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Brown Tides and Mariculture in Saldanha Bay, South Africa

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In 1997, the brown tide organism, *Aureococcus anophageffens*, was detected for the first time in Saldanha Bay, South Africa. Its presence was limited to an isolated, tidal dam that was similarly impacted during the late summer of the following two years but not in 2000. Bloom concentrations are typically of the order of 10^{-9} cells l^{-1}. This is one of the few reported occurrences of these nuisance blooms outside the north-eastern United States. A small oyster grow-out facility based in the dam has been severely affected by the reduced growth of oysters during these blooms. Reduced flushing of this culture site is a possible explanation for bloom initiation and persistence. However, *Aureococcus* blooms can be considerably more extensive as was evident during 1998 when the whole of the bay system, including Langebaan Lagoon, was affected for 6–8 weeks during late summer. © 2001 Elsevier Science Ltd. All rights reserved.

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Saldanha Bay, on the west coast, provides one of the few naturally sheltered areas for in-water mariculture operations around the South African coastline. Aquafarming of the mussel, *Mytilus galloprovincialis*, has been in progress in the bay since 1985 with current annual harvests of 2000–3000 t wet weight, inclusive of shell.

Approximately 70 ha are under cultivation on vertical ropes attached to rafts in the relatively sheltered Small Bay (Fig. 1), situated adjacent to the highly productive southern Benguela upwelling system, providing for a favourable regime of food availability for filter feeders (Pitcher and Calder, 1998). Growth rates achieved at the mussel farm, up to 80 mm in 6 months, are amongst the highest recorded for *M. galloprovincialis* (Monteiro *et al.*, 1998). In addition to mussel mariculture in Small Bay, there is an 18 ha oyster (*Crassostrea gigas*) grow-out facility in a tidally flushed dam in Big Bay (Fig. 1) that produces up to 750 000 oysters per year.

Harmful algal blooms are a regular late summer feature in the southern Benguela, with mass faunal mortalities resulting from algal toxins and anoxia/hydrogen sulphide poisoning (Pitcher and Calder, 2000). Paralytic shellfish poisoning (PSP) due to *Alexandrium catenella*, and diarrehetic shellfish poisoning (DSP) caused primarily by *Dinophysis acuminata* and *D. fortii*, pose a continual threat to shellfish culture operations and recreational harvest on the west coast. However, the dominant subtidal exchange processes between Saldanha Bay and coastal waters dictate that these toxic blooms are less severe and prolonged within the bay (Monteiro and Largier, 1999; Probyn *et al.*, 2000). Mussel harvesting in Saldanha Bay was disrupted for the first time in late summer 1994 due to PSP (Pitcher *et al.*, 1994). In subsequent years, suspension of mussel harvesting as a result of both PSP and DSP has become a regular problem for the industry in the bay. The first indication of brown tides in Saldanha Bay occurred during later summer months of 1997 when the tidal dam, site of the oyster farm, became highly discoloured and oyster growth rates were markedly reduced. The bloom was shown to be the result of small (2–3 μm), coccoid, non-motile cells of unconfirmed identity. Although the bloom disappeared over the winter months it reappeared during the latter half of summer the following year. On this occasion, the entire Saldanha Bay system including the Ramsar site, Langebaan Lagoon (Fig. 1), turned a distinctive golden brown colour that persisted for 6–8 weeks. Surface samples collected at various localities in the bay revealed unprecedented concentrations of these coccoid cells of $1–3 \times 10^9$ l^{-1} and corresponding chlorophyl *a* levels of 21–41 μg l^{-1}. Examination of sectioned material by transmission electron microscopy indicated it was most likely the brown tide organism, *Aureococcus anophagefferens*. This identity was subsequently confirmed using immunological techniques. To the best of our knowledge, Saldanha Bay is one of only a few localities outside the United States, where brown tides have been reported. Summer blooms of *Aureococcus* were first noticed in 1985 in coastal embayments of the northeastern United States,

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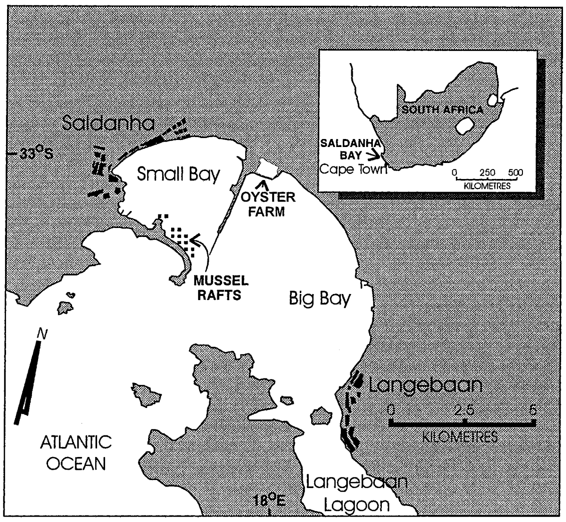

Fig. 1 Map of the Saldanha Bay system on the west coast of South Africa.

where they have recurred sporadically for a number of years. Besides the visual impact that detracts from aesthetic and recreational value, brown tides have been associated with a number of detrimental ecosystem impacts including reduction in eelgrass cover, declines in zooplankton populations and adverse effects on bivalve suspension feeders (Bricelj and Lonsdale, 1997).

Brown tides in Saldanha Bay were once again in evidence in 1999, though limited to the oyster-growing site. However, *Aureococcus* blooms failed to materialize in the bay during the summer of 2000. Such inter-annual variability typifies brown tide blooms elsewhere, a fact that somewhat counter intuitively confounds current hypotheses of bloom triggers (Bricelj and Lonsdale, 1997). LaRoche *et al.* (1997) however, suggest that this variability, in at least one Long Island Estuary (Peconic Estuary System), is linked to variations in relative levels of dissolved organic and inorganic nitrogen (DON and DIN) caused by the inter-annual variability in high DIN containing groundwater flows. Their hypothesis assumes that bloom initiation is related to the ability of *Aureococcus* to use DON efficiently, giving it a competitive advantage over the more ‘typical’ phytoplankton when DIN is in limited supply. The ability to use DON appears to be consistent with the most recent bloom in a Long Island coastal lagoon (Great South Bay). The bloom was unusual in that it occurred not in the summer, but during the 1999–2000 fall–winter period after the likely introduction of DON by the mineralization of a large summer bloom of the macroalga *Cladophora*, and just prior to a winter freeze. Cell numbers reached in excess of 5.7×10^8 l^{-1}.

Reduced water exchange, through changes in freshwater input from streams and groundwater, and hydrodynamic coupling with coastal waters, may also act as a concentrating mechanism. The oyster farm, isolated from the bay by a narrow causeway with only a 1.8 m diameter pipeline providing limited tidal flushing of surface waters, creates a suitable poor exchange scenario for *Aureococcus*. Although the initiation of the bloom in 1997 remains a mystery, the seasonal recurrence of these blooms in this small water space is likely related to the limited exchange with the larger bay system thereby facilitating accumulation. Reduced exchange with the deeper, nutrient rich bay waters will also lead to oligotrophic conditions at the site, a condition that appears to favour growth of *Aureocccocus* (Nixon *et al.*, 1994). As Saldanha Bay, including the tidal dam, receives minimal fresh water input from land drainage, exchange with coastal waters is the primary mechanism of flushing and allochthonous nutrient supply. The conditions leading to the bay-wide bloom in 1998 are unknown, though preliminary analyses of wind data suggest that they are not the result of any obvious change in meteorological or hydrographic forcing. Clearly though, the morphology of the bay and nature of exchange with coastal waters do provide a favourable environment for *Aureococcus* blooms under certain conditions. A discussion of proposed mechanisms controlling brown tides in the Long Island bays is given in Bricelj and Lonsdale (1997) and LaRoche *et al.* (1997).

Of the various hypotheses advanced for the persistence of *Aureococcus* blooms, refuge from grazing is perhaps most relevant in the present context. It is well documented that *Aureococcus* is a less than effective food source for certain bivalve species because of its small size and possibly toxic or inhibitory properties (Tracey, 1988; Bricelj and Kuenster, 1989; Gainey and Shumway, 1991; Bricelj and Lonsdale, 1997). Feeding experiments with natural Saldanha Bay *Aureococcus* populations at bloom concentrations have confirmed slower grazing rates by adult (market size) *Crassostrea gigas* on *Aureococcus* cells than on other food algae (Table 1). Clearance rates were generally considerably slower on *Aureococcus* than natural diatom assemblages found outside the bay and a *Skeletonema costatum* culture. *In vitro* experiments with isolated gills of two other oyster species have shown that the presence of *Aureococcus* cells inhibits bivalve feeding activity (Gainey and Shumway, 1991). Interestingly, high clearance rates could be maintained with natural diatom assemblages in the presence of 10^7 cells l^{-1} of *Aureococcus*, which tends to argue against toxic or inhibitory effects.

Over the longer term disruption of grazing rates will be translated into reduced oyster growth rates. The major impact of brown tides in Saldanha Bay to date has, in fact, been on oyster growth rates and yields in the tidal dam. The farm operates by sorting and harvesting oysters greater than 50 g throughout the year, with peak harvest taking place during the summer months. Prior to 1997, monthly sales for the period January to April typically exceeded 50,000 oysters. Following the appearance of *Aureococcus* in 1997, harvests over this period have declined considerably, falling to less than 10,000 oysters in 1999 (Fig. 2). As a direct result of the brown tide related fall in production the farm was

TABLE 1

Crassostrea gigas clearance rates (ml $\text{min}^{-1}\text{oyster}^{-1}$) for four feeding trials with natural populations of *A. anophagefferens* (approximately 2×10^8 cells l^{-1}), laboratory cultures of *Skeletonema costatum* (4×10^7 cells l^{-1}) and a coastal diatom dominated assemblage containing lower concentrations of *Aureococcus* (2×10^7 cells l^{-1} for feeding trial 3 and 3.5×10^6 cells l^{-1} for feeding trial 4).[a]

	Large oysters			Juvenile oysters	
	Aureococcus	*Skeletonema*	Diatoms	*Aureococcus*	Diatoms
1	1.82	21.18			
2	2.87	24.67			
3	3.99		28.55	1.07	1.95
4	4.16		9.20	0.41	0.30

[a] The diatom assemblage was comprised mainly of *Chaetoceros* spp, *Nitzschia* spp and *S. costatum* at total concentrations of 9.2×10^6 cells l^{-1} for feeding trial 3 and 3.5×10^6 cells l^{-1} for feeding trial 4. Experiments were conducted in batch mode using 15–20-l containers with 12–18 large (±50 g) oysters and 3.5-l containers with 50 small (±0.6 g) oysters. Starting chlorophyll *a* concentrations for each feeding trial were adjusted to match those of initial *Aureococcus* concentrations as estimated by fluorescence. Oysters from the cultivation site were depurated in coastal water free of *Aureococcus* for 48 and 24 h, respectively for trials 1 and 2. For the remaining trials, the oysters were used immediately after removal from the culture site, i.e. *Aureococcus*-conditioned. Clearance rates were calculated from the exponential initial portion of the fluorescence depletion curves over 0.5–4 h using the equations of Frost (1972).

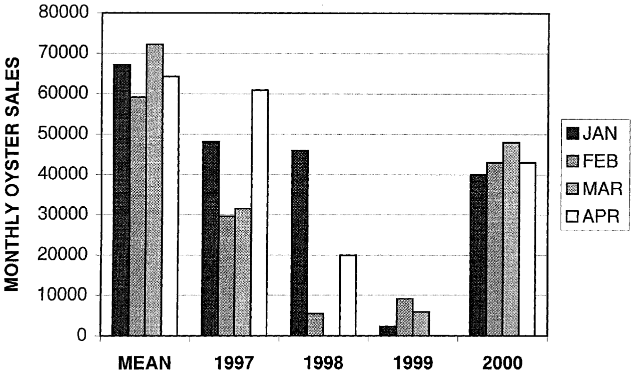

Fig. 2 Monthly sales of *Crassostrea gigas* (>50 g) for the months January–April. Mean monthly sales in recent years prior to the first *Aureococcus* bloom in 1997 are included for comparion.

subsequently placed in preliminary liquidation in April 1999. The absence of blooms in 2000 has seen a dramatic recovery in monthly sales. The bay-wide bloom in 1998 also had a negative effect on mussel farmers in Small Bay. Late summer yields from the rafts declined from values generally in excess of 70 kg rope^{-1} prior to 1998 to about 20 kg rope^{-1} during the bloom. Moreover, mussels at that time developed a ridge on the shell, characteristic of stress and growth arrest.

Saldanha Bay has been the focus of fairly intensive scientific investigation since 1994 with the primary aim of estimating the carrying capacity for mussel farming. Current estimates, based on the annual import of nitrogen into the bay, place the total carrying capacity at 8333 t C yr^{-1}, of which 21% has been calculated to be available for aquaculture of filter feeding bivalves (Grant *et al.*, 1998). This translates to a potential annual wet weight production of about 90 000 t. Based on these findings an additional 300 ha has been preliminarily allocated for mariculture in Big Bay and 50 ha in Small Bay, the latter being reserved for subsistence, community-based aquafarming. Therefore, although the present level of aquafarming in Saldanha Bay is relatively small, the potential exists for a considerable expansion of the industry in this area, up to about 1000 ha under cultivation. Realistic concerns exist over the oyster cultivation site, where the possibility exists that it may act as a refuge seed stock that can at times invade the whole bay system when conditions are favourable. Should bay-wide blooms of *Aureococcus* become a more frequent, albeit seasonal, feature of the system, they could have dire consequences for the shellfish industry in this important mariculture development area.

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Bricelj, V. M. and Kuenster, S. K. (1989) Effects of the brown tide on the feeding physiology and growth of bay scallops and mussels. In *Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms*, ed. E. M. Cosper, E. J. Carpenter and V. M. Bricelj, pp. 491–509. Lecture Notes on Coastal and Estuarine Studies. Springer, Berlin.

Bricelj, V. M. and Lonsdale, D. J. (1997) *Aureococcus anophagefferens*: Causes and ecological consequences of brown tides in US mid-Atlantic coastal waters. *Limnology and Oceanography* **42**, 1023–1038.

Frost, B. W. (1972) Effects of size and concentration of food particles on the feeding behavior of the copepod *Calanus pacificus*. *Limnology and Oceanography* **27**, 805–815.

Gainey, L. F., Jr. and Shumway, S. E. (1991) The physiological effect of *Aureococcus anophagefferens* (brown tide) on the lateral cilia of bivalve molluscs. *Biological Bulletin* **181**, 298–306.

Grant, J., Stenton-Dozey, J., Monteiro, P. M. S., Pitcher, G. and Heaseman, K. (1998) Shellfish mariculture in the Benguela system: A carbon budget of Saldanha Bay for raft culture of *Mytilus galloprovincialis*. *Journal of Shellfish Research* **17**, 41–49.

LaRoche, J., Nuzzi, R., Waters, R., Wyman, K., Falkowski, P. G. and Wallace, D. R. (1997) Brown tide blooms in Long Island's coastal waters linked to interannual variability in groundwater flow. *Global Change Biology* **3**, 397–410.

Monteiro, P. M. S. and Largier, J. L. (1999) Thermal stratification in Saldanha Bay (South Africa) and subtidal, density-driven exchange with the coastal waters of Benguela upwelling system. *Estuarine, Coastal and Shelf Science* **49**, 877–890.

Monteiro, P. M. S., Spolander, B., Brundrit, G. B. and Nelson, G. (1998). Shellfish mariculture in the Benguela system: Estimates of nitrogen-driven new production in Saldanha Bay using two physical models. *Journal of Shellfish Research* **17**, 3–13.

Nixon, S. W., Granger, S. L., Taylor, D. I., Johnson, P. W. and Buckley, B. A. (1994) Subtidal volume fluxes, nutrient inputs and the brown tide – an alternate hypothesis. *Estuarine, Coastal and Shelf Science* **39**, 303–312.

Pitcher, G. and Calder, D. (1998) Shellfish mariculture in the Benguela system: Phytoplankton and the availability of food for commercial mussel farms in Saldanha Bay, South Africa. *Journal of Shellfish Research* **17**, 15–24.

Pitcher, G. C. and Calder, D. (2000) Harmful algal blooms of the southern Benguela Current: A review and appraisal of monitoring from 1989–1997. *South African Journal of Marine Science* **22** (in press).

Pitcher, G., Calder, D., Davis, G. and Nelson, G. (1994) Harmful algal blooms and mussel farming in Saldanha Bay. *Proceedings of the Aquaculture Association of Southern Africa* **5**, 87–93.

Probyn, T. A., Pitcher, G. C., Monteiro, P., Boyd, A. and Nelson, G. (2000) Physical processes contributing to harmful algal blooms in Saldanha Bay. *South African Journal of Marine Science* **22** (in press).

Tracey, G. A. (1988) Feeding reduction, reproductive failure, and mortality in *Mytilus edulis* during the 1985 brown tide in Narragansett Bay. Rhode Island. *Marine Ecology Progress Series* **50**, 73–81.