Development of ensemble-based sea ice analysis and forecasting in the Climate Forecast System Final Report

1. General Information

Project Title: Development of ensemble-based sea ice analysis and forecasting in the Climate Forecast System

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Final Report

Grant # NA16OAR4310137

2. Main goals of the project, as outlined in the funded proposal

This proposal to the MAPP-CTB has the goals of:

- Developing a prototype ensemble Kalman Filter assimilation for monitoring and predicting sea ice properties within the Climate Forecast System (CFS) v2.
- Testing this community standard methodology to improve monitoring and prediction of sea ice conditions and testing of experimental prediction methodologies developed in the broader community.
- Moving toward "mission qualification" and further testing in an ocean/sea ice and atmosphere/ocean/sea ice environment resembling the operational environment.

3. Results and accomplishments

This grant was primarily focused on system software implementation and testing. The first year of the two year grant was mainly concerned with system tests of the CFSv2/CICE2 model framework; test of the implementation of LETKF; examination of systematic errors and exploration of new data sets. LETKF refers to the Local Ensemble Transform Kalman Filter, an ensemble data assimilation system that has also been implemented for the ocean. CICE2 is the Community Ice CodE version 2, a model of sea ice dynamics and thermodynamics which is distributed by the DOE Los Alamos Laboratory. It's testing within the MOM5 ocean system was one of the goals of the grant. The focus of the second year of the grant has mainly been directed toward carrying out a series of analysis/forecast experiments in the CFSv2 framework using both the high resolution T574 coupled atmosphere/ocean/sea ice UGCS system and the lower resolution (more cost-effective) T126 UGCS system and concentrating on the spring/summer season, 2015. In the first part of year 2 we were also still dealing with coding problems.

To provide context for these system tests the observed record of Arctic sea ice cover during 2015 is shown in **Fig. 0.1a,b**. Sea ice concentration began at near record low values in spring, 2015, significantly below the record low year 2012. As a result of a slight recovery in June the September sea ice concentration of 4.1million km^2 (the annual minimum) was a bit below the 2012 record low. Notice that much of the ice retreat occurred on the Pacific side of the Arctic (**Fig. 0.1b**). This loss has been ascribed both to ice albedo feedback and to warm water from the North Pacific (this was the summer of the ‘warm blob’ in the Northern North Pacific).

Basic LETKF Experiments
We are mainly interested in constraining two features of the sea ice cover, its concentration which ranges from 0-100% and its thickness in meters. These are two of the parameters that a sea ice model forecasts and the two parameters that have the most direct impact on atmospheric fluxes. The first set of experiments, typically carried out for 30 days, addressed a variety of aspects of the assimilation system in preparation for the seasonal re-centering experiments described below.

1: Use LETKF analysis to restart 1 ensemble member
2: Only apply ice concentration (aicen) increment with simple bound check
3: Try restarting with aicen=0.9*aicen_bkg
4: Rescale background aicen distribution to match aice analysis
5: Redo 002, masking out increments where ice is not present in the background
6: Apply increment of surface temperature, ice fraction; re-adjust ice volume for consistency of background ice thickness

Seasonal re-centering experiments
A suite of experiments (our test case 7) was carried out testing the impact of recentering ice volume by applying increment of surface temperature and ice fraction/thickness then readjusting ice volume for consistency of the background ice thickness. Recentering ensures that the ensemble of forecasts have a reasonable mean value. At the same time we re-balance ocean temperature under the sea ice to be consistent with the sea ice analysis (for example, it should be near-freezing under the ice). Excessively warm water within the shallow halocline that forms under the ice is physically unrealistic and will simply melt away any overlying sea ice. The forecast model configuration for these experiments was: GSM(T126)-MOM5-CICE5. The experiment ran from Apr 1, 2015 (beginning with CFSv2 ICs) to October 30, 2015 using a 5-day window data assimilation cycling and with re-centering of the atmosphere and ocean to CFSv2 every 5th day.
Two parallel experiments were carried out:

2.1) CICE5 - LETKF (with an ensemble of 20 members)
2.2) CICE5 – Forecast only (No-DA)

Results
In **Fig. 2.1a,b** I present the initial conditions for the two experiments (May 1). As usual we see most of the initial spread in concentration estimates along the mean sea ice edge, since it is here that the estimates are most uncertain. Gradually the spread in the ensemble itself spreads into the interior so that by September (**Fig. 2.2a**) the spread has moved into the interior pack. On the Atlantic side of the Arctic both experiments show dramatic sea ice retreat. On the Pacific side of the Arctic experiment 2.1 with assimilation does get some sea ice retreat, although not quite enough, and the spread does increase, while experiment 2.2 shows much too much sea ice.

One problem confronting ensemble data assimilation algorithms in general, which is also a handicap when applied to sea ice is the collapse of the ensemble spread so that each of the ensemble members resembles all the others. The problem occurs because of constraints on where and how sea ice can grow. This problem of the collapse of the ensemble spread is evident in comparing the spread of the ensemble in experiments 2.1 and 2.2 (Fig. 2.2). Without assimilation the spread among the ensemble members remains reasonable due to the natural spread in atmospheric forcing (each ensemble sea ice forecast is coupled to an independent atmospheric forecast so variability of the atmosphere causes variability of sea ice). The sea ice spread declines after September as the refreeze begins. With assimilation the ensemble members tend to be more similar, since they all feel the same observations, and so collapse onto the same trajectory.

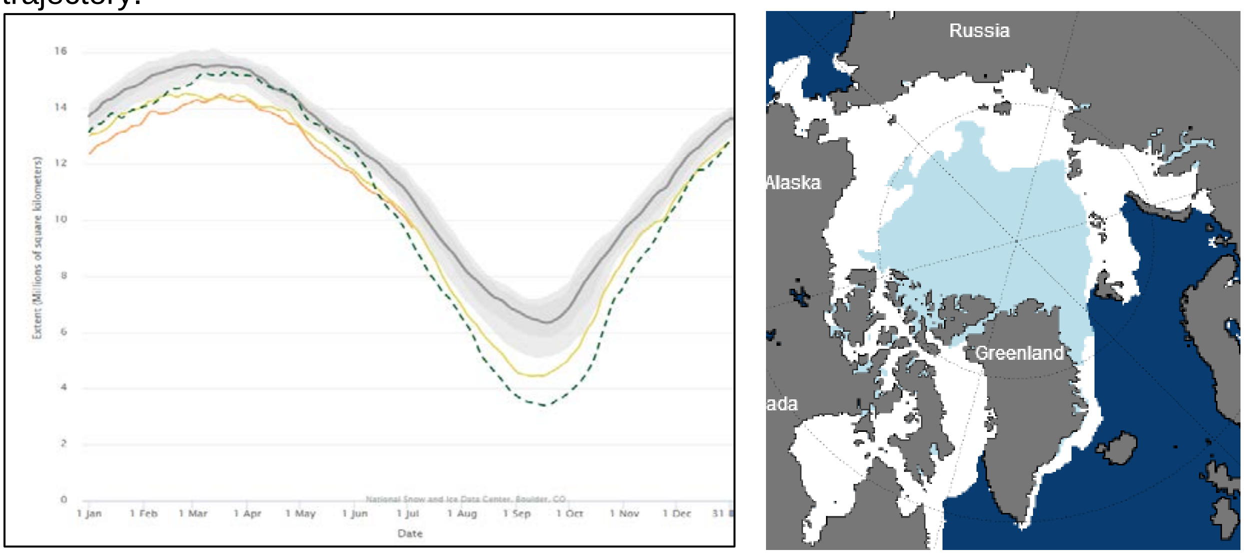

Fig. 0.1 (left) Observed record of Arctic sea ice concentration for record low 2012 (green dotted), 2015 (orange), and the 30-year average seasonal cycle (black) (from NSIDC). Our year of focus, 2015, had a nearly record low sea ice concentration in April, but recovered slightly by September. (right) Observed record of Arctic sea ice concentration for May 1 2015 (white) and September 20, 2015 (light blue) (from NSIDC). Note the dramatic retreat on the Pacific side of the Arctic.

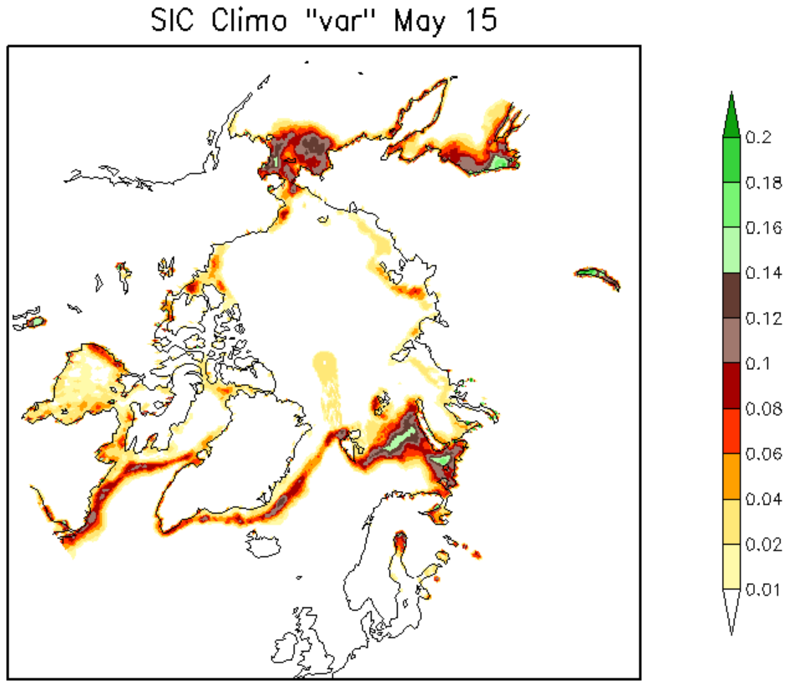

Fig. 1.1 Forecast error of sea ice concentration for one of a number of experiments begun on 1May, 2015. Bright colors indicate elevated error. Concentration of error at the mean edge of the sea ice is what we expect to happen if the system is working correctly. Note the high error in the Sea of Okhotsk where SIS1 produces excess sea ice.

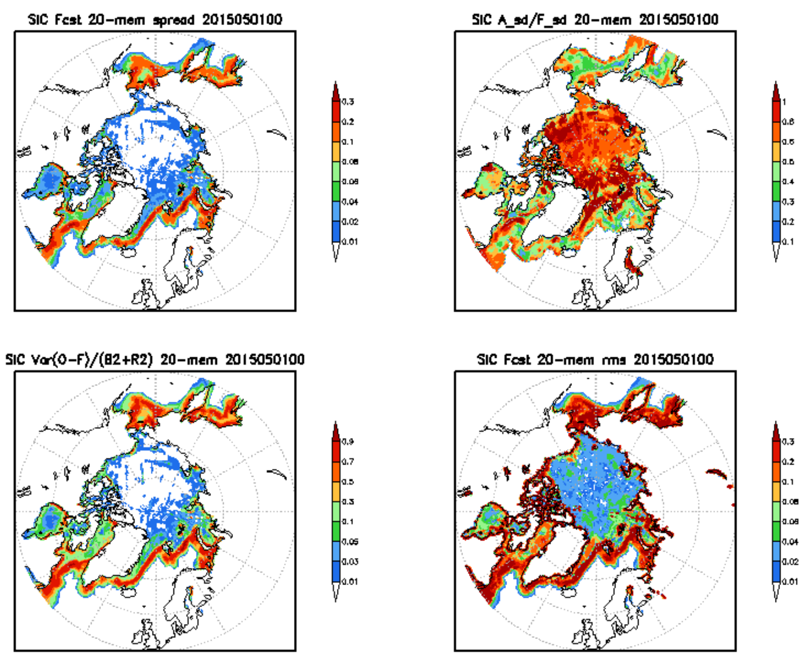

Fig. 2.1a Initial statistics (May 1, 2015) from EXPT 2.1 showing (clockwise from upper left) the sea ice concentration (0-1), ratio of the analysis to forecast sea ice concentration standard deviation, sea ice concentration forecast, and normalized sea ice concentration observation minus forecast variance.

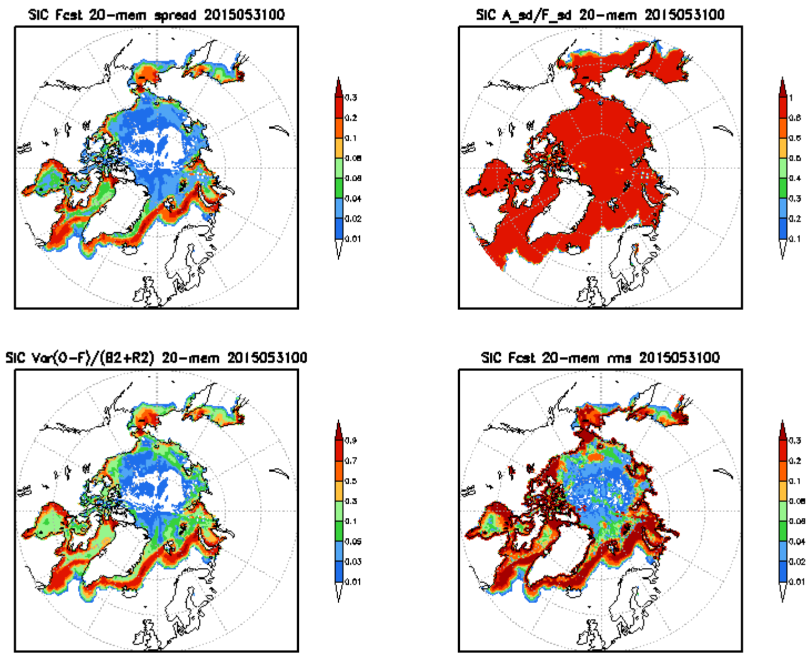

Fig. 2.1b Initial statistics (May 1, 2015) from EXPT 2.2 showing (clockwise from upper left) the sea ice concentration (0-1), ratio of the analysis to forecast sea ice concentration standard deviation (uniform since there is no updating), sea ice concentration forecast, and normalized sea ice concentration observation minus forecast variance.

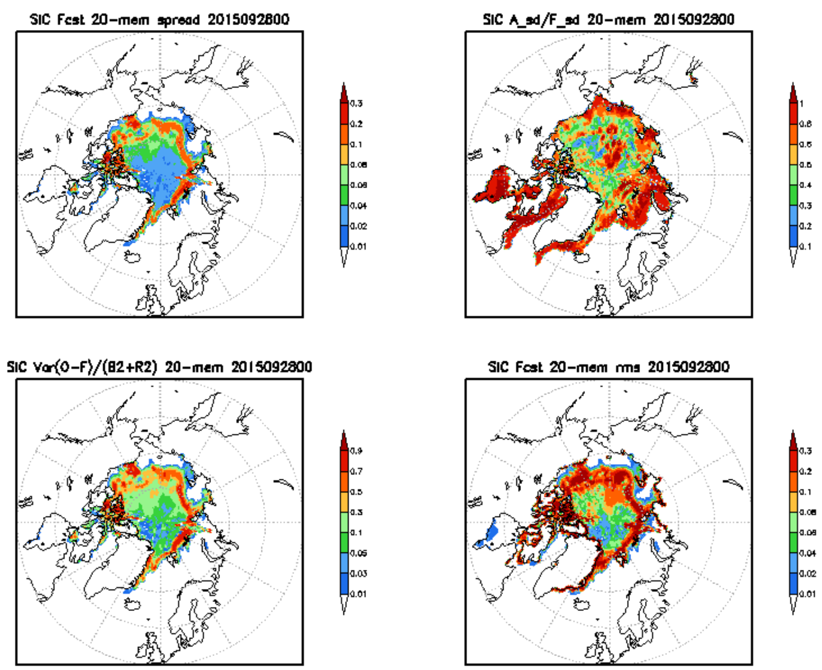

Fig. 2.2a Statistics (September 28, 2015) from EXPT 2.1 showing (clockwise from upper left) the sea ice concentration (0-1), ratio of the analysis to forecast sea ice concentration standard deviation, sea ice concentration forecast, and normalized sea ice concentration observation minus forecast variance.

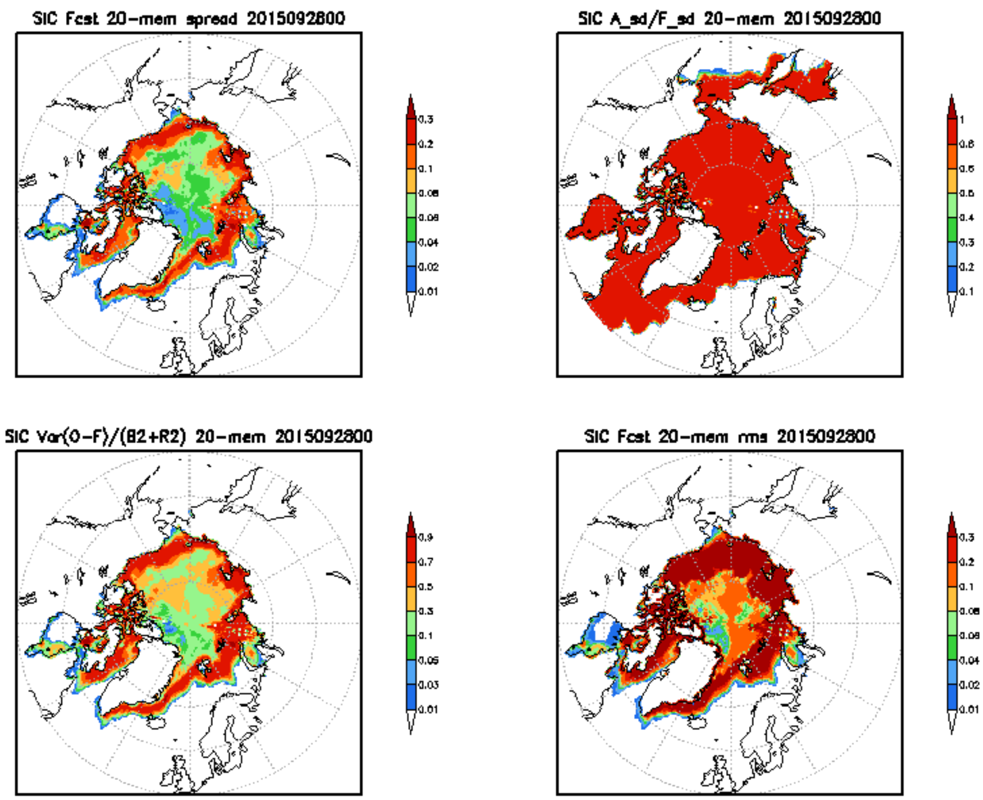

Fig. 2.2b Statistics (September 28, 2015) from EXPT 2.2 showing (clockwise from upper left) the sea ice concentration (0-1), ratio of the analysis to forecast sea ice concentration standard deviation (constant), sea ice concentration forecast, and normalized sea ice concentration observation minus forecast variance.

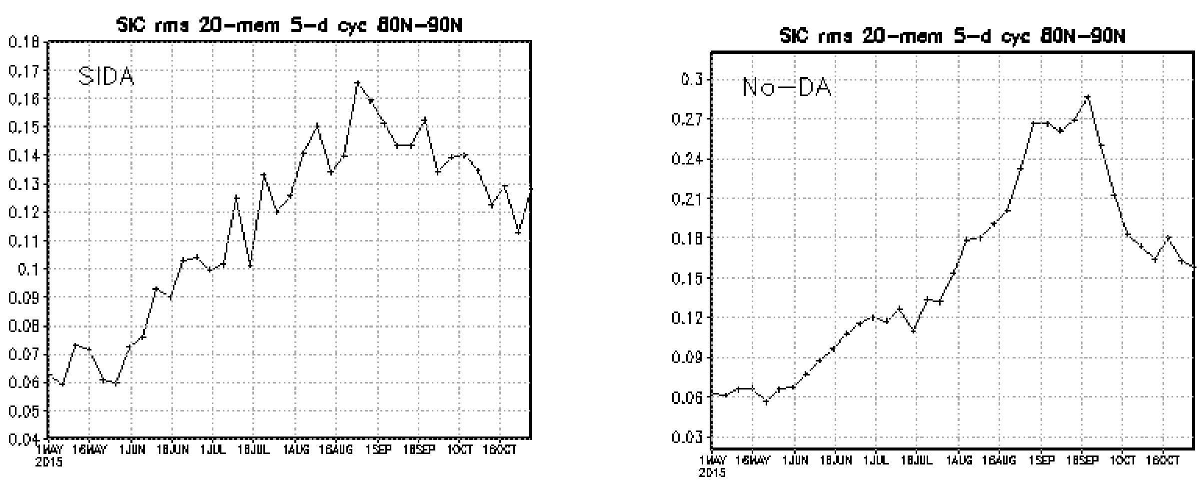

Fig. 2.3 Comparison of spread of the 20 member ensemble for experiment 2.1 (left) and 2.2 (right) with time in the deep Arctic (80-90N). Note the generally smaller spread when assimilation is applied. The spread declines after September when the refreeze begins.

4. Highlights of Accomplishments

As pointed out above, the main focus of this project was implementation of a software suite.

- Implementation of the LETKF ensemble Kalman Filter to assimilate sea ice within the coupled CFSv2 architecture.
- Developing methods to avoid the collapse of the ensemble spread, thus ensuring that the system works as designed.
- Testing the seasonal forecast system in CFSv2 during a test period beginning May, 2015.
- Exploring sensitivity to numbers of ensemble members
- Exploring sensitivity to atmospheric model resolution.

5. Transitions to Applications

The future version of CFS is now leading to the Next Generation Global Prediction System (NGGPS). NGGPS will involve several changes from the CFSv2 system which has been the focus of this grant. The ocean model will be upgrades to MOM6. The sea ice model will be upgraded to CICEv5. Finally, instead of LETKF our understanding is that moving forward we will be using a slightly different ensemble Kalman Filter that is consistent with the filter used in the atmosphere. Some features of the current project can be directly carried forward. Others, such as the specific software associated with the models, will require some rewrite and testing.

6. Estimate of current technical readiness level of work

The project has completed TRL 5 (Successful evaluation of system) and TRL 6 (Demonstration of a prototype system)

7. Publications from the Project

No publications have come from this project as of the writing of the report.

8. PI Contact Information

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Cumulative net outcomes and impacts of the project, as of the writing of the report

This grant was primarily focused on system software implementation and testing a complete coupled atmosphere/ocean/sea ice forecasting system based on the current CFSv2. The grant allowed us to implement the complete system, including sea ice assimilation and conduct ‘real world’ testing. The specifics of this system are now scheduled to be replaced as NOAA upgrades to the new NGGPS coupled atmosphere/ocean/sea ice forecasting system. However many of the findings will apply equally to the new system. These include the need to deal with the collapse of the sea ice ensemble variance, the need for recentering, and the usefulness of conducting tests on a system with a lower resolution, and thus less expensive atmosphere.