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SOME ASPECTS OF AIR-SEA INTERACTION IN THE INDIAN OCEAN DEDUCED FROM SATELLITE CLOUD PHOTOGRAPHS*

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ABSTRACT

Possible airmass modification and vertical motion accompanying passage of dry continental air over a cold and a warm ocean and cool maritime air over a warm ocean are discussed in the light of available satellite cloud photographs and meteorological data relating to Indian Ocean. Development of cellular clouds is discussed in detail and it is suggested that it occurs mostly in areas where air-sea interaction leads to conditionally unstable thermal stratification and favourable boundary layer convergence through 'thermal wind' effect of ocean surface temperature distribution.

INTRODUCTION

RECENT satellite cloud photographs relating to the Indian Ocean have revealed many interesting features of cloud distributions in different parts of this ocean during both the north-east and the south-west monsoon seasons. Some of these may be described as follows :

During the north-east monsoon season (December-February) :

The north Arabian Sea appears more or less clear of clouds or has only thin haze or stratus but equatorward of about 18°N, convective clouds appear with cells growing progressively larger and more developed as the Equator is approached. Near the Equator, a well-developed cloud band may be occasionally seen. Plate IA, which is a satellite photograph on 4th January 1967, shows the above features of cloud distributions over the Arabian Sea during northern winter.

During the summer monsoon (June-September) :

There appears to be almost complete lack of clouds in Western Arabian Sea (west of about 60°E). By contrast, the eastern Arabian Sea exhibits large amounts of cloudiness, the cloud cells becoming larger and more vertically developed as the west coast of India is approached. This typical cloud distribution is shown in Plate IB which gives a satellite photograph of cloud distributions over the Arabian Sea on 11th July 1967. Plate IC shows a satellite photograph of typical cloud distributions in south-east trade wind belt south of the Equator on 25th August 1970. The alignment of the cloud cells around the subtropical anticyclone as well as their progressive growth on approaching the Equator are well shown by this photograph. It also shows a well-defined cloud band with maximum intensity a few degrees south of the Equator.

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For a proper understanding of the above cloud distributions, it would be appropriate to study both the surface as well as upper air conditions over the Arabian Sea on the days of the satellite photographs. However, upper air data on daily basis from the Arabian Sea except a few dropsonde and ship-based radiosonde data during 1963-64 are not available. Even surface data are scarce. In these circumstances, only a qualitative discussion based on mean surface and available upper-air conditions appears feasible. A justification for this approach may be in the fact that cloud distributions similar to those shown above appear repeatedly every year during the same season, hence an attempt to explain them on the basis of mean data may not seem unreasonable. The present study thus attempts a qualitative physical explanation of the typical cloud distributions revealed by the satellite photographs (Plate I A-C) on the basis of mean surface data and available upper-air observations. In section 2, the distribution of the mean ocean surface temperature is discussed. Section 3 discusses the ocean-atmosphere exchanges and vertical fluxes of sensible heat and water vapour from the surface of the Indian Ocean. Three specific cases of interaction leading to airmass modification are considered. On the basis of observed vertical distribution of equivalent potential temperature, it is qualitatively suggested that cloud development in each of the three cases may be attributed to development of conditionally unstable thermal stratification and boundary layer convergence as the airmass moves over the warmer parts of the ocean.

Distribution of Mean Ocean Surface Temperature

Fig. 1 shows distribution of mean ocean surface temperature in the Indian Ocean during (*a*) January and (*b*) July, 1964 (Miller and Jefferies, 1967). The salient features of the temperature distribution may be described as follows : During January when the winter monsoon is most well-developed, the meridional distribution shows cold sea surface in north Arabian Sea and north Bay of Bengal and increasingly warmer seas towards and even beyond the Equator. In fact, the meridional surface temperature maximum occurs near the Equator in the eastern Indian Ocean and a few degrees south of the Equator in Western Indian Ocean. The zonal temperature distribution shows that equatorial Western Indian Ocean (west of about 60°E) is slightly colder than equatorial Eastern Indian Ocean. During July, the surface temperature in Western Arabian Sea (west of about 60°E) drops markedly due to upwelling and cold Somali current with the result that a pronounced zonal temperature anomaly develops between the western and the eastern parts of the Arabian Sea, the eastern part being considerably warmer than the western part. The meridional temperature distribution in Eastern Arabian Sea as well as in equatorial eastern Indian Ocean shows a profile which is more or less flat or level northward of about 5°S, but decreases steadily south of this latitude. In the Western Indian Ocean, particularly close to Somali coast, surface temperature is extremely low with value often reported at less than 20°C. The above features of surface temperature anomalies in equatorial Indian Ocean have been discussed by Saha (1970).

Ocean-atmosphere Exchanges—Airmass Modification

When a given airmass moves over an ocean surface, there is complex mutual interaction between the airmass and the ocean surface with exchange of properties depending, *inter-alia* upon vertical gradients of temperature and humidity across the interface. The moving airmass produces a wind stress at the ocean surface which

TABLE 1. *Vertical distribution of air temperature (°C) and humidity-mixing ratio (gm/kgm) at different locations over the Arabian Sea during early February, 1964, as measured by dropsondes. Radiosonde data of Bombay are included.*

Pressure levels (mb)	Bombay 1.2.64 (00Z)		14°N, 72°E 1.2.64 (05Z)		11°N, 72°E 1.2.64 (06Z)		8°N, 72°E 1.2.64 (07Z)		11°N, 68°E 2.2 64 (09Z)		12°N, 60°E 2.2.64 (10Z)		16°N, 60°E 2.2.64 (12Z)		18°N, 61°E 4.2.64 (06Z)	
	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.
1000	17.0	3.7	26.0	12.0	25.0	15.4	27.0	16.1	28.0	19.0	28.0	20.5	27.0	18.0	28.0	20.0
950	—	—	21.5	9.5	22.0	13.5	23.0	9.6	24.0	17.0	25.0	18.0	24.0	16.5	24.0	16.0
900	14.0	3.4	18.0	7.0	17.0	11.5	20.0	5.6	20.5	15.0	22.0	15.0	21.5	15.0	22.0	14.0
850	14.0	3.6	15.0	5.5	15.0	7.0	18.0	3.5	18.0	15.0	19.0	12.5	19.0	12.5	20.0	12.5
800	14.0	0.6	14.0	3.4	14.0	3.2	18.0	3.0	18.0	14.5	17.0	11.0	16.0	9.5	17.0	9.0
700	8.0	2.6	9.0	3.6	10.0	2.0	9.0	3.0	11.0	10.0	11.0	6.0	10.0	4.2	—	—
600	0.0	0.1	0.0	2.3	2.0	1.7	2.5	0.9	6.0	—	3.0	2.0	4.0	1.7	—	—

TT stands for air temperature and m.r. for humidity-mixing ratio.

is a complex function of the wind speed but in the present study this aspect of ocean-atmosphere interaction is not considered. It is of interest to enquire what effect by way of modification is produced by ocean surface on the properties of the moving airmass. The situations relevant to the present cases may only be considered here, *viz.*:

Case (*a*) When a dry, cold continental airmass blows first over a cold ocean and then over a warm ocean,

Case (*b*) When a dry, warm continental airmass moves first over a cold ocean and then over a warm ocean,

Case (*c*) When a cool maritime airmass moves progressively over warm ocean surface.

Cases (*a*) and (*b*) correspond to conditions over the Arabian Sea during north-east and south-west monsoons respectively and case (*c*) to conditions that are encountered in south-east trade wind belt of the southern hemisphere during the SW monsoon. The mean low-level air-currents over the Arabian Sea during the northern winter and the western Indian Ocean during the northern summer are included in Fig. 1.

Using standard flux-gradient relationships, Miller *et al.* (1963) computed mean monthly fluxes of sensible and latent heat over the Indian Ocean during 1963 and 1964 under the meteorology programme of the International Indian Ocean Expedition (1962-64) when a large volume of ocean and ships' data were available. Saha (*loc. cit.*) has discussed the salient features of these fluxes during January and July, 1964. He shows that during January, both sensible and latent heat fluxes are upward but during July, sensible heat flux is downward in western Arabian Sea where the sea surface is considerably colder than the air and upward in eastern Arabian Sea as well as in eastern Indian Ocean where the sea surface is warmer than the air. The vertical flux of water vapour is upward over all parts of the ocean surface but has maxima over western Arabian Sea as well as in southern Indian Ocean south of about 15°S. Similar distributions in mean monthly fluxes of evaporation were also observed during 1963 (Suryanarayana and Sikka, 1965).

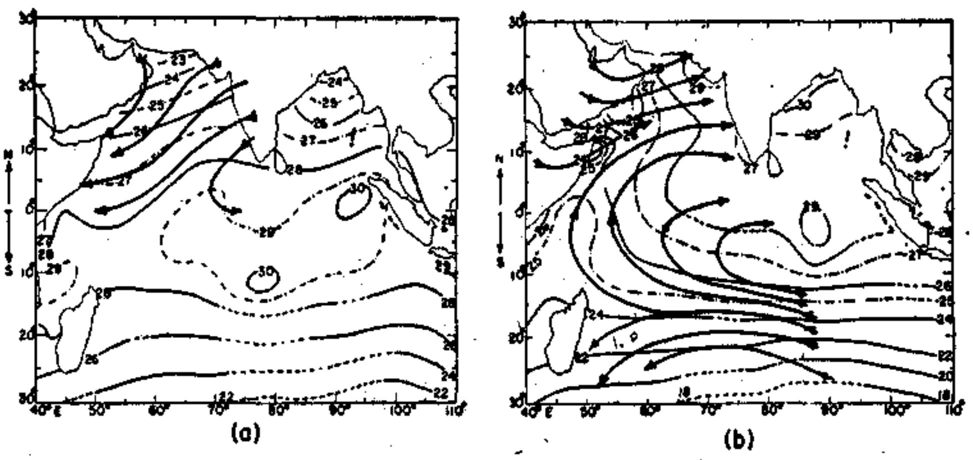

Fig. 1. Distribution of mean ocean surface temperature (°C) in the Indian Ocean during 1964: (a) January, (b) July. Direction of low-level airflow is indicated by thick lines with arrowheads.

The net effect of the above-mentioned air-sea exchanges of heat and water vapour appears to be a gradual modification of the lower layers of the airmass as it moves over the ocean surface. Adequate data to study this transformation on daily basis are virtually non-existent. However, during the period of the I.I.O.E. dropsonde as well as ship-based radiosonde data were available at a number of locations over

TABLE 2. *Vertical distribution of air temperature (°C) and humidity-mixing ratio (gm/kgm) at different locations over the Arabian Sea during period June-July, 1963, as measured by dropsondes. Radiosonde data of Bombay are included.*

Pressure levels (mb)	13°42′N 56°53′E 2 July 1963 0925Z		14°57′N 59°20′E 26 June 1963 0715Z		13°15′N 62°51′E 8 July 1963 0715Z		17°48′N 65°50′E 8 July 1963 0830Z		20°07′N 70°06′E 7 July 1963 0949Z		Bombay 7 July 1963 00Z	
	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.
1000	—	—	26.5	20.0	27.2	18.5	26.9	—	—	—	26.0	20.4
950	—	—	22.5	17.5	23.3	16.5	24.0	—	—	—	22.5	19.0
900	21.3	10.5	22.0	9.2	19.3	15.0	21.0	14.5	22.0	17.0	21.0	17.0
850	21.4	8.5	21.5	5.2	17.8	14.0	22.5	7.0	20.0	15.0	19.0	15.5
800	20.5	7.0	17.2	4.0	16.5	8.0	22.5	6.0	14.0	11.0	16.0	13.5
700	13.5	5.0	12.8	2.8	12.4	6.5	15.8	6.5	9.5	10.5	11.0	9.7
600	2.0	2.2	1.8	0.9	3.1	4.0	6.0	4.0	5.0	8.5	7.0	9.0

* TT stands for air temperature and m.r. for humidity-mixing ratio.

the Arabian Sea and equatorial Indian Ocean during periods of a few days and a study of these data appears to provide some idea of the airmass transformations that occur over the ocean. Table 1 gives the values of air temperature and humidity mixing ratio at different pressure levels over the Arabian Sea during period 1-4 February, 1964, corresponding to case (*a*). It appears to show that as the dry cold continental airmass blows over the Arabian Sea from a E/NE direction towards warmer sea, heat and water vapour diffuses to higher levels. For instance, the air temperature and humidity-mixing ratio values at 850 mb over Bombay are 14°C and 3.6 gm/kgm respectively, whereas the corresponding quantities at the same level at location 12°N, 60°E a day later are 19°C and 12.5 gm/kgm respectively. Table 2 gives the values of air temperature and humidity-mixing ratio at different pressure levels over the Arabian Sea during period 26th June-8th July, 1963, corresponding to case (*b*). In this case, dry hot continental airmass from over Arabia and northern Somalia blows from a SW'ly direction first over a cold ocean and then over a warm ocean the dividing zone being about longitude 55°E-60°E. It is evident from Table 2 that the atmosphere over eastern Arabian Sea is much more humid than that over western Arabian Sea during the period. For example, the humidity mixing ratio at 850 mb at location about 13°N, 56°E on 2nd July, 1963 is 8.5 gm/kgm, whereas it is 15.0 gm/kgm at location 20°N, 70°E on 7th July, 1963. The temperature distribution presented in Table 2 also appears to show the change in air temperature brought about by air-sea exchanges of heat. Table 3 shows the transformation that occurs in the south-east trade-wind belt of the southern hemisphere during northern summer as cool maritime air moves towards the warm Equator of Eastern Indian Ocean.

Convectively Unstable Atmosphere

The observed changes in the temperature and humidity structure of an airmass as it moves over the warmer parts of the ocean appear to be related to change in the vertical stability and development of adequate boundary layer convergence. When a dry, cold stable airmass moves over an ocean surface in which temperature increases downwind as in case (*a*), the non-adiabatic heating and the humidification of the lower layers of the airmass leads to its continual de-stabilisation resulting in a convectively unstable layer. A measure of convective instability is given by the vertical variation of the equivalent potential temperature, θe. If $\frac{\partial \theta e}{\partial z} < 0$, the atmosphere is said to be convectively unstable. Fig. 2 shows the change in the vertical distribution of equivalent potential temperature in the three cases (*a*), (*b*) and (*c*) for two locations in each case, one upstream and the other downstream. For economy of space, the distributions at intermediate locations are not presented. However, Fig. 2 would seem to suggest that the atmosphere becomes convectively unstable downstream in all the cases and that if an effective mechanism existed to produce convergence and upward motion in the boundary layer, the energy of instability would be realised to produce copious convection and condensation of water vapour. The latent heat of water vapour released by condensation may lead to warming of the air and further development of the atmospheric system which may in its turn cause increased boundary layer convergence and more upward motion. The process, in effect, may lead to formation of convective type of clouds, with the cloud cells developing under greater convective instability downstream. But, as already mentioned, for this growth of clouds, an effective convergence mechanism in the boundary layer is necessary.

Boundary Layer Convergence

What is the nature of the boundary layer convergence that produces clouds of the types observed in Plate I A-C? Recently, Ooyama (1963), Charney and Eliassen (1964), Charney (1967) and others have discussed the role of boundary layer con-

Table 3. *Vertical distribution of mean air temperature* (°C) *and humidity-mixing ratio (gm/kgm) at Mauritius, Cocos Island, Diego Garcia, and Gan Island during August*, 1963.

Pressure level (mb)	Mauritius 20.3°S 57.5°E		Cocos Island 12.1°S 96.9°E		Diego Garcia 7.2°S 72.4°E		Gan Island 0.7°S 73.2°E	
	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.
Surface	18.5	9.7	24.9	13.8	27.1	19.3	—	—
1000	—	—	24.0	13.8	26.5	—	27.5	18.5
950	17.0	—	20.8	11.4	23.5	—	23.0	15.2
900	13.2	9.1	17.4	9.6	19.7	15.1	20.0	12.5
850	10.2	7.4	13.8	8.6	17.5	13.0	17.2	10.4
800	9.3	5.9	10.9	7.0	15.3	11.1	14.6	8.8
700	7.6	2.1	9.1	2.6	10.2	7.7	8.9	5.9
600	2.6	1.1	—	—	3.1	5.0	1.8	3.6
500	—6.1	0.6	—4.9	0.4	—4.9	2.8	—2.0	—

vergence produced by friction and condensation heating in a conditionally unstable atmosphere in which θe decreases with height while considering growth of tropical circulation systems such as the tropical storms, intertropical convergence zone, etc. It is plausible that organised cloud formations such as those shown in Plate IA-C depend upon a convergence mechanism similar to those involved in the growth of the ITCZ or the tropical storm. However, in regions where horizontal temperature differences exist not only at sea surface but also in the boundary layer, it is very probable that the ' thermal wind ' effect would be a powerful mechanism to produce the necessary boundary layer convergence. This may happen particularly where an airmass has to move across steep horizontal gradients of ocean surface temperature as in cases (*b*) and (*c*). Strong horizontal gradients of ocean surface temperature exists over the Arabian Sea between longitudes about 55°E and 60°E and over eastern parts of southern Indian Ocean between latitudes about 15°S and 5°S during the northern summer. In case (*b*), the thermal wind due to ocean temperature distribution causes strong low-level wind maxima over eastern Arabian Sea and this may effectively cause increased boundary layer convergence and cloud formations in eastern Arabian Sea. In case (*c*), the south-east trade winds at surface are likely to gain increasing westerly momentum with height because of a Westerly ' thermal wind '. The consequence of this ' thermal wind ' effect producing equatorial westerlies may be that very strong boundary layer convergence may develop in the conditionally unstable atmosphere that exists over the region (Fig. 2). The convergence may cause rapid cloud growth leading to formation of a pronounced cloud band with maximum intensity a few degrees south of the Equator (Plate I C).

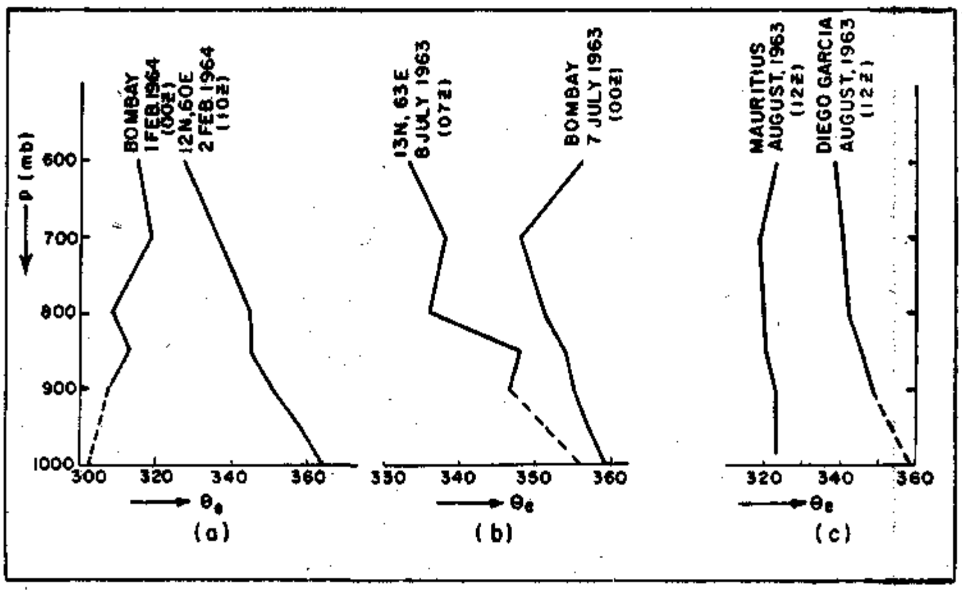

Fig. 2. Distribution of equivalent potential temperature θ (°A) with height at two locations, one upstream and the other downstream, in each of the three cases (a), (b), and (c).

Stratified and Cellular Clouds

From the foregoing analysis, one may conclude that cloud formation and development over the ocean is largely dependent upon relative properties of the ocean surface and the moving airmass. In most cases, where the moving airmass remains extremely dry with moisture mainly confined to low levels, little or no clouds may form despite long travel over the ocean surface. In some cases, when a dry, cold continental airmass moves over a progressively warm ocean surface as in case (*a*), thin haze or stratus cloud may only form during early stage of travel, with formation of convective cells later as more heat and moisture diffuses upward. However, if the moving airmass is dry and warm and moves over a cold ocean surface as in case (*b*), little or no cloud may form even after long distances of travel downwind. It is only after the airmass arrives over the warmer parts of the ocean where boundary layer convergence releases the energy of the convectively unstable atmosphere that convective clouds can form. Initially, cloud cells may be small but as the airmass moves over the warmer and warmer parts of the ocean, clouds cells grow both horizontally and vertically resulting in large cumulus or cumulonimbus clouds. Quite often, groups of large convectively developed cloud cells may be observed over the warmest parts of the ocean covering millions of square kilometers. These groups have been termed 'cloud clusters'. Concentrated boundary layer convergence under conditions of conditionally unstable thermal stratification may lead to formation of organised cloud bands such as those found associated with the intertropical convergence zones.

There appears to be some evidence to suggest that types of cloud cells in cellular convection may depend upon the difference between air and ocean temperatures. Open cells appear to form in regions where the ocean surface is warmer than the air (Hubert, 1966). But observations appear to show that this may not be uniquely so in every case, because closed cells are also found over warm waters.

Conclusion

The paper has discussed a few specific cases of cloud formations over the Indian Ocean and indicated a possibility, that ocean atmosphere interaction may play a dominant role in the formation and distribution of clouds and cloud zones. Types of clouds appear to vary with ocean surface temperature. Convective clouds with well-developed cloud cells appear to form in the warmer parts of the ocean under conditions of conditionally unstable thermal stratification and boundary layer convergence.

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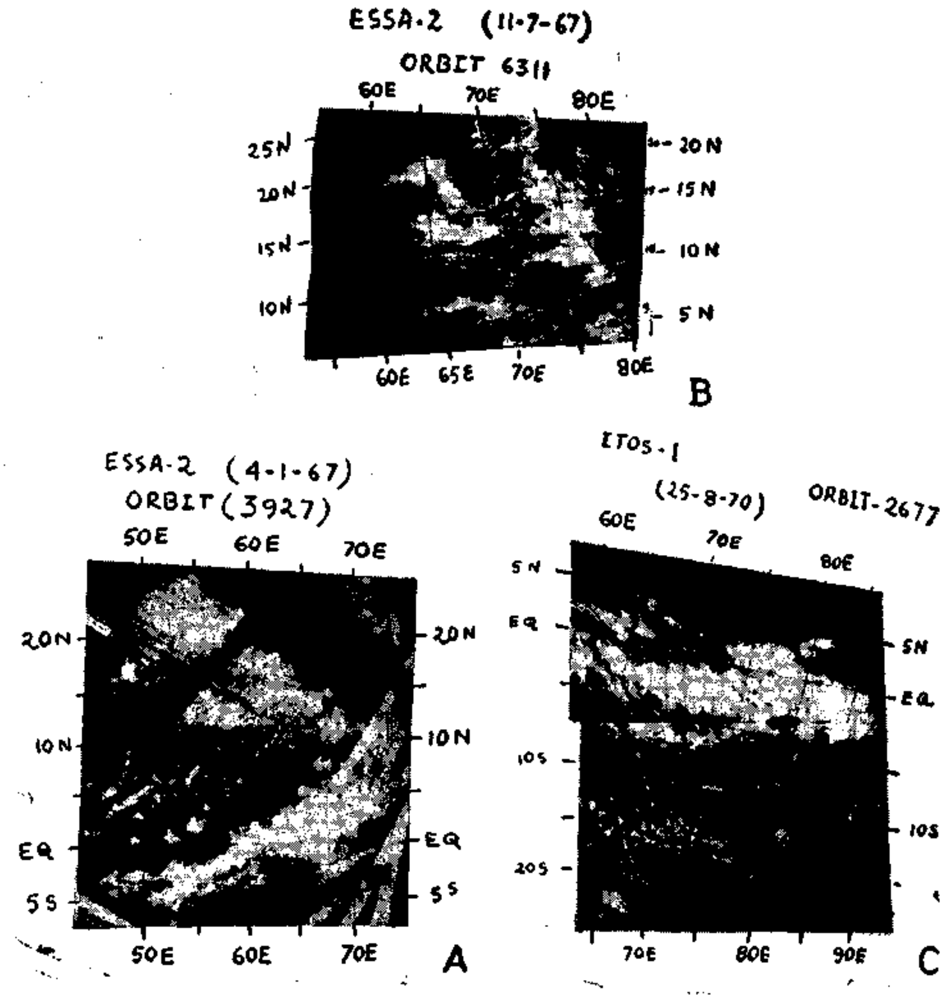

PLATE. IA. An ESSA-2 satellite view of typical cloud patterns over the Arabian Sea during northern winter on 4 January, 1967 (orbit No. 3927). B. Typical cloud patterns over the Arabian Sea during northern summer as viewed by ESSA-2 satellite on 11 July, 1967 (orbit No. 6311). C. Cellular cloud patterns in the south-east trade wind region of south Indian Ocean as viewed by ITOS-1 satellite on 25th August, 1970 (orbit Nos. 2676, 2677).

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