METEOROLOGICAL RESULTS OF MONSOON-88 EXPEDITION (PRE-MONSOON PERIOD)

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(Received in final form 22 March, 1989)

Abstract. Mean atmospheric circulation, moisture budget and net heat exchange were studied during a pre-monsoon period (18th March to 3rd May, 1988), making use of the data collected on board "Akademik Korolev" in the central equatorial and southern Arabian Sea region. The net heat exchange (R_n) is found to be about 20 W m^{-2} for a small area (0–4° N; 55–60° E), 50% less than the climatological value. The mean value of net radiation (140 W m^{-2}) is less than the climatological value, which was due to higher cloud amount. The higher SST enhanced both the latent and sensible heat fluxes.

The mean atmospheric circulation obtained from the upper air data is quite convincing. The mean exchange coefficient (C_e) estimated from the moisture budget is about 1.0×10^{-3} for a wind speed of 4 m s^{-1}. This value is slightly lower than that obtained by the usual methods.

1. Introduction

Most earlier experiments conducted in the north Indian Ocean were designed to study various aspects of monsoon dynamics, ocean-atmosphere interactions and ocean circulations during the southwest monsoon season. These experiments brought out several interesting and unknown features (Lighthill and Pearce, 1981; Krishnamurty, 1978).

To study the ocean-atmosphere interaction during the pre-monsoon and its possible influence on the summer monsoon under the project 'MONSOON-88', an Indo-USSR collaborative study – the field programme on board *RV Akademik Korolev* was undertaken, beginning in March 1988. The authors had an opportunity to participate in the expedition which lasted until 3 May, 1988.

2. Data and Methodology

Relevant data on the surface meteorological parameters were collected at 3-hourly intervals along the track shown in Figure 1. Upper air data were collected at 0000 and 1200 GMT every day using radiosondes. In all, about 90 radiosonde ascents were made during the cruise period. In addition, the available facilities and the equipments on board the ship to receive satellite cloud pictures, FAX charts and surface meteorological data from other merchant ships have

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Boundary-Layer Meteorology **48**: 333–344, 1989.

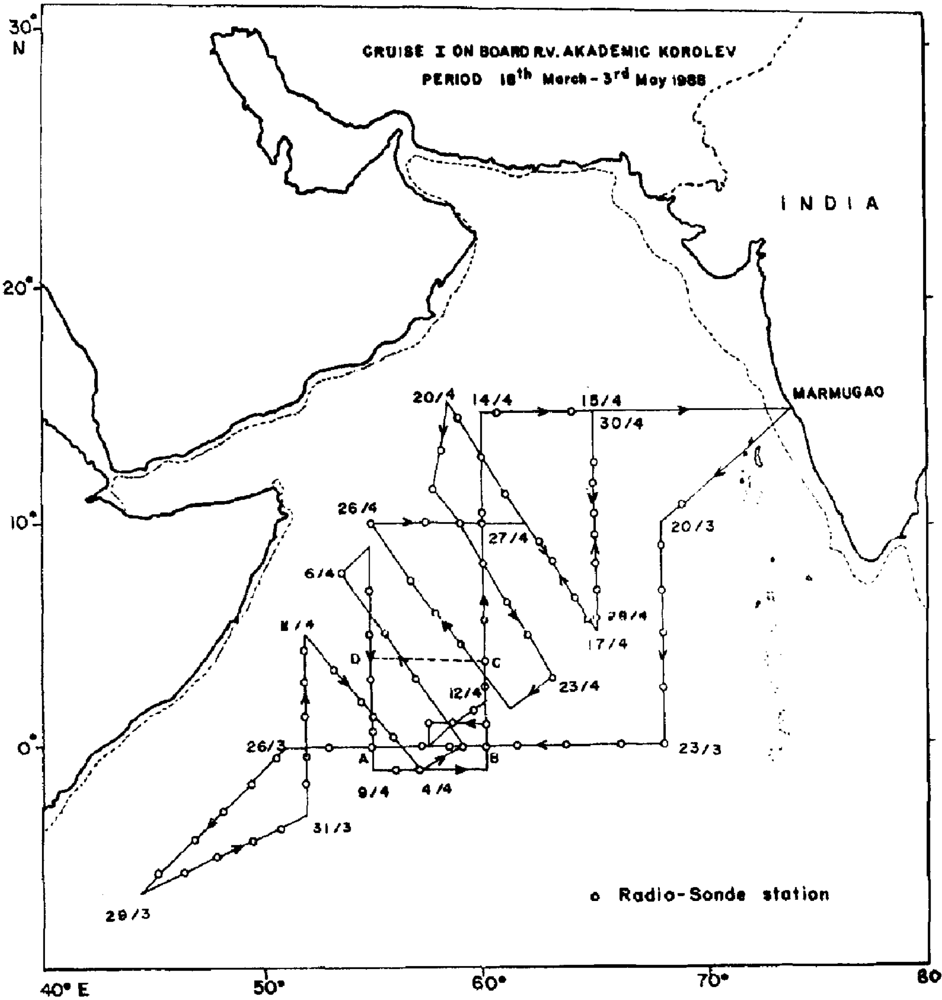

Fig. 1. Cruise track together with the radiosonde stations during the pre-monsoon period (MONSOON-88 Expedition). The data in the area ABCD which was covered repeatedly was used for the computations of heat and moisture budgets.

been used fully. Most of the surface meteorological data and the upper air data were analysed on board the ship itself.

The data collected between the equator and 4° N latitude and lying between 55 and 60° E longitude (marked as ABCD in Figure 1) were used for computing the net heat exchange (R_n) and the moisture budget.

2.1. NET HEAT EXCHANGE (R_n)

R_n was computed using Equations (1) to (5) given below:

$$R_n = R - Q_e - Q_h \tag{1}$$

where

$$R = Q_i(1-\alpha) - Q_b \tag{2}$$

$$Q_b = \epsilon\sigma T_s^4\,(0.254 - 0.00495e_a)(1.0 - 0.7C) \tag{3}$$

$$Q_e = \rho C_e L(q_s - q_a)\,U \tag{4}$$

$$Q_h = \rho C_p C_h(T_s - T_a)\,U \tag{5}$$

where R_n is the net heat exchange across the sea surface (W m^{-2}), R is the net radiation (W m^{-2}), Q_e is the latent heat flux (W m^{-2}), Q_h is the sensible heat flux (W m^{-2}), Q_i is the total incoming radiation (W m^{-2}) (computed following Seckel and Beaudry (1973), the cloud correction following Reed (1977)), α is the sea surface albedo – assumed to be 0.06 (Payne, 1972), Q_b is the effective back radiation (W m^{-2}) (Reed, 1976), ϵ is the emissivity of the sea surface, σ is Stefan Boltzman's constant (W m^{-2} K^{-4}), T_s is the sea surface temperature (°C), T_a is the dry bulb temperature (°C), e_a is the vapour pressure (mb), C is cloud amount (in tenths), ρ is the density of air (kg m^{-3}), L is the latent heat of vaporisation (W s kg^{-1}), q_s and q_a are the saturated specific humidity at T_s and humidity at deck level obtained from the dew point temperature, U is the wind speed (m s^{-1}), C_p is the specific heat of air at constant pressure (W s kg^{-1} °C^{-1}), C_e, C_h are the transfer coefficients for latent and sensible heat fluxes, respectively. A constant value of 1.4×10^{-3} is used following Rao *et al.* (1981).

It should be mentioned here that the wind speed was measured at 24 m height on board the ship while the dry- and wet-bulb temperatures were measured at 12 m height. For the computation of heat fluxes, the usual methods for estimating C_e and C_h, are intended for observations made at a standard height of 10 m from the sea surface, and application to the present set of data would introduce errors (Stevenson, 1982). However, in a study on errors due to a similar height correction (22 to 10 m), the error was found to be only 4% in wind speed and 6% in latent and sensible heat fluxes (Vinayachandran *et al.*, 1988) based on the observations made on board ORV *Sagar Kanya* during the 1986 summer monsoon.

2.2. MOISTURE BUDGET

The moisture budget is computed keeping the top boundary at 300 mb since the humidity observed is almost negligible above this level. Making use of the radiosonde ascents along the boundaries in the area ABCD (Figure 1), the net divergence of moisture flux (NDMF) is estimated after computing the moisture flux across each boundary using the following equation:

$$\text{Moisture flux across a boundary wall} = \frac{1}{g}\int_{p_1}^{p_2}\int_{0}^{L} \bar{q}\bar{V}_n\,\mathrm{d}P\,\mathrm{d}L\,, \tag{6}$$

where g is the acceleration due to gravity; $\bar{q}$ is the mean specific humidity in the layer; $\bar{V}_n$ is the average component of wind speed perpendicular to the boundary wall and p_1 and p_2 are the pressures at the top and bottom of each layer; and

$$E_2 = P + \mathrm{NDMF}\,, \tag{7}$$

where E_2 is the rate of evaporation (mm/day); P is the rate of precipitation (mm/day) and NDMF is also in units of (mm/day).

2.3. PRECIPITABLE WATER (PW)

$$\mathrm{PW} = \frac{1}{g}\int_{p_1}^{p_2} \bar{q}\,\mathrm{d}p\,. \tag{8}$$

3. Results and Discussion

3.1. NET HEAT EXCHANGE (R_n)

The mean meteorological parameters observed and the heat fluxes computed in the area specified above are compared with their climatological values (Hastenrath and Lamb, 1979a and b) in Table I.

The observed higher SST and wind speed enhanced both the latent and sensible heat fluxes. The higher cloud amount reduced the net radiation to below normal. Due to these factors, the net heat exchange was 50% less than the

TABLE I

Heat and moisture budget parameters in the area 0–4° N latitude and 55–60° E longitude during the pre-monsoon of 1988

Parameter	Present study	Climatological study*
Pressure	1010.6	1011.0
Wind speed	3.9	1.0
Cloud amount	5.5	4.5
SST	30.3	29.0
SST - Air Temperature	1.4	0.5
$e_s - e_a$	13.3	–
R	140.0	160.0
Q_e	112.0	80.0
Q_h	8.0	–
R_n	20.0	40.0
q_a	21.0	19.0
E_1	4.1	3.0
NFD	2.3	–
P	0.62	–
E_2	2.92	–
C_e	1.0×10^{-3}	–

* From Hastenrath and Lamb (1979).

climatological value (40 W/m^2). But this reduction did not affect the SST in this region, which indicates the importance of the physical processes operating in the ocean interior. This gives a clue that the heat content in the upper 0–100 m layer in the western equatorial Indian Ocean during the pre-monsoon may be a useful and better predictor of monsoon activity than the SST alone.

3.2. STRUCTURE OF THE TROPOSPHERE

Mean fields of temperature, wind speed and precipitable water (PW) are presented along the equator, 52° E, 55° E, 60° E, 65° E and 68° E in the following figures. The mean atmospheric circulation is derived mainly from the above fields and satellite cloud pictures, assuming that the synoptic conditions are nearly steady.

Figure 2 presents the overall tropospheric structure (surface-300 mb) 23–26 March from 68° E to 52° E along the equator. The mid-troposphere is generally moist near 52° E. Specific humidity is high at 52° E and low at 68° E. From the wind field and the total precipitable water, it is inferred that there is a rising branch in the western equatorial Indian Ocean (52° E) and sinking motion at 68° E.

Figure 3 shows the meridional section along 52° E starting from 2° S–4° N.

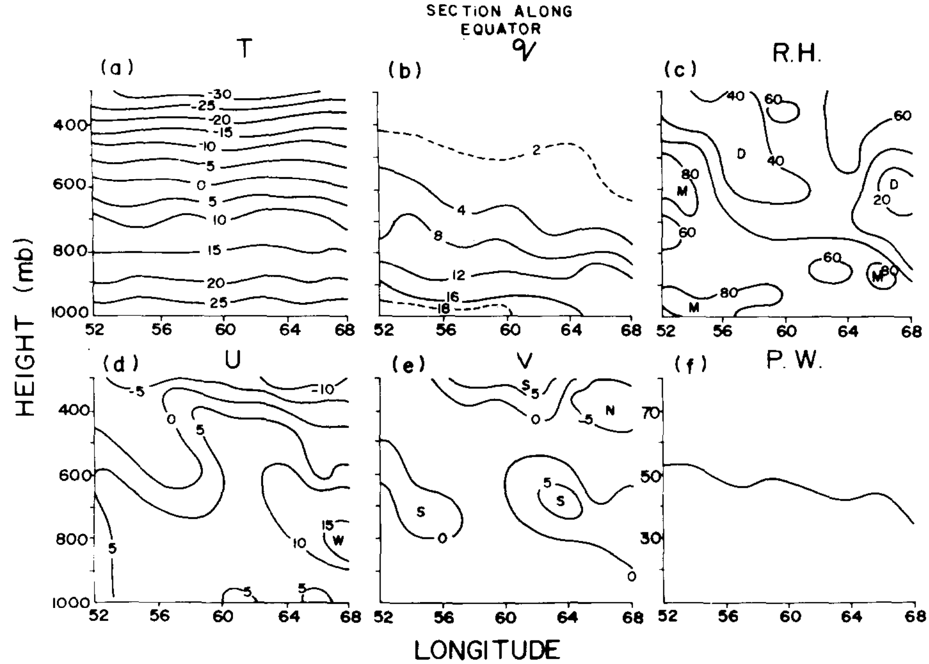

Fig. 2. Fields of temperature (T), specific humidity (q), relative humidity (RH), zonal (U) and meridional (V) components of wind speed and precipitable water (PW) along the equator from 52–68° E.

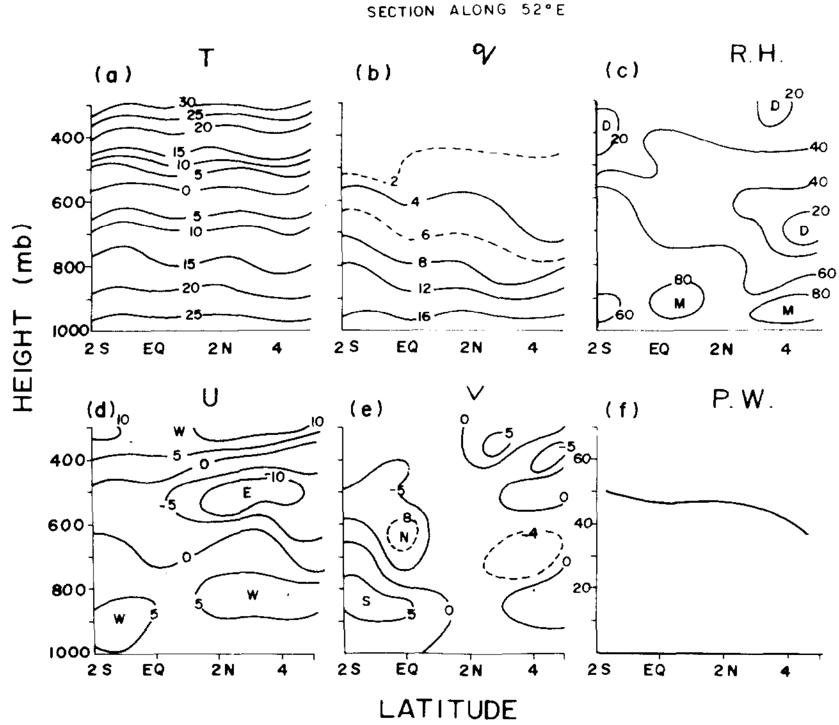

Fig. 3. Same as Figure 2 but along 52° E from 2° S to 4° N.

During this period, the ITCZ in the southern hemisphere was very active between 4° S and 6° S. Under its influence, the westerlies are noticed up to the equator in the lower levels (600–700 mb) with an intensity of 5 m sec^{-1}. Southerlies in the lower levels (800 mb) and northerlies in the middle levels (600 mb) suggest ascending motion near 2° S followed by descending motion near 4° N. The relative humidity field shows clearly the pronounced dryness due to sinking motion around 4° N. Specific humidity and PW also indicate a decreasing trend from 2° S–4° N.

Figure 4 depicts another meridional section along 55° E, from 8° N to the equator. A feeble meridional circulation exists from the midtroposphere ($\simeq$600 mb) to the upper troposphere with rising motion along 4° N supported by higher humidity and PW and sinking motion near the equator. This is clearly seen from the humidity field. The wind field (southerlies in the lower levels and northerlies in the higher ones) also supports the above circulation. The rising air parcel at 4° N probably sinks around 8° N.

From the section along 60° E, between 1° S–16° N (Figure 5), it is seen that the relative humidity is very high (80%) throughout the troposphere around 8° N followed by a dry region in the mid-troposphere around 4° N and 14° N. PW also showed its highest value at 7° N with lower values on both sides. Higher relative humidity along 1° S suggests rising motion due to the ITCZ in the southern

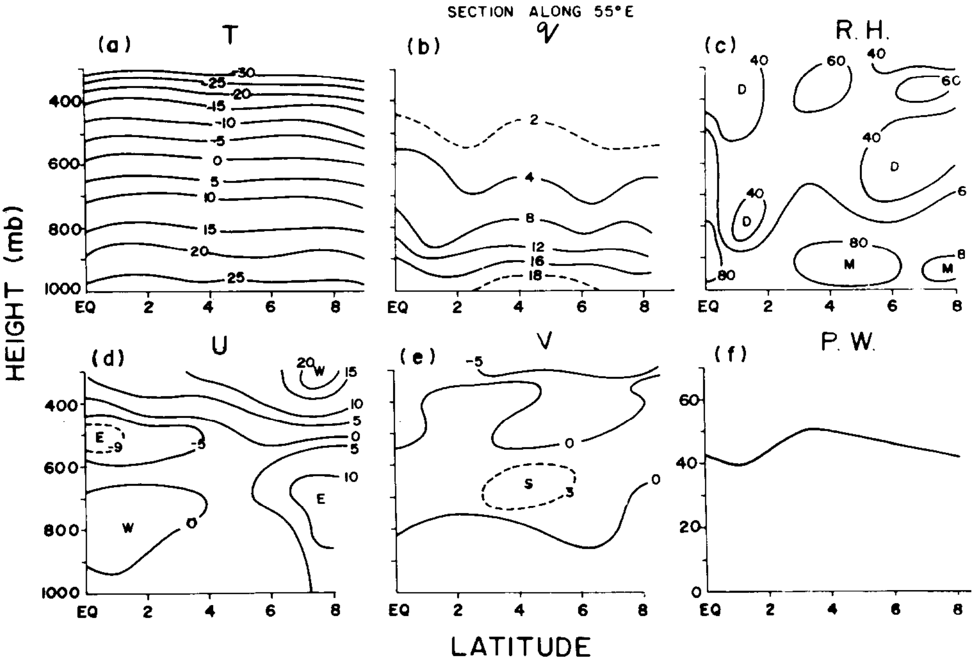

Fig. 4. Same as Figure 3 but along 55° E from equator to 8° N.

hemisphere. A mid-tropospheric warming of 2–3 °C around 4° N strongly supports the idea of sinking motion.

Figure 6 portrays the structure of the troposphere along 65° E from 5° N–13° N. Under the influence of a western disturbance, there are surface westerlies up to 16° N, south of which there are easterlies due to the ITCZ located between 4 to 6° N. It was activated by the eastward-moving trough in the westerlies. There is a decreasing trend in moisture from south to north as expected in the pre-monsoon season in this region.

Figure 7 shows the fields of temperature, humidity and wind along the section 68° E, from the equator to 8° N. A satellite picture indicated highly convective activity and the ITCZ in the northern hemisphere moved to 10° N. An easterly wave near 75° E south of 10° N was noticed. This synoptic situation enhanced convective activity and there was an increase in moisture at all levels. Near the equator, a 2–3 °C rise in temperature and a dry humidity field support the idea of sinking in the upper troposphere. The rising motion along 6° N and sinking motion near the equator (supported by the southerlies in the lower levels and northerlies in the upper levels) indicate a meridional circulation of a reverse Hadley cell.

From the overall results, the mean atmospheric circulation is derived qualitatively and presented in Figure 8. It is seen from this figure that vertical motion dominated between 2° N–5° N with a slight wavy pattern from 50° E to 70° E. A similar feature is also noticed in the southern hemisphere south of 2° S. In the absence of data, these vertical motions could not be verified. However based on

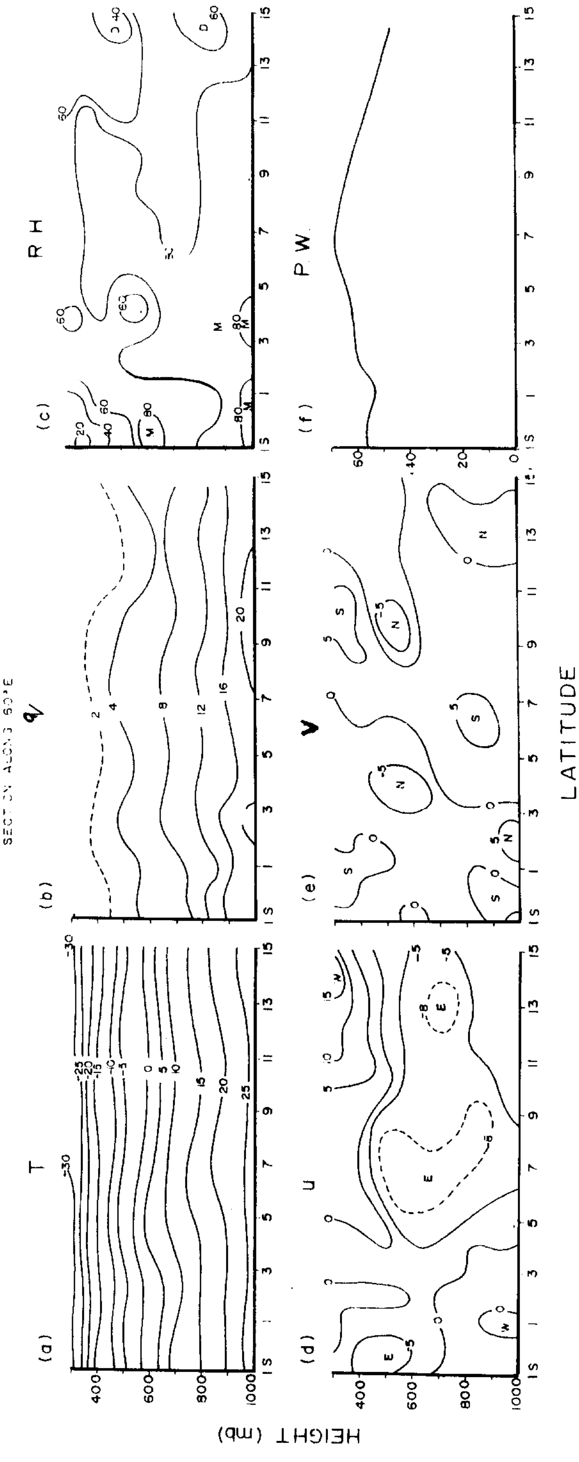

Fig. 5. Same as Figure 4 but along 60° E from 1° S to 15° N.

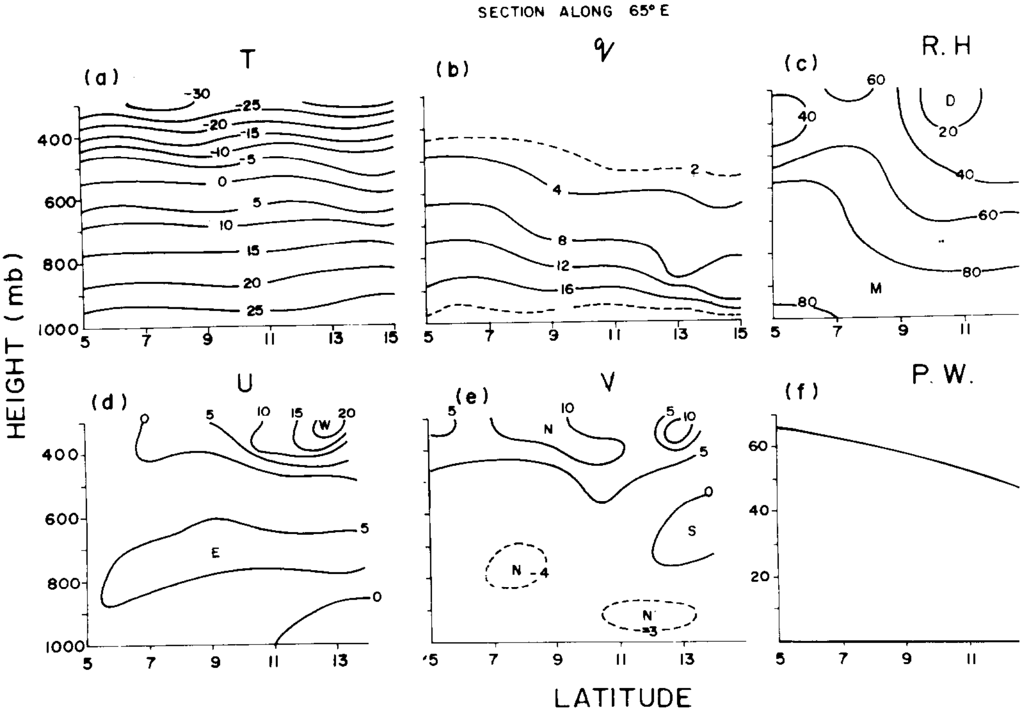

Fig. 6. Same as Figure 5 but along 65° E from 5° N to 15° N.

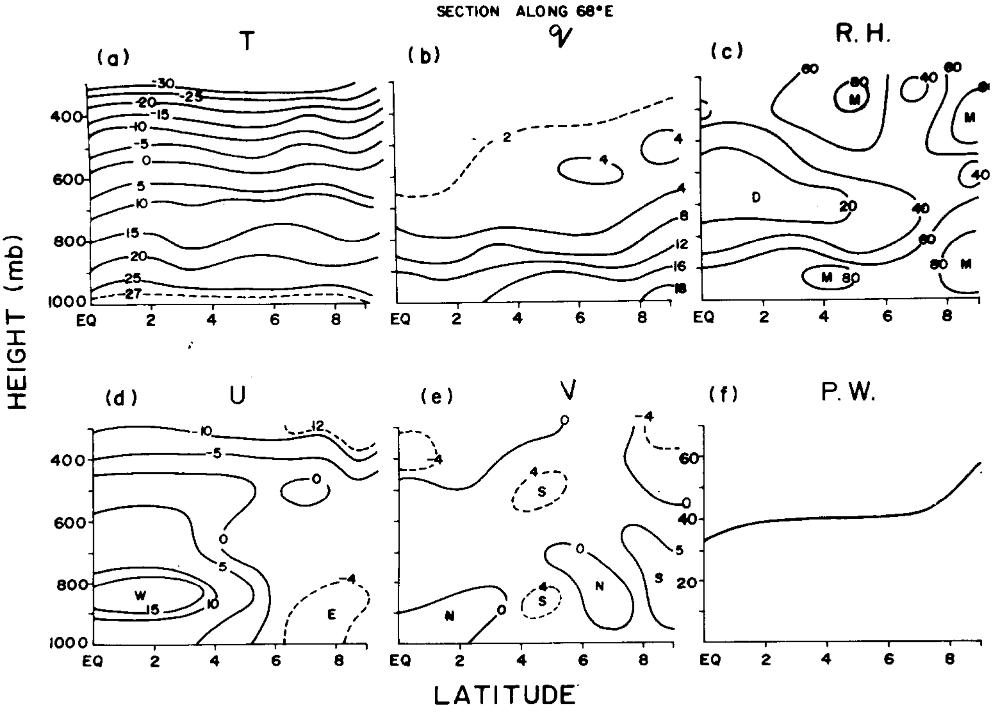

Fig. 7. Same as Figure 6 but along 68° E from equator to 8° N.

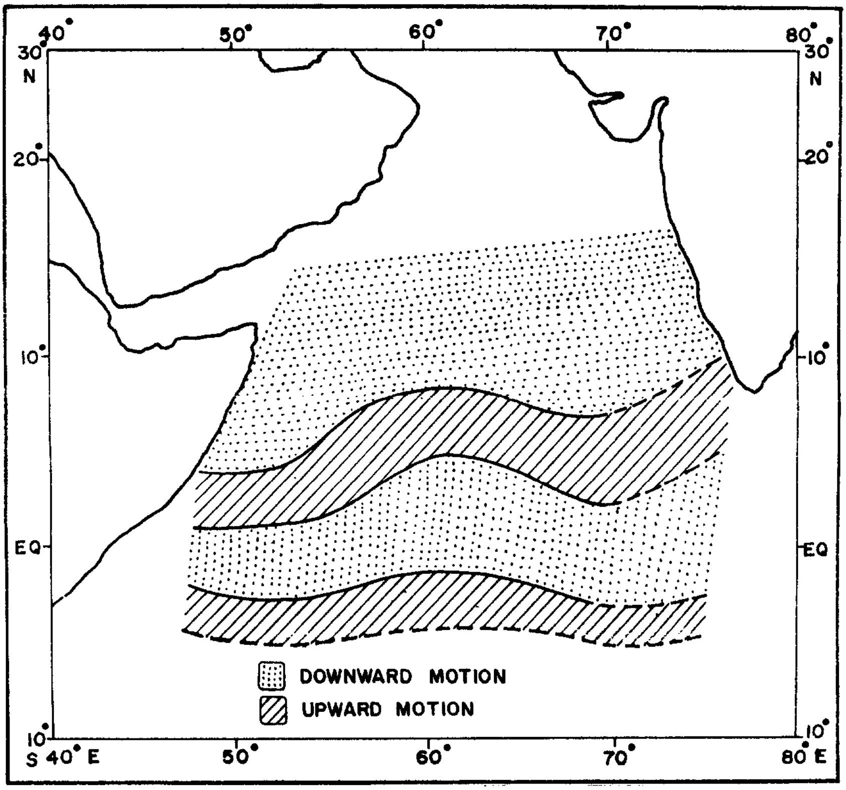

Fig. 8. Mean atmospheric circulation during pre-monsoon period (MONSOON-88 data set). Dotted portion indicates downward motion while hatched area represents upward motion.

the satellite pictures, the southern branch of the ITCZ was observed to be present around 4° S to 6° S on most of the days. So, vertical motion may be expected from 2° N–6° S in the southern hemisphere. Over the equatorial region and the central Arabian Sea, large-scale sinking is noticed. These features agree well with the general expectations and support the presence of an ITCZ in both the northern and southern hemispheres during the pre-monsoon; these features are seen clearly in the satellite cloud pictures received daily on board the ship. It may be mentioned here that the availability of data sets as well as the information from satellites. FAX and synoptic charts of surface pressure distribution greatly assisted in the interpretation of results.

3.3. MOISTURE BUDGET

The evaporation rate (E_2) obtained from the moisture divergence in the box (surface area – 0–4° N; 55–60° E; top level 300 mb) and precipitation measured using a rain gauge is compared with the value (E_1) obtained from the bulk-aerodynamic method. It is seen from Table I that values of E_1 and E_2 are 2.3 and

2.92 mm day^{-1} respectively and C_e estimated from E_2 is about 1.0×10^{-3} for a wind speed of 4 m sec^{-1}. This is slightly lower than the value obtained from the commonly used methods (Kondo, 1975). This is the first attempt to estimate a transfer coefficient for latent heat flux from the moisture budget. Further studies are in progress to validate such transfer coefficients under monsoon conditions.

4. Conclusions

(1) The mean values of R, Q_e and Q_h were 140, 112 and 8 W m^{-2} respectively during the pre-monsoon, 1988 over a small grid in the equatorial region. The higher SST enhanced both the latent and sensible heat fluxes while the higher cloud amount contributed to a decrease in the net radiation (R). Due to these factors, the net heat exchange (R_n) was lowered by 50% when compared with the climatological value of 40 W m^{-2}.

(2) The atmospheric circulation derived from the mean fields of temperature, humidity and wind in the troposphere is as expected.

(3) The value of C_e obtained from the moisture budget was 1.0×10^{-3} - a value slightly lower than the one obtained from the usual methods.

Acknowledgements

The authors are thankful to the Director, NIO for his keen interest and encouragement in the Indo-USSR collaboration programme under which this investigation was carried out. The authors are thankful to Dr Victor Golovastov, Chief of the Expedition and Mr Y. Nelipov, the ship's chief scientist and the USSR experts, especially Dr O. Pyatin for their co-operation and helpful discussions on board "Akademik Korolev". Thanks are also due to Mr Chubukov, Captain of the ship for making their stay pleasant and comfortable. They are also thankful to Dr C. S. Murthy, N.I.O. for his critical comments which improved the original version of the manuscript and to Mr Chitari and Mr Udayakumar for preparing the diagrams.

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