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Continental Shelf Research 25 (2005) 1864–1876
CONTINENTAL SHELF RESEARCH
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Internal tide—shelf topography interactions as a forcing factor governing the large-scale distribution and burial fluxes of particulate organic matter (POM) in the Benguela upwelling system

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Received 15 December 2004; received in revised form 21 June 2005; accepted 30 June 2005
Available online 29 August 2005

Abstract

This study investigates the role of internal tides in driving the sedimentation and re-suspension of biogenic POM on the Namibian shelf and give rise to stable 500–800 km long shore alternating bands of high and low POM concentrations. Temperature time series data (September 2000–March 2001) from the benthic boundary layer at three sites are used to hypothesise that the dominant forcing mechanism are internal tides and their interaction with the shelf break zones. Vertical displacements of the temperature structure by 100–150 m at the outer shelf break (depth 450 m) are shown to occur through out the 6-month time series. In contrast at non-shelf break sites the vertical displacements of temperature are negligible. The shear–stresses predicted landward of the shelf break zone from 100–150 m vertical displacements of the temperature structure are significantly higher (>0.1 Pa) than the critical shear–stresses which govern the re-suspension of biogenic particles and fine sediments (0.05–0.1 Pa). Short-term ADCP data was used to show that critical shear–stress distribution at the different POM areas is consistent with the predicted net accumulation and net erosional zones of POM across the Namibian shelf. This study hypothesises that the barotropic–baroclinic tidal coupling governs vertical particle flux dynamics whereas Ekman and inertial flows are thought to govern the horizontal advection scales that result in the observed POM distribution. The importance of this improved dynamical understanding has implications for both carbon burial efficiency as well as the variability in the suitability of benthic fisheries habitats.

Keywords: Internal tides; Shelf sediments; Particulate organic carbon; Benguela upwelling system; Namibia

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0278-4343/$ - see front matter
doi:10.1016/j.csr.2005.06.012

1. Introduction

The effectiveness of upwelling shelf systems as long term reservoirs for particulate organic carbon (POM) burial can depend as much on the scales and rates of phytoplankton new production (Chavez and Toggeweiler, 1995; Brink et al., 1995; Summerhayes et al., 1995) as on the dynamical processes that govern particle sedimentation and re-suspension near the seabed (Jones et al., 1998; Hill and McCave, 2000). Together, these processes govern the spatial scales of fluxes and long-term fate of POM (Liu et al., 2000; Berner, 1982). While the former is well constrained in shelf upwelling systems (Chavez and Toggeweiler, 1995; Brink et al., 1995; Summerhayes et al., 1995) the mechanisms and scales of the latter, especially below the gravity wave base, are inadequately understood. Most regional carbon flux models treat the shelf as a homogeneous domain separate from the slope and deep ocean but do not resolve the fine scale processes that govern heterogeneity in POM deposition, biogeochemistry and burial within the shelf (Liu et al., 2000; Tsunogai et al., 1999). The role of dynamical considerations near the seabed in constraining the spatial scales of POM sedimentation is the subject of this study.

On the continental shelf of Namibia, sediments with high concentrations of POM are confined to three well-defined long shore belts of 500–800 km length (Bremner, 1978; Bremner, 1983; Rogers and Bremner, 1991) (Fig. 1a). A detailed sector (Fig. 1b) of these features in the mid-shelf area (~20–24°S) reveals an inner shelf mud belt with highest POM concentrations (7–25%) at a depth of 50–140 m, a mid-shelf ($z = 200$–300 m) belt and an outer shelf ($z = 500$–1400 m) belt. Between these belts are sediments with lower concentrations of POM, (inner shelf: 140–200 m and outer shelf: 300–500 m) resulting in a banding effect of alternating high- and low-POM sediments across the shelf. While the low-POM band inshore ($z < 50$ m) of the inner shelf POC-rich belt can be ascribed to bed stresses generated by the long-period gravity waves of winter (Rogers and Bremner, 1991) the deeper two (150–200 m and 300–500 m depth) cannot be so easily explained. However, both are close to double shelf breaks (~180 and 350 m) that characterise much of the Namibian shelf north of 23°S (Bremner, 1978).

Their importance in shelf upwelling systems such as the Benguela lies both in constraining the carbon burial flux estimates (Liu et al., 2000) as well as in the ecological and socio-economically related consequences of hypoxia, driven by sediment biogeochemistry (Copenhagen, 1953; Froelich et al., 1988; Bailey, 1990; Chapman and Shannon, 1987) on fish resources and how those may respond to climate change (Shannon and Nelson, 1996; Lutjeharms et al., 2001). In the Namibian upwelling system, ecologically significant hypoxia events are seasonally ubiquitous in the inner shelf (Bailey, 1990; Chapman and Shannon, 1987) and often linked to, inter-annually more variable, extreme sulphide rich methane eruptions (Copenhagen, 1953). Historical work in the Benguela system suggested that, below the gravity wave base, the POM distribution in the mud belts of the Namibian shelf sediments is linked to long period physical mechanisms (Bremner, 1978; Bremner, 1983). These include both intensification of Ekman driven currents and inertial flows near the bottom at the shelf break (Lenz and Trowbridge, 1991; Smith, 1995; Shannon and Nelson, 1996; Simpson et al., 2002). This study explores an alternative understanding of POM distribution in the central Benguela upwelling shelf based on elevated bed shear–stresses generated through the interaction of internal tides with the shelf edge break.

2. Methodology

The measurement programme combined a 6-month long (October 2000–April 2001) mooring deployment at five locations across the shelf, and two ship-based sampling cruises (February and June 2001). In both cases five stations spanning a range of depths from the inner shelf (station 1) to the slope (station 5) were used as sampling locations (Figs. 1a–b).

The moorings provided hourly data from optical backscatter (OBS) units and RCM-4 current meters located 10 and 15 m off the bottom,

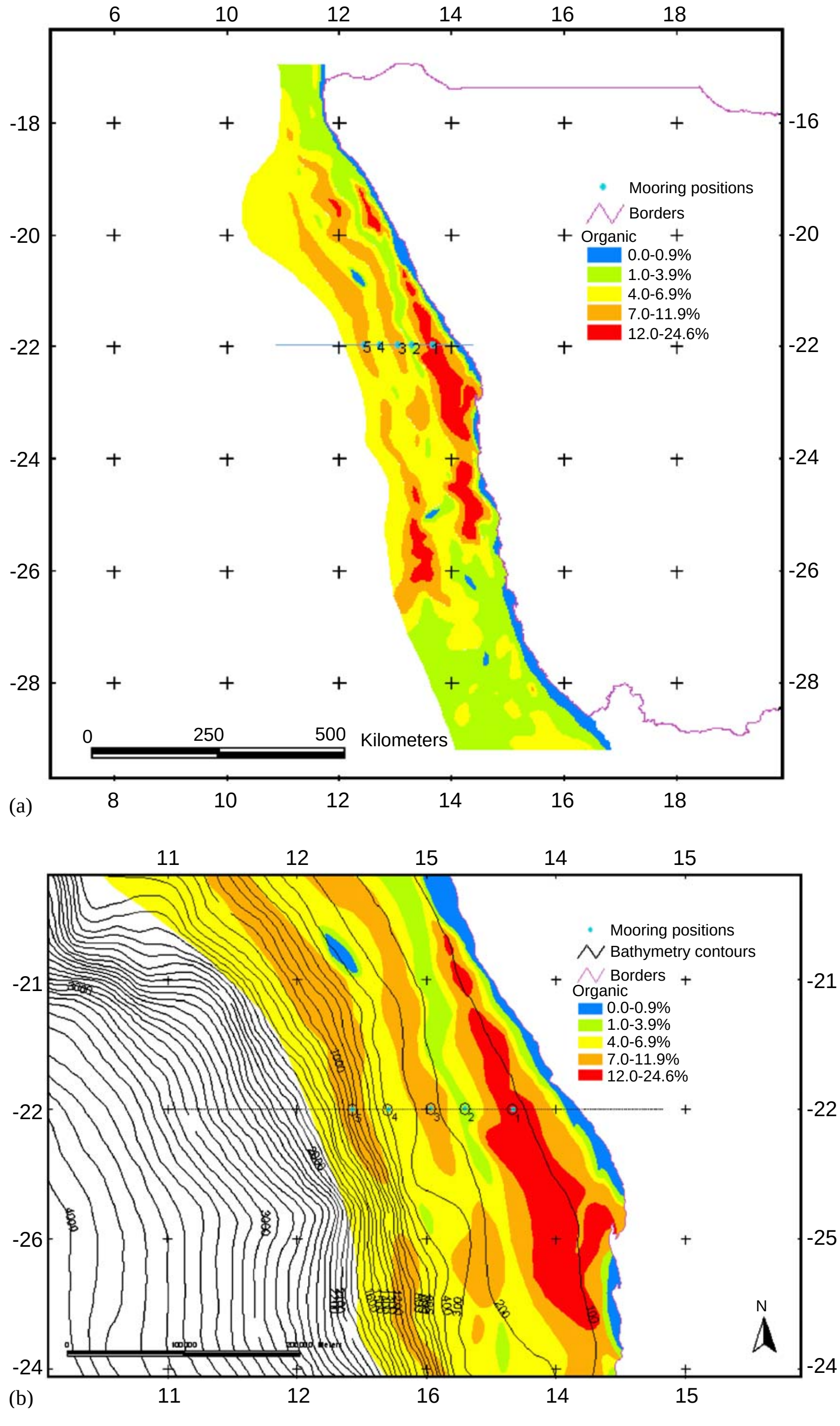


Fig. 1. Depicts the spatial distribution of the large-scale high- and low-POM bands along the Namibian shelf (adapted from Bremner, 1978). (a) Shows a length scale of approximately 800 km with the highest concentrations (POM > 25%) at the inshore mud belt. The mid-shelf belt terminates just south of 23°S where the shallower inner shelf break feature also ends. (b) Depicts a higher resolution map of the zone where the samples were taken and the moorings located. Station 1 is the sampling site closest inshore. Stations 2 and 4 are at the inner and outer shelf break zones, respectively. The moorings at stations 2 and 3 were lost.

respectively (Fig. 1b). The deepest mooring at station 5 had a current meter only. Only three (stations 1, 4 and 5) of the five moorings were recovered, which limited the findings of the study to only investigating the interaction of the internal tides with the outer shelf break (Fig. 1). The two ship-based sampling trips provided short-term (2–6 h), moored acoustic doppler current profiler (ADCP) deployments (RDI—300 KHz: downward looking 0.5 m bins: RDI Mode 1), multi-coring of sediments (Ocean Instruments-MC-200) and CTD (SBE 911) profiling. The OBS units were calibrated against total suspended matter (TSM) using filtered water samples from in situ surface water samples. POC and PON samples were measured using a CHN elemental analyser. POC concentrations were obtained from acidified sediment samples to exclude the carbonate fraction and PON were determined from the un-acidified samples to avoid loss of labile N by acidification. The percentage sediment particle analysis was undertaken by wet sieving and the mud fraction constituted the $<60\,\mu m$ fraction.

3. Results

The time series of temperature data from the three recovered moorings at stations 1, 4 and 5 are depicted in Figs. 2–4. The temperature data sets from all three sites (Fig. 2) show a remarkable contrast in scales of variability (magnitude and frequency) between the outer shelf break site (station 4: 400 m) and the two sites away from any shelf break (stations 1: 140 m and 5: 1000 m). While the former is characterised by variability with excursions of 1–2 °C at tidal frequencies superimposed in a sub-seasonal cycle, the latter are characterised by insignificant variability except for a seasonal warming trend at station 1 (Fig. 2).

The relative variability of temperature and suspended matter (OBS) are shown for stations 4 and 1 in Figs. 3 and 4. These plots further emphasise the spatial contrast between shelf break and non-shelf break sites. While at station 4 the strong OBS signals associated with short-term event scales that are associated with the largest

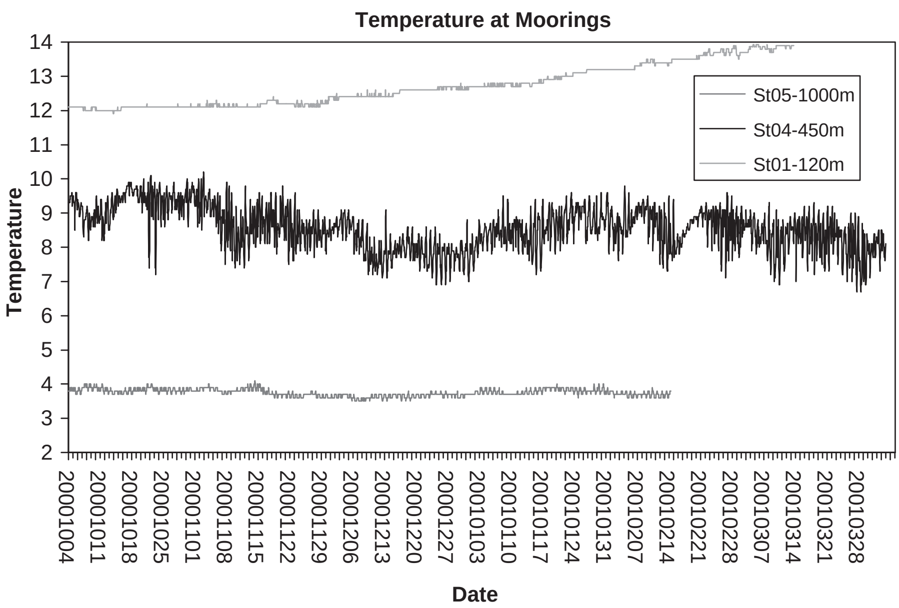


Fig. 2. Plot showing a time series of temperature variability from the benthic boundary layers at stations 1 (120 m), 4 (450 m) and 5 (1000 m) across the Namibian shelf. It shows the contrast in the amplitude of high-frequency temperature variability between the shelf break zone (station 4) and the non-shelf break zones (stations 1 and 5). In the former the amplitude of variability is 1–2 °C whereas in the latter it is mostly less than 0.1 °C.

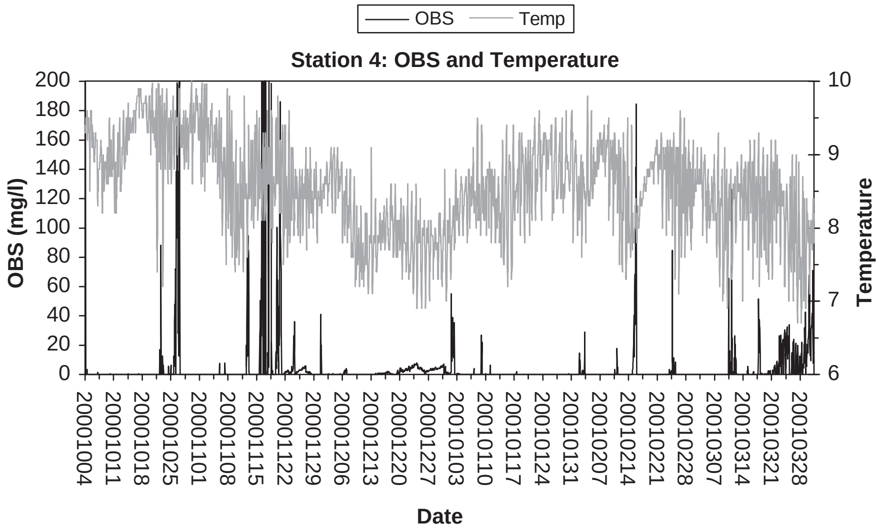


Fig. 3. A time series from the station 4 at the outer shelf break mooring showing both the temperature and OBS signals. It shows that most re-suspension events coincide with extremes of temperature oscillations.

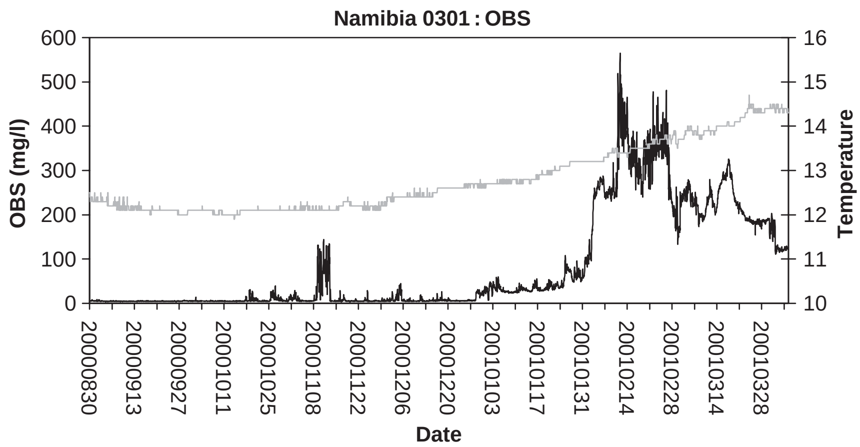
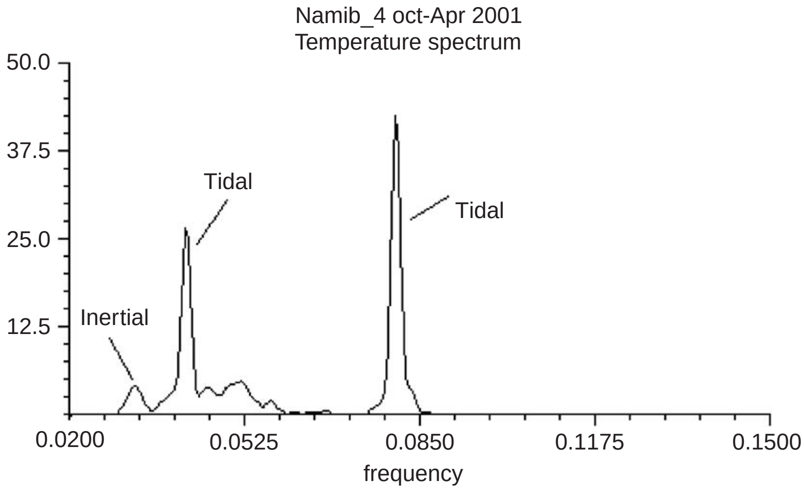


Fig. 4. A time series from the station 1 at the inshore mud belt mooring showing both the temperature and OBS signals. It shows that in contrast to the outer shelf break variability, the OBS signal has a strong biogeochemical signal, thought to be driven by methane bubble fluxes.

temperature excursions there is no such relation at station 1. Rather, the OBS signal at station 1 indicates a strong seasonal character with higher frequency variability not correlated with the most important physical forcing scales (Fig. 4). Spectral analysis of the temperature variability at the outer shelf break station 4 revealed that peaks occurred at tidal frequencies (12 and 24 h) (Fig. 5). Temperature sections of the water column across the shelf at 22°S in August 2000 and February 2001 (Fig. 6) shows that a 1–2 °C temperature excursion at 400 m outer shelf break (station 4) corresponds to vertical oscillations of 100–150 m in the temperature structure in the 7–10 °C range and a corresponding horizontal displacement of 10–15 nm. A thickening of the benthic boundary



Peaks at:	f (cy/hr)	T	E
	0.0325	1d 06h 46m	4
	0.0420	23h 49m	25
	0.0460	21h 44m	4
	0.0525	19h 03m	4
	0.0580	17h 14m	2
	0.0810	12h 21m	40

Fig. 5. A plot of the output from a spectral analysis of the temperature variability at the outer shelf break mooring. It shows the signal to be dominated by the diurnal and semi-diurnal tidal forcing.

layer at the outer shelf break is clearly seen in the February section (Fig. 6b). The plots correspond to the cool and warm period reflected in the time series from station 4 (Fig. 3).

The current velocities measured by short-term deployments of the ADCP are shown for two depths (5 and 15 m) off the sea-bottom at the outer shelf break station 4 (Fig. 7). The data were sampled in 3-min ensembles from a 300 KHz instrument. It shows a sharp offshore velocity increase, which is ascribed to a tidal bore with a high frequency variability that could be linked to turbulent energy dissipation. The benthic boundary layer averaged current speeds at all five stations across the shelf measured over 2–3 h deployments at the peak of a spring tidal cycle with the 300 KHz ADCP are summarised in Table 1. It shows that the cross shelf variability in the BBL current speed is inversely correlated with the POM distribution that gives rise to the long shore bands. This is supported by a Spearman correlation (ordinal) of $r = -0.90$ ($n = 5$ $p < 0.001$). It also shows that the variability is strongly modulated by the cross shelf velocities.

4. Discussion

The results presented above point to two important characteristics of internal tide—shelf topography interactions shared by the Namibian shelf system and other comparable systems (Simpson, 1998). Firstly, the transfer of tidal frequency barotropic forcing energy to internal tides that dissipate part of their energy at the shelf break areas. Secondly, that this results in sharp contrasts

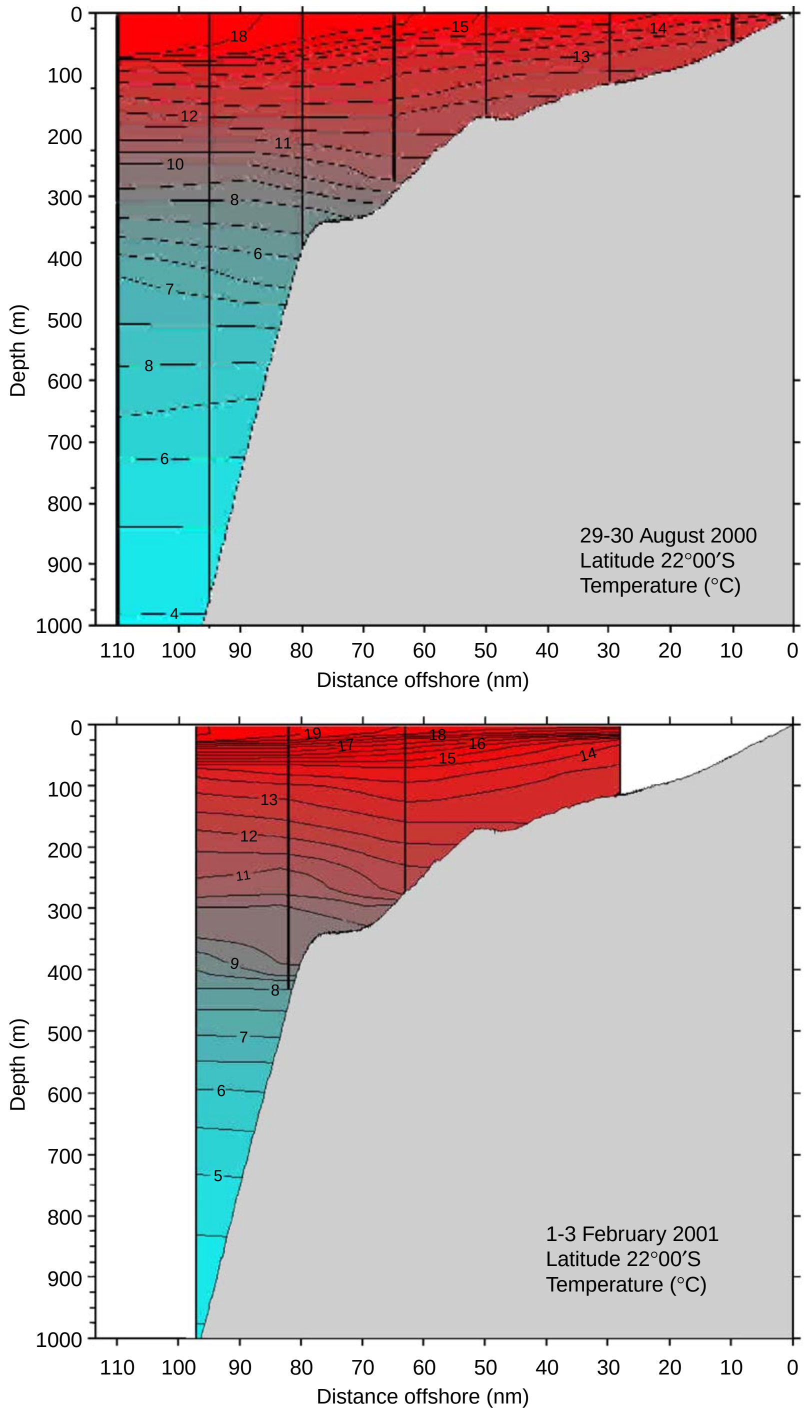


Fig. 6. A CTD temperature sections (August 2000 and February 2001) along the 22°S line across the Namibian shelf where the moorings were located. It shows the temperature structure at both shelf break regions indicating that a 1–1.5 °C oscillation at the outer shelf break is equivalent to a vertical displacement of 100–150 m. Note the thickening of the benthic boundary layer at the outer shelf break in February 2001.

in the cross shelf scales of vertical temperature variability between the shelf break, where they have large amplitudes (1–2 °C) and non-shelf break areas with low amplitude oscillations (Fig. 2), which correlate strongly with the POM variability (Fig. 1). This persistent type of energy dissipation in the vicinity of the shelf break (Holloway, 1987) is hypothesised to generate the bed shear–stresses that drive re-suspension in the benthic boundary layer inshore of the shelf break zones and give rise to the long shore bands of POM. The basis for the hypothesis is addressed in detail below.

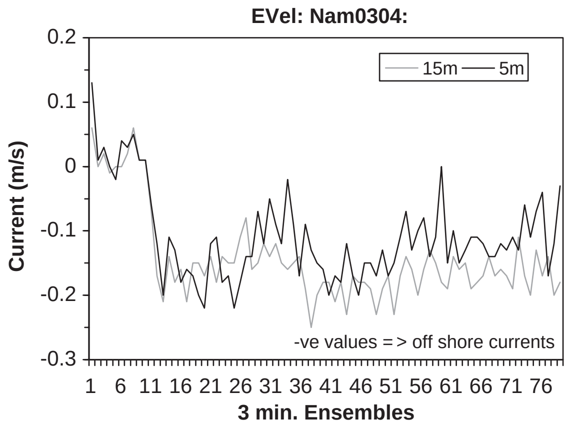


Fig. 7. A short time series of the cross shelf (v) component of ADCP derived currents at 5 m and 15 m off the bottom at station 4 on the outer shelf break. The data shows a sharp increase in the offshore current velocity at the high spring tide point after which the velocities remain high but variable possibly associated with turbulence dissipation.

4.1. Temperature variability

The energy dissipation at shelf breaks associated with internal tidal bores and high frequency (< 1 h) soliton wave packets have been well described both theoretically and observationally for a number of shelf systems which include Scotia Shelf (Sandstrom and Elliott, 1984), Celtic Sea (Pingree et al., 1985) and the Australian North West Shelf (NWS) (Holloway, 1987). These studies show non-linear vertical displacements of temperature with amplitudes of up to 50% of the water column depth (60 m in 170 m of water in the Celtic Sea and 60 m in 120 m of water in the Australian NWS) (Holloway, 1987; Simpson, 1998). The temporal resolution of the data set in this study did not resolve the required time scales (minutes) of the high-frequency energy dissipation and this mechanism is not invoked by this study. Rather, we focus on the tidal cycle variability which was resolved by the hourly sampling scale.

The time series obtained from the outer shelf break (station 4) off Namibia shows that those temperature displacements of 1–1.5 °C (occasionally up to 2 °C) occur throughout the 6-month sampling period (Fig. 2). A remarkable aspect of this dynamical character in the baroclinic field is that such large displacements (100–150 m) are occurring in relatively deep water (400–450 m) and under relatively weakly stratified conditions (200 m depth range between 7–10 °C) (Fig. 6). A spectral analysis of the variability at the lower shelf break shows it to be strongly dominated by the 12- and 24-h tidal frequencies (Fig. 5), which

Table 1
The variability of physical parameters in the benthic boundary layer (BBL) determined from short-term ADCP records and sediment biogeochemical characteristics across the Namibian shelf

Station	V_{bbl} (m s^{-1})	V_E (m s^{-1})	u_{*c}	z_0 (m)	τ_c (Pa)	POC (%)	%Mud	C:N
1	0.077	0.054	3.4E-3	609.8E-6	11.6E-3	14.5	98.2	7.7
2	0.096	0.079	5.2E-3	3.5E-3	27.8E-3	3.5	26.1	9.6
3	0.069	0.045	3.6E-3	6.7E-3	13.3E-3	4.9	53.1	10.4
4	0.176	0.105	14.1E-3	31.5E-3	203.9E-3	2.7	42.5	11.5
5	0.087	0.065	2.7E-3	3.4E-6	7.5E-3	4.8	98.6	10.7

Shown are the average speed in the BBL (V_{bbl}), the speed to the cross-shelf component of the flow (V_E), the friction velocity (u_{*c}), the bed roughness (z_0), the bed shear–stress due to current speed (τ_c), the particulate organic carbon concentration (POC), (POM = POC*2.5) the percentage mud (< 63 μ) and the C:N ratio of the POM.

confirms that most of the vertical displacement is coupled to the transfer of energy from the barotropic to the baroclinic tides. The persistence of both the large amplitude temperature displacements linked to internal tidal bores suggest that these are both present and important features of the shelf break benthic boundary layer hydrodynamics in the Namibian system. Comparable depletion of fine sediments in the southern Benguela shelf (Birch, 1975 in Monteiro, 1996) indicate that this internal tide—shelf break turbulence may be a general system characteristic throughout the Benguela system.

Of importance in respect of the POM distribution and burial is the way in which these internal tide dynamics, recorded as a temperature proxy, govern sedimentation and re-suspension in those shelf break areas. The velocities that are suggested to be associated with the variability in the sedimentation—re-suspension character of the shelf breaks are now examined in more detail.

4.2. Current velocities and bed shear–stresses

Bed shear–stresses at the outer shelf break are derived from both a simplified model that uses the horizontal transport linked to measured vertical displacements in the temperature structure as well as from observational programmes. Coupled temperature and current velocity observations in the Australian NWS area have shown vertical temperature displacements to be associated with strong current oscillations of up to 0.68 m s^{-1} (Holloway, 1987). These oscillating currents, driven by the range of high frequencies that characterise internal tidal energy dissipation, while stronger than the sub-tidal frequency flows, contribute insignificantly to net advection. It has been calculated that 95% of the energy is dissipated within one wavelength of the break, typically 20–50 km which is in good agreement with the observed cross shelf length scales of the sediment data off Namibia (Fig. 1).

On the Namibian shelf 50–150 m vertical displacements in the temperature structure at 400 m give scope to an inshore horizontal transport at the bottom friction boundary of 10–15 nm over half a tidal cycle (Fig. 6). The horizontal speeds that would be associated with such horizontal displacements are in the range 0.4–1.2 m s^{-1}, which even with relatively small estimates of bottom roughness, generate bed shear–stresses that are significantly higher than the critical shear–stresses of 0.05 Pa. The current velocity time series from the moorings could not be used to quantify the role of internal tidal forcing because the hourly vector-averaged sampling was inappropriate to resolve the short-period (<1 h) and high-velocity oscillations associated with dissipation of internal tidal energy. Mixing induced by the dissipation of the internal tidal energy at the shelf break can be seen in Fig (6b) as a thickening of the benthic boundary layer at the outer shelf break.

However, short-term ADCP sampling at 3-min. intervals and 0.5 m bin depth resolution during a spring tide (5–7 June 2001) provided support for this mechanism (Fig. 7). These data were from all five sampling sites and were used to calculate the cross-shelf variability of the depth-averaged speed in the benthic boundary layer, as well as the bed shear–stresses using a natural log correlation method (Eq. (1)) (Soulsby, 1998).

$$U(z) = \left(\frac{u_*}{\kappa}\right) \ln\ z - \left(\frac{u_*}{\kappa}\right) \ln\ z_0. \tag{1}$$

A linear regression of $U(z)$ against $\ln(z)$ was used to derive the u_* (k von Karman constant is 0.4), which was then used to calculate z_0 and the bed shear–stress (Eq. (2)):

$$\tau_0 = \rho u_*^2. \tag{2}$$

The calculated cross shelf distribution of depth-averaged current speeds in the benthic boundary layer and the bed shear–stresses is consistent with the shelf-scale bands of POM (Table 1). The highest depth average current velocities and lowest POM concentrations are at stations 2 and 4, which correspond to the inner and outer shelf-break zones where turbulence would be expected to be highest (Fig. 2). There is a significant difference in calculated bed stresses between the two shelf break sites (stations 4 and 2) where the highest values were measured but it is not clear if this is due to the weakening of the internal tidal bore between the outer and inner shelf break zones, or due to differences in the shelf break characteristics. Shelf break angle is greater in the outer shelf (Bremner, 1983). However, these ADCP results are conservative in that they are both short term as well as averaged and underestimate the peak velocities that drive re-suspension and sedimentation dynamics. Calculations from the Australian NWS show that energy dissipation through internal tide activity is approximately 20–25% of the energy of the internal tide that may be otherwise dissipated as turbulence (Holloway, 1987). The oscillating peak velocities measured with the ADCP at a height of 5 m off the seabed at the outer shelf break were 0.25–0.3 $m\,s^{-1}$ (Fig. 7). These velocities are in the same order of magnitude as those predicted by the horizontal transport distances over half a tidal cycle. These show that velocities capable of generating bed shear–stresses of >0.05 Pa, typically required for the re-suspension of POM, are achieved at the outer shelf break even though those velocities may not be as high as those observed in other more stratified systems.

One of the problems that needs to be addressed when a focussed investigation attempts to disprove this shelf break energy dissipation hypothesis is to also explain how the effect extends over such a length scale to give rise to features that are more than 500 km long. Previous work has focussed on soliton activity being associated not only with shelf breaks but also with more local physical heterogeneity (Simpson, 1998).

4.3. Biogeochemical and ecological considerations

Sites characterised by lowest average benthic boundary layer current velocities and bed shear–stresses are those where highest POM concentrations occur (Figs. 1a and b, and Table 1). This is particularly the case for the inner shelf mud belt where the highest POM concentrations (20–30%) have been measured (Fig. 1b). The inshore high-POM diatomaceous mud belt is sustained by the combined forcing of inner shelf phytoplankton new production fluxes of 300–600 $mg\,C\,m^{-2}\,d^{-1}$ (Probyn, 1992), and the persistently low bed shear–stress in this area. The POM rich mud belt is constrained between gravity-wave stresses in the 0–50 m depth range and the baroclinic turbulent energy dissipation zone above the inner shelf break at 150–200 m depth. The re-suspension dynamics in each of these coupled with upwelling-driven cross shelf advection provide additional lateral fluxes of POM into the inshore mud belt. The high rates of POM diagenesis coupled to poor vertical mixing and horizontal advective fluxes in the benthic boundary layer result in perennial sediment anoxia (Bailey, 1990; Middelburg et al., 1993). The resulting sulphide and methane gas bubble fluxes into the overlying water column and accompanying oxygen demand, contribute to persistent water column hypoxia. These are aggravated periodically by methane eruptions that also release large pulses of hydrogen sulphide into the water column and atmosphere, which can cause mass mortalities of marine organisms (Emeis et al., 2004; Weeks et al., 2004; Chapman and Shannon, 1987; Copenhagen, 1953). The biogeochemically driven gas bubble flux of methane is thought to be driving the re-suspension of POM and fine sediments in the inshore mud belt that gives rise to the strong seasonal character of the OBS signal at station 1 (Fig. 5). The methane gas bubble flux is different to the methane eruption events which have been periodically recorded in the Namibian system (Emeis et al., 2004; Weeks et al., 2002, 2004). The existence of widely dispersed methane bubbling has been recorded in fisheries research ship echo sounders (A. Kreiner, MFMR, Pers. Commun.) as well as from a recently completed year long hourly methane mooring data set (in prep.). Much of the recent focus has been on the eruption events which are of particular interest in respect of the transport of sulphide into the surface layer and atmosphere. However, the more protracted methane gas bubbling may be as important from a spatial scale consideration of sediment re-suspension.

The deeper long shore belts of POM–rich sediments, although sharing the low shear–stress characteristics with the inshore mud belt, are outside the upwelling front from where most new production is exported. These mid and outer shelf belts have higher C:N ratios (>9) (Table 1), which indicates that the POM may be derived from sediment detritus that has undergone early diagenesis of the most labile fraction in the inner shelf belt rather than from a surface phytoplankton export flux origin. Any POM deposited in the shelf-break zone by this mechanism would be rapidly re-suspended by the internal tidal bore dynamics and re-deposited in the adjacent low shear–stress areas which make up the deeper high POM bands. The turbidity flow mechanism is supported by data from the optical backscatter measurements in the mooring at station 4 (Fig. 4) where at least one event with total suspended solids concentrations of over $500\,\mathrm{mg\,l^{-1}}$ (max. $1800\,\mathrm{mg\,l^{-1}}$) lasting over 24 h was measured (Fig. 4: 15–22 November 2000). The persistence and magnitude of this event scale is in sharp contrast to the other tidally forced short-period re-suspension events.

One ecological implication of this biogeochemical variability across the Namibian shelf is the impact that it has on fish habitats. Fish habitat preference maps (Fig. 8) indicate that fish distribution and may be behaviour is responding to the cross shelf stratification of the benthic biogeochemical characteristics or to the turbulence dynamics that drive them. This response may also extend to supporting different communities of benthic macrofauna such as suspension feeders at the shelf breaks and deposit feeders at the aerobic deeper high POM bands as well as creating retention mechanisms for spawning. This relationship between benthic boundary layer hydrodynamics and habitat suitability needs to be better understood.

Apart from providing a new perspective on the dynamical considerations driving the distribution

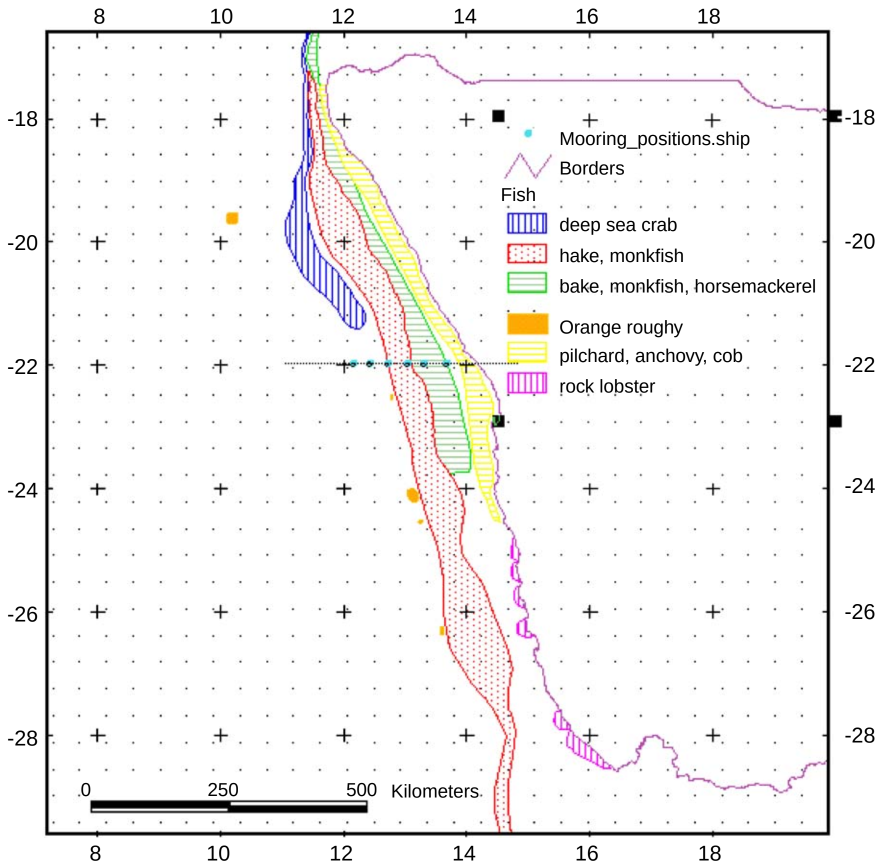


Fig. 8. A plot showing the cross shelf distribution of the main commercial fish stocks off Namibia. It shows that the distribution is responding to a degree of cross shelf variability, which could be related to either the turbulence variability or the turbidity or the habitats that area created by these factors.

of POM in bottom sediments, this study also addresses some of the difficulties encountered by past work in the Benguela and comparable systems. The Ekman model has been used to account for the containment of the inner shelf mud belt, the modulation of sediment trap fluxes and the offshore transport of POM in the benthic boundary layer (Bremner, 1983; Giraudeau et al., 2000). However, its predicted velocities ($<10\,cm\,s^{-1}$) are not sufficient to account for the re-suspension of POM. Ekman transport may drive the long shore and cross-shore transport of suspended POM but it is the intense albeit short-duration baroclinic energy dissipation mechanism that is hypothesised to govern re-suspension of POM. This study is therefore not a rejection of the importance of elevated Ekman and inertially forced bottom flows at the shelf break, rather it is proposing that while those mechanisms provide the advective component to particle transport, it is the baroclinic energy dissipation that drives the vertical particle dynamics. This mechanism is suggested to be at least as important as new production fluxes in governing biogeochemical regimes, carbon burial rates and the "continental shelf pump" in coastal upwelling systems (Liu et al., 2000).

5. Conclusions

This study has provided the basis to formulate the hypothesis that the benthic boundary layer turbulence at the shelf break zones of the Namibian shelf and probably most of the Benguela is dominated by both tidal bores and high-frequency soliton activity. It showed that the modulation of the amplitude is closely linked to the lunar and semi-diurnal barotropic tides but the frequency of variability of the baroclinic component also includes a supra-tidal frequency of less than 1 h. The high frequency variability, linked to soliton activity, was unexpected in its persistence over the sampled period of 6 months. This physical forcing may be the most important forcing factor behind the biogeochemical characteristics of the Namibian shelf system that ultimately also govern demersal fish habitat, distribution and behaviour.

Acknowledgements

The authors wish to acknowledge the financial support provided by GTZ through the Benefit Programme. The study was also made possible by the support from the CSIR, MFMR and MCM, which provided equipment and in the case of MFMR, Namibia the use of the RS Welwitchia. The Namibian Ministry of Minerals and Energy made the historical Bremner sediment data set available on GIS. PM thanks Mike Bremner for his introduction to the biogeochemical complexities of the Namibian shelf sediments. The officers and crew of the RV Welwitchia are thanked for their professional backup to the field observations. PM was supported by the STEP programme at CSIR which is funded by the Department of Science and Technology in South Africa. We would also like to thank two anonymous reviewers for their constructive feedback.

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