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GEOGRAPHICAL AND CLIMATIC FEATURES OF INDIA AND THE HYDROLOGY OF THE SURROUNDING SEAS. 1/

The peninsula of India can be divided into three distinct segments: (1) the great alluvial plains of north India, (2) the peninsula of Deccan, south of the Vindhya mountains and (3) the great mountain barrier which surrounds the plains to the west, north and east, known as the extra peninsula. Climatically India presents as great contrasts as any area of similar size. In the north-west lies the Rajaputana desert with an average annual rainfall of less than 5 inches and at the north-east in Assam is Chirrapunji with an average of about 430 inches. Temperatures as low as -49^{O}F in Kashmir and as high as 121^{O}F at Jodhpur have been recorded several times. Humidity practically zero in November to 100% in September may be present in some places like Kashmir. The mean annual range of temperature, 20^{O}F in several places at the southern tip of India is less than the daily range at many places in north India and is only about one-third of their annual range. Northern India alone presents the greatest possible contrast of dampness and dryness and if we compare this with the most southerly part such as Travancore we have in the former a climate of extreme summer heat alternating with winter cold that sometimes sinks to freezing point, and in the latter an almost unvarying warmth in conjunction with a uniformly moist atmosphere that is characteristic of the shores of the tropical seas.

Although several theories have been put forward to explain the origin of the seas around India, at the close of the Mesozoic Era the Indian Ocean was composed of a northern and southern part, while from east to west a circum-terrestrial sea, the Tethys, passed to the north of India and Arabia, terminating in what is now the Bay of Bengal. At the beginning of the Kainozoic Era, the Tethys sea began to be interrupted by the upheaval of the Alpine-Himalayan range and at the same time the uprising of the Central Asian plateau caused the obliteration of the northern part of the Indian Ocean. How far south this upheaval affected the Indian Ocean, is not yet determined but it seems probable that at the close of the Miocene a mass of land occupied the area between India, Arabia and north-east Africa and similarly a vast tract of land again extended eastward from India to the Andaman Islands obliterating the Bay of Bengal. At present, India forms a triangle of land thrusting southwards into the Indian

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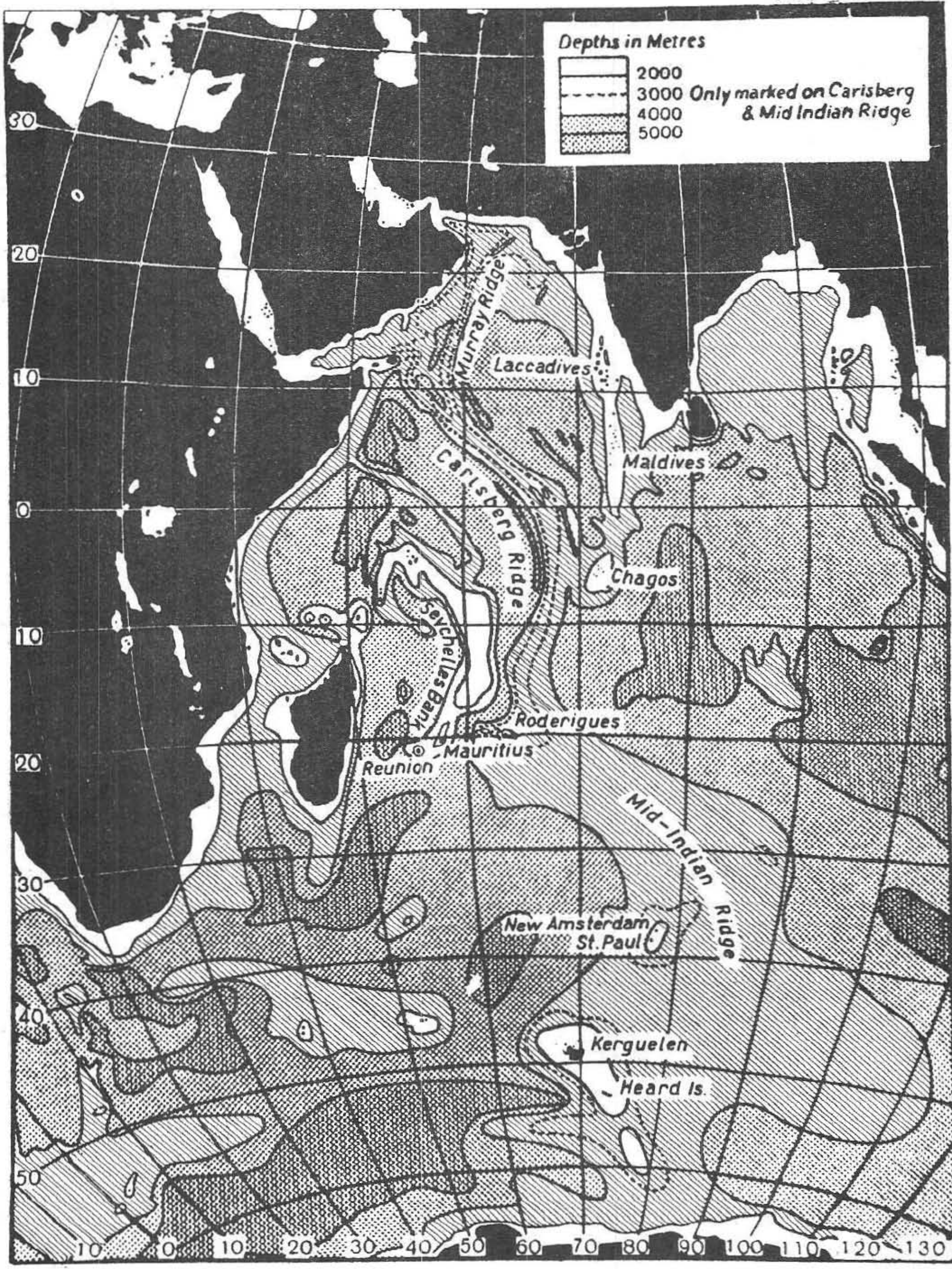

Fig. 1. Bathymetric chart of the Indian Ocean and adjacent seas.

Ocean, dividing its northern area into two parts, the Bay of Bengal on the east and the Arabian Sea on the west. Each of these areas is again subdivided into a main area and a subsidiary region by a range of islands; to the east of the Bay of Bengal the chaim of Andaman-Nicobar islands forms the western boundary of the Andaman Sea and on the south-west of India the Laccadive-Maldive and Chagos Archipelagoes form the western limit of the Laccadive Sea. The slope of the continent is generally rather steep and consequently the continental shelf is a narrow belt mostly about twenty to fifty nautical miles in width. The bathymetric features are given in figure 1.

The weather in India is characterised by an alternation of seasons known as monsoons. During winter, the dry surface air blows from land to sea in the north-east direction resulting in the north-east monsoon which is followed in summer by a complete reversal of these conditions with the moist winds of the south-west monsoon blowing from sea to land. The precipitation accompanying the north-east monsoon is small and during this period the rainfall is heaviest in the north-west and decreases towards the south and east. The humid winds of the south-west monsoon burst on the Malabar coast early in June, gradually extend northwards and establish in most part of India by the end of June. Between these principal seasons of the year there are transitional periods of hot weather months and of the retreating south-west monsoon. From January to May or June the temperature rises more or less steadily, and is followed by a steady decrease from June or July to December.

Our knowledge of the oceanography of the waters around India is derived mainly from the observations of the Challenger (1872-76), Investigator (1884-1925), Vitiaz (1886-1909), Egeria (1894), Valdivia (1898-1899), Gauss (1901-1903), Sealark (1905), Planet (1906), Dana (1920-22), Snellius (1929), Discovery II (1929-31), and Mabahiss (1933-34) and also from observations taken mostly by the surveying ships of the British Admiralty.

In the Indian Ocean, the southernmost limit of which extends, oceanographically approximately to lat. 40°S i.e., the region of the Subtropical Convergence, below the surface waters three or even four water masses exist and each stratum is in a stage of continual movement. At subsurface depths, three large water masses, the Indian Ocean Central water, the Indian Ocean Equatorial water and the the Deep water, have been shown to exist below a depth of approximately 2000

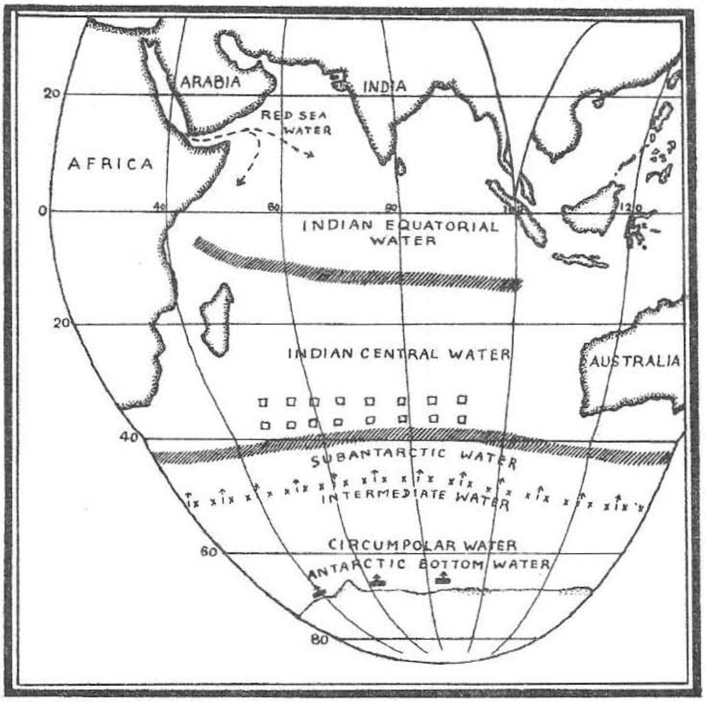

Fig. 2. The approximate boundaries of the upper water masses of the Indian Ocean. Squares indicate the regions in which the central water masses are formed; crosses indicate the lines along which the Antarctic intermediate water sinks. (After Sverdrup et al., The Oceans, 1942).

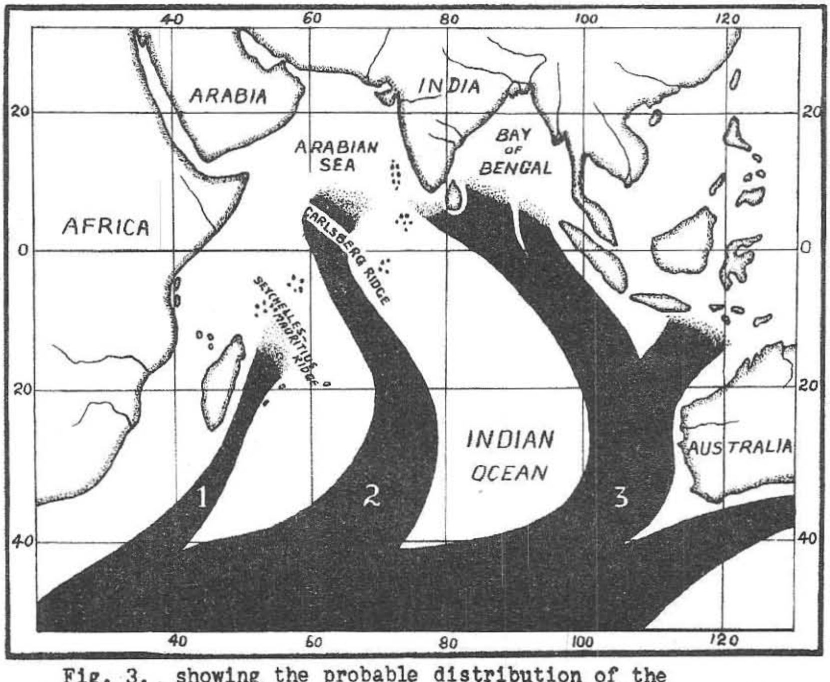

Fig. 3. showing the probable distribution of the Antarctic bottom water in the Indian Ocean. (After Sewell, 1932 with slight modifications).

meters. In addition to these, there are two types of water at mid-depths, the Antarctic Intermediate water and the Red Sea water. The boundaries of the upper water masses of the Indian Ocean are shown in fig. 2. The influx of the cold Antarctic bottom water, referred to above as the Deep water, from the south polar region through the Indian Ocean to the Arabian Sea and Bay of Bengal has great significance in the organic productivity of the water masses influenced by this. According to Sewell, there are three main tongues in this drift, the first ending on the east coast of Madagascar while the second and the third can be traced into the Arabian Sea and Bay of Bengal respectively. The second tongue strikes against the Carlsberg ridge and is deflected to the surface where the presence of this cold water of low salinity and rich in nutrients can be detected at the surface. The third tongue, part of which enters the Bay of Bengal, gets subdivided into two branches; one travels northwards between Carpenter's and Andaman-Nicobar ridges and the other meeting the obstruction of Ceylon gets divided into two, one portion continues into the Laccadive Sea while the other flows up north along the east coast of Ceylon (fig.3.)

The presence of Red Sea water in the Arabian Sea is well known and it is believed that this water penetrates southwards in depths around 500 to 1000 meters but stops its advance almost at the equator where it meets the Antarctic current. These different water masses have characteristic hydrological features.

Temperature and salinity of surface waters.

Within the surface waters, temperature increases rapidly towards the north from the Subtropical Convergence and, in the equatorial regions, it is uniformly high (25° to 30.5° C) during the greater part of the year. Temperatures as low as 22°C have been found, in August, as far south as the equator, in consequence of the upwelling under the influence of the prevailing south-west monsoon. In February, lower temperatures are similarly found in the Bay of Bengal owing to the effect of the north-east monsoon. According to Schott, the range in annual fluctuations in temperature of the surface waters of the Bay of Bengal increases from 2° to 5°C from lat.10°N to 20°N whereas, off the Ganges Delta there exist a narrow belt with temperatures ranging from 5° to 10°C. Similarly, within the same latitudes the fluctuations are within 3° to 5°C in the Arabian Sea and within 5° to 10°C in the Gulf of Oman. In the central portion of the Indian Ocean, between lats. 10°N and 10°S, is a region where the range of temperature varies from less than 1° to 2°C showing typical equatorial conditions. But surrounding this area on the west (towards the east coast of Africa), the surface water has an annual range from 2° to 4°C. Between lats. 30°S and 40°S, stretching from the east coast of Africa to almost the west coast of Australia, the surface temperatures show the greatest range, from 4° to more than 7°C.

It is a common experience that in low latitudes insolation warms the upper layers, and below a depth of about 100 meters there is usually a layer of rapidly decreasing temperature, <u>the discontinuity layer</u> or <u>thermocline</u>. In several places in the Indian Ocean, approximately between Chagos Archipelago and Mauritius the water temperature falls from 25°C at the surface to 20°C at about 70 fathoms and to 15°C at 90 to 100 fathoms. Somewhat similar results have been obtained by Sewell from the Bay of Bengal which have also been confirmed by recent observations.

The salinity of the surface waters in the equatorial and northern regions is subject to considerable annual variations which can be related to the monsoons the the annual variations in precipitation. The extent to which rainfall will influence the salinity of sea water varies from region to region and also according to the number and size of the rivers opening into it.

The highest salinities, from 36.0 to 36.5‰ are found at all times of the year in the Arabian Sea, due partly to intense evaporation under high temperatures and partly to the influence of high salinity water from the Red Sea and the Persian Gulf. Further the rainfall does not appear to be heavy and there are no large rivers flowing into it, except for the Indus, Narbada and Tapti opening at its north-eastern angle. But at the time of the south-east monsoon, the current sets to the south and east along the west coast of India carrying away the rainfall of the Western Ghats round Ceylon to the Bay of Bengal. Another area of high salinity, over 36 or even 36.5‰ is at about lat. 30°S on the eastern side of the Indian Ocean between longs. 80° and 110°E.

In the Bay of Bengal, which is in the same latitude as the Arabian Sea, low salinities are found because of the influx of large quantities of river water and also the lack of influence of water of high salinity corresponding to the Red Sea and Persian Gulf waters. No less than six large rivers, <u>viz</u>., the Cauvery, Kistna, Godavari, Mahanadi, Ganges and Brahmaputra, in addition to a large number of smaller rivers open in the Bay; further east the Irrawadi, Sittang, Salween and Tenasserim open into the Andaman Sea. The range of salinity in the Bay of Bengal is approximately from 30.0‰ near the mouths of the Ganges to slightly over 34.0‰ across the mouth of the Bay.

Surface currents.

Unlike other great oceans, the Indian Ocean is subject in places to a complete reversal of its currents with the change of the monsoon winds. In the tropical and subtropical regions of the Indian Ocean, the surface water of the southern hemisphere is driven along by the south-east trade winds and in the northern hemisphere by the alternating north-east and south-west monsoons, so that during the winter months the bulk of the surface water tends to converge on the African coast. The westerly flowing current divides into two streams in the neighbourhood of Madagascar, one turning north to form the Somali Current, while the other is reinforced by part of the south-equatorial current and these two water masses form the Agulhas Stream. The greater volume of the water of the Agulhas Stream bends sharply to the south and then towards the east thus returning to the Indian Ocean by joining the flow from South Africa towards Australia across the southern part of the Indian Ocean. During the north-east monsoon, there is a strong flow of water from the Pacific to the Indian Ocean through the Straits of Malacca into the Andaman Sea and then to the Bay of Bengal, where it joins the low salinity water of the Bay and can be traced flowing west- ward as far as the Seychelles; during the south-west monsoon this flow, from the Pacific to the Indian Ocean is either reversed or stopped, but there is, at this season, a strong flow of water westward between Malay Archipelago and Australia. In the equatorial region between lats. 5° and 10°S, there is a reverse flow from west to east, constituting the Contra-Equatorial Current.

Distribution of oxygen.

The observations made by the Discovery II indicate that the oxygen content of the Indian Ocean decreases from south towards the equator. Although the Red Sea water is characterised by low oxygen contents, increase in oxygen is evident in the direction in which Red Sea water spreads, indicating a probable mixing of the over- and under-lying water masses. There is a fair supply of oxygen in the upper levels but it diminishes rapidly with depth. At a depth of about 100 meters there is usually less than 1.0 cc of oxygen per litre of water and at 800 to 1000 meters the concentration is less than 0.1 cc. Below this minimum, there is an increase until in the deepest depths the amount present may be as much as 2.5 to 2.75 cc. per litre. This increase in the bottom levels is attributed to the presence of the Antaractic bottom water which is relatively high in oxygen.

Nutrient salts.

The data on the distribution of the nutrient salts in the Indian Ocean are mostly from the investigations conducted by the John Murray Expedition. Although it is generally believed that tropical waters are poorer in nutrient salts than temperate waters, recent observations of the John Murray Expedition show that there are several places in the Indian Ocean where there are high concentrations of nutrients. It is also believed that there is an azoic area extending eastwards from the Arabian Coast into the Gulf of Oman, between depths of about 250 to 600 meters and about 1500 meters, the upper limit varying on the two sides of the Gulf. Data collected in several stations in the Arabian Sea indicate that the nutrients are always poor in this area. The waters near the Maldive ridge are, during the north-east monsoon, characterised by relatively high nitrate content, because of the influx of water from the Bay of Bengal and Andaman Sea rich in nutrients brought down by the large rivers emptying into them. Areas over the Carlsberg ridge and near Mahe and Seychelles Islands show relatively high percentage of nutrients, owing to the upwelling of the Antarctic bottom water. Table 1 shows the maximum surface values of nutrient salts recorded in inshore waters at two places along the east coast.

Table 1

Nutrient salts - Maximum surface values recorded in inshore waters only.
Units: μg-atoms/litre.
(Data from the Central Marine Fisheries Research Station).

Months	Madras Coast Lat. 13° 10'N			Gulf of Manaar Lat. 9° 10'N		
	NO_3-N	PO_4-P	SiO_3-Si	NO_3-N	PO_4-P	SiO_3-Si
Dec.-Feb.	4.7	0.63	19.7	6.5	0.37	9.4
Mar.-May	4.4	0.64	7.0	5.3	0.29	10.7
Jun.-Aug.	20.0	1.60	23.7	4.4	0.40	6.7
Sep.-Nov.	10.0	1.00	21.8	4.0	0.32	8.3

The slightly higher values obtained off the coast of Madras than in the Gulf of Manaar are due to the influence of city effluents, a fact which has been substantiated by bacteriological investigations.

Organic production.

In the Indian Ocean, considerable growth of phytoplankton is initiated in places where upwelling causes renewal of nutrients. This occurs near the Seychelles bank and over the Carlsberg ridge. Calculations of the Phytoplankton production in eight stations between lats. 6° and 9°N and longs. 50° and 70°E, made during the John Murray Expedition, show that the production rate is 14.4 gm/m^2/day or 2.2 kg (wet weight) per square meter of sea surface in 150 days. When compared with other areas, the production rate is high and except for upwelling areas, this represents the major part of the year's production. From these observations, it may be assumed that in the waters around India, in areas where upwelling occurs, the productivity exceeds that of any temperate sea and that the open ocean is by no means as barren as has been commonly believed.
