NOTES AND CORRESPONDENCE

Simulation of Seasonal Sea Surface Temperature Variations in the North Pacific

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ABSTRACT

North Pacific sea surface temperature variations during the cooling season are simulated using climatological surface heat flux data in conjunction with a deepening mixed layer as determined by a convective adjustment model. Climatological oceanic initial conditions are constructed from the mechanical bathythermograph file of the National Oceanographic Data Center. The accuracy of the 90-day simulation depends on the accuracy of the initial and boundary conditions and on the ability to model the deepening of the mixed layer. The neglect of horizontal advection is most critical in the western boundary current region. The ability of such a model to accurately simulate SST changes over a large portion of the North Pacific indicates that the climatological surface heat fluxes computed by Clark (1967) are compatible with the decrease in the heat content of the upper ocean during this period.

1. Introduction

Temperature variations in the upper ocean occur due to fluxes of heat across the air-sea interface and due to horizontal and vertical heat transfer within the ocean itself. Although numerous studies of oceanic heat transfer have been conducted, there are still conflicting opinions regarding the relative importance of horizontal advection and vertical mixing in the upper ocean. The purpose of this note is to determine the accuracy of a model that uses climatological heat fluxes to simulate the climatological sea surface temperature (SST) variation for the North Pacific Ocean during the cooling season. The effects of horizontal advection are not included, and the oceanic mixed layer is allowed to deepen during the cooling period. The ocean basin is divided into a 4° × 5° grid in latitude and longitude, respectively. The only horizontal coupling arises indirectly through correlations between the surface heat fluxes at adjacent grid points. The study is limited to an analysis of a three-month simulation during the cooling season with particular emphasis on the simulation of the temperature variation. Climatological heat fluxes are used as boundary conditions at the air-sea interface and climatological ocean temperature profiles are used as the initial conditions. The results of the simulation are analyzed to determine 1) whether the use of surface heat fluxes alone can yield a good simulation of SST variations during the cooling season, 2) which regions are most sensitive to the neglect of horizontal advection, 3) whether similar models could be used in coupled ocean atmosphere models for seasonal climate prediction, and 4) to provide an independent check on the accuracy of the heat fluxes computed by Clark (1967).

2. Model description

A physical model is needed to predict changes in the mixed-layer depth during the three-month simulation. Mixed-layer ocean models that depend on the conservation of thermal and mechanical energy and are driven by the surface wind stress and heat fluxes have been described by Miller and Kraus (1977). Since these models are one-dimensional, they have been compared primarily with observational data from isolated ocean stations and have neglected the effects of horizontal advection. The model that will be used in the simulations here will be a simple convective adjustment model since such a model does not require the wind stress as a surface input. The convective adjustment model will lead to a final SST field that would be similar to a more sophisticated mixed-layer parameterization although the rate of cooling at specific times during the three-month period would be different. Since we are concerned here with the SST after 90 days, only

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the integrated 90-day heat flux is necessary to produce the desired results. The convective adjustment model allows the mixed-layer to deepen whenever the SST falls below the temperature at deeper levels. The final SST after 90 days can be obtained by simply requiring that the difference in oceanic heat content between the initial and final states be equal to the total heat removed or added across the air-sea interface during the 90-day period. This simple model eliminates some of the uncertainties associated with mixed-layer models such as parameterization of the dissipation and the necessity of using the surface wind stress as input. Fig. 1 shows the typical temperature structure at the beginning of the cooling season. The construction of these profiles and the choice of heat fluxes at the air-sea interface are discussed in the next section.

3. Initialization and boundary conditions

The model described in the preceding section can be used to simulate SST changes during the Northern Hemisphere cooling season if initial conditions and boundary conditions are specified. The initial conditions are generated from a large set of mechanical bathythermograph (MBT) data obtained from the National Oceanographic Data Center (NODC). Although the highest concentration of data is in the main shipping lanes, sufficient data are available to construct a good initial data set for the month of October in the North Pacific Ocean.

The NODC data are analyzed to obtain the model parameters of interest. These include the mixed-layer depth, sea surface temperature, temperature gradient below the mixed layer, and the magnitude of the temperature jump at the bottom of the mixed layer. The initial temperature profile for a particular oceanic region is determined by assuming that the mixed-layer depth $h$ is the shallowest depth at which the temperature is less than the surface temperature by some prescribed amount ($0.2^\circ$C is used here). The observed temperatures at depths $\frac{h}{2}$ and $\frac{h}{3}$ are then used to define a linear temperature gradient that is extrapolated upward to determine the temperature $T_h$ immediately below the mixed-layer. The temperature jump $T - T_h$ is then known. Profiles which yield values of $T_h$ greater than $T$ are discarded; these are a small percentage of the total. If the mixed-layer depth is less than 100 m, a second temperature gradient is constructed using the temperatures at 90 and 110 m. A typical initial profile is shown in Fig. 1. Since the average depth of the MBT profiles is ~200 m, the mixed-layer depth is constrained to deepen to a depth no greater than 200 m. This is somewhat shallower than the 250 m depth assumed by Gill and Turner (1976) as the depth below which temperature changes are minimal. The 200 m constraint on mixed-layer depths should present no difficulties except perhaps at high-latitude locations and in regions of strong boundary currents.

The ocean temperature profiles for October, which are used as initial conditions for the model, are compiled for the North Pacific Ocean between 20 and 50°N. The grid size is $4^\circ \times 5^\circ$ in latitude and longitude, respectively. The mixed-layer depths are shallower than those constructed by Bathen (1972) for the North Pacific Ocean. This difference in depths arises primarily due to the model restriction that the temperature structure in the upper ocean is isothermal down to the bottom of the mixed layer. Bathen’s mixed-layer depth requirement of a significant change in temperature gradient will usually occur at a greater depth since a small temperature gradient from the surface downward will cause the isothermal requirement to be invoked first.

The initial climatological SST field and the surface heat fluxes have been computed by Clark (1967). The initial temperature profiles determined from the MBT data are made consistent with the SST field of Clark by translating the profiles to the right or left so that sea surface temperatures match. The surface heat fluxes, which consist of the solar radiation, the net longwave back radiation, and the sensible and latent heat fluxes, are available as monthly averages.
4. Results

A 90-day simulation of the North Pacific SST variation, starting from mean October conditions, has been completed using the convective adjustment model in conjunction with the initial and boundary conditions described in the previous sections. Although this 90-day period does not account for all the seasonal cooling, significant SST changes do occur, and several features of the simulation can be studied. Fig. 2 is a difference map that is constructed by subtracting the January climatological SST from the 90-day model simulation. Positive values denote regions where model temperatures exceed climatological temperatures at the end of the three-month period.

As shown in Fig. 2, the SST simulations are quite good over a large portion of the North Pacific and are within ~15% of the climatological values. There are several regions where the simulation is less accurate—off the California coast, in the northwestern Pacific and in the western boundary current region. Overall, the eastern half of the basin appears to have cooled too little and the western half too much. The maximum error occurs in the western boundary region near 40°N where the temperature is 3°C too cold when compared to climatology. The Kuroshio Current advects warm water into this region, and as a consequence the largest values of the sensible and latent heat fluxes in the Pacific Ocean occur here. The one-dimensional model considered in the simulation does not allow for warm advection into this region, and the large sensible and latent heat fluxes therefore lead to excess cooling.

The ability to simulate the three-month temperature change accurately depends on three different factors. First, it depends on the accuracy of the climatological heat fluxes which are used as boundary conditions to drive the model. Second, it depends on the degree to which the oceanic initial conditions, which were constructed from historical data, represent the true oceanic structure at the beginning of the fall cooling season. Finally, the accuracy depends on the physical parameterizations in the model itself. It is reasonable to conclude that the principal source of error in the western boundary current region is due to an inadequate model since advection is not included. In the northeastern region, however, where the final temperatures are 1–2°C too warm, it is more difficult to determine which of the three sources of error is dominant. If the initial temperature profiles were such that the heat content was too high or if the sensible and latent heat fluxes were too small, the final SST would be too high as indicated in Fig. 2. There is some evidence that the northeastern region may be too warm because the initial ocean profiles overestimate the heat content in the region. The average mixed-layer depths for October that were used in the simulation were between 50 and 60 m deep throughout much of the northeastern region. When the same criterion for determining mixed-layer depth was applied to the data of Ballis (1973) at Ocean Weather Station P (145°W, 50°N) for the same time period corresponding to the Clark data (1951–57), the average depth was 40–50 m. The data of Bahr (1972) also indicate that a depth of 40 m is appropriate for this region. If a shallower mixed-layer depth had been

Fig. 2. Difference map generated by subtracting January climatological SST field from the 90-day simulation using the monthly heat flux data of Clark.
used as the initial condition, then the initial heat content for that location would have been reduced, and the removal of the same amount of heat would have produced a greater temperature decrease. Overall, the results indicate that a good simulation of the SST variation during the cooling season can be obtained by using only the surface heat fluxes in conjunction with a simple convective adjustment model to produce the necessary mixed-layer deepening.

5. Summary

These results show that the climatological heat fluxes calculated by Clark can be used in conjunction with knowledge of the ocean vertical temperature structure to account for temperature changes during a winter cooling season in the North Pacific. The simulated SST field after 90 days is reasonably accurate and is particularly good in mid-ocean areas. As could be expected, the neglect of horizontal advection is quite significant in the region of the western boundary current. The good agreement between the model and climatology in most regions indicates that the heat fluxes compiled by Clark are accurate since his integrated heat fluxes are in good agreement with the change in oceanic heat content during the 90-day period.

The present study was partially motivated by the possibility that mixed-layer ocean models might be coupled with atmospheric models for long-range predictions. The results here indicate that the errors in the climatological SST simulation may be of the same order as the SST anomalies that are thought to be responsible for causing changes in the atmospheric circulation. If such anomalies are to be modeled correctly, it is important that the atmospheric model contain a good parameterization of the planetary boundary layer so that the surface heat fluxes can be accurately determined. A more sophisticated mixed-layer ocean model that would include horizontal advection would be needed. Strictly one-dimensional models such as described in this paper might be useful when coupled with long-range climate models that would otherwise maintain constant mixed-layer depths.

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REFERENCES


