PHYSICAL PROCESSES CONTRIBUTING TO HARMFUL ALGAL BLOOMS IN SALDANHA BAY, SOUTH AFRICA

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The study synthesises current understanding of the predominant physical processes responsible for the seasonality of harmful algal blooms, notably *Alexandrium catenella* and *Dinophysis* spp., in the nearshore environment of Saldanha Bay on the west coast of South Africa. Saldanha Bay is one of the few naturally sheltered areas on the South African coastline suitable for *in situ* shellfish farming and is the major site for the production of black mussel *Mytilus galloprovincialis* in South Africa. Mussel farming started there in 1985 and the present level of production is some 2 700 tons per annum. Since 1994, disruption of harvesting as a result of the presence of harmful algal species has been a regular late-summer phenomenon. Toxic blooms that are ultimately advected into the bay develop on the continental shelf to the north between 32°S and St Helena Bay, a region characterized by favourable conditions for dinoflagellate growth and circulation patterns that facilitate build-up of intense blooms during late summer. Offshore dinoflagellate populations are advected shorewards and polewards in response to relaxation of upwelling at the Namaqua cell to the north. Dinoflagellate blooms are advected south from the southern Namaqua shelf during upwelling relaxation. Under such conditions, the gyre south of Elands Bay moves offshore and a barotropic flow past Cape Columbine is established. Evidence suggests that the near-surface component of the flow occurs as a sudden "flood" event. These dinoflagellate-containing shelf waters are in turn advected into Saldanha Bay when upwelling relaxes, when the density gradient between the bay and the shelf drives surface inflow and bottom water outflow. These flows are reversed with the resumption of upwelling over the shelf, resulting in intrusion and entrainment of bottom water and surface outflow. Entrainment dictates that the bay acts as a net importer of bottom water and net exporter of surface waters over a synoptic cycle. This system of exchange between Saldanha Bay and the shelf curtails the duration and severity of toxic episodes in the bay relative to the shelf.

Coastal upwelling ecosystems are often identified as regions susceptible to seasonal blooms of harmful and toxic phytoplankton. The Benguela system off the west coast of southern Africa is no exception, and harmful algal blooms are a regular occurrence along the west and south coasts of South Africa, particularly during late summer and autumn when the air pressure gradients responsible for upwelling-favourable winds weaken. There have been mass faunal mortalities resulting from algal toxins, as well as indirect effects of biomass accumulation leading to anoxia/hydrogen sulphide poisoning and gill-glogging (Grindley and Taylor 1964, Horstman 1981, Matthews and Pitcher 1996 – see review by Pitcher and Calder 2000). A number of human fatalities have also been reported. The most commonly encountered causative species include *Ceratium furca, C. lineatum, Prorocentrum micans, Alexandrium catenella*, *Dinophysis acuminata* and *D. fortii*.

The Benguela system is one of the four major eastern boundary current systems; the others are the Humbolt (Chile and Peru), Californian (California and Oregon) and Canary (North-West African – Iberian Peninsula). The Benguela is unique in that its southern boundary is demarcated by the retroflection of a major western boundary current system, the Agulhas Current. On occasions Agulhas Current water may intrude into the southern Benguela as a result of major perturbations in the retroflection region (Shannon and Nelson 1996). There are six main upwelling centres in the Benguela, all coinciding with a narrowing of the shelf: Cape Frio (18°S), Walvis Bay (23°S), Lüderitz (27°S), Namaqua (30°S), Cape Columbine (33°S) and Cape Peninsula (34°S – Shannon and Nelson 1996). The Cape Columbine and Cape Peninsula cells are more seasonal than the central Benguela ones; especially the Lüderitz cell, where upwelling is a semi-permanent feature. There is a well-developed zonal system of fronts over much of the area between Cape Frio and Cape Point, which delineate the seaward extent of upwelled water and the landward intrusion of oceanic water. Two fronts are of relevance in the present context. By analogy with the Oregon system, they have been termed the upwelling front, which separates recently upwelled water from aged upwelled water, and the coastal transition zone front, which defines the boundary between the coastal upwelling region and the adjacent ocean (Smith 1992, 1995). The strong density gradient across the coastal transition zone front sets up an equatorward jet that is most intense in summer (Smith
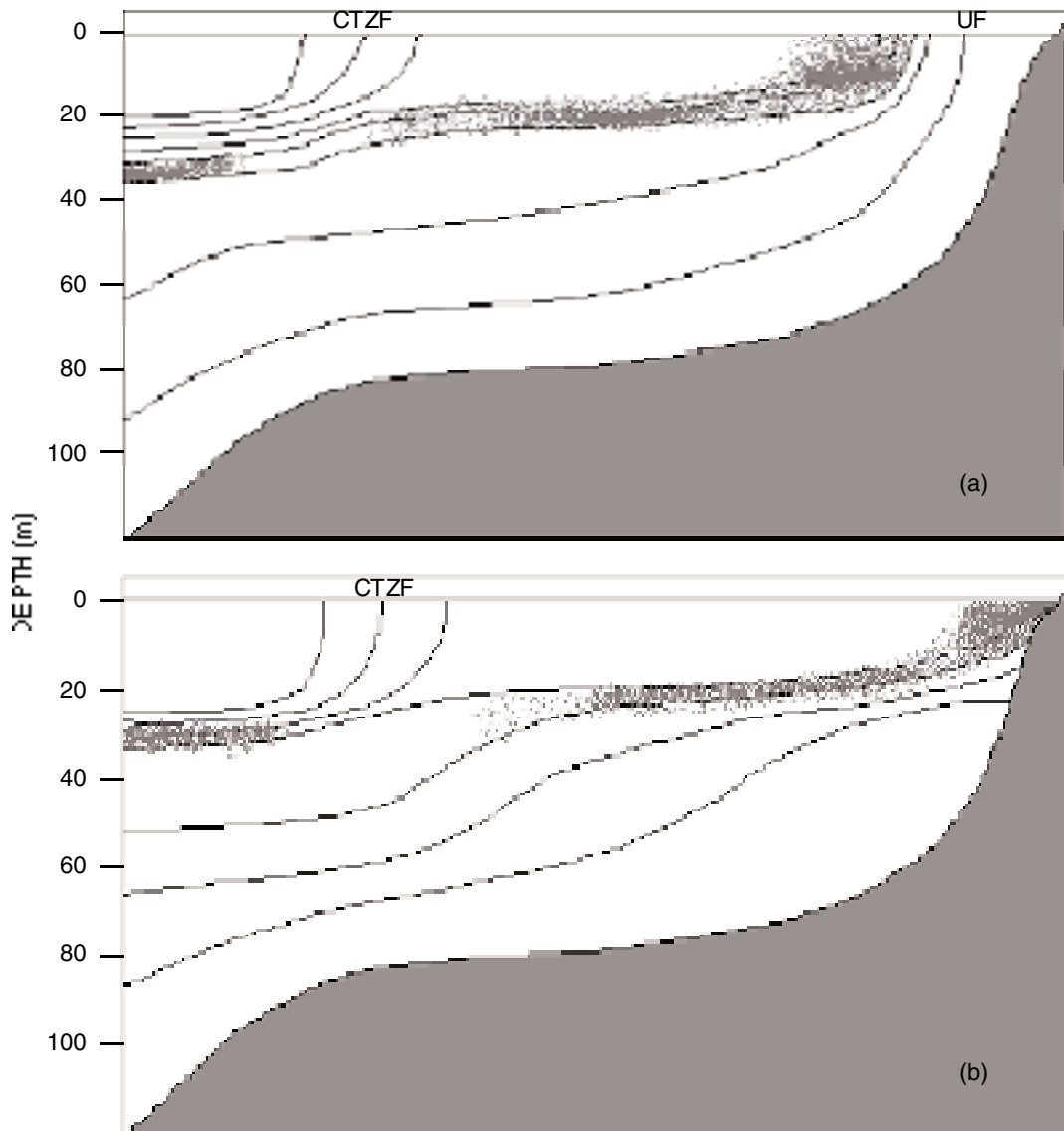
Fig. 1: Conceptualization of (a) upwelling and (b) downwelling scenarios showing the onshore advection of a frontal (upwelling front – UF) red tide population during relaxation of upwelling-favourable winds off the west coast of South Africa. Dinoflagellate assemblages offshore of the coastal transition zone front (CTZF) are dissimilar to those near the coast, and include South Coast species

1992, Strub *et al.* 1998). The transition zone between these two fronts is often characterized by long filaments extending from the coast far offshore. The coastal upwelling front forms soon after the onset of upwelling and is advected offshore as upwelling proceeds. During periods of sustained upwelling, the upwelling front may merge with the coastal transition zone front (Smith 1995). Another front may form inshore of the upwelling front, the inner-shelf front, which forms the boundary between stratified water and a well-mixed, shallow zone where surface and bottom boundary layers interact (Smith 1995). This front ex-

hibits relatively small offshore excursions by comparison with the upwelling front. In addition, an oceanic front can at times be resolved offshore of the coastal transition zone front, particularly in the northern Benguela (Shannon and Nelson 1996).

A conceptual model of red tide formation has been proposed wherein offshore dinoflagellate populations are advected inshore during upwelling quiescent or downwelling conditions (Pitcher and Boyd 1996, Pitcher *et al*. 1998). A broadening of the shelf outside of upwelling centres promotes stratification and stability, so favouring the widespread distribution of dinoflagellates across the shelf in the coastal transition zone. Dinoflagellates are particularly susceptible to turbulence and well adapted to lower energy, stratified conditions (Cullen and MacIntyre 1998, Estrada and Berdalet 1998). Stratification intensifies over the upwelling season, becoming most marked in late summer and autumn. According to the model, during upwelling the upwelling front is situated away from the coast and is often characterized by a surface manifestation of increased dinoflagellate biomass (Fig. 1). This community extends subsurface along the pynocline (at about 20 m deep) towards the coastal transition zone front. From late summer to autumn, the coastal transition zone front migrates offshore, particularly south of Lüderitz (Strub *et al*. 1998), so expanding the area potentially favourable for dinoflagellate growth. The intensity and offshore position of this front is most likely dictated by the injection of water with high dynamic heights from the Agulhas Retroflection Region offshore of the front and upwelled water with low dynamic height inshore of the front (Strub *et al*. 1998). The dynamic area that is favourable for dino-flagellate growth in this region is thus determined by bottom topography, the injection of Agulhas Current water and upwelling intensity. Turbulent conditions inshore of the upwelling front favour diatoms and, offshore of the coastal transition front, remnants of Agulhas Bank dinoflagellate communities may dominate. Red tide impacts on the coast following relaxation of upwelling, during which the onshore movement of surface water is accompanied by an onshore movement and eventual collapse of the upwelling front. Once in the nearshore environment, the red tide is propagated southwards in a net poleward surface flow caused by coastal-trapped waves or wind stress on the surface friction layer. These onshore and longshore current speeds typically range between 7 and 10 km·day^{-1} (Pitcher *et al*. 1998). A similar upwelling/downwelling sequence has been proposed for *Alexandrium* spp. associated with an offshore buoyant plume in the Gulf of Maine (Franks and Anderson 1992, Anderson 1997) and *Gymnodinium catenatum* in the Spanish rias (Fraga *et al*. 1988, Gomez Fermin *et al*. 1996).

THE SOUTHERN NAMAQUA SHELF

In the southern Benguela, the region south of the Namaqua cell between 32°S and St Helena Bay is particularly susceptible to red tide formation and its negative impacts. A historical perspective of faunal mortalities and strandings associated with red tide for this and other sectors is given in Cockcroft *et al*. (2000). The shelf is broad in this region, encouraging stratification and stability of the water column, particularly in late summer and autumn. In addition, the area is characterized by a major bottom-water thermal anomaly, where water <9°C floods the southern Orange-Namaqua shelf through a broad transverse valley at about 31.5°S (Dingle and Nelson 1993) and is propagated southwards in a quasi-permanent poleward undercurrent (Fig. 2). This water has a seasonal signal, being coldest towards the end of summer (G. Nelson, Marine & Coastal Management [MCM], unpublished data). Although surface warming and the relatively quiescent conditions typical are likely to dictate stratification of the water column, the advection of very cold water over the bottom shelf may serve to intensify the process. Such highly stratified conditions are conducive to the formation of internal tides, which are most intense in this region. Relaxation of upwelling at the Namaqua cell would thus advect red tide into an area favourable for growth and persistence, being less likely to be advected offshore with the onset of a further upwelling cycle. Internal tides, particularly at new and full moon, may impart the added benefit of passive vertical excursions in the photic zone and nutrient supply through breaking internal waves as they propagate into shallower waters. Perhaps most importantly, the region is also characterized by retentive, near-surface circulation patterns that are dominated by a cyclonic gyre some 30 km south of Elands Bay and smaller eddies in St Helena Bay (Holden 1985).

Under exceptional circumstances, the region may also be impacted by harmful algal species from the South Coast. Agulhas rings originating at the retroflection may at times impact on the West Coast shelf environment by entraining cool, frontal water offshore (Shannon and Nelson 1996). On rare occasions, Agulhas rings may be responsible for direct impacts inshore. For example, in December 1996 an Agulhas ring and associated cyclonic eddy moved close to the coast and entrained Agulhas Bank water along the shelf break as it moved up the West Coast (Duncombe Rae and Verheye in prep.). A toxic *Gymnodinium* spp. typical of the South Coast was recorded for the first time on the West
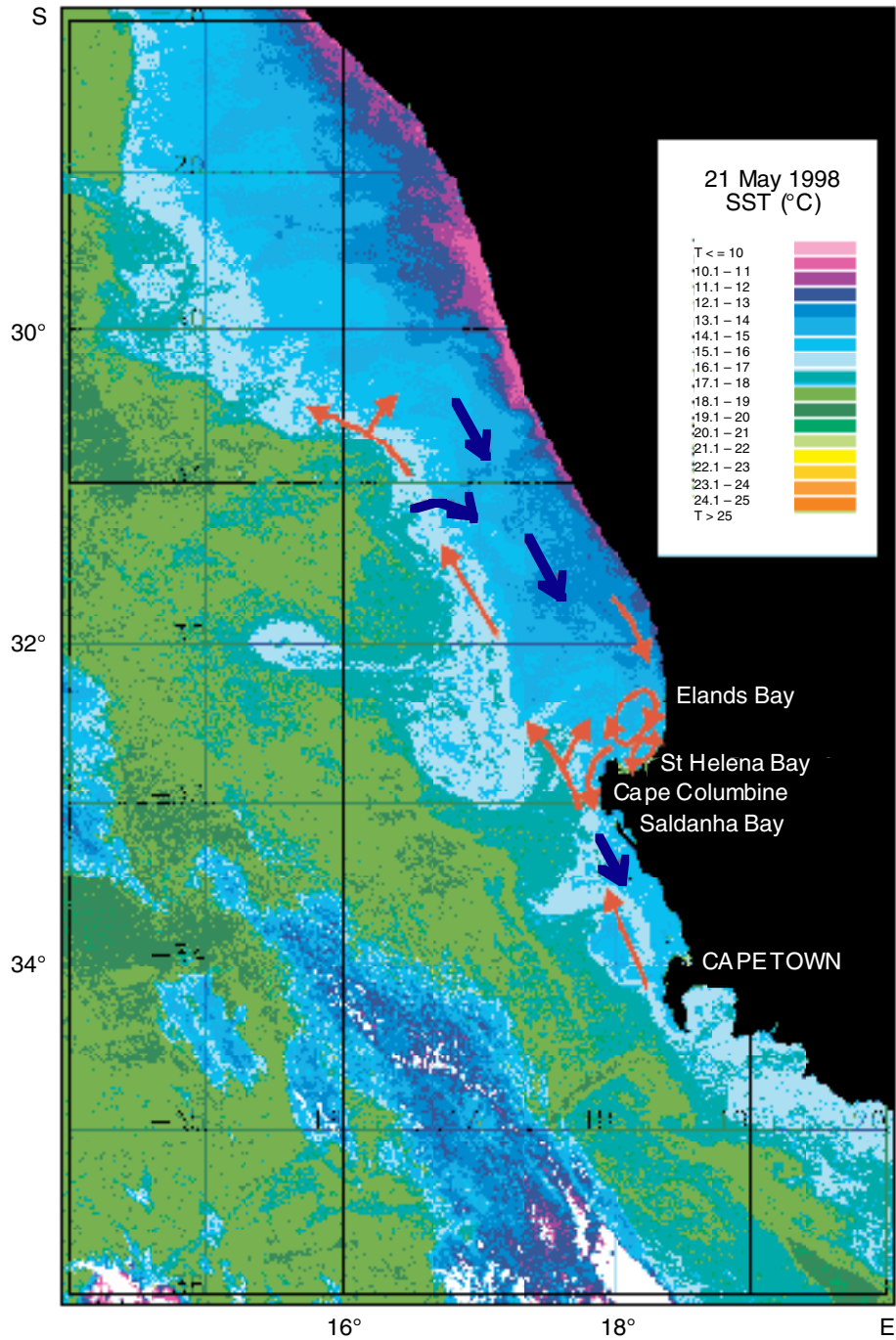
Fig. 2: Schematic of currents in the southern Benguela upwelling region superimposed on a sea surface temperature image for 21 May 1998. Red and blue arrows denote surface to midwater flow and bottom flow respectively. The southward flow around Cape Columbine shows the periodic flood of near-surface water from St Helena Bay
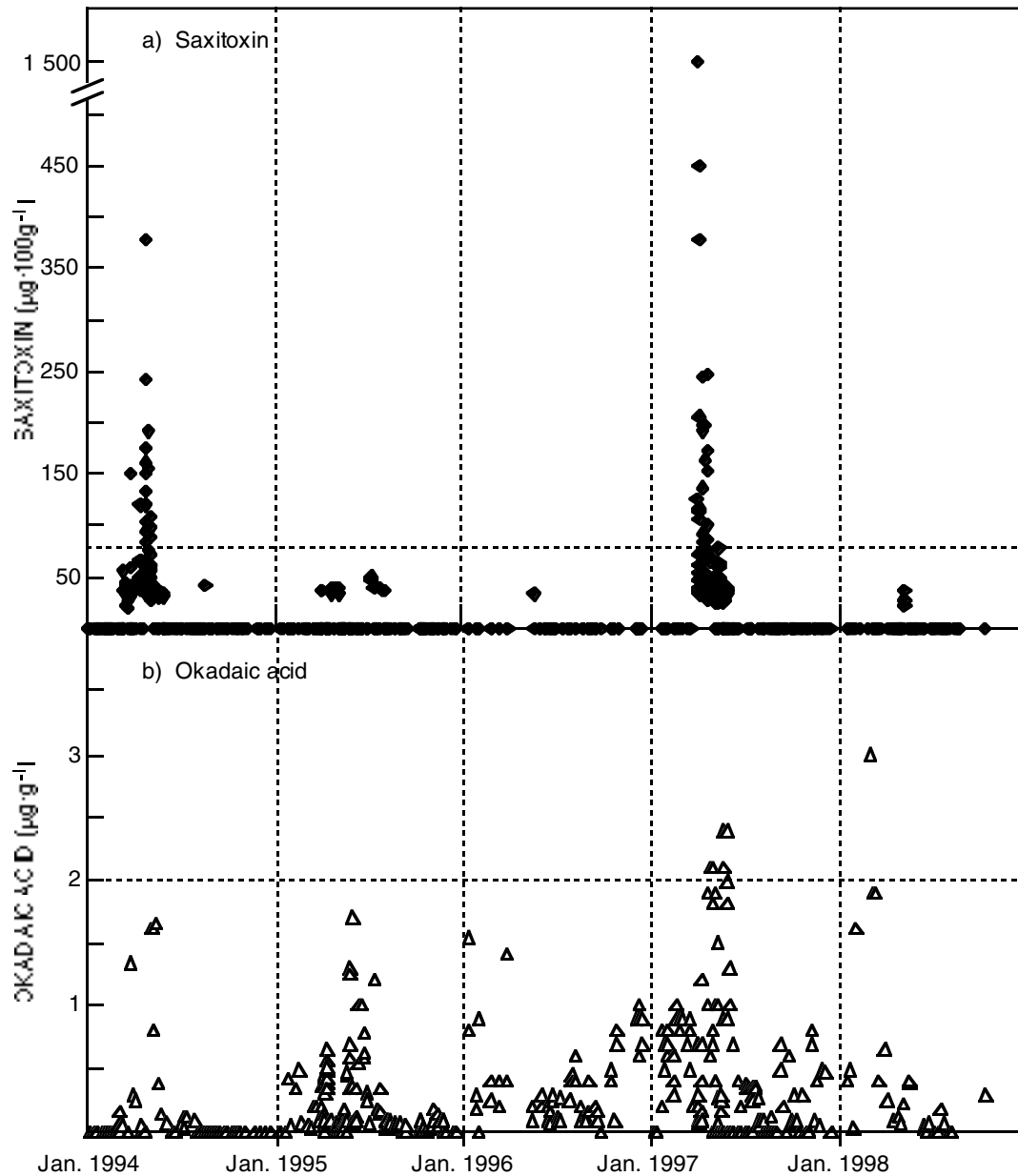
Fig. 3: Interannual mussel toxicity at a mussel farm in Saldanha Bay showing measured levels of (a) saxitoxin and (b) okadaic acid. Tests are conducted approximately twice weekly for saxitoxin using the mouse bioassay and weekly for okadaic acid using the ELISA test kit. The horizontal broken lines indicate the 80 µg saxitoxin·100 g⁻¹ edible flesh and 2 µg okadaic acid·g⁻¹ hepatopancreas public health safety limits

Coast at Elands Bay during this anomaly. An inshore bifurcation of the permanent shelf-edge jet (Fig. 2) was probably responsible for advecting this Agulhas Bank water into the nearshore environment.

The southward movement of red tide past Cape Columbine (Fig. 2) may occur as a "flood" event (Lamberth and Nelson 1987, Nelson and Hutchings 1987). At such times, the onshore wind component

increases, as does sea surface elevation. Under these conditions, the southerly current intensifies and strengthens the offshore flow in the confluence zone, driving the gyre farther from the coast (Holden 1985, Lamberth and Nelson 1987). The equatorward frontal jet deflects offshore and a barotropic southward flow is established inshore (Nelson and Hutchings 1987). The primary factor in the flow is the generation of a coastal-trapped shelf wave over the southern Namaqua shelf (Lamberth and Nelson 1987). It is this flow originating to the north that provides the impetus for advection of toxic blooms into Saldanha Bay. This statement is borne out by the drogue-tracking investigations of Lamberth and Nelson (1987), in which drogues released in St Helena Bay were recovered at the entrance to and in Saldanha Bay some 2–3 days later, having travelled against the strong south-easterly wind prevalent at the time of the study.

SALDANHA BAY

Saldanha Bay provides one of the few inshore marine systems along the South African coastline with adequate protection and food availability for large-scale, economically viable mariculture (Monteiro *et al*. 1998, Pitcher and Calder 1998). The hydrodynamics of the bay were dramatically altered in the 1970s as a result of the construction of a causeway for iron ore and oil terminals. Circulation and depositional patterns changed and two sectors of different hydrographic regimes were created, named Small Bay and Big Bay. At present, mariculture activity is limited largely to the more sheltered Small Bay. The dominant species of the present mariculture industry is the mussel *Mytilus galloprovincialis*, which are cultivated on a Spanish raft system. The suitability of the Saldanha Bay system for mussel culture is demonstrated by the high growth rates achieved there, with growth of up to 80 mm in 6 months – among the highest recorded for this species (Monteiro *et al*. 1998). Mussel culture started in 1985 in Saldanha Bay and at present the production is about 2 700 tons "green mass" (cleaned, graded and inclusive of shell) per year. In addition to mussel mariculture in Small Bay, there is also an oyster (*Crassostrea gigas*) grow-out facility in a tidally flushed dam in Big Bay, capable of producing about 750 000 oysters per year.

Saldanha Bay has been the focus of fairly intensive scientific investigation since 1994, with a primary aim of estimating the carrying capacity for mussel culture. Current estimates, based on the annual import of new nitrogen into the bay, places the total carrying capacity at 8 333 tons C·year^{-1}, of which 21% has been

calculated to be available for mussel culture (Grant *et al*. 1998). This translates to an annual potential green mass production of around 90 000 tons. Based on these findings, an additional 300 hectares has been allocated for mariculture in Big Bay and 50 hectares in Small Bay, the latter reserved for small-scale, subsistence farming. Ultimately the potential exists to expand from the present 65 hectares under cultivation to 1 000 hectares.

The first disruption of mussel harvesting in the bay as a result of red tide was in 1994, caused by *A. catenella* and *D. acuminata* (Pitcher *et al*. 1994). The most severe toxicity of mussels was in 1997, when saxitoxin levels as high as 1 500 mg·100g^{-1} mussel tissue and okadaic acid in excess of 2 mg·g^{-1} hepatopancreas were measured (Fig. 3). There appears to be no correlation between the severity of toxicity in the bay and inter-annual indices of upwelling such as sea surface temperature and zonal air pressure gradients (J. J. Agenbag, MCM, pers. comm.). In agreement with observations on the shelf, the most serious toxic episodes are generally during late summer and autumn. In addition to these toxic events, the first widespread occurrence of *Aureococcus anophagefferens* was noted between mid January and mid March 1998, during which period the whole bay system was visibly discoloured by the organism. The dominance of this brown tide species in the bay then had a substantial negative impact on mussel and oyster growth rates. It was first detected in January 1997 in the oyster growing area and persisted as a seasonal and largely restricted (except 1998) presence over the following three years.

Viewing the 1994 toxic period in more detail, it is apparent that each event was preceded by a relaxation of equatorward, upwelling-favourable winds at the upwelling centre at Cape Columbine, approximately 50 km north of Saldanha Bay (Fig. 4). These observations support the hypothesis of a link between relaxation of upwelling over the shelf and advection of *A. catenella* and *D. acuminata* into the bay. In this regard, bay processes appear coupled with far-field forcing mechanisms. This is also supported by the observation that tide-removed sea levels in the bay respond as would be expected over the open coastline, falling during upwelling-favourable winds and rising as winds relax. This response in sea level is dictated primarily by the ridging of the South Atlantic High Pressure Cell southwards round the continent (Shannon and Nelson 1996). An alternative explanation for these periods of increased cell abundance could be bursts in *in situ* growth within the bay, in response to environmentally cued germination of benthic resting stages (Anderson and Keafer 1987). However, no cysts or germling cells were observed in the water samples prior to each bloom shown in Figure 4b, effectively negating this possibility.
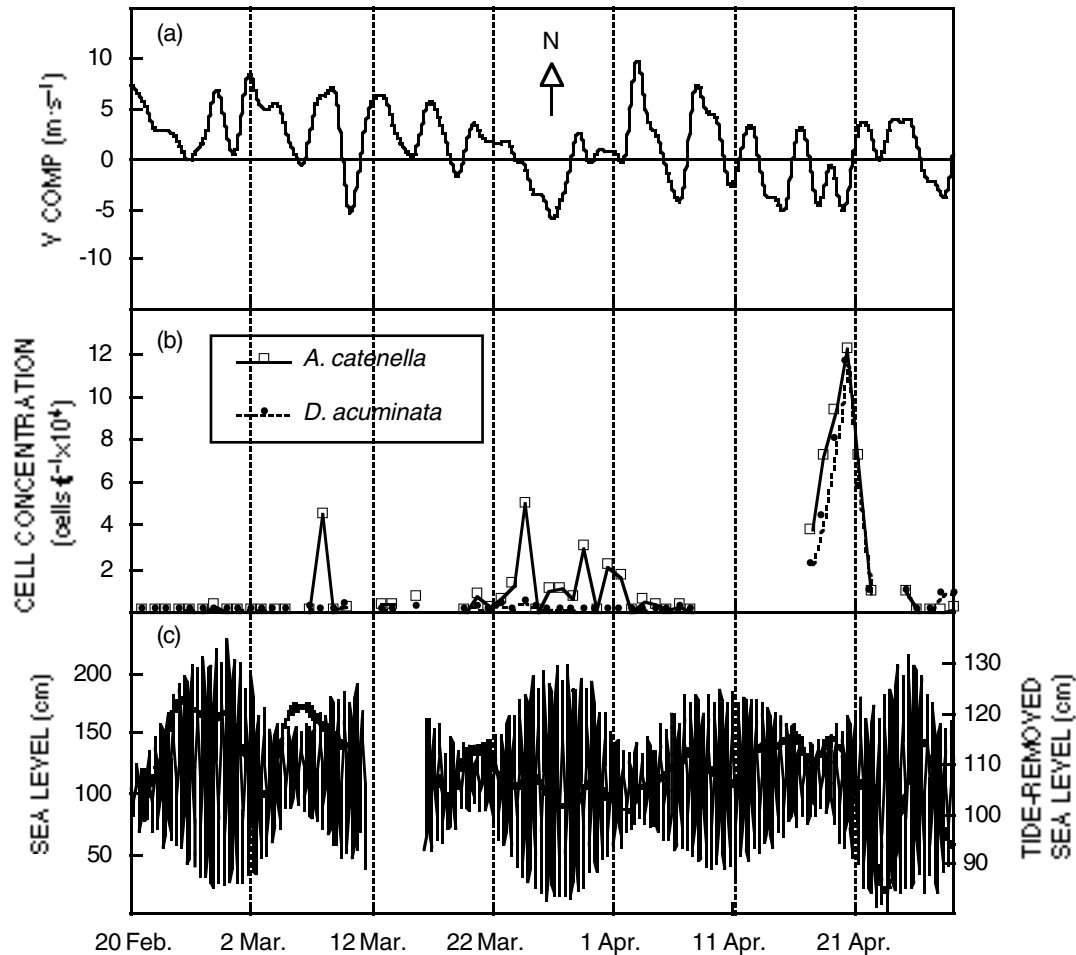
Fig. 4: Relationship between (a) the relaxation of upwelling-favourable winds at Cape Columbine (filtered series), (b) the occurrence of *Alexandrium catenella* and *Dinophysis acuminata* and (c) tidal and sub-tidal sea level variations in Small Bay, Saldanha Bay, during late summer 1994

With regard to tidal effects, there appears to be no relationship between the spring/neap tidal cycle and the appearance of blooms in the bay. However, the present dataset is limited, and lunar tidal cycles have been implicated in the appearance of red tides off the open coastline elsewhere, such as in the Gulf of Maine (Balch 1981).

The apparent correlation between active and relaxation phases in the bay and equatorward wind stress that drives upwelling on the shelf could be explained by local wind-driven Ekman dynamics extending into the bay or as a remotely forced density-driven exchange. Monteiro *et al.* (1998) and Monteiro and Largier (1999)

propose a conceptual model that may have general applicability to narrow-mouthed bays, in which density-driven exchange that is largely independent of local wind forcing dominates. Phase 0 of this model starts with a pre-upwelling, relaxation state, in which there is no density or sea level difference between the bay and inner shelf (Fig. 5). With the onset of upwelling-favourable winds in Phase 1, sea level falls by about 20 cm, with both the bay and shelf in phase. Density levels begin to rise on the shelf but not in the bay, with a time lag of the inertial period (22 h at 33° latitude), whereas local wind stress promotes mixing in the bay, almost immediately following the onset of the
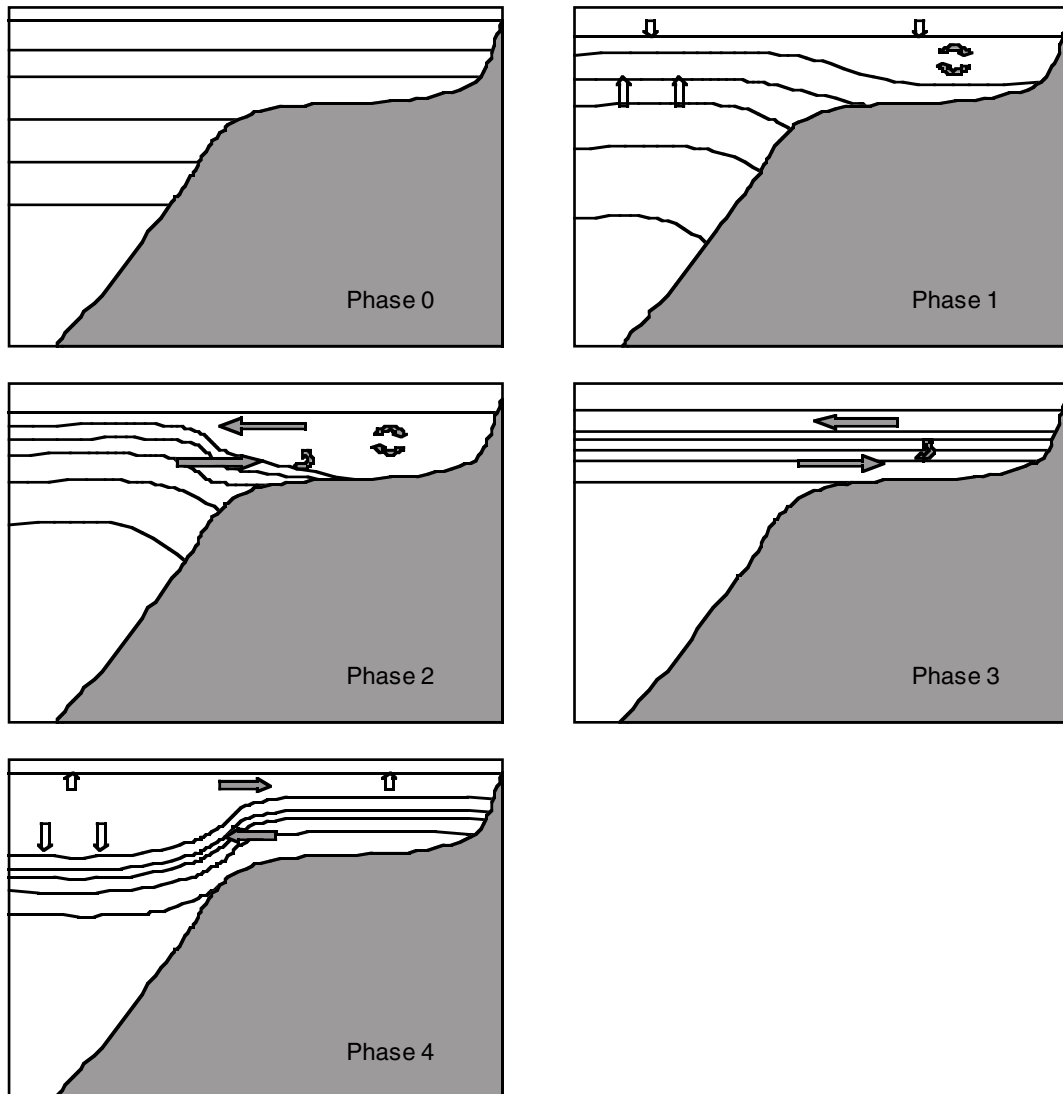
Fig. 5: Conceptual model of the intrusion of cold, bottom water into Saldanha Bay. The sequence begins with a pre-upwelling relaxed state (Phase 0), followed by the formation of a baroclinic wave (Phases 1 and 2) in response to upwelling on the shelf. Intrusion into the bay ceases in response to a relaxation of upwelling, when a density balance between the bay and the shelf is achieved (Phase 3). Persistent downwelling causes a reversal of the density gradient and subsequent bottom water outflow (Phase 4). This outflow is compensated for by an inflow of near-surface, phytoplankton-rich waters

wind event. It should be noted that winds in the bay are typically in phase, but that they are stronger than those measured at the nearby upwelling cell at Cape Columbine. A steep density gradient is set up, which drives a baroclinic wave at speeds of around 0.1 m·s^{-1} from the coast into the inner reaches of the bay. During

this period (Phase 2), persistent wind mixing prevents full intrusion of bottom water. Although intrusion of bottom water brings about stratification, this condition is also necessary to support the velocity shear associated with intrusion. Thus, ongoing wind mixing in the bay reduces the potential for stratification to develop, so de-
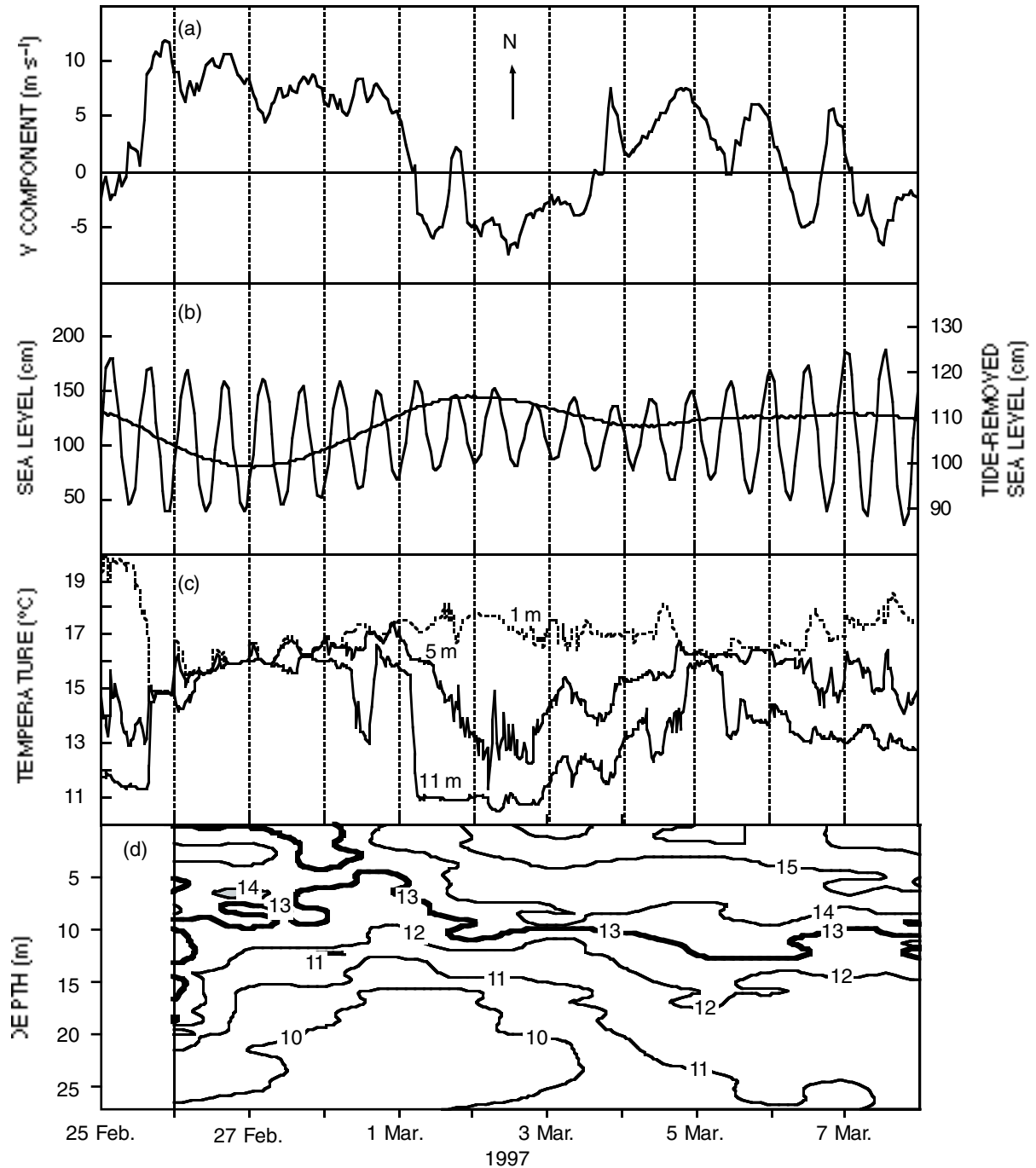
Fig. 6: (a) Variation in equatorward winds at Cape Columbine, (b) corresponding changes in sea level (including subtidal variations), (c) surface to bottom water temperature given by thermistor records at Small Bay during February and March 1997 and (d) temperature variation at the entrance to the bay – shown as an isotherm plot generated from approximately twice daily CTD casts at four stations across the mouth

laying extensive incursion of bottom water. However, there would be some entrainment of the partially intruded bottom water into the surface mixed-layer outflow.

Extensive intrusion of bottom water occurs immediately following relaxation of upwelling-favourable winds in Phase 3, and inflow stops when a density balance is achieved between the bay and the shelf. This advection of bottom water is balanced by a corresponding surface outflow. The bay is rapidly stratified through this flooding of cold, bottom water and may be intensified by surface warming. The explanation for this sudden flooding lies in the temporal lag between the immediate reduction of wind mixing over the bay and the slower decay of the remotely forced baroclinic wave. Inflow of bottom water is facilitated by removal of the de-stratifying effect of local wind mixing. Ultimately, continued relaxation of upwelling over the shelf will in turn cause downwelling of isotherms, a process not reflected in the bay. Phase 4 is therefore characterized by a reversal of the density gradient, resulting in outflow of bottom water. In the context of the introduction of near-surface blooms of phytoplankton such as red tide, this is the critical phase, because the bottom outflow is compensated for by a near-surface inflow. Periods of relaxation somewhat longer than the intertidal oscillation period, are required to bring about a complete reversal in the baroclinic pressure gradient, as shown in Phase 4. Over a period of a few days of calm conditions, all the cold water drains from the bay, leaving a residual stratification associated with surface warming typical of Phase 0.

Of crucial importance to the advection of phytoplankton into the bay is the hypothesis that, during the active Phase 2, bottom water is entrained into the surface layer and exported in the surface outflow (Spolander 1996). This implies that the residual volume of bottom water during downwelling (Phase 4) is less than the original volume advected in. The bay thus functions as a net exporter of near-surface, phytoplankton-rich waters and a net importer of cold, bottom water over a synoptic cycle. Such a scheme would tend to reduce the impact of shelf surface waters in the bay and may explain the low frequency of toxic events there. The re-establishment of upwelling following a relaxation period will also rapidly flush the bay, exporting noxious species and effectively curtailing the duration of these events. One exception is the brown tide that persisted for two months between January and March 1998.

Support for the above conceptual model is provided by a field study during February and March 1997, during which the primary objective was to study the exchange mechanisms at the bay and open coast boundary. The wind time-series from Cape Columbine displayed two mixing periods in the bay; a period dominated by very strong south-easterly winds (25–28 February) and a weaker event on 5 March (Fig. 6). Mixing within the bay was evidenced in thermistor chain data collected in Small Bay, some 2.5 km from the bay entrance (Fig. 6). The records show that stratification and de-stratification of the bay was in concert with the winds. It is noteworthy that, although small tidal incursions of cold water were evident over the period 25–28 February, mixing within the bay was sufficiently strong to prevent the establishment of vertical structure and extensive intrusion of sub-thermocline water (Phase 2). Relaxation and reversal of winds on 1 March were accompanied by a sudden drop in bottom temperature in the interior of the bay and subsequent rapid stratifying of the water column (Phase 3). Surface heating appeared to intensify the stratification. Warming of bottom water from 3 March indicates a full reversal of the baroclinic pressure gradient in response to a prolonged period of wind reversal (Phase 4). After the second mixing event, the bottom water intruding into the interior of the bay was warmer, indicating less intense upwelling on the shelf. Tide-removed sea level fluctuations corresponded with the general upwelling/relaxation sequence, but tended to lead wind fluctuations by 1–2 days. These lower frequency changes in sea level can probably be attributable to changes in atmospheric pressure, but they may also be influenced by a propagating barotropic shelf wave and winds.

A time-series section of mean temperature across the entrance to the bay during the study period revealed the presence of cold, bottom water in response to upwelling winds (Fig. 6). There was an approximately two-day delay between the onset of upwelling winds and the appearance of cold water at the mouth. This delay is consistent with an inertial period of 22 h and the time taken for an internal gravity wave to move from the coastal to the bay domain (Monteiro and Largier, 1999). The maximum volume of cold water coincided with the start of the relaxation period on 1 March, indicative of the flooding of the bay and rapid stratification during the phase. During the latter part of the relaxation phase the volume of cold water decreased, indicating its retreat from the bay domain. Concomitant with this outflow would be an inflow of near surface, phytoplankton-rich water. ADCP sections across the entrance to the bay then provide additional support for this scheme (Fig. 7). These sections were chosen to coincide with an incoming or a slack phase of the tidal cycle. On 1 March, there was clear evidence of bottom inflow and surface outflow, resulting in a strong vertical differential in currents (Fig. 7). On 2 March this pattern persisted, but it weakened during relaxation of upwelling as the density gradient between the bay and the shelf reduced. Bottom water then drained from the bay the following day, with a weak surface inflow.
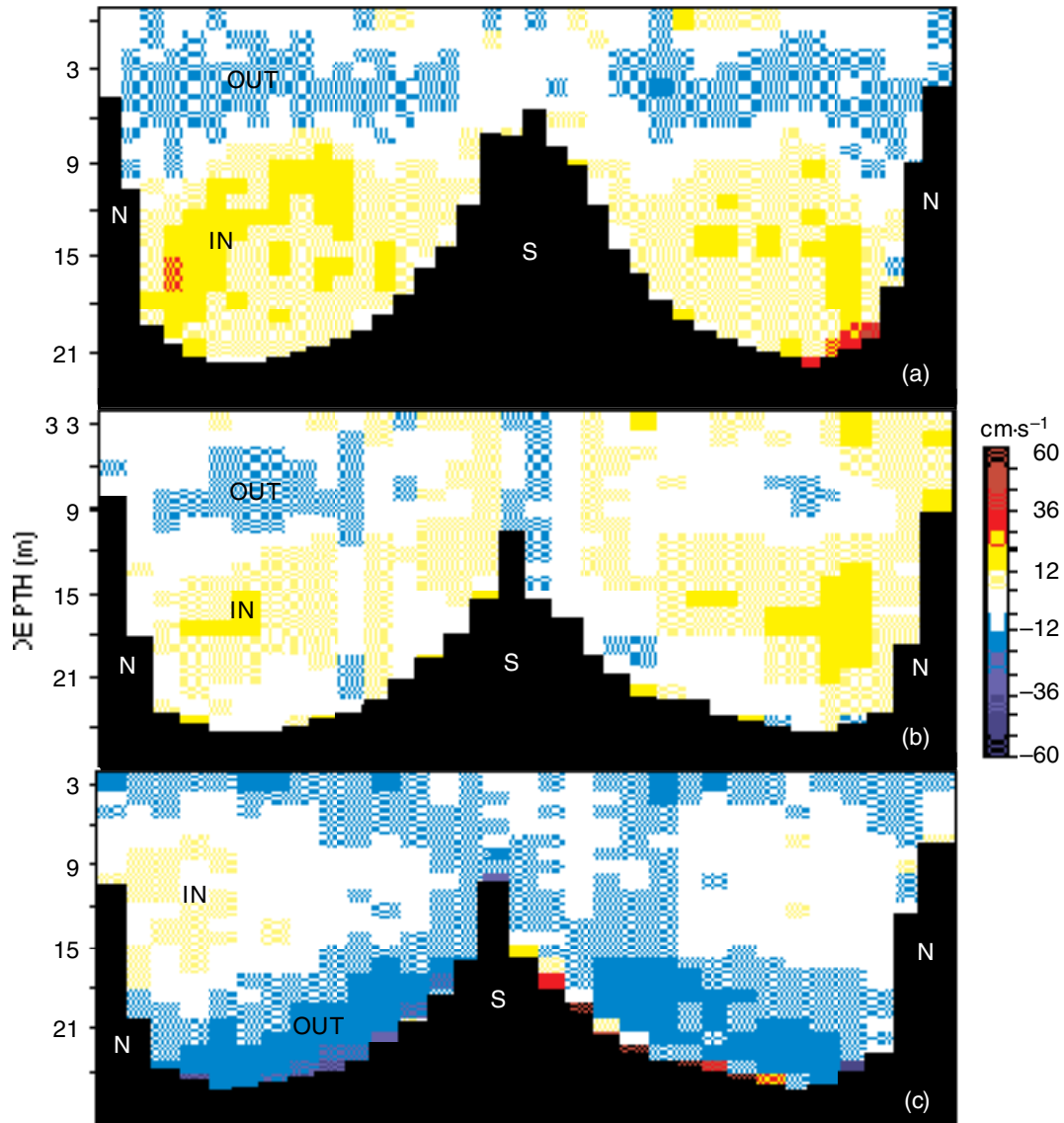
Fig. 7: ADCP sections across the mouth of Saldanha Bay during an incoming or slack phase of the tidal cycle showing the two-layered flow on (a) 1 March, (b) 2 March and (c) 3 March 1997. Sections show the north to south and south to north return trip along the same line. A clear reversal in current direction is evident from 1 to 3 March, indicating the transition between upwelling and relaxation conditions

SUMMARY

Severe toxic dinoflagellate blooms in Saldanha Bay originate on the southern Orange River-Namaqua shelf, where downwelling advects frontal populations inshore, particularly during late summer. These are propagated polewards in a nearshore surface flow into the Elands Bay and St Helena Bay region. Stable, highly stratified conditions there promote dinoflagellate growth, and displacement offshore becomes less likely with the resumption of upwelling. The region is also

characterized by gyral circulation patterns that tend to promote build-up of intense red tide blooms. Red tides are advected southwards towards Saldanha Bay under prolonged downwelling conditions, when the gyre south of Elands Bay moves offshore and a southerly barotropic flow is established. The surface manifestation of the current is not continuous, but it appears as a "flood event". Shelf waters containing red tide species are advected into Saldanha Bay under downwelling conditions, when the density gradient between the bay and open coast drives an outflow of bottom water from the bay, which is compensated by a surface inflow. With the resumption of upwelling, following a downwelling period, intrusion and entrainment of bottom water will rapidly turn over water in the bay, potentially curtailing the *in situ* development and persistence of blooms.

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