Abstract: Satellite data are used to estimate the net surface heat flux ($Q$) over the Indian Ocean during June 1979. Ten-day and monthly average fields of $Q$ and its components are produced and analyzed in relation to monsoon dynamics. When compared to ship-based estimates, the satellite-derived fluxes exhibit correct orders of magnitude and their temporal evolution is consistent with our monsoon knowledge. This study, which represents a first attempt to remotely sense from space the earth surface net heat flux, demonstrates that current satellite sensor data can be combined to accurately describe net heat flux changes in areas such as the Arabian Sea, where they are large, rapid, and spatially extended, and therefore not fully observed by ships.

Net Shortwave Irradiance

Daily net shortwave irradiance ($I_s$) over the Indian Ocean during the 1979 monsoon has been computed by Gautier (1986) from hourly GOES Visible Infrared Spin Scan Radiometer radiation observations in the visible. The computations rely on the relationship between a column's total cloud liquid water content to both cloud reflectance (satellite measured) and $C_l$, the estimated parameter instead of $N$. The parameter $C_l$ is closely related, since $C_l$ characterizes the fraction of clear sky shortwave irradiance removed by clouds. From radiative transfer calculations, we find $cN = (69 \pm 28)C_l$ (4), where the figures in parentheses are expressed in Wm$^{-2}$. The 28 Wm$^{-2}$ uncertainty in (4) reflects differences in optical properties of the various tropical cloud models used in the calculations. In (2), $I_{sd}(clear)$ is computed from twice-daily NOAA Tiros Operational Vertical Sounder (TOVS) retrievals of air temperature and water vapor mixing-ratio. The SST is also retrieved from TOVS data, but only infrared data.

Figure 1b shows the obtained 10-day average $I_s$ fields and the monthly average field. During the first period (1–10 June), the field's structure is roughly zonal, with a $J_l$ minimum (10–20 Wm$^{-2}$) along 5°N between 50°E and 90°E. Maximum values of 80–90 Wm$^{-2}$ are encountered in the northwest Arabian Sea (coastal regions) where the atmosphere is clear and dry and the surface water warm. The $J_l$ increase south of 5°N, with values reaching 60 to 80 Wm$^{-2}$ between 15°S and 20°S, is attributed to a drier and colder troposphere that reduces $I_{sd}$. During monsoon onset (11–20 June), the gradient of $I_l$ south of the equator is no longer meridional, but oriented southwest-
northeast. Smaller values (by 20–30 Wm\(^{-2}\)) are now observed south of the equator east of 50\(^{\circ}\)E. The previous period's equatorial minimum has moved north and deepened, due mainly to increased cloudiness. Along the coasts of Somalia and Saudi Arabia, \(I_1\) has decreased by 10 to 50 Wm\(^{-2}\). In the Gulf of Bengal, \(I_1\) also exhibits smaller values (by 20 to 30 Wm\(^{-2}\)), a consequence of increased atmospheric moisture and convective activity when the monsoon develops. During the last period (21–30 June), owing to augmented northeast transport of moisture and cloud displacement, the gradient of \(I_1\) is almost zonal in the Arabian Sea. The monthly average \(I_1\) field (Fig. 1b) is strongly correlated to the corresponding \(I_1\) field (Fig. 1a), except south of the equator and west of 70\(^{\circ}\)E. When compared to Molinari et al.'s (1986) results (Fig. 2b), the satellite-derived field exhibits much more spatial structure. The position of the 60 Wm\(^{-2}\) isolines nearly correspond; but southwest of India, we find

\[
I = \rho L C_i (q_s - q_a) U_a
\]  

where \(\rho\) is air density, \(L\) is latent heat of evaporation, \(q_s\) is saturation water vapor mixing-ratio at \(T_s\), \(q_a\) is near-surface water vapor mixing-ratio, and \(U_a\) is near-surface wind speed. In (5), \(C_i\) is a dimensionless coefficient that depends on wind speed and air stability. Following Liu (1986), \(U_a\), \(q_s\), and \(q_a\) are obtained from

Fig. 1. Satellite-derived 10-day and monthly average fields of net surface heat flux and its components over the Indian Ocean during June 1979.
The sensible heat flux is computed as:

\[ H_s = \rho C_p (T_e - T_a) U_a \]  

where \( C_p \) is specific heat capacity of air and \( T_a \) is air temperature near the surface. In (6), \( C_s \) is a dimensionless exchange coefficient which, like \( C_t \), depends on wind speed and air stability.

Using (6) to estimate \( H_s \) from space has not been attempted, essentially because satellite profiles have poor vertical resolution. We applied (6), however, with SMMR winds, TOVS SST's, near-surface air temperatures deduced from TOVS profiles by exponential extrapolation with pressure, and taking \( C_s = 1.3 \times 10^{-3} \).

During the three 10-day periods, the sensible heat flux \( (H_s) \) exhibits values ranging from -20 to 40 Wm\(^{-2}\) (Fig. 1d), which represent correct orders of magnitude. Large areas, however, are characterized by unrealistic negative values of about -10 Wm\(^{-2}\); but such values are within the method's accuracy. The monthly average field is dominated by the 11-20 June field, though the gradients are generally smoother. The spatial patterns, however, do not correspond to those obtained by Molinari et al. (1986) (Fig. 2d), suggesting that our method to compute \( H_s \) is not sufficiently accurate. This term, fortunately, is small.
and thus could possibly be neglected when computing $Q$.

### Net Heat Flux

The net heat flux is deduced from its components as:

$$Q = I_r - I_l - H_l - H_s$$  

(7)

Positive $Q$ values represent a heat gain for the ocean.

Figure 1e shows the $Q$ distribution during the three 10-day periods of June 1979. The $Q$ values range from $-180 \text{ Wm}^{-2}$ to $80 \text{ Wm}^{-2}$. Before the monsoon onset (first period), most of the Indian Ocean is heated by 60 to 150 Wm$^{-2}$. Two regions of maximum (about 150 Wm$^{-2}$) are noticeable along the equator, one located at 60$^\circ$E and the other at 85$^\circ$E. Negative values are observed south of the monsoon onset (second period), intense cooling characterizes the western and central Arabian Sea ($-180 \text{ Wm}^{-2}$), while heating has increased in the central part of the Indian Ocean. After the monsoon onset (last period), cooling patterns appear in the western Gulf of Bengal. Heating now extends to all the southern latitudes, and also occurs in the northern Arabian Sea (about 30 Wm$^{-2}$). The resulting monthly average field presents most of the features characterizing the monsoon onset and post-onset periods. The ocean gains heat almost everywhere, except in the northwest part of the Arabian Sea and northwest of Madagascar. Negative values would remain higher by about 100 Wm$^{-2}$, which is explained by our higher $H_l$ estimates.

### Discussion and Conclusions

Dramatic surface heat flux changes in the Arabian Sea accompany the onset of the summer monsoon. Our estimates are higher by 100 Wm$^{-2}$. The large-scale patterns roughly correspond, but both fields' values disagree with those of Hastenrath and Lamb (1979) (Fig. 2f). Adding 50 to 90 Wm$^{-2}$ to Molinari et al.'s (1986) values (see "Net Shortwave Irradiance") would give a reasonable agreement with our values in the Arabian Sea and south of the Arabian Sea west of 55$^\circ$E. South of India, the values would remain higher by about 100 Wm$^{-2}$, which is explained by our higher $H_l$ estimates.

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References


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