YALE
PEABODY
MUSEUM

P.O. BOX 208118 | NEW HAVEN CT 06520-8118 USA | PEABODY.YALE. EDU

JOURNAL OF MARINE RESEARCH

The *Journal of Marine Research,* one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The *Journal of Marine Research* has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the *Journal of Marine Research.*

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
https://creativecommons.org/licenses/by-nc-sa/4.0/

Journal of Marine Research, 43, 779–792, 1985

Features of the circulation in the Mozambique Basin in 1981

by Marten L. Gründlingh[1]

ABSTRACT

Several cruises of the RV *Meiring Naudé* in 1981 were aimed at deriving the background or average circulation in the Mozambique Basin. This information would be of direct benefit to determine the advection of isolated eddies in this area. The results reflected the existence of a strong (up to 67×10^6 m^3s^{-1}) but variable current in the vicinity of the Mozambique Ridge. An eddy associated with this current and situated east of the Ridge emerged as a significant feature of the survey. No evidence could be found of a consistent background flow in the Basin.

1. Introduction

The Mozambique Basin is located in the southwestern Indian Ocean and is delineated by a number of specific geographical features (see Fig. 1): The most prominent demarcation is the Madagascar Ridge forming the eastern boundary of the Basin and extending southward along 45E from Madagascar in the north to the Southwest Indian Ridge at 40S. The western edge of the Basin is formed by the Mozambique Ridge, a southward extension of the African continent along 35E. The eastern side of the Mozambique Ridge is characterized by a sharp drop of about 2,000 m onto the abyssal plain depth (4,500–5,000 m) of the Basin. In the north the Basin ends at the entrance to the Mozambique Channel at 25S. In the south the Basin has no rigid boundary compatible to the other sides and remains "open" into the Southern Ocean. However, the zonal flow (Gründlingh, 1978) associated with the Subtropical Convergence at 40S could be considered a suitable termination of the Basin as far as aspects of the circulation are concerned.

As far as the circulation is concerned, the vicinity of the Mozambique Basin is characterized by the following currents: about 500 km west of the Mozambique Ridge, that is, along the coast of Southern Africa, the Agulhas Current flows in a southwesterly direction along the shelf break (Gründlingh, 1983a). Although the flow is steady most of the time (Gründlingh, 1980; Pearce and Gründlingh, 1982), large perturbations of the Current have been reported (Gründlingh, 1979;1984). In the northern part of the Mozambique Basin a consistent westward contribution from the East Madagascar Current (flowing southward along the east coast of Madagascar) into the Agulhas Current was observed during the International Indian Ocean Expedition (IIOE, see

---

[1] National Research Institute for Oceanology, CSIR, P.O. Box 320, Stellenbosch 7600, South Africa.

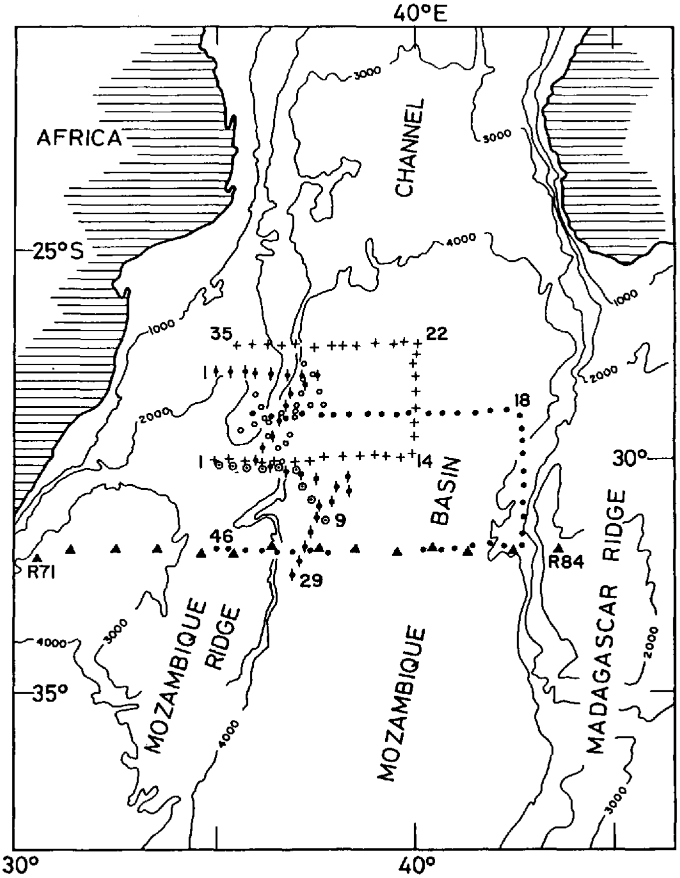

Figure 1. Bottom topography of the southwest Indian Ocean. Included are station positions of the *Robert Giraud* cruise in July 1960 (▲), and the *Meiring Naudé* cruises in February (o), March (●), April (⧫), July (⊙) and October 1981 (+).

Duncan, 1970; Wyrtki, 1971). It may be mentioned that the IIOE is still considered to represent the main source of information on the large-scale oceanographic features of the Indian Ocean. More recent results (Lutjeharms *et al.*, 1981) have suggested that the East Madagascar Current may fragment sporadically or return cyclonically (southeastward) into the Indian Ocean interior.

With intense currents along much of its perimeter the Mozambique Basin could be expected to contain eddies separated from the surrounding currents. However, it appears from data from the IIOE that the Basin is virtually void of any such mesoscale features. As an example, a vertical section of temperature obtained during a cruise of the *Commandant Robert Giraud* across the Basin in July, 1960 reveals an almost featureless progression of the isotherms (Fig. 2). The absence of any horizontal fine

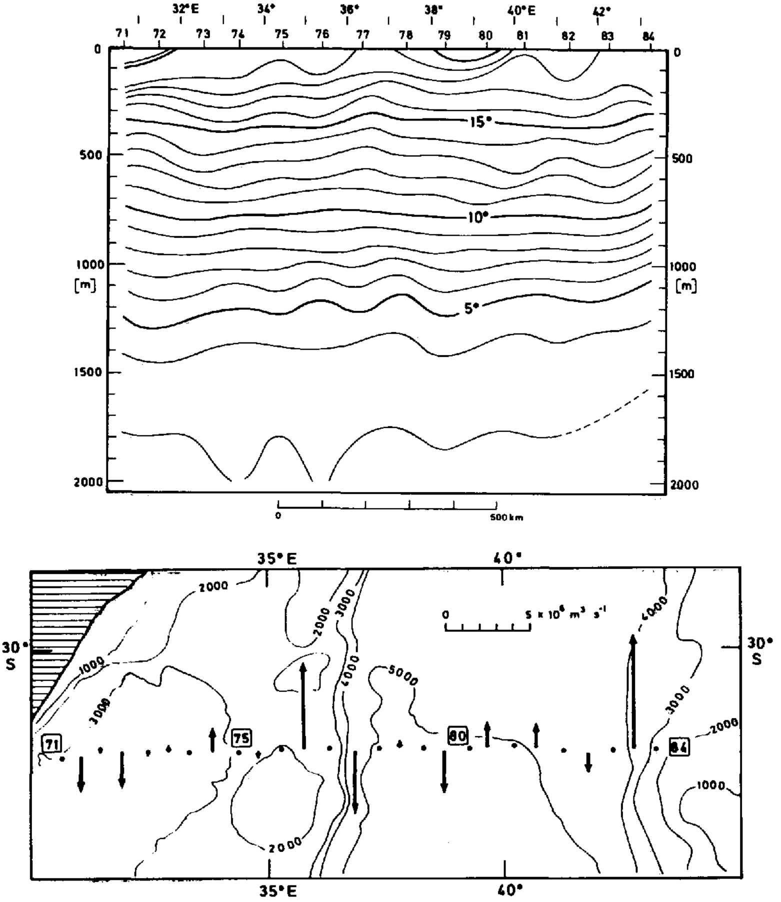

Figure 2. Results from the cruise of the *Commandant Robert Giraud*, 9–13 July 1960. Top: Vertical section of temperature for stations 71–84. Bottom: Geostrophic volume transports, relative to 1,000 m, between adjacent stations.

structure may be due to the filtering effect of the large station spacing (approximately 100 km), but intuitively one expects that, if there were any significant fluctuations in the isotherm depths, they would have been reflected in some of the station's data.

In contrast to this unexciting data, examples of well-defined mesoscale cyclonic eddies in the Basin have recently been reported (Gründlingh, 1977;1983b). Although the results did not contain any conclusive evidence about the origin of the eddies or their advection, it was suggested that the eddies were associated with water masses of a more tropical origin.

In an attempt to determine the advection of these eddies, and thus gain some insight into their fate, it was decided to obtain information on the average or *background* circulation in the Basin. It has, for example, been found in the case of Gulf stream rings (see for example, Lai and Richardson, 1977; Richardson, 1980) that the propagation of eddies due to the β-effect is normally overshadowed by the behavior of the flow in which the eddies are embedded.

An inspection of historic data showed the conflicting results that have been arrived at concerning the average flow in the Mozambique Basin. The geostrophic volume transports of the section in Figure 2 (relative to 1,000 m) varied inconsistently along the section with individual values below 10 units (of 10^6 m^3 s^{-1}). These values were of the same order as those calculated by Duncan (1970), who found that the area of the Mozambique Basin is characterized by a sluggish, recirculatory flow transporting water from the southern parts of the Agulhas Current northward in a large anticyclonic gyre. The same results indicated (see Wyrtki, 1971) that the anticyclonic gyre was also reflected in the 0–3,000 m transport.

The calculations of Duncan (1970) and Wyrtki (1971) are based on data collected over a span of many years, and fluctuating or contrasting values have been filtered out. Computations based on isolated sections seem to present a different and often contradicting picture of the flow in the Mozambique Basin. Harris (1972) found an isolated southwesterly flow totalling 40 units (rel. to 2,500 m) in the vicinity of the Mozambique Ridge, with smaller, more variable patterns further offshore in the Basin. On that occasion (1964) the Agulhas Current manifested itself only at 30S. Lutjeharms (1971) computed the transports of the *Natal* section off Durban in 1962, and found that while the Agulhas Current was well defined at 30S and transported about 47 units, the area of the Mozambique Ridge and Basin depicted variable flows, some setting northward, some setting southward, with individual values up to 31 units. Lutjeharms (1972) showed the discrepancies resulting from non-synoptic data, indicating that it may not be meaningful to compare data originating from different years, even if they belong to the same season.

The purpose of this paper is to present some results of five cruises of the RV *Meiring Naudé* in the Mozambique Basin in 1981, and to discuss features of the circulation in the Basin, based on these results. Two of the cruises (March and October) followed a rectangular grid and were specifically aimed at recording the general circulation, while the other cruises (February, April, July) were aimed at locating and surveying any eddies in the area (similar to the ones reported by Gründlingh 1977; 1983b).

2. Results of the Meiring Naudé cruises

*a. 6–10 February 1981.*The aim of the cruise was to locate any eddy in the vicinity of the Mozambique Ridge. Twenty-three NBIS-CTD stations were executed in the upper 1,000 db (see Fig. 1), the placing of the stations being dictated by the results being collected. A cyclonic eddy, not as well defined as those previously observed in the area, was located at 29S, 37E. To describe the dimensions of the eddy, the topography of the 10°C isotherm is used (Fig. 3a). This shows that the isothermal elevation at the eddy center is hardly discernible above the ambient level. The oval shape of the eddy is

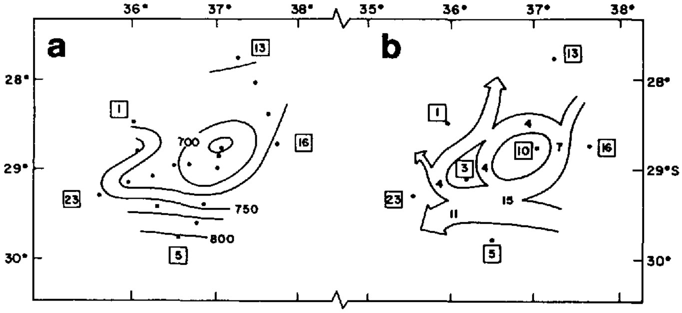

Figure 3. Topography of the 10°C isotherm in db (a) and volume transport in 10^6 m^3 s^{-1} (b) from the *Meiring Naudé* cruise 6–10 February 1981.

confirmed by the volume flux diagram (Fig. 3b) which shows that the eddy was situated on the northern perimeter of a zonal flow between 29 and 30S.

b. 10–18 March 1981. The general disposition of the stations on this cruise is indicated in Figure 1. NBIS-CTD stations were routinely occupied to a depth of 1,900 db, but adverse weather conditions excluded subsurface data to be collected at stations 34–38. An example of the data in the form of a temperature and salinity section along 29S (stations 1–18) is presented in Figure 4.

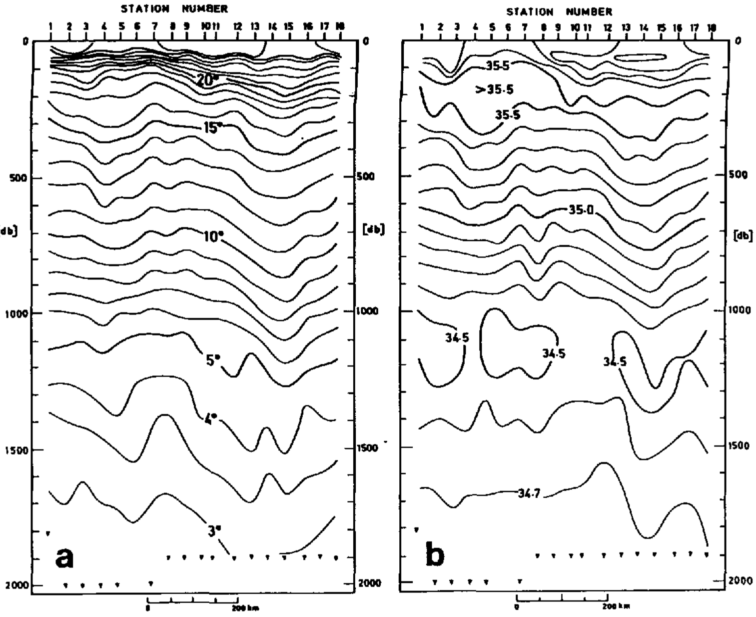

Figure 4. Vertical section of temperature (a) and salinity (b) from the *Meiring Naudé* cruise, 10–18 March 1981. Triangles denote maximum depth of measurement.

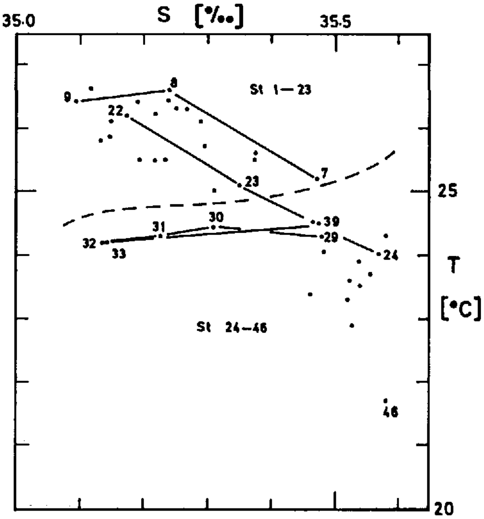

Figure 5. *T/S* distribution of the surface water on the *Meiring Naudé* cruise in March 1981. The frontal structures discussed in the text are represented by straight lines, while the apparent geographic division between stations 1–23 and 24–46 is indicated by the dashed line.

Because of the smaller station interval and continuous vertical profiling considerably more "structure" is visible in the *Meiring Naudé* section than in the *Giraud* section (Fig. 2). The core of the Subtropical Surface Water (STSW, see Duncan, 1970), characterized by the layer of high-salinity water at a depth of 100–300 db (Fig. 4b), reveals significant variations in thickness in conjunction with variations in the seasonal thermocline (Fig. 4a). For example, between stations 1 and 9, where the thermocline is relatively intense and shallow, the core of the STSW is thicker and shallower, while from station 9 to 18 the thermocline weakens and the STSW core weakens and deepens.

The core of the Antarctic Intermediate Water (AAIW), represented by the salinity minimum in 1,000–1,400 db, was occasionally interrupted by water of slightly higher salinity (for example, at stations 4 and 10–12, Fig. 4b). Gründlingh (1985) showed that this high-salinity intrusion at intermediate depth represented water of Red Sea origin that flowed in a southwesterly direction through the survey area.

The stations seemed to be geographically divided into two groups according to the surface *T/S* structure. Generally, the surface water tended to be more tropical (low density, high temperature) in the north and more subtropical (higher salinity, lower temperature) in the south (see Fig. 5). The main transition between these water masses occurred between stations 22 and 24 along the meridional section and assumed the form of temperature and salinity fronts of approximately 2°C and 0.4‰, respectively. Similar salinity fronts occurred between stations 7 and 9 and in the vicinity of station 33.

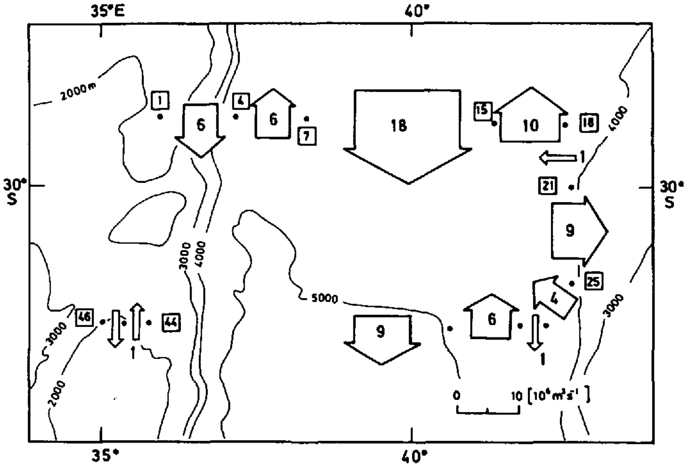

Figure 6. Geostrophic volume transports relative to 1,500 db for the *Meiring Naudé* cruise in March 1981.

For the geostrophic calculations, a reference level of 1,500 db was chosen. This choice was to a large extent dictated by the data, since this was the deepest station depth common to most stations. Many of the features described here obviously extended even beyond this depth, and it was believed that a realistic approximation of the true transport can only be obtained by assuming the deepest possible reference level. The possibility that any deep countercurrent may introduce significant errors in the transport calculations was neglected. A rough estimate of the tolerance on the transport values is about 10%. Where the flow between neighboring station pairs was found to be unidirectional, the transport was recalculated using those two stations enveloping the flow.

The geostrophic volume transport calculated relative to 1,500 db (Fig. 6) shows a significant southward flow of 18 × 10^6 m^3 s^{-1} between stations 9 and 15. A well-defined flow of this magnitude was not reflected anywhere else along the sections, and occurred in the area with water of predominantly tropical nature east of the strong thermohaline front between stations 7 and 9.

c. 22–27 April 1981. The cruise in April was planned as the second of three cruises to study the background circulation and would have followed a rectangular grid similar to that of the cruises in March and October. However, the significant flow setting southward on the first leg of stations along 28S prompted a revision of the cruise plan (see Fig. 1). Upon following the current southward the ship eventually traversed a cyclonic eddy (Fig. 7a). The elevation of the 10°C surface (Fig. 7a) shows that the center of the eddy, defined as the point of minimum depth (475 db), was located at 30°57′S, 37°34′E (assuming that the ship crossed the center). The isotherm surface dropped away steeply to all sides of the eddy and attained a depth of about 750 db on

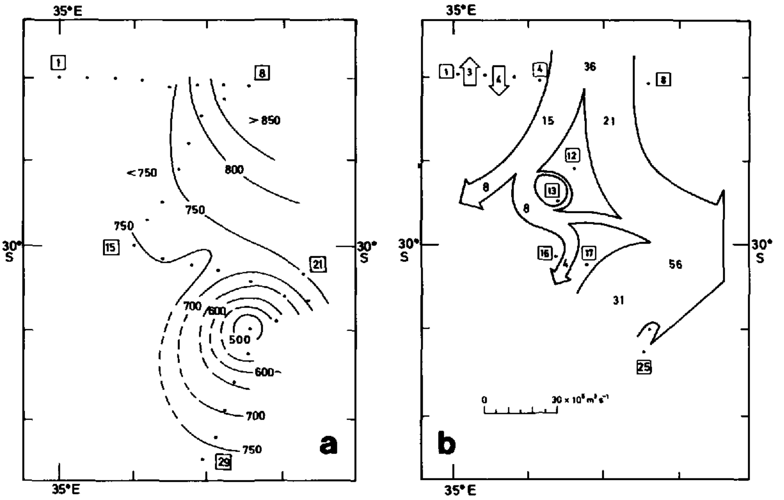

Figure 7. Topography of the 10°C isotherm in db (a) and volume transport relative to 1,500 db (b) for the *Meiring Naudé* cruise in April 1981. A certain amount of freedom was used in (a) to obtain a two-dimensional representation from the single section south of the eddy center. Also, this section contained temperature data only, causing a loss of transport calculations here (b).

the perimeter of the eddy. If the "edge" of the eddy is taken as the 650 db/10°C intersection (which is about 100–150 db above the ambient level of this isotherm), the eddy seemed to have a diameter of about 130 km.

The volume transport relative to 1,500 db (Fig. 7b) shows the southward input of some 36 units of flux (10^6 m^3 s^{-1}) between stations 4 and 8. Twenty-one units of this flow joined the 31 units already circulating the eddy to form a southeastward flow at 30S of 56 units. Equipment malfunction caused a loss of conductivity values from station 26 onward, with a corresponding loss of transport estimates. The volume transport derived relative to 2,400 db between stations 8 and 24 (isolated stations were occupied to this depth) amounted to 67×10^6 m^3 s^{-1}.

d. 23–26 July 1981. The aim of this cruise was to relocate and survey the eddy observed during the April cruise three months before. Equipment problems terminated the cruise (see Fig. 1 for station positions) after only 10 stations. Although the last station was situated in the same position where the eddy center had been located in April, no evidence could be found of the eddy.

e. 14–22 October 1981. This survey consisted of three legs, one along 27S, another along 30S and the connecting meridional line along 40E. As in the case of the March cruise, the strata of STSW and AAIW (see for example Fig. 8) have an interrupted appearance. Relatively high salinity values of approximately 34.7‰ were encountered

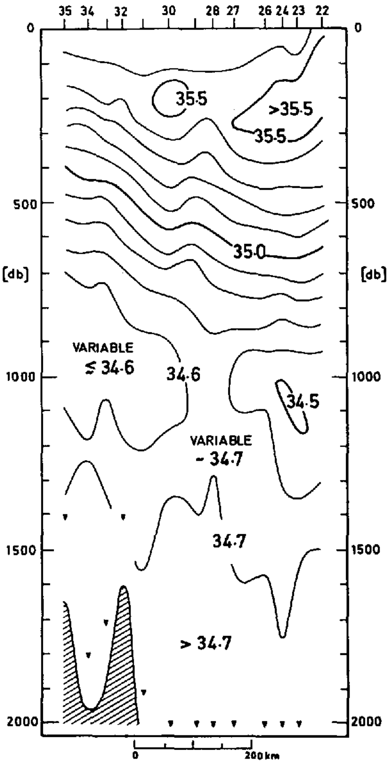

Figure 8. Vertical section of salinity of stations 22–35 of the *Meiring Naudé* cruise in October 1981.

at the depth of the AAIW in the vicinity of station 28, signifying the presence of Red Sea Water (see Gründlingh, 1985). Geostrophic volume transports (Fig. 9) were generally higher than in March 1981 (Fig. 6). Compared to the flow in April (Fig. 7b) there is a significant agreement (and difference) between the two circulation patterns. On the one hand, the April and October surveys both detected a strong meridional flow over the Ridge at 27S. On the other hand, this flow was directed toward the southeast in April but toward the southwest in October. The significance of this difference will be discussed below. No evidence could be found in October of the cyclonic eddy which was situated at 30S in April. Instead, the circulation in the area seemed to have an anticyclonic tendency in October.

3. Discussion

a. Thermohaline characteristics. The data set collected in 1981 and the one collected during the IIOE twenty years previously contrast sharply in terms of spatial and temporal variability. The 1981 data showed gradients in the thermohaline structure, associated with currents and eddies, that seemed to be absent in the IIOE data. From

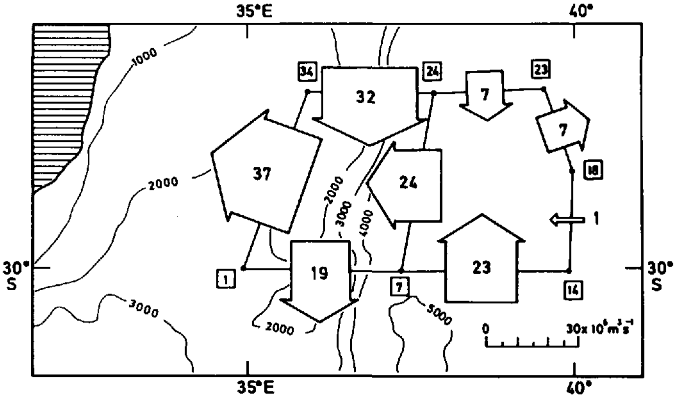

Figure 9. Geostrophic volume transports, relative to 1,500 db, of the *Meiring Naudé* cruise in October 1981.

these and other "irregularities" presented it is obvious that the 1981 data cannot be used forthwith to derive the thermohaline "climate" of the area. However, to be able to properly evaluate spatial variations in the temperature and salinity fields (as, for example in the case of the eddy observed during April) an indication of the ambient isopleth levels was desired. For this reason, 73 stations that were considered to be free of any anomalous structure (due to, for example Red Sea water, eddies, etc.) were selected from the total of 138 occupied in 1981. On the average, the 5°C isotherm was located at 1,160 ± 60 db, the 10°C at 740 ± 40 db and 15°C at 325 ± 40 db. In comparison, the IIOE Atlas (Wyrtki, 1971) displays a depth of 720 m for the 10°C isotherm. This agreement seemed to indicate that a valid approximation of the undisturbed isotherm levels could be gleaned from the 1981 data, although a large portion of the data had to be eliminated in the process. Using these values as a reference, the 5°C isotherm inside the eddy center was elevated by 210 db, the 10°C by 265 db and the 15°C by 75 db above the ambient levels.

To represent the average salinity structure, three isohalines were chosen inside the main thermocline and away from the two inversions associated with the cores of the STSW and AAIW. These isohalines namely 35.4‰, 35.0‰ and 34.6‰, were located at 350 ± 40 db, 650 ± 40 db and 950 ± 50 db, respectively. All these values are representative only of the quadrilateral enclosing the hydrographic stations.

b. Circulation. The agreement between the IIOE temperature structure and the "anomaly-free" thermohaline results collected in 1981 suggest *a priori* that the flow regime during the IIOE had also been anomaly-free and would therefore differ considerably from the fluxes reported here. This supposition was confirmed. In general, the 1981 transports were larger, more variable and seemed to have a consistent southward component, while the IIOE transports were small, steady and directed mostly to the north. Although the cruises did not cover the same area every time it is possible to postulate a composite chronological picture of the circulation in the course of 1981.

The main circulation feature during 1981 was the appearance of the strong southerly flow of 36×10^6 m^3 s^{-1} at the Ridge during the 5-week period separating the March and April cruises. After inception and approximately 300 km farther south this flow (tentatively referred to as the Mozambique Ridge Current or MRC) formed part of an intense cyclonic eddy (Fig. 7). There were indications that a fraction of the MRC at 28S was setting southwestward across the Ridge. The position and magnitude of the MRC suggest very strongly that the same current is portrayed by the high fluxes reported by Harris (1972: 40×10^6 m^3 s^{-1}) and Lutjeharms (1971: 31×10^6 m^3 s^{-1}) in the vicinity of the Mozambique Ridge. Although very little is still known about this Current, its existence now seems to be confirmed by independent observations and represents an exciting result of the 1981 surveys.

Between April and July the eddy had moved away from its original position. This distance amounted to at least one eddy radius (~65 km) and this would imply an advection rate of at least 1 cm s^{-1}. This is well within the advection speeds of several cm s^{-1} for free-drifting eddies in the Gulf Stream (see for example Cheney, 1976; Fuglister, 1977; Richardson, 1980), the Drake Passage (Joyce *et al.*, 1981) and the Kuroshio (Cheney *et al.*, 1980).

The tacit assumption that the eddy was free-drifting is not made without reason. The results obtained in October confirmed the existence of the MRC at the Mozambique Ridge (32×10^6 m^3 s^{-1}), but indicated that its flow direction had veered to the southwest. This new course, combined with the absence of the eddy, is strongly reminiscent of the process involved in cyclogenesis of Gulf Stream rings (see, for example, Fuglister, 1972) where eddies are formed through occlusion of Gulf Stream loops. The analogy seems to suggest that the MRC loop associated with the eddy in April 1981 became occluded between April and July. This occlusion separated the MRC from the eddy, which had moved away by the time of the July cruise. If this sequence of events presented here holds, it suggests that the onset of the MRC took less than 5 weeks and that the eddy had occluded within 3 months afterward.

Assuming that after becoming free-drifting the eddy had remained clear of other currents (thereby eliminating the possibility of reabsorption) it should be possible to make a rough estimate of its spindown time. According to Olson (1980) it is impossible to arrive at a quantitative estimate of eddy decay (over short periods) by using the isotherm elevation in the eddy center because an eddy can adjust its thermal structure without necessarily decaying. Richardson (1980) noted that a buoy implanted in a ring rotated at a fairly constant radius for about five months, but that the rotational period of the buoy increased from 1.9 to 2.9 days (that is, the eddy was slowing down). As the rotational speed decreases, so inevitably does the elevation of the isopycnals above their ambient levels. It should, therefore, be possible to derive an estimate of an eddy's lifetime from the isotherm elevation. Parker (1971) derived a subsidence of the 17°C isotherm of 0.6 m day^{-1}. Gotthardt (1973) found a subsidence of 1 m day^{-1} (over a period of 12 months) although short-term shrinkages were higher (see also Cheney and Richardson, 1976).

The 10°C isotherm inside the 1981 eddy was elevated about 260 m above the ambient levels in April. Assuming that the ship had crossed the center of the eddy (the point of maximum upheaval), and using a nominal subsidence rate of 1 m day^{-1}, the eddy would theoretically have had a lifetime of about 9 months. Considering its initial intensity, its long life underscores the eddy's importance to the circulation in the Mozambique Basin.

The 10°C-isotherm elevation inside the eddy under discussion was on a par with that of eddies previously observed in the Mozambique Basin (see Gründlingh, 1983b), although differences in volume transport may be attributed to differences in the choice of reference levels.

Finally, the possible mechanism through which the eddies can be generated should be addressed briefly for it is noteworthy that all the eddies reported so far were observed in the vicinity of the Mozambique Ridge. This may be merely a result of the location of the hydrographic surveys, but we prefer to consider that some direct relation exists between the Ridge and the eddies. The reason for this is that rotation sense of the eddies (cyclonic) conforms to the result expected when the potential vorticity of an inertial current (the MRC) in the southern hemisphere is conserved while it flows into deeper water. It is therefore possible that the significant increase in depth (from about 2,000 m to 4,500 m), eastward from the Ridge into the Basin could induce sufficient cyclonic vorticity into the MRC to form the eddies.

4. Conclusion

The main conclusions that can be drawn from the results are, firstly, that the circulation in 1981 was anomalous compared with the results of the IIOE (Wyrtki, 1971) but comparable in magnitude and variation to values reported previously (see e.g. Harris, 1972; Lutjeharms, 1971). The magnitude of the fluxes may be ascribed to the existence of the MRC, a current that is only starting to assume shape through observations such as those presented above. The variability could be a result of fluctuations associated with the generation of the MRC (of which nothing is known) or due to the eddies that are spawned by the MRC. Considering that several reports on eddies have appeared since 1975 (Gründlingh, 1977; 1983b; 1984), eddies in this region, although not regular, may be more than just isolated events. The large degree of variability in this region has recently been confirmed by the results of Cheney *et al.* (1983).

Secondly, the relative abundance of vortices and the presence of a current compatible in intensity to the Agulhas Current (Gründlingh, 1980) may jeopardize the whole concept of a "background flow." This, in turn, will eliminate the possibility of using this method to determine where eddies advect to, and indicate the employment of other methods (for example satellite-tracked buoys, see Richardson, 1980) for this purpose.

Acknowledgments. The assistance of the officers and crew of the R.V. *Meiring Naude* is appreciated.

REFERENCES

Cheney, R. E. 1976. A census of rings in the Gulf Stream system. NAVOCEANO Tech. Note 3700-44-76, 75 pp.

Cheney, R. E., J. G. Marsh and B. D. Beckley. 1983. Global mesoscale variability from collinear tracks of SEASAT altimeter data. J. Geophys. Res., *88,* 4343–4354.

Cheney, R. E. and P. L. Richardson. 1976. Observed decay of a cyclonic Gulf Stream ring. Deep-Sea Res., *23,* 143–155.

Cheney, R. E., P. L. Richardson and K. Nagasaka. 1980. Tracking a Kuroshio cold ring with a free-drifting buoy. Deep-Sea Res., *27A,* 641–654.

Duncan, C. P. 1970. The Agulhas Current. Ph.D. thesis, Univ. Hawaii, 76 pp.

Fuglister, F. C. 1972. Cyclonic rings formed by the Gulf Stream 1965–66, *in* Studies in Physical Oceanography, *2,* A. L. Gordon, ed., Gordon and Breach Science Publishers, New York, 137–168.

—— 1977. A cyclonic ring formed by the Gulf Stream 1967, *in* Voyage of Discovery, M. Angel, ed., Pergamon Press, Oxford, 177–198.

Gotthardt, G. A. 1973. Gulf Stream eddies in the eastern North Atlantic. U.S. Naval Oceanogr. Rept. TN 6150-16-73, 46 pp.

Gründlingh, M. L. 1977. Drift observations from NIMBUS VI satellite-tracked buoys in the southwestern Indian Ocean. Deep-Sea Res., *24,* 903–913.

—— 1978. Drift of a satellite-tracked buoy in the southern Agulhas Current and Agulhas Return Current. Deep-Sea Res., *25,* 1209–1224.

—— 1979. Observation of a large meander in the Agulhas Current. J. Geophys. Res., *84,* 3776–3778.

—— 1980. On the volume transport of the Agulhas Current. Deep-Sea Res., *27,* 557–563.

—— 1983a. On the course of the Agulhas Current. S. Afr. Geogr. J., *65,* 49–57.

—— 1983b. Eddies in the southern Indian Ocean and Agulhas Current, *in* Eddies in Marine Science, A. R. Robinson, ed., Springer Verlag, Berlin-Heidelberg, 245–264.

—— 1984. An eddy over the northern Mozambique Ridge. S. Afr. J. Sci., *80,* 324–329.

—— 1985. Occurrence of Red Sea Water in the southwestern Indian Ocean, 1981. J. Phys. Oceanogr., *15,* 207–212.

Harris, T. F. W. 1972. Sources of the Agulhas Current in the spring of 1964. Deep-Sea Res., *19,* 633–650.

Joyce, T. M. *et al.* 1981. Anatomy of a cyclonic ring in the Drake passage. Deep-Sea Res., *28A,* 1265–1287.

Lai, D. Y. and P. L. Richardson. 1977. Distribution and movement of Gulf Stream rings. J. Phys. Oceanogr., *7,* 670–683.

Lutjeharms, J. R. E. 1971. A descriptive physical analysis of water movement in the southwest Indian Ocean during the northeast monsoon season. MSc thesis, Univ. Cape Town, South Africa, 266 pp.

—— 1972. A quantitative assessment of year-to-year variability in water movement in the southwest Indian ocean. Nat. Phys. Sci., *239,* 59–60.

Lutjeharms, J. R. E., N. D. Bang and C. P. Duncan. 1981. Characteristics of the currents east and south of Madagascar. Deep-Sea Res., *28A,* 879–899.

Olson, D. B. 1980. The physical oceanography of two rings observed in the Cyclonic Rings Experiment. II. Dynamics. J. Phys. Oceanogr., *10,* 514–528.

Parker, C. E. 1971. Gulf Stream rings in the Sargasso Sea. Deep-Sea Res., *18,* 981–994.

Pearce, A. F. and M. L. Gründlingh. 1982. Is there a seasonal variation in the Agulhas Current? J. Mar. Res., *40,* 177–184.

Richardson, P. L. 1980. Gulf Stream ring trajectories. J. Phys. Oceanogr., *10,* 90–104.

Wyrtki, K. 1971. Oceanographic atlas of the International Indian Ocean Expedition. Nat. Sci. Found., Washington, 531 pp.

Received: *21 December, 1984;* revised: *10 July, 1985.*