Mausam, (1987), 38, 2, 227-232

551.526.6 : 551.553.21

The heat and moisture budgets of the atmosphere over central equatorial Indian Ocean during summer monsoon

Y. SADHURAM, V. V. GOPALAKRISHNA, V. RAMESH BABU and J. S. SASTRY

National Institute of Oceanography, Dona Paula, Goa

(*Received 26 June 1986*)

सार – ग्रीष्म कालीन मानसून के दिनों (25 से 31 जुलाई 1977) के दौरान चार रूसी जलयानों द्वारा एकत्रित सतही तथा ऊपरी वायु के आंकड़ों का प्रयोग करते हुए हिन्दमहासागर में भूमध्यरेखा (2°उ० से 2° द०, 76° पूर्व से 80° पूर्व) पर वायुमंडल (सतह से 100 मिलीबार तक) की ऊष्मा और आर्द्रता के बजट की जांच पड़ताल की गई है। अध्ययन क्षेत्र में, गुप्त ऊष्मा तथा शुष्क स्थायी ऊर्जा के कुल औसत समय और फलक्स का अपसरण क्रमशः लगभग −0.366 तथा −0.471 × 10¹³ के०/सि० पाया गया है। भंवर राशियों का योगदान सामान्यतः आर्द्रता बजट की अपेक्षा ऊष्मा बजट के लिये अधिक है। प्रेक्षणकाल में विकिरणशील शीतलन तथा वर्षण की औसत दर के बजट अनुमान क्रमशः 0.70° सें तथा 6.7 मि०मी० प्रति दिन पाए गए जो कि जलवायु विज्ञान-संबंधी मूल्यों के सदृश्य हैं।

ABSTRACT. The heat and moisture budgets of the atmosphere (surface to 100 mb) over the central equatorial Indian Ocean (2°N to 2° S; 76°E to 80°E) have been investigated utilising the surface and upper air data collected on board four Russian ships during summer monsoon days (25 to 31 July 1977). The time mean net flux divergences of latent heat and dry static energy are found to be about —0.366 and —0.471 × 10^{13} cal/sec respectively in the study area. Contributions from the eddy terms are in general higher for heat budget than those for moisture budget. The budget estimates of mean rates of radiational cooling and precipitation for the observational period are found to be 0.70°C and 6.7 mm/day respectively which are comparable with the climatological values.

1. Introduction

The moisture budget investigations over the Indian Ocean are important to know the sources and sinks of monsoon energetics. Earlier studies (Pisharoty 1965; Sikka and Mathur 1965; Saha 1970; Saha and Bavadekar 1973; Ghosh *et al.* 1978; Cadet and Reverdin 1981 a & b; Howland and Sikdar 1983) are mainly confined to the Arabian Sea. Similar information has not been documented so far over the central equatorial Indian Ocean where the presence of Southern Hemispheric Equatorial Trough (SHET) affects the Indian monsoon circulation (Washington *et al.* 1978). In this paper, we have presented the heat and moisture budgets of the atmosphere (surface-100 mb) over central equatorial Indian Ocean during monsoon season of 1977.

2. Data

Four Russian research vessels, namely, *Shoklasky* (0°, 76°E), *Okean* (2°N, 78°E), *Shirshov* (0°, 80°E) and *Priboy* (2°S, 78°E) formed a stationary polygon by remaining at their respective positions from 25 to 31 July 1977 as a part of Monsoon-77 programme (Fig. 1) and collected surface and upper air data at *00, 06, 12 and 18 GMT*. The budget parameters have been computed for the region represented by a box (hereafter referred as equatorial box) with its base coinciding with sea surface and its top with 100 mb level. The southern and northern boundary walls of the equatorial box are 2°S and 2°N respectively while its western and eastern boundary walls are 76°E and 80° E respectively.

The computations were carried out on the assumption that the individual ships are at the centre of each boundary wall and each ship's data are representative of the entire wall which is equivalent to a length of 4° latitude (440 km).

2.1. *List of symbols*

Q_e = Latent heat at the sea surface

L_p = Heating due to precipitation

Q_w = Flux of latent heat across a boundary wall

Q_s = Sensible heat at the sea surface

R_a = Radiational cooling in the equatorial box

Q_v = Flux of dry static energy across a boundary wall

l = Lengh of boundary wall

L = Latent heat of evaporation

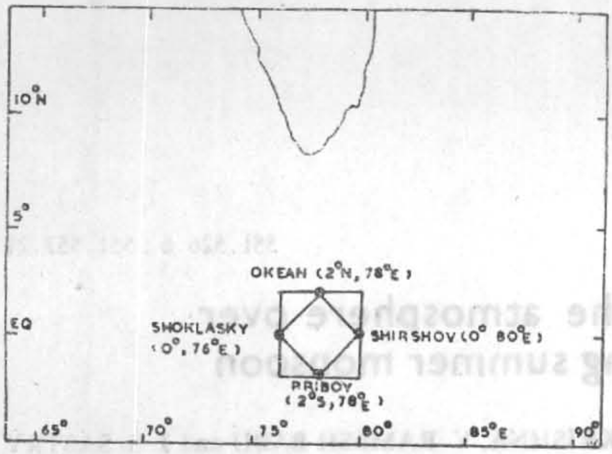

Fig. 1. Location map of the equatorial box (Monsoon-77)

$\overline{V}_n$ = Mean normal velocity component in a layer

$c_p\overline{T}$ = Mean enthalpy in a layer

$\overline{\phi}$ = Mean geopotential in a layer

$\overline{q}$ = Mean specific humidity in a layer

c_p = Specific heat of dry air at constant pressure

p_b, p_t = Pressures at bottom and top of each layer

Q_{wd} = Total net flux divergence of latent heat in the equatorial box

Q_{vd} = Total net flux divergence of dry static energy in the equatorial box

3. Methodology

The following equations are used to evaluate heat and moisture budget parameters :

$$Q_s + L_p + R_a + Q_{vd} = 0 \tag{1}$$

$$Q_e - L_p = Q_{wd} \tag{2}$$

$$Q_{wd} = \overline{Q}_{wd} + Q'_{wd} \tag{3}$$

$$Q_{vd} = \overline{Q}_{vd} + Q'_{vd} \tag{4}$$

Total flux of latent heat across a boundary wall

$$Q_w = \overline{Q}_w + Q_w' = \frac{l}{g}\int_{p_t}^{p_b} \overline{L}_q \cdot \overline{V}_n \cdot dp + \frac{l}{g}\int_{p_t}^{p_b} L_q' \cdot V_n' \cdot dp \tag{5}$$

Total net flux divergence of latent heat in equatorial box,

$$Q_{wd} = Q_{we} - Q_{ww} + Q_{wn} - Q_{ws} \tag{6}$$

where *e, w, n* and *s* in the subscripts refer to individual fluxes across eastern, western, northern and southern boundaries respectively.

Total flux of dry static energy across a boundary wall,

$$Q_v = \overline{Q}_v + Q_v' = \frac{l}{g}\int_{p_t}^{p_b} (c_p\overline{T} + \overline{\phi}) \cdot \overline{V}_n \cdot dp + \frac{l}{g}\int_{p_t}^{p_b} (c_pT' + \phi') \cdot V_n' \cdot dp \tag{7}$$

Total net flux divergence of dry static energy in the equatorial box,

$$Q_{vd} = Q_{ve} - Q_{vw} + Q_{vn} - Q_{vs} \tag{8}$$

where bar and prime indicate time mean and eddy components. The fluxes of latent heat (Q_w) and dry static energy (Q_v) at individual locations are computed by integrating at 50 mb interval from 1000 mb level onwards and in the lowest layer, the actual difference between the surface pressure and 1000 mb is considered. The lateral flux across each boundary is then obtained by multiplying individual station flux with the length of each wall. The values of Q_e and Q_s have been taken from Rao *et al.* (1985), who persented for the same polygon area and period.

4. Results and discussion

The vertical profiles of the time means of temperature ($\overline{T}$), specific humidity ($\overline{q}$), wind components ($\overline{u}$ & $\overline{v}$), mean and eddy terms of latent heat flux ($\overline{Q}_w$, Q'_w) and dry static energy ($\overline{Q}_v$, Q'_v) for each boundary wall are presented in the Figs. 2 to 5 (The mean value for the layer surface-1000 mb is plotted at 1000 mb level).

At eastern boundary wall of the equatorial box, the trends of T and q are quite normal (Fig. 2). The zonal wind component (positive eastward) is stronger than its meridional component (positive northward) throughout the troposphere. This higher zonal component in this region is due to the presence of strong westerly winds which are generally observed between 70 & 80°E during monsoon season (Cadet and Reverdin 1981b). It is interesting to see that both wind components increase with height in the lower layers indicating the steadiness of the wind direction with height. The profiles of Q_w and Q_v are similar to that of u in the lower layers. There is no systematic variation of eddy components which are 2 orders smaller than the mean components in the case of Q_w, and 3 to 4 orders in the case of dry static energy. They seem to be unimportant when compared with the mean values in the layers but their contribution towards total budget is really significant as seen from Tables 1 & 2.

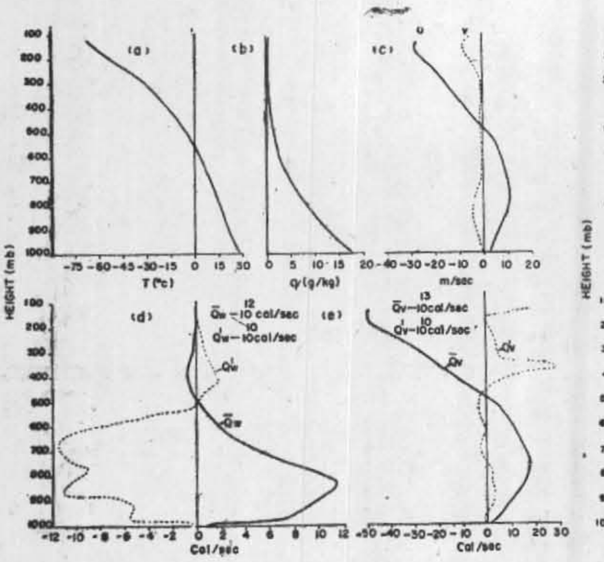

Fig. 2. Mean profiles of temperature ($\overline{T}$), specific humidity ($\bar{q}$), wind components ($\bar{u}$ & $\bar{v}$), lateral flux of latent heat ($\overline{Q}_w$ & Q'_w), and dry static energy ($\overline{Q}_v$ & Q'_v) across eastern boundary wall

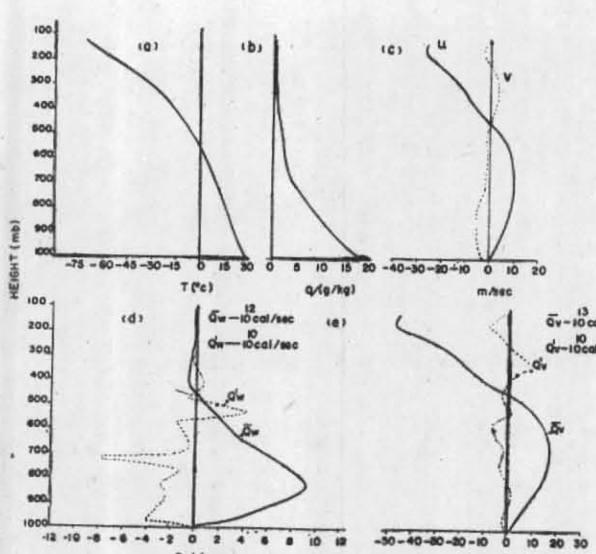

Fig. 3 Same as Fig. 2 but for western boundary wall

TABLE 1

Total flux of latent heat ($\overline{Q}_w$ & Q'_w) across walls and the net flux divergence in the equatorial box (unit : 10^{12} cal/sec)

Layer thickness	Eastern		Western		Northern		Southern		Net flux		Divergence
	$\overline{Q}_w$	Q'_w	$\overline{Q}_w$	Q'_w	$\overline{Q}_w$	Q'_w	$\overline{Q}_w$	Q'_w	$\overline{Q}_{wd}$	Q'_{wd}	Q_{wd}
Surface-700	55.64	−0.53	42.26	−0.22	−42.88	0.008	−27.2	−0.003	−2.30	−0.29	−2.59
700-400	7.69	−0.26	12.88	0.009	−0.13	0.06	−4.02	−0.083	−1.30	−0.12	−1.42
400-100	−1.70	0.03	−1.47	0.001	0.34	0.003	−0.16	−0.044	0.27	0.08	0.35
Total	61.63	−0.76	53.67	−0.21	−42.67	0.071	−31.38	−0.13	−3.33	−0.33	−3.66

TABLE 2

Same as Table 1 but for dry static energy; unit : 10^{13} cal/sec

Layer thickness	Eastern		Western		Northern		Southern		Net flux		Divergence
	$\overline{Q}_v$	Q'_v	$\overline{Q}_v$	Q'_v	$\overline{Q}_v$	Q'_v	$\overline{Q}_v$	Q'_v	$\overline{Q}_{vd}$	Q'_{vd}	Q_{vd}
Surface-700	76.0	0.005	61.0	−0.0095	−50.4	0.0024	−36.4	0.0009	1.0	0.016	1.016
700-400	28.5	−0.0055	55.0	−0.02	−0.5	0.0054	−20.2	0.0019	−6.8	0.018	−6.782
400-100	−211.5	0.067	−189.7	−0.0017	−1.0	0.0085	−28.0	−0.017	5.2	0.095	5.295
Total	−107.0	0.066	−73.7	−0.031	−51.9	0.0163	−84.6	−0.014	−0.6	0.129	−0.471

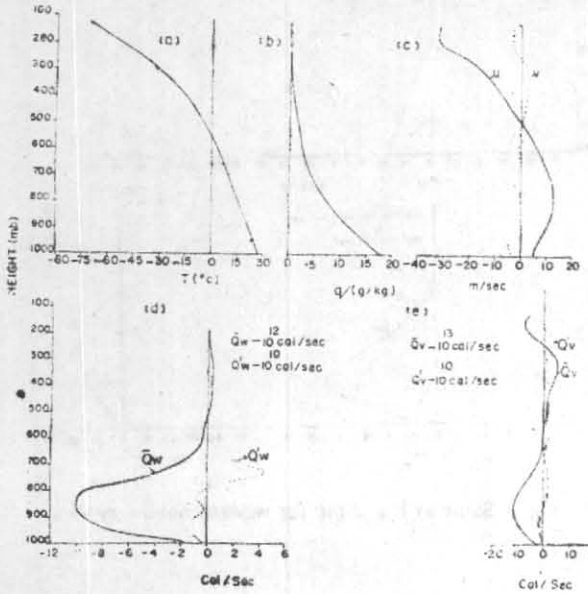

Fig. 4. Same as Fig. 2 but for northern boundary wall

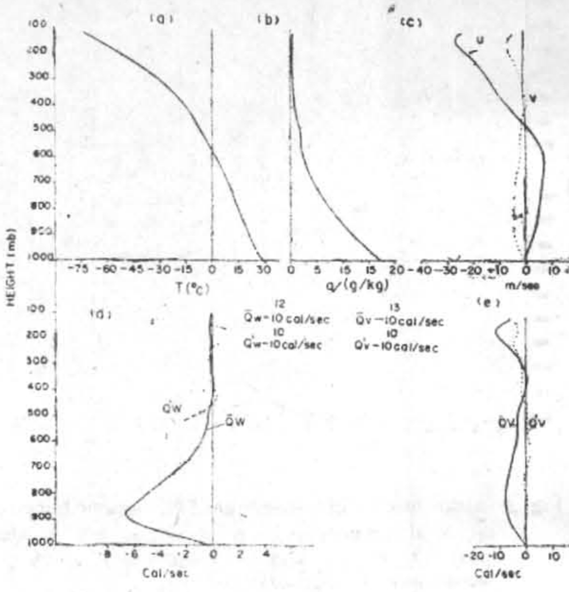

Fig. 5. Same as Fig. 2 but for southern boundary wall

Fig. 3 presents the vertical profiles of the budget parameters at western boundary wall. Here both the wind components are found to be weaker than those observed at the eastern boundary. This results in the weaker fluxes observed in both mean and eddy terms.

From the trends at northern boundary (Fig. 4), it can be said that T and q profiles are more or less similar to those observed at other boundaries but the zonal wind component is stronger throughout the troposphere. At this boundary, the signs of the eddy terms are coinciding with the mean components especially in the lower layer (1000-800 mb) whereas an opposite trend is seen at eastern and western boundary walls.

At the southern boundary wall (Fig. 5) the components of wind are found to be least. The westerlies extend to higher levels and northerlies are seen through most of the troposphere. The eddy terms are comparable with those observed at northern boundary.

In general, there is not much spatial variability in the vertical profiles of T and q. So, the deviations in the observed fluxes at the different boundaries are mainly due to the spatial variability of the normal velocity components. The mean and eddy fluxes of Q_w for the three different layers — surface to 700; 700 to 400 and 400 to 100 mb across each wall along with the net total flux divergence value Q_{wd} (negative inward; positive outward) are shown in the Table 1. The mean and eddy components are found to be maximum at the eastern wall and minimum at the southern wall in the lowest layer (surface-700 mb). This is mainly due to broad scale mean northwesterly flow dominated in the equatorial box. In general the mean fluxes decrease with height at all boundaries except at the northern boundary where minimum values are encountered in the middle layer on account of very weak winds. There is no systematic trend in eddy terms but it is seen that they are relatively higher at eastern and western boundary walls. A net flux convergence in the lower layers and divergence in the top layer are observed. The total integrated net flux divergence of mean and eddy terms of latent heat are found to be -3.33 and -0.33×10^{12} cal/sec respectively. This indicates that there is net convergence of latent heat flux in the equatorial box during the study period with 10% contribution from the eddy terms.

The mean and eddy fluxes of dry static energy in different layers across each wall and the net flux divergence are presented in the Table 2. The maximum flux is observed in the top layer at the eastern wall whereas the minimum is found in the middle layer at northern wall. The eddy components are positive and increasing with height. It is interesting to note that the divergence in the top and bottom layers is almost compensated by the convergence in the middle layer. The net flux divergence of mean and eddy components are -0.6 and 0.129×10^{13} cal/sec respectively. At individual boundary walls one could see that eddy terms are negligible compared with the mean components as they are 3 to 4 orders smaller than the mean terms. But if we look at the contributions of mean and eddy terms to the total flux divergence in the central equatorial box, the eddy terms are found to be significant. It is seen that contribution from the eddy terms is

TABLE 3

Mean fluxe s in the eqatorial box

(unit : 10^{13} cal/sec)

Parameter	Mean value
Q_e	0.509
Q_s	0.034
Q_{wd}	−0.366
Q_{vd}	−0.471
L_p	0.875
R_a	−0.438

found to be greater in heat budget than in moisture budget. This is due to relatively steady nature of fluxes of the latent heat while the sensible heat fluxes are highly fluctuating on account of variation both in temperature and geopotential height fields. It is further expected that the eddy terms would show much stronger variability on diurnal and day-to-day time scales as a result of change in the convective activity of the region.

The total integrated net flux divergences of latent heat and dry static energy (Q_{wd} & Q_{vd}) areal integrated fluxes of Q_e and Q_s and the residual terms, L_p and R_a, in the equatorial box are shown in the Table 3. A net convergence of Q_{wd} and Q_{vd} is observed and the orders of the terms are equal. Radiational cooling (R_a) is compensated by the precipitation heating and convergence of dry static energy. From the residual terms of L_p and R_a the mean rates of precipitation and cooling in the equatorial box are found to be 6.7 mm/day and 0.7° C/day which are comparable with the climatological values of 5 mm and 1.0°C/day reported for this region (Elliot and Reed 1984; Dopplick 1972). In order to validate the precipitation estimate obtained by the budget method we have also compared with the actual rainfall observed at a nearby island station, *i.e.*, at Gan Island (00°42'S, 73°E) since rainfall observations on board ships are not available. The observed rainfall rate is 10.6 mm/day which is about 1.5 times higher than the budget estimate. The difference between these two rainfall rates is normally expected in view of spatial variability in the tropical rainfall patterns.

5. Conclusions

(*i*) The differences in the lateral fluxes at the individual boundary walls of the polygon area are mainly attributed to the spatial variability of winds.

(*ii*) The mean values of Q_{wd} and Q_{vd} are found to be −0.366 and -0.471×10^{13} cal/sec respectively. It is found that the eddy terms also play a significant role especially in the heat budget affecting the dynamics of the equatorial flow.

(*iii*) From the residual terms of L_p and R_a the mean rates of precipitation and radiational cooling over the study area are found to be 6.7 mm/day and 0.7°C/day respectively which are comparable with the climatological values.

Acknowledgements

The authors are extremely thankful to Mr. M. V. Rao, P.O.D. for developing the computer programmes for this study. The authors also wish to express their thanks to Dr. H. N. Siddiquie, Director, N. I. O. for his keen interest and encouragement in this study. Thanks are also due to Ms. Sheila Vaz for typing the manuscript.

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