Journal of Coastal Research	11	3	946–958	Fort Lauderdale, Florida	Summer 1995

Southern Oscillation Influences on the Gold Coast's Summer Wave Climate

Stuart R. Phinn† and Peter A. Hastings‡

†Department of Geography
San Diego State University
San Diego, CA 92182, U.S.A.

‡Applied Climate Research Unit
Department of Geographical
Sciences and Planning
The University of Queensland
St Lucia, Brisbane
Queensland 4072, Australia

ABSTRACT

PHINN, S.R., and HASTINGS, P.A., 1995. Southern oscillation influences on the Gold Coast's summer wave climate, *Journal of Coastal Research,* 11(3), 946–958. Fort Lauderdale (Florida), ISSN 0749-0208.

Tropical cyclone-generated wave conditions coincident with extreme phases of the Southern Oscillation were examined for Gold Coast (eastern Australia) beaches over the period 1972–1989. The study expands upon similar previous research conducted on Sydney's wave climate. Values of summer (Southern Hemisphere) mean-monthly deepwater wavepower on northern Gold Coast (Australia) beaches were found to be significantly lower during El Niño Southern Oscillation (ENSO) phases of the Southern Oscillation than during the opposing anti-ENSO phases. It is proposed that Southern Oscillation-related variability of Australian/south-west Pacific tropical cyclone activity is an important mechanism underlying the observed contrast. A tropical cyclone wave generation area was constructed for Gold Coast beaches using individual tropical cyclone and site data. Possible coastal management implications of these findings are discussed.

ADDITIONAL INDEX WORDS: *Tropical cyclones, El Niño Southern Oscillation, coastal management, wave generation area.*

INTRODUCTION

In examining the characteristics and controls of the south-eastern Australian summer wave climate, PHINN and HASTINGS (1992) developed a series of interrelated hypotheses which, at the seasonal resolution, linked wave conditions to the extreme phases of the large scale Indo-Pacific region ocean/atmosphere phenomenon known as the Southern Oscillation (SO). A detailed description of the SO from the Australian perspective may be found in ALLAN (1988, 1991). SO-related variability of south-west Pacific tropical cyclone activity in terms of spatial pattern was proposed as a key underlying mechanism of inter-annual summer wave climate variability in south-eastern Australia.

Associations between the SO and tropical cyclone activity in the Australian and/or south-west Pacific regions have been documented by NICHOLLS (1979, 1984, 1985), REVELL and GOULTER (1986a,b), HASTINGS (1987, 1990), PHINN and HASTINGS (1992), EVANS and ALLAN (1992) and most recently from a global perspective by KEQIN and HOLLAND (1994). In the specific context of eastern Australian wave climates, PHINN and HASTINGS (1992), observed that during Southern Hemisphere summers over which El Niño Southern Oscillation (ENSO) phases prevailed, south-west Pacific tropical cyclone activity was displaced eastward and away from the principal wave generation area for eastern Australia. Conversely, under conditions of the opposing SO phase, here termed anti-ENSO, south-west Pacific tropical cyclone activity was concentrated in the vicinity of the eastern Australian wave generation area. A subsequent examination of February to March deepwater wavepower values at Sydney by PHINN and HASTINGS (1992) revealed that significantly lower (higher) deepwater wavepower values occurred over this period when ENSO (anti-ENSO) phases predominated.

In accordance with the suggestions for future research made by PHINN and HASTINGS (1992), this study sought to clarify SO/wave climate relationships by using data from an area north of Sydney, the Gold Coast in south-eastern Queensland (Figure 1). Here, tropical cyclone activity is

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93120 received 13 November 1993; accepted in revision 12 July 1994.

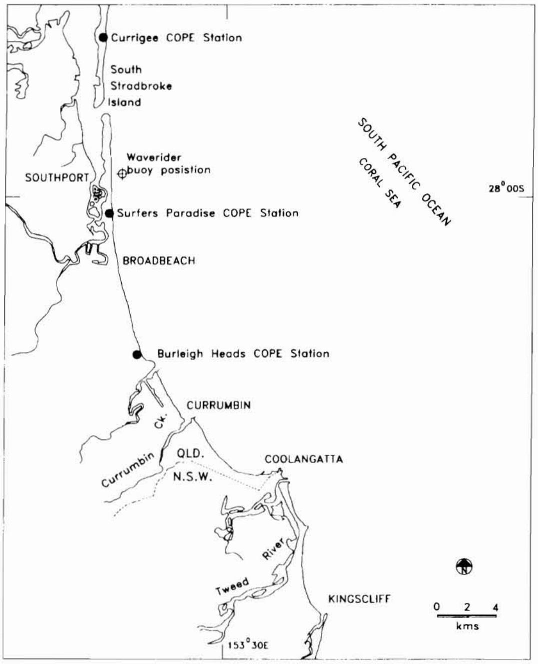

Figure 1. Location of C.O.P.E. stations and the Waverider buoy used in the project.

recognised as the dominant control of high wave conditions and beach change in summer. SO-related tropical cyclone activity would therefore be expected to cause observable wave and beach changes to a greater degree than at more southerly locations. This is because of the greater northerly and westerly extent of the Gold Coast's wave generation area.

Tropical Cyclones and the Gold Coast's Summer Wave Climate

The weather systems that are responsible for generating contrasting wave conditions along the south-eastern Australian coastline were described by studies such as McGrath and Patterson (1973), Thom (1974, 1978) and Kemp and Douglas (1981). During the summer half year (November–May), the tropical cyclone is recognised as being a major synoptic scale weather system that contributes to the wave climate of this region (Trenaman and Short, 1987; Kemp and Douglas, 1981; Gordon *et al.*, 1978). This is particularly the case along the Queensland coastline (Delft, 1970; Hopley, 1974; McGrath and Patterson, 1973; Smith and Jackson, 1990). Jackson (1990) and Smith and Jackson (1990) suggested that tropical cyclone-generated wave conditions were responsible for most of the major erosion events on the Gold Coast.

The average deepwater wavepower for the northern section of the Gold Coast is 9.59 kilowatts/metre of wave crest. Significant wave heights (H_S) range from 0.8 m to 2.0 m. They rarely fall below 0.5 m and often exceed 2.0 m under tropical cyclone influences (Chapman, 1981; Patterson and Patterson, 1983; Delft, 1986). Summer and autumn waves are generally higher, on average, than those in winter and spring due to the coincidence of the former period with the Australian tropical cyclone season (McGrath and Patterson, 1973; Kemp and Douglas, 1981; Patterson and Patterson, 1983). Tropical cyclones during these periods are responsible for the highest recorded waves on the Gold Coast (Jackson, 1990; Smith and Jackson, 1990). The systems often increase wave heights during the November to April period when conditions are otherwise dominated by short swell and seas that are produced by anticyclones and sea-breezes (H_S of 1.0 m to 1.5 m).

There is a limited amount of baseline research concerning the Gold Coast's wave conditions and beach change patterns, a situation common to most of south-eastern Queensland. Sufficient work has been completed within the eastern-Australian region, however, to establish that the degree of influence of tropical cyclones on wave climates and beach change (especially erosion) is a function of the following: (1) the systems' relative frequencies off the north-eastern Australian coast; (2) the proximity of activity to the coast; (3) the duration of the tropical cyclone season; and (4) the pre-cyclone beach state (Thom, 1974, 1978; Kemp and Douglas, 1981; Short and Wright, 1984; Smith and Jackson, 1990). This project examined variations in Factors 1 and 2 (listed above) as associated with extreme phases of the Southern Oscillation (SO).

The Problem

The aims of this investigation were to establish: (1) if seasonal contrasts in the Gold Coast's summer wave climate (November to May) could be delineated in accordance with occurrences of ENSO and anti-ENSO phases of the Southern Oscillation; and (2) whether these contrasts were linked to SO-related inter-annual variability of south-west Pacific tropical cyclone activity.

The characteristics of these relationships depend on the degree of variability of tropical cyclone activity within the Gold Coast's tropical cyclone wave generation area that can be attributed to the SO. Based upon the findings of similar work completed for Sydney (PHINN and HASTINGS, 1992), it was anticipated that the tropical cyclone-generated wave climate of the Gold Coast would likely be of higher (lower) energy during anti-ENSO (ENSO) phases due to the relatively increased (decreased) level of tropical cyclone activity immediately off north-eastern Australia at these times.

DATA AND METHODS

Tropical cyclone activity and recorded Gold Coast wave conditions were examined during extreme phases of the SO (ENSO and anti-ENSO, see ALLAN, 1988, 1991). This approach maximises the potential of detecting SO-related variability. Several stages were involved in the study: identification of extreme SO phases; definition of the Gold Coast's tropical cyclone wave generation area (WGA); analysis of tropical cyclone tracks and frequencies within the WGA during ENSO and anti-ENSO phases; and a comparative statistical analysis of Gold Coast wave conditions for summer seasons under ENSO and anti-ENSO phases.

Wave Data

Initially, a long time-series of data from a Gold Coast Waverider buoy was sought, given the knowledge that the first Waverider buoy was installed in 1968. Such a series would roughly correspond to the useable tropical cyclone data set (see following section). The majority of these wave data, however, could not be located by the responsible authorities.

Mean-monthly observations of breaker wave height (H_B) and period (T_B), for the months November to May, were subsequently obtained from daily observations at the following C.O.P.E. (Coastal Observation, Protection Engineering) stations (Figure 1): Currigee (South-Stradbroke Island), 1972–1973; Surfers Paradise Beach, 1973–1983; and Burleigh Heads, 1986–1987. The methods used to collect these data were outlined and critically assessed in PATTERSON and BLAIR (1983). From calibration with Waverider recorded observations, they are considered to approximate deepwater significant wave height (H_S) and period (T_S). Each month's H_B and T_B were input into a program, using equation 1, to calculate a corresponding mean-monthly deepwater wavepower (P_O).

$$P_o = (pgH_S{}^2C_g)/8 \qquad (1)$$

where: P_o = deepwater wavepower (watts/cm wave crest × 10^4); p = density of sea-water at one atmosphere and 20 °C (1.03); g = acceleration due to gravity (9.8); and C_g = deepwater group velocity = $(gT_S)/4pi$, where: pi = 3.14, T_S = significant wave period) (TRENAMAN and SHORT, 1987, p. 11). For the remaining period (1988–1990), daily H_S and T_S were obtained from the Waverider buoy at The Spit (Figure 1). These values were converted to monthly means and input into the program to calculate P_O values.

The C.O.P.E. stations and Waverider buoy data used are considered representative of wave conditions experienced along the northern section of the Gold Coast and each are assumed to represent corresponding variations. Limitations of the wave parameters used were outlined in PATTERSON and BLAIR (1983), SEELIG and AHRENS (1980) and REID (1989). In analysing the value of data types for assessing coastal processes and calibrating models, SMITH *et al.* (1988) classified C.O.P.E. data as "amorphous". This project was not concerned with such specific requirements and the available data were considered to be suitable for the application.

Tropical Cyclone Data

Tropical cyclones are defined as synoptic scale cyclonic systems of tropical origin that are associated with at least gale force winds (*e.g.*, REVELL, 1981). The disturbances are usually "named" systems. Hardcopy tropical cyclone data are available for the Australian region from the summary of LOURENSZ (1981) and subsequently from annual reviews appearing in the Australian Meteorological Magazine and reports within the monthly Darwin Tropical Diagnostic Statements (Darwin Regional Meteorological Centre, Australia). An Australian-region tropical cyclone database is maintained and periodically updated through the Bureau of Meteorology's Melbourne Regional Office. Recent south-west Pacific data are available from the New Zealand Meteorological Service, Wellington, Darwin Tropical Diagnostic Statements, and from REVELL (1981). Tropical cyclone data may also be extracted from global climate databases such as the World-Wide Consolidated Tropical Cyclones Data Set (TD-9636), held by the National Climatic Data Center (USA) and available commercially. The reliability

Table 1. *Recent Southern Hemipshere summers (south-west Pacific tropical cyclone seasons) over which extreme SO phases (ENSO, anti-ENSO) prevailed.*

ENSO Summers	Anti-ENSO Summers
1965/1966	1970/1971
1972/1973	1973/1974
1976/1977	1975/1976
1982/1983	1988/1989
1986/1987	

of tropical cyclone data for the Australian and south-west Pacific regions prior to the advent of regular satellite monitoring in the early to mid-1960's is considered questionable for research purposes (HOLLAND, 1981) and, in any case, was not used in this study.

Identification of Tropical Cyclone Seasons Associated with Extreme SO Phases

Southern Hemisphere summers (*i.e.*, Australian tropical cyclone seasons) since 1970, during which extreme SO phases prevailed, were derived from occurrences documented by QUINN *et al.* (1978), VAN LOON and ROGERS (1981), FU *et al.* (1986), KILADIS and VAN LOON (1988), VAN LOON and SHEA (1985) and NICHOLLS (1990). El Niño events were also listed by QUINN and NEAL (1992). Table 1 lists the ENSO and anti-ENSO summers that are widely acknowledged as such in the literature. These summers provided the framework of the study.

Definition of the Gold Coast's Tropical Cyclone Wave Generation Area (WGA)

The Gold Coast's tropical cyclone wave generation area (WGA) shown in Figures 2 and 3 was estimated by using daily position data of south-west Pacific tropical cyclones in conjunction with daily records from a Waverider buoy located at The Spit. The November to May periods of the years 1987–1991 were scrutinised. A total of 19 tropical cyclones were recognised as having occurred in the southwest Pacific region during those times.

For each tropical cyclone occurrence, Waverider buoy records were examined and periods when H_S exceeded 2.0 m noted. The tropical cyclone's position 24 hours prior to the time of $H_S > 2.0$ m was then recorded and mapped. This arbitrary lag-time represents an allowance for wave generation and travel towards the coast. In most cases for a given cyclone, collated points derived from the above procedure ultimately defined a cyclone track segment "corresponding" to coherent time

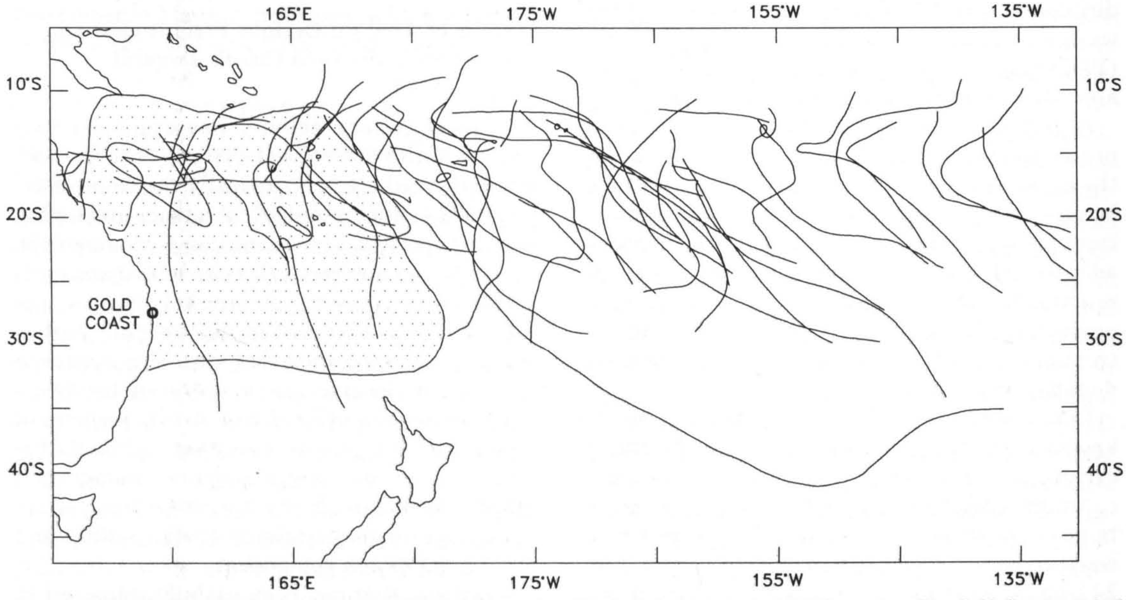

Figure 2. South-west Pacific tropical cyclone tracks (November–May) during composite ENSO seasons. The Gold Coast tropical cyclone wave generation area as determined in this study is stippled.

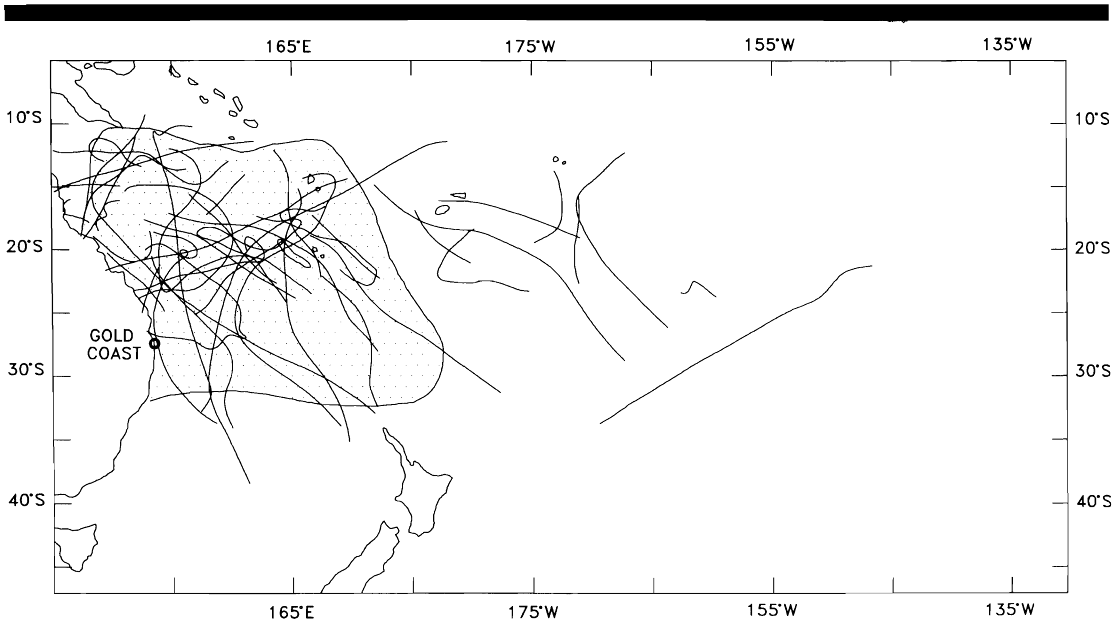

Figure 3. South-west Pacific tropical cyclone tracks (November–May) during composite anti-ENSO seasons. The Gold Coast tropical cyclone wave generation area as determined in this study is stippled.

blocks of $H_S > 2.0$ m. A boundary was then interpolated around the mapped track segments, thus delineating an approximation of the area in which tropical cyclones produce high wave conditions at the Gold Coast (*i.e.*, the tropical cyclone wave generation area). TRENAMAN and SHORT (1987) employed a comparable though simplified approach using Sydney wave data.

Although mostly held constant throughout the procedure, some flexibility was incorporated into the lag-time in cases of tropical cyclone positions being either close to or at relatively large distances from the Gold Coast. The 2.0 m H_S threshold was adopted after preliminary data inspection to represent high wave events. When two cyclones were operating simultaneously, it was assumed that the tropical cyclone closer to the Gold Coast was the dominating influence.

Limitations to the above method should be acknowledged. The method assumes that tropical cyclone intensity, including size and strength, are constant. The tropical cyclone is also considered to be the dominant wave producing the synoptic weather system in the region when it occurs. The 24 hour lag-time was arbitrarily defined and mostly held constant. To define the tropical cyclone WGA more accurately, a larger sample of tropical cyclones and a longer wave-data time series would be needed. Variable lag periods, wave height cutoffs and tropical cyclone structure would also need to be incorporated into advanced analyses.

Analysis of Tropical Cyclone Frequencies and Tracks Within the Gold Coast's Tropical Cyclone WGA

Tropical cyclone activity was examined spatially in terms of tropical cyclone "occurrence" within defined areas (principally the tropical cyclone WGA) during individual seasons and for SO phase composites. These composites combined the data from the previously defined ENSO and anti-ENSO phase seasons. A tropical cyclone was deemed to have occurred in an area if any part of its track impinged upon that area. This approach varies from the previous analyses of HASTINGS (1987, 1990) who utilised regional frequencies of tropical cyclone genesis. Contrasts of activity between SO phases were highlighted numerically and diagrammatically by means of tropical cyclone-track maps pertaining to the ENSO and anti-ENSO season composites.

A statistic that has been usefully employed in the temporal and spatial analysis of tropical cyclone incidence is the "cyclone day". Based on

NICHOLLS (1985), a cyclone day is defined here as a day on which at 0900 local standard time, a tropical cyclone was located within a defined region. In the present context, tropical cyclone activity within the Gold Coast's tropical cyclone WGA was measured in terms of cyclone days. On days when two tropical cyclones were active in the region, two cyclone days were counted and so on. Cyclone-day counts were conducted for the period of November to May and for the peak tropical cyclone period of February to March.

Statistical Analysis of Gold Coast Wave Data During ENSO and anti-ENSO Phase Tropical Cyclone Seasons

In order to assess Gold Coast wave conditions during ENSO and anti-ENSO summer seasons, mean-monthly P_O values, representing H_B and T_B variations, were used as an overall index of wave characteristics. For each season, mean-monthly P_O values were combined to produce P_O means for the November to May period and the period of peak tropical cyclone influence, February to March. Monthly P_O means within each SO phase composite were also combined to yield a single phase composite P_O mean.

To facilitate a robust analysis of whether P_O conditions at the Gold Coast significantly differed with contrasting extreme SO phases, a Student's t-test was applied to monthly P_O means of the November to May and February to March periods of the ENSO and anti-ENSO phase seasons.

RESULTS

The Gold Coast's Tropical Cyclone WGA

Figures 2 and 3 depict the tropical cyclone WGA derived for the Gold Coast in this study (based on tropical cyclones November–May 1987–1991). During the period considered, tropical cyclones occurring within this boundary were associated with H_B conditions exceeding 2.0 m on northern Gold Coast beaches. In terms of its spatial extent, the WGA extends over the southern Great Barrier Reef, north and north-east to Papua New Guinea, the Solomon Islands and Vanuatu (approximately 1,200 km) and south-east to a distance of approximately 1,350 km from the coast. In comparison to previously delineated tropical cyclone WGA's for eastern Australian locations, the one established here is significantly different. The Gold Coast tropical cyclone WGA of SMITH and JACKSON (1990), "a 300 nm (nautical mile) square with one side centred on the Gold Coast", was derived from observations of peak H_S and corresponding tropical cyclone positions for four individual tropical cyclones (1972–1974). From the reference of the tropical cyclone WGA produced in this study, it appears that this "box-style" WGA areally underestimates the zone of notable influence.

A similar but simpler approach of tropical cyclone WGA delineation to that employed by this study was applied to Sydney wave data by TRENAMAN and SHORT (1987). Peak H_S values at Sydney were recorded and corresponding tropical cyclone locations marked on a map. The final map was produced by interpolating a boundary around the tropical cyclone locations at the time of peak wave conditions at Sydney. Sydney's tropical cyclone WGA is considerably smaller than the one established in this work. This reflects the lesser control of tropical cyclones on wave conditions at locations to the south of the Gold Coast (see also PHINN and HASTINGS, 1992).

The Variability of Tropical Cyclone Activity Within the Gold Coast's Tropical Cyclone WGA

Figures 2 and 3 illustrate south-west Pacific tropical cyclone tracks of the ENSO and anti-ENSO phase composites. These maps are revised versions of those previously published by HASTINGS (1990). The current versions include 1988–1989 data, and where systems have maintained gale force winds south of 30°S, tracks have been appropriately extended. The previously defined Gold Coast tropical cyclone WGA is superimposed on each composite map.

The shift in the core region of tropical cyclone activity, with the occurrences extreme SO phases, is clearly apparent. Activity is concentrated within closer proximity to the north-east Australian coastline during the anti-ENSO phase composite as compared to the ENSO phase composite. In the latter, activity occurs in an extended band across the entire south-west Pacific region. The numbers of tropical cyclones either crossing or moving within close proximity of the Queensland coastline is, on average, greater during anti-ENSO phase seasons than during ENSO phase seasons. The effect is particularly noticeable at latitudes south of 20°S. The above findings generally complement those of NICHOLLS (1979, 1984, 1985); REVELL and GOULTER (1986a,b); HASTINGS (1987, 1990); EVANS and ALLAN (1992) and as referred to by KEQIN and HOLLAND (1994).

Table 2 lists the numbers of tropical cyclones that impinged upon the Gold Coast's tropical cyclone WGA (superimposed on Figures 2 and 3) during the selected SO phase seasons. A clear contrast between the phases is evident in total and quite consistent at the individual-season scale. Tropical cyclone activity within the WGA, as measured by cyclone days (Table 3), further reinforces the direction and strength of the overall findings. Greater tropical cyclone activity within the WGA is apparent, according to composite averages and generally at the individual season scale, during anti-ENSO phase seasons compared to ENSO phase seasons. At the sub-seasonal level (February to March), the equivalent relationship is less distinct for individual seasons. The latter statistics reflect the lack of a clear intra-seasonal patterning of cyclone days within the contrasting SO phases. It is noteworthy that the nature of the overall relationship documented above remains reasonably consistent if the more conservative Gold Coast tropical cyclone WGA of SMITH and JACKSON (1990) is substituted for that derived in the present study.

Statistical Analysis of Gold Coast Wave Data During Summer Seasons Associated with Extreme SO Phases

With the single exception of season 1972–1973 (ENSO), northern Gold Coast wavepower values plotted in Figure 4 indicate that the anti-ENSO seasons exhibited higher P_O values than the ENSO seasons during the November to May (and Nov–Apr) and February to March (peak tropical cyclone influence) periods. The mean P_O values (watts/cm wave crest $\times 10^4$) for each of the SO phase composites are presented in Table 4.

The t-test results show that at the 0.05 level of confidence with 5 degrees of freedom, values of mean-monthly deepwater wavepower for the northern Gold Coast beaches during November–May and February–March are significantly higher during anti-ENSO phases compared to ENSO phases. The SO-related variability of tropical cyclone frequencies/spatial pattern within the Gold Coast tropical cyclone WGA is suggested as a key mechanism in producing the contrasting wave conditions. As outlined, SO control on tropical cyclone occurrence directly influences the relative frequencies of tropical cyclones off the north Queensland coast and their proximities to the coast. During anti-ENSO (ENSO) phase seasons, tropical cyclones tend, on average, to be more (less) frequent within the Gold Coast tropical cyclone WGA and track closer to (further away from) the Queensland coast.

It should be acknowledged that several other wave generating weather systems exert control over the Gold Coast's wave climate during the months of November to May. These may have also contributed to the variations in P_O represented here. These systems include (in decreasing frequency of occurrence): north-easterly to south-easterly seabreezes, anticyclones, extra-tropical

Table 2. *Tropical cyclone occurrences within the tropical cyclone WGA during extreme SO phase seasons.*

SO Phase/Season	No. of Tropical Cyclones in WGA
ENSO	
1965/1966	1
1972/1973	2
1976/1977	5
1982/1983	3
1986/1987	6
Total	17
Mean	3.4
Anti-ENSO	
1970/1971	6
1973/1974	11
1975/1976	9
1988/1989	8
Total	34
Mean	8.5

Table 3. *Tropical cyclone activity as measured by cyclone days (see text for definition) within the tropical cyclone WGA during extreme SO phase seasons; November to May and February to March.*

SO Phase/Seasons	Cyclone Days (November to May)	Cyclone Days (February to Mar.)
ENSO		
1965/1966	7	7
1972/1973	12	11
1976/1977	22	12
1982/1983	24	19
1986/1987	17	6
Total	82	55
Mean	16.4	11
Anti-ENSO		
1970/1971	37	36
1973/1974	30	16
1975/1976	41	21
1988/1989	36	17
Total	144	90
Mean	36	22.5

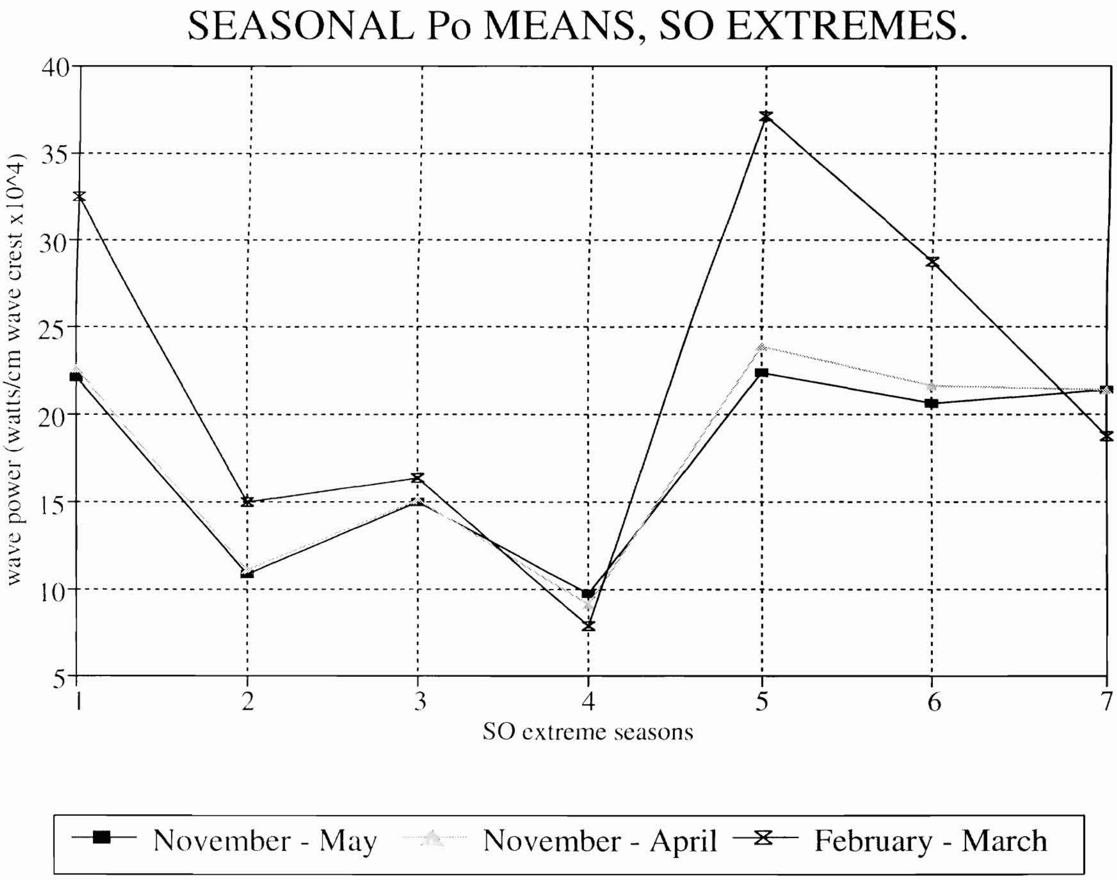

Figure 4. Summer season (November–May) mean P_0 for northern Gold Coast beaches during ENSO and anti-ENSO phase seasons. ENSO seasons: 1 = 1972–1973, 2 = 1976–1977, 3 = 1982–1983, 4 = 1986–1987; anti-ENSO seasons: 5 = 1973–1974, 6 = 1975–1976, 7 = 1988–1989.

cyclones, mid-latitude cyclones and frontal systems (SHORT and WRIGHT, 1984; TRENAMAN and SHORT, 1987). Nevertheless, after appraising the available data, it was considered that high wave conditions at the Gold Coast during the periods examined in this study were dominantly produced by tropical cyclones.

The 1991–1992 Tropical Cyclone Season

The second half of the 1991–1992 tropical cyclone season was characterised by notable activity off the north-eastern coast of Australia (particularly tropical cyclones Betsy, Esau and Fran). Given that ENSO-related sea surface temperature and atmospheric anomalies were evident over the summer (refer Climate Diagnostic Bulletins, United States Department of Commerce; NYDAM, 1993), the level of activity observed may be regarded as unusual. The genesis locations of the aforementioned systems was eastward of 170°E, as would be expected during an ENSO phase (see REVELL and GOULTER, 1986; HASTINGS, 1987, 1990; and EVANS and ALLAN, 1992). The subsequent consistent movements of the systems in a westerly direction (and into the Australian region) from this origin zone is, however, climatologically anomalous (refer to the climatologies of REVELL, 1981).

One explanation of this pattern of activity may involve the evolution of the 1991–1993 ENSO event. Historically, ENSO events have frequently matured over the SH summer, and then dissipated during the late summer/autumn period. The 1991–1993 event did not display these characteristics and persisted through 1992 and 1993 (refer Climate Diagnostic Bulletins, United States Department of Commerce; PLUMMER, 1994). The observed tropical cyclone activity may reflect a response to (or have expedited?) the protraction of the event. This aspect requires further investigation which is beyond the scope of this study.

Table 4. *Mean P_0 values (watts/cm wave crest × 10^4) for both SO phase composites during selected periods.*

SO Phase Composite	Composite Mean P_0 (November–May)	Composite Mean P_0 (February–March) (peak season)
ENSO	14.45 (28 months)	17.96 (8 months)
Anti-ENSO	21.48 (21 months)	28.18 (6 months)

DISCUSSION

The results of the present study indicate that significant differences in the Gold Coast's summer wave climate (notably, the incidence of high wave events) occur between summers that are affected by contrasting extreme phases of the SO. A major contributing factor appears to be SO-related variability of tropical cyclone activity off eastern Australia. It was demonstrated that the state of the SO affects some of the aspects of tropical cyclone occurrence that most influence wave climate and beach change in the study area; namely the frequency and the proximity of activity to the coast. These aspects were analysed with specific reference to a tropical cyclone wave generation area that was derived for the Gold Coast.

It is acknowledged that the statistical differences noted between anti-ENSO and ENSO phase P_0 values for northern Gold Coast beaches may partially reflect both SO and non-SO related variability of wave producing weather systems that were not specifically addressed in this study or that are yet to be recognised. Research into the effects of SO fluctuations on synoptic scale weather systems other than tropical cyclones is, as yet, extremely limited. The following sections discuss the implications of the present study's findings in the contexts of: comparisons to previous research; the links between the SO, tropical cyclones and beach erosion events; and models of beach change. Suggestions for potential applications of the research to coastal management and directives for future research are included in the discussions and conclusions.

Comparisons of Results to Previous Research

The overall results are consistent with the findings of a similar study conducted by PHINN and HASTINGS (1992) using Sydney wave data. This earlier study examined relationships between the SO and tropical cyclone variability within the Sydney tropical cyclone WGA defined by TRENAMAN and SHORT (1987). Subsequent links to Sydney wave conditions in February and March were made. The relationships that were identified from the Sydney study were established more firmly for the Gold Coast (Table 5). The reduced contrast between ENSO and anti-ENSO phase wavepowers at Sydney, compared to those of the Gold Coast, may be explained by the former location's relatively small, southerly displaced tropical cyclone WGA. SO-related spatial variations in southwest Pacific tropical cyclone frequencies and tracks impinge on the Gold Coast's tropical cyclone WGA (Figures 2 and 3) to a greater extent than Sydney's (see TRENAMAN and SHORT, 1987; PHINN and HASTINGS, 1992). Hence the SO, tropical cyclone and wave condition linkages are stronger at the Gold Coast. Furthermore, Sydney is located far enough south so that tropical cyclones only constitute one of its high wave generating weather systems and only for a short period of time each year. In comparison, tropical cyclones are the main high wave producing weather systems for the Gold Coast and are potentially influential over at least a six month season.

The Southern Oscillation, Tropical Cyclones and Beach Erosion Events

Records show that the majority of pronounced beach erosion episodes on the Gold Coast (here referring to depletion of beach material prior to, and during instrumental records) have been produced by wave conditions generated by tropical cyclones (DELFT, 1970, 1986; CHAPMAN and SMITH,

Table 5. *Mean February-March wavepowers at Sydney and the Gold Coast for each SO phase composite.*

SO Phase Composite	Sydney Wavepower (watts/cm wave crest × 10^4)	Gold Coast Wavepower (watts/cm wave crest × 10^4)
ENSO	19.73	17.96
Anti-ENSO	24.95	28.18

1981; JACKSON, 1990; SMITH and JACKSON, 1990). In light of the SO-related variations in both southwest Pacific tropical cyclone activity and Gold Coast wave conditions that were established in this work, an extension of the argument to include beach erosion events could be proposed. That is, during anti-ENSO (ENSO) summers, when increased (decreased) tropical cyclone activity within the Gold Coast's tropical cyclone WGA generates higher (lower) than normal wavepower conditions, more (less) frequent extreme episodes of beach erosion on the Gold Coast may be expected.

DELFT (1986) published data documenting the quantity of sand above mean sea level at the Surfers Paradise C.O.P.E. station for the period 1965–1985. Inspection of data relevant to the extreme SO phase summer seasons (as used in this study) reveals that two of the three anti-ENSO phase seasons (1973–1974, 1975–1976) corresponded to periods of notable erosion. Two of the ENSO phase seasons (1976–1977, 1982–1983) corresponded to periods of pronounced accretion. From this very limited assessment and given the findings of the present research, there is some evidence to suggest the existence of an association between the SO and beach change events. Further research into this potential relationship is warranted due to this preliminary observation, the results of this study, and the extensive literature that already intimates the links between weather systems (*e.g.*, tropical cyclones) and beach change.

Of additional interest is the consistent incidence of late-season (*i.e.*, April–May) tropical cyclone activity in the eastern Australian region in seasons immediately before ENSO-phase seasons, termed here as "pre-ENSO" seasons (HASTINGS, 1990). Pre-ENSO activity may be significant when the beach system previously experiences high wave conditions and is in a depleted state with a dissipative or storm-wave profile. Further, high wave conditions generated by late-season tropical cyclone activity during pre-ENSO seasons would then not allow sufficient time for the beach to accrete and may force further erosion. Therefore like anti-ENSO conditions, pre-ENSO conditions may produce high waves and could accentuate the existing eroded state of the beach. The testing of these and related hypotheses requires additional analyses of beach processes to further examine the effects of the SO and tropical cyclone activity in the context of the full structure of ENSO and anti-ENSO phases.

The Southern Oscillation, Tropical Cyclones and Models of Beach Change

One problem that may be encountered in establishing the connections between tropical cyclone variability, wave conditions and beach change is that the extent of beach change in response to different wave conditions depends on the pre-existing state of the beach. Nevertheless, a modelled linkage between Gold Coast wave conditions, beach change processes, and beach profile and plan configurations has already been established by JACKSON (1990). Further research could model the beach state produced by the wave conditions common during each SO phase. Based on the work completed in this study, anti-ENSO phase summers would be expected to be dominated by rising and large storm wave conditions. ENSO phase summers would experience all stages, although with less frequent occurrences of rising and storm wave conditions compared to anti-ENSO phase summers.

Another model of south-eastern Australian wave conditions, beach processes and form assemblages is the morphodynamic model of SHORT and WRIGHT (1984). This model comprises six beach types and is essentially similar to that of JACKSON (1990). Each beach type is also rated for safety in the context of beach and surf usage for recreational purposes (SHORT, 1988). The ratings were established by the New South Wales State Centre of the Surf Life Saving Association of Australia and the Coastal Studies Unit at the University of Sydney. On the basis of this model, the most frequent beach type associated with the wave conditions common during each SO phase could be established. The relative safety of the beach could then be assessed with reference to the SO. Present results indicate that anti-ENSO summers, with frequent high wave conditions, would be associated with the broad surfzone and longshore trough beach-types with moderate to high danger ratings. Having established these relationships, forecasts of SO conditions (*e.g.*, see NATIONAL CLIMATE CENTRE, 1991) may be used to determine an indication of the likelihood of dangerous beach states occurring, and therefore allow suitable planning of coastal protection strategies or allocation of sufficient/increased beach patrols for the period.

In terms of coastal management in this region, by noting forecast SO conditions, and utilising the link between summer SO phase and the frequency of high energy wave events (the tendency for more (less) frequent high wave conditions during anti-ENSO (ENSO) summers), informed decisions may be made regarding:

1. Whether or not to stabilise already eroded sections of beach during the pre-cyclone season. A suitable amount of beach stabilisation (nourishment) would be carried out to ensure the beach had the capacity to withstand expected wave conditions without damage to the frontal dune, infrastructure, amenities or buildings.
2. The timing of operations or activities using the beach system (*e.g.*, beach nourishment or construction activities).

CONCLUSIONS

The present analysis of the inter-annual variability of the Gold Coast's summer wave climate has established the following relationships:

1. During ENSO phase summers there is a tendency for:
    - reduced tropical cyclone activity within the Gold Coast's tropical cyclone WGA, with the consequence of,
    - relatively low November–May and February–March wavepower.
2. During anti-ENSO phase summers there is a tendency for:
    - increased tropical cyclone activity within the Gold Coast's tropical cyclone WGA, with the consequence of,
    - relatively high November–May and February–March wavepower.

Given these associations, the availability of SO forecasts (*e.g.*, see NATIONAL CLIMATE CENTRE, 1991), and the predictive potential that is inherent in relationships between the SO and Australian region tropical cyclone activity (NICHOLLS, 1992), SO information could be useful in providing a prior indication of the likely frequency of tropical cyclone-generated high wave conditions during summer months. This knowledge may then be used as input into coastal management decisions to enable more appropriate planning of beach stabilisation/nourishment activities (*i.e.*, confirming that a wide enough beach is maintained to withstand storm waves), to ensure assignment of sufficient beach patrol numbers for dangerous beach conditions, and for decisions concerning other activities dependent on the state of the beach system. To these ends, future research should further refine the WGA derived here and seek to expand knowledge of the SO, tropical cyclones and Gold Coast wave conditions in order to facilitate the establishments of linkages to existing models of beach change and safety.

The present research examined SO/wave climate relationships that involved SO-related variability of tropical cyclone activity off eastern Australia. Similarly argued associations may be found in other Australian regions where tropical cyclones exhibit SO-related variability and contribute significantly to the wave climate. ALLAN and EVANS (1992) documented variations of tropical cyclone distributions off northern and northwestern regions of Australia that were linked to phases of the SO. A conspicuous SO influence on the wave climates of these regions is therefore a possibility.

ACKNOWLEDGEMENTS

The assistance of the Gold Coast City Council, and particularly Mr. Angus Jackson, for providing the necessary data and financial support is acknowledged. Thanks also to Dr. Rob Allan for his comments on this paper.

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