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Long-period variations of sea-level in Australasia

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Summary. The ability of the Australian sea-level monitoring network is assessed in the investigation of long-period sea-level signals. Through the character of coastal long waves, seasonal variations in level and inter-annual level anomalies, the importance of the south coast of the Continent is identified as a coherent indicator of large-scale marine and atmospheric teleconnections. The source of the sea-level signal is investigated by the tracing of progressive features, by the numerical modelling of wind stress over the Southern Ocean, by the modelling of the effect of monsoonal rains over the Indian Ocean and the mass transport through the Indonesian Strait. These features are related to the ENSO cycle which for the first time is linked, *inter alia*, with Southern Ocean mechanisms.

Key words: El-Nino Southern Oscillation (ENSO), inter-annual sea-level, teleconnection, Australasian sea-level

Introduction

The world-scale geographical asymmetry, in a latitudinal sense, is clear, but its effect upon marine systems is nowhere so marked as in the sea-level signal. Whereas one associates response of sea-level in the northern hemisphere with phenomena of relatively small-scale, both spatial and temporal, the large interconnected water bodies of the southern hemisphere demonstrate typically long-period features associated with the transport of water and heat, and these can be of ocean scale.

Within this environment and in this context of sea-level signals, Australia occupies a strategic location which only recently has been appreciated, as a national stimulus to marine research begins to bear fruit. As an island continent, Australia stands at the threshold of contrasting marine environments but, more particularly, each coastal region is found to possess unique characteristics which are relevant in this context:

(a) The south coast is unique in that, on a world scale, it is the only major east–west coastal extent, in this case over 3000 km, which is ice-free, and also this coast is adjacent to the circumpolar southern ocean which must be important on a rotating Earth. Here meteorological perturbations of level are driven from west to east in a near-continuous sequence.

(b) The north coast lies in tropical latitudes which are associated with seasonally rectilinear monsoonal transport. The adjacent Indonesian Straits again are unique in that in no other region do major ocean systems communicate in equatorial latitudes. The opportunities for polewards heat transfer are obvious; yet the restriction of the Straits themselves interrupts flow and creates sea-level gradients.

(c) The east coast passes from a coastal lagoon environment in the Great Barrier Reef southwards into the Tasman Sea where the major features of the anti-cyclonic warm core eddies dominate the scene. Such eddies have a life in excess of 1 yr as they drift slowly southwards, but their warm low-salinity characteristics imply a sea-level topography only marginally less than 1 m in scale with an associated counter-clockwise current often in excess of 3 knots.

(d) Finally there is the west coast, which has attracted especial attention in the last five years, and which again proves to possess unique characteristics. Here we have an atypical eastern boundary with a well-developed coastal current, the Leeuwin Current, flowing anomalously southwards, and, trapped on the continental coast, turning eastwards perhaps to provide continuity across the Great Australian Bight as far as Tasmania. Traced over $\sim$5000 km this represents one of the major currents of the world ocean and it is seen to be clearly associated with a sea-level gradient from north to south (Godfrey & Ridgway 1985).

Against the background of this unique marine environment, the study of the long-period signal of sea-level along the Australasian coastline is of great significance and presages prospects of gaining an insight into a spectrum of features of several scales from coastal processes to inter-ocean transports.

The Data

It would be comforting to record that the Australian coastline is equipped with an efficient array of modern sea-level recorders which are well-maintained, regularly calibrated and tied to a first-order terrestrial levelling network. This is not the case but there are many reasons for this condition.

The scale of the continental coastline is vast whereas the resources available, and especially manpower, are strictly limited.

Except along the east coast, centres of population are widely spaced and other environmental hazards exist such as mangroves, especially in the north, or continous 100 m cliffs as in the Great Australian Bight.

Traditionally Australian tide gauges are the responsibility of local port authorities in a decentralized non-standardized system, and indeed for the most part ports are in the deep-water category with very little anxiety as to tidal condition or to sea-level variation.

Although there is now the commencement of academic attention to the monitoring array and to its maintenance, the major logistic problem of scale and natural hazards ensures that progress is slow.

A Permanent Committee for Tides and Sea-level which is sponsored by the National Mapping Council, has made some progress in this area and with the growing emphasis on the World Climate Research Project, ocean–atmosphere teleconnections, and ENSO, there are increasing prospects for the development of a powerful lobby which involves meteorologists in addition to oceanographers. Again the Tidal Laboratory of the Flinders Institute for Atmospheric and Marine Sciences (FIAMS) has received increasing support of late and has developed a national sea-level data bank which also is involved with tides and residual time series. Typically the data bank holds some 850 station years of data, mainly for the period

1966 to date. Some very valuable longer data sets have been added where quality control suggests some rigour in local maintenance has occurred.

Overall, the quality and coverage of the data is not good and often it is necessary to avoid reliance upon a single station unless it is confirmed by, or integrated with, the signal from a wider regional group. The component records are, with few exceptions, vintage analogue float-operated instruments with dates reaching back into time as far as 1866. Nevertheless the FIAMS Tidal Laboratory does contribute to IGOSS/SLPP by passing monthly sea-level anomalies to the Hawaiian Center in near-real time.

Data processing

In the processing of the sea-level data there exist certain technical hazards which require special note. Fortunately the complications of non-linear interaction of tidal constituents in shallow water are relatively rare. However, there are a number of other tidal anomalies which must be excluded from the procedures which determine the low-passed time series used for mean sea-level studies. In particular one should note the apparent variability of tidal constants produced by conventional analysis for the northern Barrier Reef coast. This is associated with the presence of unique problems of the separation of tidal lines of near speed (Lennon 1979). Of more importance is the presence of the natural resonance of coastal water bodies. In many locations the shelf waters demonstrate a strong periodic signal. Here one has in mind the diurnal resonance of the Gulf of Carpentaria, the South Australian Gulfs one of which responds to external stimulus in a period of 26 hr while the other prefers 13.5 hr. Again several sections of Continental Shelf contribute characteristic resonances such as the 8 hr period of a quarter standing wave in the broad shelf areas of the Great Australian Bight, whereas in the north-west, the Shelf has a clear semi-diurnal resonance.

It is important to be aware of this higher frequency content of the observed record when preparing a time series for interpretation of its long-period signal.

Coastal long waves

The island character of Australia and its exposure to ocean scale influence, but more particularly the presence of a shelf and its ability to act as a waveguide, suggests that progressive coastal long waves may be a common feature.

This is certainly the case. In the tropical latitudes the incidence of tropical cyclones is high in the southern hemisphere summer with characteristic peaked signatures in coastal sea-level.

Of particular relevance to what is to follow, however, is the long wave signal which is experienced along the southern coast. Along that unique west to east coastal run pass a near-continuous sequence of oscillations of level. In an area where the semi-diurnal tide attains an amplitude of 0.7 m and the supplementation of the diurnal tide is only 0.4 m, these synoptic perturbations of level have a significant influence, approximately half that of the tide, with a crest to trough excursion of ~ 1 m and a period in the range of 5–20 day.

In all examinations of the meteorological perturbations of level the single dominant fact which emerges is the coherency of synoptic energy which is maintained over the whole south coast. Fig. 1 provides a typical example of this feature over a 700 km extent from Thevenard in the Great Australian Bight, Port Pirie and Wallaroo in Spencer Gulf to Adelaide (Outer Harbor) in Gulf St Vincent. While the major synoptic perturbations are remarkably consistent, demonstrating a simple progression from the west, the major differences are

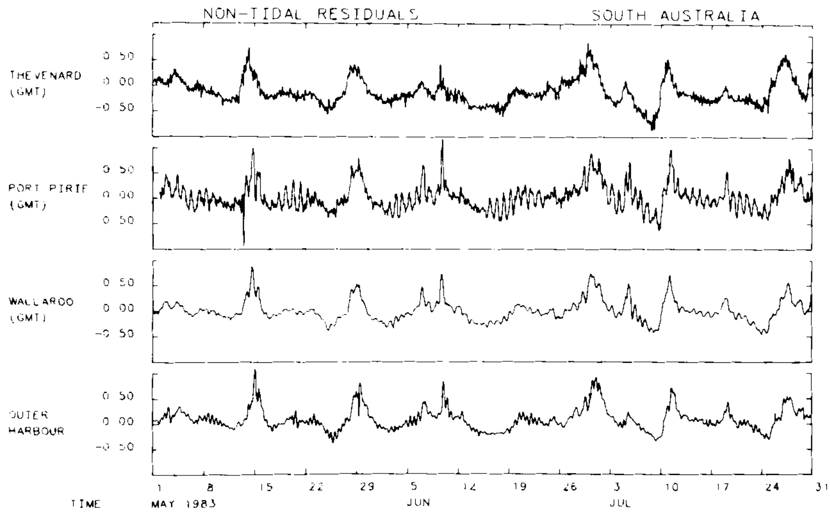

Figure 1. Simultaneous non-tidal residuals (cm) over a period three months for Thevenard, Port Pirie, Wallaroo and Adelaide (Outer Harbor). A range > 700 km in South Australian waters.

simply in the higher frequency embroidery which takes the form of the Shelf and Gulf resonances previously noted.

Further reference will be made to this spatial coherency linked to the south coast.

Seasonal variations of level

The span of latitude from the northern tropics to the temperate south is of particular significance in determining the character of seasonal variations of level. As in the case of the long waves, their amplitudes are uncommonly large with respect to the tidal excursions, so that the constituent S_a, for example, is often ranked fifth or sixth in a list of tidal constants and third at Fremantle. The seasonal oscillations attain their maximum development in the north and in particular to the west of Torres Strait where in January and February the monsoonal wind drift towards the east is impeded by the Strait. Here the seasonal range is more than 0.6 m.

What is more important, however, is the phasing of the oscillations. As is suggested above, the northern coast sees a maximum in the early months of the calendar year. Along the south coast, however, the maximum levels occur in the middle of the calendar year, perhaps associated with the strengthening of the westerly winds over the southern coastal ocean as the high pressure atmospheric cell settles in its northerly position over the central continent. Along both east and west coasts there is a graduation between these two limits but it is along the west coast that the transition shows a particularly interesting sequence.

This feature is shown in Fig. 2, where characteristic regional values were obtained by grouping the results from good tide gauges respectively from the north-west, west, south-west, south, Bass Strait, New South Wales and Queensland. Then, plotted against this anti-clockwise excursion around the Continent, and the calendar months from May to June, are the contours of the seasonal sea-level. This presentation reveals evidence of the progression of a sea-level feature in time and space. In particular the trough seen in the north-west in

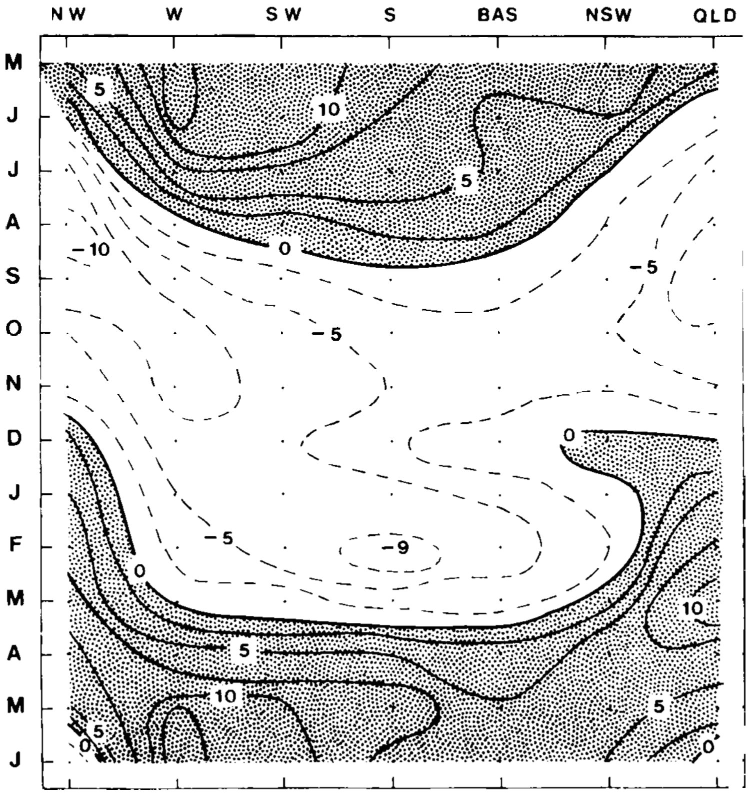

Figure 2. Geographical distribution of seasonal variations of sea-level around the Australian continent (cm). Port Groups: NW = north-west (Darwin and Port Hedland), W = west (Geraldton, Fremantle and Bunbury), SW = south-west (Albany and Esperance), S = south (Thevenard, Port Lincoln and Port Macdonnell), BAS = Bass Strait (Port Lonsdale and Georgetown), NSW = New South Wales (Camp Cove, Fort Denison and Newcastle), QLD = Queensland (Bundaberg, Mackay, Townsville, Cairns).

August is seen to progress southwards down the west coast during the later months in the year and to reach the entire south coast simultaneously in February.

Using steric heights from observations made in the deeper waters, Godfrey & Ridgway (1985) examined sea surface topography off the west coast and linked these features with the Leeuwin Current. The information in the present exercise is obtained directly from coastal tide gauges and demonstrates in a graphic fashion the progressive feature associated with the Leeuwin Current as it operates in the west during the southern hemisphere's summer. What is also of interest is the end of the feature in February/March when progression ceases and although it is understood that the Current does pass eastwards across the Bight to Bass Strait, it is considered that this is associated with wind forcing, particularly strong in the winter months.

Once again the stability of the conditions on the south coast is a notable feature throughout the year. Since continuity with east coast features is less well-marked, it is clear that the south coast features indicate the conclusion of a progressive event from the north-west. Again the depth of the trough along the south coast is unlikely to affect the timing of the Leeuwin phenomenon but will certainly affect the magnitude of the event.

Interannual variations of sea-level

As emphasis focuses upon longer period phenomena there is a need for greater reliance upon the quality of maintenance of the observing installations, and we have seen that in the Australian case there is some anxiety in this context. Bye & Gordon (1982), however, pointed out that if groups of tide gauges are used to provide a composite regional signal, and if, after stringent data quality control procedures, one eliminates rare stations which clearly do not conform, then one may be successful in achieving a meaningful geographical agreement of interannual mean sea level fluctuations with a time-scale of 3–5 yr and a magnitude of ±5–10 cm.

Fig. 3 demonstrates this feature. As in the case of the treatment of seasonal variations, the data are based upon grouped regional coastal information and for a 15 yr period ending in 1980 the annual anomalies of sea-level are represented by simple contours.

The facts which emerge from this presentation are as follows:

(a) The anomalies are of magnitude, ±5 cm but occasionally reaching 10 cm.

(b) Strong regional coherence exists as revealed by the dominant horizontal characteristics and, in view of our reservations concerning the basic data quality and the small magnitude of the signal, this is surprising.

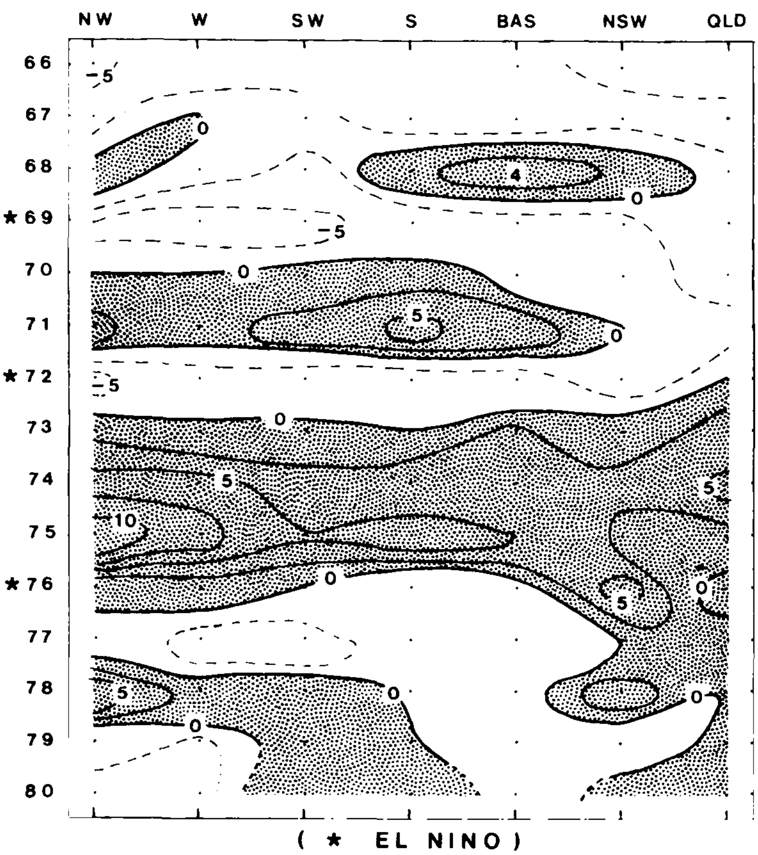

Figure 3. Geographical distribution of inter-annual anomalies of sea-level over a 15 yr period (cm).

(c) The coherence is more marked from the north-west to the south coast than for the south coast to Queensland.

(d) The time-scale of course is 3–5 yr as discovered by Bye & Gordon.

(e) There is a clear link between the sea-level anomaly and the ENSO years (1969, 1972 and 1976).

(f) In an ENSO year the sea-level tends to be anomalously low, whereas in the previous year the levels are high. At the commencement of an ENSO year there is a dramatic change from positive to negative anomalies.

(g) Again the south coast demonstrates the most clear development of the anomalous topography.

The ENSO connection

If one then accepts that the interannual mean sea-level signal for South Australia is significant, one then has the advantage that this can be determined for a longer time-scale than most from available data and Fig. 4 shows the record over a 36 yr period. The opinion is reinforced that each ENSO year is associated with a negative sea-level anomaly along the south coast and that in the anti-ENSO year sea-levels are anomalously high. But then 1982 was also an ENSO year so that it is possible to test this hypothesis and the appropriate reference is Fig. 5. Here the monthly mean levels for 1981 to 1983 are compared with the long period mean. The sequence of events is confirmed namely that, certainly for the south coast and to a lesser extent for the west coast, the ENSO year shows levels which are some 5+ cm low, whereas in the previous year the sea-level stood high, and normality resumed in

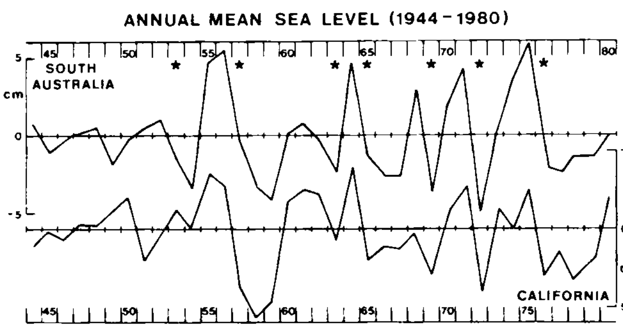

Figure 4. Comparative inter-annual anomalies of sea-level over a 36 yr period. Port Groups: South Australia comprises Thevenard, Port Lincoln, Port Macdonnell and Port Adelaide (Outer). California comprises San Francisco, Los Angeles, La Jolla and San Diego.

the post-ENSO year. The picture is further reinforced in Fig. 6, which clearly demonstrates that the ENSO signal is absent east of Bass Strait but is strong and coherent along the south and south-west coasts. In this case five ENSO years are treated (1965, 1969, 1972, 1976 and 1982) and the diagram is the composite result.

This diagram and a similar treatment of the standard deviation of these anomalies searched without success for progressive features which would be revealed by diagonal shifts in time and space. The treatment did, however, confirm the reality of the south coast sea-level signals since they invariably coincided with minima in the standard deviation,

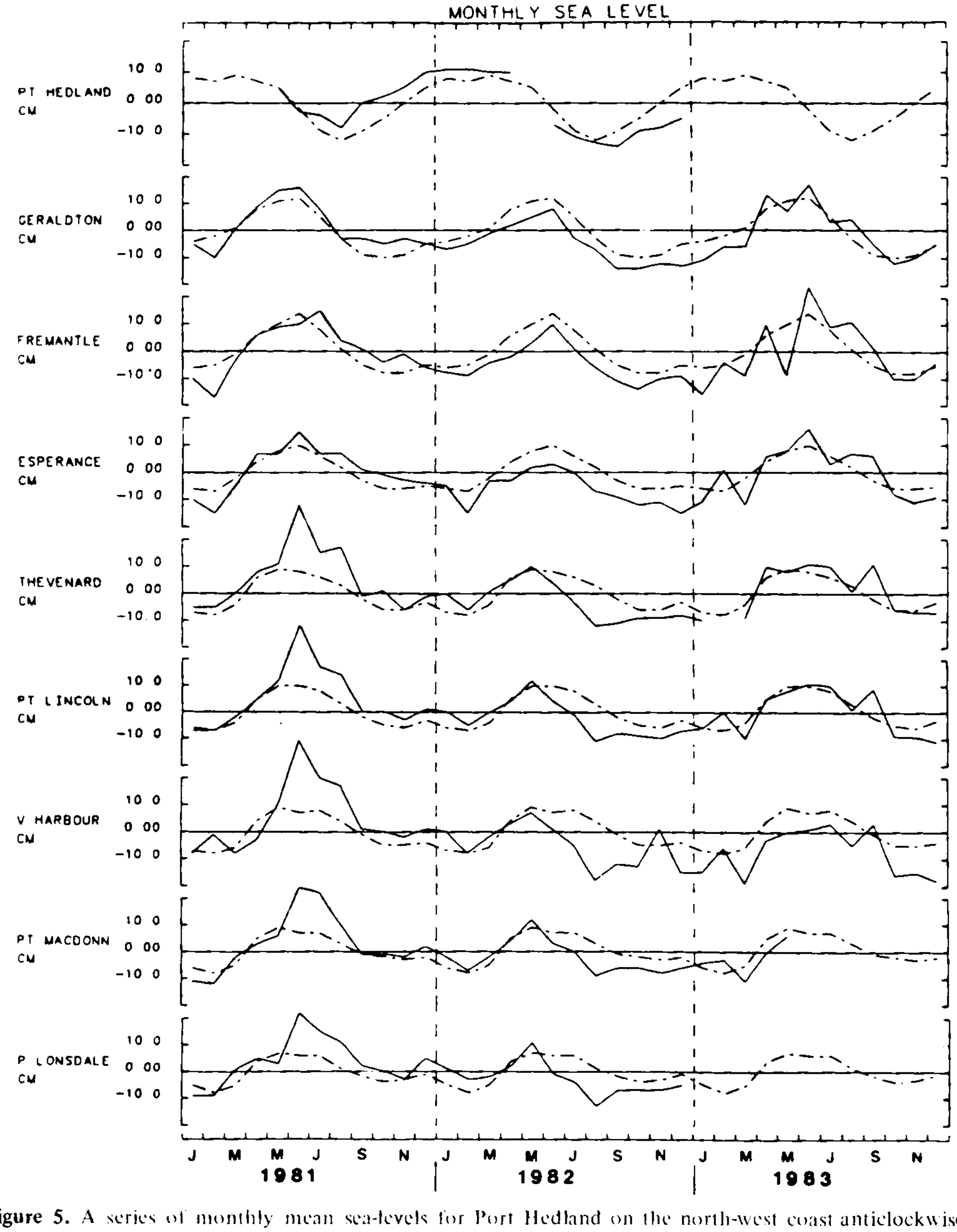

Figure 5. A series of monthly mean sea-levels for Port Hedland on the north-west coast anticlockwise to Point Lonsdale in Bass Strait for 1981, 1982 and 1983. The year 1982 was an ENSO year.

The pecked line traces the long period mean. The continous line traces the observed levels in the years indicated.

emphasizing their reality. The treatment also confirmed the identity of the unreliable stations through anomalously high values of the standard deviation.

At this stage we can summarise the evidence as follows:

In all respects the sea-level signal in South Australia shows great coherency.

The interannual signal is clearly linked with ENSO, which implies at least a Pacific-wide scale to the associated mechanism.

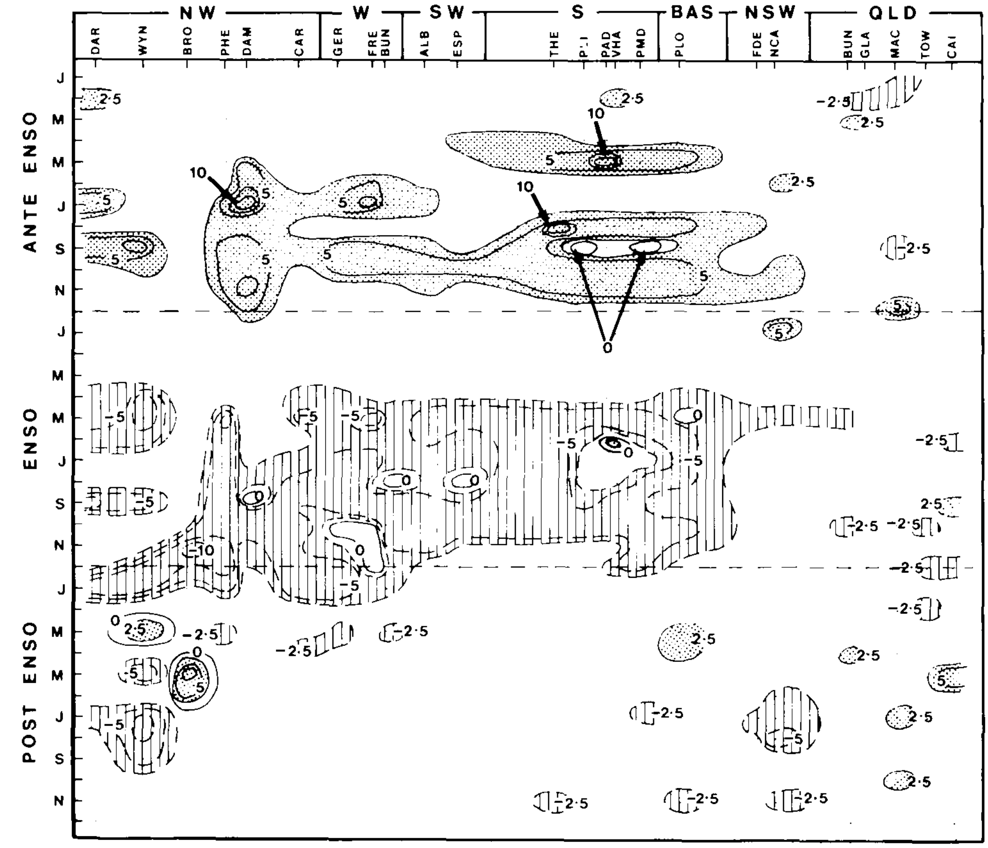

Figure 6. The contours of sea-level perturbations from the long-term mean from a composite data set comprising five ENSO events: 1965, 1969, 1972, 1976 and 1982.

From left to right the coverage is anticlockwise around the Australian coastline commencing at Darwin and using material for 24 individual ports extending to Cairns in the right margin. Anomalies are shown for ante-ENSO, ENSO and post-ENSO years (cm).

Returning to Fig. 4, as in Bye & Gordon (1982), this scale is reinforced by the remarkable negative correlation between South Australia and California mean sea-levels with its possibility of evidence of inter-ocean volume transport maintaining a delicate balance.

The complexity of teleconnections associated with ENSO is well known and the intriguing search for a trigger to the cycle has met with much frustration. The question here is that if progress can be made in the study of this new signal, by linking sea-level anomalies with a forcing function, then some welcome contribution to the ENSO puzzle may be possible.

The modelling of wind stress

Preliminary studies suggested a strong link between the wind stress applied to the Southern Ocean and the Australian sea-level anomaly, and this led to the construction of a numerical model of the circumpolar ocean over which a realistic seasonal wind would be applied. The model is linear, barotropic, depth integrated, with realistic bottom topography and linear dissipation (cf. Stommel 1948). Provision is made for variable grid size within a specific case and grid lengths between 1° and 7° have been used. Fig. 7 illustrates the general configur-

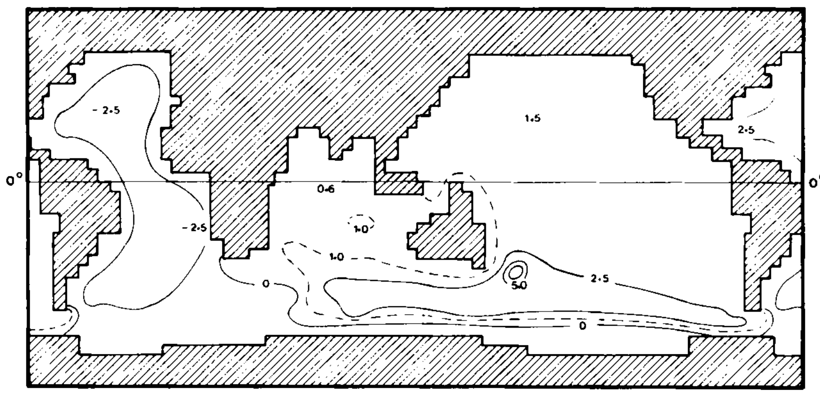

Figure 7. The computational grid selected for a hydrodynamical model, based upon finite differences, used for the treatment of wind stress superimposed upon the circumpolar Southern Ocean south of 45° S. Zonal wind stress with a constant value of 0.15 N m^{-2} has been used for this purpose.

ation of the model and for input, advantage was taken of a year-long data set of daily wind observed in 1979 in Drake Passage (Whitworth, Nowlin & Worley 1982). This wind field was accepted as characteristic of the Southern Ocean and was applied to the total surface south of 45°S. The wind elsewhere is assumed to be zero. From this exercise the following conclusions can be drawn:

(a) The restriction of Drake Passage is a dominant feature so that the application of a westerly wind field has a draining effect on the Atlantic, lowering levels in that ocean. Levels are certainly raised south of Australia and also in the Pacific. In this way, and for the first time, the Southern Ocean emerges as a significant agent in inter-ocean transport of ENSO type.

(b) In association with increased levels in the Pacific, wind stress over the Southern Ocean causes east to west water transport through the Indonesian Strait. The wind field imposed suggests that this transport amounts to 4×10^6 m^3 s^{-1} in a typical year.

(c) What is more intriguing is the fact that upon experimentation by closing the Indonesian Strait, it was found that the South Australian sea-level anomaly decreases in response, providing evidence of complex linkages with Indonesian Strait transport, but it is unclear which feature represents the drive and which the response in the real world.

The modelling of rainfall anomalies

Again since ENSO events are associated with east–west migration of rainfall zones, experiments were conducted by imposing rainfall anomalies in the equatorial latitudes. In this exercise the most significant result was a response to rain in the central tropical Indian Ocean. The consequent barotropic wave was seen to pass eastwards through the Indonesian Strait but also it generated a response with little delay on the South Australian coast. The contribution of 10 cm of rain/day in the Indian Ocean Region 89°E between latitudes 2°N and 10°N produced a response of 0.35 cm in Australia two days later.

The water characteristics

Finally a search was made for a means of identification of source through water characteristics. Few data are available but the most readily available indicator is salinity, bearing in mind that south coast shelf waters are exceptionally saline while tropical waters are deficient in salt. The evidence was inconclusive although an incomplete monthly water sample series from Bass Strait revealed a normal rapid growth to a peak in mid-year and with a slight suggestion that ENSO years show a negative anomaly of approximate size 0.6. If confirmed this would be compatible with a sequence in which the increased westward transport through the Indonesian Strait in an ante-ENSO year would provide more low salinity water to be transported south by the Leeuwin Current during the next summer.

These influences remain on weak grounds and require confirmation by much further work. It is interesting and relevant to note that the blue crab (*Portunus* sp.) found in the Southern waters is of tropical origin (South Australian Department of Fisheries, private communication).

The ENSO cycle

On the basis of the sea-level evidence so far assembled, one may then re-examine the cycle of ocean/atmosphere interactions associated with ENSO with a view to identifying new elements.

Although many inferences are still to be made we may identify elements in the ENSO cycle in simple terms as follows:

(i) In a normal year there is east to west flow through the Indonesian Strait, as a response to the western boundary accumulation of water transported by the Trade Winds. This flow is estimated in magnitude by various authors from 1 to 14×10^6 m^3 s^{-1} (e.g. Wyrtki 1961; Godfrey & Golding 1981; Wunsch, Hu & Grant 1983; Piola & Gordon 1984; Fine 1985). Also the Indonesian wet season occurs typically in the period November to January.

(ii) In an ante-ENSO year the strengthening of the Trade Winds in the Equatorial zone brings additional heat to the Western Pacific where it pools and deepens the thermocline.

(iii) It may now be postulated that the strengthening of the Trade Winds may be a larger scale phenomenon affecting the major wind gyres of the Pacific area through a strengthening of the Pacific barometric high. In this way we may see an association with the strengthening of the westerlies over the Southern Ocean which bring the positive sea-level anomaly to the south coast of Australia. Also it is noteworthy that a strengthening of the westerlies increases the westward flow through the Indonesian Strait.

(iv) Alternatively, or in supplementation, we may take note of the effect of closure of the Indonesian Strait and, based upon the obvious link between Strait flow and the South Australian sea-level anomaly, we may postulate the latter as a response, however partial to the former. The communication would be by barotropic wave mechanisms progressing rapidly at ~ 200 m s^{-1}.

(v) Previously much weight has been given to the variations of monsoonal transports through the Indonesian Strait and particularly the contributions to the ponding of heat in the Western Pacific and Indian Ocean. It is now felt that this may provide a contributory factor although the numerical model suggests that its significance is minor compared with the Southern Ocean/Trade Wind forcing system.

(vi) The ante-ENSO westerly flow anomaly through the Indonesian Strait produces climatic anomalies in the Indian Ocean with a marked increase of rainfall in mid-year. It has been seen that this would also communicate positive sea-level anomalies in South Australia which would occur rapidly by barotrophic dynamics again consistent with the sea-level observations.

(vii) The ENSO phenomenon appears to be typically a two-year event with an anomalous feature being generated in one year to be followed by the so-called ENSO year, and then the inference is that the post-ENSO year is a period of gradual return to normal with a return to normal strength of Trades and Westerlies. Sea-levels seem to be normal at this time.

Comment

In this exercise we believe that we have provided sufficient evidence to propose marine teleconnections not previously identified. As in all aspects of large-scale natural phenomena the inter-correlations are many and we cannot claim to have identified a realistic trigger. Nevertheless there has been identified a small magnitude signal to be found in monthly values of mean sea-level which is real and of large spatial scale, > 2000 km. In spite of the well-published problems of the Australian tide gauge network, the gauges installed for port operational purposes and maintained by local authorities are nevertheless responsive to careful interpretive processes to reveal a signal of magnitude ~ 5 cm on a time-scale of 1–5 yr.

The signal is seen to be compatible with a number of hypotheses and might well be a composite feature responding to multiple sources. Nevertheless what is abundantly clear is the fact that the south coast of the Continent, far more than any other region, responds with relative uniformity so that future work must focus upon this area.

There is a real and urgent need to enhance the national network in this area and also to institute systematic water-sampling programmes for chemical and biological analysis in an area incorporating the west coast, the south coast, and the south-west coast.

Acknowledgments

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