CHARACTERISTICS OF SUB-TIDAL COASTAL TRAPPED DISTURBANCES IN SEA LEVEL ALONG THE COASTS OF NAMIBIA AND SOUTH AFRICA

By

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A thesis submitted to the Faculty of Science at the
University of Cape Town in fulfillment of
the requirements for the degree of Master of Science

March 1985

The sea level disturbances are found not to be free waves but forced waves needing constant forcing in order to propagate. Along the east coast where such forcing is absent, particularly in summer, there is no general propagation. If the forcing extends further eastwards, as sometimes occurs during winter, this is reflected in the sea level response.

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Chapter 1. INTRODUCTION

Extensive studies have been made in many parts of the world of the regular variations that occur in the level of the sea. Herodotus, writing in about 450 B.C., recorded "an ebb and flow of the tide every day" at the Gulf of Suez in the Red Sea. By far the largest influence on sea level is that exerted by the gravitational forces of the sun and moon. The connection with the moon was recognised by Pytheas of Marseilles, 320 B.C., who noted the difference in tidal range between springs and neaps. However, the tides were first explained scientifically by Sir Isaac Newton in 1687 in his Philosophiae Naturalis Principia Mathematica. Having discovered the law of gravitation, he used it to develop the equilibrium theory of the tides, whereby he calculated the tides which would occur in a non-inertial ocean covering the whole earth. Newton was aware of the limitations of his theory, but it did to some extent explain the observed phenomenon.

It was only after the dynamical astronomy of the solar system had been developed and used to explain the motion of the planets, that Laplace developed a dynamic theory of the tides in the early 19th century. He considered the ideal case of an ocean of uniform depth on a rotating, spherical earth. Such an ocean would produce an infinite number of modes of oscillation, some of which might resonate with the forced tidal oscillations. The general equations of the dynamic theory are very complicated as they must allow for variations in depth and topography of the ocean basins, Coriolis force and frictional effects. No complete solution has yet been achieved.

For practical purposes, the harmonic analysis of tides was established by Lord Kelvin later in the 19th century by accepting that the observed tidal oscillations must be characterised by the same periods as the tide-generating forces. The method was developed further by Sir George Darwin, whose work provided a basis for modern methods of harmonic analysis and tidal prediction. The methods currently used in harmonic analysis have been described in detail by Schureman (1924) and by Doodson and Warburg (1941).

Table 1 shows the most important tide producing forces and their relative amplitudes at Simons Bay. The two largest semi-diurnal and diurnal partial tides, M_2, S_2, K_1 and O_1, are the most important in characterising the tide at any location. The ratio of the sum of the amplitudes of the diurnal components $K_1 + O_1$, to the sum of the amplitudes of the semi-diurnal components, $M_2 + S_2$, is designated the "Formzahl" of the tides and used to classify the tides into four types, namely: semi-diurnal; mixed, mainly semi-diurnal; mixed, mainly diurnal; diurnal.

Table 1

Most important components of the tide producing forces at Simons Bay

Name of corresponding Partial Tide	Symbol	Period (h)	Angular Velocity (^{o} h^{-1})	Amplitude (m)
Semi-diurnal:				
Principal Lunar	M_2	12.42	28.9841	0.5127
Principal Solar	S_2	12.00	30.0000	0.2307
Larger Lunar Elliptic	N_2	12.66	28.4397	0.1148
Luni-Solar	K_2	11.97	30.0821	0.0646
Diurnal:				
Luni-Solar	K_1	23.93	15.0411	0.0603
Principal Lunar	0_1	25.82	13.9430	0.0160
Principal Solar	P_1	24.07	14.9589	0.0148
Long Period:				
Lunar Fortnightly	Mf	327.86	1.0980	0.0088
Lunar Monthly	Mm	661.30	0.5444	0.0088
Solar Semi-Annual	Ssa	2191.43	0.0821	0.0168

Table 1 also contains three long-period terms. The distribution of the air masses over the oceans is not constant, but has a seasonal variation which is reflected as a seasonal change in sea level. Similarly there are annual and semi-annual fluctuations related to the prevailing winds and to the effect of heating or cooling. Frictional effects in shallow water are important when considering sea level in bays or tidal rivers. All these can be included in the harmonic analysis by including long-period terms which, although not of astronomical origin, are regular in their tidal forcing. As can be seen from Table 1, the three major long-period terms have coefficients much less than the principal lunar and solar semi-diurnal and diurnal terms.

If a large number of constituents is used, the harmonic analysis of the tide at a place gives a good approximation of the tide there. However, there are variations caused by meteorological influences, changes in water density, the effects of currents and even vertical movements in the earth's crust which are not accounted for by harmonic analysis. To study these effects other methods are needed.

The theoretical response of sea level to pressure changes at the low frequencies associated with the passage of weather systems is that of an inverted barometer (Robinson 1964). Records should show a decrease in sea level of 1.01 cm for an increase in atmospheric pressure of 1 mb. This assumes an ocean of uniform depth such that the total pressure at any fixed point on the bottom is constant. In coastal areas, over continental shelves, this is not always valid. Changes in atmospheric pressure are accompanied by changes in the velocity and direction of the wind, which also contribute to fluctuations in sea level.

Robinson (1964) first proposed a theory of continental shelf waves as a response of sea level to atmospheric changes, after Hamon (1962, 1963) had found that the relation between sea level and pressure at two ports on the east Australian coast was less than isostatic. Robinson assumed a coastline of infinite length for his theory and that the waves would be of frequency small compared with the Coriolis parameter and wavelength long compared with the shelf width. He neglected the effects of friction. The waves would then be able to travel along the shelf in the same sense as Kelvin waves with the coast on the left in the Southern Hemisphere. Sea level would have a node at the edge of the shelf and an anti-node at the coast. Sea level at any port would be the sum of the isostatic response to pressure and the elevation due to the shelf wave. Shelf waves of appreciable amplitude would only be found as a result of resonance which could only occur on a sloping shelf. As the wavelengths of the shelf waves depend only on the shelf width and Coriolis parameter, they are independent of frequency and thus non-dispersive.

Robinson's theory was extended by Mysak (1967) to include the effects of a continental slope region, deep sea stratification and longshore currents. He reached the same general conclusion although the numerical results were different. Buchwald and Adams (1968) derived a more general theory of free shelf waves for the case of an exponential shelf slope by neglecting horizontal divergence. Shorter waves than those considered by Robinson could be included. The shorter waves were found to be highly dispersive and although the phase velocities were always in the same sense as those of Kelvin waves, a certain range of wavelengths was found to have a negative group velocity indicating that energy could propagate in the opposite direction.

Robinson and Mysak both considered pressure variations to be the forcing mechanism for sea level changes, but Adams and Buchwald (1969) showed that the principal forcing mechanism is the stress of the longshore component of the geostrophic wind. The amplitude of response observed is up to two orders of magnitude greater than predicted using pressure as the forcing mechanism. As wavelengths are long (2000 km) it seems unlikely that resonance could explain this difference - a travel distance of several wavelengths would be needed to produce the observed amplitude. The correlation between sea level and pressure changes is due to the correlation between wind and pressure. Gill and Clark (1974) discussed the possibility of upwelling due to the propagation of a shelf wave through an area where such upwelling would not be expected from purely local winds. Gill and Schumann (1974) calculated the shelf wave response to different types of atmospheric forcing.

Evidence for the existence of continental shelf waves in the ocean was soon found through the analysis of tidal and current measurements. Hamon (1966) found evidence from the Australian coast where a larger than isostatic response to pressure was found in sea level records along the west coast and a smaller than isostatic response along the east coast. Cartwright (1969) used the theory of Buchwald and Adams to explain the strong diurnal tidal currents found near the island of St. Kilda. Mooers and Smith (1968) studied tidal data from the coast of Oregon. By considering the barometer effect as a function of frequency, as suggested by Hamon and Hannan (1963), they found high values at about 0.1 cpd and 0.3 - 0.5 cpd which could be explained in terms of shelf waves. Cutchins and Smith (1973) confirmed the existence of first mode free shelf waves in the frequency range 0.2 - 0.3 cpd using tidal and current data from this same area. Mysak and Hamon (1969) obtained similar results for the North Carolina coast.

In South Africa, Schumann (1982, 1983) studied fluctuations in sea level, currents and temperature along the south-east coast. He concluded that topography and the Agulhas current would inhibit the propagation of coastal trapped waves along the Natal coast. Between Port Elizabeth and Durban conditions appeared more favourable, but there was little evidence of general propagation. A single event was found to propagate from Port Elizabeth to Richards Bay. As the event was apparent in temperature data and not in sea level records, it was concluded to be a baroclinic phenomenon.

The tidal records from ports along the west and south coasts of Southern Africa are here studied. After the various scales of variation have been identified and discussed, the records are examined in detail for evidence of coastally trapped waves in the frequency range 0.1 - 0.5 cpd and for the forcing mechanism for these waves.

Chapter 2. DATA COLLECTION AND PRELIMINARY ANALYSIS

2.1 Raw data

The tidal data for this study came from two sources. The South African Navy maintains tide gauges at several ports along the Southern African coast. The data from these tide gauges were made available in the form of hourly sea level heights on computer tape. In addition, the Fisheries Development Corporation supplied data from environmental packages which they operate at Lamberts Bay and Gansbaai. Hourly values of sea level height, atmospheric pressure and wind were provided on computer tape. The complete data set is described in Table 2 and the locations of the ports, together with the local bathymetry, are illustrated in Figure 1.

The tide gauges operated by the Navy all use a float system to measure the rise and fall of the water surface in a specially constructed tide well situated somewhere in the harbour. A pen records the height of the tide on paper on a rotating drum. A clock is geared to this drum, which rotates one revolution in 24 hours. On the Kent and Lea gauges, the clock is wound manually every eight days, but on the OTT gauge the clock is operated electrically. Full calibrations of the tide gauges are undertaken regularly and, if necessary, adjustments are made to chart datum. Each tide gauge is referred to at least two bench marks which are part of the national land levelling system. Hourly values of sea level height are determined visually by reading off the paper chart at each hour

Table 2

Sites and types of tide gauges with data availability

Port and abbreviation	Latitude (°S)	Longitude (°E)	Source *	Type of Gauge	Length of data set used
Walvis Bay WB	25°56'	14 30'	SAN	OTT	1958 - 1973 monthly 1976 - 1982 hourly
Luderitz Bay LB	26°39'	15 09'	SAN	Kent	1959 - 1975 monthly 1982 hourly
Port Nolloth PN	29°15'	16 52'	SAN	Kent	1982 hourly
Lamberts Bay LA	32°06'	18 18'	FDC	Environmental package	February 1981 - Feb. 1983 hourly
Simons Bay SB	34°12'	18 25'	SAN	Lea	1958 - 1982 hourly
Gansbaai GA	34°35'	19 21'	FDC	Environmental package	February 1982 - July 1983 hourly
Mossel Bay MB	34°11'	22 09'	SAN	Kent	1960 - 1975 monthly
Port Elizabeth PE	33°58'	25 38'	SAN	OTT	1978 - 1982 hourly
Durban DU	29°53'	31 03'	SAN	Kent	1982 hourly
Richards Bay RB	28°48'	32 06'	SAN	Kent	1982 hourly

* SAN - South African Navy

FDC - Fisheries Development Corporation

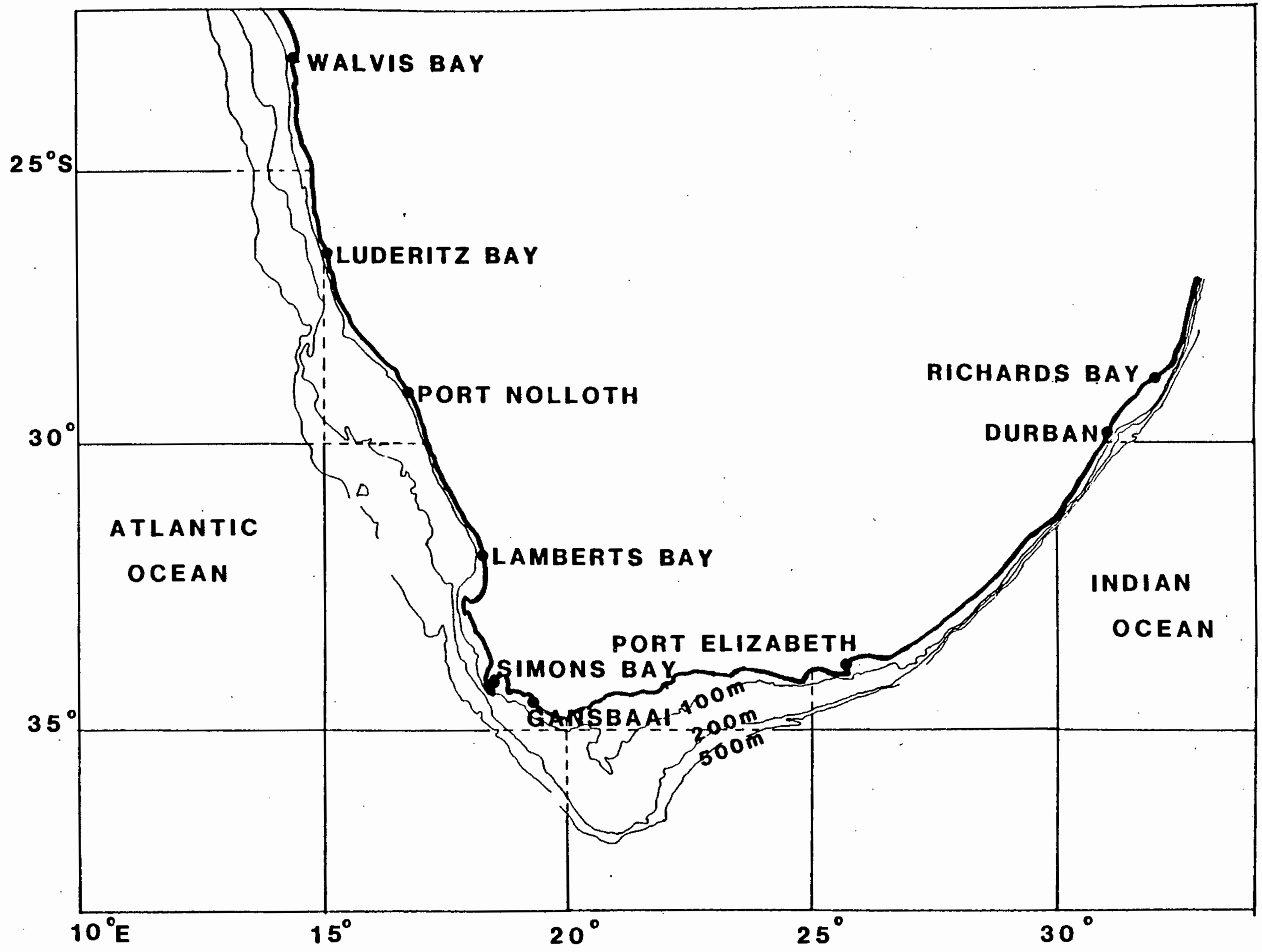


FIG.1 Southern Africa showing bathymetry and tidal stations

position, correcting for clock error if necessary. Taking into account all possible sources of error, a relative accuracy of 1% is regarded as satisfactory. The observations are measured in centimetres, to the nearest centimetre. With a tidal range not exceeding 2 m, the hourly values are considered accurate to within 2 cm.

The environmental packages operated by the Fisheries Development Corporation have the specifications as set out in Table 3. The tide gauges are pressure transducers, which operate on the principle that the pressure at any fixed point below the sea surface is proportional to the height of water above it. Changes in sea level are therefore determined by recording changes in pressure. The gauges at Lamberts Bay and Gansbaai are vented by means of a tube open to the atmosphere. This compensates for atmospheric pressure changes, so that the measurements recorded are the same as those recorded by the Navy gauges, namely unadjusted sea level heights.

At Lamberts Bay the sea level heights, atmospheric pressure and wind are recorded together at a position on the inside of the breakwater. The position of the tide station is referred to a brass stud on the breakwater capping. At Gansbaai the tide-station is situated on the off-loading quay inside the old harbour and referred to a brass stud on the quayside. Atmospheric pressure is recorded at the tide station but the wind information is obtained at a site about 500 m away.

TABLE 3

Specifications of tide gauge packages at Lamberts Bay and Gansbaai

Instrument	Manufacturer/type	Sampling rate	Range	Digital resolution
Tide gauge	Bell & Howell pressure transducer	256 samples/h	6m	0.02 m
Barometer	Thiers (W.Germany) Aneroid barometer linked to potentiometer	One spot reading/h	980 - 1050 mbar	1 mbar
Wind speed	R.W. Munro 3 cup anemometer driving a 12 pole rotor with a permanent magnet Wind speed is measured by frequency of alternating current	Cumulative average for 7½ minutes	0 - 160 km/h	1 km/h
Wind direction	In house	Spot reading every 7½ mins		22½° sectors

With a sampling rate of 256 samples per hour, a greater degree of accuracy of hourly sea level heights could be obtained from these gauges than from those operated by the Navy. Care is needed in determining hourly values. A straight average of 256 values could be in error by several centimetres at the turn of the tide, but would be very accurate midway between high and low tide. For this reason and also because the accuracy of the atmospheric pressure readings was 1 mb, the sea level height recorded on each hour was selected for use. The readings immediately before and after each hour were used to aid error detection. The 2 cm digital resolution of the tide gauges makes these hourly readings of the same accuracy as those from the Navy tide gauges. The hourly values of wind speed supplied were an average over 7.5 minutes centred on each hour and the direction a spot reading on each hour in the form of one of 16 compass points.

Monthly values of mean sea level prior to 1975 were obtained from tables published by the Permanent Service for Mean Sea Level, Bidston Observatory, England, derived from data originally collected by the South African Navy. The data for Luderitz Bay, Simons Bay and Mossel Bay for the period 1958 - 1972 were based on eight readings per day. The other monthly means were based on hourly data. Provided the sites of the tide gauges were properly levelled and regular calibrations were made, the accuracy of the monthly means should be ± 2.5 cm where eight readings a day were available and ±1.5 cm where hourly readings were used. Monthly values of mean sea level atmospheric pressure were determined from maps published by the South African Weather Bureau in their Monthly Newsletter. A typical example of these maps, for October 1982, is shown in Figure 2. The mean pressure for the month at each port can be estimated to an accuracy of 1 mb from the solid lines in Figure 2. The dotted lines show the deviation from a long-term October average.

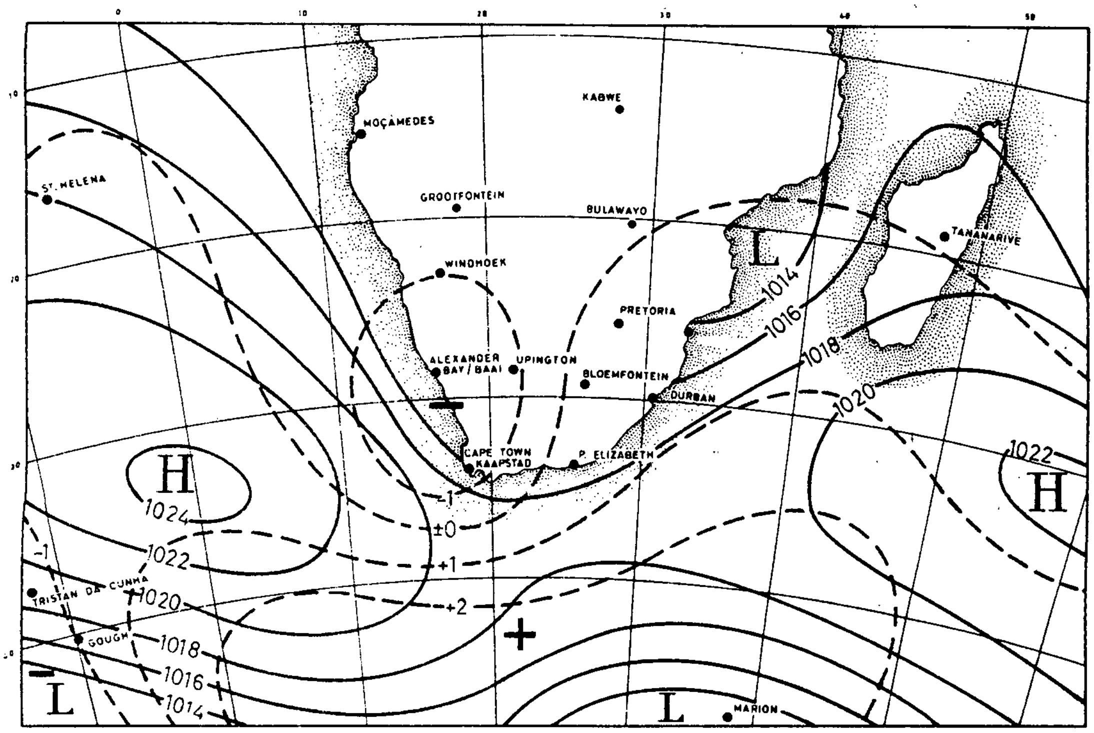


FIG. 2 Mean sea level pressure (solid lines) October 1982 (reproduced from the Monthly Newsletter, South African Weather Bureau).

2.2 Data quality control

All the sets of hourly data were checked for gross errors. The sea level heights were tested using the two Lagrangian formulae suggested by Lennon (1965)

$$\zeta_t^* = \frac{1}{6}\left(-\zeta_{t-50} + 4\zeta_{t-25} + 4\zeta_{t+25} - \zeta_{t+50}\right) \qquad (1)$$

$$\zeta_t^* = \frac{1}{6}\left(-\zeta_{t-2} + 4\zeta_{t-1} + 4\zeta_{t+1} - \zeta_{t+2}\right) \qquad (2)$$

where ζ_t is the observed height and ζ_t^* the estimated height at any time t hours. The value $|\zeta_t - \zeta_t^*|$ is then tested against a predetermined tolerance level.

When the sea level is raised or lowered as a result of a meteorological disturbance lasting longer than a day, the first and last hourly values affected by this disturbance will be rejected by (1) but passed by (2). However, hourly values at the turn of the tide may be erroneously rejected by (2) but passed by (1). It is for these reasons that Lennon recommends the use of both tests.

In this analysis, a tolerance level of 20 cm was chosen. A value of ζ_t rejected by both formulae was replaced by an interpolated value determined from (2) and checked by graphical inspection of data for several hours before and after the suspect value. A value of ζ_t rejected by one test was replaced by an interpolated value only if graphical inspection showed this to be justified. Very few errors were found in the data from the Navy . Similar checks had probably already been applied to the data. The sea level data for Lamberts Bay and Gansbaai contained several erroneous values but considering the length of the data sets, less than 0.1% of the values were faulty.

Gaps in the hourly sea level heights were not replaced by interpolated data. The Hydrographic Department of the South African Navy fills short gaps (a few hours) before supplying the data. Any remaining gaps could only be filled using predicted values which would not include any variations caused by meteorological influences. The gaps were left untreated and sections of unbroken data chosen for study. Similarly in the sea level data for Lamberts Bay and Gansbaai, all gaps were of several days duration and left untreated.

Hourly values of atmospheric pressure were checked using a five point moving average

$$P_t^* = \frac{1}{35}\left(-3P_{t-2} + 12P_{t-1} + 17P_t + 12P_{t+1} - 3P_{t+2}\right)$$

where P_t is the observed pressure and P_t^* the estimated pressure at time t hours. A value P_t was replaced by the estimated value P_t^* if $|P_t - P_t^*|$ exceeded the pre-determined tolerance level of 1.25 mb. Again, graphical inspection of the data for several hours was the final criterion for rejecting observed values. Interpolated values were used to fill several gaps of less than a day in the pressure data for both ports.

More erroneous values were found in the pressure data for Lamberts Bay than for Gansbaai. A change of 3 mb either up or down for one hour followed by a return to the previous level was a common feature, particularly in the early hours of the day. This was traced to a power fault in the equipment which was later corrected. These values were all altered. Approximately 0.5% of the data was affected by this fault.

After all checks and interpolations had been completed, the data were divided into several sets for analysis.

Data Set 1 - a long set of monthly mean sea level heights and atmospheric pressure at Simons Bay, 1958-1975. This data set contains no gaps. The accuracy of the monthly mean sea level is ± 2.5 cm for 1958-1972 where 8 readings per day were recorded and ± 1.5 cm for 1973-1975 where hourly readings were recorded. The accuracy of the monthly mean pressure is ± 1 mb.

Data Set 2 - a set of hourly sea level heights and monthly mean atmospheric pressure at Simons Bay, 1976-1982. This set contains no gaps. The accuracy of the hourly sea level heights is ± 2 cm and of monthly mean pressure ± 1 mb.

Data Set 3 - a set of monthly mean sea level heights and atmospheric pressure at Walvis Bay, Luderitz Bay, Simons Bay and Mossel Bay, 1960-1965. The set contains no gaps. The accuracy of the sea level data at Luderitz Bay, Simons Bay and Mossel Bay is the same as for Data Set 1, from which the Simons Bay data come. The sea level data at Walvis Bay are more accurate, ± 1.5 cm, being based on hourly values. The accuracy of the pressure data is the same as Data Set 1.

Data Set 4 - a set of hourly sea level heights at Walvis Bay, 1979-1982. The data set contains many gaps, particularly in the early part. The accuracy is ± 2 cm.

Data Set 5 - a set of hourly sea level heights for 1982 at nine ports from Walvis Bay round to Richards Bay. Only the data at Simons Bay and Durban are without gaps. The accuracy of the hourly data is ± 2 cm.

Data Set 6 - a set of hourly sea level heights (from Data Set 5), atmospheric pressure and wind at Lamberts Bay and Gansbaai for part of 1982. There are several gaps in this data set. The accuracy of the sea level heights is ± 2 cm, of the hourly atmospheric pressure ±1 mb, of the wind velocity ± 1 km h^{-1} and of the wind direction ± 22.5°.

2.3 Generation of filtered data sets

Values of daily mean sea level were calculated for all sets of hourly sea level heights, using the Doodson tide-killer (Doodson and Warburg, 1941). This effectively filters out the main solar and lunar semi-diurnal and diurnal constituents. Mooers and Smith (1968) and others have criticised the use of this filter because it is susceptible to aliasing from high frequency effects. Godin (1972) illustrated the spectral characteristics of this filter, showing the side lobes. For hourly data the maximum amplitude of 0.57 corresponds to a frequency of 0.39 cph (period 2.6 h). Thus data with a three hour periodicity would be aliased. Cartwright (1983) demonstrated the same effect. As the tidal records at all Southern African ports have a very low noise level, with no evidence of a three hour periodicity, this criticism was not felt to be valid. Mooers and Smith found that they achieved the same qualitative results using the Doodson filter as they did using a more sophisticated one. Using a Lanczos-cosine filter over 120 hours as recommended by R.O.R.Y. Thompson (1983) would have resulted in the loss of a significant amount of data because of the considerable number of gaps in the data sets, without a compensating increase in accuracy. The Doodson filter operates over 39 hours, yielding a loss of one day at the end of a data set.

The usual practice with the Doodson tide-killer is to take the daily mean as the centre point of the filter operating from 0000h on the day in question and running till 1400h on the next day. The daily mean is thus centred at 1900h. This method was followed for Data Sets 2 and 4. For Data Sets 5 and 6 new sets of filtered hourly sea levels were formed by replacing each hourly value with the Doodson filtered daily mean sea level centred at that hour. From these new data sets it was easy to use the value at 1200h each day as the daily mean. It should be noted that this leads to the loss of a day's data at the beginning as well as the end of each data set.

Monthly mean sea level was calculated as the average of the Doodson filtered daily mean sea level at 1900h for each month for Data Sets 2, 4 and 5. A monthly mean was calculated if at least 80% of these daily means were available for that month. These values of monthly mean sea level were then adjusted for the barometer effect. Using 1014 mb as the standard barometric pressure at all ports, the monthly deviation from this standard was added to the monthly mean sea level to give the adjusted monthly mean sea level.

The hourly wind data were converted to longshore and offshore components and the speeds converted from km h^{-1} to m s^{-1}. At Lamberts Bay a northerly wind was taken as the positive longshore component and at Gansbaai a north-westerly wind. The hourly atmospheric pressure and wind component data were then filtered using the U7 filter of Mooers and Smith (1968). This filter has a half power point of 56 hours and removes fluctuations of period less than 2 days. It is given by

$$x_t^* = \frac{1}{12}\left(x_{t-12} + x_{t+12}\right) + \frac{1}{6}\sum_{j=-2}^{2} x_{t+4j}$$

where x_t is the observed value and x_t^* the replacement value at time t hours.

The filtered and adjusted data sets available for comparison and further analysis may be summarised as follows:

Data Set 1F - an unbroken set of monthly mean adjusted sea level at Simons Bay, 1958-1982. The accuracy of the monthly values is ± 4 cm for 1958-1972, ± 3 cm for 1973-1975 and ± 2 cm for 1976-1982.

Data Set 2F - an unbroken set of monthly mean adjusted sea level at Walvis Bay, Luderitz Bay, Simons Bay and Mossel Bay, 1960-1965. The accuracy is ± 3 cm at Walvis Bay and ±4 cm at the other ports.

Data Set 3F - an unbroken set of filtered hourly sea level heights at Walvis Bay, 1979 June 11 - 1981 April 29.

Data Set 4F - an unbroken set of filtered hourly sea level heights at Simons Bay, 1980 January 2 - 1982 December 30.

Data Set 5F - a set of filtered hourly sea level at nine ports for periods in 1982 as shown in Table 4.

Table 4
Availability of sea level data 1982

Port	Hourly data available 1982
Walvis Bay	January 2 - June 2
	June 10 - December 23
	December 27 - December 30
Luderitz Bay	January 2 - December 8
	December 15 - December 30
Port Nolloth	January 2 - February 7
	February 13 - December 30
Lamberts Bay	January 2 - April 29
	May 13 - July 14
	July 20 - August 23
	September 1 - December 30
Simons Bay	January 2 - December 30
Gansbaai	February 20 - June 29
	July 31 - October 27
	November 5 - November 30
	December 8 - December 30
Port Elizabeth	January 2 - April 2
	April 15 - December 16
	December 22 - December 30
Durban	January 2 - December 30
Richards Bay	January 2 - January 30
	February 8 - March 4
	March 8 - May 22
	May 30 - June 1
	June 16 - July 7
	July 15 - September 24
	September 30 - November 29
	December 14 - December 17

Data Set 6F - a set of filtered hourly values of sea level, atmospheric pressure and longshore and offshore wind component velocities at Lamberts Bay and Gansbaai for periods in 1982 as described in Table 5.

It is clear from Table 4 that the choice of subsets of reasonable length for comparison among the hourly data sets is very limited. The data at Richards Bay contained most gaps and so separate comparisons were made between data at Durban and Richards Bay. At the other ports, the three periods

(i) 1982 February 20 - April 29 (69 days - late summer '81/82)
(ii) 1982 May 13 - June 29 (48 days - winter '82)
(iii) 1982 September 1 - October 27 (57 days - early summer '82/83)

were chosen as most representative of the ports and the seasons. Because these three periods were rather short, they were supplemented by the three 90 day periods

(a) 1982 January 2 - April 1
(b) 1982 June 10 - September 7
(c) 1982 September 10 - December 8

from which additional information could be obtained at some of the ports.

Table 5

Availability of hourly sea level, pressure & wind data from
Lamberts Bay & Gansbaai 1982

PORT	HOURLY DATA AVAILABLE 1982		
	SEA LEVEL	PRESSURE	WIND
amberts Bay	January 2 - April 29 May 13 - July 14 July 20 - August 23 September 1 - December 30	January 2 - July 15 July 20 - December 30	January 2 - July 30
ansbaai	February 20 - June 29 July 31 - October 27 November 5 - November 30 December 8 - December 30	February 19 - October 28 November 4 - November 30	January 2 - May 11 June 11 - June 30

For the data at Durban and Richards Bay, the three comparison periods chosen were

(1) 1982 March 8 - May 22 (76 days)
(2) 1982 July 15 - September 24 (72 days)
(3) 1982 September 30 - November 28 (60 days)

The subsets of hourly data for the nine periods above were filtered using a 120 point double running mean to remove the effects of periods longer than 10 days. Chelton and Davis (1982 Appendix) show the advantage of using a double running mean over a running mean. Although their work refers to monthly values it is equally valid here. All further analyses were undertaken on both unfiltered and filtered data sets to determine the effect of long term trends when considering data subsets two to three months long.

The choice of a 10 day filter for the data sets was made before power spectra were obtained showing a broad peak at 10 days to be a period of interest during the second half of the year. A range of 4 - 10 days is generally regarded as the scale of synoptic events and it was hoped to eliminate the effect of longer periods from the analyses. The effect of filtering on the correlation analyses was to sharpen the peak in the curve of correlation coefficient against lag. When some of the analyses were repeated using 12 days as the cut-off point, the results were not significantly different. The lag at which maximum correlation occurred using the 12 day filter was found to be the same as for unfiltered data but sometimes a couple of hours less when using the 10 day filter. It was not felt necessary to repeat all the analyses using a 12 day filter instead of the 10 day one.

Chapter 3. COMPARISON BETWEEN FILTERED DATA SETS

3.1 Methods of analysis

Three methods of analysis were used to describe the important features of the filtered data sets. Spectral analysis was used to demonstrate the frequency distribution of the observed variations in sea level and pressure data. The data sets were, for the most part, too short to obtain significant quantitative results using cross-spectral techniques. Cross-correlation analysis was used instead to compare sea level variations at neighbouring ports, from which it could be established if the variations at different ports were likely to share the same forcing mechanism. Cross-correlation analysis was also used to identify the relationships between atmospheric pressure, longshore wind and sea level. Regression analysis was used to a lesser extent to determine the magnitude of the barometer effect at Lamberts Bay and Gansbaai. It was also used to find the relationship between spectral energy and frequency at Simons Bay and at Walvis Bay.

3.1.1 Spectral analysis

The Blackman-Tukey method, as described by Bendat and Piersol (1971) was used to determine spectral estimates through the Fourier transform of the autocorrelation function. Consider a continuous record $x(t)$, with zero mean, defined for time t such that $0 \leq t \leq T$ which can be suitably extended beyond T. The autocorrelation function $R_x(t)$ is given by

$$R_x(t) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)\,x(t+\tau)\,dt$$

Two important properties of the autocorrelation function are

$$R_x(-\tau) = R_x(\tau)$$

and $R_x(0) \geq |R_x(\tau)|$ for all τ

For sampled data, the estimate $\hat{R}_x(\tau)$ of the autocorrelation function is given by

$$\hat{R}_x(\tau) = \frac{1}{T-\tau} \int_0^{T-\tau} x(t)\,x(t+\tau)\,dt \qquad 0 \leq \tau < T$$

and for discrete data, consisting of N data points Δt apart in time

$$\hat{R}_r = \hat{R}_x(r\Delta t) = \frac{1}{N-r} \sum_{n=0}^{N-r-1} x_n\,x_{n+r} \qquad r = 0, 1 \ldots m$$

where the x_n are the transformed values of $x(t)$ which have zero mean.

i.e. $x_n = x(n\Delta t) - \bar{x}$

r is the lag number corresponding to time displacement $r\Delta t$

m is the maximum lag.

The maximum time lag τ_{max} is related to m by

$$\tau_{max} = m \Delta t$$

The power spectral density function for a continuous record is defined as

$$G_x(f) = \lim_{\Delta f \to 0} \frac{1}{(\Delta f)} \left[\lim_{T \to \infty} \frac{1}{T} \int_0^T x^2(t, f, \Delta f) dt \right]$$

where $x(t, f, \Delta f)$ is that part of $x(t)$ in the frequency range $(f, f + \Delta f)$. For stationary data, the power spectral density function may be obtained from the autocorrelation function through the Fourier transform, viz

$$G_x(f) = 2 \int_{-\infty}^{\infty} R_x(\tau) e^{-j 2\pi f \tau} d\tau$$

$$= 4 \int_0^{\infty} R_x(\tau) \cos 2\pi f \tau \, d\tau \quad \text{since } R_x(-\tau) = R_x(\tau)$$

For discrete data, the approximation is

$$G_x(f) = 2 \Delta t \left[\hat{R}_0 + 2 \sum_{r=1}^{m-1} \hat{R}_r \cos\left(\frac{\pi r f}{f_c}\right) + \hat{R}_m \cos\left(\frac{\pi m f}{f_c}\right) \right]$$

$$\text{for } 0 \leq f \leq f_c$$

where f_c is the cut-off frequency, $f_c = \dfrac{1}{2 \Delta t}$

The resolution bandwidth, B_e is given by

$$B_e = \frac{1}{m \Delta t}$$

With a record length of $N\Delta t$, the number of degrees of freedom, n, is given by

$$n = 2B_e N\Delta t = \frac{2N}{m}$$

The normalised standard error, ϵ_r, is given by

$$\epsilon_r = \sqrt{\frac{1}{B_e N\Delta t}} = \sqrt{\frac{m}{N}}$$

To keep this small, it is therefore necessary to have $m \ll N$, and m is usually not greater than N/10. The sampling distribution obtained after smoothing with, for example the "Hanning" window, is approximately chi-square with n degrees of freedom and a $(1-\alpha)$ confidence interval for the power spectral density function G(f) based on these estimates is given by

$$\frac{n\hat{G}(f)}{\chi^2_{n;\,\alpha/2}} \leq G(f) < \frac{n\hat{G}(f)}{\chi^2_{n;\,1-\alpha/2}}$$

The limits of this interval can be determined from standard tables and graphs (e.g. Jenkins and Watt (1968), p. 82). It should be noted that this method produces spectral estimates at frequency intervals $\Delta f = \frac{1}{2m\Delta t}$, which overlap as the bandwidth $B_e = 2\Delta f$.

3.1.2 Cross-correlation analysis

Using the notation of the previous section, the correlation of two series $x(t)$ and $y(t)$ sampled at intervals Δt apart is given by

$$\hat{R}_{xy}(i\Delta t) = \frac{1}{N-i}\sum_{p=0}^{N-i-1} x_p y_{p+i} \qquad (1)$$

for $i = -m, \ldots -1, 0, 1 \ldots m$

where it is assumed that the sample means have been removed and the caret (^) denotes an estimate as before. The normalised (cross-) correlation function is given by

$$C_{xy}(i\Delta t) = \frac{\hat{R}_{xy}(i\Delta t)}{\sqrt{\hat{R}_{xx}(0)\,\hat{R}_{yy}(0)}}$$

$$= \frac{\hat{R}_{xy}(i\Delta t)}{S_x S_y}$$

where S_x, S_y are the standard deviations of $x(t), y(t)$ respectively.

The maximum value of $C_{xy}(i\Delta t)$ gives the degree of alikeness of the two series and $(i\Delta t)$ gives the time lag at which this occurs. If two series are identical except for a time shift, then the maximum value of $C_{xy}(i\Delta t)$ will be unity at the lag of the time shift. The quality s_e, defined by

$$s_e = \sqrt{1 - C_{xy}(i\Delta t)_{max}}$$

is the measure of the "goodness of fit" between the two series.

The significance of a determined correlation is tested according to R.A. Fisher using the t-distribution with n - 2 degrees of freedom

$$\hat{t} = |C_{xy}|\sqrt{\frac{n-2}{1-C_{xy}^2}}$$

For $\hat{t} \geq t_{n-2;\alpha}$, where $(1-\alpha)$ is the significance level desired, the null hypothesis is rejected. The values of $t_{n-2;\alpha}$ are obtained from standard tables (eg Sacks (1982), p.425). The 95% significance level was used as the criterion of significance (i.e. $\alpha = 0.05$).

In oceanographic time series, the number of degrees of freedom, n, is not the same as the number of data points, N, in the series, since consecutive values in the series are not independent. The degrees of freedom used here were determined following the method of Davis (1976). Davis defines a time scale τ such that

$$\tau = \sum_{i=-\infty}^{\infty} C_{xx}(i\Delta t)\,C_{yy}(i\Delta t)\,\Delta t$$

where C_{xx}, C_{yy} are the autocorrelation functions of the two series $x(t)$, $y(t)$ sampled at intervals Δt. In practice, the summation becomes

$$\tau = \sum_{i=-m}^{m} C_{xx}(i\Delta t)\,C_{yy}(i\Delta t)\,\Delta t \qquad (2)$$

where m is large compared to the lag number at which both $C_{xx}(t)$ and $C_{yy}(t)$ are statistically zero. τ is the length of time needed to gain a new degree of freedom. The number of degrees of freedom is then given by

$$n = \frac{N \Delta t}{\tau}$$

As has been stated when discussing power spectral analysis it is usual to take the maximum lag in the calculation of the autocorrelation function as not more than 10% of the total number of data points. Taking $m > \frac{N}{10}$ leads to a bias in the autocorrelation because of the denominator in equation (1), which becomes small as m increases.

For the analyses to be undertaken it was not possible to increase N to make it large enough that $C_{xx}\left(\frac{N\Delta t}{10}\right)$ and $C_{yy}\left(\frac{N\Delta t}{10}\right)$ were zero. The autocorrelation functions tended to oscillate about zero. Thus for the calculation of τ, m was taken as N/4 and τ was computed as the maximum value of the sum on the right hand side of equation (2).

$$\text{i.e. } \sum_{i=-\frac{N}{4}}^{\frac{N}{4}} C_{xx}(i\Delta t)\, C_{yy}(i\Delta t)\, \Delta t$$

$$= C_{xx}(0)\, C_{yy}(0)\, \Delta t + 2\sum_{i=1}^{N/4} C_{xx}(i\Delta t)\, C_{yy}(i\Delta t)\, \Delta t$$

$$= \Delta t + 2\sum_{i=1}^{N/4} C_{xx}(i\Delta t)\, C_{yy}(i\Delta t)\, \Delta t \qquad (3)$$

(since by definition $C_{xx}(0)$, $C_{yy}(0)$ are unity and the autocorrelation function is symmetric).

Figure 3 shows some examples of autocorrelation functions and the calculation of τ for cross-correlation between Lamberts Bay and Gansbaai for 1656 hourly sea level heights for the period 1982 February 20 - April 29. In Fig.3(a) the data sets have not been filtered using the 120 point double running mean. Fig.3(b) shows the effect of this filter on the autocorrelation functions and on the determination of τ. It can be seen that in Fig.3(a) the maximum value of τ is attained after only 67 lags whereas in Fig.3(b) τ is still increasing (albeit slowly) after $\frac{N}{4}$ lags. This can be explained by the fact that the autocorrelation functions of the two series oscillate in phase after filtering. Thus the product of the auto-correlation functions will always be positive and the sum in (2) will increase with increasing lag. Note that in Fig.3(b) taking $m = \frac{N}{10}$ would give a much smaller value of τ than taking $m = \frac{N}{4}$. It should also be noted here that filtering did not always have the effect shown in this example.

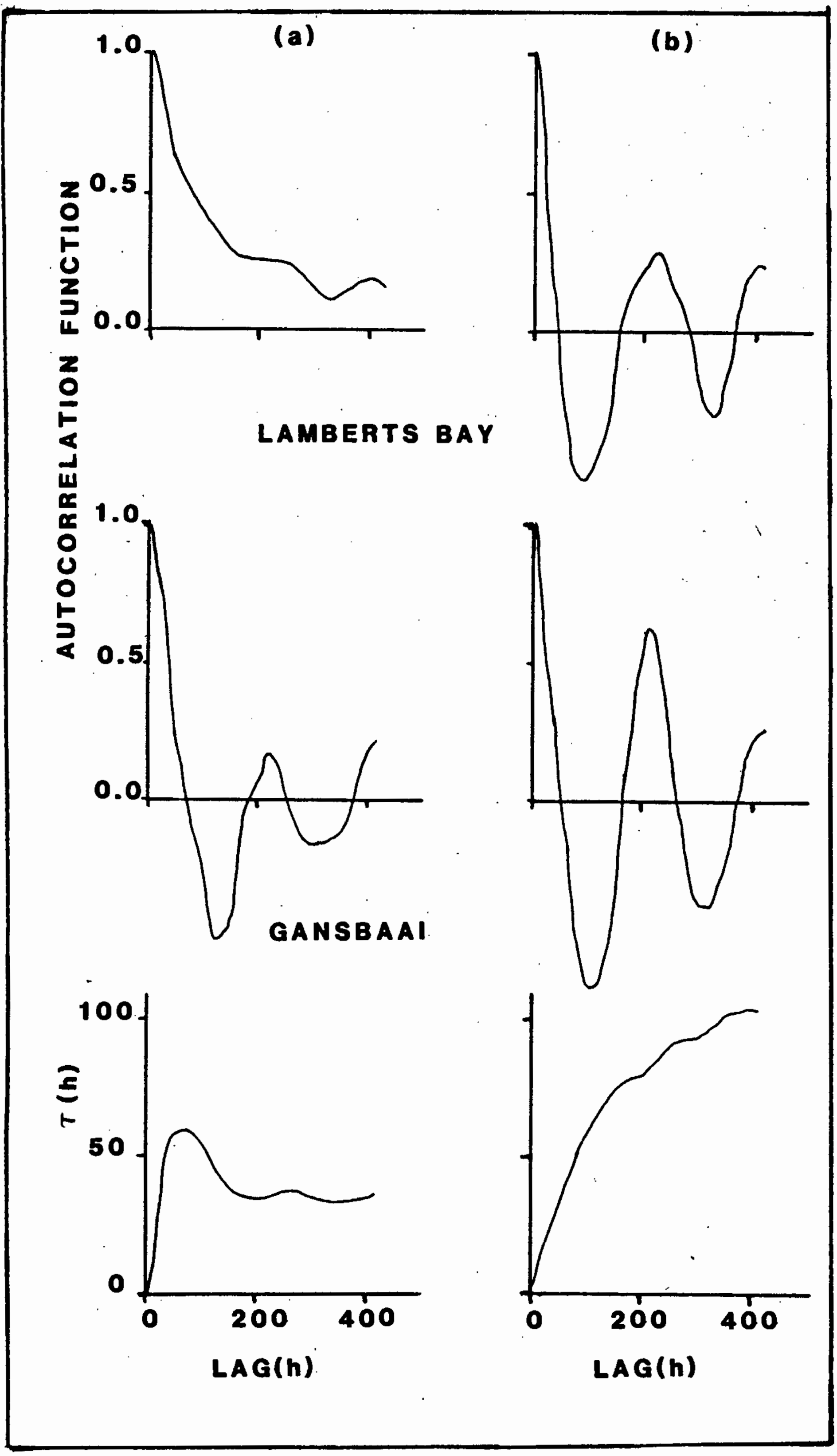


FIG. 3 Autocorrelation functions and τ for sea level at Lamberts Bay and Gansbaai 1982 February 20 - April 29
(a) unfiltered
(b) filtered with 120 point double running mean

3.1.3 Regression analysis and the barometer effect

Consider two random variables x and y between which there exists a linear relationship. There exist two regression lines, one inferring y from x and the other inferring x from y. The correlation coefficient measures the strength of the linear relationship between the two variables. If the correlation coefficient is unity, then the two regression lines coincide. If the correlation coefficient is zero, then the two regression lines are perpendicular to each other and parallel to the co-ordinate axes. The parameters of the regression lines are estimated using the method of least squares. For the estimation of y from x the equation is

$$\hat{y} = a_{yx} + b_{yx}x$$

where

$$b_{yx} = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - \{\sum x\}^2}$$

$$a_{yx} = \frac{\sum y - b_{yx}\sum x}{n}$$

$$= \bar{y} - b_{yx}\bar{x}$$ where $\bar{\ }$ denotes mean

For the estimation of x from y, the equation is

$$x = a_{xy} + b_{xy}y$$

where

$$b_{xy} = \frac{n\sum xy - \sum x \sum y}{n\sum y^2 - \{\sum y\}^2}$$

$$a_{xy} = \frac{\sum x - b_{xy}\sum y}{n}$$

$$= \bar{x} - b_{xy}\bar{y}$$

For n large, b_{yx} and b_{xy} may be written

$$b_{yx} = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

$$b_{xy} = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sum y^2 - \frac{(\sum y)^2}{n}}$$

The correlation coefficient is given by

$$r_{xy} = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sqrt{\left[\sum x^2 - \frac{(\sum x)^2}{n}\right]\left[\sum y^2 - \frac{(\sum y)^2}{n}\right]}}$$

$$\sqrt{b_{yx} b_{xy}}$$

Alternative forms may be used.

Defining s_{xy} as the covariance of x and y and S_x , S_y as the standard deviations of x and y respectively, and recalling that $S_x^2 = s_{xx}(0)$ then

$$r_{xy} = \frac{s_{xy}}{\sqrt{s_{xx}(0)\, s_{yy}(0)}}, \quad b_{yx} = \frac{s_{xy}}{S_y^2}, \quad b_{xy} = \frac{s_{xy}}{S_x^2}$$

$$b_{yx} = \frac{r_{xy}\sqrt{s_{xx}(0)\, s_{yy}(0)}}{s_{xx}(0)}$$

$$= r_{xy}\sqrt{\frac{s_{yy}(0)}{s_{xx}(0)}}$$

Taking x as atmospheric pressure and y as sea level, the barometer effect is given by b_{yx} and can be obtained through the cross-correlation analysis between negative pressure and sea level.

3.2 Analyses performed and comparisons made between data sets

The actual analyses which were performed on the data sets were:

(1) The monthly mean adjusted sea level at Simons Bay, 1958-1982, Data Set 1F, was plotted to illustrate the long term trend in the data.

(2) A spectral analysis was performed on part of this data set, using the period 1960-1978. This was to identify the frequencies present in the data. The spectrum was plotted.

(3) A two month double running mean was applied to the monthly mean adjusted sea level heights at Walvis Bay, Luderitz Bay, Simons Bay and Mossel Bay contained in Data Set 2F. The results were plotted for the six year period to show the seasonal variation at different sites. Using these filtered values, the six year average was determined for each month at the four sites. This was plotted to illustrate the average seasonal fluctuation in adjusted sea level and its variation between the northern and southern coastal areas.

(4) Spectral analyses were performed on the long, unbroken sea level records at Walvis Bay, Data Set 3F and Simons Bay, Data Set 4F, using two data points per day at 0000h and 1200h, to identify the frequencies of interest in the data. The resulting spectra were plotted and compared.

(5) Power spectra were also obtained from the 1982 sea level data, Data Set 5F. The spectra were obtained for two periods during the year corresponding roughly to the first and second halves of the year. The second period contained most of the winter data from several of the ports, with the first period ending early in June. Table 6 shows the exact periods used for each port.

Table 6

Periods of comparison for sea level spectra 1982.

Port	First period 1982	Second period 1982
Walvis Bay	January 2-June 3 (153 days)	June 10-December 24 (197 days)
Luderitz Bay	January 2-June 3	June 10-December 8 (182 days)
Port Nolloth	February 13-June 13 (121 days)	June 10-December 24
Simons Bay	January 2-June 3	June 10-December 24
Gansbaai	February 20-June 29 (130 days)	
Port Elizabeth		June 3-December 16 (197 days)
Durban	January 2-June 3	June 10-December 24

The data at Gansbaai and Port Elizabeth contained several gaps and so only one spectrum was obtained for each port. The data at Lamberts Bay contained too many gaps to be used at all for this purpose. Two data points per day were used as in analysis (4) above. As the frequencies of particular interest here are in the range 0.1 - 0.25 cpd, no significant increase in accuracy would be achieved by using data at more frequent intervals. All the resulting spectra were plotted on the same scale.

(6) The daily mean sea level heights at 1200h at all nine ports, taken from Data Set 5F, were plotted on one graph.

(7) Cross-correlations were performed using sea level data from Data Set 5F at adjacent ports for the time periods already noted in Chapter 2.3. The same cross-correlations were repeated after filtering the data with the 120 point double running mean or 10 day filter. Some analyses were also repeated after filtering the data with a 144 point double running mean or 12 day filter. For each cross-correlation the number of degrees of freedom was determined. The Doodson filtered sea level heights were plotted at daily intervals for the periods of the cross-correlations. The results of all cross-correlations were also plotted and significance levels shown on the graphs.

(8) Power spectra were obtained for the atmospheric pressure data at Lamberts Bay and Gansbaai using two data points per day. The spectra were obtained for two periods in the year for comparison with the results of analysis (5) above. The exact periods used for each port are given in Table 7.

Table 7

Periods of comparison for atmospheric pressure spectra 1982

Port	First Period 1982	Second period 1982
Lamberts Bay	January 2 - June 3 (153 d)	July 20 - December 30 (164 d)
Gansbaai	February 20 - June 29 (130 d)	June 10 - October 28 (141 d)

(9) Cross-correlations were performed between hourly sea level heights and atmospheric pressure at Lamberts Bay and Gansbaai, using Data Set 6F, for the periods (i), (ii) and (iii) in Chapter 2.3. At Lamberts Bay the same cross-correlation was performed for period (a) in chapter 2.3. These analyses were repeated after applying the 10 day filter to the data.

Using regression analysis, the size of the barometer effect was determined at the two ports for each of the periods above. Using the theoretical value of 1 mb pressure to 1 cm sea level and a baseline pressure of 1014 mb as before for monthly means, the hourly sea level heights were adjusted for pressure. The lag at which the cross-correlation between sea level and negative pressure was a maximum was used in applying the correction. The sea level heights, atmospheric pressure, adjusted sea level heights and longshore and offshore wind components were plotted for the two periods (i) and (ii) in chapter 2.3. Sea level and pressure were plotted at daily and wind components at twelve-hourly intervals. For period (ii), wind data at Gansbaai were available for only the last 20 days. Cross-correlations were then performed to investigate the possible relationships between longshore wind and sea level at each port and between pressure and longshore wind at each port. The relationship between the sea level variations at the two ports was then investigated by the following cross-correlations:

a. unadjusted sea level heights at Lamberts Bay and Gansbaai
b. adjusted sea level heights at Lamberts Bay and Gansbaai
c. atmospheric pressure at Lamberts Bay and Gansbaai
d. longshore wind at Lamberts Bay and Gansbaai
e. longshore wind at Lamberts Bay and sea level at Gansbaai
f. pressure at Lamberts Bay and sea level at Simons Bay
g. pressure at Gansbaai and sea level at Simons Bay.

These analyses were all repeated after filtering the data with the 120 point double running mean. The numbers of degrees of freedom were found for all the analyses.

CHAPTER 4 OVERVIEW OF RESULTS

4.1 Dominant scales of variability

Provided that it is of sufficient length, the sea level record at any port will provide evidence of several different time scales of variability. Usually the most obvious is the tidal scale, which may be semi-diurnal, diurnal or a mixture of both. Synoptic event scale fluctuations, of period 2-20 days, related to changes in the synoptic scale meteorology of the area, may also be apparent. There are usually seasonal fluctuations, of period 3-6 months, related to the seasonal movement of pressure systems in the atmosphere overhead. Finally, an interannual or long term scale, with a period of a few years, may be detected.

From the data available at Southern African ports, it is possible to identify all four of these time scales of variability and their magnitude. As the longest unbroken set of sea level data comes from Simons Bay, this port has been chosen for illustrative purposes. Later comparisons are made between ports where differences occur.

4.1.1 Tidal scale

Figure 4(a) shows the sea level record for the month of October 1982 at Simons Bay. It is typical of the record at all Southern African ports. The most dominant scale of variability is the tidal scale, semi-diurnal in type, with

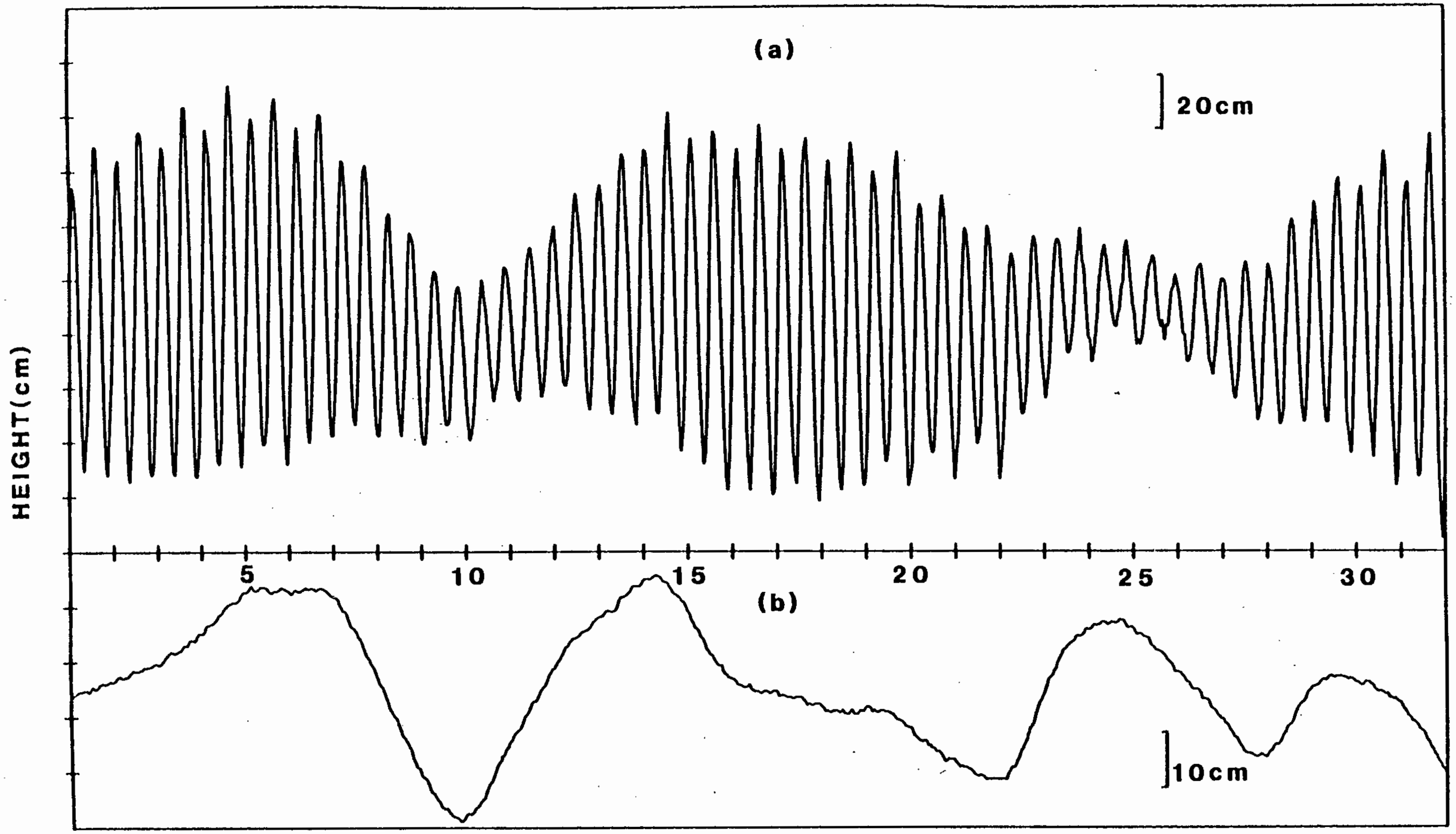


FIG.4 SEA LEVEL AT SIMONS BAY OCTOBER 1982.
(A) HOURLY OBSERVED HEIGHTS.
(B) HOURLY DOODSON FILTERED HEIGHTS.

a range of 1.5 - 2.0 m. The difference between spring tide and neap tide can be seen clearly. The diurnal inequality, though slight, is also visible.

4.1.2 Event scale

The same sea level record at Simons Bay is presented in Figure 4(b) after the Doodson tide-killer has been applied to remove the tidal component of variability. There is a change in vertical scale in Figure 4 such that 1 cm corresponds to 20 cm sea level in (a) and to 10 cm sea level in (b). Fluctuations of magnitude ± 30 cm, lasting several days, are evident in any such record. Figure 5 shows daily mean sea level at Simons Bay for 1982, from which it can be seen that these event scale fluctuations occur throughout the year and are the dominant fluctuations once the tidal component has been removed. As a detailed study of these fluctuations is the purpose of this thesis, further discussion will be reserved for a later chapter.

4.1.3 Seasonal scale

There is slight evidence in Figure 5 of a seasonal trend in the sea level data at Simons Bay. The data set used for this figure had not been adjusted for atmospheric pressure. To illustrate the seasonal trend more clearly and accurately, monthly mean pressure adjusted sea level for the period 1960-1965 from Data Set 2F were used. Figure 6(a) shows the monthly mean adjusted sea level at Simons

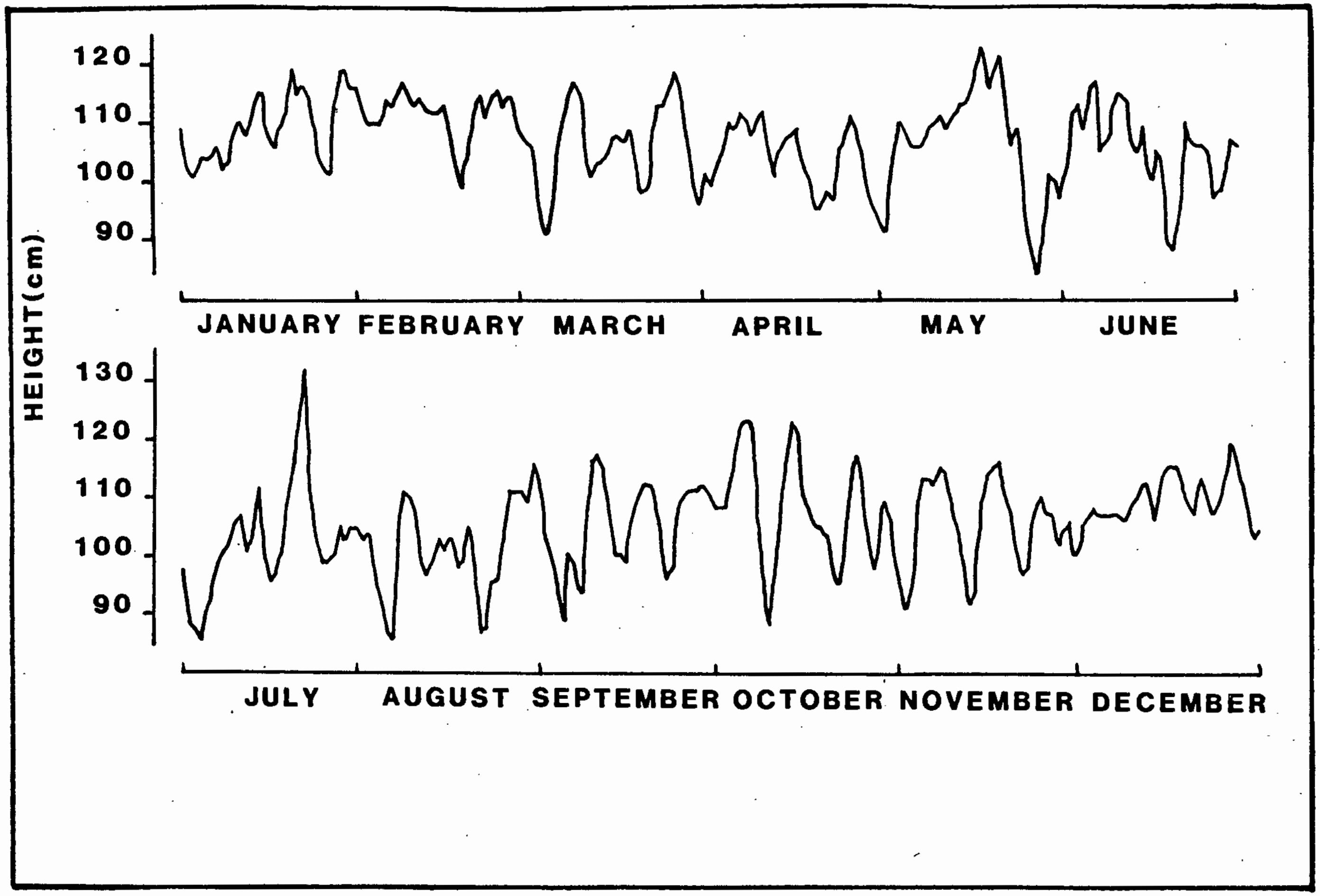


FIG.5 Daily mean sea level at Simons Bay 1982

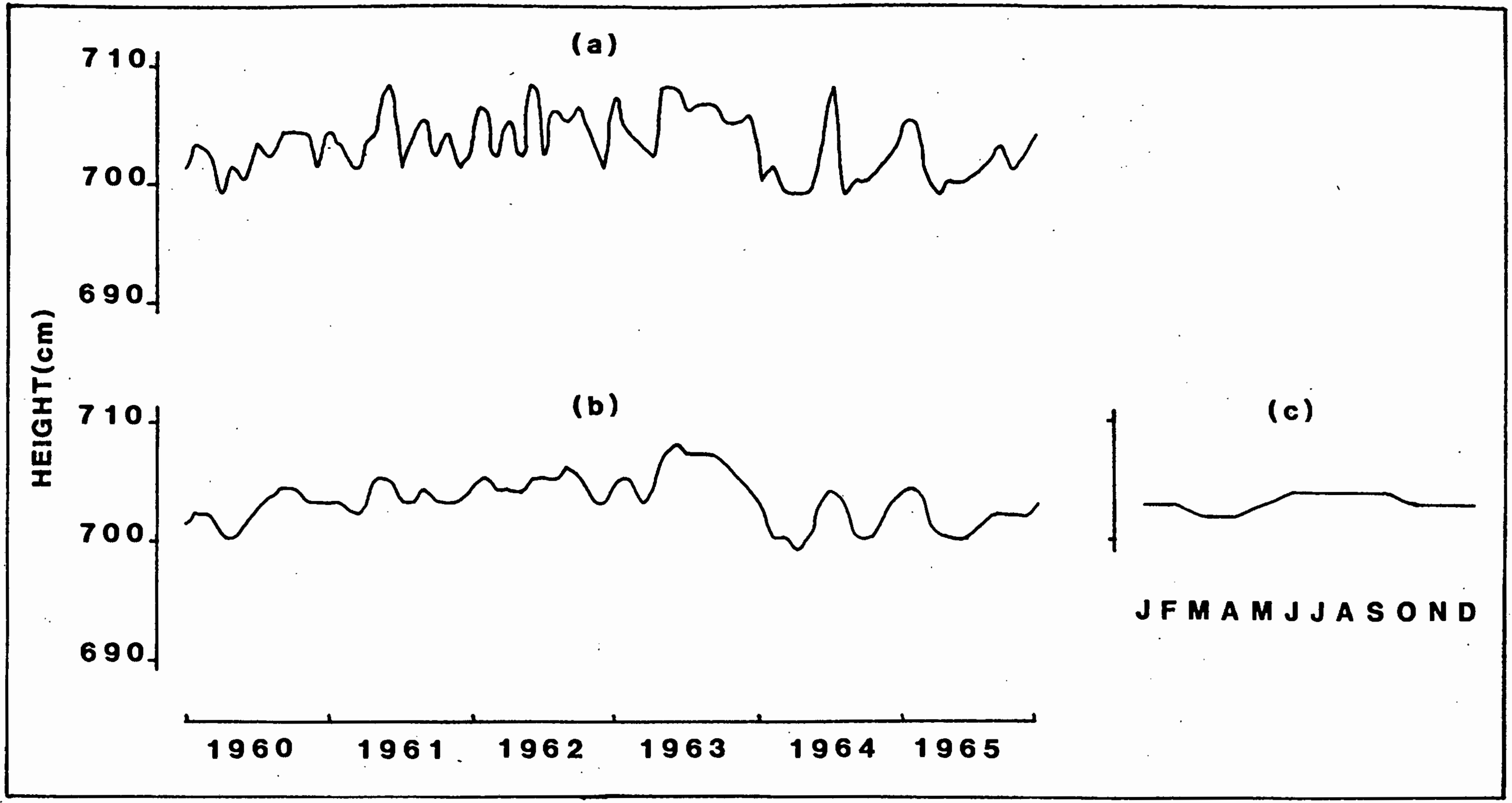


FIG. 6 Pressure adjusted sea level at Simons Bay
(a) Monthly mean 1960 - 1965
(b) Two-month double running mean 1960 - 1965
(c) Average monthly mean from (b)

Bay for this period. Figure 6(b) shows the same data after filtering with a two month double running mean. The jaggedness in the record, which occurs as a result of the influence of synoptic scale fluctuations, has been much reduced and the annual range in monthly means reduced from 10-15 cm to 3-5 cm. Figure 6(c) shows the filtered monthly means averaged over the six years. This illustrates the average seasonal cycle at Simons Bay with low sea level at the beginning and end of the year and maximum sea level in the middle of the year. The annual range in the average monthly mean sea level is reduced to 2 cm.

4.1.4 Interannual scale

Figure 7(a) shows monthly mean adjusted sea level at Simons Bay for the period 1958-1982. In 1959 there was a change of datum of unknown magnitude, accounting for the sudden jump in level. The datum was changed at least four times during 1979 and it has not been possible to join the data satisfactorily. However a long term trend can be seen in the data, with high sea level occurring in 1962-3, 1968-9 and 1978 and low sea level in 1965-6 and 1970-1. A distinct downward trend can be seen from 1980 to 1982, with a decrease in annual mean of about 4 cm between 1980 and 1982. In Figure 7(b), which shows the monthly mean adjusted sea level filtered with a twelve month double running mean for the period 1960-1977, the long term fluctuation is much more distinct and agrees with that of Figure 7(a).

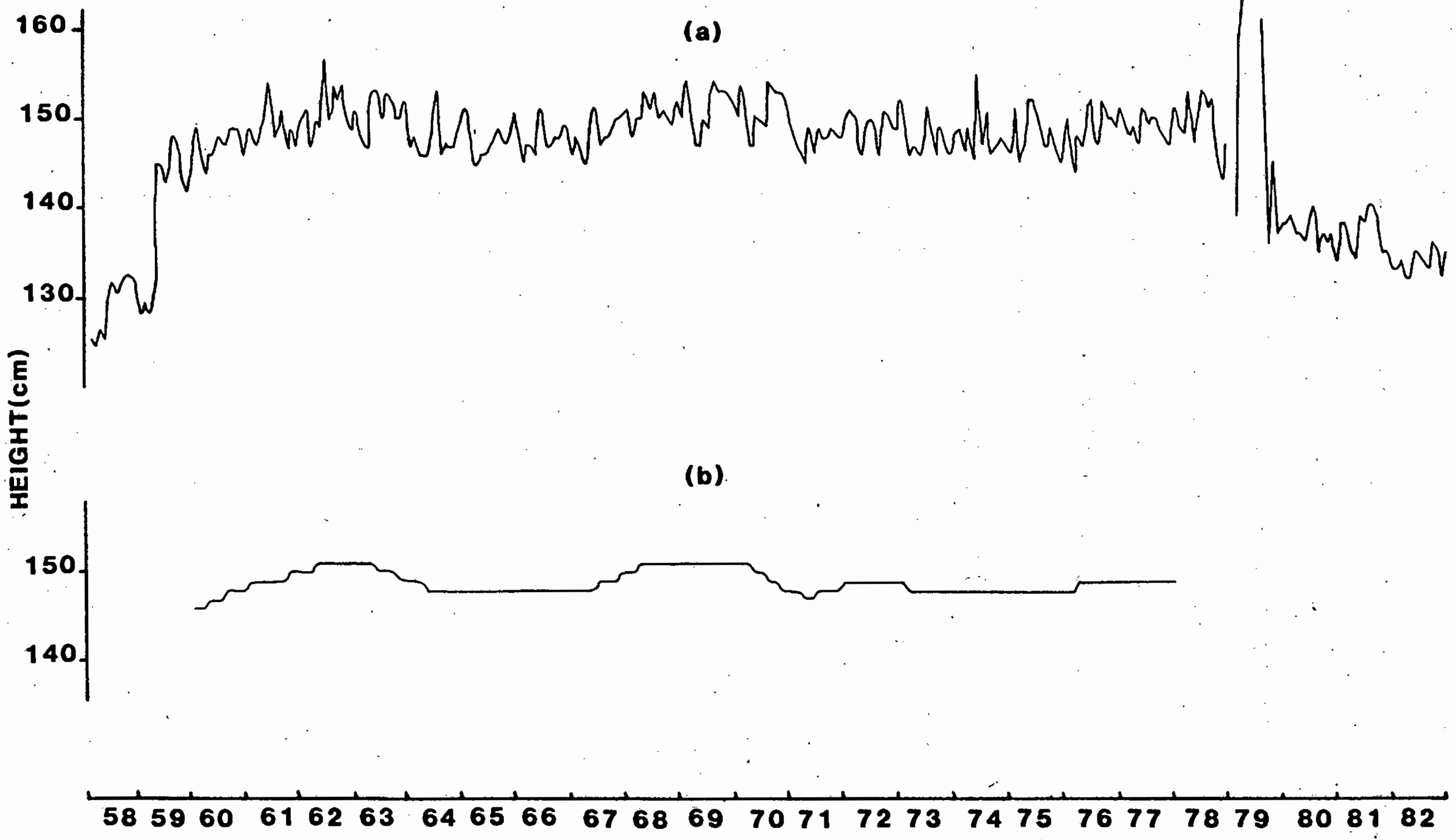


FIG.7 Adjusted sea level at Simons Bay
(a) Monthly mean 1958 - 1982
(b) Twelve-month double running mean 1960 - 1977

4.2 Power Spectrum of monthly mean adjusted sea level at Simons Bay 1960-1978

The power spectrum obtained from the monthly mean adjusted sea level at Simons Bay, shown in Figure 8, confirms the existence of fluctuations of periods corresponding to the seasonal and interannual time scales. The peaks at 12 months and 6 months may well contain contributions from the annual and semi-annual tidal variations. Using monthly data it is not possible to resolve the event scale fluctuations.

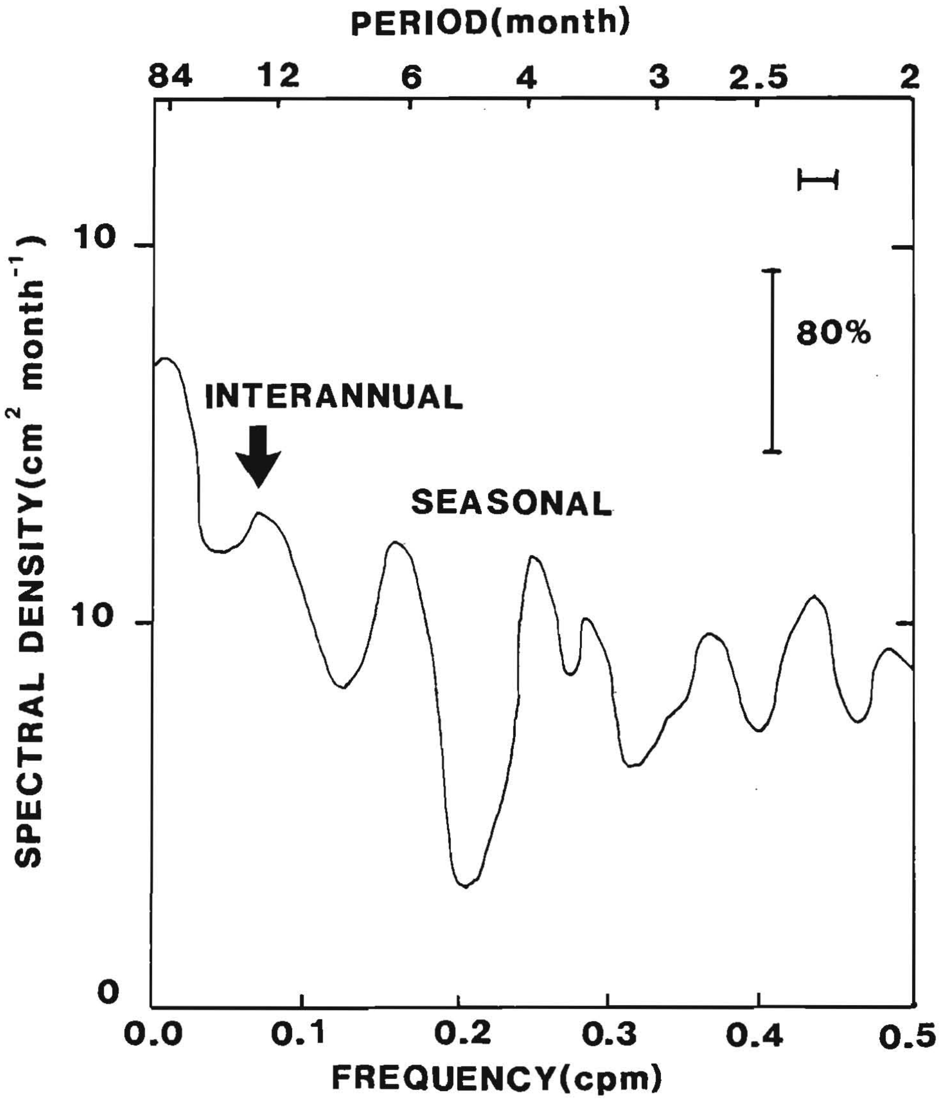


FIG.8 Power spectrum of monthly mean adjusted sea level at Simons Bay 1960 - 1978

4.3 Comparisons between sites

4.3.1 Seasonal scale

Using Data Set 2F, the monthly mean adjusted sea level heights for the period 1960-1965 at Walvis Bay, Luderitz Bay and Mossel Bay were filtered with a two month double running mean and plotted for comparison with the same data at Simons Bay. Again the average seasonal pattern was established for each port. The results, together with those from Simons Bay, are shown in Figure 9(a) and (b). The seasonal range at all ports is 2 - 9 cm per year, and the annual range in the average seasonal pattern is reduced to 2 - 5 cm.

There is a clear difference between the seasonal response at the northern ports and that at the southern ports as shown in Figure 9(b). Brundrit et al (1984) discussed this in terms of the winds "If there is a seasonal response due to seasonally strong and persistently high south winds, then the adjusted sea level should normally be depressed at the beginning and end of the year in the south, and in the middle of the year in the north". The results in Figures 6 and 9 are consistent with this explanation.

Figure 10 shows the monthly mean sea level and atmospheric pressure for 1982 for the nine ports being considered. This illustrates how the measured sea level and atmospheric pressure vary through the year. Average atmospheric pressure

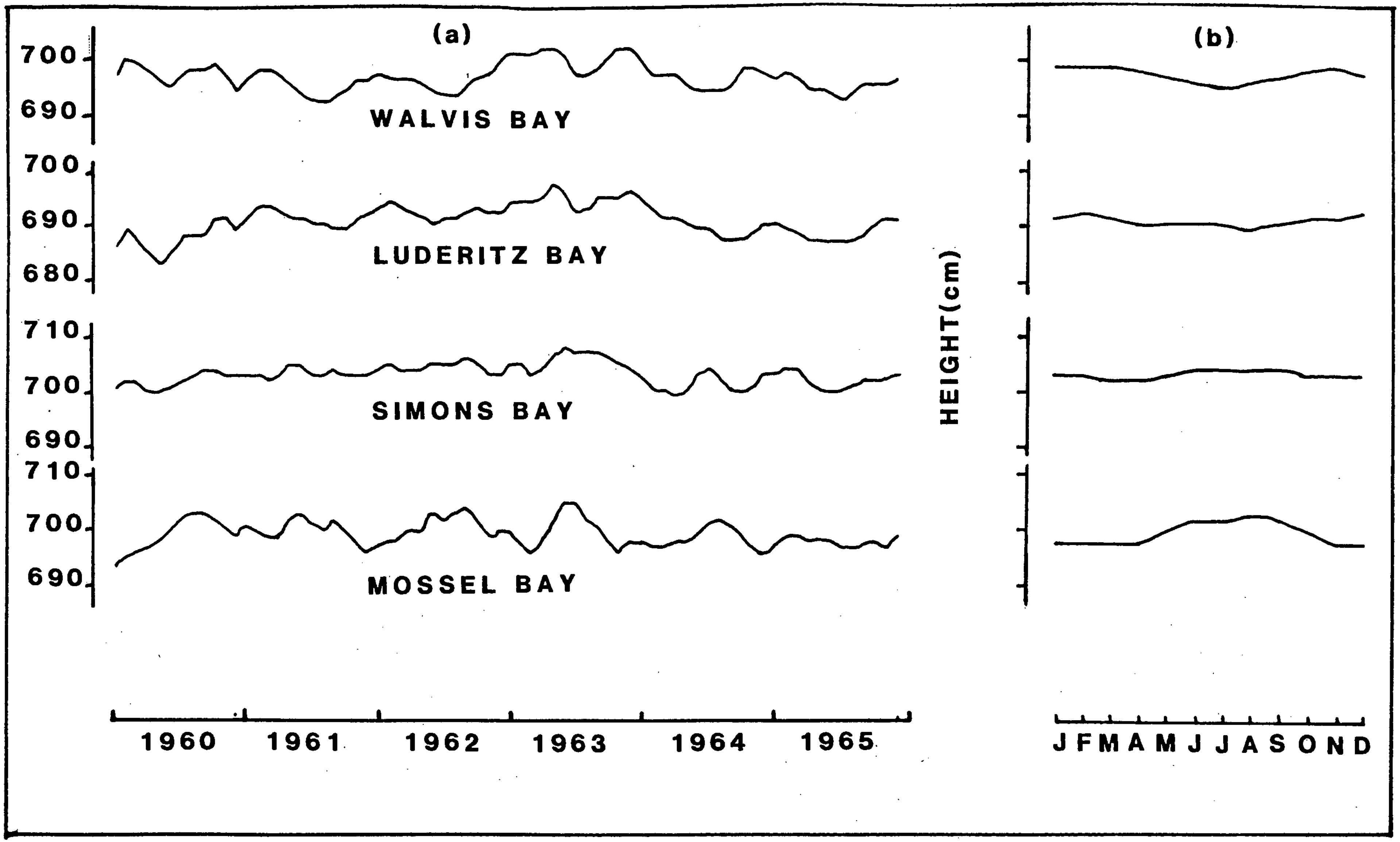


FIG. 9 Adjusted sea level at Walvis Bay, Luderitz Bay, Simons Bay and Mossel Bay
(a) Two-month double running mean 1960 - 1965
(b) Average monthly mean from (a)

is several millibars higher in winter than in summer and the opposite effect is apparent in the observed sea level. The adjusted monthly mean sea level for 1982 (not shown) compares well with the average in Figure 9(b) except towards the end of the year at the southern ports. This supports the explanation that winds are responsible for the seasonal scale fluctuations, since there was a notable absence of south-easterly winds during the summer of 1982-3 in the Southern Cape (Nelson and Walker, 1984; Hutchings et al, 1984).

4.3.2 Interannual Scale

In Figure 9(a) there is evidence that the long term trend at all four sites is similar with increased sea level in 1962-3 and low sea level in 1965. Similarly the downward trend noted in monthly mean adjusted sea level at Simons Bay between 1980 and 1982 is also very marked at Walvis Bay (not shown). Principal components analysis by Brundrit (1984) confirms that the interannual trend is of a very large spatial scale and similar at all sites along the west coast. Longer data sets would be needed to determine whether this also applies to the south coast.

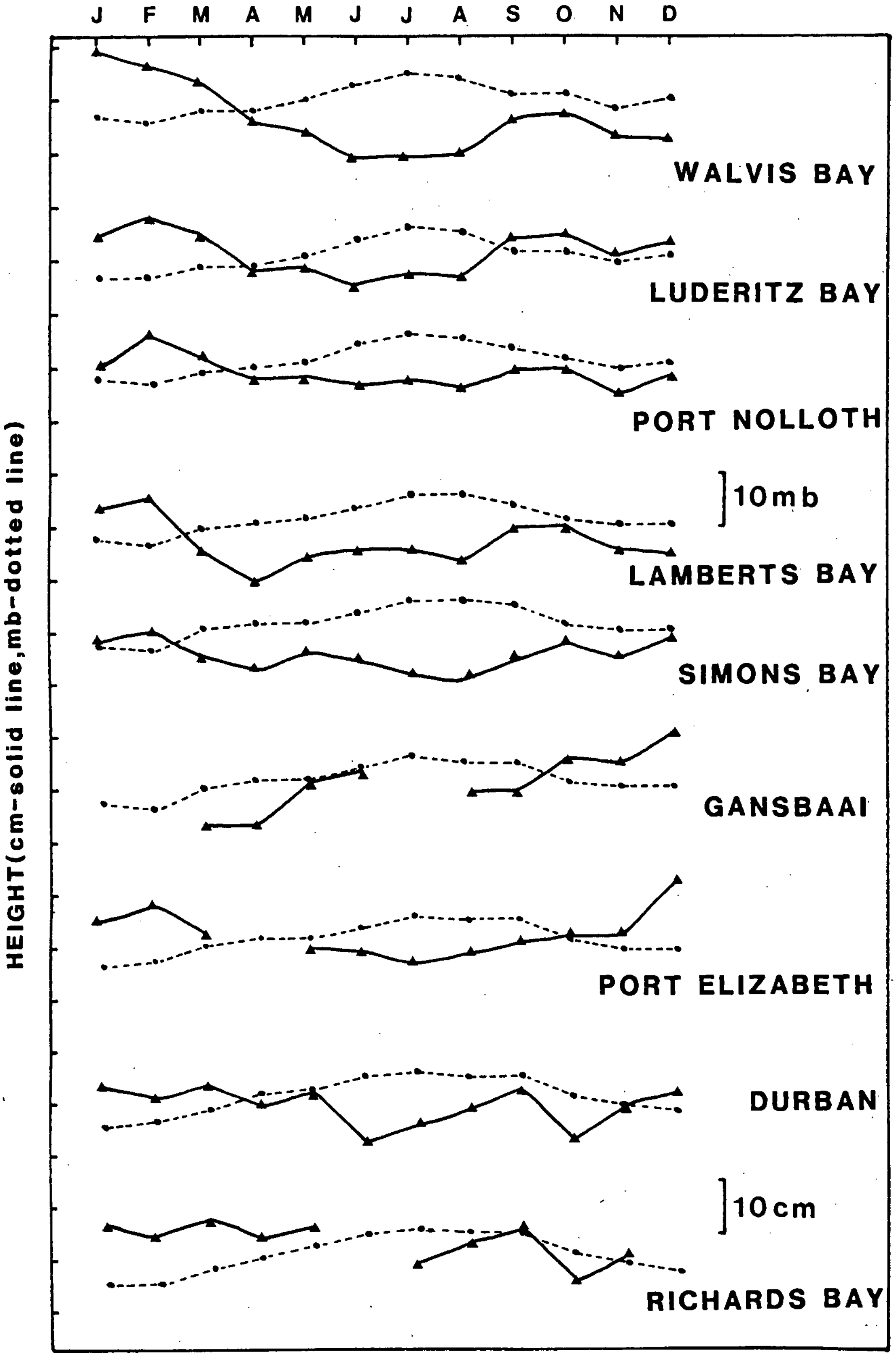


FIG.10 Monthly mean sea level (solid line) and pressure (dotted line) 1982

CHAPTER 5 EVENT SCALE DETAILS AND DISCUSSION

In the previous chapter brief mention was made of the event scale fluctuations apparent in the record of Doodson filtered daily mean sea level at Simons Bay for 1982 (Figure 4(b)). These fluctuations will now be studied in detail to establish the relationship with the synoptic scale meteorology of the coastal areas. Initially a brief overview of the data will be given and then a summary of the main meteorological features of the coastal areas of Namibia and South Africa.

5.1 Overview of the data

Daily mean sea level for 1982 at the nine ports under consideration is shown in Figure 11. This demonstrates clearly the event scale fluctuations in sea level with many events appearing coherent at all the ports from Walvis Bay to Port Elizabeth and occasionally as far as Durban and Richards Bay. Events appear to start at Walvis Bay, travel down the west coast and then eastwards along the south coast in accordance with Robinson's theory of shelf waves. The speed of propagation, as measured by the time taken between the start of an event at two adjacent ports, appears to be variable down the west coast but more constant along the south coast. Sometimes an event appears at Simons Bay on the same day as it develops at Walvis Bay; at other times there is a delay of up to two days.

Certain events are apparent only along the west coast. Early in December there is an event evident between Walvis Bay and Lamberts

FIG.11 Daily mean sea level 1982

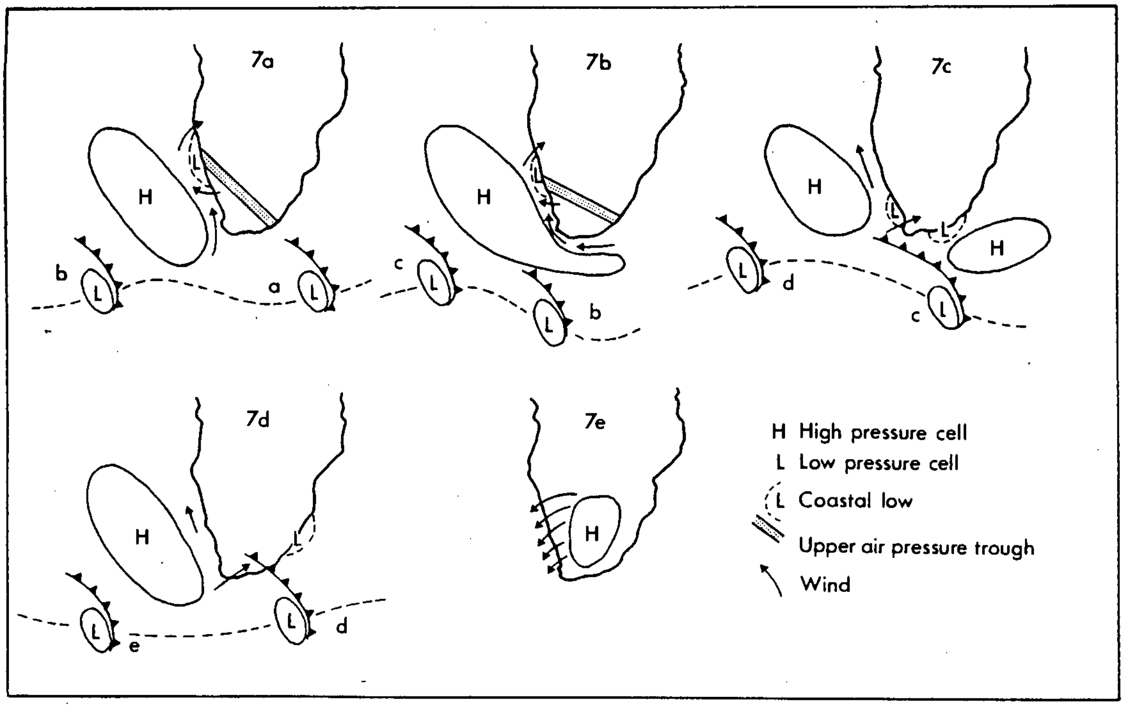
Bay. At the end of January there is a slight fluctuation in sea level which is visible only at Walvis Bay and Luderitz Bay. Similarly, some events only affect the south coast. The magnitude of the sea level variation during individual events usually appears to increase southwards with propagation. There are exceptions such as in July when the range at Port Nolloth is extremely large.

5.2 Meteorology of the coastal areas of Southern Africa

The meteorology of the Southern Hemisphere has been described in detail by Taljaard (1972). Hart and Currie (1960) discussed the meteorology of the west coast of Southern Africa in a study of the Benguela current, as did Nelson and Hutchings (1983) more recently in a review paper on upwelling. Duncan (1970) described the east coast meteorology in detail in a study of the Agulhas current. A summary of the important features is essential to any discussion of event scale fluctuations in sea level.

The winds over the coastal regions of Southern Africa are controlled by the positions of the subtropical high pressure systems over the South Atlantic and Indian Oceans and their interaction with the westerlies in the north and the south-east trades in the south. The South Atlantic high pressure system is fairly close to the continent and influences much of the south coast as well as the west coast. The Indian Ocean high pressure system has its centre far out to sea and so influences only the eastern part of the South African coast.

In summer the high pressure systems have their centres at about the latitude of Cape Town (34^oS). The westerlies blow far south of the continent with little influence on it. The winds along the west and south coasts are predominantly south or south-easterly, with their strength determined by the pressure gradient between the South Atlantic high and the low presssure system over the continent. The winds along the west coast are reinforced by the south-east trades which blow north of the Atlantic high. The winds are strongest between 25^{o}S and 30^{o}S as diurnal heating and cooling influence the velocity and direction of the wind further north. Along the east coast, the south-east trades combine with the easterly winds north of the Indian Ocean high to bring south-easterly or easterly winds to this area. The weather pattern is illustrated in the figure below reproduced from Nelson and Hutchings (1983).



Cyclic weather pattern typical of summer conditions
(a) South Atlantic high established. Coastal low at Luderitz Bay. Southerly winds at Cape Town.
(b) South Atlantic high ridging. Gale force winds at Cape Town. Coastal low moves south.
(c) South Atlantic high weakens. North west winds at Cape Town following passage of coastal low.
(d) South Atlantic high strengthens. Southerly winds along west coast.
(e) Berg wind conditions.

In winter the high pressure systems over the oceans move a few degrees northwards (van Loon, 1972) and intensify slightly. North of this the winds are as in summer, with the strongest winds at about the latitude of Walvis Bay. The entire southern region from Port Nolloth south, comes under the influence of the westerlies and mid-latitude depressions travelling east from the south-west Atlantic. These are often accompanied by cold fronts which cause the north-westerly gales followed by south-westerly winds.

An important element in the coastal meteorology is the coastal low which is found along both the west and east coasts. A strong offshore flow of air at plateau height lowers pressure over the coast forming a cell of low pressure which then travels under the influence of the prevailing surface winds. This is usually southwards along the west coast although northwards is possible. Along the south coast coastal lows always travel in a north-easterly direction.

A recent workshop on coastal lows resulted in a classification into three groups which, because of its relevance to this study, is quoted here.

"Class 1: The "summer" west coast low

Development of the west coast low begins with the zonal ridging of a high pressure cell to the south of the continent. As the anticyclone moves eastwards, offshore flow extends down the west coast bringing with it the coastal low. If the ridging is blocked, offshore flow may persist above a shallow layer of SW winds, creating a strong inversion. In these cases the coastal low may remain over the west coast and become essentially stationary. Indeed if the ridge strengthens, the coastal low can move northward in association with the forcing function.

Class 2: The travelling coastal low

This sequence of synoptic events is one in which the high pressure ridges to the south, leading to the formation of a coastal low on the west coast. The coastal low moves down the west coast as a trough of low pressure with its associated cold front approaches from the west. The forcing function shifts to the south coast and a coastal low propagates in front of the trough. As the cold front system moves along the south coast, the coastal low moves ahead as long as the forcing function precedes it.

Class 3: The "winter" south coast low

This is the situation when the South Atlantic High takes up a more northerly position and does not ridge in to the south of the continent. A series of cold fronts associated with a single westerly wave can pass over the south of the country. Prior to the passage of the first cold front, the forcing function will be established on the south coast and the coastal low will act as a leader cell. Re-establishment of the forcing function between the passage of each cold front in the series does not usually occur."

Although Class 1 and Class 3 coastal lows are classified as "summer" and "winter" respectively, all three types are found throughout the year. The synoptic situation giving rise to a coastal low of a particular class is more often found during the season prescribed.

The formation of a coastal low, in association with offshore winds, will lead to an increase in sea level. As the coastal low progresses down the west coast, the sea under it should be raised. Behind the coastal low, the increasing pressure and onshore winds will encourage a return to equilibrium. If the passage of the coastal low is blocked, the accompanying increase in sea level will not propagate. The ridging of high pressure south of the continent has associated with it southerly or south-easterly winds which cause a decrease in sea level (upwelling event).

The approach of a cold front from the west with a coastal low as leader may enhance the initial increase in sea level due to the coastal low, as the winds associated with the cold front reinforce those associated with the coastal low. After the cold front has passed, sea level will decrease. If the winds are strong, or the South Atlantic high ridges in after the cold front, this decrease will appear as an upwelling event. The lag between pressure changes and wind changes will be crucial to what happens in a particular event.

5.3 Power spectra of sea level

Using Data Set 4F power spectra were obtained for sea level data at Walvis Bay and Simons Bay to establish the periodicities of interest in the range 2-40 days. As expected most energy is found at the long period end (> 40 days) at both ports. Both spectra exhibit peaks at periods of 10-12 days and around 4 days. At Simons Bay there is also increased energy at about 20 days which is not evident at Walvis Bay. Similar peaks were, however, visible in spectra of tidal data from Port Elizabeth and Durban calculated by Schumann (1981). Preston-Whyte and Tyson (1973) published spectra of surface pressure at Cape Town for the periods 1965-6 and 1965-9. These showed peaks at a period of 20 days. The peak in sea level spectra would appear to be related to atmospheric pressure fluctuations.

The power spectra for the Doodson filtered daily mean sea level at 12-hourly intervals obtained from Data Set 5F for the time periods specified in Table 6 are shown in Figure 12(a) and (b). The vertical scale is shown in the centre of the diagram. The origins of the individual graphs have been displaced in order to accommodate all ports on one graph. The closest value (10^2 or 10^3) to the energy at 0.05 cpd has been marked on the left of the graph for each port. Energy is plotted on a logarithmic scale so that the 80% confidence limit shown is the same for all frequencies. Although the observed peaks are sometimes below the 80% confidence limits, repeated analyses with data from other years show peaks at the same frequencies. Only frequencies between 0.05 cpd and 0.425

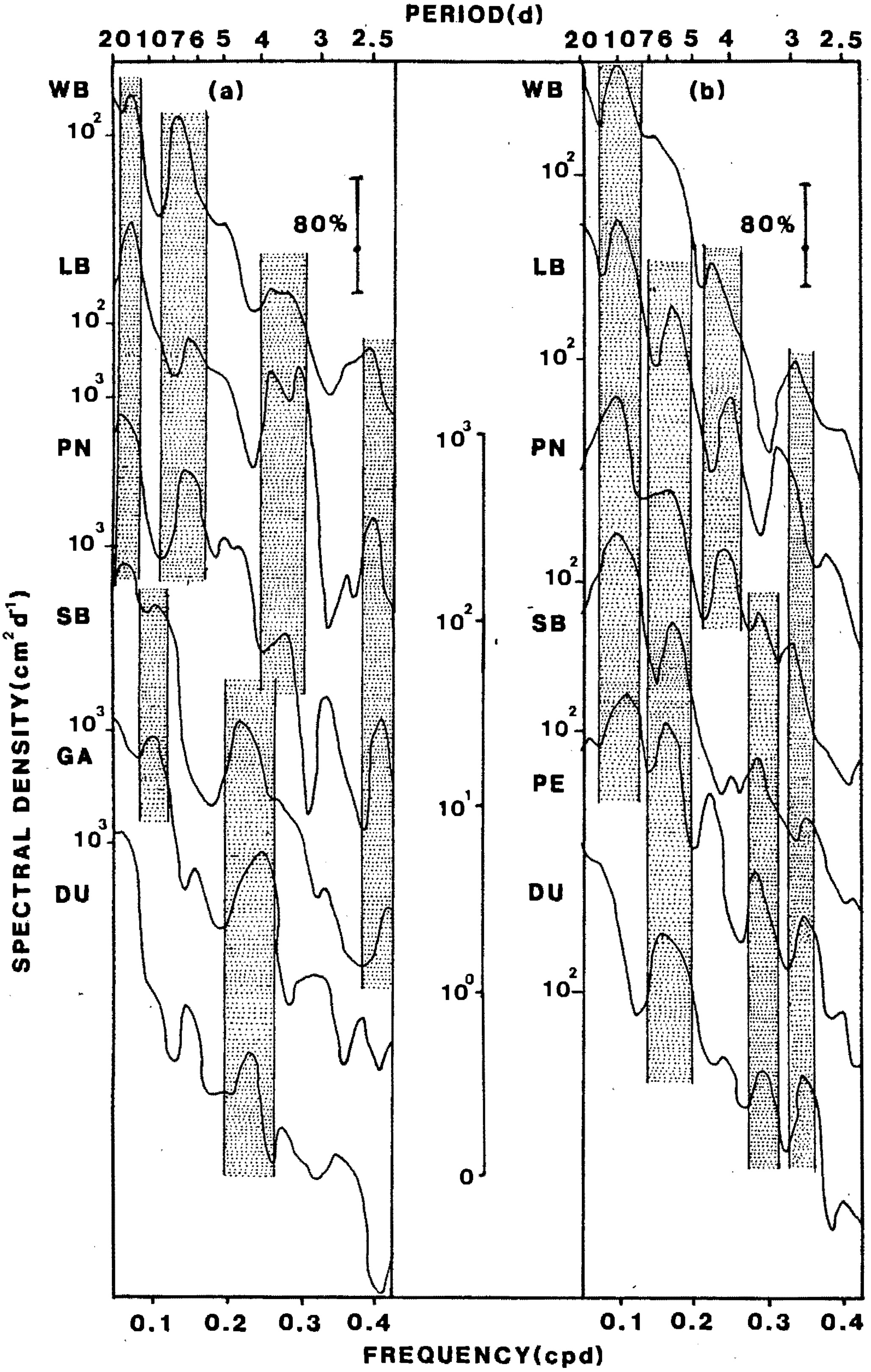


FIG.12 Power spectra of daily mean sea level 1982

(a) First period in Table 6

(b) Second period in Table 6

cpd have been plotted. Over this range of frequencies, the spectra for Walvis Bay and Simons Bay are consistent with those described previously, which were based on data for approximately 3 years. Thus 1982 may be considered a typical year for event scale fluctuations.

At Walvis Bay and Durban the long term component (not shown on the diagram) exhibits more energy than the event scale component. At the intermediate ports, the event scale peak of period 10-14 days exhibits most spectral energy. Gansbaai is an exception where the long term component is again dominant during the first part of the year. It is difficult to give absolute explanations for this difference since the second half of the year was anomalous at the southern ports. The most likely explanation is that the most energetic fluctuations are those related to the passage of cold fronts affecting the southern areas (Port Nolloth to Port Elizabeth). These occur mainly in winter (i.e. second period). Also the forcing induced along the south coast by south-easterly winds is less strong in late summer (first period). Without large scale forcing sea level response is dominated by seasonal variation.

There are peaks in the spectra at several periodicities. Shading has been used to illustrate peaks common to spectra for different ports. The dominant peaks can be divided into three classes:

1. West coast peaks (W) - common to west coast ports from Walvis Bay to Port Nolloth or sometimes as far as Simons Bay.

2. South coast peaks (S) - common to south coast ports from Simons Bay to Port Elizabeth or Durban.

3. West and south coast peaks (W-S) - common to most or all of the ports.

A seasonal variation can be detected in the distribution of spectral energy. During the first part of the year there is a spectral peak centred around 13 days along the west coast and around 10 days at the south coast ports with both periodicities evident at Simons Bay. During the second half of the year there is one broader peak centred at 10 days evident at all ports as far as Port Elizabeth. Similarly other peaks have been displaced slightly. In the second part of the year there appear to be more periodicities of common interest along the west and south coasts. It must be noted that the existence of spectral peaks at the same frequency in the spectra for different ports is not proof of the same cause. Spectra can only show the frequencies of interest. Cross-spectra or cross-correlations are needed to determine phase.

5.4 Cross-correlation analyses of sea level at adjacent ports

From the cross-correlation analyses performed using Data Set 5F, sea level at all adjacent ports from Walvis Bay to Port Elizabeth was found to be significantly correlated ($\geq$95%) at all times of the year with one exception. The sea level at Walvis Bay and Luderitz Bay was not significantly correlated during the late summer period, January 2 - April 1. The lag at maximum correlation obtained from each correlation generally suggested propagation southwards down the west coast and eastwards along the south coast. Propagation speeds were highly variable.

Cross-correlation analyses between sea level at Port Elizabeth and Durban gave conflicting results at different times of the year. Sea level at the two ports was not correlated during summer. In winter significant correlation was obtained with sea level at Durban ahead of that at Port Elizabeth. Some blocking mechanism, possibly the Agulhas current, operates between these two ports to prevent events affecting Port Elizabeth from reaching Durban. For one period in early summer (September 10 - December 8), significant correlation was found giving a propagation speed of 2 m s^{-1} from Port Elizabeth to Durban.

Between Durban and Richards Bay the sea level was significantly correlated at all times. The lag at maximum correlation corresponded to zero propagation in early summer and propagation speeds of 2.6 m s^{-1} - 4.2 m s^{-1} at other times. These results were all obtained using unadjusted sea level heights, as no hourly pressure data were readily available for the east coast. To study this easten section, longer data sets are needed and additional information from intermediate ports to establish how far along the south coast propagation continues. Schumann (1983) has used some sea level data along the Natal coast. The results here confirm his conclusions that in general coastal trapped waves do not propagate along the east coast.

The rest of the study will be concentrated on the coastal area between Walvis Bay and Port Elizabeth. The results from three periods during the year will be discussed in detail, with reference to other results where appropriate.

5.4.1 February 20 - April 29

The Doodson filtered hourly sea level heights at all the ports are shown for this period in Figure 13. The downward seasonal trend is visible at Walvis Bay and Luderitz Bay with the mean level 10-15 cm higher at the beginning than at the end. This is consistent with the average seasonal trend for this time of year shown in Figure 9(b). At these two ports, most of the event scale fluctuations are of small amplitude, with as many positive as negative events.

From Port Nolloth to Port Elizabeth, the fluctuations appear very coherent with larger amplitudes. The largest events are negative events usually preceded by an increase in sea level. The amplitudes of individual events appear to increase

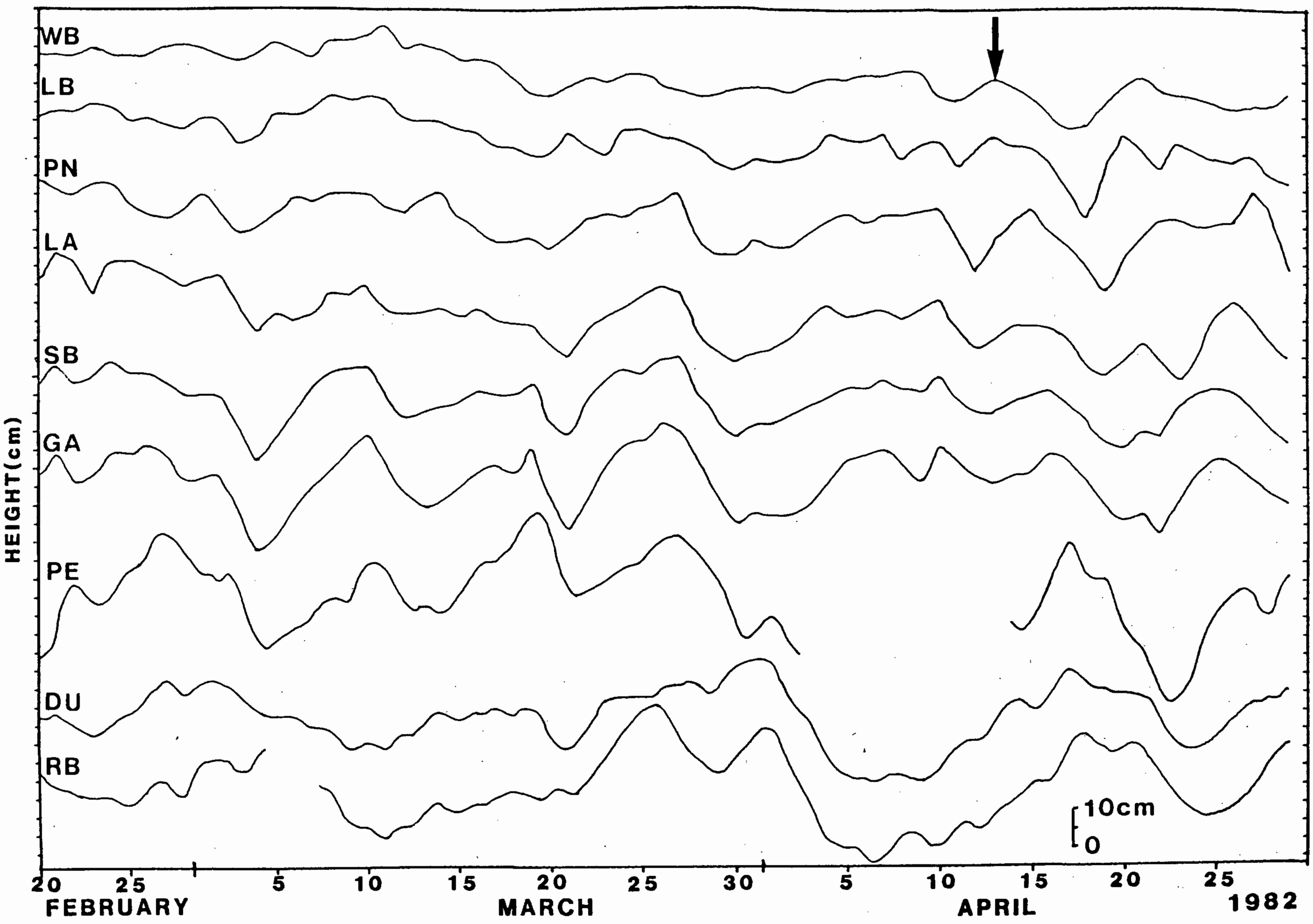


FIG. 13 Daily mean sea level 1982 February 20 - April 29

southwards and eastwards as far as Port Elizabeth. The curves for Richards Bay and Durban do not in general resemble the curves for the other ports and fluctuations at these two ports are of smaller amplitude. However the largest event, which commences at Walvis Bay on April 13 and is marked in Figure 13 with an arrow, is apparent at all ports.

The results of the cross-corrrelation analyses between sea level at adjacent ports for this period are shown in Table 8 for (a) unfiltered data and (b) data filtered with a 120 point double running mean. The distances between ports, correlation coefficients, degrees of freedom, lag at maximum correlation, significance levels and propagation speeds (where appropriate) are shown.

For cross-correlations between sea level at adjacent west coast ports from Walvis Bay to Lamberts Bay, the number of degrees of freedom is considerably increased after filtering has removed the seasonal influence. The number of degrees of freedom is not the same as the number of events as it takes into account the range in period of these events. With a large seasonal component, the range in period will be very large. Filtering will reduce this range and, depending whether the seasonal or event scale coherence is dominant, will decrease or increase the number of degrees of freedom. Thus the reduction in degrees of freedom caused by filtering the sea level data from Lamberts Bay southwards suggests that

Ports Correlated	Distance Apart (km)	Unfiltered Sea Level					Filtered Sea Level				
		Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagation Speed (ms^{-1})	Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagatio Speed (ms^{-1})
WB - LB	400	7	0.887	4,5,6,7,8,9	99.0	12.3 - 27.8	26	0.648	7	99.9	15.9
LB - PN	350	17	0.735	15	99.9	6.5	30	0.647	20	99.9	4.9
PN - LA	350	21	0.733	3,4,5	99.9	19.4 - 24.3	28	0.525	2	99.0	48.6
LA - SB	300	26	0.734	-2,-3	99.9		15	0.769	-2	99.9	
LA - GA	400	27	0.539	5,6	99.0		15	0.706	3	99.0	
SB - GA	100	20	0.903	8	99.0	3.5	9	0.934	7,8	99.9	3.5-4.0
GA - PE	580	MISSING DATA AT PORT ELIZABETH									

Table 8 Results of cross-correlation between hourly sea level at adjacent ports

1982 February 20 - April 29

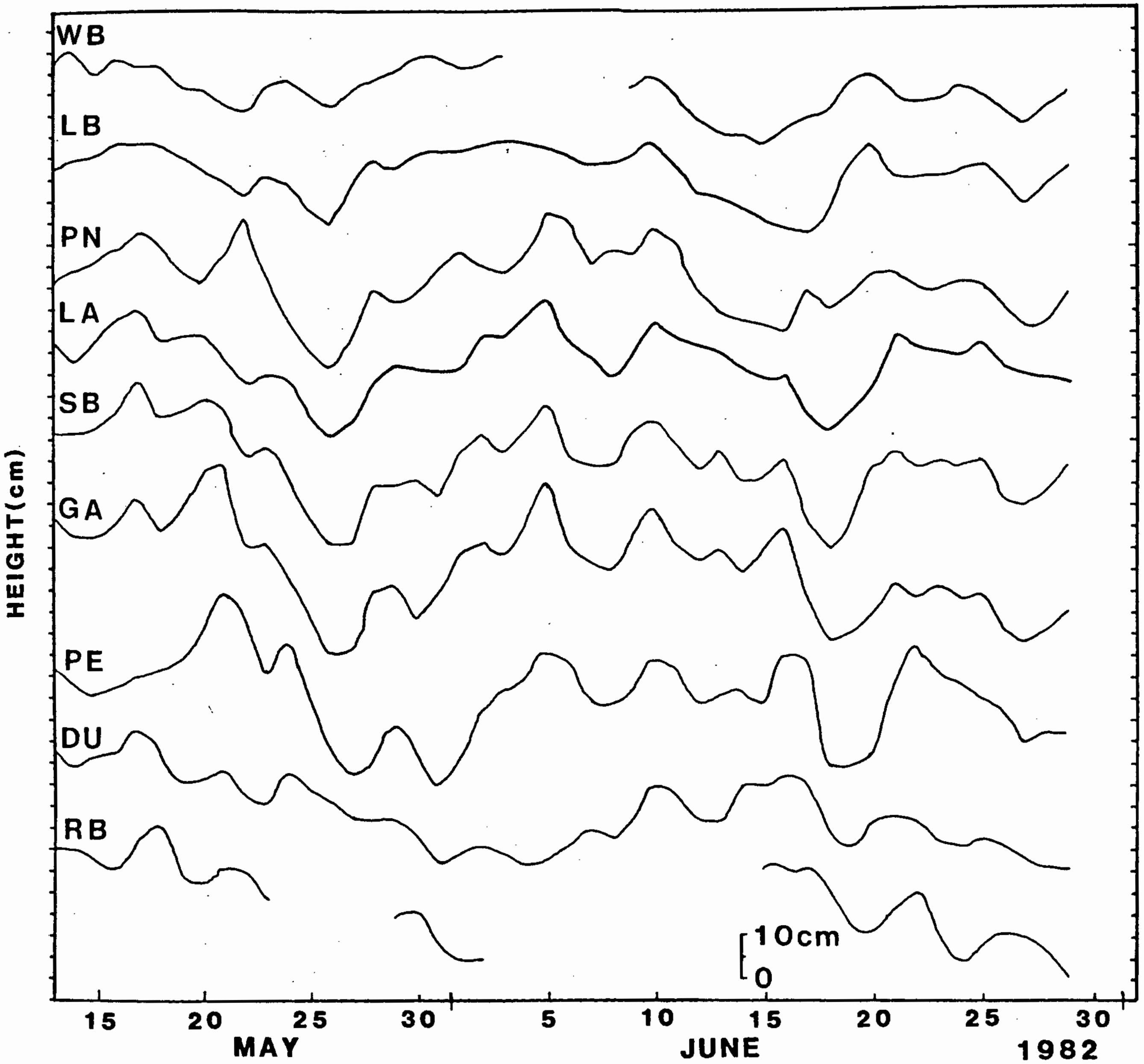
there are fewer events of period 10 days or less and that these are overshadowed by the stronger long term coherence in sea level along this section of coast. From a comparison of the number of degrees of freedom for the cross-correlations of filtered data, there appear to be fewer events along the south coast than the west coast. The slight difference in the number of degrees of freedom along the west coast suggests the likelihood of a few events starting at Luderitz Bay and not propagating further than Port Nolloth. The number of degrees of freedom for the cross-correlation between sea level at Simons Bay and Gansbaai is much less during this period than that obtained for the cross-correlation between sea level at Lamberts Bay and Gansbaai. The autocorrelation curves at Simons Bay and Gansbaai are completely in phase and thus τ increases with lag. The use of N/10 instead of N/4 in determining τ for this cross-correlation gives a value for the number of degrees of freedom in agreement with the other cross-correlation.

All the cross-correlations are significant to at least the 99% significance level. The lags at maximum correlation support the theory of propagation southwards down the west coast and eastwards along the south coast, except for the stage from Lamberts Bay to Simons Bay, which will be discussed later. Propagation speeds, calculated as distance divided by lag at maximum correlation, vary considerably from stage to stage, but appear higher along the west coast than the south. In most cases filtering had little effect on propagation speed.

5.4.2 May 13 - June 29

The Doodson filtered hourly sea level heights at all the ports are shown in Figure 14. As expected from the average seasonal variation in Figure 9(b), there is no seasonal trend evident in any of the records for this period. The curves for Walvis Bay and Luderitz Bay resemble those for the other ports for longer period events. However there are several shorter period, positive fluctuations which are only visible from Port Nolloth southwards. Apart from the unusually large event at Port Nolloth near the beginning of the data, the range during individual events appears roughly the same at all ports between Port Nolloth and Port Elizabeth, with a typical value of 20 cm. The range at the other four ports is slightly less.

The results of the cross-correlations performed on the sea level data for this period are summarised in Table 9. The number of degrees of freedom is almost the same for all the cross-correlations using unfiltered data. Filtering the data increased the number of degrees of freedom and again it is almost the same for all cross-correlations, suggesting that events of period 10 days or less are dominant. Using unfiltered data, the propagation speeds associated with the cross-correlations are of the same order of magnitude from


WB
LB
PN
LA
SB
GA
PE
DU
RB
HEIGHT(cm)
10cm
0
15
20
25
30
5
10
15
20
25
30
MAY
JUNE
1982

Ports Correlated	Distance Apart (km)	Unfiltered Sea Level					Filtered Sea Level				
		Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagation Speed (ms^{-1})	Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagation Speed (ms^{-1})
WB - LB	400	MISSING DATA AT WALVIS BAY									
LB - PN	350	11	0.732	12,13,14,15	99.0	6.5-8.1	20	0.481	4	95.0	24.3
PN - LA	350	10	0.687	13,15,16	95.0	6.1-7.5	18	0.341	8,10	NOT	
LA - SB	300	10	0.877	-1,-2	99.9		18	0.817	- 4	99.9	
LA - GA	400	11	0.836	5	99.9		18	0.760	0	99.9	
SB - GA	100	11	0.958	3	99.9	9.3	20	0.927	3	99.9	9.3
GA - PE	580	13	0.925	18,19,20	99.9	8.1-9.0	18	0.916	15	99.9	10.7

Table 9 Results of cross-correlations between hourly sea level at adjacent ports

1982 May 13 - June 29

Luderitz Bay to Port Elizabeth, with speeds along the south coast slightly faster.

Using the filtered data, the cross-correlation between sea level at Luderitz Bay and Port Nolloth gives a propagation speed which is inconsistent with the unfiltered data and the significance of this correlation is less. The sea level at Port Nolloth and Lamberts Bay are not significantly correlated over this period. As can be seen in Figure 14, the sea level at Port Nolloth appears to have some considerable fluctuations, particularly of shorter period, which are not visible elsewhere. Propagation speeds along the south coast are not much altered by filtering, although the speed between Gansbaai and Port Elizabeth is increased.

The data for the period June 10 - September 7 provide similar results to the above, with the same number of degrees of freedom around the coast. However for this period there are more degrees of freedom for cross-correlations using unfiltered data than using filtered data. This is consistent with the spectra in Figure 12(b) which show a broad band of increased spectral energy at about 10 days during the second half of the year. Some of these events would be lost in the filtering process. Propagation speeds for this period are slightly higher along the west coast than along the south coast. The speeds along the south coast are the same as during the May - June period. The sea level at Port Nolloth is significantly correlated with that at Luderitz Bay and at Simons Bay (data from Lamberts Bay unavailable). The speed of propagation doubles between these two sections of the coast.

5.4.3 September 1 - October 27

No seasonal trend is evident in this sea level data, which is shown in Figure 15. There are few short period fluctuations. This set illustrates well the apparent growth in amplitude southwards of particular events. The largest negative event, commencing at Walvis Bay on October 3 and marked in Figure 15 with arrows at Walvis Bay and Port Elizabeth, has a range of about 20 cm at Walvis Bay growing to about 40 cm at Gansbaai and Port Elizabeth. This event is not evident at Durban or Richards Bay, and indeed the records for these two ports differ substantially from those at the other ports. The other event marked on Figure 15 illustrates clearly the progression of the event along the coast. Most large events during this period are negative or upwelling events.

The results of the cross-correlation analyses for this period are shown in Table 10. There are more degrees of freedom for the two stages Luderitz Bay to Port Nolloth and Port Nolloth to Lamberts Bay than elsewhere. Between Lamberts Bay and Port Elizabeth the number of degrees of freedom is almost the same for each stage. Filtering in all cases reduces the number of degrees of freedom, as expected in the second part of the year from the spectra in Figure 12(b). The propagation speeds

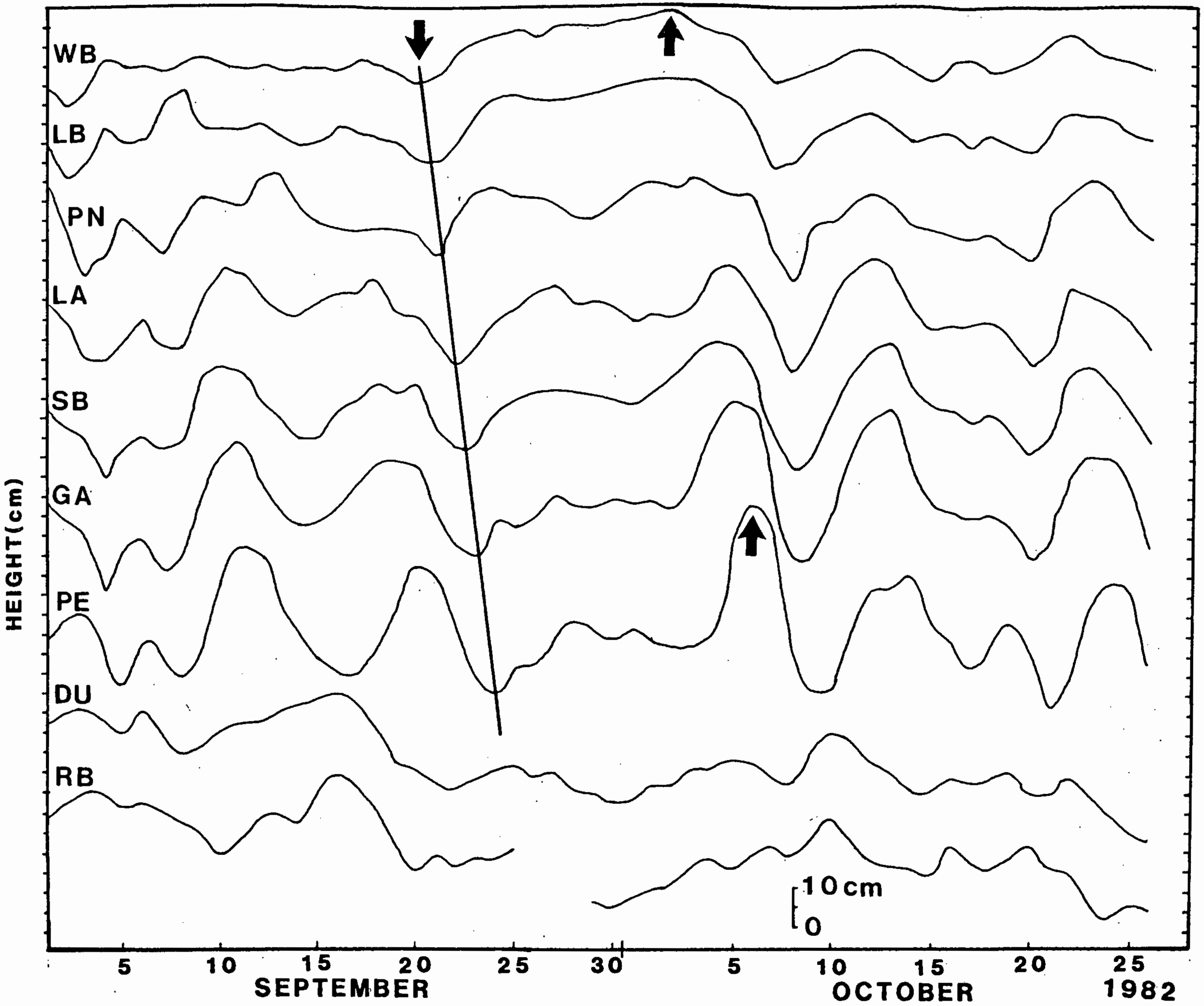


FIG. 15 Daily mean sea level 1982 September 1 - October 27

Ports Correlated	Distance Apart (km)	Unfiltered Sea Level					Filtered Sea Level				
		Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagation Speed (ms^{-1})	Degrees of Freedom	Correlation Coefficient	Lag at Max Correlation (h)	Sign. (%)	Propagation Speed (ms^{-1})
WB - LB	400	13	0.880	7,8,9,10,11	99.9	10.1 - 15.9	13	0.772	6	99.9	18.5
LB - PN	350	26	0.713	17,18	99.9	5.4 - 5.7	18	0.668	12	99.0	8.1
PN - LA	350	26	0.677	11,12	99.9	8.1 - 8.8	20	0.643	10	99.0	9.7
LA - SB	300	18	0.884	2	99.9		9	0.946	0	99.9	
LA - GA	400	19	0.894	8,9,10	99.9	11.1 - 13.9	10	0.942	8,9,10	99.9	11.1 - 13.
SB - GA	100	16	0.935	7,8	99.9	3.5 - 4.0	9	0.959	7,8	99.9	3.5 - 4.
GA - PE	580	16	0.877	22,23	99.9	7.0 - 7.3	9	0.942	23,24	99.9	6.7 - 7.

Table 10 Results of cross-correlations between hourly sea level at adjacent ports

1982 September 1 - October 27

obtained from these cross-correlations vary considerably between sections with generally higher speeds along the west coast. The results for the period September 10 - December 8 are consistent with the results described here.

5.5 Summary and general discussion of the results

At all times of the year, the results of the cross-correlation analyses suggest the propagation of sea level disturbances down the west coast and along the south coast of Southern Africa. The fluctuations during late summer appeared at first different from early summer. This was owing to the strong seasonal component in the unfiltered data from the west coast ports. Once this had been filtered out, the results from this period agreed well with the results from the early summer period. Thus for event scale activity there seem to be two seasons with different responses for each.

During summer there are more events along the west coast than along the south coast, with Lamberts Bay the transition point. The records for Durban and Richards Bay do not resemble those for the other ports. Events which are common to all the ports from Walvis Bay to Port Elizabeth appear to grow in amplitude with propagation. Propagation speeds along the west coast appear slightly faster than along the south coast but there is considerable variability in speed between sections of the coast and also between events.

During winter there are the same number of degrees of freedom round the coast from Walvis Bay to Port Elizabeth. The records for Durban and Richards Bay show considerable coherence with those for the other ports. The amplitudes of individual events appear almost the same at all ports between Port Nolloth and Port Elizabeth, but smaller at Walvis Bay, Luderitz Bay, Durban and Richards Bay. Propagation speeds are of the same order of magnitude all round the coast from Walvis Bay to Port Elizabeth but with some variability between events and between stages.

The variability in propagation speeds implies that the sea level disturbances are not free waves, whose propagation speeds would be determined by topography, but forced waves whose speed is determined by the speed of the forcing agent. In order to propagate, the waves must be continually forced. The summer sea level response suggests that the coastal lows of Class 1 play a considerable role in the forcing. The short period, positive fluctuations in sea level evident at Walvis Bay, Luderitz Bay and sometimes Port Nolloth which do not propagate further are consistent with what would be expected from coastal lows whose passage is blocked. The major events, common to ports from Walvis Bay to Port Elizabeth, are longer period, negative events often preceded by small positive fluctuations and are consistent with the response expected from west coast lows whose passage is not blocked. As the anti-cyclones ridges eastwards the coastal low comes with it. In this situation, the negative event is forced by the passage of the anti-cyclone. The coastal low may initiate the sea level response but the response is sustained and amplified by the anti-cyclone. How far along the south coast this response propagates will depend on how far eastwards the anti-cyclone extends. Certainly one would not expect it to reach as far as Durban.

The winter sea level response is consistent with the expected forcing associated with Class 2 coastal lows. The events seen at Walvis Bay and Luderitz Bay are as in summer but the response further south reaching sometimes to Durban or Richards Bay, albeit in a weakened state, is associated more with the cold fronts following the coastal lows.

The coastal low appears important in initiating sea level events but the larger scale atmospheric forcing appears to be the forcing mechanism for the major events. Where there is no large scale forcing, as for example along the east coast in summer, there is no large sea level response. This is confirmed by the sea level power spectra. At Walvis Bay and Durban where there is no large synoptic scale atmospheric forcing, the long term energy dominates the sea level spectra.

So far only unadjusted sea level heights have been used in the analyses. The cross-correlations between sea level at Lamberts Bay and Simons Bay give anomalous results with a lag at maximum correlation implying propagation in the opposite direction from all the other analyses. The same result is obtained for the section Port Nolloth to Simons Bay in winter. In the normal meteorological situation with the South Atlantic high pressure system to the west of Southern Africa, there is not much difference in pressure along the west coast (see Figure 2 for example). The use of unadjusted sea level is acceptable in this situation. However in the situations described above, associated with the major sea level events there will be a fairly steep pressure gradient between

Simons Bay and Lamberts Bay. In winter this could well extend to Port Nolloth. For these sections of the coastline the use of pressure adjusted sea level heights would be preferable, and would be expected to give more meaningful results.

At all times of the year cross-correlations between sea level at Lamberts Bay and Simons Bay and Lamberts Bay and Gansbaai have the same number of degrees of freedom. Lamberts Bay and Gansbaai thus come under the influence of the same atmospheric forcing. In summer the west coast lows which remain blocked on the west coast do not extend past Lamberts Bay. When the Atlantic high ridges south of the continent and extends eastwards, sea level at both Lamberts Bay and Gansbaai is affected. Similarly in winter the travelling coastal lows and attendant cold fronts influence both ports. The cross-correlations between the unadjusted sea level at the two ports gave significant correlation at all times with sea level at Lamberts Bay ahead of that at Gansbaai. It is thus reasonable to use data from these two ports to study the relationships between sea level, pressure and wind in more detail.

CHAPTER 6 FORCING MECHANISM AND DISCUSSION

Atmospheric pressure data were available from Lamberts Bay and Gansbaai for most of 1982. Power spectra of atmospheric pressure were obtained for two periods in the year corresponding roughly to those used to obtain spectra of sea level data.

6.1 Power spectra of atmospheric pressure

The results of the spectral analysis of atmospheric pressure at Lamberts Bay and Gansbaai are shown in Figure 16(a) and (b) for the periods specified in Table 7. The same energy scale is used as in Figure 12(a) and (b) for sea level spectra. The frequency range is 0.0 - 0.45 cpd. The shaded areas in Figure 16(a) and (b) correspond to peaks in the sea level spectra with W referring to peaks evident at west coast ports only, S to peaks at south coast ports and W-S to peaks at all or most ports.

The pressure spectra for the two ports have peaks at the same frequencies for the most part but with a slightly different distribution of energy in some instances. For example, during the second half of the year the peak at about 6 days has most energy at Lamberts Bay whereas at Gansbaai the peak at 10 days has most energy. The peaks in the pressure spectra compare well with peaks in the sea level spectra. The largest peak during the first part of the year coincides with a sea level peak evident at south coast ports. During the second part of the year the largest peaks in

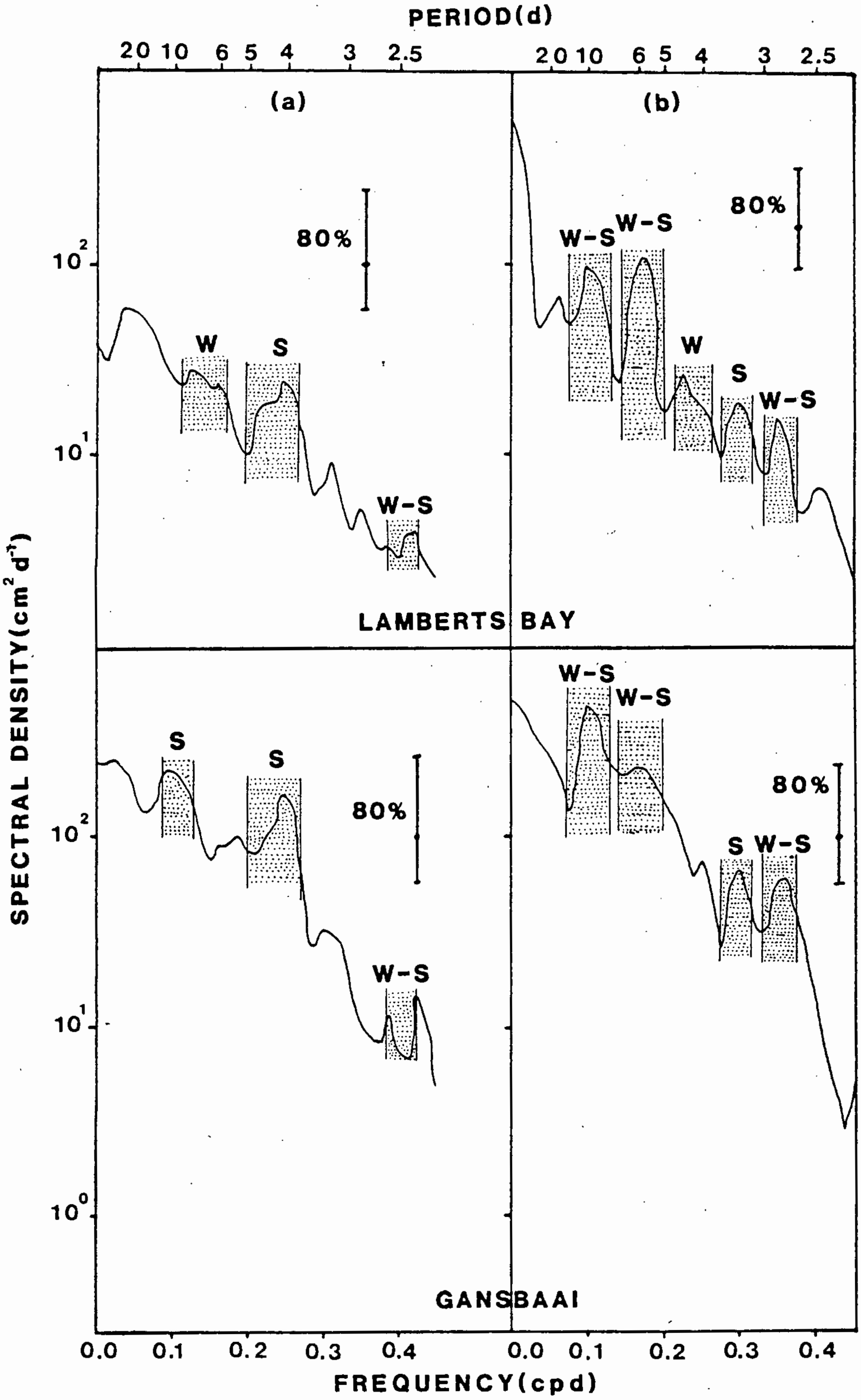


FIG.16 Power spectra of daily atmospheric pressure 1982

(a) First period in Table 7

(b) Second period in Table 7

pressure coincide with peaks in sea level spectra for both west and south coast ports. However during the first half there is a peak at 6-7 days in the Lamberts Bay pressure spectrum which is not reflected at Gansbaai and similarly a peak at 10 days in the Gansbaaai spectrum which is not reflected at Lamberts Bay. These peaks are evident in the sea level spectra for west and south coast ports respectively.

The fact that the pressure spectra exhibit the same periodicities of activity as the sea level spectra is not itself proof that pressure is the forcing mechanism for sea level changes. Cross-correlation analyses provide evidence of the link between pressure and sea level.

6.2 Cross-correlation between pressure and sea level

Atmospheric pressure data were available from Lamberts Bay and Gansbaai for the three periods discussed in Chapter 5.4. Cross-correlation analyses were undertaken between pressure and unadjusted sea level at each port using unfiltered and filtered data. The results were all significant to at least the 99% level with pressure ahead of sea level. The lag between pressure and sea level was always several hours less at Gansbaai than at Lamberts Bay and at both ports it was least during the winter period.

Using the lag at which correlation between pressure and sea level was a maximum, the sea level heights were corrected for pressure. The results are shown in Figure 17 for the early summer period, 1982 September 1 - October 27. As can be seen, by no means all of the sea level fluctuations are removed by correcting for pressure. Looking at the unadjusted sea level, the range is larger at Gansbaai than at Lamberts Bay. Similarly the range in pressure is larger at Gansbaai. After correcting for pressure the range in adjusted sea level is larger at Lamberts Bay. In other words, more of the sea level response at Gansbaai is pressure induced than at Lamberts Bay. Using linear regression, the size of the barometer effect was determined for each cross-correlation. The results of this and the cross-correlations are summarised in Table 11. Unless otherwise stated all cross-correlations are significant at the 99.9% level. At all times of the year, the barometer factor is seen to be considerably larger than isostatic at both ports, and larger at Lamberts Bay than at Gansbaai. It is closest to isostatic during

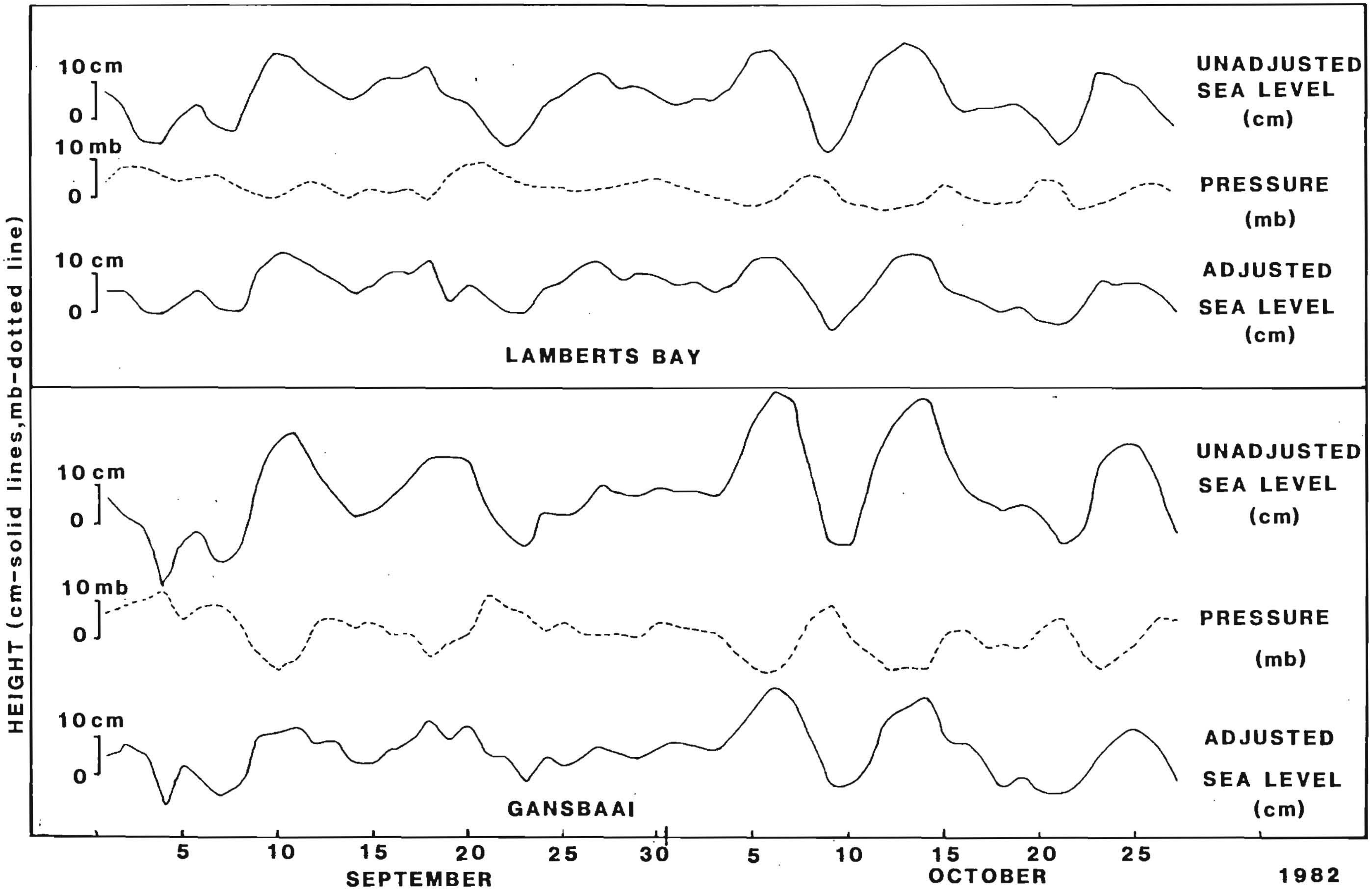


FIG. 17 Daily filtered unadjusted sea level, atmospheric pressure and adjusted sea level at Lamberts Bay and Gansbaai 1982 September 1 - October 27

winter and almost the same size at the two ports. At Gansbaai the barometer factor is considerably larger during early summer than during late summer.

Table 11

Results of cross-correlations between pressure and sea level at Lamberts Bay and Gansbaai 1982

Dates	Port	Unfiltered Data			Filtered Data		
		Corr. Coeff.	Lag (h)	Barometer Factor (cm mb^{-1})	Corr. Coeff.	Lag (h)	Barometer Factor (cm mb^{-1})
Feb 20	LA	0.522	18-20	2.04	0.718	21	1.62
-Apr 29	GA	0.867	13	1.56	0.898	13	1.51
May 2	LA	0.727	14,15,16,17	1.57	0.614	17	1.23
-June 29	GA	0.854*	8	1.47	0.849	7,8	1.21
Sept 1	LA	0.784	23,24	1.90	0.893	24	2.41
-Oct 27	GA	0.903	19	1.85	0.933	18,19	1.99

* 99.0% significant

The atmospheric pressure at the two ports was well correlated (99.9% significance) throughout the year, with pressure at Lamberts Bay ahead of that at Gansbaai. In winter the lag at maximum correlation was only four hours, but in summer it was as much as fourteen hours. In summer the lag between pressure at the two ports was a few hours longer than the corresponding lag between unadjusted sea level at the two ports. In winter the lags were the same using unfiltered data. Using filtered data unadjusted sea level was correlated with maximum lag at zero hours, while the pressure was correlated with maximum lag of four hours. This disparity was removed by using a 12 day filter as more appropriate at this time of year. Sea level at the two ports was significantly correlated with a maximum correlation at a lag of three hours.

Cross-correlations between adjusted sea level at the two ports gave significant (99%) correlation for winter and early summer for both filtered and unfiltered data. For the winter period, the lag at maximum correlation was three hours longer than the lag obtained using unadjusted sea level. In early summer, the lag at maximum correlation between adjusted sea level at the two ports was 6-8 hours compared with 8-10 hours using unadjusted sea level. For the late summer period, the cross-correlation between adjusted sea level was not significant. Using filtered data, the level of significance was 95% with maximum correlation at zero lag, or three hours less than using unadjusted levels.

In addition cross-correlation analyses were performed between atmospheric pressure at Lamberts Bay and sea level at Simons Bay and atmospheric pressure at Gansbaai and sea level at Simons Bay. The results support the view that in summer pressure changes occur at Lamberts Bay before Simons Bay, and at both ports ahead of Gansbaai. In winter pressure would appear to change first at Simons Bay.

6.3 Cross-correlation between longshore wind and sea level

Wind components are shown in Figures 18 and 19 together with sea level and pressure at Lamberts Bay and Gansbaai for the period February 20 - April 29. At Lamberts Bay the positive longshore component is northerly and onshore is thus westerly. At Gansbaai the positive longshore wind is north-westerly and the onshore wind south-westerly. Fluctuations in wind are greater at Gansbaai than at Lamberts Bay. It can be seen that the sea level fluctuations are associated with changes in the longshore wind. At Lamberts Bay on April 18 there is a decrease in sea level which would appear to be associated with a change in onshore rather than longshore wind. The same effect is also apparent in the winter record.

Pressure and longshore wind were significantly correlated at all times using filtered data. The lag at maximum correlation was almost the same at both ports. The strength of the wind does not depend purely on the local pressure but rather on the gradient between the local offshore pressure and the pressure over the interior. Although the wind is much stronger at Gansbaai, the sea level response does not appear to reflect this.

Cross-correlations were performed between longshore wind and both unadjusted and adjusted sea level at the two ports. Using filtered data, the longshore wind at Lamberts Bay was significantly correlated with unadjusted sea level with wind several hours ahead. At Gansbaai the results were also significant but with sea level ahead of the wind. This encourages the view of longshore wind as a

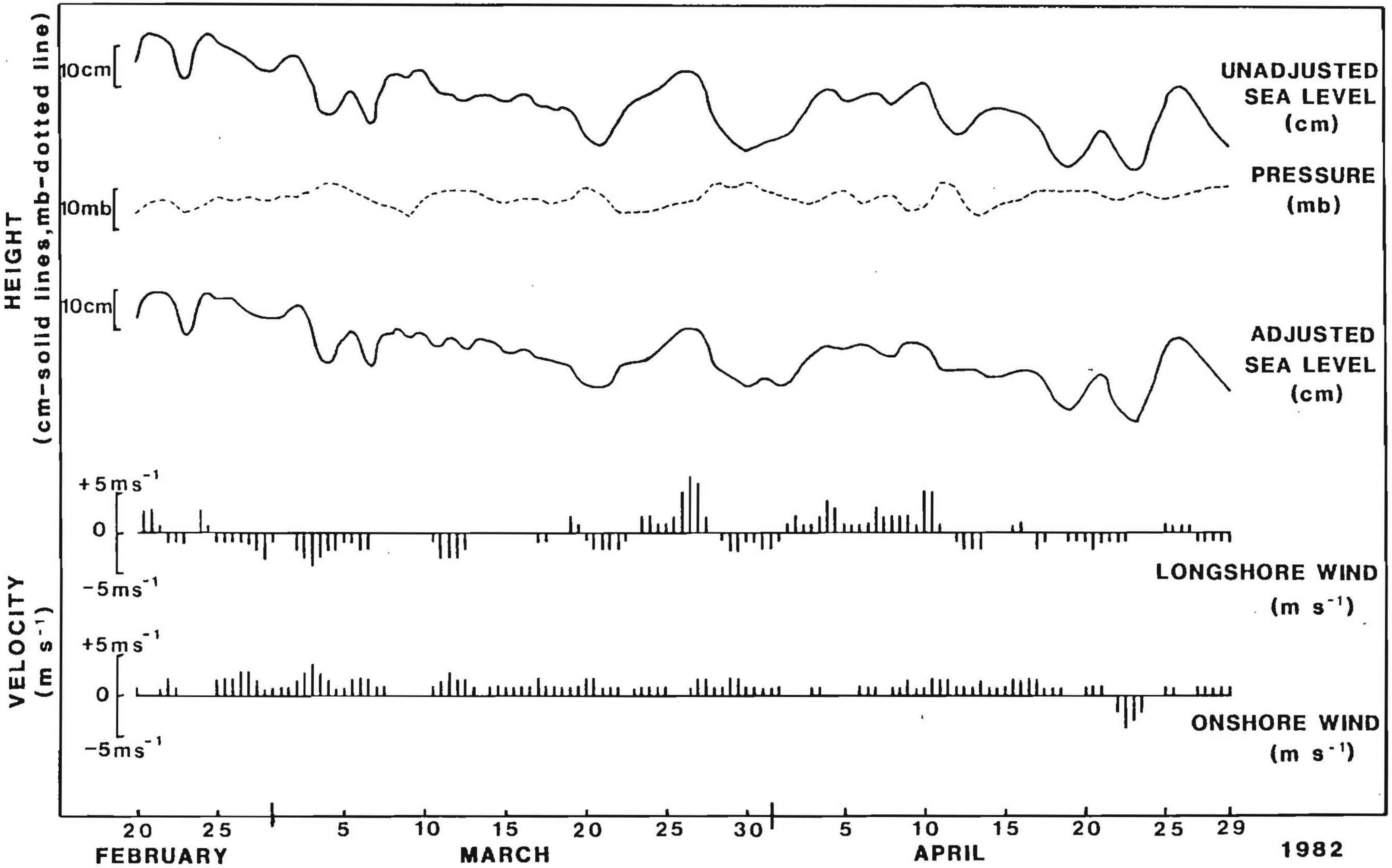


FIG. 18 Daily filtered sea level, atmospheric pressure and wind components at Lamberts Bay 1982 February 20 - April 29

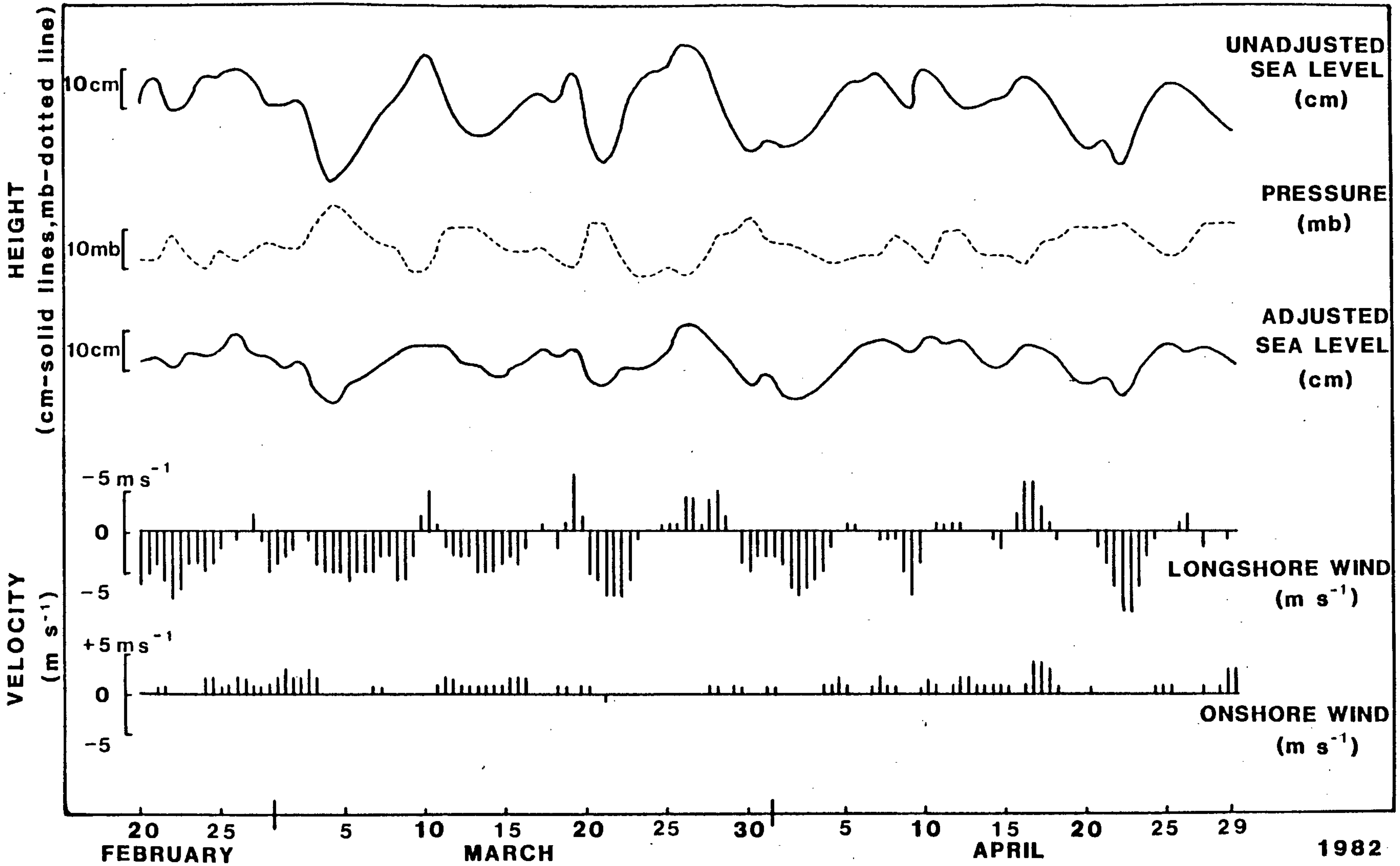


FIG. 19 Daily filtered sea level, atmospheric pressure and wind components at Gansbaai 1982 February 20 - April 29

forcing agent to explain the apparent anomaly in lag between pressure and sea level at the two ports.

Cross-correlation between longshore wind at Lamberts Bay and unadjusted sea level at Gansbaai gave significant (99%) correlation with Lamberts Bay wind 6-8 hours ahead of Gansbaai sea level. This agrees well with the difference between pressure and sea level at the two ports.

At Gansbaai correlation between longshore wind and adjusted sea level gave almost the same results as using unadjusted sea level. At Lamberts Bay the summer results were the same, but in winter longshore wind and adjusted sea level were not significantly correlated.

6.4 Discussion of forcing mechanism and comparison with other papers

The results of the last two sections suggest that the atmospheric forcing has a quite different effect on sea level in the two seasons of the year. In summer the longshore wind is more important than pressure in forcing a large sea level response. The barometer factor is much greater than isostatic and the sea level response travels much faster than the pressure changes. Sea level at both Lamberts Bay and Gansbaai is well correlated with the local longshore wind but at Gansbaai the sea level response is ahead of local wind. This confirms that sea level is responding to changes in the past history of the wind and is supported by cross-correlation between sea level at Gansbaai and longshore wind at Lamberts Bay. The fluctuations in local longshore wind do not affect the sea level response at that port as much as changes in the past history of the wind. Although the wind at Gansbaai is stronger and more variable than at Lamberts Bay, this is not reflected in the sea level. Comparison of pressure adjusted sea level at the two ports suggests that the apparent increase in amplitude of an event during propagation is due to the larger fluctuations in pressure at Gansbaai than at Lamberts Bay, rather than cumulative enhancement due to the wind forcing.

In winter the barometer factor is smaller, though still larger than isostatic. The sea level response travels at the same speed as the pressure disturbances. The sea level at Gansbaai still lags pressure by several hours less than at Lamberts Bay. At Lamberts Bay the lag between pressure and sea level is considerably less than in summer. This is consistent with additional forcing from winds associated with the frequent cold fronts which pass through the area. The sea level response associated with these winds will be more localised because of the change in direction which occurs as the cold fronts pass. The amplitude of the response during an individual event will depend critically on the speed of the pressure system in relation to the speed of the wind-driven response. At Lamberts Bay the onshore wind is seen to be important in inducing sea level fluctuations at this time of year. In winter the dominant changes in wind along the southern part of the west coast are often in an onshore-offshore direction.

Much work has been done on coastal trapped waves along the coasts of North and South America. Brink et al (1978) and Smith (1978) found low frequency (0.05 - 0.25 cpd) variations consistent with poleward propagating baroclinic Kelvin waves along the coast of Peru between latitudes 10^{o}S and $15^{o}30'$S. These waves, which have a phase speed of 2-3 m s^{-1}, were not correlated with local wind. Concluding that the source of the waves was equatorwards of these latitudes, Romea and Smith (1983) extended the study to include latitudes $2^{o}12'$S - 17^{o}S. They found consistent results, with the fluctuations south of 4^{o}S not significantly correlated with local winds. The origin of the waves was concluded to be the equatorial wave guide. Such waves on reaching the coast would travel polewards as coastal Kelvin waves.

Christensen et al (1983) studied low frequency fluctuations in sea level along the west coast of Mexico between latitudes 15°N and 28°N. The results suggested a hybrid mixture of Kelvin and shelf waves. The waves were found not to continue into the northern Gulf of California nor along the Pacific coast of Baja California. A question raised by this work was whether in fact these waves were free waves propagating polewards from the equator or forced waves generated by summer storms. Similarly, the question arises as to whether the waves observed along the coast of Namibia commence at Walvis Bay or further north. The connection with the coastal lows suggests that they are generated in the Walvis Bay-Luderitz Bay area.

Enfield and Allen (1983) analysed the sea level variability off Mexico to discover the source, frequency range and seasonal differences. They studied individual, large amplitude events which occur in that area more frequently in summer, associated with eastern North Pacific tropical storms. These storms move parallel to the coast as far north as 20°N where they move out to sea. The sea level response in summer was found to propagate with phase speeds 2.9 - 5.8 m s^{-1} south of 20°N and 2.1 - 3.5 m s^{-1} further north. These speeds were confirmation that the disturbances were forced in the south and freely propagating in the north. The latter speeds were consistent with the values of free, linear, hybrid coastal trapped waves determined from theoretical work by Brink (1982) and Allen and Romea (1980). The slower phase speeds obtained in winter, particularly in the south, were consistent with a lack of forcing. Osmer and Huyer (1978) had studied sea level fluctuations further north along the west coast of North America between latitudes 38°N and 48°N. Their conclusion, that most of the variability was associated with free coastal trapped waves, was thus in agreement with the results from the northern section of the area studied by Enfield and Allen.

Adams and Buchwald (1969) and Gill and Schumann (1974) argued that longshore wind stress is the principal driving force and that the onshore component is relatively unimportant. Along the west coast of America the longshore wind was found to be the dominant forcing mechanism for locally induced sea level changes. This is not surprising as the coastline is roughly parallel to the dominant wind direction. Csanady (1980) showed that cross-shelf wind, provided it is sufficiently strong, can also generate sea level changes. To study this, an area is needed where the predominant wind fluctuations are in an onshore-offshore direction.

Marmorino (1982) studied wind forced sea level variability along the west Florida shelf (latitude 24° - 30°N) during winter, when the area is subjected to the passage of cold fronts at regular intervals of about 6 days. The sea level data were found to have most energy in two bands corresponding to periods 6 days and 3.5 days. The atmospheric pressure and wind stress were correlated with the sea level. The rates of propagation of phase of pressure and sea level variations were found to be of similar magnitude, but considerably higher than the phase of wind stress. As a result of this the sea level along the southern part of the shelf appeared to respond faster to local wind than that further north. In general fluctuations in wind stress were ahead of fluctuations in sea level. At Key West, furthest south, sea level was found to lead wind stress at some frequencies, implying a non-local response. This is in agreement with the summer situation observed at Gansbaai.

Marmorino (1983) then studied small scale variations of the wind forced sea level response in the west Florida Bight to determine the influence of cross-shelf wind stress. The 3.5 day period events in autumn showed maximum coherence with a nearly cross-shore wind after a lag of 10 hours. In winter the long period events (>5 days) showed highest coherence with alongshore wind stress but the shorter period events (~3.5 days) had high coherence with a wide band of wind stress orientations including cross-shore. The lag between cross-shore stress and sea level response at this shorter period was much less (6 h) than between the long shore stress and sea level response (18 h). These results agreed with those found by Chuang and Wiseman (1983) for the north western part of the Gulf of Mexico along the Louisiana - Texas shelf.

CHAPTER 7 CONCLUSIONS

The astronomer Sir John Herschel (1792 - 1871) working at the Cape in 1835 wrote "observing the tides is the greatest bore upon earth, or on the waters, and the greatest exhaustion of a man's patience and trial of his temper". Since then much work has been done on sea level observations and although the routine collection of the data may be considered dull, the analysis of the data can yield interesting and informative results as the present study has shown.

The semi-diurnal tide has been established as the dominant component of variability in the sea level records at all Southern African ports. With a daily range of less than 2 m, it is smaller than the dominant tidal component in many parts of the world and exhibits no unusual features.

When this component of variability has been removed from the data by means of the Doodson tide-killer, the resultant time series of daily mean sea level show fluctuations of up to 50 cm range. The time scales of these fluctuations have been established as the synoptic event scale with period 2 - 20 days, the seasonal scale with period of a few months and the interannual scale with period of a few years. To study the latter two scales of variability, monthly mean sea level has been used after application of the isostatic pressure correction, whereby sea level decreases by 1.01 cm for an increase in atmospheric pressure of 1 mb.

The interannual scale variation in sea level at Southern African ports is best illustrated at Simons Bay where the long data set of monthly mean adjusted sea level (18 years unbroken) allows the use of a twelve month double running mean to remove the contributions of the synoptic event scale and seasonal scale variability. The interannual variability has a range of a few centimetres and has been shown by Brundrit (1984) to have a large spatial scale. It appears similar at all the west coast ports and at Mossel Bay on the south coast. There are insufficient data as yet to establish the east coast interannual variability. Chelton and Davis (1982) found that the interannual component of variability was coherent along the entire west coast of North America and was related to poleward propagating El Niño phenomena in the eastern tropical Pacific Ocean. Brundrit (1984) suggests that an identical phenomenon in the eastern equatorial Atlantic Ocean affects the west coast of Southern Africa.

In order to establish the seasonal fluctuation in sea level, the residual effect of the synoptic scale variation in the monthly means is removed by smoothing with a two month double running mean. The seasonal component, with an average annual range of 2 - 5 cm at the ports considered, has been shown to exhibit a marked difference between the northern and southern ports. The seasonal variation is a direct response to atmospheric forcing and this contrasting effect has been shown by Brundrit et al (1984) to be associated with the seasonal difference in the prevailing winds affecting the two regions.

Fluctuations on both the seasonal and interannual time scales may propagate round the Southern African coast as Chelton and Davis (1982) were able to establish for the west coast of North America. However the data sets available here are not long enough to conduct such an investigation. They do allow investigation of the synoptic scale variation which is seen to propagate round the coast in a very definite manner.

The sea level response to atmospheric forcing on the synoptic event scale is visible at all the ports under consideration, with a considerable degree of coherence. Spectral analysis of unadjusted sea level shows that at the more northerly ports on both the west and east coasts, the energy associated with these event scale fluctuations is less than that associated with the seasonal component of variability. The range during individual events at these ports seldom exceeds 20 cm. At the southern ports, where individual events have a range of 40 - 50 cm at times, the spectral energy is greater than that associated with the longer term component. This suggests that the propagation of the event scale signal is contained in the region between Walvis Bay and Durban and no information is lost by not considering ports outside these territorial limits.

These event scale fluctuations are a reflection in the sea of changes in the atmosphere. They represent the response of sea level to atmospheric forcing, taking the form of a coastally trapped or shelf wave. Cross-correlation analyses between unadjusted sea level at adjacent ports between Walvis Bay and Durban have shown that fluctuations propagate throughout the year between Walvis Bay and Port Elizabeth. They appear to start in the Walvis Bay - Luderitz Bay region and travel southwards along the west coast and eastwards along the south coast. Some events are confined to the west coast and some to the south coast. Propagation does not in general extend to the section of coast between Port Elizabeth and Durban, although on occasion this does occur. This is in agreement with the results found by Schumann (1983) for this section of coast. Exactly where the wave dissipates can only be established when data from intermediate ports can be included in the analysis.

To establish the relationship between the atmospheric forcing and the sea level response, the results of cross-correlation analyses between hourly sea level, atmospheric pressure and wind components at Lamberts Bay and Gansbaai have been presented. Regression analysis has revealed that a greater than isostatic relationship exists between pressure and sea level at both ports at all times of the year. This implies some additional forcing, correlated with pressure, which enhances the influence of pressure on sea level. In winter 1982 the regression coefficient between pressure and sea level, the barometer factor, is almost the same at both ports with a value of 1.23 cm mb^{-1} at Lamberts Bay and 1.21 cm mb^{-1} at Gansbaai. At all other times the value is higher at Lamberts Bay than at Gansbaai, with a maximum of 2.41 cm mb^{-1} at Lamberts Bay and 1.99 cm mb^{-1} at Gansbaai during early summer of 1982-3. The relative size of the barometer factor at the two ports is in contrast to the results obtained by Brundrit (1984). He found that the reduction in variability in monthly mean sea level by the pressure adjustment was considerable along the west coast (12% at Stompneus Bay) and negligible at Hermanus on the south coast. These two ports lie close to the ones under discussion here. The monthly values refer to the seasonal rather than synoptic scale but the results above suggest that some reduction in variability should be found along the south coast as well as the west coast. This is an area of study which warrants further attention to solve this apparent inconsistency. Hamon (1966) found that the barometer factor increased at low frequency at some Australian ports implying that different values would be obtained from daily compared with monthly values of sea level and pressure. The present work has shown that although the range of event scale fluctuations in unadjusted sea level is greater at Gansbaai than at Lamberts Bay, more of this can be attributed to the direct isostatic effect of pressure and the range in adjusted sea level is greater at Lamberts Bay than at Gansbaai.

The coastal low, a regular atmospheric phenomenon affecting the coastal regions of Southern Africa, seems to satisfy the requirements of a forcing mechanism for the generation of the shelf wave. A coastal low is itself a forced fluctuation in the lower atmosphere. It is highly dissipative (Gill (1977)) as is the sea level response. The coastal low cannot be seen in isolation as a forcing mechanism, without recognising its interaction with the larger scale atmospheric systems. Shelf wave theory demands large scale forcing for propagation (Robinson 1964) and this is provided by the interaction of the coastal low with the subtropical high pressure system of the South Atlantic Ocean or the mid-latitude depressions. When no such interaction occurs, the shelf wave does not propagate. The sea level response at Walvis Bay and Luderitz Bay illustrates this. Fluctuations at these ports have smaller range than further south and there are events present here which do not propagate southwards.

There is a seasonal difference in the shelf wave which is a reflection of the seasonal variation in the atmospheric forcing. Pressure changes initiate the wave but it needs constant forcing to propagate. In summer the dominant longshore wind provides extra forcing along the entire west coast and along the south coast as far as Port Elizabeth. This enhances the barometer factor as pressure and wind act together. The prevailing summer wind is the south-easter associated with the ridging in of the South Atlantic high pressure system. Each of these in turn encourages a decrease in sea level. The sea level response at this time of year, as determined by cross-correlation between atmospheric pressure at Lamberts Bay and Gansbaai, moves ahead of the pressure system. Local wind is of less importance in determining the response at a particular port than the wind affecting the history of the wave. The wind by nature of its widespread constancy of direction is effective in forcing a large sea level response.

In winter pressure provides most of the forcing and the wave propagates with the pressure system. Some additional forcing is provided by local wind but the change in wind direction associated with the passage of a cold front inhibits the propagation of a large wind-driven response. However the effect of the wind will again be to increase the barometer factor. This differs from the situation in Australia where Hamon (1966) found the barometer factor was less than isostatic along the east coast and higher than isostatic along the west coast. Although longshore wind has been shown to be the generating mechanism for shelf waves (Adams and Buchwald (1969)), onshore as well as longshore wind is seen to provide forcing at Lamberts Bay at this time of year. Similar results have been found by Marmorino (1983) for the west Florida Bight and Chuang and Wiseman (1983) for the north western part of the Gulf of Mexico.

There is no evidence of free propagation of the shelf wave. Where there is no large scale forcing, as between Port Elizabeth and Durban in summer, this is reflected in the lack of propagation of shelf waves through this region. If the coastal low were able to sustain a shelf wave by itself, there should be evidence from this part of the coast as coastal lows are a regular feature throughout the year. In winter, when the large scale forcing in the form of cold fronts penetrates further eastwards, the sea level response reflects this. Enfield and Allen (1982) considered similar storm forcing along the Pacific coast of Mexico and found forced events in the southern region, closest to the storms, and free propagation in the north. Schumann (1983) suggests that the influence of the Agulhas current may explain the lack of propagation along the Natal coast.

The form of analysis undertaken was to give an overview of the average sea level response to atmospheric forcing. For this reason cross-correlation techniques were chosen. In addition it was felt that the length of the data sets was insufficient for statistically significant results to be achieved using cross-spectral analysis as suggested by Hamon and Hannan (1963) and used by many authors. The propagation speeds obtained must be seen in this perspective. They are average speeds calculated over some months which include events of different period and periods of almost no activity. They have been obtained from the lag at maximum correlation between sea level at adjacent ports, with no error estimates included. A difference in lag of one hour can make a considerable difference to the calculated propagation speed in some instances. Enfield and Allen (1983) obtained higher propagation speeds using cross-correlations than cross-spectra because incoherent energy at high frequencies was included in the cross-correlations but could be excluded from the cross-spectra. In the present study, because of the contrasting seasonal effect between the north and south, there may be incoherent energy at low frequencies particularly in the border areas. This has been treated by filtering the hourly data with a ten day double running mean to remove frequencies less than 0.1 cpd. The results obtained from both unfiltered and filtered data have been presented to show that filtering does not have a very significant effect on propagation speeds. The speeds obtained are well within the limits expected from forcing by weather systems. Preston-Whyte and Tyson (1977) obtained speeds of 6 m s^{-1} for the pressure disturbances of period 5-6 days from cospectra between Cape Town and Port Elizabeth for 1966 but as high as 18 m s^{-1} between Cape Town and Durban over a five year period. Speeds varying between 5 m s^{-1} and 28 m s^{-1} are obtained from the cross-correlation between atmospheric pressure at Lamberts Bay and Gansbaai in the present study.

All these speeds are averages and successive events present a high degree of variability. An individual event does not always propagate with a constant speed throughout its passage. This is reflected in the propagation speeds of the sea level response. The speeds along the west coast vary between 5 m s^{-1} and 28 m s^{-1} (excluding one suspect 49 m s^{-1}) and along the south coast between 3 m s^{-1} and 11 m s^{-1}. These propagation speeds were obtained using sea level heights which had not been adjusted for atmospheric pressure. Smith (1978), studying sea level fluctuations off the coast of Peru, found that the propagation speeds obtained using unadjusted sea level were slightly faster than those obtained using adjusted sea level. Comparisons between propagation speeds from Lamberts Bay to Gansbaai using unadjusted and adjusted sea level suggest that the same is true along the Southern African coast, at least in summer. For the region between Port Nolloth and Simons Bay it would be preferable to have pressure adjusted sea level for the study of the winter situation.

Shelf wave theory as developed by Robinson (1964) established that the waves are non-dispersive. However the wind-driven response is highly dispersive, including both local and non-local effects. With the summer response to atmospheric forcing along the Southern African coast being predominantly wind-driven with non-local wind more important than local wind, cross-spectral analysis could be used to establish whether longer period (10 - 12 day) events propagate at the same speed as short period (2 - 3 day) events. In winter one would expect less dispersion. Cross-spectra could also determine whether the barometer factor is larger than isostatic at all frequencies or only at certain frequencies associated with particular events. With longer data sets becoming available, it is hoped that these analyses will be undertaken. In addition, individual events for which sea level, pressure and wind data are available for several ports, need to be studied in detail so that a more complete understanding of the exact relationship between the atmospheric forcing and the response can be achieved.

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ACKNOWLEDGEMENTS

I am grateful to the Hydrographic Department of the South African Navy and Fisheries Development Corporation for the data which they supplied and the additional assistance in solving minor problems in the data verification.

I would like to thank my supervisor, Professor G.B. Brundrit for his guidance and other members of the Oceanography department for their interest and suggestions. Finally, Mrs L. Elley deserves a special word of thanks for typing the thesis and making the numerous alterations necessary before it reached the final form.