TIDAL AND INERTIAL CURRENTS AROUND SOUTH AFRICA

by

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ABSTRACT

Limited information is available on currents in the semi-diurnal and diurnal frequency bands for the coastal ocean areas around Southern Africa. However, recently mooring data have become available from sites on the east, south and west coasts, and this paper analyses these results in an attempt to assess the importance of tidal and inertial currents.

It is clear that on the narrow shelf on the east coast the Agulhas Current dominates the energy spectrum, and tidal currents should be relatively unimportant at such sites. In the south on the Agulhas Bank the Current is still important, but comparable energy resides in inertial and tidal fluctuations. Modal analysis indicates the tides are primarily barotropic, with the inertial fluctuations mainly baroclinic.

In the absence of a major current on the west coast, most of the current variance occurs in the tidal and inertial bands; a complex vertical structure is also found. It is therefore clear that there are regions where such currents cannot be ignored.

1 INTRODUCTION

The most predictable forcing in the ocean is that due to the astronomical tides, with the tidal potentials associated with the various motions of the earth, moon and sun known to a high degree of accuracy. However, that does not mean that the response of the ocean to this forcing is necessarily predictable to the same degree of accuracy. Indeed, the ocean can respond in a variety of forms, dependent primarily on coastal and bottom topography, and the internal ocean structure.

The most obvious tidal motion is that of the surface of the ocean, with regular fluctuations in sea level ranging, in various parts of the world, from less than a metre to more than ten metres. Since such changes are of immediate interest to coastal communities, sea level tides have been known, studied, and predicted with various degrees of accuracy for many years. Prediction techniques have generally been

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dependent on sea level measurements carried out over long periods at appropriate coastal sites. This is also so in South Africa, where regular tide tables are issued by the Naval Hydrographer.

By continuity, there must also be currents associated with such movements of the sea surface. The strength of the currents is dependent on topography, with the most apparent examples occurring in estuaries and on the wider continental shelf regions.

Internal tides, dependent on the density structures within the ocean, also occur. Wunsch (1975) reviewed the nature of these fluctuations, which may cause vertical deflections of 30 m or more in the constant density surfaces. As with the surface, or barotropic tides, there are also currents associated with such baroclinic motions, although phase changes take place with depth.

There are further fluctuations in ocean currents that will be discussed here, since the periods involved are in the range of the semi-diurnal and diurnal periods of the dominant tidal forcing. These are the inertial currents, the oscillations in water set in motion and then moving over a rotating earth. The major generating force is wind stress, but with the details of the motion dependent on topography and ocean density structure. The period of such inertial oscillations depends on latitude, being given approximately by the relation 12.04/sin(latitude) hours.

Except where they are influenced by distinct coastal features such as estuaries, tidal currents around South Africa have been given little attention. To some extent this has been due to the lack of suitable measurements, but on the other hand it appears to be accepted that the effects of tidal currents should be negligible compared with currents generated by other forces. Reasons for such assumptions may be the generally straight coastlines, and the limited continental shelf areas.

This paper attempts to take a first look at tidal and inertial currents using data from moorings deployed on the east, south and west coasts of South Africa. These are distinctly different oceanic regimes, with the resulting currents also having different characteristics. It is clear that there are areas where such currents cannot be ignored, and where they may, in fact, constitute the most energetic part of the current spectrum.

2 OCCURRENCE OF TIDAL AND INERTIAL FLUCTUATIONS

The periods of astronomical tides cover a wide range, with the dominant components tending to fall into groups centered at semi-diurnal, diurnal and longer-period motions. Within these groups the frequencies are split by multiples of a cycle per fortnight, cycle per year, etc. Table 1 lists the major semi-diurnal and diurnal components of interest here.

Analyses have indicated that in many areas the tides propagate largely as Kelvin waves (e.g. Platzman, 1971; Munk, Snodgrass and Wimbush, 1970). This means that the tidal potentials can excite waves at selected periods, and that the observed amplitudes and currents then occur as a result of the propagation of these waves. They are gravity waves modified by rotation, and propagate in the southern hemisphere with the coastline on the left in the direction of propagation.

The major portion of the tidal amplitude observed at a coastal site is generally due to a barotropic type of Kelvin wave. Such a wave does not depend on stratification, and for narrow shelf regions does not depend markedly on shelf topography. Around South Africa there are no great variations in the amplitudes of the semi-diurnal and diurnal barotropic tides, with spring tide amplitudes ranging from about 1.4 to 1.8 m, and neap tides from 0,5 to 0,6 m.

The offshore scales of the baroclinic tides are the corresponding Rossby radii of deformation, generally of the order of a few tens of kilometres or less. As such, smaller-scale topographic features on a continental shelf region can exert a considerable influence on their characteristics. Usually the buoyancy frequency due to the stratification is much less than the tidal frequencies, so that resonance does not occur. The patterns of baroclinic tides also show considerable variations with respect to the more stable barotropic tides. Thus the small wavelengths make them susceptible to Doppler shifting by more energetic currents, thereby changing the frequency with respect to a stationary observer. Moreover, if measured tidal current amplitudes are strong functions of time, it can be assumed with a fair degree of certainty that they are due to baroclinic tides.

Baines (1982) discusses the internal tide generation models, where the forcing is due to the barotropic onshore-offshore tidal currents. The analysis indicates that the amplitude of such forcing will be accentuated markedly at a shelf break; the generated internal tide should therefore be sensitive to variations in stratification in such a region.

Analyses, such as those by Torgrimson and Hickey (1979) and Huthnance and Baines (1982), indicate that the propagation of tidal signals and the associated currents are complex phenomena. If the details of their structures are to be elucidated, a knowledge of the ocean stratification, ambient currents and bottom topography is needed, not only in the region of interest, but also far enough alongshore to accommodate waves moving along the coast; this again brings with it factors such as frictional dissipation.

An important factor in tidal theory is the existence of so-called "inertial latitudes", where the inertial period at that latitude is equal to one of the tidal constituents (Wunsch, 1975). For the diurnal constituents this occurs at latitudes between 26,5° and 30°, while for the semi-diurnal constituents the inertial latitudes range between 71° and 90°. Initially it was in fact thought that inertial motions occurred primarily in resonance with tides. However, Webster (1968) reviewed existing literature on the subject and discounted the idea. In particular, it is now accepted that one of the prime generators of inertial period motions is wind stress (Wang and Mooers, 1977; Mayer, Mofjeld and Leaman, 1981).

By the nature of its dependence on the local vertical component of the earth's rotation, pure inertial motion is horizontally polarised. It is also a circular motion, with an anticlockwise rotation in the southern hemisphere.

In the South African context the inertial period is close to the diurnal tidal period, possibly giving rise to interactions and making the separation of the two motions more difficult. In particular, it is worth noting that in an earlier analysis Welsh (1964) found pronounced inertial currents on the Agulhas Bank.

3 DATA AND ANALYSIS

The current data analysed here were all recorded by Aanderaa RCM-4 meters. These utilise a Savonius rotor to give a mean value of current speed over the measuring period, while a large vane gives an instantaneous value of current direction; the size of the vane effectively eliminates high-frequency fluctuations. Water temperature was also measured.

One mooring was chosen on each of the east, south and west coasts, and Figure 1 depicts the approximate positions at which the moorings were deployed, while Table 2 gives further mooring details. The mooring off Natal formed part of the Shelf Dynamics Project, with the meter mounted on a rigid stand some 3 m off the bottom. The moorings on the Agulhas Bank and off the west coast were done as part of a contract for the Southern Oil Exploration Corporation (SOEKOR). These consisted of taut-wire moorings, with the one at site W1 deployed directly from an oil drilling platform. Four meters were included in the vertical array, although good data were obtained only from three meters at the S1 site.

The depth of the shallowest meters on all the moorings should have precluded excessive contamination of the current speed record by wave-induced motions (Halpern, 1977). The rigid stand deployment, the configurations off the oil drilling platforms, and the subsurface upper buoy deployment would also have stopped or limited "rotor pumping" caused by mooring motion (Halpern and Pillsbury, 1976). As a consequence, for present purposes the values of currents and temperatures registered will be assumed to be an accurate reflection of the conditions actually present in the ocean at the time.

For all meters the data interval was set at 15 minutes. The values of currents and temperatures thus obtained were subjected to standard processing and analysis procedures before being filtered and decimated to hourly values by the operation of a Cosine-Lanczos filter with 24 distinct weights and a half power point of 0,5 cycles/hour. The hourly values served as the basis for most of the subsequent analysis, although in some cases further filtering giving three-hourly values was also applied.

Standard spectral analysis techniques were utilised to obtain the power spectra of the measured currents and temperatures (Jenkins and Watts, 1968). The resultant of any periodic, orthogonal pair of velo-

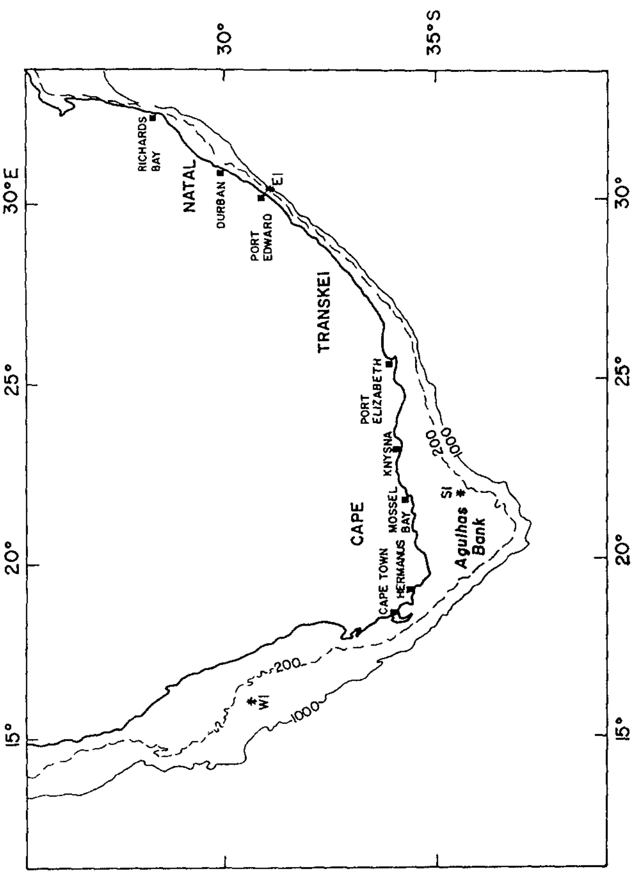

FIGURE 1. The Southern African coastline, showing bathymetry and indicating the positions of the moorings discussed in the text.

cities may also be represented as the combination of two vectors which rotate in opposite senses. Thus a velocity signal at a given frequency may be thought of as consisting of both clockwise and anti-clockwise portions. Such a decomposition can then be used to compute clockwise (S_-) and anti-clockwise (S_+) energy spectra, also referred to as rotary spectra (Gonella, 1972). The total spectrum S_t is then the sum of the two portions.

The rotary coefficient C is defined as

$$C = \frac{S_- - S_+}{S_t} = 1 - \varepsilon$$

and gives the partition of the energy S_t and the relationship with the normal ellipse eccentricity, ε. For pure circular motion the magnitude of C will be one, while it will be zero for linear fluctuations. Such an analysis is therefore important in distinguishing between inertial and Kelvin wave-type fluctuations. In the southern hemisphere inertial motion is anti-clockwise, that is, $S_+ \gg S_-$, while for Kelvin waves $S_+ \sim S_-$.

Current ellipses can thus be determined at all frequencies of interest, with the orientation of the major axis giving the dominant direction for the current fluctuations.

A further parameter of importance in this analysis is the stability of orientation of the ellipse. This gives an idea of the isotropy of the wave field generated by tides and inertial motions in the ocean; in particular, the barotropic tides should be stable, with a greater variability inherent in the internal motions.

In order to obtain more information about the nature of the internal fluctuations, empirical orthogonal mode (eom) analysis can be performed (Kundu, Allen and Smith, 1975). In essence, this technique determines the subdivision of the variance of the current fluctuations into the possible modes of oscillation, as well as giving information on their depth structure. In this way it can be ascertained whether the motion was predominantly barotropic, first mode baroclinic, etc. Of course, with four meters in the vertical it is possible to investigate only the first three baroclinic modes, although even this depends on the position of the meters relative to the density structure.

The basic technique was extended by Wang and Mooers (1977) to enable modes to be determined at specified frequencies. This involves the determination of the co-spectra and quadrature spectra, and then finding the empirical modes as eigensolutions of the cross-spectrum matrix. These methods were used in the analysis of the results from moorings deployed on the south and west coasts.

4 EAST COAST - NATAL

As shown in Figure 1, the shelf here is narrow, with the off-shore region dominated by the influence of the Agulhas Current (Pearce, 1977). This is a major western boundary current flowing polewards along the coast. Schumann (1981) analysed the data from moorings deployed off Natal and concluded that markedly different regimes existed in the region. In particular, the subtidal currents measured at the site E1 were largely associated with the Agulhas Current.

Figure 2 shows the result of rotary spectral analysis at the site E1. It is clear that, at the diurnal O_1 and K_1 tidal frequencies, a fairly significant peak emerges. The stability and ellipticity are high, as would be associated with classical Kelvin wave propagation. The abrupt drop at the inertial frequency associated with a high ellipticity indicates limited inertial motion.

A peak also emerges at the M_2 semi-diurnal frequency. The ellipse stability is lower, with a lower ellipticity, indicating a more circular type of motion than that at the diurnal periods.

However, overall it is clear that the fluctuations at the diurnal and semi-diurnal periods play a relatively minor role in the energetics at the site. It is dominated by energy at much longer periods, probably associated with the Agulhas Current.

5 SOUTH COAST - AGULHAS BANK

The Agulhas Bank comprises the widest continental shelf around South Africa, with a maximum offshore extent of about 270 km (see Figure 1). The measurements to be discussed were made on the eastern side of the Bank in water depths of less than 150 m. The Agulhas Current plays an important part in the dynamics of the region, particularly in terms of the spin-off eddies on the inshore edge which can penetrate onto the Bank itself (Lutjeharms, 1981). The influence of the Current, and the variations over the shelf, is then also apparent from the results obtained at the mooring S1 (Figure 1), particularly at longer periods.

Figure 3 shows the results of rotary spectral analysis carried out at the site S1. It is clear that there are three main contributions to the current fluctuations observed there, namely, those occurring at periods longer than about three days, and then the diurnal/inertial and semi-diurnal fluctuations. Only the latter two are of interest here, although it is worthwhile noting that, at periods of longer than about ten days a clockwise rotation dominates; this is probably associated with the spin-off eddies.

A substantial, broad peak appears in the anti-clockwise spectrum covering the diurnal and inertial periods in the range from about 18,5 to 27 hours. This is not reflected in the clockwise spectrum, indicating the existence of a dominant anti-clockwise motion. This is as expected at or near the inertial frequency, and is confirmed by the relatively high ellipse stability and low ellipticity shown in Figure 3.

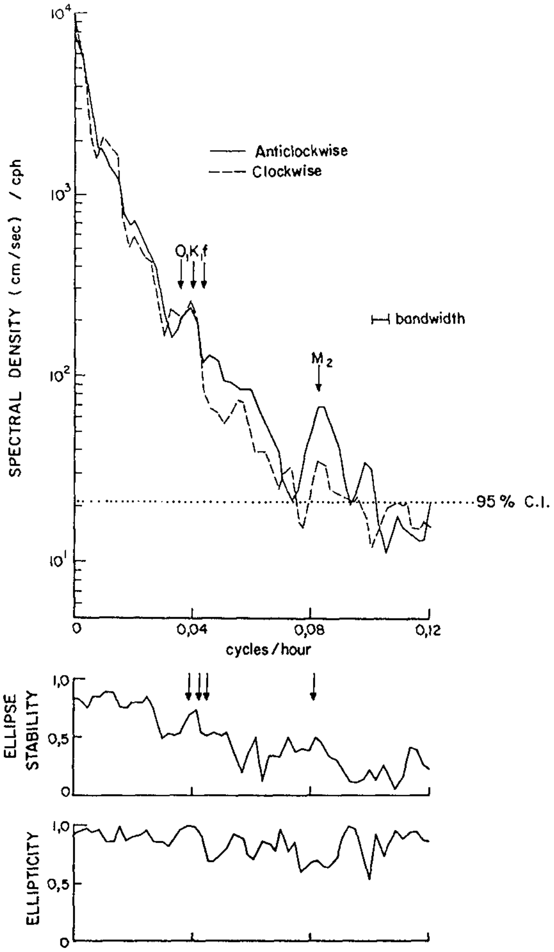

FIGURE 2. Clockwise and anticlockwise spectra for the measurements taken at site E1. Also shown are the ellipse stability and ellipticity, while the positions of the major tidal frequency bands are indicated, as well as the inertial frequency (f).

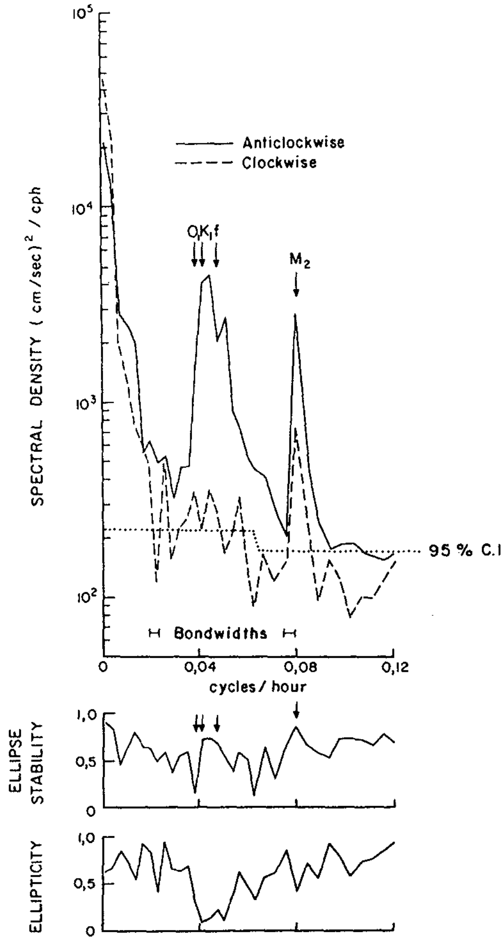

FIGURE 3. Clockwise and anticlockwise spectra and ellipse stability and ellipticity for the measurements taken at the topmost meter (depth 38m) at site S1.

A sharp, energetic peak occurs at the M_2 tidal frequency. Again the anti-clockwise spectrum dominates at this point, although there is nonetheless a substantial peak in the clockwise spectrum. A high ellipse stability is found, but with an intermediate value of the ellipticity.

The spectra determined from the measurements made at the two lower meters showed the same characteristics as those depicted in Figure 3 for the upper meter, although with slightly lower energies. However, this does not mean that the fluctuations observed were barotropic, since the analysis has merely indicated that the division of energy into the various frequency bands is similar.

Figure 4 shows the variations in coherence and phase between the east and north components of current at all three depths. It was not considered necessary to select any specific orientation for the current components, since Figure 3 did not reveal an exceptionally marked orientation for the current fluctuations.

It is clear that there is a major difference between the tidal and inertial period fluctuations. At the semi-diurnal and diurnal tidal periods a high level of coherence is found throughout the water column, with a minimal phase change with depth. At the inertial period a high level of coherence is also found, but with a phase change approaching 180° between the upper and middle meters. Calculation of the mean temperatures recorded at the three depths over the whole measuring period gives values of 16,6°C (38 m), 10,2°C (108 m) and 9,9°C (130 m). It is therefore clear that a major pycnocline existed between the upper and middle meters, giving favourable conditions for the existence of baroclinic fluctuations. On the other hand, only the inertial period fluctuations appear to respond, as indicated as well by the sharp dip in coherence between the diurnal tides and the inertial frequency in the upper meters of Figure 4.

The results of eom analysis are given in Table 3, and support the above conclusions. The vast majority of the fluctuation energy resides in the barotropic and first baroclinic modes, although there are some much smaller phase variations with depth in each of these modes; these may be associated with frictional effects or vertical propagation.

The difference between the long-period, tidal and inertial fluctuations is clear. The former are all essentially barotropic, with no more than about 10% of the energy distributed amongst the baroclinic modes. However, the inertial fluctuations are primarily dependent on the variations in density over the ocean depth, with less than 20% of the energy in the barotropic mode. This seems to be in agreement with the result that inertial oscillations in a coastal boundary or shelf region are essentially dependent on stratification (Pettigrew, 1981). It is also likely that there was considerable variability in the extent of the inertial fluctuations over the measuring period.

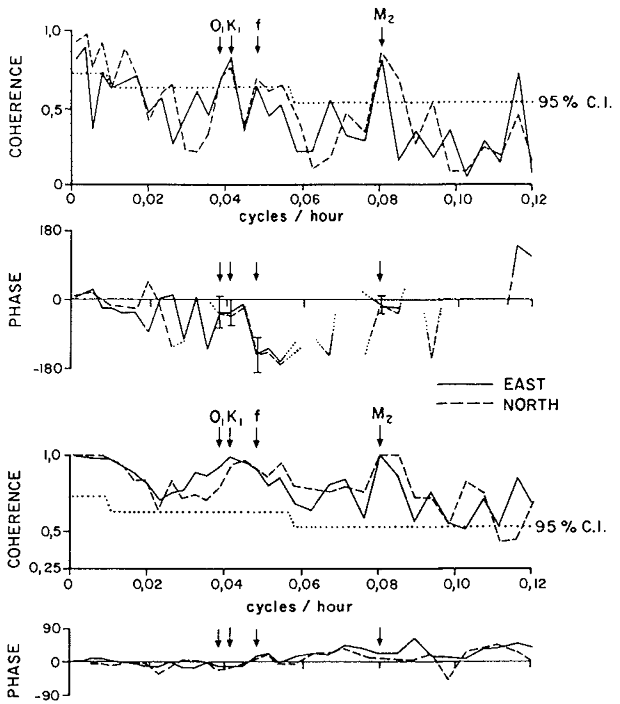

FIGURE 4. Coherence and phase between the east and north current components at site S1. The top section considers currents from the upper and middle meters (38 and 108 m), while the bottom section considers the middle and lowest meters (108 and 138 m). The 95% confidence limits are shown in the coherence, while for the upper meters the approximate error bars for phase are shown only at the indicated frequencies; for the lower meters the error in phase is less than 20°. Phase is only shown for relatively high coherence, while a positive value indicates that the lower of the two meters leads.

6 WEST COAST

The bottom topography is much more broken off this coast than either on the east or south coasts, with no well-defined shelf or slope. The Benguela Current flows northward here but should not be thought of as a well-defined current, but rather as a general movement of water northwards with eddies and current reversals.

The inertial period at this mooring is very close to the K_1 tidal period (Table 2). With the relatively short records, it was therefore not possible to resolve fluctuations at these two periods.

Figure 5 shows rotary spectral calculations at three of the four measuring depths. It is clear that the fluctuations at tidal and inertial frequencies contribute a major portion of the current energetics at the site. There is, moreover, a change with depth, with the diurnal/inertial peak highest at the upper meter, but then gradually being superseded by the semi-diurnal peak as the depth increases. However, it should be remembered that the time series at the upper meter covered only about four-fifths of that at the lower depths. The reason for the apparent emergence of a peak at about a 17-hour period is also not clear.

As expected, at the diurnal/inertial frequency the anti-clockwise peak contains most of the energy, with associated ellipticity values of less than 0,06 at all four depths. At the semi-diurnal peak the motion is also primarily anticyclonic, with ellipticity values of 0,42 at the upper meter and less than 0,28 at the deeper meters.

Figure 6 shows the coherence between adjacent meters on the mooring. Only the eastward components of the currents were considered, since again the low ellipticity values at the frequencies of interest show that any fluctuations will be reflected in all current components.

At the diurnal/inertial frequencies, there is a low coherence over the whole water column, while at the semi-diurnal M_2 frequency a very high coherence emerges. Inspection of the phase angles at the M_2 frequency shows values close to zero between all the measuring depths, that is, largely barotropic motion occurred with the semi-diurnal tidal propagation.

The eom results support these conclusions, with only the M_2 tidal fluctuations having a well-defined structure; here the barotropic mode dominated the energy partition with about 91%, with 8% in the first baroclinic mode. The long-period barotropic component comprised about 74% of that band's energy, although with more limited coherence especially near the surface. About 20% and 6% went into the first and second baroclinic modes, respectively. At the O_1, K_1 tidal and the inertial frequency bands the situation is much more confused, with little indication of barotropic motion, but with a limited vertical coherence in the baroclinic motions.

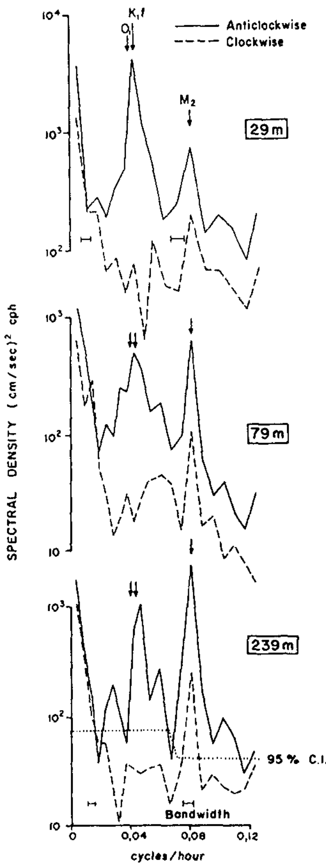

FIGURE 5. Clockwise and anticlockwise spectra from measurements at 29, 79 and 239 m depth at site W1. The 95% confidence limit shown for the bottom spectra applies to all three cases, while the bandwidths at the upper meter differ because of the shorter record.

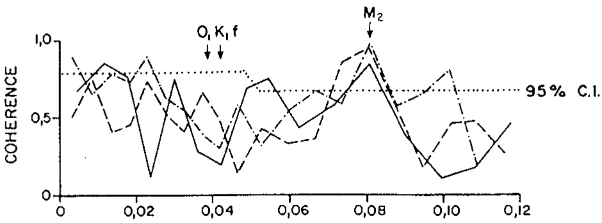

FIGURE 6. Coherence between adjacent meters on the mooring W1. Thus ——— considers the meters at 29 and 79 m, —·—·— the meters at 79 and 159 m, while — — — — is for 159 and 239 m depths.

7 CONCLUSIONS

The analysis that has been presented here has been limited by the small amount of current data available. As a result it was not possible to investigate the propagation of tidal and inertial signals, with only a limited analysis being possible of the vertical structure on the south and west coasts of South Africa.

Nonetheless, as a first look at the tidal and inertial currents, some very important differences between the coastal ocean regimes around South Africa have emerged. Moreover, it is clear that these currents cannot be ignored as a matter of course; indeed there are regions where they provide the dominant contribution to the total current variance.

Table 4 gives the comparison. The majority of spectra, particularly along the south and west coasts, have exhibited peaks at the semi-diurnal diurnal/inertial frequencies, as well as at the low-frequency limit. Consequently these peaks have been considered in the comparison; in some cases judging the extent of the peaks has been somewhat subjective, but in the majority of cases the error involved is small. The low frequency limit has included all frequencies less than about 0,014 cph (3 days).

On both the south and west coast sites the current ellipses at the tidal and inertial frequencies all rotate anti-clockwise. The ellipses themselves are not very eccentric, with the currents not showing the linear polarisation associated with the classic barotropic Kelvin wave. Nonetheless the indications are that at the M_2 semi-diurnal frequency the fluctuations were predominantly barotropic, also supported by the very consistent values found with depth in Table 4. Without more measurements the precise structure of the baroclinic fluctuations is not known, although the evidence for a strong first mode oscillation at the sharp thermocline at site S1 is clear.

The generation of the baroclinic fluctuation at tidal and inertial frequencies falls outside the scope of this paper, and indeed there are only limited data available to investigate this aspect. Nonetheless, given the proximity of the diurnal and inertial frequency bands, it is likely that some interaction occurred. Wind stress should also play a part, in which case a seasonal variation could be expected with the different seasonal winds. Changes in density structure would then markedly affect the response.

As a result, it is probable that considerable variability is likely to occur in the baroclinic fluctuations, that is, at times there may be minimal currents, but in order to achieve the mean values in Table 4, there must have been substantial currents at other times. Topographical variations and changes in ocean structure will also cause changes in the currents at the various frequencies; at present such variability across the shelf regions and with time is not known. It is nonetheless clear that in any construction or development in the ocean around South Africa, cognisance should be taken of the fact that tidal fluctuations may constitute the dominant portion of the currents actually encountered.

ACKNOWLEDGEMENTS

Much of the analysis presented here was done while one of us (EHS) was visiting the Woods Hole Oceanographic Institution. As such the PROSPECT series of programs were used, while Dr Bob Weller advised on aspects of the analysis. Acknowledgement is also given to Dr Ken Brink for the use of his eom programs, in addition to helping with the interpretation of results.

The data on the south and west coasts were collected under contract to the Southern Oil Exploration corporation, and acknowledgement is given here for permission to use the data in this analysis.

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	Tidal Symbol (description)	Period (hrs)	Coefficient
	O_1 (principal lunar)	25,82	0,415
Diurnal	P_1 (principal solar)	24,07	0,194
	K_1 (lunisolar declinational)	23,93	0,585
	N_2 (elliptical to M_2)	12,66	0,192
Semi-	M_2 (principal lunar)	12,42	1,000
diurnal	S_2 (principal solar)	12	0,466
	K_2 (lunisolar declinational)	11,97	0,127

TABLE 1: The main diurnal and semi-diurnal tidal constituents. The coefficient gives a value of the appropriate tidal potential relative to the dominant M_2 tide.

Mooring (Period)	Water Depth (m)	Meter Depth (m)	Data (days)	Inertial Period (hrs)
East E1 (Oct.1976-Jan 1977)	29	26	91	23,25
		38	93	
South S1 (Nov.1978-Jan 1979)	144	108	94	20,75
		130	94	
		29	27	
West W1 (May-Jun 1981)	255	79	35	23,73
		159	35	
		239	35	

TABLE 2: Details of the data recovered from the moorings deployed on the east, south and west coasts of South Africa. Locations of the sites are given in Figure 1.

	Long Period	O_1K_1 Tidal	Inertial (F)	M_2 Tidal
Barotropic	94	89	18	91
First baroclinic	6	10	80	9

TABLE 3: Energy partition in the various frequency bands at the mooring site S1. Only the easterly current component was used in these calculations.

Site	Depth (m)	Mean Current (cm/s) Eastward	Mean Current (cm/s) Northward	Current fluctuations (cm/s) Low Frequency	Diurnal/ Inertial	Semi-diurnal
S1	38	-11,2	-13,2	17,5	7,9	4,3
	108	-13,1	-5,5	13,3	6,8	4,0
	138	-12,6	-3,8	12,3	4,1	3,7
W1	29	-12,0	0,1	6,7	6,4	3,6
	79	-9,7	0,7	4,0	3,1	2,5
	159	-4,4	0,4	3,4	3,5	3,5
	239	-3,7	0,5	4,6	3,4	4,5

TABLE 4: Mean currents and the appropriate magnitude of current fluctuations over three frequency bands. These fluctuations have been calculated as the square root of the current variance over the bands shown.