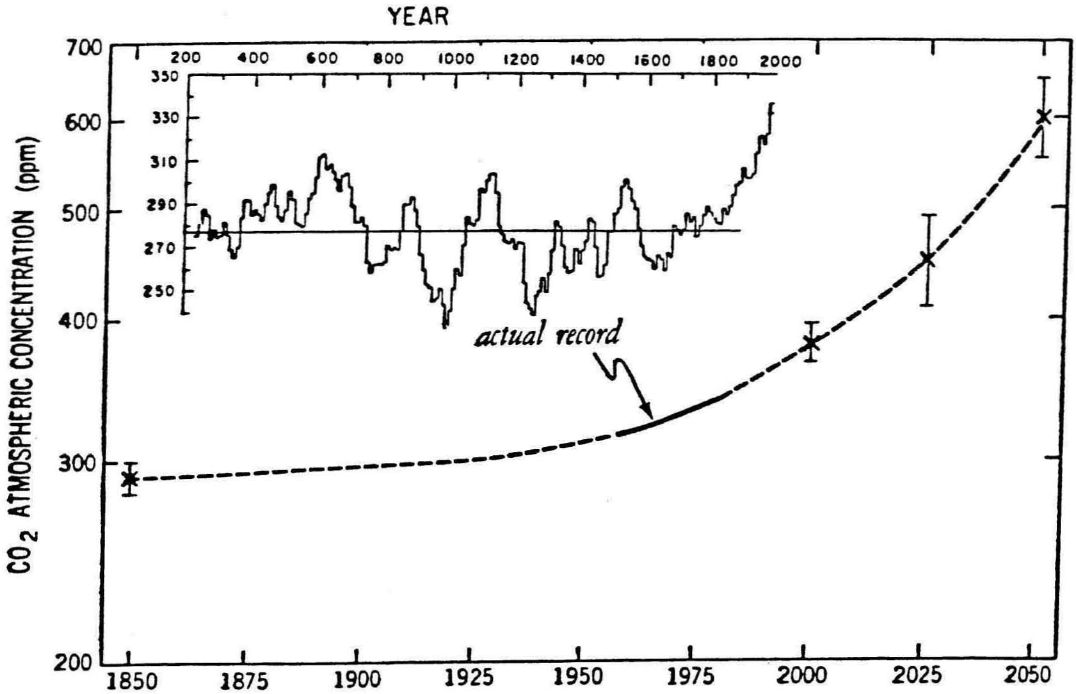


FIGURE 7. Variation of the concentration of atmospheric carbon dioxide between 1850 and 2050. Actual observations constitute the record between 1958 and the present. The remainder of the curve is estimated. The variation in carbon dioxide concentration between A.D. 200 and the present, as determined from the carbon-13 content of tree rings, is shown in the upper left. (From Stuiver 1986: used by permission)

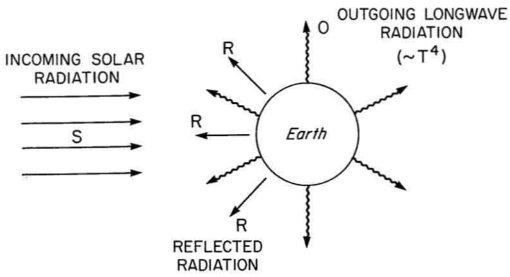
This increase has not been steady, and it is not at all clear how it is related to the increase in carbon dioxide (CO_2) as part of the greenhouse effect. Ellsaesser et al. (1986) gave a thorough review of the recorded data on global climatic trends and came to the conclusion: "Whether the overall warming constitutes a climate change remains an unresolved problem, as does the cause of the warming."

The Increase of Carbon Dioxide

One of the best-documented parameters in the changing climate system is the content of CO_2 in the atmosphere. Figure 7 shows that concentration has increased from about 315 ppm in 1960 to about 345 ppm in 1985, which can clearly be attributed to the burning of fossil fuels. It is also known that 100 yr ago, before the industrial age, CO_2 concentrations were below 300 ppm. On the other hand, geochemists have determined from the analysis of carbon-13 in tree rings that concentration of CO_2 underwent considerable fluctuations during the last 1800 yr. Fluctuations were between 250 and 310 ppm and are not related to any known climatic variations, and surely not to the burning of fossil fuels. There is of course the dramatic increase of CO_2 since 1650, but this increase started well before the industrial revolution. Scientists have extrapolated the increasing trend of concentration of CO_2, and claim that by the year 2050 the CO_2 content of the atmosphere may double to 600 ppm from the concentration in 1950.

The Greenhouse Effect

The temperature of the earth is controlled by a balance between the incoming solar radiation (S), the reflected radiation (R), and the loss of heat due to the outgoing longwave



$$\frac{\partial T}{\partial t} = S - R - \beta T^4$$

FIGURE 8. Schematic diagram of the radiation balance of the earth and the equation connecting temperature change with incoming solar radiation, reflection, and outgoing longwave radiation.

radiation (O), which is proportional to the fourth power of the absolute temperature βT^4 (Figure 8). If the amount of incoming solar radiation exceeds the heat loss due to reflection and outgoing radiation, the earth will warm. If the loss of heat due to reflection and radiation exceeds the heat gain from the sun, the earth will cool. Thus changes in any of the three components can cause an imbalance of the heat budget of the earth and either a warming or cooling.

The amount of outgoing longwave radiation βT^4 is dependent on the radiative properties of the earth, in particular on the chemical composition of the atmosphere. If this chemical composition changes, for instance by an increase of CO_2, the factor β in the equation will change, and the radiation balance of the earth will be disturbed. An increase of CO_2 will cause a decrease of outgoing radiation and consequently a warming of the earth. A higher temperature T will allow the earth to lose more heat and to reestablish the heat balance. This temperature increase is usually referred to as the greenhouse effect. A discussion of the greenhouse theory of climate change has been given by Ramanathan (1988).

Expected Changes

There is no doubt that enormous amounts of CO_2 and other gasses are steadily entering the environment from human activities, and that these gasses change the composition of our atmosphere and consequently the heat budget of the earth. How our global climate responds to these changes in the heat budget is still an open question.

Scientists have used a number of models to project the response of the global environment to an increase of CO_2. Some of these models consider only the radiation balance, others also include the changes involving atmospheric circulation, evaporation, and rainfall to varying degrees. Projected changes of global surface temperature in the next 50 yr range from 1° to 5°C and are very uncertain. An example of such a model calculation may be found in Hansen et al. (1988). The computed changes are certainly not uniformly distributed around the globe, and therefore the question arises as to where and how the effects of a temperature increase will be chiefly felt. We are interested here in the increase of temperature in the surface layer of the oceans that might cause a rise in sea level.

The change in sea level (Δh) is related to the change of upper layer temperature (ΔT) by the relation

$$\Delta h = \alpha D \Delta T$$

where α is the coefficient of thermal expansion and D the thickness of the affected layer. The coefficient α is also strongly dependent on temperature and varies from $3.4\ 10^{-3}$ at a temperature of 30°C to $0.8\ 10^{-3}$ at freezing temperatures. Consequently, a temperature increase in the tropics has more effect on sea level rise than the same amount of increase in polar waters. On the other hand, the layer affected by a temperature increase will be thinner in the tropics and thicker in mid- and high latitudes because of the winter convection. Table 1 gives typical values for three regions, which will be discussed in more detail.

A possible temperature increase in the tropics is bound to be small, because large areas of the tropics have sea-surface temperatures above 28°C, and temperatures above 30°C are not regularly exceeded in the open ocean. If sea-surface temperature rises above 30°C, atmospheric moisture and evaporation increase disproportionally, and extremely strong cloud formation and heavy rainfall are the

TABLE 1

SEA LEVEL RISE DUE TO OCEAN WARMING IN DIFFERENT REGIONS

REGION	TEMP. (°C)	ΔT (°C)	$\alpha 10^{-3}$	D (m)	Δh (cm)
Tropics	30	1	3.4	100	3.4
Mid-latitudes	10	3	1.7	400	20
Polar regions	0	4	0.8	1,000	32

consequence. This process limits any further temperature increase of the ocean surface. Consequently, the possible rise in temperature of the tropical oceans will be rather limited, probably to about 1°C. Moreover, the strong thermocline in the tropics will limit the thickness of the affected layer to the mixed layer, which in the tropics is generally 100 m or less. The expected sea level rise will therefore be rather small, only a few centimeters.

In temperate climates of the mid-latitudes, where mean annual sea-surface temperatures are around 10° to 15°C, the temperature increase is not limited in the same fashion and will probably be larger. In addition, winter convection results in a deeper mixed layer, which would be affected by a temperature rise, typically 400 m. Both effects will result in a larger rise of sea level in mid-latitudes compared to that in the tropics. In fact, the strong meridional temperature gradient observed in mid-latitude oceans will be displaced poleward, and the tropical region will become larger.

The largest temperature increase is likely to occur in the polar oceans, where winter temperatures are near 0°C. Summer temperatures will probably rise considerably and large areas now covered by ice will no longer freeze during winter. Even so, thermal expansion is small, the layer affected by winter convection is deep, and the resulting sea level rise will be relatively large.

In summary, it is likely that a global warming will make the tropical regions larger and will increase atmospheric moisture, cloud cover, and rainfall. The stronger cloud cover in turn will reflect more incoming solar radiation and may even limit a further temperature increase according to the heat balance equation in Figure 8. It is more than likely that the global environment may be sufficiently robust to counteract a temperature increase by forming more clouds and reflecting more radiation (Ramanathan et al. 1989). An expansion of the tropics may also lead to an increase of the frequency of tropical storms and hurricanes, an undesirable consequence for many low-lying tropical islands.

There are indications in the climatological record that winds over the oceans have changed during the last 100 yr (Fletcher et al. 1982). Changes in the strength of the winds will cause changes in the intensity of ocean circulation. Because a subtropical gyre is a rotating mass of warm water, the sea surface assumes a very distinct shape, which will change according to the intensity of the winds and the circulation. One can estimate that an increase in the strength of the winds over a subtropical gyre by 10% will increase the circulation by a corresponding amount, and that sea level in the center of the gyre may rise by about 10 cm and drop by a similar amount along its periphery. Some of the observed changes in sea level may be related to changes in ocean circulation, but these effects will be relatively small.

There is little doubt that an increase in global temperature will increase the moisture content of the atmosphere and result in more rain and also more snow in the polar regions. This increased snowfall may counteract the melting of the polar ice caps, but this premise is, of course, a very uncertain speculation.

Sea level has been rising rather steadily at a rate of about 1 to 1.5 mm per year during the last century. Global temperatures have also been rising, but it is not certain that this is a consequence of the increase in CO_2 since the beginning of the industrial revolution. If one simply assumes that the present trends will

TABLE 2

SEA LEVEL CHANGE

LOCATION	AMOUNT	MM/YEAR	COMMENTS
Alaska	3 m/century	+30	Land rises
Scandinavia	1 m/century	+10	Land rises
Japan	Variable	From +20	Land rises
		to − 6	Land sinks
World oceans	10 cm/century	1.0	Sea rises
Hilo, Hawaii		3.8	Land sinks
Honolulu, Hawaii		1.5	
Pago Pago, Samoa		1.4	
Kwajalein		0.9	
Truk		0.6	
Rabaul	10 cm in 15 yr	—	Land rises
Suva, Fiji		—	No change

continue during the next 50 yr, the rise of mean sea level over the oceans should not exceed 5 to 10 cm. Locally there may be a larger rise of sea level or even a drop due to tectonic effects. I feel that it is not practical and certainly most speculative to extrapolate over a time interval greater than 50 yr.

Observed Sea Level Changes in the Pacific

The longest available records of sea level at stations in the Pacific have been shown in Figure 2. Most other records are much shorter, but because they are the only source of information on relative sea level change, in particular from islands, some are shown and discussed in this section. The results are also summarized in Table 2. During the last 40 yr sea level at Honolulu rose at a rate of 1.5 mm per year, but at nearby Hilo on the island of Hawaii it rose more than twice as fast, at a rate of 3.8 mm per year (Figure 4), indicating a tilting of the Hawaiian Islands.

A 40-yr-long record at Pago Pago, Samoa (Figure 9) indicates a rise of sea level of 1.6 mm per year, similar to that at Honolulu. It should be noted that year-to-year variations of annual mean sea level are large, often more than 5 cm, and that the magnitude of the trend is not statistically significant. The computed trend of sea level rise is 0.9 mm per year at Kwajalein and 0.6 mm per year at Truk (Figure 10), but year-to-year variations at Truk are

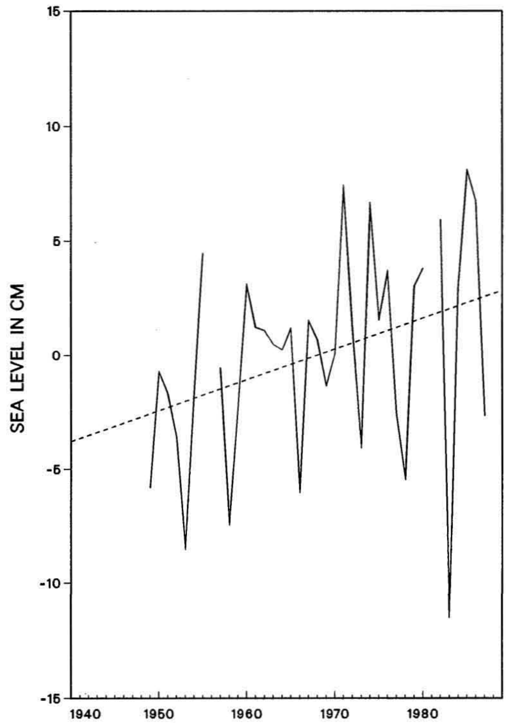


FIGURE 9. Annual mean sea level (in centimeters) at Pago Pago, Samoa from 1949 to 1987 and linear trend.

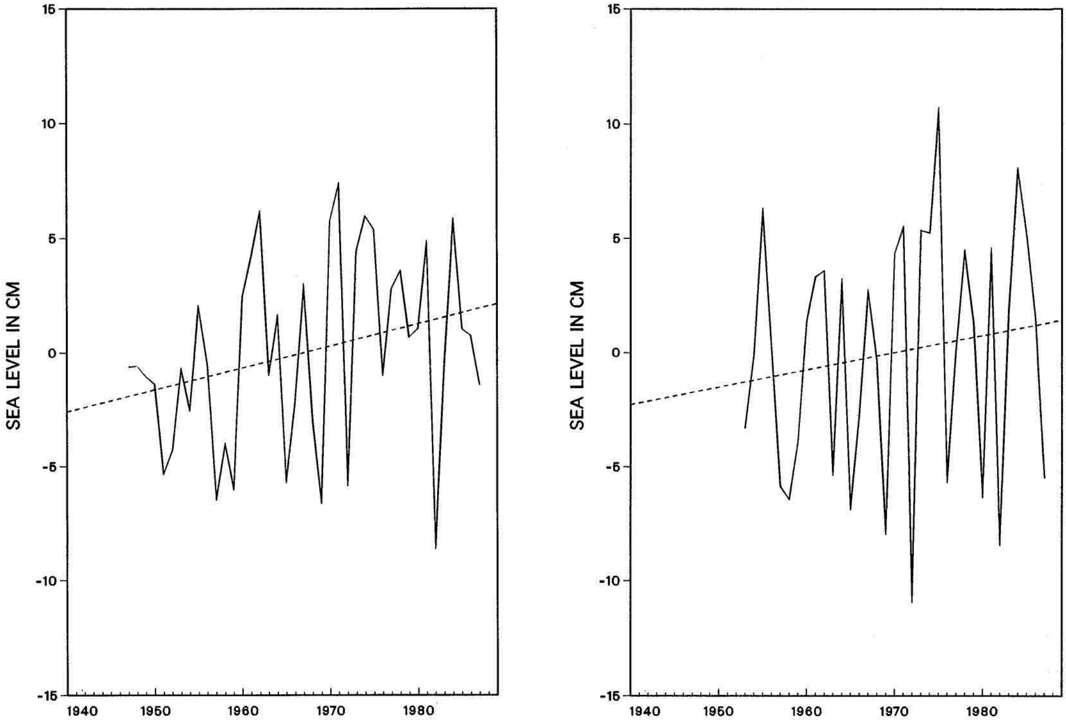


FIGURE 10. Annual mean sea level (in centimeters) and linear trends at Kwajalein (8°44′ N, 167°44′ E) (left) and at Truk (7°27′ N, 151°51′ E) (right).

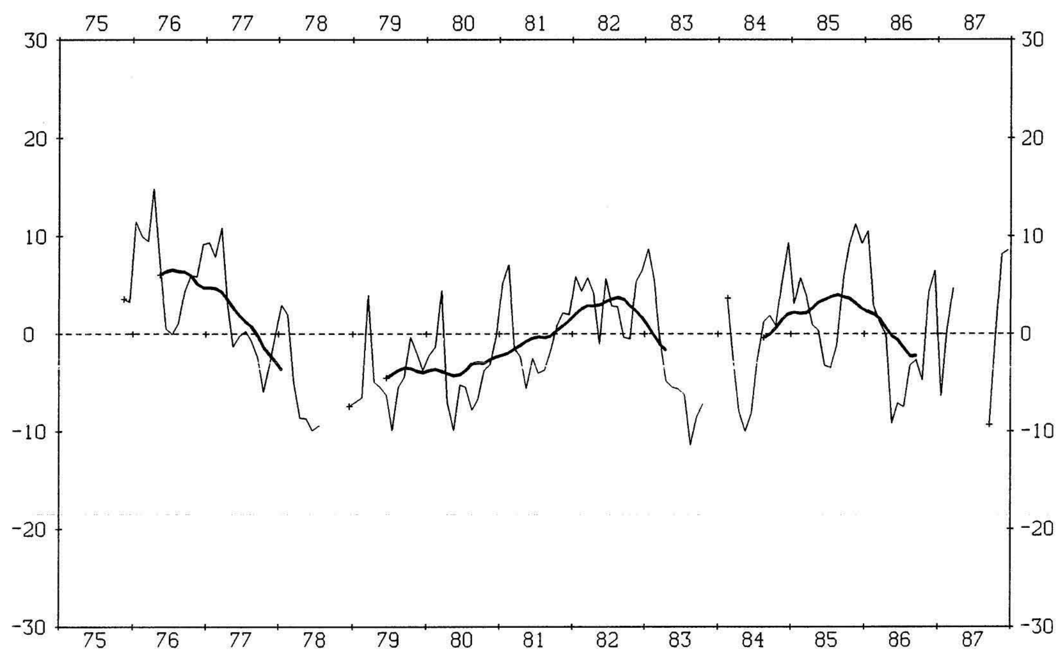


FIGURE 11. Monthly mean sea level (thin curve) and 12-month running mean (thick curve) (in centimeters) at Suva, Fiji from 1975 to 1987. No definite trend is apparent.

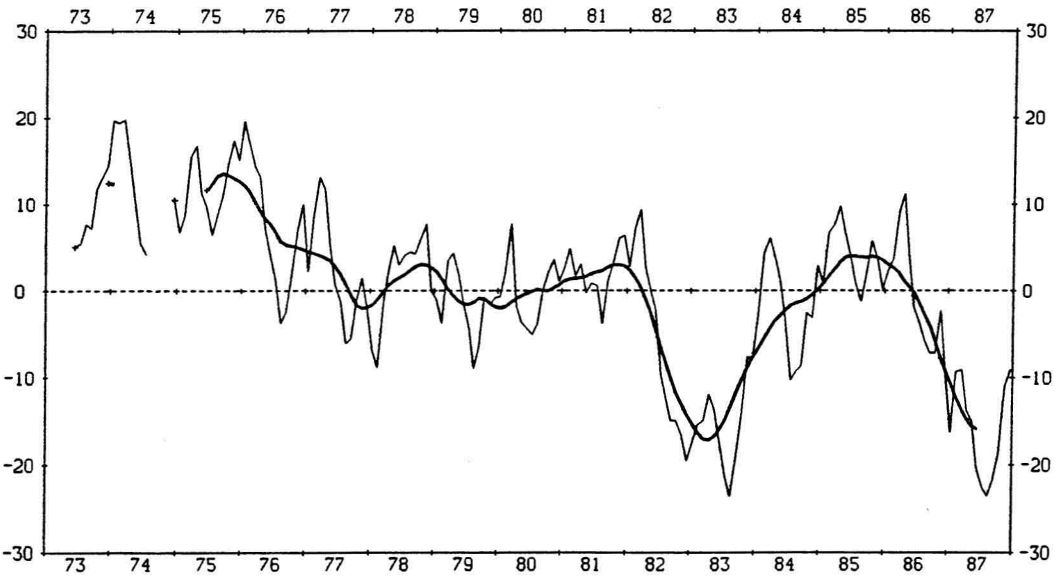


FIGURE 12. Monthly mean sea level (thin curve) and 12-month running mean (thick curve) at Rabaul, Papua New Guinea from 1973 to 1987. The large drops in sea level in 1982–1983 and in 1987 are related to El Niño events. The trend toward lower sea level is due to an uplifting of the land.

especially large, and the estimate of the trend is uncertain.

The record available for Suva, Fiji (Figure 11) does not allow the computation of a trend with any degree of confidence. The record for Rabaul (Figure 12) shows a drop in sea level, which is due to the rise of the land caused by tectonic uplifting. The longer, but interrupted, records at Christmas Island and Kanton Island (Figures 13, 14) show no discernible trend, but indicate large fluctuations of sea level associated with El Niño events, such as in 1982–1983.

These and other sea level data are available from the Tropical Ocean Global Atmosphere (TOGA) Sea Level Center at the University of Hawaii. Much of the data from Pacific islands was collected as part of the Pacific Island Sea Level Network (Wyrtki et al. 1988*a*). Data received at the Center are also used to prepare monthly sea level maps for the Pacific Ocean as part of the Integrated Global Ocean Station System (IGOSS) (Wyrtki et al. 1988*b*).

Table 2 summarizes the values of sea level change mentioned in this report and gives an impression of the wide range of the magnitude of the observed changes. The strongest of these changes are due to tectonic effects, and the estimated rise of the mean ocean level appears small in comparison.

Final Comments

In the short period of about 100 yr during which sea level data have been collected, many important changes have taken place on earth. World population has more than tripled to over 5 billion people (Figure 15). It is expected to exceed 6 billion by the turn of the century. This ever-increasing population puts an enormous strain on our environment by burning fossil fuels, by pollution, and by deforestation. The demand of this huge population on the limited resources of the earth will soon lead to water and food shortages and to political unrest. There is no doubt that the problems caused by an exponentially rising world population will be much more severe than those produced by sea level rise, the greenhouse effect, or any foreseeable climate change.

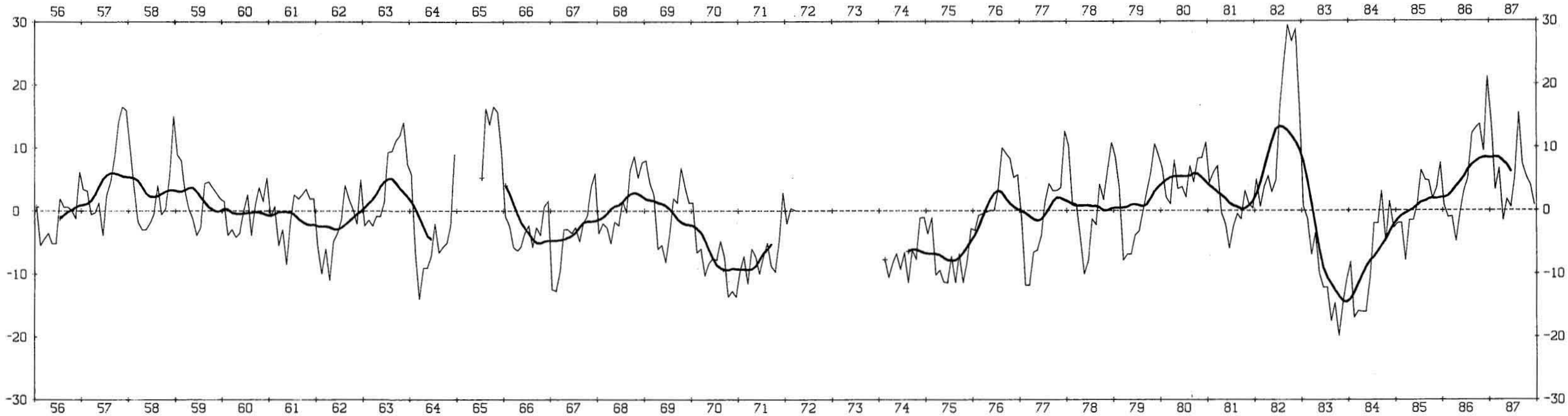


FIGURE 13. Monthly mean sea level (thin curve) and 12-month running mean (thick curve) at Christmas Island, central Pacific, from 1956 to 1987. Note the large changes of sea level during the 1982–1983 E1 Niño event. No trend in sea level is apparent.

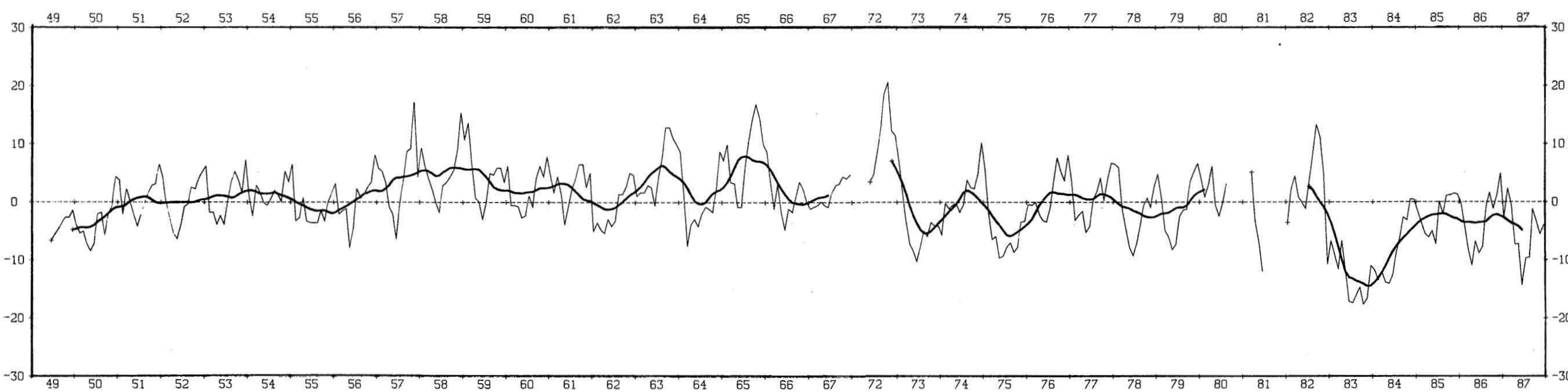


FIGURE 14. Monthly mean sea level (thin curve) and 12-month running mean (thick curve) at Kanton Island, central Pacific, from 1949 to 1987. Note the data gap from 1968 to 1972. There seems to be a trend to higher sea level in the early part of the record and to lower sea level in the later part.

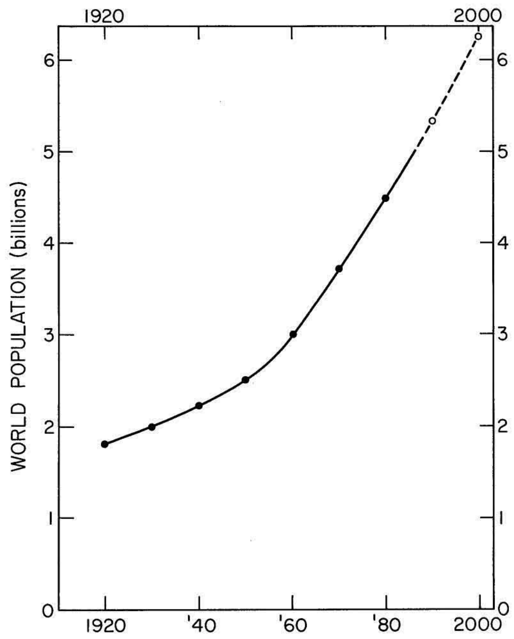


FIGURE 15. World population from 1910 to 2000 in billions of people.

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LITERATURE CITED

AUBREY, D. G., and K. O. EMERY. 1986. Relative sea levels of Japan from tide-gauge records. Geol. Soc. Am. Bull. 97:194–205.

BARNETT, T. P. 1984. An estimation of "global" sea level change: A problem of uniqueness. J. Geophys. Res. 89(C5): 7980–7988.

CHELTON, D. B., and D. B. ENFIELD. 1986. Ocean signals in tide gauge records. J. Geophys. Res. 91(B9): 9081–9098.

DIAMANTE, J. M., T. E. PYLE, W. CARTER, and W. SCHERER. 1987. Global change and the measurement of sea level. Prog. Oceanogr. 18:1–21.

ELLSAESSER, H. W., M. C. MACCRACKEN, J. J. WALTON, and S. L. GROTCH. 1986. Global climatic trends as revealed by the recorded data. Rev. Geophys. 24(4): 745–792.

FLETCHER, J. O., U. RADOK, and R. SLUTZ. 1982. Climatic signals of the Antarctic Ocean. J. Geophys. Res. 87(C6): 4269–4276.

GORNITZ, V., S. LEBEDEFF, and J. HANSEN. 1982. Global sea level trend in the past century. Science 215:1611–1614.

HANSEN, J., and S. LEBEDEFF. 1988. Global surface air temperatures: Update through 1987. Geophys. Res. Let. 15(4): 323–326.

HANSEN, J., I. FUNG, A. LACIS, D. RIND, S. LEBEDEFF, R. RUEDY, G. RUSSELL, and P. STONE. 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res. 93(D8): 9341–9364.

HICKS, S. D., and W. SHOFNOS. 1965. The determination of land emergence from sea level observations in southeast Alaska. J. Geophys. Res. 70(14): 3315–3320.

IAPSO ADVISORY COMMITTEE ON TIDES AND MEAN SEA LEVEL. 1985. Changes in relative mean sea level. Eos 66(45): 754.

JONES, P. D., T. M. L. WIGLEY, and P. B. WRIGHT. 1986. Global temperature variations between 1861 and 1984. Nature (London) 322:430–434.

MEIER, M. 1984. Contribution of small glaciers to global sea level, 1984. Science 226:1418–1421.

PIRAZZOLI, P. A. 1986. Secular trends of relative sea level (RSL) changes indicated by tide-gauge records. J. Coastal Res. SI(1): 1–26.

PUGH, D. 1987. Tides, surges and mean sea level: A handbook for engineers and scientists. John Wiley & Sons Ltd., Chichester, U.K.

RAMANATHAN, V. 1988. The greenhouse theory of climate change: A test by an inadvertent global experiment. Science 240:293–299.

RAMANATHAN, V., R. D. CESS, E. F. HARRISON, P. MINNIS, B. R. BARKSTROM, E. AHMAD, and D. HARTMANN. 1989. Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. Science 243:57–63.

SAURAMO, M. 1958. Die Geschichte der Ostsee. Ann. Acad. Sci. Fenn. Ser. A: 1–522.

STUIVER, M. 1986. Ancient carbon cycle changes derived from the Tree-Ring $^{13}C/^{14}C$. Pages 166–186 *in* J. R. Trabalka and D. E. Reichle, eds. The global carbon cycle: A global analysis. Springer-Verlag, New York.

WYRTKI, K., K. CONSTANTINE, B. KILONSKY, G. MITCHUM, B. MIYAMOTO, T. MURPHY, S. NAKAHARA, and P. CALDWELL. 1988*a*. The Pacific Island Sea Level Network. Joint Institute of Marine and Atmospheric Research Contribution 88-0137, University of Hawaii.

WYRTKI, K., B. J. KILONSKY, and S. NAKAHARA. 1988*b*. The IGOSS Sea Level Pilot Project in the Pacific. Joint Institute of Marine and Atmospheric Research Contribution 88-0150, University of Hawaii.