Real-time Data Assimilation of Satellite Derived Ice Concentration into the Arctic Cap Nowcast/Forecast System (ACNFS)

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***Abstract*- Over the last decade, ice conditions in the Arctic have changed dramatically resulting in the Arctic having a minimum in ice extent during the summers of 2007, 2008 and 2010. With this rapidly changing polar environment, the need for accurate ice forecasts is essential. The Naval Research Laboratory (NRL) has developed the Arctic Cap Nowcast/Forecast System (ACNFS), a two-way coupled ice/ocean system, to forecast ice conditions in the polar regions. This system applies the Los Alamos Community Ice CodE (CICE) coupled via the Earth System Modeling Framework (ESMF) to the HYbrid Coordinate Ocean Model (HYCOM). The Navy Coupled Ocean Data Assimilation (NCODA), a 3-Dimensional VARiational analysis (3DVAR) scheme, is used to assimilate ice and ocean observations into the forecast system. Ice concentration data from two sources: the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) and the Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E) are used as observations for the ice analysis. Results from the coupled system using both concentration input datasets will be discussed.**

I. INTRODUCTION

The Naval Research Laboratory (NRL) has developed/validated a 1/12° Arctic Cap Nowcast/Forecast System (ACNFS) [1]. This nowcast/forecast system is based on the Los Alamos Community Ice CodE (CICE) [2] coupled via the Earth System Modeling Framework [3] to the HYbrid Coordinate Ocean Model (HYCOM) [4]. The sea ice component of the system (CICE) has state of the art ice thermodynamics, updated snow layers, and the ability to forecast multiple categories of ice thickness according to the World Meteorological Organization (WMO) definitions. The ocean model (HYCOM) is designed with a generalized vertical coordinate. It is isopycnal in the open stratified ocean, but reverts to a terrain-following coordinate in shallow coastal regions with z-level coordinates near the surface in the mixed layer and where the water column is weakly stratified. The final component of the nowcast/forecast system is the Navy Coupled Ocean Data Assimilation (NCODA) [5] which is a 3-Dimensional VARiational analysis (3DVAR) scheme used to assimilate surface observations from satellites including altimeter data, sea surface temperature (SST), and sea ice concentration, as well as in-situ SSTs and temperature/salinity profiles from glider and buoy data sources. NCODA uses CICE's ice concentration forecasts as a first guess and assimilates ice concentrations derived from two sources: (1) Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Image (SSM/I) data using the Navy algorithm [6] and (2) Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E) [7]. The ACNFS produces high horizontal resolution nowcasts and 5-day forecasts of ice drift, ice concentration and ice thickness.

II. ACNFS MODEL DESCRIPTION

The 1/12° ACNFS is a coupled sea ice and ocean model that nowcasts and forecasts conditions in all sea ice covered areas in the northern hemisphere (poleward of 40° N). The sea ice component of ACNFS (CICE) was developed at the Los Alamos National Laboratory [2] and is the result of an effort to develop a computationally efficient sea ice component for a fully coupled atmosphere-ice-ocean-land global climate model. 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 as well as precipitation rates (i.e., snowfall); a model of ice dynamics that 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 transfers ice among thickness categories based on energetic balances and rates of strains.

The ACNFS also provides the capability to nowcast and forecast oceanic "weather" 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 resolution of ~6.5 km at 40°N that increases 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 [8]. 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 [9] and this version uses the K-Profile Parameterization [10].

Data assimilation is performed through NCODA [5]. NCODA is a fully 3-Dimensional VARiational analysis (3DVAR) scheme. The three-dimensional ocean analysis variables include temperature, salinity, geopotential and vector velocity components, all of which are analyzed simultaneously. NCODA can be run in stand-alone mode, however here NCODA is cycled with HYCOM/CICE to provide updates for the next model forecast in a sequential incremental cycle. Corrections to the ACNFS forecasts are based on all observations that have become available since the last analysis. All observations must be quality controlled (QC). QC is accomplished via NCODA-QC and is run operationally at Naval Oceanographic Office (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.

The ice and ocean models are set up and coupled on the same horizontal grid. Both models use the Fleet Numerical Meteorology and Oceanography Center 3-hourly 0.5° Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing [11] 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. NOGAPS forecast fields typically extend out to 120 hours and coincide with the length of a standard ACNFS forecast.

Data assimilation is essential for accurate ice/ocean predictions for many reasons. For example, many ocean phenomena are due to nonlinear processes (e.g., flow instabilities) and thus are not a deterministic response to atmospheric forcing. Errors in the atmospheric forcing and limitations in numerical algorithms and grid resolution can contribute to the accuracy of the model's prediction skill. Most of the observed data concerning the ocean surface space-time variability is obtained remotely from instruments aboard satellites. Assimilated data includes sea surface height (SSH) and SST from the Advanced High Resolution Radiometer (AVHRR) (global and local coverage), Geostationary Operational Environmental Satellites (GOES), Meteosat Second Generation (MSG) satellite, AMSR-E and ice concentration from DMSP. While these observations work well to define surface conditions, they 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.

III. MODEL SETUP

A coupled HYCOM/CICE system was setup and run using a subset of the global domain covering the Arctic Ocean (Figure 1). The system is currently run using 320 processors on an IBM Power 6 at NAVY DoD Supercomputing Resource Center (DSRC). The typical one-day forecast takes ~1.25 wall clock hours. The ice model uses a time step of 10 minutes, whereas the ocean model uses a 4 minute time step. 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 the boundaries are located in areas that have no sea ice (40°N), thus no ice flows in or out of the domain. In HYCOM the open boundaries are nested inside a 1/12° (i.e., same resolution) fully global HYCOM/NCODA system with a simple thermodynamic sea ice model in place of CICE.

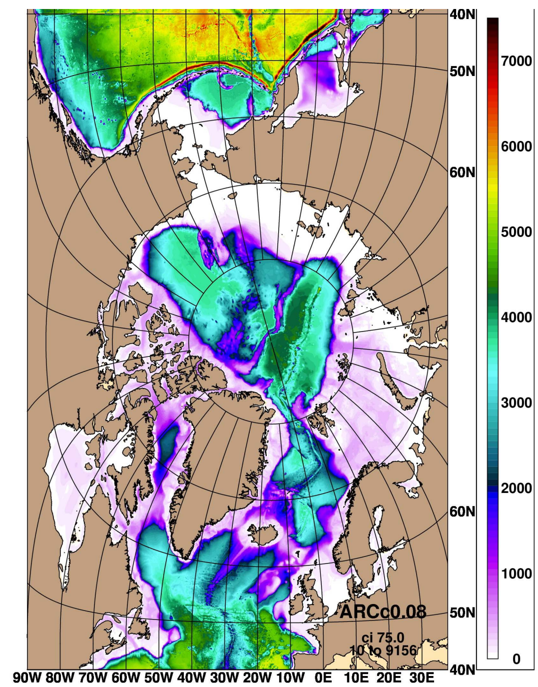

Figure 1. ACNFS bathymetry (m).

As ACNFS is a coupled system, data must be passed between the ocean and ice models. In this case, HYCOM passes ocean currents, salinity and heat fluxes (temperatures) to CICE, while ice stresses and ocean salinity and temperature fluxes due to the growth and decay of sea ice are passed from CICE to HYCOM. Data are exchanged between the two models hourly. Direct interaction between the ice and ocean model occurs in the first ocean layer which is 1 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). DBDB2 is a global database that 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 [12], 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.

Ice concentration is assimilated into the model in the following manner: NCODA first uses ACNFS 24-hour forecast ice concentration as an estimate for that day. NCODA will then assimilate ice concentration values from observations, in this case either SSM/I or AMSR-E, to produce an analysis field. Where ice concentration is less than 15%, model data are directly replaced with the NCODA analysis. Where the model data are between 15% and 40% a weighted average of the analysis and model is used. There is no assimilation where model ice concentration is above 40%.

IV. Model Comparison

Currently, data are assimilated into ACNFS from real-time SSM/I at a resolution of approximately 25 km. Since the resolution of ACNFS is approximately 3.5 km, higher resolution sea ice information from satellites is critically needed as model grid resolutions increase in sea ice forecast systems. Starting in summer of 2010, satellite derived 12.5 km ice concentration from AMSR-E was made available for use in real-time. In order to compare the effect of higher resolution satellite data in ACNFS, one year hindcasts with assimilation of ice concentration fields from SSM/I and AMSR-E were conducted.

The first test was run assimilating all available oceanic data and SSM/I derived ice concentration fields via NCODA. The SSM/I concentration field is derived using the Navy's CAL-Val algorithm [6]. The data are available in near real-time via NAVOCEANO. This simulation was integrated using NOGAPS forcing over the one year period 01 July 2009 – 30 June 2010.

The second test was the same as the first test, except AMSR-E derived ice concentration fields were substituted for SSM/I ice concentration. The AMSR-E concentration field is derived using the NASA Team 2 algorithm [7], and is made available in near real-time from the NASA Land Atmosphere Near real-time Capability for EOS (LANCE) website (http://lance.nasa.gov).

For this study, the mean distance between the independent, daily observed National Ice Center (NIC) ice edge and the ACNFS hindcasts was calculated (Table 1). Model ice edge locations are defined as those grid points that exceed a threshold value of 5% ice concentration and also have a neighboring point that falls below that value. Daily means are calculated from the distances between each NIC observed point and the nearest model-derived ice edge location. These daily means were calculated for the full Arctic and six regional seas: Greenland Sea, Barents Sea, Laptev Sea, Sea of Okhotsk, Bering/Chukchi/Beaufort Seas and the Canadian Archipelago. Figure 2 shows a time series plot of daily mean ice edge error for the Bering/Chukchi/Beaufort Seas region.

For the full Arctic region, the mean distance between the ice edge from ACNFS assimilating AMSR-E ice and the NIC ice edge was 18.1 km, compared to 21.6 km for the ACNFS with SSM/I ice concentration assimilation. This represents a 16% improvement. While overall improvement was made

Table 1: Mean distances (km) between the independent NIC ice edge and the ACNFS assimilating AMSR-E or SSM/I. Bold numbers indicate the model run with the lowest mean error.

Region	ACNFS assimilating AMSR-E	ACNFS assimilating SSM/I	% Improvement
Full Arctic	**18.1**	21.6	16%
Greenland	39.6	**35.7**	-9%
Barents	**34.9**	39.3	11%
Laptev	64.7	64.4	0%
Sea of Okhotsk	**48.2**	62.8	23%
Bering/ Chukchi/ Beaufort Seas	**46.5**	58.7	21%
Canadian Archipelago	53.8	**48.1**	-11%
Average	**43.7**	47.2	7%

assimilating AMSR-E ice concentration, it is noted that not all areas showed improvement. In particular, ACNFS with SSM/I data assimilation showed better performance in two areas: Greenland and the Canadian Archipelago. Further investigation into the satellite data in these two regions is required to understand the difference in model response.

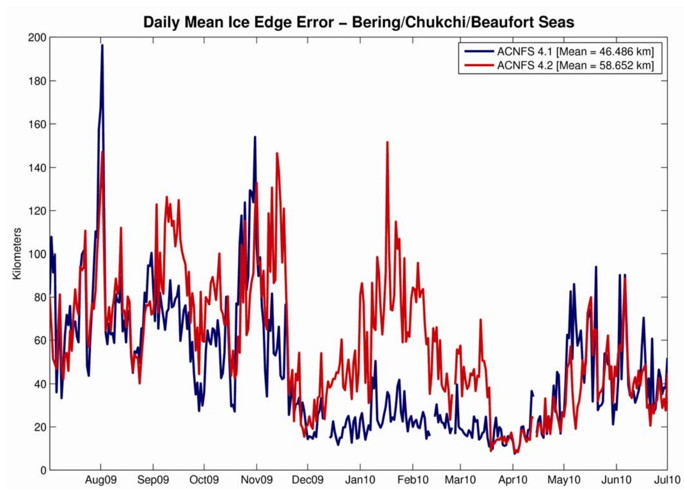

Figure 2. Daily mean distances (km) from the NIC observed ice edge locations to the derived ice edge locations from ACNFS assimilating AMSR-E (blue) and SSM/I (red) for the Bering/Chukchi/Beaufort Seas region from July 2009 – June 2010.

An important point to note is the difference in data format between the SSM/I and AMSR-E ice concentration. SSM/I ice concentration is available in swath format multiple times a day, whereas AMSR-E ice concentration is available as a gridded product once a day. Since data are assimilated once every 24 hours, all observations are considered synoptic (i.e. without time weighting for the data). The effect of multiple swath observations versus a daily gridded product is still in question.

V. CONCLUSIONS

The Arctic Cap Nowcast/Forecast System (ACNFS) has been developed/validated by NRL. The system has a resolution of approximately 3.5 km in the polar region. Several sensitivity studies have shown that daily assimilation of SSM/I ice concentration can provide a valuable improvement to the existing operational sea ice forecasts. While currently ACNFS assimilates data using 25 km SSM/I ice concentration, recently higher resolution, 12.5 km, near real time ice concentration derived from AMSR-E has been made available. In order to investigate if assimilating higher resolution data will improve ACNFS results, one year hindcasts have been performed using ice concentration from each satellite The results show that an overall improvement of 16% is achieved using the higher resolution AMSR-E data. Areas near Greenland and the Canadian Archipelago perform slightly better with SSM/I, the cause of which is still under investigation.

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