Investigating Arctic Cyclone Earth-System Interactions with a Global Coupled Model using Coupled Data Assimilation

1 Background

NOAA's 2019 Arctic Report Card recently pointed out the continued and increasing risk to Arctic ecosystems and communities while warming and sea ice decline continues in Arctic regions. The Arctic has been warming at more than twice the global rate, with October 2018-August 2019 noted as the second warmest since 1900. The Arctic sea ice extent minimum in 2019 tied for second lowest since records begin, and sea ice extent continues to not be well represented in global models – even those including Earth-system feedback processes [3, 7].

Predictability of important Arctic processes – specifically coupled feedbacks associated with summer sea ice extent – is impacted directly by synoptic-scale Arctic cyclones (ACs). Located poleward of 60°N, ACs can grow to sizes ($\sim$5000 km) greater than expected for balanced flow based on Rossby radius theory [1]. ACs are an important weather-scale feature to understand in medium to climate long simulations, and the mesoscale processes that control AC size and lifetime remain unclear. In order to understand the evolution of ACs and sea ice in the future, global models must be able to accurately represent the coupled nature of the atmosphere and sea ice and their feedbacks. Today, some of even the most sophisticated coupled global models (CGMs) do not reproduce the observed characteristics of present day ACs. One approach to improving representation of ACs is through coupled data assimilation (DA) [9]. A better understanding of AC-related processes is critical not only for climate projections, but also for understanding their impacts on mid-latitude weather.

Toward this goal, improved understanding of Earth-system model coupling is needed to accurately exchange relevant information between components and improve overall performance of CGMs. In order to expand process-based knowledge and learn about the intricate physical linkages between Earth-system components in the Arctic, specifically those related to ACs, a reliable tool capable of accurately representing such interactions is needed. This study will use a coupled CGM (including ocean, atmosphere, and sea ice components) and ensemble DA to evaluate AC sensitivities to DA coupling. This work can contribute not only to CGM development, but also to research areas where improved process-based understanding can be powerful.

2 Proposed Research

2.1 Global Coupled Modeling System

The Community Earth System Model (CESM) is a fully-coupled community global model that provides state-of-the-art modeling focused on climate scales. The modeling components include various models representing the ocean and its waves, rivers, land, sea ice, and land-ice interactions. Since my goals require the accurate interaction of Earth-system components at short- to extended-range time scales, I propose to use a version of CESM that has been implemented by my current research group at the University of Oklahoma, which replaces the default CESM hydrostatic Community Atmosphere Model with the Model for Predication Across Scales (MPAS)-A, subsequently referred to as MPAS-CESM. MPAS is a variable resolution, nonhydrostatic atmospheric model with which I have previous experience through work exploring the predictive benefit of a smoothly refined mesh with higher horizontal resolution over the Arctic region. Employing a non-hydrostatic core with high resolution grids enables us to resolve mesoscale features over the Arctic, which is important for the proposed study of ACs. While our research group is the first to employ this configuration, and more development is needed before it can be used as a research tool for the general community, I have the necessary skills and experience to leverage it to use state-of-the-art methods to evaluate forecast sensitivity to DA coupling in this system, such as the mean initial tendency and analysis (MITA) increment method [2]. Here, this method will be applied to gain process understanding of coupling between Earth-system components related to ACs. I have used this approach before to link a bias in the upper troposphere and lower stratosphere (UTLS) in an MPAS DA cycling system to poor moisture initialization. Since the necessary modifications to use this method have already been made to MPAS, relatively little effort is needed to port it to MPAS-CESM.

Evaluation of model tendencies can provide insight into physical Earth-system processes but only when interacting tendencies are not overshadowed by spin-up, which is generally on the order of the slowest timescale in a coupled system – in our case, ocean processes. To alleviate spin-up issues, MPAS-CESM will be initialized using the CESM Large Ensemble (CESM-LE), which provides a consistent dynamical coupling between all Earth-system components in the initial state. The CESM-LE uses the same modeling components as our modeling system described here except MPAS-A, as described above. Thus, the atmosphere will need spin-up time, but the more expensive ocean system is initialized from an equilibrium state. However, a disadvantage to this method is the possibility for quite large analysis errors resulting in relatively large short-term simulation errors, thus motivating the need to use coupled DA. Ensemble DA proposed in this study will use the ensemble adjustment Kalman filter (EAKF) system that employs the National Center for Atmospheric Research (NCAR) Data Assimilation Research Testbed (DART), an open-source community DA framework with support for numerical models including MPAS and CESM. I have developed an ensemble-based data assimilation system for atmospheric observations using the DART implementation of the EAKF for both Arctic and the Antarctic regions with MPAS and semi-operational NCAR Antarctic Mesoscale Prediction System. The EAKF is ideal for data sparse regions [e.g., 10] and exhibits competitive analysis skill with respect to observations and operational global analyses for mesoscale applications [8]. Together, the complete system of MPAS-CESM using DART to perform DA for Earth-system components is subsequently referred to as MPAS-CESM-DART.

Table 1: *Proposed numerical modeling experiments are summarized here. Row-shading indicates the complexity of global modeling system.*

Experiment name	**Modeling component(s)**	**DA component(s)**
E1 (Control)	MPAS-A	Atmosphere only
E2	MPAS-CESM	Atmosphere only
E3	MPAS-CESM	Atmosphere, Sea ice
E4	MPAS-CESM	Atmosphere, Ocean
E5	MPAS-CESM	Atmosphere, Sea ice, Ocean

2.2 Description of Approach

To evaluate the sensitivities of ACs to coupled DA within various Earth-system components, I propose a series of five experiments (E1-E5) outlined in Table 1. All experiments will be cycled during a period centered on the THINICE (NSF OPP #1918557) field campaign, providing special observations for verification. The proposed experiments use a model hierarchy approach, where additional modeling components are included systematically to account for intricate feedback and interaction between the atmosphere and other Earth-system components.

First, E1 will use MPAS-DART to complete a simulation with cycled ensemble atmosphere DA. This experiment serves as a control showing the baseline performance of a global Earth-system model that does not include coupled approaches. It is important to note that development and testing on this MPAS-DART configuration has already been completed dur-

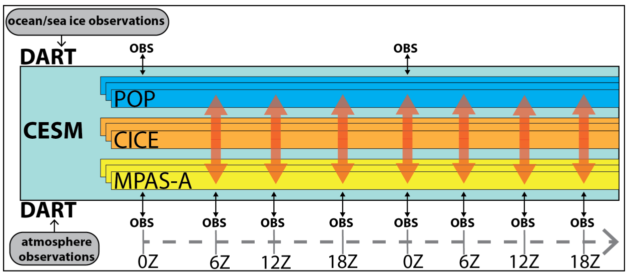

Figure 1: *Diagram of the workflow for the MPAS-CESM-DART system in a "weakly" coupled configuration. In this setup, MPAS-A is updated every 6 h while POP and CICE is updated daily. The red arrows indicate information being shared between earth system components through coupling. Diagram was adapted from [5]*

ing my PhD work, so this phase will include only the initial configuration steps and the simulation. Next E2-E4 will expand the modeling configuration to include all Earth-system components in MPAS-CESM while varying which components include DA, isolating the sensitivity from each component during cycling. The framework for these experiments has been laid out in previous work [4–6, 11], which will allow these experiments to move forward quickly. Finally, atmosphere, sea-ice, and ocean components will all include DA in E5 to evaluate the fully coupled configuration. The isolation of the experiments will allow investigation into the coupling sensitivities associated with ACs when DA is applied to different Earth-system components. Additionally, physical processes and coupled feedbacks associated with ACs will be investigated by comparing results across experiments, helping both to expand process-based knowledge and determine which processes are most impactful to CGM representation of Arctic environments.

The assimilation workflow for various components is depicted in Figure 1. These experiments will be computationally expensive. Through my graduate work, I have become familiar with NCAR's supercomputing resources. These experiments could be conducted using this infrastructure using some core hours provided to ASP post-doctoral researchers but also by requesting dedicated core hours via NCAR programs (e.g Strategic Capability) in order to maintain fair access for other researchers.

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