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AREAS OF POTENTIALLY SUCCESSFUL EXPLOITATION OF TUNAS IN THE INDIAN OCEAN WITH EMPHASIS ON SURFACE METHODS

by

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SUMMARY

The absence of widespread commercial surface fisheries for tunas in the Indian Ocean makes assessment of potential resources very speculative. Descriptions of various methods of tuna fishing and the circumstances under which they operate effectively in other parts of the World Ocean offer a starting point for reasoning out what areas of the Indian Ocean might yield various tunas and tuna-like species to the various kinds of effort. The available oceanographic data have been summarized on a monthly basis to show the gross features conducive to surface fishing success on a regional basis. Local features such as those influenced by islands, shoals, etc., which have proven to be fruitful in other oceans do not appear in these summary data, but are explained as analogues small-scale processes relating to the grosser scale features. Monthly charts of overage environmental conditions relating to the successful harvest of tunas and tuna-like fishes are provided for use in fishery development, planning and harvest strategies.

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1. INTRODUCTION

The tuna fisheries in the Indian Ocean are little developed in comparison with those of the other Oceans. With the exception of longline fishing there is little tuna fishing activity in the Indian Ocean. One obstacle to development is the absence of clear guidance of information on where the most promising areas might be. This discussion has been prepared to provide some preliminary guidance. It has been divided into three sections, a brief discussion of the biological factors which define their environmental requirements; a short discussion of effective fishing gears and how their success is determined by the environmental factors; and in the concluding section there are monthly maps of the averaged available oceanographic information which should help in both design and interpretation of exploratory fishing ventures for oceanic tunas in the Indian Ocean.

Briefly, there are three wide ranging *Thunnus* species of commercial interest in the (northern) Indian Ocean, *T. albacares*, *T. obesus* and *T. alalunga*, the yellowfin, bigeye and albacore. The skipjack tuna (*Katsuwonus pelamis*) is the fourth and potentially the most abundant of the tuna-like species which are known to occur in commercial quantities in the Indian Ocean. Another species, *T. tonggol*, the longtail tuna is locally distributed in the neritic (coastal shelf) zones of the Indian Ocean but little information is available on its commercial potential. There are presently no available reliable assessments of potential yield by all catching methods combined for any of these species due to the limited distribution of effort in any areas except the oceanic longline grounds.

In the foreseeable future it does not appear that any methods will be available for predicting either abundance or the absolute whereabouts of tunas within their ranges or habitats. The problems in these two areas relate to the complex behaviour and physiological properties which have evolved in this unique group of fishes. Their occurrence in the ocean is bounded only by low temperatures (about 15°C for the true tropical tunas) and low oxygen levels since they are obliged to swim continuously and this requires finite oxygen availability.

Over the past decade there have been numerous studies of the apparent thermal and oxygen limitations on the distribution of tunas and tuna-like species. Among the many variables determining the behaviour and distribution of each species the most important are size and developmental stage. Juvenile skipjack and albacore both appear to migrate more extensively than the adults. (Among temperate bluefin tunas this may not be the case). Tunas are more dense than sea water and are obliged to swim continuously to maintain their position in the water column. The larger tunas develop morphologically and physiologically so that their obligatory swimming speed is often lower than that of the juveniles. This is accomplished by development and increase in volume of the gas bladder or growth of the pectoral fins depending on the species. The exception to this is the skipjack whose gas bladder does not develop with maturity, so that its metabolic requirements steadily increase with size because the obligatory swimming speed increases with size. (These are not trivial effects as the respiration rate is related as a cubic function of the swimming speed). A respiration model based on laboratory experiments on skipjack swimming and respiration relations was developed and generalized to include other commercial tunas from 50 to 75 cm in length. The larger individuals of the *Thunnus* species can be assumed to tolerate lower levels of oxygen due to their reduced obligatory activity levels. During feeding or chase, however, they are known to exhibit remarkable activity levels which certainly result in high oxygen demands which must be met or the fish die.

The second process which increases respiration rate in fishes, independent of swimming activity, is temperature. Tunas are warm bodied relative to the water they swim in and may have solved some of this temperature dependence problem by thermoregulation. The smaller tunas have limited thermoregulatory capabilities and hence are more subject to thermal conditions. The interesting point is that the distribution of lower common occurrences of small tunas (35-55 cm) for each species may be used as an estimate of the lower "preference" temperature of the species. The tropical tunas (yellowfin and skipjack) apparently encounter no upper temperature limits, given adequate oxygen supply. The bigeye and albacore appear to be sensitive to high, tropical temperatures. This is observed in the distribution of common occurrence temperatures which limit the equatorial distribution of surface catches in these species, or from information on depth and temperature of capture from longline fisheries

The following table is provided as an estimate of these boundary conditions for the four subject species.

Species	Common name	Temp. pref.	10 minute tolerance
			O_2 limitation for small fish (50 to 75 cm long)
K. pelamis	skipjack tuna	20° to 32°C	2.5 or 3.0 ml/L
T. albacares	yellowfin tuna	23° to 32°C	1.5 to 2.5 ml/L
T. obesus	bigeye tuna	11° to 23°C	0.5 to 1.0 ml/L
T. alalunga	albacore	15° to 22°C	1.7 to 1.4 ml/L

There are anomalous occurrences in waters with higher surface temperatures than those indicated which are usually associated with thin warm surface layers overlying cooler habitats. Any tuna can tolerate short forays into conditions which they could not sustain, but the durations of such forays are limited by activity and size. The oxygen values are estimates for only the two sizes listed. As previously stated the *Thunnus* species at larger sizes should be less sensitive to oxygen levels than these more active sizes, unless higher activity levels are initiated.

Each species has its own set of limitations. Within each species there has been long-term selection in response to geographic conditions which result in modified capabilities and behaviour of subsets of the populations. The best examples available are the size at firs maturity and size-age information for skipjack tuna from the cooler Pacific Ocean regions in contrast to the situation in the western tropical Pacific. The western Pacific fishery yields two types of skipjack tuna. One is smaller at age and maturity and has a "local" distribution in comparison to the other (A.D. Lewis, pers. comm.). This "tropical" form, as I will term it, apparently prefers the warmest of tropical waters with a thermal structure characterized by slow temperature decreases with depth. The constraints of oxygen and temperature on the second, larger and wider ranging or nomadic form are different in that these fish appear to range over thousands of miles. Differences in behaviour and physiology likely account for the two different growth and reproductive strategies. The warmer water form has had to trade off size and nomadism to maintain itself in the warm environs it has colonized. The nomadic, larger form must find hospitable conditions to thrive and reproduce, which it does by longer, more extensive forays into the oceanic unknown, which may or may not pay off. Biologically, the payoff is reproductive success. The nomadic, faster growing form requires many more calories, much more time, and a touch of good fortune to locate its needs in the oceanic realm. Spawning is only successful if the eggs and larvae are "placed" in a situation conductive to their survival. These nursery areas are not abundant, and may not be the same location from year to year. The tropical form has adjusted its requirements to take advantage of the relatively stable situation in the region it occupies.

The reason I am iterating these comparisons and speculations in scenario is to introduce the important behavioural indicators of various genetic components. Indeed, behaviour is a fair assay of similarity where better characters are not available.

2. FISHING METHODS

Typically, areas of highest catches from longline and surface fishing effort for tunas are almost mutually exclusive. This is due to the characteristics of the gear with respect to the habitat and behaviour of the tunas. The distances separating high production areas of these gears can be small. Short descriptions of the different methods follow.

Longline fishing exploits tunas by placing baited hooks at depths where large tunas range. In the traditional method a 50 to 60 nautical mile array of about 1 000 hooks is set to fish with the hooks hanging at depths ranging from 50 to 150 metres in the water column. As we will see from examination of typical thermal sections of the Indian Ocean, this means that the hooks hang in temperatures ranging from 28°C down to about 15°C near and south of the equator; and from 20°C to below 15°C near 30°C south. These placements yield all three Thunnus species in varying proportions dependent upon the season, species abundance and environmental charateristics.

Surface gear exploits tunas, usually schools sighted at or near the surface, by either trolling lures; attracting the schools to the vessel with live bait where they are caught individually by hook and line; or entire schools are purse seined. Each of these methods has levels of technical skills and acquired knowledge involved which must be evolved as a fishery develops.

Trolling vessels fishing albacore or tropical tunas may use up to 16 lures attached to the vessel from outriggers and/or the stern. Two or three crewmen have caught over 10 tons of fish per day using this method. The usual catch considered desirable in commercial fisheries (at a minimum) is 100 fish per day or about 1 ton of fish. The fish exploited by this technique range in size from about 40 cm to 85 or 90 cm.

Baitboat fishing is really two fisheries in one. The baitfish species are often the limiting factor in production from areas where baitfishing methods are used. Bait is captured by various netting methods, and the live baitfish are put aboard the baitboat with care so as to extend their longevity or holding qualities for as great a time period as possible. In some fisheries, usually where bait is collected in cooler water ($< 26^{\circ}$C), the bait can be held for more than one month. In other areas where the baitfish are taken from tropical waters the expectation ranges from less than one day to weeks. These fisheries are necessarily based on shorter trip lengths than the fisheries with access to hardier baitfish. In tropical fisheries, bait handling techniques can be very important to the economic viability of the baitboat fishing methods.

Once the bait is aboard the vessels, the search for surface schools begins. Depending upon species and geographic location various methods are used to locate "fishing grounds". Baitfishing is rarely productive in the deep open ocean unless there are current boundaries, or other oceanic features which concentrate flotsam or appropriate food for tuna schools. Convergence zones, where two currents are directed toward one another causing a general deepening of the mixed layer, promote this process in some areas (e.g. South Pacific) and divergence zones have similar effects in others (e.g. eastern tropical Pacific). Islands and shoals tend to cause the surrounding current systems to produce similar effects in the lee in some cases and on the windward or frontal surface in others, dependent upon local current and windstress patterns.

Tunas tend to congregate about discontinuities in the physical characteristics. Discontinuities are measured as sharp gradients. The physical oceanographers measure temperature and salinity and use a combination of the two to define boundaries between two currents. The fish respond to temperature, oxygen and probably food item availability. The tunas are relatively insensitive to salinity and the definitions of physical oceanographers, but do respond to gradients of variables common to boundary currents and other frontal processes.

Most bait fisheries for tunas operate in near-shore (within 20 nautical miles) areas influenced by local current and wind field events. Tuna schools are located visually by searching for surface activity (e.g. breezing, flashing or finning schools), or often busy birds are sought as indicators. Once the bird flocks are within operating distance the process of identifying what is attracting them begins. This is done in the same fashion as if birds were not present. The baitfish are cast out in a "chum line" and the vessel is put into a turn which can clear large calm areas in even slightly choppy seas. Any feeding response from the fish school is quickly taken advantage of. In baitfishing situations it is possible for any single fisherman to catch a ton of fish in a very few minutes. The "bite" may last for merely minutes, or hours. Crew size on bait vessels differs markedly from fishery to fishery. In the eastern Pacific Ocean crews run from 8 to 16 on vessels ranging in capacity from 100 to 350 tons. In the western Pacific skipjack fishery crews of 25 are common. There are records of catches by baitboats in the eastern Pacific of up to 200 tons in a single day. More typical catches range from 3 to 30 tons per day on the fishing grounds. Seasonal variation is remarkable in most tuna fisheries. Baitfishing can exploit tunas ranging in size from 30 cm to over 200 cm. Fish larger than 75 cm usually require the combined efforts of more than one man per hook, giving meaning to the terms: 2 pole; 3 pole; and 4 pole fishing to describe the size of fish. Fish are caught using artificial "squid" hooks, or with baited hooks. Both methods are more efficient when "barbless" hooks are used.

Running out of "chum" or livebait is the end of any fishing aboard these vessels, even though literally thousands of tons of fish may be available, because the tuna schools will rarely come within range of the hooks unless enticed to do so by chum.

The previous situation of frustration due to the lack of bait in areas of abundant surface schools gave rise to the early attempts by purse seiners rigged for wet fish (sardine, anchovy, etc.) to capture tunas in the eastern Pacific. It was soon apparent that tuna schools were often too large, and stressed the gear too much for the usual light purse seine nets and winches. Larger vessels with heavier handling gear and longer, deeper nets were developed. With the advent of the heavy "Marco" power block for winching aboard the heavier net webbing in the early sixties came the purse seine revolution. The modern tuna superseiner has a capacity of over 1 000 tons, can be at sea for over 60 days, and can fish in fairly rigorous oceanic conditions. Catches in productive fleets range from 9 tons per day on the fishing grounds to recorded catches of over 400 tons per day. Entire schools are sought and captured. The method for location of schools is the same as for baitboats. Some fishery developments have resulted in purse seining at night on "fireballs" or tuna schools whose passage through the water stimulates the luminescent plankton, outlining the schools' presence. Other developments in tuna fishing have been the exploitation of aggregations about flotsam, dead or live marine mammals, and specially devised hardware for aggregation of tunas. Many more innovations are expected.

The major characteristics of a purse seine net which makes it effective relative to the environmental conditions, or ambient at the time of fishing are its depth, sinking rate and the final configuration when pursing begins. Modern seines range in length from 600 fathoms to nearly one mile. The design depth of fishing is about 40 fathoms (~80 metres) with some nets being fished to nearly 100 metres. There is a diminishing return in further size increases due to limits in net handling gear and the cost of webbing.

The interesting situation in purse seine fisheries is that if the net is set in the situation where the floor of the tuna habitat is well above the bottom of the net upon initiation of pursing, the catch rates appear to be higher than the situation where the tuna habitat is beyond the net design fishing depth. The catch rates in specific small geographic areas have been studied and in an early rigorous examination the catch rates were roughly proportional to the habitat depth. The underlying density of the local population sets the scale on which one imposes this proportionality. Figures 1 and 2 summarize these studies.

The variation in the habitat volume is a direct function of local and larger scale climatic processes. The combination of both biological and climatic variation result in the extreme temporal and geographic variation in production of surface fishing methods, particularly that of purse seine gear.

3. TUNA IN THE INDIAN OCEAN

Recently, due to EEZ developments, an interest has emerged in development of fisheries for the oceanic resources in the Indian Ocean. Unfortunately, there is little information available about abundances, seasonality or much else, except for longline fishing. There is the general observation that in the Atlantic and Pacific Ocean areas where productive longline fishing occurs there are productive surface fisheries for the same species in the

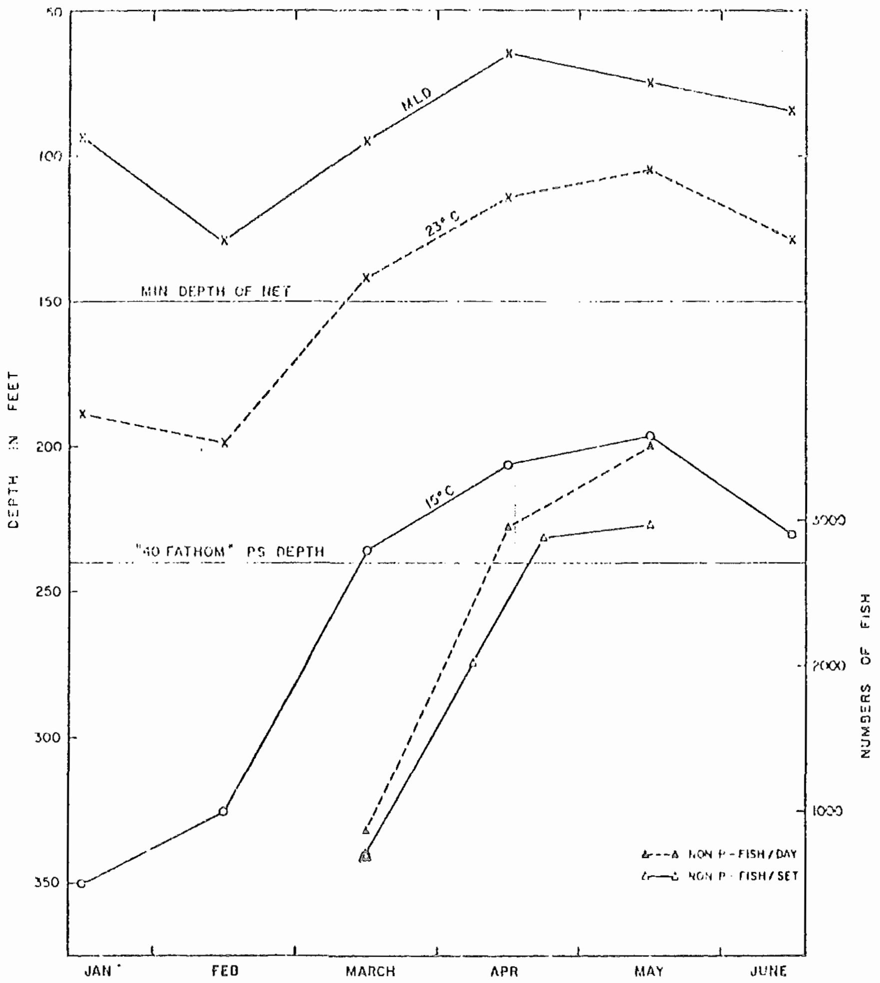


Figure 1. The flux in the thermal profile of the 1973 yellowfin tuna study area (Sharp 1978) is shown for the 6 months of the study period. The minimum effective fishing depth and design fishing depths of the modern purse seine are indicated. The mixed layer depth (MLD) and the 23°C and the 15°C isotherms are plotted. The productive fishery commenced in the second week of March. The average numbers of fish caught per successful set are indicated at the bottom right of the figure, and both daily and per set catch rates are indicated. The productivity corresponded in time with the emergence of both the 15°C and 23°C isotherms above the two limits of the fishing gear. The mixed-layer depth is not related to the vulnerability of the fish in this example.

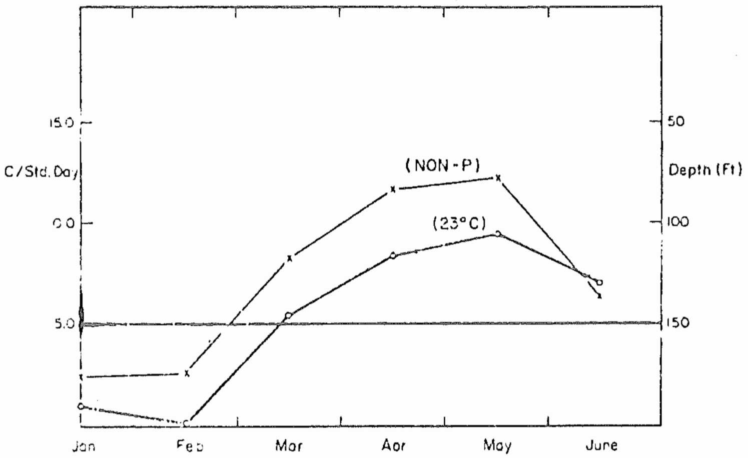


Figure 2. The catch per standard days fishing and the depth of the 23°C isotherm are plotted for the study area and period. The non-porpoise-associated catch rates follow closely the behaviour of this environmental feature (r= -0.94).

regions peripheral to or bounding the longline areas. These include the previously discussed island, shoal and oceanographic features. Given this apparent correspondence between longline and surface fishing potential it seems that there must be relatively untapped tuna resources available in the Indian Ocean, in regions peripheral to those occupied by longline fisheries. There is continuity in occurrence and fisheries for small skipjack tuna from the range of the tropical form in the western Pacific Ocean, all the way westward across the northern Indian Ocean to Somalia. South of the equator the characteristics of the Indian Ocean are comparable to the central Pacific Ocean, the habitat of the larger, nomadic form of skipjack tuna. There have been short but effective commercial ventures in the coastal extremes of the southern Indian Ocean where skipjack tuna and the other commercially sought tunas have been found.

An important consideration is that it is clearly possible that the Indian Ocean populations have succeeded in stratifying by regions in response to "local" environmental features, and as a result these might be at least as complex or diverse as the western and central tropical Pacific Ocean tuna populations which will complicate the predictions to follow.

In the following sections monthly charts are provided of the "average" thermal and oxygen properties in the Indian Ocean, which are presumed to describe zones of vulnerability of various tunas to various gears. The basic data were compiled from the available oceanographic observations up to the year 1976, on file at the National Oceanographic Data Center at the University of California, Scripps Institution of Oceanography. The data were summarized by 5° square, and plots of these data were graphically interpolated to provide the monthly charts.

There are several factors which must be recognized at the outset of any study, or efforts at prediction from events relating to Ocean features which are functions of local and larger scale climatic events. "Averages" which are extracted from available data only show gross features which cannot "represent" reality adequately because the short term and very long term variations are removed in favour of point estimates. I might add that this is often the problem in communication of most fishery situations in that the "average" event is often very rarely observed under normal operating conditions. The advantage of using averages is that they tend to reduce the "blur" of background variation. Considering the variation observed in the day to day basis by which fisheries operate in most cases, it can be frustrating to try to interpret what is meant by "average conditions". On each chart of "average conditions" there are lines which represent the average positions of several features. The features have to be, by definition, somewhere in the continuum of events, but their absolute locations vary markedly in time. In reality if one were to have to locate them from a boat at sea, a systematic search from the perspective of local conditions will usually locate the features. For example, if you are looking for the 23°C surface isotherm and you are in waters with temperatures of 24° or 25°C, the direction to proceed is toward cooler water or southward. The average positions have an inherent minimum error of ± 5° latitude or longitude in the estimated locations. Where broader zones or areas are indicated on the charts, the true situation will be that much more concise and limited distribution will exist for the features being sought, probably located within the broad zone indicated.

It should be emphasized that small-scale or local features will disappear on the charts of "averages": islands or continental borders often generate appropriate conditions in the water column which create vulnerability zones, but unless these are wide-spread events they will not occur on the charts.

So that it should be clear to the reader what is intended, a few dependable features can be pointed out. The location of the surface isotherms in the Indian Ocean is arrayed from warmer to cooler from north to south. The east to west variation in thermal and oxygen levels is significant above the equator, and decreases generally toward the south except in shoal and coastal regions. Three vertical sections, one from north to south and the other two east to west, show the general trends of these data in the Indian Ocean (Figures 3A, B and C).

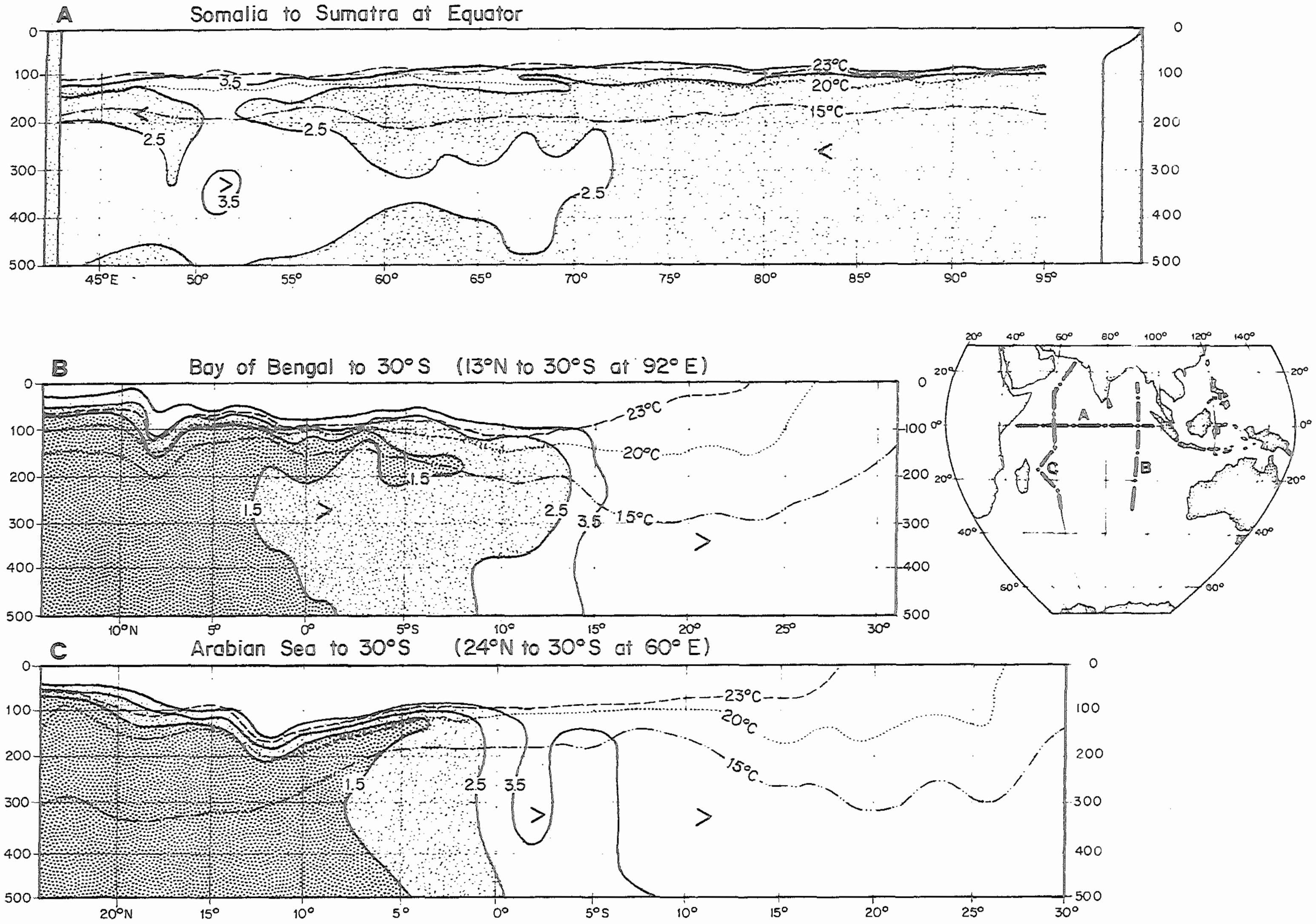


Figure 3. Thermal and oxygen profiles are shown from the results of three oceanographic transects in the Indian Ocean. The 15°, 20° and 23°C isotherms are plotted and the areas of restrictive oxygen levels as described in the text (the 1.5, 2.5 and 3.5 ml per litre) are plotted in relation to the thermal profile data. Note the great differences in importance of oxygen availability in the northern Indian Ocean in contrast to the other areas.

In the north-south section the habitat zones of the three Thunnus species are indicated. Skipjack tuna will range over the range from the 20° surface isotherm north to the coastline wherever they can encounter oxygen levels greater than 3.5 ml/L on a sustained basis. The locations of zones of highest vulnerability to surface gear can be estimated using the monthly average charts.

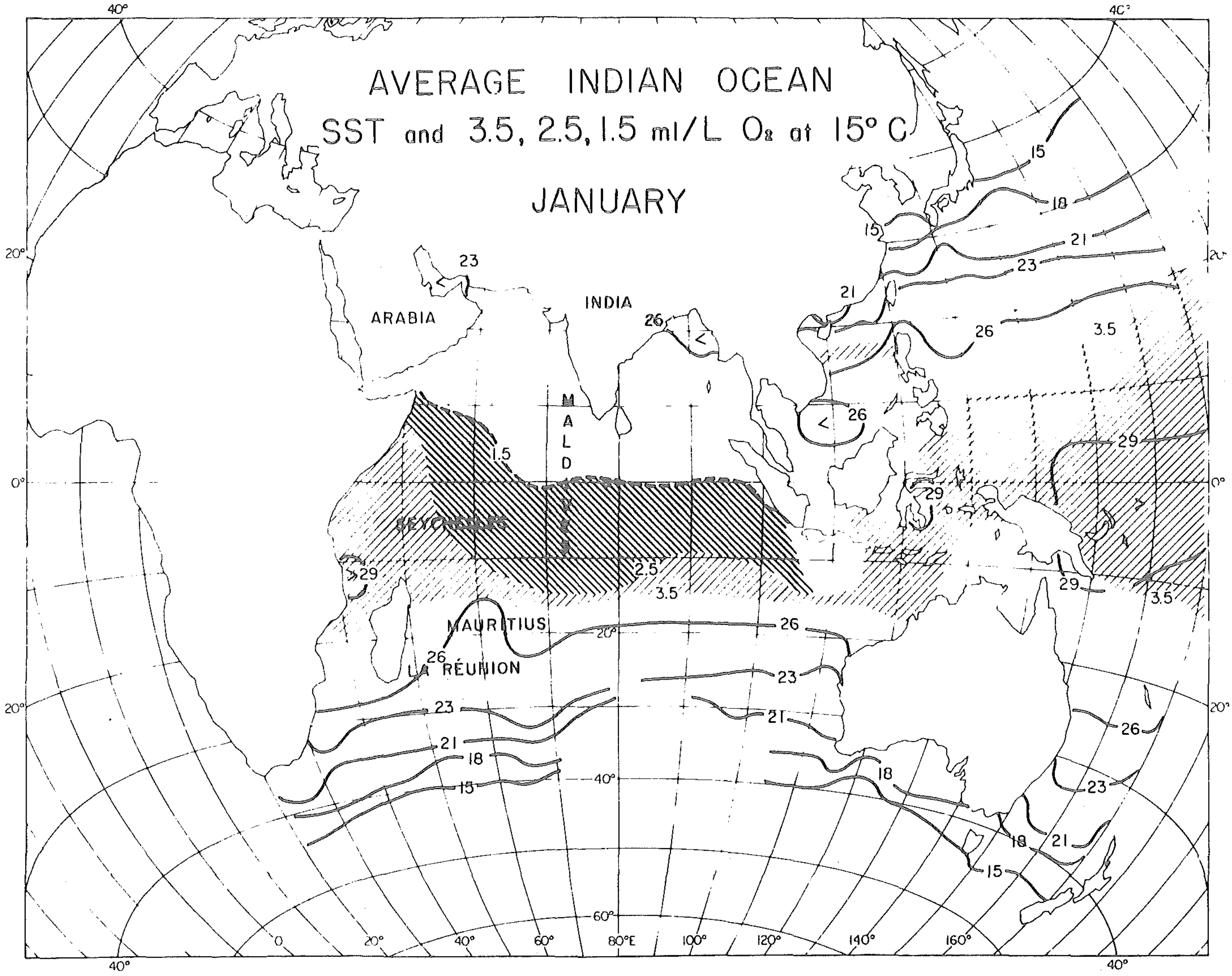
The first series of charts shows the average positions of the sea surface isotherms for each month of the year. Also indicated are the zones where the dissolved oxygen levels less than of 3.5, 2.5 and 1.5 ml/litre emerge to depths more shoal than the 15°C isotherm, and become the significant habitat limiting features.

The general trend is for the oxygen levels at 80 metres to decrease as one travels northward toward the coastline. This severely limits occurrence and activitiy of larger tunas and may result in lower overall abundances of larger tunas in the northern region, particularly in the warmer waters. The temperature isotherms were selected to range from 15° to 29° by 3°C intervals except in the interval between 21° and 23°C (a 2°C interval used here to facilitate full-scale display of isotherms of interest).

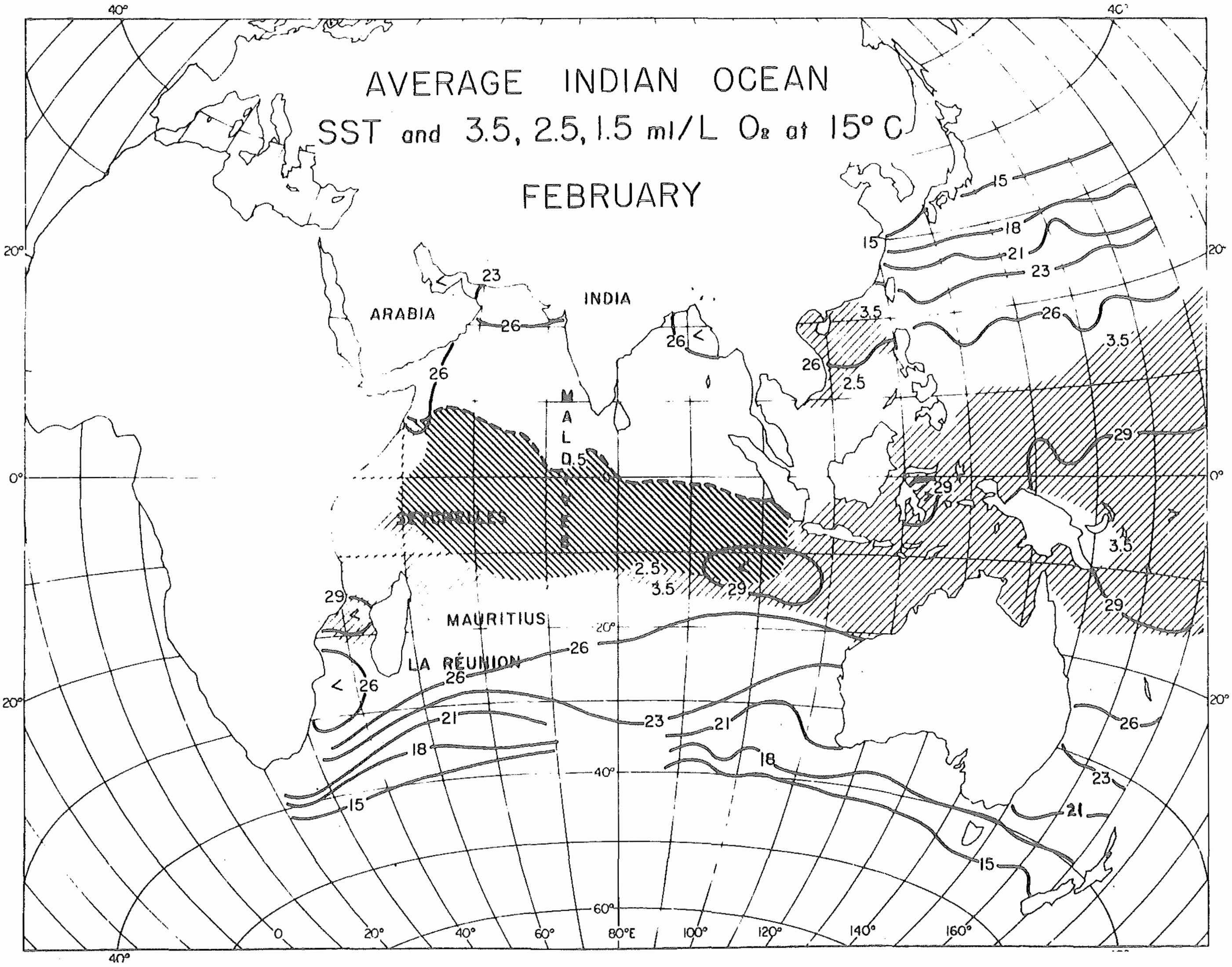
The selected isotherms and oxygen values of interest to surface fishing ventures are quite specific. The 15°C isotherm is shown to provide the lower normal boundary of occurrence for albacore; the 20°C isotherm is the usual lower boundary for commercial quantities of nomadic skipjack tuna; the 23°C isotherm is the lower boundary for yellowfin tuna; the 26° and 29°C isotherms are shown to identify the tropical zone and warmest temperature zones, respectively.

Although some quantities of tunas are encountered in temperatures below those values listed for each species, it would probably not prove of value to expend much effort in exploring these areas when more "productive" zones have been identified from previous experience. Anomalies will be obvious enough as effort increases for the species preferring cooler habitats. Certainly once a broad distribution of effort is being supplied, more information about all of the resources will evolve.

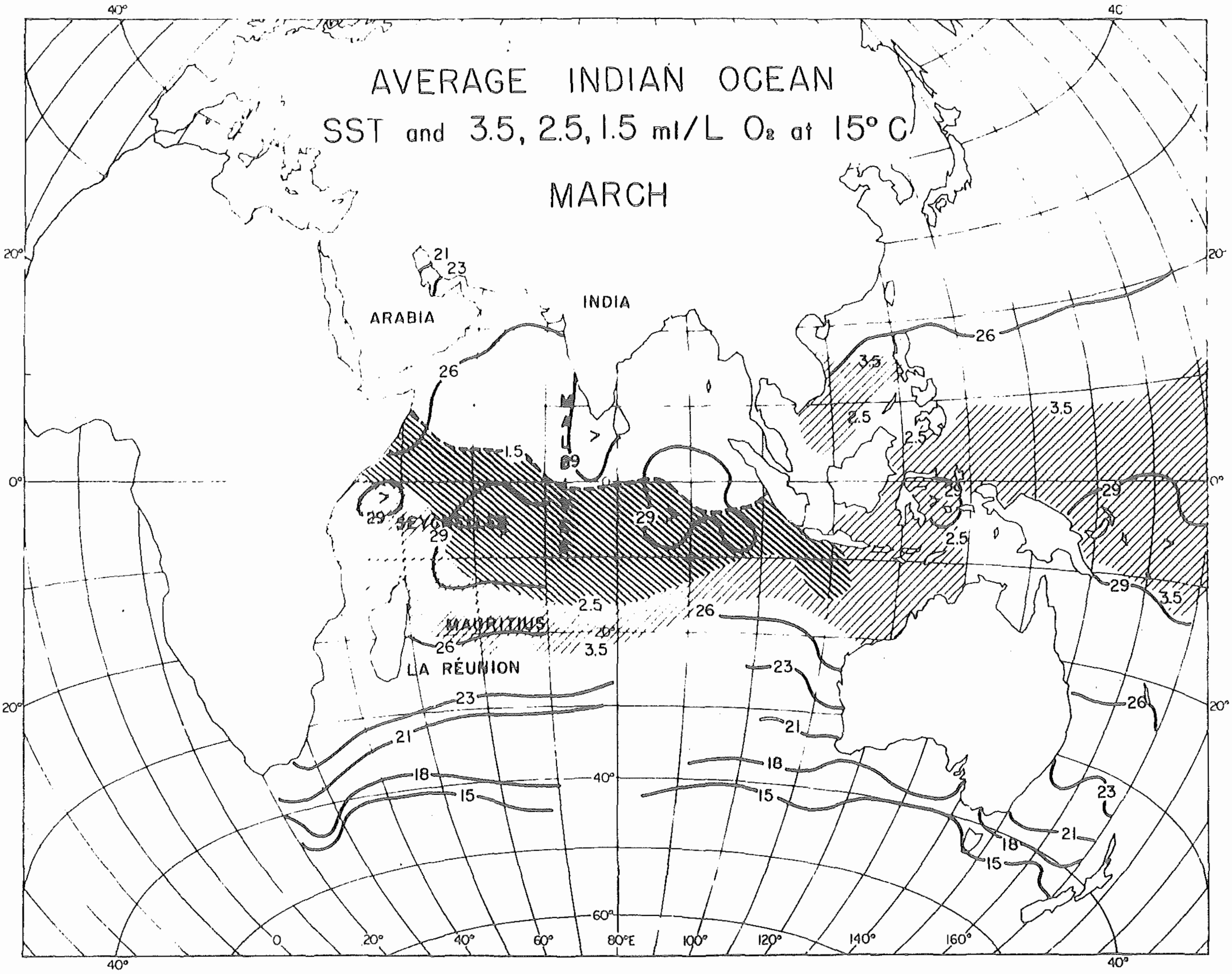
The 3.5 ml/L oxygen value represents a lower continuous exposure limit for nomadic skipjack tuna; the 2.5 ml/L value is an estimated 10 minute tolerance value for the same species group; and the 1.5 ml/L value is an estimate of the continuous exposure limit for schooling yellowfin tuna. The oxygen values likely act as limiting features for tuna distribution in the northern Indian Ocean throughout the year.



These summaries of monthly average oceanographic conditions show the sea surface temperatures, and the areas where the oxygen values in the northern Indian Ocean and western Central Pacific become limiting habitat features at depth, rather than temperature, for occurrence of skipjack, yellowfin tuna and albacore. Note the rapid changes in oxygen values from 10°S to the equatorial zone in the Indian Ocean in contrast to the western tropical Pacific.



AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O_2 at 15° C
FEBRUARY


AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O_2 at 15° C
MARCH
ARABIA
INDIA
SEYCHELLES
MAURITIUS
LA RÉUNION
1.5
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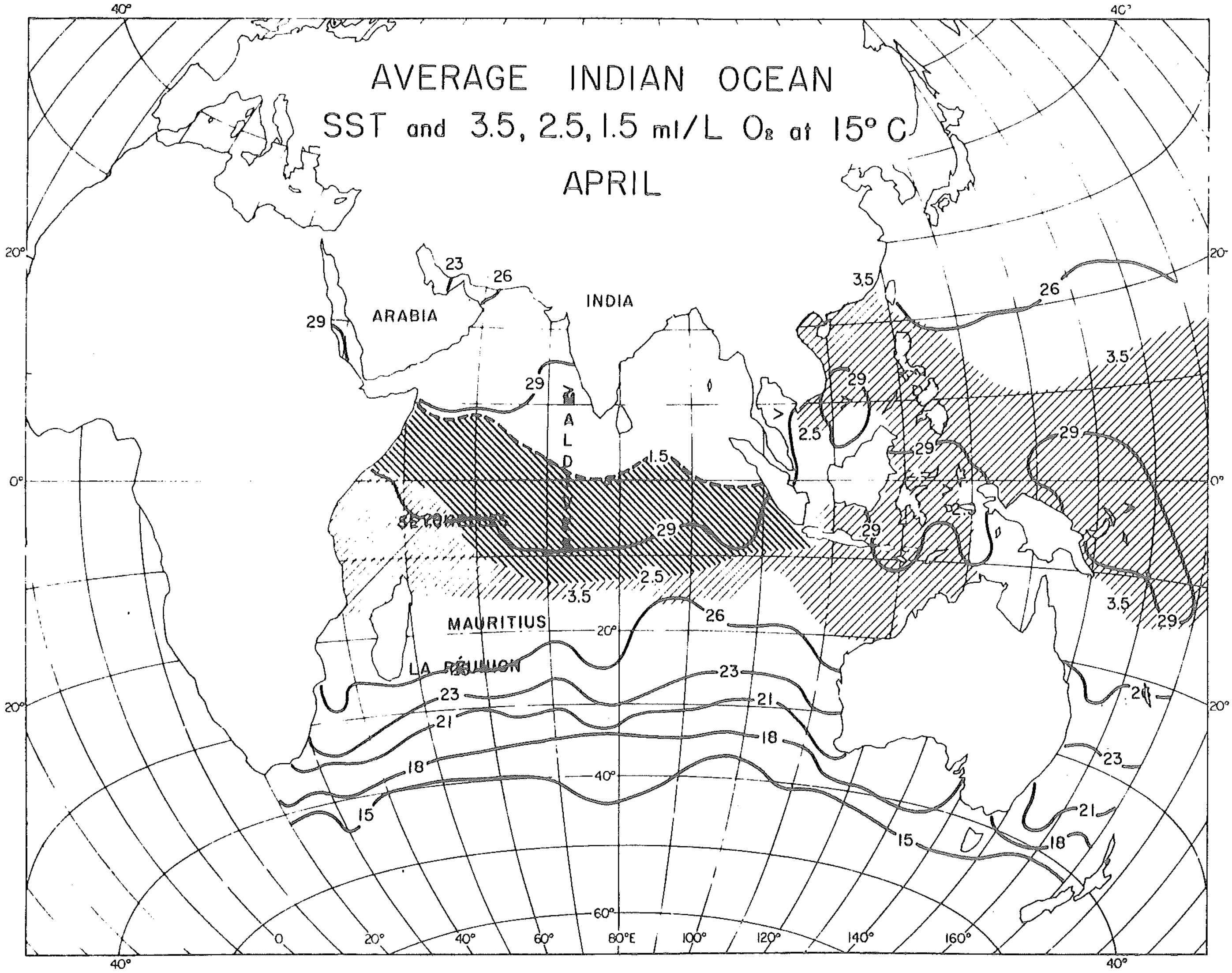
AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O₂ at 15° C
APRIL
ARABIA
INDIA
SEYCHELLES
MALDIVE
MAURITIUS
LA RÉUNION
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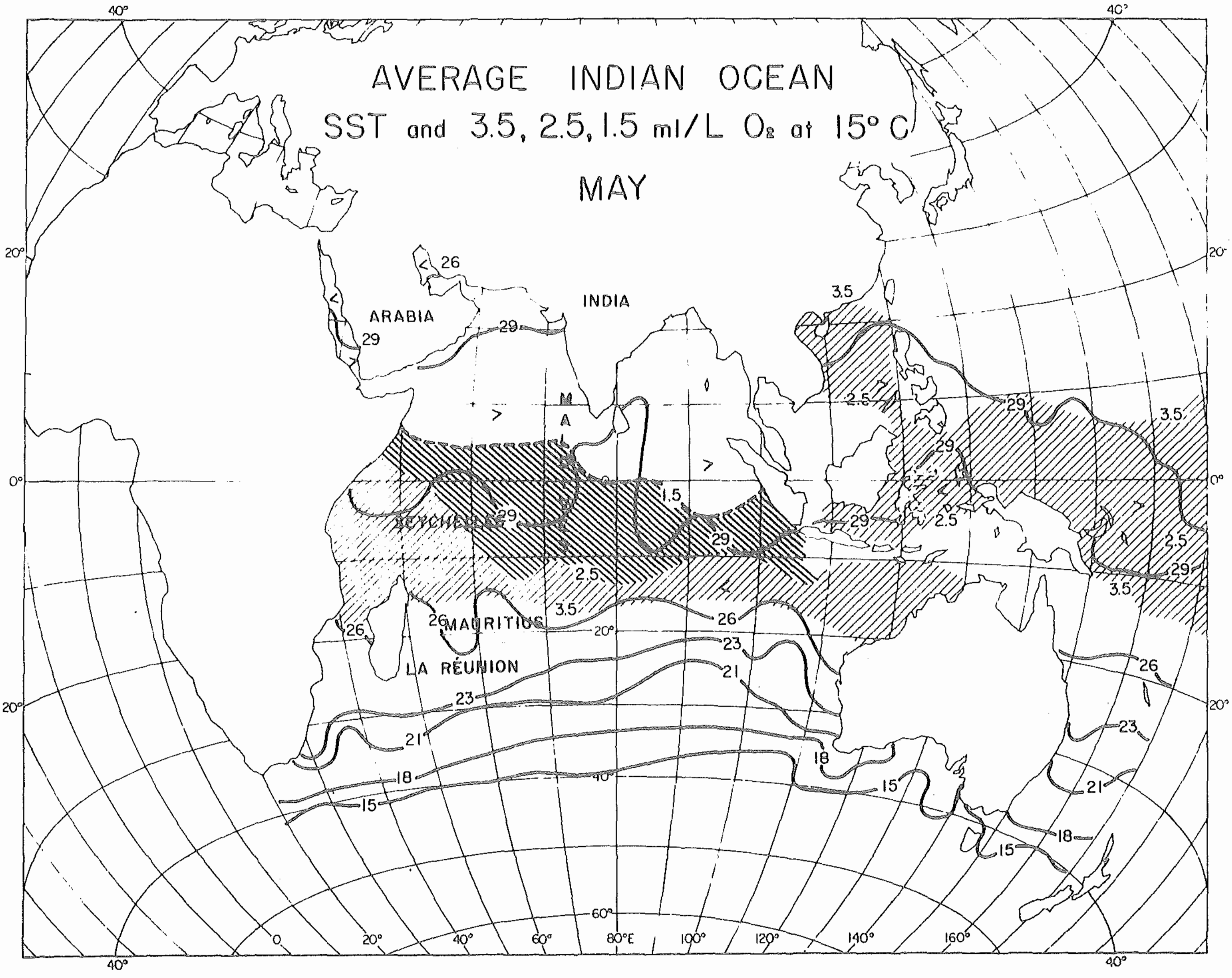
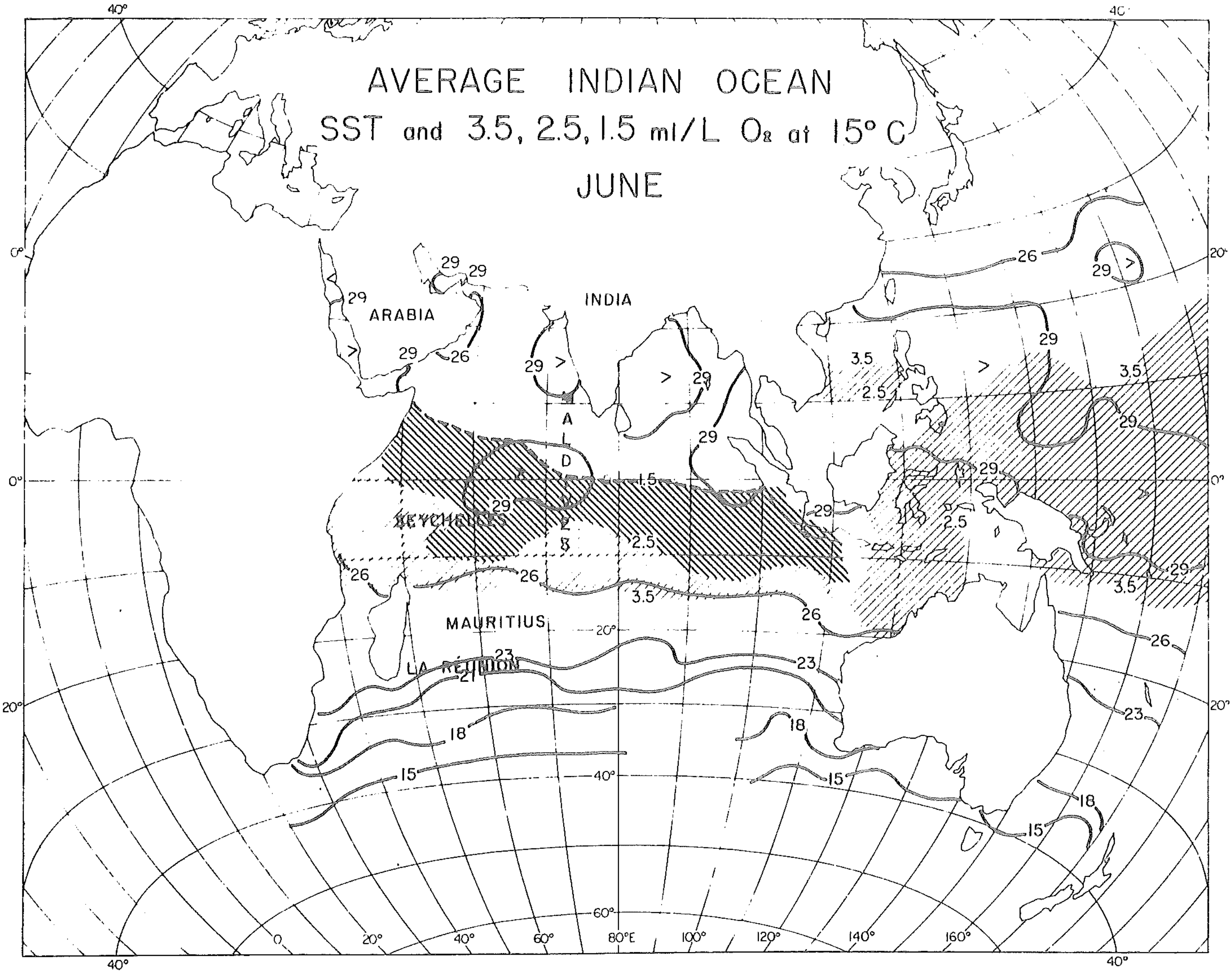


AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O_2 at 15° C
MAY


AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O₂ at 15° C
JUNE
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
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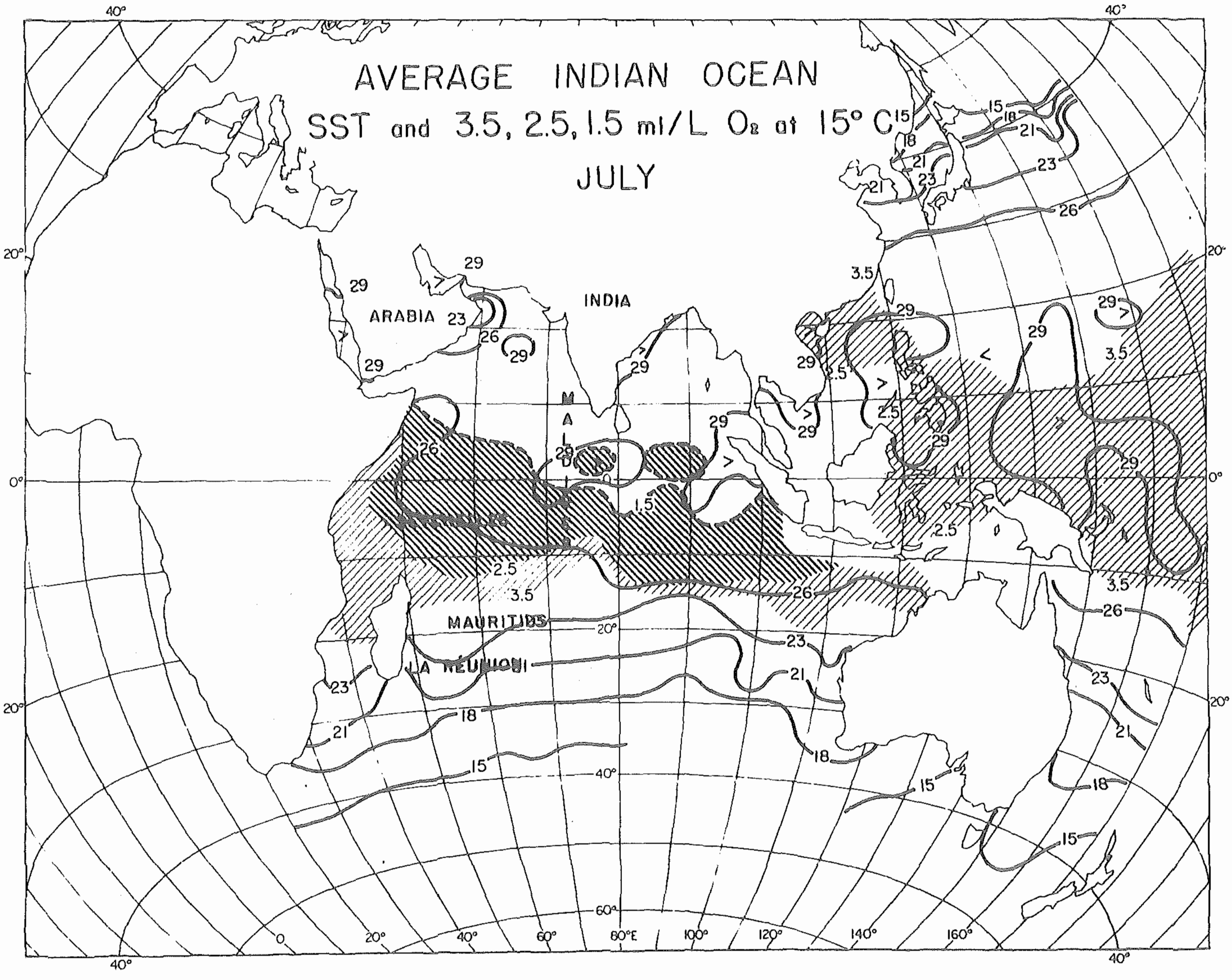
AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O₂ at 15° C
JULY
ARABIA
INDIA
MALDI
MAURITIUS
LA REUNION
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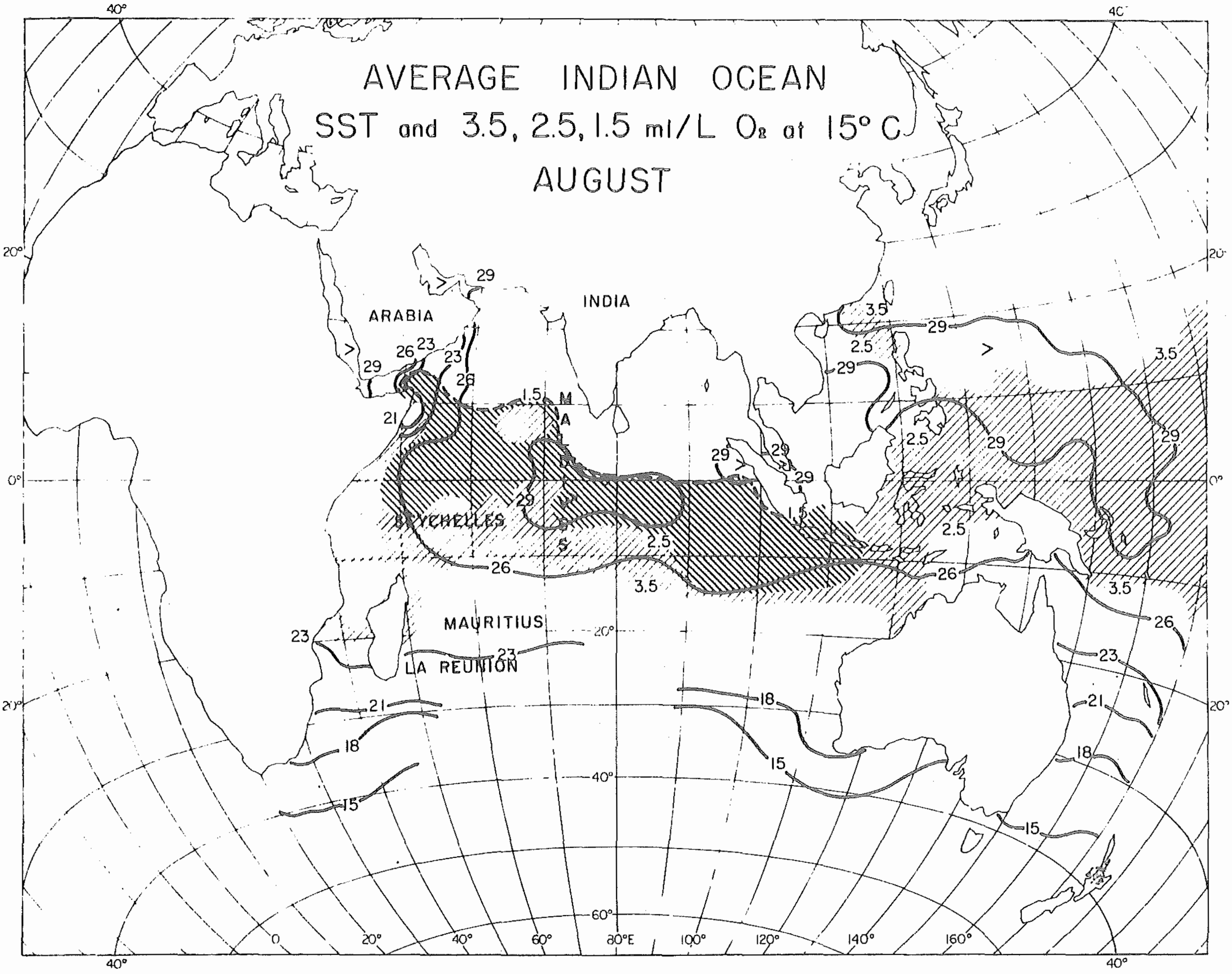
AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O₂ at 15° C
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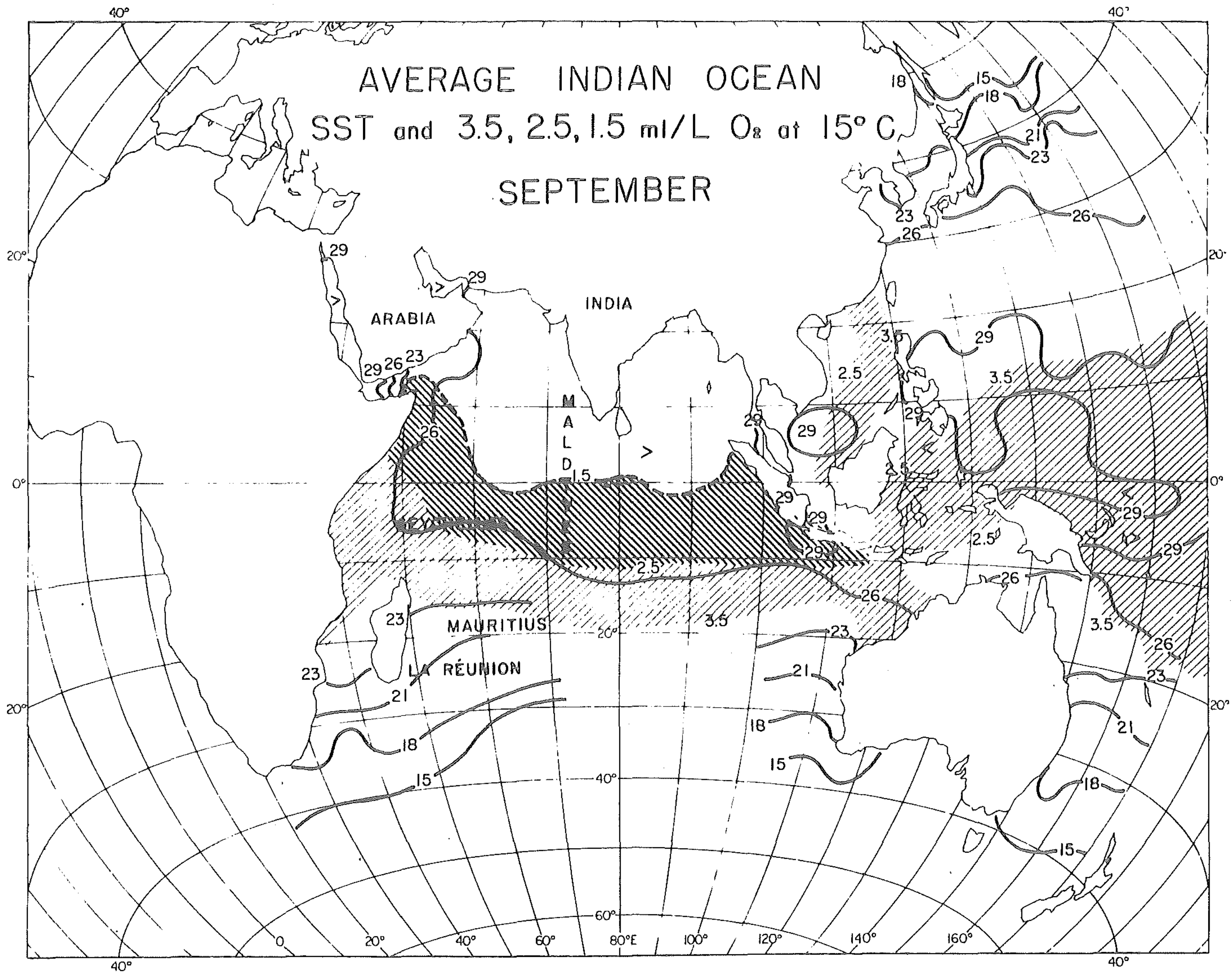
AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O₂ at 15° C
SEPTEMBER
ARABIA
INDIA
M A L D
MAURITIUS
LA RÉUNION
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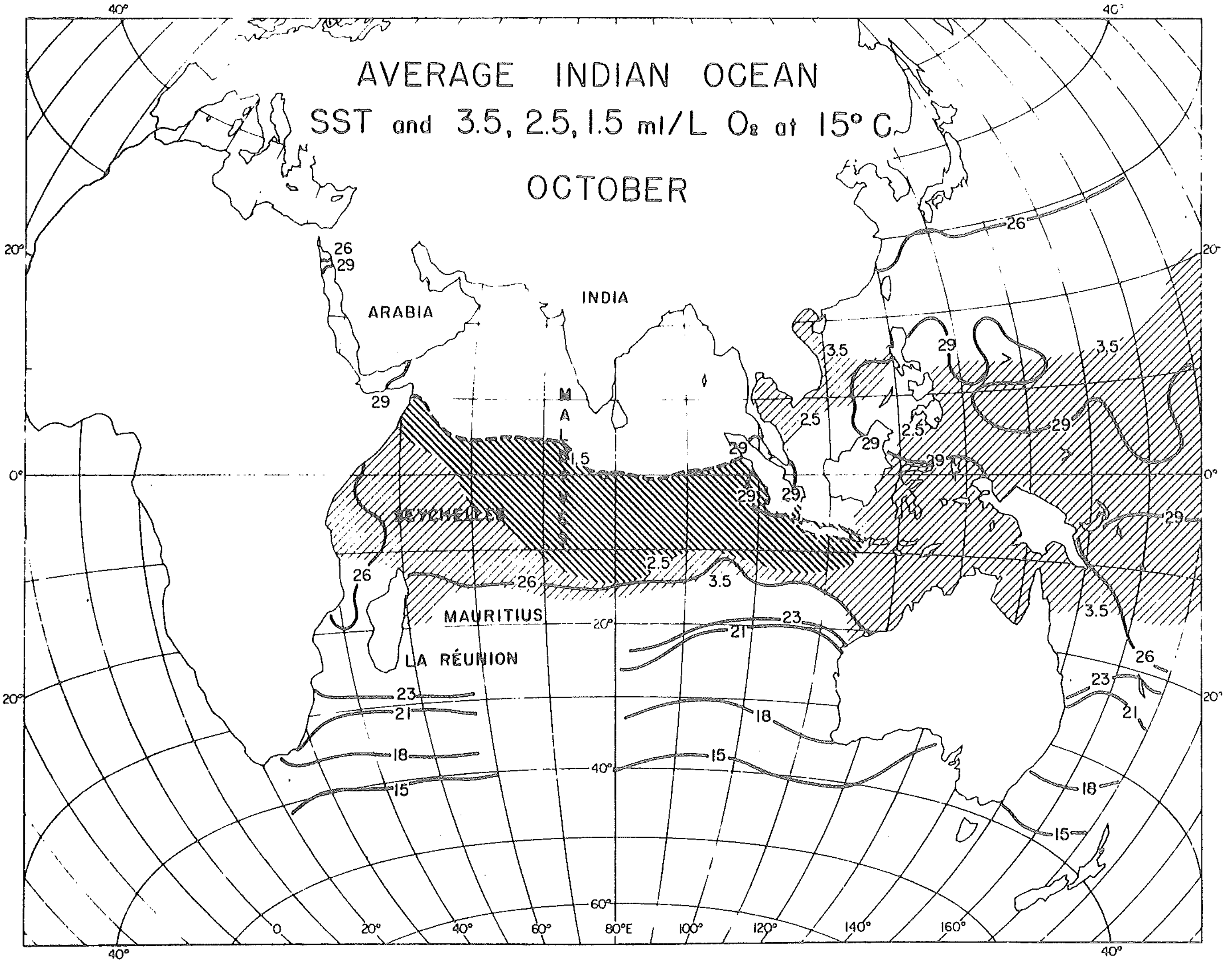
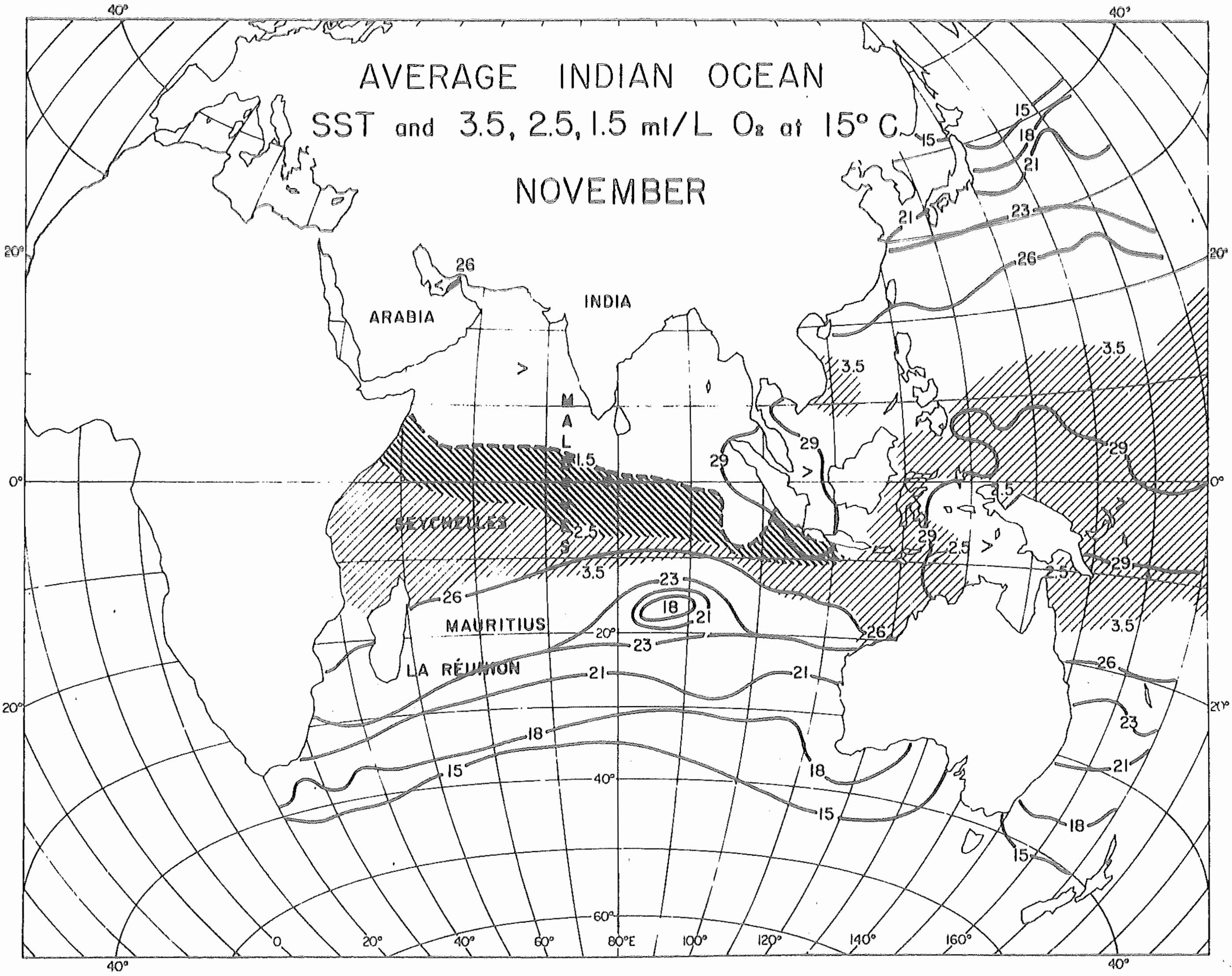
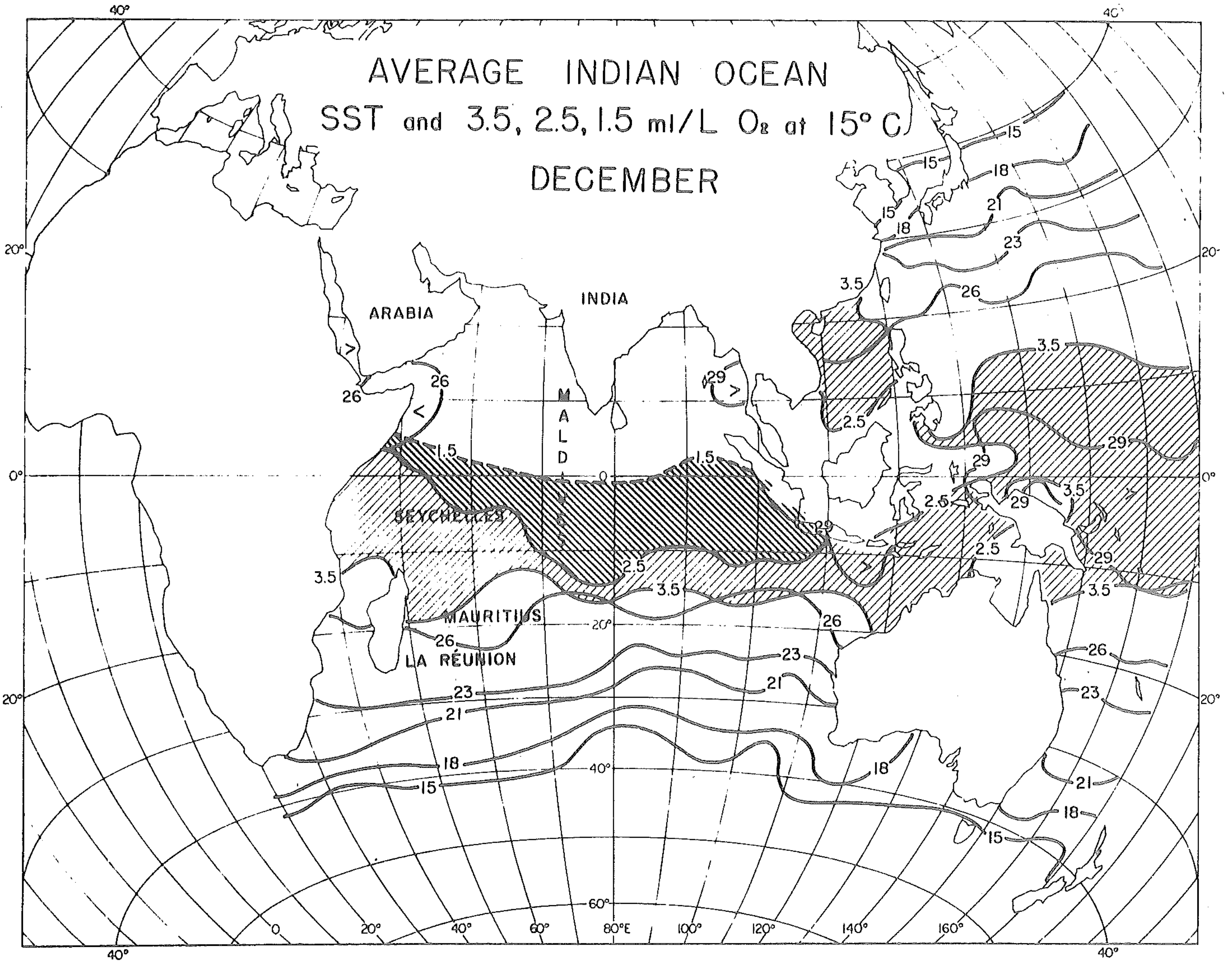
20°
40°
60°
80°E
100°
120°
140°
160°


AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O2 at 15° C
OCTOBER
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
26
29
3.5
2.5
1.5
23
21
18
15
40°
20°
0°
0
60°
80°E
100°
120°
140°
160°



AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O_2 at 15° C
NOVEMBER

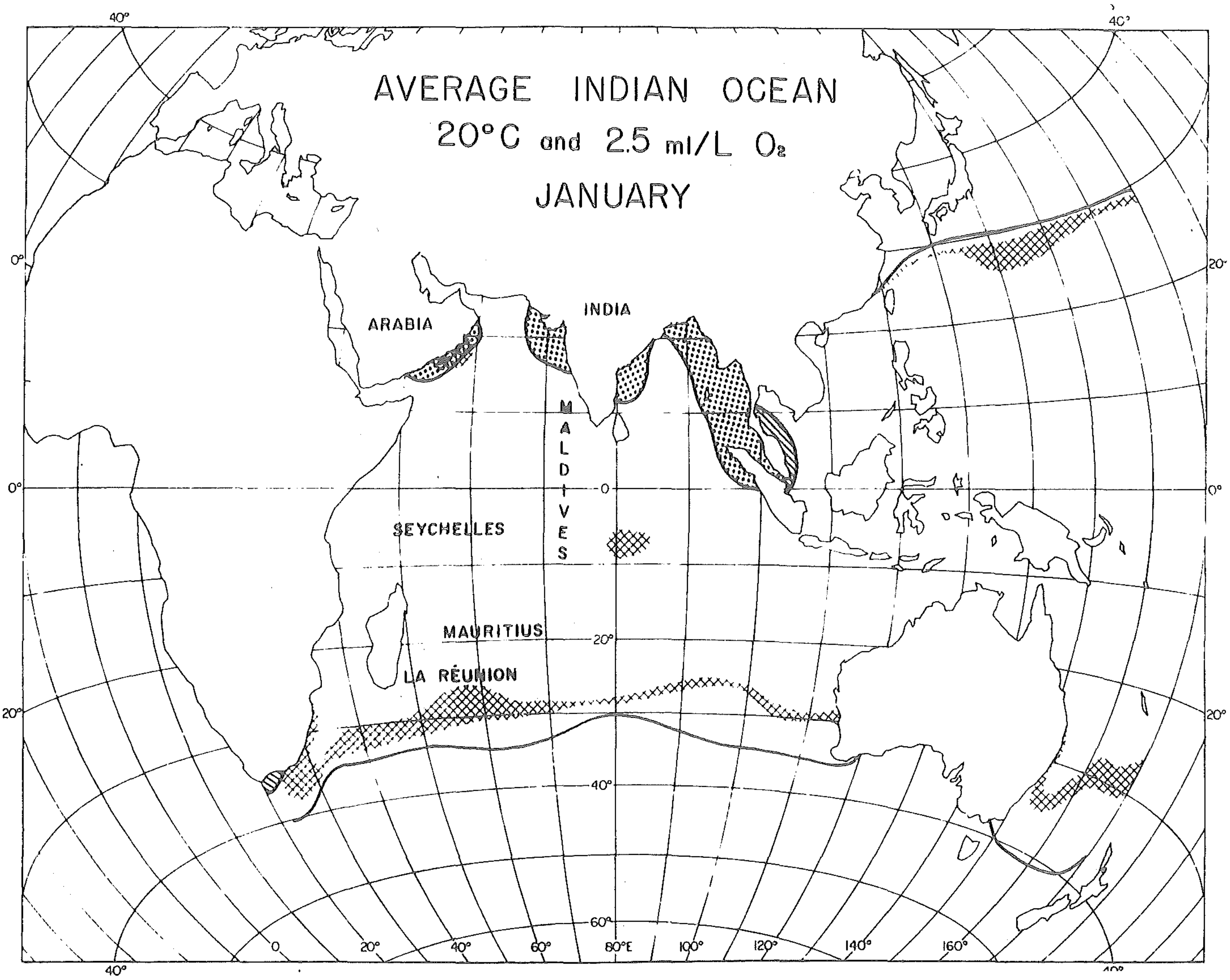


AVERAGE INDIAN OCEAN
SST and 3.5, 2.5, 1.5 ml/L O_2 at 15° C
DECEMBER

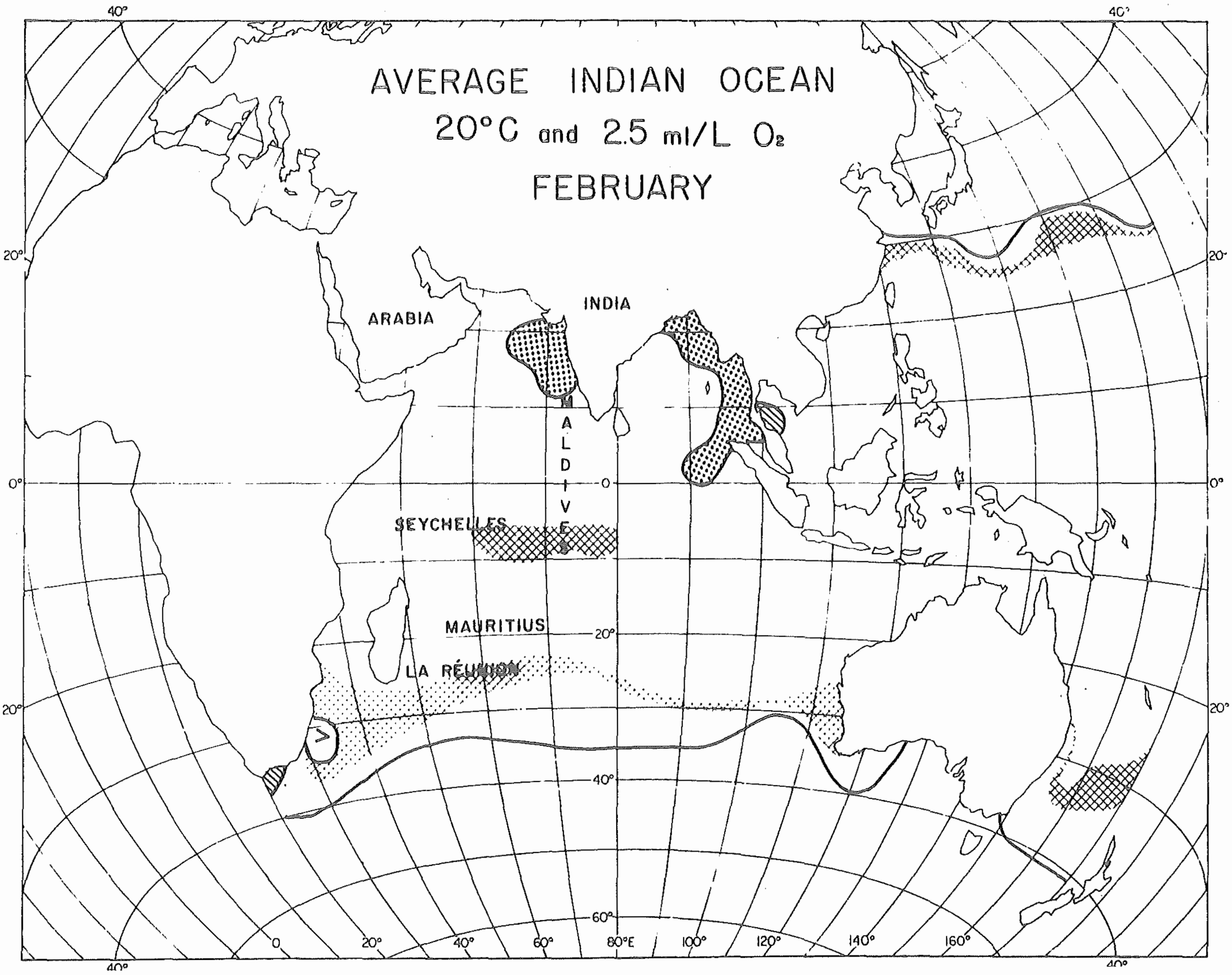
In the second set of monthly charts I have summarized the data of interest to facilitate location of areas where skipjack tuna should be vulnerable to surface gear if they comply to the physiological constraint patterns of the nomadic type of skipjack in the Pacific Ocean. The average 20°C surface isotherm location is shown as a dark line in the southern Indian Ocean. The total area between the 20°C surface isotherm in the south and the northern coastline is the range of skipjack occurrence. However, little can be said about potential vulnerability in this area without taking into account the subsurface features.

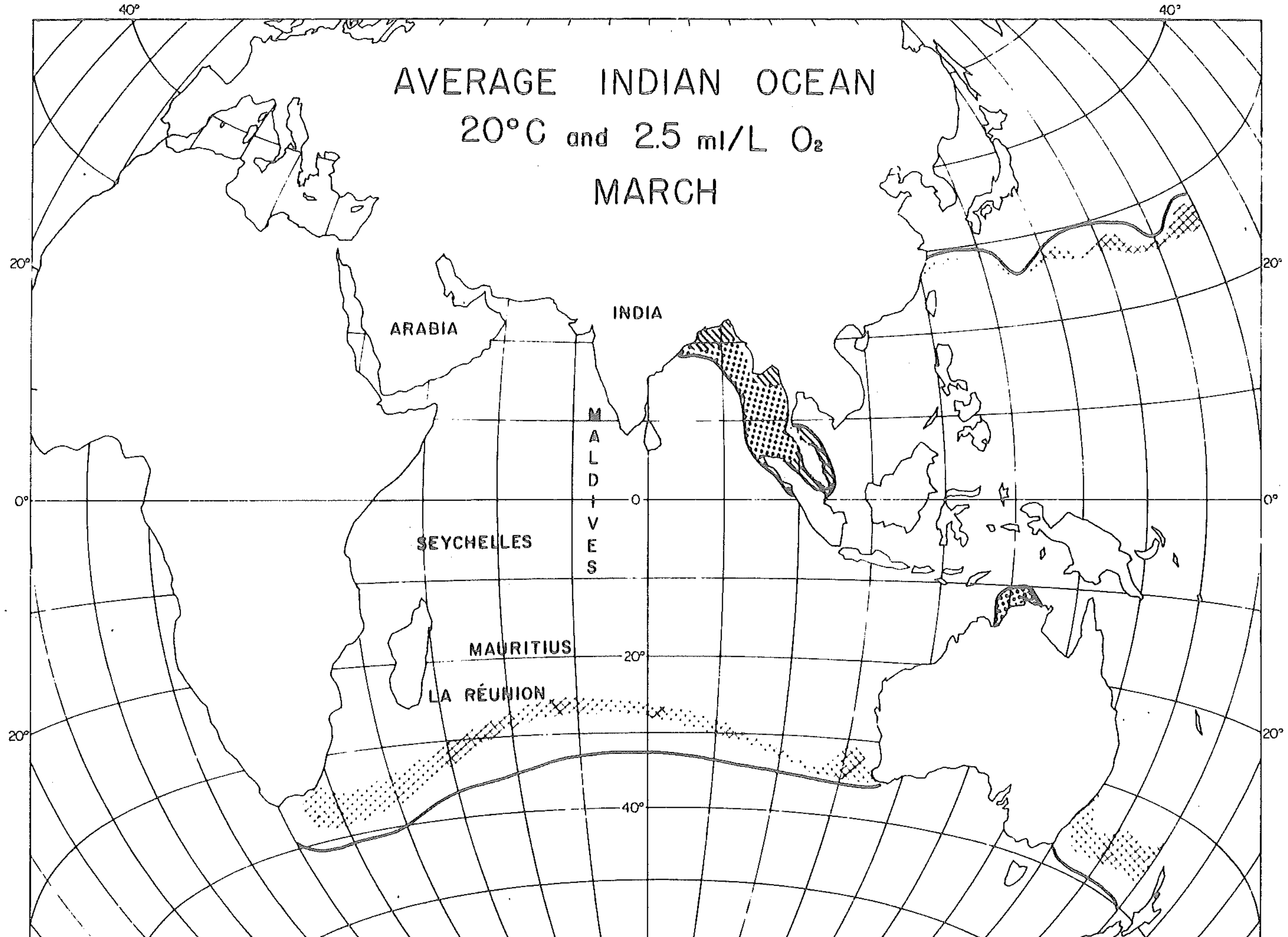
The checked pattern lying just to the north of this line indicates the zone where the 20°C isotherm lies between 50 and 80 metres, the optimum zones for surface gear vulnerabili of skipjack tuna. The dotted zones represent areas where the 2.5 ml/L oxygen levels emerge to depths between 80 and 50 metres, another habitat limitation which appears to enhance skipjack vulnerability. The cross hatched areas indicate regions where the oxygen levels are very low nearer the surface, likely excluding tunas from the region in any numbers.

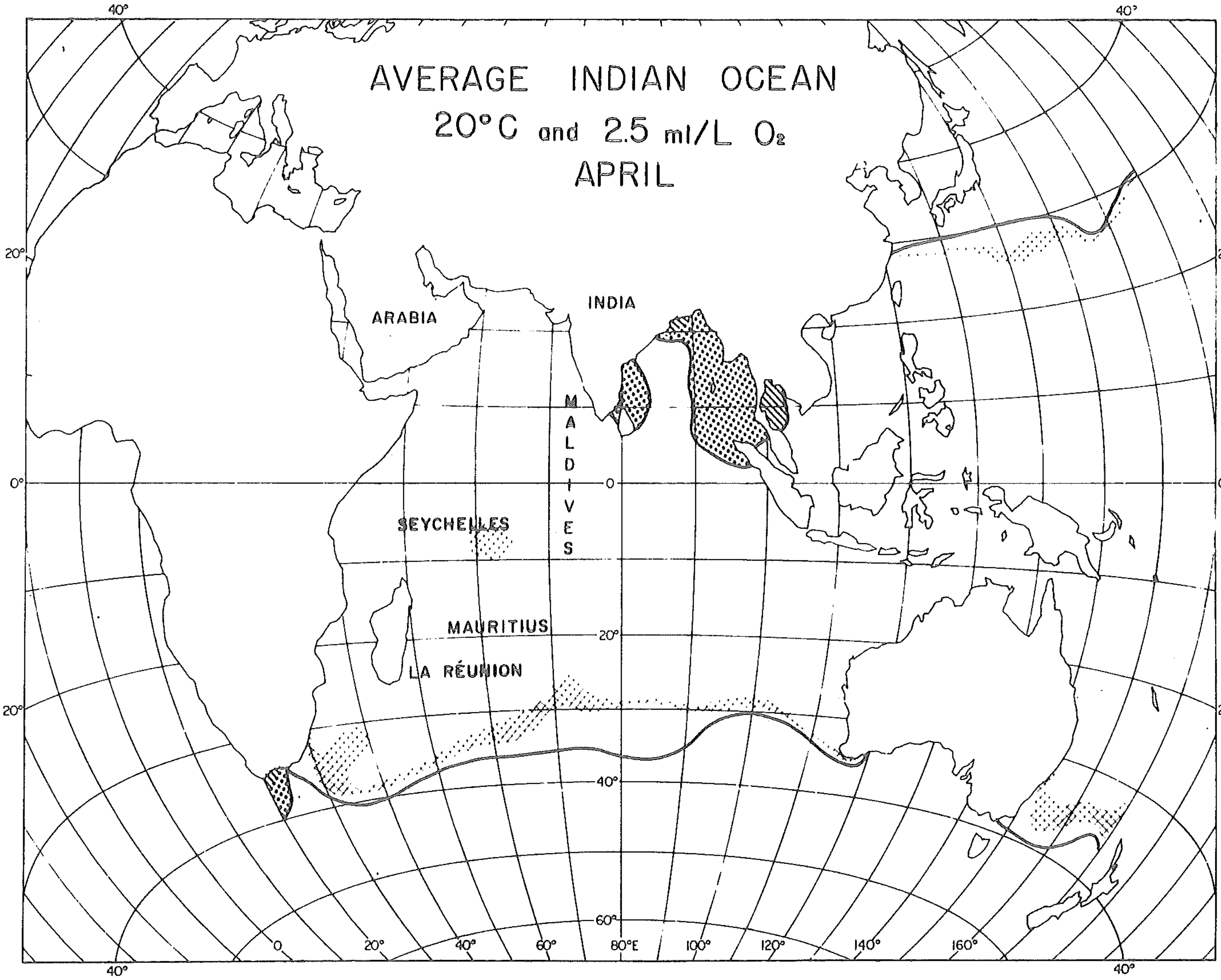
There are large areas where skipjack should be vulnerable; their positions vary in the central Indian Ocean throughout the year in response to wind field patterns. In the period from September through December the northern Indian Ocean temperature profiles respond to the wind conditions which promote upwelling of cooler water. However, the upwelling water is very low in oxygen, virtually excluding the possibility of encountering tunas in these regions due to their high metabolic requirements.



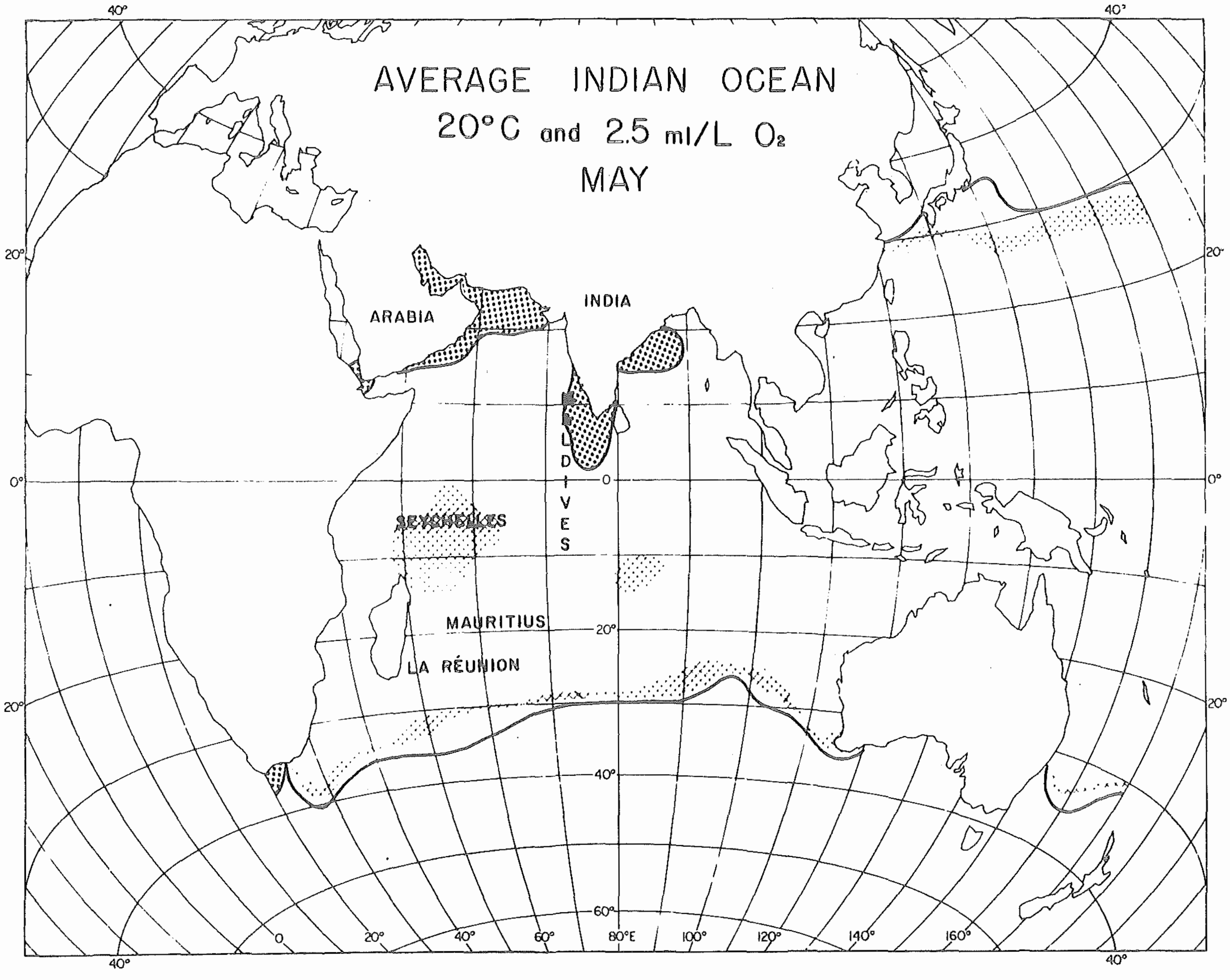
The areas where oceanographic conditions would promote vulnerability of oceanic skipjack to surface fishing methods (not including local phenomena associated with islands), are indicated by the checked and dotted areas. The heavily crosshatched areas have too little oxygen for skipjack to survive at depths less than 50 metres, so few tuna are expected to occur at these times in these areas.

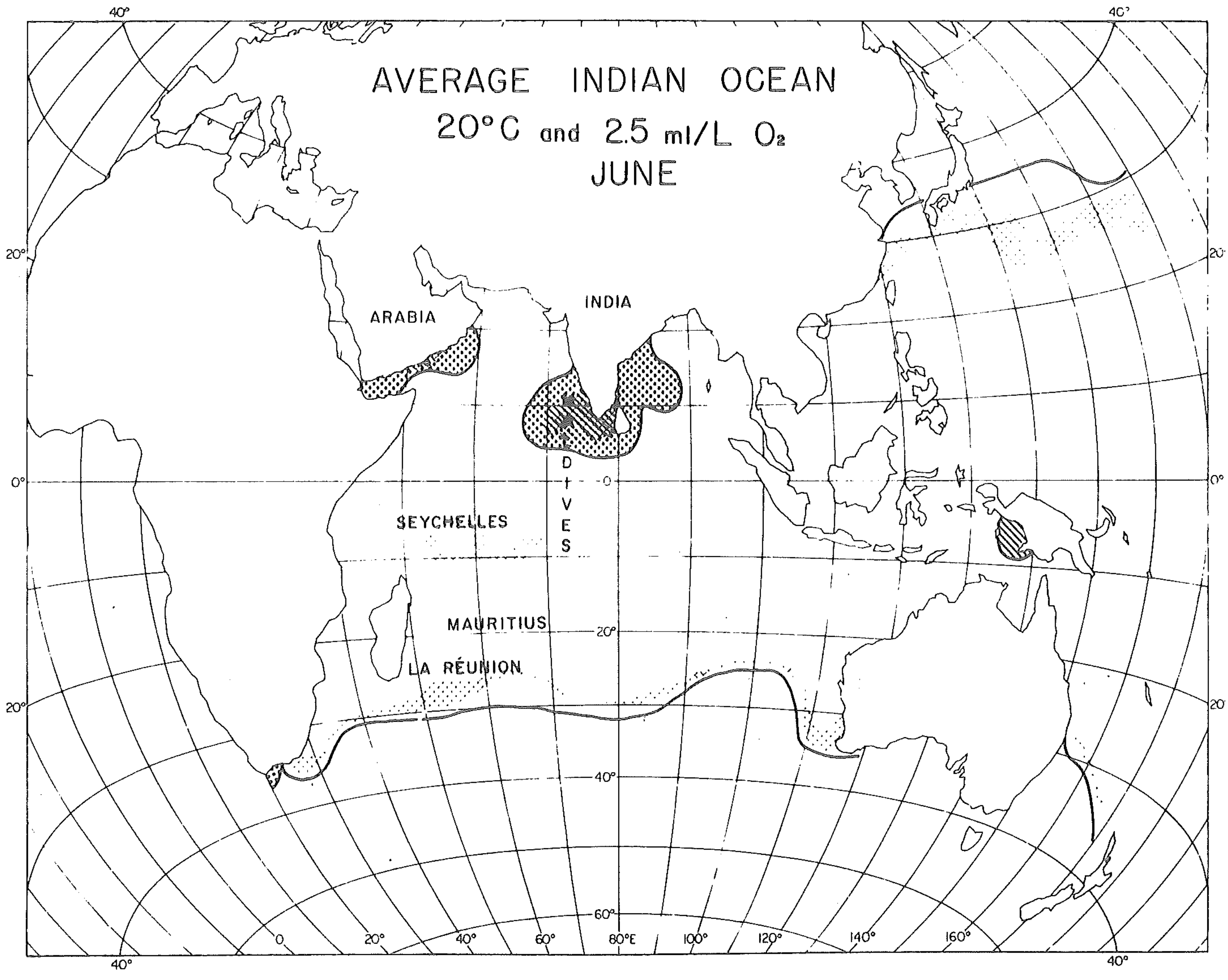

AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O2
FEBRUARY
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°

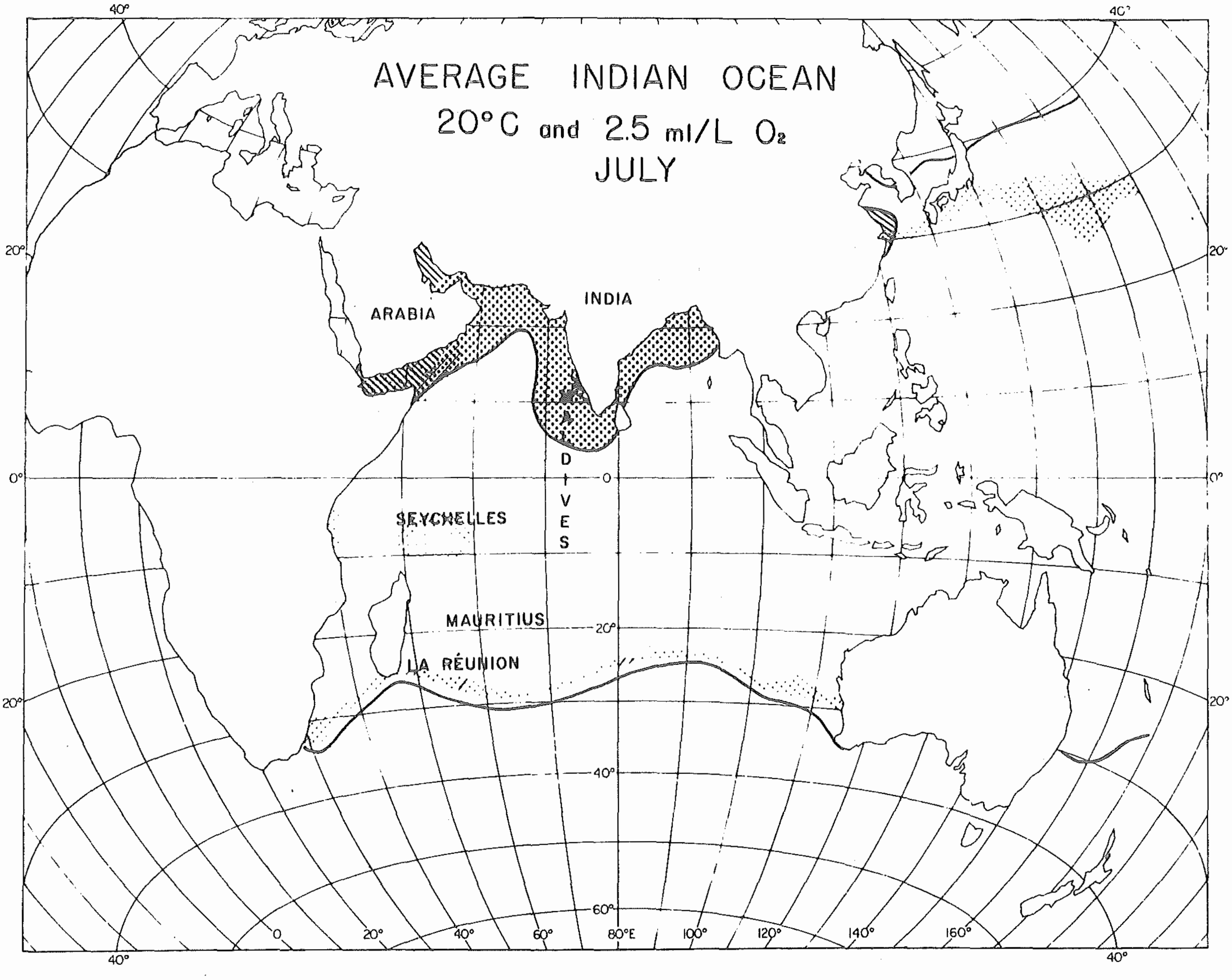

AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
MARCH
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
40°
20°
20°
0°
0°
20°
20°
0
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°
40°
40°

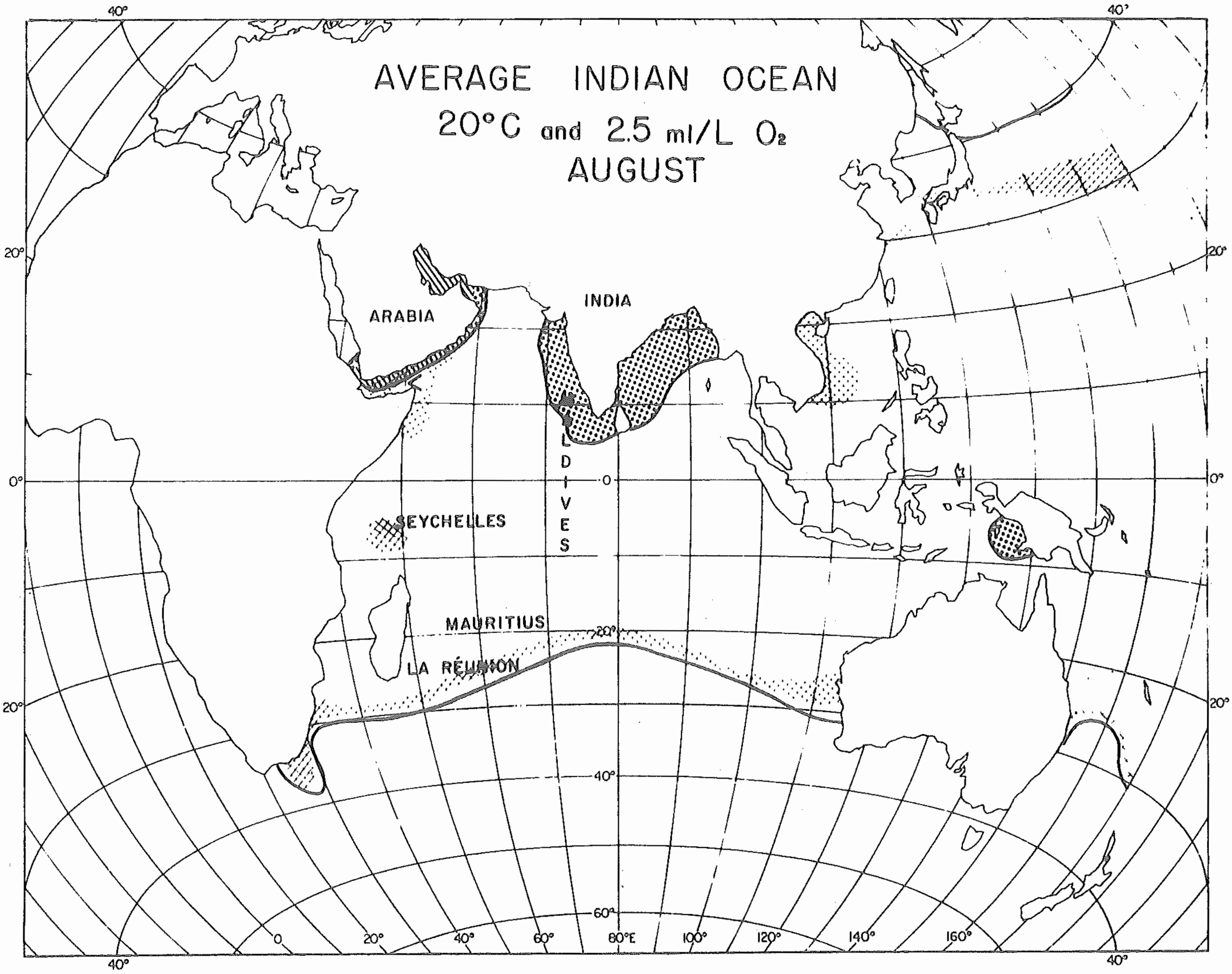


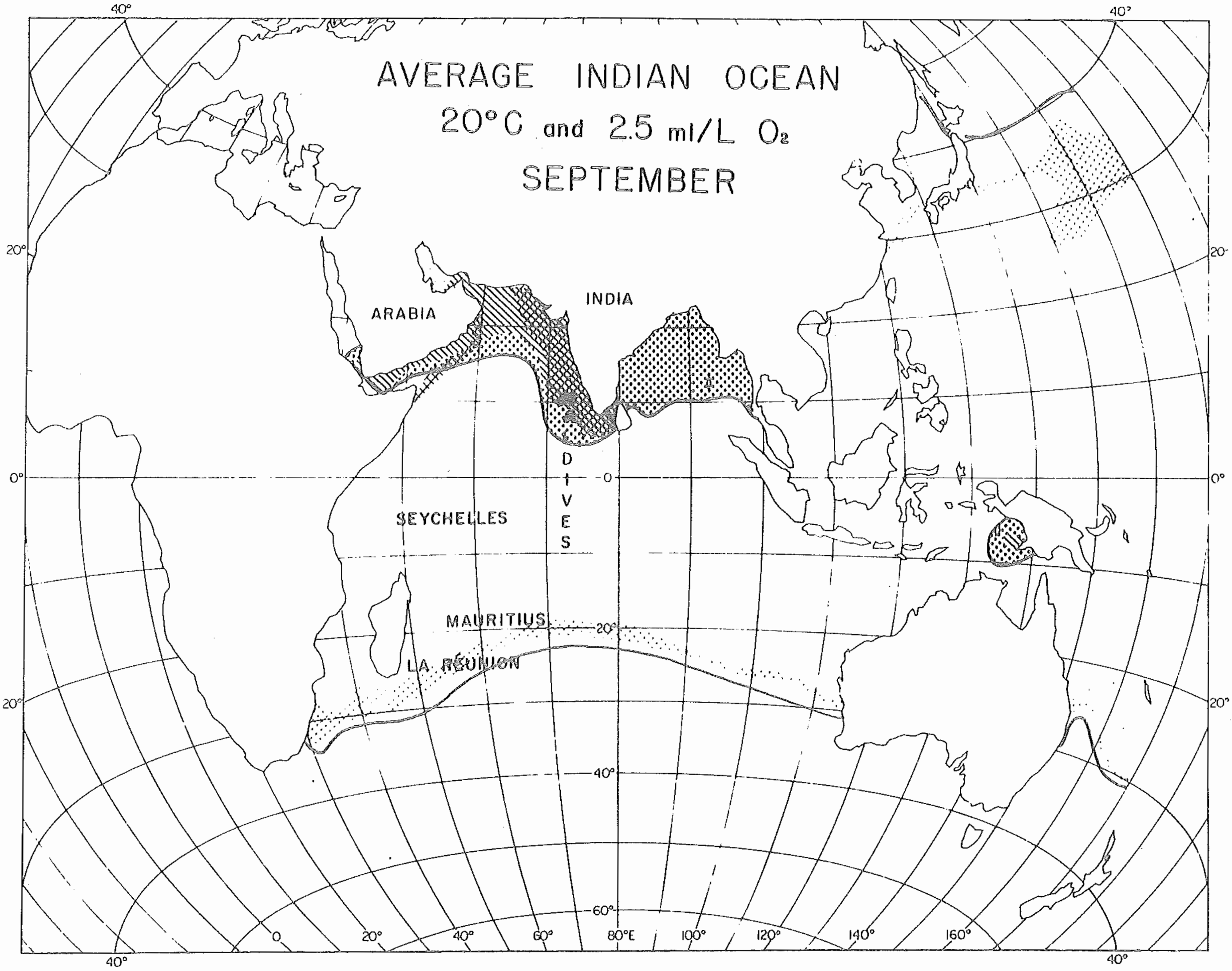
AVERAGE INDIAN OCEAN
$20°C$ and $2.5\ ml/L\ O_2$
APRIL

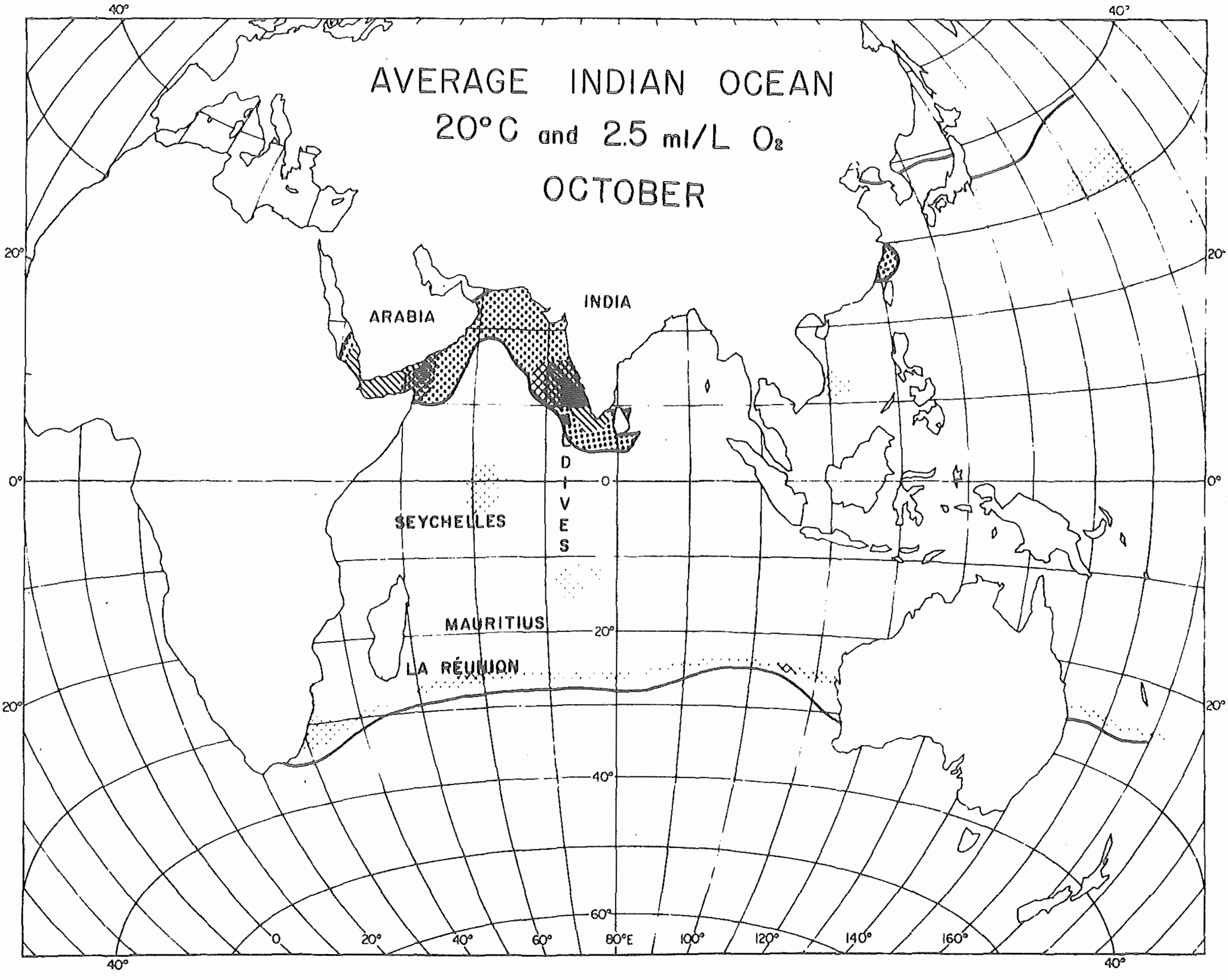

AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
MAY
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
40°
20°
20°
0°
0°
20°
20°
0
20°
40°
60°
80°E
100°
120°
140°
160°
40°
40°
20°
0
20°
40°
60°

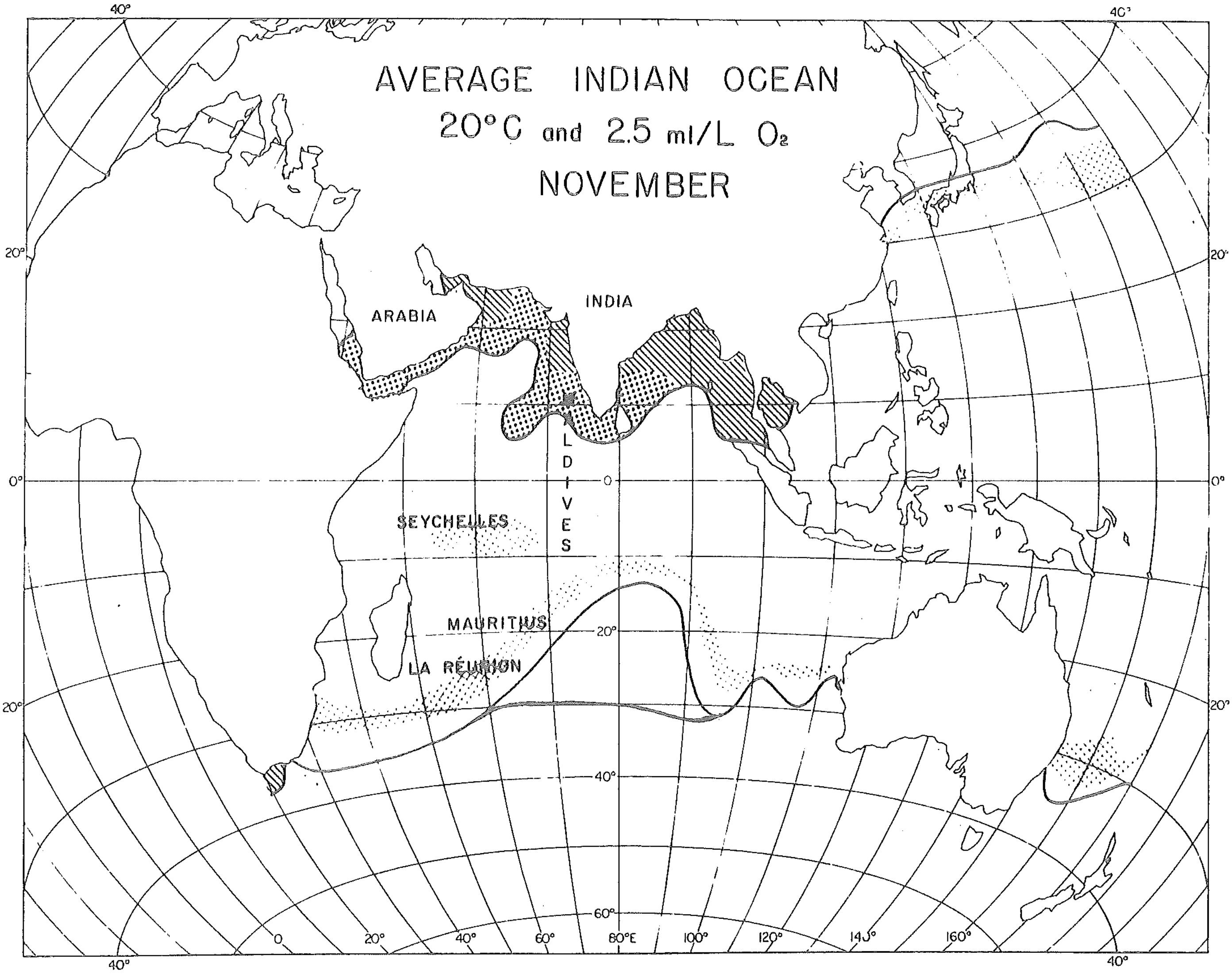

AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
JUNE
ARABIA
INDIA
D I V E S
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
0
20°
40°
60°
80°E
100°
120°
140°
160°
60°

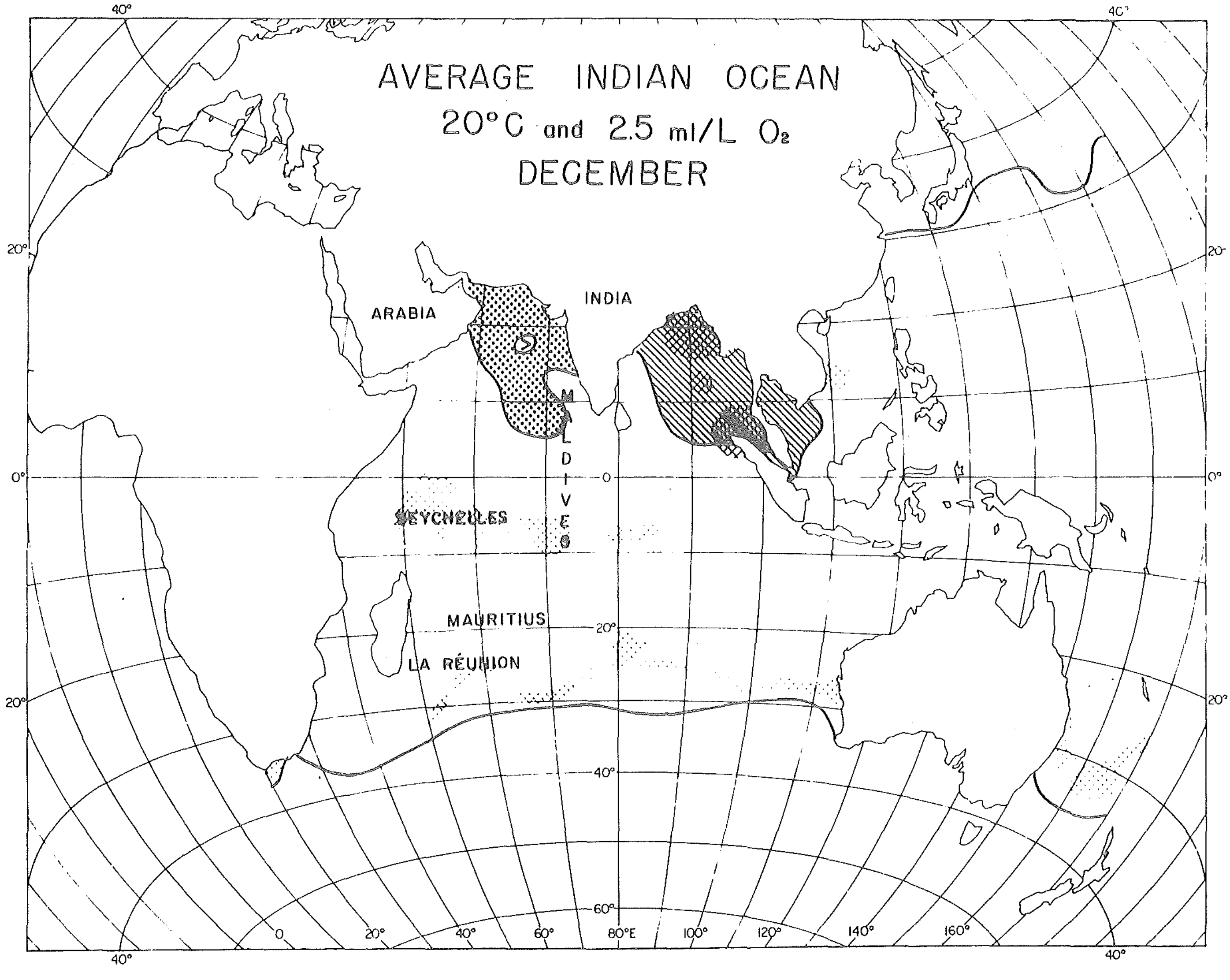

AVERAGE INDIAN OCEAN
20° C and 2.5 ml/L O₂
JULY
ARABIA
INDIA
D I V E S
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
0
20°
40°
60°
80°E
100°
120°
140°
160°
20°
40°
60°


AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
AUGUST
ARABIA
INDIA
LDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
0
20°
40°
60°
80°E
100°
120°
140°
160°
20°
0
20°
40°
60°


AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
SEPTEMBER
ARABIA
INDIA
DIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
0
20°
40°
60°
80°E
100°
120°
140°
160°
-60°
-40°
-20°


AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O₂
OCTOBER
ARABIA
INDIA
DIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
40°
20°
20°
0°
0°
20°
20°
0
20°
40°
60°
80°E
100°
120°
140°
160°
40°
40°
20°
40°
60°


AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O$_2$
NOVEMBER
ARABIA
INDIA
L D I V E S
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
40°
20°
0°
20°
20°
0°
20°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°
40°
40°


AVERAGE INDIAN OCEAN
20°C and 2.5 ml/L O2
DECEMBER
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
0
20°
40°
60°
80°E
100°
120°
140°
160°
20°
40°
60°

In the third set of charts I have combined two sets of information because there is little overlap in the variable shown. One set is for albacore and the other is for yellowfin tuna.

The thin line in the southern Indian Ocean indicates the average position of the 15°C surface isotherm. The light cross hatching to the north of this line is where the 15°C isotherm shoals to between 50 and 80 metres. The vulnerability of juvenile albacore to surface gear should be highest in the region between the thin line and the northern boundary of the thin cross hatching, particularly in the vicinity of frontal areas, islands or other land masses if the behaviour of Indian Ocean albacore corresponds with that of the eastern Atlantic and Pacific Ocean albacore.

Where the lower habitat limits shoal to levels near 80 metres, analogous processes occur to those described for the tropical tunas, and albacore become vulnerable to surface gear, particularly trolling and baitfishing methods. Purse seining for albacore is rarely successful due to 1) their diffuse schooling patterns in most cases; and 2) in the typical situation where large schools of albacore do occur, the lower habitat bounds are deeper than the nets are designed to operate effectively, so the fish can dive out of the nets without encountering any stressing factors from the environment.

It can be observed from the charts that the 15° and 18°C isotherms are located closer together than the warmer isotherms, on the average. This indicates the isotherm compression effect characteristic of the transition zone between temperate and tropical conditions. In the vertical sections you can observe that the 15°C isotherm in the tropical latitudes is also nearly the lower bound of the thermocline in that isotherms cooler than 15°C occur at nearly constant depth invervals $(\frac{dT}{dD} = \text{Constant})$.

The temperature range including the 15°C to 22°C isotherms can be considered to be the habitat of albacore any place where oxygen values are greater than 1.4 ml/L.

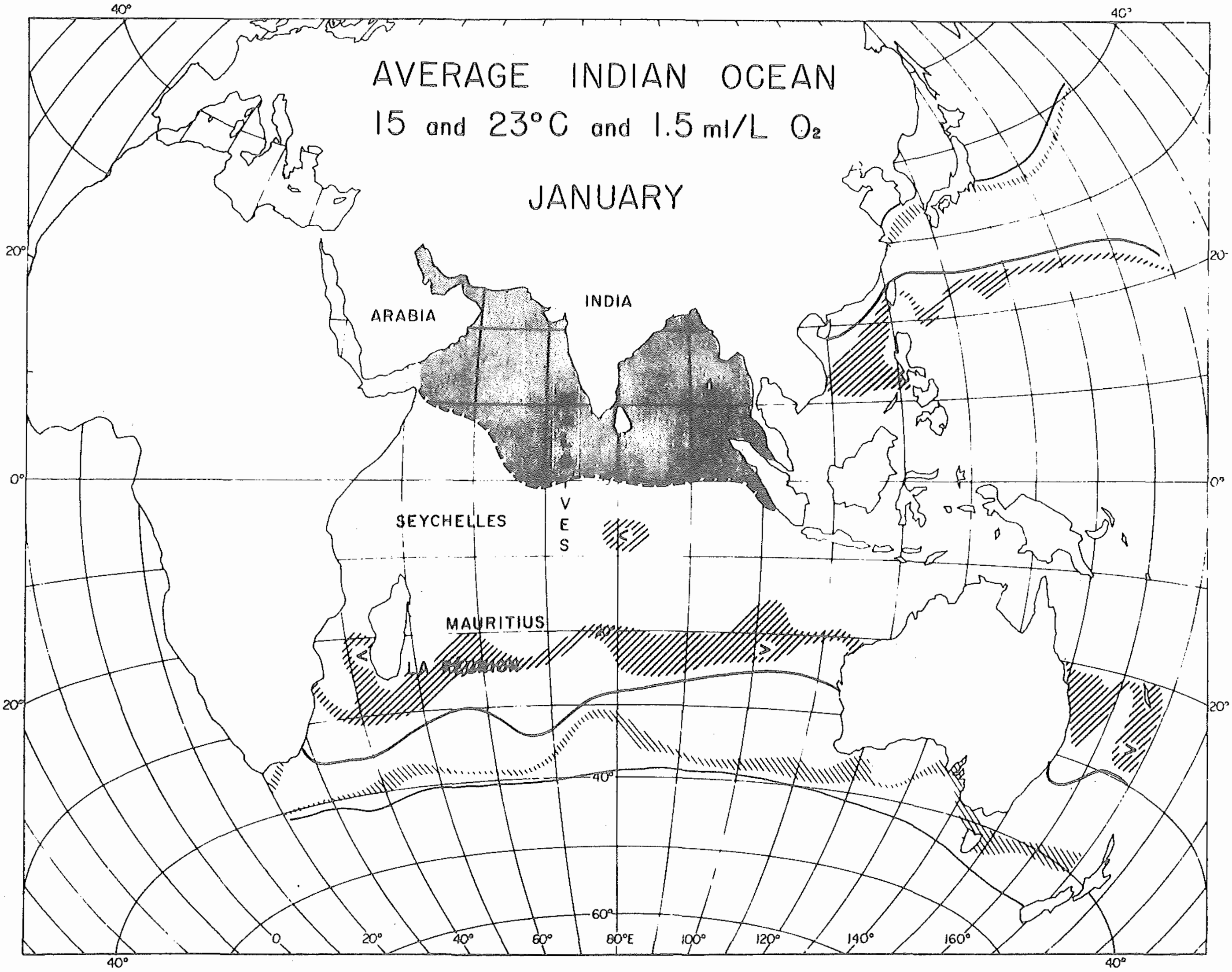
Water temperatures warmer than 22°C are the preferred habitat of yellowfin tuna. They can and do foray into cooler water but for limited periods, but usually to depth, not latitudinally.

North of the albacore information is a heavier line indicating the 23°C surface isotherm and heavier cross hatching indicating the area where the 23°C isotherm lies within 50 to 80 metres of the surface. There are large regions indicated as having optimum conditions for vulnerability of yellowfin to surface gear. The 15°C isotherm depth is the lower distribution bound (see vertical sections).

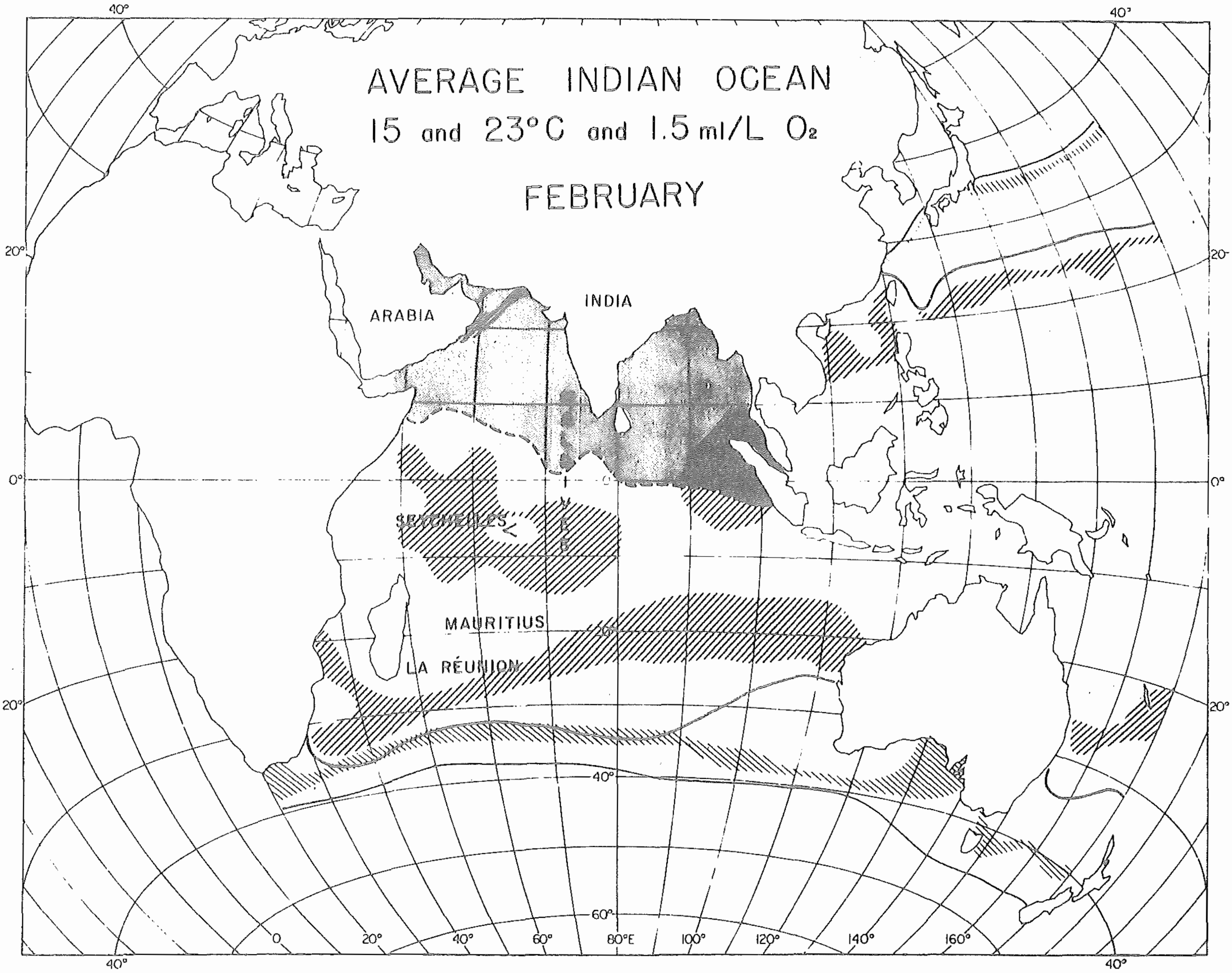
In the northern Indian Ocean I have indicated by a dashed line the southern limit of the emergence of the 1.5 ml/L oxygen level above the 15°C isotherm depth, where it becomes a significant limiting feature promoting vulnerability of yellowfin tunas. Quite marked seasonal changes in areas conforming to either thermal or oxygen limitations, or both, produce a vastly more interesting picture for the vulnerability distribution of yellowfin tuna than was observed for skipjack tuna or albacore. The occurrence of mixed species schools of yellowfin and skipjack such as observed in other ocean areas is probably also common in the Indian Ocean. This may promote even more skipjack vulnerability than the charts would indicate.

A few words about non-surface oriented fishing potential are due at this stage. The longline method primarily exploits the large adult population of tunas, and secondarily billfishes. The array of hooks exploits fish traversing the 50 mile line within perceptual vicinity of the baits. Longline catches are varied, typically three or four species of tunas, some billfish and sharks are taken in the same set. Hook rates are not typically very great averaging from 10 to 25 fish per thousand hooks in any "productive" area. The less productive areas for this method of fishing far outnumber the productive areas.

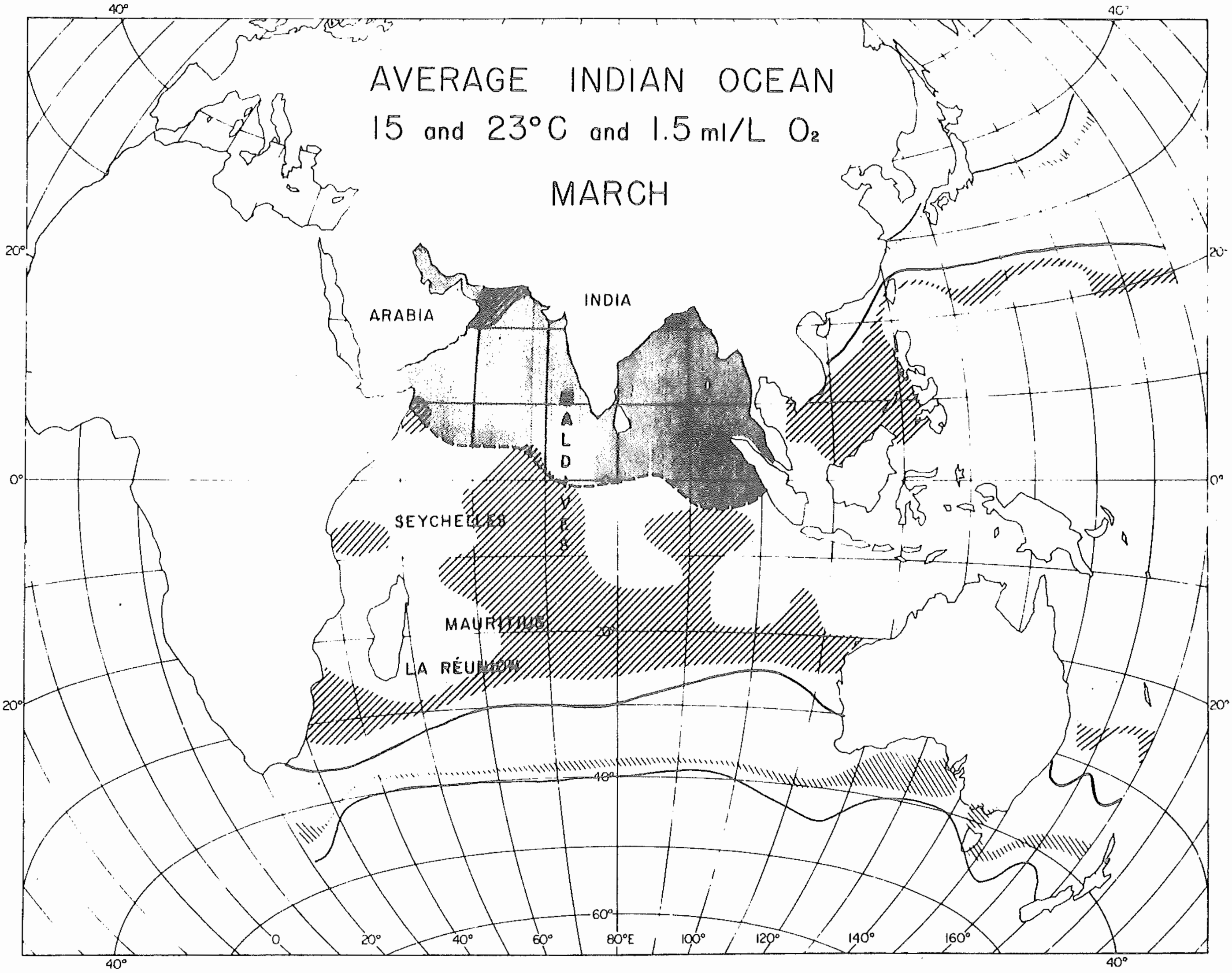
There are species-specific thermal and oxygen profiles which promote differential vulnerability to longline gear too. The charts provided can also be useful in localizing the



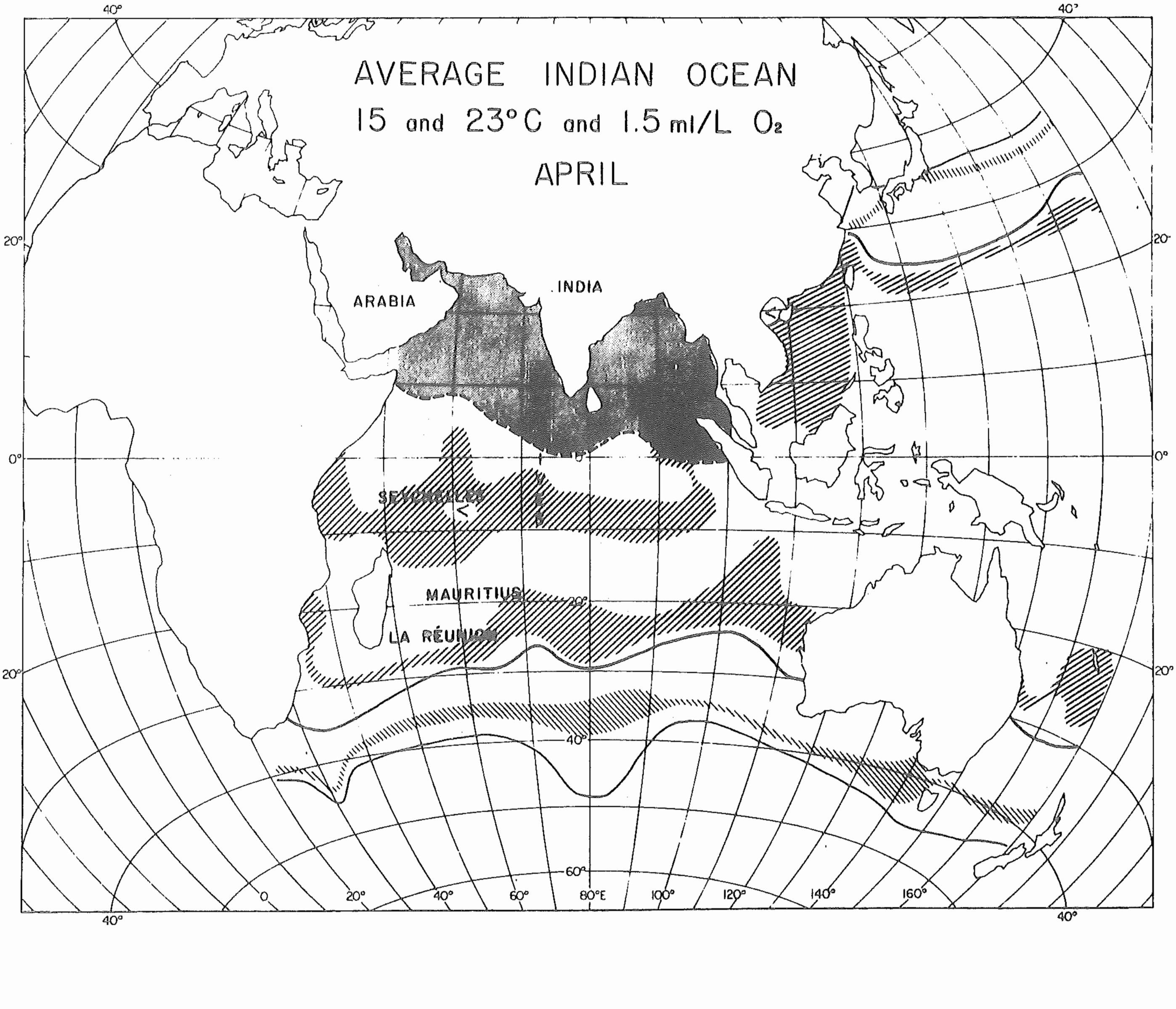
The vulnerability zones, as indicated by oceanographic conditions, which would promote vulnerability of albacore are indicated by the light crosshatched areas near to bottom of the figure. The more heavily crosshatched areas indicate similar features for yellowfin tuna. The dark shading in the northern Indian Ocean indicates where the oxygen availability at depths shoaler than 80 metres may preclude abundances of yellowfin and albacore.

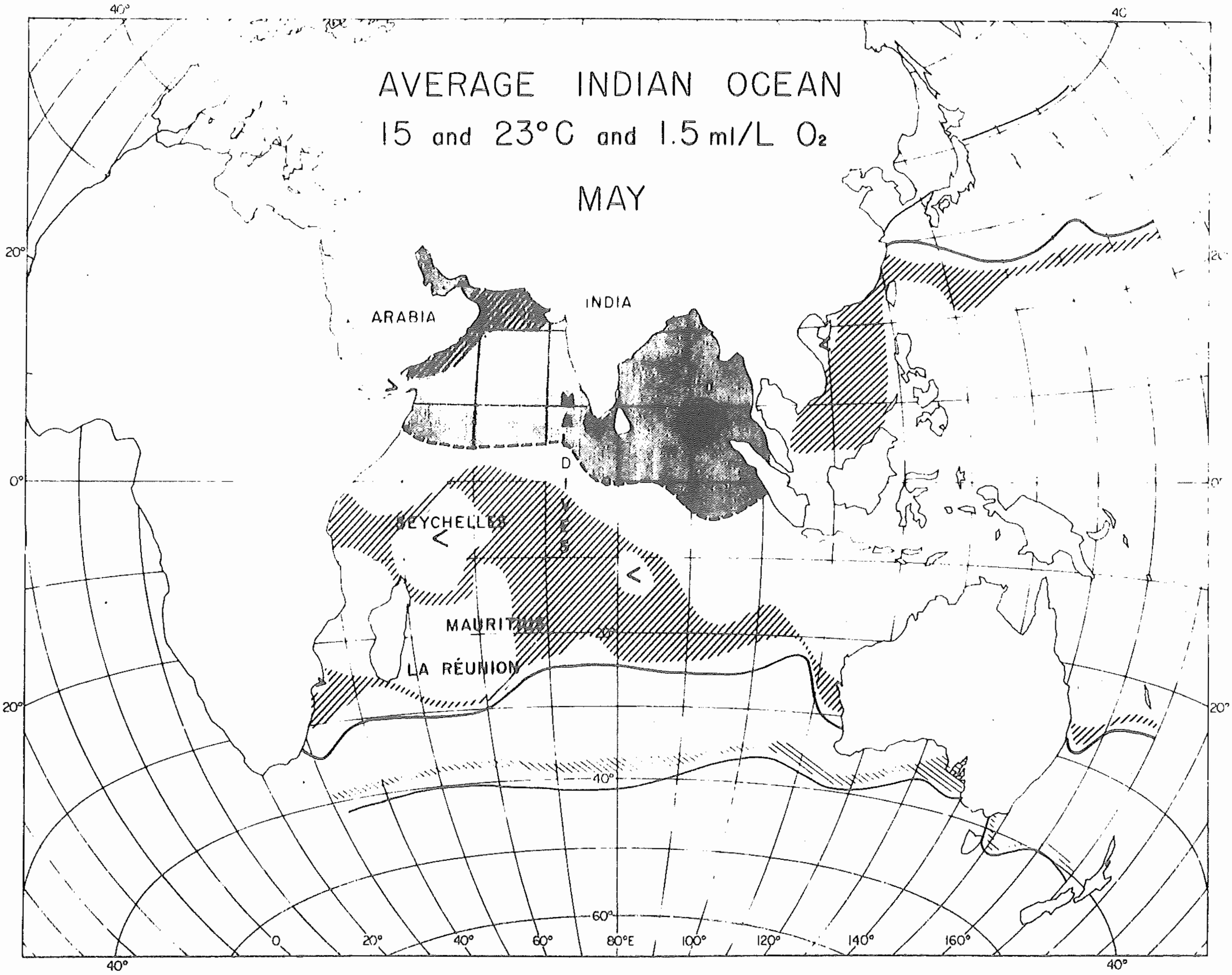


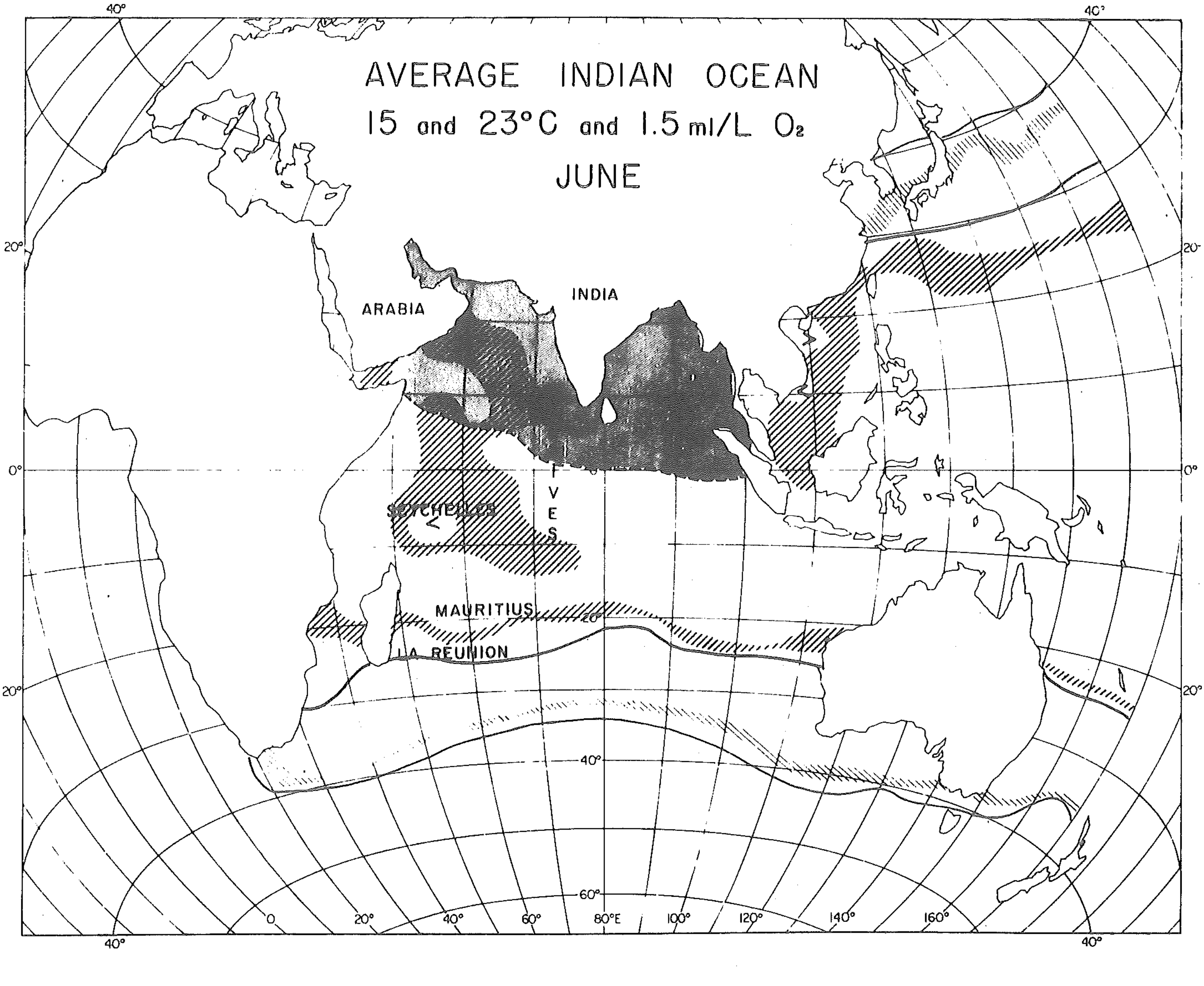
AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O_2
FEBRUARY

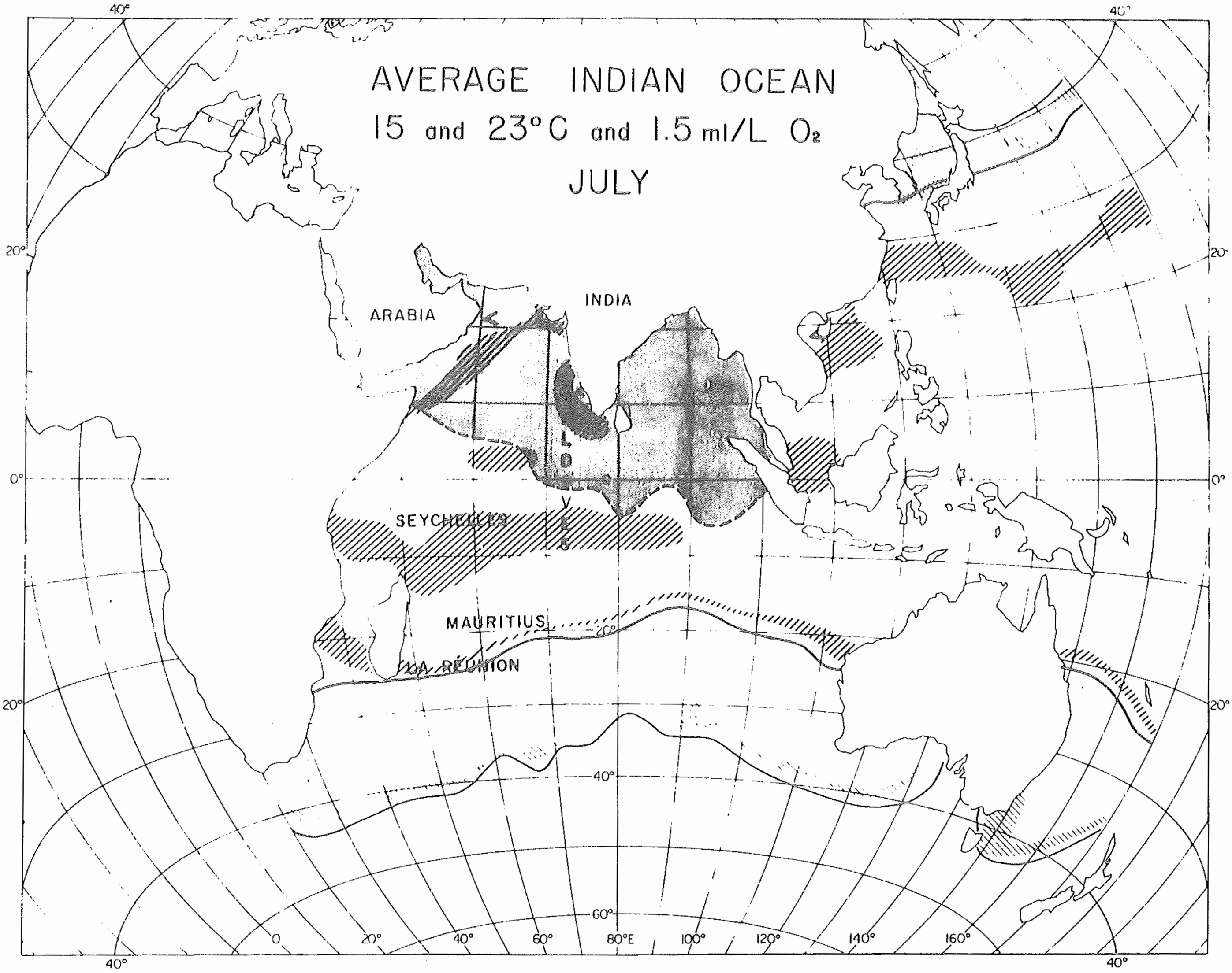


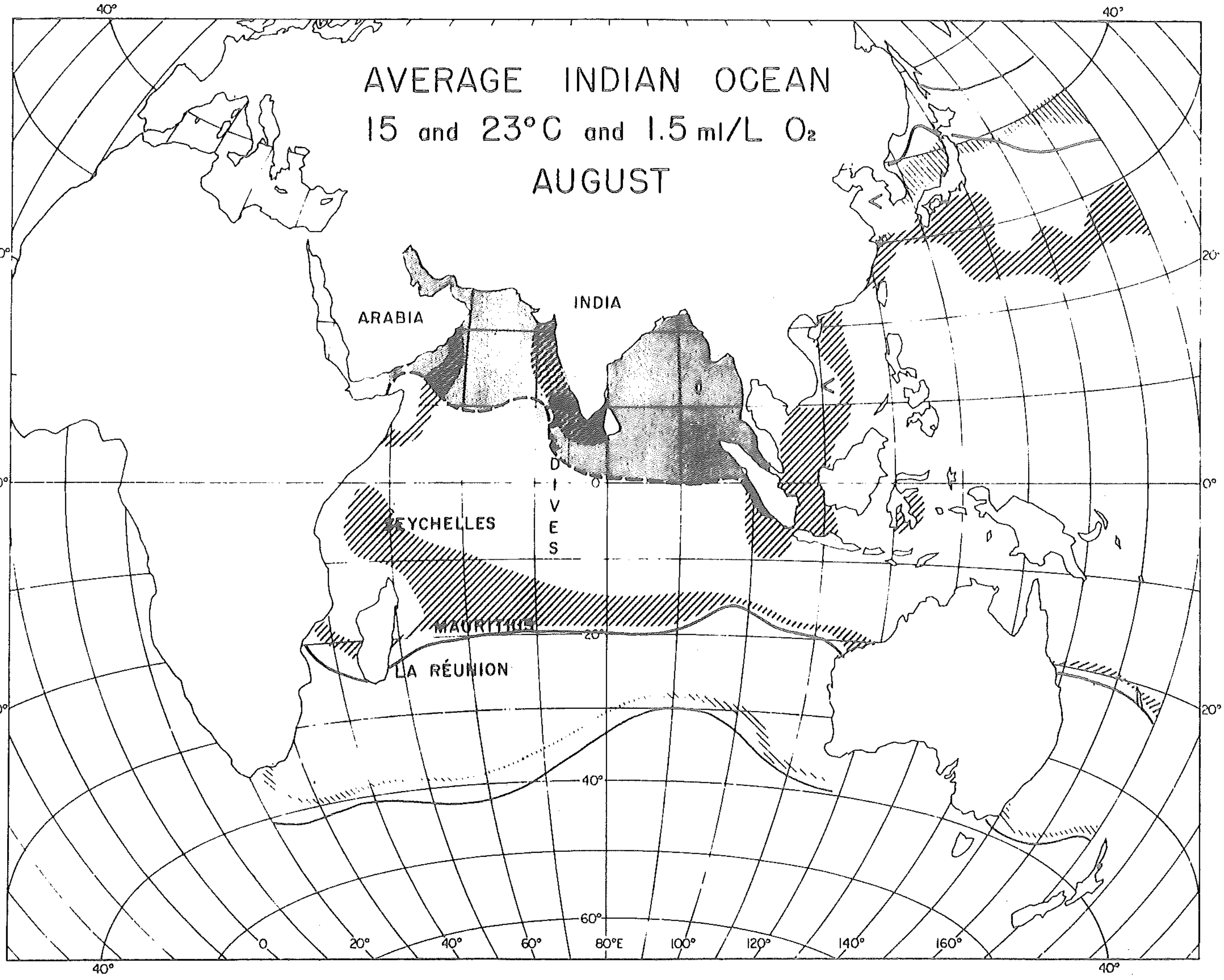
AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O_2
MARCH

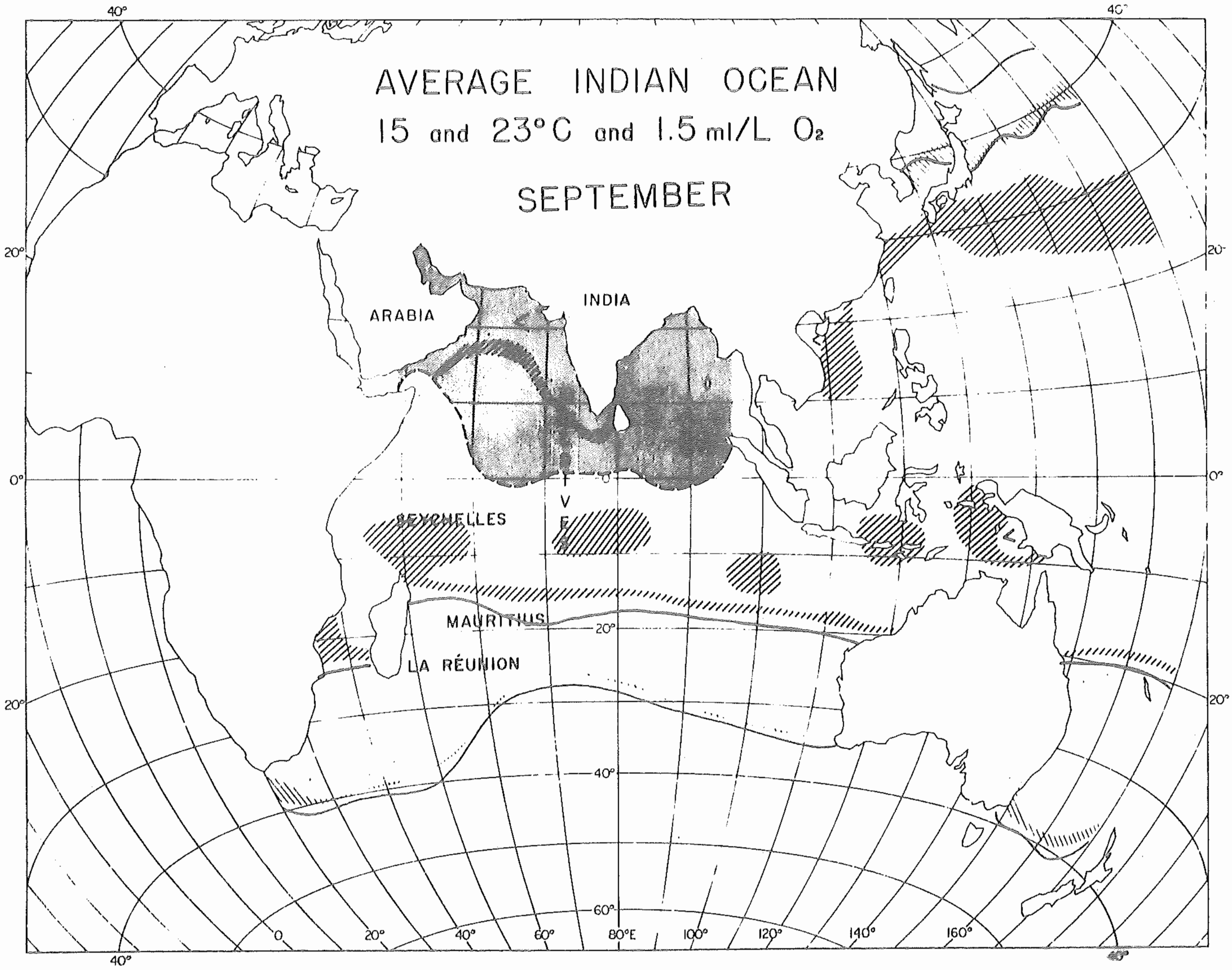

AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O₂
APRIL
ARABIA
INDIA
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°

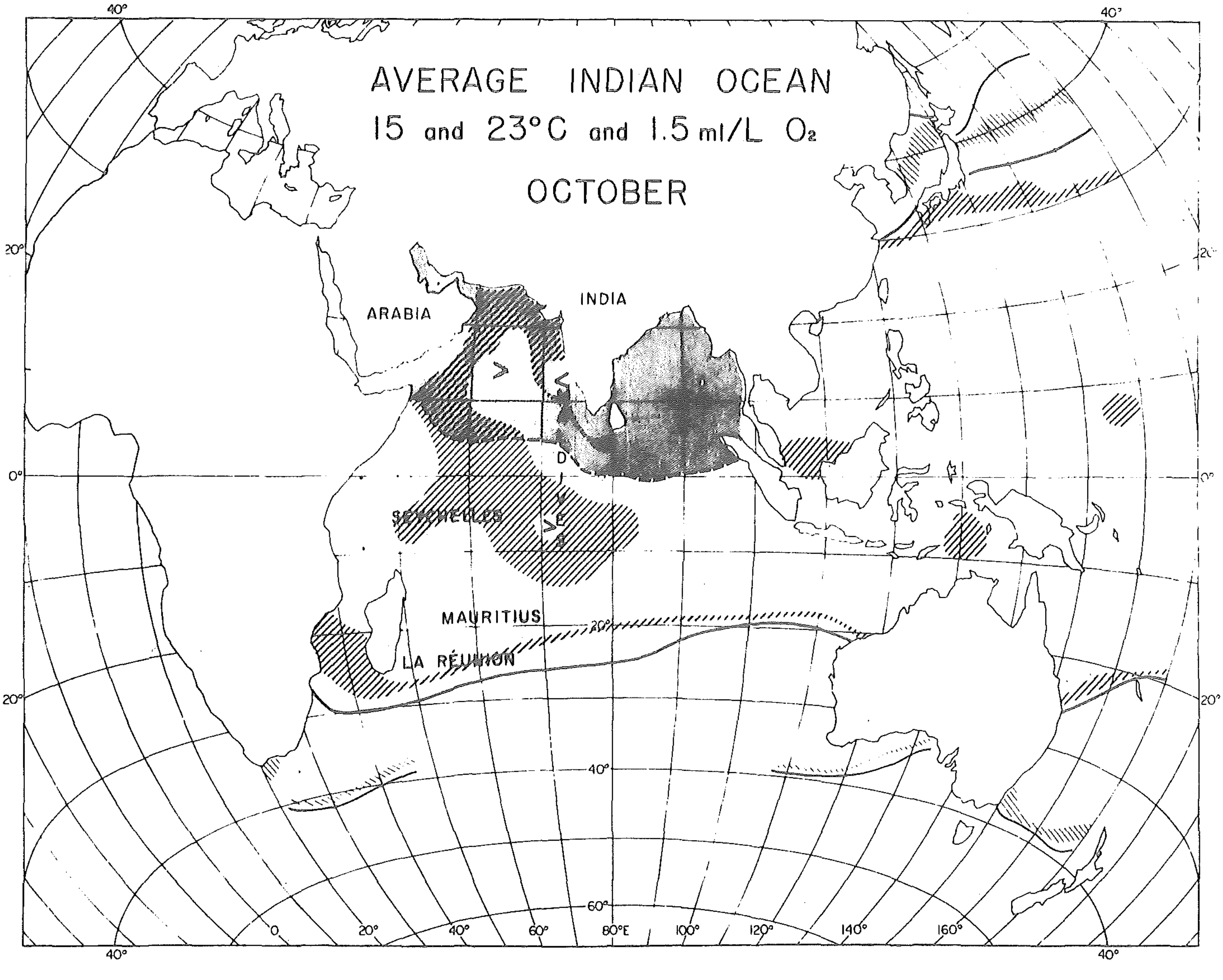

AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O₂
MAY
ARABIA
INDIA
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°


AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O2
JUNE
ARABIA
INDIA
SEYCHELLES
V
E
S
MAURITIUS
LA REUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°

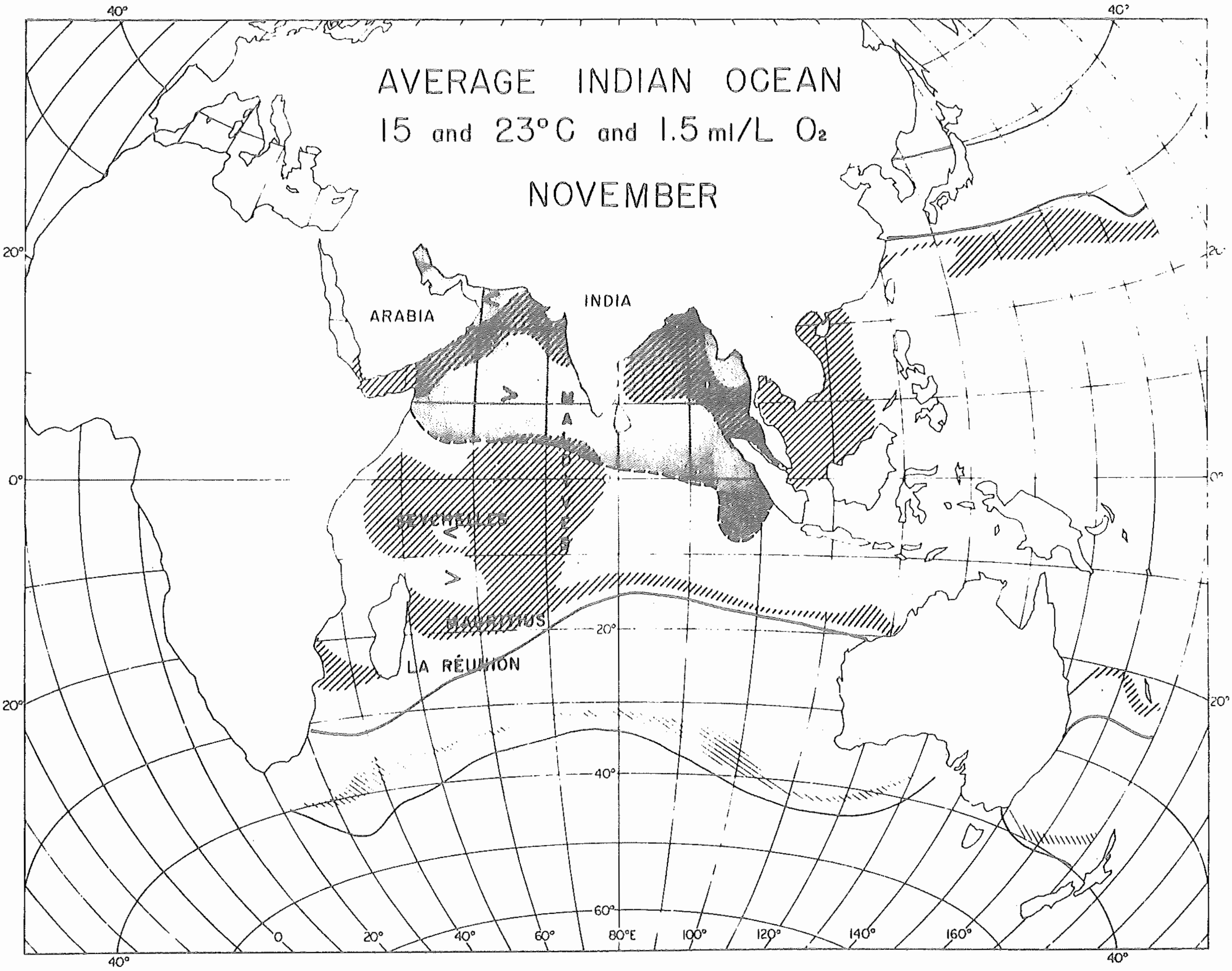

AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O_2
JULY
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA REUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°

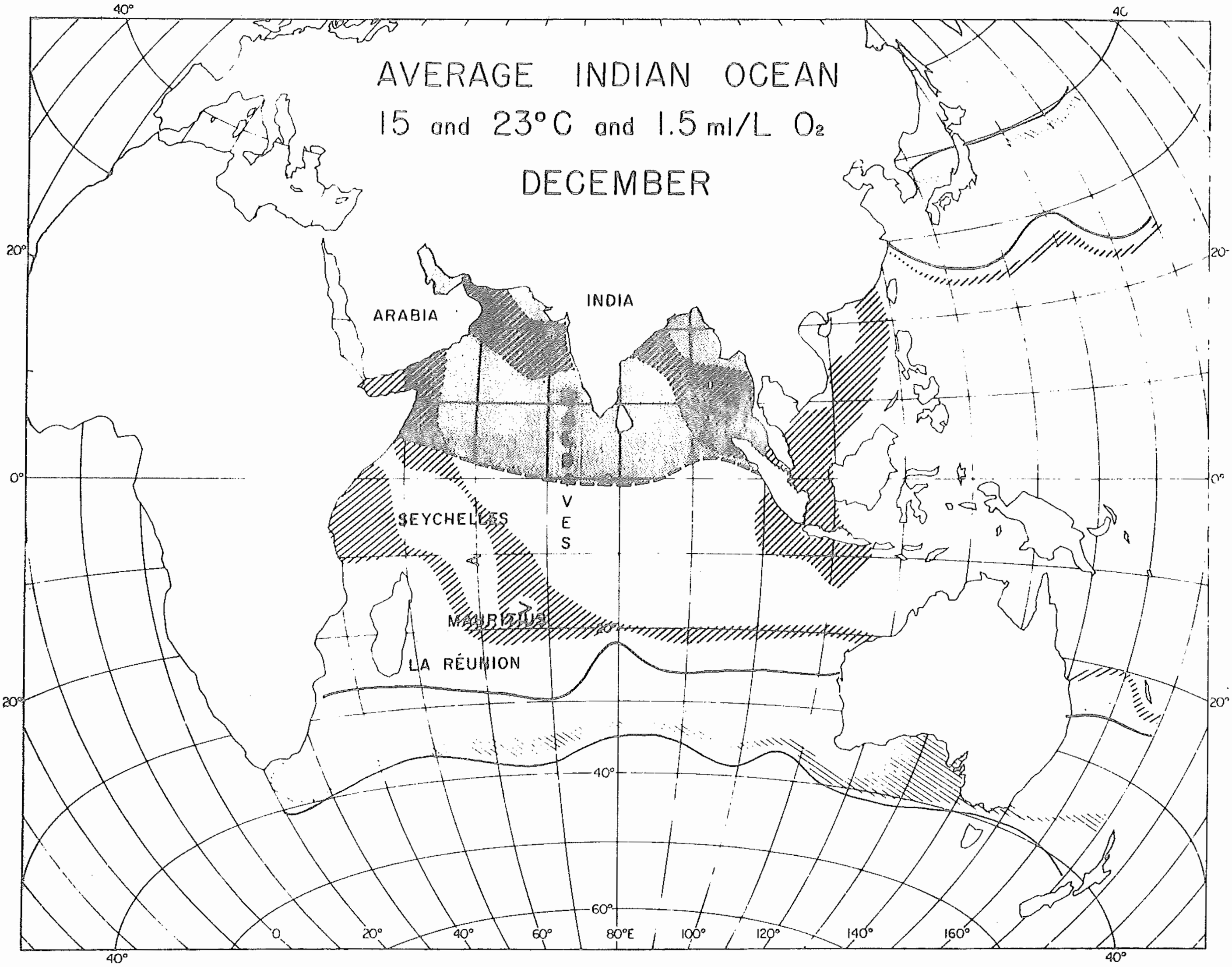

AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O₂
AUGUST
ARABIA
INDIA
SEYCHELLES
D I V E S
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°


AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O_2
SEPTEMBER
ARABIA
INDIA
SEYCHELLES
V E A
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°



AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O_2
OCTOBER


AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O₂
NOVEMBER
ARABIA
INDIA
MALDIVES
SEYCHELLES
MAURITIUS
LA RÉUNION
40°
20°
0°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°


AVERAGE INDIAN OCEAN
15 and 23°C and 1.5 ml/L O2
DECEMBER
ARABIA
INDIA
SEYCHELLES
V
E
S
MAURITIUS
LA RÉUNION
40°
40
20°
20°
0°
0°
20°
20°
40°
60°
0
20°
40°
60°
80°E
100°
120°
140°
160°
40°
40°

approximate boundaries of the longline vulnerability zones.

These are characterized by areas where the preference temperatures occur within the 50 to 200 metre depth range which is exploited by the longline gear. The gear may only place hooks to 150 metres, or modified gear may fish deeper, but fish can be attracted from well below the levels of the hooks, as well as from above.

For albacore, the traditional longline gear would be effective to the north of the lightly hatched areas indicating the 50 to 80 metre depth zone of the 15°C isotherm. Similarly, longline yellowfin tuna catches would optimize to the north of the more dense line cross hatching indicating the shoal 23°C isotherm. The catch of yellowfin tuna is adversely affected by the presence of low oxygen levels (less than 1.5 ml/L at 100 metres). The northern Indian Ocean (like the eastern tropical Pacific Ocean) would yield lower yellowfin tuna catches than other tropical ocean areas due to the shallow oxygen poor water. In some years, seasons, and areas, this oxygen distribution pattern varies so that longline catches can be substantial within the hatched zone indicating low oxygen levels.

The bigeye tuna catches would be expected to be good anywhere from the zone demarking the surface emergence of the 23°C isotherm, north to the areas where the 100 metre oxygen levels are lower than 1.0 ml/L. Recent innovations in longline gear use have shown that by fishing deeper (to over 200 metres) larger catches of bigeye tuna are possible than made by the traditional gear. Oxygen levels appear to be the major adverse factor for bigeye tuna occurrence, in that high catch rates have been observed in areas where hooks lie in waters as cold as 11°C.

There is little skipjack or other small tuna caught with longline gear due to the size selectivity of the hooks and bait. Billfishes (except swordfish) are clearly a secondary catch be the gear which is primarily set to optimize tuna catches. Broadbill swordfish are often specifically sought as indicated by the use of gear modified to fish more shoal than "tuna" gear, and at different hours during the day. The presence of marlins in catches is often a good indication of the occurrence of small tunas and other pelagic fishes as these are the staples of marlin diets.

4. CONCLUSIONS AND SUMMARY

There are few reasonable substitutes for empiricism in fishery development. There are no "rules of thumb" which can be used in oceanic situations which do not fall victim to "local conditions". Examples of such problems are also found in the oceanic fisheries for tunas and billfishes. The most productive grounds for one year type may yield virtually nil for another. Even in relative proximity the catch compositions of similar or different gear types can differ greatly. The vulnerability of the various tuna and billfish species is subject to recently identified variables (Saito 1973; Saito and Sasaki 1974; Saito 1975; Hanamoto 1974 and 1975; Sharp 1976 and 1978), and subsequently this information is being integrated into harvest strategies by various fleets.

The truly tropical species has as the lower thermal bound the 15°C isotherm. Their temperature preferences will lie somewhat above that temperature. In the case of the temperate tunas, particularly albacore, we see that their preference is only slightly above this lower bound and that the adults are found deep in the thermocline structure of the tropical oceans and poleward in the widening expanse of ocean which is bounded by 15°C and the 22°C isotherms. The younger albacore, up to about 85 cm fork length, are fished in the surface layers of the ocean within a similar temperature envelope. Bigeye tuna are only rarely encountered in abundance in surface fisheries, and usually only the small ones are involved, and only in those regions with sharp thermal gradients including the range from 17°C to 26°C. Some historical surface fisheries have harvested large bigeye near islands or over banks which disturb the current structure and cause the thermal conditions to mimic the shoal isotherm situation bringing the critical oxygen or thermal structure near the surface. Large bigeye and albacore appear to coexist over much of their range, but the lower oxygen requirements of bigeye may provide a depth advantage where oxygen levels slowly decrease in the water column within the appropriate thermal envelope.

Surface fisheries are apparently quite responsive to thermal and oxygen profiles. The habitat lower bound conditions of the tunas act as floors which the individuals may penetrate for varying times depending upon their size and condition (the analogous behaviour to holding ones breath, or a quick dask to the mailbox in the cold). The smaller individuals are more sensitive to sharp gradients which include their bounding conditions. The surface fisheries for tunas generally include the smaller individuals of a population. Exceptions occur where concentrated or compressed habitat bounding features also include food concentrating or aggregating phenomena (divergence and convergence zones, islands, sea mounts, etc.). The effects of geographical features on thermal, oxygen and food profiles is profound due to their effects on mixing and discontinuities of hydrologic features, but these effects simplify to the situations described above where habitat floors and food sources are pushed toward the surface.

In local areas where longlining is successful it is unusual to have concomitant surface fishery success for tunas. Those cases where this does occur depend on aggregation phenomena such as the wellknown marine mammal or flotsam associations. Often the factors which aggregate the tunas are created by physical processed which yield the shallow habitat, and hence surface gear vulnerability of the tunas. These are convergence zones, rips or eddy zones, and turbulent wakes in the lee of geographic features.

The northern Indian Ocean has the added complexity of seasonal monsoon conditions which reverse dramatically during the year. Each extreme of the cycle has limiting effects on seafaring activities. Dynamic changes in wind direction also have profound effects on thermal structures, upwelling and other events of importance to fishing activities, introducing short-term variation which may be masked in the "average" data summaries.

These monthly charts are provided as guides and interpretive aids for use in design and evaluation of exploratory fishing ventures for tunas in the Indian Ocean. Similar charts were prepared for the Pacific Ocean which both hind- and forecasted situations reflecting appropriate seasonality and areas of high tuna vulnerability. These were available from 1974, but were only published in 1978.

In this presentation of the Indian Ocean material perhaps too much emphasis was placed on the problems to be expected. These charts were prepared in anticipation of the development of new tuna fisheries and it was presumed that some information about the important environmental properties conducive to successful fishing would help dispel some of the inherent reluctance of fishermen and investors to explore new areas, and hence promote discovery and harvesting of whatever resources may be available.

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