THE IMPORTANCE OF ALTIMETER AND SCATTEROMETER DATA FOR OCEAN PREDICTION

Harley E. Hurlburt
Naval Ocean Research and Development Activity
Code 324
NSTL, MS 39529 USA

ABSTRACT

The potential for ocean prediction within the next decade is discussed in terms of the crucial elements: data, computing power, and models. The paper outlines a strategy for a global ocean prediction system that is based on appropriate satellite data, Class 7 computers ($\sim$1 gigaflop and 32-128 million words), and eddy-resolving basin or global scale models. The paper is focused on the prediction of meandering currents, frontal positions, and eddies, but prediction of other oceanic phenomena is also surveyed.

1. INTRODUCTION

The next decade should be to numerical prediction of the ocean circulation what the 1950's and 1960's were to numerical weather prediction, a time when the essential elements came together to permit major advances in forecasting skill. These elements are 1) adequate data input, 2) adequate computing power, and 3) properly designed and adequately validated models for both data assimilation and forecasting. Ten years ago none of these requirements were satisfied for many aspects of ocean prediction. Meandering currents and eddies provide a notable example: (1) clear prospects for adequate data with high density and global coverage from satellite-borne instruments have become evident only in the last few years, (2) Class 7 computers with a sustainable speed of $\sim$1 gigaflop and 32-128 M words of memory are required for eddy-resolving forecasts in major ocean basins, and (3) notable differences from meteorology are required in model design and in data assimilation.

The U.S. Navy has determined a requirement for an ocean prediction capability, and has established a research program to meet the requirement. This paper is an overview of the requirements for data and computing power, and the issues of model design and data assimilation primarily in the context of the effort at the Naval Ocean Research and Development Activity. It should be stressed that there are many types of ocean prediction aimed at different aspects of the motion, internal structure, and surface of the ocean. These provide several important roles for satellite data. This paper is focused on one important aspect of ocean prediction where altimeter data can play a central role. In particular, there will be a demonstration of the role that satellite altimeter data can play in detailed surface and subsurface forecasts of meandering currents, eddies, and frontal locations, forecasts that may extend up to several months.

2. DIFFERENT TYPES OF OCEAN PREDICTION

2.1 Classes of Response to Atmospheric Forcing

Before concentrating on a particular type of ocean prediction, it is useful to survey the scope of the problem. Table 1 from Hurlburt (1984) shows three classes of oceanic response to atmospheric forcing that cover many phenomena for

Table 1 *

Classes of oceanic response to atmospheric forcing where predictive skill is feasible.

Class	Implications	Examples
1. Strong, rapid (< 1 wk) and direct	A. short-range forecasts limited by the time scale for atmospheric predictive skill B. less sensitive to errors in the initial state; more sensitive to errors in the forcing functions	surface mixed layers, surface and some internal waves, Ekman drift currents, some coastal and equatorial processes such as upwelling (in some cases), coastal storm surges, and the onset of some equatorial and coastal waves
2. Slow (weeks to months) and indirect	A. long-range forecasts (potentially a month or more) B. more sensitive to errors in the initial state, less sensitive to errors in the forcing functions C. statistical properties of features and ensembles may be predicted by skillful simulation D. prediction of individual features requires oceanographic data. Altimeter data are the most promising operational source now on the horizon	mesoscale eddies, meandering currents, some frontal positions, features caused by mesoscale flow instabilities.
3. Slow (weeks to years) but direct (i.e. integrated response)	A. long-range forecasts B. sensitive to errors in atmospheric forcing functions on long time scales (e.g. monthly means); but less sensitive to errors on short time scales (e.g. daily fluctuations) C. nowcasting and forecasting are potentially feasible without good oceanic data by means of simulations that use appropriate ocean circulation models	El Nino, much of the tropical ocean circulation (in the Atlantic, Pacific, and Indian Oceans), equatorial waves, part of the large-scale ocean circulation, features such as gyres directly driven by persistent or repeated patterns in the wind, often in conjunction with geometric constraints, e.g. most of the circulation features in the Mediterranean Sea with scales > 100 km.

***From Hurlburt (1984)**

which prediction appears to be feasible and useful. It is not all-encompassing (e.g. tides and tsunamis are omitted), but it is intended to help put the multi-faceted problem of ocean prediction into perspective, identify phenomena where predictive skill is feasible, clarify the potential roles of satellite data, and to define the focus of the paper, which is primarily on Class 2. Fortunately, many phenomena are sufficiently decoupled that it is possible to design forecast models that can simulate and predict certain phenomena while suppressing or parameterizing the statistical effects of the remainder.

2.2 Nowcasting

"Nowcasting" is important in all three classes. To nowcast the models are integrated forward in time while driven by new atmospheric forcing functions and assimilating appropriate new ocean data as they become available. This allows the models to

a. Fill in temporal gaps in the data by using their predictive skill.
b. Convert better observed surface fields into subsurface structure,
c. Convert better observed atmospheric forcing functions into oceanic information.

2.3 Class 1: Strong, Rapid, and Direct

Until now ocean prediction efforts have concentrated primarily on tides and certain phenomena in Class 1, a class which to some extent includes the cumulative effects of fine scale phenomena that are predicted via empirical or semi-empirical parameterizations. Storm surges have received the most attention (Welander, 1961; Jelesnianski, 1967; Crawford, 1979), but recently the U.S. Navy has initiated hemispheric forecasts of surface waves (Pierson, 1982) and the upper mixed layer (Clancy and Martin, 1981; Clancy and Pollak, 1983).

The output from atmospheric prediction models and satellite-borne instruments measuring surface wind speed and direction (scatterometer) or even wind speed alone (scanning multi-frequency microwave radiometer (SMMR)) show great promise in facilitating predictions in Class 1 and Class 3. Scatterometers and microwave radiometers can provide adequate coverage, accuracy, and spatial and temporal resolution except for coverage near coastal boundaries (Jones et al, 1982; Wentz et al, 1982; Lipes, 1982; Satellite Surface Stress Working Group, 1982; Mueller, 1982). For mixed layer forecasting, measurements of sea surface temperature (SST) (multi-channel infrared and microwave radiometers) would be of value. Some work has also been done on satellite measurement of latent heat flux (Liu, 1984) and incident solar radiation at the surface (Gautier, 1981), the two heat fluxes that are usually the largest at the air-sea interface.

Although a satellite altimeter can measure surface wind speed and significant wave height in addition to sea surface elevation (Fedor and Brown, 1982), the value of a single altimeter with only a nadir beam is severely degraded when applied to prediction of phenomena in Class 1. This is due to the inverse relation between spatial and temporal resolution that prevents adequate resolution for these phenomena in both space and time simultaneously. However, the altimeter can be useful in constructing climatologies of wind speed and significant wave height (Chelton et al., 1981; Wentz et al., 1982; Mognard et al., 1983), in validation and tuning of certain models and in some research problems involving these quantities. Because tides are repetitive with known periods, the altimeter should be important in refining the global knowledge of tidal phase and amplitude (Cartwright and Alcock, 1981; Brown and Hutchinson, 1981; Diamante and Nee, 1981; Mazzega, 1983).

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2.4 Class 2: Slow and Indirect

The prediction of mesoscale (~50-500 km) eddies, meandering currents, and frontal positions (phenomena in Class 2) is the focus of this paper. It poses a problem where altimeter data should play a central role. This is because (1) individual mesoscale eddies and current meanders are often not driven directly by the wind or by any other external forcing function, and (2) eddies can persist for more than a year after their initial generation (Lai and Richardson, 1977). Thus, oceanic data are crucial for reliable prediction of individual eddies and current meanders. With sufficient oceanic data, we anticipate that the prediction of these features can be treated as an initial value problem in which the future forcing functions are representative but not accurate on time scales greater than a few days. Without oceanic data input, simulation can be used to predict the statistical properties of features and ensembles, but usually not the evolution and movement of individual features.

There has been little work on the prediction of Class 2 phenomena except for the work on prediction of mesoscale eddies, using limited-area models, by A.R. Robinson's group at Harvard (Robinson and Haidvogel, 1980; Robinson and Tu, 1982; Miller and Robinson, 1983). However, there is a substantial body of literature on the simulation and ocean dynamics of Class 2 phenomena which is very useful in the design of ocean circulation prediction models (Holland and Lin, 1975; Rhines, 1977; Semtner and Mintz, 1977; Holland, 1978, 1982; McWilliams and Flierl, 1979; Cox, 1979; Hurlburt and Thompson, 1980, 1982; Lin and Hurlburt, 1981; Schmitz and Holland, 1982; Heburn et al., 1982). Many of these have simulated some features of the ocean circulation with substantial success using simple models, rectangular domains, and simple steady forcing functions. This is an indication of potential predictive skill, but one largely unverfied at this time.

As an example, Figure 1 illustrates model simulation skill for a Class 2 phenomenon in the Gulf of Mexico. The model has two active layers, realistic geometry and bottom topography, and horizontal resolution sufficient for major current systems and eddies. Surprisingly, no eddy-resolving ocean modeling study published to date has included all of these features in a deep ocean basin where planetary vorticity advection was important and the model was integrated to statistical equilibrium. This calculation was performed by A. Wallcraft (personal communication) using the model of Hurlburt and Thompson (1980). The ability to handle detailed coastline geometry was added by Wallcraft. The model was driven from rest to statistical equilibrium solely by a steady inflow through the Yucatan Straits between Cuba and Mexico which was compensated by outflow through the Florida Straits.

Figure 1 compares "instantaneous" upper ocean flow patterns (a) from the numerical model and (b) from observations by Leipper (1970). The Loop Current is the major current system depicted. At this point it is about to shed an eddy. The Loop Current is observed to penetrate into the Gulf, bend westward, and to shed an eddy with a period of approximately one year. This "annual" cycle was long thought to be due to seasonal variations in the flow through the Yucatan Straits (Cochrane, 1965). However, The model Loop Current exhibits an approximately annual eddy-shedding period when the inflow is steady, contradicting the earlier hypothesis. Although time variations are not essential, they can still play a significant role in the eddy shedding (Hurlburt and Thompson, 1980). The model Loop Current also spontaneously shed eddies with realistic diameters, amplitudes, and westward propagation speeds. The dynamical basis for the agreement between the observations and a circulation model with low vertical resolution is discussed by Hurlburt and Thompson (1980, 1982). Additional information on the simulation in Figure 1 is found in Hurlburt (1984), including the spontaneous generation of a

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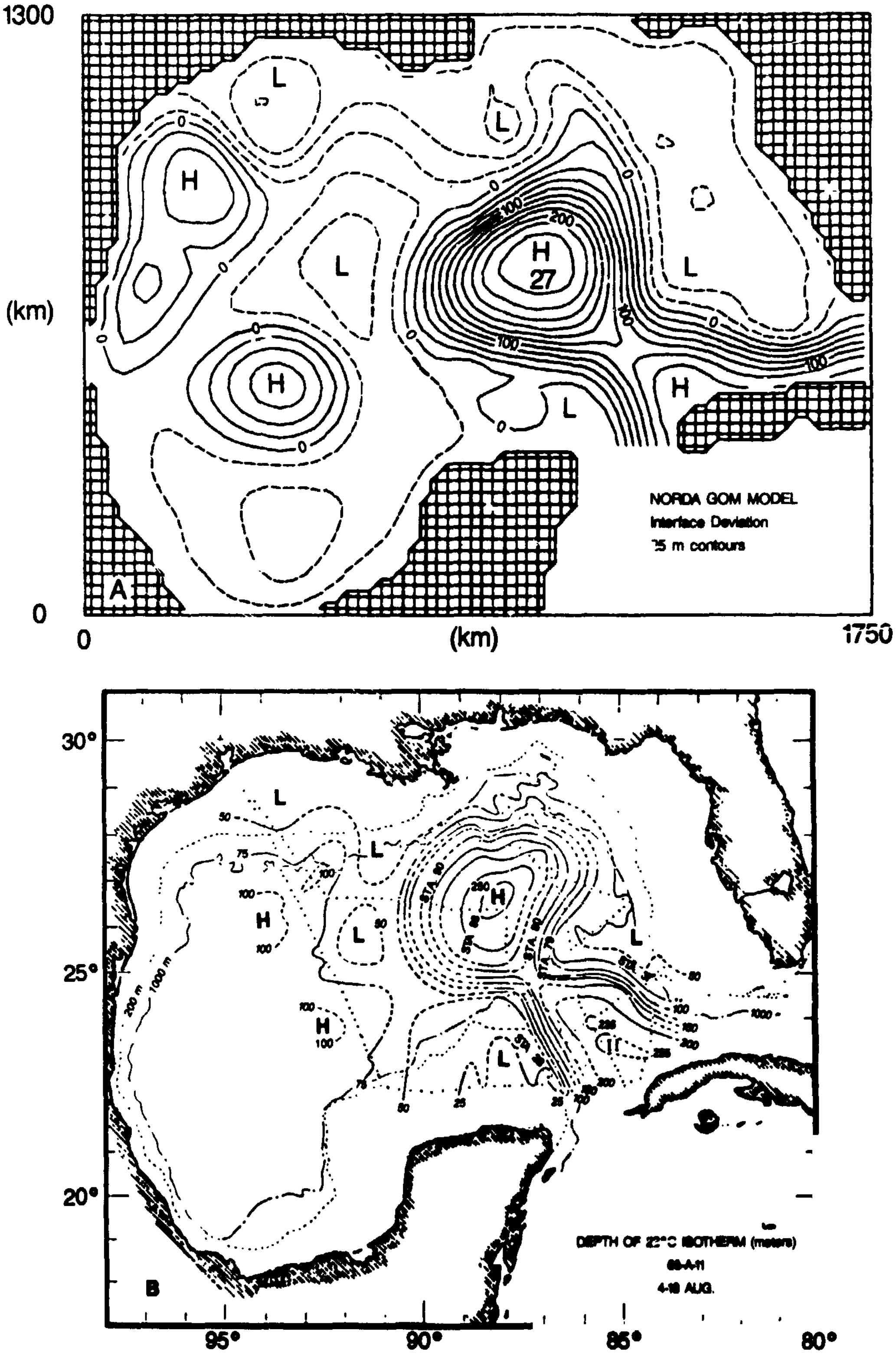

Figure 1. (a) Instantaneous view of the interface deviation in a two-layer simulation of the Gulf of Mexico driven from rest to statistical equilibrium solely by inflow through the Yucatan Straits. The contour interval is 25 m with solid contours representing downward deviations. (b) Depth of the 22°C isothermal surface, 4-18 Aug 1966 (Aliminos cruise 66-A-11) from Leipper (1970). The contour interval is 25 m. (From Hurlburt, 1984)

counter-rotating vortex pair as the eddy propagates westward. Such a feature has been observed repeatedly in the western Gulf of Mexico.

2.5 Class 3: Slow and Direct

Phenomena in Class 3 are a direct response to atmospheric forcing, but on much longer time scales than those in Class 1. Because they are a much more integrated response to the wind, the requirements for temporal resolution and accurate depiction of daily atmospheric fluctuations are not as stringent as in Class 1. This should permit forecasts on time scales greater than the few-day time scale for atmospheric predictability. In Class 3 "nowcasting" and forecasting may be feasible by using new atmospheric forcing functions without new oceanic data. The addition of altimeter-derived sea surface elevation accurate on the scales of major ocean basins as well as on mesoscales would reduce the burden on the simulation skill of the model. Examples of Class 3 simulation and prediction studies include the work by Haney (1980) on predicting large-scale anomalies in the North Pacific, by Busalacchi et al (1983) on the tropical Pacific, and by Preller and Heburn (1983) on the western Mediterranean Sea.

3. RESOLUTION REQUIREMENTS FOR ALTIMETER AND SCATTEROMETER DATA

The horizontal and temporal resolution required for the forcing functions is dictated primarily by the space and time scales of the atmosphere. Thus, scatterometer-derived wind stress data would be needed on a daily basis to resolve the evolution of atmospheric storm systems. The spatial resolution of the wind stress data should be sufficient (~ 50 km) to resolve the wind stress curl associated with atmospheric cyclones, anti-cyclones and fronts. Winds as close to coastlines as possible are highly desirable. In these regions horizontal resolution should be 20 km or better. Since a satellite scatterometer with an orbit altitude of about 850 km has about a 1500 km swath width (with gaps), a single satellite in conjunction with atmospheric models and the existing data base could meet these requirements adequately (Satellite Surface Stress Working Group, 1982).

Altimeter data is essential for <u>global</u> prediction and representation of individual current meanders and eddies. Cheney and Marsh (1981) have already demonstrated the ability of the SEASAT altimeter to detect the Gulf Stream and mesoscale eddies when using either repeat tracks or a geoid, and Cheney et al (1983) have used nine sets of 3-day repeat tracks from SEASAT to produce a global map depicting the RMS mesoscale variability of the sea surface elevation during Sep - Oct, 1978. Tapley et al (1982) and Wunsch and Gaposhkin (1980) review the problem of obtaining accurate measurements of current-related variations in the sea surface elevation from a satellite altimeter and the success achieved with SEASAT. To be useful in ocean circulation prediction, the altimeter data must, of course, resolve major current systems and eddies in time, amplitude, and horizontal dimension. However, the amplitude dependence on horizontal scale should also be noted. For currents in geostrophic balance

$$\hat{k} \times f\vec{v}_g = -g\nabla\eta$$

where f is the Coriolis parameter, $\vec{v}_g$ is the velocity of the geostrophic surface current, g is the acceleration due to gravity, and η is the sea surface elevation above the geoid related to oceanic surface currents. The maximum velocity (V) for typical, significant, persistent, mesoscale (~ 50 to 500 km) features in the ocean ranges from about 10 cm/sec to 1 m/sec. Up to 2 m/sec is not uncommon in the stronger currents. For an altimeter which can usefully measure oceanographic features with a minimum amplitude of η = 10 cm, the minimum radius of an eddy or half-width of a current (L) with V = 10 cm/sec is L = 100 km at 42° Lat and L = 150 km at 27° Lat. For V = 100 cm/sec, L = 10 km at 42° Lat, and the Rossby number, $R_o = V/fL = 1$. For $R_o \ll 1$ the flow is geostrophically balanced. For $R_o \gg 1$ vortices can develop cyclostrophic balance,

$$\frac{v_\Theta^2}{r} = -g\frac{\partial \eta}{\partial r}$$

where v_Θ is the tangential velocity and r is the radius of curvature. In this case the amplitude of η associated with the vortex is dependent on v^2 but is nearly independent of the scale of the vortex. However, a velocity scale > 2 m/s is required for a signal in the sea surface elevation > 10 cm.

From this we conclude that a satellite altimeter able to measure variations in the sea surface elevation > 5 cm, which are associated with oceanic currents, should provide usable information for the more significant currents and eddies with scales greater than a few tens of kilometers. This accuracy is feasible with current technology (TOPEX Science Working Group, 1981). Altimeter track spacing of about 30 km and at most 50 km at mid-latitudes is needed for horizontal resolution of most detectable eddies. Experiments by J. Kindle at NORDA have shown that three ascending or descending tracks with error-free data are sufficient to adequately map an eddy with a nearly circular shape. Repeat intervals up to a month should provide adequate temporal resolution for most mesoscale features, particularly with the aid of predictive models to fill in the temporal gaps. To minimize the time required for altimeter tracks to span a given eddy, the orbit should be chosen so that adjacent tracks are one day apart. This requirement should override any concern about tidal aliasing, since the tides are relatively large scale and because removal of the tidal contributions to the sea surface elevation appears feasible (Schwiderski, 1980; Cartwright and Alcock, 1981; Brown and Hutchinson, 1981; Diamante and Nee, 1981; Mazzega, 1983). However, as noted in some of the preceding references, accurate determination of the tidal phases and amplitudes would be facilitated by at least once having an altimeter in an orbit relatively free of tidal aliases with long periods.

A single satellite in a 20-day repeat orbit which carried a multi-beam altimeter (Bush et al, 1984) could easily meet the preceding requirements. Minimal satisfaction of the requirements could be achieved by using a single satellite with a nadir beam altimeter in a 40-day repeat orbit, if a numerical model was able to bridge the temporal gaps. In the absence of an adequate geoid, it would be necessary to use a mean sea surface, so that only deviations from the mean would be available to the model. In that case the model could obtain the mean from its own or observed climatology. Bandpass filtering could be required to remove short (< 0(10 km)) and long wave (> a few thousand km) errors, the scales with the greatest errors (TOPEX Science Working Group, 1981).

4. STRATEGY FOR OCEAN PREDICTION

Highly efficient models with low vertical resolution have demonstrated a remarkable ability to simulate meandering currents and eddies, but high horizontal resolution (~ 10 km) is required to resolve them. To avoid serious limitations on data assimilation and predictive skill, it is advantageous to use domains which cover major ocean basins or semi-enclosed seas where the phenomena of interest are generated within the domain, and where the open boundary segments are either small (such as flow through a strait) or very distant from the region of interest.

Circulation models on subdomains of major ocean basins which have extensive open ocean boundaries are extremely dependent on some source like a large-scale model for boundary conditions during both the data assimilation and prediction phases (Miller and Robinson, 1983). To provide useful boundary conditions, the large-scale model must also have resolution sufficient for the currents and eddies. To model major ocean basins with high horizontal resolution and low vertical resolution, a Class 7 computer (~ 1 Gigaflop and 32M to 128M words) is required. The introduction of Class 7 computers is anticipated in the middle and late 1980's.

Currently, satellites and atmospheric forecast models provide the only real prospects for oceanic data and forcing functions with global coverage and resolution adequate for use in ocean circulation models. For this purpose, the fields of greatest value, which are observable from satellites, are altimeter-derived sea surface elevation, scatterometer-derived wind stress, and heat fluxes. Successful ocean prediction appears feasible without extensive subsurface data collection by using the simulation skill of the model to convert the potentially well-observed fields at the surface into subsurface information. This looks more promising than attempting to assimilate the extremely sparse subsurface data, a process likely to do more harm than good. Where eddy-resolving subsurface data with useful coverage is available (nowhere at present), it should, of course, be used, especially if it is available on a regular basis and its statistical properties are well known. In the long term, acoustic tomography shows promise in this area (Munk and Wunsch, 1982), but we anticipate that subsurface data acquisition adequate for prediction of mesoscale features will, at best, be limited in coverage for at least the next decade. Some subsurface data and major field programs are essential for the local and regional subsurface validation of the forecast models.

The surface to subsurface data conversion process would be accomplished by using both the altimeter data and the atmospheric data as forcing functions. Although this is an untested hypothesis at this time and the assimilation of the altimeter data could be troublesome, the potential for surface to subsurface conversion is enhanced by noting that (1) a single internal vertical mode explains much of the oceanic variability (Richman et al, 1977; Flierl, 1978), (2) in a layered circulation model with a single internal mode there is a one-to-one correspondence between variations in the sea surface elevation and variations in the depth of the pycnocline, (3) such a model can be initialized by altimeter data alone, except near the equator where wind stress is necessary, and (4) such models have demonstrated remarkable simulation skill in certain situations (Busalacchi et al, 1983; Lin and Hurlbut, 1981; Hurlburt and Thompson, 1980, 1982), although they miss the sometimes important effects of topography and baroclinic instability (Holland and Lin, 1975; McWilliams et al, 1978; Hurlburt and Thompson, 1983). These require at least one additional vertical mode and we recommend no less than three in an operational forecast model. High vertical resolution can be obtained by coupling the circulation model with low vertical resolution to an array of one-dimensional mixed layer models with high vertical resolution. A hemispheric array makes up the mixed-layer forecasts by the U. S. Navy (Clancy and Martin, 1981).

Among the ideas proposed for application to ocean prediction, some that show promise are 1) the use of satellite altimeter and scatterometer data, 2) the conversion of surface into subsurface information, 3) the partial decoupling of the ocean circulation problem from the turbulent thermodynamic mixed layer problem, 4) eddy-resolving circulation models with low vertical resolution and basin or global-scale domains, and 5) Class 7 computers. Some that are not promising (at least within the next decade or more) are 1) eddy-resolving models for major ocean basins with many fixed levels in the vertical, 2) the inclusion of sophisticated mixed layer physics in eddy-resolving circulation models covering major ocean basins, 3) the assimilation of sparse in situ data by ocean circulation models, 4) coarse grid, non-eddy-resolving prediction models for the ocean circulation, and 5) sub-basin-scale models with extensive open boundaries except when they can obtain boundary conditions from an eddy-resolving basin scale model. "Nowcasts" and short-range forecasts (a few days) from stand-alone limited-area models appear feasible in regions with adequate subsurface sampling (none at present). The first two ideas lack promise only because of the anticipated computing power within the next decade or more.

Within the next decade the appropriate satellite data, Class 7 computers, and eddy-resolving basin or global-scale models should become available, and they should be used to form the heart of a global ocean prediction system. In the meantime, alternate methods can provide a more limited capability which is applicable in some situations. Forcing functions from atmospheric models should permit useful nowcasting and predictive skill for Class 1 and Class 3 phenomena listed in Table 1 prior to the availability of satellite altimeter and scatterometer data.

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