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A field study of the three-dimensional structure of the Rottnest Island wake

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ABSTRACT: Field data collected in the vicinity of Rottnest Island, located on the continental shelf off Fremantle, Western Australia are presented. Satellite imagery from the study area indicate the presence of a relatively cold patch of water to the north of the island. During the summer months, the prevailing southerly winds drive a northward current on the continental shelf. Interaction between these shelf currents and the island results in the formation of a wake to the north of the island, although flow separation does not occur. Under these conditions it is most likely that upwelling of colder water in this wake occurs due to secondary circulation induced by flow curvature off the tip of the island. This colder water is then advected northwards and rises to the surface, thus resulting in the observed patch of cold water to the north of the island.

INTRODUCTION

The three-dimensional structure of island wakes has been documented by many authors (eg. Wolanski et al., 1984; Heywood et al., 1990; Deleersnijder et al., 1992; Geyer, 1993). On the basis of field measurements of a tidal eddy in the lee of Rattray Island, Wolanski et al. (1984) proposed a theoretical model for eddy generation in the wake. The model was based on the concept of the generation of vorticity at the tip of the island, flow separation and final dissipation of the vorticity within the downstream eddy. They suggested that the imbalance between pressure gradient and centrifugal force in a thin bottom Ekman layer resulted in a radial velocity towards the center of the eddy. The convergence of this radial velocity caused an upward motion of water (upwelling, due to the Ekman pumping) in the center of the eddy. They emphasised the importance of upwelling in the wake of islands and headlands, a feature absent in depth averaged two-dimensional numerical or analytical models. However, their model could not explain the observed concentrated downwelling around the tip of Rattray Island where flow separation occurred resulting in a large eddy in the wake region (Wolanski, 1994).

Deleersnijder et al. (1992) studied the wake of Rattray island using a three-dimensional numerical model and concluded that, in addition to the Ekman pumping within the eddy, topography has an important role in the vertical transport of water. They suggested that the vertical motion of water was a result of both up/downslope motion due to changes in topography as well as up/downwelling motion of water due to mechanisms such as the Ekman pumping. Interestingly, their modelling results showed the presence of both upwelling and downwelling areas around the tip and even on the upstream side of Rattray Island. However, the spatial flow structure around the tip of the island, responsible for the upwelling or downwelling, was not fully described.

Using field observations of tidal flow around Gay Headland, Massachusetts, Geyer (1993) showed that there was a secondary circulation induced by flow curvature alone. This secondary flow, which was in the plane normal to the direction of the mean flow, was directed seaward near the surface and landward near the bottom. It was suggested that this secondary flow may result in upwelling (Geyer, 1993) but no direct observations of vertical velocity around the tip of the headland were reported.

In both Rattray Island and Gay Headland, flow separation occurred at the tip of the topographical feature. In reality, the flow separation results in a complex flow structure in the vicinity of the tip due to the generation of a free shear layer between the separated flow and a relatively quiescent water in the lee of the island. The free shear layer, initiated at the separation point, may consist of many vortices. The

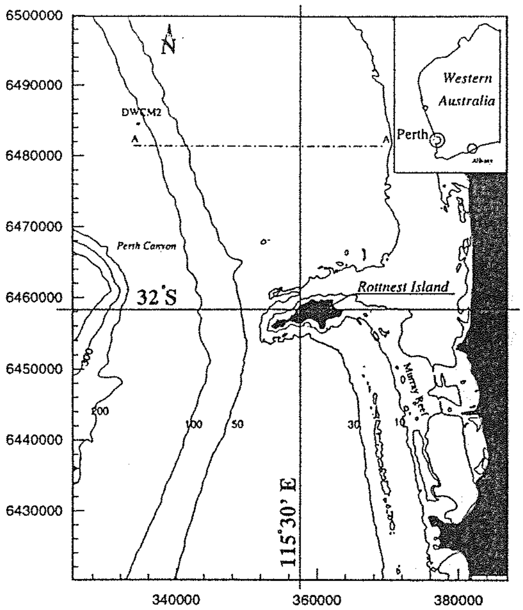

Figure 1. Location of the study area and bathymetry in the vicinity of Rottnest Island. Location of the current meter station DWCM2 and transect AA is also shown.

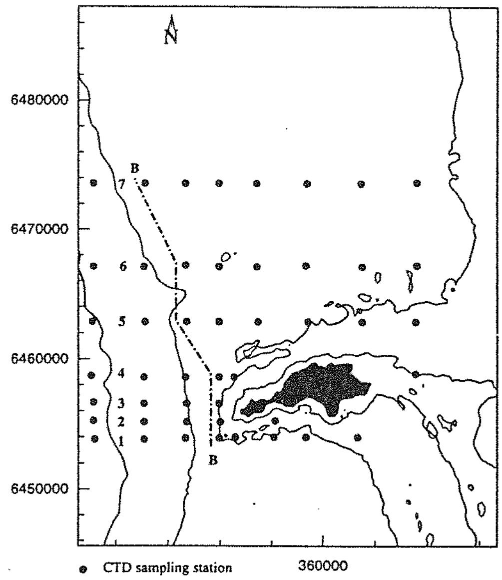

Figure 2. Locations of the intensive CTD sampling stations for February 1995. Transect numbers as referred to in the text are shown as well as the location of transect BB.

localised upwelling within the vortices (Wolanski, 1994) influence the flow structure on the downstream side of the separation point. Consequently, the flow separation at the tip of an island or headland may result in a very complex three-dimensional flow structure in the tip region. To understand the flow behaviour in this region extensive field observations are required.

In this study, we consider the simple case in which the flow separation either does not occur or does not result in a recirculation (eddy) in the wake. Under these conditions, which is defined as '*attached flow*', the structure of the flow around an island or headland is free of flow separation effects. In addition, at *attached flow conditions* any signature of upwelling in the wake region or in the lee of an island could be due to a mechanism other than Ekman pumping. The aim of this paper is to illustrate the three-dimensional structure of an island wake at attached flow conditions using field data collected off Rottnest Island, South Western Australia.

Study Area

Rottnest Island, 10.5 km long and 4.5 km wide, is located close to the shelf break 30 km off the Perth coastline, south western Australia (Figure 1). The island is the extension of the Murray Reef System (the location of an ancient shoreline), and the western tip of Rottnest Island behaves as a headland. The shape and location of the shelf edge makes the situation unique: the regions to the north and south of the island are uniform, while the angular shaped shelf edge located off the western tip of Rottnest Island allows cold water to move up onto the shelf slope, and this water may be used as a passive tracer of fluid motion.

An additional advantage of the site is that the water temperature on the continental shelf changes slightly within the water column. This allows use of the temperature structure of the flow together with current meter data to track the horizontal and vertical movements of water.

During the summer months, predominant northerly currents with speeds up to 0.50 m/s are present on the continental shelf as a result of persistent southerly winds (Pattiaratchi et al., 1994). During this period other types of currents are negligible: the maximum tidal currents and baroclinic currents are of order of 0.02 m/s (Pattiaratchi et al., 1994). In addition, the Leeuwin Current (LC), a warm, low salinity southward current flowing along the WA coastline (Smith et al., 1991) is located far offshore and therefore does not

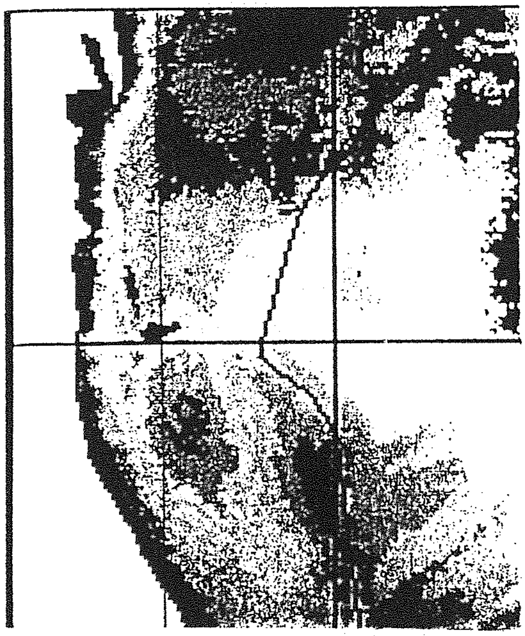

Figure 3. Satellite image (AVHRR) obtained on 21 December 1993 showing the presence of the cold patch to the north of Rottnest Island. Lighter shades of grey indicate warmer water.

influence the study area. The interaction between the wind driven current and Rottnest Island produces a wake to the north of island which may be identified by the presence of a patch of cold water on the sea surface during the summer months. The size and temperature of the patch differs from time to time, but the location does not appear to vary and we argue below that the patch of cold water is the product of upwelling in the wake.

The island wake parameter, P (Wolanski et al., 1984; Pattiaratchi et al., 1987) maybe used to classify the Rottnest Island wake. The wake parameter is defined as $P=UH^2/WKz$ where U is the ambient flow velocity, H is water depth, W the half of width of the island and Kz is the vertical eddy viscosity. Pattiaratchi et al. (1987) used $Kz=10^{-1}$ m^2s^{-1} for several islands and suggested that the wake parameter was in good agreement with the observed wake regimes. Using the same value for the vertical eddy viscosity and taking H = 40 m, results in $P = 0.3$ which corresponds to the attached flow condition (Wolanski et al., 1984; Pattiaratchi et al., 1987).

1. DATA COLLECTION

A detailed field study designed to identify the regional water circulation in the Perth coastal area was undertaken as part of the Perth Water Coastal Study (PCWS), as described in Pattiaratchi et al.(1994).

Wind, current, wave and CTD data were collected at different stations location of the deep water current meter station (DWCM2) and the cruise path for CTD measurements. At DWCM2, the outer shelf mooring with total depth of 110m, four current meters including temperature sensors were deployed at different water depths (23, 48, 75 and 100m below the sea surface) for the period from March 1993 to January 1994. From this data set, the observations from December 1993 is a very good example of the summer flow regime in Rottnest region.

CTD (Conductivity, Temperature and Depth) surveys conducted in the Rottnest region have been undertaken using a high resolution CTD instrument (eg. the resolution of the temperature sensor is 0.005 °C with a data acquisition rate of 50 Hz). During PCWS, CTD surveys were carried out regularly but were limited to the inner shelf region. However, ten CTD surveys extending to the deep outer shelf region along transect A-A (Figure 1), were also carried out. The CTD data depicted the temperature and salinity structure of the water column, mostly corresponding to the summer wake region, to the north of Rottnest Island. To achieve a clearer picture of three-dimensional structure of the wake an intensive CTD survey was also carried out on February 7 1995 (Figure 2).

NOAA/AVHRR satellite imagery were used to infer current patterns in the region as well as defining the sea surface temperature distribution in the vicinity of Rottnest Island. The satellite images showing the distribution of sea surface temperature (SST) were acquired for cloud free days from the West Australian Department of Land Administration (DOLA).

2. RESULTS AND DISCUSSION

Satellite imagery during the summer period, between November and March (southern hemisphere), consistently indicate a patch of relatively cold water located in the wake region to the north of Rottnest Island (Figure 3). In the following sections we present observations of the summer wake of Rottnest Island corresponding to two different summer periods: December 1993 and February 1995. The data from December 1993 describes the flow in the region as well as indicating the extent of the vertical motion of cold waters from deep layers of the outer shelf onto the shallow inner shelf region. The December 1993 data also depicts the correlation between the vertical excursion of the isotherms and the flow direction. The final data set illustrates a three-dimensional picture of the wake obtained on February 7, 1995.

2.1 December 1993

The temperature distribution of the water column obtained on Day 93348 (13 December 1993), alongthe east-west transact A-A (Figure 1) indicates warmer water near the shoreline (Figure 4). Temperature generally decreases with distance offshore and after the shelf edge (50 m depth) begins to increase. The increase in temperature offshore is due to the Leeuwin Current. On the continental shelf doming of isotherms may be identified indicating an upwelling process. Time series of current speed and direction together with temperature at station DWCM2 (Figure 1) indicates a correlation between current direction and the vertical excursion of isotherms (Figure 5). Northward currents cause a decrease in the temperature at the recording point (100 m below the surface) indicating upward migration of the isotherms (Figures 5b and 5e). In contrast, when the flow is southward, excursion of the isotherms is downward with an increase in temperature.

The temperature structure in the cross-shelf transect (Figure 4) indicates that the deeper colder waters were forced upslope, leading to an isotherm doming on the shelf. On first inspection, the temperature structure of the flow suggest an upslope movement of deep cold water onto the shelf region. However, time series of cross-shelf components of current at DWCM2 (directed at 65°) at 75 and 100 m below the sea surface, reveal that during the event the local onshore current component either did not exist or was negligibly small (Figure 5c and 5d). It may therefore be concluded that the cold water, spreading over the shelf, did not originate from the deeper layers in the same cross-shelf plane (i.e. plane A-A). Rather, the cold water must have been advected onto the site.

The satellite image corresponding to 14th December 1993 (a day after the CTD survey) is shown in Figure 6. In this image a patch of cold water can be clearly observed to the north of Rottnest island and interestingly, the CTD cruise path (A-A) had crossed the patch area. Thus the

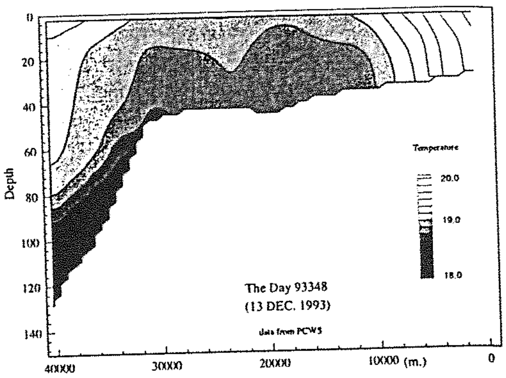

Figure 4. Temperature distribution across the continental shelf (Transect AA) obtained on 13 December 1993)

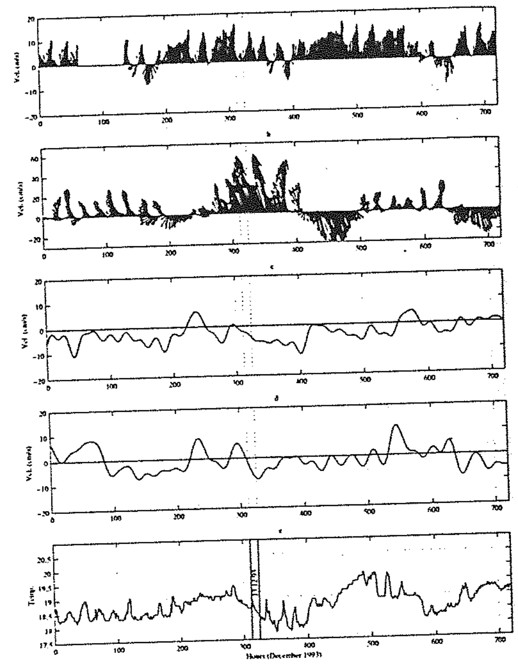
Figure 5. (a, b, c, d, e from top) Time series of wind, currents and temperature for December 1993 recorded at station DWCM2.

temperature transect shown in Figure 4 can be considered as a cross-shelf vertical section of the patch. The current data shows that the northward current continued for two days after the CTD survey. It is likely that the upslope movement of deep cold waters continued, at least, for the same period. Therefore, the isotherm doming on the shelf is likely to grow with the increase in northward current velocity and thus penetrated the surface mixed layer and appeared as a patch of cold water on the sea surface. After the current direction was changed toward the south, the isotherms on the shelf slope moved downward (Figure 5). It implies that in the presence of the northward in the region the forcing for the upwelling vanishes and it may be expected that the patch weakened gradually while it was advecting southward.

2.2 February 1995

While a persistent southerly wind prevailed during January and early February 1995 the Leeuwin Current was located offshore and as a result a northward current was present on the continental shelf. Thus, an extended CTD survey (Figure 2) was carried out on February 7 1995 to define the spatial temperature and salinity structure of the flow around the island and in the wake region. Figure 7 shows the temperature structure of the flow along different east-west transects. The spatial development of upslope motion of the deep cold waters is illustrated in these transects.

Transect 1, to the south of the island (upstream), shows there is no signature of colder bottom waters on the shelf. The shelf waters to the south of the island are vertically well mixed. However, there is only a very weak horizontal stratification probably due to the varying water depth observed on the shelf region. The temperature structure of the flow around the western tip of Rottnest Island, however, suggests an upslope movement of deep cold water which can be traced from transect 2 to 4. Transects 5 and 6 indicate that the cold water is spread onto the shelf, while in transect 7 an isothermal doming is clearly evident. Transects 5 to 7 are very similar to the temperature distribution obtained on 13 December 1993 (Figure 4). From these series of east-west transects, it is clear that the vertical excursion of deep cold water was initiated from the vicinity of the western tip of Rottnest Island.

The horizontal temperature structure of the flow at different depths is depicted in Figure 8. The Transect HT5 in Figure 8 illustrates the distribution of vertically averaged temperature between 4 m and 5m water depth. A patch of cold water can be seen to the far north of the island. The patch is located almost at the same location at which satellite imagery recorded the presence of the cold patch of at the sea surface a day after the CTD survey (Figure 9). Transect HT25 (at 25m depth) shows a clearer picture of the cold water, and also another signature of cold water is evident in the downstream side of the western tip of Rottnest Island. At the shelf edge (50m depth) the horizontal distribution of water temperature (HT50), implies that the cold water, from the outer shelf, is limited to the vicinity of the western tip of Rottnest Island.

Figure 6. Satellite image (AVHRR) obtained on 14 December 1993. Lighter shades of grey indicate warmer water.

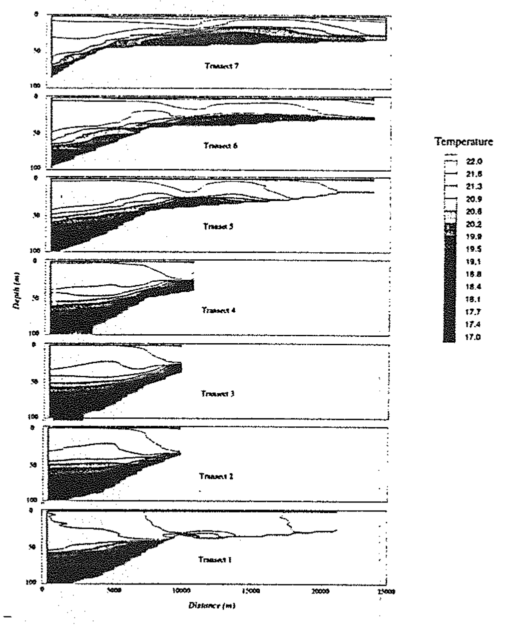

Figure 7. Temperature distribution on the continental shelf obtained from Transects 1 to 7 on 7 February, 1995.

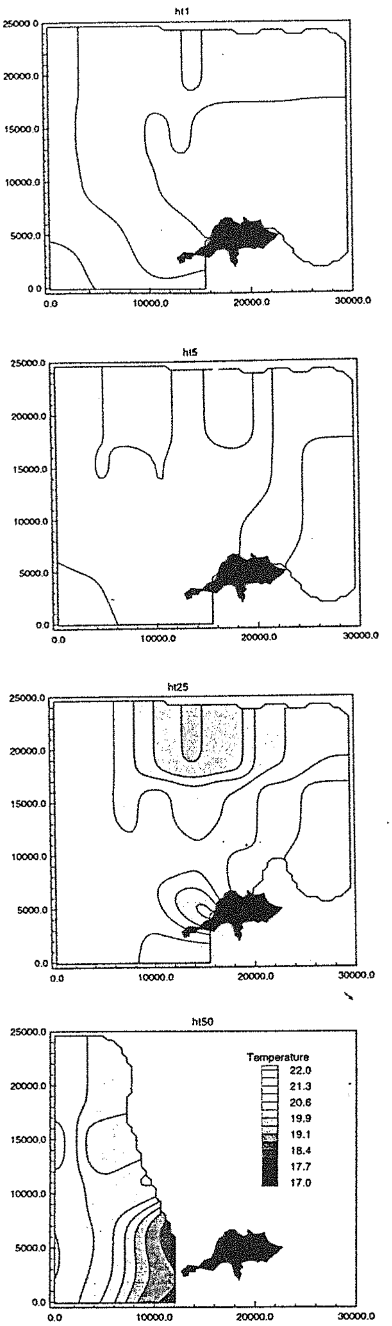

Figure 8. Horizontal distribution of temperature in the vicinity of Rottnest Island at different depths (1, 5, 25 and 50 m) corresponding to 7 February, 1995.

The temperature structure of the flow in a vertical plane along the shelf edge, B-B (Figure 2) is shown as Figure 9. It is clear that the cold water entered

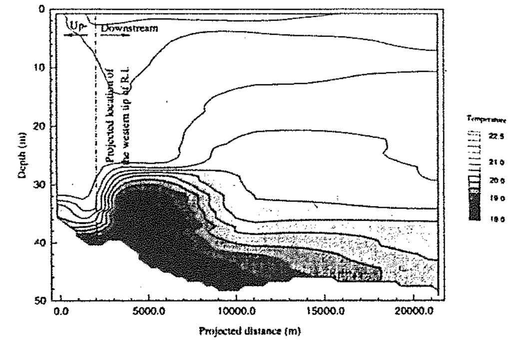

Figure 9. Temperature distribution along the continental edge (Transect BB) obtained on 7 February 1995

onto the inner shelf through a small region off the western tip of Rottnest Island and apparently, does not extend along the shelf edge.

This suggests that the main source of the cold water on the shelf, shown in HT5 and HT25, is the deep cold water pumped onto the shelf through the small region. Thus there must be a process in the vicinity of the tip, different from the rest of the region, to transport water onto the shelf. Is most likely process operating here is the secondary circulation (SC) due to the curvature of the flow (Geyer, 1993) around the western tip of Rottnest Island. In this case the Coriolis effect enhances the strength of SC, and as a result, a relatively strong offshore component of SC is produced near the surface, in the plane normal to the mean flow. In turn a strong landward component of SC is generated near the bottom, in the same plane, which moves the cold waters upslope and injects it onto the shelf region. This is then advected with the main flow northwards and is evident at the surface some distance away from the Island (cf. Figure 3).

3. CONCLUSION

Field observations obtained in the vicinity of Rottnest Island under northward flow conditions result in an *attached flow condition* and indicate that the patch of cold water located to the north of Rottnest Island is due to secondary flow generated at the tip of the western end of Rottnest Island which is advected northward.

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REFERENCES

Deleersnijder, E., Wolanski, E., and Norro, A. (1989). *Numerical simulation of the three-dimensional tidal circulation in an island's wake*, In: Carlomagno and Brebbia, C.A. (eds), Computers and experiments in fluid flow, Computational Mechanics Publications, Springer-Verlag, Berlin, 355-381.

Geyer, W.R. (1993). *Three-dimensional tidal flow around headlands*, Journal of Geophysical Research, 98: 955-966.

Heywood, K., Barton, E., and Simpson, J. (1990). *The effects of flow disturbance by an oceanic island*, Journal of Marine Research, 48: 55-73.

Pattiaratchi, C., Imberger, J., Zaker, N., and Svenson, T. (1994). *Perth Coastal Waters Study: Project P2: Physical Measurements*, Report Prepared for the Water Authority of Western Australia, Centre for Water Research Report No. WP 947 CP.

Pattiaratchi, C.B., James, A.E., and Collins, M.B. (1987). *Island wakes and headland eddies: a comparison between remotely-sensed data and laboratory experiments*, Journal of Geophys. Research, 92:783-794.

Smith, R., Huyer, A., Godfrey, S.J., and Church, J. (1991). *The Leeuwin Current off Western Australia*, Journal of Physical Oceanography, 21: 323-345.

Wolanski, E., Imberger, J., and Heron, M. (1984). *Island wakes in coastal waters*, Journal of Geophys. Research, 89:10553-10569.

Wolanski, E. (1994). *Physical oceanographic processes of the Great Barrier Reef*, CRC Marine Science Series.