March 1988

Storminess and high tide beach change, Stanwell Park, Australia 1943-1978

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Abstract

Coastal storms have been considered significant agents in transporting sediment, modifying morphology and causing recent beach erosion. Along the New South Wales coast, the concomitance of storms, warmer sea surface temperatures and poleward movement of the Hadley cell was linked to beach erosion on Stanwell Park beach between 1943 and 1978. This result was defined using an accurately constructed compilation of coastal storms and a precisely measured time series of high tide positions taken from 105 oblique photographs. The two data sets are amongst the best of their kind in the world. Indices of storm magnitude, representing cumulative significant wave height, were constructed at quarterly intervals and for the year prior to each photograph. The quarterly and cumulative storm indices explain 9.9% and 16.6% respectively, of the high tide variance at Stanwell Park. Each unit increase in the latter index, equivalent to an additional 1 m in storm wave height, shifts the high tide position shoreward by 0.47 m. This is equivalent to the effect produced by a 1 cm rise in sea level. While storminess is a crucial variable controlling high tide position on this beach, its role cannot be separated easily from that produced by rainfall, sea levels, sea surface temperatures, and atmospheric circulation along the East Australian coast and across the Pacific Ocean. Over 40% of the high tide data variance on Stanwell Park beach can be accounted for, in decreasing order of importance, by rainfall, storminess, tropical Pacific Ocean air circulation and sea level. These results have implications for other beaches in that single factors such as increased storminess or rising sea levels may not necessarily be the best factors for explaining recent worldwide beach erosion.

Keywords

storms, beach change, Australia, NSW, Stanwell Park, over time

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

This article was originally published as Bryant, EA, Storminess and high tide beach change, Stanwell Park, Australia 1943-1978, Marine Geology, 79(3), 1988, 171-187. The original article is available here.

STORMINESS AND HIGH TIDE BEACH CHANGE, STANWELL PARK, AUSTRALIA, 1943–1978

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(Received October 20, 1986; revised and accepted September 2, 1987)

Abstract

Bryant, E., 1988. Storminess and high tide beach change, Stanwell Park, Australia, 1943–1978. Mar. Geol., 79: 171–187.

Coastal storms have been considered significant agents in transporting sediment, modifying morphology and causing recent beach erosion. Along the New South Wales coast, the concomitance of storms, warmer sea surface temperatures and poleward movement of the Hadley cell was linked to beach erosion on Stanwell Park beach between 1943 and 1978. This result was defined using an accurately constructed compilation of coastal storms and a precisely measured time series of high tide positions taken from 105 oblique photographs. The two data sets are amongst the best of their kind in the world. Indices of storm magnitude, representing cumulative significant wave height, were constructed at quarterly intervals and for the year prior to each photograph. The quarterly and cumulative storm indices explain 9.9% and 16.6% respectively, of the high tide variance at Stanwell Park. Each unit increase in the latter index, equivalent to an additional 1 m in storm wave height, shifts the high tide position shoreward by 0.47 m. This is equivalent to the effect produced by a 1 cm rise in sea level. While storminess is a crucial variable controlling high tide position on this beach, its role cannot be separated easily from that produced by rainfall, sea levels, sea surface temperatures, and atmospheric circulation along the East Australian coast and across the Pacific Ocean. Over 40% of the high tide data variance on Stanwell Park beach can be accounted for, in decreasing order of importance, by rainfall, storminess, tropical Pacific Ocean air circulation and sea level. These results have implications for other beaches in that single factors such as increased storminess or rising sea levels may not necessarily be the best factors for explaining recent worldwide beach erosion.

Introduction

Since the classic observations both of the effects of Hurricane Carla in 1961 upon the normally inactive barrier islands of the Central Texas coast (Hayes, 1967), and of a late autumn storm upon Point Barrow, Alaska (Hume and Schalk, 1967), large magnitude storms have been viewed as a major agent of sediment transport and large-scale geomorphic change in the coastal zone. Storms supposedly shape in a few hours, features that would take decades to achieve under normal conditions. Since 1967, research has shown that storms dominate barrier washovers, inlet breaches and sedimentation in estuaries, bays and lagoons (Hayes, 1978; Leatherman, 1981). Nowhere in the coastal zone have the effects of storms been so preponderant as on the continental shelf. Here, grading of sediment is controlled by storms through landward facies displacement over thousands of years, by sorting of sediment under high-energy and then waning energy conditions, by migration of megaripples and by bottom liquefaction (Figueiredo et al., 1982). The idea that storms dominate the formation and preservation potential of coastal morphology (Ball et al., 1967; Kumar and Sanders, 1978; Kreisa, 1981) has led to the views that recent worldwide coastal

erosion can be attributed partially to increased storminess (Bird, 1985), and that the rates and preferred locations of coastal erosion by storms is somehow different from that attributable to everyday processes. Dolan and Hayden (1983) have proven that the spatial variation in long-term rates of erosion of barrier islands along the east coast of the United States is not only induced by storms, but that those places showing the highest historical rates of erosion produced by lesser events, also tend to be the most eroded during large storms such as the Great Ash Wednesday Storm of 1962. Bryant (1979) showed similar results for the barrier island complex of Kouchibouguac Bay in the Gulf of St. Lawrence. Here, changes in gross island morphology over the past 150 yrs were linked to wave power patterns characteristic of the overall wave climate. Catastrophic storms added to, rather than detracted from, that average wave climate.

In the past 15 yrs, studies based on beach profiling at regular time intervals have permitted the morphologic effects of low-frequency storms to be assessed relative to day-to-day hydrodynamic processes (Fox and Davis, 1973; Thom and Bowman, 1980; Eliot and Clarke, 1982, 1986; Clarke and Eliot, 1983; Wright et al., 1985; Lins, 1985). These studies cover periods ranging from several days to 16 yrs. Another method of resolving the relative impact of storms would be to have a large number of random samplings of shoreline position over a longer time period. This approach has merit if the period of observation can be extended beyond the durations used in the above studies. Such an approach can be used on Stanwell Park beach on the south coast of New South Wales, Australia. Here, plan-form maps of the high tide line along a 800 m beach have been accurately constructed (± 2.5 m) from 146 oblique and vertical photographs using the direct linear transformation method of coordinate resectioning for the period 1895–1980 (Bryant 1983a, b). Since 1930, these photographs have numbered more than 1/yr. The 85 yr record represents one of the best and most accurately documented time series of beach change in the world.

Stanwell Park is situated 30 km south of Sydney, and is one of the more important, long-term, meteorological and oceanographic data recording centres in the southern hemisphere. For the time span of photograph coverage, accurate time series of monthly sea level at Sydney, and of rainfall near Stanwell Park have permitted the establishment of significant relationships between these two variables and beach change (Bryant, 1983a, 1985). In addition, monthly records of sea surface temperature (SST) within 100 km of Stanwell Park have allowed a unique prognostic relationship between SST and beach change to be defined for the period 1943–1978 (Bryant, 1988). In 1985, one of the best compilations of storm magnitudes and frequencies for any coastline in the world became available for the West Tasman Sea (Blain et al., 1985). The record goes back virtually uninterrupted for 100 yrs. It is fortuitous that one of the best records of storm magnitude and frequency has been prepared for a coastline having one of the best records of beach change. This paper examines the effect of storms on Stanwell Park beach for the most detailed part of the record — the 36 yr period between 1943 and 1978 inclusive.

The data

Description of storm data

Storm magnitudes for the New South Wales coast are summarized in the Blain et al. (1985) study for the years 1880–1980 for four separate sections of coastline as follows: (1) North coast north of Smoky Cape (2) mid-north coast between Sugar loaf Point and Smoky Cape (3) central coast between Jervis Bay and Sugar loaf Point and (4) south coast, south of Jervis Bay (Fig.1). For each section, storm magnitudes were classified into four categories depending upon hindcast wave height as follows: X — extreme (>6 m wave height), A — significant (5–6 m), B — fairly significant (3.5–5 m) and C — disrupts shipping (2.5–

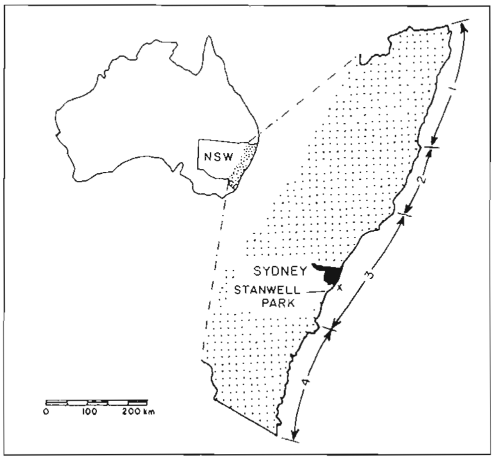

Fig.1. Location map of Stanwell Park and the New South Wales coast. The four sections of coast used to hindcast storm waves in the Blain et al. (1985) study are numbered as follows: *1* = north coast; *2* = mid-north coast; *3* = central coast; *4* = south coast. The C.S.I.R.O. station measuring sea surface temperature (SST) since 1943 is marked with an "x".

3.5 m). Hindcasting procedures followed the Sverdrup – Munk – Bretschneider method (C.E.R.C., 1977) and utilized original 24 hr meteorological charts. Gaps were filled using the Monthly Weather Review of daily charts and newspaper weather maps. Some of the drawbacks of these sources include loss of detail during the war years, change in emphasis from marine to inland weather systems, breakdown in continuity of newspaper maps due to strikes or holidays and poor temporal resolution due to the 24 hr sampling interval.

Except for the period 1944–1956, storm magnitudes in the Blain et al. (1985) report have been validated using a second independent source such as newspaper accounts, the Monthly Weather Review and after 1970, wave rider records. Comparison of hindcast wave conditions with wave rider buoy data confirm the occurrence of most high wave energy events. Some events registering on wave rider buoys could not be hindcast either because the temporal resolution of charts was inadequate or because waves originated from pressure systems developing beyond the boundaries of the Tasman Sea. The hindcasting results are the most accurate for two periods, between 1920 and 1944 when the Foley Weather Charts were used for hindcasting, and between 1967 and 1980 when the Monthly Weather Review significantly improved in quality. Source data between 1944 and 1956 are of poorer quality because they are based solely upon Sydney newspaper weather maps and contain some discontinuities. For these reasons Blain et al. (1985) tend to ignore this latter period when summarizing storm characteristics for the New South Wales coast. The storm data between 1944 and 1956 may not be as inaccurate as these authors would lead one to believe. Cross checking with our sequential beach change record indicates that almost all major erosional episodes appearing in the Stanwell Park record during this time span contemporaneously correspond with major storms or storm periods.

Blain et al. (1985) recognized six classes of storms: tropical cyclones, easterly trough lows, inland trough lows, continental lows, secondary lows and anticyclonic intensification. Tropical cyclones originate in the Coral Sea and rarely travel south of 30°S. The Stanwell Park coastline is not influenced directly by these cyclones; however it is affected by decayed, long-period swell generated by these systems. Easterly trough lows develop in autumn or winter as depressions over the North Tasman or South Coral Sea, and generate a strong wind field up to 1000 km southward which can produce high waves at Stanwell Park. Inland trough lows develop mainly in late summer in the quasi-permanent low-pressure trough situated over inland Queensland throughout the year. Continental lows usually develop in winter over the Indian Ocean or the Great Australian Bight and tend to intensify upon reaching the east coast. Together, both of the latter two systems have similar characteristics and mainly affect the central and south coast waters. These storms have been described by Thom et al. (1973) as having a profound potential for beach erosion on central and south coast beaches. Secondary lows, a prominent feature of the Southern

Tasman Sea in autumn and winter, are usually associated with the passage of low pressure systems south of 40°S and appear to develop as lee waves east of the Great Divide. Their intense localized nature has been conjectured, but not proven, as a response to warmer pools of surface water offshore. The latter type of low has not been described previously in the Australian coastal erosion literature and it induces the greatest short-term variance in beach erosion along the coast. Secondary lows are also the most difficult storm to detect on weather maps or to evaluate for their erosional impact. The May 25 storm of 1974, which began one of the severest storm periods on record along the southern half of the New South Wales coastline, began as a secondary low. Anticyclonic intensification refers to the strengthening and/or stalling of easterly moving high-pressure systems in the South Tasman Sea. Subsequently, strong and prolonged easterly or southeasterly winds are directed onto the coast. Such systems usually develop pressures above 1030 mbar and may be associated with the development of trough systems and continental lows. Anticyclonic intensification may be devoid of rain, but may give rise to wave heights in excess of 4 m along long stretches of coastline over severral days. The event of June 8–14, 1974, capping the worse recorded phase of beach erosion along the south coast falls into this category.

Kemp and Douglas (1981) considered that the combination of a persistent long wave trough in the upper atmosphere over Eastern Australia and a relatively high positive SST anomaly in the adjacent Tasman Sea could produce conditions favourable for the formation or deepening of several different types of storm cells. Blain et al. (1985) stated that the preponderance of storms in the first 6 months of 1978 was due to offshore surface waters at 2°C above normal. Thom (1978) considered that the poleward aseasonal movement of Hadley cells, concomitantly with warmer SSTs, especially in late autumn and early winter, gives rise to intensification of upper air depressions which stall off the New South Wales coast and lead to extreme beach erosion. None of these statements has been evaluated using SST or quantitative beach erosion data.

Quantitative indexing of storm magnitude

The highest total incidence of storms in the Blain et al. (1985) data set occurs in the central coast region (Fig.2) which receives about 20% more storms than adjacent sections of coast. Stanwell Park occupies the southern portion of this sector and as a result is not necessarily affected by all storms forming in, or entering this region. For instance, storms originating in the far north do not severely influence Stanwell Park beach. In May 1985, a storm centred off Port Stephens generated 10 m high, deep-water waves which cut back all the Newcastle beaches on the central coast, yet this storm only raised a 4 m swell off Stanwell Park beach, with limited erosional impact.

In order to utilize the complete record of storms catalogued for the New South Wales coastline, each storm was weighted according to its area of location. A north coast or mid-north coast storm was given a weighting of 0.5, a central coast or Eastern Tasman Sea storm was given a weighting of 0.8 and a south coast storm was given a weighting of 1.0. The 0.8 weighting applied to central coast storms is the

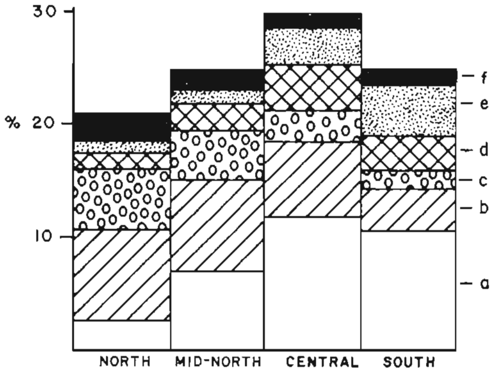

Fig.2. Incidence of storms by sector along the New South Wales coast. Letters refer to storm types in descending order of frequency: *a* — secondary lows; *b* — easterly trough lows; *c* — tropical cyclones; *d* — inland trough lows; *e* — continental lows; *f* — anticyclonic intensification.

approximate correlation of wave heights between the Botany Bay and Port Kembla wave rider buoys situated on the central coast and 20 km south of Stanwell Park respectively. The 0.5 weighting for north coast storms is based upon the decay coefficient for a wave generated in that region, and travelling 550 km to Stanwell Park (C.E.R.C., 1977, pp.3:43–3:44). The Blain et al. (1985) report gives actual hindcast wave heights for some storms and for all storms, an alphanumeric classification is given. For consistency we have assigned significant wave heights of 8, 5, 4 and 3 m to the X, A, B, and C alphanumeric storm categories respectively. The weighting of 8 m for category X storms is based upon hindcast heights appearing for such storms in this report and upon wave rider data collected by the Maritime Services Board at Botany Bay and Port Kembla for such storms since 1970.

No attempt was made to weight storms according to duration or according to their effect upon a beach. Both these aspects are important. For instance, a storm remaining stationary off the coast for several days will obviously direct more effective energy onto a section of coastline than a storm of the same magnitude lasting less than a day. Similarly, a storm striking a beach when it is at its maximum accretional state will have less of an effect than the same storm striking the beach after a long period of erosion.

All storms between 1943 and 1978 were culled from the Blain et al. (1985) records and weighted according to the above criteria. Because at least 10% of the Stanwell Park photographs could only be dated to the nearest quarter, the weighted scores were totalled for each 3 monthly period to form a quarterly or "seasonal" storm index effective at Stanwell Park. To account for the fact that erosion on the foreshore could reflect storm erosion which occurred months previously, a cumulative or "annual" storm index was also calculated by summing the seasonal index for the existing and the previous three quarters. For visual presentation, weighted indices for storms in each calendar year are plotted in Fig.3.

Description of Stanwell Park beach high tide data

Stanwell Park beach forms a compartmentalized, exposed, ocean beach with no permanent

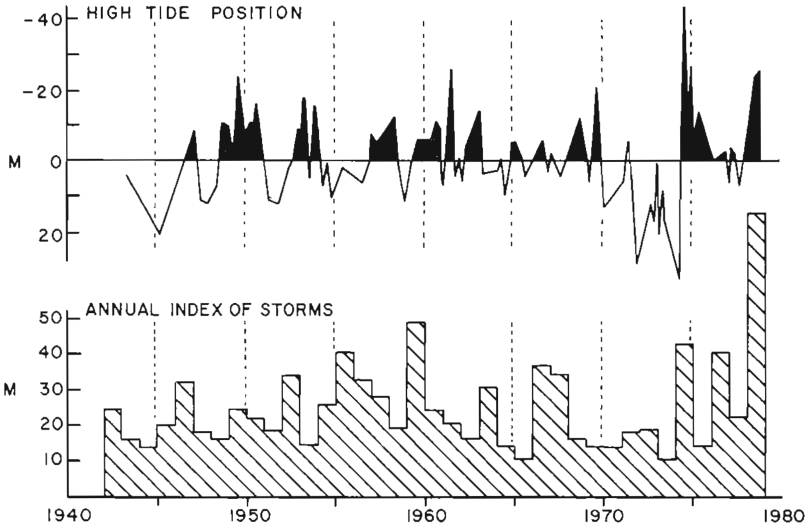

Fig.3. Time series of beach change and storminess for Stanwell Park, 1943–1978. The annual index of storms is the sum of indexed storms in a calendar year. The index represents a weighted score for the effect of storms at Stanwell Park. The plot of beach change refers to the deviation from mean high tide position averaged for the whole of Stanwell Park beach for the period of study. Periods of retreat beyond the mean high tide position are shaded.

longshore leakage of sediment and little human interference. The beach faces the main southeast swell originating in the Tasman Sea (Fig.1). This swell averages 10 s in period and 1.2 m in wave height. While the beach is modified to some extent by swell from all directions, refracted south-southeast waves bear the greatest wave power (Bryant, 1984). Inshore topography varies rapidly from alternating shore-tied shoals and rip channels to a single, shore-parallel bar trough in response to storm waves which often exceed a deep-water height of 4 m (Youll, 1981).

Deviations of the high tide beach position averaged for the whole of Stanwell Park beach were determined for the period 1943–1978 from 105 oblique photographs accurately dated to the nearest year and sequentially ordered using cultural information, vegetation changes and dates supplied by donors. For photographs where an exact date was not known, an algorithm was developed to give the time of year within 2 weeks using the location and length of shadows of accurately positioned objects. Some photographs (< 10%) could only be dated to the nearest season because of a lack of information from any of the above sources (e.g., the sun date cannot be determined under cloudy conditions).

The high tide position refers to one of two locations depending upon whether the beach is accreting or eroding. Under accretion, this position is the top of berm, while under erosion it becomes the most frequent limit of swash run-up. Both of these locations can be identified clearly by tonal and textural changes on the photographs. The ground location of the high tide position was resectioned from photographs using the direct linear transformation method of photo coordinate resectioning (Bryant, 1983b); a method which uses a minimum of six control points (a minimum of eight were always used in the present study) to produce highly accurate results. The average standard error in control point resectioning on over 145 photographs analyzed to date is 0.5 and 0.7 m in the onshore–offshore and alongshore directions respectively. The ground location of a feature cannot be mapped from a single oblique photograph unless the height of that feature is also known. The high tide position, surveyed on 30 profiles along the beach during various seasons, averages 3.36–3.5 m above low tide (with a standard error of < 0.56 m). A comparison of ground surveys and maps resectioned from oblique photographs taken at the same time indicates that the high tide position can be accurately located to within ±2.5 m using a height of 3.5 m. On 80% of the photographs where resectioned control points were situated at the high tide position, this accuracy is within ±1 m.

For the period 1895–1980, the average high tide beach position shows no tendency for continuous retreat or progradation. However, there have been prolonged periods when either accretion or erosion was favoured. Generally, the high tide line retreated in the period 1910–1930, underwent substantial seaward advance in the period 1930–1948, and, beginning in 1948, had undergone aperiodic retreat except for a period of maximum advance between 1970 and 1973 (Bryant, 1983b). The sequence of high tide beach change data between 1943 and 1978 is also plotted in Fig.3.

Factors previously related to high tide data

A wide range of meteorological, oceanographic and astronomical variables has been examined to account for the high tide beach changes between 1943 and 1978. Statistically significant relationships with rainfall, mean sea level, the Southern Oscillation (SO) index and a combination of sea level and SST have already been described (Bryant, 1983a, 1985, 1988). A 1 m change in annual rainfall results in 0.79 m of high tide beach change while a 0.01 m change in sea level produces a shift in high tide beach position of 0.44 m. Rainfall and sea level both exacerbate beach erosion by increasing watertables — a process which has been found to affect beach profiles (Chappell et al., 1979; Lanyon et al., 1982). The C.S.I.R.O. SST data set consists of 2640 weekly surface readings measured at 34°05′S and 151°15′E

(Fig.1). The data were found to account for over 60% of the variance in SST collected by ships in the Tasman Sea for the 10 yr period 1967–1976. A 1°C change in water temperature off Sydney results in a 1.06 m high tide change. Erosion is more probable at times of warmer seas and higher sea levels because these conditions can intensify low pressure cells, giving rise to highly erosive wave conditions (Thom, 1978). The SO refers to tropical easterly wind fluctuations in the equatorial Pacific region. Its strength is determined by the pressure difference between Tahiti and Darwin, Australia. When the SO index is positive, easterly equatorial flow in the western Pacific is strongest. When the index is negative, easterly trade winds diminish or reverse. The SO has teleconnections with meteorological and oceanographic variables worldwide (Angell, 1981; Horel and Wallace, 1981). It also has a prognostic relationship with rainfall and sea level at Sydney. As the index becomes more positive (stronger tropical easterlies), beach retreat increases.

Methodology

The role of storms in controlling high tide position was evaluated in four ways. Firstly, temporal changes in the "seasonal" storm index and correspondence to the high tide time series were evaluated using simple linear Pearson product–moment correlation (Davis, 1973). Both of these time series contain autocorrelation. For example, it is possible for two photographs in our data set to record the same erosional or accretional event even though the photographs were taken weeks apart. The autocorrelation coefficients for the high tide data decrease from 0.36 at lag 1 to effectively 0.00 at lag 9. The use of the "annual" storm index, because of its construction, also incorporates overlap in storm events even though photographs may be taken up to 1 yr apart. "Seasonal" and "annual" storm indices have autocorrelation coefficients of 0.41 and 0.79 respectively at lag 1, and −0.13 and 0.29 respectively at lag 9. Angell (1981) presents the following correction factor which effectively reduces the size of a data set to compensate for autocorrelation:

$$n_{\text{eff}} = n/(1.0 + 2r_1 r'_1 + 2r_2 r'_2 + \ \dots \ \infty) \quad (1)$$

where n_{eff} = the effective sample size, n = the number of cross-correlated points in the data set, r_i = autocorrelation coefficients of time series 1 at lag $i = 1, 2 \dots n$ and r'_i = autocorrelation coefficients of time series 2 at lag $i = 1, 2 \dots n$. Using this formula, our effective sample size is reduced from 105 to 78 and 55.5 for cross-correlations involving the "seasonal" and "annual" storm indices respectively. The adjusted results are shown in Fig.4 and summarized in Table 1.

Secondly, the relationships between the quarterly or "seasonal" storm index and (1) Troup's SO index (2) the mean position of the Hadley cell at the East Australian coastline (3) sea level at Sydney (4) rainfall at Stanwell Park and (5) the SST off Sydney were examined in turn to define the type of oceanographic and meteorological conditions enhancing storminess and the side effects conducive to high tide

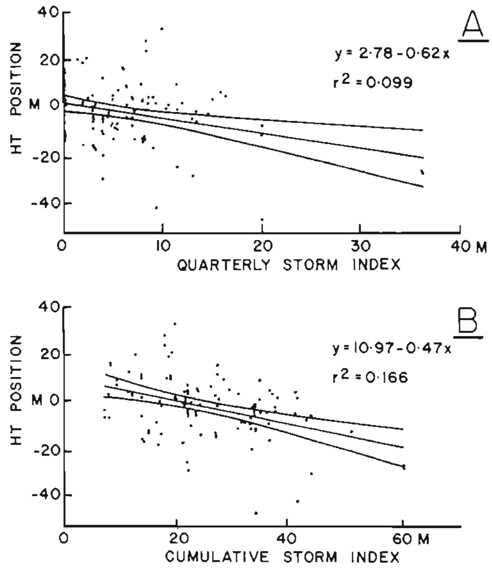

Fig.4. Regression plots with 95% confidence limits of Stanwell Park high tide positions against (A) the quarterly ("seasonal") storm index and (B) the cumulative ("annual") storm index, 1943–1978.

TABLE 1

Correlation between high tide beach position at Stanwell Park and the quarterly ("seasonal") and cumulative ("annual") storm indices, 1943–1978

Variable	Amount of change over time (m/yr)	Change (m) in high tide position for 1 m change in index value	Percentage explanation
"Seasonal" storm index	0.06	0.62***	9.9%
"Annual" storm index	—	0.47**	16.6%

** — significant at the 0.05 level.
*** — significant at the 0.01 level or less.

beach retreat produced by storms. Mean monthly values of the above-mentioned variables were used for this analysis. Cross-correlations between time series were performed using lags of up to 6 months, and corrected for autocorrelation effects using eqn.1. Even though it does not correlate significantly with the high tide position, the Hadley cell position was included in this part of the analysis because it plays a crucial role in Thom's (1978) scenario for the generation of intense erosive coastal storms. These results are shown in Table 2.

Thirdly, because of the nonlinear relationships between SST and high tide position found in previous work (Bryant, 1988), the storm indices were recorrelated to high tide beach change in combination with other variables using trend surface analysis. Trend surface analysis is typically used to describe the

TABLE 2

Cross-correlation between the quarterly ("seasonal") storm index and (1) Troup's Southern Oscillation (SO) index (2) the mean position of the Hadley cell at the East Australian coastline (3) sea level at Sydney (4) rainfall at Stanwell Park and (5) sea surface temperature (SST) off Sydney, 1943–1980. Negative lag refers to the storm index lagging behind the environmental variable. Values in parentheses refer to seasonally detrended cross-correlations. n_{eff} is the effective sample size after accounting for autocorrelation

Variable	Cross-correlation coefficients (lags in months)				
	−6	−3	0	+3	+6
SO index	−0.08	−0.01	0.01	0.01	0.00
$n_{eff}=123$	(−0.09)	(0.02)	(0.02)	(−0.01)	(0.02)
Hadley cell	−0.21**	−0.15	0.27***	0.16	0.00
$n_{eff}=146$	(−0.25)*	(0.06)	(0.24)***	(−0.09)	0.10
sea level	−0.09	0.09	0.38***	0.06	−0.09
$n_{eff}=107$	(0.07)	(0.17)*	(0.22)**	(0.14)	(0.07)
rainfall	−0.14	−0.18**	0.40***	0.11	−0.13
$n_{eff}=139$	(−0.07)	(−0.07)	(0.39)***	(−0.01)	(−0.05)
SST	−0.08	−0.33***	0.18	0.34***	−0.03
$n_{eff}=131$	(−0.06)	(0.01)	(0.07)	(−0.05)	(0.16)*

* — significant at the 0.10 level.
** — significant at the 0.05 level.
*** — significant at the 0.01 level or less.

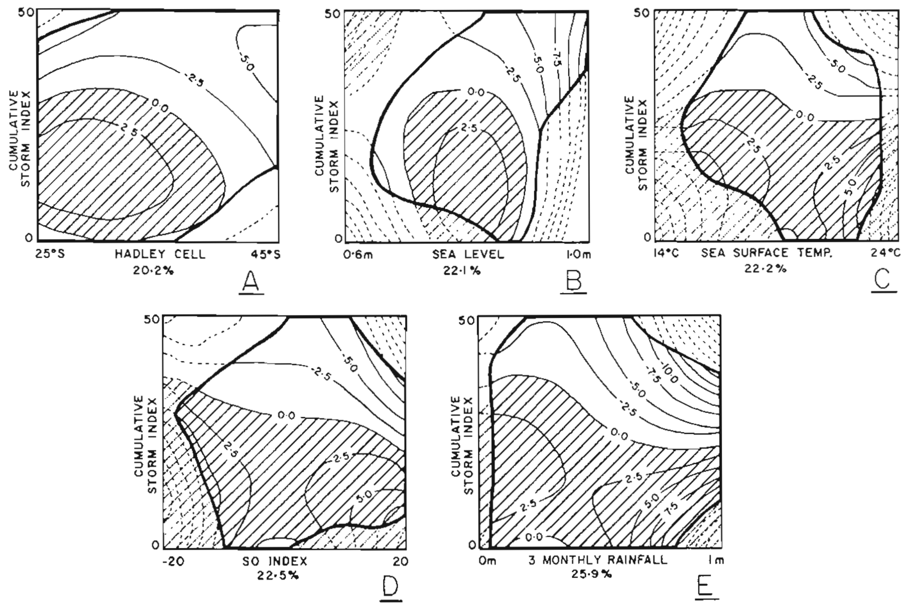

Fig.5. Cubic trend surface results mapping high tide beach change as a function of the cumulative ("annual") storm index and (A) the centre of the Hadley cell along the East Australian coast (B) sea level measured at Sydney (C) SST measured at 34°05′S, 151°15′E (D) the SO index measuring the pressure difference between Tahiti and Darwin and (E) 3 monthly rainfall at Stanwell Park. The area of high tide retreat is shaded, contour interval is 2.5 m. The actual range of paired independent variables sampled in the Stanwell Park record is enclosed by a heavy line. Contours within this area are drawn with a solid line. Percentage values refer to the degree of explanation of the surface.

spatial trend of a variable (Davis, 1973). However, it can be considered a two-dimensional multiple regression technique whereby any two independent variables ("seasonal" storm index and one other variable) can be linearly correlated to an independent variable (high tide beach change). The technique has one added advantage in that it can incorporate successively higher polynomial fits or surfaces to the data. This technique permits the nonlinear relationship between a primary factor and high tide beach change to be investigated together with one other variable. These results are shown in Fig.5 for combinations involving the cumulative yearly or "annual" storm index, and in Fig.6 for combinations involving other variables such as the SO index, sea level, 3 monthly rainfall, SST and the position of the Hadley cell.

Finally, the combinations of variables accounting for the highest degree of variance in the high tide beach change time series, using trend surface analysis, were incorporated as extra variables in a larger data set containing fourteen other single or combined factors which have been significantly related to, or hypothesized as affecting high tide beach position. The relative importance of variables was then assessed using stepwise multiple linear regression analysis (Nie et al., 1975). Multiple stepwise regression analysis permits the relationship between a dependent variable and a group of independent variables to be analyzed, excluding the interdependence amongst the contributing independent variables. These results are shown in Table 3.

Results

Storm indices and high tide beach position

There was no statistically significant change in the magnitude of storminess as defined by the quarterly or "seasonal" storm index over the period under consideration. Our analysis does not support increased storminess as a

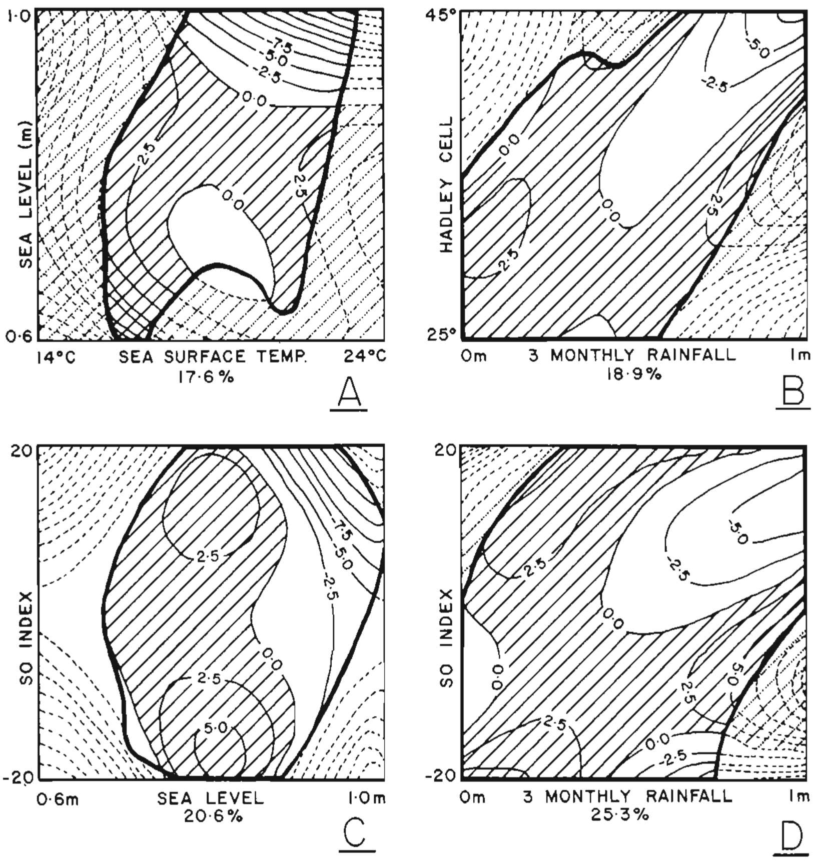

Fig.6. Trend surface results mapping high tide beach change as a function of combinations of environmental variables. A. SST and sea level. B. 3 monthly rainfall at Stanwell Park and position of the Hadley cell. C. sea level and the SO index. D. 3 monthly rainfall at Stanwell Park and the SO index. The actual range of paired independent variables sampled in the Stanwell Park record is enclosed by a heavy line. Contours within this area are drawn with a solid line. Percentage values refer to the degree of explanation of the surface. Surface (A) is cubic; the others are 4th order surfaces.

TABLE 3

Multiple stepwise regression results between high tide beach position at Stanwell Park and all environmental variables individually or in combination with each other using trend surface analysis results

Factor	Multiple stepwise regression	Percentage contribution	Percentage added contribution
Storm (1 yr)–rainfall (3 months)	0.510	26.0	26.0***
SO–rainfall (3 months)	0.591	34.9	8.9***
Annual rainfall	0.619	38.3	3.4**
SO–sea level	0.635	40.4	2.1*

* — significant at the 0.10 level.
** — significant at the 0.05 level.
*** — significant at the 0.01 level or less.

cause of accelerated beach retreat along the central and south coasts of New South Wales. There is however, a strongly significant relationship between high-tide beach position and both the "seasonal" and the "annual" storm indices ($r = -0.31$, significant at the 0.01 level and $r = -0.41$, significant at the <0.05 level respectively). The "annual" storm index for the previous year accounts for 16.6% of variance in high tide beach position indicating that a preponderance of storms in the previous year favours high tide beach retreat. The degree of explanation between high tide position and any single environmental parameter is the highest found to date. The relationships also imply that the Stanwell Park high tide line will move shoreward from its mean long-term position when the storm index exceeds 23.2 m for the previous year or 4.5 m for that "season". These values are equivalent to five moderately sized storms in the past year or to one moderately sized storm within that "season". For each unit increase in the "annual" storm index (equivalent to a 1 m increase in storm wave height at Stanwell Park), the high tide position will shift shoreward by 0.47 m. This value is equivalent to the effect generated by a 0.01 m rise in mean sea level. A unit increase in the "seasonal" storm index shifts the high tide position 0.62 m shoreward. The latter rate indicates that a jump from a class B storm (wave heights of 3.5–5 m) to a class X storm (wave heights in excess of 6 m) can increase the average high tide retreat on Stanwell Park beach by 1.5 m.

The "annual" storm index has a high degree of significance in predicting beach retreat. No previously defined environmental parameter could be related to high tide beach change more than 3 months in advance (Bryant, 1988). A linear cross-correlation was performed between the "seasonal" and "annual" indices. It was found that 22.9% of the data variance in the "seasonal" index could be accounted for by the "annual" index for the previous year. One of the points about the May–June 1974 storms, which were the worse documented for Stanwell Park beach, is the fact that actual beach retreat began 4–5 months prior to occurrence of the storms. Present results would indicate that the tendency for beach retreat can be predicted far earlier. The effect of storms on beach retreat tends to accumulate and if the index has been building up over the past year, it can be stated that the beach is likely to undergo retreat irrespective of present sea level, rainfall or SO conditions. The reverse situation is also true. If storms have been absent or diminishing in intensity over the previous year, then Stanwell Park beach is more likely to undergo seaward progradation.

"Seasonal" storm index and other environmental variables

Thom's (1978) scenario for increased beach erosion on south and central coast beaches involves a combination of storminess and at least two other variables — a warmer SST and poleward movement of the Hadley cell. This relationship, together with those relating storm magnitude to increased rainfall and sea levels, was investigated using cross-correlation analysis (Table 2). Firstly, there appears to be a significant link between the "seasonal" magnitude of storms and the position of the Hadley cell as hypothesized by Thom (1978). If the Hadley cell moves poleward, then storminess increases. However, the relationship between storminess and SST is not direct. It would appear that increased storminess is related to the occurrence of cooler offshore waters in the previous quarter. A major storm in the first week of August 1986 which caused significant cutback of beaches in the Stanwell Park area has confirmed this relationship. Warmer SST's following storms may be a direct consequence of the oceanographic effects of coastal storms.

While the data partially support Thom's (1978) hypothesis, they still do not account for the fact that no significant relationship between the position of the Hadley cell and high tide position on Stanwell Park beach could be found for the 1943–1978 period. This lack of correlation could be due to the incomplete

temporal resolution of our photographic record. Even so, our analysis shows that the lack of correspondence may be irrelevant because stronger relationships can be found between storms and other variables. For instance, increased storminess is accompanied by a highly significant, direct increase in sea level, accounting for 14.2% of the variance in the Sydney sea level record over the period 1942–1980. Whether the result is cause-and-effect or coincidental is beyond the scope of this paper. However, the observed storm surge effects documented for the 1974 storms (Foster et al., 1975; Bryant and Kidd, 1975) suggest that increased storminess will probably raise sea levels through wind-induced setup. The strongest association with increased storminess occurs with rainfall. Over 16% of the variance in the rainfall record at Stanwell Park can be related to storms in the Tasman Sea. We have argued previously that rainfall occurs independently of storms (Bryant, 1988); however, results here indicate that a significant proportion of rainfall-induced beach retreat may be related to high rainfalls occurring during storms. It is important to note that both sea level and rainfall are two of the most important variables which can be related to beach retreat through their effect on the beach watertable (Bryant, 1983a, 1985). The question arises whether beach retreat during storms is due to these two variables or their coincidence with times of higher storm wave activity. It is also noteworthy that drought conditions in the previous 3 months will lead to increased storminess. This result undoubtedly relates to the tendency for droughts to be suddenly broken by heavier than normal rainfall which may also be accompanied by increased storm activity. The most obvious timing for this occurrence is at the collapse of droughts associated with El Niño–SO (ENSO) events. These events peak in December and are usually followed by drought-breaking rainfall in February–April along the East Australian coastline. In light of the current trend to relate all climatic extreme events in the southern hemisphere to the SO, it is noteworthy that we could find no statistically significant association between increased storminess and the SO index, even when lagging was performed. The occurrence of storms off the New South Wales coast is virtually unrelated to the SO.

The above-mentioned relationships reflect seasonal changes in the parameters. Of more interest may be the aseasonal abnormality of storms related to abnormalities in other parameters. Cross-correlations between the above-mentioned variables for seasonally detrended data are shown in parentheses in Table 2. The data were detrended by subtracting the mean for each season from individual values. Three strong associations remain after seasonal detrending. If the incidence of storms is above the seasonal average after detrending it is also likely that the Hadley cell is more poleward, sea levels are higher and rainfall is heavier than usual for that season. This is virtually a restatement of Thom's (1978) hypothesis for storm erosion of beaches along the New South Wales coast. There remains a weak tendency (a 0.10 level of significance) for abnormal movement of Hadley cells towards the equator, resulting in increased storminess 6 months later.

Combinations of variables including storm indices

In studying the causative mechanisms for changes in high tide position on Stanwell Park beach, the question has always arisen whether or not relationships between variables are linear. The present study casts some doubt on the relevance of sea level and rainfall individually as causative factors influencing beach change. The fact that higher sea levels and rainfalls occur at times of increased storminess may simply mean that most documented high tide retreats are due to more erosive storm waves. Trend surface analysis permits the nonlinearity of relationships and the relative importance of combinations of variables to be evaluated.

The results shown in Fig.5 indicate that there are indeed nonlinear relationships with

high tide beach position. Only trend surfaces with a degree of explanation greater than the 16.6% produced individually using the "annual" storm index for the previous year are included. No combination of variables involving the "seasonal" storm index met this criterion. Cubic surfaces having degrees of explanation higher than 20% were the highest significant surfaces generated. The boundaries of the plots in Fig.5 represent the possible range of measurements over the study period. The actual range of paired independent variables sampled in the Stanwell Park record is enclosed by a heavy line. Contours within this area are drawn with a solid line. Trend surfaces involving the SO index and the SST have the same degree of explanation (22.2–22.5%) but the greatest level of explanation is produced by storminess in conjunction with rainfall for the previous 3 months (25.9%).

The relationships can be summarized succinctly as follows: Firstly, increased storminess in combination with poleward movement of the Hadley cell leads to high tide retreat (20.2% explanation). An increase in either of these variables results in erosion. A decrease in storminess and/or migration of the Hadley cell towards the equator (a winter time condition) leads to accretion. Secondly, increased storminess in combination with increased sea level leads to rapid high tide retreat (22.1% explanation). Increased sea levels always generate erosion; however, when sea level is at mean elevations for the New South Wales coast (0.7–0.8 m), changes in high tide position are controlled mainly by the degree of storminess, with Stanwell Park beach accreting as the level of storminess decreases. Finally, storminess in conjunction with SST, the SO index or rainfall for the previous 3 months generates similar patterns of high tide change. In each case, increased storminess always produces high tide retreat — an effect that is exacerbated at times when Walker circulation is strong (very positive SO indices), when SST's are above 22°C, or when rainfall for the previous 3 months is above 600 mm. Higher rainfall in conjunction with increased storminess results in a dramatic increase in high tide retreat. The beach is always in an accretional phase during calm, non-storm periods (the "annual" storm index falls below 25 m) regardless of the behaviour of the SO, the SST or rainfall. There is some evidence to suggest that in the absence of storms, increases in these last three variables (trends which should lead to high tide retreat) amplify this accretional process.

Combinations of variables excluding storm indices

Nonlinear effects have been investigated for other combinations of variables including a combination of SST and sea level (Bryant, 1988). Trend surfaces for all possible combinations of variables other than storminess were performed on the data. Again, only those analyses where the degree of explanation of the high tide data variance exceeds 16.6% are shown (Fig.6). These additional relationships can be succinctly summarized as follows. Firstly, higher sea levels produce high tide retreat which is exacerbated by higher SST's when sea levels exceed 0.85 m (17.6% explanation). At lower sea levels, the beach progrades irrespective of the SST behaviour. Secondly, as rainfall over the past 3 months increases concomitantly with the poleward movement of Hadley cells, high tide beach retreat occurs (18.9% explanation). The higher the amount of rainfall or the more poleward the position of the Hadley cell, the greater the rate of erosion. Thirdly, the beach erodes dramatically if sea levels are high at times of enhanced Walker circulation (high positive values of the SO index) (20.6% explanation). When sea levels fall below 0.85 m, the beach is always accretional regardless of the state of the SO. This accretion will be enhanced by drought conditions as indicated by very negative values of the SO index. Finally, as rainfall during the previous 3 months increases and the SO index becomes positive or tropical easterlies intensify, high tide beach retreat takes place (25.3% explanation). If either the SO index or rainfall

decreases, seaward progradation of the high tide line pervades. These results indicate that sea level and rainfall are still important variables controlling high tide beach position at Stanwell Park, but that some of their effects involve the SO, the location of the Hadley cell or the SST. The Hadley cell relationship is important, because as a separate variable, the location of the Hadley cell does not correlate with the high tide beach position.

Stepwise multiple regression analysis including all variables

The importance of storminess compared to these other environmentally significant factors in beach erosion can be usefully evaluated using stepwise multiple regression analysis. The trend surface results mentioned above were appended, together with the "seasonal" and "annual" storm indices, to a data set consisting of fourteen other single variables. The statistically significant results (Table 3) are dominated by rainfall or rainfall in combination with other variables. The greatest degree of explanation in high tide beach position is accounted for by the cubic trend surface combining rainfall for the previous three months and the "annual" storm index (26.0% of the data variance). A combination of Troup's SO index and rainfall for the previous 3 months accounts for a further 8.9% of the data variance. Note that this contribution is totally unrelated to the contribution of storminess and rainfall. Annual rainfall contributes an additional 3.4% to the data variance. All of the above results are significant at the 0.05 level of significance or less. Finally, a SO–sea level term, significant at the 0.06 level of significance, contributes 2.1% to the data variance. No other factor, either individually or in combination, contributes to the data variance at the 0.10 level or lower. The stepwise multiple regression results indicate that rainfall, associated with storms and working in conjunction with storm-induced waves, is the primary controlling factor in this data set, affecting the high tide beach position at Stanwell Park. In addition, rainfall and sea level in conjunction with the SO have a strong association with high tide beach position. Of all these variables, rainfall is probably the single most important factor influencing beach retreat on Stanwell Park beach. Together, the above-mentioned factors account for 40% of the high tide data variance.

Conclusions

This paper has attempted to evaluate the effect of randomly occurring storms upon changes in the high tide position of Stanwell Park beach between 1943 and 1978. There have been many previous studies alluding to the importance of storms in controlling changes in coastal morphology. The present study differs in the method of measuring beach change and in the time span examined. Beach change was documented by measuring, to an accuracy of ± 1 m in 80% of cases, the average high tide position using 105 mainly oblique photographs. The study is not without flaws. Firstly, some temporal resolution in measurement of the high tide position has been sacrificed to obtain a record of data twice as long as any previously examined. This lower temporal resolution has meant that an index of storm magnitude for Stanwell Park had to be constructed on a quarterly or "seasonal" basis. Secondly, the random nature of sampling implies that some storm erosional events may have been missed in the high tide data. Thirdly, while the record of storm frequency and magnitude for the period of study represents one of the best documented in the world, it is possible that some storm magnitudes and durations have been misrepresented because hindcasting techniques were used. None of these factors seriously negate the results of the study.

Two indices of storminess were used in the study. The "seasonal" storm index gives the magnitude and frequency of storms around the time of each photograph. The index is equivalent to the sum of the mean storm wave heights for each 3 month quarter, and includes the decay effect of distant storm events. The

"annual" storm index accounts for the cumulative effect of storms for the year prior to each photograph. Simple linear regression between high tide data and these storm indices indicates that storms from the previous year have a marked impact on high tide position on Stanwell Park beach. The "seasonal" and "annual" storm indices account for 9.9% and 16.6% of the variance in high-tide position respectively. The latter value is greater than for any other variable previously examined, including sea level, rainfall and SST. A one unit increase in the "annual" storm index (equivalent to an additional 1 m in storm wave height) shifts the high tide line 0.47 m shoreward. This has the same effect as raising sea level by 0.01 m. When the annual storm index exceeds 23.2 m or the "seasonal" index exceeds 4.5 m, the high tide line retreats shoreward of its mean long-term position. These values are generated by five medium sized storms over the past year or by one medium sized storm in the past season. The "annual" storm index also bears the best prognostic value of nine environmental parameters examined to date. As the frequency of storms increases in the previous year, beach erosion becomes more probable. Conversely, as fair weather begins to dominate in the long-term, the beach is likely to undergo seaward progradation.

It was possible to compare the impact of storms to that produced by other environmental variables. There is a significant link between the magnitude of storms in a quarter and both the position of Hadley cells and the SST. If SST's are cold in the previous quarter and if the Hadley cell is moving polewards, then storminess increases. Storminess also accounts for 14.2% and 16% of the variance in the sea level at Sydney and in the Stanwell Park rainfall records respectively. Storm surge and storm rainfall may be important mechanisms for beach erosion along this coast. Storminess is unrelated to the SO — a fact which is unusual given the climatic teleconnections which have been associated with this phenomenon.

The nonlinear relationship between storminess and high tide change was evaluated in association with one other variable using trend surface analysis. Generally, the results support the conclusions drawn above. Once the "annual" storm index rises above 25 m, increased storminess in conjunction with increases in the poleward movement of the Hadley cell, sea level, SST's, SO indices, or rainfall is associated with beach retreat. It is clear that many variables, either individually or in combination with each other can explain beach change. Stepwise regression analysis was used to rank these variables according to their importance. Over 40% of the variance in the high tide record can be resolved using the following four variables in order of importance: rainfall, storminess over the previous year, the SO and sea level. Rainfall in conjunction with storms for the past year accounts for 25.9% of the high tide data variance. Rainfall, either in conjunction with the SO or individually, accounts for a further 8.9% and 3.4% of the variance respectively. The above-mentioned values are all statistically significant at less than the 0.05 level. Sea level and the SO together account for 2.1% of the variance but only at the 0.06 level of significance.

Finally, it should be pointed out that this study does not emphasize storms as catastrophic events solely responsible for beach erosion at Stanwell Park. In the long-term, storms should be viewed as ordinary events playing a significant role in beach erosion along with many other environmental variables such as rainfall, sea level and atmospheric circulation factors. Even the 1:100 yr storms of May–June, 1974 fit within the overall picture of high tide response on this beach. This result is similar to one found for east coast beaches in the United States. The presence of fair weather is not a separate entity, but part of a fair weather–storm continuum. It is generally believed that sea level increases (the so-called Bruun Rule) or increased storminess are responsible for recent sandy beach erosion. However, this study has shown that these factors are part of a suite of changing variables (that also includes rainfall

regimes and the SO) which may be eroding beaches. Furthermore, the variables are interrelated. Changes in storminess, rainfall regimes, sea level and other climatic factors reflect the large-scale climatic change which the Earth is presently undergoing. The more dramatic and measurable increases in temperature (supposedly leading to ice cap melting and higher sea levels) have unfortunately detracted from the more significant nature of that change — namely the increasing variability of climate since 1948 (Gribbin, 1982). This increase has accelerated since 1970.

The present work completes our analysis of obtainable factors which have contributed historically to high tide fluctuations on Stanwell Park beach. Undoubtedly, wave energy variation plays a significant role in controlling high tide position but without detailed wave height information for the period of study, the exact influence of waves cannot be resolved. The storm indices incorporate wave information to a certain extent. The high degree of explanation accounted for by these indices indicates that wave energy cannot be ignored. Since 1980, measurements of the high tide position on Stanwell Park beach have been taken at 4–6 weekly intervals. Wave information is available from wave rider buoys for this period, and research is now continuing to evaluate the role of waves at this time scale in controlling high tide changes.

Acknowledgements

The staff of the New South Wales Coastal Engineering Branch of Public Works Department greatly assisted in obtaining access to the storm data. Over 60 people and six New South Wales State government departments or agencies responded to advertisements or direct requests for old photographs. Advertisements for photographs were paid for with a Wollongong University Research Grant. The staff of the Geography Department at Wollongong University contributed continually to the progress of this research. Prof. Trinder of the School of Surveying at New South Wales University gave direction to the resectioning of computer programs. SST data was supplied by the C.S.I.R.O. Division of Oceanography at Cornulla. Dr. Chandra Gulati of the Mathematics Department at Wollongong University aided in clarifying some of the statistical techniques and an anonymous referee pointed out problems in the cross-correlations involving autocorrelation.

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