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Three-months extended and seasonal forecast of sea surface temperature anomalies for thermodynamic climate prediction

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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 mar y de sus cambios mensuales para periodos extendidos de tres meses, así como para la predicción estacional de estas anomalías en los océanos Pacífico y Atlántico del Hemisferio Norte. La ecuación incluye el transporte horizontal de calor por corrientes oceánicas y por remolinos turbulentos, así como calentamiento por radiación de onda corta y larga, evaporación y calor sensible cedido a la atmósfera por transporte turbulento vertical. En este trabajo llevamos a cabo una verificación de las predicciones para el periodo de junio 1980 a mayo 1984; los resultados muestran que este modelo tiene cierta habilidad en la predicción de las anomalías de la temperatura de la superficie del mar de gran escala y de sus cambios mensuales para periodos extendidos de tres meses, así como en la predicción estacional de estas anomalías.

PALABRAS CLAVE: Predicción mensual y estacional, temperatura superficial oceánica, modelo termodinámico.

ABSTRACT

Conservation of thermal energy applied to the upper mixed layer of the ocean is used to predict sea surface temperature anomalies (SSTA) and their monthly changes for periods up to three months, and for seasonal prediction in the North Pacific and North Atlantic oceans. The conservation equation includes horizontal transport of heat by mean ocean currents and by horizontal turbulent eddies, as well as heating by short-and long-wave radiation, evaporation and sensible heat transmitted to the atmosphere by vertical turbulent transport. Computations for the period from June 1980 to May 1984 show that this model has some skill in predicting the large scale SSTA and monthly changes for periods as long as three months, and in predicting the seasonal SSTA.

KEY WORDS: Monthly and seasonal prediction, sea surface temperature, thermodynamic model.

INTRODUCTION

Early studies on the prediction of large-scale sea surface temperature anomalies (SSTA) in the northern oceans were carried out in the early sixties. Using a model, in which the thermodynamic energy equation is applied to the Atmosphere-Ocean-Continent system, Adem (1964) accomplishes a monthly prediction of the anomalies of the mean temperature in the troposphere and of the surface temperature anomalies of the oceans and continents for January 1963. The results for this particular case showed some skill of the model in predicting the sign and the size of large-scale SST anomalies in the Pacific and Atlantic oceans. The skill of the model for this particular case was verified in Adem and Jacob (1968) and Adem (1969), for a large set of cases. Namias (1959), obtained a good estimate of the SSTA in the North Pacific, using only the anomalies in the surface ocean currents, which were computed from the classic theory of Ekman for wind drift ocean currents. Clark (1967) and Jacob (1967) showed that vertical transfer processes, especially evaporation, played an important role in the predictions of SSTA. Later, Adem (1970) used a version of the thermodynamic model which incorporates the horizontal transport of heat by ocean currents and by large-scale turbulence. The anomalies of the surface air-temperature, of the mean temperature in troposphere and of the atmospheric sea-level pressure (SLP) are prescribed. Numerical experiments show that this approach yields an improvement in the predictions of the SSTA and of their month-to-month changes.

Davis (1976) showed a physical connection to exist between the anomalies of the ocean temperature and the anomalies of the atmospheric SLP, in a time scale of one-month to a year. He concluded that the anomalies of the atmospheric SLP are responsible for generating important large-scale SSTA in the mid-latitudes. Haney *et al.* (1978) used a 10-level primitive equation model in a closed rectangular basin with the approximate dimensions of the North Pacific. Using surface anomalous wind as atmospheric forcing, they developed realistic SSTA for a period of 30 days. The mechanism for the development of the SSTA was the advection of mean temperature by anomalies in the wind drift ocean currents.

We have carried out predictions of the SSTA and their month-to-month changes for the Northern Hemisphere, using the Adem thermodynamic model. For periods of a month our results showed some degree of success (Adem and Mendoza, 1987, 1988). Recently we also carried out monthly predictions for the 48-month period from June 1980 to May 1984 obtaining good skill in the results (Adem *et al., 1995*).

In this work we present a method that allows to extend the predictions to periods as long as three months and to carry out seasonal predictions of the SSTA, using the same version of the thermodynamic model and the same 48-month period as in Adem *et al.* (1995). The monthly extended or seasonal predictions of SSTA can be used in a model of long-range numerical prediction, in which the predicted SSTA are incorporated as external forcing in the monthly extended or seasonal prediction of the atmospheric and surface temperature anomalies and the precipitation anomalies as in Adem *et al*. (1997).

THE BASIC MODEL

The thermodynamic energy equation integrated vertically over the upper mixed layer of the ocean is (Adem *et al.,* 1995):

$$h_s\left[\frac{\partial T_s}{\partial T}+V_{ST}\cdot\nabla T_s-K_s\nabla^2 T_s\right]+W=\frac{1}{\rho_s c_s}(E_s-G_2-G_3) \quad (1)$$

where h_s is the depth of the mixed layer; T_s is the sea surface temperature (SST); V_{sT} is the horizontal velocity of the ocean current in the layer defined as seasonal climatological current observed at the surface corrected for pure drift currents computed from the classical Ekman formulas; K_s is a constant large-scale horizontal exchange coefficient; W is the rate of cooling due to upwelling; $\rho_s = 1.035\ kgm^{-3}$ is the water density; $c_s = 4186.0\ J\,kg^{-1}\,K^{-1}$ is the specific heat; E_s is the rate at which the energy is added by radiation; G_2 is the rate at which the sensible heat is given off to the atmosphere by turbulent transport, and G_3 is the rate at which the heat is lost by evaporation.

The rate at which the energy is added by radiation, E_s, is computed as (Adem, 1962):

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

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, $\sigma = 5.6697\times10^{-8}$ *watt* $m^{-2}\,K^{-4}$ is the Stefan-Boltzman constant, T_{C2} is the temperature at the bottom of the layer of clouds taken as a constant, and $E(T^*) = \sigma T^{*4}$ - F (T^*, 8μ, 13μ) is the energy per unit area and per unit time emitted by a horizontal boundary at temperature T^* in an atmospheric layer. The function $F(T^*)$ represents the energy per unit area and per unit time which is not absorbed by the atmospheric layer in the window between 8μ and 13μ.

For $\alpha_1 I$ we use the following formula (Budyko, 1956; Adem, 1964):

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

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 bulk formulas (Jacobs, 1951):

$$G_3=K_4|\mathbf{V}_a|[0.981e_s(T_s)-Ue_s(T_a)] \quad (4)$$

$$G_2=K_3|\mathbf{V}_a|(T_s-T_a) \quad (5)$$

where $K_3 = 2.68\ Jm^{-3}K^{-1}$ and $K_4 = 40.5\times10^{-3}$, $|\mathbf{V}_a|$ 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 the ship-deck air temperature, respectively, and U is the sea surface relative humidity. For the saturation vapor pressure we use the following formula:

$$e_s(t^*)=a_1+b_1t^*+c_1t^{*2}+d_1t^{*3}+l_1t^{*4}$$

where e_s is in millibars and, $t^* = T^*$ - 273.16°C, T^* is the absolute temperature; $a_1 = 6.115$, $b_1 = 0.42915$, $c_1 = 0.014206$, $d_1 = 3.046\times10^{-4}$ and $l_1 = 3.2\times10^{-6}$ (Adem, 1967).

SEA SURFACE AIR TEMPERATURE AND RELATIVE HUMIDITY

As in a previous paper (Adem *et al.*, 1994), for the sea surface air temperature, we assume:

$$T_a=T_{aN}+(T_{ac}-T_{aNc}) \quad (6)$$

where T_{aN} is the observed normal value of T_a taken from the Marine Climate 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 computed from the formula:

$$T_{ac}=T_{850}\left(\frac{1016}{850}\right)^{R\gamma/g} \quad (7)$$

where T_{850} is the temperature at 850 mb level; R is the gas constant, γ is the standard constant lapse rate in the tropospheric layer and g is the gravity acceleration. For T_{aNc} we replace the temperature at 850 mb by its normal value in Eq. (7).

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

$$U = U_N + A_N(T_{ac} - T_{aNc}) \tag{8}$$

where U_N is the observed normal value of U and

$$A_N = -\left[\frac{d}{dT_{aN}} 1\mathrm{n} e_s(T_{aN}) - \frac{1}{T_{aN}}\right] U_N . \tag{9}$$

Normal values are defined as long-term monthly or seasonal means at each geographical point.

ADVECTION BY MEAN OCEAN CURRENTS

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

$$\mathbf{V}_{ST} = \mathbf{V}_{sW} + (\mathbf{V}_s - \mathbf{V}_{sN}) \tag{10}$$

where $\mathbf{V}_{sW}$ is the horizontal normal seasonal ocean velocity in the layer, $\mathbf{V}_s$ is the velocity of the resultant pure drift ocean current in the layer and $\mathbf{V}_{sN}$ is the corresponding normal value of $\mathbf{V}_s$.

To evaluate $\mathbf{V}_s$ we use the classical Ekman formulas for a pure drift current. Thus, the components of the ocean current in the layer will be expressed (Adem, 1970) by

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

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

where φ is the latitude; u_s and v_s are the x and y components, of the resultant velocity of the pure drift current in a layer of depth h; and u_a and v_a are the x and y components of the surface wind. The range of values of C_1 and θ are limited to $45° \leq \theta \leq 90°$ and $0.235 \leq C_1 \leq 1$.

For $\theta = 45°$ and $C_1 = 1$ we obtain the resultant pure drift current in a very shallow layer. For $\theta = 90°$ and $C_1 = 0.235$ we have the resultant pure drift current in the Ekman layer.

Namias (1959, 1965 and 1972); Eber(1961); Jacob (1967); Clark (1972); and Adem (1970 and 1975) have estimated changes in SSTA due to advection by mean ocean currents. The relation that they use to evaluate the ocean currents corresponds to the case $C_1 = 1$ and $\theta = 45°$.

Formulas (11) and (12) correspond to the case $|V_a| > 6$ m s^{-1}, where $|V_a|$ is the ship-deck wind speed. For $|V_a| \leq 6$ m s^{-1} we have used the factor $0.0259/\sqrt{|V_a|}$ instead of 0.0126 (Adem, 1970). The normal drift current V_{sN} is computed from the normal values of the surface wind with formulas (11) and (12).

NUMERICAL EXPERIMENTS

The local rate of change of the SST can be obtained from Eq(1) written as

$$\frac{\partial T_s}{\partial t} = AD_1 + AD_2 + TU + HE - \frac{W}{h} \tag{13}$$

where

$$\begin{aligned} &AD_1 = -(\mathbf{V}_s - \mathbf{V}_{sN}) \cdot \nabla T_s, \\ &AD_2 = -\mathbf{V}_{sW} \cdot \nabla T_s, \\ &TU = K_s \nabla^2 T_s \text{ and} \\ &HE = (1/\rho_s c_s h_s)(E_s - G_3 - G_2). \end{aligned} \tag{14}$$

The terms in (14) describe the effect on the changes in SST of the wind drift ocean current (AD_1), of temperature advection by normal seasonal ocean current (AD_2), of horizontal turbulent transport of heat by large scale eddies (TU), of the net surface heat flux (HE) and of the cooling in the mixed layer by turbulent entrainment of colder water from the thermocline (W/h_s).

According to Frankignoul (1985), the surface currents act mainly by distorting the normal SST gradient, since one has that over most of the oceans $\nabla T_{sN} >> \nabla(T_s - T_{sN})$, where T_{sN} is the normal value of T_s and $(T_s - T_{sN})$ is the SST anomaly. This is in agreement with Namias (1959), Eber (1961), Jacob (1967) and Adem (1970), who showed that $(\mathbf{V}_s - \mathbf{V}_{sN}) \cdot \nabla(T_s - T_{sN})$ can be neglected in AD_1. Thus for AD_1 and AD_2 in equation (19) we may use ∇T_{sNob} instead ∇T_s, where T_{sNob} is the observed normal SST.

In (11) and (12) we use for the advection term AD_1, C_1 equal to 0.235 (which corresponds to the resultant pure wind drift current in the whole frictional layer), and $\theta = 0$ corresponding to the case in which the wind drift current has the same direction as the geostrophic wind (Adem and Mendoza, 1988). For the advection term AD_2 we use $\mathbf{V}_{SW} = C_{1W}\, \mathbf{V}_{SO}$ where $\mathbf{V}_{SO}$ is the horizontal normal seasonal ocean velocity observed at the surface, obtained from the available data of NCAR network, and $C_{1W} = 0.235$ is an empirical constant, assuming that the seasonal ocean currents have a vertical profile in the whole frictional layer similar to the pure wind drift current. The exchange coefficient K_s for the horizontal turbulent transport of heat (TU) is taken as 1×10^8 cm^2 sec^{-1}.

For the heating term (HE), we use, as in a previous paper (Adem *et al.*, 1995), the values $\rho_s = 1 gmcm^{-3}$, $c_s = 4.189 \times 10^3$ $J\ kg^{-1}$ and $h_s = 100m$. In Eqs. (2) and (3) we assume seasonal normal values for cloudiness, and in Eqs. (4) and (5) we take seasonal normal values for the ship deck wind speed.

The term $-W/h_s$ in equation (13) is neglected, because non-negligible changes of SSTA associated with this term would require upward velocity values of the order of (1/2.6) $\times 10^{-2}$ cmsec^{-1} (Adem, 1970) and the upward velocity for oceanic large-scale circulation is only of the order of 2×10^{-5} cm sec^{-1} (Wyrtki, 1961).

In order to approximate the time derivatives in Eq. (13) we use the Euler formula with time steps of one day. Thus for each monthly prediction 30 time steps are used.

For the spatial derivatives we use centered finite differences. Equation (13) is integrated over the NMC uniform grid of 1977 points with a grid interval of 408.5 km, superposed on the stereographic projection of the Northern Hemisphere. The integration is carried out in the oceanic regions, using at the boundary of the integration area only the heating term (HE) in Eq. (13). 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 closest neighboring grid points inside the continent.

We carry out monthly prediction of SSTA for extended periods as long as three months in the area of the Pacific and Atlantic oceans for 48 months, from June 1980 to May 1984. The extended predictions overlap by two months, so that we obtain 46 three-month overlapping periods which give a total of 138 cases of monthly predictions.

From the extended predictions, we obtain 46 quarterly predictions by averaging the three months predicted in each one of the overlapping periods. Of these quarterly predictions, 16 correspond to seasonal predictions, beginning with March (spring), June (summer), September (fall) and December (winter), and 30 correspond to overlapping seasonal predictions which contain months of two different seasons. Thus the quarterly prediction that results from averaging the extended monthly predictions for July - August -September corresponds to an overlapping season (two months of summer and one month of fall).

THE PREDICTION PROCEDURE

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

The procedure for the second and third months of extended prediction is similar but instead of using the observed and observed normal values of SST as input, we use the corresponding computed values for the previous month. The predicted month-to-month anomaly changes over a period of three months of extended prediction are obtained by subtracting from the predicted SSTA the observed SSTA of the previous month to the first month of the extended prediction.

For the monthly atmospheric anomalies (T_{ac} - T_{aNc}) in equations (6) and (8), as well as for the monthly pure drift ocean current anomalies in (10), we use the values of the month preceding to the first month of the extended prediction. These anomalies remain fixed through the whole period of the extended prediction, which is equivalent to assuming persistence in the atmosphere. Thus the input data in the predictions are the monthly mean values prior to the first month of the extended prediction of the following variables: (a) SST; (b) 850 mb-temperature, to estimate the surface air temperature anomalies according to equation (7); and (c) the atmospheric SLP to obtain the geostrophic surface wind components which are used to compute the anomalies of pure drift ocean currents from equations (11) and (12).

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 NCAR NMC Grid Point Data Set contained in a compact disk.

EVALUATION OF THE PREDICTIONS

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

(a) By determining the percentage of signs of the correctly predicted SSTA. As control prediction we use the persistence, which uses the signs of the initial observed SSTA as a prediction of the signs of the SSTA.

(b) By determining the percentage of correctly predicted signs of the month-to-month changes of the SSTA. As a control prediction we use the return to normal, which uses the opposite sign of the initial observed SSTA as a prediction of the sign of the month-to-month changes of the SSTA.

(c) By determining the root mean square error (RMSE) of the predicted SSTA. As a control prediction we use the RMSE of the predicted SSTA by persistence, i.e., the RMSE that is produced when the value of the initial observed SSTA is used as a prediction of the value of the SSTA.

Table 1 shows the evaluation of the percentage of signs of the SSTA correctly predicted for the total area of the Pacific and Atlantic oceans together, for the period from June 1980 to May 1984. The first, second and third rows contain the results for the first, second and third month of the extended prediction. The second, third and fourth columns show the model prediction, the control prediction (persistence) and the difference between the two predictions. Each percentage is the result of averaging 46 percentages obtained from 46 cases of prediction. The last three columns of Table 1 show the number of cases (in total 46) in which the model prediction was better, worse or equal to the prediction control. The last row in Table 1 shows the general average of the results for the first, second and third month of the extended prediction.

The percentages in Table 1 suggest that the skill of the model and the persistence to predict correctly the sign of the SSTA decreases from the first to the third month; however, the differences in the fourth column show that the skill of the model is always better than the skill of persistence. The skill of the model is also evident in the last three columns, where the number of cases where the model is better than persistence is always greater than the number of cases in those in which the model is worse that persistence.

Table 2 shows the evaluation of the percentage of signs of the month-to-month change of the SSTA correctly predicted by the model and by return to normal. Unlike Table 1, Table 2 shows that the skills of the model and return to normal increase from the first to the third month. In this table the skill of the model is always superior to the skill of the control.

Adem (1970), discussed the skill of return to normal for a particular case, showing that the opposite sign of the SSTA observed in September 1969 is a good prediction of the sign of the change of the SSTA from September to October of 1969. This observation is true not only for the particular case under consideration but for any month of any year.

The percentages shown in the third column indicate that the skill of return to normal is not only superior to 50%, but increases from 58.9% for the first month to 65.0% for the third month. These skills are due to the evaporation, sensible heat given off to the atmosphere, and the large scale horizontal turbulent transport that tend to decrease the absolute value of the SSTA.

The three last columns of Table 2 show that the number of cases in which the model is better than return to normal is verified only until the second month.

Table 3 shows the evaluation of the RMSE of the SSTA predicted by the model and by persistence, in degrees Celsius. This table shows that the RMSE of the model and of persistence increase from the first to the third month, and the RMSE of the model is smaller than that of persistence only for the first month. In the second and third months the RMSE of persistence is slightly smaller than that of the model. The last row shows that on the average, the RMSE of the model and of persistence are practically equal.

The last three columns of Table 3, show that for the first month of the prediction only, the number of cases in which the model results are better than persistence is larger than the number of cases in which the model results worse that persistence. The last row shows that on the average, the number of cases in which the model is better and worse that persistence is practically equal.

We do not show the results of the predictions for the first, second and third month, corresponding to the Pacific and Atlantic Oceans separately, since they are similar to the results of the Pacific and Atlantic combined.

Table 1

Evaluation for the Pacific and Atlantic total area of the percentage of signs of the SST anomalies correctly predicted by the model and by the persistence and the difference of the model minus persistence, as well as the number of cases in which the model is better, worse or equal than persistence, for the first, second and third month in the monthly extended prediction, for the period from June 1980 to May 1984

	Percentage of Signs Correctly Predicted.			Number of cases in which the model is better, worse or equal than persistence.		
Month	Model	Persistence	Difference	Better	Worst	Equal
1est	72.1	69.8	2.3	35	11	0
2nd	63.7	61.6	2.1	30	16	0
3th	59.7	58.7	1.0	25	20	1
Average	65.2	63.4	1.8	30	16	0

Table 2

Evaluation for the Pacific and Atlantic total area of the percentage of signs of the month-to month changes of SST anomalies correctly predicted by the model and by the return to normal (R to N) and the difference of the model minus return to normal, as well as the number of cases in which the model is better, worse or equal than return to normal, for the first, second and third month in the monthly extended prediction, for the period from June 1980 to May 1984

Percentage of Signs Correctly Predicted.				Number of cases in which the model is better, worse or equal than return to normal.		
Month	Model	R to N	Difference	Better	Worst	Equal
1est	62.3	58.9	3.4	30	15	1
2nd	64.0	62.7	1.3	23	21	2
3th	65.6	65.0	0.6	21	24	1
Average	64.0	62.2	1.8	25	20	1

Table 3

Evaluation for the Pacific and Atlantic total area of the RMSE (in °C) of the SST anomalies predicted by the model and by the persistence and the difference of the persistence minus the model, as well as the number of cases in which the model is better, worse or equal than persistence, for the first, second and third month in the monthly extended prediction, for the period from June 1980 to May 1984

RMSE of the SST Anomalies Predicted.				Number of cases in which the model is better, worse or equal than persistence.		
Month	Model	R to N	Difference	Better	Worst	Equal
1st	0.54	0.59	0.05	38	8	0
2nd	0.68	0.67	-0.01	18	24	4
3th	0.74	0.72	-0.02	7	33	6
Average	0.65	0.66	0.01	21	22	3

Table 4 shows the evaluation of the percentage of signs of the seasonal SSTA correctly predicted by the model and by persistence for the area of the Pacific ocean and for the total area of the Pacific and Atlantic oceans for the period from June 1980 to May 1984. The 16 seasons of this period are indicated with an asterisk and the two last digits of the corresponding year are indicated in brackets. The 30 overlapping seasons are without asterisk. For prediction by persistence we use the sign of the SSTA observed in the previous season. For the Pacific ocean there are 29, 16 and 1 cases in which the model is better, worse and equal than persistence, respectively. For the Atlantic and Pacific combined we find a total of 29, 17 and 0 cases in which the model is better, worse and equal than persistence, respectively.

To illustrate the results of Table 4, Figure 1 shows one of the best seasonal predictions accomplished with the present model. Figure 1A shows the SSTA for winter (December -January -February) 1983-84 predicted by the model and 1B shows the corresponding observed seasonal anomalies.

The general evaluation of the prediction of the SSTA for the area of the Pacific Ocean and for the combined area of the Pacific and Atlantic Oceans is shown in Tables 5, 6 and 7. Table 5 shows the percentage of signs of the anomalies correctly predicted by the model and by persistence, for the cases of monthly, seasonal and average extended prediction, for the period from June 1980 to May of 1984.

Table 6 shows the evaluation of the percentage of signs of the month-to-month or of season-to-season changes of the SSTA, correctly predicted by the model and by return to normal. For the seasonal prediction by return to normal, we use the opposite sign of the anomalies of the previous season as

Table 4

Evaluation for the Pacific and for the Pacific and Atlantic total area of the percentage of signs of the seasonal SST anomalies correctly predicted by the model and by persistence and the difference of the model minus persistence, for the period from June 1980 to May 1984 .The 16 seasons are indicated with an asterisk, 30 overlapping seasons do not have asterisk and the year is indicated between bracket.

Seasons	Pacific			Pacific and Atlantic		
	Model	Persistence	Difference	Model	Persistence	Difference
*JJA (80)	73.9	50.1	23.8	78.8	58.9	19.9
JAS	58.4	56.9	1.5	67.0	62.7	4.3
ASO	63.2	58.4	4.8	73.8	67.3	6.5
*SON	60.9	66.3	-5.4	73.6	74.0	-0.4
OND	63.5	66.0	-2.5	73.4	74.9	-1.5
NDJ	60.9	56.1	4.8	69.6	65.3	4.3
*DJF (80-81)	51.6	43.9	7.7	63.5	58.1	5.4
JFM	64.3	45.0	19.3	71.0	57.7	13.3
FMA	78.2	69.4	8.8	77.5	73.1	4.4
*MAM	74.2	66.6	7.6	68.1	63.8	4.3
AMJ	74.2	68.0	6.2	71.6	64.6	7.0
MJJ	73.6	60.9	12.7	68.6	61.8	6.8
*JJA	71.1	52.1	19.0	69.7	56.6	13.1
JAS	59.5	53.8	5.7	63.5	56.6	6.9
ASO	64.0	59.8	4.2	65.7	61.8	3.9
*SON	64.0	70.0	-6.0	63.1	68.1	-5.0
OND	67.1	57.8	9.3	68.4	62.0	6.4
NDJ	54.1	63.5	-9.4	58.7	67.5	-8.8
*DJF(81-82)	62.9	62.0	0.9	65.3	69.9	-4.6
JFM	70.0	66.0	4.0	66.2	64.0	2.2
FMA	64.6	65.7	-1.1	64.2	59.6	4.6
*MAM	77.9	72.2	5.7	75.5	64.9	10.6
AMJ	82.7	82.7	0.0	70.8	76.0	-5.6
MJJ	75.1	83.8	-8.7	68.3	71.6	-3.3
*JJA	64.9	69.1	-4.2	65.3	62.9	2.4
JAS	73.9	73.4	0.5	67.7	67.3	0.4
ASO	68.8	80.4	-11.6	71.0	68.3	2.7
*SON	69.1	73.6	-4.5	62.9	68.4	-5.5
OND	66.9	72.5	-5.6	59.2	65.7	-6.5
NDJ	67.7	73.6	-5.9	60.9	66.4	-5.5
*DJF(82-83)	76.2	79.6	-3.4	70.7	73.6	-2.9
JFM	77.0	85.0	-8.0	67.2	72.7	-5.5
FMA	87.2	83.6	3.6	74.2	74.0	0.2
*MAM	83.0	82.7	0.3	78.4	72.3	6.1
AMJ	79.6	78.7	0.9	72.9	75.1	-2.2
MJJ	69.4	75.6	-6.2	69.4	73.2	-3.8
*JJA	74.2	78.2	-4.0	72.7	75.6	-2.9
JAS	73.9	84.7	-10.8	62.7	75.1	-12.4
ASO	79.3	71.7	7.6	71.4	64.2	7.2
*SON	66.6	63.5	3.1	61.4	59.0	2.4
OND	80.4	60.6	19.8	74.2	52.8	21.4
NDJ	63.2	58.6	4.6	62.2	53.5	8.4
*DJF(83-84)	76.5	58.9	17.6	74.7	62.4	12.3
JFM	88.1	64.0	24.1	79.5	64.9	14.6
FMA	78.2	74.8	3.4	74.2	69.9	4.3
*MAM	81.6	80.4	1.4	74.9	75.6	-0.7
Average	70.8	67.8	3.0	69.2	66.4	2.8

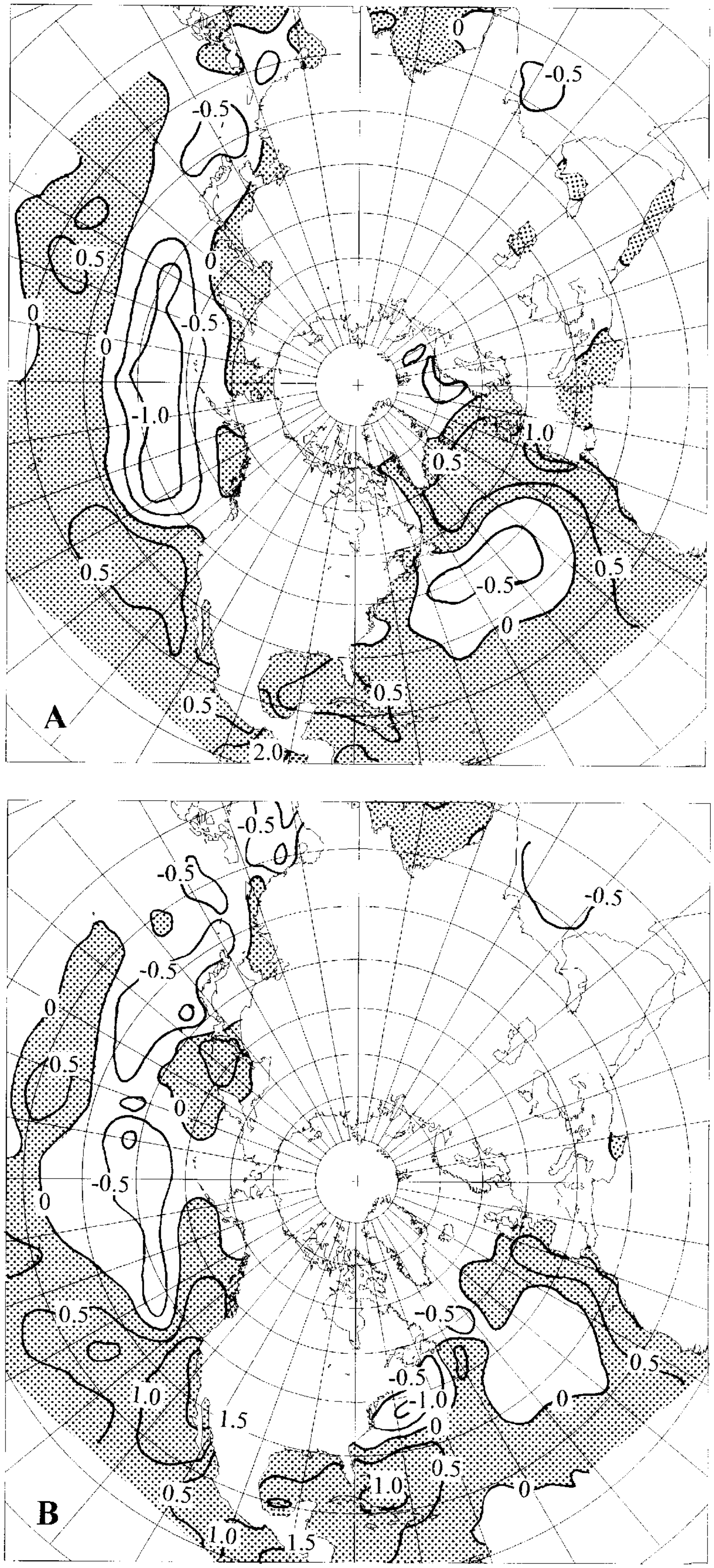

Fig. 1. Surface temperature anomalies (°C) for the winter (December-January-February) 1983-84: (A) predicted by the model and (B) observed.

Table 5

Evaluation for the Pacific ocean and for the Pacific and Atlantic total area of the percentage of signs of the SST anomalies correctly predicted by the model and by persistence and the difference of the model minus persistence, for the cases of monthly (46 months), seasonal (46 trimesters) and average extended prediction (138 months) of the SST anomalies for the period from June 1980 to May 1984

Prediction	Pacific			Pacific and Atlantic		
	Model	Persistence	Difference	Model	Persistence	Difference
Monthly	72.4	70.3	2.1	72.1	69.8	2.3
Seasonal	70.8	67.8	3.0	69.2	66.4	2.8
Extended	66.3	64.7	1.6	65.2	63.4	1.8

Table 6

Evaluation for the Pacific ocean and for the Pacific and Atlantic total area of the percentage of signs of the monthly and seasonal changes of SST anomalies correctly predicted by the model and by return to normal (R to N) and the difference of the model minus return to normal, for the cases of monthly (46 months), seasonal (46 trimesters) and average extended prediction (138 months) of the SST anomalies for the period from June 1980 to May 1984

Prediction	Pacific			Pacific and Atlantic		
	Model	R to N	Difference	Model	R to N	Difference
Monthly	61.9	57.9	4.0	62.3	58.9	3.4
Seasonal	67.8	63.4	4.4	67.2	65.0	2.2
Extended	64.0	61.1	2.9	64.0	62.2	1.8

Table 7

Evaluation for the Pacific ocean and for the Pacific and Atlantic total area of the RMSE (in °C) of the SST anomalies predicted by the model and by the persistence and the difference of persistence minus the model, for the cases of monthly (46 months), seasonal (46 trimesters) and average extended prediction (138 months) of the SST anomalies for the period from June 1980 to May 1984

Prediction	Pacific			Pacific and Atlantic		
	Model	Persistence	Difference	Model	Persistence	Difference
Monthly	0.56	0.61	0.05	0.54	0.59	0.05
Seasonal	0.56	0.62	0.06	0.54	0.60	0.06
Extended	0.67	0.68	0.01	0.65	0.66	0.01

a prediction for the sign of the season-to-season changes. The evaluation of the RMSE of the SSTA predicted by the model and by persistence is shown in Table 7.

CONCLUDING REMARKS

The results in Tables 5, 6 and 7 show that the present model has some skill to predict the large scale anomalies in the Pacific and Atlantic oceans, and their month-to-month changes for extended periods as long as three months as well as to predict the seasonal anomalies and their season-to-season changes.

We have shown that the present model, in which the conservation equation of thermal energy is applied to mixed layer of the oceans, yields predictions for extended period as long as three months, as well as seasonal predictions of the SSTA, with a skill to predict the sign of the anomalies and of their month-to-month changes superior to the persistence and to the return-to-normal, respectively.

However, the results shown in Table 7 indicate that the skill of the model in predicting adequately the size of the anomalies in the monthly, seasonal and extended prediction is not significant.

Some of the predictions obtained in this work were incorporated as external forcing in a more complete thermodynamic model applied to the atmosphere-oceans-continents system to carry out three-month extended and seasonal predictions of the atmosphere temperature anomalies as well as of the precipitation anomalies with a skill superior to that of persistence in regions such as Mexico (Adem *et al.,* 1997).

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