

LATITUDINAL VARIATION OF AIR SEA FLUXES IN THE WESTERN INDIAN OCEAN DURING AUSTRAL SUMMER AND FALL

(Research Note)

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Abstract. Daily and zonal (latitudinal belt) averages of heat and momentum fluxes were computed using bulk aerodynamic formulae, from the meteorological parameters measured onboard 'M. S. Thuleland' during the sixth Indian scientific expedition to Antarctica (26th November, 1986 to 22nd March, 1987). Both estimates showed significant variations, the momentum flux showing the largest variation. The maximum values of sensible and latent heat fluxes were observed over the 30°–40° S and 10°–20° S zones during the southern summer and fall respectively while the minimum values of latent heat flux were observed in the 60°–70° S zone for both seasons. The sensible heat flux minimum was observed in the 50°–60° S and 60°–70° S zones for summer and fall, respectively. Higher momentum flux values over the 40°–50° S zone in summer shifted to the 50°–60° S zone during fall.

1. Introduction

Knowledge of heat (latent and sensible) losses from the ocean to the atmosphere is of particular importance for studies on heat balance as well as moisture and energy budgets of the atmosphere. A detailed study of heat exchange between the ocean and the overlying atmosphere may explain in detail the mechanism which affects the atmospheric motion and may help improve long-range weather forecasts. Studies on air-sea fluxes on a seasonal scale over the southern and southwest Indian Ocean can shed light on the atmospheric circulation over this region. Such air-sea interaction studies (Kangos, 1960; Albrecht, 1961; Zillman, 1972; Ramage, 1984; Taljaard and Van Loon, 1984) are few, mainly due to the relative paucity of data over these regions. In this paper, we present the daily and zonal (latitudinal) averages of heat and momentum fluxes computed for two seasons, viz., austral summer and fall. The cruise track along which the various surface meteorological parameters have been collected and the ship's mid-day (1200 GMT) positions during the onward and return journey are shown in Figure 1.

2. Equipment

The meteorological equipment used in the present study were mainly provided by the India Meteorological Department and included the following:

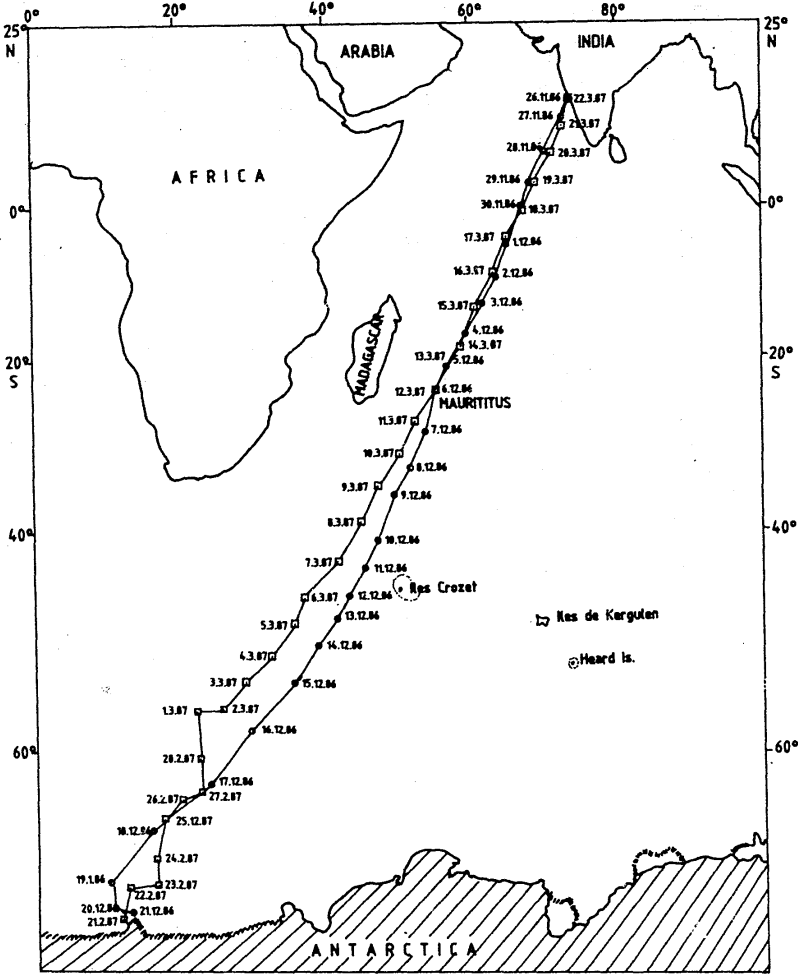


Fig. 1. Cruise track of 'M. S. Thuleland' with ship's mid-day (1200 GMT) positions during onward and return journey.

- (a) Assmann psychrometer and whirling psychrometer for dry- and wet-bulb temperatures.
- (b) Conventional sea-water-bucket and mercury-in-glass thermometer for sea surface temperature.
- (c) DR wind vane and anemometer with indicator panel for wind direction and speed.
- (d) Conventional mercury barometer, barograph and aneroid barograph for atmospheric pressure.

Cloudiness and cloud type were measured by visual observations.

In addition to this, the meteorological instruments fitted onboard 'M. S. Thuleland' for recording surface weather observations were used.

3. Data and Methodology

Data on surface meteorological parameters – air/sea and dewpoint temperatures, wind speed, cloudiness, mean sea level pressure, etc. – have been collected at six-hourly intervals (standard synoptic hours viz., 0000, 0600, 1200 and 1800 GMT) on board 'M. S. Thuleland' during the sixth Indian scientific expedition to Antarctica (26th November, 1986 to 22nd March, 1987). Data collected from 29th November to 23rd December, 1986 and 23rd February to 22nd March, 1987 are chosen to represent southern summer and fall conditions, respectively.

The latent and sensible heat fluxes were computed using the bulk aerodynamic formulae (Levastu and Hubert, 1970) and the momentum flux following Jacobs (1980). They are as follows:

$$\tau = \rho C_D W^2$$

$$Q_e = (0.126 + 0.037 W)(0.98 E_w - E_A) \times L \times 0.04854$$

$$\text{if } E_w - E_A > 0$$

$$= 0.037 W(0.98 E_w - E_A) \times L \times 0.04854$$

$$\text{if } E_w - E_A < 0$$

$$Q_s = 18.90(0.26 + 0.077 W)(T_w - T_A)$$

$$\text{if } T_w - T_A > 0$$

$$= 1.45 \times W \times (T_w - T_A)$$

$$\text{if } T_w - T_A < 0$$

$$Q = Q_e + Q_s$$

$$\beta = \frac{Q_s}{Q_e}$$

$$L = 597.0 - 0.6 \times T_w,$$

where Q_e = latent heat flux (W/m^2), Q_s = sensible heat flux (W/m^2), Q = total heat flux (W/m^2), β = Bowen ratio, τ = momentum flux (N/m^2), ρ = air density = (1.16 kg/m^3), C_D = drag coefficient = 1.52×10^{-3} , W = wind velocity (m/sec), T_w = sea surface temperature ($^{\circ}\text{C}$), T_A = air temperature ($^{\circ}\text{C}$), E_w = saturation vapour pressure at sea surface temperature (mb), E_A = vapour pressure at dew point temperature (mb), and L = latent heat of evaporation.

4. Results and Discussion

Tables I and II give the mean daily estimates of air-sea temperature difference ($T_w - T_A$), vapour pressure gradient ($E_w - E_A$), latent heat flux (Q_e), sensible heat flux (Q_s) and momentum flux (τ) for the southern summer and fall, respectively. From Table I, it is obvious that maximum latent and sensible heat fluxes were observed during the period 8th to 10th December, 1986 between 33° S and 41° S. These large values of Q_e and Q_s can be mainly attributed to the large vapour pressure gradients and air-sea temperature differences rather than to wind speed. There was a sudden drop of Q_e from 10th to 11th December (from 81.4 W/m² to 19.0 W/m²), which could be mainly attributed to a drop in vapour pressure gradient even though the winds were quite strong on 11th December (13 m/sec on the 11th as compared to 10 m/sec on the 10th). There was a similar drop in Q_s values also (from 30.6 W/m² to -23.6 W/m²) from 10th to 11th

TABLE I

Daily average values of latent heat flux (Q_e), sensible heat flux (Q_s) (both in W/m²), momentum flux (τ) ($\times 10^{-3}$ N/m²), air-sea temperature difference ($T_w - T_A$) (in °C), vapour pressure gradient ($E_w - E_A$) (in mb) along with the ship's mid-day (1200 GMT) positions for November-December, 1987.

Date	Latitude (degrees)	Longitude (degrees)	Q_e	Q_s	τ	$T_w - T_A$	$E_w - E_A$
29/11/86	02.5 N	68.8 E	67.7	09.9	058.2	0.7	7.2
30/11/86	01.8 S	66.9 E	52.1	06.7	006.7	-0.6	9.8
01/12/86	06.1 S	65.0 E	73.7	08.9	015.7	1.0	11.6
02/12/86	10.3 S	63.0 E	75.4	15.9	048.0	1.2	8.6
03/12/86	14.2 S	61.2 E	98.9	14.0	058.2	1.1	9.4
04/12/86	18.7 S	58.5 E	59.1	18.4	037.7	1.5	7.1
05/12/86	20.6 S	57.0 E	52.8	09.8	022.2	1.1	7.7
06/12/86	24.9 S	55.2 E	39.7	00.6	068.5	0.0	3.8
07/12/86	29.2 S	53.3 E	40.7	-00.9	068.5	-0.2	4.0
08/12/86	33.2 S	51.2 E	76.1	28.4	141.3	1.2	5.3
09/12/86	37.0 S	49.2 E	97.0	07.3	093.0	0.5	11.6
10/12/86	40.8 S	47.0 E	81.4	30.6	193.4	1.5	5.8
11/12/86	44.0 S	45.0 E	19.0	-23.6	329.1	-1.1	1.0
12/12/86	46.9 S	42.9 E	41.2	-02.6	455.3	-0.6	1.6
13/12/86	48.9 S	41.5 E	22.4	-06.6	375.6	-0.4	1.2
14/12/86	51.5 S	38.8 E	19.1	-15.2	222.6	-0.9	1.3
15/12/86	55.1 S	35.0 E	06.4	-11.0	178.1	-0.8	0.4
16/12/86	59.0 S	29.4 E	09.3	-01.2	045.9	-0.8	1.2
17/12/86	62.3 S	23.4 E	09.6	-01.2	075.7	-0.3	0.8
18/12/86	65.0 S	15.2 E	04.5	-02.8	068.1	-0.5	0.5
19/12/86	67.9 S	09.8 E	02.0	-24.5	271.8	-1.4	0.0
20/12/86	68.9 S	10.6 E	09.0	-18.8	242.8	-1.3	0.4
21/12/86	69.9 S	12.8 E	36.3	06.3	430.4	0.1	1.7
22/12/86	69.7 S	12.5 E	14.0	-00.9	185.5	-0.3	0.8
23/12/86	69.7 S	12.1 E	04.0	-06.1	120.6	-0.5	0.4

TABLE II

Same as Table I but for February–March period.

Date	Latitude (degrees)	Longitude (degrees)	Q_e	Q_s	τ	$T_w - T_A$	$E_w - E_A$
23/02/87	68.0 S	16.0 E	009.2	-10.9	157.3	-0.9	00.7
24/02/87	66.2 S	17.0 E	008.5	12.4	174.8	0.5	00.5
25/02/87	64.0 S	17.0 E	011.2	05.6	050.4	0.3	01.2
26/02/87	63.0 S	18.5 E	006.1	-08.2	089.6	-0.7	00.6
27/02/87	62.2 S	22.0 E	003.3	-11.1	217.8	-0.7	00.3
28/02/87	60.1 S	22.0 E	015.2	-03.1	133.6	-0.2	01.2
01/03/87	57.5 S	22.0 E	014.5	-07.7	259.2	-0.2	00.9
02/03/87	57.0 S	25.5 E	017.7	-12.2	394.2	-0.5	00.8
03/03/87	55.4 S	28.9 E	026.8	21.7	427.9	0.8	01.3
04/03/87	52.3 S	32.4 E	026.2	11.5	390.1	0.4	01.3
05/03/87	49.3 S	35.7 E	018.1	12.7	203.4	0.6	01.6
06/03/87	46.3 S	38.0 E	015.7	00.2	080.9	-0.4	01.8
07/03/87	42.7 S	41.8 E	018.4	00.4	066.0	-0.1	01.7
08/03/87	38.9 S	45.1 E	022.1	-12.5	132.1	-0.7	01.7
09/03/87	35.2 S	47.9 E	064.7	12.5	167.0	0.6	04.9
10/03/87	31.4 S	50.6 E	051.8	09.0	108.9	0.4	04.5
11/03/87	27.4 S	53.2 E	072.6	07.8	113.4	0.3	05.8
12/03/87	22.8 S	55.9 E	076.2	08.6	065.7	0.6	08.5
13/03/87	20.8 S	57.0 E	132.1	35.1	078.7	1.0	10.5
14/03/87	17.4 S	59.2 E	161.4	18.3	070.2	1.3	13.6
15/03/87	13.3 S	61.6 E	203.9	92.8	364.5	3.4	12.7
16/03/87	09.1 S	63.6 E	103.6	16.5	027.2	1.5	13.7
17/03/87	04.2 S	65.8 E	092.1	10.7	025.0	1.2	13.5
18/03/87	00.4 S	67.6 S	077.6	10.1	020.1	1.3	12.8
19/03/87	04.3 N	69.4 E	129.5	06.5	078.1	0.4	12.4
20/03/87	08.5 N	71.4 E	133.7	12.6	091.1	1.1	13.0

December. Here both the air-sea temperature difference and the wind speed were contributing factors. The mean daily values of Q_s were in general one order less south of 55° S. The sensible heat fluxes were negative south of 44° S, indicating that the heat flux was from the atmosphere to the ocean over these regions. In the case of momentum, maximum fluxes were observed from 11th to 13th December between 44° S and 49° S and also on 21st December. The air temperatures were in general lower than the sea surface temperatures (SST) till 40° S, whereas south of 40° S, SST's were in general lower than air temperatures. In general, maximum air-sea temperature differences were observed in the tropics as compared to middle latitude and polar regions. Similarly, larger vapour pressure gradients were also observed in the tropics.

A comparison of Q_e values for summer and fall (Tables I and II) showed that the daily values were higher during fall than summer, which can be due mainly to the larger vapour pressure gradients observed during this period. The sensible heat fluxes were also larger during fall as compared to summer with the largest

value observed on 15th March (92.8 W/m^2). These large values were due to the combined effects of large air-sea temperature differences (3.5°C) and high wind speeds (mean wind speed of about 12 m/sec).

Figure 2 depicts the zonal means of latent heat flux (Q_e), sensible heat flux (Q_s), momentum flux (τ), total flux (Q) and Bowen ratio (β) for both summer and fall. The results indicate that the latent heat flux (Figure 2a) is positive in both seasons, with a minimum in the zone $60^\circ\text{--}70^\circ\text{S}$. The zone of maximum Q_e shifted from $30^\circ\text{--}40^\circ\text{S}$ in summer to $10^\circ\text{--}20^\circ\text{S}$ in fall. In general, Q_e values were larger in fall at all latitude belts except $30^\circ\text{--}50^\circ\text{S}$, which may be due to the larger vapour pressure gradients in summer over this area.

The sensible heat flux is not always positive as in the case of latent heat flux. During the summer, values south of 40°S are negative, whereas in fall only south of 60°S values are negative. The minimum values are observed in the zone $60^\circ\text{--}70^\circ\text{S}$ during both seasons in the case of latent heat flux. In the case of sensible heat flux, the minima were observed at $50^\circ\text{--}60^\circ\text{S}$ and $60^\circ\text{--}70^\circ\text{S}$ for summer and fall, respectively (Figure 2c).

The momentum flux exhibits larger variation (Figure 2b), which could be due to the larger variation in wind speeds. The values, in general, are larger during fall than summer at all latitude belts except $40^\circ\text{--}50^\circ\text{S}$.

Figure 2d shows the latitudinal variation of total heat loss (Q). Maximum heat loss is seen in the zone $30^\circ\text{--}40^\circ\text{S}$ during summer, whereas in fall the maximum loss occurs over the belt $10^\circ\text{--}20^\circ\text{S}$. The zonal variation of the Bowen ratio is given in Figure 2e. The ratio exhibits more variation during summer (from -0.78 to 0.25) than in fall (from -0.41 to 0.29). Minimum values were observed in the belts $50^\circ\text{--}60^\circ\text{S}$ and $60^\circ\text{--}70^\circ\text{S}$ in summer and fall, respectively.

A comparison of the total heat flux (Q) values of the present study and earlier studies (Albrecht, 1961; Hastenrath and Lamb, 1979; Ramage, 1972; Bunker, unpublished) is given in Table III. From the table, it can be seen that Albrecht's (1961) values extracted from Zillman (1972) are quite high. Bunker's values were extracted from the climatological data set prepared by Bunker for the Indian Ocean for the period 1948–1972. The density of Bunker's data set, especially in the zones $40^\circ\text{--}50^\circ\text{S}$ and $50^\circ\text{--}60^\circ\text{S}$ over the study area, is very poor. The Hastenrath and Lamb (H & L) values were extracted from the "The Climatic Atlas of the Indian Ocean. Part-II The Oceanic Heat Budget". Ramage *et al.*'s (1972) values were extracted from the "Meteorological Atlas of the International Indian Ocean Expedition Surface Meteorology over the Indian Ocean" for the years 1963 and 1964. Bunker's values agree very well with those of Hastenrath and Lamb (1979), for the study area from equator to 30°S . Our values are in general lower than those in all the studies mentioned except at a few locations. These large differences may be due to the use of different exchange coefficients for the computations of Q_e and Q_s . Another reason could be the interannual variation of fluxes as can be seen from the study of Ramage *et al.* (1972), which

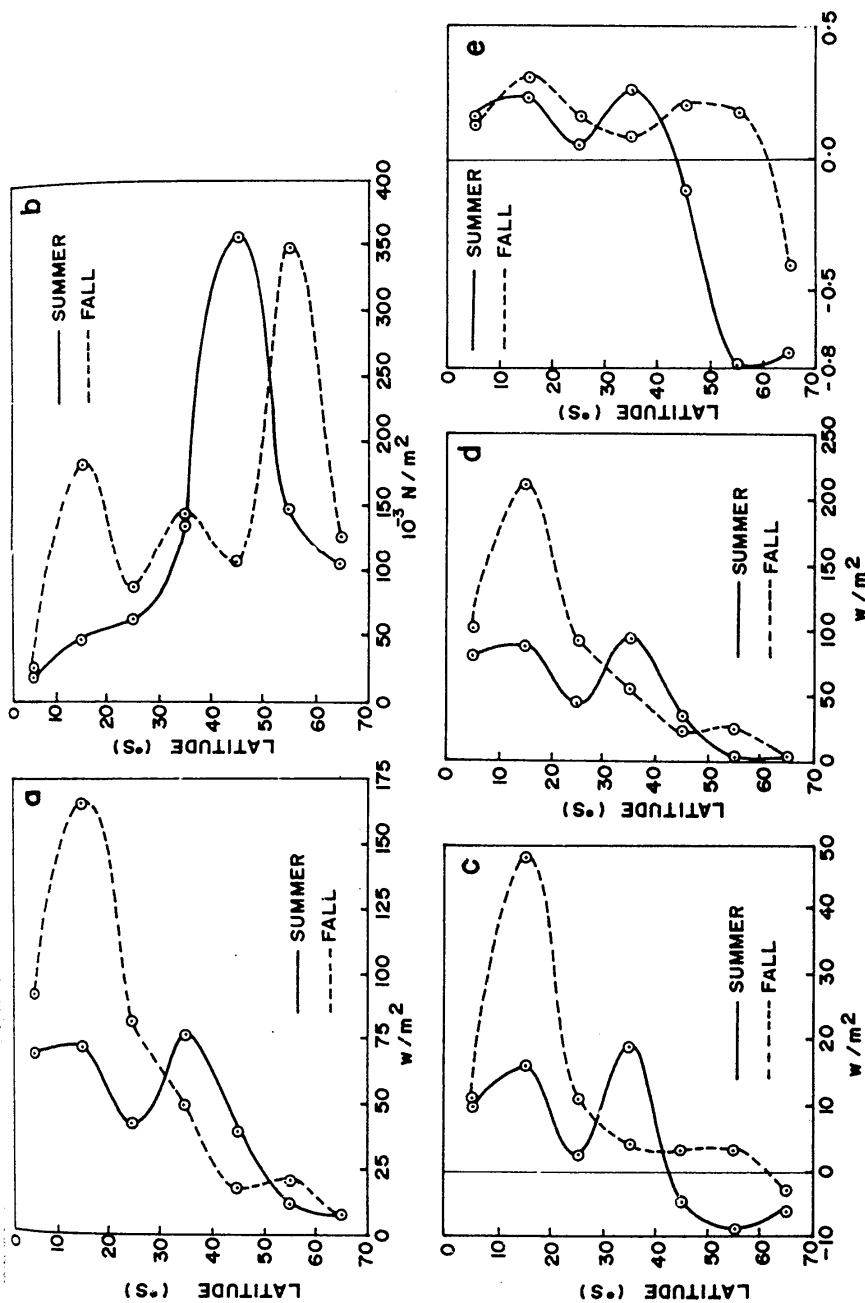


Fig. 2. Zonal means of (a) latent heat flux, Q_e (in W/m^2), (b) momentum flux, τ (in $\times 10^{-3} N/m^2$), (c) sensible heat flux, Q_s (in W/m^2), (d) total heat flux, Q (in W/m^2), and (e) Bowen ratio, β , for austral summer (—) and fall (---), respectively.

TABLE III

Comparison of the total heat flux (Q) (in W/m^2) obtained from various sources along with the number of observations (N) used in the present study, for Summer and, in brackets, Fall

Latitude (° South)	N	Present study	Albrecht (1961)	Bunker	H & L (1979)	Ramage <i>et al.</i> (1972)
00-10	09(09)	79(102)	118(119)	096(094)	082(072)	103(097)
10-20	11(10)	87(213)	130(142)	105(103)	103(103)	129(125)
20-30	10(09)	44(092)	120(133)	091(125)	093(126)	079(135)
30-40	11(11)	95(054)	064(125)	093(140)	-	055(100)
40-50	14(12)	34(021)	032(076)	091(093)	-	026(043)
50-60	12(18)	03(023)	005(035)	027(002)	-	-
60-70	28(22)	02(005)	-08(019)	-	-	-

showed large variations in the total heat flux over the study area for the years 1963 and 1964.

Hence only a systematic large-scale data collection programme over the southern Indian Ocean (especially south of 30° S) can throw more light on the atmospheric circulation over the study area and its influence on the monsoon circulation over the Arabian Sea and Indian subcontinent.

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