

FORECASTING THE OCEANIC ENVIRONMENT

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Abstract

A review will be given of the technical problems associated with forecasting the ocean, as compared to weather prediction. The required ingredients of large-scale computers, numerical models and oceanic data bases (including satellite data) will be discussed, along with the status of operational forecasting by the Navy.

Introduction

In this paper, I will confine myself to some managerial and technical points which may shed light on the short history of ocean forecasting: how it got started, where it is today, and how it relates to other Navy environmental programs. I will then illustrate, with a few examples, our modeling successes in selected areas of ocean forecasting.

Five years ago a workshop was held in Monterey where both Navy labs and the academic community were represented. Because of recent improvements in the various active and passive sound surveillance systems and the increased use of electrooptic (EO) devices in the marine boundary layer, it was determined that the Navy should acquire increasingly accurate predictions of the marine boundary layer. Long-range weather prediction and ship routing (both surface and subsurface) were also in need of better surface temperature and current predictions. Up to that time, ocean forecasting was an unheard-of venture, except from some mixed-layer depth forecasts; the meteorologists had a 20-year jump on us oceanographers. It became clear that, at the very least, ocean forecasting will depend on three crucial factors: (a) scientifically accurate ocean models; (b) sufficiently large and fast computers; and (c) availability of an adequate data base for initialization and surface forcing.

Since the ocean is driven mainly by atmospheric momentum and heat fluxes and not by its own density gradients (unlike the atmosphere), ocean forecasting depends crucially on the availability of weather forecasts and the best available monthly climatologies of winds and heat fluxes. The latter is needed because the lifetime of energetic oceanic eddies and dynamic adjustments is much greater than foreseeable periods of atmospheric forecasts. The exact utilization of these fluxes is outlined below. As expected, we shall try and

utilize all the techniques developed by weather forecasters for 4-D data assimilations and forecasting; nevertheless for the above-mentioned reasons, ocean forecasting requires the development of additional new approaches in data handling and forecasting.

1. Oceanic Space-Time Scales and Data Sources

A great stimulus for attempting ocean forecasting comes from the successful performance of the satellite SEASAT, in 1978, and the proposed launches of other oceanic satellites such as GEOSAT (altimeter) and TOPEX (altimeter and scatterometer). In addition, the IR and microwave signals of all satellites that can be used to deduce sea surface temperatures will be used. The satellites have proved that continuous, high-resolution space-time coverage of the ocean surface temperature, winds, foaminess, surface topography, and surface wave characteristics can be obtained from such platforms. The altimeter carried by SEASAT measured sea surface topography to an accuracy of <10 cm, and TOPEX hopes to do it within 6 cm or so. This elevation can be related through geostrophy to surface current strengths which, in turn, can serve as the missing constant of integration when computing currents from density values. Altimeters can provide an all-weather, all-time surveillance of frontal and eddy positions, even subsurface ones since these, too, have surface pressure signatures. The initially planned NOSS satellite carrying many remote sensing instruments was killed for budget reasons, but a cheaper one called GEOSAT, flying only an altimeter, will be launched in late 1984. In addition, a satellite called TOPEX, carrying an altimeter and a scatterometer (for wind measurements) with improved orbit and track spacing characteristics, is being planned for the late 1980s.

In order to appreciate the impact these satellites can make in ocean forecasting, one must look at the currently available set of oceanic observations and their adequacy for forecasting purposes. At the present time, FNOC receives about 250 XBT reports a day on upper ocean thermal measurements, but this number is expected to decrease due to the increasing cost of XBTs, and the planned reliance on remote sensing. Moreover, these XBT measurements are scattered irregularly in space-time, the densest grid of observations hugging the main shipping lanes of the world, so that observations in many tactically important areas must be made just prior to Navy operations.

Since the spatial scales of the most unstable baroclinic waves and eddies in the ocean is about 400 km near the surface and about 200 km in the deep water, 250 XBTs could not cover even a 2000 X 2000 km² area in the Northwest Atlantic, much less the global ocean. One must compare this with the atmospheric situation where the spatial scale of the energetic cyclones is ~2000-3000 km, and the number of radiosonde observations is an order of magnitude larger. IR and altimeter signals have resolutions on the order of 2 and 20 km, respectively, and so the surface of the ocean at least can be adequately sampled. An offsetting feature of the small scale of oceanic eddies is their relatively long lifetime, on the order of weeks or months, so that observations need not be made on a daily basis.

In addition to satellites and XBTs, some other measuring instruments that have been looked at are drifting buoys that carry thermistor chains and radio position and data to satellites for collection, Raman lasers for obtaining subsurface temperature and salinity values, and recoverable XBTs and current profilers. However, few of these instruments will be available for operation use in the near future.

2. Ocean Models for Prediction and Data Assimilation

It is hoped that ocean models can supplement the lack and disparity of oceanic data in three ways:

a) In the surface layers where atmospheric forcing is dominant, mixed layer models can predict thermal structure even in data-poor areas;

b) Due to the long time scale of oceanic current instabilities and eddy drifting, a reasonably good prediction can be made on the order of weeks if sufficient data was obtained at least one or two months apart;

c) The models can help blend high resolution surface data from satellites, and the sparse set of XBT observations.

It has been shown that satellite data can only be reliably converted to wind stress and surface heat flux data if the local sea-air exchange processes are concurrently simulated. Since the winds constitute about 50-90% of the driving forces for ocean currents, with the rest coming from density differences and tidal forces, proper utilization of satellite data can go a long way toward making ocean forecast possible. This is particularly true for altimeter data, since so far little research has been done on how to utilize this new oceanographic data in dynamic ocean models.

I will now demonstrate that mixed layer evolution can be successfully modeled on both the diurnal and seasonal time scales with both bulk-type and differential-type models of various orders of turbulence closure. Figure 1 illustrates the comparison of the computed and observed temperature profiles at day 33 of the MILE

experiment (Warn-Varnas et al., 1981) when the model was initialized at day 0 with an observed profile and forced with observed surface fluxes. MILE took place August 1977 in the North Pacific at Weathership Station P (50°N, 145°W). Figure 2 illustrates the seasonal evolution of mixed layer depth for the year 1961 at Weathership N in the Pacific (30°N, 140°W).

The instability and eddy shedding of large ocean currents can also be modeled successfully with models that are surprisingly simple in several respects. Figure 3 illustrates a comparison between observed and computed contours of thermocline deformation for the Loop Current in the Gulf of Mexico, a strong current that enters through the Yucatan Straits and exits through the Florida Straits, eventually becoming the Gulf Stream. Figure 4 illustrates a sequence in the eddy shedding process, whose mean period of ~330 days has been reproduced to within ±15 days in the model (Hurlburt and Thompson, 1980). These results were obtained with a 2-layer model, where the layers represent fluid between two density surfaces and the equations represent the integrated momentum for the whole layer, as well as the (variable) thicknesses of the layers. Other types of ocean models have fixed grid points in the vertical (Ref. 5). Both these models and the sigma-coordinate model ($\sigma = z/\text{depth of bottom}$) had success in predicting various oceanic phenomena, with the semi-implicit layered models being most economical in terms of computer storage and execution time.

Embedding of mixed layer models into both layer and level type hydrodynamic models has also been successfully completed (Adamec et al., 1982).

I must point out that in view of the current data situation, the most practical models to be developed are regional models with open boundary conditions. We will need global satellite data, preferably both temperature and altimeter data, to initialize and update world or basin-size ocean models. There is a marked difference in the initialization problem for weather and ocean forecast. In the former, models are initialized from observations which have been analyzed and dynamically balanced in some way. The scale of meteorological cyclones is marginally to adequately resolved by the observations. The initial state is the only data input on which the forecast normally depends. This approach used in meteorology is not generally feasible in oceanography because the observational network in space-time is much coarser and, as noted above, the spacial scales of the important energy-containing eddies are much smaller.

An ocean forecast initialized from inadequately analyzed data would suffer from the following problems (Hurlburt, 1976): (a) there would be aliasing of large amplitude small features to large scales; (b) the forecast would never be able to evolve in a dynamically realistic manner or exhibit certain important features not resolved by the analyzed data, even if the model grid could resolve them. Much of the forecast changes would simply represent model spin-up of dynamical features required by the physics and geometry of the model, not evolution of the ocean circulation; and

(c) four-dimensional data assimilation could cause excitation of spurious large-amplitude waves (such as Rossby or Kelvin) which would persist in a several month forecast. A possible remedy to these problems would be to perform ocean forecasts on a regional basis, particularly in areas where additional, higher density observations could be made available because of some Navy interest. The dynamical balancing of this finer data might be possible using 4-D data assimilation (Smagorinsky et al., 1970). A further help can come from satellite coverage, if the surface values of wind stress and temperature can be successfully used to determine sub-surface currents and density structure. In regions where no improvements in the available data base can be made, the following procedure will be introduced.

Since the external forcing functions are better known than the state of the ocean at any given time, the ocean will be driven from an arbitrary initial state to the present by a historical set of forcing functions (Hurlburt, 1976). This then will become the initial state for forecasting which could be updated by integrating the model forward in time as new data for the forcing functions (wind stress, atmospheric temperature, solar insolation, etc.) become available. For example, if a forecast is desired for the period June 21-26, 1982, mean monthly observed winds and temperatures from FNOG for the period June 1-20 would be used to prepare the model for the final initial state on June 21. Finally, the predicted winds for the period June 21-26 by FNOG would be used to make the derived forecast. Step one need not be repeated if continued forecasts are being made every week or so. This procedure would allow the model to forecast from internally consistent initial states without artificial imbalances, and it would allow the model to exhibit the full range of physical phenomena of which it was capable. Many of these oceanic phenomena could not be resolved by traditional observational data, and would develop in a forecast only after periods ranging from weeks to years. The suggested approach would allow the model to develop realistically such features as fronts and long-time-scale physical instabilities, and would prevent spurious excitations of persistent large amplitude signals such as Kelvin and Rossby waves, except as excited by erroneous changes in the external forcing functions. Although the detailed development of individual ocean eddies could not be predicted accurately, the evolution of an ensemble and its properties (location, size, structure, and amplitude) could be. The success of this procedure would depend on the ability of the model to develop a realistic ocean climatology, as well as its predictive capability.

The above procedure is best suited for applications to whole ocean basins where the boundary conditions are well posed. The initial-boundary value problem for limited area models (LAM) forecasts using the primitive hydrostatic equations is generally not well posed if an arbitrary collection of physically measured quantities are used as the boundary condition. This is due partly to the fact that many classes of phenomena have been filtered out by the hydrostatic approximation that

the measured boundary conditions incorporate. Another reason is that many phenomena whose characteristic scale is resolved on the mesoscale is not resolved by the global model. A partial solution to these problems is to filter the boundary conditions and to correctly reintroduce phenomena into the LAM model that were filtered by the global analysis. The following numerical problems may arise: a mesh separation of the solutions may occur if the resolution is too coarse to resolve the viscous sub-layer that develops near such boundary points where the solution is trying to adjust to the imposed conditions. A spurious convection may also occur near the boundaries if the pressure distribution on the boundary points does not match the ambient static field outside the boundary, as required by the hydrostatic approximation. As will be discussed in the next section under computers, the requirements to resolve ocean eddies leads to desired mesh spacing of ~25 km or so. One can run ocean models with that kind of resolution over the world's oceans only with limited degrees of freedom in the vertical. As we have seen, a 2-layer model succeeded in simulating the dynamic behavior of the highly energetic Loop Current very well. On the other hand, it's clear that two layers will not provide in any way the needed vertical acoustic velocity profiles. The optimum strategy developed for the time being is to couple a thermodynamic model (a mixed layer model at N locations, customarily referred to as the $N \times 1$ -D model) to the output of the 2-layer hydrodynamic model. The $N \times 1$ -D model contains advection terms for which the currents are provided by the hydrodynamic model (the geostrophic part) and by the $N \times 1$ -D model (the Ekman part). A simplified mixed layer model will also be added to the hydrodynamic model, producing a 3-layer hydrodynamic model that can handle fronts.

3. Computer Outlook for the Eighties

Let us begin with a discussion of the present computers since this was the main determinant as to which models could be developed and put into operational evaluation in the near future at FNOG. Until December 1980, the biggest computer of FNOG was the SPC, a Cyber 175 essentially dedicated to satellite data processing and worth half a CDC 7600. The only time available on this machine was the development of a hemispheric thermodynamic ocean prediction model (TOPS) that predicted mixed layer depth (MLD) and sea surface temperature (SST) distributions. This model was driven by wind stresses and heat fluxes obtained from a hemispheric atmospheric prediction model (Clancy and Martin, 1981). Both TOPS and the atmospheric model have a 63×63 grid on a polar stereographic grid, resulting in a 250-300 km resolution at mid-latitudes. Figure 5 shows a typical mixed layer depth distribution over the Northern Hemisphere, and Figure 6 shows the statistical improvement of the forecast over persistence and climatology. No hydrodynamic ocean model correctly treating western boundary currents and associated rings could be run on such a coarse grid.

Since the beginning of 1981 development of both hydrodynamic and thermodynamic ocean models has shifted to the new CYBER 203 that FNOG has

acquired. This machine has a 1 M 64-bit words core and executes at a rate of ~40 megaflops. It will be upgraded to a 2 M word CYBER 205 in November 1982, at which point 32-bit arithmetic will also be available, effectively quadrupling the available storage and doubling execution speed. In late 1981 a new global general circulation model will be installed on the CYBER 203, which will provide atmospheric momentum and heat fluxes on a 2.5° global grid. The first hydrodynamic model planned for this computer is a 1-layer reduced gravity model with $1\frac{1}{4}^\circ$ global resolution. Further models feasible on this machine will be an Indian Ocean model with 25 km resolution and a North Atlantic with 15 km resolution. To run a 3-layer world ocean model with 25 km resolution would require a machine with 30 M word storage. It appears that in the 1986-88 time frame such machines will be available.

In summary, it appears to this author that adequate numerical models and computers will be available in the next 5-10 years to satisfy Navy oceanography needs, but an adequate data base will only appear upon careful planning and funding. The big job will be to develop models that satisfy Navy environmental requirements, and at the same time can function with available computers and data bases.

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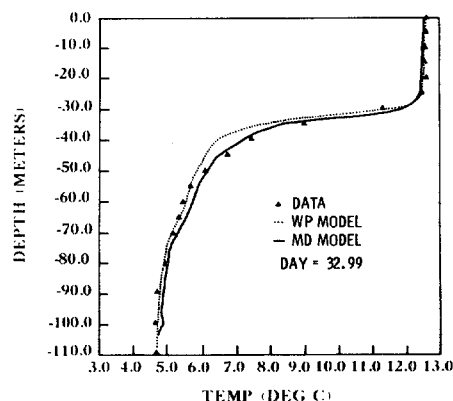


Figure 1. Temperature profiles on day 33 of MILE experiment.

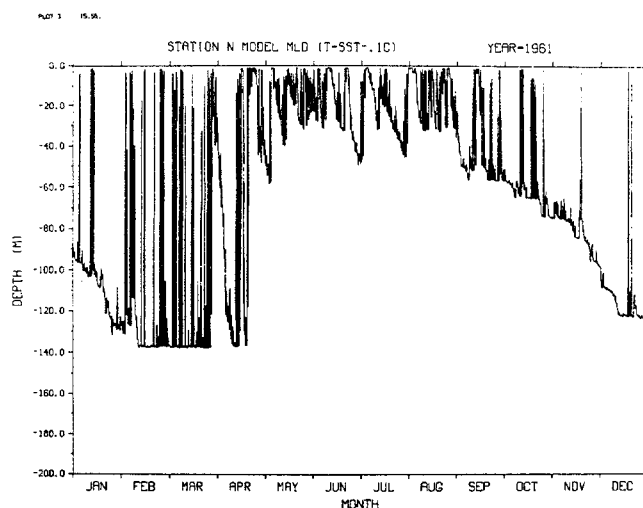


Figure 2. Seasonal evolution of the model-predicted mixed layer depth at Ocean Station N in the North Pacific with modified level 2.5 turbulence closure model

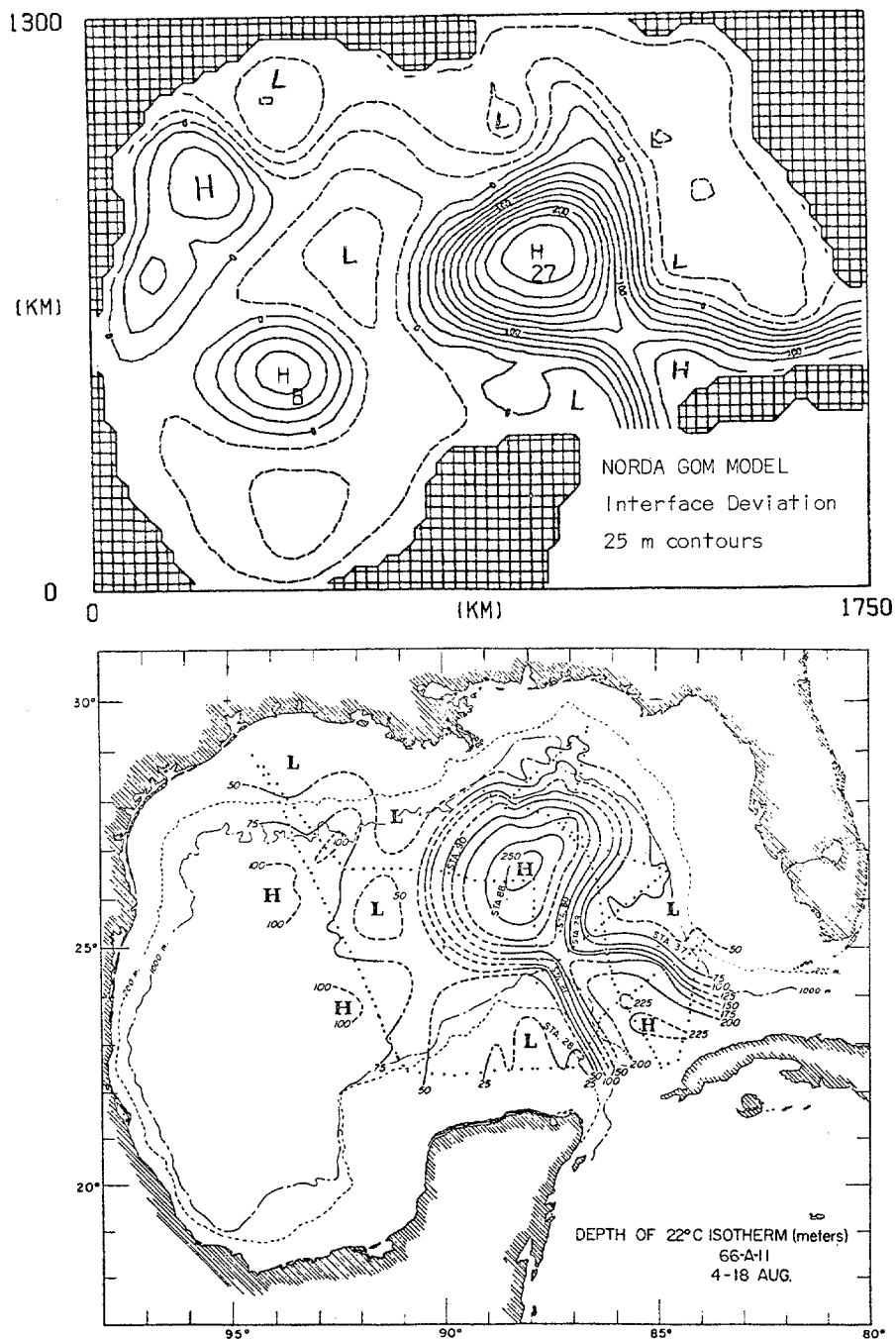


Figure 3. Comparison of NORDA's Gulf of Mexico numerical model results with observations. (a) "Snapshot" of the deviation (in m) of an initially horizontal interface between two homogeneous layers of different densities. The model has been "spun up" to statistical equilibrium by constant inflow transport through the Yucatan Strait. In (b) the depth of the 22°C isothermal surface optional from a near-synoptic mapping by Leipper (1970) is shown.

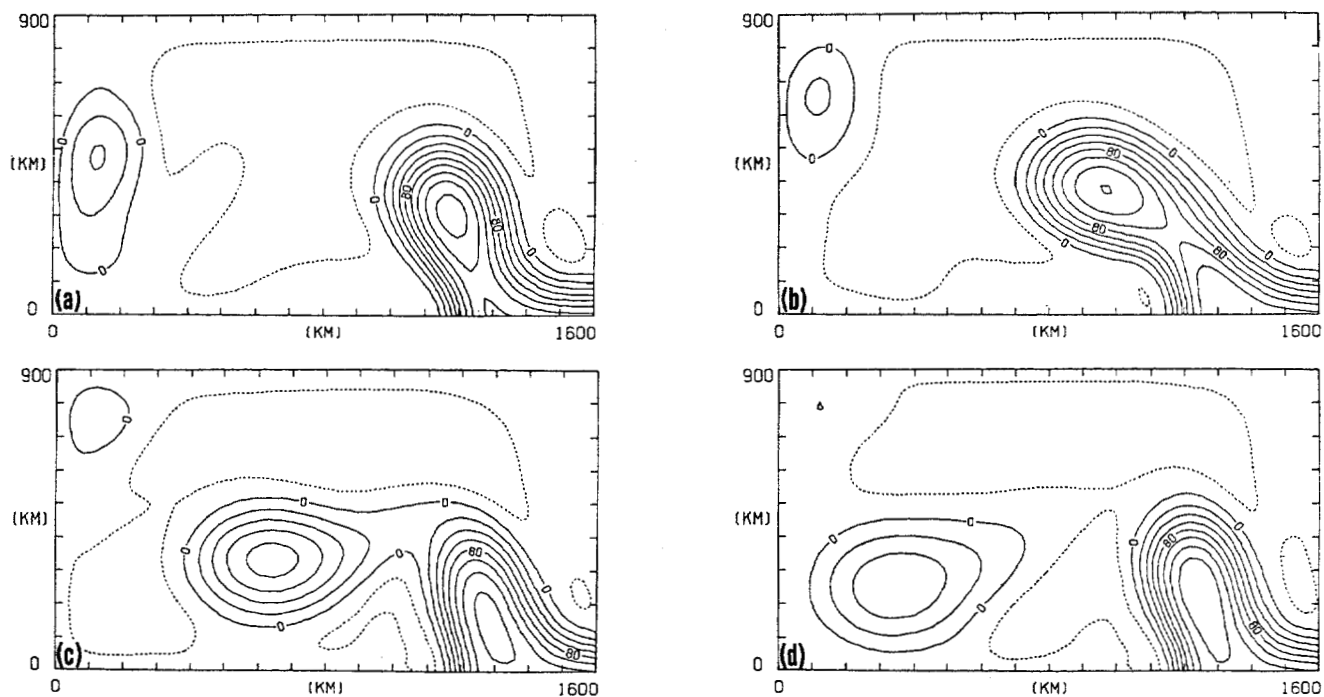


Figure 4. Sequence of synoptic maps of PA at 70-day intervals showing the life cycle of an eddy starting at day 2210. The contour interval is 20 m. In all the figures dashed contours are negative. PA is positive downward.

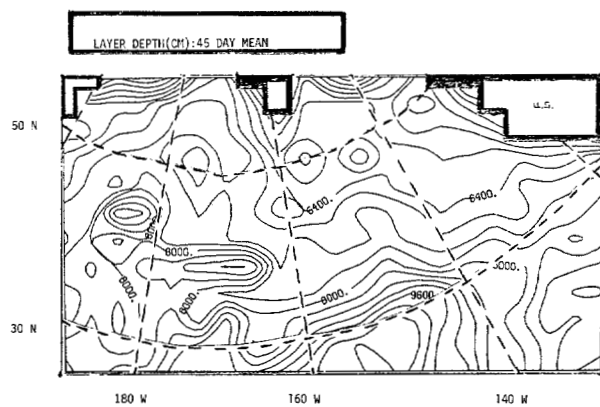


Figure 5. Contours of mixed-layer depth, averaged over 45 days in November-December 1976, North Pacific

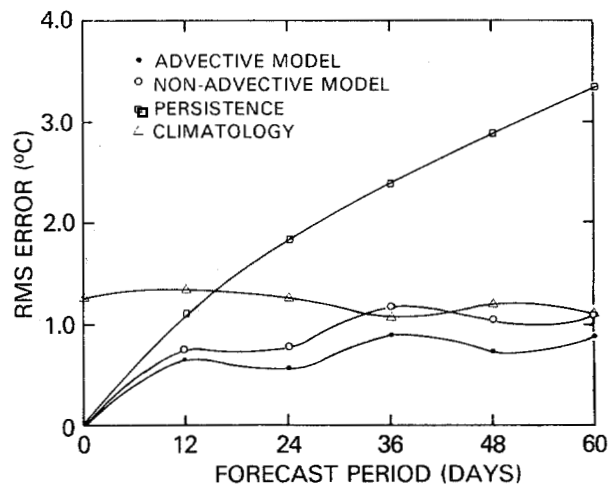


Figure 6. Root-mean-square (RMS) sea surface temperature forecast errors in the TRANSPAC region of the North Pacific produced by the advective TOPS model (\bullet), non-advective TOPS model (\circ), persistence (\square), and climatology (Δ) for 60-day forecasts from 29 October 1976.