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On the simulation of the sea surface temperature in the Gulf of Mexico using a thermodynamic model

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RESUMEN

Se usa un modelo termodinámico para simular el ciclo anual de la temperatura normal superficial del mar en el Golfo de México.

El modelo incluye como ecuación básica, la ecuación de energía térmica aplicada a la capa de mezcla del océano. Esta ecuación está integrada verticalmente e incluye el transporte horizontal de calor por corrientes oceánicas medias y por remolinos turbulentos, así como el calentamiento por radiación, el calor sensible cedido a la atmósfera y la evaporación.

El modelo termodinámico se adaptó, usando una malla uniforme en el Golfo de México, con una distancia de 60 km entre puntos consecutivos. En los experimentos numéricos se prescriben las corrientes marinas superficiales observadas y el transporte horizontal de calor a través del Canal de Yucatán, así como las condiciones atmosféricas.

Una comparación objetiva, para todos los meses del año, de las temperaturas calculadas con las observadas, muestra buena concordancia.

ABSTRACT

A thermodynamic model is used to simulate the annual cycle of the sea surface temperature (SST) in the Gulf of Mexico.

The model includes as the basic equation the thermal energy equation applied to the upper mixed layer of the ocean. This equation is vertically integrated and includes the horizontal transport of heat by mean ocean currents and by turbulent eddies, as well as the heating by radiation, sensible heat given off to the atmosphere and evaporation.

The thermodynamic model is adapted, by using a regular grid with a distance of 60 km between adjacent points, covering the whole area of the Gulf of Mexico. In these numerical experiments the observed surface currents and the horizontal transport of heat through the Yucatan Channel are used as prescribed fields, as well as the atmospheric conditions.

An objective comparison of the values of the computed SST with those observed, shows a good agreement.

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Introduction

The large-scale interactions between the ocean and the atmosphere have been studied by several researchers. Among them: Kraus and Morrison (1966), Merrell and Morrison (1981), Cox (1970), Namias (1972) and Namias *et al.* (1988), O'Brien (1971), Haney (1974) and Haney *et al.* (1978), Bryan *et al.* (1975), Huang (1978, 1979), Hurlburt and Thompson (1980) and Han (1984a, b).

We are currently experimenting with a climate thermodynamic model, which uses equations that are expressions of the first law of thermodynamics applied to the troposphere, to the mixed layer of the oceans and to the continental surface. The equations are coupled through heating, radiation and transport terms (Adem, 1982).

This model has been applied with some success to long-range weather prediction (Adem, 1964, 1970b; Donn *et al.*, 1986), to ocean temperature prediction (Adem, 1970a, 1975; Adem and Mendoza, 1987), and to climate simulations (Adem, 1981, 1982, 1988; Adem and Garduño, 1984).

In this study we are using only the thermodynamic equation in the mixed layer of the oceans, over a regular grid with a distance of 60 km between consecutive points, which is adapted to the Gulf of Mexico area, for the purpose of simulating the SST in response to month-to-month prescribed atmospheric conditions and prescribed ocean currents.

Brief description of the model

We will use the conservation of thermal energy equation for the ocean mixed layer, as was derived in a previous paper (Adem, 1970a), and which is the following:

$$\rho_s c_s h_s \frac{\partial T_s}{\partial t} = \rho_s c_s h_s(-\vec{V}_{s_T} \cdot \nabla T_s + K_s \nabla^2 T_s) + (E_s - G_2 - G_3) - \rho_s c_s W \tag{1}$$

Where T_s is the SST, ρ_s a constant density, c_s a constant specific heat, h_s the depth of the upper layer, $\vec{V}_{s_T}$ the horizontal velocity of the ocean current in the layer, K_s a constant austausch coefficient, E_s the rate at which the energy is added by radiation, G_2 the rate at which sensible heat is given off to the atmosphere by vertical turbulent transport, G_3 is the rate at which the heat is lost by evaporation, and W is the heat given off to the thermocline. In the Gulf of Mexico W is small compared with $h_s \vec{V}_{s_T} \cdot \nabla T_s$, and therefore will be neglected (Etter, 1983). In equation (1), the terms $-\rho_s c_s h_s \vec{V}_{s_T} \cdot \nabla T_s$ and $\rho_s c_s h_s K_s \nabla^2 T_s$ are the horizontal transport of heat by mean ocean current and by turbulent eddies respectively and the term $(E_s - G_2 - G_3)$ is the total heating in the upper layer of the ocean.

To compute E_s we shall use for the net long wave radiation Budyko's formula (Budyko, 1974), obtaining the following expression for E_s:

$$E_s = -\delta\sigma T_a^4[0.254 - 0.0066 U e_s(T_a)](1 - c\epsilon)$$

$$-4\delta\sigma T_a^3(T_s - T_a) + \alpha_1 I \tag{2}$$

Where $\delta = 0.96$ is the emissivity of the sea surface, $\sigma = 8215 \times 10^{-14}$ cal $\mathrm{cm}^{-2} K^{-4}$ 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, ϵ is the fractional cloudiness, $c = 0.65$ is a cloud cover coefficient which was taken from Budyko (1974), and $\alpha_1 I$ is the short wave radiation absorbed by the ocean layer.

For $\alpha_1 I$ we use the Berliand-Budyko's formula (Budyko, 1974), which is the following:

$$\alpha_1 I = (Q+q)_o[1-(a+b\epsilon)\epsilon](1-\alpha)$$

where $(Q+q)_o$ is the total radiation received by the surface with clear sky, $a = 0.35$ and $b = 0.38$ are constants, which were taken from Budyko (1974); and α is the albedo of the sea surface.

For the heat lost by evaporation at the surface and the turbulent vertical transport of sensible heat at the surface we will use the so called "bulk" formulas (Jacobs, 1951):

$$G_3 = K_4\,|\vec{V}_a|\,[0.981e_s(T_s) - Ue_s(T_a)] \tag{3}$$

$$G_2 = K_3\,|\vec{V}_a|\,(T_s - T_a) \tag{4}$$

Where K_3 and K_4 are constants, $|\vec{V}_a|$ is the ship-deck wind speed, $e_s(T_s)$ is the saturation vapor pressure at the surface ocean temperature. For the saturation vapor pressure we shall use a linear function of temperature (Clapp *et al.*, 1965).

In equation (1), the austausch coefficient K_s is taken as 3.0×10^7 cm^2 sec^{-1}. This value is in agreement with the determination of the horizontal eddy diffusion coefficient by different authors (Montgomery, 1939; Semtner and Mintz, 1977; Huang, 1978).

For the depth of the mixed layer in the Gulf of Mexico, h_s, we use a value of 60 m (Adem, 1964; Etter, 1983).

For the horizontal velocity of the ocean current $\vec{V}_{sT}$, we use $\vec{V}_{sT} = C_1\,\vec{V}_{sw}$ where C_1 is a constant coefficient and $\vec{V}_{sw}$ is the normal seasonal ocean velocity observed in the surface. In this work as in previous papers (Adem, 1970a; Adem and Mendoza, 1987) we use $C_1 = 0.235$, which corresponds to the resultant pure drift current in the whole frictional layer (Adem, 1970a). The values of T_a were taken from the U. S. Navy Marine Climatic Atlas of the World (1981); U and $|\vec{V}_a|$ from various atlases (U. S. Weather Bureau, 1952; U. S. Navy, 1955-58); $(Q+q)_o$ from Budyko (1955); ϵ from maps of normal cloud cover (London, 1957); α from albedo charts prepared by Posey and Clapp (1964); and $\vec{V}_{sw}$ from Secretaría de Marina (1974).

The method of solution

Equation (1) is integrated explicitly using Euler's formula:

$$\left(\frac{\partial T_s}{\partial t}\right)_i = \frac{T_{s_{i+1}} - T_{s_i}}{\Delta t}$$

where sub-index i will be used to specify the time-step. We use time-steps of $\Delta t = 1$ day or $\Delta t = 5$ days, on a uniform grid with 60 km resolution. To determine the permissible time-step, we carried out an analysis in a similar way as Adem (1971). It consists in calculating the truncation error made when one approximates the time derivative of the SST by the Euler's formula and uses a forward time-step. Given an upper limit for the truncation error (10%), the permissible time-step depends on the scale of the SST observed in the Gulf of Mexico, the surface wind speed $|\vec{V}_a|$, the ocean current speed $|\vec{V}_{sT}|$ and the austausch coefficient K_s. For the case in which we include only the total heating term in equation (1), the permissible time-step is of 5 days. For the case in which we include besides the total heating term, the horizontal transport of heat by mean ocean currents and by turbulent eddies, the permissible time-step is of one day. The normal atmospheric conditions and the short wave radiation, as well as the ocean currents are prescribed month-by-month, so that they change after 30 or 6 time-steps corresponding to each month.

For the spatial derivatives we use centered finite differences. The integration area and the grid points are shown in Fig. 1, the integration is carried out only in the oceanic region.

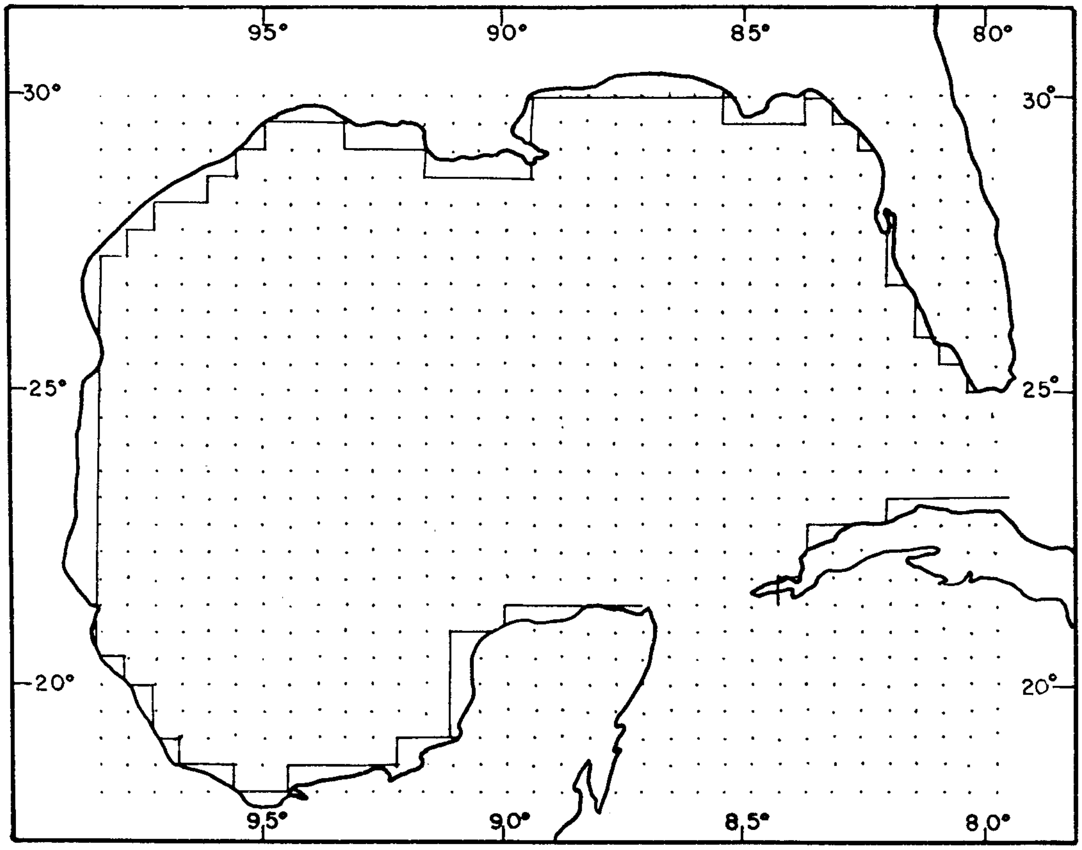

Fig. 1. Region of integration and position of the grid points.

We start the computations with an initial uniform SST of 25°C at the boundary and the interior of the integration region, this value is the observed annual average. Starting in January, the integration was carried out for 4 years, until the computed average value of SST for each of the 12 months of the year had a difference of less than 0.01°C with the corresponding value of the previous year. The explicit method of integration used is stable to variations up to 10°C in the initial condition of the SST, therefore we considered that the annual cycle obtained is independent of the initial condition. We assume that there is no horizontal transport of heat by mean ocean currents and by turbulent eddies in the closed boundaries (coast). Therefore, we apply there equation (1) with only the total heating term. In the open boundaries, we assume that there is a horizontal transport of heat due only to the mean ocean currents and therefore equation (1) can be written:

$$\frac{\partial T_s}{\partial t} = \frac{1}{\rho_s c_s h_s}(E_s - G_2 - G_3 + F_H) \qquad (5)$$

Where F_H is the horizontal transport of heat by mean ocean currents, so that, its value is null in the closed boundaries, while in the open boundaries is computed with the following formula:

$$F_H = -\rho_s c_s h_s \vec{V}_{s_T} \cdot < \nabla T_s > \qquad (6)$$

Where $< \nabla T_s >$ is the horizontal mean temperature gradient in the Yucatan Channel and the Florida Strait. The horizontal mean temperature gradient has been obtained from the observed monthly SST maps (Hastenrath and Lamb, 1977).

In the Florida Strait, for all the months $\vec{V}_{s_T}$ and $< \nabla T_s >$ are for practical purpose perpendicular and therefore we assume that $F_H = 0$, whereas for the Yucatan Channel $\vec{V}_{s_T}$ and $< \nabla T_s >$ are practically parallel for all months.

Results

Table 1 shows the computed values of F_H for the Yucatan Channel for each month of the year in watts per square meter. The table shows that the horizontal transport of heat has a maximum from January to February, and a minimum from June to September.

Table 1. Mean monthly horizontal transport of heat through the Yucatan Channel (F_H), in W m^{-2}, obtained with formula (6).

MONTH	F_H
JAN	140.5
FEB	140.5
MAR	70.0
APR	70.0
MAY	42.2
JUN	14.0
JUL	14.0
AUG	14.0
SEP	14.0
OCT	28.0
NOV	70.0
DEC	70.0

Fig. 2 shows the resultant seasonal ocean current ($\vec{V}_{sT} = C_1 \vec{V}_{sw}$) for winter in the Gulf of Mexico, in cm $\sec^{-1}$.

In figures 3 and 4 are shown respectively the normal SST for January and July computed using in equations (1) and (5) only the total heating term. The corresponding values of the observed normal SST (Hastenrath and Lamb, 1977) are shown in Figs. 5 and 6.

A comparison of Figs. 3 and 4 with the corresponding Figs. 5 and 6 shows that the temperature patterns for winter and summer are relatively well simulated by this simplified model.

In Figs. 7 and 8 are shown respectively the normal SST for January and July, computed using in equations (1) and (5) all the terms. A comparison of these figures with Figs. 5 and 6, shows a good agreement. Comparison of Fig. 7 with Fig. 3 shows that for January the computed isotherms pattern is highly influenced by the horizontal transport of heat by mean ocean currents and by the transport of heat through the Yucatan Channel, improving the simulation of the SST pattern.

Fig. 9 shows the annual cycle of the average for the total region of integration (Gulf of Mexico) of the normal SST for the observed values (continuos line) and for the corresponding computed values using equations (1) and (5), with all the terms included (dashed line). The agreement between the two curves is excellent.

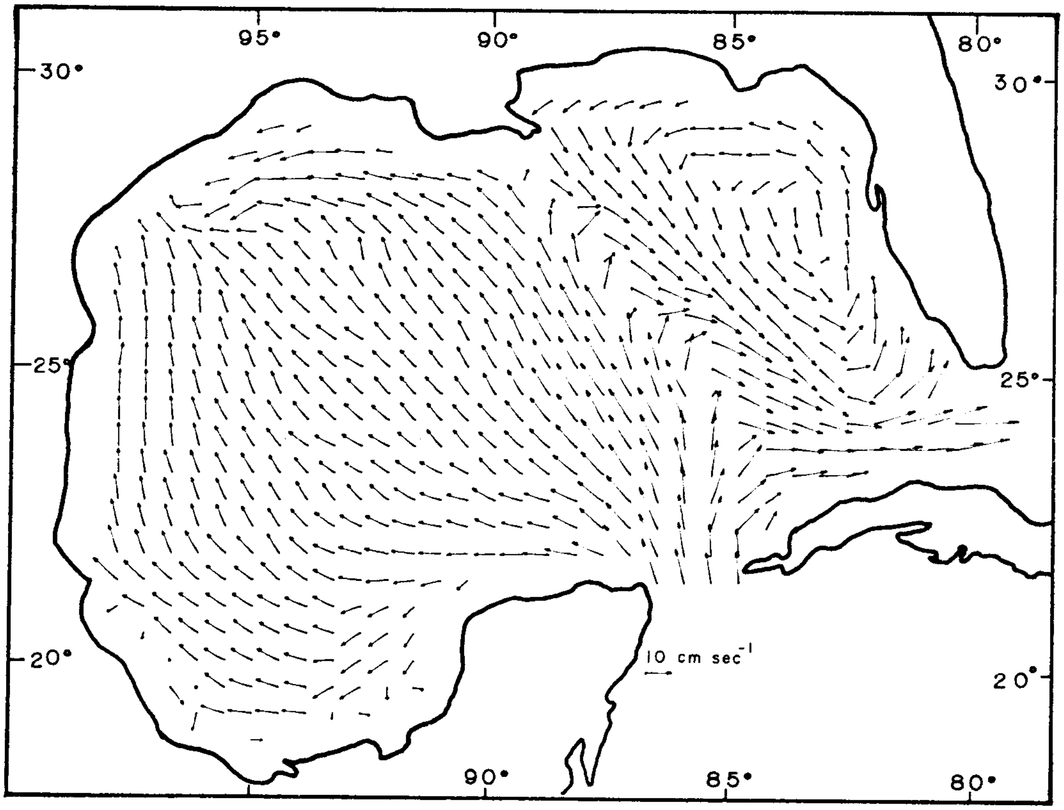

Fig. 2. Resultant seasonal ocean current in the mixed layer in the Gulf of Mexico for winter in cm $\sec^{-1}$.

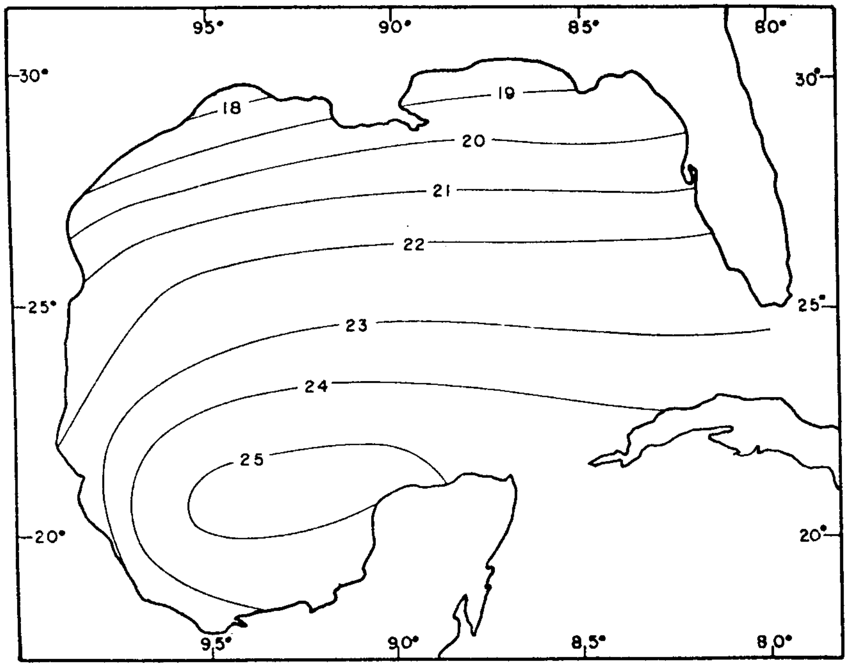

Fig. 3. Computed normal sea surface temperature (SST °C) for January, using only heating by radiation, sensible heat given off to the atmosphere, and heat lost by evaporation.

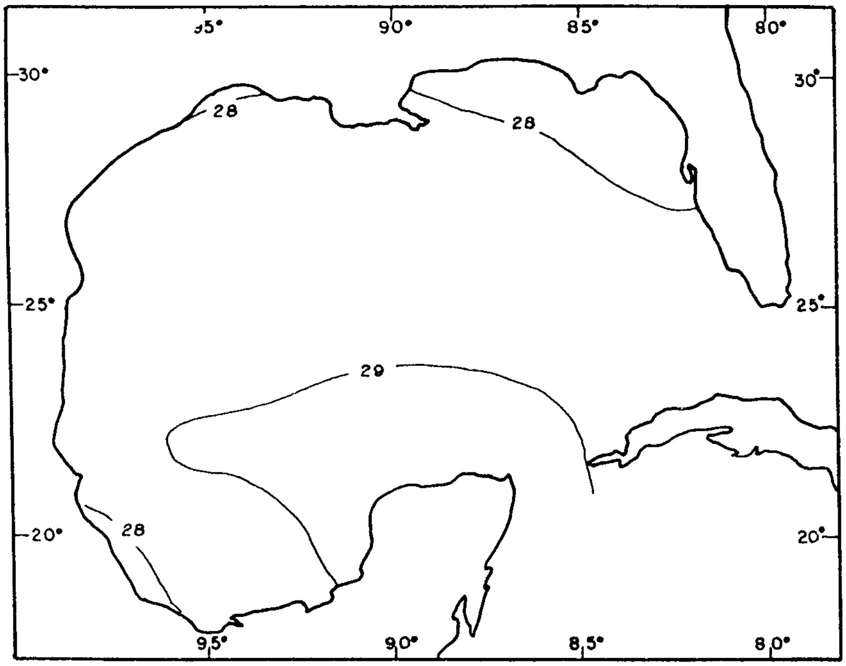

Fig. 4. Computed normal SST (°C) for July, using only heating by radiation, sensible heat given off to the atmosphere, and heat lost by evaporation.

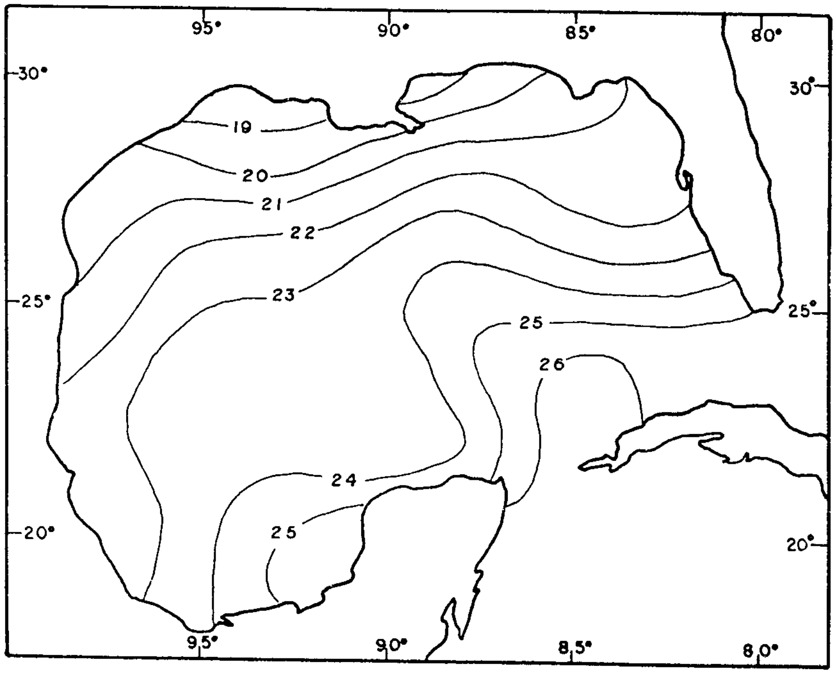

Fig. 5. Observed normal SST (°C) for January (Hastenrath and Lamb, 1977).

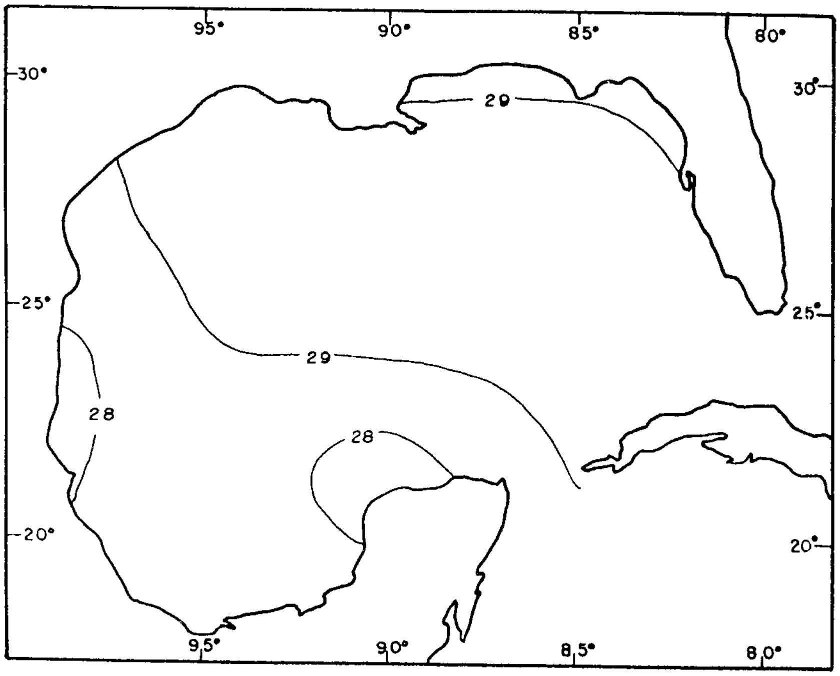

Fig. 6. Observed normal SST (°C) for July (Hastenrath and Lamb, 1977).

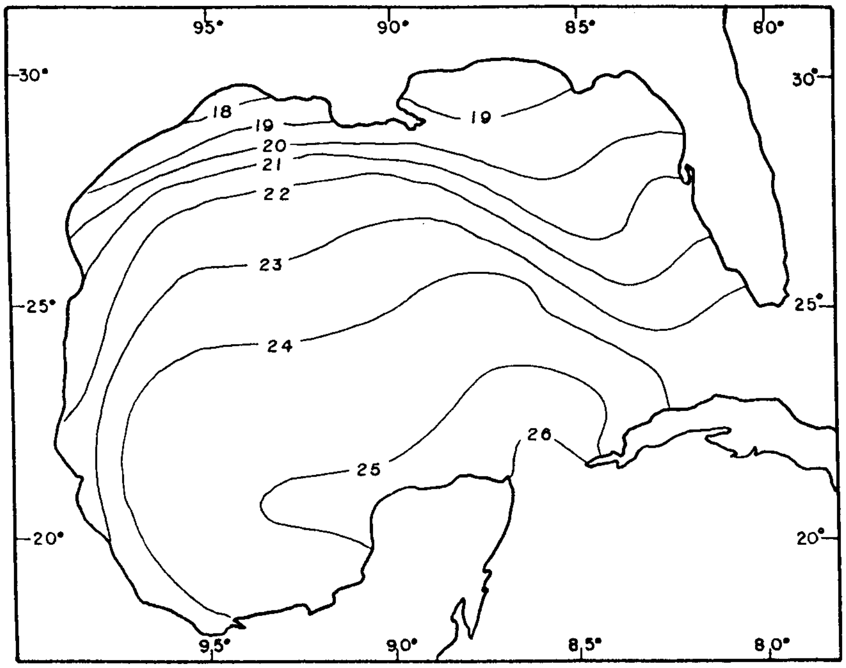

Fig. 7. Computed normal SST (°C) for January, using the complete model.

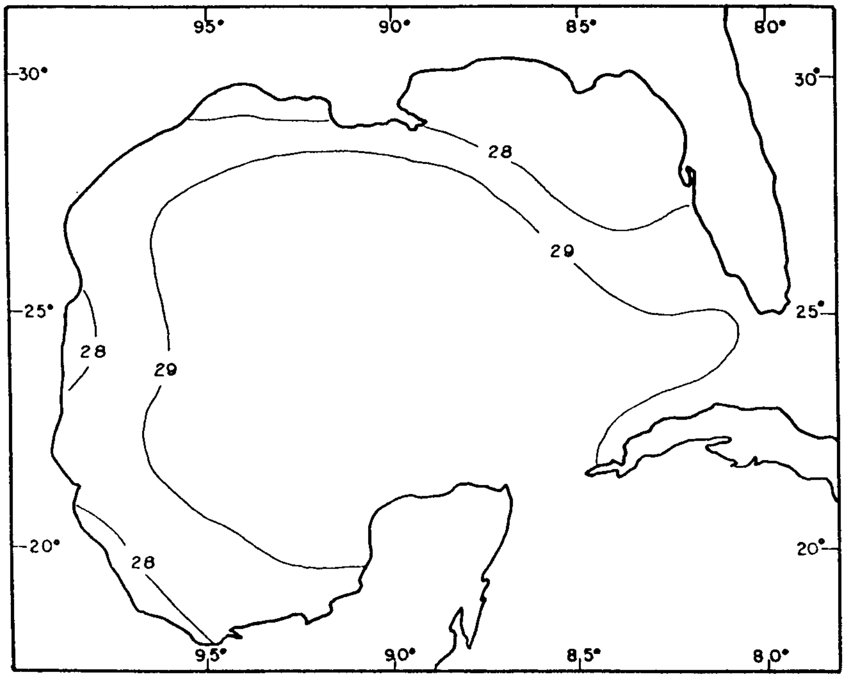

Fig. 8. Computed normal SST (°C) for July, using the complete model.

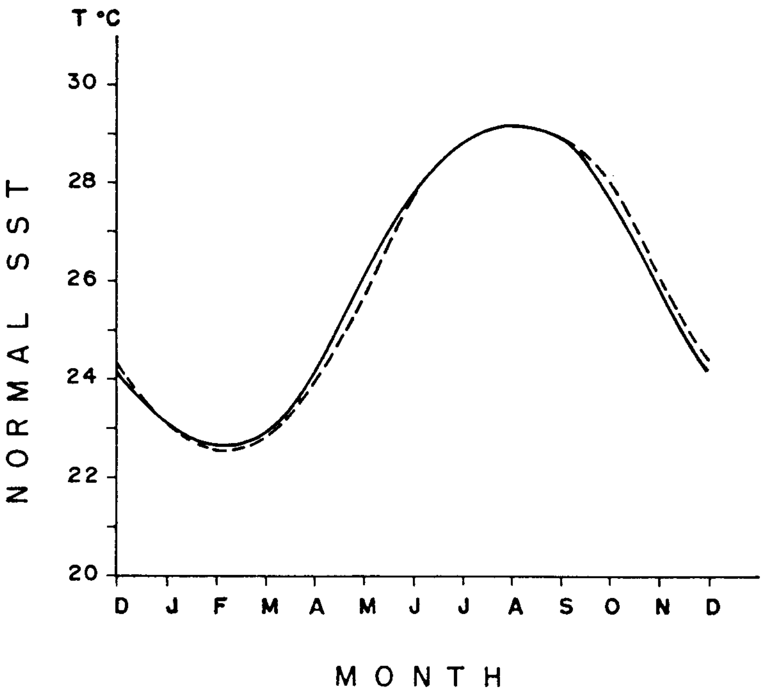

Fig. 9 Annual cycle of the average normal SST (°C) in the Gulf of Mexico. Continuos line: observed. Dashed line: computed, using the complete model.

To evaluate in an objective way the numerical simulations, we computed the correlation coefficient and the root mean square error (RMSE) between the observed and the simulated SST values. For the case in which we include the total heating and the transport terms in equation (1), the correlation coefficient is equal to 0.88, 0.95, 0.98, 0.89 and 0.92 for the months included in winter, spring, summer, fall and the whole year respectively. When only the total heating term is included, these values are reduced by 0.04, 0.01, 0.00, 0.01 and 0.01 respectively.

Similarly for the case in which we include the total heating and the transport terms in equation (1), the RMSE, in Celsius degrees, is equal to 0.85, 0.60, 0.84, 0.85 and 0.79 for the months included in winter, spring, summer, fall and the whole year respectively. When only the heating terms are included, these values are increased by 0.10, 0.00, 0.02, 0.09 and 0.05 respectively.

These two evaluations show that the simulation of SST for all months is good in the two experiments carried out, but better for the case when, besides the total heating, the horizontal transport of heat by mean ocean currents and turbulent eddies is included. The largest effect due to the horizontal transport of heat appears to occur in winter and fall, and the smallest in spring and summer, in the way illustrated for January in the comparison of Fig. 7 with Fig. 3 and for July in the comparison of Fig. 8 with Fig. 4.

Final remarks and conclusions

Starting from a uniform temperature of 25°C at all grid points the 12 monthly maps of the normal SST (annual cycle) in the Gulf of Mexico were simulated using equation (1). The solution is obtained after four years of integration with time-steps of 1 or 5 days. In the experiments we prescribed in the Gulf of Mexico the monthly atmospheric forcing, the seasonal ocean current, as well as the horizontal transport of heat through the Yucatan Channel, which was computed from observations. The simulated temperatures are in good agreement with the observed temperatures.

The Gulf of Mexico circulation is highly influenced by the transport of heat through the Yucatan Channel (Maul, 1977), therefore, in this model we used a variable inflow as boundary condition at such Channel. The results show that the horizontal transport of heat imposed in the Yucatan Channel together with the horizontal transport of heat by mean ocean currents improves the solution obtained when only total heating is included. In particular, it produces in the January case (Fig. 7) the isotherm of 26°C, which is also present in the corresponding observed values of SST (Fig. 5).

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