Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability, and Management

Edited by

Kenneth Sherman

Director, Narragansett Laboratory; Chief, Oceanography Branch, Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration; Adjunct Professor of Oceanography, Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island

Ezekiel N. Okemwa

Director, Kenya Marine and Fisheries Research Institute, Mombasa, Kenya

Micheni J. Ntiba

Professor, University of Nairobi, Department of Zoology, Nairobi, Kenya; Executive Secretary, Lake Victoria Fisheries Organization (LFVO), Jinga, Uganda

Blackwell Science

Editorial Offices:
350 Main Street, Malden, MA
02148-5018, USA
Osney Mead, Oxford OX2 0EL, England
25 John Street, London WC1N 2BL, England
23 Ainslie Place, Edinburgh EH3 6AJ,
Scotland
54 University Street, Carlton, Victoria 3053,
Australia

Other Editorial Offices:
Blackwell Wissenschafts-Verlag GmbH
Kurfürstendamm 57
10707 Berlin, Germany

Blackwell Science KK
MG Kodenmacho Building
7–10 Kodenmacho Nihombashi
Chuo-ku, Tokyo 104, Japan

First published 1998

Acquisitions: Nancy Hill-Whilton
Production: Ellen Samia
Manufacturing: Lisa Flanagan
Typeset by Northeastern Graphic Services, Inc.
Printed and bound by Edwards Brothers, Inc.
Printed in the United States of America
98 99 00 01 5 4 3 2 1

Distributors
Marston Book Services Ltd
PO Box 269
Abingdon, Oxon OX14 4YN
England
(*Orders*: Tel: 44-01235-465500
Fax: 44-01235-465555)

USA
Blackwell Science, Inc.
Commerce Place
350 Main Street
Malden, MA 02148-5018
(*Orders*: Tel: 800-759-6102
617-388-8250
Fax: 617-388-8255)

Canada
Login Brothers Book Company
324 Saulteaux Crescent
Winnipeg, Manitoba, R3J 3T2
Canada
(*Orders*: Tel: 204-224-4068)

Australia
Blackwell Science Pty Ltd
54 University Street
Carlton, Victoria 3053
(*Orders*: Tel: 3-9347-0300
Fax: 3-9349-3016)

Library of Congress Cataloging-in Publication Data

Large Marine Ecosystems of the Indian Ocean:
Assessment, sustainability, and management / edited by Kenneth Sherman, Ezekiel Okemwa, Micheni Ntiba.
p. cm.
The studies published in this volume were selected from among those presented at the Symposium on the Status and Future of Large Marine Ecosystems of the Indian Ocean, held in Mombasa, Kenya in 1993.
Includes bibliographical references and index.
ISBN 0-632-04318-0
1. Marine ecology—Indian Ocean Region— Congresses. 2. Marine resources —Indian Ocean Region—Management —Congresses. I. Sherman, Kenneth, 1932– . II. Okemwa, E. (Ezekiel) Ntiba, M.J. (Micheni J.) IV. Symposium on the Status and Future of Large Marine Ecosystems of the Indian Ocean (1993: Mombasa, Kenya)
QH94.L37 1998 97-43188
577.7'5 — dc21 CIP

8

Role of Oceanic Fronts in Promoting Productivity in the Southern Indian Ocean

Harilal B. Menon

Abstract

The role of oceanic fronts as highly productive areas are discussed. Using hydrographic data, the mean positions of fronts have been delineated. Surface chlorophyll *a* data were used to study productivity. From 16 crossings, the mean positions of the Subtropical Front (STF) and the Antarctic Polar Front (APF) in the western region are found to be at 41°9′S and 50°43′S, respectively, whereas it is observed that the mean positions of the STF, the Subantarctic Front (SAF), and APF from 20 crossings in the eastern region are at 38°57′S, 47°9′S, and 51°6′S, respectively. As the morphology of the fronts varies in the study area, the area has been divided into two regions, western and eastern. Although all fronts are highly productive in nature, the productivity varies. In the western region, the concentration of chlorophyll *a* at the STF is comparable with that at the APF, 0.5 and 0.6 mg/m^3, respectively. Similarly, in the eastern region, the chlorophyll *a* concentration at the STF is 0.15 mg/m^3 and at the SAF and APF are 0.6 and 0.9 mg/m^3, respectively. The incidence of high chlorophyll *a* values at the frontal zones has been discussed, and it is observed that among the different factors affecting the biota, stability plays a major role.

Introduction

The Antarctic Circumpolar Current (ACC) contains several current cores with large eastward speed relative to the water in which they are embedded. These were first described in detail by Deacon (1) and Mackintosh (2). The current cores observed in the Drake Passage are high velocity (35 cm/sec at the surface), narrow (50 km) bands embedded in slower and wider zones (3,4). These current cores are frontal zones with pronounced horizontal gradients of temperature, salinity, density, and nutrients. Generally, there are three fronts in the Southern Ocean: Antarctic Polar Front (APF), Subantarctic Front (SAF), and Subtropical Front (STF). But the Drake Passage region of the Southern Ocean STF is absent, whereas another front, Continental Water Boundary (CWB), is found nearer the Antarctic continent (5). A front analogous to the CWB is found at some locations but generally not where the ACC is far from land. The works of Emery (6) and Clifford (7) show that only SAF and APF are circumpolar in extent. Edwards and Emery (8) emphasized the existence of the STF in the Australasian Southern Ocean. Its existence south of Africa has been discussed by Lutjeharms (9), whereas its presence throughout the Indian Ocean sector of the Southern Ocean was established by Menon (10).

Oceanic fronts also affect the biota of an area, because they are associated with increases in nutrients that determine productivity and species composition. Pingree and Mardell (11) and Pingree et al. (12) have studied biologic enhancement at tidal fronts.

Investigations of Marra et al. (13) have shown an increase in the concentrations of surface chlorophyll at shelf-break fronts. Different hypotheses have been put forth to explain the mechanism behind the relationship between fronts and productivity. Moreover, the Southern Ocean, being a region characterized by well-demarcated fronts, is an ideal area to test some of the proposed hypotheses. It has further been noted that the primary production of the Southern Ocean as a whole is quite low, despite the presence of fronts (14–18). Therefore, there is a need to understand how fronts contribute to productivity in the Southern Ocean. Less attention has been paid to open-ocean fronts and productivity, especially in the Indian Ocean sector of the Southern Ocean (20° to 115°E). Hence, these fronts, because of their unique spatial characteristics and their variation in intensity from west to east, may be considered as areas for studying not only the interaction between physical and biologic factors in promoting open-ocean biologic productivity in general but also the Southern Ocean's primary productivity in particular.

Data and Methodology

All available published and unpublished hydrographic data collected from the Indian Ocean sectors of the Southern Ocean have been used for the present

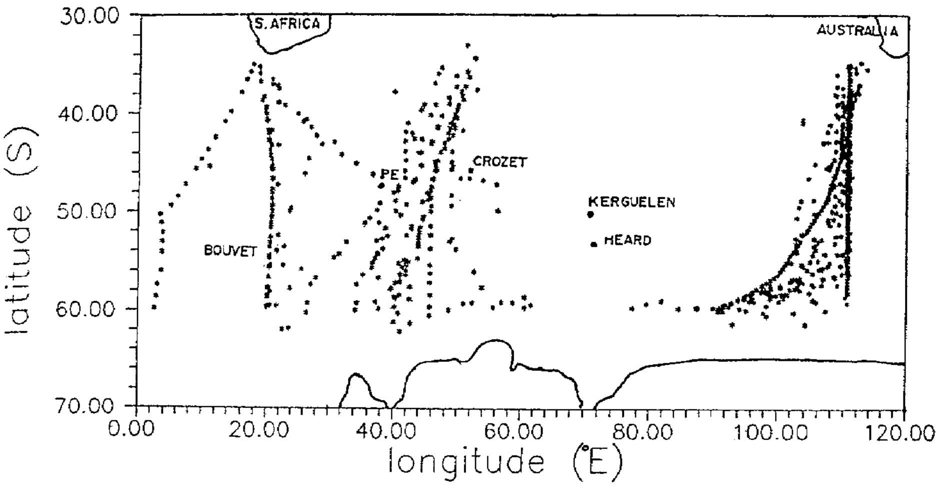

Figure 8-1. Location of station positions.

study. In addition to the above data, expendable bathythermograph (XBT), and sea-surface temperature observations have been used. To study the relationship between fronts and productivity, surface chlorophyll *a* data have been used. The station locations of the hydrographic, XBT, and sea-surface temperature observations are given in Figure 8-1. The details of chlorophyll *a* data are given in Table 8-1.

Table 8-1. Data source for the present work, collected during Japanese Antarctic Research Expedition (JARE) cruises aboard Shirase and Fuji

Cruise Number	Year	No. of Chlorophyll *a* data	Method
9	1967–68	127	Fluorometry
14	1972–73	129	Fluorometry
16	1974–75	139	Colorimetric
17	1975–76	127	Colorimetric
18	1976–77	135	Colorimetric
19	1977–78	134	Colorimetric
20	1978–79	202	Fluorometry
21	1979–80	191	Colorimetric
22	1980–81	150	Colorimetric
25	1983–84	3525	Fluorometry

Identification of Fronts

The most common method used to identify fronts involves the determination of relatively large horizontal gradients in surface hydrographic properties. Occasionally, the APF does not manifest in a sharp gradient in surface temperature, especially in summer when warming of the surface layer obliterates the gradient. Because the data for the present study were taken during the summer, the position of the APF is identified as the northern limit of a 2°C isotherm in the subsurface temperature-minimum layer (19). But the position of the APF, from the surface data, has been identified according to the definition of Ostapoff (20), which states that the APF is the maximum sea-surface temperature gradient between 2 and 6°C.

The front that is found at the most vertically oriented isotherm within a subsurface temperature gradient between 3 and 5°C is the SAF. To identify the SAF from surface data, the method of Lutjeharms and Valentine (21) has been adopted. According to that, the SAF is the strongest surface temperature gradient occurring within the temperature range of 3.5 to 11°C and the latitudinal range of 42°40′S to 49°S. Usually, the SAF corresponds to the steepest horizontal gradient in temperature between the STF and APF. Because a large variation is seen in the properties of major fronts in the Southern Ocean, a statistical analysis has been done with all the hydrographic, XBT, and surface observations. The quality of the data varies. All the crossings (sections) have been subdivided into three groups. These are surface readings, XBT readings, and hydrographic casts. Although average parameter values were calculated from each category, it was found that the average values are not different. Hence, by combining all data, statistical analyses have been done to study the characteristics of the fronts. The various characteristics of each front, like its midlatitude position, width, and range of temperature and salinity with their gradients, have been computed for every meridian crossing.

Classification of Waters into Different Regions

For this study, the chlorophyll *a* concentration of surface waters has been used to assess the standing stock of phytoplankton, thus representing potential primary production in the Southern Ocean. Because major fronts in the area show strong distinction in their structure from the western to eastern region, the study area has been divided into two regions: one west of 60°E and the other east of 85°E (85 to 115°E). The general characteristics in the respective regions are derived by averaging that region's properties. Additional data based on several crossings of ships of opportunity, which include both surface and XBT observations, have also been considered to obtain the general properties of different water regions in the Indian Ocean sector of the Southern Ocean.

The data used in the eastern region are from early summer, whereas the western region data are from the late summer. This facilitates the study of chlorophyll *a* concentrations at each frontal zone with the advance of the summer season. The latitude 60°S is taken as an arbitrary southern limit of the study area, because south of it the presence of pack ice together with icebergs affect the concentration of chlorophyll *a*. The study area therefore covers from 35 to 60°S. The number of data points used to obtain the average surface chlorophyll in the western and eastern regions is 2220 and 2638, respectively. In the western regions of the study area, only two fronts, STF and APF, are discernible; however, in the eastern region, the SAF is also present between the STF and APF. In the western region, either the SAF is absent or merged with the STF (10). Hence, waters in the western and eastern regions can be grouped into different regions as follows:

Western region

1. Subtropical waters between 35°S and the northern boundary of the STF;
2. Waters within the STF zone;
3. Waters within the APF zone;
4. Waters between the APF and 60°S.

Eastern region

1. Subtropical waters between 35°S and the northern boundary of the STF;
2. Waters within the STF zone;
3. Waters between the STF and SAF;
4. Waters within the SAF zone;
5. Waters between the SAF and APF;
6. Waters within the APF zone;
7. Waters between the APF and 60°S.

Tables 8-2 and 8-3 present the means and SDs of various characteristics of different frontal zones for the western and eastern regions, respectively.

To study the physical processes in the frontal zones affecting productivity, the stability at the frontal zones has been examined. For this, the surface and subsurface positions of the STF, SAF, and APF were plotted (Fig 8-2) using the hydrographic data to obtain the north-south frontal slopes that influence the congregation of phytoplankton.

Table 8-2. Fronts in the western region of the Indian Ocean sector of the Southern Ocean

		Latitudinal Location				Temperature (°C)					Salinity (ppt)				
		From	To	Middle	Width (km)	From	To	Middle	Range	Gradient (°C/km)	From	To	Middle	Range	Gradient (%/km)
STF	Mean	40°29′	43°19′	41°59′	309.63	18.16	10.25	14.12	7.72	0.038	35.21	33.99	34.60	1.22	0.004
	SD	1.67	1.45	1.36	167.24	3.17	2.53	2.52	2.76	0.044	0.32	0.35	0.22	0.52	0.003
APF	Mean	49°27′	51°58′	50°43′	275.59	5.32	3.37	4.36	1.94	0.008					
	SD	1.38	1.41	1.17	169.02	1.02	1.09	0.98	0.90	0.005					

Data are from 16 crossings.

Table 8-3. Fronts in the eastern region of the Indian Ocean sector of the Southern Ocean

		Latitudinal Location				Temperature (°C)					Salinity (ppt)				
		From	To	Middle	Width (km)	From	To	Middle	Range	Gradient (°C/km)	From	To	Middle	Range	Gradient (%/km)
STF	Mean	37°31′	40°23′	38°57′	315.31	15.96	12.34	14.15	3.62	0.016	35.35	34.79	35.07	0.56	0.0039
	SD	1.48	1.88	1.36	224.3	1.58	1.44	1.28	1.58	0.100	0.39	0.37	0.37	0.19	0.0042
SAF	Mean	46°31′	48°03′	47°09′	188.56	9.13	6.32	7.71	2.83	0.019					
	SD	1.7	1.24	1.34	113.04	1.5	1.50	1.42	0.96	0.009					
APF	Mean	50°01′	52°10′	51°06′	237.24	4.95	3.05	4.01	1.89	0.010					
	SD	1.10	1.12	0.87	151.09	0.77	0.65	0.56	0.83	0.006					

Data are from 20 crossings.

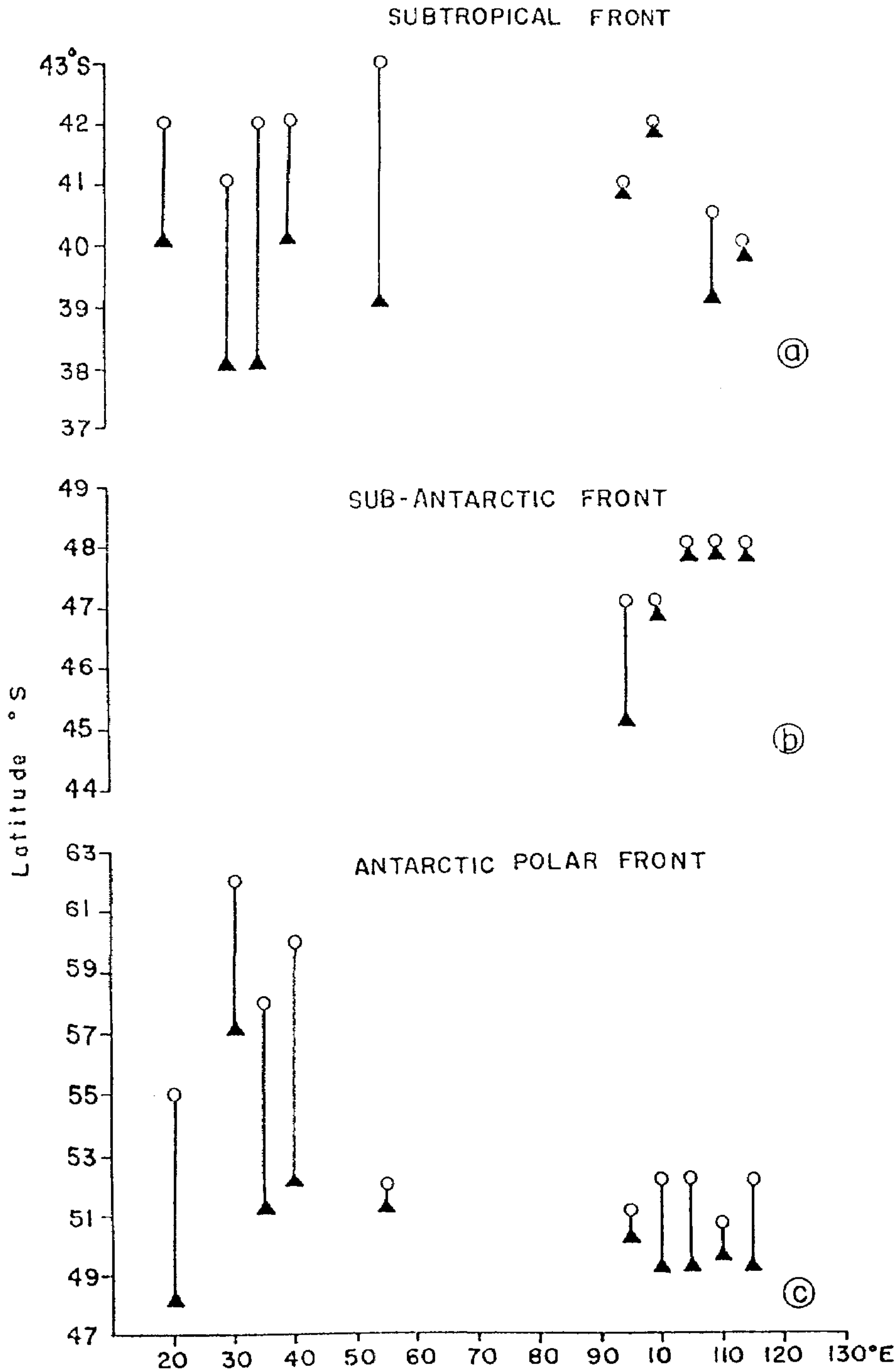

Figure 8-2. Latitudinal locations of surface (○) and subsurface (△) expressions of (a) Subtropical Front, (b) Subantarctic Front, and (c) Antarctic Polar Front; three fronts along different longitudes.

Results

Western Region

SUBTROPICAL FRONT Sixteen crossings were made to delineate the mean structure of the STF (see Table 8-2). In the western region of the study area, the STF lies between latitudes 40°29′S and 43°19′S, with its mean axis at 41°59′S. The mean width of the STF zone is 310 ± 167 km, whereas the temperature is 7.7°C. The mean temperature and salinity gradients across the STF are 0.04°C/km and 0.004 psu/km, respectively. The STF zone has a mean temperature of 14°C and a mean salinity of 34.6 psu. The surface expression of the STF is far south of the subsurface expression (see Fig 8-2) indicating its northward down sloping. The average horizontal distance across which the front maintains its slope is around 3° latitude.

ANTARCTIC POLAR FRONT The mean axis of the APF from 16 crossings in the western region of the Indian Ocean sector of the Southern Ocean is 50°43′S (see Table 8-2). The average width of the frontal zone is 276 ± 167 km. The APF has a mean temperature of 4.4°C and its mean thermal gradient is 0.01°C/km, which is four times less than that of the STF. Further, the APF does not have a large salinity gradient across it. The subsurface expression of the APF is farther north than its surface expression, again indicating northward down sloping like in the case of the STF. The average horizontal distance across which the front maintains its slope is 5.5° latitude.

Eastern Region

In this region, another front, namely the SAF between the STF and APF, is conspicuously present and causes the difference in the frontal morphology of the study area. Data were collected from 20 north-south crossings.

SUBTROPICAL FRONT The mean position is found to be at 38°57′S, with an SD of ±1.4° latitude. The average width of the STF is found to be 315 ± 224 km (see Table 8-3). Although the width of the STF is similar in the western and eastern regions of the study area, the SD is considerably higher in the eastern region, indicating that the STF in the east is more dynamically unstable. The temperature range across the STF in the east is 3.6°C, which is nearly half that found in the west. This results in a smaller temperature gradient, 0.02°C/km, compared with 0.04°C/km in the western region. The salinity gradient across the STF is 0.004 psu/km with a mean salinity of 35.07 psu, which is higher than that in the west. There is less northward down sloping, because both surface and subsurface expressions are not very far apart (see Fig 8-2), whereas in the west, the slope was considerably higher.

SUBANTARCTIC FRONT The SAF is found at a mean location of 47°S, with an SD of ±1.34° latitude (see Table 8-3). Its mean width is approximately 189 km, which is low in comparison with the STF in the eastern region, and the SD of the width is also low (113 km) compared with the STF. The mean temperature of the SAF is approximately 8°C, and the SAF has a slightly higher temperature gradient (0.02°C/km) than the STF. This is stronger than the APF, whose intensity is 0.01°C/km, thus establishing the SAF as the most prominent front in the eastern part of the study area.

ANTARCTIC POLAR FRONT The mean position of the APF in the east is given as 51°S (see Table 8-3). The width of the APF is 237 ± 151 km. The mean temperature of the APF zone is 4°C with a range of 1.9°C and a thermal gradient of 0.01°C/km. In the eastern region, the downward tilt of the APF is greater compared with corresponding tilts of the STF and SAF, but it is less than that of the APF in the west (see Fig 8-2). In general, the downward tilting of fronts is considerably higher in the west than in the east, suggesting a greater intermingling of surface and intermediate water masses in the west.

Meridional Distribution of Surface Chlorophyll *a*

Before presenting the mean horizontal profiles of chlorophyll *a* for different water regimes of the western and eastern regions, it is best to examine a few individual meridional sections typically representing western and eastern regions. Two profiles are selected for this purpose, one between Africa and Antarctica (along 20°E) and the other between western Australia and Antarctica (along 110°E). This facilitates a study on the variability of physical properties and associated chlorophyll *a* concentration.

ALONG 20°E (BETWEEN AFRICA AND ANTARCTICA) The surface distribution of chlorophyll *a* along with surface temperature and salinity is shown in Figure 8-3. The chlorophyll *a* values range from 0.88 to 0.55 mg/m^3. The striking feature of the chlorophyll *a* distribution is the presence of two pronounced maxima around 41° and 50°S. These two maxima represent the STF and APF zones as seen from distributions of hydrographic properties. The first zone of chlorophyll *a* maxima, coinciding with the STF, is due to the convergence of subtropical and subantarctic waters. From there, chlorophyll *a* concentrations decrease, and after reaching a lower value of around 46°S, chlorophyll *a* concentration again picks up at the APF where it registers the highest value of 0.55 mg/m^3.

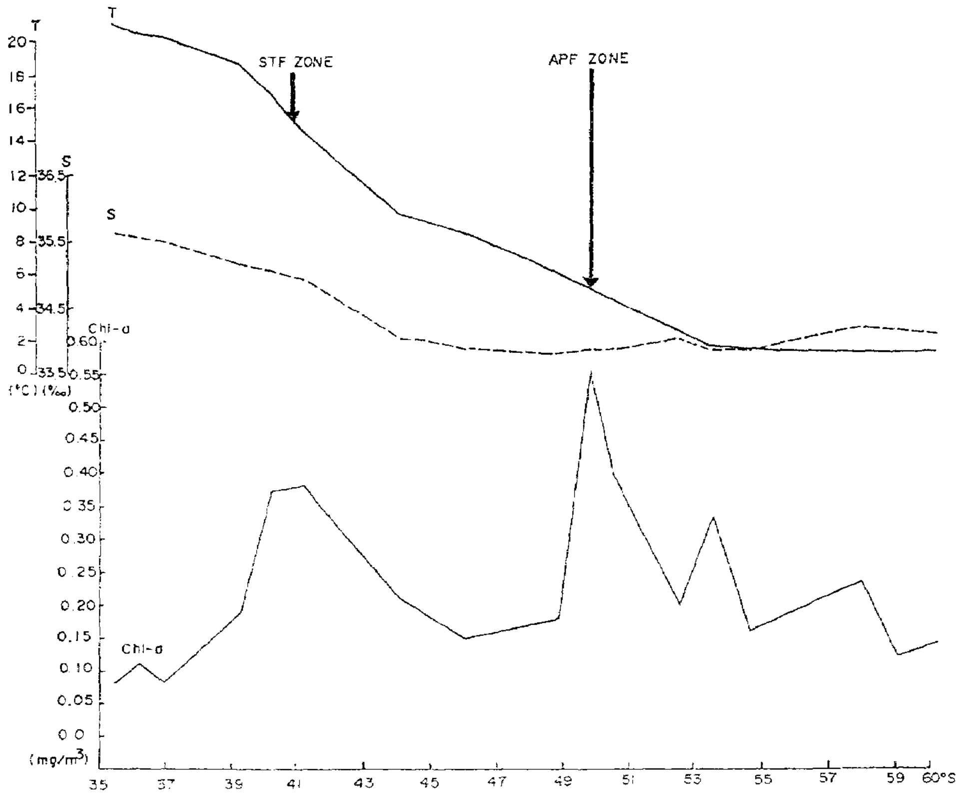

Figure 8-3. The distribution of hydrographic properties and chlorophyll *a* along 20°N.

Further south it shows a complicated structure characterized by the incidence of intermittent high and low values. The remarkable association of maximum values with the frontal zone is the most conspicuous feature of the meridional distribution.

ALONG 110°E (BETWEEN WESTERN AUSTRALIA AND ANTARCTICA) Figure 8-4 shows the distribution of surface chlorophyll *a*, temperature, and salinity along 110°E. The association of maximum chlorophyll *a* with the frontal zone is further confirmed as seen from the coincidence of peaks of chlorophyll *a* concentration with the STF, SAF, and APF. At the STF, the chlorophyll *a* concentration is approximately 0.27 mg/m^3. Although in this region the SAF is stronger than the APF, the intensity of the chlorophyll *a* concentration at the SAF is lower than at the APF. However, the general occurrence of higher chlorophyll *a* suggests the importance of the Antarctic waters as a productive regime.

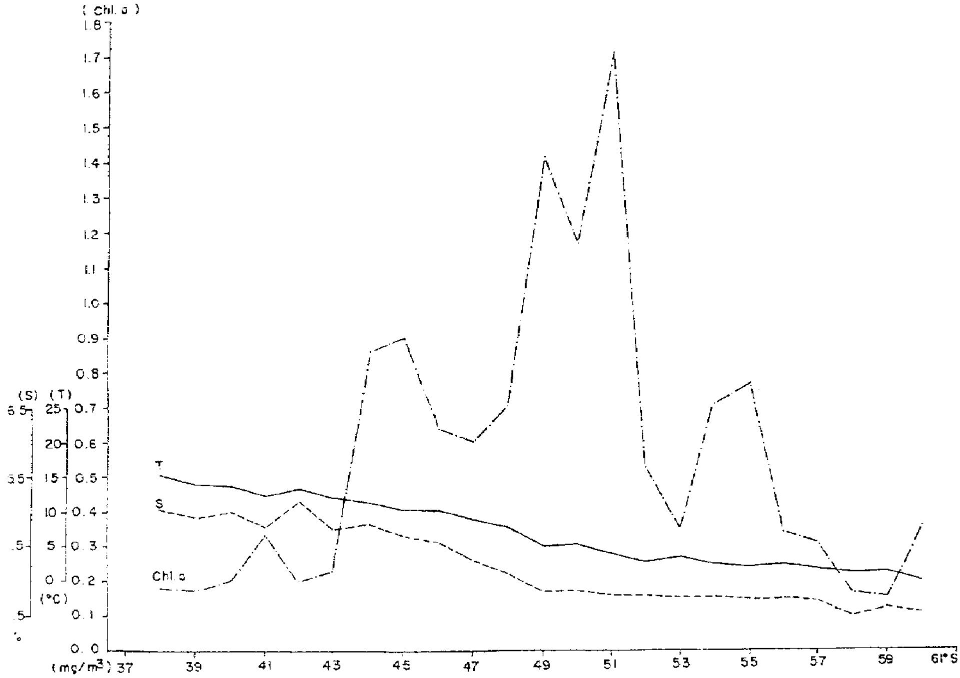

Figure 8-4. The distribution of hydrographic properties and chlorophyll *a* along 110°E.

Mean Distribution of Chlorophyll *a* in Different Water Regimes

The mean and SD of surface chlorophyll *a*, as shown by a dot and dashed line for each regime of the western and eastern region of the study area, are given in Figures 8-5 and 8-6, respectively.

WESTERN REGION Figure 8-5 shows the presence of two well-defined maxima in chlorophyll *a* values from the subtropical region to 60°S. It shows an increase of approximately 0.3 mg/m^3 in the mean surface chlorophyll *a* values from subtropical waters to the waters within the STF zone, where a chlorophyll *a* value of approximately 0.5 mg/m^3 is encountered. Further south, again chlorophyll *a* concentration increases to greater than 0.6 mg/m^3 at the APF zone. Between the APF and 60°S, a sharp declination in chlorophyll *a* is discernible. The incidence of higher chlorophyll *a* SDs at both the APF (± 0.72) and the STF zones (± 0.54) reveals their complex dynamic nature.

EASTERN REGION The latitudinal distribution of chlorophyll *a* and its SD for different water regimes in the eastern region of the study area are shown in Figure 8-5. As in the western region, the incidence of maximum values (>0.09 mg/m^3) along with a high SD (± 0.37) takes place in the APF zone. Figure 8-6

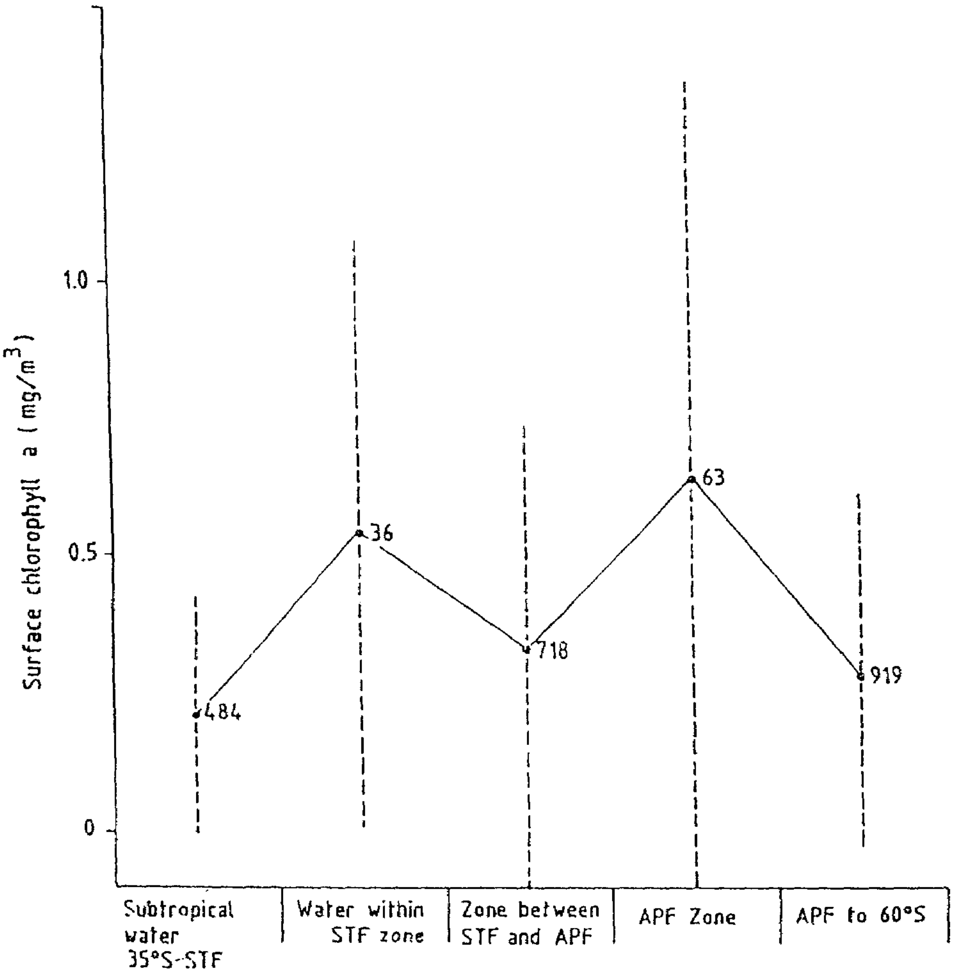

Figure 8-5. Mean and SD of surface chlorophyll *a* in different water regimes in the western region. The number of data points used for each regime is also indicated at the center of the dashed line.

shows a gradual increase in the surface chlorophyll *a*, from approximately 0.15 mg/m^3 in subtropical waters to a maximum value (>0.6 mg/m^3) at the SAF, without the presence of any intermediate maximum at the STF as in the west. South of the SAF, chlorophyll *a* concentrations decrease considerably to a value of 0.53 mg/m^3. From there, another rise occurs in chlorophyll *a*, reaching greater than 0.9 mg/m^3 at the APF zone and then a subsequent fall to 0.5 mg/m^3 in the region between the APF and 60°S.

Compared with the western region (see Fig 8-5), a conspicuous feature is that all the eastern region water's, except in the STF zone, have higher mean

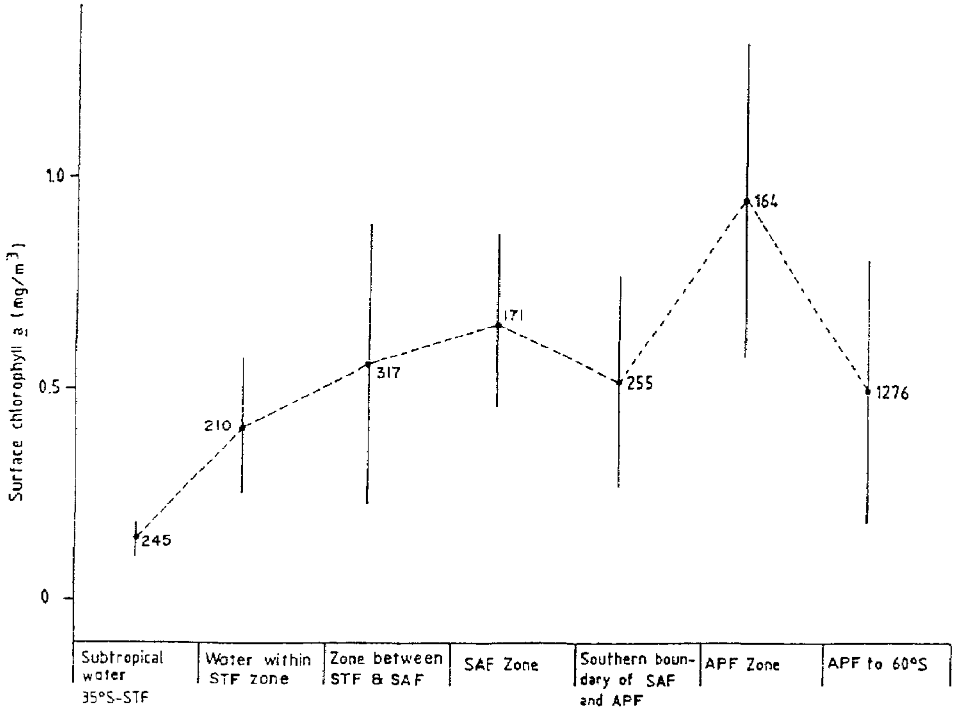

Figure 8-6. Mean and SD of surface chlorophyll *a* in different water regimes in the eastern region. The number of data points used for each regime is also indicated at the center of the dashed line.

chlorophyll *a*. On the other hand, mean chlorophyll *a* concentrations have higher SDs throughout the western region where the data have been collected during late summer (March). Although in both regions the APF zone shows maximum chlorophyll *a*, the chlorophyll *a* concentration peaks up to 1.0 mg/m^3 in the eastern region. The eastern data have been collected during the early summer when icebergs and pack ice in Antarctic waters start melting and the phytoplankton blooms that are present in these marginal ice waters are entrained in the APF zone of the eastern region; this results in higher chlorophyll *a* concentrations than in the western region.

Discussion

Based on 16 crossings, the mean position of the STF in the western region is found at 41°59′S, with a mean midtemperature of 14°C and an SD of ±2° (see Table 8-2). These results closely agree with those presented by Lutjeharms and

Valentine (21), who obtained an average of the STF on the basis of 17 crossings between Antarctica and the south of Africa. The STF in the west is an intense tumultuous front, making this area renowned for its extremely high variability (22). The STF in the east is found shifted north by about 3° latitude, in comparison with the STF in the west, although both regions have similar mean frontal widths and midtemperatures. However, the SD of the width (±224 km) in the east is higher than that in the west (±167 km). On the other hand, the SD in the mean midtemperature is almost double (±2.5°C) in the west, in contrast to its lower deviation (±1.3°C) in the east. The east-west variation in the SD suggests that the strength of the STF is not consistent throughout the study area. On the whole, the STF is quite strong in the west with a mean thermal gradient of approximately 0.04°C/km, whereas in the east its strength is reduced by about half. The results of Edwards and Emery (8) also indicate a weak STF in the eastern Indian Ocean sector of the Southern Ocean.

The absence of the SAF in the west and its clear manifestation in the east are conspicuous features of the present study. The mean position of the SAF in the east is 47°9′S, with an SD of ±1.3° latitude. However, the studies of Lutjeharms (10) have shown the presence of the SAF far west of the present study area.

In the present study, the APF is seen as the most prominent and stable front throughout the Indian Ocean sector of the Southern Ocean. The mean location of the APF axis in the western region is at 50°43′S. In the eastern region it is shifted slightly southward and is found at 51°6′S. The mean positions of the APF are comparable with those obtained by Lutjeharms and Valentine (21) south of Africa. The corresponding widths of the APF in the west and east are approximately 275 and 237 km, respectively. The surface chlorophyll *a* distribution combined with hydrographic properties show that frontal zones are areas of high biomass. The confluence characteristics of the fronts, especially those of the APF, increase the concentration of phytoplankton, which are not mobile on their own. The higher concentration of chlorophyll *a* at the sea surface of the frontal structure is due to the convergence of water masses accumulating the surface organisms. The statistically significant correlation between chlorophyll *a* concentration at the sea surface and potential primary production made by Allanson et al. (17) demonstrates that the concentration of chlorophyll *a* at the frontal zones is truly due to enhanced productivity.

The strong association of chlorophyll *a* with fronts indicates that the frontal zones are very important places for primary production in the Southern Ocean. A comparison between the western and eastern regions (see Figs 8-5 and 8-6) demonstrates this, with the exception of the STF zone in the east. In both the western and eastern study areas, a peak in chlorophyll *a* is seen in the APF zone.

Of all frontal regions in the eastern study area, chlorophyll *a* values were highest (1.0 mg/m^3) in the APF zone. The consistent relation between chlorophyll *a* and the APF was also noticed by Pomazanova (15) and Jacques and Minas (18). According to the studies of Hart (23) and Hasle (24), the peak in phytoplankton density shifts more to the south as the austral summer season advances.

The factors that control the productivity of a region, other than water-mass stability, are availability of light and nutrients in the upper layer of the water column. The primary production at the polar region is higher than that in subtropical regions. During winter, very poor illumination due to limited sun hours and stronger reflection from ice results in decreased photosynthesis. Thus, chlorophyll *a* concentration in the Antarctic waters increases by about 50% as the summer season progresses. Mean chlorophyll *a* values in the region between the APF and 60°S are around 0.25 mg/m^3 in the beginning of summer (see Fig 8-5) and in late summer around 0.5 mg/m^3 (see Fig 8-6). This could be explained on the basis of the melting of ice. When ice melts, the surface salinity decreases; this in turn gives rise to a higher stability in the eastern water column. Thus, during the summer, a shallow mixed layer causes photosynthesis to increase further. Hart (23,25) found continuous bursts of phytoplankton growth soon after midsummer at the southern latitudes. Fogg and Hayes (26) and Wietak et al. (27) also found these processes increased productivity.

Thermal stability is mainly responsible for peaks in surface chlorophyll *a* in the Southern Ocean fronts. The surface and subsurface expression of these fronts do not coincide, especially the fronts in the western study area. The maximum distance between the surface and subsurface expression of the APF area shows their inclined nature with depth. The maximum distance between the surface and subsurface expression of the APF in western region, for instance, is 638 km. Similarly, the STF also has a maximum slope in the west. A sloping front of this kind causes a higher degree of stability in the water column and hence retains phytoplankton within the euphotic zone. Thus, higher chlorophyll *a* values (0.60 mg/m^3) occur in the STF zone of the western region compared with the lower values of 0.40 mg/m^3 in the eastern region. However, the comparatively low chlorophyll *a* values associated with the APF in the western region, although its slope is high, can be attributed to a seasonal effect. Further, at the STF in the western region, the high chlorophyll *a* values, as compared with those in the east, may be due to the stronger gradient (see Fig 8-5) in the west. The meandering of the front causes a vertical motion, especially at the northern side of the meandering front. The additional pumping of water from the subsurface at the frontal edge causes a large flux of nutrients into the euphotic zone, increasing phytoplankton production.

References

1. Deacon GER. Hydrology of the Southern Ocean. Discovery Rep 1937;15:1–124.
2. Mackintosh NA. The Antarctic Convergence and the distribution of surface temperature in Antarctic waters. Discovery Rep 1946;23:177–212.
3. Nowlin WD, Whitworth T, Pillsbury RD. Structure and transport of Antarctic Circumpolar Current at Drake Passage from short-term measurements. J Phys Oceanogr 1977;7:788–802.
4. Nowlin WD, Clifford M. The kinematic and thermohaline zonation in the Antarctic Circumpolar Current at Drake Passage. J Mar Res 1982;40:481–507.
5. Nowlin WD, Klink JM. The physics of Antarctic Circumpolar Current. Rev Geophys 1986;24:469–490.
6. Emery WJ. Antarctic Polar frontal zone from Australia to Drake Passage. J Phys Oceanogr 1977;7:811–822.
7. Clifford MA. A descriptive study of the zonation of Antarctic Circumpolar current and its relation to wind stress and ice cover. MS Thesis. College Station, TX: Texas A&M University, 1983.
8. Edwards RJ, Emery WJ. Australasian Southern Ocean frontal structure during summer 1976–77. Aust J Mar Freshwat Res 1982;33:3–22.
9. Lutjeharms JRE. Location of frontal system between Africa and Antarctica. Some preliminary results. Deep Sea Res 1985;32:1499–1509.
10. Menon HB. Fronts in the Indian Ocean sector of Southern Ocean. PhD Dissertation. India: Cochin University, 1990.
11. Pingree RD, Mardell GT. Slope turbulence, internal waves and phytoplankton growth at the celtic sea shelf-break. Phil Trans R Soc Land A 1981;302:663–682.
12. Pingree RD, Mardell GT, Hollogan PM, et al. Celtic sea and Armorian current structure and the vertical distributions of temperature and chlorophyll. Continental Shelf Res 1982;1:51–116.
13. Marra J, Honghton RW, Boardman DC, Neale PJ. Variability in surface chlorophyll-*a* at a shelf-break front. J Mar Res1982;40:575–591.
14. Planke J. Phytoplankton biomass and productivity in the Subtropical Convergence area and shelves of the western Indian Subantarctic islands. In: Lianda GA, ed. Adaptations within Antarctic Ecosystems. Smithsonian Institution, Washington, DC, 1977:51–73.
15. Pomazanova NP. Divergence of drift currents in the Antarctic sector of the Indian Ocean. Trgidromet Inst 1980;80:110–115.
16. Ainley DG, Jacobs SS. Sea bird affinities for ocean and ice boundaries in the Antarctic. Deep Sea Res 1981;10A:1173–1185.
17. Allanson BK, Hart RC, Lutjeharms JRE. Observations on nutrients, chlorophyll and primary productivity of the Southern Ocean South of Africa. South Afr J Antarc Res 1981;11:3–14.
18. Jacques G, Minas M. Production primarie danslescteur indien de l'Ocean Antarctoique en fin d'ete. Oceanol Acta 1981;4:33–41.
19. Gordon AL. Structure of Antarctic waters between 20°W and 170°W. In: Bushnell V, ed. Antarctic map folio series, Folio 6. New York: Am Geophys Soc, 1967.
20. Ostapoff JR. The salinity distribution at 200m and the Antarctic frontal zones. Dt Hydrogr Z 1962;15:133–141.

21. Lutjeharms JRE, Valentine HR. Southern Ocean thermal fronts south of Africa. Deep Sea Res 1984;31:1461–1475.
22. Lutjeharms JRE, Baker DJ. A statistical analysis of the mesoscale dynamics of the Southern Ocean. Deep Sea Res 1980;27:145–159.
23. Hart TJ. Phytoplankton productivity in Antarctic surface water. Discovery Rep 1942;21:261–356.
24. Hasle GR. An analysis of the phytoplankton of the Pacific Southern Ocean. Abundance, composition and distribution during the Brategg Expedition, 1947–1948. Hvalradets skr 1969;52:1–168.
25. Hart TJ. On the phytoplankton of the Southwest Atlantic and the Bellingshausen Sea. Discovery Rep 1934;8:1–268.
26. Fogg GE, Hayes PK. The relative importance of nutrients and hydrographic features for the growth of Antarctic plankton. Joint Oceanographic Assembly, Halifax, 1982:60–61.
27. Wietak Z, Pastuszak M, Grelowski A. Net phytoplankton abundance in western Antarctic and its relation to environmental conditions. Meeresforshund 1982;29:166–181.