Sea-Surface Temperature and High-Tide Beach Change, Stanwell Park, Australia, 1943-1978

Edward Bryant

Department of Geography
University Wollongong
Wollongong, Australia 2500

ABSTRACT


Along the east Australian coastline, warmer sea-surface temperatures (SST) in the Tasman Sea can give rise to more intense cyclogenesis which leads to 'storm' events that can exacerbate ongoing beach retreat. Sea-surface temperature patterns in the equatorial Pacific and around Australia also provide an indication several months in advance of coastal rainfall trends which have been linked to HT retreat on Stanwell Park beach. This retreat has been measured to an accuracy of 1.0 m using oblique photographs for the period 1943-1978. At the same time SST collected weekly offshore from Sydney, 30 km to the north, was found to represent the general surface pattern of ocean temperatures in the Tasman Sea. The two records are amongst the best of their kind in the world. Linear modelling using these parameters, as well as sea-level and rainfall data, shows that SST in combination with sea-level accounts for 17.6% of the HT data variance while annual rainfall accounts for a further 7.2%. It appears that warm SST must occur concurrently with higher sea-levels for retreat to be evident. Analysis of environmental conditions for 6 'storm' events indicates that, over the short term, factors conducive to beach retreat do not operate all the time. It is only when long term trends are examined that warmer SST, and higher sea-level and rainfall, can be correlated to HT retreat. The prognostic ability of SST to forecast periods of likely beach retreat is at present lacking until more information becomes available on the relationship between SST and the intensity and tracking of low pressure cells.

ADDITIONAL INDEX WORDS: Australia, beach change, beach retreat, cyclogenesis, Tasman Sea.

INTRODUCTION

Over the past few years a series of papers (BRYANT, 1983a,b; 1984a,b; 1985) has been written describing beach change at Stanwell Park beach New South Wales, Australia (Figure 1) for the period 1895-1980. Over 90% of the beach change data was determined for the whole of an 800 m long beach to an accuracy of 1 m using the direct linear transformation method of co-ordinate resectioning on 146 oblique photographs. Since 1930 these photographs average over 1/year. The 85 year 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 which is one of the more important meteorological and oceanographic data recording centres in the southern hemisphere. An accurate time series of monthly sea-level at Sydney over the time span of photo coverage permitted a significant relationship between sea-level and beach change to be established (BRYANT, 1983b). In addition long records of rainfall near Stanwell Park also permitted a unique relationship between rainfall and beach change to be defined (BRYANT, 1985).

Earlier work (THOM, 1978) has hypothesized that sea-surface temperature (SST) is an important factor in erosion of beaches along the Stanwell Park section of coastline. THOM (1978) using studies by SIMPSON and DOWNEY (1975) postulated that more poleward positioning of the Hadley cell, coupled with above average SST offshore, should give rise to development of intense extra-tropical depressions which would exacerbate erosion along this coastline mainly in late autumn or winter. This hypothesis was based on the SST and climatic state at the time of the May-June 1974 'storms' which were the worst to effect the N.S.W. Central and South coast this century. Subsequent to that study there have been many reports published showing good correlations between SST
and rainfall around the Australian continent

Sydney also has one of the most complete time series of monthly SST data anywhere in
the world. The data collected weekly by the C.S.I.R.O. offshore from Sydney extends back to 1943.
It is fortuitous that one of the best records of beach change lies 30 km from one of the best
records of SST. This paper examines the relationship between Sydney SST and Stanwell
Park beach change for the period 1943-1978.

DESCRIPTION OF THE STANWELL PARK DATA

Stanwell Park beach (situated 30 km south of Sydney) forms a compartmentalized, exposed,
ocean beach having no permanent longshore leakage of sediment and little human interference.
The beach situated on the east coast of Australia faces the main south-east swell origi­
nating in the Tasman Sea (Figure 1). This swell averages 10 sec in period and 1.2 min
wave height. While the beach is modified to some extent by swell from all directions,
refracted SSE waves contain the greatest wave power (BRYANT, 1984a). Inshore topography
varies rapidly from alternating shore-tied shoals and rip channels to a single, shore-par­
allel, bar-trough in response to storm waves which often exceed a deep water height of 4 m
(YOULL, 1981). A collection of 146 oblique photographs of Stanwell Park beach has been com­
plied for the period 1895-1980. This record consists of one photograph every 5 years between
1895-1920, one photograph every two years between 1920-1930 and one or more photo­
graphs per year thereafter. The HT beach location can be measured from these photographs to
an accuracy of 1.0 m 90% of the time using the direct linear transformation method of photo
co-ordinate resectioning (BRYANT, 1983a).

The average HT beach position shows no tendency for continuous retreat or progradation over
the the 85 year period; however there have been prolonged periods when either accretion or
erosion are favoured. Generally, the HT line retreated in the period 1910-30, underwent sub­
stantial seaward advance in the period 1930-48, and beginning in 1948 has undergone a periodic
retreat except for a period of maximum advance between 1970-73. Throughout the record,
'storms' of equal magnitude were superimposed upon these trends. The greatest 'storm' erosion present in the data occurred in 1974 when HT beach position shifted over 100 meters during a
six month period.

It should be pointed out that, except for these 1974 'storms,' 'storm' events in the Stanwell
Park data have a constant frequency of occurrence and magnitude throughout both erosional
and accretional periods. In this paper the term 'storm' is used simply as a matter of conven­
ience and refers to a period of beach retreat usually culminating in one or more noticeable
high-energy wave events. It is recognized that individual 'storm' events undoubtedly account
for considerable variance in the Stanwell Park data,—an aspect which is the focus of continu­
ing research; however for the most part 'storms' only exacerbate ongoing coastal erosion. It
should also be noted that seasonal fluctuations account for little of the variance. There is no
tendency in the HT beach record to suggest that any one season is biased towards beach retreat
or progradation.

A wide range of meteorological, oceanographic and astronomical variables has been
examined to account for the HT beach changes. Statistical relationships with rainfall, mean
sea-level, the Southern Oscillation (SO) Index, the mean position of the Hadley cell along the
east Australian coastline and astronomical variables such as the 11 and 22 year sunspot cycles
and the 18.6 M\text{N} year lunar tide have been investigated (BRYANT, 1983a,b; 1984b). Sig­
nificant linear correlations at the 0.05 level of significance were obtained only with rainfall,
mean sea-level and the SO Index. Higher annual rainfall was found to result in greater
beach retreat at a higher level of significance than with any other variable. A 100 mm change
in annual rainfall resulted in 0.79 m of HT beach change. As sea-level rose 10 mm, the HT
beach position retreated landward 0.44 m. This rate is in close agreement to that reported by
others invoking Bruun's rule for shoreline retreat with sea-level rise on equilibrium beach
profiles. Rainfall and sea-level both exacerbate beach erosion by increasing water table levels,
-a process which has been found to affect beach profiles (CHAPPELL et al., 1979; LANYON et
al., 1982). An index of the Southern Oscillation was derived from work compiled by WRIGHT
(1975). The Index measures the pressure differ­
ence between the Darwin, Australia and Tahiti areas. When the Index is positive easterly equatorial flow in the Western Pacific is strongest. When the index is negative easterly trade winds diminish or reverse. The Southern Oscillation has teleconnections with meteorological and oceanographical variables worldwide (ANGHELL, 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. Significant relationships at the 0.05 level were not found with other variables.

DESCRIPTION OF THE SST DATA

In one of the earlier papers (BRYANT, 1983b), HT beach change was also correlated to 10 years of monthly SST data measured between 1967-1976 for the the one degree area 33°S - 153°E approximately 100-150 km directly offshore from Sydney (EDWARDS, 1979). No significant correlation was found between HT beach change and this time series— a result due to the limited timespan of the record. This data consisted of monthly summaries of water temperatures measured from ship engine cooling intakes. The C.S.I.R.O. data set is more accurate. It consists of weekly sea temperature profiles measured at 10 m intervals to a 50 m depth at 34°05'S and 151°15'E (Figure 1). All surface temperatures (2640 readings) were extracted from the data set and averaged for each month over the period 1943-1978. Where monthly data were missing (twice in the record), values were linearly interpolated from adjacent months.

The C.S.I.R.O. data set may be severely limited. It simply may not be representative of SST further offshore or over a wider area of the Tasman Sea. Examination of weekly SST maps along the New South Wales coast between August 1982-December 1984, indicates that inshore SST often does not disclose the presence of extensive warm tongues or pools of water further offshore (Australian Oceanographic Data Centre, 1984 & 1985). These vortices can persist for up to a year and, depending upon their position relative to Sydney, direct either warm or cold water onto the coastline. In addition warm or cold pockets of water can persist for months at preferred locations along the coast. Such pockets can change water temperature up to 5°C over a 100 km distance. Some attempt at assessing the representativeness of the C.S.I.R.O. data set was made by correlating it to the SST data compiled at monthly intervals, 1967-1976, for 8 one degree squares in both the Coral and Tasman Seas (locations in Figure 1) using the ship observations mentioned above (EDWARDS, 1979). This analysis is summarized in Table 1.

Except in the Coral sea, over 60% of the var-

<table>
<thead>
<tr>
<th>1° Square location</th>
<th>Correlation Coefficient</th>
<th>Percent Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (°S)</td>
<td>Longitude (°E)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>151</td>
<td>.670</td>
</tr>
<tr>
<td>16</td>
<td>167</td>
<td>.734</td>
</tr>
<tr>
<td>23</td>
<td>156</td>
<td>.783</td>
</tr>
<tr>
<td>23</td>
<td>170</td>
<td>.852</td>
</tr>
<tr>
<td>33</td>
<td>153</td>
<td>.810</td>
</tr>
<tr>
<td>34</td>
<td>170</td>
<td>.798</td>
</tr>
<tr>
<td>49</td>
<td>149</td>
<td>.809</td>
</tr>
<tr>
<td>39</td>
<td>170</td>
<td>.826</td>
</tr>
</tbody>
</table>

Figure 1. Location map of Stanwell Park and Sydney. Also shaded are the location of one degree squares where Edwards (1979) has summarized ship observations of sea-surface temperature for the period 1967-1976.
iance in the C.S.I.R.O. SST data can be accounted for by SST collected by ships anywhere in the Tasman Sea for this 10 year period. These correlations are significant at the 0.001 level or less. Surprisingly the highest correlation was not with the closest one degree square approximately 100-150 km away, but with the area just southeast of New Caledonia. SST directly offshore from Sydney is always warmer than at the C.S.I.R.O. site, especially when overall water temperature decreases. Much of the remaining 40% or less of unexplained variance probably results from the spatial variation in temperature due to warm core eddies in the Tasman Sea.

These correlations do not describe the seasonal abnormalities in SST. To examine this correlation for anomalous SST, the C.S.I.R.O. data and readings for the closest one degree area, 33S - 153E, were seasonally detrended and then lagged. The highest correlation occurred when inshore temperature lagged offshore temperature by 2 months ($r = 0.29$, significance level $<0.01$). However significant lags in the C.S.I.R.O inshore temperatures can occur 2-3 months before and after offshore responses ($r = 0.20-0.29$, significance level $<0.05$). This limited analysis indicates that the C.S.I.R.O. SST data set is probably representative of the general surface temperature pattern of the Tasman Sea and of large scale anomalies within 1,000-1,500 km of the coastline. It is still feasible that pools or tongues of aseasonally warm or cold water can exist offshore independent of temperatures monitored at the C.S.I.R.O. site.

**METHODOLOGY**

For period 1943-1978, deviations of the HT beach position averaged for the whole of Stanwell Park beach were determined from 105 photographs accurately dated to the nearest year and ordered sequentially 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 two weeks using the position 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 (for example the sun date cannot be determined under cloudy conditions). For each photograph information was obtained on the sea-level elevation for the previous month, annual rainfall, total rainfall for the previous 3 months, Troup’s SO Index, the monthly average position of the centre of the Headley cell along the east Australian coast (PITTOCK, 1978), sea-surface temperature averaged for the previous 3 months, deviations in SST from the monthly average, and the accumulative deviation in SST for the previous year.

Some variables differ slightly from those investigated previously. Total rainfall for the previous 3 months has been included to give a more accurate reflection of the effect of rainfall on HT beach change. Troup’s SO Index measures the pressure difference between Darwin and Tahiti standardized to a value of 10 for the years 1933-1977. It is slightly different from the index used in earlier work (BRYANT, 1983b) which was based on principle component analysis of a range of pressure for the Pacific region. The latter index is a better representation of overall southern Pacific circulation but it cannot be updated easily after 1974. Troup’s Index is easily updated and accessible with current monthly values published in the NOAA Climate Diagnostics Bulletin. Three monthly averaged and accumulative yearly deviations in SST were used because of the possibility of considerable lag of SST behind a change in meteorological conditions (including rainfall), a fluctuation in beach water tables and subsequent beach change.

The sequence of HT beach change data is plotted between 1943-1980 in Figure 2a, and smoothed, seasonally detrended SST, rainfall, sea-level, Hadley cell latitude and SO Index series are presented together in Figure 2b. For presentation purposes only, the latter data were detrended using deviations from monthly averages and smoothed using a 11 term weighted filter. The smoothing removed from the data small peaks which detracted from the visual presentation of the series. Times of retreat shoreward of the average HT beach position and of above normal meteorological and oceanographical conditions which can be postulated as leading to HT beach retreat are shaded.

The data were analyzed in three ways. Firstly the HT beach change time series was linearly correlated to all of the above variables using simple Pearson product-moment correlation...
Figure 2a. Deviation from mean of HT beach position averaged for whole of Stanwell Park beach, 1943-1978. Times of retreat shoreward of the average position are shaded. Arrows refer to the timing of 'storm' events or 'non-events' discussed later in the text and summarized in Table 5.

2b. Seasonally detrended and smoothed time series of monthly sea-surface temperature at 34°15'S and 151°15'E, monthly Helensburgh rainfall, monthly Sydney sea-level, the monthly position of the Hadley cell at the east Australian coast, and Troup's Southern Oscillation Index, 1943-1978. Values plot standard deviations about the mean. Shaded areas represent times of above normal conditions which are hypothesized as conducive to HT beach retreat.
TABLE 2. Correlation of HT beach position on Stanwell Park to sea-level elevation for the previous month, annual rainfall, total rainfall for the previous 3 months, Troup's southern Oscillation Index (the difference between air pressure at Darwin and Tahiti only), latitude of the Hadley cell centre along the east Australian coast, sea-surface temperature averaged for the previous 3 months, deviations in sea temperature from the monthly average, and the annual accumulative deviation in sea-surface temperature.

<table>
<thead>
<tr>
<th>Variable</th>
<th>change over time (lyr)</th>
<th>correlation coefficient</th>
<th>HT beach change relationship (meters) $y = a + bx$</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT Position</td>
<td>-0.004 m</td>
<td>0.003***</td>
<td>$y = -0.004 + 0.007 x$</td>
<td>0.394**</td>
</tr>
<tr>
<td>Rainfall</td>
<td>-3.554 mm</td>
<td>-0.027***</td>
<td>$y = -10.785 + 0.012 x$</td>
<td>0.225**</td>
</tr>
<tr>
<td>3 month rain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea-level</td>
<td>0.193 cm</td>
<td>0.318***</td>
<td>$y = 33.636 - 0.429 x$</td>
<td>0.230**</td>
</tr>
<tr>
<td>SO Index</td>
<td>0.018</td>
<td>0.019***</td>
<td>$y = -1.126 - 0.139 x$</td>
<td>0.093**</td>
</tr>
<tr>
<td>Hadley cell</td>
<td>0.038° Lat.</td>
<td>0.085**</td>
<td>$y = 7.679 - 0.268 x$</td>
<td>0.098**</td>
</tr>
<tr>
<td>sea temp</td>
<td>0.014° C</td>
<td>0.066**</td>
<td>$y = 19.246 - 1.056 x$</td>
<td>0.147*</td>
</tr>
<tr>
<td>deviation in sea temp</td>
<td>0.017° C</td>
<td>0.192***</td>
<td>$y = -1.085 - 1.165 x$</td>
<td>0.132**</td>
</tr>
<tr>
<td>accum. dev. in sea temp</td>
<td>0.225° C</td>
<td>0.115**</td>
<td>$y = -1.083 - 1.145 x$</td>
<td>0.052**</td>
</tr>
</tbody>
</table>

* significant 0.10 level
** significant 0.05 level
*** significant 0.01 level
ns not significant

TABLE 3. Comparison of rates of HT beach change for each variable in Table 1 significant at the 0.05 level between 1943-1978 to rates for the 1895-1980 period.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Amount of Change</th>
<th>Rates of HT beach change 1943-1978</th>
<th>Rates of HT beach change 1895-1980</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual rainfall</td>
<td>100 mm</td>
<td>0.70 m</td>
<td>0.79 m</td>
</tr>
<tr>
<td>Previous quarterly rainfall</td>
<td>100 mm</td>
<td>1.20 m</td>
<td>1.62 m</td>
</tr>
<tr>
<td>Sea-level previous month</td>
<td>10 mm</td>
<td>0.43 m</td>
<td>0.44 m</td>
</tr>
</tbody>
</table>

(DAVIS, 1973). Results are presented in Table 2. Rates of beach retreat for variables significant at the 0.05 level in Table 2 are compared with rates for the 85 year period in Table 3. Secondly it was recognized from this analysis that SST might not correlate linearly with HT beach change. SST was re-correlated to HT beach change in combination with other variables in turn using trend surface analysis. Trend surface analysis is usually used to describe the spatial trend of a variable (DAVIS, 1973); however it can be considered a two-dimension multiple regression technique whereby any two independent variables (SST and one other variable) can be linearly correlated to an independent variable (HT 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 SST and HT beach change to be investigated in tandem with one other variable. Finally the combination of variables accounting for highest degree of variance in the HT beach change time series using trend surface analysis (Figure 3) was incorporated as an extra variable in the 1943-1978 data set and the relative importance of variables ascertained 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 with the
RESULTS

Beach Change Correlations

The results of this study are slightly different from previously reported work (BRYANT, 1983b) in that the time span has been reduced from 85 to 36 years and a different index of the Southern Oscillation has been used. For the shorter period investigated in this study, there was no statistically significant trend between 1943-1978 in HT beach position, rainfall, the SO Index, the position of the Hadley cell, SST or accumulative deviations in sea temperature (Table 2). There was a significant increase in sea-level which rose at the rate of 1.93 mm/yr (3 times the rate for the 85 year period) and a tendency for SST to become aseasonally warmer. All the data show considerable variation since 1943. For example monthly SST offshore from Sydney ranged from 14.4°C to 24.1°C. Aseasonal variations range from a low of 4.8°C below normal in February 1963, to a high of 2.5°C above normal in July 1976. Below average temperatures occurred throughout 1948 while above average temperatures persisted throughout 1976.

Correlations between various environmental variables and HT beach change agree with results derived from the longer term study. There was a strong correlation, significant at the 0.05 level, between HT beach position and (1) annual rainfall, (2) monthly rainfall for the previous 3 months, and (3) previous monthly sea-level ($r = -0.304, -0.225$ and $-0.230$ respectively). Each 100 mm of increased annual rainfall, 100 mm of increased rainfall for the previous 3 months or 10 mm rise in sea-level led to 0.70, 1.20 and 0.43 m of beach retreat respectively (Table 3). These values compare favourably to values of 0.79 m of HT beach change per 100 mm of annual rainfall, 1.62 m of change per 100 mm of rainfall in the previous 3 months and 0.44 m of change per centimeter of sea-level determined for the 85 year period (BRYANT, 1984a). For the shorter term of analysis there was no statistically significant correlation at less than the 0.10 level between HT beach position and both Troup's SO Index and the position of the Hadley cell along the east Australian coastline. In a previous study (BRYANT, 1983b) a weak correlation was found between Wright's SO Index and beach change. The present study used monthly measurements instead of quarterly values,—a procedure which has probably introduced enough additional variance in the SO data to reduce correlation levels given the fact that about 10% of the beach data cannot be dated to the nearest month.

In the present study there was a weak correlation, significant at the 0.10 level, between HT beach position and SST ($r = 0.147$). A 1°C increase in SST resulted in 1.06 m of HT retreat. This result does not strongly substantiate THOM's (1978) hypothesis that beach erosion is most prevalent when SST is warmer than normal. The correlation between HT beach change and the deviation in SST from the norm ($r = 0.132$) was not significant at the 0.10 level. The correlation between HT beach change and the accumulated deviation in SST for the previous year was virtually non-existent. As seen above the lack of correlation between SST and HT beach change cannot be put down to the C.S.I.R.O. data sets' unrepresentativeness of general offshore temperature.

Non-Linear Relationships Between SST, Sea-Level and HT Beach Change

The poor linear correlation between SST and HT beach change was not expected. Trend surface analysis was performed to evaluate the non-linear relationship between HT beach change and SST in conjunction with other variables in turn. While statistically significant models could be constructed using SST and most other variables, when all the models were used in multiple stepwise regression only that

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>stepwise multiple correlation coefficient</th>
<th>Percent added variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sea-level-SST</td>
<td>.420</td>
<td>17.63%</td>
</tr>
<tr>
<td>2</td>
<td>Annual rain</td>
<td>.497</td>
<td>7.15%</td>
</tr>
</tbody>
</table>
using SST in conjunction with sea-level contributed a significant degree of explanation of the variance in HT beach change. The cubic surface was the highest statistically significant surface that could be constructed using a combination of SST and sea-level (Figure 4). This surface accounted for 17.6% of the variance in HT beach position. When SST and sea-level are high then the beach undergoes erosion. This supports Thom’s hypothesis for erosion of New South Wales beaches. The model also indicates that these two variables must exist in conjunction with each other for erosion to occur. Closer examination of the data indicates a non-linear relationship between HT beach position and both sea-level and SST. If sea-level is high then there is a linear relationship between HT beach position and SST; however if sea-level is low then extreme SST leads to beach accretion while average SST produces slight erosion. If SST is warm then there is a linear relationship between HT beach position and sea-level; however if SST is cool then the beach will always remain accretional no matter what happens to sea-level.

Multiple Stepwise Regression Model of HT Beach Change

The trend surface results consisting of predicted HT values determined from SST and sea-level data were incorporated, together with all meteorological and oceanographic variables used in the study, into a multiple stepwise regression model of HT beach change. The resulting model is very simple (Table 4). The cubic trend surface model of combined SST and sea-level accounted for the greatest amount of HT beach position variance (17.6%). Annual rainfall contributed a further 7.2% explanation to the variance. In total both variables accounted for 24.8% or 1/4 of the HT beach position variance. A value significant at the 3.0% level of significance. No other variable contributed any further degree of explanation at the 10% level of significance or lower. The model contains 2 of the more important variables, rainfall and sea-level, defined in previous studies as well as the third variable, SST, which THOM (1978) has hypothesized as significant in accounting for erosion of beaches along the Stanwell Park section of coast.

SST as a Prognostic Indicator of Beach Retreat

The question arises whether or not SST can be used to forecast beach retreat? This point was evaluated in two ways. Firstly SST was lagged and cross-correlated at monthly intervals to the two variables, rainfall and sea-level, which directly relate to HT beach position on Stanwell Park and to two variables, the position of the Hadley cell along the east coast of Australia and Troup’s SO Index, which correlate significantly with rainfall and sea-level. Correlograms plotting raw and seasonally detrended, but unsmoothed, data are presented in Figure 4. Negative lags represent a SST response after a change in one of the variables. Superimposed on each correlogram are the 0.05 and 0.01 levels of significance.

Secondly the conditions conducive to beach retreat were examined for a number of erosional events in the Stanwell Park record. The erosion ‘scenario’ states that beach erosion is most probable when rainfall and sea-level are high, or when cyclogenesis is enhanced because the Hadley cell is centred well south of the continent and SST is above normal, especially in the autumn or winter (THOM, 1978). The events to be examined include the April-May 1949, August-September 1967, May-June 1968, May-June 1974, November 1974 and June 1978 ‘storms’. All these ‘storms’ have been accounted for by the author or documented in CHAPMAN et al. (1982), and are evidenced to within a few weeks on Stanwell Park photographs by substantial average beach retreat exceeding 20 m or by rapid changes in shoreline position. The ‘storms’ between 1967-1978 represent all the major ‘storm’ activity along this section of coast within that timespan. Two ‘non-events’ occurring in early 1971 and the spring of 1976 when SST may have been favourable for HT beach retreat were also examined. No evidence existed in the data or elsewhere to indicate that substantial beach erosion occurred at these later times along the New South Wales coast. The crucial meteorological and oceanographic parameters for all these events are presented visually in Figure 1 and summarized in Table 5. Values in Table 5 represent deviations from averages and are depicted in bold type where they exceed 2 standard deviations. Weather pattern descriptions are based upon 24 hr weather...
Figure 4. Correlograms comparing sea-surface temperature to (a) the monthly position of the Hadley cell at the east Australian coast, (b) monthly rainfall at Helensburgh, (c) the standardized monthly difference in pressure between Darwin, Australia, and Tahiti, and (d) monthly Sydney sea-level. A negative lag represents sea-surface temperature responding after a change in each of the variables. Both raw (solid line) and seasonally detrended (dashed line) correlations are presented at monthly lags for a one year period. The 5% and 1% significance levels have been superimposed on each correlogram (n = 432).
TABLE 5. Meteorological and oceanographic characteristics of some 'storm' events and 'non-events' influencing the Stanwell park coastline 1949-1978. Values departing more than 2 standard deviations from the mean are in bold type. Standard deviations based on all available data 1943-1978.

<table>
<thead>
<tr>
<th>Weather Pattern</th>
<th>Local Rain previous quarter (sd = 94mm)</th>
<th>Sea-level Sydney for event (sd = 5.4cm)</th>
<th>sea temp. dev. off Sydney for event (sd = 0.9° C)</th>
<th>Hadley cell latitude for event (sd = 4.8°)</th>
<th>SO Index for event (sd = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Storms' Apr-May 1949</td>
<td>intense lows off NSW coast</td>
<td>+360mm</td>
<td>-4.9 cm</td>
<td>+2.6°C</td>
<td>0.2°</td>
</tr>
<tr>
<td>Aug-Sept 1967</td>
<td>intense lows off NSW coast</td>
<td>-42</td>
<td>+5.3</td>
<td>0.0°</td>
<td>+2.5°</td>
</tr>
<tr>
<td>May-June 1968</td>
<td>intense lows off NSW coast</td>
<td>-212</td>
<td>8.1</td>
<td>-0.2°</td>
<td>-6.6°</td>
</tr>
<tr>
<td>May-June 1974</td>
<td>intense lows off NSW coast</td>
<td>+415</td>
<td>11.9</td>
<td>+0.3°</td>
<td>+10.0°</td>
</tr>
<tr>
<td>Nov. 1974</td>
<td>low NSW coast intense low off NSW coast</td>
<td>+209</td>
<td>8.7</td>
<td>+0.6°</td>
<td>+5.6°</td>
</tr>
<tr>
<td>June 1978</td>
<td></td>
<td>+190</td>
<td>17.5</td>
<td>+0.2°</td>
<td>-3.8°</td>
</tr>
<tr>
<td>'Non-events' Summer 1971</td>
<td>weak lows off NSW coast</td>
<td>+222</td>
<td>1.0</td>
<td>+0.5°</td>
<td>+5.2°</td>
</tr>
<tr>
<td>Winter 1976</td>
<td>weak to intense lows off East Aut. coast</td>
<td>-138</td>
<td>+9.3</td>
<td>+2.2°</td>
<td>-1.3°</td>
</tr>
</tbody>
</table>

Cross-Correlations Between SST and Other Variables

SST on a seasonal basis directly responds to, or lags by 1-2 months, movement of the Hadley cell (r = 0.46-0.51, significance level <0.001). As the Hadley cell moves southward with summer, wind circulation along the Sydney coastline becomes more easterly and the warm East Australian current penetrates southward along the N.S.W. South coast. Comparison of weekly SST maps of the Tasman Sea between 1982-1984 (AUSTRALIAN OCEANOGRAPHIC DATA CENTRE 1984,1985) to meteorological charts clearly shows SST changing concomitantly with Hadley cell movement. Noteworthy is the fact that SST could change before or after seasonal shifts in pressure patterns. In this sense neither variable can be used to forecast the other. However if the seasonal pattern is removed from the data, then SST tends to lag 1-2 months behind aseasonal shifts of the Hadley cell (r = 0.220-0.198, significance level <0.001).

SST on a seasonal basis also responds directly to, or lags by 1-2 months, rainfall at Helensburgh 5 km from Stanwell Park (r = 0.122-0.259, significance level <0.01). This relationship may be due to either warmer SST increasing the instability of onshore winds and hence leading to higher rainfall, or to rainfall increasing SST directly through runoff or precipitation. The effect of rainfall on sea temperature can be shown clearly if the seasonal pattern is removed from the data. SST now lags rainfall by 0-3 months with the peak correlation occurring at 2 months (r = 0.170, significance level <0.05). In some cases the onset of beach retreat at Stanwell Park due to increased rainfall could be considered an omen for warmer ocean temperature offshore.

PITTOCK (1978) found a strong link between rainfall and the SO Index. Changes in the Southern Oscillation occur several months before changes in rainfall regime along the east Australian coastline (PITTOCK, 1978; BRYANT,1985). Additionally there are strong links between SST and El Niño - Southern Oscillation events across most of the equatorial Pacific (WYRTKI, 1982; RASMUSSON and CARPENTER, 1982; GLANTZ, 1984). The SO Index should be an ideal index to monitor for forecasting possible beach shoreline changes due to rainfall or SST changes. The present study does not support any direct association between Sydney SST and the SO Index. Only a weak correlation existed after the seasonal charts distributed by the Bureau of Meteorology.
effect was removed with SST either lagging the index by 2-4 months ($r = 0.085$, significance level $<0.05$) or preceding it by 6 months ($r = 0.093$, significance level $<0.05$). The latter correlation is difficult to explain given existing observations and hypotheses on the relationships of SST to changes in the Southern Oscillation in the Pacific region.

On a seasonal basis SST lags sea-level by 2-6 months ($r = -0.097$ to -0.132, significance level $<0.05$) with the peak correlation occurring at 4 months. Correlations are negative. Many of the associations between SST and the Southern Oscillation in the Pacific are thought to be due to responses in sea-level either through piling up of water in the East Pacific by easterlies during more normal phases of Walker circulation, or through propagation of a Kelvin wave across the Pacific through the failure or relaxation of easterlies during El Niño - Southern Oscillation events (WYRTKI, 1982; BUSALACCHI et al., 1983; HARRISON and CANE, 1984). The negative correlation between Sydney SST and sea-level does not fit this pattern. HSIEH (per communication, 1984) found that since 1950 downwelling has occurred along the Sydney coastline during El Niño events contemporaneously with increased SST because air pressure is also higher at such times. After the seasonal pattern is removed from the data SST correlates positively to sea-level, with lags ranging from $+11$ to $-8$ months ($r = 0.091$-$0.286$, significance level $<0.05$). The positive correlation is suggestive of a direct density-temperature effect such that more dense water, being cooler, depresses sea-level; however the range in lags is difficult to explain.

**SST and Environmental Conditions During 'Storm' Events**

Thom et al. (1973) have described the weather patterns heightening beach erosion along the New South Wales coastline. The most important feature is the presence of extra-tropical low pressure cells associated with either the passage of cold fronts or with the development of an upper air trough over New South Wales. The effectiveness of these low pressure cells depends upon their intensity and length of duration off the coast. Often the more intense lows appear to strengthen upon reaching coastal waters and stalling over the Tasman Sea (BRYANT and KIDD, 1975). All of the 'storm' events and 'non-events' listed in Table 5 were dominated by such patterns; however the pressure cells of April-May 1949, May-June 1968, May-June 1974, and June 1978 were particularly intense, prolonged and clustered over a 2-3 week timespan. These low pressure cells can occur in all months of the year but are more intense and frequent between May and October. Coastal low pressure cells present during the 'non-events' were generally weak.

Except for the August-September 'storms' of 1967 all of the 'storm' events were characterized beforehand by above normal rainfall. For this reason Stanwell Park beach was probably already undergoing retreat before the 'storm' events occurred. This shows up in the data most clearly for the May-June 1974 event with the beach undergoing more than 40 m of average retreat in the three months leading up to the 'storms' (BRYANT, 1983a). The May-June 1974 'storm' cluster is exceptional in that sea-level also was unusually high and the Hadley cell had shifted 10° further south than normal for this time of year. SST at least off the Sydney coastline was not much warmer than the seasonal norm. This 'storm' event emphasizes one of the conclusions which can be drawn from research on Stanwell Park,—namely that long term beach change is not related solely to a single variable, but to the sweep of meteorological and oceanographic parameters which can be linked theoretically and empirically to changes in shoreline position.

Given the results of the present study, there is little evidence of a concurrent high sea-level and warm SST during any 'storm' event listed. The data in Table 5 also indicate that while above-normal rainfall and sea-level can lead to beach retreat, there have been occurrences when neither variable was conducive to substantial erosion. The August-September 1967 'storms' occurred following a dry winter, with normal SST, slightly higher-than-normal (but not exceptional) sea-level and tracking of high pressure systems along average latitudes for this time of year. This event also shows that the effect of some 'storms' can attenuate rapidly along the coast. The 1967 'storms' were strong enough to be documented as important along the Sydney coastline (CHAPMAN et al., 1982), but they had minimal effect on Stanwell Park beach 30 km away.
The 'non-events' emphasize the point that while variables may be conducive to beach erosion, erosion doesn't have to take place. Both 'non-events' had low pressure cell patterns conducive to the initiation of above average wave conditions. Rainfall was above normal in the summer of 1971, and sea-level and SST were both above average in the winter of 1976. Except for the crucial variable sea-level, the 1971 'non-event' was similar to the November 1974 erosional period documented in the Stanwell Park data set. Neither 'non-event' evidenced beach degradation in the Sydney-Stanwell Park area.

**CONCLUSIONS**

THOM (1978) hypothesized that beach erosion along the Central and South coast of New South Wales, Australia, was exacerbated during 'storm' events when sea-surface temperatures (SST) were above normal. At these times Hadley cell positioning was more poleward than normal, and intense cyclogenesis leading to high energy waves more probable. Accurately dated measurements of the HT beach position were taken from 105 oblique photographs of Stanwell Park between 1943-1978. In addition weekly SST data collected by the C.S.I.R.O. offshore from Sydney were collected and found to be representative of the gross surface temperature pattern of the Tasman Sea. The Stanwell Park HT beach and Sydney SST time series represent two of the most complete records of their kind in the world. In this paper they have been used to examine the relationship between SST and HT beach change.

Simple linear regression between HT data and environmental variables between 1943-1978 substantiates the beach change results found previously for the longer time span 1895-1980, namely that a 100 mm change in annual rainfall or a 10 mm change in sea-level lead to a 0.70 m and 0.43 m of HT beach change respectively. SST for the previous three months correlated weakly at the 0.10 level with HT beach change such that a 1°C increase in water temperature resulted in a 1.06 m retreat of the HT line. Trend surface analysis showed that SST in combination with sea-level accounted for 17.6% of the HT data variance. This was a greater degree of explanation than determined using any variable singly. It appears that the HT line on Stanwell Park beach retreats only if both sea-level and SST are above normal. For other conditions the beach remains mainly accretional. It would appear that SST might be used to forecast periods of beach erosion, especially induced by the type of 'storm' events theorized by THOM (1978). Additionally SST has attracted considerable attention in Australia and the Pacific region because of its prognostic value for rainfall prediction especially during or following El Niño - Southern Oscillation events. Rainfall is a significant factor controlling beach retreat. The links between SST and rainfall, sea level, position of the Hadley cell and the SO Index were examined to evaluate the prognostic value of SST as a harbinger to beach retreat. Surprisingly it was found that SST both predicts and is predicted by rainfall and sea-level variables. Rainfall can be induced by the increased instability imparted to air masses by heating from below, or rainfall can increase SST through surface runoff or direct precipitation effects. The relationship with sea-level only indicates that sea-level at Sydney responds to a range of meteorological and oceanographic factors, — some of which correlate directly or indirectly to ocean temperature. It was also found that SST responds immediately or lags shifts in the Hadley cell. No significant correlation was found between ocean temperature and an index of the Southern Oscillation. From this analysis it can be concluded that SST at Sydney cannot be used to predict increased rainfall or higher sea-level responsible for beach retreat because the so-called controlling variable is itself dependent at times on rainfall and sea-level behaviour.

As a further examination of the role of SST on beach erosion, meteorological and oceanographic data at the time of six erosional 'storm' events and two 'non-events' were examined. In this analysis 'storms' often culminated and exacerbated ongoing beach retreat. It was found that rainfall was often higher than normal before peak periods of beach retreat. In two cases, the May-June 1974, and June 1978 'storm' events, both heavy rainfall and higher sea-levels worked in conjunction to induce HT beach retreat. Above normal SST or poleward displacement of the Hadley cell did not stand out in the data sets as crucial variables associated with erosion during these single erosional events.
The following three points about beach retreat along the New South Wales Central and South coast in the short-term can be deduced from this study:

(1) Beach retreat cannot be predicted using a single variable. It is probably related to a sweep of meteorological and oceanographic parameters of which rainfall, sea-level and SST appear to be the most important.

(2) Beach retreat can take place even when rainfall is not abnormally heavy, sea-levels high or SST warm.

(3) Even if synoptic patterns, rainfall, sea-level or SST are conducive to HT beach change, there are isolated cases when the shoreline planform position has remained unchanged.

The following three points about beach retreat in the long term can be deduced:

(1) Beach retreat is most significantly related to first, a combination of SST and sea level, and secondly to rainfall.

(2) High energy wave events ('storms') appear to have little cumulative effect on long term trends in HT beach positioning. A record of 'storm' events over the timespan of HT beach position data is presently being studied to substantiate this conclusion.

(3) While long term trends in sea-level, rainfall and SST temperature can be defined for past decades, unless these variables can be predicted in the future there is presently little chance of predicting long term trends in HT beach position on compartmentalized beaches which have a balanced sediment budget, are tectonically stable and free of human interference.

At present we are continuing to monitor HT beach change at Stanwell Park, the spatial structure of SST in the Tasman sea and the behaviour of low pressure systems over the Tasman Sea. It is possible for the East Australian current to extend southward along the New South Wales coastline as a tongue of warm water or as warm-core, isolated vortices about 100 km from shore. These features can persist for months and lead to abnormally warm offshore SST in the late autumn or winter. Low pressure systems in the upper troposphere or attached to cold fronts can intensify and become either locked over warm pools or track along the warm tongue of water. Only with the advent of satellite sensors and frequently updated SST charts will it be possible to relate completely the development and paths of low pressure cells to ocean temperature patterns offshore from the New South Wales coastline. The study of beach change in relationship to these pressure patterns appears to be the only fruitful avenue of research to pursue in trying to predict by one month-to-one year beach change along the New South Wales coastline using SST data.

ACKNOWLEDGEMENTS

Over 60 people responded to advertisements requesting old photographs of Stanwell Park beach. The N.S.W. Department of Lands, Department of Public Works Coastal Engineering Branch, State Rail Authority, and Tourist Bureau together with National Mapping, Wollongong Library, Stanwell Park Historical society, Mitchell Library, Murray View Postcards and De Miller Publishing provided additional photographic material and dates. Michael Adams greatly assisted with accurate dating and Professor John Trinder, School of Surveying, N.S.W. University provided computer programs on the direct linear transformation method. Dr. A.B. Pittook; Bureau of Meteorology, Melbourne; C.S.I.R.O. Division of Oceanography, Cornulla; Australian Oceanographic Data Centre, Hydrographic Office, Royal Australian Navy, Sydney; N.S.W. Maritime Services Board provided rainfall, pressure pattern, sea-level and sea temperature information gratis. Robyn Schweers and Dr. Bob Young aided with photographic preparation and surveying respectively. Advertising monies for old photograph donations were provided by the University of Wollongong.

LITERATURE CITED


EDWARDS, R.J., 1979. Tasman & Coral Sea ten year mean temperature and salinity fields. CSIRO (Australia) Division of Fisheries and Oceanography Report 88.


A lo largo de la costa Este Australiana, las altas temperaturas superficiales del mar (Sea-Surface Temperature, SST) en el Mar de Tasmania son fuentes generadoras de fenómenos ciclónicos capaces de producir tempestades que aceleran el retroceso de las playas. La distribución de las temperaturas superficiales del mar en el Pacífico Ecuatorial y alrededor de Australia provee también una indicación, con varios meses de adelanto sobre la distribución de lluvias costeras, que se ha ajustado con el retroceso de la
la línea de pleamar (High Tide, HT) en la playa de Stanwell Park. Este retroceso se ha medido con una precisión de 1 m utilizando 105 fotografías oblicuas tomadas en el período 1943-1978. Al mismo tiempo, se ha obtenido que las SST medidas 30 Km al Norte de Sydney representan la distribución superficial general de las temperaturas oceanicas en el Mar de Tasmania. Los dos registros se encuentran entre los mejores de su especie en el mundo. El modelado lineal, utilizando estos parámetros, así como los datos de niveles del mar y precipitación muestran que las SST en combinación con los niveles del mar son la causa del 17.6% de los datos de variación de HT, mientras que la precipitación anual es la causa de otro 7.2%. Parece ser que las altas SST deben producirse en conjunción con niveles altos del mar para que el retroceso de las playas sea evidente. El análisis de las condiciones ambientales de 6 temporales indica que, a corto plazo, los factores que conducen al retroceso de la playa no son operativos en todo tiempo. Sólo cuando se analizan las distribuciones a largo plazo puede correlacionar el retroceso HT con las altas SST, altos niveles del mar y precipitación. La utilización de las SST para la previsión del retroceso de las playas se encuentra actualmente a falta de obtener más información acerca de las relaciones entre las SST y la intensidad y trayectorias de las células debajo presión.—Department of Water Sciences. University of Santander, Santander, Spain.

RESUME

Les températures de surface de la mer (TSM) de Tasmanie, plus chaudes à l’Est de la côte australienne, provoquent une intense cyclogenèse qui conduit à des phénomènes de tempête. La répartition des TSM dans l’Océan Pacifique équatorial et autour de l’Australie donne, plusieurs mois à l’avance, la tendance des pluies côtières qui doit être reliée au retrait du niveau des pleines mers (PM) sur laplage de Stanley Park. Ce retrait a été mesuré à 1 m d’après 105 photos obliques prises entre 1943 et 1978, en même temps que les TSM hebdomadaires étaient collectées au large de Sydney, 30 km plus au Nord. Ces TSM donnent une bonne idée de la répartition des TSM dans la mer de Tasmanie. Des modèles linéaires utilisant ces paramètres, le niveau de la mer et les précipitations montrent quels la TSM combinée au niveau de la mer entre pour 17,6% dans la variance des PM alors que les précipitations ne contribuent qu’au 7,2%. Il ressort que la TSM la plus chaude doit se produire en même temps que des niveaux de la mer plus hauts pour que le retrait soit évident. Le retrait ne s’opère pas à chaque fois que se produit une “tempête”. Ce n’est que l’analyse à long terme qui montre la corrélation entre les TSM plus chaudes, le niveau de la mer plus haut et les pluies, avec le retrait du niveau des PM. Tant que manquera plus d’information sur les relations TSM et intensité et cheminement des bassespressions, on ne pourra aller plus loin dans la prédiction des périodes de retrait par la TSM.—Catherine Bressolier, EPHE, Mont­trouga, France.