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Preliminary experiments on the prediction of sea surface temperature anomalies in the Gulf of Mexico

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RESUMEN

Se usa un modelo termodinámico para predecir anomalías medias mensuales de la temperatura de la superficie del mar y de sus cambios mes a mes en el Golfo de México. La ecuación de predicción básica del modelo es la ecuación de la energía térmica aplicada a la capa de mezcla del océano, la cual incluye el transporte horizontal de calor por corrientes oceánicas estacionales y por remolinos turbulentos, así como el calentamiento por radiación de onda corta y larga, evaporación y calor sensible. Se hace un estudio comparativo sobre la relativa importancia para la predicción de los términos de calentamiento y transporte. Se presenta una verificación objetiva de las predicciones para cada estación y para todo el periodo de marzo de 1986 a febrero de 1987, la cual muestra habilidad en los signos correctamente predichos de las anomalías de la temperatura de la superficie del mar y de sus cambios mes a mes, cuando únicamente los términos de calentamiento son incluidos en las predicciones. Sin embargo, la habilidad se incrementa cuando también es incluido el transporte horizontal de calor.

PALABRAS CLAVE: Predicción, modelo termodinámico, Golfo de México.

ABSTRACT

A thermodynamic model is used to predict the mean monthly sea surface temperature anomalies and their month-to-month changes in the Gulf of Mexico. The basic predicting equation of the Model is the thermal energy equation applied to the upper mixed layer of the ocean, which includes the horizontal transport of heat by seasonal ocean currents and by turbulent eddies, as well as the heating by short and long-wave radiation, evaporation and sensible heat. A comparative study is carried out on the relative importance for the prediction of the heating and transport terms. An objective verification of the predictions is presented for each season and for the whole period from March 1986 to February 1987, which shows skill in the signs correctly predicted of the sea surface temperature anomalies, as well as of their month-to-month changes, when the heating terms are only included in the predictions. However, the skill is increased when the horizontal transport of heat is also included.

KEY WORDS: Prediction, thermodynamic model, Gulf of Mexico.

1. INTRODUCTION

Several works concerning long-range numerical weather prediction have been carried out using the thermodynamic climate model of Adem (1970a). The basic predicting equation of this model is the conservation of thermal energy, applied to the tropospheric layer, to the ocean mixed layer and to the surface continental layer (Adem, 1964a; 1964b; Adem, 1991). Other conservation laws are used together with semi-empirical relations to parameterize the heating and transport components.

The model has also been used with success for predicting the sea surface temperature (SST) anomalies in the Northern Hemisphere (Adem, 1970a, b; 1975). To improve these predictions, Adem and Mendoza (1987) optimized some parameters that appear in the heating and transport terms. Afterwards, in order to determine the importance of the different factors on which the predictions are dependent, and to establish the degree of skill of the predictions, Adem and Mendoza (1988) carried out an objective verification in the Pacific and Atlantic oceans for a 36-months period. The results showed some degree of skill due to the heating, the horizontal turbulent transport, and the transport of heat due to the wind drift ocean currents. Another verification was carried out for the Gulf of Mexico and the Caribbean Sea by Adem (1976), showing also good results.

In order to study the SST anomalies in smaller oceanic areas, a version of the Thermodynamic Climate Model for the ocean has been adapted to the physical features of the Gulf of Mexico. In this model, Adem *et al.* (1991) have incorporated some specific parameterizations for heating by radiation, which are adequate for the latitude and the cloudiness patterns existing in the area. To obtain a finer resolution in the results, the model is integrated numerically in a regular grid with 60 km between points. For the horizontal turbulent transport of heat, a constant exchange coefficient equal to 3×10^7 cm^2 sec^{-1} is used, which is an order of magnitude smaller than the one used for SST prediction in the Pacific and Atlantic oceans. Numerical experiments to simulate the annual cycle of the normal mean sea surface temperature in the Gulf of Mexico, showed good agreement with the observed temperatures.

The Gulf of Mexico is an area where the transference and distribution of heat is driven by circulation features such as the Loop Current and the Loop Current Rings shed via instability processes (Hurlburt and Thompson, 1980). Therefore, the variations of SST in the upper layer have been studied in relation to the Loop Current intrusion and the shedding process that bring a flux of water with relatively high heat content from the North Atlantic and Caribbean, which together with fluxes of salt and momentum, play a major role in the Gulf's climatology (e.g., Elliot, 1982, Etter, 1983). Furthermore, several authors (Colon (1963), Hastenrath (1968), Hastenrath and Lamb (1977), Etter (1983), Adem *et al.* (1993)), using observed data, parameterizations and numerical models, have studied important factors for possible SST changes related to ocean-atmosphere heat fluxes.

In this paper we carry out predictions of SST anomalies and their month-to-month changes in the Gulf of Mexico, for a period of 12 months (March 1986 to February 1987).

2. THE BASIC EQUATIONS

The model used in the predictions is described in detail in previous papers (Adem *et al.*, 1991; Adem *et al.*, 1993), therefore, only a brief description will be given here.

The thermodynamic energy equation for the upper layer of the oceans, as derived by Adem (1970a), is:

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

where T_s is the sea surface temperature (SST), ρ_s is a constant density and c_s is the specific heat; h_s is the depth of the layer; $\mathbf{V}_{s_T}$ is the horizontal velocity of the ocean current in the layer; W is the rate of cooling due to upwelling; K_s is the constant exchange coefficient; E_s is the rate at which the energy is added by radiation; G_2 is the rate at which 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. In the derivation of equation (1), the vertical eddy flux of heat at the base of the thermocline is taken as zero.

As in previous studies (Adem *et al.*, 1991), the horizontal transport of heat by ocean currents and by turbulent eddies at the closed boundaries (coasts) is also taken as zero. Therefore, we apply equation (1) with only the heating terms (E_s - G_2 - G_3).

At the open boundaries, we assume that the horizontal transport of heat due to the turbulent eddies is negligibly small compared with the horizontal transport due to the mean ocean currents and therefore equation (1) can be written as:

$$\rho_s c_s h_s \frac{\partial T_s}{\partial t} = F_H + E_s - G_2 - G_3 \quad (2)$$

where F_H is the horizontal transport of heat by mean ocean currents, which is computed with the following formula:

$$F_H = -\rho_s c_s h_s \mathbf{V}_{s_T} \cdot \langle \nabla T_s \rangle \quad (3)$$

where $\langle \nabla T_s \rangle$ is the horizontal mean temperature gradient in the open boundaries. In the Florida Strait, for all months, $\mathbf{V}_{s_T}$ and $\langle \nabla T_s \rangle$ are for practical purpose, perpendicular and therefore F_H=0, whereas for the Yucatan Channel $\mathbf{V}_{s_T}$ and $\langle \nabla T_s \rangle$ are practically parallel for all months.

The radiation balance E_s at the sea surface is computed as in a previous paper (Adem *et al.*, 1991), using the formulas of Berliand-Budyko and Budyko (1974) for the short wave radiation and the long-wave radiation, respectively. E_s is written as follows:

$$E_s = -\delta\sigma T_a^4 [0.254 - 0.0066 U e_s(T_a)](1 - c\,\epsilon) - 4\delta\sigma T_a^3 (T_s - T_a) + \alpha_1 I \quad (4)$$

where δ=0.96 is the emissivity of the sea surface, σ=8215x10^{-14} cal cm^{-2} K^{-4} min^{-1} is the Stefan-Boltzmann 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 amount of cloudiness, c=0.65 is a cloud cover coefficient and $\alpha_1 I$ is the short wave radiation absorbed by the ocean layer.

For $\alpha_1 I$ we use the Berliand-Budyko formula:

$$\alpha_1 I = (Q+q)_o [1 - (a + b\,\epsilon)\,\epsilon](1 - \alpha) \quad (5)$$

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 use the following formulas (Jacobs, 1951):

$$G_3 = K_4 |\mathbf{V}_a| [0.981 e_s(T_s) - U e_s(T_a)] \quad (6)$$

$$G_2 = K_3 |\mathbf{V}_a| (T_s - T_a) \quad (7)$$

where K_3=19.68 gr cm^{-1} s^{-1} K^{-1} and K_4=29.75x10^{-3}, $|\mathbf{V}_a|$ is the ship-deck wind speed; and e_s (T_s) is the saturation vapor pressure at the surface ocean temperature.

For the saturation vapor pressure we use the following formula:

$$e_s(t^*) = a_1 + b_1 t^* + c_1 t^{*2} + d_1 t^{*3} + l_1 t^{*4} \quad (8)$$

where e_s is in millibars and t^*=T^*-273.16°C, T^* is the absolute temperature; a_1=6.115, b_1=0.42915, c_1=0.014206, d_1=3.046x10^{-4} and l_1 = 3.2x10^{-6} (Adem, 1967).

3. DETERMINATION OF SEA SURFACE AIR-TEMPERATURE AND RELATIVE HUMIDITY ANOMALIES

Due to the lack of reliable surface air temperature data, we use the 850 mb values, adapted from the following formula (Adem, 1970b):

$$P^* = P\left(\frac{T^*}{T}\right)^{g/R\beta} \tag{9}$$

where P^* and T^* are the atmospheric pressure and temperature in some level z; P and T are the corresponding values of P^* and T^* at the top of the tropospheric layer; g is the gravity acceleration, R is the gas constant and β is the standard constant lapse rate in the tropospheric layer.

Using formula (9), we can obtain the temperature in some isobaric surface from the temperature at the 850 mb level:

$$T^* = T_{850}\left(\frac{P^*}{850}\right)^{R\beta/g} \tag{10}$$

where T_{850} is the temperature at 850 mb level.

To obtain the computed sea surface air temperature T_{a_c} we take P^*=1016 mb that corresponds to the standard constant pressure in the Gulf of Mexico for the lower atmospheric level; then:

$$T_{a_c} = T_{850}\left(\frac{1016}{850}\right)^{R\beta/g} \tag{11}$$

For normal values of Ta_c, we use a similar formula replacing the temperature in 850 by its observed normal value.

For the sea surface air-temperature, we assume that:

$$T_a = T_{aN} + \left(T_{ac} - T_{aN_c}\right) \tag{12}$$

where T_{aN} is the observed normal values[1] of T_a taken from previous paper (Adem *et al.*, 1991); T_{aNc} is the normal sea surface air temperature computed from formula (11). In formula (12) the term between parenthesis is the computed sea surface air-temperature anomaly.

It is also necessary to incorporate the sea surface air relative humidity anomalies in formula (6) because the anomalies of T_a could distort the heat lost by evaporation if we use only normal values of U.

To compute the sea surface air relative humidity anomalies, we assume that the water vapor per unit volume at the sea level remains fixed for small changes of T_a and U. The water vapor per unit volume at the sea level can be expressed by the following formula (Adem, 1967):

$$\rho_v = \frac{0.622}{R}\frac{e_s(T_a)}{T_a}U \tag{13}$$

where ρ_v is the water vapor per unit volume at the sea level. Differentiating equation (13) we obtain:

$$d\rho_v = \frac{0.622}{RT_a}\left[U\left(\frac{d}{dT_a}e_s(T_a) - \frac{e_s(T_a)}{T_a}\right)dT_a + e_s(T_a)dU\right] \tag{14}$$

Using the hypothesis of ρ_v fixed:

$$d\rho_v = 0$$

and replacing the differential d by the increment Δ in (14), yields:

$$\Delta U = -\left[\frac{d}{dT_a}\ln e_s(T_a) - \frac{1}{T_a}\right]U\Delta T_a \tag{15}$$

where $\frac{\Delta T_a}{T_a} << 1$ and $\frac{\Delta U}{U} <<1$.

From formula (15) we may obtain a parametric formula for the sea surface air relative humidity, using $\Delta U= U-U_N$ and $\Delta T_a=T_{ac}-T_{aNc}$; therefore,

$$U = U_N + A_N\left(T_{ac} - T_{aN_c}\right) \tag{16}$$

where:

$$A_N = -\left[\frac{d}{dT_{aN}}\ln\, e_s(T_{aN}) - \frac{1}{T_{aN}}\right]U_N \tag{17}$$

where U_N is the observed normal value of U, as used in a previous paper (Adem *et al.*, 1991).

Using the Clausius-Clapeyron equation in formula (17), we found that the normal coefficient A_N for observed normal values of T_a, in the Gulf of Mexico, is negative; therefore, according to formula (16), positive anomalies of T_a yield negative anomalies in the relative humidity U, and vice versa, this result produces a balance in the heat lost by evaporation.

4. THE NUMERICAL EXPERIMENTS

The local rate change of the surface ocean temperature can be obtained from equation (1), which can be written as:

$$\frac{\partial T_s}{\partial t} = AD + TU + HE \tag{18}$$

[1] Normal values are defined as long-term monthly means at each geographical point.

where:

$$AD = -\mathbf{V}_{sT} \cdot \nabla T_s$$

$$TU = K_s \nabla^2 T_s$$

$$HE = \frac{1}{\rho_s c_s h_s}(E_s - G_2 - G_3)$$

where the term W/h_s is taken as zero as in a previous paper (Adem, *et al*, 1991).

In this paper, for the advection term *(AD)* we use $\mathbf{V}_{sT} = C_1 \mathbf{V}_{sw}$ where C_1 is a constant coefficient and $\mathbf{V}_{sw}$ is the horizontal normal seasonal ocean velocity observed in the surface. We use C_1=0.235, assuming that the currents in the Gulf of Mexico have a vertical profile in the whole frictional layer similar to the pure dift current (Adem, 1970a).

The observed seasonal ocean currents ($\mathbf{V}_{sw}$) were obtained from Secretaría de Marina (1974) and have been conformed in direction subjectively with the use of ocean currents computed from a geostrophic dynamic model (Monreal-Gómez, 1985), because the directions of the observed currents are inexact in some regions near the coast of the Gulf of Mexico. The modified vectorial field of $\mathbf{V}_{sw}$ used in the prediction is shown in Figure 1 for winter.

For the horizontal transport of heat by mean ocean currents through the Yucatan Channel, formula (3) is used, assuming that the anomalies of F_H are null. The normal values of F_H have been computed by Adem *et al.* (1991) and their values are shown in Table 1.

The exchange coefficient K_s for the horizontal turbulent transport of heat *(TU)* is considered constant and its value is taken as 3×10^7 cm^2 sec^{-1}. This value agrees with the determination of K_s by different authors (Montgomery, 1939; Semtner and Mintz, 1977; Huang, 1978).

For the coefficient in the heating term *HE*, we take the values ρ_s=1 gm cm^{-3}, c_s=1 cal gm^{-1} and h_s=60 m as in a previous papers (Adem *et al.*, 1991 and 1993). In this term we use formulas (4), (5), (6) and (7), assuming a seasonal normal value for cloudiness (ϵ), (Adem *et al.*, 1991) and seasonal normal values for ship-wind speed taken from maps of the revised scalar wind speed (Isemer and Hasse, 1987; Charts 37-42).

Formula (18) is applied to the time-average of one month. To specify the time-step considered, we used the subindex i, so that the ith step can be written as:

$$\left(\frac{\partial T_s}{\partial t}\right)_i = (AD)_i + (TU)_i + (HE)_i \qquad (19)$$

For the time derivative we used the Euler formula:

$$\left(\frac{\partial T_s}{\partial t}\right)_i = \frac{(T_s)_{i+1} - (T_s)_i}{\Delta t} \qquad (20)$$

Substituting (20) in (19), we obtain:

$$(T_s)_{i+1} = (T_s)_i + \Delta t\left[(AD)_i + (TU)_i + (HE)_i\right] \qquad (21)$$

Formula (21) allows to compute the SST for the i +1 time-step from values in the i time-step. In these experiments we use 30 time steps of 1 day to complete a one-month prediction. In the initial step we use the observed values of the previous month. The spatial derivatives are centered finite differences. The integration area and the grid points were shown by Adem *et al.* (1991). The integration is carried out only in the Gulf of Mexico using the considerations of section 2, for closed and opened boundaries.

4.1. The prediction method

The method for the prediction of monthly SST anomalies (or month-to-month anomaly changes) is essentially the same described in previous papers (Adem, 1970a; Adem and Mendoza, 1988) . We carry out first a prediction for the normal values using the observed normal values of the previous month as initial condition, and then another prediction, for the considered month, using the observed values of the previous month as initial condition. The predicted SST anomalies are obtained by substracting from the computed values the corresponding computed normal values. The monthly atmospheric initial conditions are maintained fixed through the whole integration.

The predicted month-to-month anomaly changes are obtained by substracting from the predicted SST anomalies the observed SST anomalies in the previous month.

In this method, for the seasonal atmospheric fields ϵ and $|\mathbf{V}_a|$ we take the values of the season corresponding to the month of the prediction, and for the total radiation received by the surface with clear sky $(Q+q)_o$, we use the monthly values corresponding to the month of the prediction.

We carried out prediction experiments using (21), for SST anomalies and their monthly changes for the different terms in this formula, for the 12-months period from March 1986 to February 1987. As input data we use the sea surface temperature, and the 850 mb-temperature to estimate surface air temperature anomalies according to formula (11). The SST values were obtained from the National Weather Service-NOAA, Washington, D. C., and their corresponding normals from the Atlas by Hastenrath and Lamb, (1977). The 850 mb-temperature values and their corresponding normals were obtained from the NCAR, NMC Grid Point Data Set (CD-ROM).

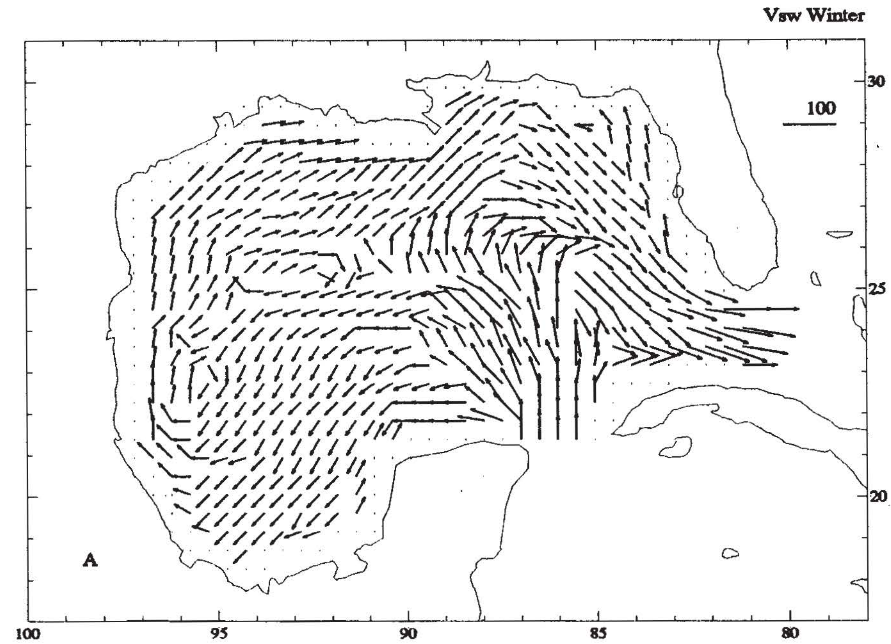


Fig. 1. Modified seasonal ocean currents in the mixed layer, in the Gulf of Mexico, for winter, in cm s^{-1}.

Table 1

Mean monthly horizontal transport of heat through the Yucatan Channel (F_H), in W m^{-2}, obtained with formula (3).

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

4.2. Evaluation of the predictions

As in a previous paper (Adem and Mendoza, 1987), we evaluated the skill of predictions in three different ways:

1) The percentage of signs of the SST anomalies correctly predicted.

2) The percentage of signs of the month-to-month changes of the SST anomalies correctly predicted.

3) The root mean square error (RMSE) of the predicted SST anomalies.

As control predictions we use in 1) the percentage of signs correctly predicted by persistence (the previous month values as prediction); in 2) the percentage of signs correctly predicted by "return to normal" using opposite signs of the previous month's anomalies as prediction of the sign of the month-to-month change in the anomalies of the sea surface temperature; and in 3) the RMSE of a prediction using persistence.

For the evaluation of the percentage of signs and RMSE, we take 476 points of the grid model showed in a previous paper (Adem *et al.* 1991), this sample corresponding to 73.2% of the points at the integration area.

To determine the importance in the predictions of the different terms that appear in formula (19), we carried out several experiments, which were evaluated using the three methods described above.

4.3. Description of the results

Table 2, shows the percentage of signs of SST anomalies correctly predicted. Table 3 the percentage of signs of the month–to-month changes of the SST anomalies correctly predicted and Table 4 the root mean square error (RMSE) of the SST anomalies.

The first column in the three tables, indicates the control model, and the terms of (18) included in the prediction. From the second to the fifth columns the average percentages for each season are shown, and in the sixth column the average percentage for the whole period is shown.

In Tables 2 to 4, the first line shows the values for the control. The other lines show the values of the model mi–

nus the control, except in Table 4 in which the value shown is the control minus the model, so that for all the tables when the value shown is positive, the model is better than the control.

Table 2

Average of the percentages of signs correctly predicted of the sea surface temperature anomalies for the seasons and for the whole period of 12 months from March 1986 to February 1987. In the first line are the values of the control prediction (persistence). In the subsequent lines the excesses over the control of the model predictions when using, in the right side of (18), the terms indicated in the first column.

Model	Winter	Spring	Summer	Fall	Average
Persistence	69.5	74.7	47.3	57.3	62.2
HE	2.3	-1.8	6.7	5.6	3.2
HE+TU	4.2	0.9	6.8	5.1	4.3
HE+TU+AD	4.5	0.8	6.5	6.0	4.5

Table 3

Average of the percentages of signs correctly predicted of the month-to-month changes of the sea surface temperature anomalies for the seasons and for the whole period of 12 months from March 1986 to February 1987. In the first line are the values of the control prediction (return to normal). In the subsequent lines, the excesses over the control of the model predictions when using, in the right side of (18), the terms indicated in the first column.

Model	Winter	Spring	Summer	Fall	Average
R. to N.	60.3	66.6	77.3	63.9	67.0
HE	12.4	0.1	2.9	5.3	5.2
HE+TU	13.7	4.5	1.5	-0.4	4.8
HE+TU+AD	13.6	3.6	1.8	0.1	4.8

Table 4

Average for the seasons and for the whole period from March 1986 to February 1987 of the RMSE (in°C) for the predictions of SST anomalies in the Gulf of Mexico for persistence, and for the other cases, model minus control.

Model	Winter	Spring	Summer	Fall	Average
Persistence	0.89	0.63	0.66	0.66	0.71
HE	0.09	0.13	0.13	0.10	0.11
HE+TU	0.15	0.15	0.17	0.13	0.15
HE+TU+AD	0.15	0.15	0.17	0.13	0.15

4.4. Discussion of the results

In the following discussion we carry out comparisons of the results of the different cases shown in Tables 2 and 3, relative to percentages of signs correctly predicted, and then, for those of Table 4, relative to the values of RMSE.

When only the heating term *HE* is included in the model, the predictions are better than the control for all seasons except spring (Table 2).

The inclusion of the *TU* term (*HE+TU* case) improves the skill of the prediction for the sign of the anomalies, for winter, spring and the average for the whole period, summer remains practically the same and fall decreases (Table 2).

For the case of the sign of month-to-month changes (Table 3), the skill of the prediction is increased for winter and spring, and decreased for summer and fall. These results indicate that perhaps these seasons require an adjustment in the value of the exchange coefficient K_s.

A comparison of the results for the *HE+TU+AD* case, with those of the *HE+TU*, shows that the inclusion of the term *AD* does not improve the average skill of the prediction of the sign of the anomalies and their monthly changes. However, this result can possibly be improved with the inclusion of the sea surface current anomalies in the Gulf of Mexico, as shown in a previous paper (Adem and Mendoza, 1987) for the North Pacific and Atlantic oceans using pure wind drift ocean current anomalies (Ekman's approach).

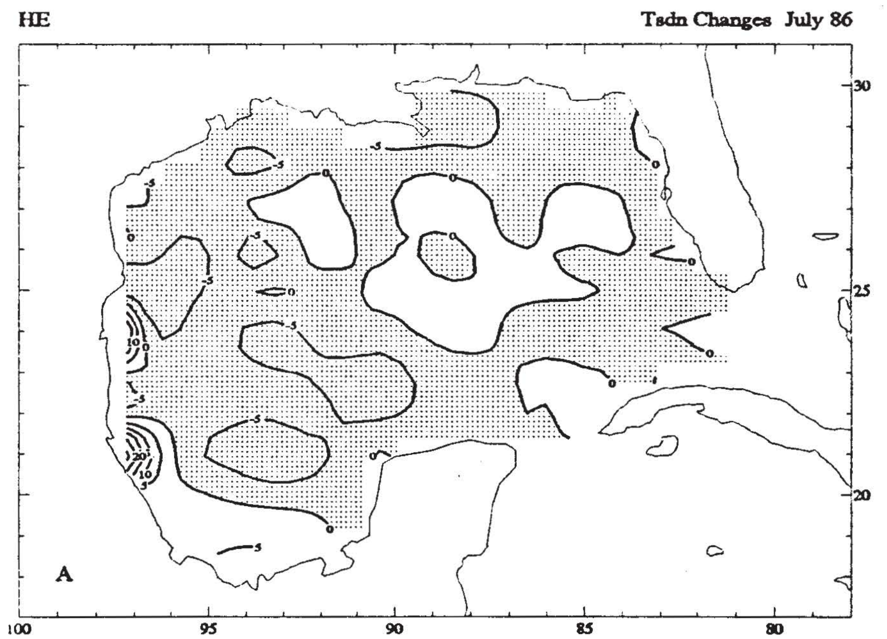
The RMSE evaluation in Table 4, shows that for all seasons the RMSE of the simplest model (*HE* case) is smaller than the control. It also shows that the inclusion of the term *TU* improves the prediction of the SST anomalies. The values of RMSE for the complete model (*HE+TU+AD*) are the same as those obtained for *HE+TU* case.

The results shown in the figures 2 to 5 are the predictions of the change of SST anomalies from June to July 1986 (Figures A) and from December 1986 to January 1987 (Figures B). These monthly changes are representative of summer and winter, respectively.

Figure 2 shows the predictions when in formula (18) the heating term *HE* is included only, using formulas (12) and (16) for the sea surface air temperature and relative humidity, respectively.

Figure 3 shows the results when besides the heating term, the horizontal turbulent transport term *TU* is included (*HE+TU* case).

Figure 4 shows the results when all the terms are used in formula (18), except W/h_s term, which correspond to the complete model (*HE+TU+AD*).



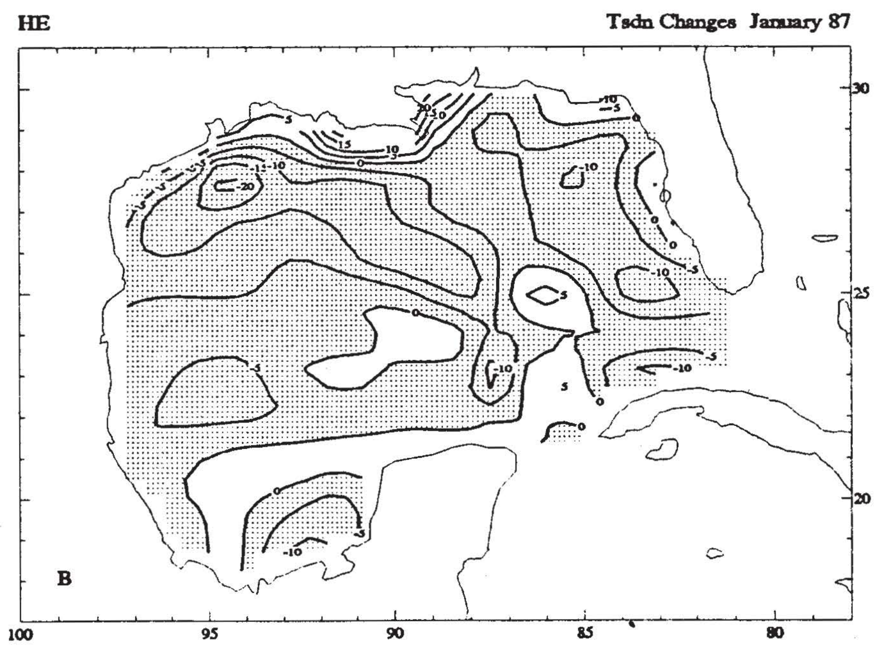


Fig. 2. Predicted changes of SST anomalies, in tenths of Celsius degrees, using only the heating term (HE): from June to July 1986 (A) and from December 1986 to January 1987 (B).

Comparing Figures 2 and 3 with the observed changes (Figure 5), we find that the inclusion of the horizontal turbulent transport *TU* magnifies substantially the size of the change of the SST anomalies and, in a minor degree improves also the percentage of signs of the monthly change of SST correctly predicted, improving the predictions. These results are in agreement with those of Table 3.

5. CONCLUDING REMARKS

We have shown that for a sample of 12 months, the predictions of SST anomalies and of their month-to-month changes show good skill, when only the anomalies of the heating by radiation, evaporation and sensible heat given off to the atmosphere are included. We have also shown that a substantial improvement is obtained when, in addition to the heating terms, we include the horizontal turbulent transport term. However, the inclusion of the horizontal transport of heat by normal seasonal surface ocean currents does not increase the predictability in any appreciable way.

Further improvements in the prediction can be expected with the incorporation of the surface ocean current

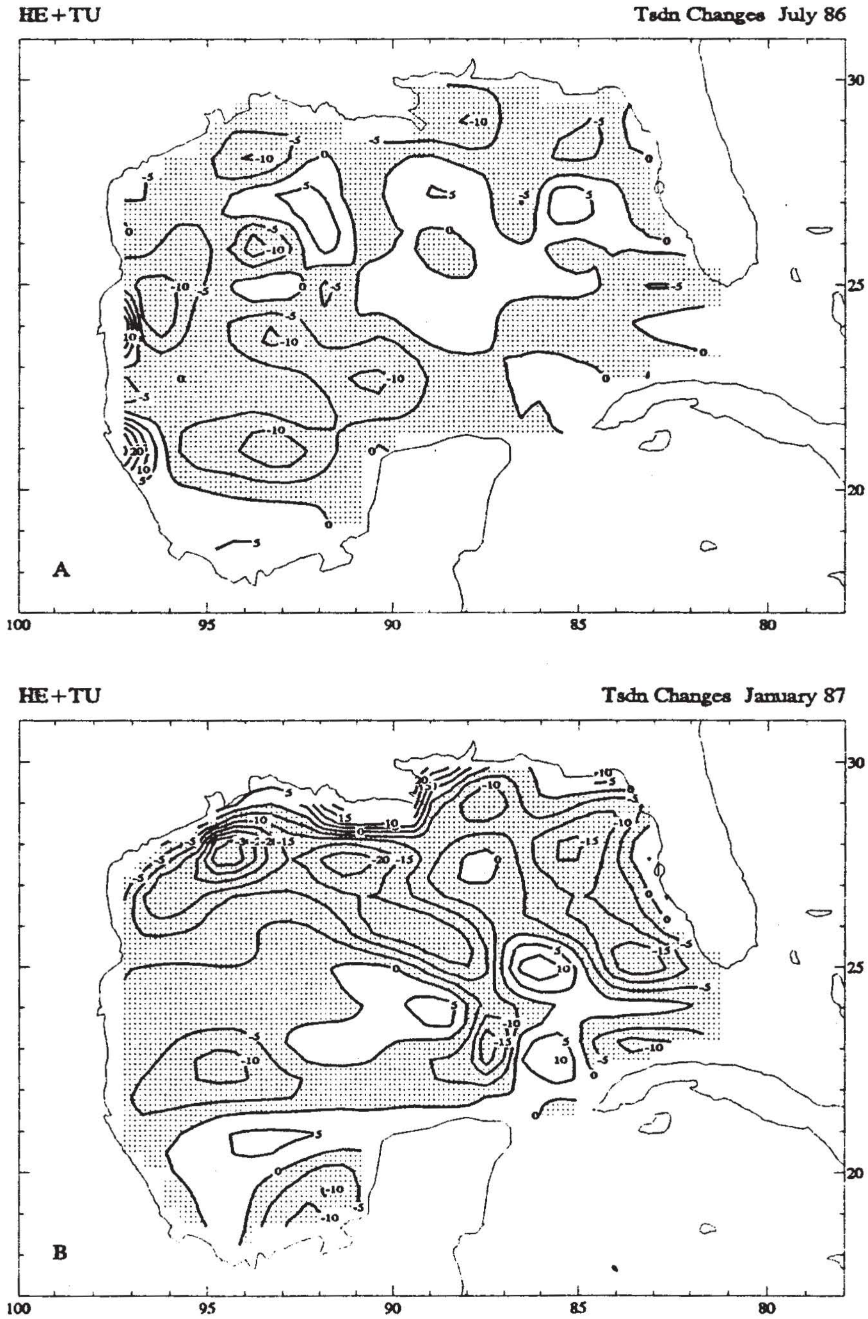


Fig. 3. Predicted changes of SST anomalies, in tenths of Celsius degrees, using the heating and horizontal turbulent transport terms (*HE* + *TU*): from June to July 1986 (A) and from December 1986 to January 1987 (B).

anomalies and with the use of a better approximation for the exchange coefficient. As mentioned before, in the present model we use a constant coefficient. This coefficient could be replaced by seasonal or monthly normal values as functions of latitude and longitude.

The lack of T_a and U data forced us to incorporate methods to compute the monthly anomalies of these variables, which were determined with formulas (11) and (16). The skill in the predictions suggests that these formulas are a good approximation to compute T_a and U.

Both the long and short wave radiations given in formula (4) are sensitive to the distribution of clouds (ϵ). Therefore, the inclusion of the cloudiness anomalies in E_s of the term *HE* could improve the skill of the predictions.

The lack of ship-wind speed data for the months considered in the predictions is a limitation. Therefore, considerable research is needed to provide an adequate parameterization for the sea surface wind speed anomalies in the Gulf of Mexico in terms of available data.

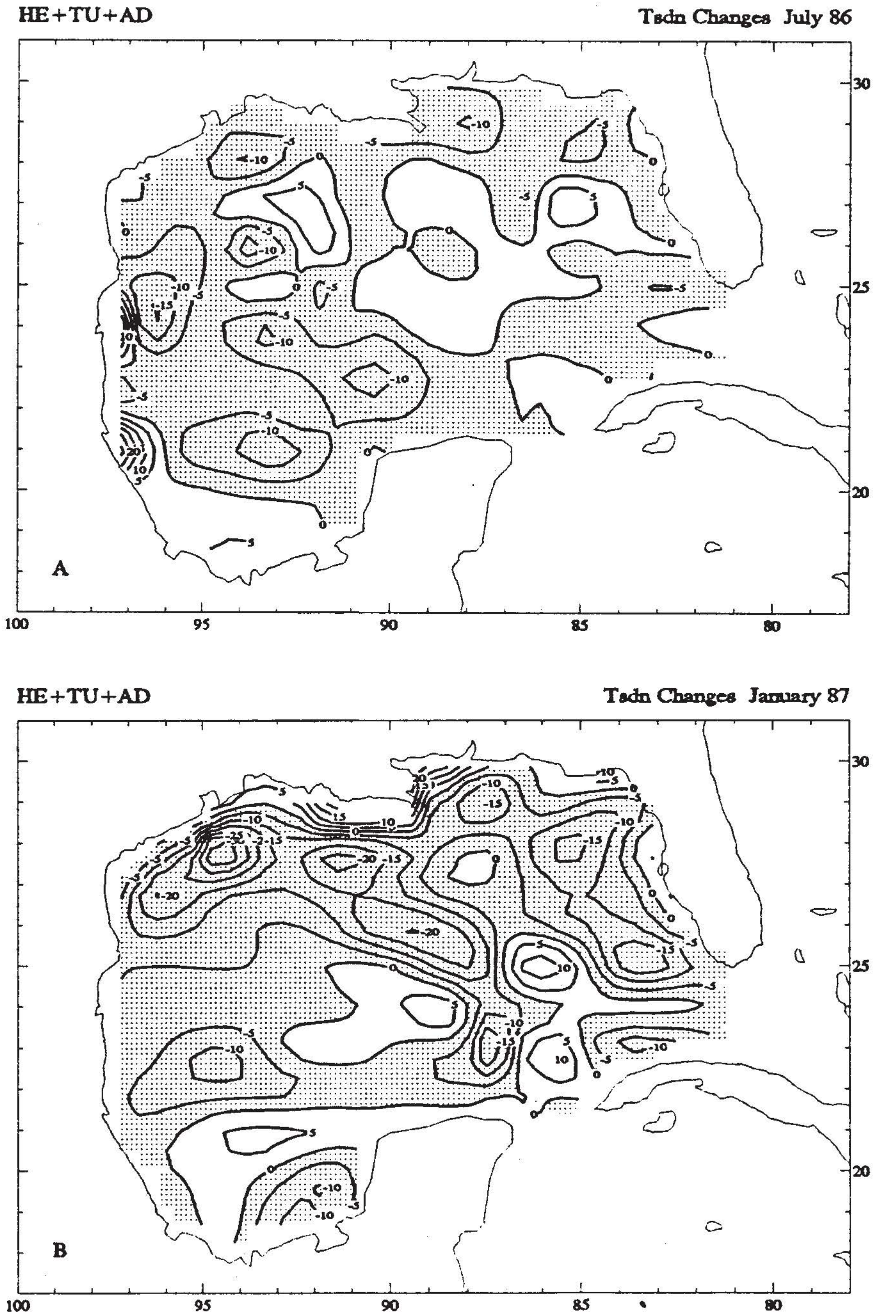


Fig. 4. Predicted changes of SST anomalies, in tenths of Celsius degrees, using the complete model (*HE+TU+AD*): from June to July 1986 (A) and from December 1986 to January 1987 (B).

The upwelling term could be important to generate changes in the SST anomalies which would not be negligible in some cases, such as cold air outbreaks, tropical storms (Lewis and Hsu, 1992), and hurricanes (Price, 1981, 1983). In these cases, the term W/h_s must be incorporated in the model with adequate parameterization.

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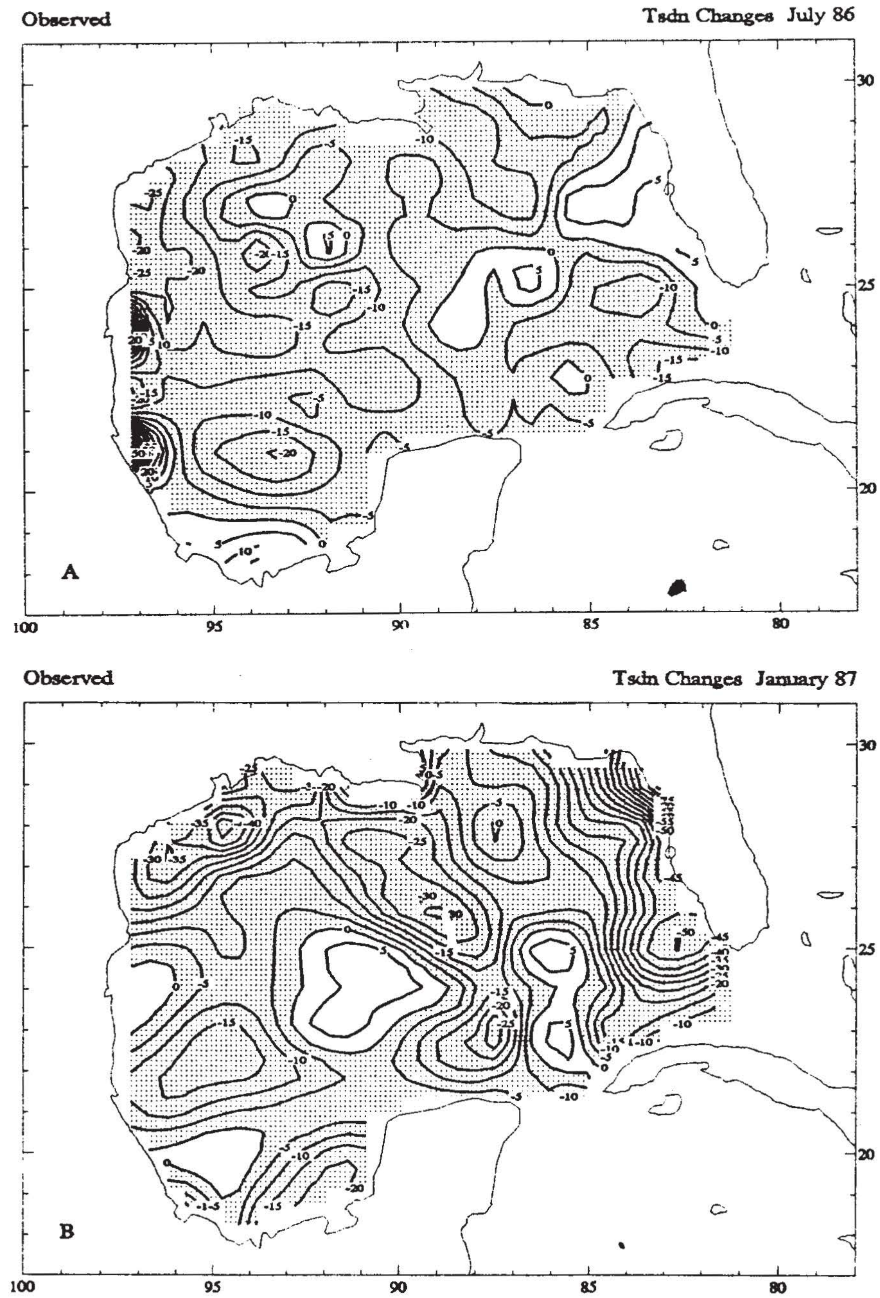

Fig. 5. Observed changes of SST anomalies, in tenths of Celsius degrees: from June to July 1986 (A) and from December 1986 to January 1987 (B).

BIBLIOGRAPHY

ADEM, J., 1964a. On the physical basis for the numerical prediction of monthly and seasonal temperatures in the troposphere-ocean-continent system. *Mon. Wea. Rev., 92,* 91-103.

ADEM, J., 1964b. On the normal thermal state of the troposphere ocean-continent system in the Northern Hemisphere. *Geofís. Int., 4,* 3-32.

ADEM, J., 1967. Parameterization of atmospheric humidity using cloudiness and temperature. *Mon. Wea. Rev., 95,* 2, 83-88.

ADEM, J., 1970a. On the prediction of mean monthly ocean temperature. *Tellus, 22,* 4, 410-430.

ADEM, J., 1970b. Incorporation of advection of heat by mean winds and by ocean currents in a thermodynamic model for long-range weather prediction. *Mon. Wea. Rev., 98,* 10, 776-786.

ADEM, J., 1975. Numerical-thermodynamical prediction of mean monthly ocean temperatures. *Tellus., 27*, 6, 541-551.

ADEM, J., 1976. Predicción de la temperatura media mensual en la superficie de los océanos utilizando un modelo termodinámico. ICCRA-II Symposium on Progress in Marine Research in the Caribbean and Adjacent Regions. FAO Fisheries Report No. 200. Supplement, 9-20.

ADEM, J., 1991. Review of the development and applications of the Adem thermodynamic climate model. *Climate Dynamics, 5*, 145-160.

ADEM, J. and V. M. MENDOZA, 1987. Sensitivity experiments on ocean temperature predictions with a thermodynamic climate model. *Geofís. Int., 26*, 4, 525-543.

ADEM, J. and V. M. MENDOZA, 1988. Recent numerical thermodynamic experiments on sea surface temperature prediction. *Geofís. Int., 27*, 3, 309-325.

ADEM, J., V. M. MENDOZA, E. E. VILLANUEVA-URRUTIA and M. A. MONREAL-GOMEZ, 1991. On the simulation of the sea surface temperature in the Gulf of Mexico using a thermodynamic model. *Atmósfera, 4*, 2, 87-99.

ADEM, J., E. E. VILLANUEVA and V. M. MENDOZA, 1993. A new method for estimating the seasonal cycle of the heat balance at the ocean surface, with application to the Gulf of Mexico. *Geofís. Int., 32*, 1, 21-34.

BUDYKO, M. I., 1974. Climate and life. International Geophysics Series, 18, Academic Press, Inc. 508 pp.

COLON, J. A., 1963. Seasonal variations in heat flux from the sea surface to the atmosphere over the Caribbean Sea. *J. Geophys. Res., 68*, 1421-1430.

ELLIOT, B. A., 1982. Anticyclonic rings in the Gulf of Mexico. *J. Phys. Oceanogr., 12*, 1292-1309.

ETTER, P. C., 1983. Heat and freshwater budgets of the Gulf of Mexico. *J. Phys. Oceanogr., 13*, 2058-2069.

HASTENRATH, S. L., 1968. Estimates of the latent and sensible heat flux for the Caribbean Sea and the Gulf of Mexico. *Limnol. Oceanogr., 13*, 322-331.

HASTENRATH, S. L. and P. J. LAMB, 1977. Climatic Atlas of the Tropical Atlantic and Eastern Pacific Oceans. University of Wisconsin Press. 54 pp.

HUANG, J. C. K., 1978. Numerical simulation studies of oceanic anomalies in the North Pacific Basin: I. The ocean model and the long-term mean state. *J. Phys. Oceanogr., 8*, 755-778.

HURLBURT, H. E. and J. D. THOMPSON, 1980. A numerical study of Loop Current intrusions and eddy shedding. *J. Phys. Oceanogr., 10*, 1611-1651.

ISEMER, H. and L. HASSE, 1987. The Bunker Climate Atlas of the North Atlantic Ocean. Volume 2: Air-Sea Interactions. Springer-Verlag. 252 pp.

JACOBS, W. C., 1951. The energy exchange between the sea and the atmosphere and some of its consequences. *Bull. Scripps Inst. of Oceanography*. University of California, *6*, 27-122.

LEWIS, J. K. and S. A. HSU, 1992. Mesoscale air-sea interactions to tropical and extratropical storms in the Gulf of Mexico. *J. Geophys. Res., 97*, C2, 2215-2228.

MONREAL-GOMEZ, M. A., 1985. Modélisation du mode barotrope et du premier mode barocline dans le Golfe du Mexique. Ph. D. dissertation. University of Liège, Belgium.

MONTGOMERY, R. B., 1939. Ein Versuch, den vertikalen und seitlichen Austausch in der Tiefe der Sprungschicht im äquatorialen Atlantischen Ozean zu bestimmen. *Annalen der Hydrographie and Maritimen Meteorologie 67*, 242-246.

PRICE, J. F., 1981. Upper ocean response to a hurricane. *J. Phys. Ocean., 11*, 153-175.

PRICE, J. F., 1983. Internal wave wake of a moving storm. Part I: Scales, energy budget and observations. *J. Phys. Ocean., 13*, 949-965.

SECRETARIA DE MARINA, 1974. Atlas Oceanográfico del Golfo de México y Mar Caribe. Secc. 1. Mareas y Corrientes. OSM.1000.

SEMTNER, A. J., Jr. and Y. MINTZ, 1977. Numerical simulation of the Gulf Stream and mid-ocean eddies. *J. Phys. Oceanogr., 7*, 208-230.

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