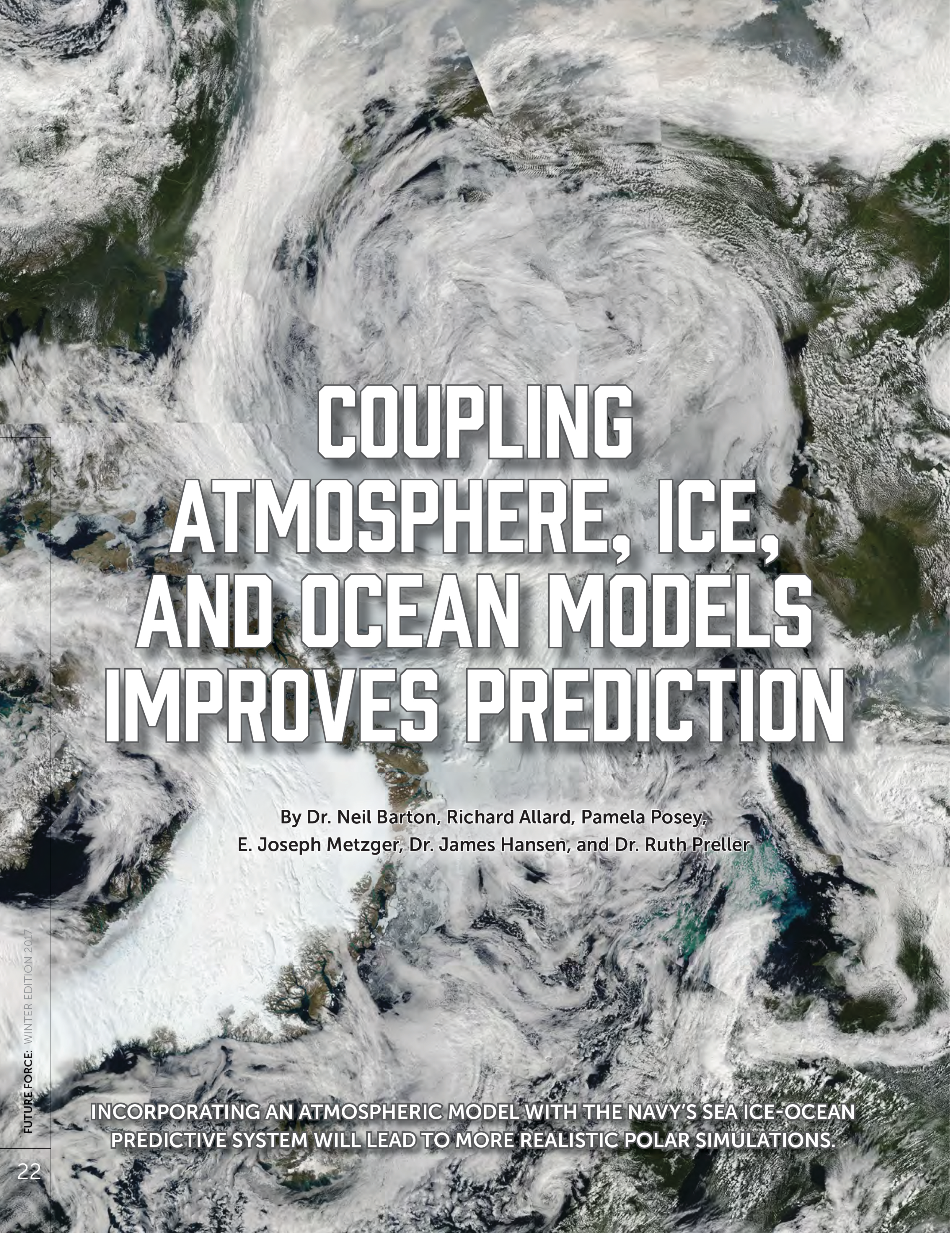

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COUPLING ATMOSPHERE, ICE, AND OCEAN MODELS IMPROVES PREDICTION

By Dr. Neil Barton, Richard Allard, Pamela Posey, E. Joseph Metzger, Dr. James Hansen, and Dr. Ruth Preller

INCORPORATING AN ATMOSPHERIC MODEL WITH THE NAVY'S SEA ICE-OCEAN PREDICTIVE SYSTEM WILL LEAD TO MORE REALISTIC POLAR SIMULATIONS.

The Arctic is a challenging environment to simulate and predict. The dynamic sea ice surface is strongly connected to the overlying atmosphere and its underlying ocean. The link between these three Earth systems is strongest at the surface, which is where naval forces typically operate. The US Navy has benefited from world-leading Arctic sea ice and ocean predictions systems developed at the Naval Research Laboratory (NRL), such as the Polar Ice Prediction System, the Arctic Cap Nowcast/Forecast System, and, more recently, the Global Ocean Forecasting System (GOFS) 3.1, which provides global coverage of ice prediction. These sea ice prediction systems are driven by atmospheric forecasts, but no information is exchanged from the sea ice-ocean system to the atmosphere. NRL is now adding a dynamic atmosphere to these world-leading sea ice prediction systems, resulting in a more realistic representation of the earth system and new prediction capabilities.

The importance of adding a dynamic atmosphere to the sea ice and ocean prediction systems is shown by an Arctic storm that occurred in August 2012. This storm brought warm and windy conditions to regions of the Arctic that aided in accelerating sea ice melting. Over the course of three days, about 77,200 square miles of sea ice (equivalent to the size of Nebraska) melted each day. Many factors affect sea ice loss, such as temperature, winds, and sea ice thickness, and each storm may not have such a pronounced effect as the 2012 storm. To understand and predict future storms, a modeling system that is able to simulate the dynamic interactions of sea ice, atmosphere, and ocean is needed.

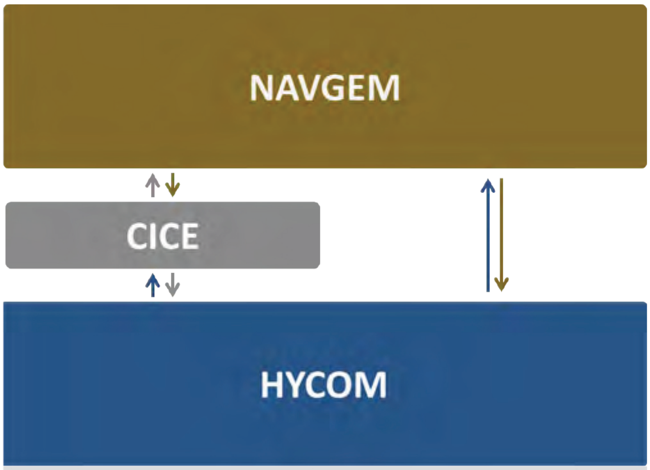
Current operational atmospheric-only and sea ice-ocean predictions extend out to only seven days. Adding an atmospheric model component to the sea ice and ocean prediction systems enables a capability of long-range predictions for the first time. As highlighted in the Navy's Arctic Roadmap of 2014, naval operations are expected to increase in the Arctic, and sea ice forecasts longer than seven days are required to provide commanding officers with ample time to plan how to safely traverse the Arctic. A forecast model that simulates sea ice, atmosphere, and ocean in one modeling system is essential for these long-range forecasts.

Development Based on Current Systems

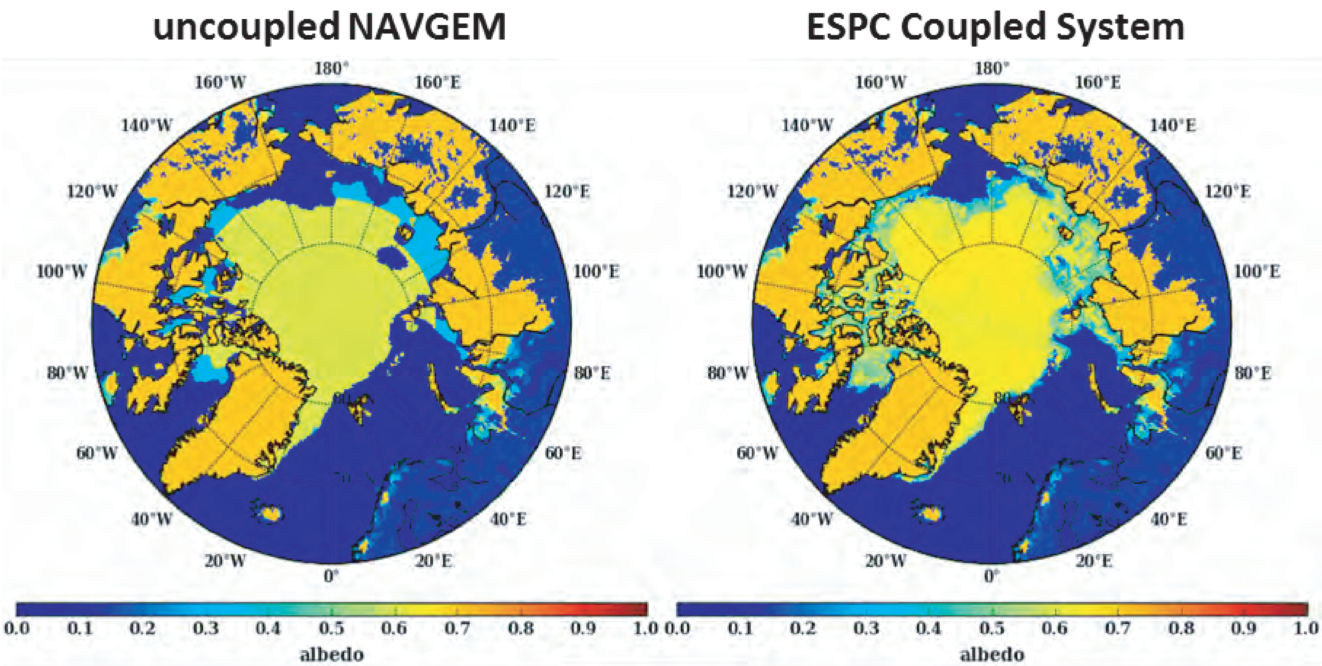
Scientists from NRL's marine meteorology and the oceanography divisions are developing a new modeling system to predict Arctic sea ice, atmosphere, and ocean conditions within one system, as part of the Navy Earth System Prediction Capability (ESPC) program sponsored by the Office of Naval Research. Historically, NRL's oceanography division developed the ocean and sea ice prediction systems (which did not include an active atmosphere), and the marine meteorology division developed the atmosphere prediction systems (which did not include active sea ice and ocean models).

Though the ESPC system is a new paradigm for Navy predictions, this model framework largely uses existing operational or preoperational systems. The ESPC model components include: the Los Alamos National Laboratory Community Ice Code (CICE) for sea ice prediction, the Navy Global Environmental Model (NAVGEM) for atmospheric prediction, and the Hybrid Coordinate Ocean Model (HYCOM) for ocean prediction. All of these component models are currently used in naval operations, but not together as one system.

Initial developments in the ESPC system focused on how the Navy's mature models communicate with each other in one system framework. Running the models in a manner where they communicate with one another is called coupled modeling. New code development for coupling between mature models is the major part of a national ESPC effort, and NRL uses tools similar to those of other national agencies (such as



Schematic of the Navy Earth System Prediction Capability global coupled model. The Navy Global Environmental Model (NAVGEM) is used for the atmosphere, the Community Ice Code (CICE) is used for sea ice, and the Hybrid Coordinate Ocean Model (HYCOM) is for the ocean. The arrows represent variables being communicated to and from each model. This results in a fully coupled model. The three systems are currently used in naval operations as uncoupled models.



The currently uncoupled NAVGEM uses simple static sea ice properties with the surface albedo being constant (left figure). In the coupled model system, sea ice properties are from the sea ice model, CICE, which are much more sophisticated and result in more realistic sea ice properties (right figure).

the Department of Energy, the Air Force, and others) to allow communications between models. In particular, NRL is using the National Unified Operational Prediction Capability (NUOPC) code, which is based on tools developed for the Earth System Modeling Framework.

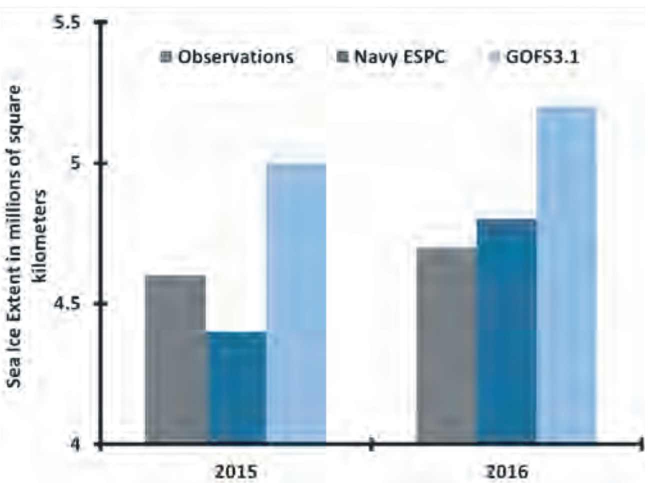
For communication between models, the NUOPC tools are added to the mature models, and minimum updates are needed to the mature models. The inclusion of these tools does not affect how the mature models run in a noncoupled mode, but it allows for models to exchange variables when they are coupled. For example, in the Navy ESPC system, the sea ice is predicted in CICE and then passed to NAVGEM and HYCOM.

Coupled Modeling Benefits Predictions

A benefit of coupled models is that the atmosphere model uses a more realistic representation of sea ice and ocean, while a more realistic atmosphere is used by the sea ice and ocean models. For example, in NAVGEM, sea ice concentrations stay constant throughout the seven-day forecast. In the Navy ESPC system, the atmosphere sees the changing sea ice concentrations predicted by CICE. Of course, more properties than sea ice concentration are passed to NAVGEM when run within the Navy ESPC system. For example, the albedo of sea ice is an important driver of the surface energy budget. The albedo of sea ice with fresh fallen snow is very high (0.87), reflecting much of the incoming solar radiation, while melt ponds over the sea ice have a lower albedo, allowing solar radiation to be absorbed within the melt pond and promote additional melt. Within the Navy ESPC system, CICE calculates surface albedo using a much more sophisticated method compared to NAVGEM on its own. This leads to more realistic values of surface albedo in NAVGEM and aids in better predictions across systems.

In a coupled modeling system, the interaction between each model is better represented compared to uncoupled models. As one might expect, the movement of sea ice is very much connected to near-surface winds. In the current Navy operational sea ice and ocean models, atmospheric near-surface winds are not altered when there are changes in the sea ice or ocean. In the Navy ESPC system, atmosphere near-surface winds from NAVGEM take into account multiple factors, including variables from the sea ice and ocean simulations, resulting in a better representation of movement of ice from near-surface winds. A need for a better representation between near-surface winds and ice movement has been noted in the Navy's 2016 Arctic Ice Exercise debrief, which stated that "models need more information for … ice … movement resulting from wind stress."

A significant benefit from the Navy ESPC modeling system is the ability to forecast sea ice at time scales greater than current operational forecasts. Presently, NAVGEM and GOFS 3.1 forecasts occur out to seven days. Within this time frame, realistic forecasts are obtained without coupling variables between the systems. When performing longer forecasts, the sea ice, atmosphere, and ocean need to change at the same time consistently with each other. For example, realistic Arctic atmosphere predictions can be obtained when keeping sea ice constant for seven days. If a month's forecast is required, however, keeping sea ice characteristics constant would generate a fair amount of error as sea ice can change substantially over a 30-day period.



Predictions of the September Arctic sea ice extent for 2015 and 2016 from the initial Navy ESPC coupled model and GOFS 3.1 for the Sea Ice Prediction Network international model inter-comparison program. The new Navy ESPC system predicted September Artic sea ice extent two months in advance with slightly better accuracy than the current system for these two years.

Long-range sea ice predictions have been produced using the Navy's ESPC coupled system in 2015 and 2016 through an international effort called the Sea Ice Prediction Network (https://www.arcus.org/sipn) to forecast the September minimum Arctic sea ice extent months in advance. The Navy ESPC model performed well and was comparable with the more mature Navy GOFS 3.1 and other international models. The September sea ice extent in 2015 was 4.6 million square kilometers (1.77 million square miles), and from runs starting in June, the Navy ESPC system predicted 4.4 million square kilometers and the GOFS 3.1 system predicted 5 million square kilometers. In 2016, the September sea ice extent was 4.7 million square kilometers, and the Navy ESPC system and GOFS 3.1 system predicted 4.8 and 5.2 million, respectively.

Next Steps

The Navy ESPC model is not expected to be fully operational until the 2020s, with initial operational capability expected at the end of 2018. Research and development is currently being performed to increase the fidelity of the modeling system. NRL researchers are developing the model for long-range predictions and wisely using data near the surface to initialize the atmosphere, sea ice, and ocean models together. Different physical processes may control the accuracy for coupled longer-range forecasts compared to the current short-range forecasts, and the current methods in which the stand-alone models simulate physics need to be tested and possibly updated for these long-range forecasts. Ensembles, or parallel execution of multiple similar forecasts, are essential when examining predictions greater than seven days. These ensembles aid in characterizing the forecast errors or "uncertainties" and can be used to quantify risk assessment, and new techniques to best characterize forecast uncertainty are currently being examined. NAVGEM and GOFS 3.1 have separate methods for how observations are used to initialize model simulations. Techniques to communicate model initialization across the atmosphere, sea ice, and ocean are currently being developed.

The Navy's ESPC modeling system will supply Arctic predictions across multiple time scales (from days to months) and Earth systems (sea ice, atmosphere, and ocean). For the first time in Navy operations, Arctic predictions for atmosphere, sea ice, and ocean will be produced within one modeling system enabling the Navy to prepare for Arctic operations from days to months ahead.

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