Energy transfer from the Arabian Sea, the Bay of Bengal and the north Indian Ocean

T. K. RAY
Meteorological Office, New Delhi
(Received 17 January 1983)

1. Introduction

In the past, sufficient work has been done on estimating the thermodynamic variables like evaporation, sensible and latent heat transfer, Bowen ratio and the total energy transfer to atmosphere. Previous workers Venkateswaran (1956) and Privett (1959) used climatological data. Pisharoty (1965) while examining the water vapour flux across the boundaries of the Arabian Sea during southwest monsoon, concluded that a large amount of water vapour carried over by the monsoon current is due to evaporation over the Arabian Sea. Garstang (1967) studied various thermodynamic parameters over the western Atlantic based on the data collected during a forty-six-day cruise of an oceanographic research vessel. The present study is to find a distant correlation, if any, among various parameters during pre-monsoon season and the subsequent behaviour of monsoon that follows.

2. Data

The data used for the present study consist of ships data during the period 1961 through 1966. The author proposes to present detailed study based on data for last two decades in near future. The main parameters used for the study are sea surface temperature, air temperature, dew point temperature, atmospheric pressure and wind speed. Monthly means for all these parameters have been used for every 5-degree latitude/longitude square covering an area extending from 15 deg. S to 25 deg. N latitude and 40 deg. E to 105 deg. E longitude. This data has undergone extensive zonal, horizontal and climatological quality control checks.

3. Formula used for computations

The following form of equation as suggested by Jacob (1951) and Sverdrup (1951) has been used for evaporation:

\[ E = K(e_e - e_a) V \]  

where  

\[ K = \rho_m \, C_D \]

and \( e_e \) and \( e_a \) are the vapour pressures at the sea surface and in air (6 metres above sea surface) respectively. \( V \) is wind speed and \( K \) is the evaporation coefficient. \( K \) being a highly variable quantity depending on the height (6 metres in this case) wind speed and roughness of the sea. \( \rho_m \) is density of moist air \((1.2 \times 10^{-4})\) and \( C_D \) is a constant similar to drag coefficient. The value of \( K \) puts a serious limitation on the use of Eqn. (1) which is why the results obtained by different workers may vary.

For south Indian Ocean Venkateswaran (1956) and Privett (1959) used \( 2.0 \times 10^{-4} \) and \( 1.4 \times 10^{-4} \) respectively as values of \( K \). Privett (1959) used the above average value of \( K \) for his work even though he evaluated values of \( K \) for different ocean areas. Suryanarayana and Sikka (1973) used \( 1.62 \times 10^{-4} \) as the value of \( K \). This value is almost the mean of those used by Venkateswaran and Privett. Garstang (1967) calculated values of \( C_D \) for different wind regimes for tropical western Atlantic. Pisharoty (1965) used \( 2.0 \times 10^{-4} \) as the value of \( K \) for the formulation:

\[ E = K (q_s - q_a) V \]  

where \( q_s \) and \( q_a \) are specific humidities over water surface and in air respectively. Other variables are
Fig. 1. Mean latent heat ($Q_v$) flux during February (cal/cm²/day)

Fig. 2. Meridional distribution of $E$ values (cal/cm²/day) along 65°-75° E during the year (mean value for 1961-66)

Fig. 3. Evaporation (cal/cm²/day) in May 1961

Fig. 4. Evaporation (cal/cm²/day) in May 1966

Fig. 5. Latent heat transport in February 1961

Fig. 6. Latent heat transport in April 1966
### TABLE 1
Energy transport under varying wind condition

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>4.5</td>
<td>7.5</td>
<td>10.805</td>
<td>0.6580</td>
<td>724.98</td>
<td>0.019</td>
<td>0.002</td>
<td>735.80</td>
<td>0.353.99</td>
</tr>
<tr>
<td>Feb</td>
<td>4.0</td>
<td>8.8</td>
<td>7.0602</td>
<td>0.6270</td>
<td>643.69</td>
<td>0.014</td>
<td>0.002</td>
<td>650.69</td>
<td>0.326.79</td>
</tr>
<tr>
<td>Mar</td>
<td>4.0</td>
<td>7.5</td>
<td>6.8886</td>
<td>0.18.4475</td>
<td>619.39</td>
<td>0.013</td>
<td>0.006</td>
<td>625.01</td>
<td>0.224.49</td>
</tr>
<tr>
<td>Apr</td>
<td>4.0</td>
<td>7.8</td>
<td>8.3991</td>
<td>0.14.195</td>
<td>680.14</td>
<td>0.014</td>
<td>0.004</td>
<td>688.54</td>
<td>0.340.67</td>
</tr>
<tr>
<td>May</td>
<td>6.0</td>
<td>12.0</td>
<td>6.4391</td>
<td>0.6.907</td>
<td>823.36</td>
<td>0.010</td>
<td>0.015</td>
<td>827.68</td>
<td>0.361.83</td>
</tr>
<tr>
<td>Jun</td>
<td>7.0</td>
<td>12.8</td>
<td>6.8587</td>
<td>0.16.2862</td>
<td>750.71</td>
<td>0.012</td>
<td>0.008</td>
<td>749.77</td>
<td>0.190.55</td>
</tr>
<tr>
<td>Jul</td>
<td>7.0</td>
<td>14.0</td>
<td>9.3017</td>
<td>0.16.2142</td>
<td>786.61</td>
<td>0.014</td>
<td>0.018</td>
<td>787.52</td>
<td>0.59.71</td>
</tr>
<tr>
<td>Aug</td>
<td>7.0</td>
<td>13.8</td>
<td>5.7380</td>
<td>0.16.8800</td>
<td>792.87</td>
<td>0.011</td>
<td>0.019</td>
<td>787.79</td>
<td>0.63.49</td>
</tr>
<tr>
<td>Sep</td>
<td>4.0</td>
<td>11.5</td>
<td>5.5205</td>
<td>0.13.5005</td>
<td>748.09</td>
<td>0.011</td>
<td>0.008</td>
<td>751.08</td>
<td>0.218.86</td>
</tr>
<tr>
<td>Oct</td>
<td>4.0</td>
<td>9.0</td>
<td>24.1889</td>
<td>0.14.1161</td>
<td>783.88</td>
<td>0.005</td>
<td>0.004</td>
<td>785.21</td>
<td>0.358.36</td>
</tr>
<tr>
<td>Nov</td>
<td>5.3</td>
<td>7.8</td>
<td>10.7901</td>
<td>1.2499</td>
<td>731.38</td>
<td>0.017</td>
<td>0.003</td>
<td>742.17</td>
<td>0.406.45</td>
</tr>
<tr>
<td>Dec</td>
<td>4.8</td>
<td>8.8</td>
<td>12.5076</td>
<td>0.9208</td>
<td>805.52</td>
<td>0.026</td>
<td>0.002</td>
<td>810.95</td>
<td>0.404.79</td>
</tr>
<tr>
<td>Annual</td>
<td>5.1</td>
<td>10.1</td>
<td>9.5414</td>
<td>0.7.5385</td>
<td>740.88</td>
<td>0.019</td>
<td>0.042</td>
<td>744.77</td>
<td>0.275.83</td>
</tr>
<tr>
<td>Annual mean</td>
<td>7.62</td>
<td>1.0</td>
<td>510.85</td>
<td>-0.012</td>
<td>510.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Units: $W$ = metre sec$^{-1}$, $Q_a$ = cal cm$^{-2}$ day$^{-1}$, $Q_c$ = cal cm$^{-2}$ day$^{-1}$

### TABLE 2
Values of sensible heat ($Q_h$), latent heat ($Q_c$) fluxes, Bowen’s ratio and total energy transport ($Q_t$)

(a) Good Monsoon years

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
<th>Mean</th>
</tr>
</thead>
</table>

(b) Bad Monsoon years

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
<th>Mean</th>
</tr>
</thead>
</table>

Units of $Q_h$, $Q_c$ and $Q_t$: cal cm$^{-2}$ day$^{-1}$

As in (1) above. In this study a value of $1.64 \times 10^{-4}$ has been used throughout for $K$.

For the computation of sensible heat flux ($q_h$) from sea to atmosphere the following formulation have been used:

$$ Q_h = \frac{4.15 \left( T_H - T_a \right) V_n}{5.742 \left[ \ln \left( \frac{a + z_0}{z_0} \right) \right]^2 + 0.16 V_n} $$

$$ Q_c = \frac{9.5 \left( T_c - T_a \right) V_n}{5.742 \left[ \ln \left( \frac{a + z_0}{z_0} \right) \right]^2 + 0.16 V_n} $$

Where $T_H$ and $T_a$ are temperatures of water surface and that of air respectively, $V_n$ is the wind speed (in cm/sec) at the height of observation and $z_0$ is the roughness parameter. The thickness of the laminar boundary layer is assumed constant at 0.16 cm and corresponding to this the value of $z_0$ is taken as 14. The latent heat flux due to evaporation ($Q_c$) has been calculated using the formula:

$$ Q_c = 0.585 E $$
where $E$ is the evaporation in cal cm$^{-2}$ day$^{-1}$.
Bowen ratios have been evaluated by two formulae:

$$B_R = \frac{Q_h}{Q_e}$$  \hspace{1cm} (5)

and

$$B_{OWRA} = 0.64 \frac{P}{1000} \frac{(T_w - T_a)}{e_w - e_a}$$  \hspace{1cm} (6)

$P$, being atmospheric pressure.

Total heat fluxes ($Q_i$) has been calculated by the formula:

$$Q_i = Q_h + Q_e$$  \hspace{1cm} (7)

4. Analysis and computation

Thermodynamic parameters like evaporation (using vapour pressures both in mb and inches of mercury) sensible and latent heat fluxes, Bowen ratio values (using both Eqns. 5 and 6 above) and total energy exchange have been calculated for every month at every 5-degree square block for the area under discussion. Computations have also been done jointly for all the years together to obtain a composite mean picture. To visualize the difference between Good monsoon and Bad monsoon years and Early onset and Late onset years data have been composited separately and all the computations repeated. Maps for all these computed values have not been presented here for obvious reasons of space. Only those maps that have significant features have been presented.

5. Discussion

Evaporation as computed generally agrees with the studies of earlier workers like Venkateswaran (1956), Privett (1959) and Suryanarayana and Sikka (1973). Similarly mean values of latent heat transport for the month of February (Fig. 1) broadly agrees with those presented by Gartslang (1967) for western Atlantic. Bowen ratio values though calculated separately by Eqns. (5) and (6) generally agree with each other. The maximum and minimum values of Bowen ratio varied from +0.019 to -0.042. Mean energy transport in the form of sensible and latent heats and Bowen ratio values under varying wind conditions during the year for the six years composite have been presented in Table 1. All the parameters calculated for Good monsoon (1961 to 1964) and Bad monsoon (1965 to 1966) years as well as for Early onset (18 May 1961) and Late onset (8 June 1966) years. Table 2 shows maximum/minimum of the parameters for the whole area under study. Early onset year evaporation chart shows high E values dominated a major portion of south Arabian Sea and Indian Ocean region right from 40 deg. E to 90 deg. E. Even in the month of February high evaporation values dominated Arabian Sea between 5 deg. and 15 deg. N. On the other hand in the late onset year high E values were restricted mainly to the eastern side (Bay of Bengal) and Arabian Sea was dominated by low to moderate values of evaporation. Meridional distribution of E values along 65 deg.-75 deg. E blocks during the year (Fig. 2) show somewhat higher values compared to those obtained by earlier workers even though broad pattern remains same. Jagannathan and Ramasastri (1964) have also got somewhat higher values. This may be due to different period of averaging and to somewhat higher values of wind speed in the present study. This meridional distribution pattern changes very interestingly from year to year. Due to lack of adequate data coverage meridional distribution for other blocks could not be studied with authenticity.

Evaporation calculated by converting vapour pressure into inches of mercury and wind speed in knots show somewhat interesting patterns for early onset year (1961) and late onset year (1966). In Fig. 3 high values of E dominated the vital area of Arabian Sea (10 deg.-15 deg. N and 60 deg.-70 deg. E longitude) and Bay of Bengal (5 deg. -10 deg. N and 85 deg.-90 deg. E longitude). In contrast, same chart for May 1966 shows (Fig. 4) comparatively lesser high values dominate more southern latitudes and more eastern longitudes. Similar striking contrast can be noticed between Fig. 5 and Fig. 6 which is the distribution of latent heat fluxes in early and late onset years.

6. Conclusion

One of the objectives of the present study is to find a distant correlation between distribution of various thermodynamic parameters and the behaviour of the monsoon that follows. The study of the charts bring out the following salient features:

1. During years of good monsoon values of thermodynamic variables are considerably higher than those for bad monsoon.
2. Total energy exchange from sea to atmosphere shows upwards trend right from the month of March-April in good monsoon years whereas these values start picking up only in June-July in the case of bad monsoon years.
3. Annual mean values of the variables remain more or less constant, only the pattern of their rate of change varies from year to year.
4. Areas of prominent high values of evaporation occupy areas bound by latitudes 7.5 deg. N right in the month of May for years of early onset whereas in case of years of late onset high evaporation areas are not so prominent and they occupy much southern latitudes in corresponding months.

Acknowledgement

The author wishes to acknowledge his indebtedness to Dr. H. S. Bedi, India Meteorological Department and Shri D. R. Sikka, Asstt. Director, Indian Institute of Tropical Meteorology, Pune for their useful suggestions during preparation of this study.

References


Jacobs, W.C., 1951, Large scale aspects of the energy transformation over the oceans, Compendium of Meteorology, pp. 1052-49.


