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Rainfall and beach erosion relationships, Stanwell Park, Australia, 1895-1980: worldwide implications for coastal erosion

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Abstract

Beach erosion is often associated with sea-level rise, sediment depletion or variation in wave conditions; however above-normal rainfall can cause beach retreat by increasing water-table elevation on the foreshore. On Stanwell Park beach, New South Wales, Australia annual rainfall accounts for 12.4% of the variance in the long-term, high-ride position measured accurately to ±2.5 m for the whole beach using 135 oblique photographs dated between 1895-1980. Sea-level changes account for an additional 4.6%. A 100 mm increase in annual rainfall or a 1 cm rise in sea-level results in 0.79 or 0.44 m retreat respectively of the average high-tide position for this beach. Because of relationships with the Southern Oscillation, initiation of above-normal rainfall periods can be forecast by several months in the Southern Pacific area, The southern Oscillation refers to a fluctuation in atmospheric pressure between the East Pacific and Indo-Australian regions, and has worldwide climatic teleconnections. The worldwide variation in rainfall and sea-level for the period 1960-1979 was accessed using information from NOAA and Permanent Service for Mean Sea Level tapes. There is far more information on rainfall characteristics than on sea-level changes. Results indicate that sea-level has not risen uniformly worldwide in the last two decades; it has fallen in Western Europe and western North America. Most stretches of world coastline where rising sea-level has traditionally been invoked to account for beach retreat are also areas where rainfall regimes have become wetter or more variable. The main factor initiating worldwide alterations in rainfall, as well as influencing sea-levels, is the recent shift in climate since 1948 when, with a cooling globe, rainfall has increased in mid and high-latitudes. Since 1970 meteorological events, including rainfall, have become more variable. In areas with low rates of sea-level rise, changes in rainfall regime may be an important cause of beach change. In areas with a rising sea-level, regime alterations may exacerbate beach erosion.

Keywords

beach erosion, rainfall, sea-level rise, global, New South Wales, Australia

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Rainfall and beach erosion relationships, Stanwell Park, Australia, 1895–1980: worldwide implications for coastal erosion

by

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with 7 figures and 2 tables

Summary. Beach erosion is often associated with sea-level rise, sediment depletion or variation in wave conditions; however above-normal rainfall can cause beach retreat by increasing water-table elevation on the foreshore. On Stanwell Park beach, New South Wales, Australia annual rainfall accounts for 12.4% of the variance in the long-term, high-tide position measured accurately to ±2.5 m for the whole beach using 135 oblique photographs dated between 1895–1980. Sea-level changes account for an additional 4.6%. A 100 mm increase in annual rainfall or a 1 cm rise in sea-level results in 0.79 or 0.44 m retreat respectively of the average high-tide position for this beach. Because of relationships with the Southern Oscillation, initiation of above-normal rainfall periods can be forecast by several months in the Southern Pacific area. The Southern Oscillation refers to a fluctuation in atmospheric pressure between the East Pacific and Indo-Australian regions, and has worldwide climatic teleconnections.

The worldwide variation in rainfall and sea-level for the period 1960–1979 was accessed using information from NOAA and Permanent Service for Mean Sea Level tapes. There is far more information on rainfall characteristics than on sea-level changes. Results indicate that sea-level has not risen uniformly worldwide in the last two decades; it has fallen in Western Europe and western North America. Most stretches of world coastline where rising sea-level has traditionally been invoked to account for beach retreat are also areas where rainfall regimes have become wetter or more variable. The main factor initiating worldwide alterations in rainfall, as well as influencing sea-levels, is the recent shift in climate since 1948 when, with a cooling globe, rainfall has increased in mid and high-latitudes. Since 1970 meteorological events, including rainfall, have become more variable. In areas with low rates of sea-level rise, changes in rainfall regime may be an important cause of beach change. In areas with a rising sea-level, regime alterations may exacerbate beach erosion.

Introduction

Sandy beach erosion has been attributed to a number of factors, including increased storminess, tectonic subsidence, eustatic sea-level rise, decreased shoreward sediment movement from the shelf, permanent longshore leakage of sediment from beach

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Table 1. Stepwise multiple regression analysis of beach change in meters, Stanwell Park against a) rainfall in meters at Helensburgh, b) sea-level in meters at Sydney and c) the Southern Oscillation index measuring pressure between Darwin and Tahiti areas standardized to a value of 1.0.

Variable	Rate of Change	Correlation with beach change (y) coefficients	Stepwise multiple correlation	Percent added variance explained
a) rainfall (annual 1897–1980)	NS	r=0.35** y=12.9–0.0079 x (mm)	r=0.35**	12.4%
b) sea-level (monthly 1897–1980)	0.64 mm/yr*	r=–0.27** y=38.1- 46.9 x (m)	r=0.41**	4.6%
c) SO index (quarterly 1897–1974)	0.013/yr*	r=–0.19* y=1.65–2.73 x	r=0.41*	0.1%

* significant 0.05 level, ** significant 0.01 level, NS not significant.

compartments, shifts in global pressure belts resulting in changes in the directional component of wave climates, and human interference (BIRD 1981; BRYANT 1983a). In a recent paper (BRYANT 1983a), evidence was found for a significant relationship between monthly sea-level oscillation and shoreline change on Stanwell Park beach, New South Wales, Australia between 1895–1980 (table 1). A 1 cm rise in sea-level resulted in a 0.44 m recession of the high-tide line. While sea-level variation worldwide appears to be eustatically induced, at an average rate around 1.5 mm/yr (BARNETT 1983), off the east coast of Australia sea-level has only been rising 0.64 mm/yr, apparently due to regional meteorological and oceanographic factors. One of these factors is easterly onshore air flow, and a significant link has been found between beach erosion and the strength of the Walker circulation or easterly onshore air flow across the equatorial Pacific ocean (BRYANT 1983a). Since the Walker circulation oscillates in strength every 2–3 years (termed the Southern Oscillation or SO) and has teleconnections with meteorological variables worldwide (ANGELL 1981; HOREL & WALLACE 1981), short-term global climatic changes occurring over several years may account for a substantial portion of beach erosion in areas where changes in sea-level have been less than the average eustatic rate, and very much less than the current 3 mm/yr rate reported during the 1970's for low and mid-latitudes of the Northern Hemisphere (EMERY 1980).

In this paper rainfall is examined as an obvious but neglected cause of beach erosion, and shown to be correlated with beach retreat along the southeast coast of Australia because of linkages to the Southern Oscillation. In addition the roles of changing rainfall regime and sea-levels are evaluated as probable causes of coastal erosion or accretion worldwide for the 1960's and 70's, using rainfall data obtained from United States National Oceanic and Atmospheric Administration tapes, and tide records from the United Kingdom Permanent Service for Mean Sea Level data bank.

Analysis of Stanwell Park shoreline changes

Stanwell Park, 30 km south of Sydney, is a SE-orientated, 900 m long sandy beach with a stable self-contained sediment budget (fig. 1). The beach is dominated by a cuspate bar and channel system which dissipates wave energy across a 100–150 m wide surf zone. Under accretion during fair-weather conditions these bars weld to shore to form a shoal-and-pool topography, with large amounts of sediment moving landward to form a berm at the high-tide mark. The wave climate can be termed high energy, with 1.2 m high modal waves approaching from the SE quadrant over 60% of the time (LAWSON & ABERNETHY 1975). The record of erosion-accretion for this beach is based upon an analysis of the high-tide position for the whole of the beach, measured from oblique photographs taken between 1895–1980. This record, consisting of 135 photographs, averages one photograph every 4 years between 1895–1920, one every 2 years between 1920–1933, and more than one per year thereafter. The photographs were dated to the nearest year, and ordered sequentially using cultural information, and dates supplied by photo donors. High-tide position was measured to within $\pm$2.5 m on the ground (80% of photos mapped accurate to within 1 m) using the direct linear transformation method of photo co-ordinate resectioning (BRYANT 1983b). These data, plus the yearly sea-level record for Sydney and the Southern Oscillation index for the same period, are plotted in fig. 2. The Southern Oscillation index closely approximates the pressure difference between Darwin and Tahiti, and has been standardized to a value of 1. Positive values indicate increased easterly equatorial air circulation which has been associated with a raised sea-level and beach erosion at Stanwell Park (BRYANT 1983a). Throughout the record storms have had a consistent magnitude and frequency, and have been superimposed on a general period of accretion between 1929–1948, and erosion thereafter. The date 1948 is thought to represent a local and global climatic turning point (GRIBBIN 1978; RILEY 1982), and rainfall has certainly increased along the east coast of Australia since then (PITTOCK 1975; CORNISH 1977; DURY 1980). Yearly averages of rainfall measured at Helensburgh 4 km from Stanwell Park are also plotted in fig. 2. Annual rainfall, sea-level and the SO index were correlated with the high-tide data using multiple step-wise regression analysis (NIE et al. 1975).

Results summarized in table 1 indicate that when annual rainfall at Helensburgh exceeds 1635 mm (the yearly average is 1455 mm) each 100 mm increment results in 0.79 m of beach retreat from the mean high-tide position calculated for the data series. Rainfall accounts for 12.4% of the data variance, and is significant at the 0.01 level. Sea-level rise and the SO index only account for a further 4.6% and 0.1% of the variance respectively; however both are correlated with Helensburgh rainfall at the 0.05 level of significance or lower (table 2). The causal link between rainfall and erosion cannot be accounted for by stream erosion. Often when local streams flood, sediment is flushed out of the streams and lagoons into the surf zone, and very quickly returns to the beach causing local progradation of the high-tide line. In an earlier paper (BRYANT 1983a), the relationship between beach erosion and sea-level rise was accounted for using BRUUN's hypothesis and rising water-tables. BRUUN's hypothesis states that as sea-level rises, equilibrium profiles with little longshore sediment movement (conditions applicable to Stanwell Park) must retreat landward, so that beaches erode. Various authors (DUBOIS 1977; ROSEN 1978; CLARKE & ELIOT 1983) have found rates of shoreline recession close to the 0.44 m/cm rise determined for Stanwell Park using this hypothesis. Additionally

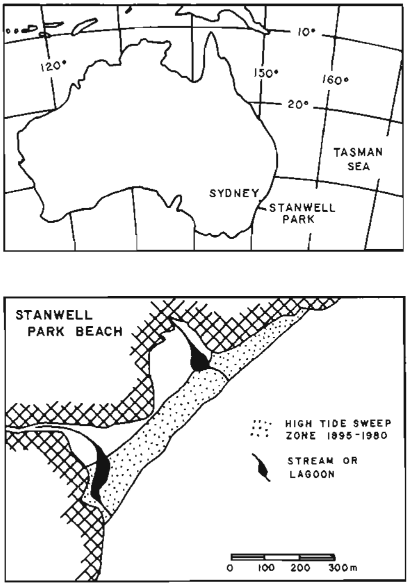

Fig. 1. Location map of Stanwell Park beach. Enlargement shows high-tide sweep zone 1895 – 1980.

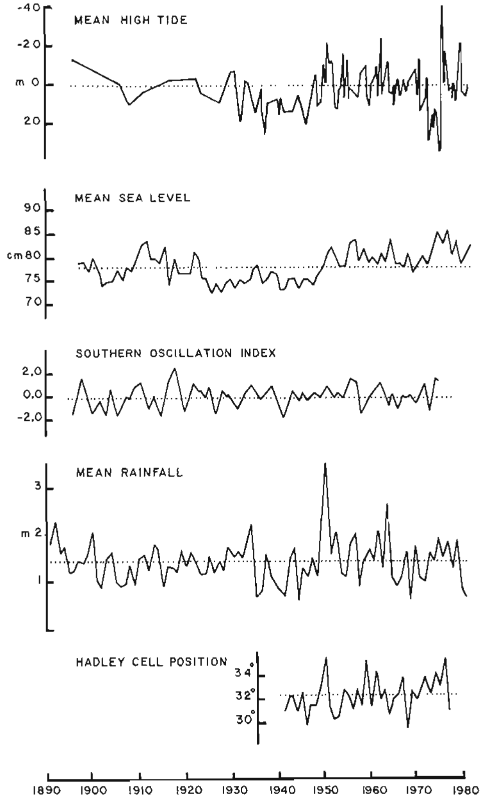

Fig. 2. Changes at varying periods 1895 – 1980 in average high-tide position for Stanwell Park beach (values measure deviations from mean record), annual sea-level at Sydney, Southern Oscillation index (values measure the pressure difference between Tahiti and Darwin areas standardized to a value of 1.0), mean annual rainfall at Helensburgh (4 km from Stanwell Park), latitude of the Hadley cell position along the east coast of Australia.

sea-level rise must raise the base line of beach water-tables, a condition that also leads to erosion (CHAPPELL et al. 1979; ELIOT & CLARKE 1982). It is this link between water-table elevation and beach erosion which accounts for the relationship between rainfall and beach retreat. There have been months when up to 1000 mm of rain has fallen in the Stanwell Park area. The sandy backshore absorbs this rainfall, and acts as a slow filter for subsequent discharge of rain water to the sea through the lower foreshore. This discharge leads first to decreased sediment shear resistance and then liquefaction on the beach face followed by seaward transport of sand and shoreline retreat. Under intense rainfall sand elutriation may occur.

There have been many studies postulating rising sea-level as a major cause for increased beach erosion, and HARRISON (1970) emphasised the importance of groundwater variations in beach geometry, but changes in rainfall regime have been neglected as a cause for increased beach erosion. In many respects rainfall has better predictive aspects for beach change at Stanwell Park than storms, sea-level rise or other factors. At this point it should be noted that rainfall along the east Australian coast often occurs independently of storms associated with higher erosive wave activity. While such storms may account for a substantial portion of the variance in high-tide position on this beach, they have only short term effects except when they occur as clusters over several months or seasons. There is no evidence that the frequency or magnitude of storm erosion has increased recently. Instead erosive, high-energy wave events have had a constant recurrence during periods of both longer term accretion and erosion. The prediction of erosive storms to date has been extremely poor. Sea-level variations along the N.S.W. coast are also difficult to predict because they are dependent upon a variety of temporally variable and often negatively cross-correlated meteorological and oceanographic factors. For instance the movement of high pressure cells into the Tasman Sea decreases sea-level by increasing atmospheric pressure, but the easterly onshore circulation that results moves sea water towards the coast. Rainfall in eastern Australia can be predicted to a certain degree. A significant correlation has been found between precipitation and 1) the annual mean position of the Hadley cell (PITTOCK 1975) and 2) the Southern Oscillation index (TROUP 1965; PITTOCK 1978). Both correlations have quasi-biennial periodicities (COUGHLAN 1978; NICHOLLS & WOODCOCK 1981). Spring rainfall over eastern Australia has also been predicted using the preceding winter pressure at Darwin (NICHOLLS & WOODCOCK 1981). Pearson product-moment correlation was carried out between Helensburgh rainfall and the SO index, 1897–1974, and between rainfall and the mean monthly Hadley cell position along the eastern Australian coast, 1941–1980 (table 2). Rainfall at Helensburgh lags three months behind an increase in the SO index, – a result confirmed elsewhere in equatorial Pacific areas (HOREL & WALLACE 1981). A poleward shift in the position of the Hadley cell ±1 month was highly indicative of increased rainfall, even when seasonality was removed from the data.

Table 2. Pearson product-moment correlation coefficients between rainfall and a) Southern Oscillation index (1897–1974), b) latitude of Hadley cell east coast of Australia (1941–1980) and c) Sydney sea-level (1897–1980). Lag refers to lag in rainfall.

a) n=312			b) n=480			c) n=108		
Lag in months	r	r (no season)	lag in months	r	r (no season)	lag in months	r	r (no season)
−9	0.022	0.000	−3	0.057	0.090	−3	0.153***	0.174***
−6	0.030	0.010	−2	0.056	0.040	−2	0.157***	0.167***
−3	0.126*	0.115*	−1	0.189**	0.117*	−1	0.132***	0.132***
0	0.153**	0.149**	0	0.494***	0.433***	0	0.067*	0.061*
+3	0.172**	0.160**	+1	0.182**	0.095*	+1	0.035	0.033
+6	0.151**	0.142**	+2	0.096*	0.025	+2	0.025	0.029
+9	0.096	0.084	+3	0.056	0.043	+3	−0.038	−0.030

* significant 0.05 level, ** significant 0.01 level, *** significant 0.001 level.

Discussion of worldwide implications

Rainfall

In summary the present study indicates that since 1948 beach retreat at Stanwell Park has increased concomittantly with sea-level rise, a poleward shift in the Hadley cell, increased strength of easterly equatoral air flow as indicated by more positive values of the SO index, and increased rainfall. Of these four variables, increased rainfall correlates best with beach erosion. Variations in rainfall regime and subsequent beach change in eastern Australia can be predicted by local Hadley cell movement and by global shifts in the Southern Oscillation. The fact that rainfall changes elsewhere in the Pacific region are linked to changes in the Southern Oscillation (HOREL & WALLACE 1981), could lead to the prediction of periods of beach erosion over a much wider area than Stanwell Park beach.

Apart from areas in the Pacific Ocean affected by the Southern Oscillation, there is a wealth of data on rainfall variability worldwide. In fact there is more information on changing global rainfall patterns (LAMB 1972) than on sea-level changes (EMERY 1980; BARNETT 1983). For instance there are 6475 stations in Australia with rainfall information this century, but less than 40 stations monitoring sea-level, only one of which was recording before 1900. Over the 60 km of coastline south of Stanwell Park beach there are more than 120 sporadic rainfall series within 40 km of the coast for the past century. Twenty of these sets are complete back to 1930. Over the same distance there is only one tide gauge with less than 20 years of data.

Average annual rainfall totals along most of the eastern Australian coastline have increased by up to 15% between the periods 1913–1945 and 1946–1974 (PITTOCK 1981) with such geomorphic ramifications as higher lake levels, increased flood frequencies and fluvial channel expansion (RILEY 1982; ERSKINE & BELL 1982). The date 1948 has already been pointed out as a global climatic turning point with decreasing temperatures being the most noticeable feature up to 1975; however the predominant meteorological characteristic since 1948 has been the increasing frequency of weather extremes, including flood and drought (LAMB 1981; GRIBBIN 1983). While large sections of the world have undergone significant drought, areas such as the east coast of Australia and higher latitude coastlines in the Northern Hemisphere have become wetter (LAMB 1972, 1981). Even if rainfall has remained seemingly constant over periods of decades, the increased climatic variability has lead to wider fluctuations in year-to-year rainfall. The extreme aridity and record-breaking rainfalls across the southern Pacific Ocean associated with the 1982–83 El Niño-Southern Oscillation (ENSO) event attest to this fact (GLANTZ 1984). While year-to-year rainfall may be highly variable, the spatial change in precipitation can be just as great. Rainfall may be uniform for long distances along the eastern seaboard of the United States and the west coast of Europe, but along the west coasts of North and South America, and the coastlines of Africa and Australia rainfall fluctuates over short distances mainly because of orographic variation. Average annual rainfalls decrease up to 30%, 30 km south of Stanwell Park because of increasing distance from an inland escarpment. The drier conditions southwards have been invoked to account for slightly wider backshores on some beaches compared to Stanwell Park (BRYANT 1984). In the same area short term rainfall is very inconsistent. Major rainfall events have been known to drop 200–400 mm of rainfall along some sections of the coast and less than 100 mm 30–40 km away (NANSON & HEAN 1984).

To assess the variability of rainfall globally as a possible contribution to beach erosion, world rainfall records were analysed between 1950–1979 using approximately 2500 stations, of which 604 had more than 26 years of measurement. The mean change in rainfall for the period 1960–79 over the preceding decade (1950–59) was calculated together with the standard deviation of the data for the three decades. Areas of decreased and increased rainfall for the period 1960–1979 are cross-hatched and stippled respectively in fig. 3. Within these areas, coastlines having a change in rainfall regime >20% are drawn with a thicker line. Areas with inadequate records on the NOAA tapes repesent the majority of the map left blank. The standard deviations of rainfall for the period 1950–1979 are contoured in fig. 4. Areas where the standard deviation is greater than 200 mm are lightly shaded while areas greater than 400 mm are cross-hatched. The data have evidenced considerable changes in rainfall regime globally over the past two decades. The patterns are very similar to those compiled by LAMB (1972, 1981) for departures of individual decades from the 1931–1960 mean. Most of Africa and the Southeast Asia have become drier, while the temperate mid-latitudes and polar regions have become wetter. The latter patterns are characteristic of a cooling globe (GRIBBIN 1983). Parts of eastern South America, southern Africa and northwestern Australia, together with the High Arctic regions of Canada and the U.S.S.R., had rainfall increases greater than 20%. It is in these regions that rainfall could have contributed to beach erosion.

The variability in rainfall regime over the period 1950–79 is even more dramatic. Standard deviations greater than 200 mm have been judged important because the Stanwell Park rainfall standard deviation lies above this value. Most of the northern hemisphere, except for the eastern seaboard of the United States and scattered locations in western Europe and the Mediterranean, had little yearly rainfall variability. However most of the Southern Hemisphere, together with India and Southeast Asia, had a variable

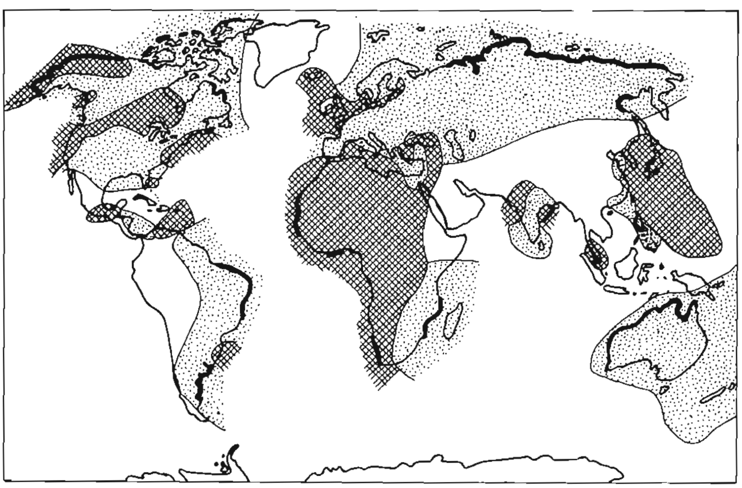

Fig. 3. Changes in mean annual world rainfall for the period 1960–79 compared to the 1950 decade. Areas with decreasing rainfall are cross-hatched, areas with increasing rainfall are stippled. Coastline drawn with a thicker line represents more than a 20% change.

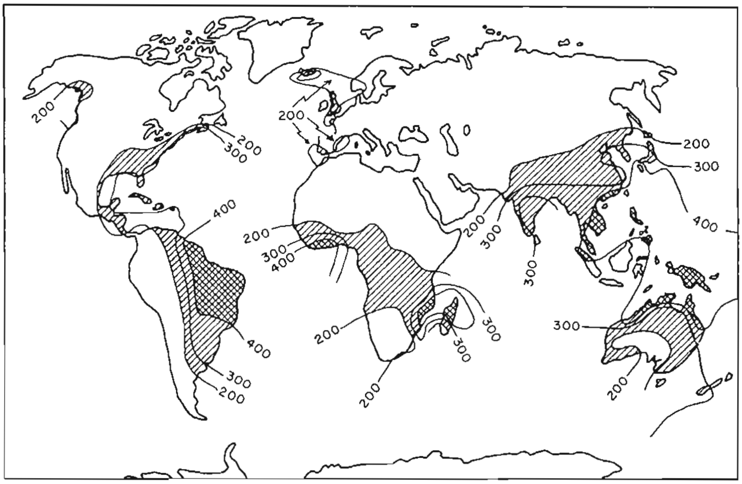

Fig. 4. Standard deviations in mm of mean annual world rainfall. Lightly shaded areas have values exceeding 200 mm, cross-hatched areas have values in excess of 400 mm.

rainfall regime similar to or more erratic than that of Stanwell Park beach. It should be noted that the coast of the United States from which data have been collected supporting BRUUN's hypothesis had a slightly more erratic rainfall regime than Stanwell Park, and rainfall-induced beach change should therefore also be considered. Extensive areas, notably in Brazil, the Mozambique and Ivory Coast regions of Africa, and the area between Japan and Australia have standard deviations exceeded 400 mm; in the Mozambique and Australian regions values exceeded 1000 mm.

Sea level

Sea level is also temporally and spatially variable. According to BARNETT (1983) there has been over the past century a general eustatic rise in sea-level of 15.1 ± 1.5 cm which may or may not have been accelerating in recent years (EMERY 1980). BARNETT (1983) has shown from an analysis of astronomical observations of length of day and pole position, that the most probable cause of this increase has been equal melting of ice from the Greenland and Antarctic ice caps rather than thermal expansion of oceans or deceleration of ocean gyres; however melting of mountain glaciers and increased pumping of groundwaters by man must also have contributed. Seasonally mean sea level has been found to fluctuate between 15 and 54 cm in such diverse locations as the Bay of Bengal, west coast of Mexico, north-eastern Siberia and Australia (PATTULLO 1963). Over periods of days or months sea level can fluctuate several decimeters because of changes in atmospheric pressure, sea temperature, salinity, onshore wind stress, current impingement on the coastline, mixing of surface and deep ocean waters, and river discharge. Short term variations can also be due to storm surge, tectonic activity and the presence of shelf waves (PATTULLO 1963; LISITZIN 1974; WALCOTT 1975). All of these changes can act over a long enough period for BRUUN's hypothesis of shoreline retreat due to rising sea level to take place. One of the most persistent inter-annual fluctuations in sea level, with changes up to 30 cm over several months, occurs with El Niño-Southern Oscillation (ENSO) events in the equatorial Pacific region (MEYERS 1982; WYRTKI 1982). During the 1982–83 event, sea level fluctuated by up to 40 cm (HARRISON & CANE 1984), and remained high for long enough in some locations to cause beach retreat. However the role played by raised sea-level during ENSO events may be difficult to evaluate because such raised sea levels are often accompanied by increased rainfall (BRYANT 1984). Sea levels associated with ENSO events also have high spatial diversity. It is becoming increasingly apparent that sea levels can commonly fluctuate over short distances because of shelf waves, storm surge or river discharge. Shelf waves, with a periodicity of 1 to 7 days and amplitudes exceeding 50 cm have been found to travel anti-clockwise around the southern half of Australia (PROVIS & RADOK 1979). LANYON et al. (1982) found shelf wave periodicities of 10–20 minutes in beach water-table records 30 km from Stanwell Park beach, and postulated that such waves could influence shoreline position. The storm of May 25 1974, which severely eroded N.S.W. South Coast beaches, produced spatially variable sea level oscillations of the order of 20 cm over a 200 km stretch of coastline. The same storm produced a higher surge in estuaries than along the open coast (FOSTER et al. 1975). River discharge can also accelerate beach erosion. Warilla Beach, 40 km from Stanwell Park, has undergone accelerated retreat since 1948, partly because of increased flood frequencies resulting from higher rainfall along the eastern Australian coastline (BRYANT 1984). One flood in 1961, exiting to the ocean from a small lake at the north end of Warilla Beach, could have raised water levels up to 50 cm higher here than on other parts of the coast, including Stanwell Park.

To assess the variability of sea level worldwide as a possible contribution to beach erosion, records for 725 stations were analysed to determine local and regional trends in sea level for the period 1960–1979, the period for which most studies invoking BRUUN's hypothesis have been carried out. Of these stations, 219 had adequate data ($\geqq$ 15 years of measurement) to make this assessment. Over 50% and 75% of the trends were statistically significant at the 95% and 90% level of confidence respectively. Coastlines with decreases >1 mm/yr and increases >2 mm/yr are stippled and cross-hatched respectively in fig. 5. Coastlines with sufficient data to be included in the study are drawn with a thick line. Since the variability, and not just the trend, in sea-level may be responsible for beach erosion, those coastlines having standard deviations in annual sea-level exceeding 25 mm are shown in fig. 6 together with macrotidal coastlines (tides >4 m), storm surges greater than 2 m, or sea-level fluctuations dominated by the Southern Oscillation (DAVIES 1980; MEYERS 1982; HARRISON & CANE 1984). Macrotidal environments have sea levels which can be amplified unpredictably by slight storm surges, or by long-period astronomical occurrences such as maxima in the 18.6 year M_N lunar tide, or the 179 year alignment of planets (latest occurrences 1973 and 1982 respectively). Storm surges, while infrequent and unpredictable, can either obliterate or completely remould beach profile shape, not necessarily because of the sea level influences according to the BRUUN hypothesis, but also because surges are accompanied by higher energy waves, which are lifted in elevation above the long term active beach zone. The area affected by the Southern Oscillation has already been shown to have large scale sea level variations which must exert a profound influence on equatorial Pacific island beaches. Coastlines which are perennially ice-locked are also shown in fig. 6, as beach morphology in these areas is most likely dominated by ice (DAVIES 1980).

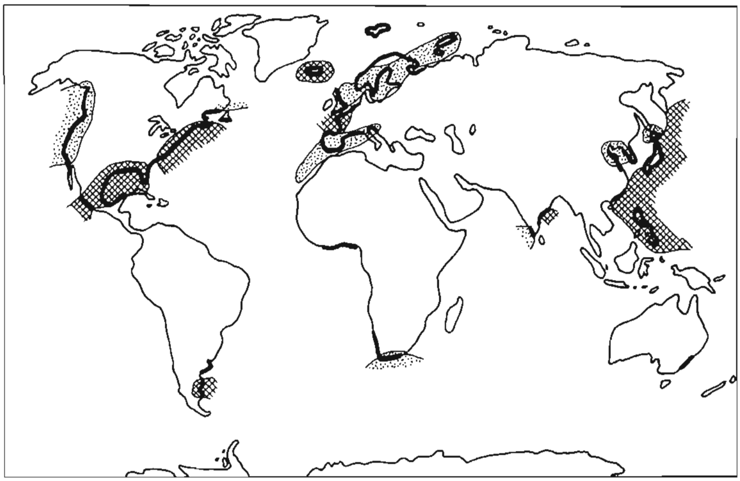

Fig. 5. Rates of change of mean annual world sea-level for the period 1960–79. Areas with sea-level decreases >1 mm/yr are stippled, areas with sea-level increases >2 mm/yr are cross-hatched. Coastlines appearing in the Permanent Service for Mean Sea Level records are drawn with a thicker line.

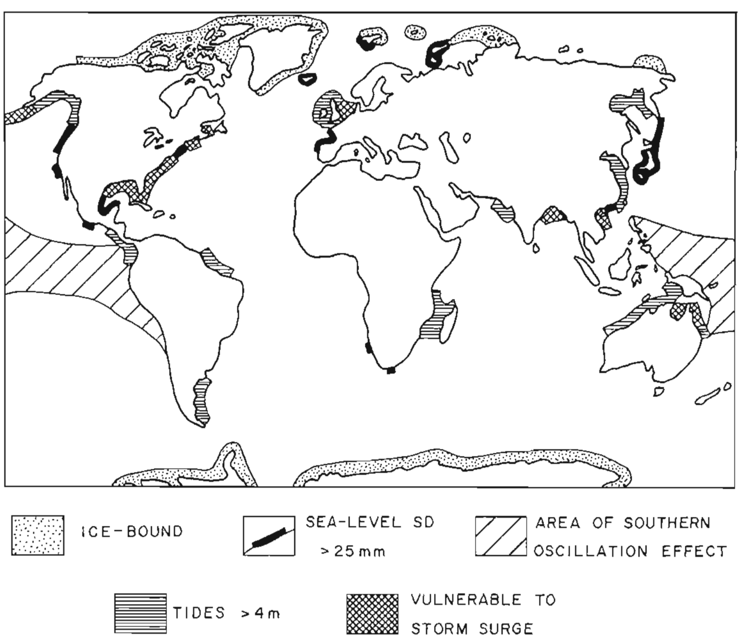

Fig. 6. Areas of coastline having standard deviations of mean annual sea-level for the period 1960–79 greater than 25 mm, macro-tides >4 m, storm surge vulnerability or Southern Oscillation influences.

Rainfall and beach erosion relationship

Figure 5 indicates that contrary to the general belief that sea level is rising worldwide, significant stretches of coastline, mainly in Western Europe and western North America, have had a trend towards decreased sea level since 1960. Some of these areas are outside zones affected by glacial deloading, while others are in the zone of collapsing forebulge submergence where theoretically sea level should still be rising (CLARK et al. 1978). Most of the sectors with raised sea levels are along the Gulf of Mexico and the eastern coastlines of North America and Japan. These areas include locations where most of the studies supporting BRUUN's hypothesis for sea-level rise as a cause of beach erosion have been carried out (SCHWARTZ 1965; ROSEN 1978; FISHER 1980). It would appear that the case for sea level change as a major, long-term cause of beach erosion has been based on evidence collected on only a small proportion of the world's coastline.

Figure 6 indicates that it may be that short-term variation in sea level is more applicable as a cause of beach erosion, because the proportion of world coastline susceptible to large short-term fluctuations in sea level is greater than the length of coastline influenced by a definable steadily rising trend. In these areas the BRUUN hypothesis may still be applicable, but accretion during intervening phases of falling sea level must also be considered. If the BRUUN rule is to account for long-term beach erosion in these locations, then the disequilibrium between erosion and accretion rates must be included. It takes a shorter time to remove material seaward during erosional, rising sea level phases then it does to return it to the beach during accretional, falling sea level periods. If eroded sediment has not been returned to the beach before the next higher sea level phase, then the beach undergoes retreat. BRUUN's hypothesis provides the mechanism by which responses to shifts in sea level operate. The more frequent the changes in sea level, the greater the rate of erosion. BRUUN's hypothesis as developed to date is thus static, a result already confirmed by ALLISON & SCHWARTZ (1981). The hypothesis is usually based on simple upward or downward sea level changes, but it is now realised that the frequency of sea level oscillations may also be a factor. Beach erosion studies should consider such fluctuations, and the reasons for their increased frequency. Undoubtedly a major factor has been the worldwide climatic change which has occurred since 1948, and the tendency for meteorological extremes to become more variable, especially since 1970 (GRIBBIN 1984). Part of this climatic modification includes alterations of rainfall regimes. Rainfall data has an extensive global coverage, and should be considered in attempts to unravel the natural causes of recent worldwide beach retreat.

The above data can be used to construct a map (fig. 7) showing coastlines which are most susceptible to fluctuations in shoreline position or to long term erosion because of fluctuating or long term increases in rainfall regime and/or sea-level. The following criteria have been used to construct this map:

1. rainfall increases 1960–79 exceed 20% the 1950–59 average;
2. rainfall fluctuates from year-to-year with standard deviations >200 mm;
3. sea-level rises 1960–1979 greater than 2 mm/yr;
4. sea-level fluctuates from year-to-year with standard deviations >25 mm; and
5. sea-level fluctuates from year-to-year because of storm surge, tidal ranges >4 m, or the effect of the Southern Oscillation.

Coastlines on the map have been categorized into three groups, according to the most probable relative importance of the following three factors influencing beach erosion: 1. sea level changes, 2. rainfall regime variability and 3. a combination of sea level and rainfall changes. Areas left blank are ice-dominated, have sea levels rising at less than 2 mm/yr, or

Fig. 7. Areas of world coastline affected 1960–1979 by increased rainfall or rainfall variability (cross-hatched), increased sea-level or sea-level variability (full shading), or both rainfall and sea-level factors (stippled). Coastlines with incomplete or inaccessible rainfall and/or sea-level data are drawn faintly. Coastlines left blank are dominated by ice, have sea-level increases <2 mm/yr or have inadequate rainfall data.

lack evidence of rainfall variability. Coastlines lacking incomplete rainfall and sea level data on NOAA and Permanent Service for Mean Sea Level tapes are drawn faintly. For simplicity, Pacific island areas have not been included on this map; however the majority are affected by a combination of rainfall and sea level factors. There are very few areas of the world where rising sea level or year-to-year fluctuations in sea level can be invoked as a major reason for beach erosion. The most extensive sections of coastline that have rainfall data where BRUUN's hypothesis can be applied are in Western Europe and southern Alaska. In all other cases, except for the west South American coastline where rainfall records are lacking, fluctuating or rising sea-levels exist in areas of increased or fluctuating rainfall. Even on the Pacific coast of South America it is doubtful if sea level change is the major cause of beach erosion, because this coastline comes under the influence of extreme rainfall variability associated with the Southern Oscillation (GLANTZ 1984). On the other hand there are lengthy segments of coast where rainfall variability, in the absence of comprehensive sea level records, could possibly be related by researchers to beach erosion. These include the Atlantic coasts of South America and Africa and most of the extra-tropical coastline of Australia. Given more information on rainfall, much of Southeast Asia could fall into this latter category, since there is published evidence of high rainfall variability throughout the area (QUINN et al. 1978; PANT & PARTHASARATHY 1981).

Conclusion

Research into beach erosion has shown a number of causal factors, of which sea level rise is only one. The present study has shown that rainfall regime characteristics are another variable which can contribute to beach retreat (and accretion). Analysis of the modern worldwide beach retreat should include assessment of the effects of rainfall variation as well as sea level regimes. At the regional and local level, additional factors are superimposed onto responses to sea level changes and rainfall variability.

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