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On interactions between the Southwest Monsoon Current and the Sea Surface over the Arabian Sea*

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ABSTRACT. Some aspects of interactions that take place between the water surface of the Arabian Sea and the summer monsoon circulation are investigated. Over large portions of the Arabian Sea (and also the Bay of Bengal) there is a rapid warming of the surface water during late winter and early spring. The maximum temperatures are observed around May, at the time of the establishment of the southwest monsoon circulation. There is then cooling of the waters to a minimum observed in August-September, followed by a secondary maximum in October-November. This trend differs from what is commonly observed over most of the tropical oceans, where there is a single water temperature maximum in late summer and a minimum in late winter. The water cooling in early summer appears to be a direct result of the establishment of the southwest monsoon regime. The resulting inter-relationships have pronounced effects on the properties of both the water body and the monsoon circulation.

In order to assess the role of heat flux in the water cooling, computations of components of the energy balance were carried out for various stations in the Arabian Sea and vicinity. Rather large rates of heat flux by evaporation were obtained in the west central portions of the Arabian Sea. It is shown that the evaporation makes a major contribution to the water cooling in that area.

Effects of the air-sea interactions on the atmospheric current are investigated by analysis of aerological soundings along the monsoon surface trajectory. A characteristic low level inversion in the levels from 900 to 700 mb is found over most of the oceanic area. The moisture is concentrated below the inversion. Above the inversion the air is dry and unstable. Some of the implications of the presence of this thermal and moisture distribution on monsoon weather are discussed briefly.

1. Introduction

Inspection of the space and time variations in the water temperature over the Arabian Sea previous to and during the southwest monsoon suggests the presence of important interactions and feedback effects on a grand scale between the ocean and atmosphere which have profound effects on the properties of the southwest monsoon circulation. The water temperatures over the Arabian Sea show maximum values of over 29°C in April—May, which are about the highest anywhere in the oceans not just in May, but over the entire summer season as well. After May there is a decrease in temperature; a minimum is observed in July—September followed by a secondary maximum in October. After October the temperature decreases rapidly to the winter minimum in February. The summer cooling leads to a seasonal variation which differs from the normal picture for most ocean area, which consists of a single wave with maximum in late summer and minimum in late winter.

The early summer water cooling in the northern Indian Ocean is clearly the result of the establishment of the southwest monsoon circulation. These observations provide a remarkable example of large scale effects of an atmospheric system over a large oceanic body with important effects also on the properties of the atmospheric current. The purpose of this report is to discuss some aspects of this interaction, particularly from the point of view of its results on the thermal and moisture properties of the monsoon

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** Written while on leave at the International Meteorological Centre, Colaba Observatory, Bombay 5, India

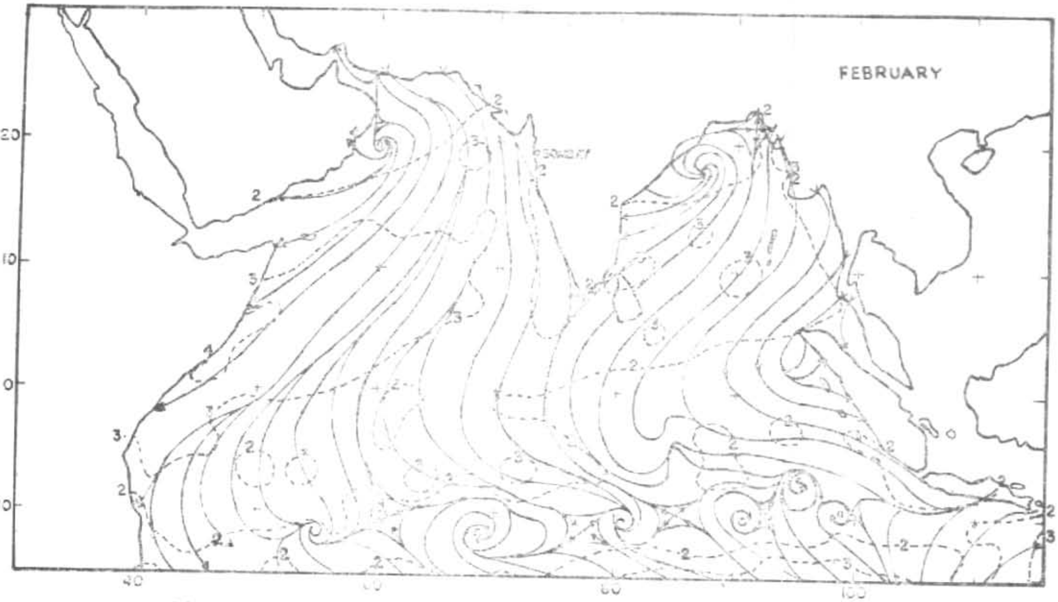

Fig. 1. Normal wind circulation over Northern Indian Ocean for February
Streamlines in solid curves, isotachs (Beaufort Force) in dashed curves

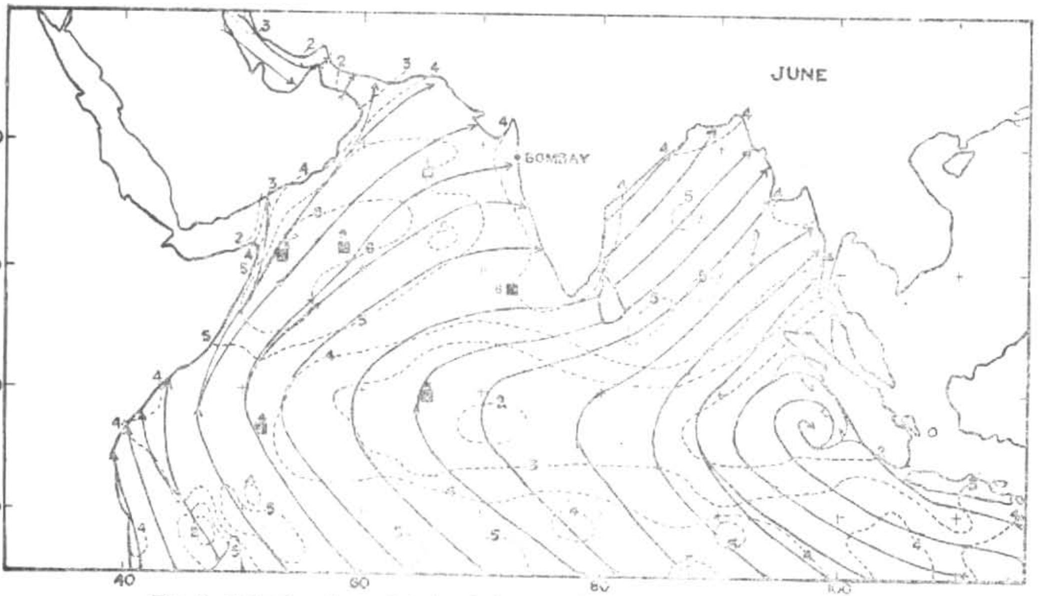

Fig. 2. Normal surface wind circulation over Northern Indian Ocean for June
Streamlines in solid curves, isotachs (Beaufort Force) in dashed curves
(Locations for which sea-air heat exchanges were computed are shown by numbered squares)

current before it strikes on the western coast of the Indian sub-continent. Attention is called also to some problems of interest to the understanding of Indian monsoon weather. Data sources used were the U. S. Navy Marine Atlas (U. S. Navy 1957) and the Dutch Indian Ocean Oceanographic and Meteorological Data collection (Royal Neth. Met. Inst. 1952). In the analysis of the low level properties of the monsoon current, observations made by the U.S. Weather Bureau research aircraft during June—July 1963 and by some oceanographic vessels were utilized.

The plan of this paper is as follows—first, the seasonal variations in the atmospheric low level flow and in water temperature over the Arabian Sea are illustrated and discussed briefly. The results of computations of components of the oceanic heat balance are presented. These computations were made in an attempt to assess the role of the heat flux from the ocean to the atmosphere in the cooling of the waters. The influence of the exchange processes on the monsoon flow are discussed next. Dropsonde data by the research aircraft and temperature soundings from vessels participating in the International Indian Ocean Expedition are used to discuss the thermal and moisture stratification of the monsoon air and its changes downstream along the oceanic trajectory.

Field of flow at low levels and water temperature variations over the Arabian Sea

The main properties of the atmospheric flow near the surface and its variations with time are shown in Figs. 1—3. During winter (Fig. 1) the northeast monsoon prevails. The heat trough is located in February around latitude 10° S. The flow over the Arabian Sea is generally weak except in association with cyclonic perturbations. Weather conditions are usually characterized by dry weather and clear skies.

Weak northeast flow dominates over the Arabian Sea until around May. With the northward shift of the sun, the heat trough also shifts northward and by May or early June it reaches into the northern Arabian Sea and northern India. With this shift, the southwesterly monsoon current invades the area. Fig. 2 shows the monsoon flow in full swing in June. The wind speed is rather weak in the vicinity of the equator but increases downstream northeastward on account of cross-isobaric flow towards lower pressures. Winds of Beaufort Force 4 or more are observed over the entire Arabian Sea north of latitude 10°N. The centre of maximum speeds lies in the western sector, where the mean winds are close to 30 knots and reports of 40-45 knots are quite frequent in the daily maps.

The southwest monsoon continues in full strength until September. The mean charts for July, August and September show very little change from what appears in Fig. 2. By late September the heat low starts shifting southward, changes in circulation become more frequent and the wind flow in general becomes weaker. By October (Fig. 3) the Arabian Sea anticyclone makes its appearance in the mean charts and the thermal trough appears near the equator. After October, the northeast monsoon becomes more and more dominant with time.

The seasonal variations in water temperatures are shown for selected locations in the Arabian Sea and vicinity in Figs. 4—9. These locations are numbered from 1 to 6 in Fig. 2. Stations 4, 2 and 1 are located approximately along the downstream trajectory, close to the centre of the strongest flow, which reaches India in the vicinity of Bombay. At station 4 (Fig. 4), in the upstream end of the trajectory, the water temperatures are maximum in April and minimum in July-August and there is a cooling of about 4°C from April to July. At station 2 (Fig. 5) the maximum occurs in May, the minimum in August and the summer cooling is also of about 4°C. A secondary maximum is observed in October and a secondary minimum in January-

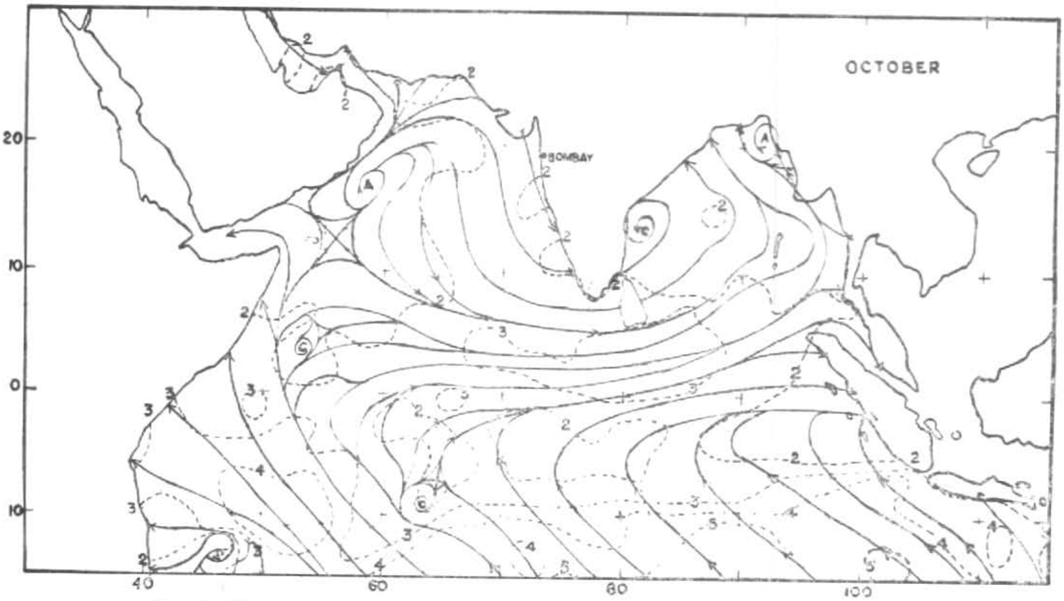

Fig. 3. Normal surface wind circulation over Northern Indian Ocean for October
Streamlines in solid curves, isotachs (Beaufort Force) in dashed curves

(Analyses in Figs. 1–3 by C. S. Ramage from data in Dutch Indian Ocean Atlas)

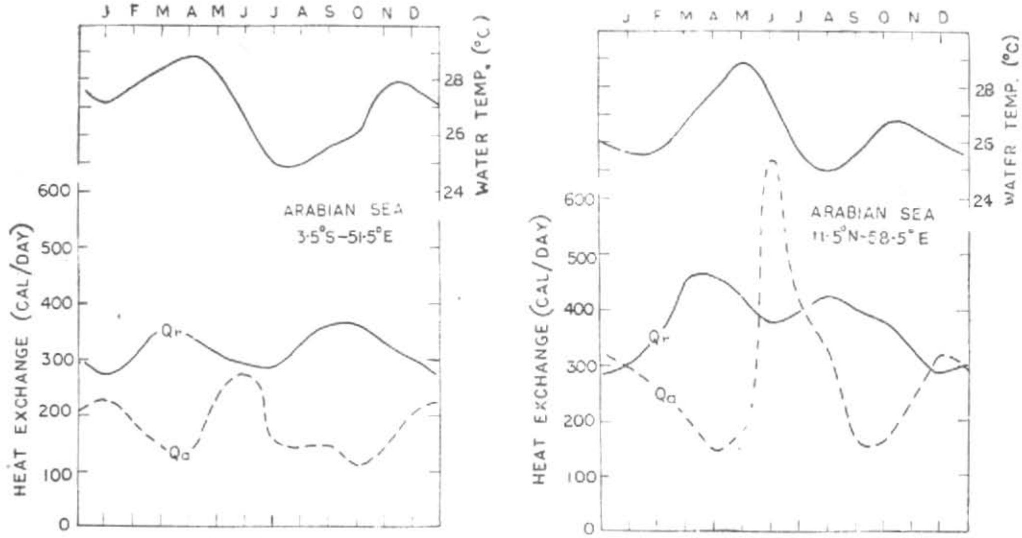

Fig. 4

(For area near 3·5°S, 51·5°E; location 4 in Fig. 2)

Fig. 5

(For area near 11·5°N, 58·5°E; location 2 in Fig. 2)

Figs. 4–5. Annual variations in water temperature, net radiation balance Q_r and net sea-air heat flux Q_a

Unit : cal/cm²/day (ly/day)

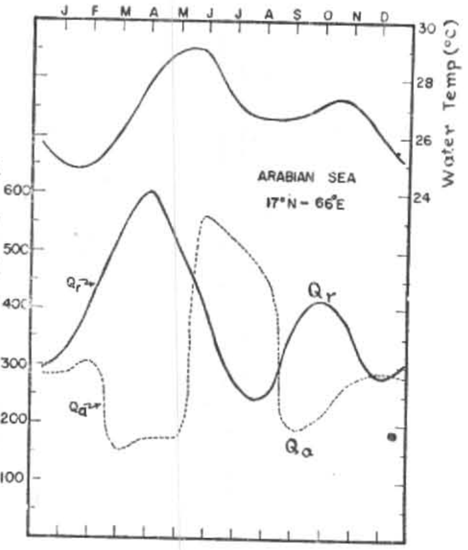

Fig. 6

(For area near 17°N, 66°E; location 1 in Fig. 2)

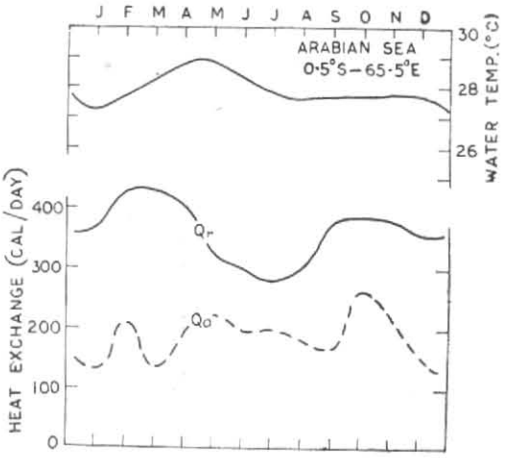

Fig. 7

(For area near 0·5°S, 65·5°E; location 5 in Fig. 2)

Figs. 6–7. Annual variations in water temperature, net radiation balance Q_r and net sea-air heat flux Q_a

Unit : cal/cm²/day (ly/day)

February. Further downstream at station 1 (Fig. 6) the temperature is maximum, about 29°C, in May-June. There is a secondary minimum of 27°C in August and a main minimum of about 25°C in January-February. At stations 5 and 6 (Figs. 7 and 8), which lie outside the region of strong flow, the magnitude of the summer cooling is less. Station 5 located near the equator in a region of a generally weak, variable flow, shows maximum in April-May and minimum in January, with an annual range of less than 2°C. At station 6, on the southeast section of the sea, the maximum occurs in April and the minimum in August-September with a summer cooling of about 2°C. Station 3 (Fig. 9), located in the main centre of upwelling, in a region of relatively strong flow close to the coast of Somalia, shows very pronounced cooling from about 28°C in May to 22·5°C in August.

The maximum temperatures are observed at the various regions from April to May and the magnitude of the temperature decrease in early summer varies from place to place. Generally the locations closer to the equator exhibit an earlier maximum. This is due to a combination of solar influence resulting from the annual march of the sun and factors generated by the somewhat earlier establishment there of the monsoon circulation. In general the association between the variations in water temperature and the onset of the monsoon circulation is unmistakable and leaves little doubt as to the influences of the atmospheric circulation on the water temperature regime. The physical processes by which the water cooling is brought about are well known. There is one : increase in heat flux from the sea surface to the atmosphere; two : water motions forced by the wind stress which lead to advection of cold waters, both vertically (upwelling) and horizontally; and three : reduction in the net absorbed radiation due to increase in mean cloudiness. In the Arabian Sea upwelling is quite

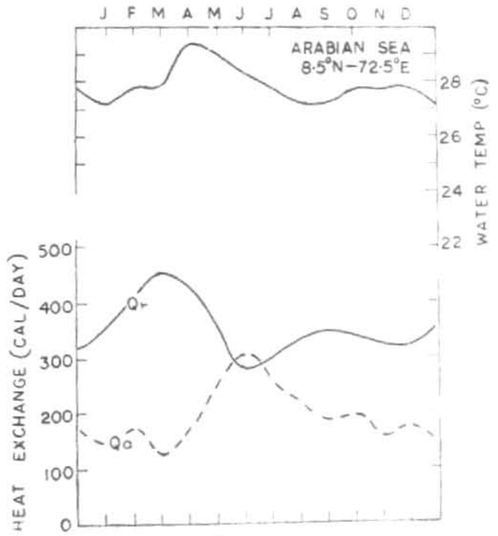

Fig. 8

(For area near 8·5°N, 72·5°E; location 6 in Fig. 2)

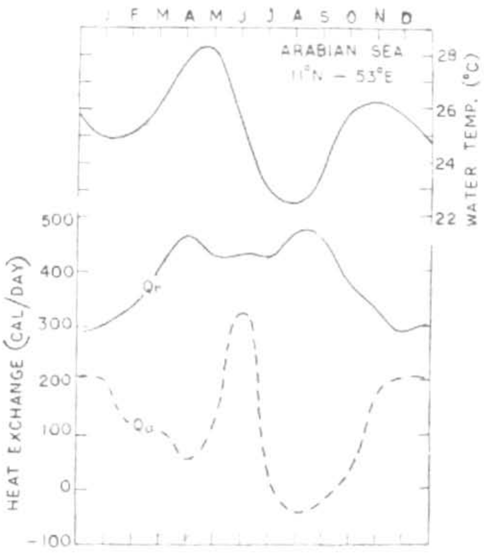

Fig. 9.

(For area near 11°N, 53°E; location 3 in Fig. 2)

Figs. 8–9. Annual variations in water temperature, net radiation balance Q_r and net sea-air heat flux Q_a

Unit: cal/cm²/day (ly/day)

pronounced along the west coast: the main centres are located off the coast of Somalia near latitude 10°N and on the coast of Arabia near latitude 20°N. Evaporation over the tropical oceans is usually minimum in summer, but over some sections of the Arabian Sea it is extremely large and seems to play a prominent role in the water cooling.

The establishment of conditions of large heat flux from the ocean surface to the atmosphere has also important repercussions from the point of view of atmospheric processes, since the heat and moisture gained by the atmosphere have important effects on the thermodynamic properties of the monsoon circulation. These in turn have an important bearing on condensation and precipitation processes over the Indian sub-continent.

2. The oceanic heat balances

The contribution of the sea-air heat flux to the water temperature variations can be assessed quantitatively by computations of components of the heat balance for the water body. Such computations are presented for a location in the Arabian Sea near 15°N—60°E in the work of Budyko (1956). Another report: "Atlas of the Heat Balance" edited by M.I. Budyko, 1955, which contains charts of components of the oceanic heat balance for all oceans, has also been referred to in the literature, but it was not possible for us to obtain these charts for study. It was decided, therefore, to carry out new computations for a few selected locations in the Arabian Sea which would show conditions at several locations along the low level air trajectory.

Monthly mean data published in the U.S. Navy Marine Atlas (U.S. Navy 1957) were found adequate for evaluations of the heat flux to the atmosphere and of absorbed radiation. The heat flux was computed with the formulae—

$$Q_e = \rho C_d \, L \, (q_s - q_a) \, v \qquad (1)$$

$$Q_s = \rho C_d \, c_p \, (T_s - T_a) \, v \qquad (2)$$

where Q_e is the latent heat flux by evaporation; Q_s is the heat conduction; ρ is the air density; C_d is the drag coefficient; c_p is the specific heat of air at constant pressure; L is the heat of vaporization; q_s is the saturation specific humidity at the temperature, T_w, of the water; q_a and T_a represent the specific humidity and temperature of the air and v is the wind speed. The computations were made using mean monthly values of the parameters involved. The applicability of these formulae to mean data has been amply discussed in the literature (Jacob 1951, Malkus 1962). The drag coefficient was taken as $1 \cdot 4 \times 10^{-3}$ for wind speeds less than 15 knots and $2 \cdot 0 \times 10^{-3}$ for speeds above 15 knots (Sheppard 1958, Wilson 1960, Deacon and Webb 1962). With the large range of wind speeds observed, over 25 knots in the monsoon period and less than 10 knots in winter and spring, it seemed advisable to recognise the variations in the drag coefficient with wind speed.

The net absorbed radiation Q_r was evaluated with the relation (Budyko 1956)—

$$Q_r = AQ_o \, [1-(1-k) \, c]-Q_{bo}\,(1-k''c^2) \qquad (3)$$

where A is the absorption coefficient for sea water; Q_0 is the incoming short wave radiation at the earth's surface for clear skies; c is the cloudiness in tenths; Q_{bo} is the net long-wave radiation at the surface for clear skies; k and k'' are numerical parameters, which vary slightly with latitude. For the latitudes of the Arabian Sea k is around $0 \cdot 34$, and k'' varies from $0 \cdot 50$ to $0 \cdot 54$ (Budyko 1956). The values for Q_o and Q_{bo} were adopted from Budyko (1956); the absorptivity, A, was taken as $0 \cdot 94$ (Sverdrup 1942).

The results are shown in Figs. 4 to 9. The heat flux by conduction was quite small and the net heat flux, Q_a, $(Q_a = Q_e + Q_s)$ was essentially given the latent heat flux due to evaporation. The heat flux is positive for transfer from the water surface to the air above. The radiation Q_r, on the other hand is normally considered positive for net absorption of heat by the system. Thus positive values of net radiation imply a heat gain, positive values of heat flux Q_a, imply a heat loss by the water body.

At station 4 (Fig. 4), in the upstream end of the monsoon current, the heat flux was relatively low, on account of weak winds. The maximum, about 270 ly day^{-1}, was observed in June. Minimum values were obtained in March—April and in August to October. The radiation showed distinct spring and fall maxima. It was also relatively low, on account of large cloudiness, but exceeded the heat flux throughout the year, by a relatively large amount from January to April and from August to December and by a very small amount in May and June.

At station 2, near 12°N—58°E, the radiation balance showed larger magnitudes (Fig. 5). The maximum was about 460 ly day^{-1} in spring and large magnitudes were also observed during summer and fall. The heat flux showed a pronounced maximum of about 670 ly day^{-1} in June. It decreased rapidly in July and August. Minimum values of about 145 ly day^{-1} were observed in April and September—October. In this area the heat flux exceeded the radiation balance by about 300 ly day^{-1} in June and by a very small amount in July and December.

Fig. 6 shows the picture farther downstream in the north central Arabian Sea. There, the heat flux was quite large from June to August, while the radiation showed a large reduction from a maximum of 600 ly day^{-1} in April to a minimum of 250 ly day^{-1} in August. This reduction in radiation was due to a sizeable increase in cloudiness. The heat flux varied from about 550 ly day^{-1} in June to about 150—200 ly day^{-1} from March to May and in September. There was a secondary maximum of close to 300 ly day^{-1} in winter. From March to May the radiation gain at the surface exceeded the heat loss by about 400 ly day^{-1} while from June to August the heat loss exceeded the radiation gain by about 200 ly day^{-1}. These facts are reflected well in the water temperature variations from February to May and from June to August.

The large differences between stations 1 and 2 are of some interest since they are located fairly close to each other along the strongest monsoon current. They are due largely to the seasonal march of mean cloudiness at the two locations. During the northeast monsoon in winter and early spring there is increase in mean cloudiness downstream from station 1 to station 2, while during the southwest monsoon in summer there is increase downstream from station 2 to station 1. As a result the annual range in cloudiness is larger, from 0·80 in July and August to 0·05 in March, at station 1 than at station 2, where it ranges from 0·46 in June to 0·20 in March and April. These differences in cloudiness are reflected in the computed absorbed radiation.

The results at the other 3 stations reflected somewhat different conditions. At stations 5 and 6 (Figs. 7 and 8) the heat flux was also relatively low on account of weak winds. At station 5, it ranged from 270 ly day^{-1} in October to 130 ly day^{-1} in January. The radiation balance showed maximum in spring and fall and exceeded the heat flux throughout the year. At station 6 the heat flux ranged from 300 ly day^{-1} in June to 125 ly day^{-1} in March and exceeded the radiation in June, but by a very small amount. The radiation was maximum, about 450 ly day^{-1} in March and decreased rapidly to around 300 ly day^{-1} in June and July, on account of increase in cloudiness.

The variations at station 3 are of great interest. It is located in a region where the water temperatures decrease quite rapidly from May to August, due mostly to upwelling, and where the air circulation at the surface is quite strong throughout the summer monsoon. The mean surface wind velocity is from 24 to 30 knots (Beaufort 6 and 7) in June, July and August, and reports of 40 to 50 knots in the daily synoptic scale are quite frequent. The mean cloudiness is low about 0·20–0·30 throughout the year (Royal Neth. Met. Inst. 1952). This region holds great interest with respect to the monsoon rainfall distribution over the Indo-Pakistan sub-continent, since it appears to be an important source region for surface air that flows into the extremely dry region of Gujarat, Rajasthan and West Pakistan. The radiation shows maxima in April and August—September, but is also quite large throughout the summer on account of low cloudiness. The heat flux shows a secondary maximum in winter, due mostly to evaporation due to large value of moisture gradient between the surface and the air above. After a minimum in spring produced by very low wind speed, there is a sharp increase to a pronounced peaked maximum of 320 ly day^{-1} in June. In June the moisture gradient is still relatively high and with large wind speed the computed evaporation is high. However, from July to September the water temperature is so cold that in spite of the large wind speed, the evaporation is very low. The heat conduction, conversely, is high and directed downward so that the net mean flux is almost zero in July and negative (from air to water) in August and September.

The result of these computations indicate generally higher magnitudes than previous ones published in the literature by Budyko (1956), Privett (1960) and Venkateswaran (1956)*. The differences were not, as a rule, large and can be ascribed in part to differences in the magnitude of the drag coefficient used for computation. In the region of station 1 our annual average radiation of 394 ly day^{-1} compared with a value of 345 ly day^{-1} reported by Budyko (1956). The mean annual heat flux of 301 ly day^{-1} compared better with the value of 286 ly day^{-1} obtained by Budyko. The annual range was significantly higher in our results. Privett (1960) presented seasonal values of heat flux and radiation for the southern

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*The study by Venkateswaran came to our attention after the first draft of this report had been completed

Indian Ocean. His seasonal values of heat flux and radiation in the region of stations 4 and 5 differ very little from ours, while differences in heat flux magnitudes can be traced to his different value of $1 \cdot 8 \times 10^{-3}$ for the drag coefficient. Venkateswaran (1956) computed seasonal values of heat flux over the Indian Ocean, which were omewhat smaller than ours in the west central Arabian Sea, but differed little in other areas.

Attempts were made to evaluate the complete heat balance of the water at some of the stations under study. The heat balance for an oceanic column can be adequately expressed by the radiation :—

$$Q_t = Q_r - Q_a - Q_v \qquad (4)$$

where Q_t represents the local change in heat content of the water, the so-called storage term, integrated over the volume under consideration; and Q_v is the divergence of heat transport by the water motions. Various other processes that contribute to the heat balance can be disregarded since they are usually negligibly small. The term Q_r, as usual, is considered positive to mean a heat gain; Q_e and Q_v are considered positive for heat divergence from the volume under consideration. The sign of Q_t, according to its definition is positive or negative depending on whether the mean temperature of the water is increasing or decreasing. Q_r and Q_a were defined and computed above. Attempts made to carry out independent evaluation of the heat storage and the heat divergence resulting from the water motions were unsuccessful on account of insufficient data. Knowledge of the temperature and field of water motion below the surface is required. Such information is practically non-existent. Some information on the seasonal variation in temperatures below the surface is available for the location near 17°N—66°E, our station 1, in a report by Pattullo (1957). However, the information was based on only 109 bathythermograph observations. Values of the heat storage computed from these data were found to be quite high and could not be harmonized into a sensible heat balance with the values of radiation and heat flux shown in Fig. 6 or with Budyko's results (Budyko 1956). It is hoped that a new analysis of this term based on more plentiful documentation can be made once the new data being collected by vessels participating in the International Indian Ocean Expedition become available. It is worth noting, however, that the data presented by Pattullo (1957) showed a pattern of temperature changes at the surface similar to that shown in Fig. 6 which persisted to a depth of about 50 m. At the next level for which data were shown, 100 m, the annual variation seemed to follow more closely the more normal trend of maximum in August—September and minimum in February.

No reliable quantitative estimates of the contribution by the ocean currents on a monthly or seasonal picture could be made either due to insufficient information. The seasonal picture appears to be quite complex. The surface water currents reverse direction in accordance with the changes in wind circulation. On the annual picture, on the other hand, it can be shown that there is a sizeable export of heat from the Arabian Sea to other areas (Budyko 1956).

Considerable information and insight about the physical processes that determine the water temperature variations and about the role of the monsoon circulation can, nevertheless, be inferred from the material contained in Figs. 4—9 and reference to equation 4. There was a remarkable increase in the heat flux from the water surface to the atmosphere coincident with the onset of the southwest monsoon circulation. In some areas it was accompanied by a significant decrease in the net absorbed radiation. There was also an increase in heat flux downstream along the monsoon trajectory from the equatorial region to the central Arabian Sea. The maximum mean rates of evaporation were close to 1 cm per day, which are as high as computed anywhere in the tropical oceans.

The large excess of radiation over the heat flux in spring and early fall and the excess of heat flux over radiation in the monsoon period observed at station 1, and to some extent also at station 2, are largely responsible for the water temperature variations. The heat loss of about 200 ly day^{-1} observed at station 1 from June to August can be shown by calculation to be sufficient to account for the observed water cooling (about 1°C per month) in a layer 60 metres in depth. Thus, in that vicinity, the increase in heat flux in summer would largely account for the observed water cooling. From an order of magnitude analysis, the magnitude of the heat divergence, Q_v, appeared to be small in spring and summer in the vicinity of stations 1 and 2. The picture is not quite the same in the upstream regions. At location 2 there was a large net loss of heat, about 290 ly day^{-1} in June, but in the other months cold advection by the water motions must evidently make an important contribution to the water cooling. The same is true also in the vicinity of the other locations studied.

The contribution of the cloudiness in the region near location 1 was also important. The large decrease in radiation balance in summer was mainly a result of the increase in cloudiness during the southwest monsoon period. This reduction in radiation heating contributed to the large loss in heat at the water surface.

In summary, we have that during spring conditions are such that most of the incoming solar radiation is expended in increasing the temperature of the water. By May the water temperatures reach values which are about the highest observed anywhere in the oceans. With the establishment of the southwest monsoon widespread cooling takes place on account of cold advection and increase in heat flux to the atmosphere. There are in turn important effects on the low level properties of the monsoon current, which are discussed next.

3. Low level properties of the monsoon current

Until recently the properties of the monsoon current could be inferred only from surface observations at sea and from aerological soundings along the west coast of the Indian sub-continent. These soundings, however, revealed the characteristics of the stratification at the end of the oceanic trajectory. Very little information on the properties in the upstream regions of the trajectory was available. With the organization of the International Indian Ocean Expedition part of this deficiency is being remedied. Valuable information has already been collected which permit a first glance at the modifications introduced during the path of the air over the Arabian Sea.

During the period 26 June to 2 July 1963, the research aircraft of the U.S. Weather Bureau carried out an extended mission from Bombay to Nairobi to investigate the low level monsoon flow. Two DC-6 aircraft departed Bombay on 26 June at altitudes of 1500 ft and 500 mb on a path upstream along the surface flow. After a stop overnight in Aden, the track was continued to a position near 2°N—47°E (Fig. 10). A reverse track was flown on 1—2 July. A complete programme of meteorological observations, which included a series of dropsondes from 500 mb was carried out. Only the dropsonde observations are discussed here. The soundings recorded on the northward track on 1—2 July are shown in Figs. 11 and 12. The positions where the soundings were made are numbered from 5 to 1 in Fig. 10.

The data revealed a general increase in temperature downstream at low levels (Fig. 11). At the surface there was an increase of 4-5°C from the equatorial region to Bombay. The lapse rate in the surface layer was nearly dry-adiabatic, more so in the downstream position in the central Arabian Sea, indicating well mixed conditions. Another important feature was the presence of an

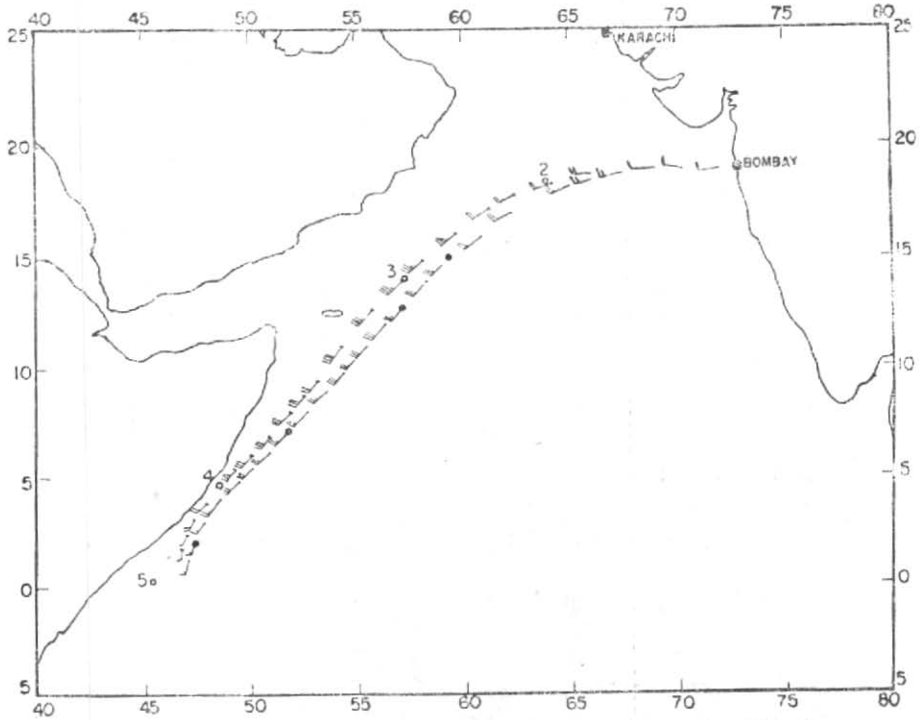

Fig. 10. Track and wind reports at 1500 ft recorded by research aircraft during 26 June to 2 July 1963

The track marked with dots was made in the southward mission on 26-27 June 1963; the one marked with X's was made on the northward mission on 1-2 July 1963. The small numbered circles show the positions where dropsonde data illustrated in Figs. 11 and 12 were recorded.

inversion in the layer from 900 to 750 mb which was also more pronounced in the downstream positions (*see* positions 3 and 2 in Fig. 11). The pronounced instability of the layer above the inversion was also of interest. Closer to Bombay there was a pronounced tendency for a breakdown of the inversion. The sounding at Bombay reflected rainy conditions prevalent at the time of observation.

The moisture data (Fig. 12) showed a definite increase in moisture content downstream near the surface. Of particular interest were the soundings at positions 3 and 2 which revealed very high moisture near the surface and dry conditions aloft. The top of the moist layer was located around 900 to 925 mb, at the base of the temperature inversion. The drop in moisture in the inversion was quite remarkable. In many respects this resembles the distribution in the trade winds of the Atlantic and Pacific Oceans.

The sounding for Santacruz Airport, Bombay, at the end of the trajectory, showed a very large moisture content at all levels reflecting the rainy weather present there. The data on the southward mission on 26-27 June (not illustrated) showed essentially the same features mentioned above. Interpretation of the data as above implies a certain degree of steadiness in the flow so that observations taken over 2-day period can be considered representative of changes downstream along the trajectory. This is no doubt true in the surface layer where the steadiness of the southwest monsoon current is remarkably high.

The cloud field observed during the course of these missions reflected well the

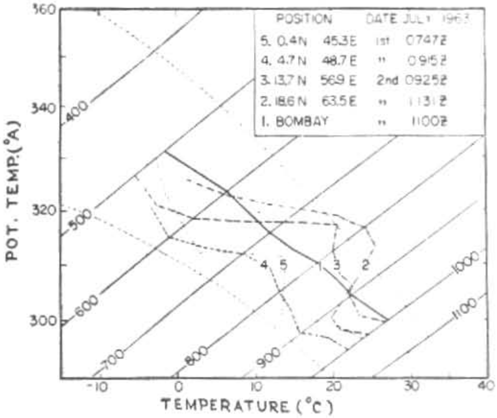

Fig. 11. Tephigram with temperature soundings at various positions downstream along the monsoon current

distribution of temperature and moisture revealed by the dropsondes. Near the equator the cloud formations were to some extent of convective nature; lines of cumuli oriented parallel to the low level flow were observed. There was a decrease in convective cloudiness northward. The predominant cloud deck from about 7°N to 15°N was a low level stratocumulus layer with base around 1500 ft and top near 3000 ft. There was also, specially north of latitude 10°N, a layer of haze near the surface. In the west central sections of the sea there was a definite lack of convective clouds; over large areas there were no middle or high clouds. Farther downstream, from about longitude 65°E eastward to Bombay, the amount of middle and high clouds and the weather activity increased. Widespread cloudiness and rainy conditions predominated through the oceanic area just west of Bombay.

Additional information on the temperature and moisture stratification was obtained by means of radiosonde soundings made from oceanographic vessels. Two soundings made aboard the ATLANTIS II on 11, 14 August 1963, are illustrated in Fig. 13. The one shown by a dashed curve, recorded near 15°N-58°E, shows a nearly dry adiabatic layer from the surface to 915 mb; a deep stable layer from 910 to 810 mb, an unstable layer from 800 to 500 mb, and a moist adiabatic lapse rate above 500 mb. The moisture was not available, but similar features were observed in soundings made further to the west, which showed well the moisture discontinuity at low levels. The other sounding illustrated, near longitude 68°E, showed the mixed surface layer extending to about 840 mb. A thin inversion was present from 840 to 815 mb and a relatively unstable layer above. The moisture discontinuity was not very pronounced in this case.

An interesting feature of the soundings in Fig. 13 is the unstable layer above the inversion. A similar property was also noted in the dropsonde data in Fig. 11 and appears to be a characteristic property of the statification. It is probably associated with the air of African and or Arabian origin which overrides the southwest surface current. The presence of this layer is of great importance to the rain-producing potential of the monsoon current, since once the inversion is destroyed there is a favourable stratification for rapid release upward of the moisture leading to condensation and precipitation.

The causes of the inversion itself appear to be air mass differences between the moist, relatively cool current with a long oceanic trajectory near the surface and the hot, dry air current of land (northeast Africa and Arabia) origin above it. The surface oceanic air mass is quite shallow; the southwesterly flow at the surface in the western sections of the Arabian Sea changes rapidly with height to a westerly flow coming from land. At the 850-mb level the flow reaching India as far south as the southern tip of the peninsula seems to be in large measure of African origin. Over the northern sections of the Arabian Sea northwesterly flow predominates at the 850 mb level in summer (Raman and Dixit 1963).

As it approaches the coast of India, the air suffers considerable modification. The coastal region east of about longitude 68°E

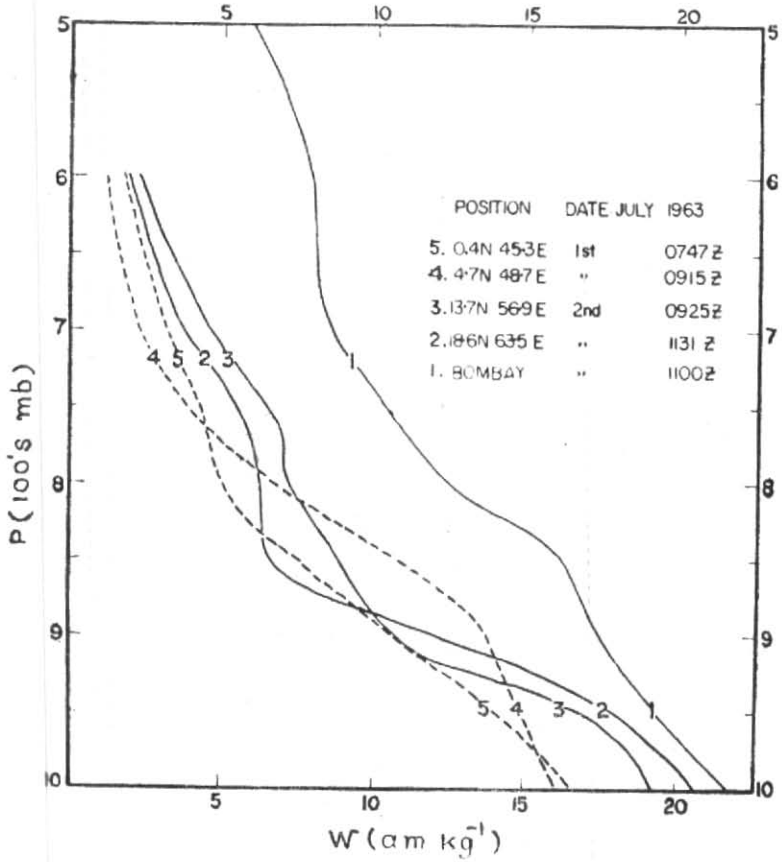

Fig. 12. Moisture soundings associated with temperature data of Fig. 11

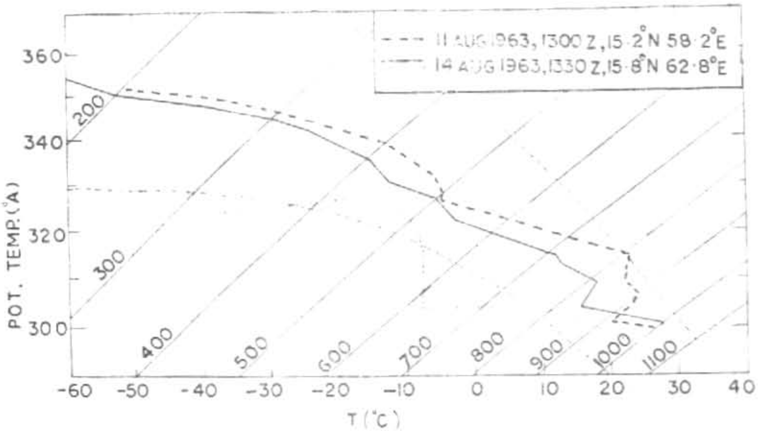

Fig. 13. Tephigram with temperature soundings over Arabian Sea recorded aboard the oceanographic vessel **ATLANTIS II**

is a favoured one for the occurrence of increased cloudiness and precipitation (Meteorological Office, London 1949). A deeper moist layer and weaker inversion seems to prevail there (Fig. 13). There is at present no accepted explanation behind this preferred region of weather. Several possible factors can be mentioned, none of which have so far been fully evaluated. There may be oceanic interactions and vertical mixing processes in the low levels, acting in a manner similar to what has been proposed in connection with the trade wind inversion (Riehl 1954). In the scheme envisioned there, vertical mixing takes place across the inversion layer; the penetration of active cloud formations across the inversion base leads to mixing and diffusion of moisture upward, which result in a lifting of the inversion. Pick-up of sensible heat and moisture from the sea surface enhances the convective processes downstream. Another feature to be considered in the east Arabian Sea is the orographic effects caused by the Western Ghats—a mountain range which runs north-south along the west coast of India and whose influence probably extends some distance upstream. However, the weather area seems to extend too far upstream for orographic effects to be solely responsible. One other factor that may prove to be of great importance is the tendency for formation of perturbations in the low level flow in the vicinity of the coast (George 1956). Recent observations and studies now in progress* indicate the possibility that the formation of these perturbations may be connected with developments in the middle troposphere. Thus the breakdown of the inversion may be linked to the occurrence of convergence patterns associated with synoptic scale developments.

4. Summary and Conclusions

A study of seasonal change in the atmospheric surface flow and water temperature regimes over the Arabian Sea has led to an evaluation of some interesting air-sea relationships, which may prove to have a influence on the time and space variations

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* A study of mid-tropospheric cyclones, and their relationship to rainfall along the west coast of India, is being completed by F.R. Miller, R.N. Keshavamurthy and C.S. Ramage

of the monsoon rains. These interactions reach their most interesting phase during the southwest monsoon season from May to October. The establishment of the southwest monsoon currents near the surface brings about important changes in the water currents and in the magnitudes of heat flux from ocean to atmosphere which affect in turn the thermal properties of the water and of the monsoon flow as well.

Computations of some of the components of the heat balance on a monthly basis were presented for six locations representative of the varying conditions present in different sectors of the Arabian Sea. The highest magnitude of heat flux mainly by evaporation, 670 ly day^{-1} or an evaporation rate of about 1·2 cm day^{-1}, was obtained in the west central portion of the sea along the strongest part of the southwest current, but away from the centre of upwelling. The minimum heat flux obtained in the upwelling areas along the African coast, where the evaporation is quite low in spite of prevalent strong winds, and the heat conduction is generally directed from air to sea.

The temperature and moisture content increase downstream along the monsoon current, in accordance with the heat flux regime. The combination of the moist southwest current in the surface layer and a dry warm air mass above that flows eastward from Africa and Arabia produces a characteristic thermal inversion that in some respects resembles the famous trade wind inversion. There is a large concentration of moisture below the inversion. The surface layer shows frequently a nearly dry-adiabatic lapse rate. The inversion is located around 900 to 800 mb. Above, a dry and quite unstable layer with lapse rate close to the dry-adiabatic prevails. The distribution of clouds observed by research aircraft showed a stratocumulus layer with base around 1500 ft and tops mostly around 3000 ft prevailing to the west of longitude 65°E. There were very little amounts of middle and high clouds and definitely no clouds of convective nature. Another typical feature, more pronounced in the northern sections of the Arabian Sea, is a thick layer of dust-haze, which appears to originate in air from the sandy areas of Africa and Arabia.

As the air approaches the Indian coast there is a tendency for lifting and weakening of the inversion and for development of considerable layer cloudiness and precipitation. The causes of this favoured weather area are not known with certainty, but preliminary results from further study of this problem indicate dry adiabatic upward motion in the surface current that flows northeastward towards India plus a more violent overturning near the coast linked apparently to convergence patterns in synoptic scale.

The most direct and noticeable effects of the interactions between the water body of the Arabian Sea and the circulation above are probably those discussed in this report. However, there are probably many other feedback effects, covering a wide scale in time and space, and many of which are not easily detectable. The discussion presented here has brought out factors of importance in the diagnosis and forecasting of monsoon weather. First of all, it appears that the establishment of the monsoon current by itself is not enough to guarantee the release of rainfall. There is a vast reservoir of moisture near the surface, but a suitable mechanism must exist to overcome the thermal inversion and release the moisture upwards for condensation and precipitation to occur. This mechanism must as a rule be produced by patterns of convergence associated with synoptic scale perturbations. This is a rule which applies to the rainfall production in other parts of the world. The monsoon rains do not appear to be an exception.

Consideration of the stability of the monsoon air during its oceanic trajectory may help in developing a fruitful line of approach in the study of the synoptic and physical aspects of the monsoon rains. Additional documentation and study is needed about the space and time variations in the low level stratification over the Arabian Sea. The causes underlying the modification of the monsoon air as it approaches the Indian coast but while still far out at sea; the presence and nature of low level perturbations in that area, and the nature of the cloud formations that are instrumental in producing rain are some of the unknown questions of importance for the study of monsoon weather, as well as the general problem of air-sea interactions and rainfall production.

REFERENCES

Budyko, M. I.	1956	The heat balance of the earth's surface, Gidrometeorologischeskoe izdatel's stvo. Lenningrad, pp. 255. Translated by Nina A. Stepanova and distributed by the U.S. Weather Bureau, Washington, D.C., 1958.
Deacon, E. L. and Webb., E. K.	1962	Small scale interactions between Sea and Air, *The Sea*, Ed. M.N. Hill, Interscience Publishers, New York, pp. 43-87.
George, P. A.	1956	*Indian J. Met. Geophys.*, **7**, pp. 225-240.
Jacobs, W. C.	1951	The exchange between the Sea and Atmosphere and some of its consequences, *Bull. Scripps Instn. Ocean*, **6**.
Malkus, J. S.	1962	Large scale interactions between Sea and Air, *The Sea*, Ed. M.N. Hill, Interscience Publishers, New York, pp. 88-294.
Met. Office, London	1949	Monthly meteorological charts of the Indian Ocean, M.O. 519, Air Ministry, H.M.S.O., pp. 98.
Patullo, J. G.	1957	The seasonal heat budget of the Oceans. Ph.D. Thesis, Univ. Calif, Los Angeles.
Raman, C. R. V. and Dixit, C. M.	1963	Analyses of monthly mean resultant winds for standard pressure levels over the Indian Ocean and adjoining continental areas. Report presented at symposium in Tropical Meteorology at Rotorun, New Zealand, Nov. 4-13, 1963.
Riehl, H.	1954	*Tropical Meteorology*, McGraw-Hill Book Co., New York, pp. 392.
Royal Neth. met. Inst.	1952	Indian Ocean Oceanographic and Meteorological Data, Second Edition, 1952, pp. 31 and 24 charts.
Sheppard, P. A.	1958	*Quart. J. R. met. Soc.*, **84**, p. 205.
Sverdrup, R. U., Johnson, M. W. and Fleming, R. H.	1942	*The Oceans*, Prentice-Hall Inc., New York, pp. 1097.
U.S. Navy, Chief of Naval Operations	1957	Marine Climatic Atlas of the World, **3**, Indian Ocean NAVAER 50-1C-530.
Venkateswaran, S. V.	1956	*Indian J. Met. Geophys.*, **7**, pp. 265-284.
Wilson, B. W.	1960	Notes on surface wind stress over water at low and high wind speeds. *J. geophys. Res.*, 65, 3377-3382.

Discussion

Ramanathan (K. R.) : As one examines the streamline charts both at the surface and in the lowest 2 or 3 km over the whole Indian Ocean, and their development particularly in June/July/August, one notices southeast trades crossing the equator and becoming the southwest monsoon. However, at 1 km, the air reaches the western Arabian Sea from Arabia. Over any of the western lands, the lapse rate is entirely dry adiabatic but as it comes over the sea, the lower air cools, moistens and then is, of course, responsible for the inversion over the west. But at Trivandrum or even Goa or Bombay, that Arabian air is less important. The air is mainly the Southern Hemisphere trade air which has been converted into monsoon air. In Karachi airplane observations were taken daily for a large number of years. The air came south down the Persian Gulf, roughly parallel to the coast, and then entered near Karachi. One could see the gradual build up of the moist air as the season advanced. During the monsoon in Karachi there is an almost permanent stratus layer on many days, which dispppears about 10 to 11 hr and a light drizzle which disappears at about 12 hr. It is quite understandable for it is extremely dry heated air from land, coming over the cool ocean. Of course there is also upwelling on the Somalia and Arabian coasts to assist the process. All these factors conspire together as a whole. But is there any information about the effect of the large fluctuations in the waves of the sea? In the monsoon, even before the monsoon, the sea gets very rough. Naturally the momentum balance between the atmosphere and sea and correspondingly water vapour flux between sea and atmosphere should increase considerably with the roughness of the sea. This should contribute significantly to the water vapour flux.

Colon : I agree perfectly with the points you raise concerning the trajectories aloft. I purposely limited my discussion to the surface layer; at upper levels the trajectory is not precisely as indicated for the surface.

In regard to upwelling, there is no question of its presence in large scale over the western coastal sector, but the computed magnitudes of evaporation over the central Arabian Sea are quite large and I believe in that area the principal factor in causing the water cooling is heat flux rather than upwelling. This particular analysis was limited to the central portions of the Arabian Sea; over the western border the story is quite different.

Srinivasan (V.) : Probably the decrease in the water temperature in July/August has something to do with the absence of tropical storms in the Arabian Sea. But at the same time in the southwest Pacific Ocean and South China Sea tropical storm formation is at its peak. Why does the water temperature fall in the Arabian Sea and why does it not fall in the South China Sea ?

Colon : The strength of the surface wind flow over the South China Sea is much lower than here. Actually, the temperatures also decrease in early summer in the South China Sea, but not as much as in the Arabian Sea.

Pisharoty (P. R.) : 1. When you made these observations by aircraft, I imagine there was a lot of dust haze, which will show distinctly that the trajectory is from a dusty area. 2. The sea surface temperature increases toward the northeast. Can you say there is not ocean current coming across for the lowering of the sea temperature? So if there is a cooling, the evaporation is one of the reasons that apply. 3. Mr. Gangopadhyaya told me that experiments conducted in the USSR show that evaporation can be 100 times more when ocean waves are breaking and water sprayed than when evaporation is taking place with low winds.

Colon: Regarding the first question : The fact that you have dust haze indicates trajectories from land, but these are probably above the surface layer, which explains the dryness aloft. The high degree of steadiness in the flow over the Arabian Sea implies that the streamlines are good approximations to trajectories. Some computations can be made which indicate that the surface trajectories that reach the vicinity of Bombay are mainly of oceanic origin.

Ramanathan: We are not dealing with same air at the surface and aloft. We have had many ascents over Habbanayia and if you compare the temperature there at the higher level with the temperature over Karachi, you will find they are the same. The upper air is the same. Only the lower air has been moistened and cooled.

Colon: Regarding ocean currents, it is very difficult to compute the divergence of heat transport by them; we have some information on the currents at the surface in the climatological charts, but there are no data on how far down the currents extend, how much is the water transport and how much heat is transported.

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