

# Southern Oscillation Influences on the Wave Climate of South-Eastern Australia

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## ABSTRACT

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Southern Oscillation (SO) controls on wave climate in the south-eastern Australian region during the southern hemisphere summer are discussed and an analysis is undertaken of Sydney wave characteristics coincident with periods of established El-Niño Southern Oscillation (ENSO) and anti-ENSO extreme SO states. In the late summer (February-March) period, anti-ENSO (ENSO) extremes were found to be associated with significantly higher (lower) values of Sydney deep water wave power. SO related inter-annual variability of eastern Australian and south-west Pacific tropical cyclone activity in terms of frequency of occurrence and spatial pattern is proposed as one mechanism underlying the identified SO/wave climate relationships.

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

## INTRODUCTION

The Southern Oscillation (SO) principally describes an irregular but coherent fluctuation of the large scale atmospheric circulation systems across the Indian/Pacific region. In turn, the phenomenon is closely related to the occurrence, magnitude and spatial patterning of equatorial Pacific sea-surface temperature (SST) anomalies, including the occasional widespread warmings known as El Niño (e.g. RASSMUSSON and CARPENTER, 1982; VAN LOON and SHEA, 1985; KILADIS and VAN LOON, 1988).

El-Niño Southern Oscillation or ENSO events represent one extreme state of the SO. In the most general sense, ENSO events are characterised by positive sea surface temperature anomalies in the eastern and central equatorial Pacific and anomalously high (low) sea level atmospheric pressures over the Australasian region (central Pacific). At the other extreme, anti-ENSO, the broadscale patterns of oceanic and atmospheric anomalies are approximately reversed (ALLAN, 1988; KILADIS and VAN LOON, 1988). Once established, these extreme states may persist for a year or more, their "lifecycle" being loosely locked into the annual cycle (NICHOLLS, 1990).

During the past two decades, significant relationships have been identified within the Australian region between the SO and atmospheric circulation, rainfall, sea surface temperatures, sea levels and ocean currents, most notably at times of SO extreme states. These aspects have been reviewed by ALLAN (1988) and are schematised in Figure 1. Importantly, the existence of lags within the ocean-atmosphere system allows opportunities for prediction of these SO related anomalies (e.g. NICHOLLS, 1990).

The recognition of relationships between various scales of atmospheric systems and processes of coastal modification is potentially advantageous to both the long and short term management of beach systems in eastern Australia and other locations. Previous research investigating links between the SO and variables controlling beach change in south-eastern Australia has largely been confined to discussions of independent atmospheric and oceanographic variables. For example, indices of the SO have been successfully correlated with sea-level variations, foreshore water-table levels and resultant erosion and accretion of the subaerial beach (BRYANT, 1983, 1985). Relationships have also been reported with regard to changes of subaerial sediment volume associated with the occurrence of onshore winds (ELIOT and CLARKE, 1988) and to coastal erosion events

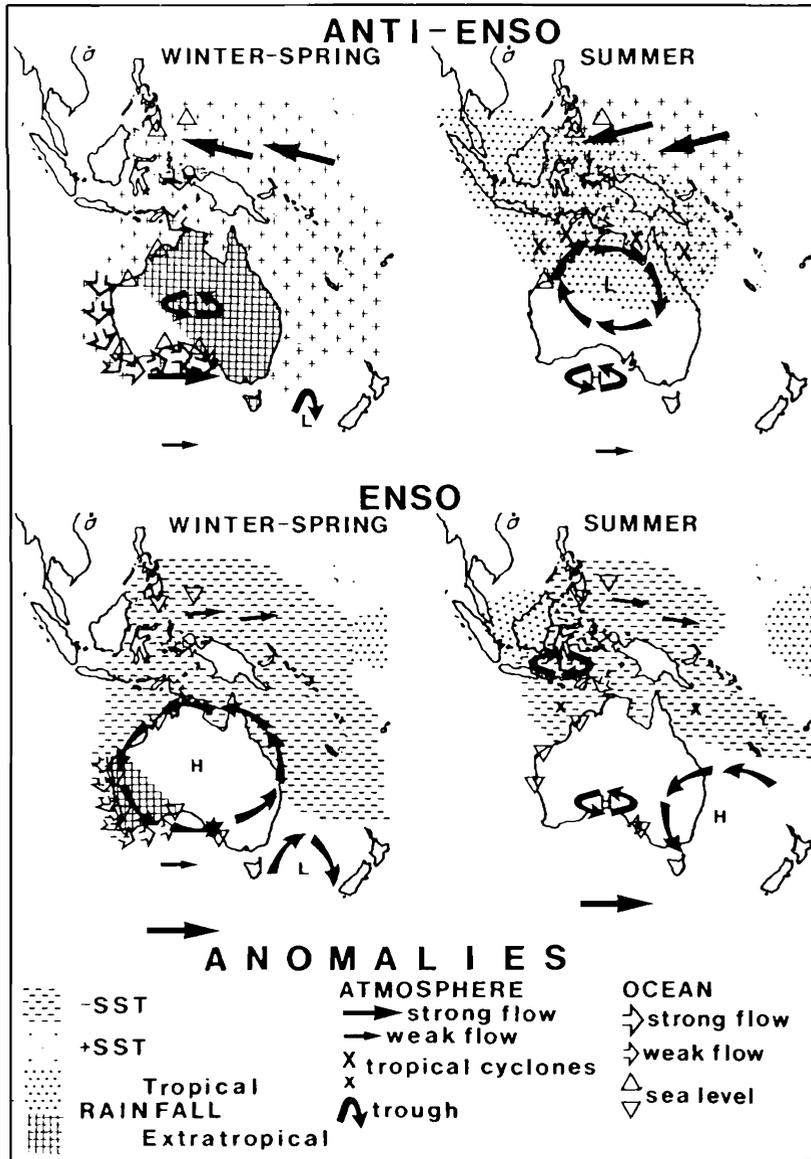


Figure 1. Winter-spring and Summer season low level atmospheric and oceanographic anomalies in the Australasian region associated with Southern Oscillation extreme states (Allan, 1988:333). ENSO (anti-ENSO) extremes are generally associated with weak (strong) equatorial easterly surface wind flow, negative (positive) sea-surface temperature and sea-level anomalies, decreased (increased) tropical and extra-tropical rainfall incidence in eastern Australia, decreased (increased) incidence of tropical cyclones and the overall establishment of higher (lower) atmospheric pressure over the Australian continent.

in general (THOM, 1978). These studies have, however, largely neglected to examine the principal control of beach change processes in the south-eastern Australian region, that of variations in wave conditions (wave climate).

This paper will seek to develop hypotheses which

describe some of the SO controls on the wave climate of south-eastern Australia. Particular emphasis will be afforded to SO related variability of tropical cyclone activity and the resultant variation in tropical cyclone generated waves as part of the south-eastern Australian wave climate.

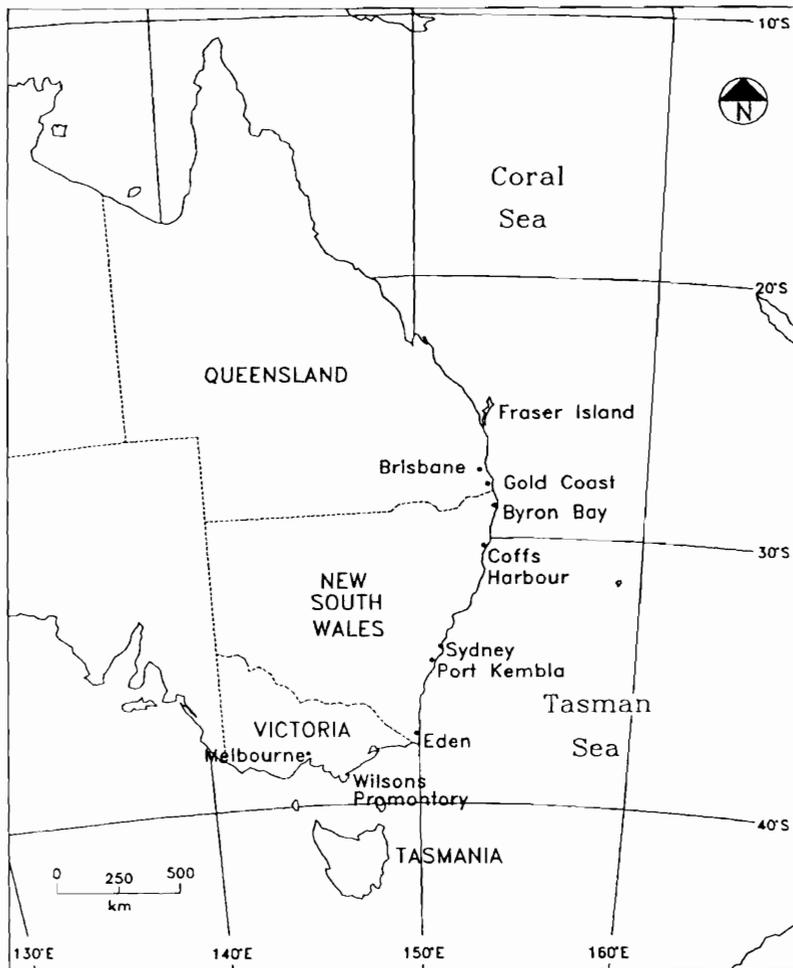


Figure 2. Eastern Australian locations referred to in the text.

Due to the unavailability of appropriate and comprehensive wave data and beach change records for much of the south-eastern Australian coastline, the opportunities to critically assess specific hypotheses examining beach change, wave conditions and the SO are limited. As a first step toward investigating SO/wave climate/beach change relationships, tropical cyclone season wave conditions at Sydney (Figure 2) will be examined during times of opposing extremes of the SO.

#### The South-Eastern Australian and Sydney Wave Climate and its Tropical Cyclone Component

##### (1) Overview

The coastline of south-eastern Australia, defined here as extending from Wilsons Promontory

in Victoria to Fraser Island in Queensland (Figure 2), comprises several beach types, the dominant and most studied type being the sandy beach as described by SHORT (1987). The status of this and other beach types and operations of coastal processes in New South Wales (N.S.W.) have been reviewed by CHAPMAN *et al.* (1982), SHORT and WRIGHT (1984) and GORDON (1987). The general wave climate of N.S.W. has been summarised by WEBB and KULMAR (1989) using Waverider buoy records from Byron Bay, Coffs Harbour, Port Kembla and Eden for the period 1974 to 1988. SHORT and WRIGHT (1981) and TRENAMAN and SHORT (1987) focussed more specifically on the patterns and processes of Sydney's wave climate.

Emergent from the above studies has been the

recognition of the importance of wave climate in controlling beach change on the coast. The morphology of the beach and inshore zones of the central N.S.W. coast, for example, have been found to be highly dynamic in response to the region's moderate to high energy wave climate. Temporal variations in beach state occur as a function of the wave climate of the region (SHORT, 1978; CHAPMAN *et al.*, 1982).

The weather systems responsible for generating contrasting wave conditions along the south-eastern coast of Australia are described by THOM (1974, 1978) and KEMP and DOUGLAS (1981). Regional studies have been undertaken by THOM *et al.* (1973), THOM and BOWMAN (1980) and CLARKE and ELIOT (1988) for southern N.S.W. beaches; SHORT and WRIGHT (1981) and TRENAMAN and SHORT (1987) for Sydney beaches; and for northern N.S.W. and south-eastern Queensland beaches by GOURLAY (1975), McGRATH and PATTERSON (1973), GORDON *et al.* (1978) and PATTEARSON and PATTERSON (1983). In summary, the relative occurrences and behaviour of cyclonic (tropical, extra-tropical and mid-latitude cyclones), anticyclonic and inter-anticyclonic systems (fronts) are prominent in the determination of wave climate for south-eastern Australia including the Sydney area. Each of these weather systems generates distinctively different wave conditions which are dependent upon the controlling system's latitudinal location, path of movement, duration, recurrence, seasonality and intensity.

## (2) The Tropical Cyclone Component

The AUSTRALIAN BUREAU OF METEOROLOGY (1978) defines tropical cyclones as non-frontal synoptic scale cyclonic rotational low pressure systems of tropical origin, in which ten minute mean winds of at least gale force (63 kilometres per hour) are realised. Their occurrences off the north-eastern coast of Australia during summer and late summer (commonly November to April) is a feature of Australian regional climatology (LOURENSZ, 1981).

Although tropical cyclones are a low frequency event (incidence off north-eastern Australia ranges from zero to six per season), their wind strength and available fetch produce high energy swell waves which have a significant impact on beach change and on the size and variability of the summer wave climate on south-eastern Australian beaches (TRENAMAN and SHORT, 1987). Their seasonal significance, most notably in February–

March, is highlighted in discussions of their control on high wave energy conditions experienced at Sydney (*e.g.* SHORT and WRIGHT, 1981; TRENAMAN and SHORT, 1987). In addition, Sydney's mean monthly deepwater wave power is noted to exhibit two distinct peaks of high energy conditions (wave energy flux >350 watts/cm wave crest). The first, during March, is produced by tropical cyclone generated moderate to high waves (2–3 metres) from the north-east and east (*e.g.* SHORT and WRIGHT, 1981), while the second peak, during June, is a consequence of the incidence of intense mid-latitude cyclones in the Tasman Sea. Both of these peak periods are coincident with times of significant erosion of Sydney beaches, although in the absence of the driving meteorological systems, the periods can be marked by episodes of accretion (SHORT and WRIGHT, 1981).

TRENAMAN and SHORT (1987) further attempted to define the area of ocean off eastern Australia within which tropical cyclone occurrence generated waves that were incident on Sydney beaches. In constructing the "Sydney tropical cyclone wave generation area" from simultaneous analyses of tropical cyclone location and peak recorded deep water wave heights at Sydney, it was found that greater wave heights were associated with tropical cyclones tracking to more southerly latitudes off eastern Australia (*e.g.* beyond 20°S).

In the regional context of south-eastern Australia, THOM (1974) has recognised the importance of tropical cyclone activity to the region's wave climate in general and has observed that the majority of high magnitude wave events within the region were associated with tropical cyclone occurrences. Furthermore, THOM (1978) noted that the incidence of major coastal erosion events within the region was linked to the relative frequency of tropical cyclones and extra-tropical depressions. Tropical cyclones' proximity to the coast and the duration of the tropical cyclone season are also thought to be significant in this regard (THOM, 1974, 1978; KEMP and DOUGLAS, 1981).

Erosion resulting from tropical cyclones is attributed to the effects of moderate to high energy breaking waves, raised sea levels and an onshore gale (THOM, 1974). In addition, the magnitude of tropical cyclone induced beach change experienced is also dependent in part on the existing morphodynamic state of the beach prior to the cyclone occurrence (SHORT and WRIGHT, 1984). The beaches of Sydney and those extending northward to south-eastern Queensland are usu-

ally approaching a fully accreted beach state prior to the tropical cyclone season and hence exhibit a high potential for erosion of the subaerial beach and subsequent development of a storm or dissipative profile (SHORT and WRIGHT, 1981).

To the north of the central N.S.W. coast the contribution of tropical cyclone generated waves to beach erosion events increases (THOM *et al.*, 1973; GORDON *et al.*, 1978). The most severe tropical cyclone related beach erosion events have occurred along the Queensland coastline (Figure 2) as reported by DELFT (1970), MCGRATH and PATTERSON (1973), HOPLEY (1974) and SMITH and JACKSON (1990). Farther southward, GORDON *et al.* (1978) have noted tropical cyclones as being the most dramatic erosion producing event in the Byron Bay-Hastings Point embayment.

In developing a climatological model of south-eastern Australian coastal erosion, THOM (1978) identified erosion events in some years to be associated with a tendency for a relative southerly displacement of eastern Australian tropical cyclone activity and proposed a possible link to the SO. Since that time, more detailed investigations have resolved a clearer relationship between intensity and spatial variability of Australian region tropical cyclone activity and the SO. Hence, opportunity now exists for a more detailed appraisal of relationships between the SO and beach change, particularly with reference to changes in wave climate resulting from SO related tropical cyclone variability.

#### Southern Oscillation Influences on Tropical Cyclone Activity

To date, research aimed at clarifying the relationships between the large scale atmospheric perturbations characteristic of the SO and synoptic scale weather features has been sparse (*e.g.* ALLAN, 1988). Progress has been made, however, in identifying associations between the SO and tropical atmospheric circulation features of the Australian region including the Australian summer monsoon (HOLLAND, 1986) and significantly, Australian tropical cyclone activity.

NICHOLLS (1979, 1984, 1985) has demonstrated that significant and stable correlations exist between indices of the SO and Australian region (105°E–165°E) tropical cyclone activity as measured by tropical cyclone number and tropical cyclone “days”. For example, it was found that at times when the Darwin mean sea level atmospheric pressure (MSLP) anomaly was consis-

tently highly positive prior to the tropical cyclone season onset (which usually reflects the establishment of ENSO conditions), reduced tropical cyclone activity on average was experienced in the Australian region during that season. Conversely, relatively active seasons were associated with persisting negative Darwin MSLP anomalies (characteristic of “anti-ENSO” conditions).

In addition to the frequency relationships outlined above, the spatial pattern of tropical cyclone activity in selected areas also varies with fluctuations of SO. The displacement of tropical cyclone origin points within the south-west Pacific region (145°E–150°W) has been examined by REVELL and GOULTER (1986) who found statistically significant, though weak correlations between averaged origin positions and values of a commonly used Southern-Oscillation index (SOI = Tahiti minus Darwin normalised atmospheric pressure anomaly). Specifically, it was found that tropical cyclones had a tendency to form further towards the north and east during periods of negative SOI than when the SOI was positive.

The nature of this relationship was further clarified and illustrated by HASTINGS (1990), who after identifying tropical cyclone seasons which coincided with marked ENSO and anti-ENSO periods, composed and mapped tropical cyclone tracks of the south-west Pacific region pertaining to the SO extremes (Figure 3). The diagrams clearly demonstrate a shift in the “centre of action” under the contrasting circulation and sea surface temperature extremes and reinforce the conclusions of NICHOLLS regarding SO/tropical cyclone activity relationships, at least for the eastern Australian region (145°E–165°E).

The data of HASTINGS and NICHOLLS also suggest some variation in the timing of the Australian tropical cyclone season with the advent of extreme SO states. A tendency for a relatively early onset of the tropical cyclone season (time of occurrence of the first tropical cyclone of the region) in association with anti-ENSO conditions was noted, while late season onsets were typical during ENSO events. Relatively late seasonal activity was evident, particularly off eastern Australia, in those seasons immediately prior to the establishment of peak ENSO conditions (*i.e.* pre-ENSO seasons, as termed by HASTINGS, 1990).

While the cited investigations have essentially been statistical in nature, both REVELL and GOULTER (1986) and HASTINGS (1990) have suggested that the observed relationships are consis-

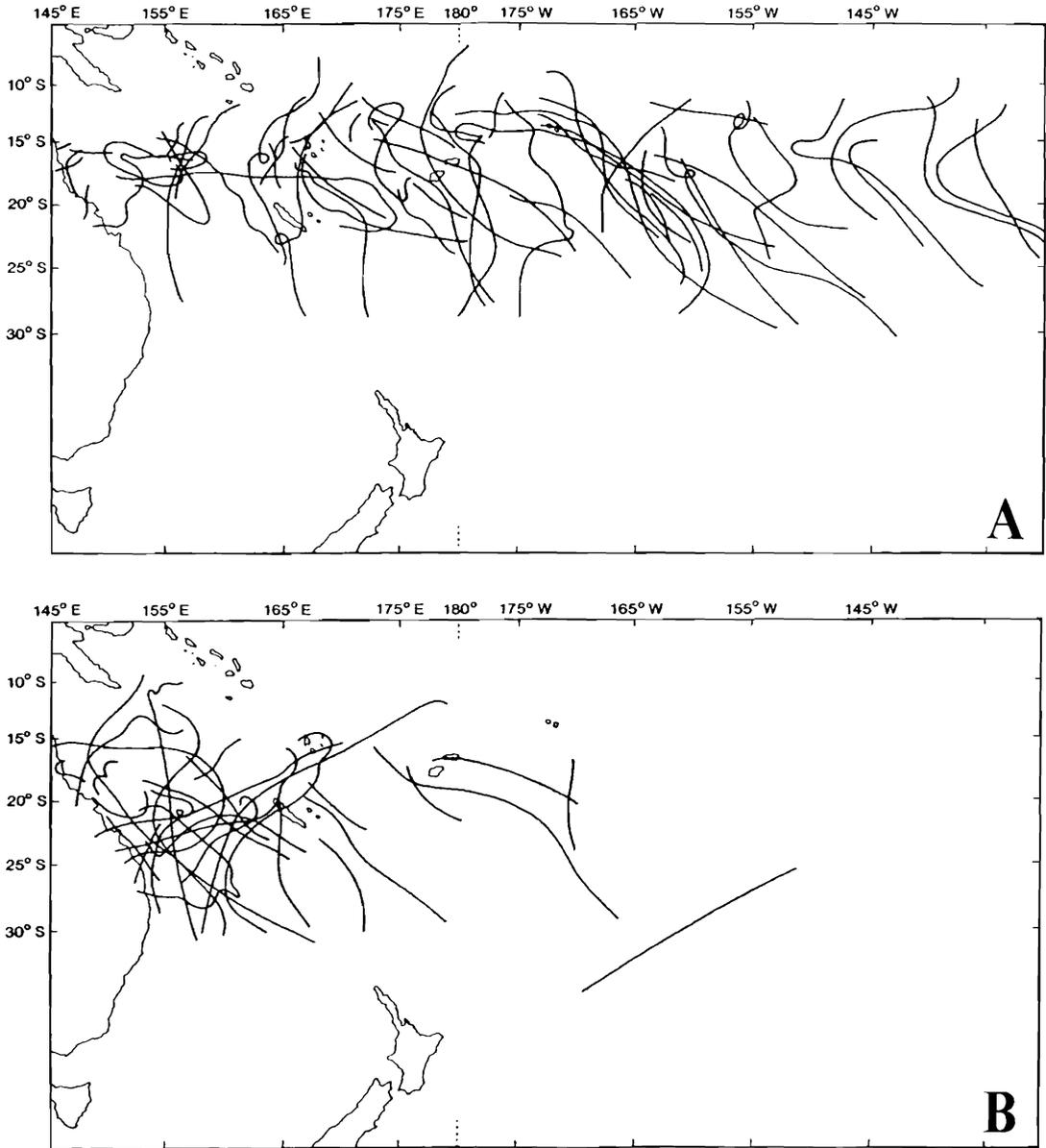


Figure 3. South-west Pacific region tropical cyclone tracks (Hastings, 1990:296). (A) ENSO composite (1972/73, 1976/77, 1982/83, 1986/87). (B) Anti-ENSO composite (1970/71, 1973/74, 1975/76).

tent with the known behaviour of large scale atmospheric circulation systems in relation to SO fluctuations and the subsequent interaction of tropical cyclones with these features.

Hence a degree of explanatory power has been

developed in accounting for inter-annual variability of tropical cyclone activity in the Australian region and the spatial distribution of activity in the south-west Pacific by considering the effects of SO related fluctuations.

### SOUTHERN OSCILLATION INFLUENCES ON THE TROPICAL CYCLONE WAVE CLIMATE IN SOUTH-EASTERN AUSTRALIA

The above mentioned relationships between the SO and tropical cyclones together with those of tropical cyclones, wave climate and beach erosion, facilitate the development of specific hypotheses describing the links between all of these variables for the south-eastern Australian situation.

(1) A tendency for increased (decreased) incidence of tropical cyclone generated wave events would be expected during anti-ENSO (ENSO) extremes in accordance with SO related variability of tropical cyclone activity.

(2) Tropical cyclone origin points are displaced more to the south-west (north-east) within the south-west Pacific region with tropical cyclones tending to track closer to (further away from) the Queensland coast during anti-ENSO (ENSO) extremes. As a result, the tropical cyclone wave generation area for the south-eastern Australian coast is displaced further to the south-west (north-east).

(3) Tropical Cyclone activity in the eastern Australian region tends to be enhanced (reduced), with an earlier (later) onset of the season during anti-ENSO (ENSO) extremes, producing a longer (shorter) season of tropical cyclone generated wave events wherein tropical cyclone generated waves are comparatively more (less) frequent. Pre-ENSO seasons are likely to be associated with a relatively late cessation to the tropical cyclone wave season of eastern Australia.

(4) Due to the increased (decreased) level of tropical cyclone activity close to the eastern Australian coast over longer (shorter) periods during anti-ENSO (ENSO) summers, the mean monthly wave power at south-eastern Australian beaches during summer months is increased (decreased) as a result of more (less) frequent high energy tropical cyclone generated wave events.

In addition to these aspects, several other oceanic variables controlled by the extreme states of the SO may influence beach change produced by tropical cyclone generated waves during the anti-ENSO and ENSO extremes and, in particular, either enhance or suppress erosion potential in general at the times of SO extreme states.

(1) Eastern Australian sea levels increase (decrease) during anti-ENSO (ENSO) extremes (ALLAN, 1988), increasing (decreasing) the potential for erosion of the subaerial beach upon the advent of high wave conditions.

(2) In general, increased (decreased) rainfall tends to occur over eastern Australia during anti-ENSO (ENSO) extremes (PITTOCK, 1975; ALLAN, 1988) and as a consequence, would serve to increase (decrease) foreshore water-table elevation and thus result in an increased (decreased) erosion potential of the subaerial beach (BRYANT, 1985).

In summary, a general hypothesis may be stated. The tropical cyclone generated wave climate of south-eastern Australia is likely to be of longer (shorter) duration and of higher (lower) energy during anti-ENSO (ENSO) periods. In combination with the other SO controlled variables of sea-level and rainfall or groundwater level, it may be expected that the overall impact of tropical cyclone generated wave events during an extreme anti-ENSO (ENSO) period would increase (decrease) the potential for erosive beach change on south-eastern Australian sandy beaches.

While a comprehensive examination of the stated hypotheses is not possible at this time given current data and resource constraints, a broad appraisal of selected aspects of the suggested relationships is facilitated by available wave records for Sydney.

### TROPICAL CYCLONE GENERATED WAVE CONDITIONS AT SYDNEY DURING CONTRASTING ENSO AND ANTI-ENSO EXTREMES

#### Data and Methodological Overview

Hypotheses outlining relationships between states of the SO, eastern Australian/south-west Pacific tropical cyclone activity and south-eastern Australian summer wave conditions were examined using tropical cyclone movement data for the eastern Australian/south-west Pacific region and deepwater Waverider buoy data from offshore of Botany Bay in Sydney for the months of February and March from 1972 to 1991 (20 years).

Mean monthly significant wave parameters (height and period) were obtained from the Waverider buoy, operated by the Maritime Services Board of N.S.W., located 5.0 km to the south-east of the entrance of Botany Bay (Sydney) in 80 m of water. Wave records were taken from this buoy as it provided the longest contiguous wave records for any moderate to high wave energy environment along the eastern Australian coast.

As an overall index of wave character, mean monthly deepwater wave power for each month

Table 1. Eastern Australian region (145°E–165°E) tropical cyclone days for February + March of Southern Oscillation extreme seasons. See text for definition.

Tropical Cyclone Days (Feb + Mar)	
ANTI-ENSO Seasons	
1970/71	34
1973/74	16
1975/76	20
1988/89	10
ENSO Seasons	
1963/64	6
1965/66	6
1969/70	8
1972/73	5
1976/77	13
1982/83	19
1986/87	0

of the data set was calculated using the corresponding height and period data in the equation employed by TRENAMAN and SHORT (1987:11).

$$P_o = (\rho g H_s^2 C_g) / 8 \quad (1)$$

where  $P_o$  = deep-water wave power (watts/cm wave crest  $\times 10^4$ );  $\rho$  = 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 =  $(gT_s) / 4 \pi$ , where  $\pi = 3.14$ ,  $T_s$  = significant wave period). February and March were selected as the months most suitable to examine tropical cyclone generated wave events in south-eastern Australia since tropical cyclones, as previously outlined, are the region's (including Sydney's) most dominant wave generating weather system during these months.

For the present analysis, the state of the SO has been expressed in terms of phases, as employed by HASTINGS (1990), and which are based upon occurrences of SO extreme states documented by QUINN *et al.* (1978), VAN LOON and ROGERS (1981), FU *et al.* (1986), KILADIS and VAN LOON (1988) and VAN LOON and SHEA (1985). As argued by HASTINGS (1990), the use of extreme phases in this type of analysis offers an opportunity to maximise the potential for distinguishing SO related variability of the dependent variables.

Table 1 provides a listing of Southern Hemisphere (SH) summers (*i.e.* Australian tropical cyclone seasons) since 1960 during which extreme SO conditions were reported, by the above mentioned sources, to have prevailed. Individual event intensity was not considered.

In addition to the formerly described ENSO and anti-ENSO states, the "pre-ENSO" phase, considered where appropriate, refers to the period of the SH Summer and Autumn immediately prior to an ENSO peak (usually in the SH Spring/Summer). Australian regional atmospheric and sea-surface temperature anomalies at this time are more analogous to anti-ENSO than ENSO conditions, although large scale atmospheric and oceanic systems are restructuring to facilitate the development of an ENSO "peak" (*e.g.* RASSMUSSEN and CARPENTER, 1982). February and March of ten of the years in the 1972–1991 data set were not considered to be within extreme ENSO, anti-ENSO or pre-ENSO periods (1975, 1978–1981, 1984, 1985, 1988, 1990, 1991).

Tropical cyclone data pertinent to this study were derived from the data summaries of LOURENSZ (1981) and subsequent tropical cyclone season reviews appearing annually in the Australian Meteorological Magazine; specifically, LYNCH (1982), BATE (1983), KINGSTON (1986) and MANCHUR (1987). Most recent data were supplied by the Bureau of Meteorology, Brisbane Regional Office. Tropical cyclone data prior to 1960 could not be considered in this analysis as their quality for research purposes is questionable (HOLLAND, 1981).

#### Data Analysis and Discussion

Due to the limited periods for which tropical cyclone and wave data were available, rigorous statistical investigations over a long time series were not possible. In this analysis, however, several relationships were derived from the data used, but require subsequent longer term verification.

With the view to a preliminary appraisal of the hypotheses outlined, this section, using Sydney wave data when applicable, will attempt to: (a) confirm the existence of a relationship between the SO and tropical cyclone variability off eastern Australia during the identified key period of February–March; (b) examine the spatial relationship between eastern Australian tropical cyclone activity and the Sydney tropical cyclone wave generation area during opposing SO extremes; and (c) test for differences of Sydney deepwater wave power pertaining to opposing extremes of the SO.

##### (a) SO Related Variability of Tropical Cyclone Activity (February + March)

Table 1 indicates tropical cyclone activity, as measured by "tropical cyclone days", in the east-

ern Australian region (145°E–165°E) during February and March of designated SO extreme tropical cyclone seasons (SH summers). Tropical cyclone days are defined in accordance with NICHOLLS (1985) as a day on which at 0900 Local Standard Time, a tropical cyclone was located within, in this case, the eastern Australian region. If two tropical cyclones were located within the region at that time, then two tropical cyclone days were counted and so on.

The table illustrates a propensity for greater activity during anti-ENSO as compared to ENSO years/seasons. While data sparsity precludes meaningful statistical testing of differences, the observed relationship at this “sub-seasonal” time scale is consistent with those reported previously using seasonal statistics (*e.g.* NICHOLLS, 1984, 1985).

The comparatively low figure of 10 for 1988/89 (anti-ENSO) and high figure of 19 for 1982/83 are counter to the overall trend. The latter is the result of one tropical cyclone’s persistence within the region for the unusually extended period of 19 days. February–March 1988/89 preceded a time of particularly high activity in the following months (three regional tropical cyclones in April/May).

These data are therefore compatible with the hypothesis of increased (decreased) incidence of tropical cyclone generated wave events during February and March of anti-ENSO (ENSO) seasons in the study region. In the following sections this relationship is assessed with respect to tropical cyclone activity within the wave generation area of Sydney and Sydney deepwater wave power during extreme SO states.

#### (b) Sydney Tropical Cyclone Wave Generation Area and Tropical Cyclone Variability

Figure 4 displays a superimposition of the Sydney tropical cyclone wave generation area determined by TRENAMAN and SHORT (1987:68) and collated tropical cyclone tracks of ENSO and anti-ENSO periods (*i.e.* Figure 3). The resultant combination map reveals that, proportionately, more tropical cyclones approach the vicinity of and/or enter the wave generation area in the case of the anti-ENSO composite than for the ENSO composite.

At this broad level then, the results suggest that an increase in tropical cyclone generated wave events and increased beach erosion potential might be expected at Sydney in association with anti-

ENSO conditions compared to ENSO conditions. Further investigation into intra-seasonal correlations are required in order to refine this relationship, in particular for the February–March period and the remainder of the tropical cyclone season. Table 1 however, provides some evidence that the relationship identified would hold at greater resolution.

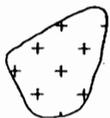
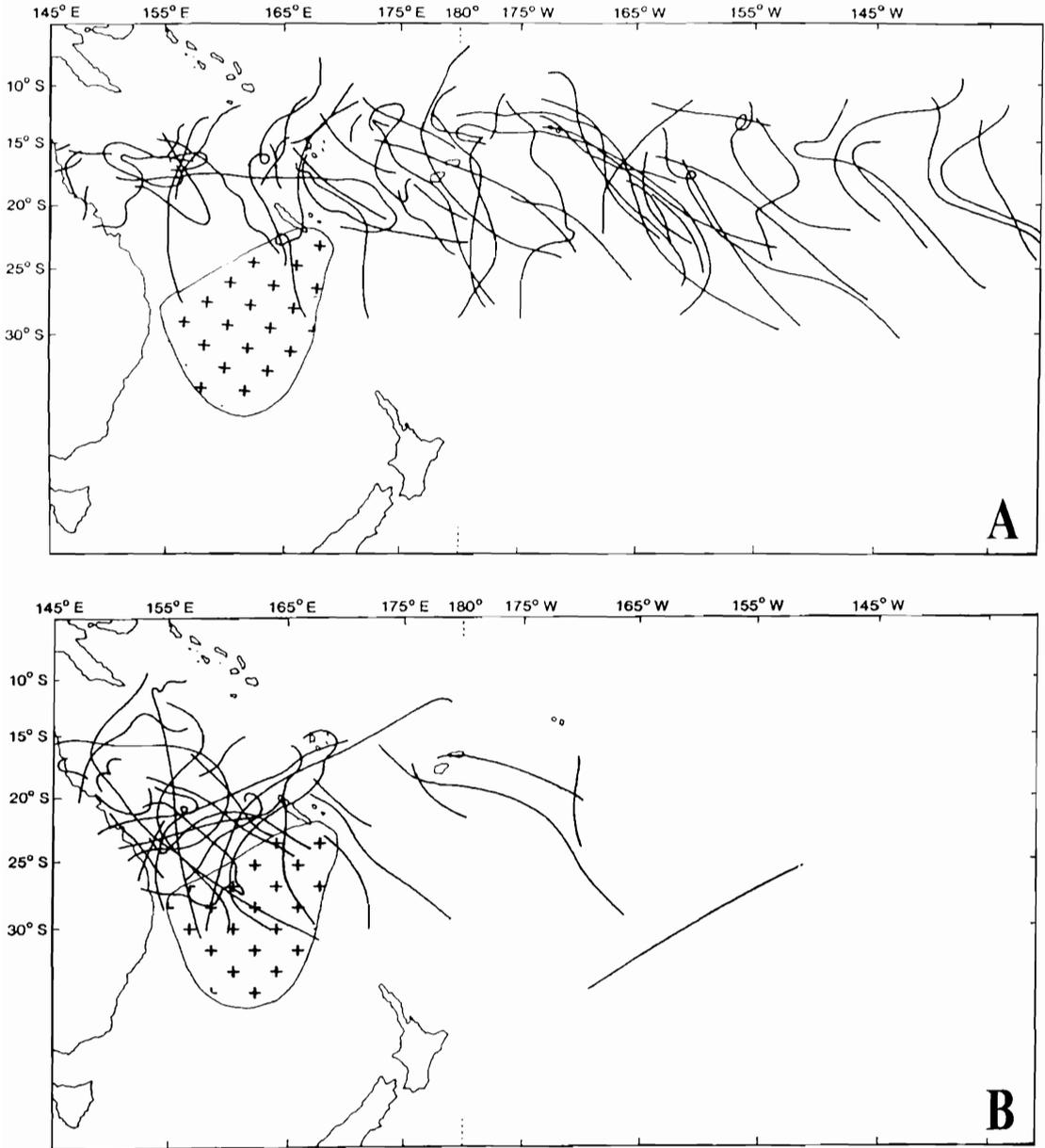
#### (c) Sydney Wave Power During SO Extreme States

To describe the wave conditions during the period most influenced by tropical cyclones at Sydney, an average wave power value for the months of February and March was calculated from their mean monthly values for each of the 20 years of data (1972–1991) using the Botany Bay Waverider buoy. The variation of the mean wave power during February and March at Botany Bay for the period 1972–1991 is shown in Figure 5.

Several trends become evident when ENSO, anti-ENSO and pre-ENSO periods are indicated on the graph. All ENSO extreme periods’ (1973, 1977, 1983, 1987) mean wave power values occupy major troughs on the graph being less than 22 watts/cm wave crest  $\times 10^4$ . By comparison the anti-ENSO periods occupy higher energy positions on the graph with mean wave power values exceeding 22 watts/cm wave crest  $\times 10^4$ . Pre-ENSO periods (1972, 1976, 1982, 1986) exhibit a range of values, from a minimum close to the lowest ENSO period value (1975) to a maximum exceeding all of the anti-ENSO periods (1972). The mean wave power values for each of the Southern-Oscillation extreme composites were:

Composite	Wave power (watts/cm wave crest $\times 10^4$ )	Months
ENSO	19.73	8
anti-ENSO	24.95	6
pre-ENSO	23.79	8

To determine if the mean wave power at Botany Bay was significantly different between the small sample of ENSO and anti-ENSO tropical cyclone seasons, their composite means were subjected to a *t*-test. The results of the *t*-test indicated that at the 0.1% level of confidence (12 degrees of freedom) that mean monthly wave power at Botany Bay during February and March was significantly higher in anti-ENSO periods than in ENSO periods.



Tropical cyclone wave generation area for waves reaching Sydney (Trenaman and Short 1987:68).

Figure 4. Overlay of the tropical cyclone wave generation area for Sydney from Trenaman and Short (1987:68) onto South-west Pacific region ENSO and anti-ENSO tropical cyclone track composites (Hastings, 1990:296). (A) ENSO composite, (B) Anti-ENSO composite.

## SYDNEY WAVE POWER Feb-Mar, 1972-1991.

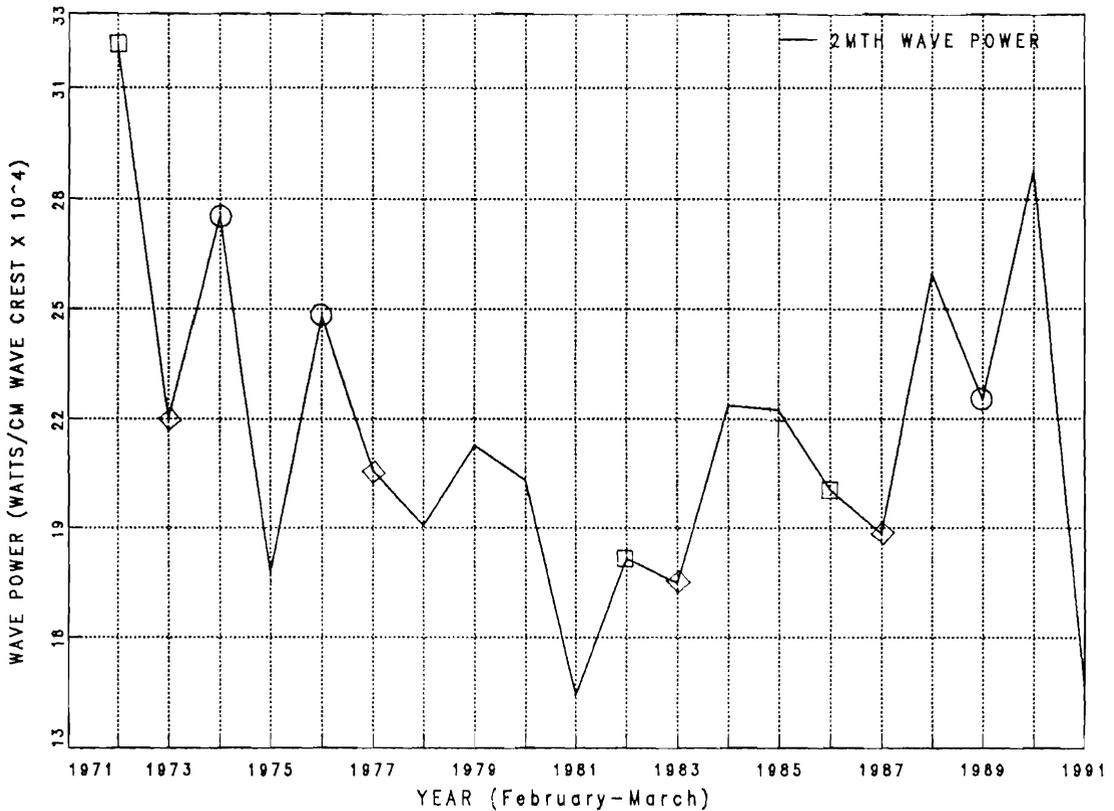


Figure 5. Mean monthly wave power, Botany Bay, Sydney, February-March 1972-1991.  $\diamond$  ENSO,  $\circ$  Anti-ENSO,  $\square$  Pre-ENSO.

Several other wave generating weather systems control Sydney's wave climate during the months of February and March and contribute to the variations in wave power represented in Figure 5. These systems include (in decreasing frequency of occurrence) north-easterly seabreezes, anticyclones, extra-tropical cyclones, mid-latitude cyclones and frontal systems (SHORT and WRIGHT, 1981; TRENAMAN and SHORT, 1987). High wave conditions are commonly produced by extra-tropical and mid-latitude cyclones.

Extra-tropical cyclones occur off eastern Australia with approximately the same frequency as tropical cyclones during March and as a result of their proximity to Sydney, available fetch and wind-strength across the Tasman Sea, produce the highest wave conditions experienced at Syd-

ney (SHORT and WRIGHT, 1981; P.W.D., 1985; TRENAMAN and SHORT, 1987). According to THOM (1978) and TRENAMAN and SHORT (1987), occurrences of extra-tropical cyclones (their location, intensity, frequency) are associated with anticyclonic blocking activity, SST anomalies and anomalous SST gradients in the Tasman Sea. Changes to each of these controlling factors have been associated with ENSO and anti-ENSO periods in previous research (ALLAN, 1988). Due to the still limited understanding of the spatial and temporal characteristics of these SO controls, it was beyond the scope of this work to investigate SO controls on extra-tropical cyclone generated wave conditions at Sydney.

Daily synoptic weather maps during February and March for the ten years which were not con-

sidered extreme ENSO, anti-ENSO or pre-ENSO periods (1975, 1978–1981, 1984, 1985, 1988, 1990, 1991) were also inspected to establish the type and duration of wave generating weather systems for Sydney. These weather systems were responsible for the variation of February–March mean monthly wave power represented in Figure 5 during years unaffected by SO extreme related tropical cyclone activity. Although each of the previously listed February–March wave generating weather systems was observed, their relative dominance and contribution to high and low wave power conditions at Sydney (in non-extreme SO years in Figure 5) could not be established given the temporal resolution of the available data set. Examination of daily wave power records for the same period, could allow the relative contribution of each wave generating weather system to the recorded variation in wave conditions to be determined.

#### Evaluation of Hypotheses (in Terms of Sydney Case Study Findings)

In summary, the results from the analyses of available wave data for Sydney (Figures 4 and 5 and the *t*-test) offer support to hypothesis four, as well as tentatively confirming the physical basis for the difference in wave power presented in hypotheses one and two. That is, in February and March during anti-ENSO (ENSO) periods there is an increase (a decrease) in tropical cyclone activity (hypothesis one) within the area of the Coral and Tasman Seas necessary to generate waves to reach Sydney (hypothesis two); producing more (less) tropical cyclone generated wave events, indicated by the significantly higher (lower) wave power recorded at Botany Bay during this period over the past 20 years.

#### CONCLUSION

Wave conditions experienced along the south-eastern coast of Australia during February and March, which are predominantly generated by tropical cyclone activity over the south-west Pacific region (including the Coral and Tasman Seas), were hypothesised to contrast at times of opposite extremes in the state of the Southern Oscillation. A contrast was identified in Sydney wave data, most probably effected by the control of the Southern Oscillation on the spatial pattern of tropical cyclone incidence off eastern Australia and hence tropical cyclone frequency of occurrence within key wave generation regions. During

anti-ENSO (ENSO) periods, increased (decreased) incidence of tropical cyclone activity off eastern Australia at the time of maximum tropical cyclone influence (February–March), is a feasible cause of observed relative increases (decreases) in wave power being recorded at Sydney at that time. From composite data, tropical cyclone tracks during anti-ENSO periods were found to approach the vicinity of and/or enter the designated tropical cyclone wave generation area for Sydney with greater relative frequency than was the case for ENSO periods.

The relative frequencies of several other weather systems, particularly extra-tropical cyclones, were identified from previous research, along with tropical cyclones, as the controls of variations in wave power at Sydney during non-extreme SO periods.

In combination, the stated findings provide some confirmation for proposals of THOM (1978), with regard to SO fluctuations and coastal erosion events in south-eastern Australia. Caution in the interpretation of results is, however, recommended as analyses were unavoidably hindered by data sparsity.

#### Further Research

To the north of the principal location examined in this research (Sydney), on the northern N.S.W. and south-eastern Queensland coasts, tropical cyclone generated wave events become the dominant erosion producing force. High energy wave events and episodes of summer/autumn beach erosion are clearly recognised to be predominantly produced by tropical cyclones. The tropical cyclone wave generation area for these locations extends further to the north and east than that of Sydney (Figure 4), indicating that greater variation in wave conditions as a result of Southern Oscillation related tropical cyclone variability might be expected. The authors are currently in the process of securing data for, and examining wave conditions at a south-eastern Queensland location.

A database of major recorded south-eastern Australian beach change events is also being compiled, as a longer term indication of south-eastern Australian wave conditions. This will complement the work proposed above and supplement the temporally limited available wave data for locations along the south-eastern Australian coast. A longer term assessment will then be possible of the SO/tropical cyclone/wave climate relation-

ships identified in this work, using recorded beach change events and their spatial variability along the south-eastern Australian coastline.

Further work planned will also seek to identify controls of the Southern-Oscillation on extra-tropical and mid-latitude weather systems in eastern Australia, particularly extra-tropical cyclones and blocking anticyclones, which are responsible for high energy wave events and erosion on the more southern beaches of south-eastern Australia.

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□ RESUMEN □

En este trabajo, se discute el control que posee la Oscilación del Sur (SO) sobre el régimen de olas en la región sudeste de Australia, durante la época de verano del hemisferio sur. Se efectúa un análisis de las olas características de Sydney coincidentes con los periodos establecidos para El Niño-Oscilación del Sur (ENSO) y el anti-ENSO, estados extremos de la (SO). Durante el último verano (Febrero-Marzo), se halló que, anti-ENSO, (ENSO) extremos estaban asociados con valores significativamente más altos (menores) de la potencia de las olas en aguas profundas de Sydney. La Oscilación del Sur (SO) relacionaba la variabilidad interanual de la actividad ciclónica tropical del este de Australia y del Pacífico sudoeste, en términos de frecuencia de ocurrencia y del esquema espacial, también se ha propuesto un mecanismo fundamental que identifica la relación (SO)/olas.—Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.