Deep-Sea Research, Vol. 33, Nos 11/12, pp. 1563–1576, 1986.
Printed in Great Britain.

0198-0149/86 $3.00 + 0.00
Pergamon Journals Ltd.

Abyssal currents during the formation and passage of a warm-core ring in the East Australian Current

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(*Received* 13 *November* 1985; *in revised form* 2 *April* 1986; *accepted* 14 *April* 1986)

Abstract—Measurements of currents and temperatures at abyssal depths in the Tasman Sea are compared with near-surface observations of the East Australian Current (EAC) System to ascertain the extent to which the deep and near-surface flows are related. The deep measurements come from three instruments which were moored at different locations on the Tasman Abyssal Plain from early December 1983 to late March 1984. They included an Anderaa current meter, recording velocity and temperature, a second temperature sensor, and an instrument which recorded fluctuations in temperature and the vertical component of the ambient electric field (from which zonal velocity is inferred).

During this period a meander of the East Australian Current moved southwards and pinched off to form a warm-core ring. Both the current meter and the vertical electric field instrument recorded current surges to the east when the surface front first arrived at their positions. The maximum speed recorded by the current meter was 35 cm s^{-1} (when the flow was southward). Strong abyssal currents (over 10 cm s^{-1}) were usually in the same approximate direction as the surface current at the EAC front and associated with the movement of the front before the ring pinched off. The abyssal temperature fluctuations increased in magnitude with the increase in water velocity as the front moved past, but the temperature records do not indicate that any thermal effect of the eddy extended to the sea floor.

INTRODUCTION

There has been a great deal of research into western boundary currents and their warm-core rings (Robinson, 1983), but relatively little is known about the depth of these features and their interaction with sea-floor topography. Work in the Gulf Stream (Kelley *et al.*, 1982; Weatherly, 1984) suggests a reasonably high correlation between surface and abyssal flows. More recently, Kelley and Weatherly (1985) and Weatherly and Kelley (1985) found that bottom currents were strongly influenced by Gulf Stream meanders or warm-core rings, and that bottom current directions were generally parallel to the fronts associated with these features. On the other hand, Joyce (1984) found no detectable current 2000 m below a warm-core ring, but that an associated cyclonic barotropic ringlet had currents of 10–15 cm s^{-1}. Further work on ringlets associated with warm-core rings (Kenelly *et al.*, 1985) found currents of 20–80 cm s^{-1}.

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Relatively little work on this problem has been carried out in the region of the East Australian Current (EAC). BOLAND and HAMON (1970) and HAMON (1970) obtained absolute velocity profiles beneath the EAC with a combination of hydrographic casts and Swallow floats. Currents at 3000 m depth were on the order of 5–10 cm s^{-1}. The measurements, however, were limited in number and of short duration, and the correlation found between near-surface and deep flows was somewhat uncertain.

Using archived hydrographic data, MULHEARN (1983) showed a strong correlation between near-surface and deep parameters down to 4500 m, and that the velocity difference between 4000 and 2000 m was about 6 cm s^{-1}. The average direction of the deep current relative to the surface current, however, could not be determined from these data alone.

As part of the Tasman Project of Seafloor Magnetotelluric Exploration, TPSME (FERGUSON *et al.*, 1985; FILLOUX *et al.*, 1985; LILLEY *et al.*, 1986a), direct measurements of both abyssal and barotropic currents in the EAC were obtained. In early December 1983 a series of instruments of the Scripps Institution of Oceanography (SIO) was placed on a sea-floor traverse across the Tasman Sea, to be retrieved at the end of March 1984. The majority of the instruments recorded fluctuations in the ambient electric and magnetic fields, and were intended primarily to examine the electrical conductivity structure of the solid earth (FILLOUX, 1982). In addition to the SIO instruments, an Aanderaa recording

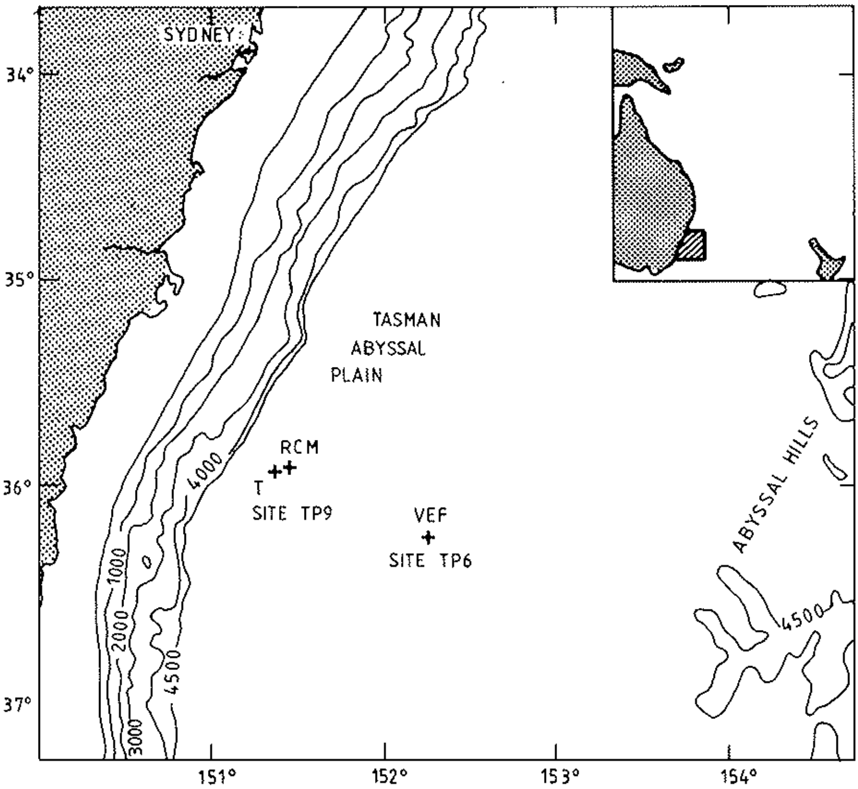

Fig. 1. Map showing positions of recording current meter (RCM), trial instrument (T) and vertical electric field (VEF) instrument. Insert map shows experiment area in relation to Australia and New Zealand.

current meter (RCM) was placed on the abyssal plain approximately 30 km from the foot of the Australian continental slope (Fig. 1).

On the deployment and recovery cruises for the TPSME experiment hydrographic casts were made between Australia and the Lord Howe Rise (MULHEARN, 1985), and during the observation period the surface and near-surface currents and temperatures of the Tasman Sea near the Australian coast were monitored. Fortunately a strong event occurred in the EAC when the Tasman Front moved south and formed a warm-core ring.

SOURCES OF SURFACE DATA AND SOME NOTES ON ABYSSAL INSTRUMENTATION

Surface and near-surface data

The position of the EAC was determined from a synthesis of surface observations. Because of its familiar nature, the information can be summarized as follows: (1) records of expendable bathythermographs (XBTs), which were deployed regularly from the Royal Australian Navy (RAN) oceanographic research ships HMAS *Cook* (five cruises) and HMAS *Kimbla* (one cruise), from other RAN ships on frequent exercises and from Royal Australian Air Force Orion aircraft (6 surverys with AXBT's); (2) eleven satellite images, in the form of standard black and white prints supplied by the National Oceanic and Atmospheric Administration (NOAA) of the United States; (3) data supplied by the Division of Oceanography of the Commonwealth Scientific and Industrial Research Organization (CSIRO) obtained during the Australian Coastal Experiment 'ACE' (CLARKE and THOMPSON, 1984), which also took place during the austral summer of 1983–1984. Data consist of XBTs and ship's sets from four cruises by R.V. *Sprightly*; one infrared image of 29 March 1984 processed from tapes supplied by the New Zealand Bureau of Meteorology; the paths of three satellite-tracked buoys; and currents from moorings over the Australian continental slope down to 2000 m depth. A CTD section taken in January 1984 from R.V. *Sprightly* was also helpful.

The abyssal instrumentation

Information on the instruments moored on the sea floor is summarized in Table 1 and their positions are shown in Fig. 1. They consist of: (1) an Aanderaa current meter type

Table 1. *Summary of the abyssal instrumentation contributing the data discussed in this paper*

Instrument	Parameters recorded	Position		Site code	Water depth (m)	Instrument height above bottom (m)
		Lat. (S)	Long. (E)			
Aanderaa RCM-5	Velocity, temperature (absolute)	35°54.4′	151°23′	TP9	4850	100
Sensor on trial instrument	Temperature (relative)	35°55′	151°22′	TP9	4850	0.75
VEF	(a) Vert. electric field, (b) Temperature (relative)	36°14′	152°15′	TP6	4836	(a) Span 2 to 162 (b) 1 approx.

Site positions were determined by ship's satellite navigation system. Position accuracy estimated to be 0.5 km or better.

RCM-5 moored at site TP9, 100 m above the sea floor, which recorded every 15 min but whose temperature sensor had not been modified for deep work and so only had a resolution of 0.024°C per least count and an accuracy of ±0.05°C; (2) a vertical electric field instrument (VEF) at site TP6 which measured the fluctuating electric field between two electrodes 160 m apart on a cable. The lower electrode was within a metre or so of the sea floor, and the upper electrode was held vertically above it by a float. The principles of the instrument are described by FILLOUX (1980), and the present data are discussed by BINDOFF *et al.* (1986), especially with regard to their evidence of inertial and internal waves, turbulence, tides, and mesoscale motions. Because the present paper centres on the time scale of mesoscale activity, the VEF data are presented below with an empirically estimated drift removed, and daily-mean values taken. Values of horizontal fluid velocity v_y in a magnetic east to west direction are calculated (as explained in BINDOFF *et al.*, 1986) on the basis of

$$v_y = E_z/B_x,$$

where E_z is the vertical component of electric field (positive upwards) and B_x is the horizontal north component of the earth's static magnetic field. Such a simple interpretation is valid only for large-scale fluid motions of wide lateral extent, and the zero level of the velocity values depends on the validity of the drift estimate.

The VEF velocities are averages between the two electrodes, the lower of which is effectively at the sea floor. Any bottom boundary layer will therefore reduce velocity values below those which would be measured by a current meter 100 m above the bottom at the same site. The temperature near the lower electrode was also recorded. (3) A temperature sensor attached to a trial instrument not otherwise discussed here. This was approximately 1 km southwest of the RCM and 0.75 m above the sea floor.

RESULTS

Frontal movements

Detailed maps were constructed for the EAC region, using the sources of near-surface information described above. Each map synthesizes the available data for successive periods of approximately 8 days. Examples of two such detailed maps are given in Figs 2a and b. These two maps are for periods approximately 1 month apart, and cover a critical period during which the Tasman Front moved south and a warm-core ring formed from it. A simplified series of such maps is presented in Fig. 3.

From 8 to 23 December 1983 the EAC was well separated from the coast south of 33°S. It flowed southward to approximately 35°S, and then turned eastwards before heading back to the north, so that the front lay to the north and east of the bottom moorings. By 8–15 January 1984 this meander had moved further south and west, close but just north of the moorings, and appeared to be over them from 16 January to 7 February.

From 8 to 19 February the meander moved further south relatively rapidly over the moorings, pinching off on about 16 February, to form an ellipitical warm-core ring which continued to move south. Evidence of a "necking-in" of the meander can be seen in a number of earlier maps. From 23 February to 19 March 1984 the ring remained near 37°S with, until 11 March, its long axis rotating, probably anticlockwise. No information was available from 20 to 25 March. The mooring recovery cruise indicated no front near the

VEF or RCM from 26 March to 4 April. An infrared satellite image of 29 March showed the northern edge of the ring near 38°S and the EAC well to the north and east of these two instruments.

Abyssal time series

The abyssal data for the period in question are presented in Fig. 4. The start of the recording period indicated a cold, northwards bottom current (8 cm s^{-1}) against the continental slope, as discussed in Mulhearn *et al.* (1985). The flow did not persist, however, and currents at site TP9 were generally small until 20 January when the temperature dropped abruptly and the current increased sharply to 22.2 cm s^{-1} and then dropped back to approximately 10 cm s^{-1} and swung to the south. The current flowed predominantly southwards until 18 February, and for much of this time had a strength of over 15 cm s^{-1}, with a peak value of 33.2 cm s^{-1}. Inspection of the maps (Fig. 3) shows that from 20 January to 18 February the surface front moved southwards, reached the position of the current meter, and then moved further south over the mooring positions. Comparable deep currents have been reported underneath the Gulf Stream (Hendry, 1982; Kelley and Weatherly, 1985).

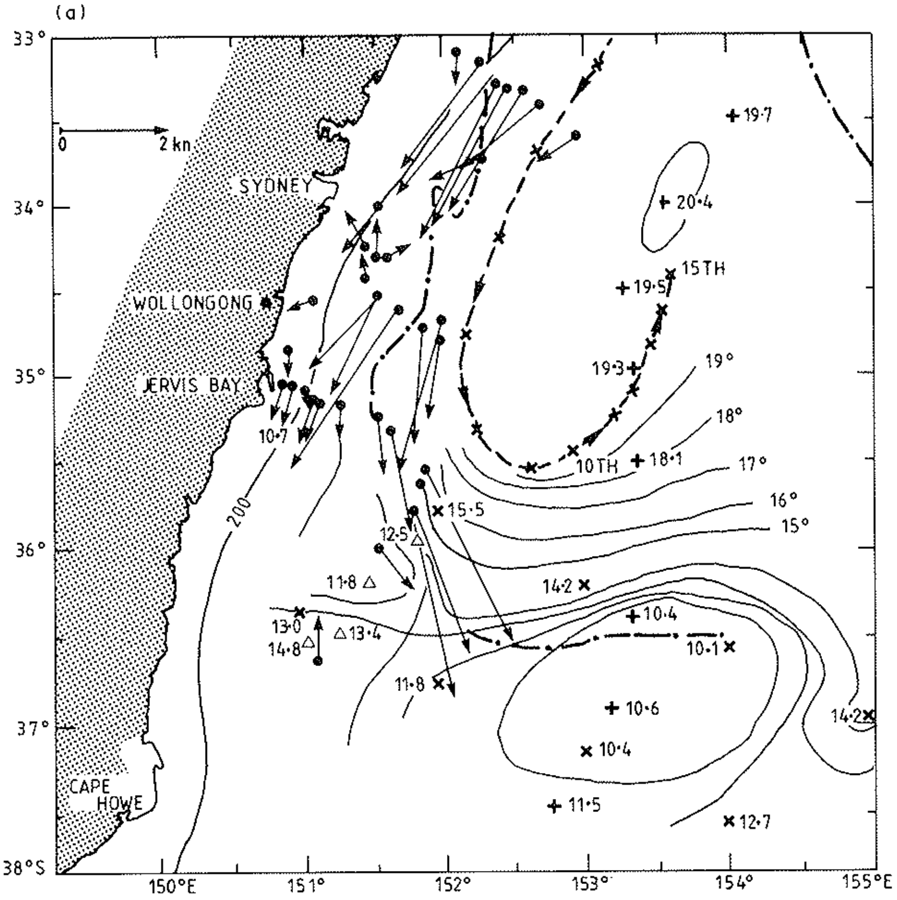

Fig. 2a.

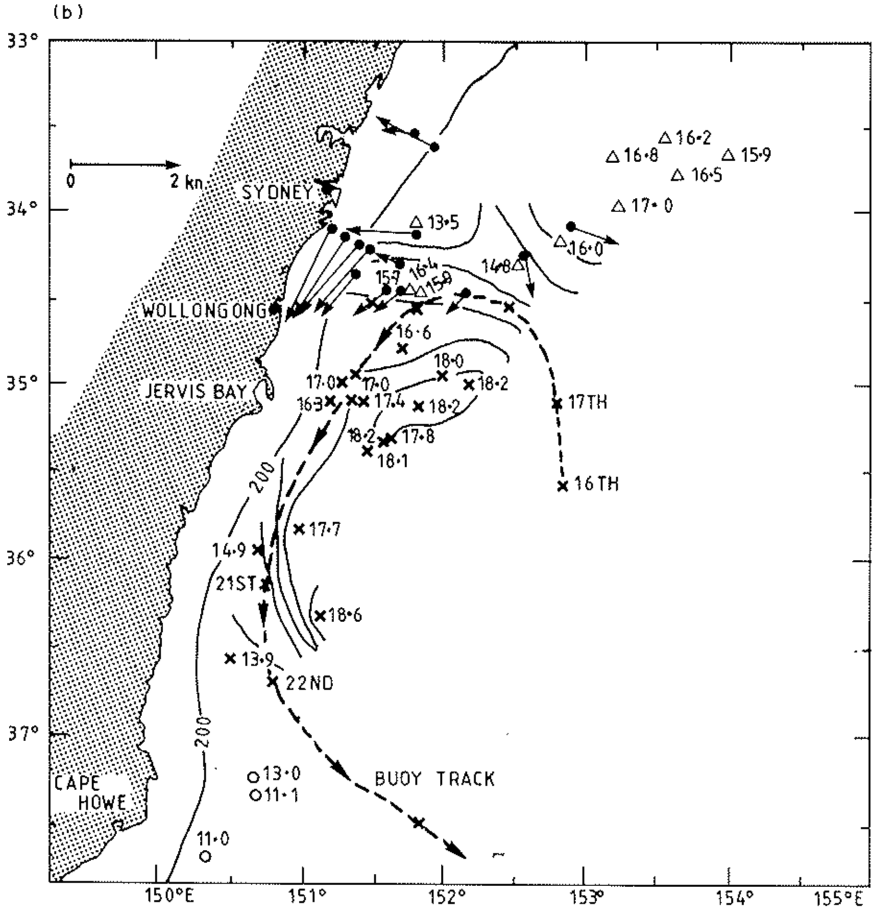

Fig. 2. Examples of distribution of near-surface data: (a) 8–15 January 1984. Data points are for 250 m depth temperatures: +, AXBT survey 8 January 1984; ×, AXBT survey 10 January 1984; △, R.V. *Sprightly* XBT data 15 January 1984. Thin continuous lines are inferred 250 m temperature contours. Arrows are ship set vectors from *Sprightly* 10–15 January 1984. Dashed line is a buoy track for 1–15 January 1984 with daily positions shown by crosses. Dot-dashed lines show frontal positions from infrared satellite image of 7 January 1984. (b) 17–19 February 1984. Data-points are for 250 m temperatures: ×, navy XBT data; ●, HMAS *Cook* XBT data; △, *Sprightly* XBT data. Thin lines are inferred 250 m temperature contours. Dashed line is a buoy track for 16–23 February 1984. Arrows are ship sets from *Sprightly*.

Pinch-off of the warm-core ring at the surface occurred between approximately 16 and 19 February. After 18 February the abyssal current at site TP9 dropped below 7 cm s^{-1}, then swung to the west and westnorthwest and increased to 11.5 cm s^{-1} by 24 February, when (from surface evidence) the northern edge of the warm-core ring was close to the current meter position. The magnitude of this deep current then decreased to approximately 3 cm s^{-1} on 14 March. Current direction stayed roughly constant from 22 to 29 February and then swung slowly through southwards to be eastwards by 11 March, as the ring moved away.

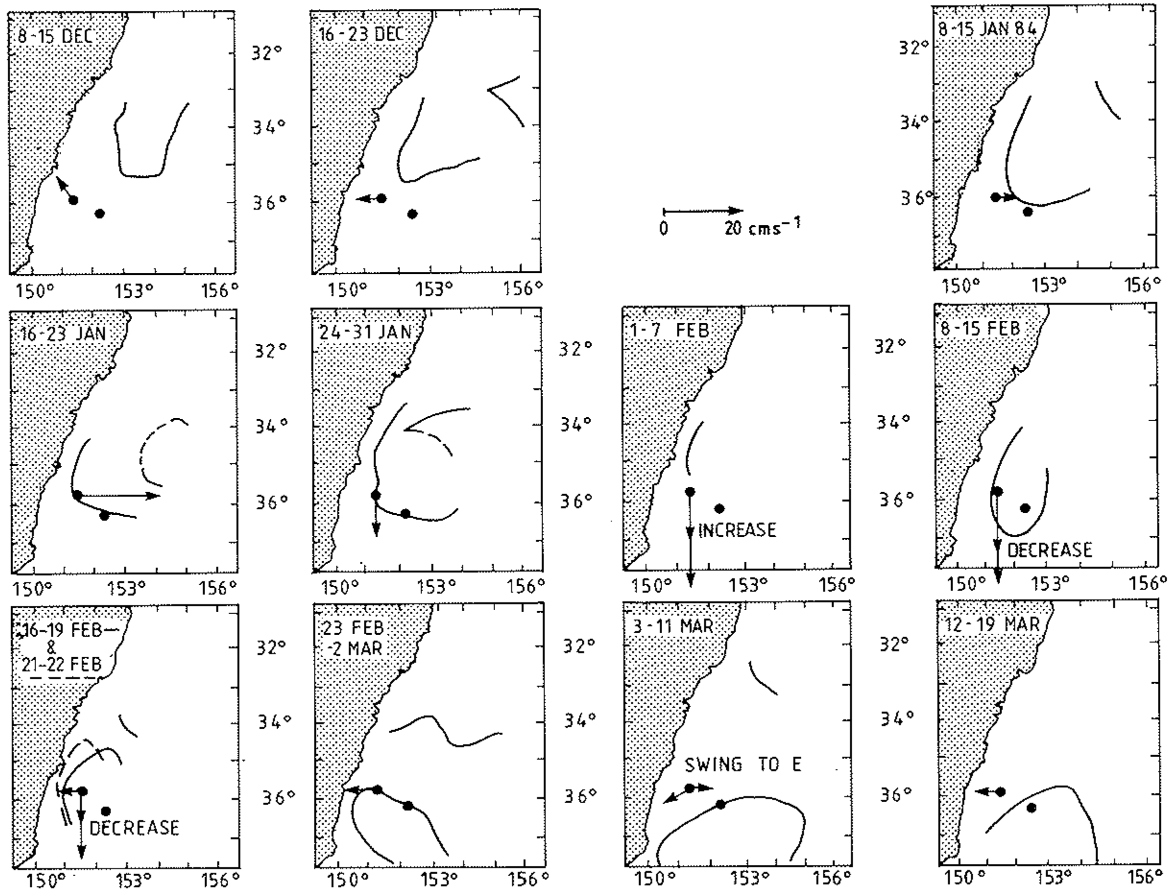

Fig. 3. Charts of positions of surface fronts and the warm-core ring for periods of approximately 8 days. Sea-floor measurement sites are shown by black dots and velocity vectors at RCM site by arrows.

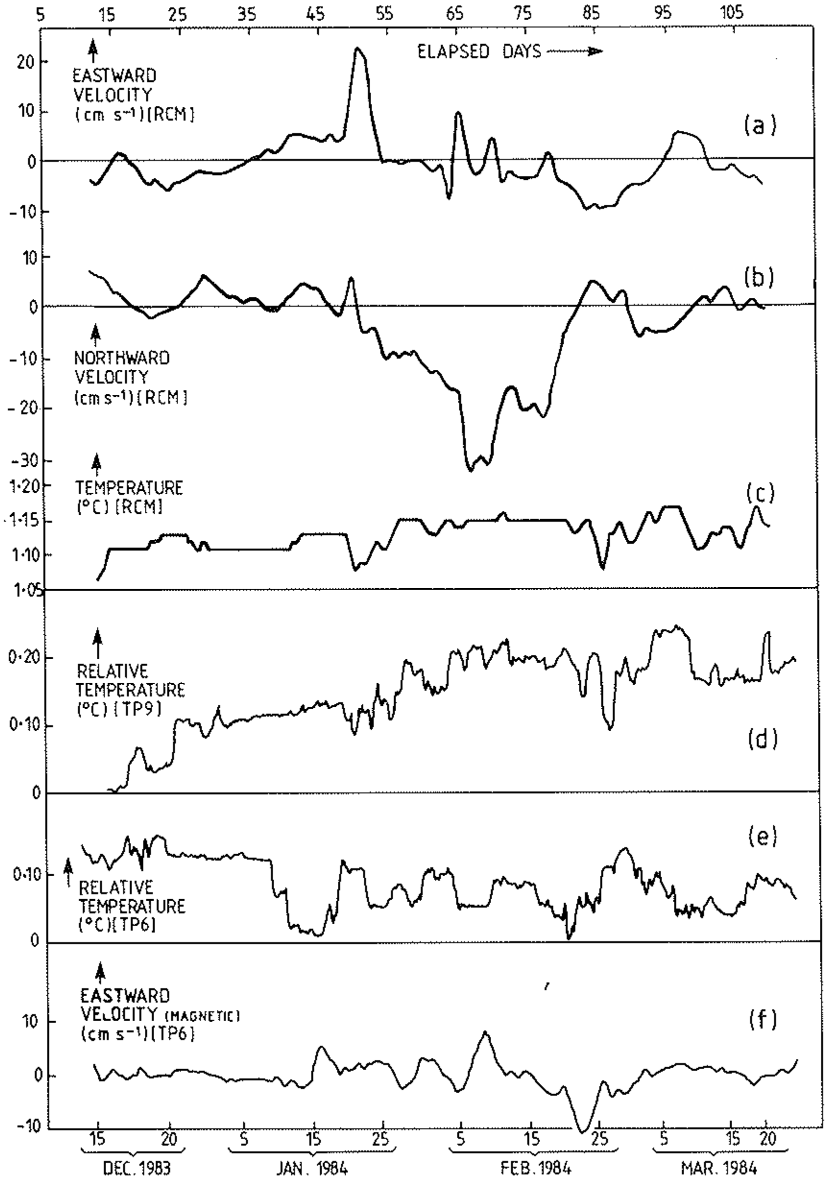

Fig. 4. Time series of abyssal data. Day zero is the 1 December 1983, UT. (a) The (geographic) eastwards velocity component for the recording current meter at site TP9, with tidal components removed. (b) As for (a), but the (geographic) northwards velocity component. (c) The temperature record from the recording current meter at site TP9. (d) Daily averages of the temperature record from the trial instrument near the current meter at site TP9, but with temperature sensor only 0.75 m from the sea floor. (Data are relative to an arbitrary zero.) (e) Daily averages of the temperature record from the VEF instrument at site TP6. (Data are relative to an arbitary zero.) (f) Daily averages of the (magnetic bearing) west to east velocity component at site TP6, estimated from the VEF data.

It appears that the strong abyssal currents at site TP9 occurred while the surface front was still part of the EAC, and before the ring had pinched off. The mesoscale signal associated with the southward passage of the EAC meander and subsequent ring can be seen best in the meridional velocity component (Fig. 4b). Fluctuations with shorter time scales are very apparent in the zonal velocity component and temperature signals, but are also present in the meridional component.

To compare the abyssal current information with the surface data, approximate average velocity vectors at the RCM site are shown in Fig. 3. It can be seen that the bottom current was large before and just after the ring pinched off, when the surface front was close by. At this time the current's direction was approximately parallel to the front, and in the same direction as the surface current except during rapid ring movement after pinch-off in late February. Kelly and Weatherly (1985) also found that bottom current directions were generally parallel to surface fronts, and that strong bottom currents were associated with both pinched-off rings and meanders.

Standard statistical analysis has been carried out on the RCM data, and the eddy kinetic energy per unit mass was 58 $cm^2 s^{-2}$, while the standard deviation in temperature was 0.02°C. The signal from the temperature sensor, 2(±1) km to the southwest of the current meter, is shown averaged over successive 4 h periods in Fig. 4d. As noted earlier, this sensor was approximately 0.75 m above the sea floor compared to the 100 m height of the current meter. After 23 January the two temperature records are highly correlated but the temperature range on the lower sensor was almost twice that at the higher RCM temperature sensor. Before 20 January the lower sensor showed a gradual temperature rise, with a few excursions. This gradual rise was not apparent on the higher RCM sensor. The behaviour at the two sites was quite dissimilar in mid-December.

The VEF instrument was at TP6 approximately 40 km to the eastsoutheast of the current meter. Its temperature signal had relatively small variations until 7 January when variations of order 0.1°C with a time scale of 5–10 days commenced and continued until the end of the record. Velocity variations were small to about 12 January and were then of order 5 cm s^{-1} to the end of February, after which they decreased again. These temperature and velocity variations began when the surface front moved close to the VEF site, and the first velocity pulse was eastwards (i.e. in the same direction as the surface current) with magnitude of 8 cm s^{-1}.

Subsequently there was little correlation between the velocity fluctuations at the VEF site and the weekly syntheses of surface flow till approximately 8 February. It may be that the front, which is almost stationary over the VEF site in January on the surface analyses of Fig. 3, was in fact wandering back and forth with an approximate 5-day time scale. Through February to early March the front moved south and the ring pinched off and moved further south over the sea-floor instruments. About 8 February a sharp maximum in the southward flow occurred at the RCM site with a simultaneous eastwards peak in the current at the VEF. About 24 February there was a sharp westwards peak at the VEF site when the southwards current at the RCM was rapidly decreasing, prior to the flow swinging westwards. VEF currents were small thereafter. These abyssal flow directions (from 8 February to early March) agree well with the surface analyses in Fig. 3 showing the passage of a warm-core ring.

At all three sites, the magnitude of the temperature variations changed little from mid-January until the end of the record. The variation in the velocity measured by the VEF decreased after the last sharp peak centred on 21 February, a time shortly after ring pinch-off. There also was a very sharp temperature minimum just before the last velocity peak.

Comparison of surface and deep data

The near-surface observations used to construct Fig. 3 have a different character from the abyssal data. The former are near instantaneous point measurements spread over a large area and combined every 8 days, whereas the latter are nearly continuous at only three points, and show many features which would be obscured in an 8-day time frame. To make the abyssal data more amenable to comparison with the surface data, weekly mean averages of various surface and abyssal parameters have been estimated and are presented in Fig. 5 (for the RCM site) and Fig. 6 (for the VEF site).

Figures 5a and b show the passage over the site of the western side of the EAC meander/warm-core ring with its associated increase in temperature and surface speed. Within the period of strong surface current, surface and abyssal flow directions became very similar, the deep temperature rose slightly and the abyssal current increased markedly.

Figures 6a–d show the passage of the centre of the meander/ring with surface-speed peaks at the leading and trailing edges of this structure and the associated swing from eastwards to westwards of the current direction. A comparison between the surface and abyssal magnetic-eastwards velocities (Figs 6d and f, respectively) reveals less correlation between surface and sea floor than can be seen by inspection of Fig. 4f due to the strongly attenuating effect of the weekly means in Fig. 6f. However the flow is predominantly eastwards from 10 January to mid-February and then westwards until early March. The deep flow is thus similar in direction to that at the surface.

DISCUSSION

Prominent features of the abyssal records (Fig. 4) are velocity and temperature fluctuations with a time scale of order 5 days, the magnitude of the velocity fluctuations being about 10 cm s^{-1} and temperature fluctuations 0.1°C. These fluctuations may be caused by cyclonic, barotropic eddies with diameter of order 30 km such as those found on the edges of Gulf Stream warm-core rings (KENELLY *et al.*, 1985). Such eddies are not discernible on the NOAA infrared satellite images, but an eddy of the appropriate scale (50 km diameter) is visible at the VEF site on the image of 29 March 1984 enhanced by CSIRO (LILLEY *et al.*, 1986b). This eddy may account for the decrease in the VEF signal at the end of the record.

The range of the temperature signal 100 m above the bottom at the RCM site is 0.16°C, that at the nearby temperature sensor 0.75 m above the bottom is 0.25°C, and that 1 m above the bottom at the VEF site, approximately 40 km to the eastsoutheast is 0.15°C. These values contrast with a temperature range of 0.04°C at 4000 m depth (approximately 850 m above the bottom) from archived hydrocast data for the area off the New South Wales coast between 32°30′S and 36°S, and west of 153°E. A similar increase in temperature variance near the sea floor was found by WEATHERLY and KELLEY (1982) in the western North Atlantic and was attributed to advection back and forth of a "cold filament" found at the foot of the continental slope. Results discussed in MULHEARN *et al.* (1985) support the existence of a cold current at the foot of the New South Wales continental slope, and the RCM was located within or close to this current

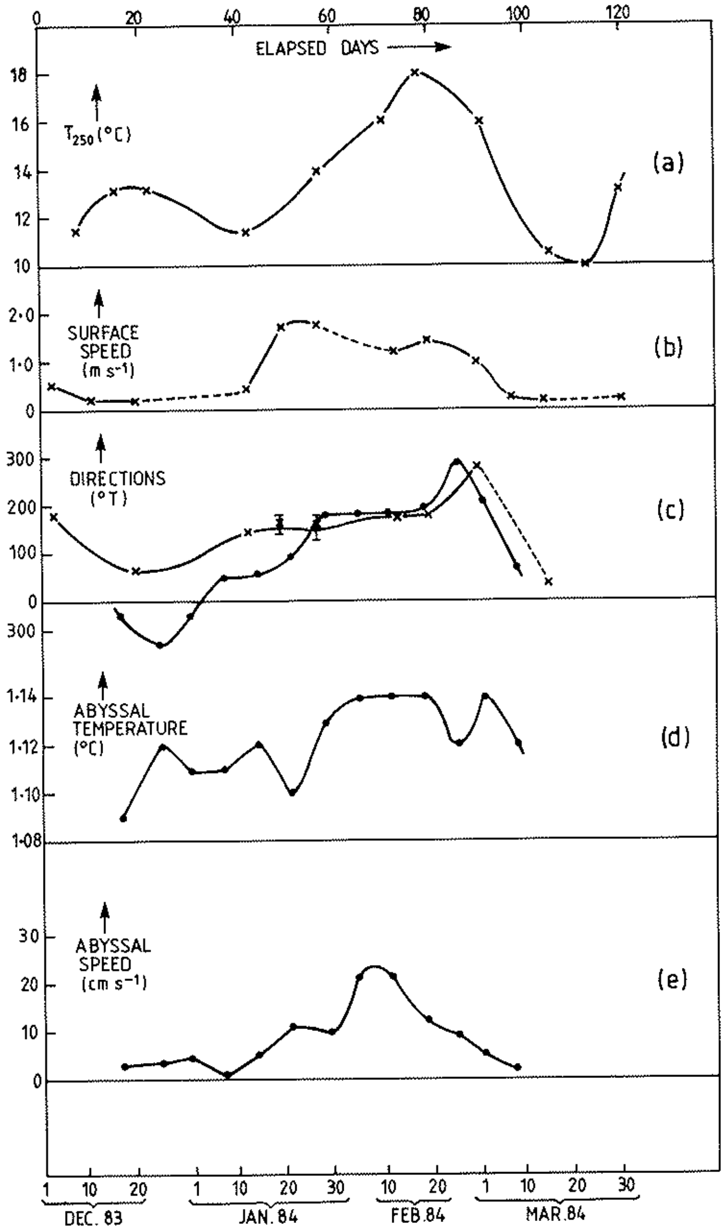

Fig. 5. Comparison of surface and deep data at site TP9 of the recording current meter, taking weekly values. (a) Water temperature at 250 m depth. (b) Near-surface water speed (estimated from ship sets). When speed is low and unknown, a value of 0.2 cm s^{-1} is shown. (c) Directions (true geographic) of currents: ×, near-surface; ●, deep. * indicates the value is uncertain but within this range. (d) Abyssal temperature at RCM (100 m above sea floor). (e) Abyssal water speed (from RCM).

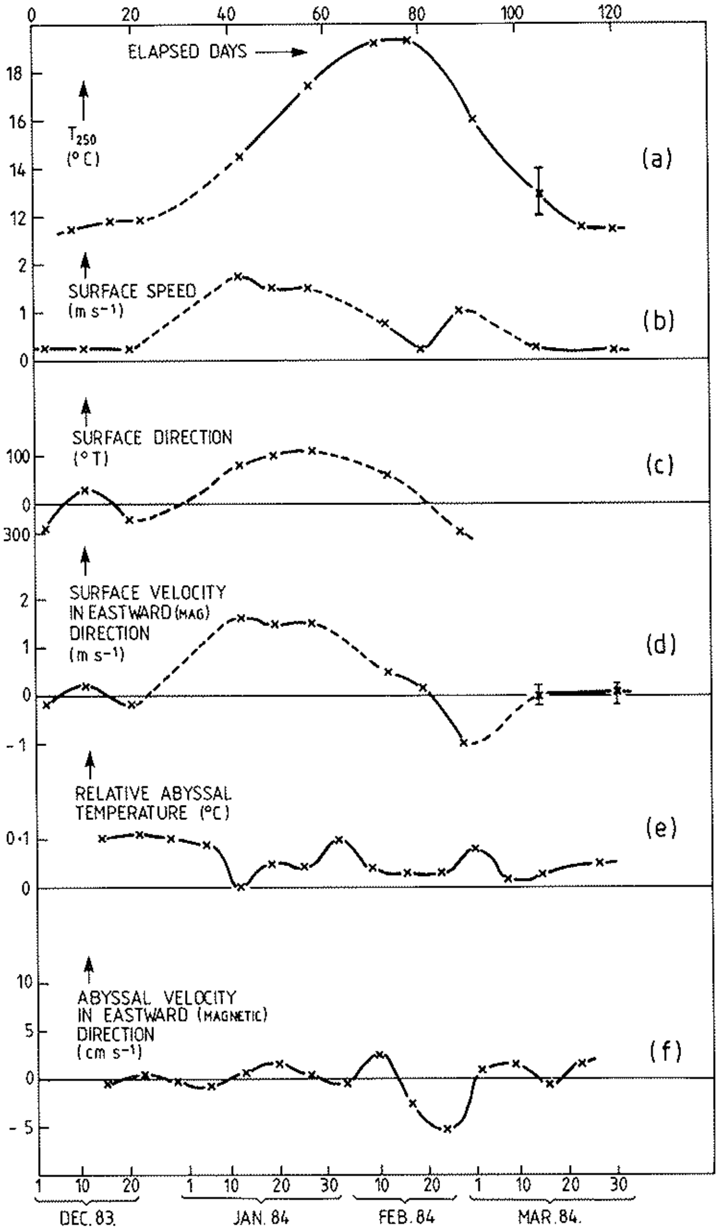

Fig. 6. Comparison of surface and deep data at site TP6 of the VEF instrument, taking weekly values. (a) Water temperature at 250 m depth. (b) Near-surface water speed (if speed is low and uncertain a value of 0.2 cm s^{-1} is plotted). (c) Direction of near-surface current. (d) Component of near-surface current in (magnetic) west to east direction. (e) Abyssal temperature at VEF instrument (1 m above sea floor) (zero level is arbitrary). (f) Component of abyssal current in (magnetic) west to east direction, deduced from VEF data. Note increased scale relative to that of Fig. 5c.

in mid-December 1983. The current did not persist, but was probably disrupted by the southward advance of the EAC meander. Throughout the measurement period, water from the cold current may have been entrained intermittently by the EAC, the warm-core ring, or any associated barotropic, cyclonic eddies. Intermittent passage of this water mass, which does not rise above 4000 m depth, would account for the relatively large temperature variation found in the abyssal records (Fig. 4).

At the RCM, the eddy kinetic energy of 58 $cm^2 s^{-2}$ compares with maximum measured values of 50 $cm^2 s^{-2}$ and 100–150 $cm^2 s^{-2}$ 4000 m beneath the Kuroshio Extension and Gulf Stream, respectively (SCHMITZ, 1984a). The standard deviation in temperature at the RCM of 0.02°C compares with maximum measured values of 0.01 and 0.04°C at 4000 m beneath the Kuroshio Extension (SCHMITZ, 1984b) and the Gulf Stream (HENDRY, 1982). The record length in the present case of 100 days is considerably shorter than the two year record lengths for the results obtained for the Kuroshio and Gulf Stream, but it appears that kinetic energy levels below the EAC are comparable with those below the Gulf Stream and the Kuroshio Extension.

CONCLUSIONS

Between December 1983 and March 1984 a warm-core ring formed and passed across mounted sea-floor instruments. The velocity pattern associated with the formation of a warm-core ring penetrated to the sea floor, but the thermal structure of the ring evidently did not penetrate to such depths.

In comparing the (near) surface and abyssal information, the mismatch in detail must be considered. The abyssal records show major changes on time scales too short to be apparent in the weekly averages of surface data. The implication is that a similar measurement of surface parameters would also show more detail than that suggested by the weekly compilations. Nevertheless the surface compilations clearly show a period of quiescence, followed by movement of the front and formation of the warm-core ring. Increased temperature fluctuations at depth accompanied increased movement of water, but there was no lasting warming effect associated with the passage of the warm-core ring overhead. In fact, at both the current meter and the VEF sites the first temperature change associated with the arrival of the front was one of cooling, possibly due to entrainment of colder water into the front at depth. The associated current surges at both deep sites were in the same direction as the corresponding surface currents. At the RCM site southward abyssal currents of up to 30 $cm\ s^{-1}$ were simultaneous with estimated overhead near-surface, southward currents of 150–175 $cm\ s^{-1}$.

Acknowledgements—The deployment and recovery of the sea-floor instruments was carried out from HMAS *Cook*, with the recording current meter recovered by R.V. *Sprightly* under charter to CSIRO. H. Moeller, G. Pezzoli and T. Koch of SIO were essential members of the field team. The joint work of SIO and the Australian National University (ANU) is being carried out under the US–Australia Agreement for Science and Technology, and US participation is supported in part by US National Science Foundation grants OCE 83-01216 and OCE 83-12339. Discussions with R. W. Griffiths of the Australian National University, T. M. Joyce of Woods Hole Oceanographic Institution and D. B. Olson of the Rosenstiel School of Marine and Atmospheric Science were beneficial. P. M. Tate of the Department of Geology and Geophysics, University of Sydney and L. J. Hamilton of the RAN Research Laboratory are thanked for their help with data analysis, and J. Church of CSIRO is thanked for supplying ancillary data from the Australian Coastal Experiment. N.L.B. and I.J.F. are the recipients, respectively, of an Australian Commonwealth Postgraduate Research Award and an ANU Postgraduate Scholarship.

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