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A new method for estimating the seasonal cycle of the heat balance at the ocean surface, with application to the Gulf of Mexico

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RESUMEN

Se aplica la ecuación de conservación de energía térmica a la capa superior oceánica del Golfo de México, usando parametrizaciones para los términos de calentamiento y transporte. Se simula la temperatura de la superficie del mar, el ciclo anual del balance de radiación, los flujos de calor latente y calor sensible así como el balance de calor oceánico. Los resultados se comparan con los obtenidos por otros autores.

PALABRAS CLAVE: Golfo de México, simula, balance de radiación, calor latente, calor sensible, balance de calor oceánico.

ABSTRACT

The conservation of thermal energy applied to the upper layer of the ocean is used together with parameterizations of the heating and transport terms in order to simulate the sea surface temperature, the annual cycle of the radiation balance, the latent and sensible heat fluxes and the rate of oceanic heat storage in the Gulf of Mexico. The results are compared with those obtained by other authors.

KEY WORDS: Gulf of Mexico, simulate, radiation balance, latent heat, sensible heat, oceanic heat storage.

INTRODUCTION

Hastenrath (1968) derived monthly mean values of latent and sensible heat fluxes at the sea-air interface of the Caribbean and Gulf of Mexico areas: (1) from the multiannual mean of the oceanic heat budget; (2) from the atmospheric energy budget, on the basis of the available radiosonde data for the entire year 1960; and (3) by the bulk-aerodynamic method, using ship observations. He also discussed the oceanic heat budget of the Gulf of Mexico (1976) on the basis of ship observations during 1911-1970. Colon (1963) studied the atmosphere-ocean heat energetics of the Caribbean Sea and obtained the heat flux as a residual from computation of the heat balance of the water body. Etter (1975) presented a complete study of the heat budget in the Gulf of Mexico using readily available climate summaries of oceanographic and meteorological data. In 1983, he updated his work revising and expanding the calculation of the rate of oceanic heat storage, which he examined together with the surface heat exchanges determined by Budyko (1963), Hastenrath and Lamb (1978) and Bunker (1976-supplemented with more detailed but unpublished monthly results). Isemer and Hasse (1987) have computed for the North Atlantic Ocean, including the Gulf of Mexico, some of the most important sea-air interaction fields, such as the short and long wave radiation components and the turbulent fluxes of sensible and latent heat. They include two sets of fields: one obtained from data, parameterizations and coefficients used originally by Bunker (1976), and another revised set, which is obtained using Bunker's data together with revised parameterizations of the sea-air heat fluxes.

Adem *et al.*, (1991) adapted the thermodynamic model to the mixed layer of the Gulf of Mexico using a square grid with a spacing of 60 km to simulate the annual cycle of the sea surface temperature (SST). The observed surface ocean currents and the horizontal transport of heat through the Yucatán Channel were used as prescribed fields as well as the atmospheric conditions. The simulated monthly normal SST were in good agreement with those of Hastenrath and Lamb (1978).

In the present work we show that the simulation of the SST yields at the same time a method for determining the radiation balance, the latent and sensible heat fluxes and the rate of oceanic heat storage.

BRIEF DESCRIPTION OF THE MODEL

The model uses the conservation of thermal energy equation applied to the mixed layer of the Gulf of Mexico, as derived in a previous paper (Adem, 1970):

$$\rho_s c_s h_s \left(\frac{\partial T_s}{\partial t} + V_{ST} \cdot \nabla T_s - K_s \nabla^2 T_s \right) = E_s - G_2 - G_3 \qquad (1)$$

where T_s is the sea surface temperature (SST), ρ_s is a constant density, c_s is a constant specific heat, h_s is the depth of the upper layer, V_{ST} is the horizontal velocity of the ocean current in the layer, K_s is a constant Austausch coefficient, E_s is the rate at which the energy is added by radiation, G_2 is the rate at which the sensible heat is given off to the atmosphere by vertical turbulent transport, and G_3 is the rate at which the heat is lost by evaporation.

Equation (1) can be written

$$Q_R = Q_A + Q_T + Q_V, \tag{2}$$

where:

$Q_R = E_s$, is the radiation balance at the sea surface;

$Q_A = G_3 + G_2$, is the net turbulent heat flux from the sea surface;

$Q_T = \rho_s c_s h_s \dfrac{\partial T_s}{\partial t}$, is the rate of oceanic heat storage;

and

$Q_V = \rho_s c_s h_s (V_{ST} \cdot \nabla T_s - K_s \nabla^2 T_s)$, is the heat flux divergence due to oceanic motions, assuming $\nabla \cdot V_{ST} = 0$.

$Q_T + Q_V$, is the net oceanic heat gain.

Etter (1983) has shown that in the Gulf of Mexico the contribution of the vertical component of the currents to the heat flux divergence is relatively small, which implies that the assumption $\nabla \cdot V_{ST} = 0$ is justified.

The radiation balance Q_R at the sea surface is computed in the model considering the short-wave radiation ($\alpha_1 I$) and the long-wave radiation or effective back radiation, using the formulas of Berliand-Budyko and Budyko (1974), as in a previous paper (Adem *et al.*, 1991).

Then Q_R is written as follows:

$$\begin{aligned} Q_R = & -\delta\sigma T_a^4 [0.254 - 0.0066 U e_s(T_a)](1 - c \in) \\ & - 4\delta\sigma T_a^3 (T_s - T_a) + \alpha_1 I \end{aligned} \tag{3}$$

where $\delta = 0.96$ is the emissivity of the sea surface, $\sigma = 8215 \times 10^{-14}$ cal cm^{-2} K^{-4} min^{-1} is the Stefan-Boltzman constant, T_a is the ship-deck air temperature, U is the ship-deck air relative humidity, $e_s(T_a)$ is the saturation vapor pressure at the ship-deck air temperature, $\in$ is the fractional cloudiness and $c = 0.65$ is a cloud cover coefficient.

The net turbulent heat flux from sea surface Q_A is obtained with the following formula:

$$Q_A = K_4 |V_a| [0.981 e_s(T_s) - U e_s(T_a)] + K_3 |V_a| (T_s - T_a), \tag{4}$$

where $|V_a|$ is the ship-deck wind speed in ms^{-1}, $e_s(T_s)$ is the saturation vapor pressure at the ocean surface temperature in dynes cm^{-2} computed as a linear function of temperature (Clapp *et al.*, 1965), and K_4 and K_3 are constants computed from the following expressions:

$$K_4 = \rho_a L \frac{0.622}{p} C_E$$

and

$$K_3 = \rho_a C_{pa} C_H,$$

where L is the latent heat of vaporization for the Gulf of Mexico (2.44×10^{10} erg g^{-1}), p is the pressure at the surface (1×10^6 dynes cm^{-2}), C_{pa} is the specific heat of the air at constant pressure (1004×10^4 erg K^{-1} g^{-1}), ρ_a is the air density (1.225×10^{-3} g cm^{-3}), C_E is a transference latent heat coefficient, and C_H is a transference sensible heat coefficient. We use $C_E = C_H = 1.6 \times 10^{-3}$ which is a value between the one used by Budyko (1963), $C_E = C_H = 2.1 \times 10^{-3}$, and the one used by Hastenrath and Lamb (1978), $C_E = C_H = 1.4 \times 10^{-3}$.

In this work K_3 is expressed in g cm^{-1} s^{-1} K^{-1}, Q_A in erg cm^{-2} s^{-1} or Wm^{-2}, and K_4 is a non-dimensional constant.

The heat flux divergence due to oceanic motions is calculated by the following expression:

$$Q_V = \rho_s c_s h_s V_{ST} \cdot \nabla T_s - \rho_s c_s h_s K_s \nabla^2 T_s, \tag{5}$$

in which the horizontal velocity of the ocean current V_{ST} is taken as $V_{ST} = C_1 V_{SW}$, where C_1 is a constant and V_{SW} is the normal seasonal surface ocean current. As in previous papers we use $C_1 = 0.235$, which corresponds to the resultant pure drift current in the whole frictional layer (Adem 1970, Adem *et al.*, 1991). For the Austausch coefficient K_s we use the value of 3×10^7 cm^2 s^{-1} (Adem *et al.*, 1991).

Substituting (3), (4) and (5) in (2) we obtain a second-order differential equation in T_s, which is solved using the initial and boundary conditions as described in a previous paper (Adem *et al.*, 1991). Substituting the computed T_s in the expressions for Q_R, Q_T, Q_A and Q_V we obtain these variables, so that the heating and transport components are variables that, together with the surface temperature, are computed from the above system of simultaneous equations.

The normal seasonal surface ocean current V_{SW} is obtained from the Atlas Oceanográfico del Golfo de México y Mar Caribe (Secretaría de Marina, 1974), T_a is taken from the U. S. Navy Marine Climatic Atlas of the World (1981), U and $|V_a|$ from the U. S. Weather Bureau (1952) and U. S. Navy (1955-58); $\in$ is obtained from maps of normal cloud (London, 1955), and α from albedo charts prepared by Posey and Clapp (1964).

RESULTS

We have computed, for the Gulf of Mexico, maps of the different heating components for the twelve months of the year. However, we will show only January and July, which will be compared with the corresponding maps of the *revised set* of Isemer and Hasse (1987).

Figures 1 and 2 show the radiation balance for July and January respectively, where parts A are the values computed from the model and B those computed by Isemer and Hasse (1987).

For July the computed radiation balance, shown in Figure 1A, presents an important zonal variation from 250 Wm^{-2} in the NW of the Gulf to 220 Wm^{-2} in the Strait of Florida. In the Bay of Campeche (SW of the Gulf of Mexico) the range of values obtained was between 210 Wm^{-2} in the north, and 170 Wm^{-2} in the south. Such distribution of values is in some agreement with those presented in Figure 1B, where a decrease is observed from the middle of the Gulf to the Bay of Campeche. However, the gradients of 1B are much smaller than those of 1A.

The computed radiation balance contours for January (Figure 2A) show a north-south variation between 80 and 140 Wm^{-2}. The corresponding values of Isemer and Hasse (1987) are between 60 and 100 Wm^{-2} (Figure 2B).

Figures 3 and 4 show the turbulent latent heat flux (G_3), for July and January, respectively, where parts A are the values computed by the model and B those computed by Isemer and Hasse (1987).

The turbulent latent heat flux is the principal cause for the loss of heat in the oceans. In general it is smaller in summer than in winter, as can be see by comparing Figures 3 and 4. The patterns are due mainly to the surface wind speed and to the specific humidity. In July, the values computed by the model vary between 100 and 150 Wm^{-2} (Figure 3A), while Isemer and Hasse's values vary from 120 to 150 Wm^{-2} (Figure 3B). Larger values of latent heat flux occur in January where the model reaches the value 200 Wm^{-2} in almost all the Gulf (Figure 4A). The maximum value obtained by Isemer and Hasse is 270 Wm^{-2} (Figure 4B).

Figure 5 shows the sensible heat flux (G_2) for July, where in part A are the values simulated by the model and in part B those computed by Isemer and Hasse (1987). The simulated patterns have larger gradients; however, the average values for the Gulf of Mexico are in good agreement. Figure 6 shows the sensible heat flux for January, the simulated patterns (part A) are in agreement with those obtained by Isemer and Hasse (1987) (part B).

The rate of oceanic heat storage (Q_T) computed by the model is presented in Figures 7 and 8, for July and January, respectively. In July the rate of oceanic heat storage is between 40 and 170 Wm^{-2} with increasing values towards the northern part of the Gulf (Figure 7). In January the values are between -50 and -150 Wm^{-2} and also with increasing absolute values towards the north (Figure 8).

Table 1 shows a comparison of the values of mean annual radiation balance, short-wave radiation and long-wave radiation simulated by the model, with those computed by Budyko (1963), Bunker (Etter, 1983), Hastenrath and Lamb (1978) and the revised set by Isemer and Hasse (1987). The corresponding annual cycles of radiation balance are plotted in Figure 9, which shows that the curves are very similar, except for that of Hastenrath and Lamb which is somewhat lower than the others.

Table 2 includes the mean annual values of the turbulent heat flux (Q_A) from the sea surface of the Gulf of Mexico, as well as its components, latent heat flux G_3 and sensible heat flux G_2, obtained by the thermodynamic model and by other authors. The simulated values are in good agreement with the averages of the other values.

The annual cycle of the turbulent heat flux (Q_A) is plotted in Figure 10 showing that the model simulation is in agreement with the results of other authors.

Table 3 shows a summary of seasonal and annual mean values of the radiation balance Q_R, the turbulent heat flux Q_A, the oceanic heat gain ($Q_T + Q_V$), the rate of oceanic heat storage Q_T and the horizontal transport of heat by ocean currents and by turbulent eddies Q_V, in the Gulf of Mexico, computed by: (A) the thermodynamic model, (B) Etter (1983) and (C) Isemer and Hasse (1987), who did not compute values of Q_T and Q_V.

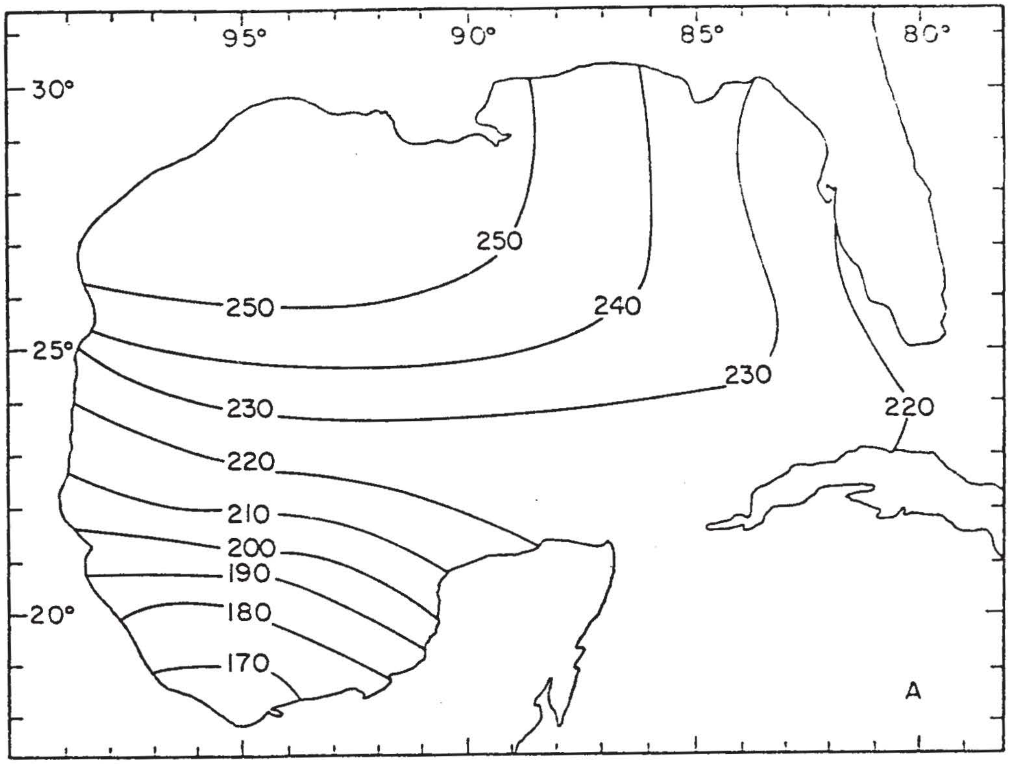
Etter (1983), estimated Q_V as a residual by substracting Q_T from the net oceanic heat gain, and took Q_R and Q_A as the average of Bunker (1976- supplemented with more detailed but unpublished monthly results), and Hastenrath and Lamb (1978). The Q_T values estimated by Etter represent the means of the annual marches of the rates of oceanic heat storage in the NW, NE, SW and SE regions of the Gulf of Mexico, when weighted by region size.

The graphs of annual cycle of Q_T, Q_R, Q_A and $Q_T + Q_V$, obtained by the model simulation, are shown in Figure 11.

FINAL REMARKS

The advantages of the method proposed in this paper to estimate the components of the heat budget is that all of them are computed as variables of a system of equations which satisfies the heat balance equation, without having to treat one of the components as a residue.

The method can be improved by improving the parameterizations used. Furthermore, a more general formulation can be used, considering the model applied to the complete ocean-atmosphere-continent system as described in previous papers (Adem, 1982; Adem and Donn, 1981).



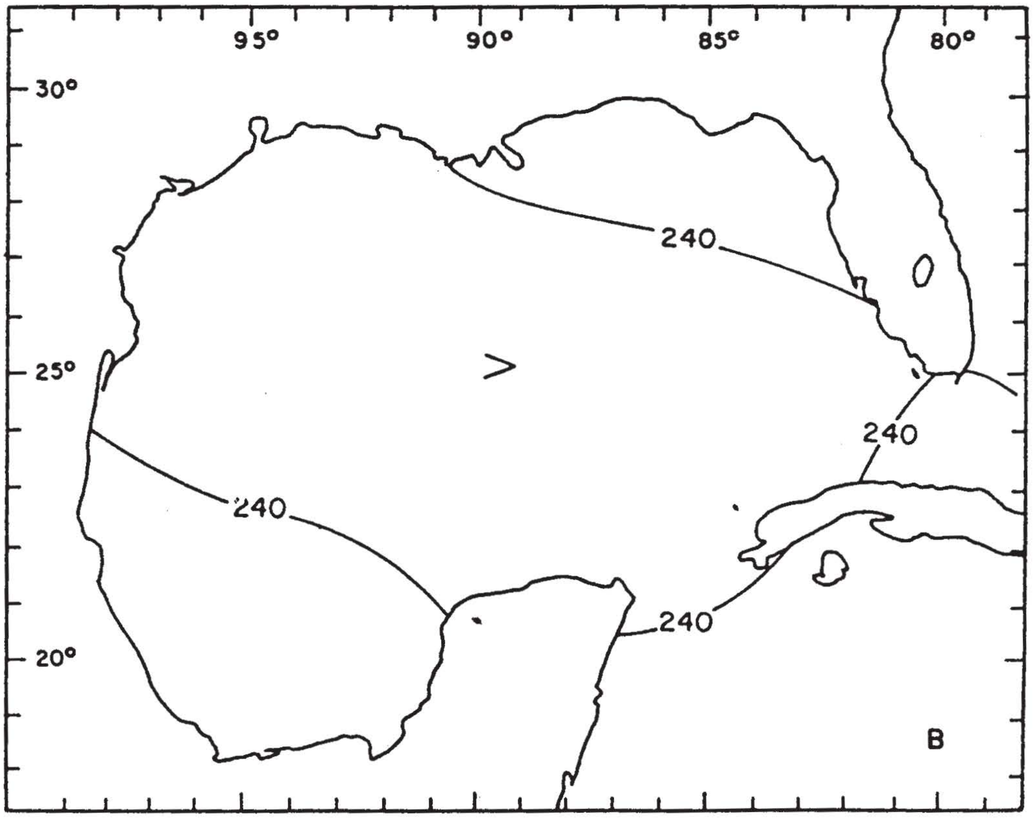


Fig. 1. Net radiation in Wm^{-2}, obtained for July: **A**, Model Simulation; **B**, revised set by Isemer and Hasse (1987).

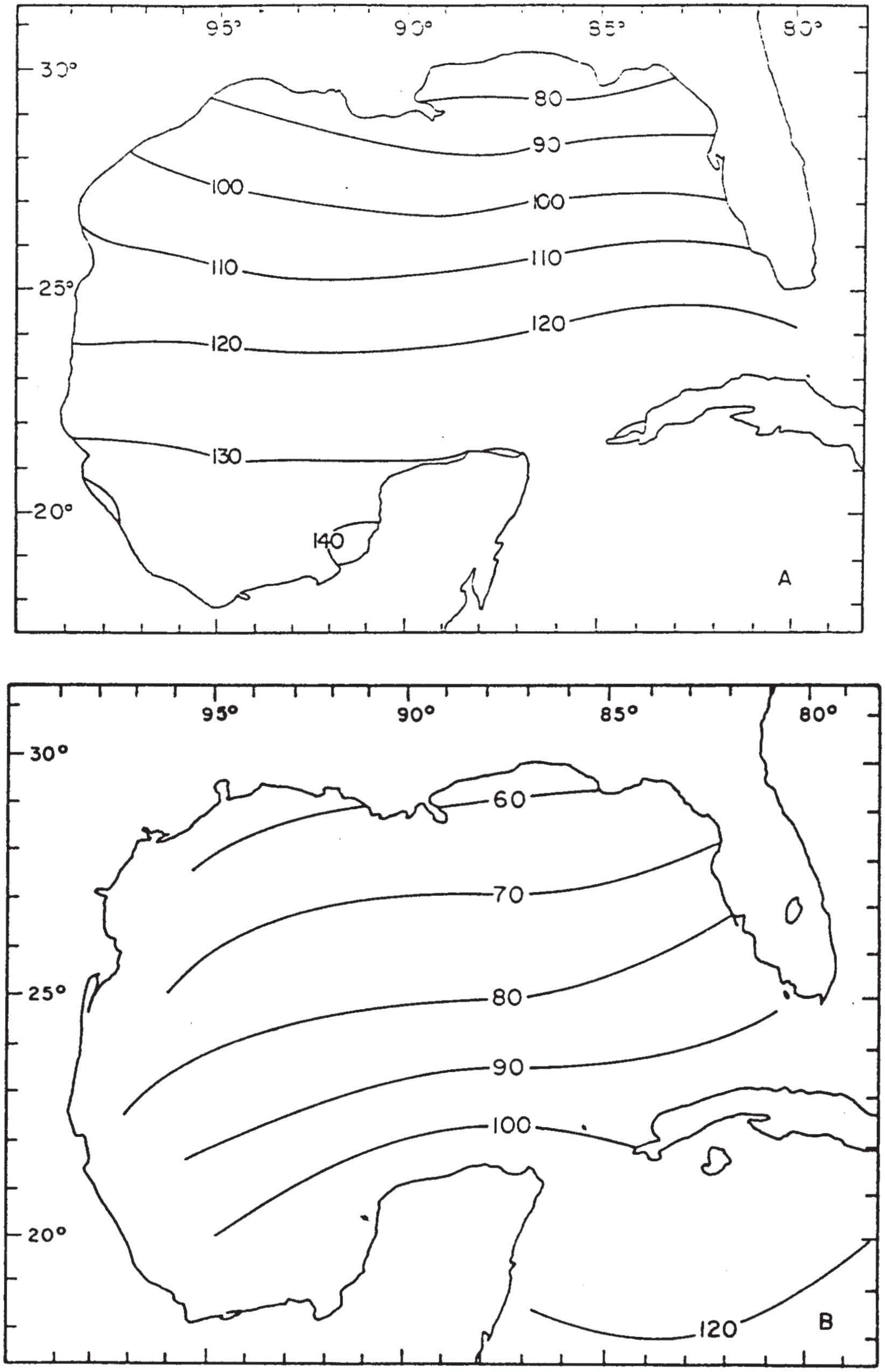


Fig. 2. Net radiation in Wm^{-2}, obtained for January: **A**, Model Simulation; **B**, revised set by Isemer and Hasse (1987).

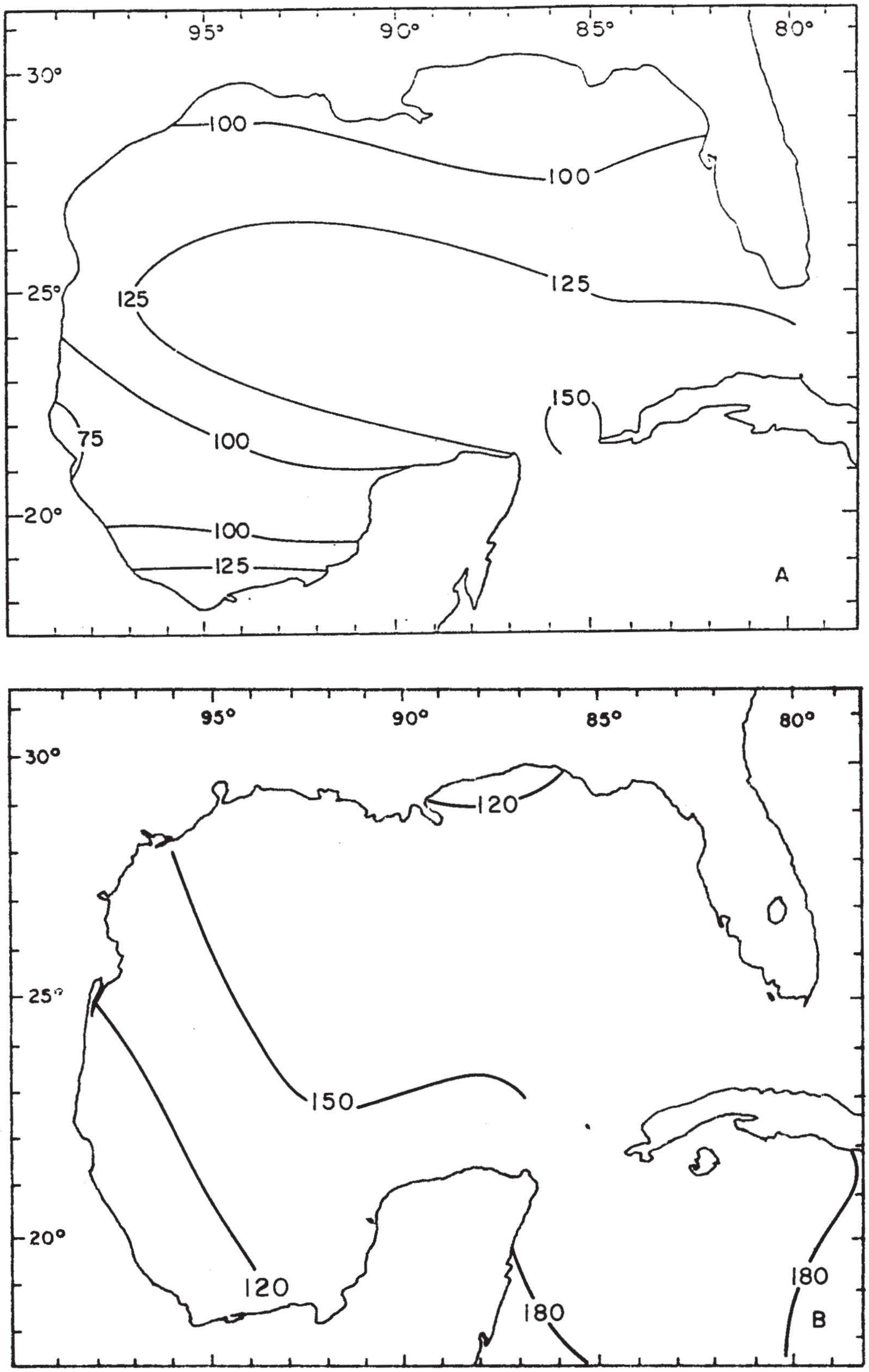


Fig. 3. Latent heat flux in Wm^{-2}, obtained for July: **A**, Model Simulation; **B**, revised set by Isemer and Hasse (1987).

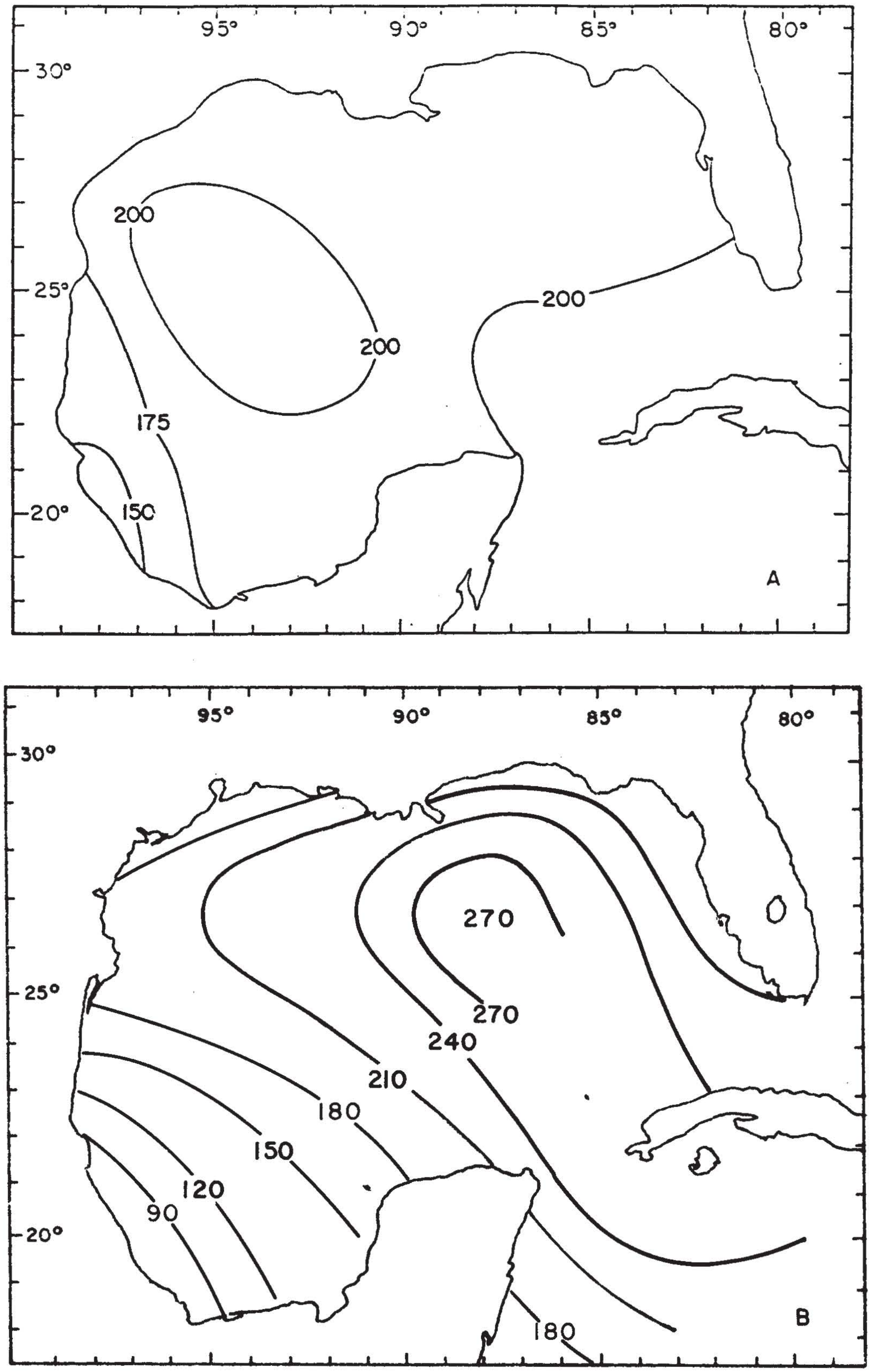


Fig. 4. Latent heat flux in Wm^{-2}, obtained for January: **A**, Model Simulation; **B**, revised set by Isemer and Hasse (1987).

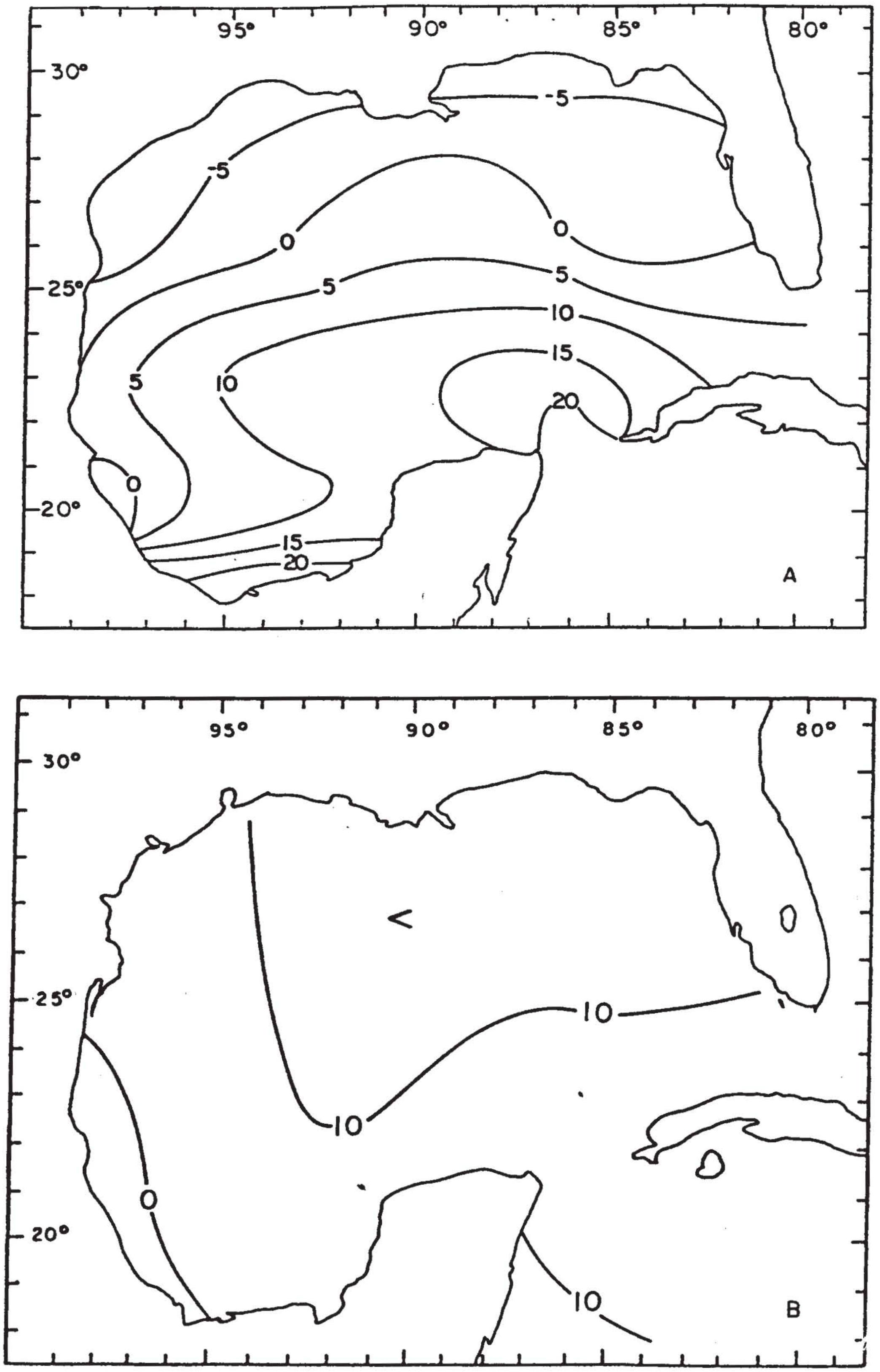


Fig. 5. Sensible heat flux in Wm^{-2}, obtained for July: A, Model Simulation; B, revised set by Isemer and Hasse (1987).

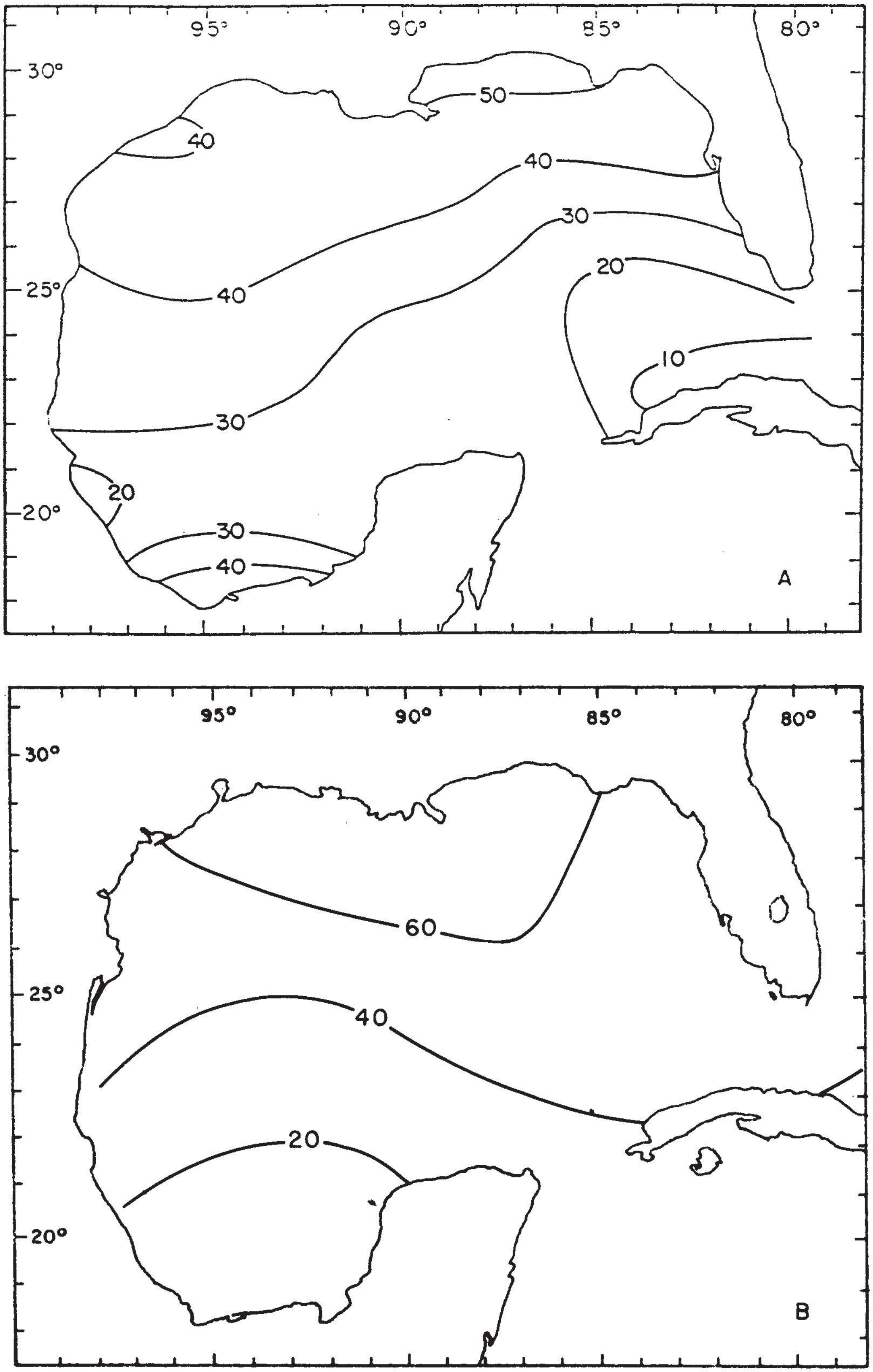


Fig. 6. Sensible heat flux in Wm^{-2}, obtained for January: **A**, Model Simulation; **B**, revised set by Isemer and Hasse (1987).

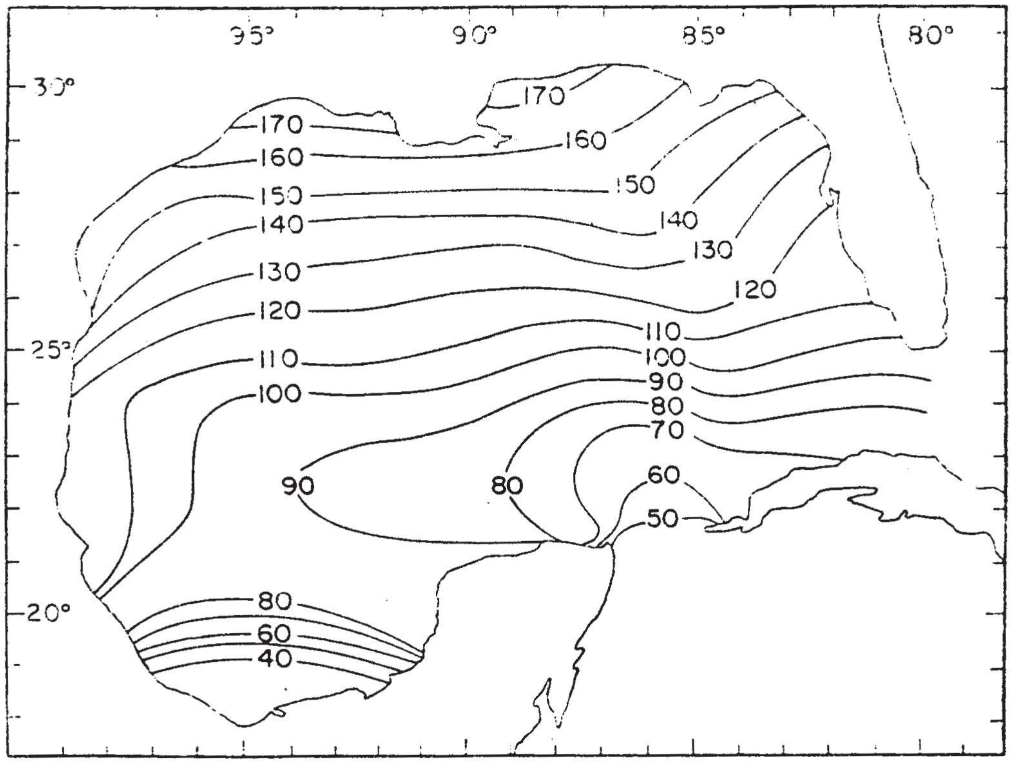


Fig. 7. Rate of oceanic heat storage (Q_T) computed by Model Simulation for July in Wm^{-2}.

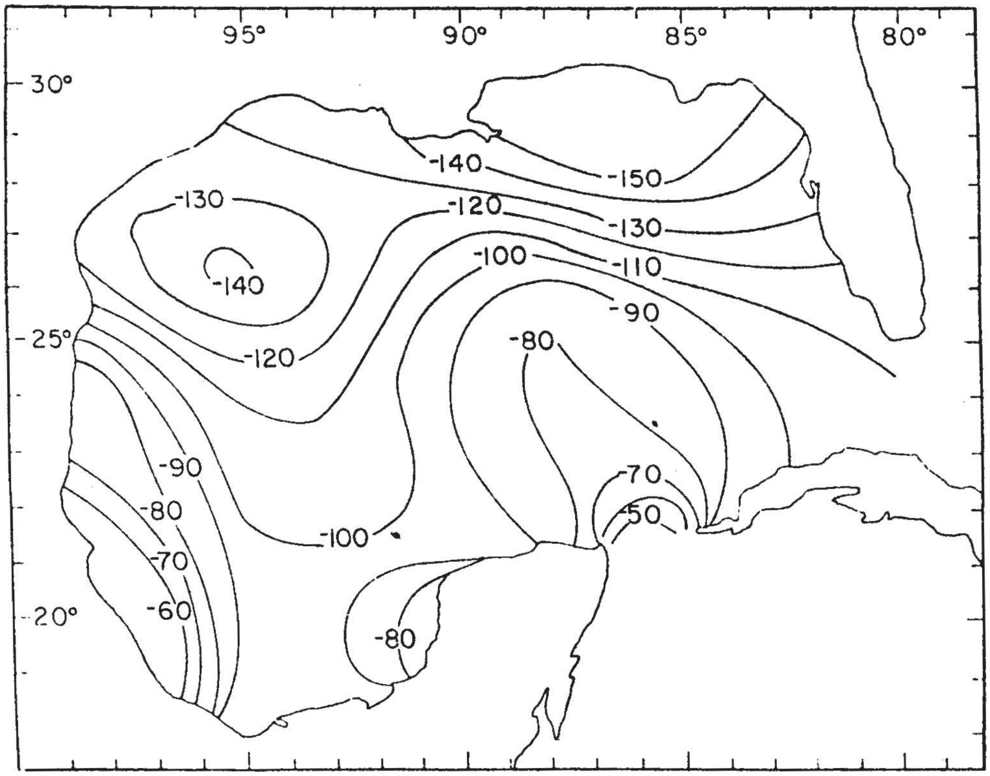


Fig. 8. Rate of oceanic heat storage (Q_T) computed by Model Simulation for January in Wm^{-2}.

Table 1

Annual means of radiation balance (Q_R), short-wave radiation ($\alpha_1 I$), and long-wave radiation (Q_B), for the Gulf of Mexico in Wm^{-2}.

	Q_R	$\alpha_1 I$	Q_B
Model Simulation	176	226	50
Budyko (1963)	158	204	46
Bunker (Etter, 1983)	148	203	55
Hastenrath and Lamb (1978)	109	181	72
Isemer and Hasse (1987)	168	209	41

Table 2

Annual means of turbulent heat flux Q_A, latent heat flux G_3 and sensible heat flux G_2, for the Gulf of Mexico in Wm^{-2}.

	Q_A	G_3	G_2
Model Simulation	179	164	15
Budyko (1963)	158	139	19
Bunker (Etter, 1983)	169	150	19
Hastenrath and Lamb (1978)	136	126	10
Isemer and Hasse (1987)	213	193	20

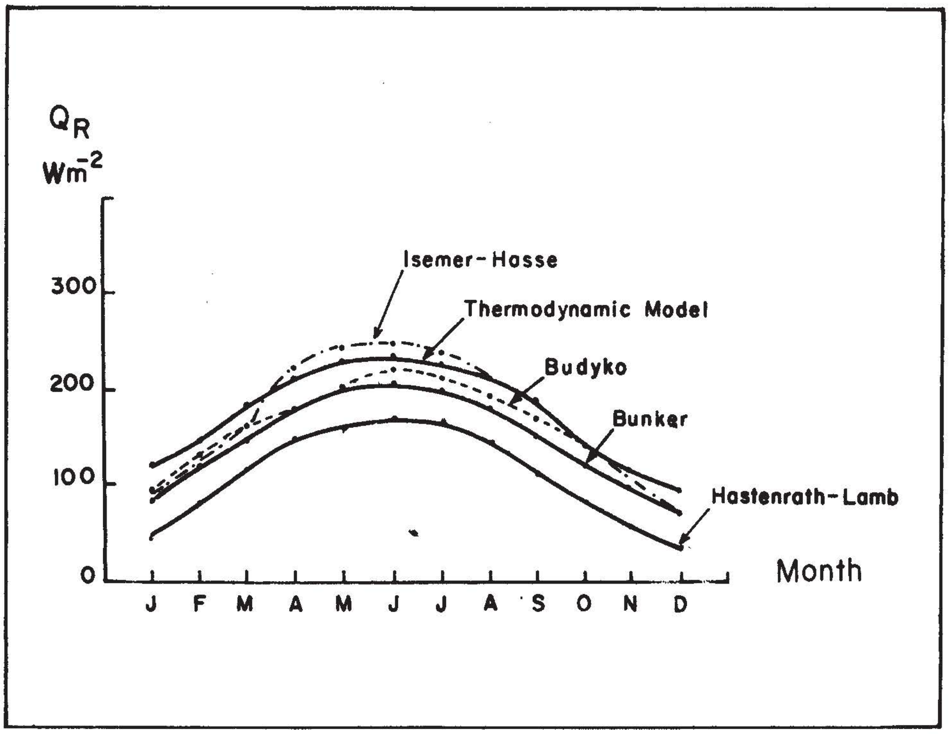


Fig. 9. Annual cycle of radiation balance (Q_R) in the sea surface of the Gulf of Mexico in accordance with the Model Simulation, revised set by Isemer and Hasse (1987), Budyko (1963), Hastenrath and Lamb (1978) and Bunker (Etter, 1983) in Wm^{-2}.

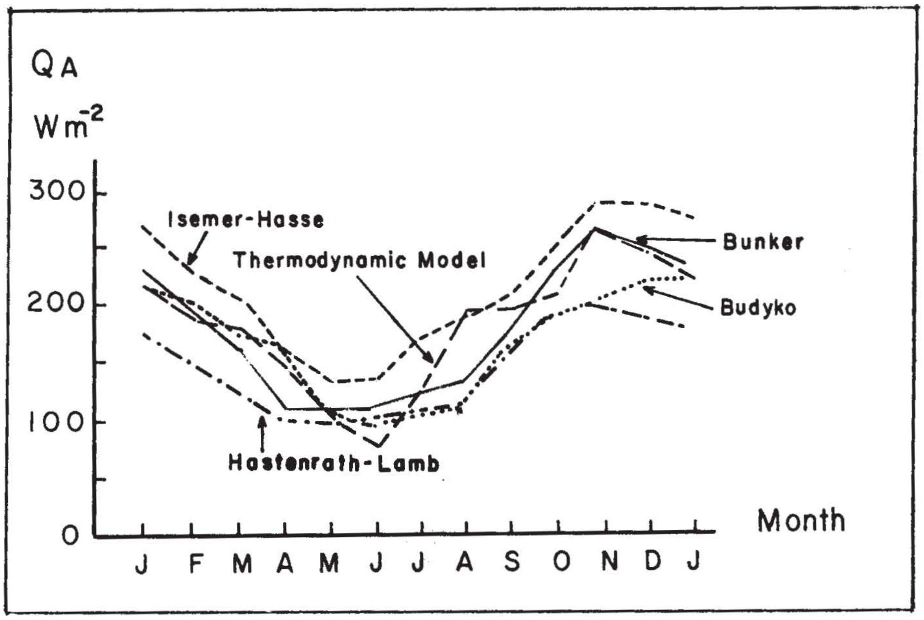


Fig. 10. Annual cycle of net turbulent heat flux (Q_A) in the sea surface of the Gulf of Mexico in accordance with: the Model-Simulation, revised set by Isemer and Hasse (1987), Budyko (1963), Hastenrath and Lamb (1978) and Bunker (Etter 1983) in Wm^{-2}.

Table 3

Summary of seasonal and annual mean values of the radiation balance (Q_R), the turbulent heat flux (Q_A), the oceanic heat gain ($Q_T + Q_V$), the oceanic heat storage (Q_T) and the horizontal transport of heat by ocean currents and by turbulent eddies (Q_V) in the Gulf of Mexico in Wm^{-2}. Computed from: **A** Thermodynamic Model, **B** Etter (1983), **C** Isemer and Hasse (1987). Spring is from March to May, summer from June to August, autumn from September to November and winter from December to February.

	Q_R	Q_A	$Q_T + Q_V$	Q_T	Q_V
SPRING					
A	213	148	82	72	9
B	160	114	46	103	-57
C	203	165	37		
SUMMER					
A	226	126	102	101	1
B	178	109	69	89	-20
C	238	168	73		
AUTUMN					
A	149	218	-69	-69	0
B	106	195	-89	-60	-29
C	136	256	-120		
WINTER					
A	117	222	-93	-99	6
B	73	194	-121	-132	11
C	95	265	-170		
ANNUAL					
A	176	179	5	1	4
B	129	153	-24	0	-24
C	168	213	-45		

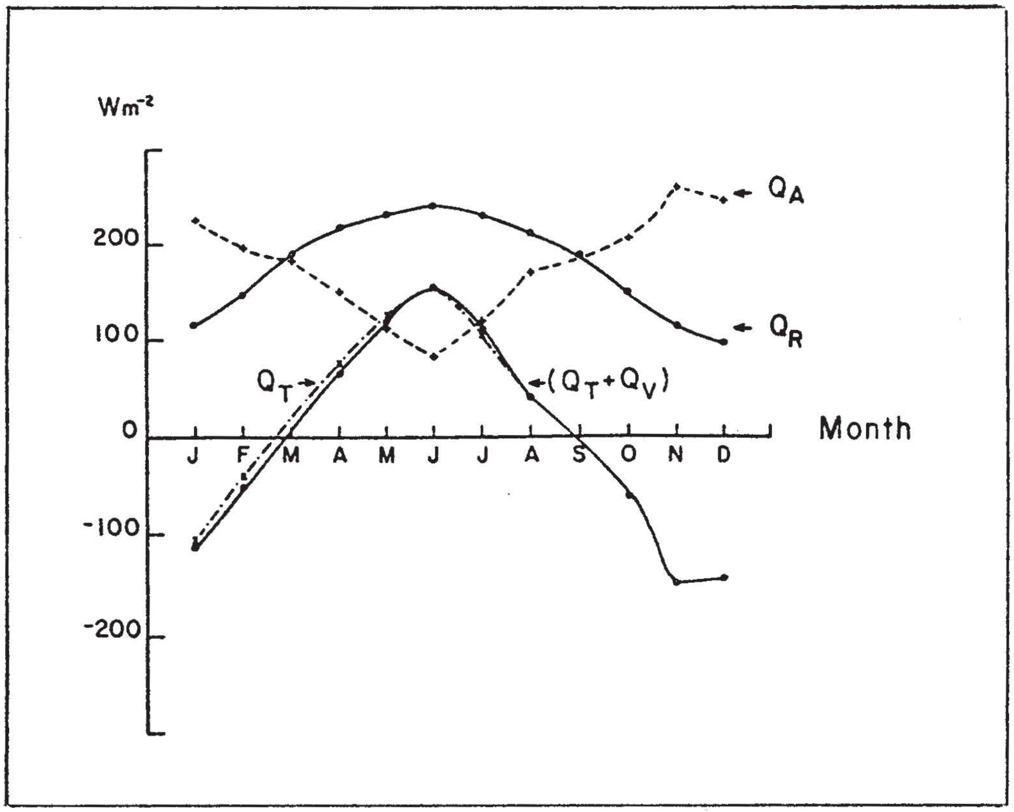


Fig. 11. Model Simulation of the annual cycle of the net heat gain ($Q_T + Q_V$), the oceanic heat storage (Q_T), the radiation balance (Q_R) and the total turbulent heat flux (Q_A), for the Gulf of Mexico, in Wm^{-2}.

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