JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. C11, PAGES 12,979-12,984, NOVEMBER 15, 1986

BAROTROPIC FLOW OF A WARM-CORE RING FROM SEAFLOOR ELECTRIC MEASUREMENTS

F. E. M. Lilley,[1] J. H. Filloux,[2] N. L. Bindoff,[1] I. J. Ferguson[1] and P. J. Mulhearn[3]

Abstract. A seafloor array of recorders spanning the Tasman Sea has measured the electric field signature of a major warm-core ring embedded in the East Australian Current. Theory for motional electromagnetic induction allows the electric measurements to be interpreted in terms of barotropic water velocity. Water transport and kinetic energy estimates thus obtained show a concentration of mesoscale activity near the Australian coast. The total circulation of the particular ring is estimated to be of the order of 100 Sv.

Introduction

The Tasman Project of Seafloor Magnetotelluric Exploration (TPSME), sited to examine the geomagnetic coast effect of eastern Australia and the electrical conductivity structure beneath the Tasman Sea, also crossed an active part of the East Australian Current (EAC), the western boundary current of the South Pacific Ocean [Nilsson and Cresswell, 1981]. The observing sites referred to in the present paper are shown in Figure 1.

During the observing period from December 1983 to March 1984, satellite photos and other data show that a meander of the EAC moved south across the line of seafloor instruments and pinched off to form a warm-core ring. The present paper reports the passage of this ring as evident in the horizontal electric field recordings (HEF). Figure 1 shows that the distribution of the HEF instruments was such as to give a wide coverage across the EAC with, beneficially, a denser spacing near the coast, where both western boundary current activity and geomagnetic coast effect should be most pronounced.

Electric fields are generated in the ocean according to the basic principles of electromagnetic induction, by the movement of seawater through the earth's steady magnetic field. An important consequence of the theory for seafloor horizontal electric fields is that such seafloor data may be interpreted to give an estimate of the mean water flow (i.e., barotropic velocity) through the water column directly above the instrument in question. While such an estimate is approximate only, it may be of great value in oceanography, as upon such mean flow data rest estimates of fluid mass transport.

[1] Research School of Earth Sciences, Australian National University, Canberra.

[2] Scripps Institution of Oceanography, University of California at San Diego, La Jolla.

[3] Defence Science and Technology Organisation, Weapons Systems Research Laboratory, RAN Research Laboratory, Darlinghurst, New South Wales, Australia.

Paper number 6C0492.
0148-0227/86/006C-0492$05.00

In the present case, surface and near-surface activity in the EAC was monitored by a range of traditional means during the TPSME recording period. Thus the surface and near-surface fluid motions simultaneous with the present HEF data are quite well known, though smoothed in space and time in the manner typical of such data.

There is also a variety of abyssal information at two sites, TP6 and TP9. These surface and abyssal data are presented by Mulhearn et al. [1986] and make possible comparisons of surface, mean and abyssal currents associated with the passage of the warm-core ring.

Seafloor HEF Data

The present seafloor HEF data were recorded by short-span salt bridge instruments incorporating switched electrodes [Filloux, 1980]. These free-fall instruments are released over a ship's side above an area of flat seafloor and sink to the ocean bottom, where they record the two horizontal components of the electric field. At a preset time they detach from their anchor tripods and float to the surface for ship retrieval.

The HEF records of the TPSME experiment are presented together in Figure 2 as plots of successive hourly mean values of the data, which in original form are spaced at intervals of 64 per hour. Such hourly mean values smooth out any high-frequency signal present in the original data.

However, even in the compressed plots of Figure 2 a variety of signals can be observed. Irregular electric signals induced in the sea by ionospheric and magnetospheric currents associated with magnetic activity can be discerned in places, and in more regular evidence are repetitive oscillations associated with the ionospheric magnetic daily variation and with the oceanic tides.

The switching-electrode salt bridge system used for HEF recording eliminates electrode and many other forms of very long period noise. A correct electric field zero baseline is thus ensured, and in turn a correct zero reference for inferred water velocities. This characteristic is essential for recording long-period or "slow" variations, which are attributed to mesoscale fluid motions in the ocean.

These slow signals can be seen clearly in Figure 2. At sites TP6 and TP7 they commence about day 35 with the arrival of an oceanic front and continue through to the end of the records. The signals are strongest in the sites nearest the Australian coast.

The present paper focuses on this evidence of mesoscale ocean activity. A separate analysis will be made of the information in the HEF data on electric fields associated with ocean tides and with the magnetic daily variation. Use of high-frequency HEF data in a magnetotelluric analysis for one site has been reported by Ferguson et al. [1985] and Filloux et al. [1985].

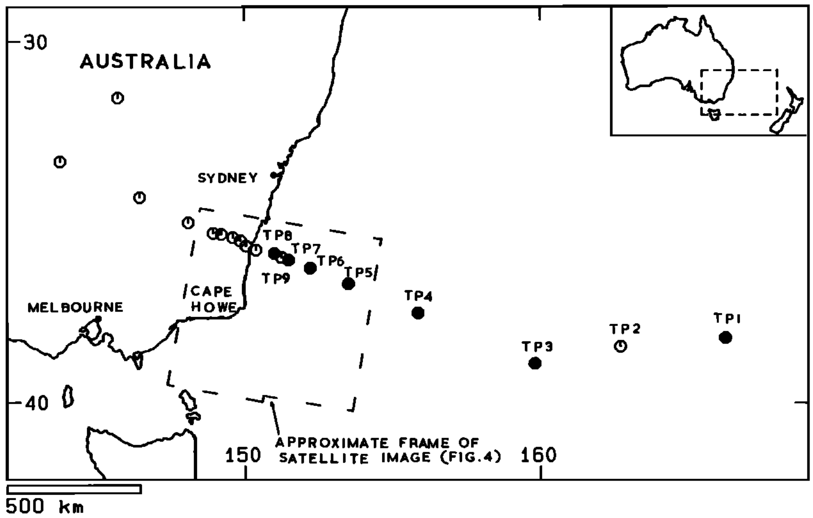

Fig. 1. Map of the observing sites of the Tasman Project of Seafloor Magnetotelluric Exploration (TPSME), with deep ocean sites marked with site numbers. Sites at which horizontal electric field observations were recorded are shown by solid circles; other sites are shown by open circles.

Other oceanographic aspects of the TPSME experiment are reported by Lilley et al. [1986], Bindoff et al. [1986], and Mulhearn et al. [1986].

Theory for Oceanic Induction

When a water current flows through the earth's steady magnetic field, electric fields and currents are established by induction according to Ohm's law for a moving medium:

$$\underset{\sim}{J} = \sigma\,(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B}) \tag{1}$$

where $\underset{\sim}{J}$ is the induced electric current, $\underset{\sim}{E}$ is the electric field, $\underset{\sim}{v}$ is the velocity, σ is the electric conductivity of the medium, and $\underset{\sim}{B}$ is the steady geomagnetic field.

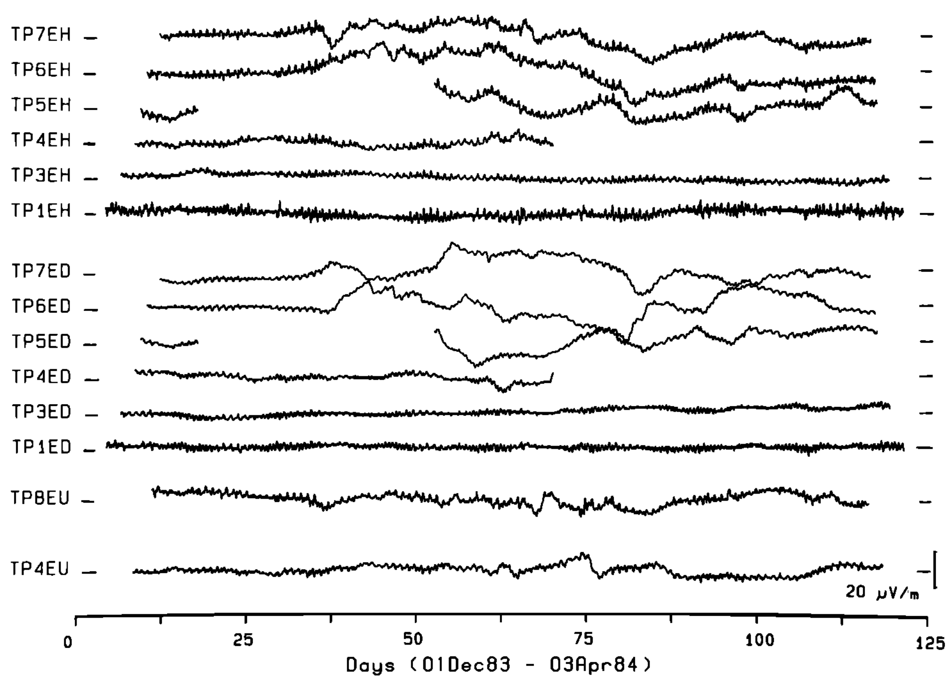

Fig. 2. Horizontal electric field data from the TPSME experiment. TP7EH marks the component in the direction of magnetic north of the seafloor HEF field recorded at site TP7; TP7ED marks the corresponding component in the direction of magnetic east. TP8EU and TP4EU mark single component traces at sites 8 and 4, recording the electric field component in the magnetic directions of 349° and 206°, respectively. The vertical scale mark is for an electric field change of 20 μV m^{-1}.

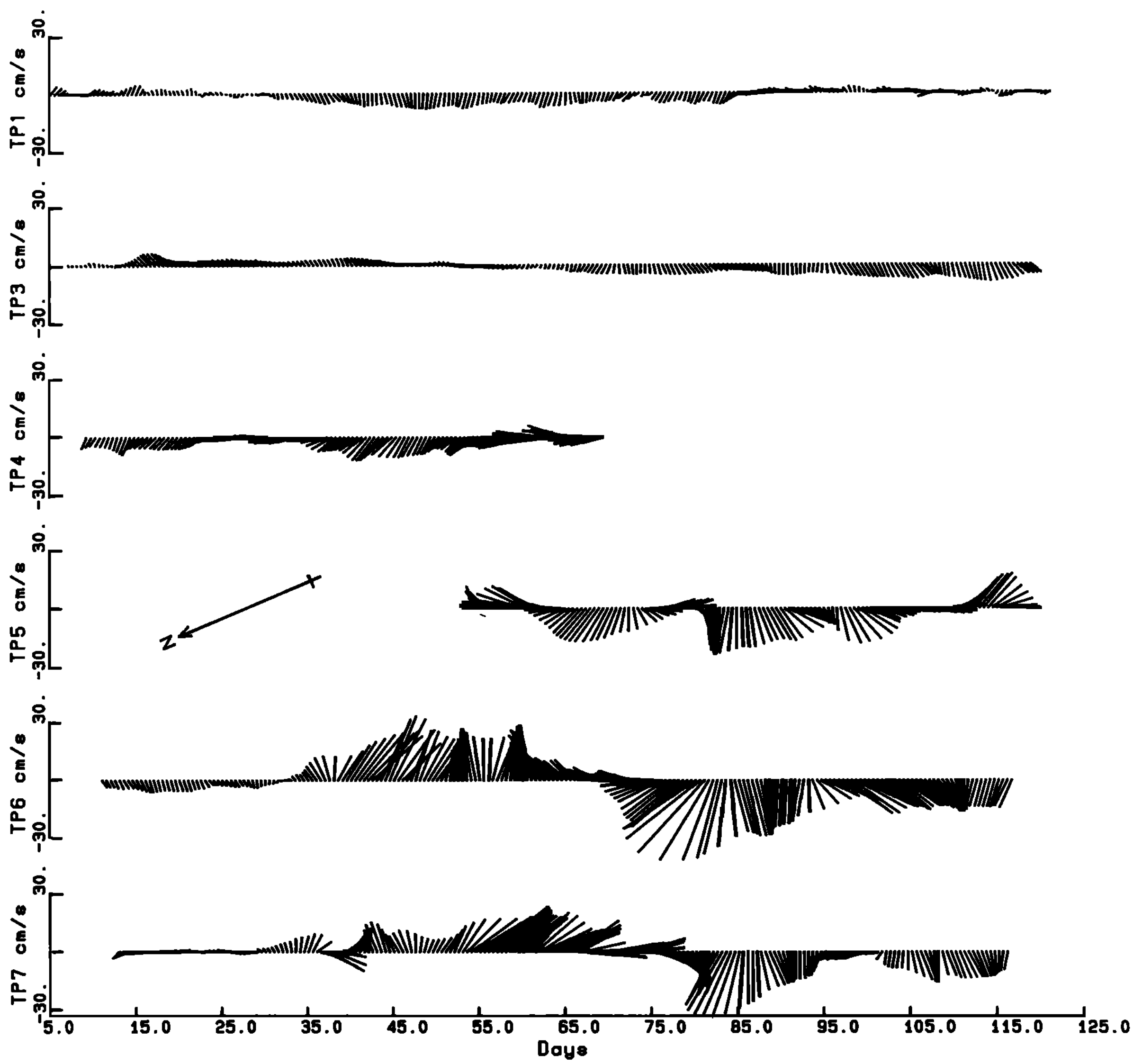

Fig. 3. The data of Figure 2 taken as 24-hour mean values every 12 hours and converted to vectors of fluid current $\bar{v}$ using equations (3) and (4). The orientation of the vectors is such that the northward longshore direction (parallel to the Australian coast) is to the top of the diagram. Time advances going down the figure, and the data are arranged in the same relative positions as are the station sites in Figure 1.

For water motions with a scale size much greater than the depth of the ocean, such as mesoscale eddies, current meanders, and tides, basic theory [Longuet-Higgins et al., 1954; Sanford, 1971, 1982] shows that for a laterally unbounded ocean of uniform electrical conductivity the horizontal electric field observed at the seafloor is a measure of the mean water flow through the water column above the instrument. This result means that with a single stationary instrument it is possible to measure the water velocity averaged over the water column (i.e., the barotropic flow).

Consider axes such that fluid motion in the horizontal y direction, v_y, causes electric field and current in the x direction, J_x and E_x, by motional induction with the vertical component of the earth's magnetic field B_z (here taken as positive upwards).

If the seafloor were nonconducting electrically, then the electric current J_x integrated over the full water column (from z = 0 at the seafloor to z = H at the sea surface) would be zero. Then, from equation (1),

$$E_x = -\bar{v}_y B_z \tag{2}$$

where the barotropic water velocity $\bar{v}_y$ is given by

$$\bar{v}_y = (1/H)\int_0^H v_y \, dz$$

However, seafloor electrical conductivity generally has an important effect in allowing "leakage" electric currents to return on paths beneath the ocean water. Equation (2) is then modified to

TABLE 1. Kinetic Energy and Transport Estimates

	Site			
	TP7	TP6	TP3	TP1
Position	36°00'S, 151°36'E	36°14'S, 152°15'E	38°54'S, 159°50'E	38°13'S, 166°11'E
Water depth, m	4840	4836	4980	2550
Mean kinetic energy of the barotropic component, per unit mass, cm^2 s^{-2}	133	196	11	9
Mean transport north Sv km^{-1}	-2.3×10^{-1}	-2.6×10^{-2}	3.3×10^{-2}	3.5×10^{-2}
Mean transport east Sv km^{-1}	-9.6×10^{-2}	-8.5×10^{-2}	-7.8×10^{-2}	-5.2×10^{-2}

The directions for the transport estimates are magnetic north and magnetic east. Transport estimates are in units of sverdrups of flow per horizontal kilometer of ocean current. Kinetic energy and transport estimates are based on the common 101-day recording period at all sites: December 15, 1983, to March 25, 1984 (day 14.7 to day 115.7).

$$E_x = -\bar{v}_y^* B_z \quad (3)$$

where $\bar{v}_y^*$ is an apparent barotropic velocity, related to $\bar{v}_y$

$$\bar{v}_y^* = \bar{v}_y / (1 + \lambda) \quad (4)$$

with the quantity λ being the ratio of the vertical conductance of the seafloor material (integrated to the depth where the leakage currents are zero) to the vertical conductance of the ocean.

For sites such as TP6 and TP7 on the Tasman Abyssal Plain, the most important path for leakage currents is expected to be through the sedimentary layer at the seafloor (with estimated vertical conductance of 1000 S), so that for an ocean with vertical conductance of 12,000 S, λ is estimated to be of the order of 0.1. Thus estimates of barotropic velocity obtained from E_x/B_z values are increased in this paper (in Figure 3 and Table 1) by 10% to correct for the effects of seafloor leakage currents.

The above theory and calculations are for seawater of uniform electrical conductivity. Errors due to departures of the actual seawater from this model are difficult to estimate but are thought to be generally less than 10%. When the seawater motion is concentrated near the surface, where the electrical conductivity is generally highest, such errors would cause the barotropic flow to be overestimated.

Barotropic Velocity Information for the Tasman Sea

To smooth out the effects of the magnetic daily variation and of the tides, arithmetic means over 24 hours have been taken every 12 hours for the records of Figure 2. These mean values for electric field have then been converted to velocity values, using equations (3) and (4) and known values (from world charts) of B_z. The velocity values thus derived are plotted in Figure 3 in "stick figure" format. The patterns of Figure 3 demonstrate several major points:

1. The oceanic activity is strongest at the more western sites. These sites are the nearest to the Australian coastline, so the pattern shows clearly this aspect of a western boundary current.

2. For the two western stations TP6 and TP7, the smoothed stick figure pattern is simple. A period of quiet is followed by the arrival of a front. There is a period of flow to the east and, as the warm-core ring passes, a period of flow to the west. This pattern is consistent with a warm-core ring (of anticlockwise rotation) moving from north to south across the line of instruments.

3. Further, between the east and west flows there is an intermediate stage at about day 70 with south flow at TP7 and north flow at TP6. This characteristic is consistent with the center of the ring having passed between the two sites.

The mesoscale activity in the EAC at the time of the HEF observations has been well documented by Mulhearn et al. [1986] and indicates that the patterns observed in Figure 3 can be attributed to the formation of a particular ring structure. The ring structure pinched off from a current meander and moved southward, in the manner typical of such rings in the EAC. Infrared satellite images, though much obscured by clouds, track the ring's southward progression. The first cloud-free satellite image of the ring is shown in Plate 1, taken after the ring had travelled south of the line of instruments.

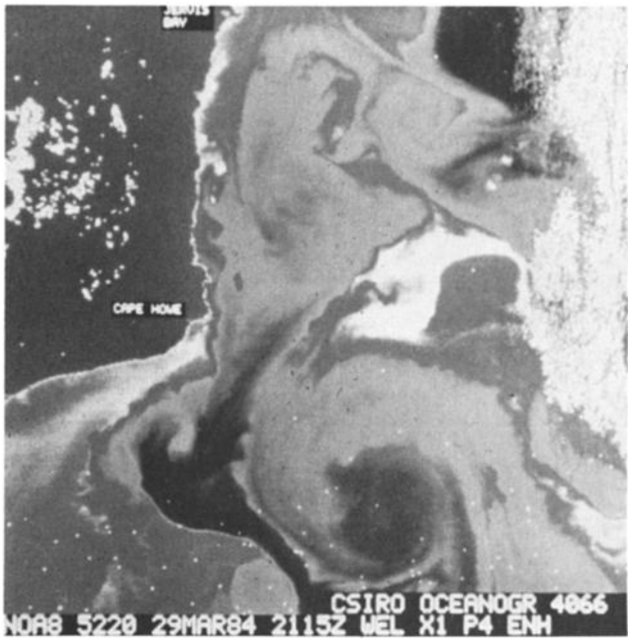

Plate 1. An infrared satellite image of the southeast Australian coastline and the Tasman Sea, taken March 29 1984. (The color version and a complete description of this figure can be found in the separate color section in this issue.)

(Plate 1 is shown here in black and white. The color version can be found in the separate color section in this issue.)

A major significance of the results of Figure 3 is that they are estimates of barotropic water velocity, integrated over the full depth of the water column. It is therefore of interest to compare the results with the estimates for both surface and abyssal water velocities for the same mesoscale activity, which have been obtained by Mulhearn et al. [1986].

The surface velocities are based on ship's sets and some buoy motions, and they indicate maximum fluid currents typically with strength of order 100 cm s^{-1}. The abyssal current meter, moored 100 m above the seafloor at site TP9, indicates fluid currents at this depth of the order of 20 cm s^{-1} peaking to 30 cm s^{-1}. Inspection of Figure 3 indicates the barotropic velocity in the water column to be of order 20 cm s^{-1} during the passage of the ring, requiring that (for a simple ring flow structure with velocity decreasing monotonically with depth) the surface velocity must decrease rapidly with depth to allow the magnitude of the abyssal velocity to be comparable to that of the barotropic value. This result is compatible with findings of Nilsson and Creswell [1981], and it is noteworthy that the magnitudes of the abyssal and barotropic currents are so similar.

The HEF data also make possible some quantitative barotropic results, as given in Table 1. The estimates, for each of the four stations for which there is a full record, are for the 101 days of common recording time.

The mean north and mean east transports through the water column above each station are directly obtained by taking means of the velocity time series, derived as was described above. Such mean transport values show a pattern of westward transport across the line of sites, coupled with northward transport in the centre and east of the Tasman Sea and southward transport in the west near the Australian coast. The pattern is in fact similar to that for a large anticyclonic circulation with its northern limit across the line of stations, though the present results may be expected to be dominated by the particular mesoscale activity, and a time longer than 100 days may be needed to estimate long-term mean transport in the Tasman Sea.

To study kinetic energy, it is of interest to form mean values over the time series of squared velocity values, derived as was described above. These sums (halved) are listed in Table 1 in the form of estimates of the mean kinetic energy of the barotropic component, per unit mass. The barotropic kinetic energy values listed in Table 1 show clearly the increase in oceanic activity in the western part of the Tasman Sea.

Finally, Figure 3 allows an estimate of the total flow in the warm-core ring of Plate 1. Taking a typical barotropic velocity of 20 cm s^{-1} over a width of 100 km in water 5 km deep indicates that the circulation in the warm-core ring may be as great as 100 Sv (where 1 Sv = 10^6 m^3 s^{-1}).

Acknowledgments. We thank the Royal Australian Navy for the services of the oceanographic ship HMAS Cook in skilful deployment and retrieval of the instruments, and we thank G. Pezzoli, T. Koch, and H. Moeller for technical assistance. R. W. Griffiths and J. A. Church have provided valuable comments on eddies in western boundary currents. The TPSME experiment is run under the U.S./Australia Science and Technology Agreement. Funding for the U.S. collaboration has been provided by the U.S. National Science Foundation. The enhanced satellite image of Plate 1 was kindly supplied by P. C. Tildesley of the Division of Oceanography, Commonwealth Scientific and Industrial Research Organisation, Hobart, Tasmania. The satellite data were supplied by the New Zealand Meteorological Office.

References

Bindoff, N. L., J. H. Filloux, P. J. Mulhearn, F. E. M. Lilley and I. J. Ferguson. Vertical electric field fluctuations at the floor of the Tasman Abyssal Plain, Deep Sea Res., 33, 587-600, 1986.

Ferguson, I. J., J. H. Filloux, F. E. M. Lilley, N. L. Bindoff and P. J. Mulhearn. A seafloor magnetotelluric sounding in the Tasman Sea, Geophys. Res. Lett., 12, 545-548, 1985.

Filloux, J. H. Observation of very low frequency electromagnetic signals in the ocean, J. Geomagn. Geoelectr., 32, suppl. I, SI1-SI12, 1980.

Filloux, J. H., F. E. M. Lilley, I. J. Ferguson, N. L. Bindoff and P. J. Mulhearn, The Tasman project of seafloor magnetotelluric exploration, Explor. Geophys., 16, 221-224, 1985.

Lilley, F. E. M., P. J. Mulhearn, J. H. Filloux,

N. L. Bindoff and I. J. Ferguson, Pressure fluctuations on the open-ocean floor: mid-Tasman Sea at 38°30'S., 162°38'E., near the Lord Howe Rise, Aust. J. Mar. Freshwater Res., 37, 27-37, 1986.
Longuet-Higgins, M. S., M. E. Stern and H. Stommel, The electric field induced by ocean currents and waves, with applications to the method of towed electrodes, Pap. Phys. Oceanogr. Meteorol., 13 (1), 1-37, 1954.
Mulhearn, P. J., J. H. Filloux, F. E. M. Lilley, N. L. Bindoff and I. J. Ferguson, Abyssal currents during the formation and passage of a warm-core ring in the East Australian Current, Deep Sea Res., 33, in press, 1986.
Nilsson, C. S. and G. R. Cresswell, The formation and evolution of East Australian Current warm-core eddies, Prog. Oceanogr., 9, 133-183, 1981.
Sanford, T. B., Motionally induced electric and magnetic fields in the sea, J. Geophys. Res., 76, 3476-3492, 1971.
Sanford, T. B. Temperature transport and motional induction in the Florida Current, J. Mar. Res., 40, suppl., 621-639, 1982.

N. L. Bindoff, I. J. Ferguson and F. E. M. Lilley, Research School of Earth Sciences, Australian National University, G.P.O. Box 4, Canberra, A. C. T. 2601, Australia.
J. H. Filloux, Scripps Institution of Oceanography, Mail Code A030, University of California at San Diego, La Jolla, CA 92093, U.S.A.
P. J. Mulhearn, Defence Science and Technology Organisation, Weapons Systems Research Laboratory, RAN Research Laboratory, P.O. Box 706, Darlinghurst, N. S. W., 2010, Australia.

(Received June 12, 1986;
accepted August 4, 1986.)

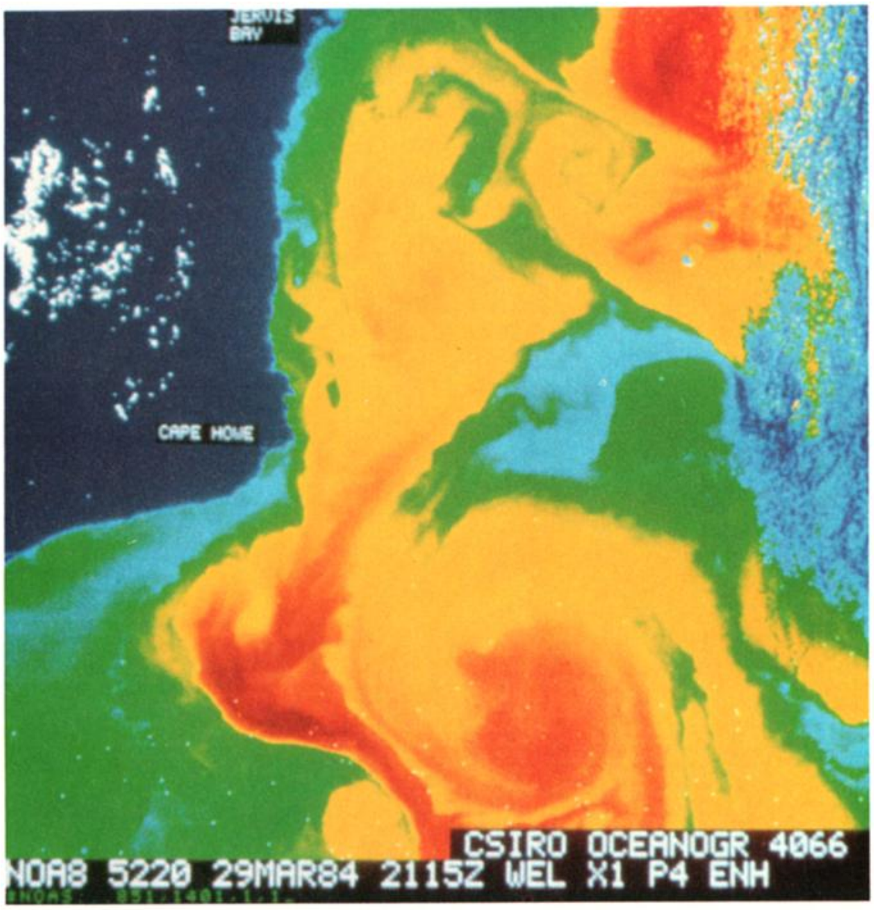

Plate 1. [Lilley et al.] An infrared satellite image of the southeast Australian coastline and the Tasman Sea taken March 29, 1984. The oceanic eddy which earlier (when further north) gave rise to the HEF signals in Figures 2 and 3 is now at the bottom of the photo, with the center in a southeast direction from Cape Howe.