The Mozambique channel revisited

Canal de Mozambique
Niveau moyen
Vent
Flux méridien
Tourbillon anticyclonique

Mozambique Channel
Mean sea level
Wind
Meridian flow
Anticyclonic gyre

Jean-René DONGUY, Bernard PITON

Centre ORSTOM de Brest, B.P. 70, 29280 Plouzané, France.

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ABSTRACT

The meridian flow through the Mozambique Channel is investigated by the difference between the sea level on each side of the channel and by the influence of the wind components measured at two low islands. From these data, it is inferred that the resulting variations in meridian flows in the northern and southern Mozambique Channel are roughly in phase and that the meridian transport is subjected to a seasonal cycle. Moreover, three unpublished cruises (1974-1975) in the Mozambique Channel show an anticyclonic gyre in the northern part (12°-16°S) and a large southward flow across the narrows of the channel. According to the results of the cruises, this northern anticyclonic gyre is submitted to seasonal and also year-to-year variations.

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RÉSUMÉ

Le canal de Mozambique revisité

Le flux méridien à travers le Canal de Mozambique est étudié en utilisant la différence entre les niveaux moyens des deux côtés du Canal et en estimant l'influence des composantes du vent mesuré sur deux îles basses situées dans le Canal. Les flux méridiens dans le nord et le sud du Canal de Mozambique sont à peu près en phase et le transport méridien est soumis à un cycle saisonnier. Trois croisières inédites (1974-1975) dans le Canal de Mozambique révèlent dans la partie nord (12°-16°S) un tourbillon anticyclonique soumis à des variations saisonnières et interannuelles et un fort flux portant au sud à l'endroit le plus étroit du Canal.

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INTRODUCTION

According to Clowes and Deacon (1935), the North Atlantic Deep Water is exported to the Indian and Pacific Ocean by the Antarctic Circumpolar Current. The compensating flow would come within the warm water in the thermocline layer (Gordon, 1986). The itinerary of such a water would be: Pacific to Indian Ocean through the Indonesian straits, Indian Ocean in the 10-15° S latitude belt, southward flow in the Mozambique Channel (Fig. 1 *a*) and entry into the South Atlantic by a branch of the Agulhas current. This hypothesis relies on the existence of a southward surface current between Madagascar and Africa. This current, usually called Mozambique current, is indicated on Figure 1 *a* from Saetre (1985). However, reliable evidence of this current is not compelling and the

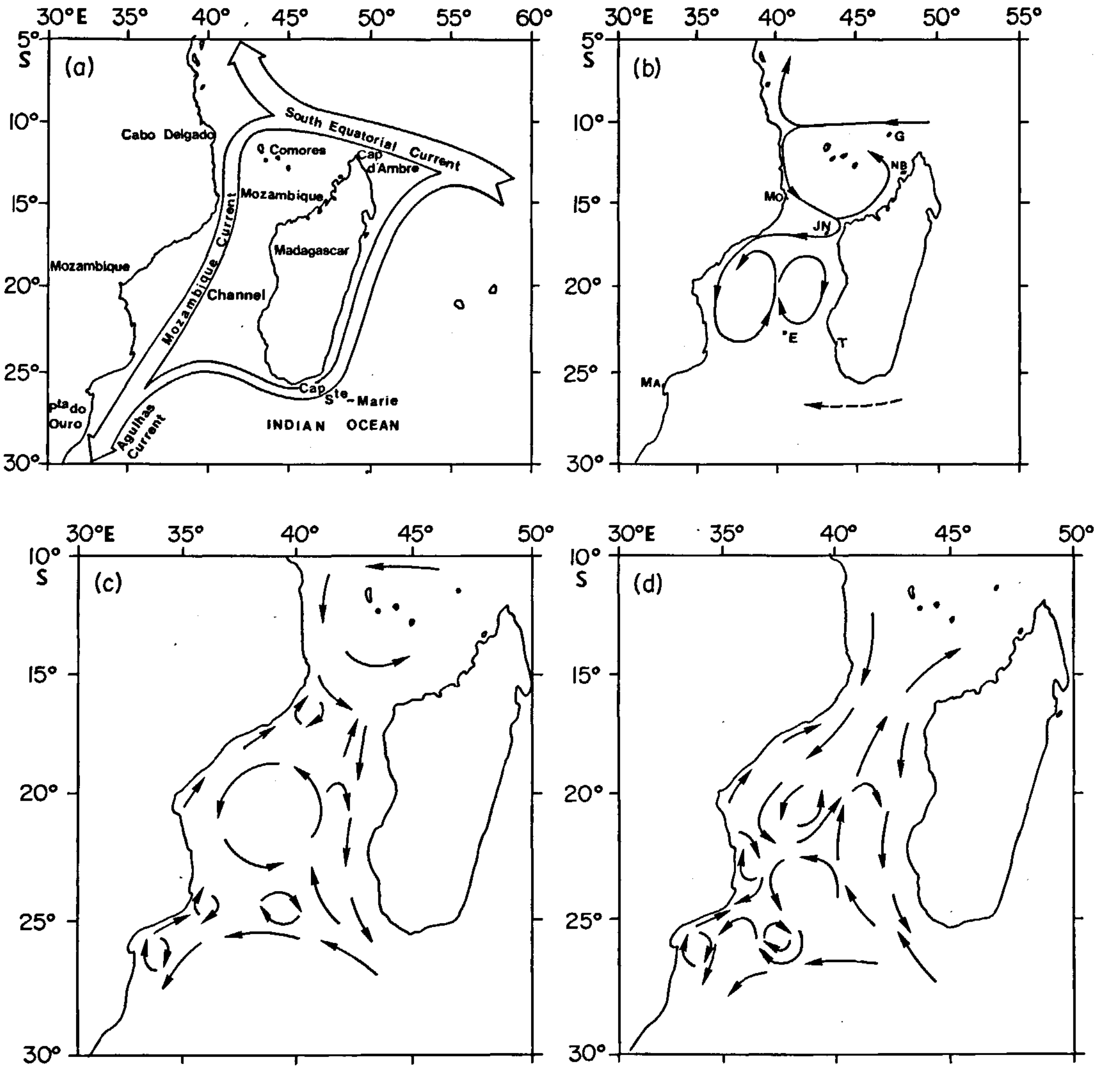

Figure 1

Surface circulation in the Mozambique Channel: a) historical scheme from Saetre (1985); b) scheme submitted by Soares (1975). Meteorological and tide gauge stations are located on this map: G, Glorieuses Islands; JN, Juan da Nova; E, Europa; MO, Moçambique Island; NB, Nosy-Bé; MA, Maputo; T, Tulear; c) scheme submitted by Saetre and Da Silva (1984) during the southern summer; d) same as c) except during the southern winter.

Circulation de surface dans le canal de Mozambique : a) schéma historique, d'après Saetre (1985) ; b) schéma proposé par Soares (1975). Position des stations météorologiques et des marégraphes : G, Iles Glorieuses ; JN, Juan da Nova ; E, Europa ; MO, Ile Moçambique ; NB, Nosy-Bé ; MA, Maputo ; T, Tuléar ; c) schéma proposé par Saetre et Da Silva (1984) en été austral ; d) même schéma que c) mais en hiver austral.

southward flow through the Mozambique Channel seems more complicated than this schematic pattern, as illustrated on Figures 1 *b*, 1 *c* and 1 *d* from Soares (1975) and Saetre and Da Silva (1984). Our intention here is to provide new evidence of this flow and its seasonal variability.

DATA

The meridional flow through the entire channel can be investigated by the difference between the sea level on each side of the Mozambique Channel. To illustrate the variability of this flow, we shall rely on sea-level records by tide gauges kindly provided by EPSHOM (Brest) and

Table 1

Location of the tide gauge stations in latitude and longitude and the period of records available.

Position des marégraphes en latitude et longitude et période d'enregistrement disponible.

	Latitude	Longitude	Record time
Nosy-Bé	13° 24 S	48° 18 E	Jan.1958-June 1967
Moçambique Island	15° 02 S	40° 44 E	Jan. 1963-Dec. 1964
Tulear	23° 22 S	43° 40 E	March 1963-Dec. 1967
Maputo	25° 59 S	32° 34 E	Jan. 1961-Dec. 1967

Table 2

Sequence of events connected to the monsoon in the North and in the South Mozambique Channel.

Séquence des événements rattachés à la mousson au nord et au sud du canal de Mozambique.

		M	A	M	J	J	A	S	O	N	D	J	F
NORTH MOZAMBIQUE CHANNEL													
				SW monsoon						NE monsoon			
Sea level	Madagascar				Low						High		
	Africa	Low							High				
Gyre				Anticyclonic						Anticyclonic			
Flow anomaly					Northward						Southward		
SOUTH MOZAMBIQUE CHANNEL													
		M	A	M	J	J	A	S	O	N	D	J	F
				SW monsoon						NE monsoon			
Sea level	Madagascar						Low				High		
	Africa								Low		High		
Gyre							weak changes						
Flow anomaly			Northward								Southward		

PSMSL (Birkenhead), at four locations in the Mozambique Channel (Nosy-Bé and Tulear in the East, Moçambique Island and Maputo in the West; Tab. 1; locations on Fig. 1 *b*) in 1963 and 1964. This data set is representative of coastal areas (Fig. 2 and Tab. 2) on both sides of the Mozambique Channel.

The wind was recorded between 1970 and 1975 at two low islands located in the northern and southern Mozambique Channel: Glorieuses (11°30 S, 47°22 E), Europa (22°21 S, 40°21 E). The meteorological stations located on these islands are operated by the French Meteorological Service ; measurements are made every three hours. Wind observations at Juan de Nova located in the centre of the channel (17°03' S, 42°43' E) started only in 1974.

French oceanographic cruises were numerous in the Mozambique Channel from 1965 to 1975, due to the presence of the R/V Vauban at the Centre ORSTOM de Nosy-Bé (Madagascar). This vessel carried out several cruises in the area not only with classic hydrographic measurements but also with direct surface current measurements using a Geomagnetic Electro Kinetograph (GEK), the accuracy of which has been estimated at ± 0.04 m s^{-1} in velocity and at ± 8° in direction (Piton and Poulain, 1974). As the measurements reached only 550 m depth, the geostrophic flow has been calculated relatively to 500 dbar. It is known that the near surface circulation extends deeper (Lutjeharms, 1976) and also that the seasonal variability does penetrate deeper (Donguy and Piton, 1969). The scarce distribution of the hydrographic stations is not able to resolve all the

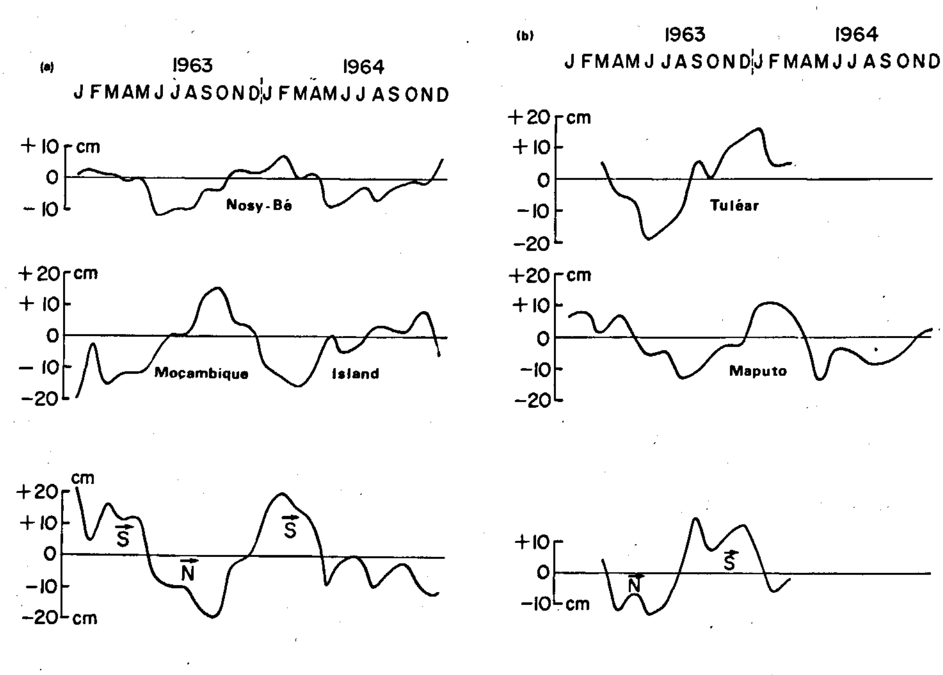

Figure 2

1963-1964 sea level and sea level difference (in cm): a) at Nosy-Bé (up) and Moçambique Island (down); (b) at Tulear (up) and Maputo (down). In the lower case, sea level difference and direction of the inferred flow.

Niveau moyen et différence de niveau moyen en 1963-1964 : a) à Nosy-Bé et à l'île Moçambique ; b) à Tuléar et à Maputo. En bas, différence de niveau moyen et direction du flux.

scales of the circulation within the channel. However, the qualitative agreement between the geostrophic estimate and the absolute surface current from GEK measurements suggests that the essence of the near-surface variability in the dynamic height field has been captured.

Piton (1989) has presented the hydrographic sections (0-600 m) and the current measurements as well as the wind recorded at three meteorological stations operated on low islands of the Mozambique Channel by the French Meteorological Service: Glorieuses (11° 30' S, 47° 22' E), Juan de Nova (17° 03' S, 42° 43' E) and Europa (22° 21' S, 40° 21' E) (locations on Fig. 1 *b*). Three cruises will be considered : two during the warm season (*Mozambique* cruise February-March 1974 and *Juan de Nova* 4 cruise , March 1975) and one during the cool season (*Europa* cruise, June-July 1974). Both geostrophic currents and absolute surface current measurements from GEK were collected.

MERIDIAN CIRCULATION IN THE MOZAMBIQUE CHANNEL

Conditions in the northern Mozambique Channel

The conditions in the northern Mozambique Channel (north of 17°S, where the channel is narrowest) are first considered:

Sea level data at Nosy Bé and Moçambique Island (Fig. 2 *a*) and the wind field at Glorieuses Island (north of Mozambique Channel; Fig. 3) are compared. Annual variations are obvious in sea level at both stations. These are partly related to the sea surface temperature variations associated with the seasonally varying air-sea exchanges (Colborn, 1975). The wind field also presents an annual variability for both meridian and zonal components.

Hastenrath and Lamb (1979) do not report zonal change of the air-sea flux of heat in the channel but the space resolution of the data in the atlas is not sufficient to ascertain that the only cause of the variability of the zonal sea level slope is the intensity of meridian flow.

SW monsoon

In 1963 and 1964 along the coast of Madagascar (Nosy Bé), the sea level is low in this season and rather high at the African coast (Moçambique Island), particularly during September-October 1963 (Fig. 2 *a*). The sea level difference between Nosy Bé and Moçambique Island indicates a northward surface flow relative to the mean which is probably located close to Madagascar under the form of a coastal flow associated with upwelling. Off the African coast, the flow is usually southward (Donguy and Piton, 1969); high sea level is an index of weak current. The wind at Glorieuses Island (Fig. 3) has also a northward component which is consistent with the flow and also with the coastal current off Madagascar. A weak southward current in the west of the Mozambique Channel and a coastal northward flow in the east infer the existence of an anticyclonic eddy. Harris (1972) indicates that an anticyclonic eddy was indeed present in September-October 1964.

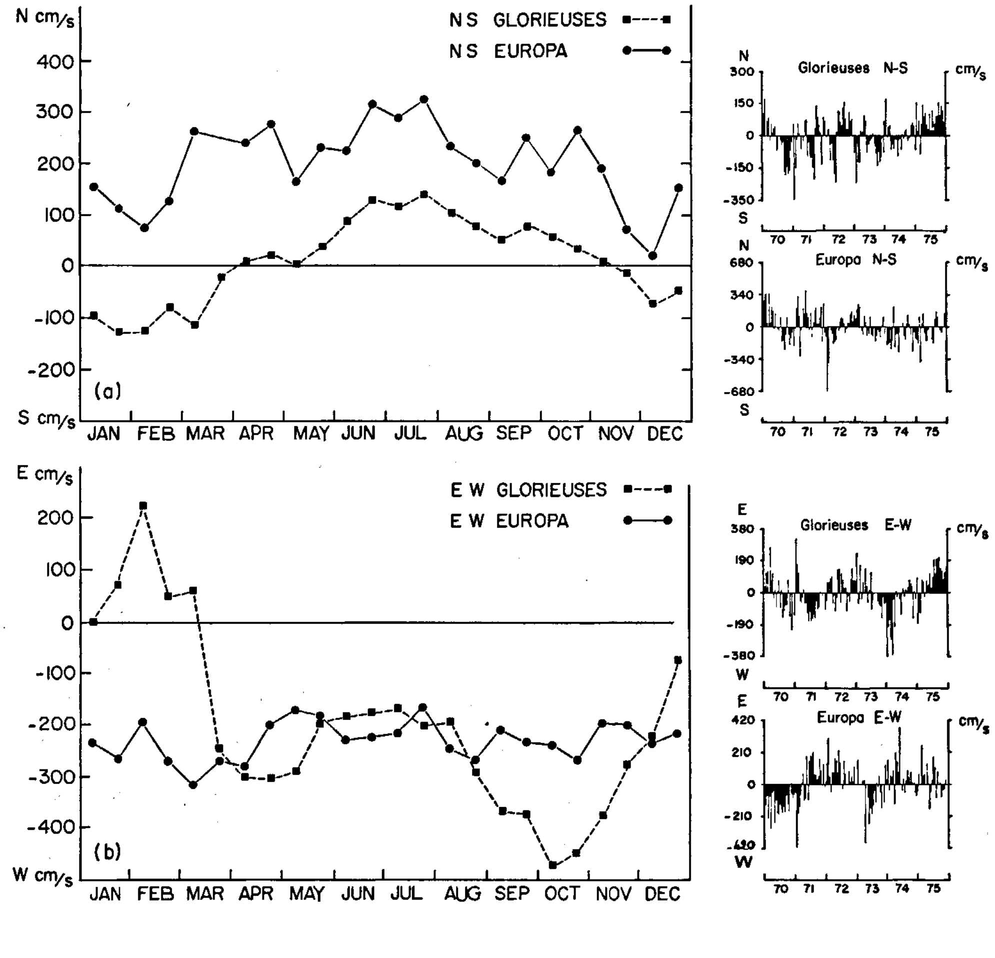

Figure 3

Evolution at Glorieuses and Europa Islands of the: a) meridian; and b) zonal component of the wind, two weeks data averaged, from 1970-1976 measurements. Right: anomalies relative to average.

Évolution aux Iles Glorieuses et Europa de la composante du vent méridienne (a) et zonale (b), par moyenne de deux semaines, à partir de mesures faites de 1970 à 1976. A droite : anomalies par rapport à la moyenne.

NE monsoon

Along the coast, in the northern Mozambique Channel, the sea level (Fig. 2 *a*) is low at the coast of Africa where upwelling occurs ; it is high at the coast of Madagascar. The sea level difference between Nosy Bé and Moçambique Island indicates a maximum southward flow which, at this season, is mostly concentrated along the African continental shelf, according to Nehring *et al.* (1984). Off the coast of Madagascar, the flow is usually northward (Donguy and Piton, 1969) and weak as the sea level is high. A strong southward flow in the west of the Mozambique Channel and a weak northward flow in the east infer the existence of an anticyclonic eddy (Lutjeharms, 1976).

Colborn (1975), by analysis of the thermal structure in historical data of the Mozambique Channel, shows that the seasonal changes of the thermal structure are consistent with the sea level observed at Moçambique Island (west of the Channel): a shallow thermocline occurs during the NE monsoon at the time of low sea level. Moreover, the monthly mean topography of the 20° C isotherm in the northern Mozambique Channel (Quadfasel, 1982) is consistent with Colborn's analysis. On the other hand, Donguy and Piton (1969) present for Nosy Bé (east of the channel) a different seasonal cycle of temperature with the lowest thermocline during the NE monsoon.

Based on the wind field by Cadet and Dielh (1984), Ekman pumping has been calculated for the same period as the sea level record (1963-1964) at locations off the sea level gauges at Nosy Bé and Moçambique Island, but the values are not consistent with the sea level seasonal cycle. This discrepancy may be explained by the differences of the conditions induced by boundary currents and those induced by the gyre-scale circulation in the open ocean.We now consider the conditions of the southern Mozambique Channel:

Conditions in the southern Mozambique Channel

SW monsoon

During the greater part of the SW monsoon, the sea level is low on each side of the Mozambique Channel (Tulear and Maputo; Fig. 2 *b*) and also in the centre according to the isotherm depths (Colborn, 1975). So, the change in the anticyclonic component of the circulation is not obvious. However, the sea level difference between Tulear and Maputo indicates first a surface northward flow between March and August and then a southward flow relative to the mean until the end of January.

NE monsoon

During the NE monsoon, the sea level is high on each side of the Mozambique Channel (Tulear and Maputo; Fig. 2 *b*) and also in the centre according to the isotherm depth (Colborn, 1975). The sea level difference between Tulear and Maputo indicates a southward flow relative to the mean in accordance with a southward 15 sverdrup (Sv, 10^6 m^3 s^{-1}) flow relative to 600 dbar found by Nehring *et al.* (1984).

In the south of the channel, at Europa Island, SE trade winds are prevailing throughout the year without apparent influence on the seasonal variations of the resulting flow.

In conclusion, it seems that the regime of the surface circulation in the northern Mozambique Channel is as follows (Tab. 2):

- from March to November, *i. e.* from the end of the NE monsoon to the end of the SW monsoon, an anticyclonic gyre prevails. The zonally averaged flow anomaly is northward;
- from November to March, an anticyclonic gyre prevails also, but the resulting flow anomaly is southward.

In the southern Mozambique Channel, the flow anomaly is northward from March to August and southward from August to February.

It is important to note that the resulting flows in the northern and southern Mozambique Channel are roughly in phase, with a net seasonal cycle of the meridian transport through the channel. These features are to be compared with the circulation observed during several unpublished cruises in the Mozambique Channel from classical hydrographic measurements and direct absolute current measurements with GEK.

UNPUBLISHED CRUISES IN THE MOZAMBIQUE CHANNEL

Mozambique cruise (22 February-28 March 1974; Fig. 4)

In the northern part of the Mozambique Channel, an anticyclonic eddy clearly appears, as already suggested by Donguy and Piton (1969), Lutjeharms (1976) and confirmed by Nehring *et al.* (1984). This eddy is fed in the north by the westward flowing South Equatorial Current. The South Equatorial Current accelerates as it passes the Cap d'Ambre, north of Madagascar, reaching a velocity of 1.5 m s^{-1} measured both by GEK and calculated from dynamic heights and transporting 23 Sv from the surface to 300 m depth [with a reference at 500 dbar; Piton, 1989 (Swallow *et al.*, 1988 found 7 to 18 Sv with a reference level at 1100 dbar)]. At 12° S, the velocity decreases from 1.3 m s^{-1} at 45° E to 0.5 m s^{-1} in the vicinity of Africa and the current separates into two coastal branches, one flowing northwestward and carrying 11 Sv up to 300 m depth, the other called the Mozambique Current southward and carrying 15 Sv. At 17° S, the current crosses the channel reaching 2 m s^{-1} according to GEK measurements with a transport of 19.4 Sv according to geostrophic estimate referred at 500 dbar. At the Madagascar shelf, the current again separates into two branches : a southeastward one (16 Sv) and a northward one (9 Sv), this latter as a part of the anticyclonic eddy extending over the northern Mozambique Channel. Due to the lack of measurements between Madagascar and Comoro Islands it is not possible to estimate how much flow from the anticyclonic eddy recirculates into the South Equatorial Current.

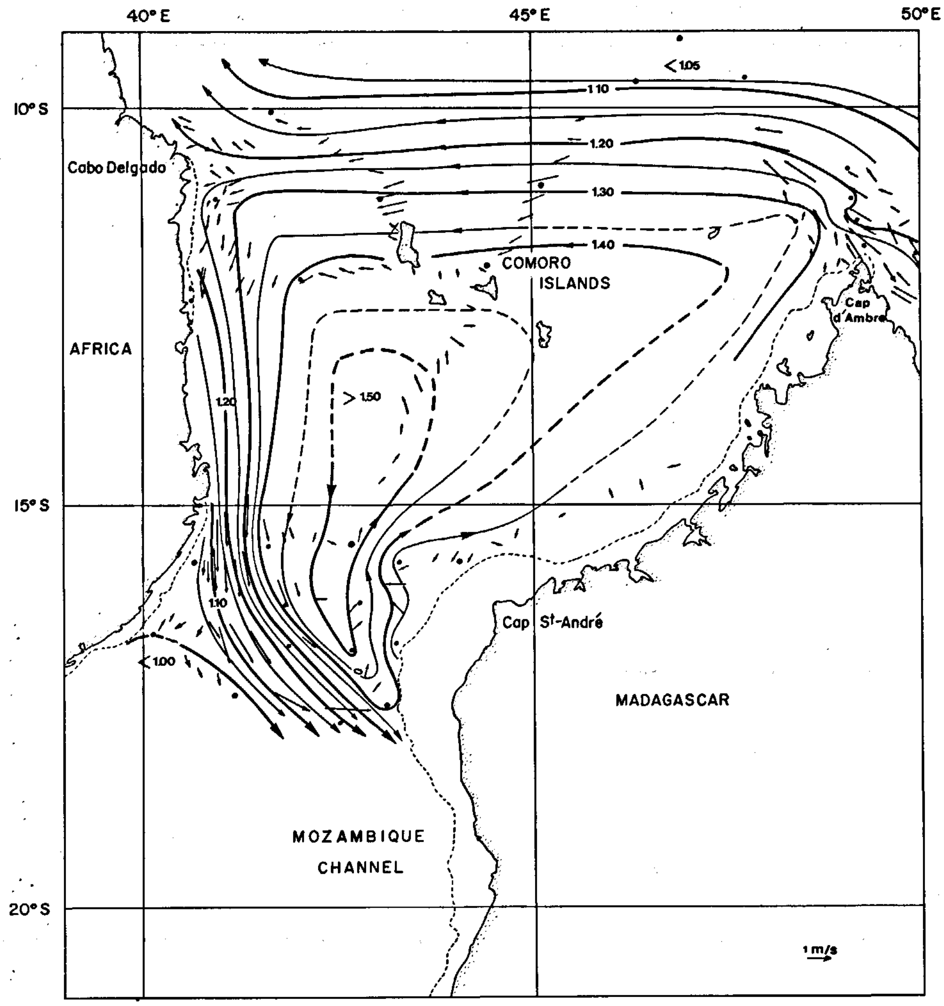

Figure 4

Cruise Mozambique *(22 February-28 March 1974). Surface circulation inferred from surface dynamic heights relative to 500 decibars and from GEK measurements. Note that the current velocity scale for GEK measurements is different from Figures 5 and 6.*

Croisière *Mozambique* (22 février-28 mars 1974). Circulation de surface d'après les hauteurs dynamiques relatives à 500 décibars et d'après les mesures de GEK. Noter que l'échelle des vitesses mesurées au GEK est différente de celle des figures 5 et 6.

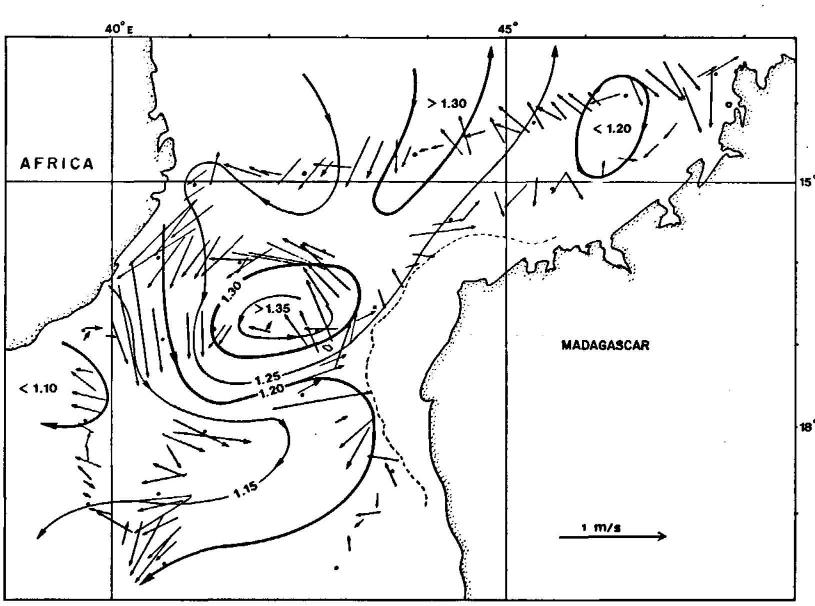

Figure 5

Cruise Juan de Nova IV *(7-21 March 1975). Surface circulation inferred from surface dynamic heights relative to 500 decibars and from GEK measurements.*

Croisière *Juan de Nova IV* (7-21 mars 1975). Circulation de surface d'après les hauteurs dynamiques relatives à 500 décibars et d'après les mesures de GEK.

The salient feature of this cruise is the strong flow crossing the Mozambique Channel through the narrows between 15° and 17°S. This feature is consistent with the wind regime prevailing during the cruise. In the north of the channel (Iles Glorieuses) the wind was mainly ENE. In the centre (Ile Juan de Nova), the wind was variable: first NE, then NW and finally ESE. In the south (Ile Europa), easterly wind prevailed. The wind conditions in the channel were rather favourable to a southward Ekman transport of the surface waters, but the velocity of the wind was small (2 m s^{-1}) and consequently Ekman transport calculated from the wind measured at Juan de Nova Island was weak (0.5 Sv).

Juan de Nova cruise (7-21 March 1975; Fig. 5)

An anticyclonic eddy centred on 16° 30 S is present as it was in 1974 during the *Mozambique* cruise but with a smaller velocity (always less than 1 m s^{-1}). South of around 18° S, the current becomes southwestward. The 0-300 m flow is also smaller than in 1974: the southward flow of the Mozambique Current is only 5.7 Sv at 15° S, whereas the maximum flow through the channel is 9.4 Sv (17°S), but only 4.7 Sv are then going southward (18° S), and the remaining flow northward. In contrast with the previous year, a low atmospheric pressure (less than 1 010 mbar) prevailed over the channel during the early part of 1975, associated with tropical storms or cyclones. In the north of the channel (Iles Glorieuses) the wind was weak and variable. In the centre (Ile Juan de Nova) the wind was SSW, whereas in the south (Ile Europa) a SE wind prevailed. A southward transport of the surface waters was not favoured by such heterogeneous winds. It is interesting to note that this unsettled wind regime was associated with a circulation weaker in February-March 1975 than in February-March 1974.

Europa cruise (17 June-13 July 1974; Fig. 6)

In the central part of the channel, a southeastward current (0.8 m s^{-1}) is again present with a 0-300 m flow carrying 14 Sv at 17° S, feeding a 5.7 Sv northward flow. At 18° S, the current is southwestward with a flow of 7.3 Sv. South of 18° S, several convergent and divergent meanders are observed, centred at 20°-21° S, at 24° S and at about 26°-30° S. The meteorological conditions during the *Europa* cruise are characteristic of the southern winter: high atmospheric pressure, reaching as much as 1 017 mbar in the north and 1 022 mbar in the south. The wind, during the

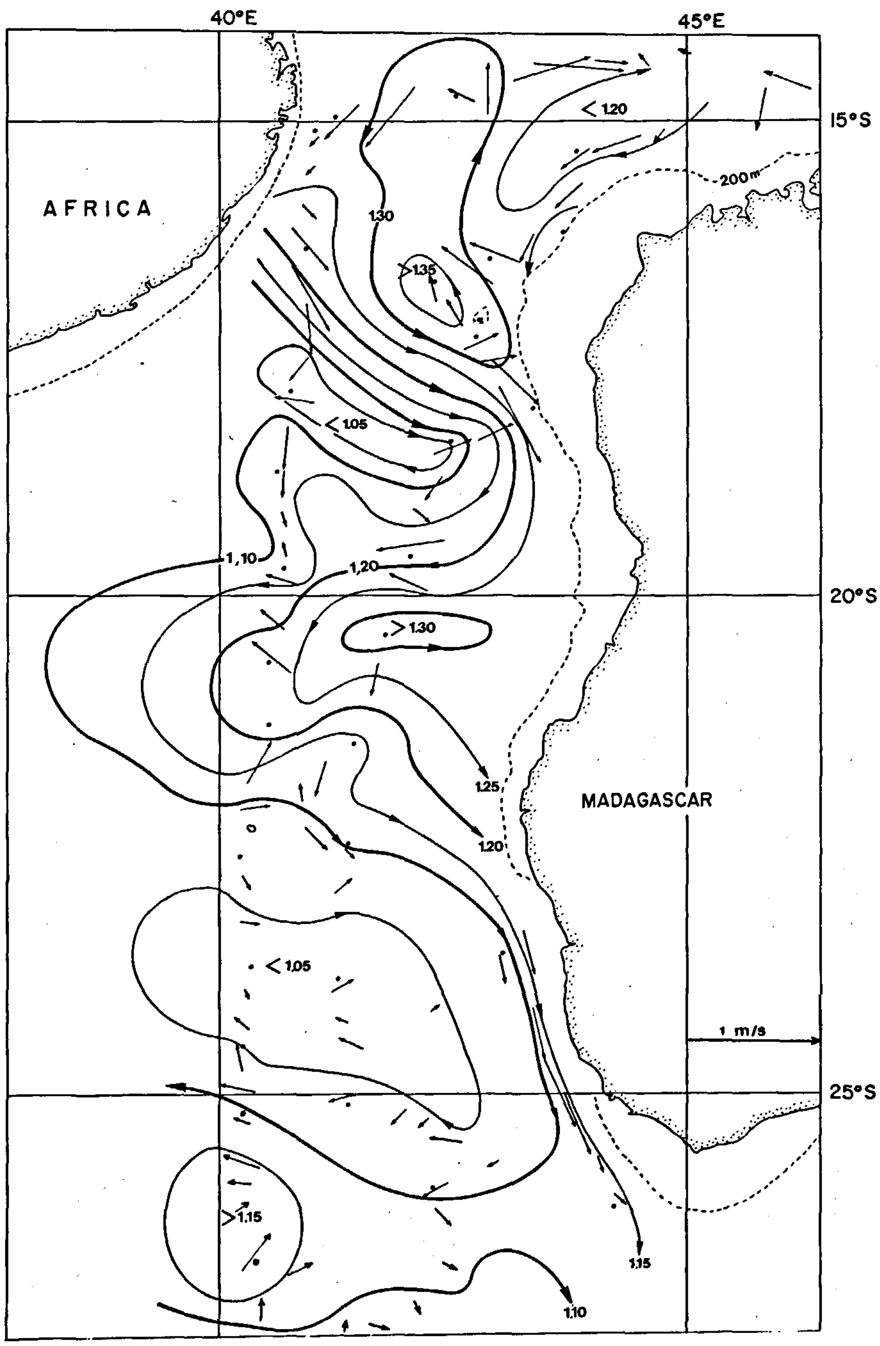

Figure 6

Cruise Europa *(17 June-13 July 1974). Surface circulation inferred from surface dynamic heights relative to 500 decibars and from GEK measurements.*

Croisière *Europa*. Circulation de surface d'après les hauteurs dynamiques relatives à 500 décibars et d'après les mesures de GEK.

cruise, is related to the South Indian anticyclone. In the north of the channel (Iles Glorieuses), the wind is ESE, in the centre (Ile Juan de Nova) and in the south (Ile Europa), it is SE.

In summary, considering the results of the three cruises carried out by R/V Vauban, it is possible to compare the southward flow from the surface to 300 m depth at three locations (Tab. 3) :

- at 15°S along the African coast in the northern eddy (Mozambique Current);
- at 17°S in the "narrows" of the Channel;
- at 18°S along Madagascar in the southern eddy.

Table 3

Geostrophic flow in sverdrup relative to 500 decibars at three latitudes in the Mozambique Channel during each cruise, the flow being southward at 15°S, directed to the southeast at 17°S and westward at 18°S.

Flux géostrophique en sverdrups relatif à 500 décibars calculé à trois latitudes dans le canal de Mozambique lors de chaque croisière, le flux portant au Sud à 15° S, au Sud-Est à 17° S et à l'Ouest à 18° S.

Cruises	15° S S	17° S SE	18° S W
Mozambique	15	19.4	16.6
Juan de Nova	5.7	9.4	4.7
Europa	4.7	14	7.3

The main features and associated questions are:

- The large (15-20 Sv) southward flow of the Mozambique Current in the western boundary at 15° S, mainly during the *Mozambique* cruise. On the other hand, during a cruise of R/V A. von Humboldt, also in February-March (1980) and at 15° S, the transport of the Mozambique Current was larger than 15 Sv.

- The large southeastward flow across the narrows of the channel at 17° S. This flow seems always greater than the southward flow along the African coast at 15° S. This raises the question whether a recirculation occurs or whether the 500 dbar reference level is not appropriate near the coast.

- The strong variability of the flow across the narrows of the channel. This variability seems to be connected with the wind and pressure conditions.

DISCUSSION

The most characteristic features existing during the three cruises studied are an anticyclonic eddy in the northern channel and a well established current flowing south-eastward in the central part of the Mozambique Channel (Fig. 7). The origin of this current is the south part of the South Equatorial Current which diverges off the Cap Delgado at 11°S. The southward branch, called the Mozambique Current, flows along Africa, and crosses the channel with a speed reaching 2 m s^{-1}, inducing a 0-300 m transport of the order of 20 Sv. At 17-18°S, off the Madagascar continental shelf, the flow is divided into two branches. The northward one constitutes the eastern part of an anticyclonic gyre of variable size capable of extending into the entire northern Mozambique Channel, whereas the southern one constitutes mainly the southward flow connecting the South Equatorial Current to the Agulhas Current through a system including several southward meanders. The northern gyre is submitted to seasonal and interannual variabilities which are mostly due to the wind. It has been observed by several authors (Donguy and Piton, 1969; Duncan, 1970; Harris, 1972; Soares, 1975; Lutjeharms, 1976; Parfenovich, 1980; Piton *et al.*, 1981) following the synthesis made by Saetre and Da Silva (1984). At 18°S, the southward transport may reach 16 Sv but the mean transport in the southern part of the channel is close to 10 Sv (Piton, 1989), as suspected by Gordon (1986). Harris (1972) considers a transport of 10 Sv through the narrows as representative.

However, seasonal and interannual variations in sea level on each side of the northern Mozambique Channel (Fig. 2) must induce changes in the southward flow. According to Swallow *et al.* (1988), in the South Equatorial Current, the largest depth responding to seasonal variation off Cap d'Ambre is 200 m. For a 20 cm variation in sea level, the calculation shows that the resulting variation in the southward flow of the Mozambique Current from the surface to 200 m depth at 14°-15°S is 10 Sv. This result is consistent with the measurements noticed in Table 3: the southward flow measured at 15°S varies from 4.7 to 15 Sv.

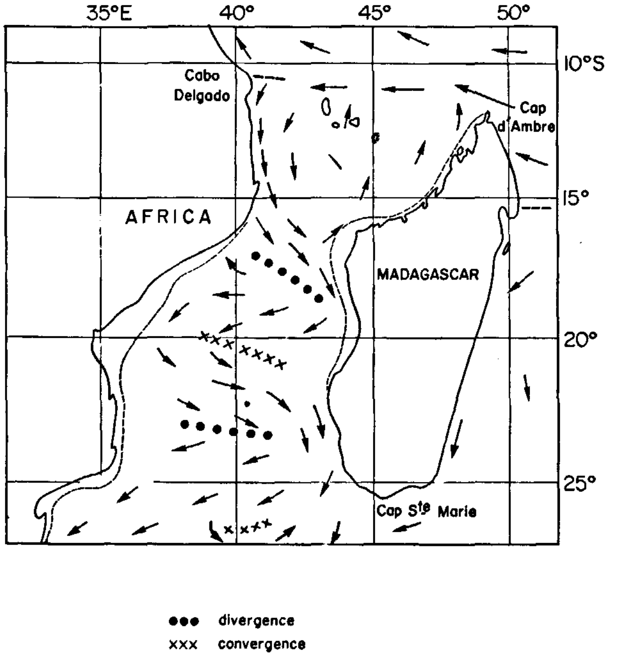

Figure 7

Possible surface circulation scheme in the Mozambique Channel.

Schéma possible de la circulation de surface dans le canal de Mozambique.

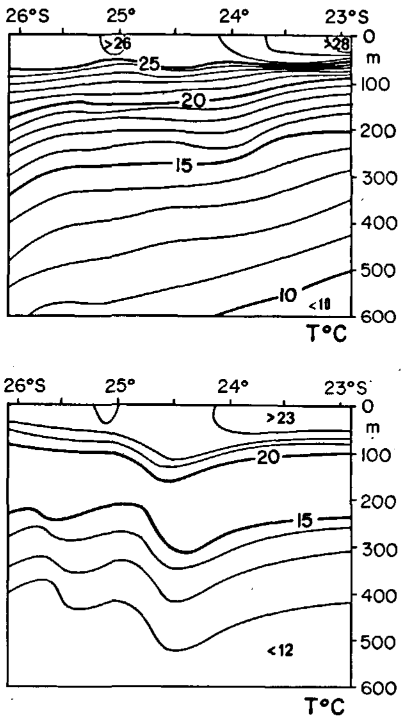

Figure 8

Vertical distribution of temperature approximately along 39°E meridian, 23°-26°S, in February-March 1980 (top) and July-September 1960 (bottom).

Distribution verticale de la température située approximativement le long du méridien 39° E, de 23 à 26° S, en février-mars 1980 (haut) et juillet-septembre 1960 (bas).

In the central and southern Mozambique Channel, the available cruises covering the entire area have been carried out only during the SW monsoon (the cold season; Cdt Robert Giraud 1, 2, 4 and Almirante Lacerda). However, other cruises mainly devoted to biological research have covered parts of the channel during the NE monsoon and the warm season, particularly the African continental shelf. From this data set, Saetre and Da Silva (1984) show that another anticyclonic gyre is located in the central Mozambique Channel with a centre approximately at 20°S, *i. e.* consistent with the circulation scheme from geostrophic and absolute GEK measurements during the Europa cruise. In the same way, near the coast of Madagascar, the strong southward flow observed south of 23°S during the Europa cruise is in good agreement with the results of the other cruises.

During the NE monsoon (the warm season), it seems that the variability of the circulation characterized by a southward flow is not influenced by wind (SE trade winds). Circulation and hydrographic conditions are mostly dependent on the thermohaline conditions. An important heat content is stored seasonally as indicated by the high sea level observed simultaneously at Maputo and Tulear (Tab. 2) and also in the center due to the great depth of the isotherms (Colborn, 1975).

Hydrographical observations resulting from the second cruise of R/V Cdt Robert Giraud (Soares, 1975) during the cold season (July-September 1960) and from a cruise of R/V A. von Humboldt during the warm season (February-March 1980; Nehring *et al.*, 1984) show a common transect close to 39°E between 23°S and 26°S (Fig. 8). There are large differences in the surface temperatures. The depth of the 20°C isotherm is the same at 23°S in both seasons but considerably deeper at 26°S during February-March. Moreover, there is a layer of waters warmer than 25°C (50 m in February-March) which is not present in July-September (cold season). This greater heat content during the warm season is also consistent with the high sea level observed at the same time. On the other hand, slowly meandering surface waters are warmed and reach a temperature 1°C greater there than east of Madagascar (Soares, 1975). These features are associated with the seasonal presence of the Intertropical Convergence Zone of the wind and its associated convective activity, which must result in a net heating of the ocean.

CONCLUSION

Continuous sea level data from four tide gauges on each side of the Mozambique Channel and wind data at two islands provide information on the variations in meridian transport through the channel. In addition, data from three unpublished cruises give more details on the surface circulation, mainly in the northern part of the channel where an anticyclonic gyre occurs. This gyre is monitored by wind, whereas in the southern part of the channel, the circulation is mostly thermohaline. The meridian flow is submitted to a seasonal cycle but the existence of a resulting southward transport is not obvious.

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