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14. ABSTRACT

Since the late 1980's, ice forecasting systems developed by the Naval Research Laboratory (NRL) have been predicting conditions in the Arctic Ocean and several of its marginal seas for use by the U.S. Navy. Each day a 120-hour forecast of ice drift, ice thickness and ice concentration is run operationally at the Naval Oceanographic Office (NAVOCEANO). Presently, a high resolution Arctic two-way coupled ice/ocean nowcast/forecast system based on the Community Ice CodE (CICE) and the HYbrid Coordinate Ocean Model (HYCOM) is being tested using the Navy Coupled Ocean Data Assimilation (NCODA) system. Ice concentration data from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) is used as initialization for the model's ice concentration field. Results from the coupled system both with and without the use of ice concentration data for initialization will be discussed.

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ice concentration, multivariate optimum interpolation, sea surface height, SST

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Real-time Data Assimilation of Ice Concentration into a Coupled Ice/Ocean Forecast System

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***Abstract*- Since the late 1980's, ice forecasting systems developed by the Naval Research Laboratory (NRL) have been predicting conditions in the Arctic Ocean and several of its marginal seas for use by the U.S. Navy. Each day a 120-hour forecast of ice drift, ice thickness and ice concentration is run operationally at the Naval Oceanographic Office (NAVOCEANO). Presently, a high resolution Arctic two-way coupled ice/ocean nowcast/forecast system based on the Community Ice CodE (CICE) and the HYbrid Coordinate Ocean Model (HYCOM) is being tested using the Navy Coupled Ocean Data Assimilation (NCODA) system. Ice concentration data from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) is used as initialization for the model's ice concentration field. Results from the coupled system both with and without the use of ice concentration data for initialization will be discussed.**

I. INTRODUCTION

Over the last decade, ice conditions in the Arctic Ocean have changed dramatically resulting in a minimum areal ice extent during the summer of 2007. With this rapidly changing polar environment, the need for accurate ice forecasts is essential. Currently, the operational coupled sea ice forecasting system run daily at NAVOCEANO is the Polar Ice Prediction System (PIPS 2.0) at a resolution of ~27 km. NRL has developed a new coupled ice/ocean system to forecast high resolution ice conditions in the polar regions. This nowcast/forecast system is based on the HYbrid Coordinate Ocean Model (HYCOM) [1] coupled via the Earth System Modeling Framework [2] to the Los Alamos Community Ice CodE (CICE) [3]. The two-way coupled system will be referred throughout the paper in two ways: as a) HYCOM/NCODA/CICE when using data assimilation or b) HYCOM/CICE without data assimilation. The ocean model (HYCOM) is an eddy-resolving, real-time global ocean prediction system. The second component of the nowcast/forecast system is the Navy Coupled Ocean Data Assimilation (NCODA) [4] which is a multivariate optimal interpolation scheme used to assimilate surface observations from satellites (altimeter data, sea surface temperature (SST) and sea ice concentration) as well as in-situ SSTs and temperature/salinity profiles. The sea ice component of the system (CICE) has: the latest ice thermodynamics improvements, updated snow layers and the capability to forecast multi-categories of ice thickness according to World Meteorological Organization definitions. A HYCOM/NCODA/CICE hindcast of ice concentration, both with and without SSM/I ice concentration initialization, is presently being validated against independent observations.

A. HYCOM/NCODA/CICE model description

The HYCOM/NCODA system provides the capability to nowcast and forecast the oceanic "weather", some including the three-dimensional (3-D) ocean temperature, salinity and currents structure, the surface mixed layer and the location of mesoscale features such as eddies, meandering currents and fronts. HYCOM has a horizontal equatorial resolution of 1/12° (~9 km) with increasing resolution to ~3.5 km in the Arctic region. The system employs 32 hybrid vertical coordinates surfaces with potential density referenced to 2000 m and it includes the effects of thermobaricity [5]. Vertical coordinates can be isopycnals (density tracking), often best in the deep stratified ocean, levels of equal pressure (nearly fixed depths), best used in the mixed layer and unstratified ocean and σ-levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step. The model makes a dynamically smooth transition between coordinate types by using the layered continuity equation. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal sea and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. HYCOM is configured with options for a variety of mixed layer submodels [6] and this version uses the K-Profile Parameterization [7].

NCODA is a fully 3-D multivariate optimum interpolation (MVOI) scheme. The three-dimensional ocean analysis variables include temperature, salinity, geopotential and the vector velocity components which are all analyzed simultaneously. NCODA can be run in stand-along mode but here is cycled with HYCOM/CICE to provide updated initial conditions for the next model forecast in a sequential incremental update cycle. Correction to the HYCOM/NOCDA/CICE forecasts are based on all observations that have become available since the last analysis.

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All observations must be quality controlled (QC) and this is done via NCODA-QC which is run operationally at NAVOCEANO. By combining these various observational data types via data assimilation and using the dynamical interpolation skill of the model, the 3-D ocean environment can be more accurately predicted.

CICE is the result of an effort to develop a computationally efficient sea ice component for a fully coupled forecast system. CICE has several interacting components: a thermodynamic model that computes local growth rates of snow and ice due to vertical conductive, radiative and turbulent fluxes, along with snowfall; a model of ice dynamics, which predicts the velocity field of the ice pack based on a model of the material strength of the ice; a transport model that describes advection of the areal concentration, ice volumes and other state variables; and a ridging parameterization that transfer ice among thickness categories based on energetic balances and rates of strains.

Both the ocean and ice model use the Fleet Numerical Meteorology and Oceanography Center 3-hourly 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing [8] that includes: air temperature at 2 m, surface specific humidity, net surface shortwave and longwave radiation, precipitation, ground/sea temperature, zonal and meridional wind velocities at 10 m, mean sea level pressure and dewpoint temperature at 2 m. Typically atmospheric forcing forecast fields extend out to 120 hours (i.e. the length of the HYCOM/NCODA/CICE forecast).

Data assimilation is essential for accurate ice/ocean predictions for many reasons: (a) some ocean phenomena are due to nonlinear processes (i.e., flow instabilities) and thus are not a deterministic response to atmospheric forcing, (b) errors exist in the atmospheric forcing and (c) coupled models are imperfect, including limitation in numerical algorithms and in resolution. Most of the information concerning the ocean surface's space-time variability is obtained remotely from instruments aboard satellites (sea surface height, SST and ice concentration). These observations are insufficient for specifying the subsurface variability. For this reason, vertical profiles from expendable bathy-thermographs (XBT), conductivity-temperature-depth (CTD) profilers, and profiling floats (e.g., Argo) provide another substantial source of data. By assimilating these different types of real-time observations, a more realistic ice/ocean forecast will be produced.

II. Model Setup

A coupled HYCOM/CICE system was setup and run using a subset of the global 1/12° equatorial resolution (~ 3.5 km in polar latitudes) for a domain covering the Arctic Ocean (Fig. 1). The system is currently run using 320 processors on an IBM Power 6 at NAVOCEANO. The typical one-day forecast takes ~20 wall clock minutes. The ice (ocean) model uses a time step of 10 (4) minutes. For both the ice and ocean models, the lateral "open" boundaries are defined away from any sea-ice covered regions to avoid possible contamination of any forecasted fields. In CICE these boundaries are closed and in areas that have no sea ice. In HYCOM they are nested inside a 1/12° (same resolution) fully global HYCOM/NCODA system with a simple thermodynamic sea ice model in place of CICE. The global HYCOM/NCODA simulation started in July 2007, so a non-assimilative global HYCOM run was used from June 2005 to June 2007.

In this coupled system, HYCOM provides input to CICE in terms of ocean currents, salinity and heat fluxes (temperatures). The ice model provides to the ocean model, surface stresses as well as salinity and temperature fluxes due to the growth and decay of sea ice. These fields are passed between the two models hourly. Direct interaction between the ice and ocean model occurs in the first ocean layer which is 3 m thick.

The ocean model bathymetry is based on the NRL Digital Bathymetric DataBase 2 min (DBDB2) (see http://www7320.nrlssc.navy.mil/DBDB2_WWW/. This global database is derived from a number of sources including: the NAVOCEANO global dataset (DBDBV, available online at http://gcmd.nasa.gov/records/GCMD_DBDBV.html), the Smith and Sandwell global dataset [9], the Data Assimilation and Model Evaluation Experiments North Atlantic data, the International Bathymetric Chart of the Arctic Ocean data, the Australian Bathymetric and Topographic data, and regional datasets from the Gulf of Mexico and Yellow Sea. Several of these datasets were hand-edited to improve the flow through narrow passages and straits

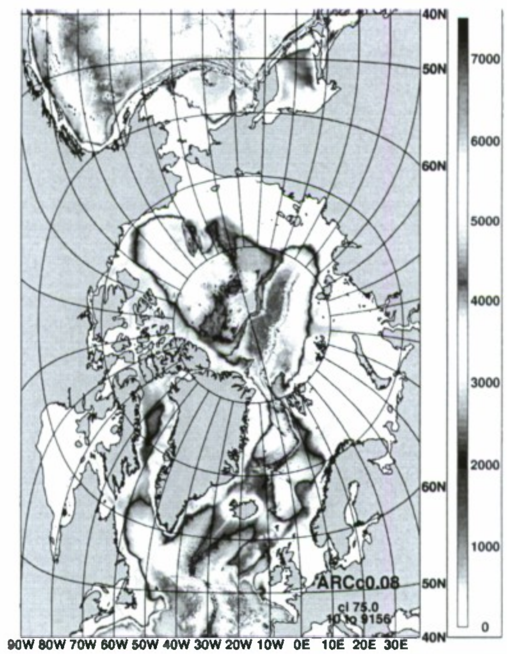

Figure 1. 1/12°HYCOM/CICE Arctic Ocean bathymetry (m).

III. Model Verification

A. Non-Assimilative Study

The HYCOM/CICE system was integrated without assimilation (i.e. without NCODA), using NOGAPS forcing over the period 01 June 2005 - 31 July 2008. Even with data assimilative open ocean boundaries, the ocean and sea ice in the interior is typical of a non-assimilative system. Overall, the coupled model without assimilation produced reasonable seasonal ice trends in many locations. Figure 2 shows the typical winter (15 March 2007) and summer (03 August 2007) ice concentration analyses. Even with the unusual extreme conditions during 2007 (warm atmosphere, thinner ice, atypical wind patterns, etc), the HYCOM/CICE simulations agreed fairly well to the observations. However, for the purpose of daily real time ice edge forecasting, the model must be capable of having greater accuracy at the ice edge. Daily assimilation from ice edge observations should enable the system to produce more realistic forecasts.

concentration forecasts as a first guess and assimilates ice concentration from SSM/I. The NCODA analysis was then directly inserted into the ice model near the ice edge only (where ice concentration < 15 %).

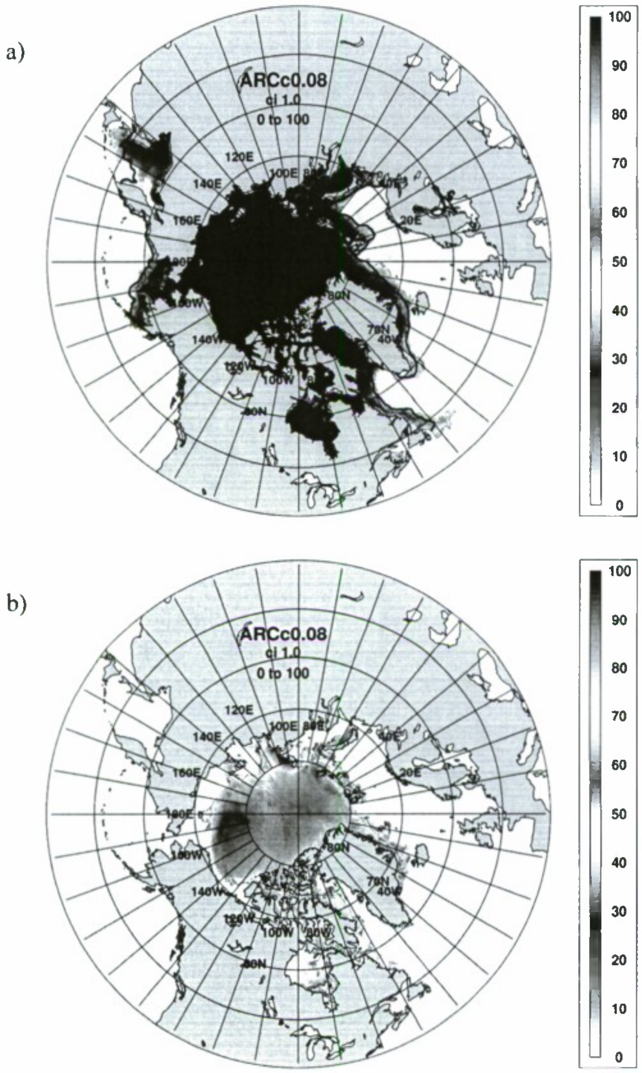

Figure 2. Ice Concentration (in percent) from HYCOM/CICE without any data assimilation. Images represent two seasons a) winter (15 March 2007) and b) summer (03 August 2007).

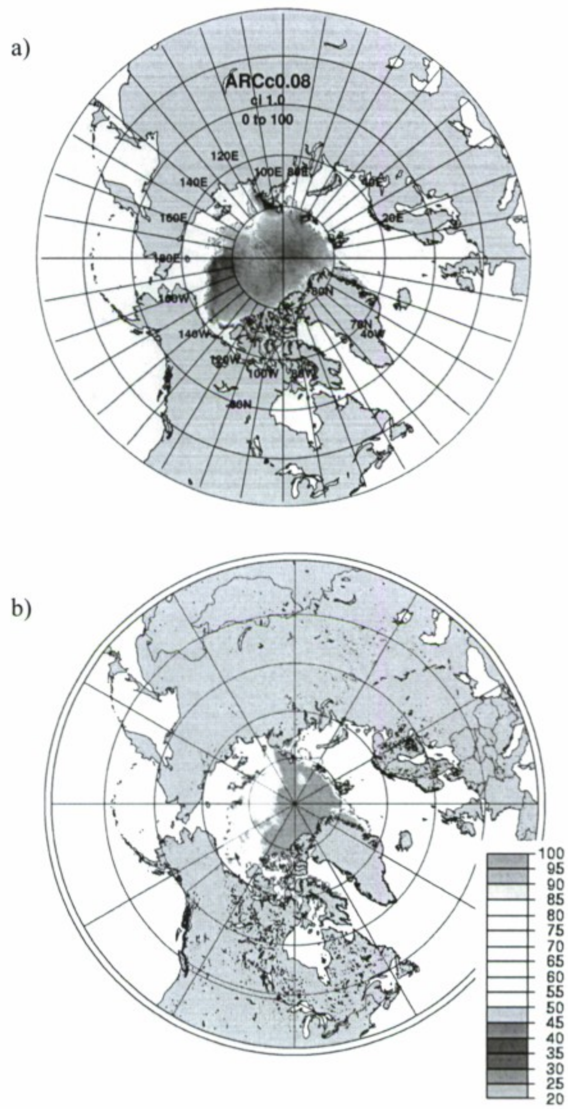

Figure 3. Ice Concentration (in percent) from a) HYCOM/NCODA/CICE data assimilation and b) SSM/I. Images valid for 03 August 2007.

B. Assimilative Study

The second test was then run using assimilation of all available oceanic data and SSM/I derived ice concentration fields via NCODA into the system. Since data assimilative boundary conditions were available starting in July 2007, the second simulation was integrated using NOGAPS forcing over the period 01 July 2007 – 31 December 2008. The SSM/I concentration field is derived using the Navy's CAL-VAL algorithm [10] and has a resolution of 25 km before it is interpolated to the model grid. NCODA uses CICE's ice

Figure 2b shows summer-time ice concentration from HYCOM/CICE without any data assimilation versus figure 3a HYCOM/NCODA/CICE with data assimilation for 03 August 2007. The assimilative test compares better to the SSM/I valid for the same day (figure 3b) especially in Hudson Bay and east of Baffin Island. Note that Figure 3b has a slightly different colorbar than the other figures. The ice edge location in eastern Arctic region (Barents Sea and east of Greenland) has also improved dramatically in the assimilative case as opposed to the non-assimilative test. Only the ice concentration near the ice edge from the SSM/I observations are assimilated into the ice model. These results demonstrate that by assimilating real time observations, the two-way coupled system produces more realistic results when compared to independent observations. Previous sensitivity studies [11] have shown that daily initialization from SSM/I ice concentration can improve sea ice forecasts.

As stated before, the ice concentration field the HYCOM/NCODA/CICE system uses is derived from the DMSP satellite with an original resolution of 25 km. With such a significant mismatch between the real-time data and the model grid resolution (25 vs 3.5 km), higher resolution sea ice information from satellites is critically needed as model grid resolution increases in forecasting systems.

III. Conclusions

Since the 1980's, NRL has been running sea ice forecasting systems in various regions of Navy interest. Currently, the operational coupled sea ice forecasting system run daily at NAVOCEANO is the Polar Ice Prediction System (PIPS 2.0) and has a resolution of ~27 km. The HYCOM/NCODA/CICE system is undergoing final validation testing and has a resolution of ~3.5 km in the polar region. During July 2007 through present, tests have been performed in order to validate the system's hindcast results both with and without data assimilation of ice concentration. SSM/I ice concentration has been archived and evaluated by NRL for several years as a tool for initialization of the model ice concentration fields. Several sensitivity studies have shown that daily initialization from SSM/I ice concentration can provide a valuable improvement to the existing operational sea ice forecasts. Testing is underway to investigate the improvements in daily ice forecast when higher resolution initialization data are used.

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