

Surface heat budget of the Caribbean Sea during the pre-hurricane period (April–May) of 1990

V. S. N. MURTY,¹ S. PRASANNA KUMAR,² PHILBERT E. BROWN,² CALVIN R. GRAY,³ JUSTIN HULSE,⁴ PATRICK JEREMIAH,⁵ A. B. WAGH,¹ AND B. N. DESAI¹

MURTY, V. S. N., S. P. KUMAR, P. E. BROWN, C. R. GRAY, J. HULSE, P. JEREMIAH, A. B. WAGH, and B. N. DESAI. 1991. Surface heat budget of the Caribbean Sea during the pre-hurricane period (April–May) of 1990. *Caribb. Mar. Stud.* 2(1&2): 87–96.

Analysis of surface meteorological observations in the Caribbean Sea in the Caribbean Oceanographic Resources Exploration (CORE) Project during April and May, 1990 are presented. The computed latent heat flux over the west central Caribbean Sea was affected by the movement of cold fronts and high pressure systems. The estimated net oceanic heat gain shows that the waters between the Bahamas and Antigua lost heat energy ($60 \text{ W} \cdot \text{m}^{-2}$) from the air–sea interface and this may form a source of heat energy to the overlying atmosphere during the pre-hurricane period. In contrast the waters to the south, between Belize and Guyana, gained heat energy at the sea surface. Part of this heat energy may be transferred to the colder upwelling regions. The evaporation rate is low ($3 \text{ mm} \cdot \text{d}^{-1}$) near the Guyana coast and is high ($8.5 \text{ mm} \cdot \text{d}^{-1}$) between the Bahamas and Antigua. The estimated net heat gain at the sea surface during the pre-hurricane period may have an influence on the growth and development of hurricanes moving over the region from the eastern Atlantic Ocean.

Voici une étude d'observations météorologiques superficielles effectuées dans la Mer des Caraïbes lors du Projet d'Exploration des Ressources Océanographiques des Caraïbes (CORE — Caribbean Oceanographic Resources Exploration Project) au mois d'avril et mai 1990. L'on a découvert que le flux de chaleur latente calculé qui s'étend par la zone centrale de l'ouest de la Mer des Caraïbes est touché par le mouvement de fronts froids et par de systèmes de haute pression. L'augmentation de la chaleur océanique nette approximative indique que les eaux situées entre les Iles Bahamas et Antigua ont subi une perte d'énergie calorifique ($60 \text{ W} \cdot \text{m}^{-2}$) par conséquence du croisement aérien et maritime et ceci peut constituer une source d'énergie calorifique à l'atmosphère qui s'étend par-dessus avant le commencement de la saison des ouragans. Par contre les eaux qui se trouvent au sud, entre Belize et Guyane, ont augmenté d'énergie calorifique à la surface de la mer. Une partie de cette énergie calorifique peut être transférée aux régions turbides plus froides. Le taux d'évaporation est bas ($3 \text{ mm} \cdot \text{jour}^{-1}$) près de la côte guyanaise et s'avère élevé ($8,5 \text{ mm} \cdot \text{jour}^{-1}$) entre les Iles Bahamas et Antigua. L'augmentation de la chaleur nette approximative qui a lieu à la surface de la mer avant le commencement de la saison des ouragans peut influencer la croissance et le développement d'ouragans qui traversent la région à partir de la zone de l'est de l'Océan Atlantique.

He aquí un estudio de observaciones meteorológicas superficiales llevadas a cabo en el Mar Caribe a lo largo del Proyecto de Exploración de Recursos Oceanográficos del Caribe (CORE — Caribbean Oceanographic Resources Exploration Project) durante abril y mayo de 1990. Se descubrió que el flujo de calor latente calculado que se extiende por la zona central del Mar Caribe se afecta por el movimiento de frentes fríos y por sistemas de alta presión. Indica el aumento del calor oceánico neto calculado que las aguas situadas por entre las Islas Bahamas y Antigua perdieron energía calorífica ($60 \text{ W} \cdot \text{m}^{-2}$) por el cruce aéreo marítimo y esto puede proveer una fuente de energía calorífica a la atmósfera por arriba antes del comienzo de la estación de los huracanes. Por el contrario, las aguas que se hallan en el sur entre Belice y Guayana, aumentaron energía calorífica en la superficie del mar. Una porción de esta energía se puede transferir a las regiones de surgencia más frías. La tasa de evaporación es baja ($3 \text{ mm} \cdot \text{día}^{-1}$) cerca de la costa de Guayana y resulta elevada ($8,5 \text{ mm} \cdot \text{día}^{-1}$) entre las Islas Bahamas y Antigua. El aumento de calor neto aproximativo que tiene lugar en la superficie del mar antes del comienzo de la estación de los huracanes puede influir el crecimiento y el desarrollo de huracanes que cruzan la región desde la zona del este del Océano Atlántico.

Introduction

The Caribbean Sea is situated in the northern trade wind belt with prevailing winds from the east and north-east. The meteorological conditions in the lower layers of the atmosphere over the Caribbean Sea are influenced by the

¹National Institute of Oceanography, Dona Paula, Goa-403 004, India.

²National Meteorological Service, Kingston 10, Jamaica, West Indies.

³National Meteorological Services, Norman Manley International Airport, Kingston, Jamaica, West Indies.

⁴Belize Weather Bureau, Belize City, Central America.

⁵Meteorological Office, Antigua and Barbuda.

movement of cold fronts and high and low pressure systems over the Atlantic Ocean. The low pressure systems are mainly of tropical cyclonic disturbances. The cold fronts weaken while passing over warm waters of the Caribbean Sea and these weather systems affect the temperature and humidity of the air over the region. This in turn affects the transfer of heat energy across the air-sea interface and the heat budget at sea surface. Many notable studies on the air-sea interaction of the Caribbean Sea and adjacent regions have been carried out (Hastenrath 1968; Bunker 1976; Hastenrath and Lamb 1978; Ismer and Harse 1987; Etter et al. 1987) based on multi-year surface meteorological observations. In this report, the meteorological conditions and surface heat budget of the Caribbean Sea during the pre-hurricane period (April and May) of 1990, using the meteorological data collected on board the R.V. *Sagar Kanya* in the Caribbean Oceanographic Resources Exploration (CORE) Project, are presented.

Data and Methods of Analysis

A total of 137 sets of surface meteorological observations comprising dry and wet bulb temperatures, sea surface temperatures, wind speed and direction, atmospheric pressure, and cloud cover and type were collected at three hourly intervals along the tracks of the cruises (Legs I to IV) covering the Exclusive Economic Zone (EEZ) of the Caribbean Islands from the Belize coast to the Guyana coast (Map 1, p. 4). The incoming global solar radiation (both direct and diffuse) reaching the sea surface was measured with an on board pyranometer at 10-min intervals from local sunrise to sunset. These data were averaged at 1-h intervals and then daily averages of global radiation were obtained and later corrected to albedo at sea surface. The daily averaged solar radiation (Q_i) was also computed using the empirical formula of Seckel and Beaudry (1973) with a cloud correction factor given by Reed (1977) and a correction factor due to albedo (Payne 1972). Dry and wet bulb temperatures were obtained at a 10-m height above the sea surface using an un aspirated psychrometer. Wind observations were recorded with anemometers installed at a 22.6-m height above the sea surface.

The fluxes of latent heat (Q_E), sensible heat (Q_H), back radiation (Q_B) at the air-sea interface were computed using the standard bulk aerodynamic formulae (Stevenson 1982). These computations were carried out for each set of observations and their daily and spatial averages obtained. The equations for the computations of the above heat-budget components are given in Appendix I. The computational procedure outlined in Stevenson (1982) was adopted. The heat budget components are expressed in $W \cdot m^{-2}$.

The net oceanic heat gain (Q_{net}) at the sea surface was estimated from the daily averages of global solar radiation, back radiation, and turbulent heat fluxes (latent heat and sensible heat) as:

$$Q_{net} = Q_i (1 - a) - Q_B - Q_E - Q_H$$

where a = albedo at sea surface (6%; Payne 1972).

The evaporation (E) rate ($mm \cdot d^{-1}$) at sea surface was obtained from the latent heat flux as:

$$E = 86.4 \times Q_E / L$$

where L = latent heat of vaporization ($2241 W \cdot s \cdot g^{-1}$).

The bulk exchange coefficients of moisture (C_E) and heat (C_H) are known to vary with the wind speed and atmospheric stability (Kitaigorodski et al. 1973; Kondo 1975; Pond et al. 1974; Large and Pond 1981, 1982). Since the observed wind speeds over the Caribbean Sea varied from calm conditions to strong winds, the exchange coefficient (C_E) was computed following Kondo (1975) and later corrected to atmospheric stability following the procedure outlined in Stevenson (1982). However, for C_H a constant value was chosen for stable (0.82×10^{-3}) and unstable (1.12×10^{-3}) conditions (Stevenson 1982). Since the air temperature measurements (dry and wet bulb) were obtained at a 10-m height, no height correction was applied. As the measured wind speeds were obtained at a height of 22.6 m, as mentioned above, a height correction factor was used to reduce the measured winds to a standard height of 10 m (outlined in Stevenson 1982).

The Richardson number (R_i) and stability parameter (z/l) were computed for each set of observations to determine the stability of the atmosphere overlying the sea surface.

Results and Discussion

The computed diabatic moisture coefficient (C_E) for each set of observations varied between 1.13×10^{-3} and 3.5×10^{-3} (at lower wind speeds) and each value was used in the computation of latent heat flux for each set of observations. The mean value of C_E averaged over the number of observations in each area of the study (Leg I to Leg IV) varied between 1.61×10^{-3} and 1.83×10^{-3} . These values of C_E are within the reported range of values (Kondo 1975; Bunker 1976; Etter et al. 1987) in the Caribbean Sea and Atlantic Ocean.

The meteorological parameters and the computed heat-budget components are presented below, for the different areas covered by each leg of the cruise.

(a) Leg I: Jamaica-Belize-Jamaica

Figure 1 represents the daily means of the observed meteorological parameters and computed heat-budget components and net oceanic heat gain at the sea surface in this area. The sea surface temperatures (SST) were high ($>28.5^\circ\text{C}$) off south-eastern Jamaica (15-16 April) and low ($<26.5^\circ\text{C}$) off north-western Jamaica (22-23 April). In the central area between Jamaica and Belize the SST was uniform at 27.5°C . The wind speed (U) and atmospheric pressure (P) attained maximum values in this area on 19-20 April in association with the

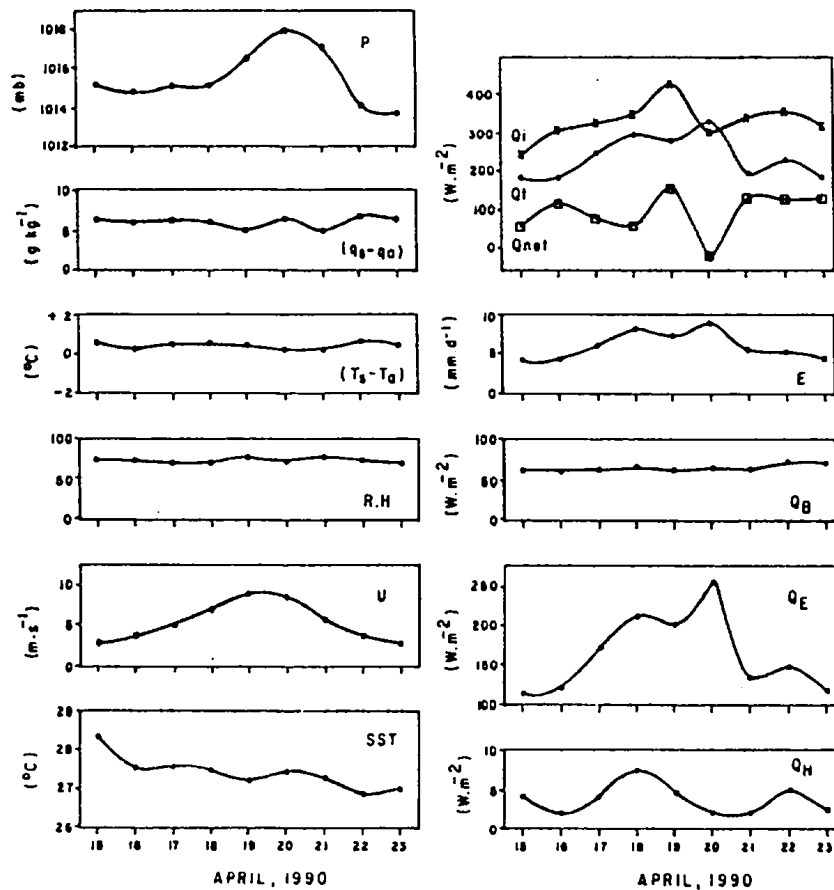


FIG. 1. Daily means of meteorological parameter, sensible heat, latent heat, back radiation, evaporation, incoming solar radiation, total heat loss, and net heat gain in the region between Jamaica and Belize.

movement of a ridge of high pressure into the central Caribbean area (Fig. 2). The relative humidity (R.H.) and the difference in sea and air specific humidity ($q_s - q_a$) were in phase and both exhibited a slight variation on 19-20 April due to the ridge of high pressure. The

values of differences between sea and air temperature ($T_s - T_a$) were small and positive throughout. This indicated the presence of unstable conditions in the overlying atmosphere. The fluxes of sensible heat (Q_s), latent heat (Q_l) and back radiation (Q_b) were relatively

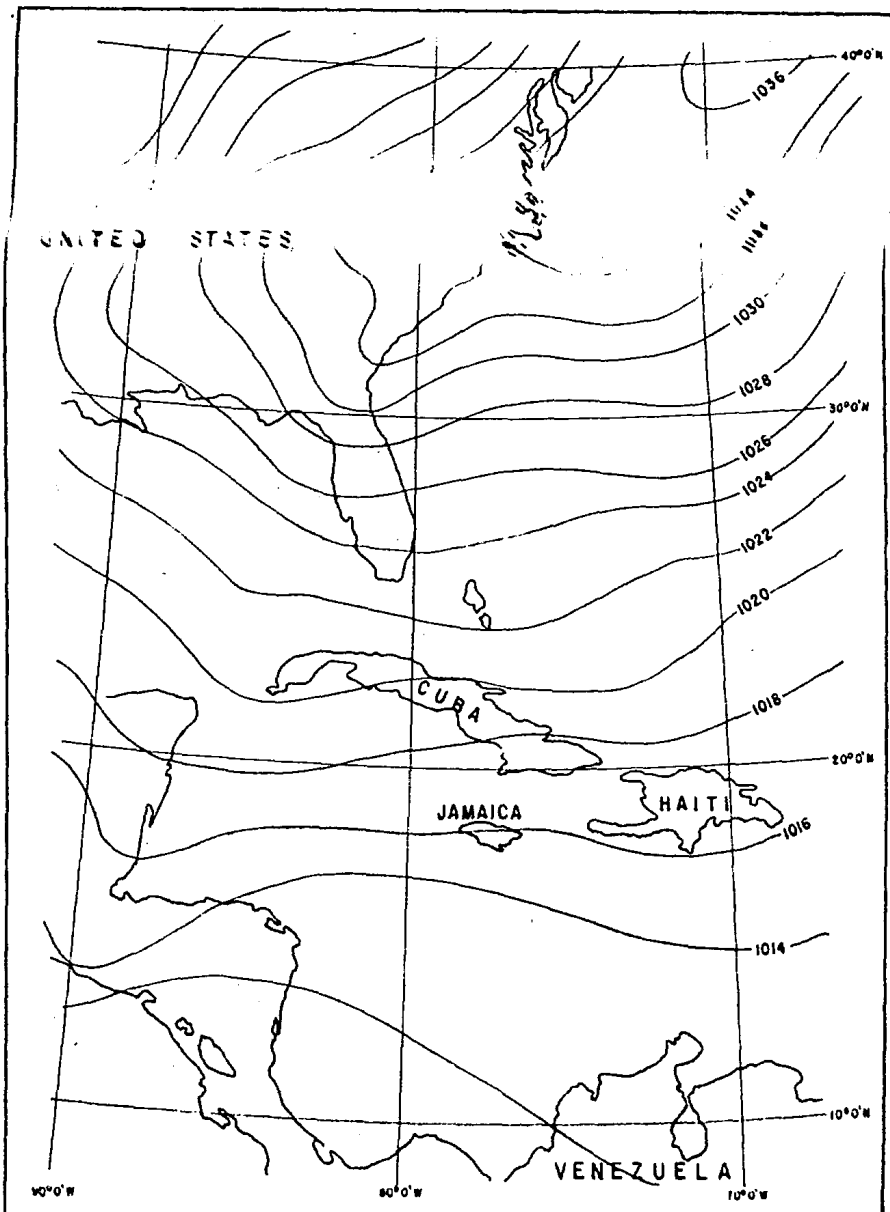


FIG. 2. Surface pressure (mb) on 20 April at 1200 Z over the tropical North Atlantic Ocean and north-western Caribbean Sea.

higher off north-western Jamaica than those off south-eastern Jamaica. These fluxes exhibited variations in the central region where the latent heat and evaporation (E) attained higher values ($275 \text{ W} \cdot \text{m}^{-2}$ and $8 \text{ mm} \cdot \text{d}^{-1}$) on 20 April. These variations were associated with the movement of the ridge of high pressure (relatively dry air) which enhances specific humidity differences ($q_s - q_a$) and thereby latent heat and evaporation. The sudden drop in Q_E from 20 April to 21 April may not be real, for the computation was made from one set of observations on 21 April. Associated with the dominant high pressure system, clear sky conditions prevailed in the west central Caribbean Sea except offshore near south-eastern Jamaica.

As a consequence, here the sea surface received relatively less incoming solar radiation (Q_i). The incoming solar radiation and total heat loss (Q_o) due to sensible heat, latent heat, and back radiation were in phase. Further, it is seen that the waters of this area gained ($>100 \text{ W} \cdot \text{m}^{-2}$) heat energy at the air-sea interface. The higher latent heat on 20 April dominated the heat energy received at the sea surface and thereby led to a net heat loss of $20 \text{ W} \cdot \text{m}^{-2}$ on this day.

(b) *Leg II: Jamaica-Bahamas-Barbados*

Figure 3 shows the observed meteorological parameters and heat budget components in this area. The observations in this area form two

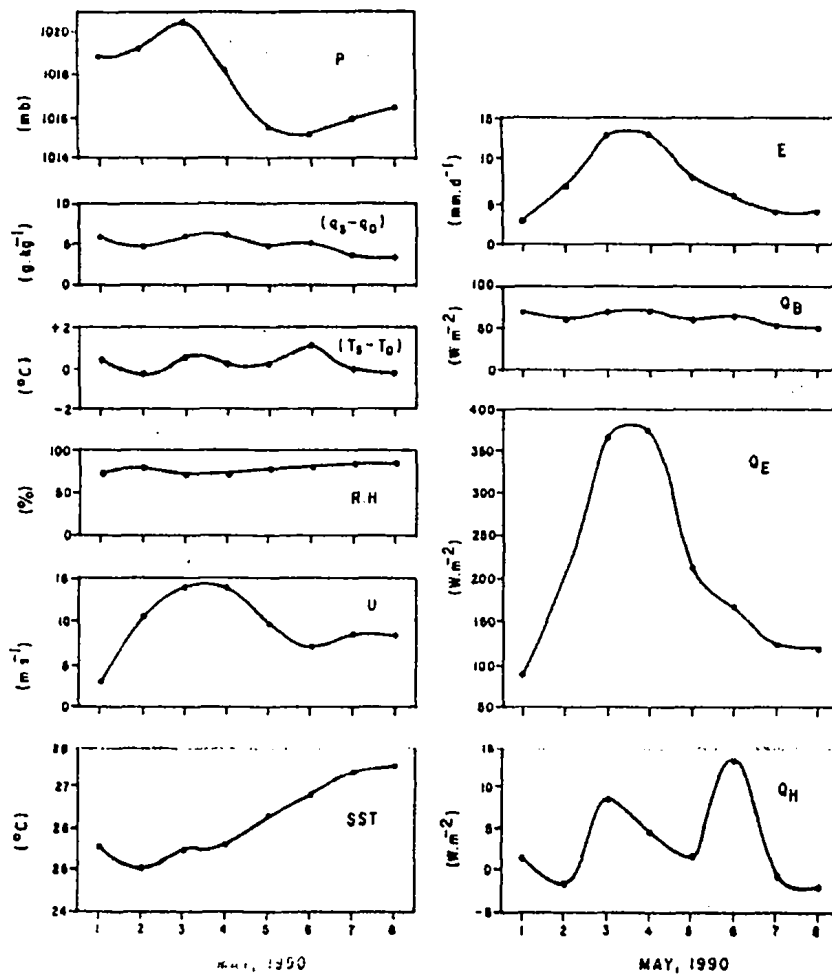


FIG. 3. Daily means of meteorological parameters, sensible heat, latent heat, back radiation, evaporation, in the region between the Bahamas and Antigua.

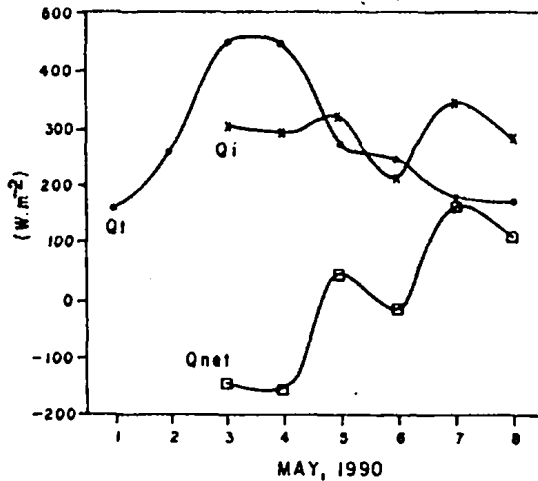


FIG. 4. Daily means of incoming solar radiation, total heat loss, and net oceanic heat gain in the region between the Bahamas and Antigua.

groups separated by 17° N with one group lying between the Bahamas and Antigua north of 17° N and the other group south of 17° N up to Barbados. In the northern group, a high pressure system prevailed from 1 May to 5 May and the winds were relatively strong ($14 \text{ m} \cdot \text{s}^{-1}$). The SST exhibited a gradual increase from 24.6°C near the Bahamas to 27.6°C near Barbados. The differences in sea and air temperature showed little variation from 1 May to 5 May. The effect of the high pressure system could also be seen in relative humidity and in differences in sea and air specific humidity patterns during that period. The higher winds speeds ($14 \text{ m} \cdot \text{s}^{-1}$) and higher specific humidity differences ($6 \text{ g} \cdot \text{kg}^{-1}$) contributed to higher latent heat ($375 \text{ W} \cdot \text{m}^{-2}$) on 3 and 4 May. The back radiation was nearly uniform throughout. Correspondingly, higher total heat loss occurred on 3 and 4 May (Fig. 4). However, due to higher clouding, the incoming global solar radiation reaching the sea surface was less and constant than the total heat loss during 3, 4, and 5 May. This led to loss of heat energy ($150 \text{ W} \cdot \text{m}^{-2}$) from the sea surface north of 17° N during 3, 4, and 5 May and heat gain ($150 \text{ W} \cdot \text{m}^{-2}$) on 7 May south of 17° N.

(c) *Leg III: Barbados – Trinidad and Tobago*
Figure 5 shows the observed meteorological

parameters and computed heat budget components and net heat gain at the air–sea interface in this region. The winds were constant from the north-east with speeds of around $5 \text{ m} \cdot \text{s}^{-1}$. The SST varied between 27°C and 28°C . The relative humidity was approximately 76% and was uniform over the region. Sea and air temperature differences were near zero around Barbados and attained small positive values in the waters off Trinidad. The sea and air specific humidity differences decreased from Barbados to Trinidad and Tobago. The atmospheric pressures did not show appreciable variation. Sensible heat was always positive and attained a maximum of $4 \text{ W} \cdot \text{m}^{-2}$ on 14 April. The latent heat flux was high ($140 \text{ W} \cdot \text{m}^{-2}$) in the central region between Barbados and Trinidad and Tobago. The back radiation was approximately $50 \text{ W} \cdot \text{m}^{-2}$ throughout. The total heat loss pattern was in phase with that of latent heat. The net heat gain at the sea surface followed the pattern of incoming radiation. The waters of the central region received relatively less heat at the sea surface whereas the waters near Trinidad and Tobago gained a higher amount of heat ($290 \text{ W} \cdot \text{m}^{-2}$).

(d) *Leg IV: Offshore Guyana*

Typical variation of hourly mean measured incoming solar radiation is shown for Georgetown, Guyana on 25 April (Fig. 6). The broken line in this figure represents the day's mean solar radiation reaching the sea surface in this region. Figure 7 shows the observed meteorological parameters and computed heat budget components in this area. The variations in the meteorological parameters in this area were similar to those recorded in the Barbados – Trinidad and Tobago passage except for the atmospheric pressure which was lower. Similarly, the sensible heat and back radiation did not change much between these two areas. The latent heat and evaporation values were lower off the Guyana coast.

Summary

A summary of the surface heat budget around the Islands of the Caribbean Sea during the pre-hurricane period (April–May) is presented in Table 1.

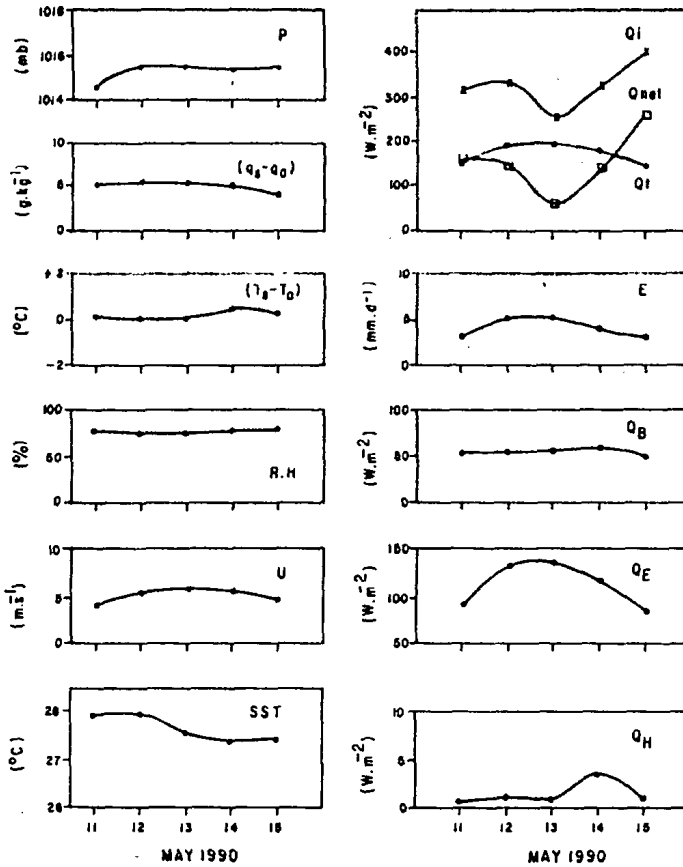


FIG. 5. Daily means of meteorological parameters, sensible heat, latent heat, back radiation, incoming solar radiation, total heat loss, and net heat gain in the region between Barbados and Trinidad.

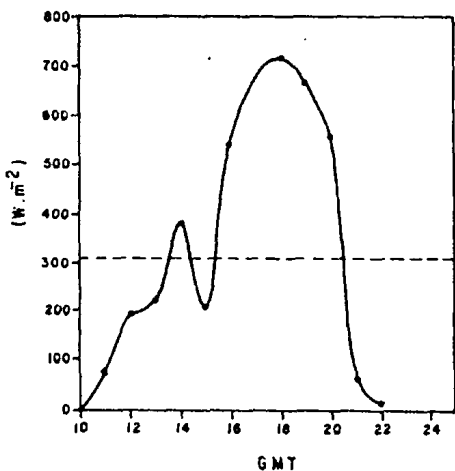


FIG. 6. Measured incoming solar radiation at Georgetown on 25 May 1990.

The incoming solar radiation exhibited wide variation off Jamaica with lower levels ($242 \text{ W} \cdot \text{m}^{-2}$) of radiation in the south-east due to high clouding. Elsewhere in the Caribbean Sea the solar radiation reaching the sea surface varied between $314 \text{ W} \cdot \text{m}^{-2}$ and $348 \text{ W} \cdot \text{m}^{-2}$. The overall mean solar radiation was $319 \text{ W} \cdot \text{m}^{-2}$. The total heat loss due to sensible heat, latent heat, and back radiation increased westward from $143 \text{ W} \cdot \text{m}^{-2}$ off the Guyana region to $251 \text{ W} \cdot \text{m}^{-2}$ in the central Caribbean Sea. However, the total heat loss north of 17° N between Antigua and the Bahamas was high, exceeding $390 \text{ W} \cdot \text{m}^{-2}$. The waters of the eastern Caribbean Sea gained heat energy at the air-sea interface varying between 135 and $182 \text{ W} \cdot \text{m}^{-2}$. However, the western Caribbean Sea gained relatively less heat energy at the sea

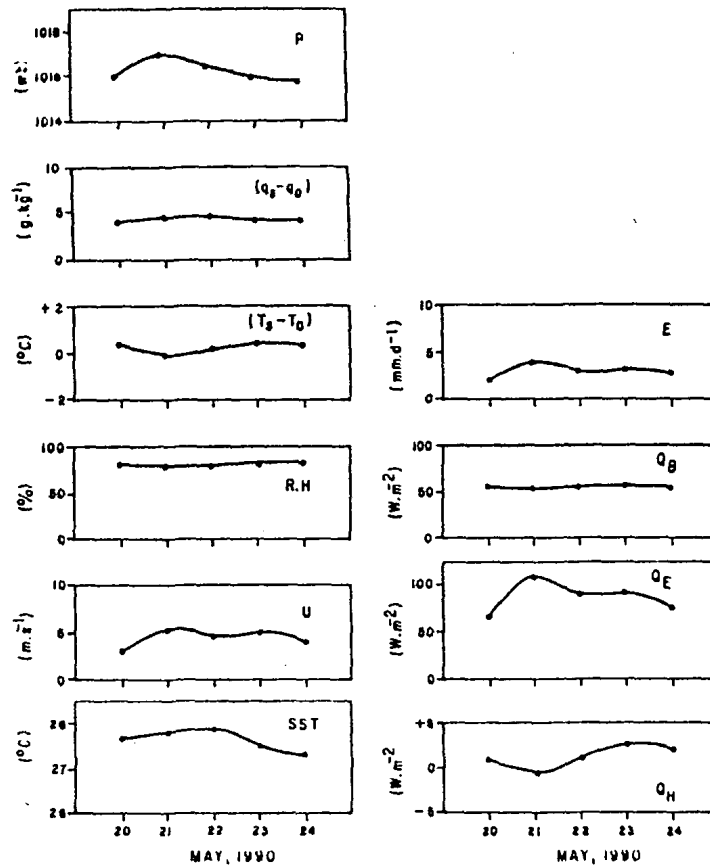


FIG. 7. Daily means of meteorological parameters, sensible heat, latent heat, back radiation, evaporation in the region between Trinidad and Guyana.

TABLE 1 — Daily average of heat budget parameters and net heat gain (Q) along with evaporation (E) in the area of Leg I

Date	Q_S	Q_H	Q_E	Q_B	Q	E
	$(W \cdot m^{-2})$					$(mm \cdot d^{-1})$
15.4.90	242	4	118	62	58	4
16.4.90	300	1	123	61	115	1
17.4.90	321	4	185	65	67	7
18.4.90	283	8	227	65	-17	8
19.4.90	283	5	214	61	3	8
20.4.90	302	2	275	64	-39	10
21.4.90	303	2	142	58	101	5
22.4.90	303	5	153	72	73	5
23.4.90	323	2	122	68	131	4
Overall mean	296	4	173	64	55	6

surface than that of the eastern Caribbean Sea. North of $17^\circ N$, the sea surface lost heat energy ($63 W \cdot m^{-2}$) to the overlying atmosphere

due to higher latent heat flux. The evaporation rate was low ($3 mm \cdot d^{-1}$) off the Guyana coast and increased gradually towards the west central Caribbean Sea to $6.5 mm \cdot d^{-1}$. A higher rate of evaporation was recorded north of $17^\circ N$ between Antigua and the Bahamas. The overall mean values of net oceanic heat gain and rate of evaporation were $102 W \cdot m^{-2}$ and $5 mm \cdot d^{-1}$, respectively, during the pre-hurricane period in the area of study of the Caribbean.

The values of net heat gain recorded in this study are comparable with published values (Hastenrath and Lamb 1978; Etter et al. 1987).

The present study was based on observations collected in a single survey in a single year during the pre-hurricane period. The estimated

net heat gain at the sea surface was of such order of magnitude as to have some possible influence on the growth of tropical hurricanes passing through the region from the eastern Atlantic. It must be emphasized that the net heat gain at the sea surface may be utilized partly to increase the temperature of the water column and partly be advected to the surrounding colder water regions where upwelling is present. Though the net heat storage in the upper layers of the sea is negligible on an annual basis, the same may not be true for a season. This suggests that further studies be carried out to estimate the heat storage in the upper layers of the Caribbean Sea during the pre-hurricane months and to determine the advection of heat, if any, to the surrounding regions.

Acknowledgements

The authors are thankful to the Department of Ocean Development and the Council of Scientific & Industrial Research, Government of India, the CARICOM Secretariat; and the Commonwealth Science Council (CSC) for the successful execution of the CORE Project. Special thanks are due to Dr Thyagarajan, ex-secretary, CSC; Dr S. Molomo, Chief Project Officer, CSC, and Mr Byron Blake, Director, Economics and Industry, CARICOM Secretariat for their keen interest in this study and financial support. The authors are thankful to Dr J. S. Sastry, Head POD, NIO for his comments on the manuscript.

- Bunker, A. F. 1976. Computation of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. *Mon. Weath. Rev.* 104: 1022-1040.
- Etter, P. C., P. J. Lamb, and D. H. Portis. 1987. Heat and freshwater budgets of the Caribbean Sea with the revised estimates for the central American seas. *J. Phys. Oceanogr.* 17: 1232-1246.
- Hastenrath, S. 1968. Estimates of latent and sensible heat for the Caribbean Sea and Gulf of Mexico. *Limnol. Oceanogr.* 13: 322-331.
- Hastenrath, S., and P. J. Lamb. 1978. Heat budget atlas of the tropical Atlantic and eastern Pacific oceans. Univ. Wisconsin Press. 104 pp.
- Ismer, H. J., and L. Hasse. 1987. The Bunker Atlas of the North Atlantic Ocean. Vol 2: Air-sea interactions. Eds. M. Ghil, R. Sudoury, and J. Sundermann, Springer-Verlag, New York.
- Kitaigorodski, S. A., O. A. Kuznetsov, and G. N. Panin. 1973. Coefficients of drag, sensible heat and evaporation over the surface of the sea. *Tr. Akad. Nauk SSSR Atmos. Ocean Phys.* 9: 644-647.
- Kondo, J. 1975. Air-sea bulk transfer coefficients in air-sea interface. *Bound. Layer Meteorol.* 9: 91-112.
- Lager, W. G., and S. Pond. 1981. Oceanic momentum flux measurements in response to mixed layer. *J. Phys. Oceanogr.* 11: 67-88.
- Payne, R. E. 1972. Albedo of sea surface. *J. Atmos. Sci.* 29: 959-970.
- Pond, S., D. B. Fissel, and C. A. Paulson. 1974. A note on bulk aerodynamic coefficients for sensible heat and moisture fluxes. *Bound. Layer Meteorol.* 6: 333-339.
- Reed, R. K. 1977. On estimating insolation over the ocean. *J. Phys. Oceanogr.* 7: 482-485.
- Seckel, G. R., and F. H. Beaudry. 1973. The radiation from sun and sky over north Pacific Ocean (Abstr.). *Trans. Am. Geophys. Union* 54: 1114.
- Stevenson, J. W. 1982. Computation of heat and momentum fluxes at sea surface during the Hawaii to Tahiti Shuttle Experiment. Hawaii Inst. Geophys., Univ. Hawaii, Honolulu.

APPENDIX I

Incoming solar radiation

$$Q_i = A_0 + A_1 \cos l + B_1 \sin l + A_2 \cos 2l + B_2 \sin 2l$$

$$Q_i = Q_c (1 - 0.62 N_{av} + 0.0019) \text{ where}$$

Q_c = daily averaged shortwave solar radiation ($W \cdot m^{-2}$) under clear sky conditions

Q_i = daily averaged shortwave solar radiation ($W \cdot m^{-2}$) corrected to cloud cover and noon altitude of the sun

$$A_0 = -15.82 + 326.87 \cos l$$

$$A_1 = 9.63 + 192.44 \cos (l + \pi/2)$$

$$B_1 = -3.27 + 108.70 \sin l$$

$$A_2 = -0.64 + 7.80 \sin 2(l - \pi/4)$$

$$B_2 = -0.50 + 14.42 \cos 2(l - \pi/36)$$

$$l = \text{latitude in radians} = (t - 21) \times 2\pi/365$$

$$t = \text{time of the year in Julian days}$$

$$N_{av} = \text{daytime average cloud amount in tenths}$$

$$O_s = \text{noon altitude of the sun in degrees}$$

Latent heat flux

$$Q_E = a C_E L_E (q_s - q_{10}) U_{10} \text{ where}$$

$$a = \text{air density (1178 g} \cdot \text{m}^{-3}\text{)}$$

$$L_E = \text{latent heat of vaporization (2441 W} \cdot \text{s} \cdot \text{g}^{-1}\text{)}$$

- q_s = saturation specific humidity at sea surface temperature
 q_{10} = specific humidity of the air at 10 m height above the sea surface
 U_{10} = wind speed ($\text{m} \cdot \text{s}^{-1}$) at 10 m height above the sea surface
 C_E = moisture coefficient

Sensible heat flux

$$Q_H = C_p C_H (T_S - T_{10}) U_{10} \text{ where}$$

- C_H = heat transfer coefficient
 T_S = sea surface temperature
 T_{10} = air temperature (dry bulb) at 10 m height above sea surface

C_p = Specific heat of sea water
 at constant pressure ($= 1020 \text{ J} \cdot \text{kg}^{-1} \cdot \text{°K}^{-1}$)

Back radiation (longwave)

$$Q_{B_0} = \epsilon \sigma T_S^4 (0.39 - 0.05 \sqrt{e_{10}}) + 4 T_S^3 (T_S - T_{10})$$

where

- Q_B = longwave back radiation ($\text{W} \cdot \text{m}^{-2}$) under clear sky conditions
 ϵ = emissivity of sea surface (0.97)
 σ = Stefan-Boltzmann's constant [$5.678 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} (\text{°K})^{-4}$]
 e_{10} = water vapor pressure in the air at 10 m height above sea surface (mb)
 $Q_B = Q_{B_0} (1 - 0.7 N)$ where
 Q_B = longwave back radiation ($\text{W} \cdot \text{m}^{-2}$) corrected to cloud cover
 N = cloud amount in tenths