CSIRO
Marine Laboratories

REPORT 161

# Water masses in East Australian Current Eddy H

M. Tomczak jr.

1983

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION
MARINE LABORATORIES
P.O. BOX 21, CRONULLA, NSW 2230, AUSTRALIA

**National Library of Australia Cataloguing-in-Publication Entry**

Tomczak, M. (Matthias), 1941– .

Water masses in East Australian Current eddy H.

Bibliography

ISBN 0 643 03473 0.

1. East Australian Current. 2. Eddies. I. Commonwealth Scientific and Industrial Research Organization (Australia). Marine Laboratories. II. Title. (Series: Report (Commonwealth Scientific and Industrial Research Organization (Australia). Marine Laboratories); 161).

551.47'578

Printed by CSIRO Melbourne

83.474-600

# Water Masses in East Australian Current Eddy H

*M. Tomczak jr.*

Division of Oceanography
CSIRO Marine Laboratories
P.O. Box 21, Cronulla, NSW 2230

CSIRO Marine Laboratories Report No. 161 (1983)

*Abstract*

An unusual anticyclonic eddy off the east Australian coast was used in May 1979 for a study of the water mass distribution in eddies. The eddy, which had only a shallow surface mixed layer and an unusually low core temperature, moved rapidly towards the continental slope during the 14-day observation period. Salinity anomalies of up to $0.2 \times 10^{-3}$ between 200 and 300m depth are interpreted as indications of entrained coastal water and were used to determine the hydrological structure in the eddy. Contours of maximum coastal water contribution do not align with isopycnals. Tentative conclusions include two possible schemes for the entrainment into, and distribution of water masses in, an eddy. The first scheme assumes a low rate of change in eddy hydrology over a rotational period, the second scheme is based on a high rate of change.

## Introduction

Eddies formed by western boundary currents are among the most energetic features of the oceanic circulation. Two types of eddies can be distinguished: cyclonic, cold core eddies and anticyclonic, warm-core eddies (cyclonic eddies rotate clockwise in the southern hemisphere, anticlockwise in the northern hemisphere). In the Gulf Stream area, cold core eddies outnumber warm core eddies (Lai and Richardson, 1977); in the Kuroshio area, warm core eddies seem to be slightly in the majority (Kawai, 1972; Kitano, 1975), and in the East Australian Current, most eddies are of the warm core type (Nilsson and Cresswell, 1981).

Studying eddy generation and decay is essential for an understanding of the role eddies play in the transport of heat and momentum. Whereas generation is controlled by the dynamics of the boundary current and therefore is similar for both types of eddies, eddy decay occurs after the eddy becomes dynamically independent. Processes likely to be important in eddy decay are lateral friction (with no associated transport of water mass properties), diffusion (causing transport of properties into and out of the eddy) and entrainment (resulting in unidirectional transport of properties into the eddy only). Of these, at least the last two depend on the hydrographic structure of the eddy. It can therefore be expected that the two classes of eddies *display different decay behaviour.*

This study deals with the decay phase of a warm core eddy off the East Australian coast. Its aim is to contribute to the stock of observational data necessary for testing existing theories on eddy decay. The number of theoretical papers on eddy decay is small, and very few address themselves to warm core eddies. Andrews and Scully-Power (1976) suggested that entrainment of surface water may be important during eddy generation, and Scott (1978) interpreted salinity anomalies observed at mid-depth as indications of sub-surface entrainment of coastal water.

Theoretical studies of Csanady (1979), Flierl (1979) and Matsuura (1980), on the other hand, all indicated that during eddy decay interfacial friction may be the dominant process.

A change from entrainment to frictional control should be detectable in the distribution and changes in water mass properties. Apparently, the reputation of mature eddies for being deeply mixed in the centre due to winter cooling (Nilsson and Cresswell, 1981) seems to have deterred oceanographers from water mass analyses in eddies. This study describes an attempt to collect data suitable for detailed water mass analysis in an East Australian Current eddy.

## Data and Methods

The data were collected during cruise SP7/79 of R.V. "Sprightly". During 1977/1978 the generation and movement of East Australian Currwent eddies had been surveyed extensively (Boland and Church, 1981), (Nilsson and Cresswell, 1981); but after December 1978, information on the location of existing eddies became scarce. When R.V. "Sprightly" left Sydney in June 1979 for the cruise, the first objective, therefore, was to find an eddy for the study. Available information from cruises in January and May indicated no eddy-like features north and east of Sydney (Hamon, 1979), so the search was directed towards the south-east. A rather unusual eddy was found off Jervis Bay (35°S) and surveyed with XBTs, and another XBT survey was done 10 days later, before the end of the cruise. Between the two surveys, 6 hydrographic sections were taken across the frontal zone of the eddy, covering the depth range 0-700m with 5 to 11 Nansen stations per section.

Originally it was intended to mark the frontal zone, i.e. the region of the strongest currents, by a buoy equipped with a VHF transmitter and to perform all sections in the vicinity of the buoy. This procedure, it was hoped, would result in a repeated section within roughly the same part of the eddy while it rotated around the eddy centre. Unfortunately, radio contact with the buoy was lost during heavy weather after a day, and the buoy could not be located later in the cruise. The sections were therefore positioned according to the best available estimate of the position of the eddy centre and of the strongest currents, based on hydrographic data from the previous section and on ships's drift.

Temperature, salinity, nitrate and silicate were determined from Niskin station samples. In order to collect sufficient information on the stratification in the upper 700m and at the same time resolve possible intrusions of water at a smaller scale, bottle spacing varied between stations. Since earlier observations (Scott, 1978) suggested entrainment at the depth of the main thermocline, a spacing of 25m was chosen for the Niskin bottles in the

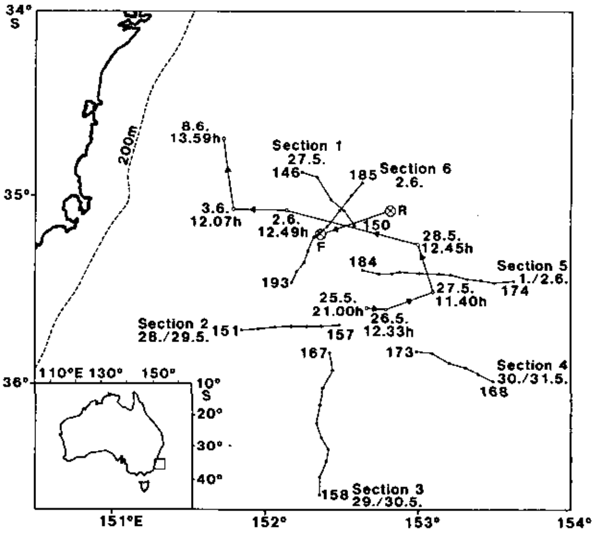

Figure 1. Positions of Niskin stations. Release position of the VHF buoy is indicated by R (released at 1900hr, 26 May 79), and the first and only fix by F (obtained at 1530hr, 27 May 79). Positions of the satellite-tracked buoy are shown with corresponding dates. All times are Australian Eastern Standard time EST = GMT + 9h.

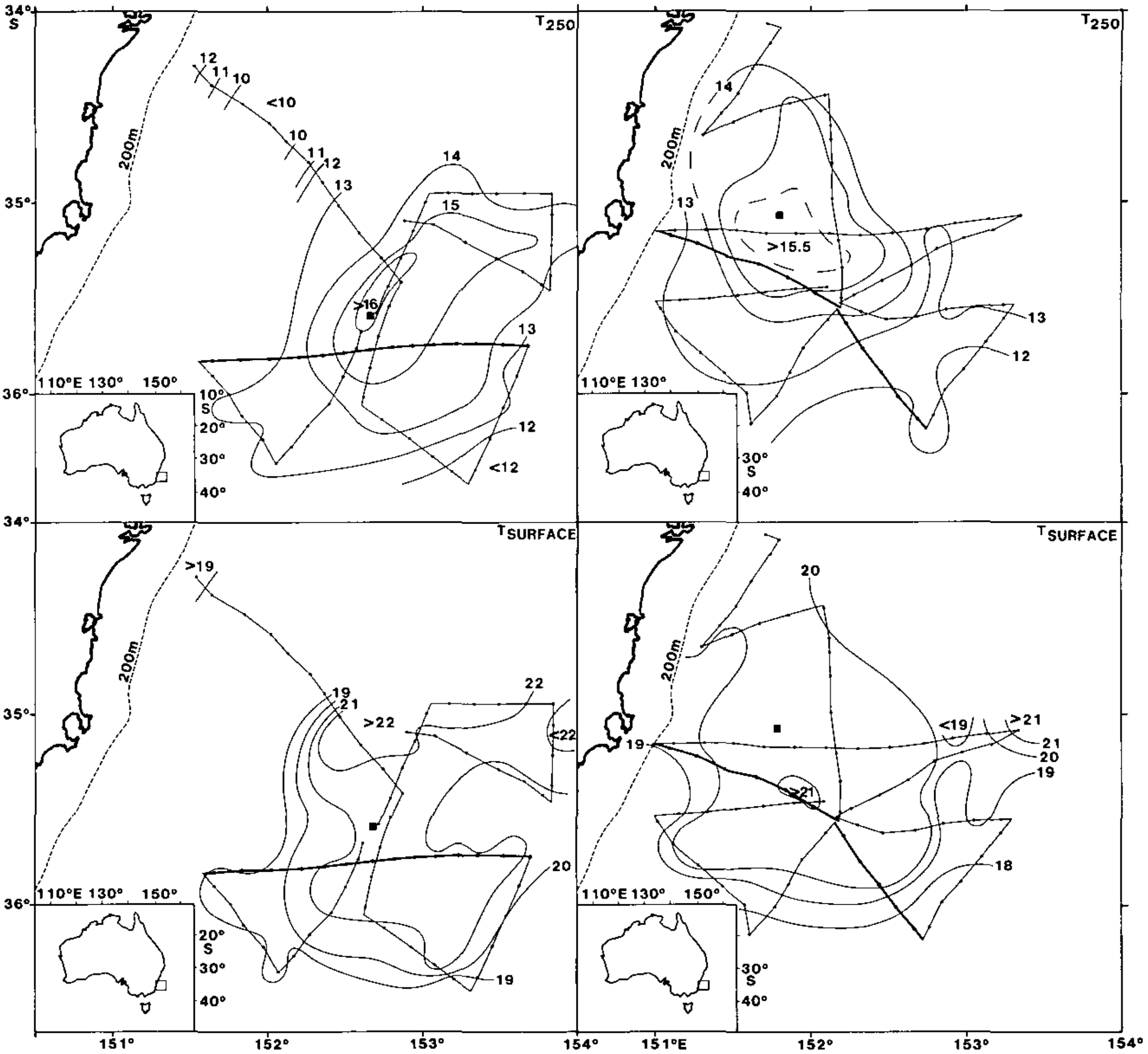

Figure 2. Temperature at 250m ($T_{250}$) and at the surface at the beginning (left) and at the end (right) of the cruise. Dots along the cruise track are XBT positions. Squares indicate the positions of the satellite buoy at the time of release (2100hr, 25 May) and at the beginning for the second survey (1107hr, 3 June). A heavy line along the cruise track shows the positions of the sections of Figure 3.

---

vicinity of the 15°C isotherm, the depth of which was established from an XBT before the cast during the first few stations and could be estimated reasonably well thereafter. In addition, Niskin bottles were used at fixed depths of 0, 150, 300, 500 and 700m.

**Description of Eddy H**

Figure 1 shows the area of the cruise, the positions of the sections as they resulted from the successive estimates of the eddy centre, the two known positions of the VHF buoy and the track of a buoy released at the beginning of the cruise in the eddy centre. This buoy was of the drogued satellite-tracked type (Cresswell *et al.*, 1979), and information on its position was not obtainable until several weeks later. Its movement confirms the estimates of eddy motion made during the cruise.

Figure 2 shows the distribution of temperature at the surface and at 250m depth ($T_{250}$) for the beginning and for the end of the cruise. $T_{240}$ was first proposed as a means to delineate East Australian Current eddies by Hamon (1968), and the method (slightly adjusted from $T_{240}$ to $T_{250}$) has remained satisfactory after the replacement of the mechanical BT by the deeper-reaching XBT (Andrews and Scully-Power, 1976). The observed $T_{250}$ distribution indicates a net movement of the eddy of about 80 km towards 300°. It is also seen that the eddy was not quite circular in shape and seems to have undergone some rotation of its main axis over the period. The Figure also confirms that the movement of the satellite-tracked buoy which was drogued with a parachute at 20m depth can be regarded as representative for the eddy centre.

The eddy, which has been named eddy H in CSIRO's record of the East Australian Current System, can be characterized by the following particular features:

1. The maximum observed $T_{250}$ values were just above 16°C, compared to 18°C or more in strong eddies (Nilsson and Cresswell, 1981).

2. The translational speed of the eddy as an entity was large. The buoy released at the centre had speeds of 0.22, 0.36, 0.33, 0.19, 0.38 and 0.46 m $s^{-1}$ between successive satellite fixes. Because of the proximity of the buoy to the eddy centre, the rotational component of the buoy motion was probably small and the observed speeds can be regarded as upper estimates for the translational speed. A lower estimate, derived from the $T_{250}$ distributions (80 km over 10 days), is 0.10 m $s^{-1}$. This compares with an estimate given by Boland and Church (1981) for all 1978 eddies, of 0.04-0.05 m $s^{-1}$.

3. The maximum rotational currents were smaller than those reported from other eddies. The only fix of the VHF buoy obtained the day after its release gave a minimum speed of 0.60 m $s^{-1}$ which is in good agreement with speeds of 0.50-1.50 m $s^{-1}$ deduced from ship's drift.

Unfortunately, it is impossible to ascertain the life history of this particular eddy in any greater detail. The eddy showed no subsurface mixed layer, while its surface mixed layer was quite warm and less than 100m deep in the centre, suggesting that it was formed during the summer period and, therefore, less than 6 months old. It appears that the eddy had contact with the continental slope at the end of the observation period (Fig. 3) and ceased to exist soon after the cruise. The satellite-tracked buoy ended its northward drift in mid-June at 34°S and rapidly moved eastward into the central Tasman Sea where it arrived a month later at 160°E. No trace of the eddy was found during a cruise in July when R.V. "Sprightly" attempted to locate an eddy suitable for a series of biological studies. The fact that the translational speed of the present eddy increased towards the end of the cruise, nearly approaching its maximum rotational speed, also suggests that the eddy may have been close to coalescing with the East Australian Current or the southern end of another eddy.

## Water Masses in Eddy H

In the upper kilometre of the water column, Tasman Sea water displays a nearly linear temperature-salinity (TS) relationship. Pearce (1981) determined mean TS-curves for the western Tasman Sea which he divided into 5° latitude bands. His results show a slight change towards higher salinities as one moves from north to south, but Tomczak (1981) argued that this is the effect of occasional intrusions of coastal

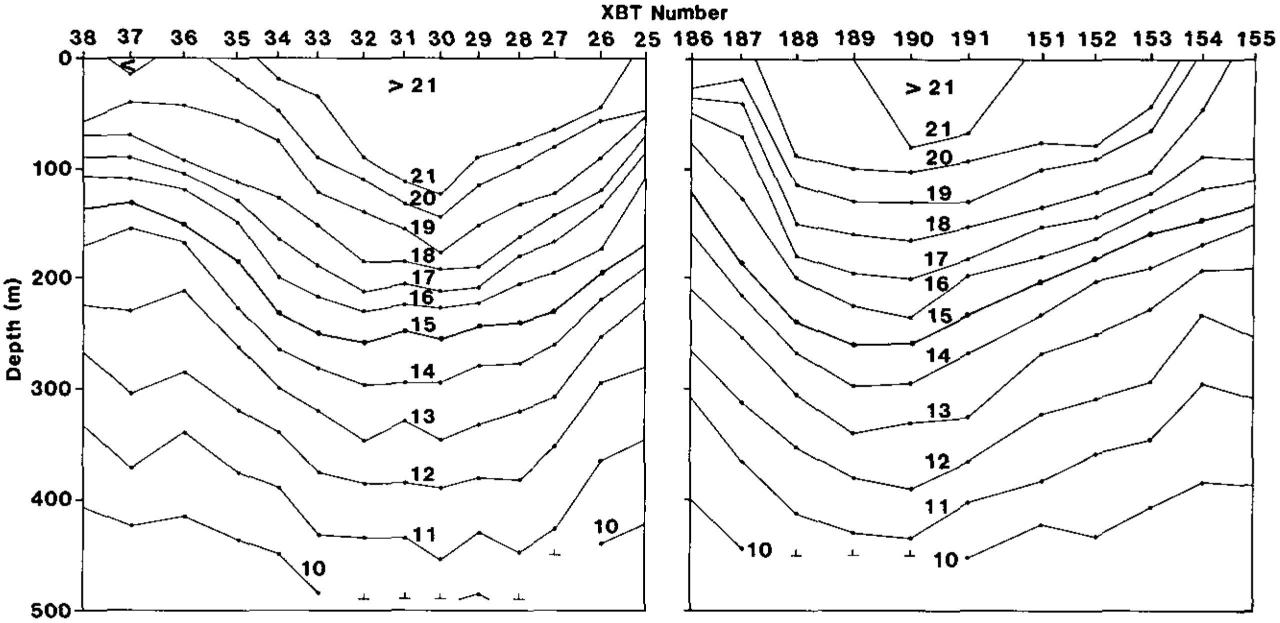

Figure 3. Vertical distribution of temperature (from XBT records) at the beginning (left) and at the end (right) of the cruise. XBT positions are shown by tick marks on top. The coast is on the left, and the length of the sections is approximately 180 km. For location of sections see Figure 2.

water formed in Bass Strait which sink down the continental shelf and enter the Tasman Sea at intermediate depths. Stations not affected by Bass Strait Water are believed to show the same TS-characteristics irrespective of position in the western Tasman Sea. It is thus doubtful whether water from the northern Tasman Sea, when trapped in and transported south by an eddy, can be distinguished from water outside the eddy on the basis of temperature and salinity.

A feature observed with the East Australian Current, and used by Boland and Church (1981) as a definition of the Current, is a band of warm, low-salinity water along the axis of the current at the surface. This water which is advected from the surface layers of the Coral Sea can be found in recently formed eddies near the surface. The surface layer is excluded from the present analysis which applies TS-diagram techniques, and as a consequence, surface water from the Coral Sea is not considered here.

Scott (1981) analysed the distribution of temperature, salinity and nutrients in an East Australian Current eddy and suggested the presence of Bass Strait Water in the vicinity of the thermocline, believed to be entrained from the shelf edge. Northward propagation on the shelf and along the slope is a very likely path for Bass Strait Water (Godfrey *et al.*, 1980), and its high salinity makes it a good indicator for admixtures of coastal water.

Figure 4 is a TS-diagram from all observations of the cruise. In general, points tend to align along a linear TS-relationship better than the mean curves of Pearce (1981), indicating very limited amounts of Bass Strait Water, if any, in the eddy. The scatter seen in the TS-diagram is only marginally above a level which may be expected in near-coastal areas, but a look at TS-diagrams from individual sections reveals some organized structures. The clearest example was found at section 3 (Fig. 5): a weak salinity maximum can be traced over a

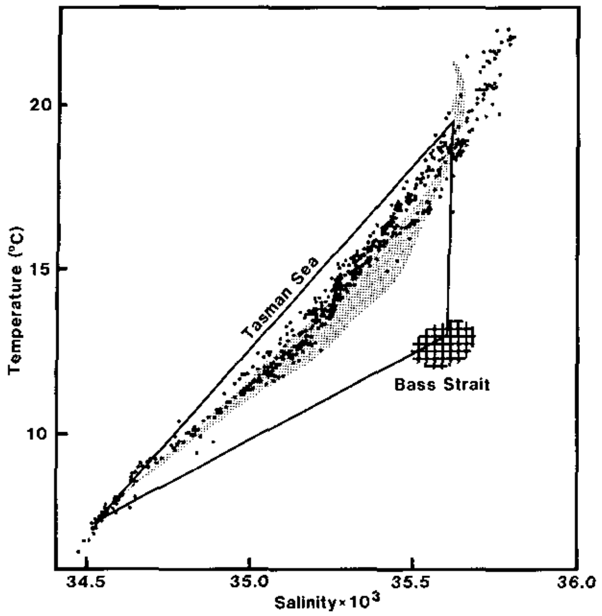

Figure 4. Composite TS-diagram of all SP7/79 stations. The shaded area is the envelope of mean TS-curves for the western Tasman Sea as computed by Pearce (1981); the upper limit corresponds to 25-30°S, the lower limit corresponds to 35-40°S. The cross-hatched area shows typical TS-values for Bass Strait Water (Godfrey *et al.*, 1980). The triangle is used for water mass analysis (see text for details).

distance of 10 nautical miles at Stations 162-164, varying in depth from less than 200m to about 250m towards the eddy centre.

The signal can be enhanced by replacing temperature and salinity with temperature and salinity differences against a linear TS-relationship as a base. This is formally achieved by defining three water types as given in Table 1 and determining the percentage of Water Type 3 in each sample. Figure 4 shows the mixing triangle defined by the water types at its corners. It will be noticed that Water Type 3 coincides with Bass Strait Water and that deviations from the base line larger than those created by the curvature of the Tasman Sea TS-relationship can be interpreted as evidence for the presence of Bass Strait Water in the eddy. This is in accordance with the general hydrography; but the data necessary to prove the connection of water in the eddy with water on the shelf or slope are lacking, and the term "Bass Strait Water" is used here for Water Type 3 without further proof of its identity.

Figure 6 shows the result of the analysis expressed as percentage content of Bass Strait Water (BSW). An organized pattern emerges in all sections, so the scatter in the TS-diagram is not random. A most surprising result is that the isopleths of BSW content do not align with the density field. The Figure does not contain a correction for the intermediate maximum produced from the systematic difference between the straight line connecting Water Types 1 and 2 and the slightly curved mean TS-curve for the Tasman Sea. However, this maximum is linked with a constant

**Table 1. Definition of mixing triangle**

| Water type | Temperature (°C) | Salinity (x $10^3$) | Nitrate (μg at/ℓ) |
|---|---|---|---|
| 1 (surface) | 19.5 | 35.62 | 3 |
| 2 ( ~700m) | 7.5 | 34.55 | 28 |
| 3 (Bass Strait) | 12.5 | 35.60 | 0 |

density surface irrespective of position. The fact that this has not been observed points toward the presence of different water masses in the eddy.

In order to relate the observed distribution of BSW to the dimensions of the eddy, the 26.2 $\sigma_t$-surface is included in Figure 6. Usually, the extent of the eddy is estimated from the slope and position of the main thermocline. The 26.2 $\sigma_t$-surface corresponds to the 15°C isothermal surface (which is found in the thermocline) to within about ± 25m and may be a better indicator in areas of significant deviations from the mean TS-curve. (It is also the surface of the intermediate maximum produced

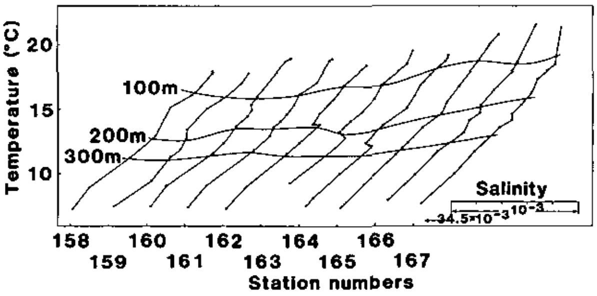

Figure 5. TS-diagrams from Section 3. The tick marks at the bottom indicate 34.5 x $10^{-3}$ for the corresponding station. The eddy centre is to the right; the depth range covered is 0-700m, nominally.

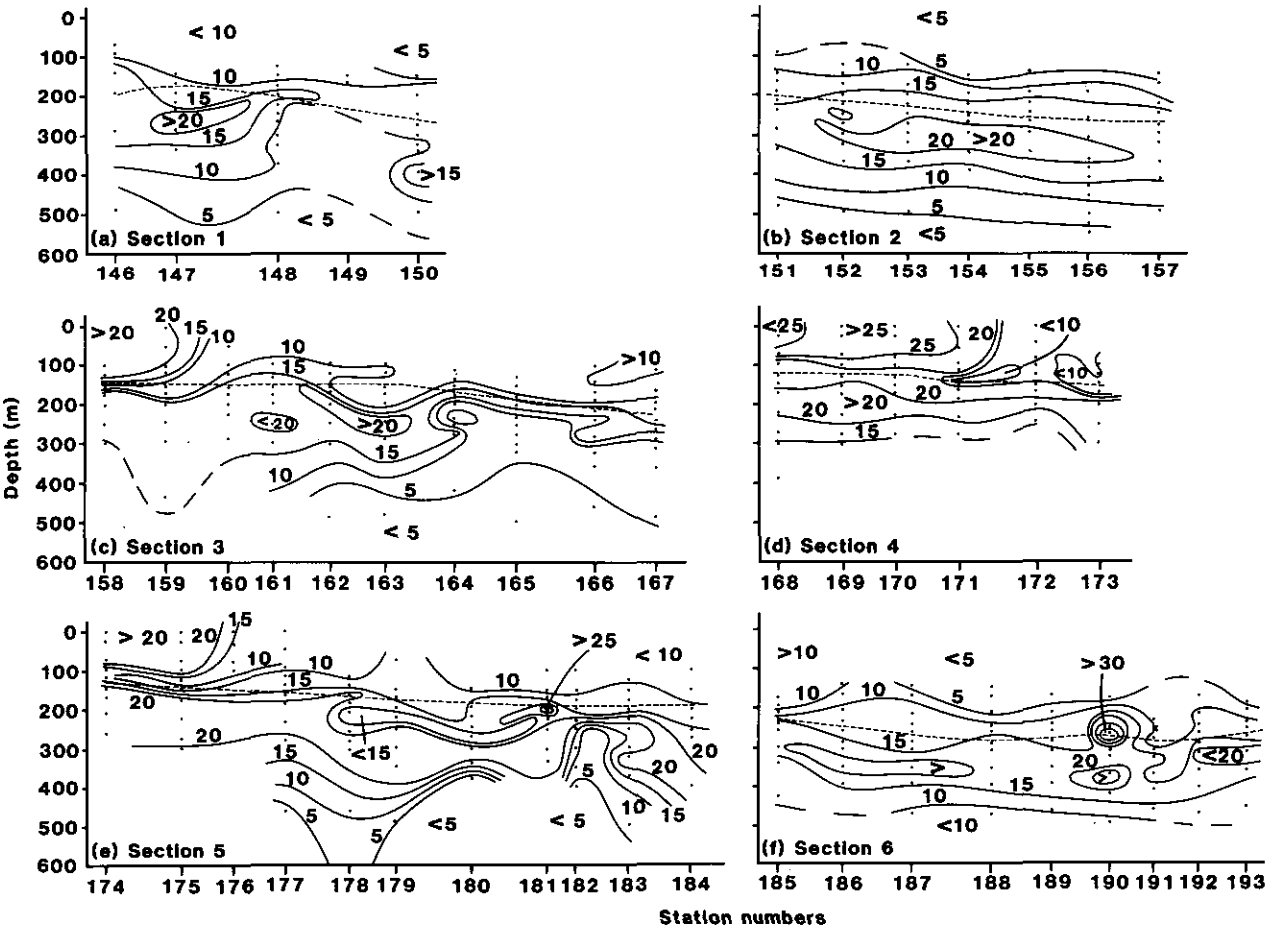

Figure 6. Bass Strait Water content (%) in the eddy. Section positions are shown in Figure 1. The dotted line is the $\sigma_t$ = 26.2 isopycnal. The eddy centre is to the right in all sections. The error in percentage content is a function of errors in temperature and salinity determination and estimated at < 3 percentage units.

by the curvature of the Tasman Sea TS-curve). Two situations can be seen. In Section 4, the 26.2 $\sigma_t$-surface coincides with a BSW content minimum; in Section 2 it is linked with a BSW content maximum. Section 3 demonstrates how both situations fit together. On the eddy perimeter, the pycnocline is an area of minimum BSW content; further inward the BSW content of the near-surface layers decreases and the lower maximum moves upward into the pycnocline which it then joins in its downward trend towards the eddy centre. Section 5 shows a similar picture, but it is somewhat confused by an intermediate minimum at stations 178-180. Section 1 can possibly be explained as resembling the central part (Stations 161-166, say) of Section 3. Section 6 does not seem to fit into any scheme, but its position relative to the eddy is also badly defined. (There is no clear upward or downward trend of the 26.2 $\sigma_t$-surface.)

## Discussion

The results of this investigation demonstrate that there is sufficient structure in an eddy to make a study of mixing and entrainment during eddy decay possible. The present study is inadequate, mainly because of the lack of synoptic information on the eddy. Without such information it is impossible to link observed hydrological structure to the circulation or to estimate life times for observed features.

The observations suggest some possible mechanisms if certain assumptions are made. That water with a high content of BSW is drawn into the eddy from the shelf or slope, regardless of the origin of BSW itself, can be accepted with some confidence; there is no known source of high salinity water at the 26.2 $\sigma_t$-surface in the open Tasman Sea. If it is assumed that the rate of change in the hydrological field is small over the rotational period of the eddy (approximately 5-7 days), the water mass structure should be similar around the eddy. The resulting scheme is sketched in Figure 7a. BSW was drawn in from the west some rotational periods earlier and is carried around the eddy perimeter. It may have entered the eddy circulation in one entity, extending from the surface to the depth of the shelf (TS-analysis excludes the surface layer, so the upper limit of the BSW intrusion is not known.) The observed BSW content minimum outside the eddy at the 26.2 $\sigma_t$-surface would then indicate outward motion, while the inward extent of the BSW content maximum along the same surface could be interpreted as inward entrainment.

There is some supportive evidence for a low rate of change in the hydrological structure from the nutrient data. Plots of temperature *v.* nitrate concentration and temperature *v.* silicate concentration show distributions very similar to the TS-distribution of Figure 4: a nearly linear Tasman Sea relationship and deviations (towards lower nutrient value) of varying degree at individual observations. Replacing salinity by either nitrate or silicate concentration in the water mass analysis produces coherent contours which tend to align in a way similar to those computed from temperature and salinity. However, quantitative agreement between results is poor, indicating that nutrients are not conserved over time scales typical for mixing of temperature and salinity. It is generally believed that eddies are poor environments for biological activity during the period of winter cooling when convective overturn in the eddy centre extends well beyond the euphotic zone. Once convection stops and summer heating produces stable conditions, nutrients are rapidly taken up and recycled. Tranter *et al.* (1980) compared nutrient changes over a 10-month period with changes in temperature and salinity in the centre of a

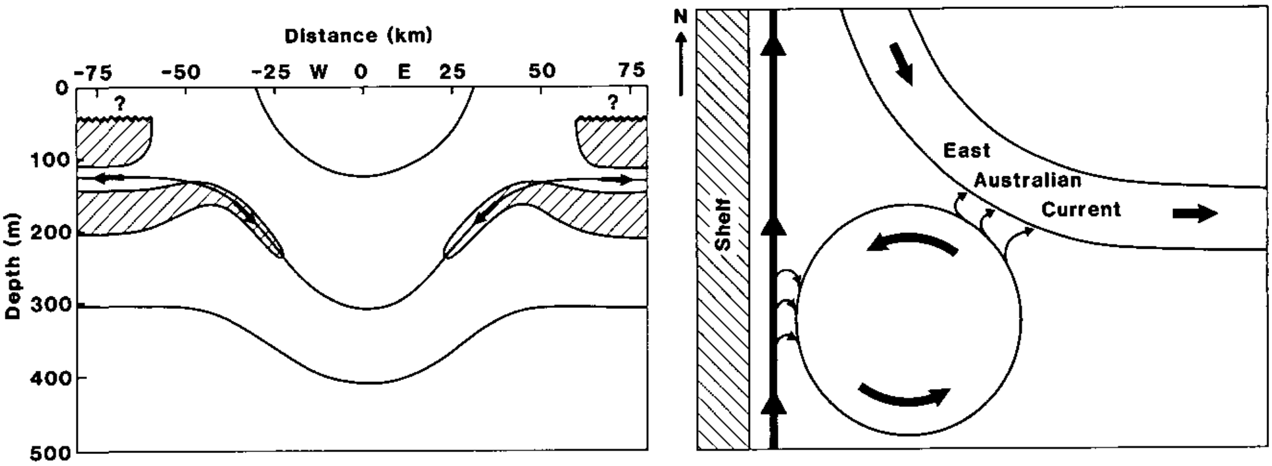

Figure 7. Two possible interpretations of the observations.

large eddy; they found virtually no change in T and S but drastic variations in nutrients and concluded that exchange across the eddy boundaries was minimal. The present observations, while suggesting some entrainment from the shelf or slope, do not contradict their findings in principle.

Nevertheless, several notes of caution should be added to the scheme of low rates of exchange between the eddy and its surroundings. There is considerable current shear in the upper few hundred metres. Geostrophpic currents decreased to about half their surface strength over the top 300m. Similar values were found by Hamnon (1965) in other eddies. The BSW content maximum observed above the 26.2 $\sigma_t$-surface outside the eddy, therefore rotates faster than the maximum observed below; it may be the expression of an earlier or later (but in either case independent) intrusion. While this would not invalidate the idea of slow hydrological change, it would eliminate the outward motion from Figure 7a. The rate of change of the eddy shape is certainly not small over a rotational period; Figure 3 shows that the eddy was deformed during the cruise by contact with the continental slope. This may have resulted in a new entrainment event at intermediate depth.

Finally, it may be recalled that the water mass distribution on Section 6 was difficult to explain. This section is in the north-eastern corner of the eddy where contact with the East Australian Current is most likely. Proximity of the Current makes it an area of large horizontal shear, increasing the intensity of mixing and exchange of water mass properties. Surface advection of Coral Sea surface water carried south with the Current has been observed in this area, accompanied by surface fronts of irregular size and extent (Brandt *et al.*, 1981). It is possible that the small-scale features of the water mass distribution in Section 6 - which were not observed at the other sections - are sub-surface expressions of the high level of variability in the area. A conceptual scheme of an eddy circulation with strong interaction with the eddy environment is given in Figure 7b. It represents the opposite extreme of a large rate of change in the hydrology (at least along the perimeter): water is drawn in from the northward flowing coastal or slope current, carried around the eddy over about 5/8 of a rotation and shed into the East

Australian Current. Any entrainment towards the eddy centre would have to be initiated over this time span (approximately 4 days).

The East Australian Current and its eddies form a highly time-variable system, and it is unreasonable to expect the two processes outlined in Figure 7 to dominate a particular eddy through its entire lifespan. They probably alternate and interact with each other, depending on the position of the eddy relative to the continental slope and to the East Australian Current, and on the extent of the northward flowing slope current. (Tomczak (1983) provides evidence for a continuous subsurface flow of Bass Strait Water along the slope.)

It is possible to discriminate between the two processes in observations if the experiment is properly designed. A number of satellite-tracked buoys with instant-position-readout facility is the minimum necessary for keeping track of the position and shape of the eddy. Infra-red satellite imagery can help to estimate interaction with the East Australian Current. Continuous vertical profiles of temperature and salinity are necessary for better resolution of hydrological structure.

## References

Andrews, J.C., and Scully-Power, P. (1976). The structure of an East Australian Current anticyclonic eddy. *Journal of Physical Oceanography* 6, 756-765.

Boland, F.M., and Church, J.A. (1981). The East Australian Current 1978. *Deep-Sea Research* 28A, 937-957.

Brandt, S.B., Parker, R.R., and Vaudrey, D.J. (1981). Physical and biological description of warm-core eddy J during September-October, 1979. *CSIRO Division of Fisheries and Oceanography Report* 126.

Cresswell, G.R. Richardson, G,.T., Wood, J.E., and Watts, R. (1979). The CSIRO satellite-tracked "torpedo" buoy. *CSIRO Division of Fisheries and Oceanography Report* 82.

Csanady, G.T. (1979). The birth and death of a warm core ring. *Journal of Geophysical Research* 84, 777-780.

Flierl, G.R. (1979). A simple model for the structure of warm and cold core rings. *Journal of Geophysical Research* 84, 781-785.

Godfrey, J.S., Jones, I.S.F., Maxwell, J.G.H., and Scott, B.D. (1980). On the winter cascade from Bass Strait into the Tasman Sea. *Australian Journal of Marine and Freshwater Research* 31, 275-286.

Hamon, B.V. (1965). The East Australian Current, 1960-1964. *Deep-Sea Research* 12, 899-921.

Hamon, B.V. (1968). Temperature structure in the upper 250 metres in the East Australian Current area. *Australian Journal of Marine and Freshwater Research* 19, 91-99.

Hamon, B.V. (1979). Direct measurements of ocean currents over the continental slope off Sydney. *Australian Journal of Marine and Freshwater Research* 30, 833-836.

Kawai, H. (1972). Hydrography of the Kuroshio extension. In 'Kuroshio, its Physical Aspects'. (Eds. H. Stommel and K. Yoshida.) 235-352. (University of Tokyo Press : Tokyo).

Kitano, K. (1975). Some properties of the warm eddies generated in the confluence zone of the Kuroshio and Oyashio currents. *Journal of Physical Oceanography* 5, 245-252.

Lai, D.Y., and Richardson, P.L. (1977). Distribution and movement of Gulf Stream rings. *Journal of Physical Oceanography* 7, 670-683.

Matsuura, T. (1980). On a decay process of isolated, intense vortices in a two-layer ocean. *Journal of the Oceanographic Society of Japan* 36, 39-45.

Nilsson, C.S., and Cresswell, G.R. (1981). The formation and evolution of East Australian Current warm-core eddies. *Progress in Oceanography* 9, 133-183.

Pearce, A.F. (1981). Temperature-salinity relationships in the Tasman Sea. *CSIRO Division of Fisheries and Oceanography Report* 135.

Scott, B.D. (1978). Hydrological features of a warm core eddy and their biological implications. *CSIRO Division of Fisheries and Oceanography Report* 100.

Scott, B.D. (1981). Hydrological structure and phytoplankton distribution in the region of a warm core eddy in the Tasman Sea. *Australian Journal of Marine and Freshwater Research* 32, 479-492.

Tomczak, M. Jr. (1981). Bass Strait Water intrusions in the Tasman Sea and mean temperature-salinity curves. *Australian Journal of Marine and Freshwater Research* 32, 699-708.

Tomczak, M. Jr. The Bass Strait Water Cascade during winter 1981. *Continental Shelf Research* (submitted).

Tranter, D.J., Parker, R.R., and Vaudrey, D.J. (1980). *In vivo* chlorophyll *a* fluorescence in the vicinity of warm-core eddies off the coast of New South Wales 4. December 1978. *CSIRO Division of Fisheries and Oceanography Report* 113.

# CSIRO
## Marine Laboratories

comprise

Division of Fisheries Research
Division of Oceanography
Central Services Group

**NEW SOUTH WALES LABORATORY**
202 Nicholson Parade, Cronulla, NSW
P.O. Box 21, Cronulla, NSW 2230

**TASMANIAN LABORATORY**
Reserve Bank Building, Hobart, Tas
G.P.O. Box 1538, Hobart, Tas 7001

**QUEENSLAND LABORATORY**
233 Middle Street, Cleveland, Qld
P.O. Box 120, Cleveland, Qld 4163

**WESTERN AUSTRALIAN LABORATORY**
Leach Street, Marmion, WA
P.O. Box 20, North Beach, WA 6020

ISSN 0725-4598