Numerical prediction of the sea surface temperature in the Pacific and Atlantic oceans

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RESUMEN

La ecuación de conservación de energía térmica aplicada a la capa de mezcla oceánica se utiliza para la predicción de las anomalías de la temperatura de la superficie del océano y de sus cambios mensuales en el Hemisferio Norte. La ecuación incluye transporte horizontal de calor por corrientes oceánicas y por mezcla turbulenta horizontal, así como el calentamiento por radiación de onda corta y larga, evaporación y calor sensible. Como datos de entrada usamos la temperatura en la superficie del océano, la temperatura en 850 mb y la presión atmosférica en superficie en el mes previo, así como sus correspondientes valores normales. Se obtiene un estudio comparativo de la importancia relativa del calentamiento de la capa y del transporte horizontal; este estudio también se extiende a los cambios en la distancia entre los puntos de la malla de integración. Se presenta una verificación objetiva para los océanos Pacífico y Atlántico, para un período de 48 meses (junio 1980 a mayo de 1984). Cierto grado de habilidad en las predicciones se debe a los términos de calentamiento, el cual mejora cuando se incluye el transporte horizontal de calor por mezcla turbulenta y por corrientes oceánicas en superficie. La habilidad se incrementa substancialmente en la semi-predicción, en donde las corrientes oceánicas de deriva y el calentamiento se calculan usando la presión atmosférica en la superficie del océano y la temperatura en 850 mb para el mes actual en vez de los del mes previo.

PALABRAS CLAVE: Predicción mensual, temperatura superficial oceánica, modelo climático.

ABSTRACT

The conservation of thermal energy equation applied to the upper mixed layer of the oceans is used for the prediction of the sea surface temperature anomalies and their month - to - month changes in the Northern Hemisphere. The equation includes horizontal transport of heat by ocean currents and by horizontal turbulent mixing as well as heating by short and long wave radiation, evaporation and sensible heat. As input we use the sea surface temperature, the 850 mb temperature and the atmospheric surface pressure in the previous month as well as their corresponding normal values. A comparative study is carried out on the relative importance of the heating and transport terms and of the change in the grid distance. An objective verification of the prediction is presented for the Pacific and Atlantic oceans, for the 48-month period from June 1980 to May 1984. Some degree of skill in the predictions is due to the heating terms. The best skill is obtained when the horizontal transport of heat by turbulent mixing and surface ocean currents is also included. The skill is substantially increased in the semi-prediction for which the wind drift ocean currents and the heating are computed with the atmospheric surface pressure and the 850 mb-temperature for the current month, instead of the previous month.

KEY WORDS: Monthly prediction, sea surface temperature, climatic model.

1. INTRODUCTION

A thermodynamic model for the Northern Hemisphere has been developed and applied to predict mean monthly anomalies of surface temperature (Adem, 1964a, 1964b, 1965, 1970a, 1970b; Adem and Mendoza, 1987). Verifications of predictions and semi-predictions of sea surface temperature (SST) and their month -to-month changes over the Pacific and Atlantic oceans, have been carried out showing good skill for this model (Adem and Mendoza, 1988).

In a previous paper on the predictions of SST anomalies, the model was integrated over a uniform grid of 512 points with a grid interval of 817 km superposed on the polar stereographic projection of the Northern Hemisphere. In the present work, an NMC grid of 1977 points with grid intervals of 408.5 km is used instead of the NMC grid abridged to 512 points as used in previous works. This allows a better resolution for the correct incorporation of the distribution of continents and oceans as well as the effect

of the horizontal turbulent mixing and the ocean currents. Using this new grid it is possible to carry out a more realistic verification of the predictions of SST anomalies.

In the present paper we apply a revised version of the model which includes non-linear formulas for the heating by long-wave radiation and evaporation at the sea surface, using a data set prepared by NCAR which consists of 48 months (June 1980 to May 1984).

We show the most recent verification of the predictions and semi-predictions of the SST anomalies and their month - to - month changes over the Pacific and Atlantic oceans for different factors and we establish the degree of skill of the predictions.

2. THE BASIC EQUATIONS

The Adem thermodynamic model uses the equations of conservation of thermal energy applied to an atmospheric layer of about 10 km thickness, an upper mixed layer of

the oceans and an upper thin layer on the continents. In this work, we carry out experiments using only the equation for the oceans:

$$h_S\left[\frac{\partial}{\partial t}T_S + V_{ST}\cdot\nabla T_S - K_S\nabla^2 T_S\right] + W = \frac{1}{\rho_S c_S}(E_S - G_3 - G_2)$$
(1)

where T_S is the SST, ρ_S is a constant density and c_S is the specific heat; h_S is the depth of the layer; V_{ST} is the horizontal velocity of the ocean currents in the mixed layer; W is the rate of cooling due to upwelling; K_S is the constant Austausch coefficient; E_S is the rate at which the energy is added by radiation; G_3 is the rate at which the heat is lost by evaporation and G_2 is the rate at which sensible heat is given off to the atmosphere by vertical turbulent transport.

2.1 The heating functions

The radiation balance at the sea surface E_S is computed as in Adem (1962), using the non-linear formula:

$$E_S = -\sigma T_S^4 + E(T_a) + \varepsilon\left[\sigma T_{C2}^4 - E(T_{C2})\right] + \alpha_1 I$$
(2)

where ε is the fractional cloudiness, T_a is the ship-deck air temperature, $\alpha_1 I$ is the short wave radiation absorbed by the ocean layer, $\sigma = 8215 \times 10^{-14}$ cal cm^{-2} K^{-4} min^{-1} is the Stefan - Boltzman constant, T_{C2} is the temperature at the bottom of the layer of clouds considered in the radiation model as a constant and $E(T^*)$ is a non-linear function of the temperature T^* which represents the energy per unit area and per unit time emitted by a horizontal boundary of an atmospheric layer as given in the above paper.

For $\alpha_1 I$ we use the formula (Adem, 1964):

$$\alpha_1 I = (Q+q)_0\left[1-(1-k)\varepsilon\right](1-\alpha)$$
(3)

where $(Q + q)_0$ is the total radiation received by the surface with clear sky, k is a function of latitude 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):

$$G_3 = K_4|V_a|\left[0.981\,e_S(T_S) - U\,e_S(T_a)\right]$$
(4)

$$G_2 = K_3|V_a|(T_S - T_a)$$
(5)

where $K_3 = 26.8$ gr cm^{-1} s^{-1} K^{-1} and $K_4 = 40.5 \times 10^{-3}$, $|V_a|$ is the ship-deck wind speed; $e_S(T_S)$ and $e_S(T_a)$ are the saturation vapor pressure at the surface ocean temperature and at the ship-deck air temperature, respectively, and U is the sea surface relative humidity.

For the saturation vapor pressure we use:

$$e_S(t^*) = a_1 + b_1 t^* + c_1 t^{*2} + d_1 t^{*3} + l_1 t^{*4}$$
(6)

where e_S is in millibars and $t^* = T^* - 273.16$ °C, T^* is the absolute temperature; $a_1 = 6.115$, $b_1 = 0.42915$, $c_1 = 0.014206$, $d_1 = 3.046 \times 10^{-4}$ and $l_1 = 3.2 \times 10^{-6}$ (Adem, 1967).

We also carry out experiments with the linear formulas used in Adem and Mendoza (1988):

$$E_S = F_{34} + \varepsilon_N F'_{34} + F_{35}T'_a + F_{36}T'_S + \alpha_1 I$$
(7)

$$G_3 = G_{3N} + K_4 B|V_{aN}|\left[0.981(T_S - T_{SN}) - U_N A_7(T_m - T_{mN})\right]$$
(8)

$$G_2 = G_{2N} + K_3|V_{aN}|\left[(T_S - T_{SN}) - A_7(T_m - T_{mN})\right]$$
(9)

In Eq. (7), ε_N is the seasonal normal value of ε; $T'_a = T_a - T_{a0}$ and $T'_S = T_S - T_{S0}$, with $T_{a0} = T_{S0} = 288$ °K; $\alpha_1 I$ is given by (3) using ε_N instead of ε; and F_{34}, F'_{34}, F_{35} and F_{36} are constants given by

$$F_{34} = -F(T_{S0})$$
$$F'_{34} = F(T_{C2})$$
$$F_{35} = 4\sigma T_{S0}^3 - \left(\frac{\partial F}{\partial T^*}\right)_{T^*=T_{S0}}$$
$$F_{36} = -4\sigma T_{S0}^3$$

where $F(T^*)$ is a non-linear function of the temperature T^*, which is related to $E(T^*)$ by $E(T^*) = \sigma T^{*4} - F(T^*, 8\mu, 13\mu)$. The function $F(T^*)$ represents the energy per unit area and per unit time which is not absorbed by the atmospheric layer of the model in the window betwen 8μ and 13μ (Adem, 1962).

In Eqs. (8) and (9), 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; B is a constant; A_7 is an empirical constant parameter equal to 0.4 (Adem y Mendoza, 1987); $|V_{aN}|$ is the seasonal normal value of $|V_a|$, and U_N is the normal value of U.

Eq. (7) has been derived from Eq. (2), using the linear relation

$$E(T^*) = E(T_0^*) + \left(\frac{dE}{dT^*}\right)_{T_0^*} T^{*'}\quad,$$

where T_0^* is a basic constant temperature and $T^{*'}$ is a small departure from T_0^*.

Eqs. (8) and (9) have been obtained from Eqs. (4) and (5) respectively, by assuming a constant lapse rate and normal values of $|V_a|$ and U; and by approximating the saturation vapor pressure by the linear formula:

$$e_S(T^*) = A + BT^*$$

where A and B are constants equal to -349.084 mb and 1.28 mb K^{-1}, respectively. Eqs. (8) and (9), with $A_7 = 1$, were derived by Clapp *et al.* (1965) as an adaptation of Jacobs' (1951) bulk formulas (4) and (5), and have been used in the thermodynamic model (Adem, 1964a, 1964b and 1982).

2.2 The advection by mean ocean currents

For the horizontal velocity of the ocean currents in the mixed layer we assume that

$$V_{ST} = V_{SW} + (V_S - V_{SN}) \qquad (10)$$

where V_{SW} is the velocity of the observed normal seasonal ocean current, V_S is the velocity of the pure drift current and V_{SN} is the corresponding normal velocity of the pure drift current.

To evaluate V_S and the corresponding normal values V_{SN} we have used Ekman's formulas. Therefore the components of the velocity V_S can be expressed by the following equations (Adem, 1970a):

$$u_S = C_1 \frac{0.0126}{\sqrt{\sin\varphi}} (u_a\cos\theta + v_a\sin\theta) \qquad (11)$$

$$v_S = C_1 \frac{0.0126}{\sqrt{\sin\varphi}} (v_a\cos\theta - u_a\sin\theta) \qquad (12)$$

where u_S and v_S are the x and y components respectively of the velocity V_S; φ is the latitude; u_a and v_a are the x and y components of the surface wind, respectively, which is considered as geostrophic; C_1 is a constant coefficient and θ is the angle that measures the direction of the vector surface ocean current to the right of the surface wind direction.

2.3 Sea surface air temperature and relative humidity anomalies

For the sea surface air temperature, we assume

$$T_a = T_{aN} + (T_{ac} - T_{aNc}) \qquad (13)$$

where T_{aN} is the observed normal values of T_a taken from the Marine Climatic Atlas of the World (U.S. Navy, 1981); T_{ac} is the computed sea surface air temperature and T_{aNc} is the corresponding normal value of T_{ac}, both temperatures computed from Adem *et al.* (1994):

$$T_{ac} = T_{850} \left(\frac{1013}{850}\right)^{R\beta/g} \qquad (14)$$

where T_{850} is the temperature at 850 mb level; R is the gas constant, β is the standard constant lapse rate in the tropospheric layer and g is the gravity acceleration. For T_{aNc} we replace the temperature in 850 mb by its normal value in Eq. (14).

To compute the sea surface air relative humidity, we use (Adem *et al.*, 1994):

$$U = U_N + A_N (T_{ac} - T_{aNc}) \qquad (15)$$

where U_N is the observed normal value of U, and A_N is given by

$$A_N = -\left[\frac{d}{dT_{aN}} \ln e_S(T_{aN}) - \frac{1}{T_{aN}}\right] U_N \qquad (16)$$

3. THE NUMERICAL EXPERIMENTS

The local rate of change of the SST can be obtained from (1):

$$\frac{\partial}{\partial t} T_s = AD_1 + AD_2 + TU + HE - \frac{W}{h_s} \qquad (17)$$

where

$$AD_1 = -(V_S - V_{SN}) \cdot \nabla T_S \qquad (18)$$

$$AD_2 = -V_{SW} \cdot \nabla T_S \qquad (19)$$

$$TU = K_S\nabla^2 T_S \qquad (20)$$

$$HE = (1/\rho_S c_S h_S)(E_S - G_3 - G_2) \qquad (21)$$

In Eq. (11) and (12) we use for the advection term AD_1 the values C_1 equal to 0.235, which corresponds to the resultant pure drift current in the whole frictional layer, and θ equal to zero degrees corresponding to the case in which the wind drift current has the same direction than the geostrophic wind (Adem and Mendoza, 1988). For the advection term AD_2 we use $V_{SW} = C_1 V_{S0}$ where V_{S0} is the horizontal normal seasonal ocean velocity observed in the surface obtained from the available data of NCAR network. The exchange coefficient K_S for the horizontal turbulent transport of heat (TU) is taken as constant and equal to 1×10^8 cm^2 sec^{-1}.

For the coefficients in the heating term (HE), we take the values $\rho_S = 1$ gm cm^{-3}, $c_S = 1$ cal gm^{-1} and $h_S = 100$ m as in Adem (1970). We use Eqs. (2) and (3) assuming seasonal normal values for cloudiness, and in Eqs. (4) and (5) we take seasonal normal values for the ship deck-wind speed.

The term $- W/h_S$ is neglected, because non-negligible changes of SST would require upward velocity values of the order of $(1/2.6) \times 10^{-2}$ cm sec^{-1} (Adem, 1970a). According to Wyrtki (1961), the upward velocity for oceanic large-scale circulation is only of the order of 2×10^{-5} cm sec^{-1}.

For the time derivative in Eq. (17) we use the Euler formula with time steps of one day. Thus for each of the monthly predictions 30 time steps are used.

For spatial derivatives we use centered finite differences. Equation (17) is integrated over two different uniform grids superposed on the stereographic projection of the Northern Hemisphere, one corresponding to the NMC grid of 1977 points with a grid interval of 408.5 km (high - resolution grid), and another corresponding to the NMC grid abridged to 512 points with grid interval of 817 km (low - resolution grid). The integration area and the high - resolution grid are shown in Figure 1. The integration is carried out only in the oceanic regions, using at the boundary of the integration area only the heating term (HE) in Eq. (17). In order to evaluate the derivatives at the ocean - continent boundary, we define a surface temperature inside the continent by assigning the normal value of SST of the ocean grid points to the close neighboring grid points inside the continent.

3.1 The prediction method

The first step consists in making a prediction for the normal values, using observed normal values of the previous month as initial conditions and another prediction for the given month using the observed values of the previous month as initial condition (normal plus anomaly). The predicted anomaly is obtained by substracting from the computed values in the first time step the corresponding computed normal values. For the next time step the procedure is repeated but the initial ocean temperature anomaly is the one computed in the previous time step.

The predicted month - to - month anomaly changes are obtained by substracting from the predicted SST anomalies the observed SST anomalies for the previous month. The atmospheric initial conditions remain fixed through the whole integration.

We carry out predictions for 48 months, from June 1980 to May 1984. As input data we use the previous month values of SST, atmospheric surface pressure and 850 mb-temperature to estimate the surface air temperature anomalies from Eqs. (13) and (14). The SST values and the corresponding normal values were obtained from the National Weather Service-NOAA. The atmospheric surface pressure and 850 mb-temperature values and their corresponding normal values were obtained from the NCAR NMC Grid Point Data Set (CD-ROM).

In addition to the prediction experiments we carried out semipredictions in which the atmospheric fields are prescribed for the current month instead of the previous month.

3.2 Evaluation of the predictions

We evaluate the skill of the predictions in three different ways:

(a) By determining the percentage of correctly predicted signs of the SST anomalies. As control we use the signs of the SST anomalies of the previous month as a prediction of the signs of the SST anomalies (persistence).

(b) By determining the percentage of correctly predicted signs of the month - to - month changes of the SST anomalies. As control prediction we use the percentage of signs by assuming a return to normal (i.e., using the opposite sign of the SST anomalies of the previous month as a prediction of the sign of the month - to - month change of the signs of the SST anomalies).

(c) By determining the root-mean-square error (RMSE) of the predicted SST anomalies. As control prediction we use the RMSE of the previous month values of SST anomalies assuming persistence.

3.3 Description and discussion of the results

First we consider the results of the predictions using the high - resolution grid, in order to evaluate the importance in the prediction of the different terms that appear in (17) and to determine the best parameterizations for the heating functions.

Table 1 shows the evaluation of the correctly predicted percentage of the signs of SST anomalies, Table 2 the percentage correctly predicted of the sign of the month-to-month changes of the SST anomalies, and Table 3 the root mean square error (RMSE) of the SST anomalies, for the Pacific and Atlantic oceans combined.

Table 1

Average of the percentage of correctly predicted signs of the sea surface temperature anomalies for the whole period of 48 months from June 1980 to May 1984. In the first row are the values of the control prediction (persistence). In the subsequent rows, the excesses over the control, when using in the right side of Eq. (17) the terms indicated in the first column. The second and third columns show the values for the semipredictions and the predictions, respectively. In the fourth column are the values of the second column minus the values of the third column.

Case	Semiprediction	Prediction	Difference
Persistence		70.1	
HE	3.4	2.2	1.2
TU+HE	3.6	2.4	1.2
AD_2+TU+HE	3.5	2.3	1.2
AD_1+AD_2+TU+HE	3.7	2.2	1.5
AD_1+AD_2+TU+HE_L	2.8	2.0	0.8

In the first column of each of these tables we indicate the terms of (17) included in the prediction or semiprediction. We use the terms alone or in combination. For the
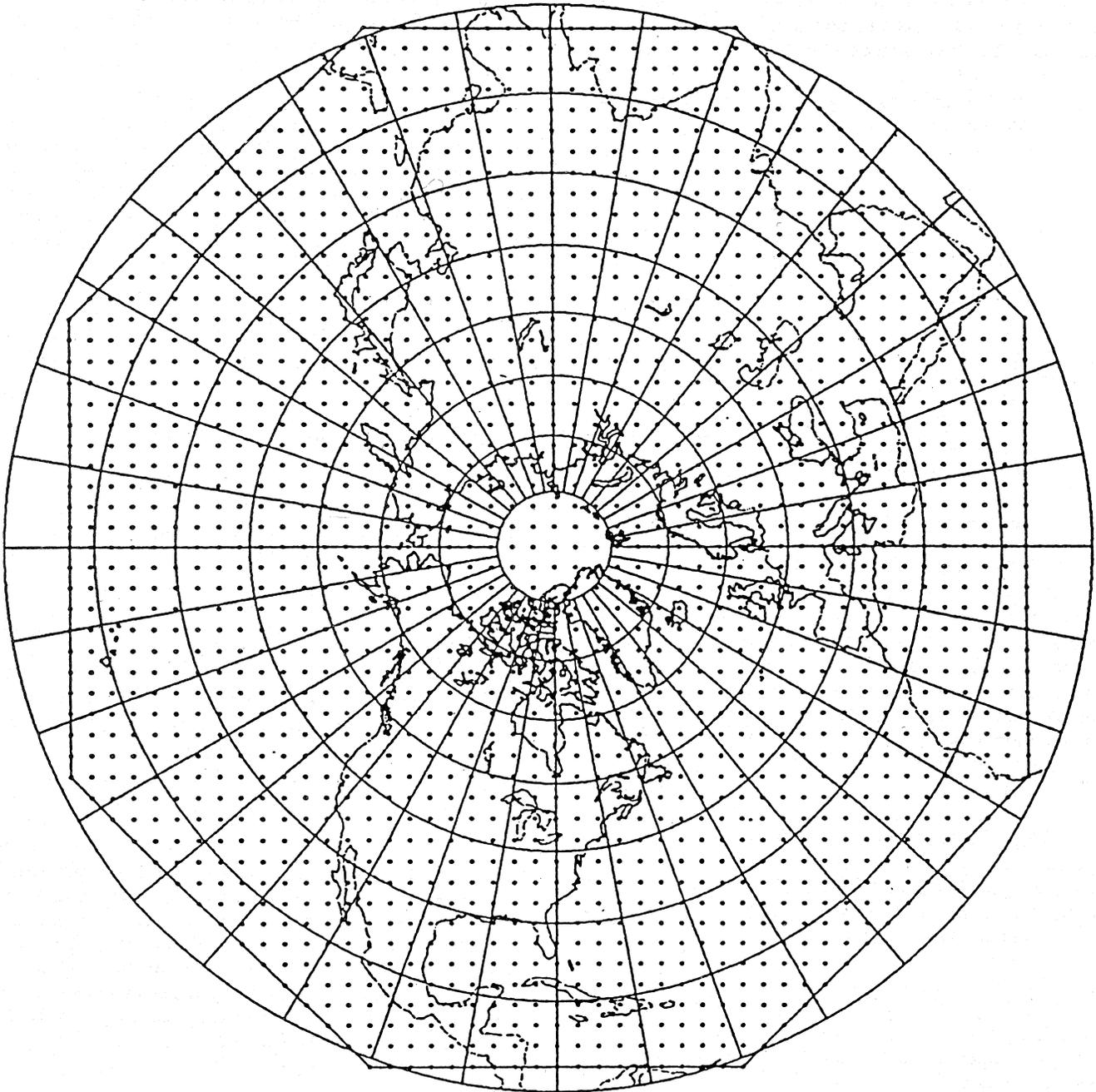
Fig. 1. The region of integration and the grid points.

heating term HE, which depends on the parametric formulas used, subindex L means that the linear Eqs. (7) to (9) are used. No subindex means that the non linear Eqs. (2), (4) and (5) are used. The second column shows the values for the semipredictions, and the third column shows the values for the predictions. The fourth column contains the differences (semipredictions minus predictions).

Each table shows in the first row and in the third column the control prediction; the other rows in Tables 1 and 2 show values of the model semiprediction, or prediction minus the control prediction, in percent of signs correctly predicted. Table 3 shows values of the RMSE of the control prediction minus the RMSE of the model semiprediction or prediction. In all three tables, when the value is positive the model prediction is better than the control prediction.

In all cases, and for all evaluations, the semipredictions are better than the predictions. These results agree with those obtained in a previous paper (Adem and Mendoza, 1988). This suggests that a more complete model for pre-

dicting the atmospheric variables as well as the ocean temperature would improve the predictions. In all evaluations, the semipredictions and predictions which neglect the transport by mean ocean currents and by turbulent eddies (Case HE) or include this term(the other cases in column 1), are better than the control predictions.

Table 2

Average of the percentage of correctly predicted signs of the month - to - month changes in sea surface temperature anomalies for the whole period of 48 months from June 1980 to May 1984. In the first row are the values of the control prediction (return to normal). In the subsequent rows, the excesses over the control, when using in the right side of Eq. (17) the terms indicated in the first column. The second and third columns show the values for the semipredictions and the predictions, respectively. In the fourth column are the values of the second column minus the values of the third column.

Case	Semiprediction	Prediction	Difference
Return to Normal		58.8	
HE	5.7	2.6	3.1
TU+HE	6.1	3.2	2.9
AD$_2$+TU+HE	5.9	3.4	2.5
AD$_1$+AD$_2$+TU+HE	6.5	3.4	3.1
AD$_1$+AD$_2$+TU+HE$_L$	5.2	3.2	2.0

In Tables 1 and 2, a comparison between the cases HE and TU + HE shows that the inclusion of the turbulent term (TU) improves the predictions and the semipredictions. Comparing the case TU + HE with AD$_2$+ TU + HE shows that the inclusion of the horizontal transport of heat by seasonal ocean currents, in general, does not improve the predictions and semipredictions, except for the prediction of the month - to - month changes in SST anomalies (Table 2). However, a comparison of the case AD$_2$ + TU + HE with AD$_1$ + AD$_2$ + TU + HE shows that the inclusion of the horizontal transport of heat by anomalies of pure drift current improves the predictions and semipredictions. A comparison of the complete cases where different equations for the heating term were used (the two last cases of the first column) shows that the non-linear Eqs. (2), (4) and (5) yield the best results.

Table 3 shows that the values of the RMSE are very similar.

Table 4 shows the results for the complete model, AD$_1$ + AD$_2$ + TU + HE, for the month - to - month changes of SST anomalies and for the return to normal corresponding to each month of the whole period for the Pacific and Atlantic oceans combined. Table 5 shows the average results for each season and for the whole period of 48 months. In this case we consider the Pacific ocean, and the Pacific and Atlantic oceans combined.

Table 3

Average of the RMSE (in °C) of the predictions of monthly sea surface temperature anomalies for the whole period of 48 months (from June 1980 to May 1984). In the first row are the values of the control prediction (persistence). In the subsequent rows, the values of the control prediction minus the model prediction, when using in the right hand side of Eq. (17) the terms indicated in the first column. The second and third columns show the values for the semipredictions and the predictions respectively. In the fourth column are the values of the second column minus the values of the third column.

Case	Semiprediction	Prediction	Difference
Persistence		0.59	
HE	0.08	0.05	0.03
TU+HE	0.08	0.06	0.02
AD$_2$+TU+HE	0.08	0.06	0.02
AD$_1$+AD$_2$+TU+HE	0.08	0.05	0.03
AD$_1$+AD$_2$+TU+HE$_L$	0.07	0.05	0.02

Table 4 shows that there are 26 months in which the model predictions are significantly better than the control predictions (excess larger than +1 %), while 9 months are close to the control predictions (excess between +1 % and -1 %) and 13 months are significantly lower than the control predictions (excess below -1 %).

In Table 5 the best results correspond to the fall in the Pacific ocean area and in the whole area. The model predicted correctly the signs of the month - to - month changes in the SST anomalies in 65.8 % and 64.4 % of the areas respectively, being 2.6 % and 3.3 % better than the control prediction respectively. However, a higher excess over the control is obtained for winter in both cases, with values of 6.7 % and 5.6 % respectively.

To illustrate the results in this paper, Figures 2 and 3 show a good prediction and the corresponding semiprediction, respectively. The monthly changes presented are from March to April 1982, for the case when the complete equation (17) is used in the high - resolution grid model, with non-linear formulas for the heating functions. Figure 4 gives the corresponding observed changes.

Comparison of Figures 2 and 3 with the corresponding observed changes (Figure 4) shows that the signs of the changes of SST anomalies, as well as the positions of some of the maxima and minima are well predicted. Furthermore, the predicted changes are of the correct order of magnitude. This comparison shows again that the semiprediction is better than the prediction.

Table 4

Percentage of correctly predicted signs of the month - to - month changes in sea surface temperature anomalies by the model and by the return to normal for the 48 months, from June 1980 to May 1984.

Pacific and Atlantic

Month	Model	Return to Normal	Diff.	Month	Model	Return to Normal	Diff.
1980				1982			
June	59.2	55.5	3.7	June	65.5	61.1	4.4
July	72.9	72.0	0.9	July	59.4	65.9	-6.5
Aug.	69.4	61.6	7.8	Aug.	71.8	71.0	0.8
Sept.	58.3	44.1	14.2	Sept.	62.0	51.7	10.3
Oct.	53.1	57.2	-4.1	Oct.	64.0	65.7	-1.7
Nov.	61.3	55.2	6.1	Nov.	49.6	57.9	-8.3
Dec.	67.7	67.5	0.2	Dec.	54.2	54.4	-0.2
1981				1983			
Jan.	58.1	50.2	7.9	Jan.	53.1	54.2	-1.1
Feb.	64.4	59.4	5.0	Feb.	66.4	54.2	12.2
Mar.	65.7	66.2	-0.5	Mar.	60.5	48.5	12.0
Apr.	64.8	65.9	-1.1	Apr.	56.3	55.7	0.6
May	69.0	66.6	2.4	May	56.3	59.4	-3.1
June	64.2	51.7	12.5	June	61.3	61.4	-0.1
July	72.1	75.7	-3.5	July	46.1	49.3	-3.2
Aug.	67.0	57.9	9.1	Aug.	50.9	54.1	-3.2
Sept.	70.1	65.7	4.4	Sept.	82.5	80.8	1.7
Oct.	65.5	61.1	4.4	Oct.	72.9	57.4	15.5
Nov.	59.6	62.4	-2.8	Nov.	73.4	73.6	-0.2
Dec.	54.6	46.7	7.9	Dec.	67.5	57.0	10.5
1982				1984			
Jan.	65.7	70.9	-5.2	Jan.	67.5	57.9	9.6
Feb.	66.4	60.3	6.1	Feb.	67.9	53.3	14.6
Mar.	55.5	54.4	1.1	Mar.	53.5	45.8	7.7
Apr.	62.2	45.2	17.0	Apr.	54.1	56.8	-2.7
May	47.2	45.2	2.0	May	55.7	54.8	0.9

Table 5

Average for the seasons and for the whole period, from June 1980 to May 1984, of the percentage of correctly predicted signs of the month - to - month changes in sea surface temperature anomalies by the model and by the return to normal.

Season	Pacific			Pacific and Atlantic		
	Model	Return to Normal	Diff.	Model	Return to Normal	Diff.
Winter	62.5	55.8	6.7	62.8	57.2	5.6
Spring	57.2	51.5	5.7	58.4	55.4	3.0
Summer	62.4	60.2	2.2	63.3	61.4	1.9
Fall	65.8	63.2	2.6	64.4	61.1	3.3
Average	62.0	57.7	4.3	62.2	58.8	3.4

To determine the effect of a change in the grid distance on the terms in (17), we compare the predictions of the model integrated over the high - resolution grid with those of the model integrated over the low - resolution grid. In order use as control prediction the low - resolution grid, we will include in the evaluation of the prediction with the high - resolution model the same 512 grid points of the low - resolution model.

Tables 6, 7 and 8, show the three evaluations of the predictions as in Tables 1, 2 and 3. Tables 6 and 7 show in the first column the terms used in the model; the second and fifth columns contain the percentages for high - resolution grid (HRG) corresponding to semiprediction and prediction, respectively, while the third and sixth columns show the percentages for low - resolution grid (LRG) for semiprediction and prediction. Finally, the fourth and seventh columns contain the differences of the values of high - resolution minus low - resolution. Table 8 shows the
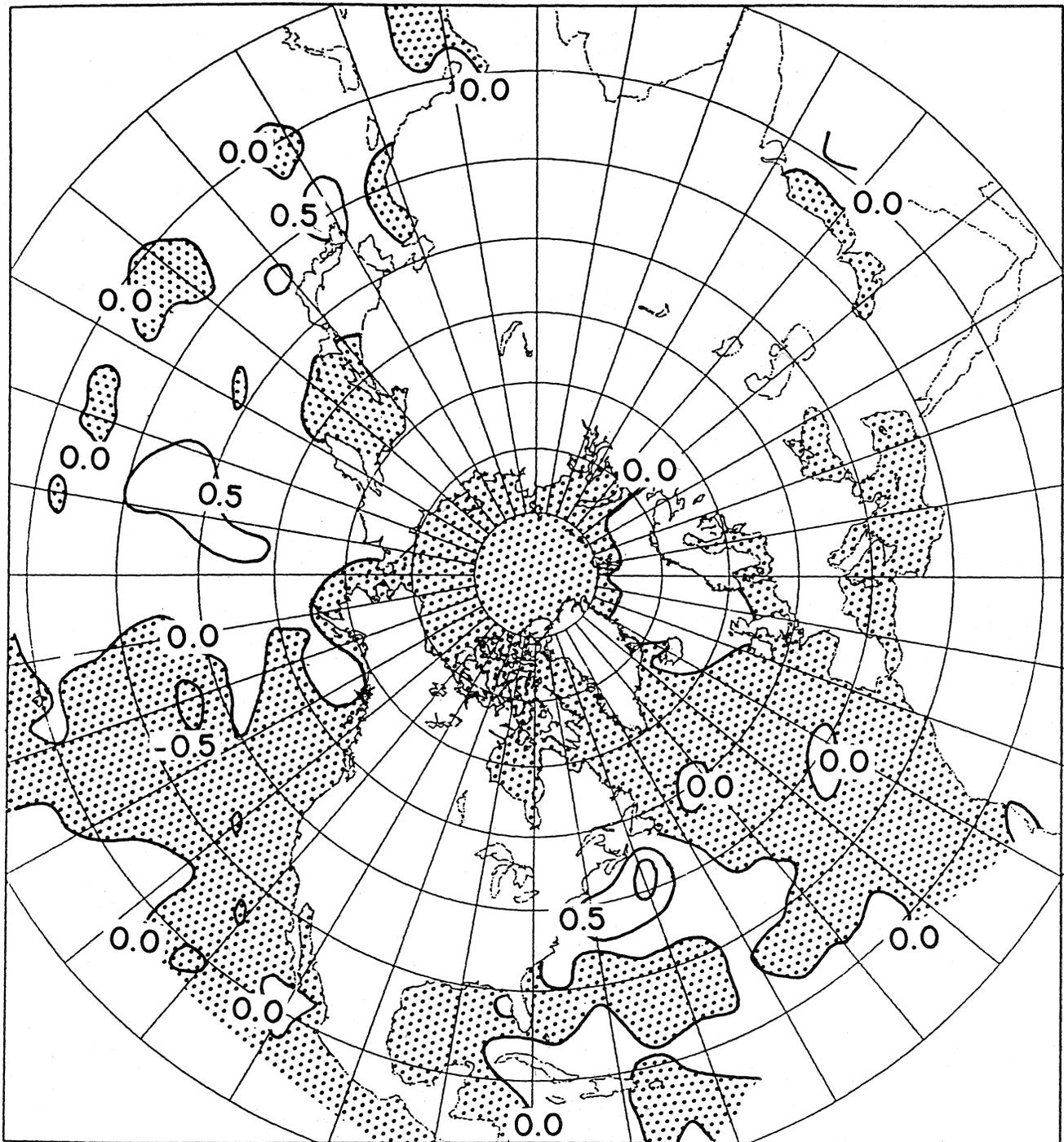
Fig. 2. Predicted change in the sea surface temperature anomalies from March to April 1982, in degrees Celsius.

RMSE values for the high - resolution grid (second and fifth columns) and for low - resolution grid (third and sixth columns). In the forth and seventh columns are the differences of the values of low - resolution minus high - resolution.

Tables 6 and 7 suggest that, if only the heating term (HE) is included, the results are independent of the resolution. However, when the turbulent term (TU) or the turbulent term plus the advection terms ($AD_1 + AD_2 + TU$) are

also included, the skill of the predictions and the semipredictions is improved. This result is expected because the heating term has a local effect on the SST anomalies (the heating term contains no horizontal spatial derivatives), while the turbulent and advective terms depend on the horizontal resolution of the model.

Table 8 shows that the RMSE is the same for the two resolution grids.
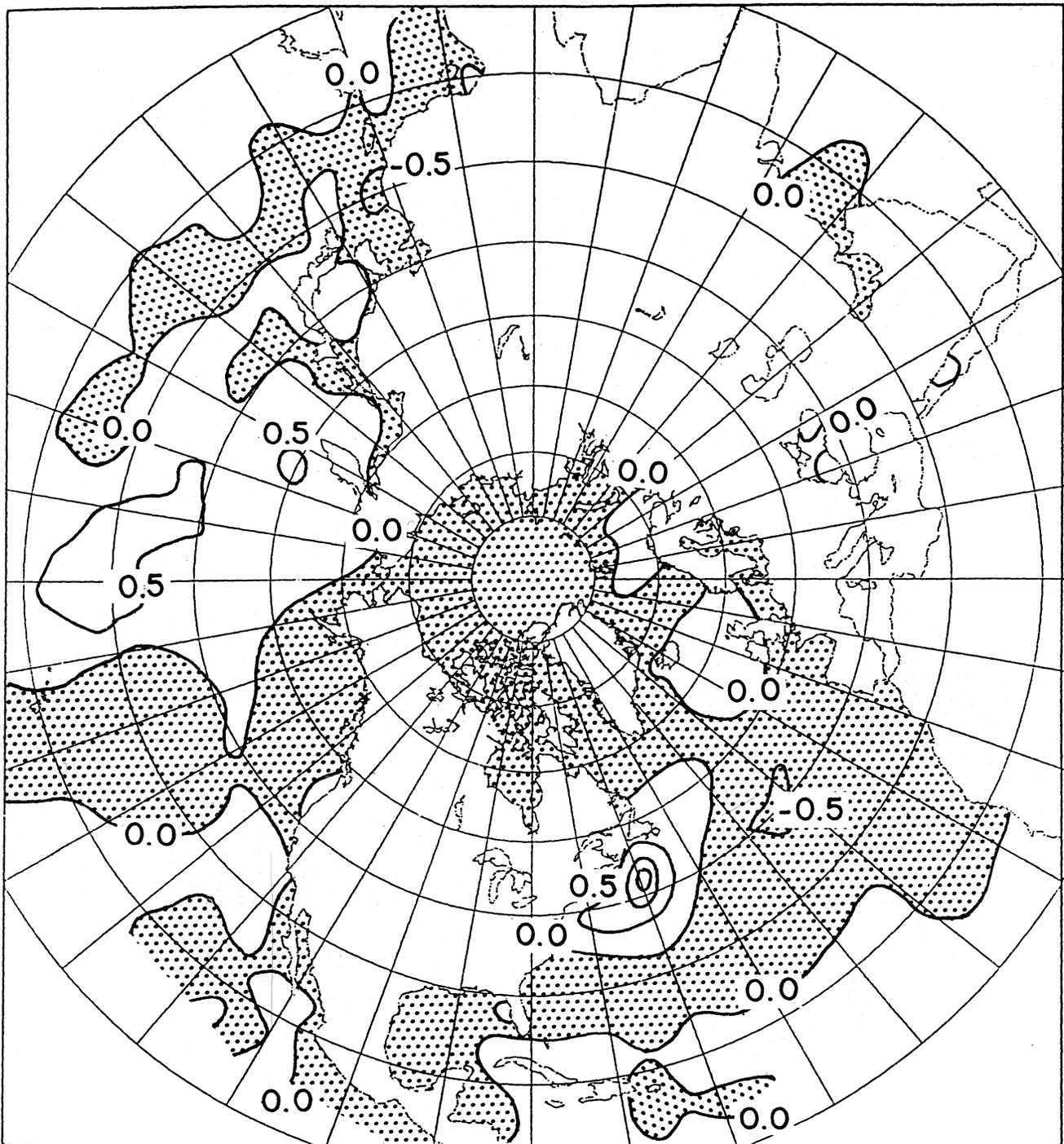
Fig. 3. Semiprediction of the change in the sea surface temperature anomalies from March to April 1982, in degrees Celsius.

4. CONCLUDING REMARKS

For a sample of 48 months, the predictions of SST anomalies and their month - to - month changes have skill when the heating in the mixed layer by radiation, evaporation and vertical turbulent transport of sensible heat given off to the atmosphere from the surface are taken in acount.

A substantial improvement is obtained when, besides the heating terms, we also include the turbulent term.

These results show that the large-scale horizontal turbulent transport of heat, parameterized by an Austausch coefficient, is an important process that should be included in SST anomalies modeling.

The inclusion of the horizontal transport of heat by normal seasonal surface ocean currents (AD_2 + TU + HE), does not improve the prediction. This could be due to the lack of available data for vertical profiles of the ocean
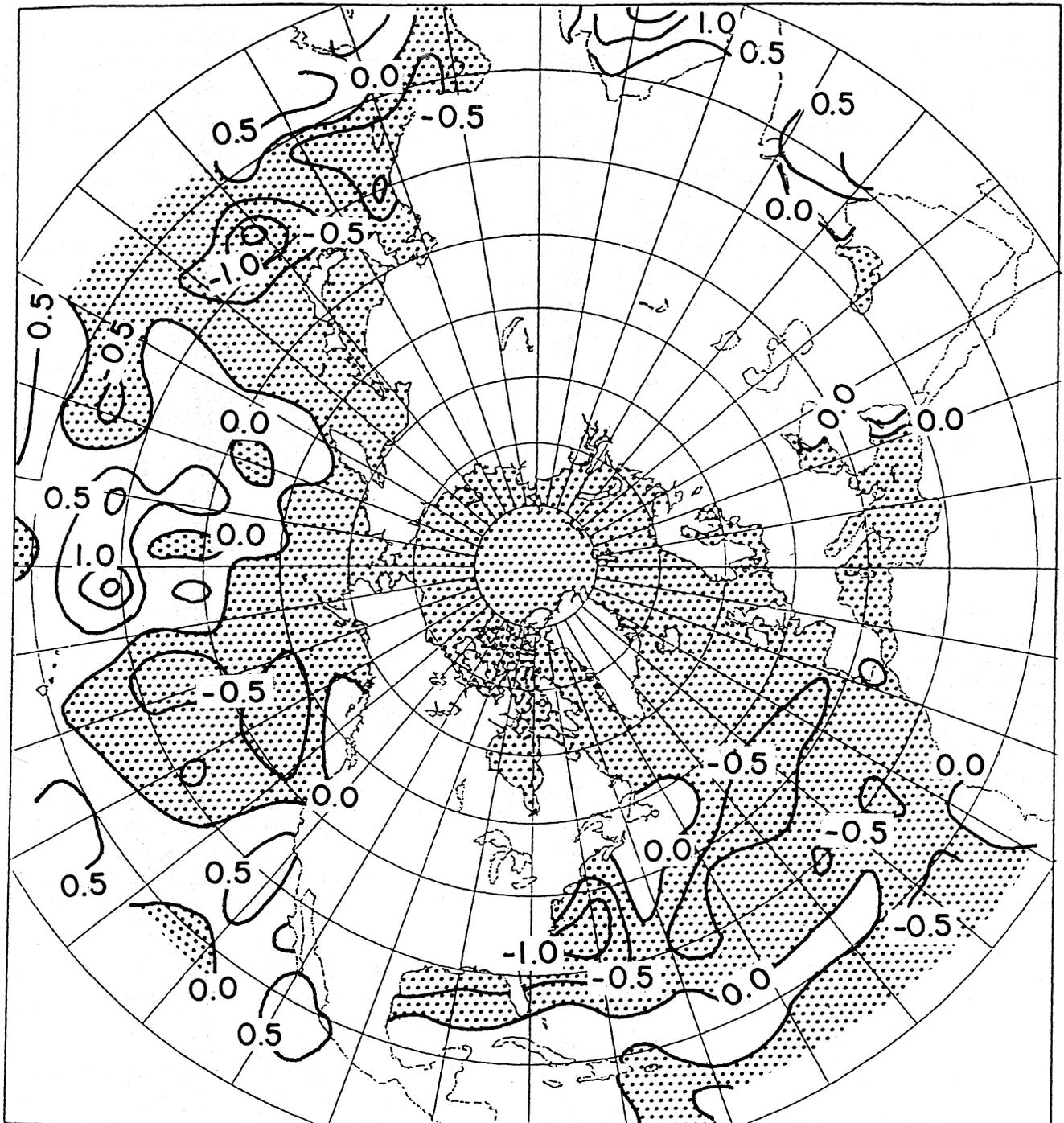
Fig. 4. Observed change in the sea surface temperature anomalies from March to April 1982, in degrees Celsius.

currents in the upper layer, which caused us to assume that the horizontal normal seasonal ocean current in the whole mixing layer is equal to the normal seasonal ocean current observed at the surface times the coefficient $C_1 = 0.235$ (which corresponds to the resultant pure drift current in the whole frictional layer). However, the results obtained with the more complete model ($AD_1 + AD_2 + TU + HE$) show that the including the horizontal transport of

heat by anomalies in the pure drift currents improves the model.

The comparison of the complete cases where different formulas for the heating term are used, shows as expected that the non-linear formulas (2), (4) and (5) are better parameterizations for the heating functions than the linear formulas (7), (8) and (9).

Table 6

Average of the percentages of correctly predicted signs of the sea surface temperature anomalies for the whole period of 48 months from June 1980 to May 1984. The first column contains the terms used in the right - hand side of Eq. (17). The second and fifth columns show the values of percentages for high - resolution grid (HRG) corresponding to semipredictions and predictions, respectively. The third and sixth columns show the values of percentages for low - resolution grid (LRG) corresponding to semipredictions and predictions, respectively. The fourth and seventh columns show the differences of the values of HRG minus LRG.

| | Pacific and Atlantic | | | | | |
| Case | Semiprediction | | | Prediction | | |
	HRG	LRG	Diff.	HRG	LRG	Diff.
HE	70.6	70.6	0.0	69.4	69.4	0.0
TU+HE	70.7	70.7	0.0	69.6	69.4	0.2
AD_1+AD_2+TU+HE	70.5	70.2	0.3	69.5	68.9	0.6

Table 7

Average of the percentages of correctly predicted signs of the month - to - month changes in sea surface temperature anomalies for the whole period of 48 months from June 1980 to May 1984. In the first column, the terms used in the right - hand side of Eq. (17). The second and fifth columns show the values of percentages for high - resolution grid (HRG) corresponding to semipredictions and predictions, respectively. The third and sixth columns show the values of percentages for low - resolution grid (LRG) corresponding to semipredictions and predictions, respectively. The fourth and seventh columns show the differences of the values of HRG minus LRG.

| | Pacific and Atlantic | | | | | |
| Case | Semiprediction | | | Prediction | | |
	HRG	LRG	Diff.	HRG	LRG	Diff.
HE	63.0	63.0	0.0	60.5	60.5	0.0
TU+HE	63.6	63.0	0.6	61.1	60.9	0.2
AD_1+AD_2+TU+HE	63.8	62.3	1.5	61.8	60.8	1.0

Finally, a reduction in the grid interval from 817 km to 408.5 km yields a better resolution for the correct incorporation of the horizontal transport of heat by turbulent mixing and by ocean currents.

ACKNOWLEDGEMENTS

Table 8

Average of the RMSE (in °C) of the predictions of monthly sea surface temperature anomalies for the whole period of 48 months from June 1980 to May 1984. In the first column, the terms used in the right - hand side of Eq. (17). The second and fifth columns show the values of RMSE for high - resolution grid (HRG) corresponding to semipredictions and predictions, respectively. The third and sixth columns show the values of RMSE for low - resolution grid (LRG) corresponding to semipredictions and predictions, respectively. The fourth and seventh columns show the differences of the values of LRG minus HRG.

| | Pacific and Atlantic | | | | | |
| Case | Semiprediction | | | Prediction | | |
	HRG	LRG	Diff.	HRG	LRG	Diff.
HE	0.58	0.58	0.0	0.60	0.60	0.0
TU+HE	0.58	0.58	0.0	0.60	0.60	0.0
AD_1+AD_2+TU+HE	0.57	0.58	0.01	0.60	0.60	0.0

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