

*SENSITIVITY EXPERIMENTS ON OCEAN TEMPERATURE PREDICTIONS
WITH A THERMODYNAMIC CLIMATE MODEL*

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RESUMEN

Un modelo termodinámico del clima es usado para predecir las anomalías de la temperatura de la superficie de los océanos para periodos de un mes en el Hemisferio Norte.

Se realizan experimentos numéricos para calibrar algunos parámetros oceanográficos del modelo y para estimar la importancia, en las predicciones, del transporte horizontal de calor por corrientes de deriva y por remolinos turbulentos de gran escala asociados con un coeficiente de difusión horizontal, así como del calentamiento debido a evaporación, calor sensible cedido a la atmósfera y radiación.

Verificaciones en los océanos Pacífico y Atlántico, para el periodo de 24 meses de junio 1980 a mayo 1982, muestran habilidad en las predicciones.

ABSTRACT

A thermodynamic climate ocean-atmosphere model is used to predict the anomalies of surface ocean temperatures for periods of a month in the Northern Hemisphere.

Numerical experiments are carried out to calibrate some oceanographic parameters of the model and to estimate the importance, in the predictions, of the horizontal transport of heat by pure wind drift mean ocean currents and by large scale eddies, associated with a horizontal "austausch" coefficient, as well as of the heating due to evaporation, sensible heat given off to the atmosphere and radiation.

A verification in the Pacific and the Atlantic oceans, for the 24 month period from June 1980 to May 1982, shows good skill in the predictions.

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INTRODUCTION

During the last two decades a Northern Hemisphere thermodynamic climate model has been developed and applied to predict mean monthly anomalies of surface temperature (Adem, 1964a, 1964b, 1965, 1970a, 1970b, 1979, 1982). Verifications of predictions over the contiguous U. S., have been carried out showing a useful skill in the predictions (Adem and Jacob, 1968; Adem, Bostelman and Polger, 1970; Adem and Donn, 1981; Donn, Goldberg and Adem, 1986).

Verifications of predictions of sea surface temperature anomalies and their month-to-month changes over the Atlantic and Pacific oceans have also been carried out (Adem, 1970a, Adem, 1975) showing good skill.

The purpose of this paper is to report recent sensitivity experiments related to possible improvements on the prediction of sea surface temperature.

DESCRIPTION OF THE EQUATIONS USED

The equations used are those of conservation of thermal energy applied to an atmospheric layer of about 10 km thickness and to the upper layer of the oceans and continents. In this paper we will carry out sensitivity experiments using the equation for the ocean which is the following:

$$\frac{\partial T_S}{\partial t} = AD + TU + HE \quad (1)$$

where $\partial T_S / \partial t$ is the local rate of change of the sea surface temperature T_S . The terms AD, TU, and HE are the rates of change of T_S due to the horizontal transport of heat by mean ocean currents, the horizontal turbulent transport, and the total heating in the upper layer of the ocean, respectively.

The terms AD, TU and HE are given by:

$$AD = - V_{ST} \cdot \nabla T_S$$

$$TU = K_S \nabla^2 T_S$$

$$HE = (1/h \rho_S C_S) (E_S - G_2 - G_3)$$

where V_{ST} is the surface ocean current, K_S the horizontal exchange coefficient, h the depth of the layer, ρ_S the density, C_S the specific heat, E_S the heating by radiation G_2 the sensible heat given off to the atmosphere, and G_3 the heat lost by evaporation.

For G_3 and G_2 we will use the formulas:

$$G_3 = G_{3N} + K_4 B |V_{aN}| [0.981(T_S - T_{SN}) - A_7 U_N (T_m - T_{mN})] \quad (2)$$

$$G_2 = G_{2N} + K_3 |V_{aN}| [(T_S - T_{SN}) - A_7 (T_m - T_{mN})] \quad (3)$$

where T_m is the 700 mb temperature; G_{3N} , G_{2N} , T_{SN} and T_{mN} are the normal values of G_3 , G_2 , T_S and T_m respectively; $|V_{aN}|$ is the ship-deck normal wind speed; U_N is the normal value of the surface relative humidity, and K_4 , K_3 , A_7 and B are constants.

Formulas (2) and (3), with $A_7 = 1$, were derived by Clapp *et al.* (1965) as an adaptation of Jacobs (1951) bulk formulas and have been used in the thermodynamic model (Adem, 1965, 1979).

In V_{ST} we will include only the pure wind drift ocean current using Ekman's (1902) approach. The horizontal components of such current will be computed with the following formulas (Adem, 1970a):

$$u_S = C_1 \frac{0.0126}{\sqrt{\sin \phi}} (u_a \cos \theta + v_a \sin \theta) \quad (4)$$

$$v_S = C_1 \frac{0.0126}{\sqrt{\sin \phi}} (v_a \cos \theta - u_a \sin \theta)$$

where u_S and v_S are the x and y components respectively of the resultant pure drift current in the layer of depth h ; ϕ is the latitude, and u_a and v_a are the x and y components of the surface wind respectively. C_1 is a constant coefficient and θ the angle that measures the direction of the vector surface ocean current to the right of the surface wind direction.

The range of values of θ and C_1 is:

$$45^\circ \leq \theta \leq 90^\circ$$

$$.235 \leq C_1 \leq 1$$

For $\theta = 45^\circ$ and $C_1 = 1$ we have the resultant pure drift surface current in a very shallow layer. For $\theta = 90^\circ$ and $C_1 = 0.235$ we have the resultant pure drift current in the whole frictional layer (Adem, 1970a).

DEPENDENCE OF THE PREDICTIONS ON SOME OCEANOGRAPHIC PARAMETERS

We shall study the sensitivity of the predictions of sea surface temperature anomalies to the variation of the following parameters:

θ , C_1 , K_S , h , K_3 , K_4 and A_7

The method used for the predictions is described in detail in a previous paper (Adem, 1970a).

In all the experiments we will use for the time derivative the Euler formula, with a time step of one month.

As initial data we use the sea surface temperatures and the atmospheric surface pressures, as well as the corresponding normals from NMC-NOAA. We also use the 700 mb temperatures from NMC-NOAA, but for 700-mb normals, we use the 8 years average 1976-1984 of the NMC-NOAA values, prepared by Donn and Goldberg in the Lamont-Doherty Geological Observatory (private communication).

We shall evaluate the root mean square error (RMSE) of the predicted anomalies of sea surface temperature in the way described by Adem and Donn (1981). As control prediction we will use persistence and evaluate also its RMSE, so that when the difference of the values of persistence minus those of the model are positive, the model is better than persistence.

The experiments presented in this section include the five months January to May 1981. The results are the averages for such a period over the Pacific and Atlantic oceans.

In the numerical experiments we used equation (1) with the three terms of the second member or with only one of these terms. Seven numerical experiments were carried out, whose characteristics are summarized in Table 1, where in the first column is the number of the experiment, in the second column the terms included, in

the third column the parameters varied in the experiment, and in the fourth column, the number of the figure where the results of the experiment are shown. In each of the seven figures the abscissa is the parameter that is varied and the ordinate the RMSE in Celsius degrees. The curves labeled M are the predictions by the model and the horizontal line, labeled P, is the corresponding values of the control prediction (persistence).

Table 1
Sensitivity experiments on the dependence of the skill of
monthly sea surface temperature prediction on some parameters

Experiment	Terms included in Eq. (1)	Variable Parameter	Figure
1	TU	K_S	1
2	HE	A_7	2
3	HE	h	3
4	HE	K_4	4
5	HE	K_3	5
6	AD + TU + HE	K_S	6
7	AD + TU + HE	$C_1 \text{ \& } \theta$	7

Experiment 1

We included only the horizontal turbulent mixing (TU). In this case equation (1) becomes

$$\frac{\partial T_S}{\partial t} = K_S \nabla^2 T_S \quad (5)$$

and the solution depends only on the exchange coefficient K_S and on the ocean temperature in the previous interval.

Fig. 1 shows the results of the experiment. The abscissa is the exchange coefficient (K_S) in $10^8 \text{ cm}^2 \text{ sec}^{-1}$. This figure shows that the predictions by the model are better than persistence for $0 < K_S < 5$, and that the best results are obtained for values of K_S of about $3 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$, for which the RMSE is minimum.

It is interesting to point out that equation (5) with this value of K_S has been used in previous numerical experiments (Adem, 1970a, 1975) showing good skill in the predictions.

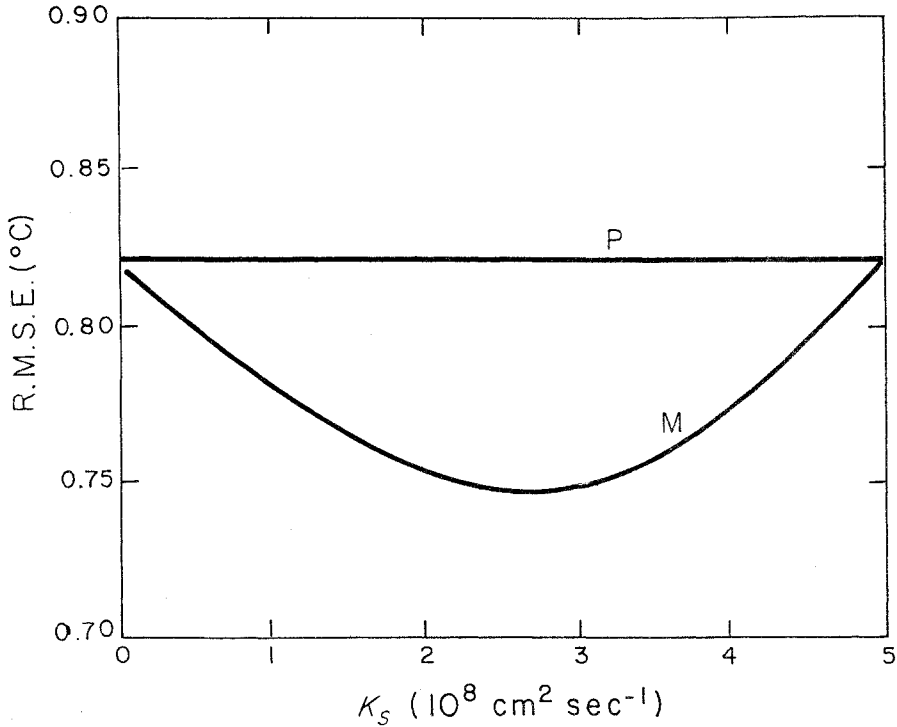


Fig. 1. Dependence of the RMSE of the predicted sea surface temperature anomalies on the Horizontal mixing coefficient (K_S). Curve M: Using Eq. (5). Line P: Using persistence.

Experiment 2

In this case we use only the heating terms (HE) in Eq. (1). Therefore the forecasting equation is:

$$\frac{\partial T_S}{\partial t} = \text{HE} \quad (6)$$

In this experiment we varied the coefficient A_7 of the formulas (2) and (3), prescribing K_3 and K_4 as given by Jacobs (1951), and $h = 100\text{m}$. The results are shown in Fig. 2 where the abscissa is A_7 . The RMSE of the model predictions are smaller than that of persistence for $0 \leq A_7 \leq 1$. However, the smallest value of the RMSE, which correspond to the best skill in the prediction, is obtained for A_7 equal to 0.4.

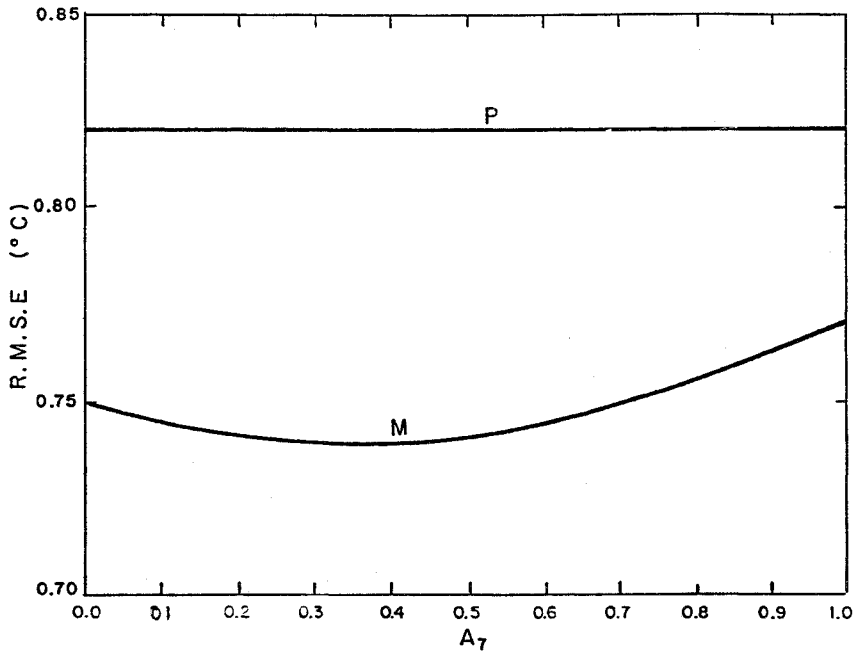


Fig. 2. Dependence of the RMSE of the predicted sea surface temperature anomalies on the coefficient A_7 . Curve M: Using Eq. (6). Line P: Using persistence.

Experiment 3

We use equation (6), with the same values of K_3 and K_4 as in experiment 2, and with $A_7 = 0.4$. In this case the depth of the layer is varied. The results are shown in Fig. 3 in which the abscissa is h in meters. The minimum value of the RMSE of the model predictions is close to 100 m and is smaller than that of persistence, showing that this value, yields the best predictions.

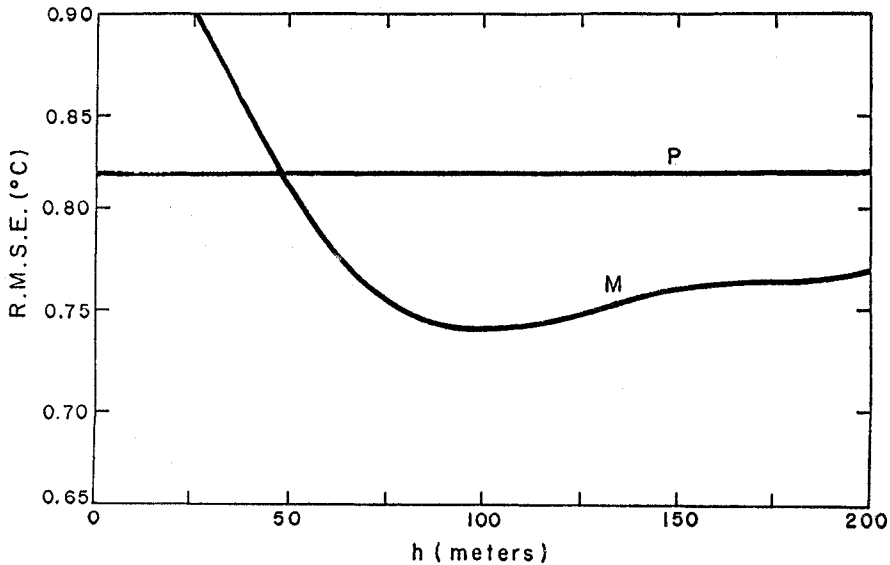


Fig. 3. Dependence of the RMSE of the predicted sea surface temperature anomalies on the depth of the ocean layer (h). Curve M: Using Eq. (6). Line P: Using persistence.

Experiment 4

As in experiments 2 and 3 we used only the heating terms (HE) in Eq. (1). In this case we varied the coefficient (K_4) of the evaporation formula, prescribing $A_7 = 0.4$ and K_3 as given by Jacobs (1951). The results are shown in Fig. 4, where the abscissa is $K_4 \times 10^{-3}$. The RMSE of the model predictions is smaller than that of persistence for $0 < K_4 < 83 \times 10^{-3}$. The minimum value of the RMSE, which corresponds to the best skill in the predictions, is obtained for a value of K_4 very close to 40.5×10^{-3} , which is the value given by Jacobs (1951) in the bulk formula for evaporation at the surface of the oceans.

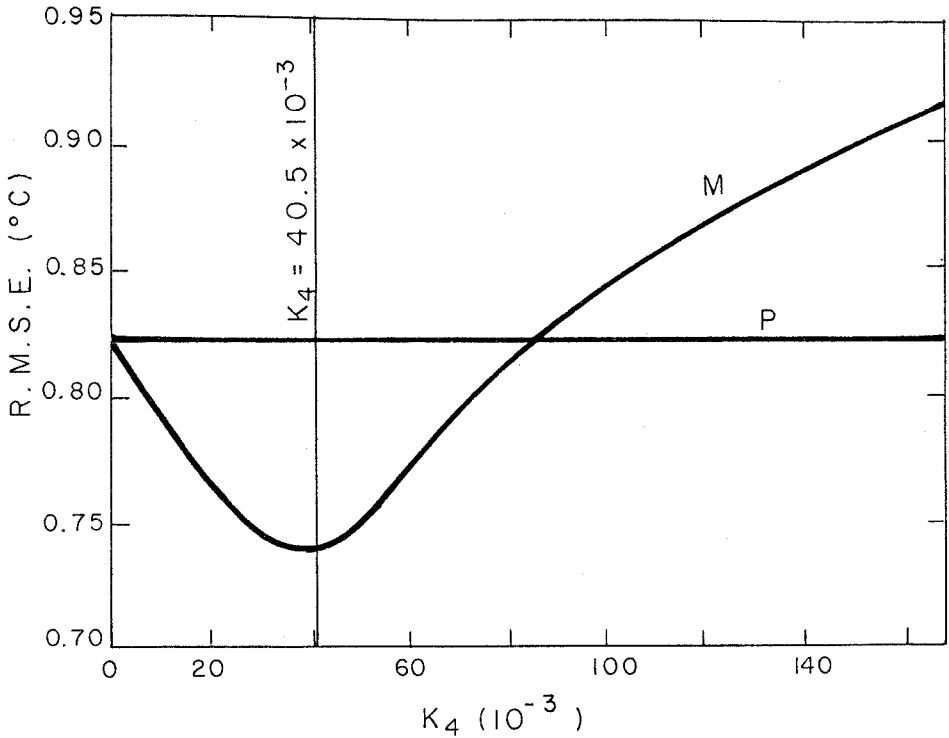


Fig. 4. Dependence of the RMSE of the predicted sea surface temperature anomalies on the coefficient (K_4) of the bulk formula for evaporation. Curve M: Using Eq. (6). Line P: Using persistence.

Experiment 5

As in experiments 2, 3 and 4, we used only the heating term (HE) in Eq. (1). In this case we varied the coefficient K_3 of the sensible heat given off to the atmosphere from the surface of the oceans, and prescribe $A_7 = 0.4$ and K_4 as given by Jacobs (1951). The results are shown in Fig. 5, where the abscissa is K_3 in $\text{gm sec}^{-2}\text{cm}^{-1} \text{°K}^{-1}$. Fig. 5 shows that the RMSE of the model predictions is smaller than that of persistence for $0 < K_3 < 54$. The minimum of the RMSE is obtained for a value of K_3 very close to 26.8 which, as in the previous experiment, is the value given by Jacobs (1951) in the bulk formula for sensible heat given off to the atmosphere.

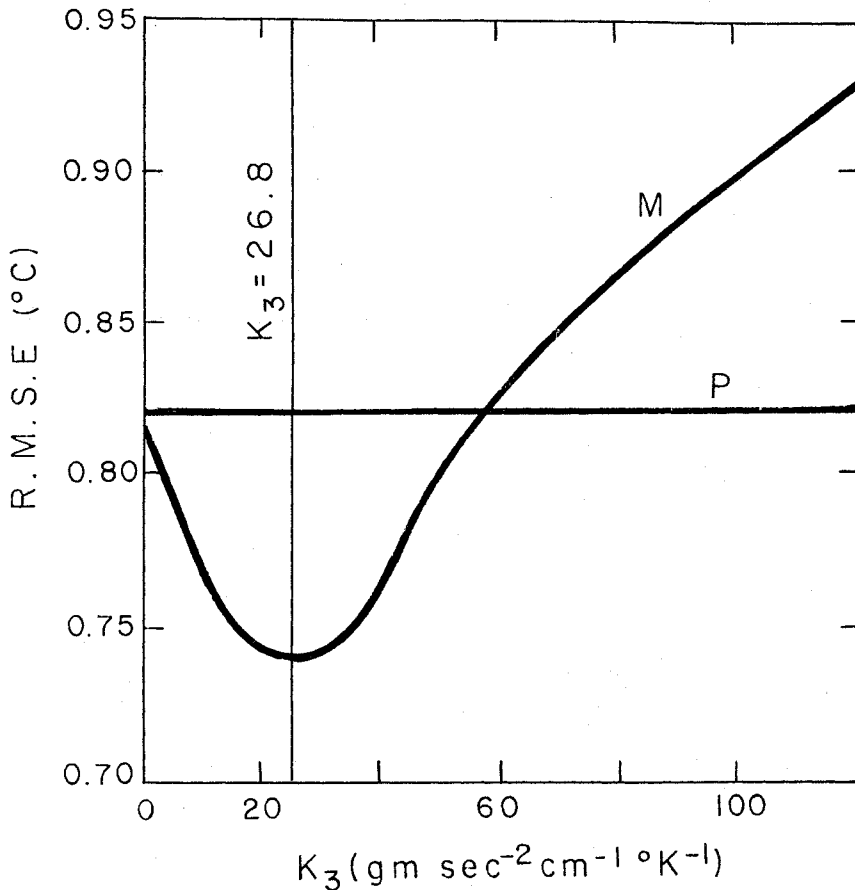


Fig. 5. Dependence of the RMSE of the predicted sea surface temperature anomalies of the coefficient (K_3) of the bulk formula for sensible heat given off to the atmosphere from the surface. Curve M: Using Eq. (6). Line P: Using persistence.

Experiment 6

We used the complete equation (1), prescribing $C_1 = .235$ and $\theta = 90^\circ$ which correspond to the resultant pure drift surface current in the whole frictional layer (Adem 1970a); $h = 100$ m, $A_7 = 0.4$, and Jacobs (1951) values of K_3 and K_4 . The results of this experiment in which we vary K_S , are shown in Fig. 6 in which the abscissa is K_S in $10^8 \text{ cm}^2 \text{ sec}^{-1}$. For the range of values $0 \leq K_S \leq 3$ the RMSE of the model predictions is smaller than that of persistence, and the minimum corresponds to a value very close to $K_S = 1$, showing that this value yields the best predictions.

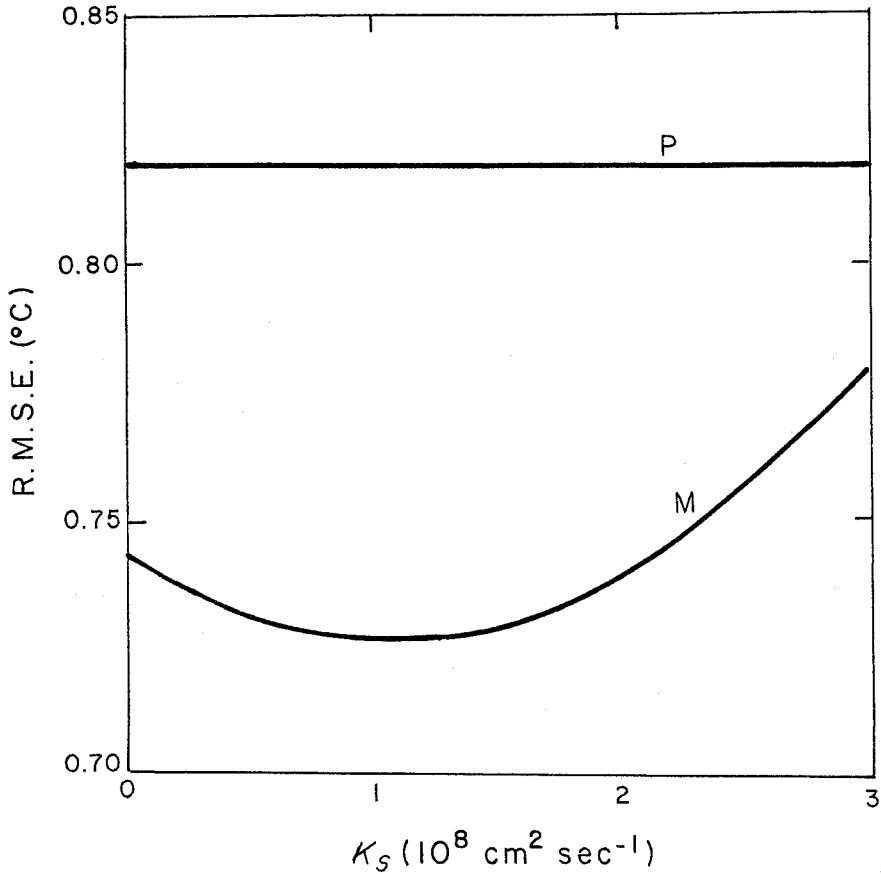


Fig. 6. Dependence of the RMSE of the predicted sea surface temperature anomalies on the horizontal mixing coefficient (K_S). Curve M: Using Eq. (1). Line P: Using persistence.

Experiment 7

We use the complete equation (1) with $A_7 = 0.4$, $h = 100 \text{ m}$, $K_S = 1 \times 10^8 \text{ cm}^2 \text{ sec}^{-1}$ and Jacobs (1951) values of K_3 and K_4 . The results are shown in Fig. 7 in which the abscissa is the coefficient C_1 and the three curves correspond respectively to the values of θ with which they are labeled.

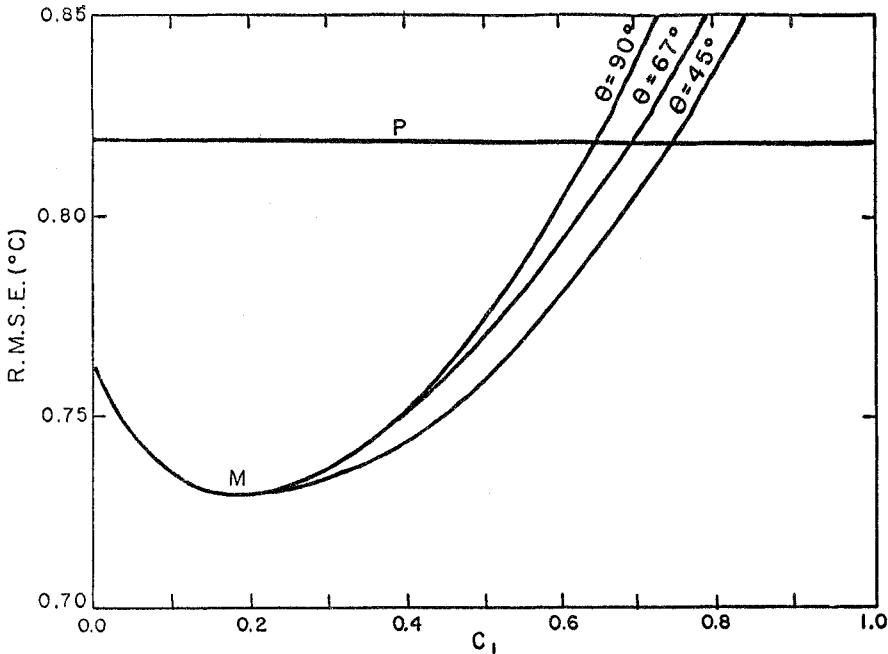


Fig. 7. Dependence of the RMSE of the predicted sea surface temperature anomalies on the parameters C_1 and θ of formulas (4). Curves M: Using Eq. (1) with the value of θ shown. Line P: Using persistence.

This figure shows that the minimum value of the RMSE of the three cases is very close to $C_1 = 0.235$, which, together with $\theta = 90^\circ$, corresponds to the case when we use, in Eq. (1), the resultant pure drift current in the whole frictional layer.

These values of θ and C_1 , together with those of h , K_S , K_3 , and K_4 and A_7 used in this experiment, seem to be a good choice in the applications of equation (1) in ocean temperature prediction.

An example of such predictions is shown in Fig. 8, in which part A shows the predicted changes of anomalies from March to April 1981 and part B the corresponding observed changes.

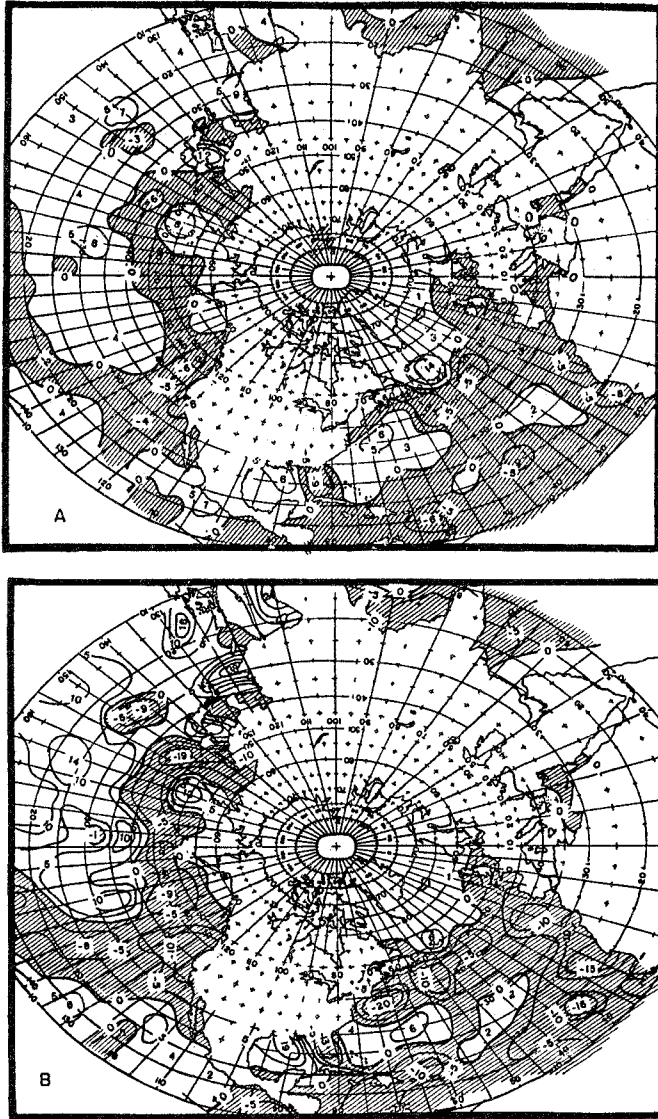


Fig. 8. Changes of surface ocean temperatures, in tenths of Celsius degrees, from March to April 1981: (A) predicted by the model; (B) observed.

THE RELATIVE IMPORTANCE OF THE TRANSPORT AND HEATING TERMS

Using the above mentioned values of the oceanographic parameters, we shall carry out experiments to evaluate the importance, in the prediction of surface ocean temperature anomalies, of the transport and heating terms in Eq. 1. In the experiments we will use the two years of predictions from June 1980 to May 1982.

As in the previous section, we shall evaluate the root mean square error (RMSE) of the predictions by the model and by persistence which is used as control prediction.

The results are shown in Table 2 where the RMSE of the predicted anomalies of sea surface temperature have been evaluated. The first line shows the values of persistence and the other lines the values of persistence minus those of the model predictions.

Table 2

Average of the RMSE (in $^{\circ}\text{C}$) of the predictions of sea surface temperature anomalies for the whole period of 24 months, from June 1980 to May 1982

In the first line are the values of the control prediction (persistence). In the subsequent lines, the values of the control prediction minus the model prediction, when using in the second member of Eq. (1) the terms indicated in the first column.

Case	Pacific	Pacific and Atlantic
Persistence	0.70	0.67
AD	0.00	0.00
TU	0.04	0.04
HE	0.07	0.06
TU + HE	0.08	0.06
AD + TU + HE	0.09	0.07

In the first three cases we include only one of the following terms: advection by wind drift ocean current (AD) horizontal turbulent transport (TU) or heating (HE). The case denoted TU + HE, includes both terms TU and HE; and finally the case denoted by AD + TU + HE uses the complete equation (1).

This table shows that the best predictions are obtained when all the terms are included in equation (1), (AD + TU + HE) with values of RMSE which are .07 and .09 smaller than persistence for the cases of both oceans and the Pacific Ocean respectively.

For the case when only the heating and the turbulent transport terms are included (HE + TU), the corresponding values are .06 and .08 showing that the inclusion of the advection term improves slightly the skill of the predictions. However, when only this term is included (AD), the skill is the same than that of persistence. In the cases when only turbulent transport (TU) or heating (HE) are used alone, the corresponding values of the RMSE are smaller than those of persistence, showing good skill in the predictions.

Table 2 also shows that the best skill in the predictions is obtained in the Pacific Ocean.

A second verification will be carried out on the percentage of signs correctly predicted by the model, and we will use also persistence as control prediction.

Table 3 shows the verification of the percentage of signs of the anomalies correctly predicted. Persistence predicted correctly 61.6 percent over the Pacific and

Table 3

Average of the percentages of signs correctly predicted of the sea surface temperature anomalies for the whole period of 24 months, from June 1980 to May 1982.

In the first line are the values of the control prediction (persistence). In the subsequent lines, the excesses over the control when using in the second member of Eq. (1) the terms indicated in the first column.

Case	Pacific	Pacific and Atlantic
Persistence	61.6	65.6
AD	2.2	1.8
TU	3.7	3.1
HE	2.7	2.7
TU + HE	3.1	2.8
AD + TU + HE	3.1	2.2

65.6 over both oceans. For the model predictions we show only the excess over persistence. In this verification all the predictions show good skill, including the case AD. Although, the best predictions are obtained for the case TU. The cases that include the term HE are also good, but the term AD does not improve the skill. Furthermore, the best predictions are also obtained in the Pacific ocean.

Finally a third verification will be undertaken on the percentage of signs correctly predicted in the month-to-month changes of temperature anomalies. In this case the control prediction is return to normal or the opposite sign of the anomalies of the previous month. This verification was used in the first experiments on ocean temperature prediction (Adem, 1969, 1970a, 1975).

Table 4 shows the verification of the percentage of signs of the month-to-month change of the temperature anomalies correctly predicted. In this case the control prediction, is equal to 58.6 in the Pacific Ocean and to 57.7 in both oceans. For the model predictions we show only the excess over return to normal. In this verification all the predictions are better than the control, except in the case AD, in which the model is 12.5 and 12.9% below return to normal. This is expected because the transport by the wind drift ocean currents is not a process that produces return to normal. In this verification the best prediction is obtained for the case TU + HE. The case AD + TU + HE is slightly worse than TU + HE, showing that the term AD has not improved the skill of the predictions.

Table 4

Average of the percentages of signs correctly predicted of the month-to-month changes in sea surface temperature anomalies for the whole period of 24 months, from June 1980 to May 1982.

In the first line are the values of the control prediction (return to normal). In the subsequent lines, the excesses over the control when using in the second member of Eq. (1) the terms indicated in the first column.

Case	Pacific	Pacific and Atlantic
Return to normal	58.6	57.7
AD	-12.5	-12.9
TU	0.6	1.8
HE	3.4	3.3
TU + HE	3.6	4.0
AD + TU + HE	3.3	3.4

A comparison of the values in Tables 2, 3 and 4 shows that the skill varies according to the verification used. The prediction using only transport of heat by pure wind drift (AD) is above persistence when evaluating the signs of the anomalies, is equal to persistence when evaluating the RMSE, and is considerably worse than return to normal when evaluating the signs of the month-to-month changes of anomalies.

It is interesting to point out that the three cases that include the term HE show a consistent good skill in the three verifications. This is also true for the last case (AD + TU + HE) which includes all the terms of Eq. (1). However, in this case, the inclusion of pure drift ocean currents improves the skill of the predictions only when evaluating the RMSE, as can be seen from a comparison of cases (TU + HE) and (AD + TU + HE) in tables 2, 3 and 4.

FINAL REMARKS

In the sensitivity experiments carried out in this paper we have used only the equation of conservation of thermal energy applied to the ocean mixed layer. The complete model includes besides Eq.(1), the equation of conservation of thermal energy applied to an atmospheric layer of about 10 km thickness, and adequate parameterizations of the heating and transport terms (Adem, 1975). The equation for the atmospheric layer can briefly be written as:

$$A_1 \frac{\partial T_m}{\partial t} + AD_1 + TU_1 = HE_1 \quad (7)$$

where T_m is the mean atmospheric temperature, A_1 is a constant, AD_1 is the advection by mean wind, TU_1 the horizontal turbulent transport, and HE_1 the rate at which energy is added by radiation, sensible heat given off from the surface and condensation of water vapor at the clouds.

In previous numerical experiments we have used a model in which equation (7) has been coupled with equation (6) and in which the transport by ocean currents is neglected.

In this case we use backward time differences and an implicit method of integration. This model has been applied for predictions of mean monthly surface ocean temperature anomalies. A verification of a sample of 73 predictions (Adem, 1975) shows that the percentage of the month-to-month change of the sign of the anomalies correctly predicted is 3.7 higher than that of return to normal. This value is

somewhat higher than the corresponding value (3.3) that appears in Table 4, showing the importance of the contribution of Eq. (7) in the predictions.

The model in which Eqs. (6) and (7) are used has also been applied for predicting monthly anomalies of surface temperature over continents (Adem, 1964a, 1965, 1970b, Adem and Donn, 1981). Recent verifications with a sample of 93 months over the contiguous U. S., have shown a useful skill in the predictions (Donn, Goldberg and Adem, 1986).

In the above experiments a time step of one month has been used. Experiments with equation (5) in which shorter time steps are used, show that the skill of the predictions increases substantially when time steps of 1 to 5 days are used (Adem, 1975; Adem and Mendoza, 1981).

We are currently working on a new version of the model in which the complete equations (1) and (7) are used. In equation (7) backward time steps will be used and it will be integrated with an implicit method, while in (1) forward and shorter time steps will be used. A grid of 1977 points will be used instead of the 512 of the present model. This will allow a more adequate resolution for the correct incorporation of the distribution of continents and oceans, and of the effect of ocean currents and snow and ice conditions.

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