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Evidence of a large seasonal coastal upwelling system along the southern shelf of Australia

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[1] We report observational existence of a large seasonal coastal upwelling system that establishes in austral summer (December–April) along Australian southern shelves. Wind-driven upwelling events occur simultaneously in three upwelling centres spanning a distance of ~800 km. During each summer period there are ~2–3 major upwelling events, each lasting ~1 week. The simultaneous, rapid response of SST to wind forcing in the upwelling centres, which display vastly different shelf widths, points to the existence of a larger-scale process that carries cold water onto the shelf prior to the upwelling season. Exploration of a major upwelling event in March 1998 shows the evolution of peak surface chlorophyll-a concentrations of >4 μg/L lagging the onset of upwelling by ~1 week. The associated (exponential) growth rate can be estimated at 0.4 d^{-1}. Another week later we found a distinct sub-surface chlorophyll-a maximum at a depth of 50 m centred along the upwelling front. Reasons for the formation of this maximum are not fully understood. *INDEX TERMS:* 4572 Oceanography: Physical: Upper ocean processes; 4528 Oceanography: Physical: Fronts and jets; 4504 Oceanography: Physical: Air/sea interactions (0312); 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4599 Oceanography: Physical: General or miscellaneous. **Citation:** Kämpf, J., M. Doubell, D. Griffin, R. L. Matthews, and T. M. Ward (2004), Evidence of a large seasonal coastal upwelling system along the southern shelf of Australia, *Geophys. Res. Lett.*, *31*, L09310, doi:10.1029/2003GL019221.

1. Introduction

[2] Coastal upwelling produces about half the World's fish supply. Major coastal upwelling regions (eg the Peruvian) are located at the eastern margins of subtropical ocean gyres and are governed by classical wind-driven upwelling dynamics [e.g., *Mann and Lazier*, 1996]. Coastal upwelling involves a wide range of temporal and spatial scales from daily to decadal and from the mesoscale (few kilometres) to several hundred kilometres. Owing to this high variability, knowledge of the upwelling dynamics and its ecosystem response is still incomprehensive. It has been known for 25 years that coastal upwelling occurs in summer along the Bonney Coast (BC hereafter) (Figure 1), between Cape Jaffa and Portland [*Rochford*, 1977; *Lewis*, 1981; *Schahinger*, 1987; *Griffin et al.*, 1997]. Long-term mooring measurements over the period 1973–77 provided first insights into the seasonal and intradecadal variability of upwelling features in this region. *Lewis* [1981] reported values of >6–7 mmol m^{-3} (nM) nitrate at a depth of 50 m being 30–70 times greater than the average background level. The source of upwelling water has been identified as Sub-Antarctic Surface Water (SASW) of a temperature <12°C and salinity <35.2 [*Lewis*, 1981]. *Hahn* [1986] mentions the occurrence of summer upwelling southwest of Kangaroo Island (KI hereafter). On the basis of a few samples taken from the western Great Australian Bight (GAB), GAB waters have been previously classified as very low in nutrient concentrations [*Motoda et al.*, 1978]. First hints on the existence of an upwelling system in the eastern GAB (see Figure 1) was the finding that juvenile southern bluefin tuna (thunnus maccoyii) aggregate in this area during the summer months and achieve at least 50% of their annual growth during this 3–4 month period [*Hearn*, 1986]. This is confirmed by the fact that the eastern GAB currently supports the most valuable pelagic ecosystem in Australian waters. *Middleton and Platov* [2003] (hereinafter referred to as M&P) give an overview of circulation on the Australian southern shelves. In their study, M&P employed a numerical model to study the mean summertime circulation in this region. The model was forced with a climatological averaged, stationary wind-stress field. Model results show the occurrence of coastal upwelling off southern Eyre Peninsula (EP hereafter), but the BC upwelling was almost suppressed. Overall, simulated coastal upwelling jets were much weaker (~3 cm/s) than those derived from altimeter data (>30 cm/s) [see *CSIRO Marine Research*, 2001]. Likely reasons of this biased description of the upwelling dynamics are a relatively coarse lateral grid spacing >3.5 km that only marginally resolves the internal deformation radius (~5–10 km), and forcing by monthly-averaged winds which ignores high-magnitude synoptic wind variations.

[3] The objective of this paper is to address the spatial and temporal variability of coastal upwelling along Australian southern shelves on the basis of in-situ and satellite observations. To this end, we have analysed satellite-derived SST and Ocean Colour (SeaWiFS) data together with coastal wind data for the period 1992–1998 in conjunction with high-resolution in-situ field measurements undertaken in the eastern GAB in March 1998 during the occurrence of a major upwelling event. In addition to CTD profiling, water samples were taken from the surface and at 50-m depth to derive chlorophyll-a concentrations.

2. Results

[4] Figure 2 gives an example of the simultaneous appearance of upwelling in three distinct upwelling

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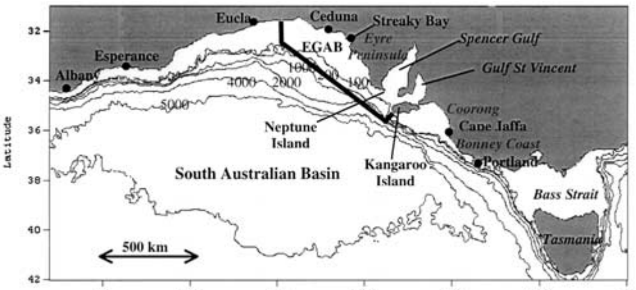


Figure 1. Geography of Australian southern shelves. Isobaths are in meters. The solid line indicates the areal extension of the eastern Great Australian Bight (EGAB).

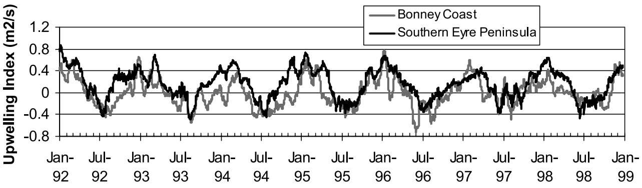
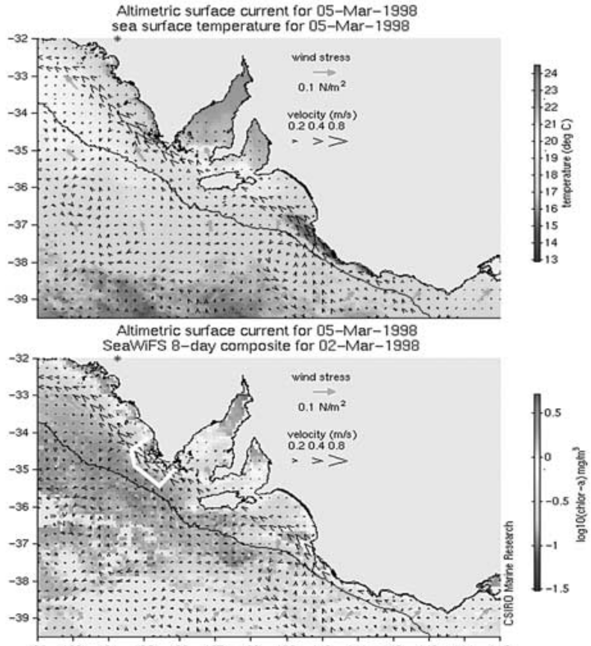


Figure 3. Monthly-averaged upwelling indices for southern Eyre Peninsula and the Bonney Coast for 1992–1998. Wind data is taken from Neptune Island and Portland meteorologic weather stations, respectively. See color version of this figure in the HTML.

centres: EP, KI and BC. SST drops locally by ~2–3°C and surface chlorophyll-a concentrations (SSC) increase to >4 μg/L, being tenfold greater compared with ambient water. Summer-mean winds blow northwestward along the coast and thus support classical wind-driven upwelling, as seen in monthly-averaged UI (Figure 3) that measures offshore Ekman transport in the upper ocean. Intra-annual wind conditions do not differ significantly among the upwelling centres and we found high temporal correlations of UIs between southern EP and BC (correlation coefficient >0.7; averaged over 8 successive summer periods 1991/92–98/99). Summer-mean values of UIs in both regions are positive, with BC's UI being about half that for EP. SSTs among the upwelling centres respond in phase to the wind forcing (Figure 4) displaying 2–3 major upwelling events per year, each ~1 week in duration. This unison SST response is reflected by a high correlation coefficient of ~0.84 (averaged over successive summer periods). This implies that most of the SST variability observed along the upwelling region is caused by synoptic coastal wind forcing. Nevertheless, there are still a few events where cooling occurs during upwelling unfavourable winds, as also reported by *Griffin et al.* [1997] and M&P. Notice that the El-Niño summer 1997/98 does not seem to have a particular impact on upwelling intensity.

[5] In the following the focus is placed on a major upwelling event that occurred in the period 3–10 March 1998 (also shown in Figure 2). Figure 5 displays the evolutions of UI, SST derived from 5-day composite satellite maps, and SSCs, derived from 8-day composite ocean-colour satellite maps for EP and BC for the period Jan–April 1998. Although the satellite data is of relatively poor temporal resolution, drops of SSTs and subsequent increases in SSCs in response to the wind forcing are apparent. These responses occur simultaneously (but much less pronounced) off KI, as shown in Figure 2. Upwelling events display synoptic time scales of the transient wind forcing. Maximum SSCs lag peak UIs by ~1 week. In-situ measured SSCs agree with the satellite data (allowing for differences of 50% associated with sampling errors and other error sources) (Figure 6, compare with Figure 2). In-situ data reveal a rapid decrease of SSCs to ambient low levels within a few days after the upwelling event. This detail is not resolved in the satellite data. Sub-surface chlorophyll-a levels remain low (<0.5 μg/L) (Figure 6) during the upwelling event. Interestingly, about 1 week after the surface bloom we observe an elongated sub-surface


Altimetric surface current for 05-Mar-1998
sea surface temperature for 05-Mar-1998

Altimetric surface current for 05-Mar-1998
SeaWiFS 8-day composite for 02-Mar-1998

CSIRO Marine Research

Figure 2. Satellite-derived SST (top panel; 5-day composite) and chlorophyll-a (bottom panel; 8-day composite) distributions centred at 2/5 March 1998. Data source: *CSIRO Marine Research* [2001]. The white line borders the area shown in Figure 6. See color version of this figure in the HTML.

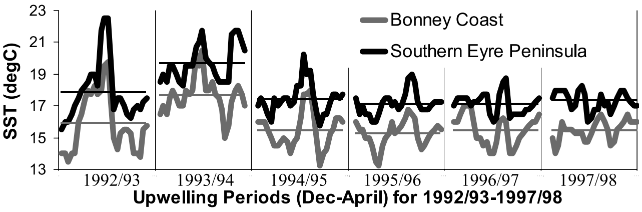


Figure 4. Evolution of satellite-derived SST during summer (December–April) in the upwelling centres off southern Eyre Peninsula and along the Bonney Coast for 1992–1998. Data source: *CSIRO Marine Research* [2001]. See color version of this figure in the HTML.

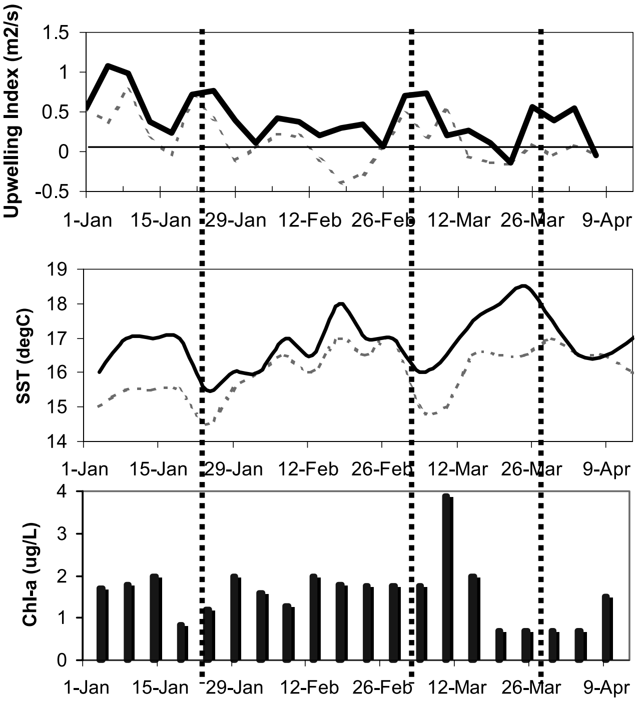


Figure 5. Daily-averaged upwelling index (top panel), satellite-derived SST (middle panel), and satellite-derived SSC (bottom panel) for Jan–April 1998 in the upwelling centres of southern Eyre Peninsula and along the Bonney Coast. Both regions display roughly the same SSC response. Data source: *CSIRO Marine Research* [2001]. See color version of this figure in the HTML.

chlorophyll-a maximum at a depth of 50 m and a distance of ~20 km away from the coast running along the upwelling front. Note that our data resolves this feature only by three data points.

3. Discussion and Conclusions

[6] Our findings indicate the existence of a large wind-driven coastal upwelling system that establishes during austral summer along Australian southern shelves to span a long-shore distance of ~800 km; that is, from Ceduna to Portland. Coastal upwelling occurs simultaneously in three upwelling centres: off southern Eyre Peninsula, off south-western Kangaroo Island, and along the Bonney Coast. The shelf width varies greatly between the upwelling centres and ranges from the narrow (~20 km) shelf along the BC to the much broader (~100 km) shelf of the eastern GAB. A typical offshore Ekman transport of ~1 m^2/s (see Figure 5) relates to an onshore flow in the bottom Ekman layer of ~0.1 $m\ s^{-1}$ when taking this layer to be 10 m thick. Accordingly it would take >12 days for shelf bottom waters off EP to travel the distance of the shelf width, whereas along the BC this would only take ~2 days. This time lag is in conflict with our measurements showing an unison SST response of similar magnitude in these regions. Therefore, we conclude that, at least in the eastern GAB, there must be a pre-existing larger-scale process that lifts cold (<12°C) water onto the shelf. On the basis of process-oriented modelling, *Herzfeld and Tomczak* [1997] suggested that this upwelling off EP be driven by an eastern intensified convergence of bottom Ekman transport along the slope, which could not be verified by our data. Another likely vehicle of this preconditioning might be a net upward displacement of the thermocline in response to successive upwelling events that accumulatively move deeper water upward on the slope. This accumulative effect can be seen in the numerical findings of M&P, who used a stationary climatological mean wind-stress forcing. Figure 3 suggests that this preconditioning already commence in Oct/Nov each year. It is worth noting that M&P simulated the deepest upwelling occurring to depths of 150 m, whereas our water mass analyses (not shown) in conjunction with data

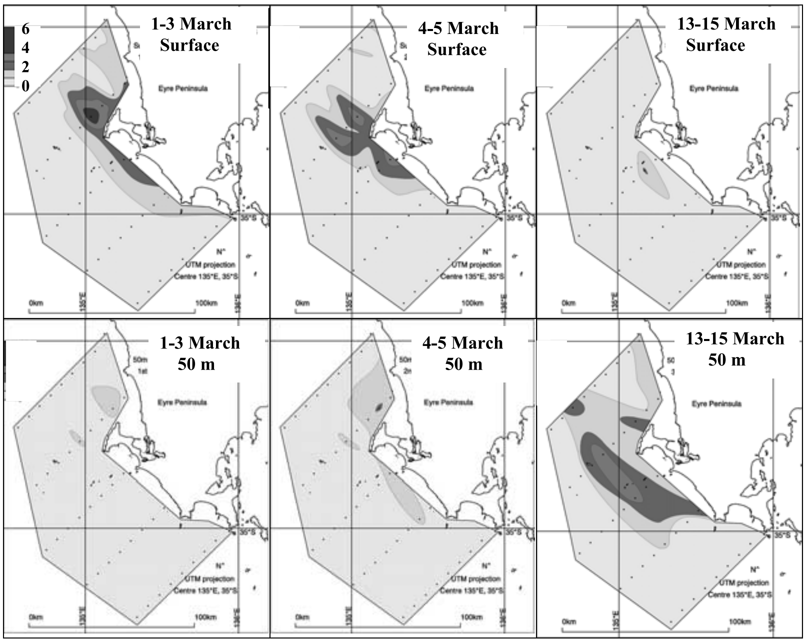


Figure 6. In-situ chlorophyll-a concentrations in the upwelling centre off southern Eyre Peninsula. Shown are surface and 50-m values. Dots indicate the location of field stations. See color version of this figure in the HTML.

presented by *Lewis* [1981] and *Hahn* [1986] suggest a source water depth of >350 m. Further field studies are required to explore sub-surface water-mass distributions along the upwelling system.

[7] During the major upwelling event in early March 1998 SSCs increase to maximum values of >4 μg/L. Phytoplankton dynamics in upwelling regions are complex [e.g., *Richardson and Cullen*, 1996] and a discussion thereof would be beyond the scope of this study. On the basis of our SSC data and nitrate concentrations reported by *Lewis* [1981], we can make a rough first estimate of phytoplankton growth rates for the South Australian coastal upwelling system. Simple calculations (not shown) give an exponential growth rate of $\sim$0.4 d^{-1} to match the observed change in SSC. This seems to be less ($\sim$50%) compared with values reported from other upwelling regions [e.g., *Chavez et al.*, 1996]. Moreover, we report a sub-surface chlorophyll-a maximum along the upwelling front lagging the surface bloom by $\sim$1 week. Previous studies [e.g., *Stevenson et al.*, 1974; *Suginohara*, 1977; *Brink et al.*, 1983] suggest that this feature relate to frontal downwelling, but our field data is not sufficient to verify this. Nevertheless, hydrodynamic reasons of this sub-surface maximum are very likely, given that observed chlorophyll-a concentrations are commonly low throughout the region except the upwelling zone.

[8] The South Australian coastal upwelling system supports a rich and diverse coastal ecosystem, evidenced by large numbers of sharks, whales, sea lions and fur seals colonies. This study provides new insights into spatial and temporal scales inherent with this upwelling system and forms a first basis for future research.

[9] **Acknowledgments.** Assistance and cooperation of the captain and crew of R/V Ngerin are gratefully recognised. Wind data was obtained from the Bureau of Meteorology, Australia. This study was supporteed by the Aquafin Commonwealth Research Centre (Aquafin CRC), Australia.

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