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RECENT NUMERICAL-THERMODYNAMIC EXPERIMENTS ON SEA SURFACE TEMPERATURE PREDICTION

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RESUMEN

La conservación de la energía térmica aplicada a la capa superior de los océanos se utiliza para predecir las anomalías medias mensuales de la temperatura de la superficie del mar en el hemisferio norte. Como datos iniciales utilizamos la temperatura de la superficie del mar, la temperatura a 700 mb y la presión del aire en la superficie correspondientes al mes anterior, según se prepara en la NOAA. Se lleva a cabo un estudio sobre la importancia relativa, para las predicciones, de las anomalías del transporte horizontal por las corrientes oceánicas de deriva y por la mezcla horizontal turbulenta, así como también el calentamiento por evaporación, el calor sensible emitido a la atmósfera y las radiaciones de onda corta y larga.

Para computar las corrientes oceánicas de deriva utilizamos el modelo de Ekman forzado con un viento geostrófico superficial. Los experimentos numéricos, variando el ángulo entre el viento geostrófico superficial y la corriente marina superficial resultante, demuestran que las mejores predicciones son las que se obtienen con un ángulo igual a cero grados.

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Una verificación en los océanos Pacífico y Atlántico durante un periodo de 36 meses, de junio de 1980 a mayo de 1983, muestra algún grado de eficiencia en las predicciones debido a los términos de calentamiento y de mezcla turbulenta. Sin embargo, se obtiene mayor eficiencia cuando, junto a estos términos, se incluyen en las predicciones las anomalías del transporte por corrientes oceánicas de deriva.

La eficiencia mejora sensiblemente cuando, para computar las corrientes marinas de deriva y el calentamiento, utilizamos el viento geostrófico y la temperatura a 700 mb prescritos para el mes en curso en vez de las del mes anterior. Estos experimentos de semipredicción muestran que un modelo más completo en el cual se predigan el viento geostrófico en la superficie del mar y la temperatura del aire conducirá a un mejoramiento considerable en las predicciones.

ABSTRACT

The conservation of thermal energy applied to the upper layer of the oceans, is used to predict mean monthly sea surface temperature anomalies in the Northern Hemisphere. As input data we use the sea surface temperature, the 700-mb temperature and the surface air pressure in the previous month, as prepared by NOAA. A study is carried out on the relative importance, for the predictions, of the anomalies of the horizontal transport by wind drift ocean currents, and by horizontal turbulent mixing, as well as the heating by evaporation, sensible heat given off to the atmosphere, and short and long wave radiation.

To compute the wind drift ocean currents we use an Ekman model forced with a geostrophic surface wind. Numerical experiments varying the angle between the geostrophic surface wind and the resultant surface current shows that the best predictions are obtained for an angle equal to zero degrees.

A verification in the Pacific and Atlantic oceans for the 36-month period from June 1980 to May 1983 shows some degree of skill in the predictions due to the heating and the turbulent mixing terms. However, the best skill is obtained when, besides these terms, the anomalies of the transport by wind drift ocean currents are included in the predictions.

The skill is still substantially increased when, for computing the wind drift ocean currents and the heating, we use the prescribed geostrophic wind and the 700-mb temperature for the current month, instead of the ones for the previous month. These semiprediction experiments show that a more complete model in which the surface geostrophic wind and the air temperature are predicted, will lead to a considerable improvement in the predictions.

INTRODUCTION

The problem of explaining and possibly predicting the large scale monthly and seasonal sea surface temperature anomalies, relating them to the anomalies of wind drift ocean currents, heat lost by evaporation, sensible heat given off to the atmosphere, large scale horizontal turbulent transport and upwelling, has been the subject of several papers. Namias (1959) was the first in estimating sea surface temperature anomalies from the transport of thermal energy by wind drift ocean currents, using an Ekman approach (1902). Eber (1961), Arthur (1966) and Clark (1972) also carried out experiments using the same approach. Jacob (1967) carried out semipredictions of monthly sea surface temperature, showing that besides the wind drift ocean currents forcing, the heat lost by evaporation and sensible heat given off to the atmosphere are an important factor in the formation of monthly sea surface temperature anomalies. The senior author of this paper (Adem, 1970) formulated a prediction model based on the conservation of thermal energy in the upper mixed layer of the oceans, which included, besides wind drift ocean currents, and evaporation and sensible heat given off to the atmosphere, the large scale horizontal turbulent transport of thermal energy as well as the vertical transport of heat at the bottom of the mixed layer. The numerical experiments showed that the large scale horizontal turbulent term added a substantial skill to the predictions (Adem, 1970, 1975). However, the contributions of the vertical transport of heat at the bottom of the layer was shown to be negligibly small (Adem, 1970). This could be due to the crudeness of the parameterization used to evaluate this term.

Numerical experiments carried out by Haney, Shiver and Hunt (1978), and Haney, Houtman and Little (1983) indicate that the vertical transport of heat at the bottom of the layer caused by the divergence of the wind drift ocean currents (Ekman pumping) has a negligible effect in the generation of large scale temperature anomalies, while the horizontal transport of heat by wind drift ocean currents has an important effect in the generation of such anomalies.

Daly (1978) showed some examples of ocean temperature anomaly predictions for the North Atlantic Ocean, in which both the wind drift horizontal transport of heat and the cooling due to the heat lost by evaporation and sensible heat given off to the atmosphere are important factors in the predictions.

More recently Lanzante and Harnack (1983), based on a large set of data, carried out a statistical study in which they showed that the wind drift horizontal transport of heat computed with the Ekman approximation has a significant correlation with the monthly changes of temperature anomalies in the North Pacific.

Adem and Mendoza (1987) have revised the Adem (1970, 1975) models by optimizing some of the parameters that appear in the heating and transport terms. In the present paper, we apply this revised model to a systematically prepared set of data, which consists of 36 months from June 1980 to May 1983, in order to determine the importance of the different factors on which the predictions depend and to establish the degree of skill of the predictions.

THE MODEL

We use the conservation of thermal energy equation applied to the upper layer of the ocean, as derived in detail by Adem (1970), and which is the following:

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

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

$$AD = -\mathbf{V}_{S_T} \cdot \nabla T_S$$

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

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

where $\mathbf{V}_{S_T}$ 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.

In $\mathbf{V}_{S_T}$ 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, 1970):

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

$$(2)$$

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

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 geostrophic wind respectively. C_1 is a constant and θ the angle that measures the direction of the vector surface ocean current to the right of the surface wind direction.

For G_2 and G_3 we will use the formulas:

$$G_2 = G_{2_N} + K_3 |V_{a_N}| [(T_s - T_{s_N}) - A_7(T_m - T_{m_N})] \tag{3}$$

$$G_3 = G_{3_N} + K_4 B |V_{a_N}| [0.981 (T_s - T_{s_N}) - A_7 U_N (T_m - T_{m_N})] \tag{4}$$

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

Formulas (3) and (4), 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, 1964a, 1964b, 1982).

For E_s we will use the same formula as in previous experiments (Adem, 1970).

NUMERICAL EXPERIMENTS

We carry out experiments for the 36 months from June 1980 to May 1983. As input data we use the sea surface temperature, and the atmospheric surface pressure, as well as the corresponding normals for NMC-NOAA. We also use the 700 mb temperature 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).

Following our previous experiments (Adem and Mendoza, 1987) on the optimization of some of the parameters that appear in (2), (3) and (4), we use for K_3 and K_4 Jacobs (1951) values which are equal to 26.8 gm $sec^{-2}cm^{-1}\,{}^{\circ}K^{-1}$ and 40.5×10^{-3} respectively, and for K_5, h, C_1 and A_7 the values $10^8 cm^2 sec^{-1}$, 100 m, 0.235 and 0.4 respectively. For B we use, as in previous papers, the value 1.28×10^3gm $sec^{-2}cm^{-1}\,{}^{\circ}K^{-1}$ (Adem, 1971).

In order to determine the importance of the angle θ in the predictions, we carry out experiments with values of this parameter from 0° to 90°, and indicate in each particular case the value of θ used.

Besides the prediction experiments in which we use as input data the previous month values of sea surface temperature, atmospheric surface pressure and 700 mb temperature, we carry out semipredictions in which the atmospheric fields are prescribed for the current month, instead of the ones for the previous month.

The integration method is the same as the one described by Adem (1970). For the time derivative we use the Euler formula and use time steps of 5 days, so that for each of the monthly predictions 6 time steps are used.

The spatial derivatives are centered finite differences. The integration area and the grid points are shown in Fig. 1. The integration is carried out only in the oceanic regions. To evaluate the spatial derivatives at the continental boundaries we assume that in the continental boundary points the temperature value is equal to the closest ocean temperature value.

The method of prediction for the first step consists in making a prediction for the normal values using normal observed values of the previous month as initial conditions and another prediction for the month considered using the observed values of the previous month as initial conditions (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 subsequent time steps this procedure is repeated except that as initial ocean temperature anomaly we take the one computed in the previous time step.

The atmospheric initial conditions are maintained fixed through the whole integration.

To illustrate the type of predictions included in this paper, Figs. 2 and 3 show respectively the prediction and the semiprediction of the change in the sea surface temperature anomalies from December 1981 to January 1982, for the case when the complete Eq.(1) is used, with an angle θ equal to 45° in formulas (2). Fig. 4 shows the corresponding observed change.

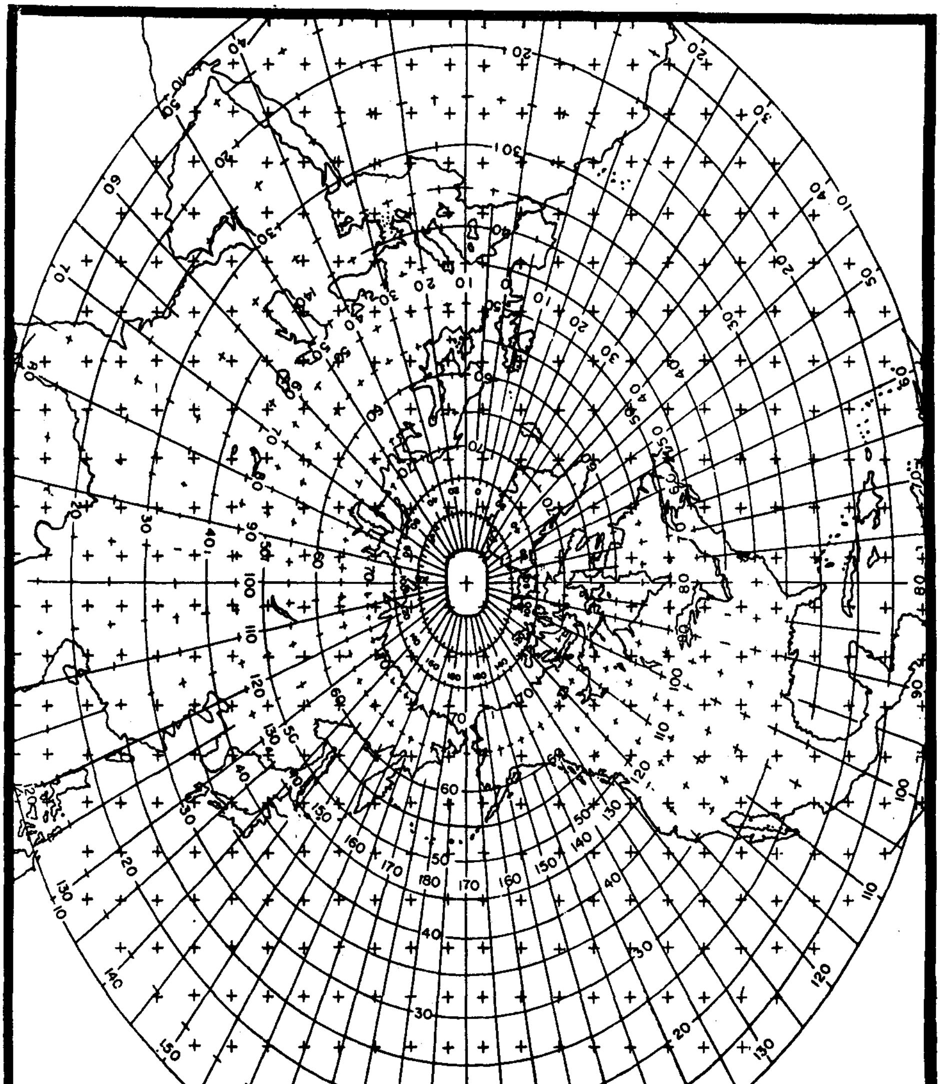

Fig. 1. The region of integration and the grid points.

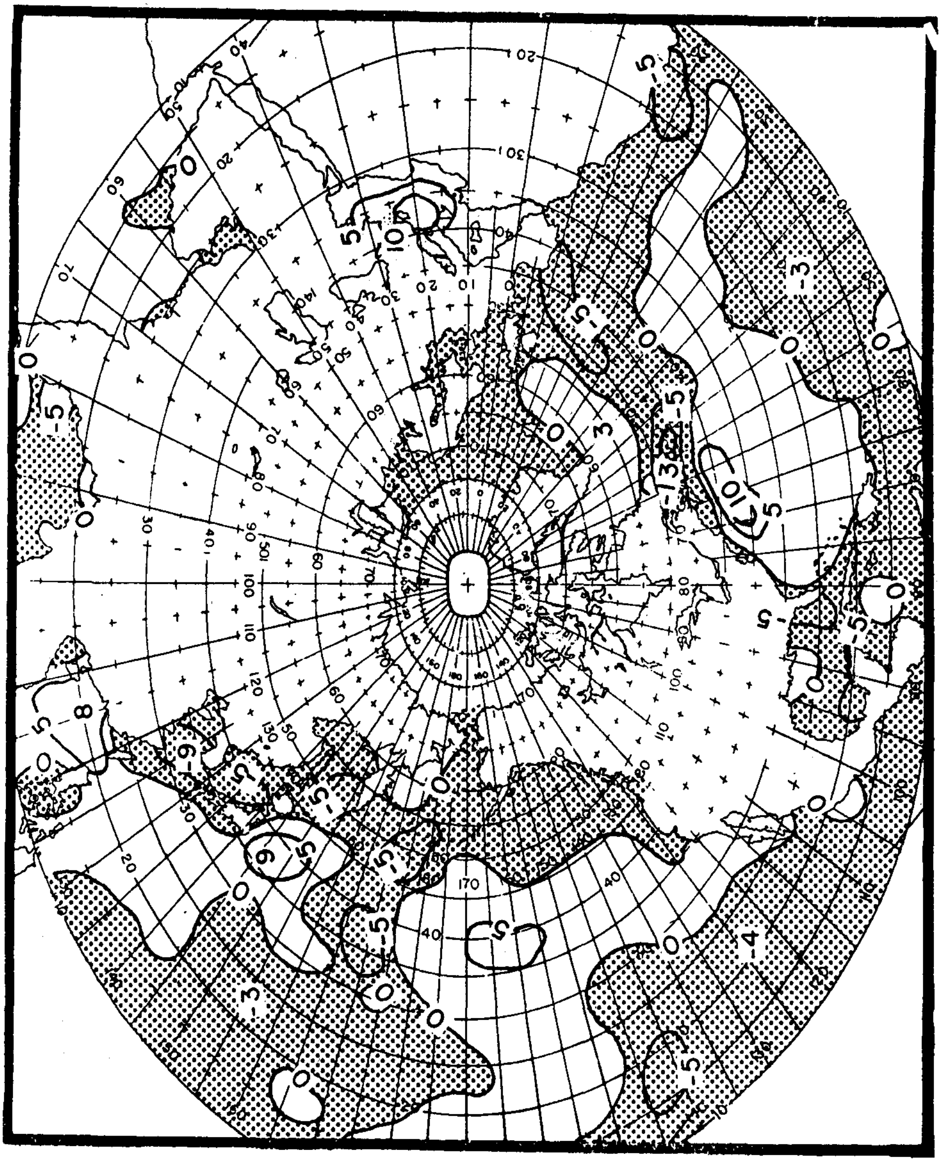

Fig. 2. Predicted change in the sea surface temperature anomalies from December 1981 to January 1982, in tenths of Celsius degrees.

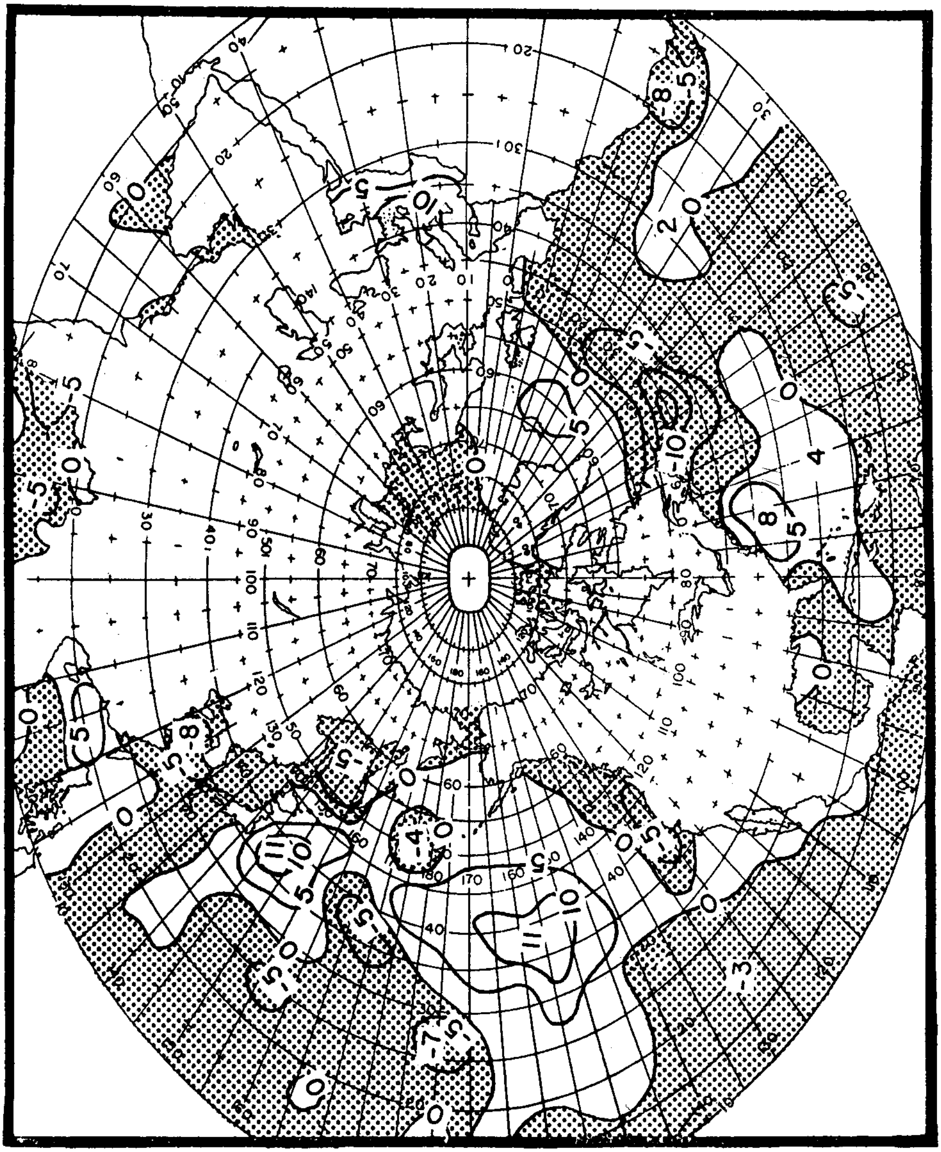

Fig. 3. Semiprediction of the change in the sea surface temperature anomalies from December 1981 to January 1982, in tenths of Celsius degrees.

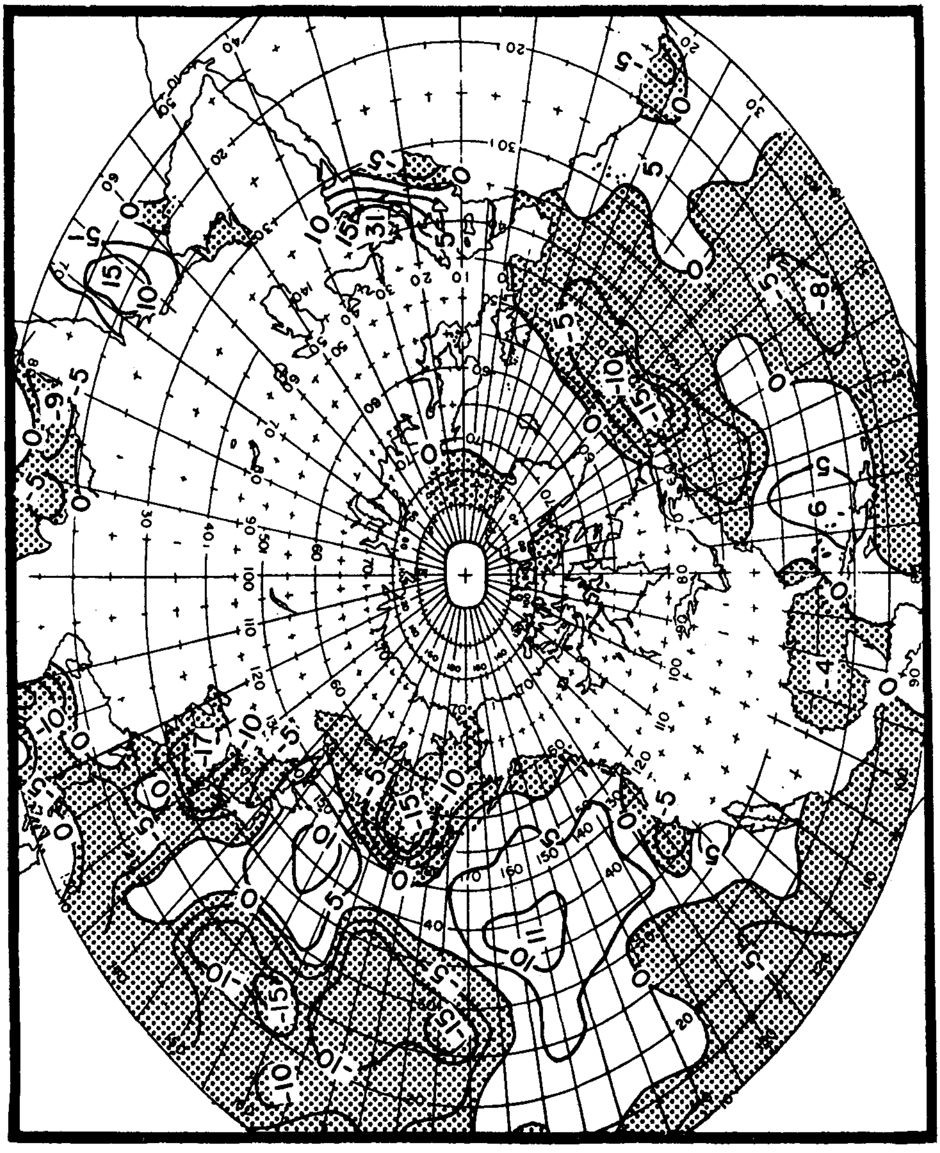

Fig. 4. Observed change in the sea surface temperature anomalies from December 1981 to January 1982, in tenths of Celsius degrees.

As in our previous experiments (Adem and Mendoza, 1987) we evaluate the skill of predictions in three different ways:

a) the percentage of signs of the sea surface temperature anomalies correctly predicted.

b) the percentage of signs of the month-to-month changes of the sea surface temperature anomalies correctly predicted.

c) the root mean square error (RMSE) of the predicted sea surface temperature anomalies.

Table 1

Average of the percentages of signs correctly predicted of the sea surface temperature anomalies for the whole period of 36 months from June 1980 to May 1983*

Case	Semiprediction	Prediction	Difference
Persistence		65.6	
AD(90)	1.4	1.4	0.0
AD(45)	2.3	1.9	0.4
AD(0)	2.9	2.5	0.4
TU		3.1	
HE	3.1	2.7	0.4
TU + HE	3.3	2.8	0.5
AD(90) + TU + HE	3.2	2.4	0.8
AD(45) + TU + HE	3.5	2.8	0.7
AD(0) + TU + HE	4.1	3.0	1.1

* 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 right hand side of (1), 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.

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

To determine the importance in the predictions of the different terms that appear in (1) we have carried out several experiments. The predictions have been evaluated using the three methods described above. Table 1 shows the evaluation of the percentage correctly predicted of the sign of sea surface temperature anomalies, table 2 the percentage correctly predicted of the sign of the month-to-month changes of the sea surface temperature anomalies, and table 3 the root mean square error (RMSE) of the sea surface temperature anomalies.

Table 2

Average of the percentages of signs correctly predicted of the month-to-month changes in sea surface temperature anomalies for the whole period of 36 months, from June 1980 to May 1983*

Case	Semiprediction	Prediction	Difference
Return to normal		57.2	
AD(90)	-9.1	-9.4	0.3
AD(45)	-6.1	-8.4	2.3
AD(0)	-6.7	-9.4	3.3
TU		2.9	
HE	4.9	2.7	2.2
TU + HE	4.7	3.4	1.3
AD(90) + TU + HE	4.8	3.0	1.8
AD(45) + TU + HE	5.5	4.0	1.5
AD(0) + TU + HE	5.7	4.3	1.4

* 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 right hand side of (1), 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.

Table 3

Average of the RMSE (in ^{o}C) of the predictions of monthly sea surface temperature anomalies for the whole period of 36 months, from June 1980 to May 1983*

Case	Semiprediction	Prediction	Difference
Persistence	0.67	0.67	
AD(90)	–0.02	–0.03	.01
AD(45)	–0.01	–0.02	.01
AD(0)	0.00	–0.02	.02
TU		0.03	
HE	0.06	0.05	.01
TU + HE	0.07	0.06	.01
AD(90) + TU + HE	0.07	0.06	.01
AD(45) + TU + HE	0.08	0.06	.02
AD(0) + TU + HE	0.07	0.06	.01

* 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 right hand side of (1), 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.

In the first column of the three tables we indicate the terms of (1) included in the prediction. We use the terms alone or a combination of them. For the advection term, which is a function of θ , we indicate the angle used. For example AD(90) means a prediction using the advection term with $\theta = 90^{o}$.

In the three tables the second and third columns show the values for the semipredictions and the predictions respectively. In the fourth column are the differences, semipredictions minus predictions.

The three tables show in the first line and in the third column the value of the control prediction. The other lines, in table 1 and 2 show values of the model semipredictions or predictions minus the control prediction, in percent of signs correctly predicted, while table 3 shows values of the RMSE of the control prediction minus the RMSE of the model semipredictions or predictions.

In the three tables when the value is positive the model prediction is better than the control prediction.

INTERPRETATION OF RESULTS AND CONCLUSIONS

Tables 1, 2, 3 show that in all the cases and for the three evaluations the semipredictions are better than the predictions. This result implies that a more complete model in which besides the ocean temperature, the atmospheric variables are predicted, would improve the predictions. In previous papers the senior author developed a coupled model in which an equation similar to (1) is used for an atmospheric layer, and the term HE is only used for the equation applied to the ocean layer. In the experiments carried out with such a model, one time step of 30 days was used with backward time steps and an implicit method of integration. 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 with this model is 3.7 higher than that of return to normal. This value is between the prediction (2.7) and the semiprediction (4.9) values of the corresponding case (HE) of table 2.

Tables 1, 2, 3 show that in the three evaluations the semipredictions and the predictions with the model in which the transport by mean ocean currents is neglected (TU + HE) or included (AD + TU + HE), are in all the cases better than the control predictions.

The skill of the complete case (AD + TU + HE) is a function of θ and tables 1 and 2 show that the best skill is obtained with $\theta = 0^{\circ}$. This result is in agreement with the numerical experiments of Clark (1972) who showed that the best correlation between the changes of the surface ocean temperature anomalies computed using (2) and the corresponding observed changes, is obtained when the wind drift current has the same direction than the geostrophic wind, namely $\theta = 0^{\circ}$.

The RMSE of the predicted sea surface temperature anomaly has little variation with θ. The value of the control minus the model remains equal to .06 for the three values of θ considered in the case of the predictions, and is equal to .07 for θ equal to 90° and 0°, and equal to .08 for $\theta = 45^{\circ}$, in the semipredictions.

Comparison of the values of the case AD(90) + TU + HE with those of TU + HE show that when $\theta = 90^{\circ}$ the inclusion of the term AD(90) does not improve the predictions. This is in agreement with the results of a previous paper (Adem and Mendoza, 1987) in which we carried out experiments using only $\theta = 90^{\circ}$ for 24 predictions, for the period June 1980 to May 1982.

However, comparison of the values of the cases AD(45) + TU + HE and AD(0°) + TU + HE with those of TU + HE show that in these cases the predictions and the semipredictions are improved when the term AD is included, especially in the semipredictions in which the percentages of signs correctly predicted of the anomalies and their month-to-month changes are substantially larger than those corresponding to the control predictions and to the predictions in which the transport by ocean currents is neglected.

It is of interest to point out that, according to Table 1, when evaluating the percentage of signs of the temperature anomalies correctly predicted, the semipredictions and the predictions in which only the transport by wind drift ocean currents is included (AD) have fair skill, which also increases as θ decreases. However, Tables 2 and 3 show that when evaluating the month-to-month changes and the RMSE of the temperature anomalies the same predictions have no skill.

In contrast with this result the predictions using only the horizontal turbulent transport term (TU), and the semipredictions and predictions using only the heating term (HE) show good skill in the three verifications in agreement with previous results (Adem and Mendoza, 1987). However, Tables 1, 2 and 3 show that both the predictions and the semipredictions with the complete case with $\theta = 45^{\circ}$ and $\theta = 0^{\circ}$ yield much better predictions. The case $\theta = 0^{\circ}$ being the best one.

In a previous paper (Adem, 1971) a study was carried out on the truncation errors due to the time steps used in the integration of equation (1). Such study suggested that time steps of few days would yield better results than one single time step of one month. Numerical experiments (Adem, 1975; Adem and Mendoza, 1981) have shown that time steps of five days seem to yield the highest skill in the predictions. To confirm this, we also carried out the numerical experiments shown in Tables 1, 2 and 3 using a single time step to integrate equation (1) obtaining, as expected, slightly lower skill in the predictions.

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