A comparison of observed upwelling mechanisms off the east coast of Australia

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Abstract

The East Australian Current (EAC) forms the western boundary current of the South Pacific sub-tropical gyre. Locally it plays an important role in the nutrient enrichment of the oligotrophic coastal waters of New South Wales (NSW), Australia. Observations from two detailed hydrographic surveys conducted during November 1998 and February 1999 are used to delineate the processes influencing nutrient enrichment across the continental shelf off the central east coast of Australia. Four nutrient enrichment mechanisms are identified: wind-driven upwelling, upwelling driven by the encroachment of the EAC onto the continental shelf, acceleration of the current resulting from the narrowing of the continental shelf at Smoky Cape, and the separation of the EAC from the coast.

This study demonstrates that both the strength of the current and its proximity to the coast determine the nature of the upwelling response. An increase in nutrient concentrations occurs downstream as a result of each of the mechanisms identified. The highest nutrient concentration is attributable to the encroachment of the current onto the shelf, whilst separation induced upwelling is the most widespread.

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1. Introduction

Upwelling on the central east coast of Australia is a persistent feature during the austral spring and summer and may be either widespread or localised (Rochford, 1984). Associated with this upwelling are sporadic blooms of phytoplankton and subsequent swarms of zooplankton on the continental shelf (Hallegraeff and Jeffrey, 1993). Further observations of blooms of toxic dinoflagellates (commonly known as red tides) have increased recently (e.g. Anderson, 1989; Hallegraeff, 1988) and it is therefore important that the mechanisms driving these nutrient enrichment events are fully understood.

Satellite observations of ocean temperature and colour can be used to identify concentrations of phytoplankton. Fig. 1 shows an AVHRR image of sea surface temperature (SST) and a Sea-viewing Wide Field-of-view Sensor (SeaWiFS) image of ocean colour off the New South Wales (NSW) coast. The East Australian Current (EAC) is seen to flow southward along the NSW coast at the
shelf break to Smoky Cape (30°55'S) where it separates from the coast. South-ward of the point of separation is a region of localised productivity extending along the 5°C temperature front dividing EAC and shelf waters. This region of high productivity is indicative of a localised nutrient upwelling event, however, the non-coastal nature of the biological response suggests that the current and not the wind could be the cause.

Wind-driven upwelling is commonly accepted as the dominant nutrient enrichment mechanism in many coastal regions globally. Coastal waters on the east coast of Australia are generally poor in nutrients, and although wind-driven upwelling occurs in response to seasonal north and north-easterly breezes, it is not a persistent feature and is by no means massive. Wind-driven upwelling events along the coast of NSW have generally been observed to be both localised and short-lived (9–15 days). Upwelling is, however, a common feature in the Smoky Cape region (Rochford, 1975) and often this upwelling appears not to be related to local wind forcing. The next most obvious forcing mechanism is the vertical circulation associated with the swiftly flowing EAC and its separation (Godfrey et al., 1980).

1.1. Upwelling mechanisms

Following Rochford (1991) the term uplift is used here to refer to the raising of cold water and nutrients towards, but not reaching the surface, and the term upwelling to a raising of nutrients to the surface proper. The term slope water intrusion is used here to describe the uplift of slope water adjacent to the continental slope to a shallower depth on the upper continental slope or shelf.

Upwelling on the east coast of Australia can occur when the EAC flows near to the coast and Rochford (1975) observed upwelling events as a consequence of EAC intrusions rather than local wind events. These slope water intrusions were

Fig. 1. AVHRR image of SST and SeaWiFS images of ocean colour on 27 December 1998. High chlorophyll-a concentrations (2 mg m⁻³) and warm temperatures (26°C) are represented by the warm colours (red), low concentrations (0.03 mg m⁻³) and cool temperatures (22°C) are represented by the cool colours (blue).
identified by Rochford (1975) and Pearce (1980) as the primary source of nutrient enrichment along the NSW coast. Boland (1979) found that the bottom Ekman flux associated with the poleward flowing EAC is the main mechanism which pumps nutrient-rich waters up onto the continental shelf. Gibbs et al. (1998) found that bottom Ekman forcing alone is not sufficient to cause upwelling further to the south off the Sydney coast, as certain conditions can cause the bottom boundary layer (BBL) to shut down (MacCready and Rhines, 1993). They concluded that the proximity of the EAC to the coast preconditions the region by uplifting the isopleths, following which upwelling occurs under favourable wind conditions.

Hallegraeff and Jeffrey (1993) observed blooms of phytoplankton extending along the east coast from Cape Hawke (32°S) southward to Maria Island (43°S). Typically, these phytoplankton blooms occurred in spring and summer which Hamon (1968) attributed to the seasonal nature of the EAC. Godfrey et al. (1980) later proposed that surface waters inshore of the EAC flowed northward towards the EAC separation point and that this northward counter current over the continental shelf may also play a role in the vertical enrichment process.

Another physical mechanism possibly associated with uplift finally resulting in upwelling is related to the separation of the EAC which generally occurs along a line extending southeast from Sugar Loaf Point (32°30′S). From the examination of accumulated bottom sediments Godfrey et al. (1980) concluded that this point of separation had been pronounced for a considerable period of time. Southward of the separation point it is common to find upwelled waters in the region bounded by the coast and the warmer current offshore. Often a temperature change of ~5°C occurs over a very short distance, accompanied by a visible change in colour from the tropical blue waters of the EAC to cooler green, phytoplankton-rich upwelled waters (Church and Cresswell, 1986). Associated with the front is a rapid change in current speed which modifies the surface wave pattern, and which is often accompanied by the accumulation of surface debris.

Numerical studies by Oke and Middleton (2000) indicate that alongshelf topographic variations in the vicinity of Cape Byron (northern NSW) can have a significant impact on the nearshore and shelf circulation. They suggest that a narrowing of the continental shelf accelerates the alongshelf flow, resulting in an area of high bottom stress which then drives an upwelling BBL flow. They found there was a high level of vertical mixing between upwelled BBL water and interior shelf waters, as well as ‘along-isopycnal mixing’. This mixing provides a mechanism for the entrainment of nutrient-rich slope water into the EAC mean flow. With the exception of the well-known effects of local wind forcing, these diverse theories all point to the highly variable influence of the EAC as being responsible for uplift, and perhaps also upwelling and nutrient enrichment.

1.2. Nutrient enrichment

Although generally low, nutrient concentrations in the NSW shelf waters have been found to vary both seasonally and spatially. The low and sporadic nutrient concentrations found at the edge of the continental shelf off Sydney (Roughan, 1997) are similar to those found by Furnas and Mitchell (1993) in the central Great Barrier Reef region. The fact that surface nutrient values remain low over a span of 25° of latitude (>2500 km) highlights the oligotrophic nature of the surface waters of the EAC. Hallegraeff and Jeffrey (1993) found that in the vicinity of Smoky Cape, EAC surface waters have low nitrate concentrations (<2 μmol l⁻¹) increasing immediately west of the current towards the coast.

Coastal nutrient concentrations in surface waters remain low throughout the year, with mean nitrate values of less than 1 μmol l⁻¹. Mean nitrate levels at depths of 150–200 m were found to peak at 8–9 μmol l⁻¹ towards the end of winter (October) and decrease throughout the summer to a minimum of 2 μmol l⁻¹ in May (Rochford, 1984). In the Laurieton region however, spring upwelling increases the surface nitrate concentrations to 4–12 μmol l⁻¹. Further to the north at Evans Head, this spring increase also occurs although
on a lesser temporal and spatial scale (Rochford, 1984).

Upwelling in the Smoky Cape/Laurieton region has been seen to be a persistent feature during spring and summer. Rochford (1975) defined ‘Laurieton Upwelling’ as a rapid decrease in temperature, a decrease in salinity, a lowering of the surface oxygen concentration and, in particular, an increase in surface nutrients such as nitrates. This upwelling was observed to begin approximately 9 km to the north of Laurieton moving 18–28 km in the space of 5 days. The seaward extent of the upwelling (i.e. its effect on nutrients) did not extend more than 10–12 km offshore. Often a marked front was visible between the nutrient-rich upwelled water and the near surface waters offshore which were nutrient poor. It was found that newly upwelled water had temperature and salinity properties consistent with those found in deeper water off the continental slope.

Horizontal sections of potential density and mean nitrate concentrations along the east coast of Australia are obtained from the Climatology of Australian Regional Seas (CARS) data set (Ridgway et al., 2002) and are shown in Fig. 2. In surface waters the mean density ranges from 24 to 26 kg m\(^{-3}\) and mean nutrient concentrations are <1 \(\mu\)mol l\(^{-1}\) (Fig. 2a and d). At a depth of 250 m the potential density of the water adjacent to the coast is \(\sim 27.5\ \text{kg}\ \text{m}^{-3}\) and the mean nutrient concentrations are as high as 15 \(\mu\)mol l\(^{-1}\) and extend the length of the coast (Fig. 2c and f). Higher in the water column over the continental shelf at a depth of 125 m mean densities range from 26.5 to 27.5 kg m\(^{-3}\) and nutrient

![Fig. 2. Mean potential density (a–c) and nitrate concentrations (d–f) in the Smoky Cape region, NSW, Australia. Mean fields are obtained from CARS, at three depth layers: 10, 125, 250 m.](image-url)
concentrations along the coast are ~5–15 μmolL⁻¹ (Fig. 2b and e). However, the maximum values of both density and nutrient concentrations are found adjacent to the coast, immediately south of Smoky Cape. As well as highlighting the oligotrophic nature of the surface waters this shows that a nutrient pool exists at depth. Most importantly, however, the increase in mid-shelf, mid-depth density and nutrient concentrations south of Smoky Cape indicates a persistent pattern of uplift and advection at, and southward of, Smoky Cape.

A pertinent question posed by Tranter et al. (1986) relevant to many facets of biology and oceanography is: ‘How (do) western boundary currents increase productivity of the adjacent coast?’ The primary aim of this study is to answer this question with regard to the EAC by identifying and describing the key processes responsible for upwelling, and to investigate the frontal nature and the three-dimensional structure of the EAC, in order to pinpoint the mechanisms driving upwelling.

A comprehensive study consisting of both hydrographic and in situ measurements conducted in the vicinity of the separation point of the EAC is described. The study site was chosen for its complex dynamics in terms of upwelling, coastal processes, and frontal dynamics. This study is significant in that it is the first high density nearshore hydrographic survey to span the separation point of the EAC concurrent with in situ moored current and temperature measurements. Here, we compare observations of four contrasting nutrient enrichment mechanisms which occurred during the experimental period. In this paper, the experimental program is described in Section 2. Observations of the four upwelling mechanisms; wind induced, encroachment induced, topographically induced and Separation Induced are examined in Sections 3–6 respectively. Finally, the different events are compared in Section 7, and conclusions are drawn in Section 8.

2. The experimental program

The present study site extends alongshore from Urunga (30°S) to Point Stephens (33°S), NSW, Australia, and offshore from the coast to the 500 m isobath. This region spans the widely recognised location of EAC separation, as well as Smoky Cape; the narrowest point (16 km) of the NSW continental shelf. North of the separation point the EAC tends to hug the coast and flows in excess of 2 m s⁻¹ are observed at the shelf break. Immediately downstream of the separation point, the interaction of the current and the shelf waters results in a strong thermal front and high velocity shear.

The experimental program was carried out during the 1998–1999 Austral summer (November–February) to capture the full strength and variability of the EAC during the summer season when biological productivity is at a maximum. Shipboard hydrographic measurements were obtained during two cruises aboard the R.V. Franklin (FR1498 and FR0199). Conductivity, temperature and depth (CTD) and acoustic doppler current profiler (ADCP) measurements were taken along transects across the continental shelf during both cruises, in conjunction with an intensive biological sampling regime which included EZ and Neuston net tows, minibat tows and water samples. Current meter moorings were also deployed across the continental shelf at two latitudes during the first cruise and were retrieved during the second cruise.

2.1. Methodology

Vertical profiles of temperature (T), salinity (S), fluorescence, light and dissolved oxygen were acquired from a Neil Brown WOCE standard CTD. During the first cruise (14–27 November 1998) 116 CTD casts were completed along four shore normal transects, starting inshore at a depth of 25 m and moving offshore to a depth of up to 2000 m. The four main transects, Urunga, Smoky Cape, Point Plomer and Diamond Head, were named because of their proximity to geographical features and were repeated twice on each cruise. During the second cruise (20 January–4 February 1999) 154 CTD casts were completed along a total of nine transects. These transects included repeats of the original four transects, as well as an additional five transects further downstream, across the strong thermal front associated with
the separation of the EAC. These transects captured the alongshore advection of the EAC as it moved southward. The locations of the CTD transects and the mooring arrays are shown in Fig. 3. The fluorometer was calibrated with in vivo fluorescence from underway water samples to obtain an estimate of chlorophyll-a concentrations.

Shore-normal ADCP transects were run along the CTD lines immediately after the completion of each CTD transect. The R.V. Franklin was fitted with an RDI 150 kHz narrow band ADCP which recorded in 3 min ensembles with a bin depth of 8 m. The ADCP was in bottom track mode when the water was less than ~400 m deep, which accounted for 88% of the sampling time. The across-shore (x) and alongshore (y) components of velocity were rotated to align with the bottom bathymetry.

Standard underway sampling consisted of GPS measurements of latitude, longitude, ship’s direction, speed and depth which was continuously recorded at or averaged over 5 min intervals. Temperature and salinity were measured continuously using a thermosalinograph. Meteorological data including atmospheric temperature, humidity and pressure, wind speed and direction were also recorded at 5 min intervals.

Wind velocity measurements (10 min averages logged manually every 3 h) were obtained from the weather station at Smoky Cape Lighthouse at South West Rocks (Fig. 3). The anemometer was

![Map of the experiment region showing CTD sections completed during two cruises aboard the R.V. Franklin, November 1998 (left) and February 1999 (right). The CTD casts are denoted by *, thermistor mooring locations are denoted by ◊, and the anemometer at South West Rocks is denoted by ★. The 100, 200, 1000 and 2000 m isobaths are shown. The 200 m isobath is marked in bold. Distance scales are defined as: 1° of latitude = 60 nautical miles = 111 km.](image)
10 m above ground which was 117 m above sea level. Readings from the land based weather station were compared with the ship’s wind records in order to assess their representation of the true marine winds. Comparisons showed that whilst direction was represented accurately, coastal wind records tended to slightly underestimate the magnitude of those experienced at sea.

2.2. Mooring arrays

Two across-shelf mooring arrays were deployed over a 3 month period from November 1998 to January 1999, one at Smoky Cape (30°55’S), where the shelf is 16 km wide, and the other 90 km to the south, directly offshore from Diamond Head (31°44’S) where the shelf widens to 30 km. The arrays were designed to examine the three-dimensional nature of the EAC. The data from these arrays are described in full by Roughan and Middleton (in preparation).

Optic Stowaway and Titbit temperature sensors were located on the inshore moorings of both arrays. The sampling interval was set to 3 min averages each 15 min period. The inshore mooring at Smoky Cape (SCA) was in 50 m of water and had thermistors at depths of 8, 35 and 48 m (Table 1). The inshore mooring at Diamond Head (DHAA) was in 30 m of water and had thermistors at depths of 8, 16 and 28 m (Table 1).

3. Wind-driven upwelling

During wind-driven upwelling water in the surface layer is driven offshore by the alongshore component of the wind stress ($\tau_y$) and water upwells near the coast to replace the offshore directed Ekman transport (Smith, 1981). This replacement is confined to the coastal zone with an offshore scale given by the baroclinic radius of deformation defined as $R_{oi} = NH/|f|$, where N is the vertically averaged buoyancy frequency, H is the water depth and f is the local value of the Coriolis parameter (Smith, 1981). Calculations for the study region give values of $R_{oi}$ between 5 and 8 km.

Contrary to the Oregon and Peruvian coasts (Smith, 1981; Fahrbach and Brockmann, 1981), upwelling favourable winds are rarely present for long periods along the NSW coast. Typically, local winds are highly variable in strength and direction. Hence, wind-driven upwelling is not a dominant process along the NSW coast; however, it does play a limited role. In this study wind records measured at Smoky Cape Light House are used to calculate the alongshore wind stress using the formulation of (Large and Pond, 1981). High frequency variability in the alongshore wind stress is removed using a lowpass filter with a half power point of 36 h and a cosine taper and is shown in Fig. 4 from 2–26 November 1998.

Three periods are noteworthy. The first is from 12–14 November (the two days prior to the first cruise), when persistent northerly (upwelling favourable) winds dominate, with a wind stress maximum of $0.1 \text{Pa}$ (unfiltered maximum $0.4 \text{Pa}$). The second period occurs during the first cruise (18–21 November 1998) where the wind stress is strongly downwelling favourable. Shipboard winds reached a maximum of $20 \text{ms}^{-1}$ from the southwest during this period. The third period is towards the end of cruise 1 (21–23 November 1998) concurrent with an EAC encroachment event characterised by light northerly winds.

Evidence of possible wind-driven uplift at Urunga and Smoky Cape in response to the upwelling favourable winds (12–14 November) is apparent in the ADCP velocity measurements and the hydrographic data obtained during this time. Fig. 5 shows shore normal sections of alongshore
current and density and Fig. 6 shows shore normal sections of nitrate and chlorophyll-\(a\). The sections come from Urunga, Smoky Cape and Diamond Head (November 1998, rows 1 and 2) and Urunga, Point Plomer, Diamond Head, Crowdy Head and Point Stephens (January 1999, rows 3 and 4). The Crowdy Head and Point Stephens sections are south of the original four sections and were obtained to enable a study of the EAC front, after separation. The ADCP transect at Urunga (16 November 1998) shows a strong southward flow with a maximum velocity of 1.6 m s\(^{-1}\), occurring 40 km from the coast (Fig. 5). There is also a slight offshore component of the flow (0.1 m s\(^{-1}\)) eastward of the 300 m isobath. The Urunga CTD transect (Fig. 6) shows the 14°C isotherm uplifted by 100 m, from a depth of 200 m approximately 40 km offshore to a depth of 100 m within 20 km of the coast. High concentrations of nitrate, (10 \(\mu\)mol l\(^{-1}\)) are uplifted 80 m at the shelf break (from 180 to 100 m). Concentrations at the base of the euphotic zone are significantly greater than average levels obtained from CARS (7.5 \(\mu\)mol l\(^{-1}\) at 100 m depth, 10 \(\mu\)mol l\(^{-1}\) at 200 m). The chlorophyll-\(a\) peak of \(\sim 4.5\) mg m\(^{-3}\) over the shelf break (Fig. 6) overlies the nutrient maximum and is associated with a density of 25–25.3 kg m\(^{-3}\) \((T = 20–21^\circ\mathrm{C}, S > 35.6\ \text{psu})\). In a SeaWiFS image (not shown) obtained for the period immediately prior to the experiment, significant chlorophyll-\(a\) blooms extend the length of the mid-north coast.

The Smoky Cape transect has similar characteristics with the 14°C isotherm uplifted 100 m in the water column (Fig. 6). The chlorophyll-\(a\) peak \(\sim 4.5\) mg m\(^{-3}\) which is located further inshore extends almost to the surface (Fig. 6). Again this peak is associated with densities of 25–25.3 kg m\(^{-3}\), overlying the nutrient maximum and the dissolved oxygen minimum, and underlying the extent of the light penetration (not shown). Nutrient values are similar to the previous transect, but extend further towards the coast, thus covering a larger area, and are constrained by the 100–200 m isobaths.

Average nitrate concentrations at Smoky Cape are only marginally higher at 100 m depth than those at Urunga (8.5 \(\mu\)mol l\(^{-1}\)), whilst at depths greater than 100 m they are the same. Observed nitrate concentrations are higher, with 15 \(\mu\)mol l\(^{-1}\) uplifted from 250 m to less than 100 m, indicating the presence of significant uplifting. Surface nutrient concentrations are, however, negligible, which could be attributed to a rapid uptake of nutrient in the euphotic zone, indicated by the surface chlorophyll-\(a\) bloom evident in Fig. 6.

Remnant wind-driven uplift is also present further south at Point Plomer (not shown). Very high fluorescence levels occur in two distinct pockets, one of which is high up on the shelf, adjacent to the coast in less than 50 m of water. The other is overlying the shelf break, and somewhat shallower than the nutricline. Maximum chlorophyll-\(a\) values are 4–4.5 mg m\(^{-3}\). The offshore chlorophyll-\(a\) pocket is found at the same depth as the Urunga pocket, in warmer EAC waters \((T = 20^\circ\mathrm{C}, S = 35.6\ \text{psu})\) which indicates poleward advection of the bloom. Conversely the coastal pocket of high chlorophyll-\(a\) is found in cooler less saline waters \((T = 18–19^\circ\mathrm{C},\)
Fig. 5. Cross sections of alongshore ADCP velocity (rows 1 and 3), where the bold line represents \( v = 0 \text{ m s}^{-1} \), the dashed line represents \( v = -1 \text{ m s}^{-1} \), negative velocities are southward and the contour interval (CI) = 0.25 m s\(^{-1}\). The second and fourth rows show cross sections of potential density (\( \sigma_\theta \)) where the dashed line represents the \( \sigma_\theta = 25.25 \) isopycnal and the CI = 0.25 kg m\(^{-3}\). The location and date of each transect is labelled above each velocity–density pair.
Fig. 6. Cross sections of nitrate concentration (rows 1 and 3) with temperature (CI = 2°C) overplotted. The $\sigma_0 = 25.25$ isopycnal is represented by the dashed black line. The crosses represent the position of the CTD casts and the black dots show the position of each individual bottle sample throughout the water column. The location and date of each transect is labelled above each pair.
$S < 35.6$ psu), indicating the uplift at the coast. Rochford (1972) cites a southward spread of cold water intrusions at a approximately 3.5 km per day. From our observations it appears that rather than spreading, the fluorescence is actually advected southward at a more rapid rate as it is entrained into the EAC, and dispersive diffusion is enhanced by the current shear. This entrainment is investigated more fully in numerical simulations and particle trajectories by Roughan et al. (accepted for publication).

The average wind-driven vertical velocity ($w$) is calculated from the time series of the mean hourly wind stress. This uplift velocity is compared with the temperature anomalies as measured inshore at Smoky Cape (SCA) and Diamond Head (DHAA) which are detrended and lowpass filtered with a 36 h cut off and sub-sampled hourly (Fig. 7). The maximum negative uplift (downwelling) occurred between 18 and 20 November 1998, prior to mooring deployment. Both the ADCP and CTD transect at Diamond Head reflect this downwelling and homogenisation of the water column (Figs. 5 and 6). Fig. 7 clearly shows two extended periods of positive uplift. The first is centred around 13 December 1998 and shows homogenisation of the water column and a bottom temperature anomaly of $-3^\circ$C for a 3 day period at both SCA and DHAA. Cross correlations were calculated between temperature and wind-driven uplift (not shown). Maximum correlations occur in the bottom boundary layer with a time lag of approximately 2 days and decrease towards the surface.

Fig. 7. Time series of wind-driven uplift ($w$) in metres per day and ($T_a$), temperature anomaly ($^\circ$C) inshore at (a) Smoky Cape (SCA) and (b) Diamond Head (DHAA).
The second event started on 2 January 1999 and occurred over a more extended period, resulting in a greater decrease in temperature \((\Delta T = -4^\circ C\) at SCA). However, the magnitude of \( w \) was less than that during the first event and the temperature began to drop before the wind-driven uplift commenced. Vertical isothermal displacement was estimated from the magnitude of the wind-driven uplift using background stratification obtained from CARS (Roughan, 2002). From comparisons with the actual isothermal uplift measured at the Smoky Cape moorings, it is apparent that local wind forcing contributed little to the uplift of isotherms, suggesting there was another mechanism driving the decrease in bottom temperature.

4. Encroachment, pre-conditioning and upwelling

Rochford (1975) recognised that the proximity of the EAC to the coast plays a role in nutrient uplift. Encroachment is defined here as the onshore movement of a current at any latitude as time progresses. This onshore movement can be delineated by the inshore edge of the temperature front, which is evident in satellite images of SST, or by the distance from the coast to the core of the current as is evident in cross sections of alongshore velocity. Observations presented here show that as the core of the current moves inshore towards the coast, upwelling occurs. Onshore advection due to encroachment is readily distinguishable from the response to downwelling favourable winds. For persistent equatorward winds, onshore movement occurs in the surface layers and ultimately results in an equatorward barotropic current. The across shelf velocity \((u_e)\) of water in the Ekman layer \((H_e)\) attributed to an alongshore wind stress \((\tau^y)\) is given by \(u_e = \tau^y / \rho H_e f = Q / H_e\). In the encroachment case the entire axis of the current moves onshore as a jet. Rather than reversing the direction of the barotropic current as in the downwelling case this accentuates the alongshore current and causes nutrient enrichment.

Whilst downwelling causes homogenisation and depression of the isotherms, encroachment causes uplift and nutrient enrichment. Encroachment aids pre-conditioning of the isotherms, and if the strength of the current is sufficient, enhanced Ekman pumping will occur through the BBL. Furthermore, encroachment can aid topographic acceleration of the current (as outlined in Section 5) which can also result in upwelling. As noted by Cresswell (1994), episodic incursions of slope water rapidly overwhelm existing current patterns and results in the flushing and replacement of shelf waters.

AVHRR satellite images of SST are particularly useful for obtaining a synoptic view of the EAC. Pre- and post-encroachment images are shown in Fig. 8a and b, respectively. At Smoky Cape (Fig. 8a) the edge of the current delineated by the marked thermal front overlies the shelf break along the 200m isobath. Fig. 8b (1 week later) shows that the current is more defined and has moved closer to the coast. Fig. 9 shows SST images of the study region in January 1999, of particular note is the increase in temperature that occurred in the 2 months between images.

Surface current velocities along the four ADCP transects during the same period reflect this pattern. Fig. 10a shows the velocities before the encroachment (14–19 November 1998). At the two northern transects (Urunga and Smoky Cape) the current flows parallel to the 200m isobath at a speed of more than 1.5 m s\(^{-1}\). At the southern two transects (Point Plomer and Diamond Head) the current flows diabatically with an eastward (offshore) component. Inshore of the southward flowing current there is evidence of a weak northward flow extending up the coast.

From the ADCP transects at Smoky Cape transects on the 16 November 1998 (Figs. 5 and 10a) it is evident that prior to the encroachment of the EAC, the current’s core flow is located offshore, with a maximum alongshore velocity of 1.6 m s\(^{-1}\) positioned over the 500m isobath and an across-shore flow of \(\sim 0.2\) m s\(^{-1}\) eastward of the 300m isobath. After encroachment on the 21 November 1998 (Figs. 5 and 10b) the core of the current has moved onshore significantly at Smoky Cape, with very strong coastal currents of 0.4 m s\(^{-1}\) occurring 2 km from the coast in a depth of 50m, where previously the alongshore current was negligible.
After the strong southerly winds (18–20 November 1998) significant homogenisation of the surface waters accompanied by a deepening of the mixed layer is evident in the coastal region at Diamond Head (Fig. 5). Associated with the depression of the isotherms is a weak northward current in the near shore zone, with a maximum speed of $0.4 \text{ m s}^{-1}$. The maximum southward current of $1.2 \text{ m s}^{-1}$ is found 45 km offshore. Diabathic flow is a positive maximum in the surface, associated with the maximum southward flow. Although concentrations of surface nutrient and chlorophyll-$a$ are low due to homogenisation and depression of the surface waters, nitrate concentrations at depths of 100–200 m remain high (Fig. 6).

Onshore advection resulting from the along-shore wind stress is calculated using Ekman theory. Using the 3-hourly lowpass filtered wind records to calculate the alongshore wind stress at Smoky Cape and assuming an Ekman layer depth $H_e$ of 75 m and a mean Ekman layer density $\rho$ of 1024.5 kg m$^{-3}$, onshore advection occurs at a rate of $\sim 0.01 \text{ m s}^{-1}$, which is equivalent to $\sim 3 \text{ km}$ in 2 days. However, from the ADCP transects at Smoky Cape (Figs. 10a and b) the core of the current actually moved more than 6 km towards the coast in the 2 day period, hence, the onshore movement of the current cannot be attributed to local wind forcing.

By 21 November 1998, the onshore movement of the current rapidly overwhelms the downwelling scenario. At Smoky Cape homogenisation resulting from the southerly winds is still evident in the surface mixed layer, yet as the current moves onshore the isotherms are again uplifted parallel to the bottom topography. Surface currents are a maximum at Point Plomer (Fig. 10b) and are again parallel to the shelf break. Hence, it is clear that as the core of the current moves onshore it...
accelerates the coastal currents and uplifts the isotherms.

In the space of only 4 days the isotherms are again uplifted at Diamond Head and stratification occurs in the density profiles (Fig. 5). As the core of the EAC moves onshore at Smoky Cape, uplift, and hence preconditioning of the coastal waters has been re-established. The 14°C isotherm is uplifted over a vertical distance of 130 m whilst the surface temperatures have increased by 2°C as the warm surface waters move onshore.

The size and extent of the fluorescence plume is larger by comparison than that observed earlier at Diamond Head, and to the north at Smoky Cape. A chlorophyll-a maximum of 2.5 mg m\(^{-3}\) has formed immediately below the pycnocline (Fig. 6), where 4 days previously there had been no evidence of biological activity.

From 15 to 20 November 1998 the entire current system encroaches shoreward. The weak and variable winds are neither strong enough nor persistent enough to counteract the strong downwelling event which occurred prior to the onshore encroachment. Thus, uplift of isotherms and nutrients is a rapid response to an EAC encroachment event which results in a bloom of phytoplankton.

5. Upwelling from topographic effects

After examining correlations between wind direction and upwelling, Rochford (1975) suggested that the narrowing of the continental shelf to the north of Laurieton was a contributing factor to occasional (approximately 5 times per year) upwelling events. Numerical simulations presented by Oke and Middleton (2000) indicate that alongshore topographic variations can impact the shelf circulation by accelerating the alongshelf flow through a narrowing shelf cross section. As a result, near bottom currents increase, thus...
increasing bottom stress on the shelf and slope which acted to drive an onshore flow through the BBL. As the EAC accelerates due to the funnelling effect of the narrow continental shelf, the gradient Richardson number is reduced to below the critical value ($Ri < 0.25$). Vertical mixing is enhanced, thus decreasing the buoyancy frequency which in turn reduces the Slope Burger number, $S = N^2 x^2 / f^2$. This enhanced mixing and the subsequent reduction of the Slope Burger number acts to lengthen the time it takes for the BBL to shut down (MacCready and Rhines, 1993). Hence, deeper waters are transported up the slope for a longer period of time resulting in more extensive upwelling.

Oke and Middleton (2001) examine nutrient enrichment off Port Stephens but they do not make the distinction between separation induced upwelling and topographically induced upwelling. In an idealised numerical simulation, they show that the narrowing of the shelf topography at Smoky Cape causes uplift of slope water onto the continental shelf, which is then upwelled to the surface as the EAC separates from the coast. Here, the two scenarios are isolated and examined independently; however, it is possible that they are actually related, and it is the topographic effects that make the separation so clean at Smoky Cape.

Fig. 9a shows the EAC flowing southward on the 18 January 1999 in a narrow jet (~100 km) which separates from the coast just to the north of Diamond Head. The surface waters are anomalously warm (27°C), related to heating occurring...
in the Coral Sea possibly resulting from the strong La Nina phase (Berkelmans and Oliver, 1999). In the coastal regions from Diamond Head south to Port Stephens the surface waters are cooler (20°C). One week later (Fig. 9b) the jet structure appears less defined owing to cloud cover in the images. However, the point of separation has moved >90 km to the south as the EAC water encroaches upon the coast. The vector plot of surface ADCP currents (Fig. 11) shows an overview of the prevalent conditions from 21–30 January 1999.

At Urunga, a weak northward flow occurs near the coast due to a small recirculation north of the point, and a narrowing of the jet occurs towards Smoky Cape. The current velocities at Point Plomer are stronger than those to the north, indicating a Lagrangian acceleration. South of the separation there is a slight northward current inshore. A vertical profile of the alongshore current from a shore normal ADCP transect at Urunga out to 35 km offshore is shown in Fig. 5. Inshore the currents are northward flowing at 0.2 m s\(^{-1}\). Surface currents (top 50 m) over the shelf break decrease with depth from 1.5 to 1 m s\(^{-1}\).

From the Urunga CTD transect (Fig. 6) we see the signature of the EAC in the temperature measurements with maximum temperatures of 27°C in the surface waters associated with the core of the current, overlying the shelf break. Salinities in the surface EAC waters are 35.4 psu, with a salinity maximum (35.7 psu) at 100 m depth. The isopycnals reveal a gentle downturn towards the coast reflecting the weak northward flowing current evident in the ADCP plots. There is a peak in chlorophyll-a below the EAC waters, i.e. \((T < 25°C, S > 35.5 \text{ psu})\). The maximum concentration is \(\sim 4 \text{ mg m}^{-3}\) located at a depth of 30–60 m over the shelf break.

The shore normal ADCP transect at Point Plomer (Fig. 5) shows that the EAC has increased in strength to a maximum of 2 m s\(^{-1}\) above the shelf break, at a distance of 20 km offshore. The width of the core is less than 5 km across, and the maximum temperature is 27°C. Across-shore uplift of the isotherms is more prominent than in the previous transect, so that the isotherms are now parallel to the bottom. Water with a temperature of 15°C is uplifted more than 150 m to less than 50 m depth, whilst velocities of 1 m s\(^{-1}\) are found near the bottom. There is also a highly stratified BBL, a flow of nutrients up through the BBL and the beginnings of a chlorophyll-a bloom in the surface waters with trace concentrations (\(\sim 1 \text{ mg m}^{-3}\)).

At Diamond Head, 90 km further to the south (Fig. 6), there is a strong thermal gradient between the warm (27°C) EAC water flowing at 2 m s\(^{-1}\) southward, and the cooler coastal water. The horizontal temperature change of 7°C occurs over 4 km at a depth of 25 m. Associated with this thermal front is a change in current direction, with maximum velocities offshore from this point being.

Fig. 11. Vector plot of the current velocity (ms\(^{-1}\)) at 16 m depth, measured underway using the shipboard ADCP, for 21–30 January 1999.
Inshore of the front currents reverse and flow northward at 0.2 m s\(^{-1}\). Maximum current speeds occur over the shelf break, and maximum horizontal current shear is in the surface waters, 15 km from the coast (Fig. 11). The highest concentrations of chlorophyll-\(a\) are found inshore of the front, underlying the southward current and are associated with the highest nutrient concentrations mid-shelf. The bloom at Diamond Head now appears in the surface waters where further to the north at Smoky Cape the bloom is found at depth. This reflects the process of topographic upwelling and southward advection, beginning at Smoky Cape and resulting in a surface chlorophyll-\(a\) peak at Diamond Head.

An ADCP transect run at Smoky Cape during January (not shown) reveals a weakening of the current. The associated SST image shows a broadening of the EAC jet, which is associated with a relaxation in current strength. Maximum current speeds are 1.2 m s\(^{-1}\) and located 10 km offshore. As the current weakens, despite the core being within close proximity of the coast, the isotherms lie deeper in the water column and the upwelling response attributed to the western boundary current pre-conditioning is reduced. There is distinct horizontal stratification, with the surface, less saline waters of lower density extending from 4 km inshore all the way to the end of the transect, 20 km offshore. This contrasts with the pre-conditioned scenario where the isotherms, although stratified, are uplifted parallel to the bottom bathymetry. Furthermore, as the current weakens at Smoky Cape, the effects of pre-conditioning are reduced, horizontal stratification returns, nutrient supply ceases as does the biological response. Thus, it appears that upwelling is only induced topographically under certain current regimes, defined by proximity and velocity.

6. Western boundary current separation and enrichment

The third current-driven upwelling mechanism occurs as the strong western boundary current separates from the coast. A theoretical study by Janowitz and Pietrafesa (1982) found that on the cyclonic side of a fast flow with low Rossby number (i.e. where rotation effects outweigh advection) isobath divergence should induce upwelling and associated onshore flow. They give the example of the western side of the Gulf Stream, where the onshore transport, associated with the divergence of a jet 100 km wide, carrying 100 Sv, is of the order of 2 Sv/100 km (or 20 m\(^2\) s\(^{-1}\)). In the Southern Hemisphere, upwelling should be seen on the inshore side of the EAC as it separates from the coast.

The latitude at which the EAC separates varies temporally and spatially as a consequence of the near semi-annual (150–180 days) westward propagation of baroclinic Rossby waves across the Pacific Ocean. These Rossby waves arrive at the Australian coast and then propagate poleward as sea level anomalies with a speed of ~0.06 m s\(^{-1}\) (Mata et al., 2000). As these anomalies move southward eddies may be pinched off from the main EAC flow. The point of separation moves northward as the eddy is shed and the process starts all over again. Inshore of the separated current there is often a large cyclonic eddy which, through Ekman pumping, raises the thermocline to a point where the region is pre-conditioned to upwelling. For this reason upwelling is often observed inshore of the separated EAC.

A series of transects (both ADCP and CTD) were taken in February 1999 south of the point where the EAC separated from the coast crossing the thermal front. Two of these transects are shown in Figs. 5 and 6. The first is taken at Crowdy Head, immediately poleward of the separation point. The second is taken at Point Stephens almost 150 km downstream of the separation point.

The ADCP transect at Crowdy Head (Fig. 5) shows that the current strength has decreased since separation to 1.6 m s\(^{-1}\) and the core is located ~20 km from the coast. There is a strong thermal gradient across the front from 27°C in the core to ~20°C near the coast (Fig. 6). Isotherm uplift is present in the BBL where water of 18°C is seen extending to within 5 km of the coast. There is a slight pooling of nutrients occurring 5–10 km from the coast where nitrate concentrations reach...
5 \text{mmol} \cdot \text{l}^{-1} (\text{Fig. 6}). Associated with this is a surface chlorophyll-\text{a} signature, inshore of the thermal front which underlies the warm (26°C) less saline (35.3 psu) surface waters, coinciding with the region of highest dissolved oxygen (not shown). This chlorophyll-\text{a} bloom increases in size and concentration moving southward to Port Stephens.

The strong frontal structure continues southward and is still present in the most southerly transect at Point Stephens (Fig. 5). Current strengths remain high in the warm water, whilst inshore a current reversal occurs, where a weak northward current (0.2 m s\textsuperscript{-1}) extends 10 km offshore. The core of the current is more than 45 km from the coast, due to the fact that the coast bends westward south of Sugar Loaf Point (Fig. 11). The vertical change in velocity (\(\partial v/\partial z\)) is large, and is associated with the strong horizontal temperature gradients across the front. The nutrient plume has expanded so that it now extends for 15 km across the continental shelf (Fig. 6), with nitrate concentrations reaching 9 \text{mmol} \cdot \text{l}^{-1}. Most noteworthy is the expansion of the chlorophyll-\text{a} plume which now overlies the nutricline, extending from the front to within 5 km of the coast. This chlorophyll-\text{a} bloom does not reach the coast, indicating a frontal process rather than a coastal process. Concentrations are highest (>3 mgm \cdot m^{-3}) immediately inshore of the thermal front.

As the current separates from the coast the current strength decreases slightly downstream of the separation point. Nutrients are brought to the surface as the flow proceeds downstream, with a strong bloom resulting inshore of the front. Although concentrations are lower than those associated with the previous scenarios, the nutrient pool covers a far greater area over the continental shelf. The chlorophyll-\text{a} concentrations are of similar magnitude to those seen previously; however, their extent is again far greater. Both the nutrient pool and the chlorophyll-\text{a} bloom are centred at a distance of ~18 km from the coast. This distance is greater than the internal Rossby radius (Roi) for this region, i.e., outside the direct area of influence of wind-driven coastal upwelling. Furthermore, northerly (upwelling favourable) winds are not present. At the same time an EAC relaxation occurs as the current broadens and decreases in strength and the alongshore steady flow that results is not upwelling favourable. Despite a strong temperature gradient, the uplifting and upwelling effects are minimal.

7. Comparisons of the various mechanisms

The previous sections have described the different mechanisms which drive slope water into the surface waters. It is now desirable to identify and compare the magnitude of these events. A review of the various contributions to shelf edge circulation by Huthnance (1995) shows that the circulation contribution from a western boundary current is at least one order of magnitude larger than that from either coastal currents or slope currents in other regions, regardless of the forcing. Huthnance (1995) compares the magnitude of cross shelf exchange associated with the various physical processes occurring at the shelf edge and concludes that cross shelf exchange resulting from upwelling attributed to the divergence of a western boundary current is 20 times greater than the exchange associated with wind-driven upwelling.

Rochford (1975) defined upwelling in the Smoky Cape/Laurieton region as a rapid drop in the SST. Here, there is a temperature decrease of 3°C in the surface waters at Smoky Cape and at Diamond Head during the wind-driven event. During the current-driven event the temperature change is not seen in the surface waters at Smoky Cape, however, at depth and in the surface waters at Diamond Head the drop is greater (\(\Delta T=4^\circ\text{C}\)). Furthermore, the isotherms are depressed for a longer period of time.

7.1. Nutrient concentrations

The magnitude of an upwelling event can be quantified by comparing the concentration of the nutrients that are brought to the surface. (Hallegraeff and Jeffrey, 1993; Furnas and Mitchell, 1993). Measured nitrate concentrations are shown for the Urunga (15 November 1998), Diamond Head (24 January 1999) and Point Stephens (30 January 1999) sections in Fig. 12 as indications of...
the upwelling concentrations during a wind-driven upwelling (Fig. 12a), an encroachment-driven upwelling (Fig. 12b) and a separation induced upwelling (Fig. 12c). For comparison, plots of average nitrate concentration derived from CARS data are shown for the same three sections (Fig. 12d–f).

The Urunga cross section shows that measured sub-surface nutrient concentrations after a wind-driven uplifting event are 50% greater than average concentrations, (14 μmol l⁻¹ at 150 m depth). The increase in nutrient is generally restricted to the shelf break and tends to follow the bottom bathymetry. The Diamond Head section shows an example of uplifting induced by encroachment and possible topographic acceleration. Here, the concentrations are slightly lower (≈10 μmol l⁻¹); however, they are more widespread horizontally and extend further up into the water column. This is indicative of uplift further to the north and downstream advection. The average concentrations at both Urunga and Diamond Head are similar in magnitude.

The final example from Point Stephens shows that higher average concentrations are more widespread. The ≈8 μmol l⁻¹ isopleth is uplifted to a depth of 75 m. This indicates a persistent pattern of nutrient uplift, most probably associated with the semi-permanent EAC separation feature. Measured nitrate concentrations are the lowest ‘upwelling’ concentrations observed (7 μmol l⁻¹), however, the bloom extends across the entire continental shelf and is lifted throughout the entire water column. The presence of a

Fig. 12. Observed nitrate concentrations during events at: (a) Urunga (wind-driven); (b) Diamond Head (encroachment driven); (c) Point Stephens (separation driven); (d–f) mean nitrate concentrations at each location, obtained from CARS. Maximum concentration is 10 μmol l⁻¹. The contour interval = 2 μmol l⁻¹ and the thick black line represents 8 μmol l⁻¹.
persistent pool of nitrate-rich water on the continental shelf immediately below the euphotic zone explains the regular occurrence of algal blooms at Point Stephens (Hallegraeff and Jeffrey, 1993).

8. Discussion and conclusions

By combining in situ measurements of temperature with CTD and hydrographic data, satellite images of sea surface temperature and the circulation derived from ADCP measurements, a conceptual model is constructed of the three-dimensional nature of current-driven upwelling in the vicinity of the separation point of the East Australian Current.

The hydrographic sections from Smoky Cape and Diamond Head show clear evidence of long shore variability over a short spatial scale (~90 km). We conclude that the acceleration of the current at Smoky Cape transports and lifts colder nutrient-rich water via the bottom boundary layer (BBL) to the euphotic zone in the Diamond Head region. This is reflected in the cross sections of chlorophyll-a where the regions of high fluorescence are associated with the colder water. At Smoky Cape, the fluorescence peak is at the base of the water column, at a depth of 80 m. Further to the south at Diamond Head, the fluorescence maximum has been upwelled to the surface, overlying the 80 m bathymetric contour.

A higher abundance of zooplankton was found at Diamond Head associated with the higher fluorescence levels, whilst virtually no zooplankton was found at Smoky Cape (Dela Cruz, pers. comm.). It is highly likely that this biological variability is associated with the acceleration of the EAC which increases upwelling, south of Smoky Cape (to the north of Laurieton) combined with the effects of separation of the current anywhere in this region which also drives upwelling. In contrast, at Evans Head encroachment-driven upwelling is most likely to occur, with the occasional separation induced event as the point of separation moves equatorward and south again.

The results of this study show evidence of four different upwelling mechanisms, three of which are driven by the EAC. These current events are compared with a wind-driven coastal upwelling event. During November 1998 an EAC encroachment event occurred, which totally overwhelmed the existing downwelling conditions present on the shelf. This onshore movement of the core of the current is evident from the rapidly re-established uplift of the isotherms. During February 1999 the effects of topographically induced upwelling were observed combined with the effects of separation of the EAC downstream from Smoky Cape. However, it is topographically induced upwelling combined with encroachment which produces the largest upwelling events observed. As the current comes within close proximity of the shelf at Smoky Cape, alongshore acceleration occurs in an Eulerian sense ($\partial\vec{v}/\partial t$) whereas with topographic acceleration the current strengthens in an advective sense ($\vec{v} \cdot \Delta \vec{v}$) and it is difficult to isolate the upwelling response from the two cases downstream of Smoky Cape. Separation induced upwellings on the east coast as the southerly winds are stronger and more persistent than the northerly winds. However, the pre-conditioning effects of the EAC allow weaker northerly wind events to have a greater effect on isotherm displacement than southerly wind events of the same strength, which first have to counteract the pre-conditioning effects. Thus, it follows that an encroachment event that overwhelms a downwelling event is most likely to be bigger than any wind-driven upwelling.

In a multi-year study of upwelling on the northern NSW shelf, Rochford (1972) showed that upwelling at Laurieton was more pronounced than that observed further to the north at Evans Head. At Laurieton we have the contributing effects of topographic upwelling related to the narrowing and hence acceleration at Smoky Cape (to the north of Laurieton) combined with the effects of separation of the current anywhere in this region which also drives upwelling. In contrast, at Evans Head encroachment-driven upwelling is most likely to occur, with the occasional separation induced event as the point of separation moves equatorward and south again.
upwelling, whilst being smaller in magnitude, appears to have a far greater effect on the waters downstream of the separation point. Thus, although the upwelling response may differ in time, extent, and magnitude it is clear that the acceleration of the current in the Smoky Cape region drives upwelling. Hence, this semi-permanent upwelling is seen in the nutrient climatology, which explains the historically regular occurrence of algal blooms downstream of both Smoky Cape and the EAC separation point.

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References


