Data Assimilation Challenges for High-Resolution Reanalysis in the Polar Regions: The Arctic System Reanalysis*

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1. Introduction

In the polar regions, it is difficult to place current weather and climate trends in a long-term climatological perspective, primarily because the meteorological records there are limited in time and space in comparison with other regions. The low spatial density of observational data makes it challenging to separate local changes from regional or even continental-scale changes. Reanalyses, which perform extensive assimilation of all available observations to deliver physically consistent, regularly-spaced and comprehensive datasets, can be especially helpful in high latitudes. These efforts are especially pronounced given the recently-observed dramatic changes in Arctic land ice, sea ice, and permafrost regions.

In response to the Arctic's enhanced sensitivity to climate change, the Study of Environmental Arctic Change (SEARCH) project inspired extensive, interdisciplinary, multi-scale studies of high northern latitudes (Overland et al. 2003). To integrate observations and modeling efforts through data assimilation into a comprehensive picture of the regional climate and synoptic meteorology, SEARCH supported efforts toward a multi-year reanalysis of the Arctic that would employ all available remote-sensing and in-situ data.

The Arctic System Reanalysis (ASR), a new physically-consistent integration of Arctic data will be achieved through high-resolution reanalysis of the northern high-latitude region. The large domain includes northward flowing rivers from their headwaters in mid-latitudes to their mouths in the Arctic (Fig. 1). The ASR is a collaboration of the Ohio State University's Byrd Polar Research Center (BPRC) and Ohio Supercomputer Center (OSC) along with the National Center Atmospheric Research (NCAR), the University of Colorado, and the University of Illinois. The production phase of the ASR is funded by the U.S. National Science Foundation as an International Polar Year (IPY 2007-2009) project. The ASR will provide a high resolution description in space (10 km) and time (3 h) of the coupled atmosphere-sea ice-land surface system of the Arctic. Ingested historical data streams, along with measurements of the physical components of the Arctic Observing Network being developed as part of IPY will drive the ASR. Gridded output fields from the ASR will serve a variety of uses such drivers for coupled ice-ocean, land surface and other models, and will offer a focal point for coordinated model inter-comparison efforts. The ASR will permit detailed reconstructions of the Arctic system's variability and change, thereby complementing the global reanalyses. The project will also shape the legacy observing network of the IPY by providing a vehicle for observing system sensitivity studies of the Sustained Arctic Observing Network (SAON). To achieve its goals, the ASR will require an Arctic-friendly atmospheric numerical model with state-of-the-art dynamics.

2. Brief Summary of the ASR

The first generation ASR will span the years 2000-2010 including the IPY. The ASR will be based on a polar-optimized version of the state-of-

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the-art Weather Research and Forecasting (WRF) model and the WRF-Var data assimilation capabilities that are being enhance through this project. Various input data consideration issues, reanalysis verification and reanalysis output tasks are being addressed by the University of Colorado and the University of Illinois. The computing platform is OSC's IBM Cluster 1340 known as "Glenn" and recently expanded to 8000 cores. The Arctic atmospheric model development is being carried out by Polar Meteorology Group of the BPRC. Arctic enhancements to the Noah land surface model are being implemented by NCAR's Research Applications Laboratory (RAL). Data assimilation capabilities are being developed by the WRF-Var Development Team of NCAR's Mesoscale and Microscale Meteorology Division (MMM). The current data assimilation plan for ASR is to use 3DVAR in 3-hour cycling mode.

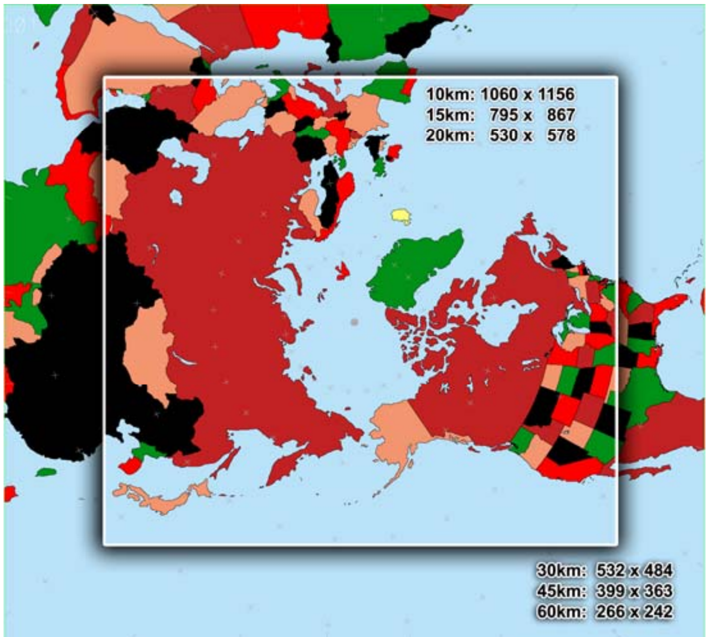

Figure 1. Tentative high-resolution and outer domain for the Arctic System Reanalysis.

The ASR encompasses a broad surface domain within the high-resolution region. The planned ASR high-resolution grid shown in Fig. 1 includes all of the watersheds of the northward flowing rivers emptying into the Arctic Ocean. A lower resolution outer grid will be used to feed the high resolution domain. The third-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) or the U.S. National Centers for Environmental Prediction Global Forecast System (GFS) will be used to drive the ASR. To treat the Arctic land regions, the ASR will also include optimized high-resolution land data assimilation (HRLDAS) capabilities. Current work at NCAR on the unified Noah land surface model (LSM), a feature within the WRF model (Chen and Dudhia 2001; Skamarock et al. 2006), includes HRLDAS development for the ASR. This involves the blending of atmospheric and land-surface observations with the LSM, with the goal of providing a long-term evolution of soil and vegetation features, the surface hydrologic cycle, and the surface energy cycle. The HRLDAS runs off-line from WRF in between interacting with WRF at intervals of a few hours. Additionally, a previous improvement to the Penman evaporation in the Noah LSM resulted in reduced sublimation under stable conditions and a reduced specific humidity bias.

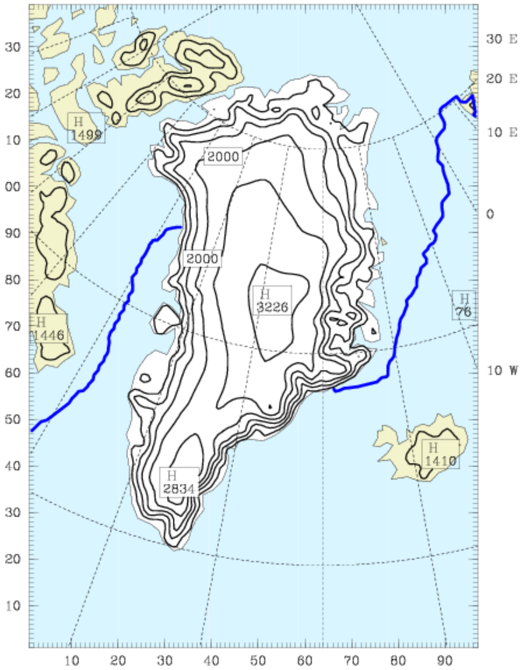

Figure 2. Domain of Polar WRF simulations of the North Atlantic and Greenland. Solid blue line shows mean boundary of sea ice during December.

3. Polar WRF

Earlier work by the Polar Meteorology Group of the BPRC resulted in a polar-optimized version of the 5th generation Penn State/NCAR Mesoscale Model (MM5). Tests of "Polar MM5" showed that the model achieved a much improved performance for both Arctic and Antarctic regions (e.g., Bromwich et al. 2001). To advance this work into the future, a polar-optimized version of WRF-ARW has been recently developed by the Polar Meteorology Group. "Polar WRF" will serve as the base model for the ASR, and will require evaluations and optimizations for boundary layer

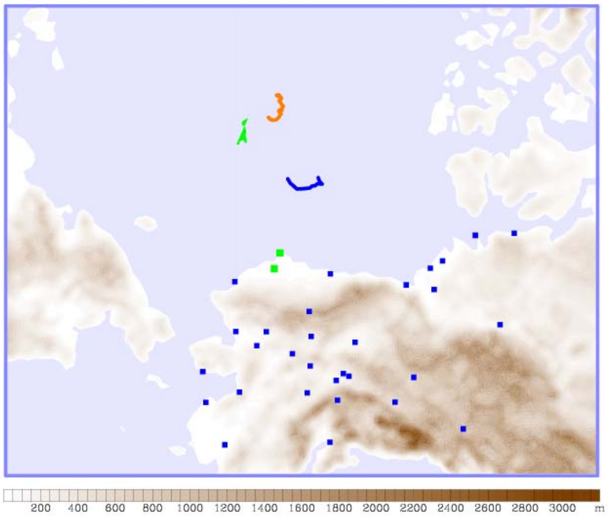

Figure 3. Domain for the Polar WRF simulations of the western Arctic. Squares show station locations. Marks in the Arctic Ocean show the location of Ice Station SHEBA during January (blue), June (green) and August (red) 1998.

parameterization, cloud physics, snow surface physics and sea ice treatment, analogous to the methods used to develop Polar MM5 (Bromwich et al. 2001). The model is undergoing tests for the Greenland and Antarctic ice sheets, the Arctic Ocean, and Arctic land environments.

4. Arctic results with Polar WRF

Testing and development work for Polar WRF began with simulations for ice sheet surface conditions using the Greenland area domain shown in Fig. 2 with 24-km horizontal resolution. The blue curves in Fig, 2 show the December locations of the southern sea ice boundary. Hines and Bromwich (2008) provide a detailed description of the simulations and results. The winter month December 2002, and the summer month June 2001 are simulated in a series of integrations initialized daily at 0000 UTC. The initial 12 hours are taken as model spin-up for the atmospheric hydrology and boundary layer processes. The output from hours 12-36 of the simulations is merged into a month-long field at 3-hourr intervals. The results motivated several improvements to Polar WRF, especially to the Noah LSM and the snowpack treatment. Best results are achieved via the use of the modified Noah LSM, the Mellor-Yamada-Janjic atmospheric boundary layer formulation, and WRF single-moment 5-class microphysics scheme

The next round of testing was over the Arctic Ocean using a western Arctic grid with 25-km resolution (Bromwich et al. 2009). The 141×111 domain for the simulations is displayed in Fig. 3. A crucial new component is the modified ocean surface treatment that allows for fractional sea ice between 2 to 100% coverage. The fractional sea ice capability is now an available option with the standard release of WRF 3.1 during April 2009. The atmospheric surface layer routine is called for all horizontal grid points in the domain, including separate calls for the ice and open-water components of pack ice grid points. Over the oceans, the LSM is called only for the ice portion of pack ice grid points. The new simulations also include the fully-two-moment ice and liquid water microphysics of Morrison et al. (2005).

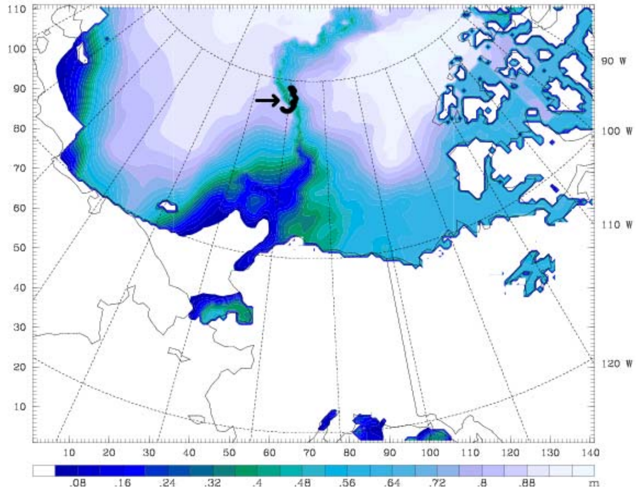

Figure 4. Color scale of average sea ice fraction during August 1998. The track of Ice Station SHEBA during August is shown next to the arrow. Land and ice-free grid points are unshaded.

Figure 4 shows the fraction of sea ice for ocean grid points with model domain during August 1998, when the Arctic open water fraction is considerably larger than during most other months. For this round of simulations, the initial spin-up time for the simulation is increased to 24 hours, and the model output from hours 24-45 is combined into the month-long fields. Arctic conditions are simulated for the selected months: January 1998, June 1998, and August 1998 representing mid-winter, early summer and late summer conditions, respectively from the Surface Heat Budget of the Arctic (SHEBA, Persson et al. 2002; Uttal et al. 2002) observational study. High quality observations are available for many atmospheric and oceanic fields during SHEBA (e.g., Persson et al. 2002). Relevant locations of Ice Station SHEBA are shown in Figs. 3 and 4. Over the Arctic pack ice the ice surface conditions change greatly over the course of late spring, then summer, and finally into Autumn (Perovich et al.

2007). Based upon in upon in-situ and remote-sensing observations, the albedo of sea ice is specified as a function of time and latitude for June and as a function of time for August. Details are presented in Bromwich et al. (2009).

Simulation results are compared with the observations of the drifting ice station SHEBA in the Arctic ice pack. The Polar WRF simulations show good agreement with observations for all three months. The model appears to be a good tool for studies of the atmospheric climate over the Arctic Ocean. Additional testing of Polar WRF is ongoing over Arctic land (Hines et al. 2009; Wilson et al. 2009) and the Antarctic continent. Work is also progressing on the data assimilation, land surface modeling, and data acquisition capabilities of the Arctic System Reanalysis.

5. Timetable for the Arctic System Reanalysis

A low-resolution test of the ASR is currently underway for the December 2007 fields. By September 2009, full-resolution tests of the December 2007 (winter) and August 2008 (near seasonal minimum Arctic sea ice) cases will be performed. By September 2010, an initial full-resolution test of the IPY period (2006-2009) will be performed. The final version of the 2000-2010 ASR will be completed by September 2011.

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