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Multi-scale Predictability with a New Coupled Non-hydrostatic Global Model over the Arctic Annual Report

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LONG-TERM GOALS

We are addressing scientific issues related to Arctic weather and the Arctic Oscillation. The dynamics we are focusing on begins with tropopause polar vortices, which are prevalent circulation features over the Arctic that play a major role in the evolution of surface pressure anomalies that ultimately affect sea ice distributions and climate. Furthermore, these features are multiscale with coupled dynamical processes and interactions that are poorly understood due to the limited capabilities of current Numerical Weather prediction (NWP) modeling systems. Our longer-term goals affirm the Navy's interest in next-generation global NWP systems with longer-term prediction capability through a direct application to a relevant scientific problem.

OBJECTIVES

The primary objective is to test a new atmospheric nonhydrostatic dynamical core from the Model for Prediction Across Scales (MPAS), embedded within the Community Atmosphere Model (CAM) of the Community Earth System Model (CESM), on medium to long range weather prediction (week - months) focusing on the Arctic region. In applying our primary objective to a relevant science application over the Arctic, we are also seeking to gain a better understanding of Arctic processes with potential implications of improving predictability of the Arctic system.

APPROACH

We are working with MPAS to implement a coupled MPAS-CESM modeling system to determine its ability to capture atmosphere, ocean, and sea-ice feedbacks that may be necessary for accurate

Table 1: List of major task targets and status

Major task	Target goal	Status
MPAS-A Atmosphere only	End of 2012	Operating
MPAS-CESM Atmosphere only	End of 2013	In progress
MPAS-CESM Fully coupled	End of 2014	Has not begun

prediction on the order of weeks to months. Specific experiments have been designed to examine the evolution, dynamics and predictability of summer season Arctic surface pressure anomalies that are likely associated with the dynamics of tropopause polar vortices (TPVs). During the summer, Arctic surface pressure anomalies correlate with the phase of the Arctic oscillation (AO) and the flow anomalies have a significant impact on sea ice movement and extent in the summer season. A correct representation of the ocean and of sea ice is crucial since energy fluxes between the atmosphere and ocean depend strongly on the fractional coverage of sea ice.

The Arctic environment during the summer of 2006 and 2007 was characterized by two strongly contrasting cyclonic and anticyclonic pressure and tropospheric circulation anomalies and will allow us to answer specific questions regarding its ability to reproduce the appropriate AO signatures as well as the ability to predict the evolution of weather patterns that may be important for subsequent sea ice evolution. In particular, we are examining the dynamics from a test case of a long-lived TPV and associated surface cyclone where model predictive capability may depend on accurately representing the two-way interactions between atmospheric wind and dynamic sea ice.

WORK COMPLETED

The major tasks proposed in this project and their status are summarized in Table 1. The MPAS atmospheric model (MPAS-A) has been configured to run atmosphere-only numerical simulations, and we are currently analyzing test simulations using the NCAR Nesting Regional Climate Model (NRCM) physics suite. We refer to this configuration as 'MPAS-A Atmosphere only.' Results of these tests will be summarized in the following section. A physics configuration of MPAS-A utilizing the NCAR Community Atmosphere Model (CAM) physics suite is currently being implemented, which we refer to as the 'MPAS-CESM Atmosphere only' configuration. Once this task is complete, we will perform identical experiments to those that have been performed using the MPAS-A atmosphere only configuration in order to identify the strengths and weaknesses deriving from these representations of physics over the Arctic.

RESULTS

MPAS-A Atmosphere only simulations have been performed for the entire duration of a TPV located over the Arctic Ocean from July-September 2006. Each simulation is separated by an initialization time of approximately two weeks beginning 24 July and ending 19 September. Simulations have also been performed with various initialization times for the same time period in 2007. Since a relatively strong cyclone was observed over the Arctic in 2006 and not in 2007, a greater number of experiments are performed for summer 2006 than in summer 2007 in order to identify specific sensitivities in the model's ability to reproduce the cyclone in 2006. For the remainder of this report, we will focus on highlighting the largest issues that we continue to evaluate.

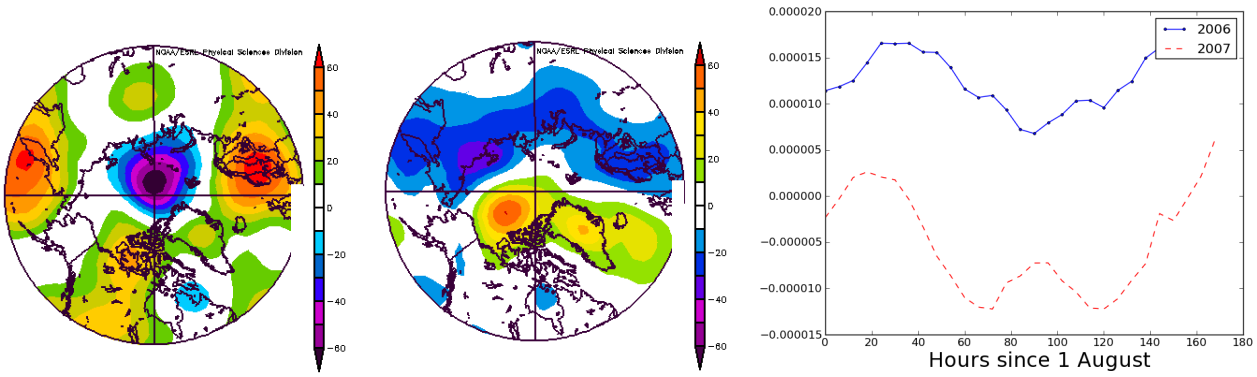

Figure 1: *500 hPa geopotential height anomalies from NCEP/NCAR Reanalysis data for June-August of (a) 2006, (b) 2007 in units of meters. (c) Absolute vorticity averaged over the Arctic for the period 1 August - 9 August during the MPAS simulations in 2006 (blue) and 2007 (red) in units of* s^{-1}*. Anomalies are defined as departures from the long-term time–mean.*

The mean 500 hPa height anomalies averaged over the summer of 2006 and 2007 from NCEP/NCAR Reanalysis (Kalnay and collaborators 1996) show that 2006 was characterized by anomalously low 500 hPa geopotential heights with implied high vorticity while 2007 was characterized by anomalously high 500 hPa geopotential heights with implied low vorticity over the central Arctic region (Fig. 1a,b). A time series from corresponding MPAS simulations during 2006 and 2007 for a week-long period starting 1 August shows that absolute vorticity is substantially greater over the central Arctic in 2006 than in 2007, which indicates that MPAS forecasts are reproducing the correct mean tropospheric circulation patterns (Fig. 1c). While the mean patterns are favorable regarding the ability of MPAS to encapsulate the overall patterns of these two summers, it does not provide insight into the predictive capabilities of forecasting individual weather systems over long periods of time. The accurate prediction of individual weather systems is likely an important component in accurate sea ice forecasts, given that particular cyclones have been shown to have a substantial impact on summer sea ice breakup over the Arctic (e.g. Simmonds and Rudeva 2012; Parkinson and Comiso 2013; Zhang et al. 2013). To address this aspect, we next summarize some highlights of our experiments in forecasting the strength and location of an individual TPV located over the Arctic during much of the summer during 2006.

Two MPAS grids have been designed to isolate the effects of the MPAS numerical solutions to horizontal resolution (Fig 2). In the mesh we refer to as ‘x4,’ cell spacing in the region of finest resolution is lower by a factor of approximately four. In ‘x4’, the finest resolution is located over the Arctic, where cell spacing is uniformly ∼25-km poleward of 60°N latitude and the transition zone from fine to coarse resolution is located in the Northern Hemisphere midlatitudes. In the mesh that we refer to as ‘x7,’ cell spacing in the region of finest resolution is lower by a factor of approximately seven. The region of finest resolution in this mesh is expanded to include both the Arctic and Northern Hemisphere midlatitudes, roughly poleward of 10°N latitude, such that the transition zone from fine to coarse resolution is located outside the most active areas where lower latitude waves potentially influence polar processes.

Some key experiments that highlight both the sensitivity to our choice of horizontal resolution and physics are listed in Table 2 for the 2006 cyclone. To systematically evaluate the ability of MPAS to predict the evolution of this cyclone, we compute differences from the MPAS forecasts with Climate

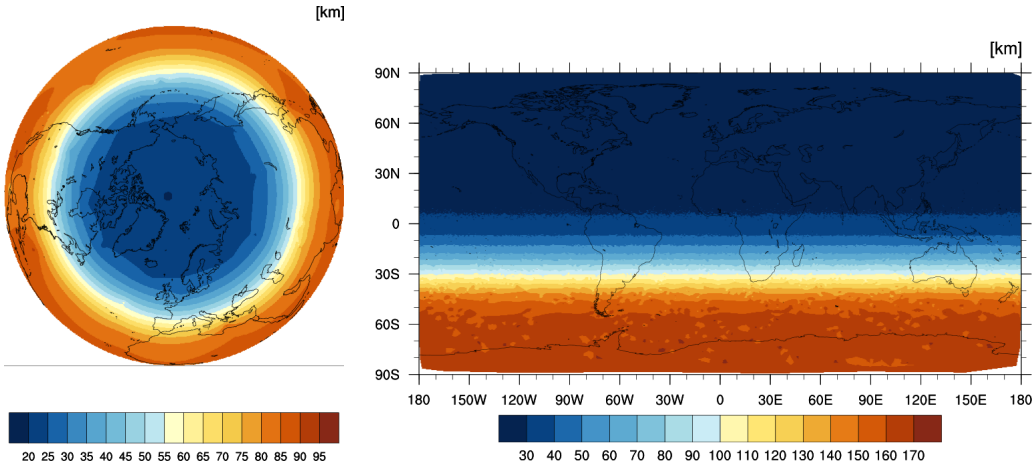

Figure 2: *MPAS meshes with the horizontal grid spacing (units of km) between cell centers for domains with relatively fine resolution (a) over the Arctic only and (b) over the entire Northern Hemisphere. The range of horizontal cell spacing is from 25-92 km in (a) and 25-175 km in (b). Since the ratio of coarse to fine cell spacing is approximately 4 in (a) and 7 in (b), these meshes are subsequently referred to as 'x4' and 'x7' for brevity.*

Table 2: Summary of select experiments for 2006 cyclone.

Experiment name	Cell spacing	Physics test
x4_t	Transition zone in midlatitude Northern Hemisphere	Tiedtke cumulus
x4_kf	Transition zone in midlatitude Northern Hemisphere	Kain-Fritsch cumulus
x7_t	Uniform high resolution over midlatitude Northern Hemisphere and Arctic	Tiedtke cumulus
x7_kf	Uniform high resolution over midlatitude Northern Hemisphere and Arctic	Kain-Fritsch cumulus

Forecast System Reanalysis (Saha and collaborators 2010) data for forecasts initialized approximately every 2 weeks through the duration of the cyclone lifetime; we consider these differences as the MPAS forecast error. Cyclone intensity errors are shown in Fig. 3a while cyclone location errors are shown in Fig. 3b. During the early stages of cyclone development, MPAS short-term intensity forecasts exhibit large differences from CFSR reanalyses (Fig. 3a). Closer examination shows that during this stage of cyclone development, it is located over the coastline of Siberia and an unfrozen section of the Arctic Ocean (Fig. 4). These differences indicate that further testing needs to be performed with MPAS to evaluate whether surface fluxes are appropriately forcing the lower atmospheric boundary layer. This initial intensity error subsequently leads to large track errors later during this particular simulation (Fig. 3b).

In comparison, forecasts initialized during the first week of August are characterized by relatively low intensity and track error. Our initial experiments for this time period resulted in both large errors as well as a strong sensitivity to the choice of cumulus parameterization. We found that errors were substantially reduced to what is shown in Fig. 3 after a change was implemented in our version of the

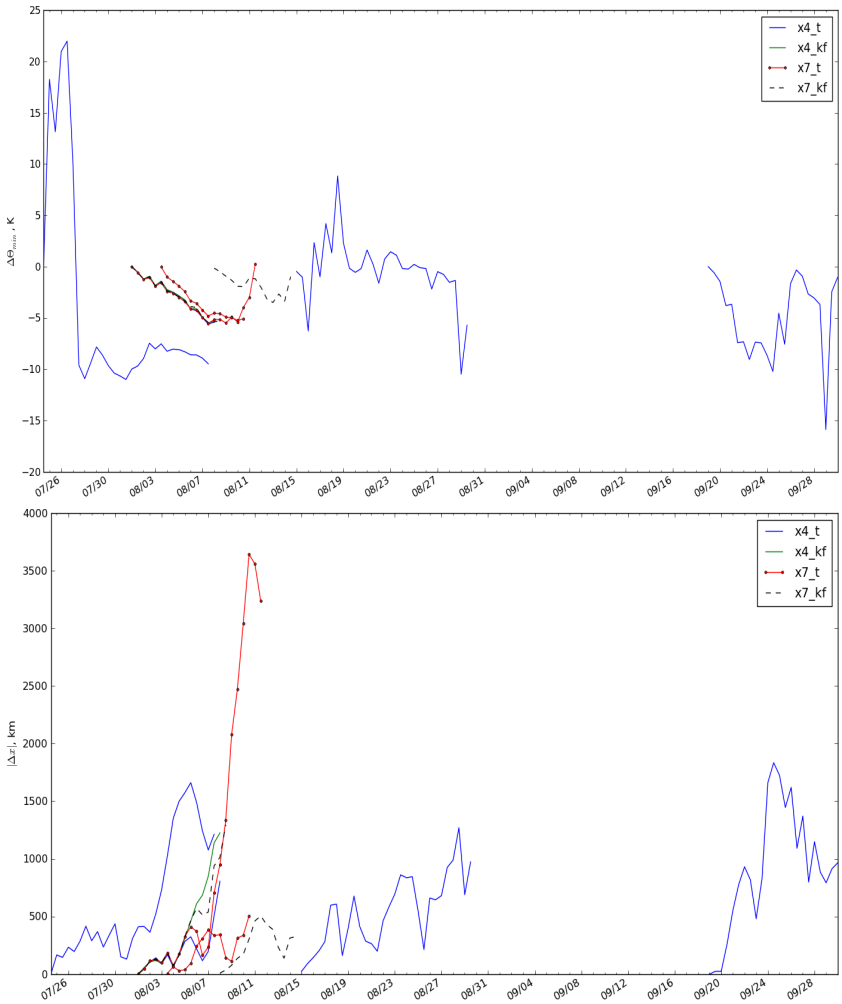

Figure 3: *TPV core value error and track error vs. initialization and experiment. Vortex (a) intensity error in Kelvin and (b) track root mean square error in kilometers diagnosed on the tropopause with potential temperature for various initialization times and experiments. The date of the verifying forecast times are listed on the abscissa.*

longwave radiation physics scheme (Cavallo et al., 2011) that has been shown to reduce forecast errors in the Weather Research and Forecasting (WRF; Skamarock et al. 2008) model. Fig. 5 highlights the consistency between the choice of MPAS physics in the simulation initialized 1 August 2006. However, while cyclone intensity forecast errors are relatively low for this initialization time, track errors grow large for forecasts beyond 7d. We attribute this to the misrepresentation of a midlatitude wave packet, that grows upscale from convective heating in the North Atlantic Ocean (Compare panels with the anticyclonic feature located in Northern Norway in CFSR in Fig. 5a). Due to the differences in the extent this wave into the Arctic between MPAS and CFSR, the impact of the circulation from this wave onto the tropopause cyclone also differed, resulting in the larger track error. Since the convection that initiates the wave packet that erroneously influences the tropopause cyclone occurs in the transition zone of the MPAS x4 mesh (cell spacing is ∼65-km in this region), we perform tests for this case on the x7 mesh to examine the possibility that there is a sensitivity in horizontal resolution where the convection is located. Tests reveal that there is very little sensitivity to whether resolution is uniformly

fine or whether the convection occurs in the transition region of the mesh, indicating the sensitivities derive from initial conditions rather than physics; we will continue to explore this sensitivity in the upcoming months. Forecasts from subsequent initialization times exhibit comparatively less forecast error. In order to provide some additional benchmarks for comparison, we are currently designing a configuration of the WRF model where tests will be performed in parallel to those experiments performed here. Additionally, we plan to evaluating MPAS forecasts with the Global Forecasting System (GFS) model forecasts.

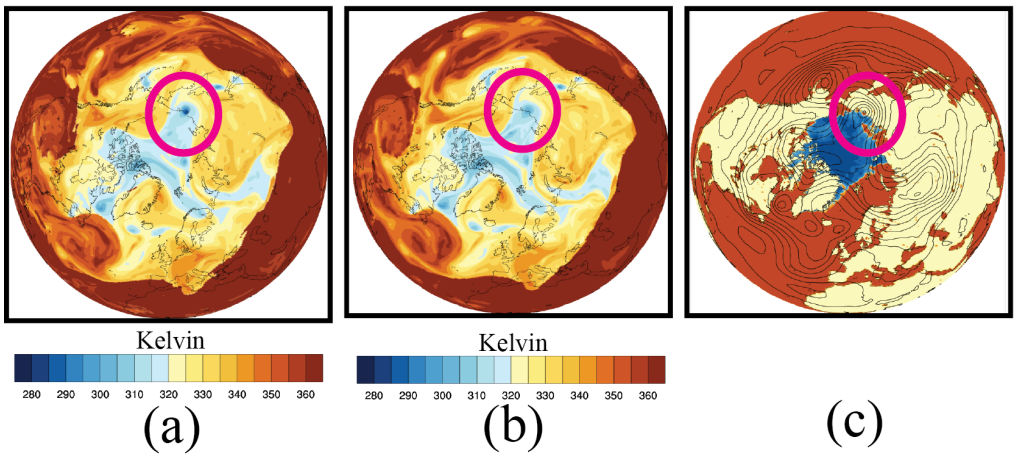

Figure 4: *Initialization from 12 UTC 24 July, 12-h forecast valid 00 UTC 25 July. 12-h forecast of tropopause potential temperature valid 00 UTC 25 July from (a) CFSR and (b) MPAS with units of Kelvin. (c) Corresponding MPAS sea ice fraction (red for grid cells with no sea ice, blue shadings for grid cells with sea ice) and 500 hPa geopotential height contours in meters. The magenta circle shows the location of the tropopause polar cyclone.*

IMPACT/APPLICATIONS

The MPAS modeling system will potentially be useful tools for longer-term prediction needs. Such applications are those pertaining to regional climate predictions or those where global and/or coupled interactions can have significant impacts on forecast skill. Examples of such processes include the Madden-Julien Oscillation, the El Nino Southern Oscillation, the Arctic Oscillation, and sea ice variability, where longer-term prediction is required beyond the range of significant forecast skill capability exhibited by traditional NWP models. Furthermore, it is not clear whether traditional Global Climate Models (GCMs) have the capability of accurate prediction of finer-scale processes, which may be crucial for predicting initial perturbations that grow upscale in time and space.

TRANSITIONS

None.

RELATED PROJECTS

None.

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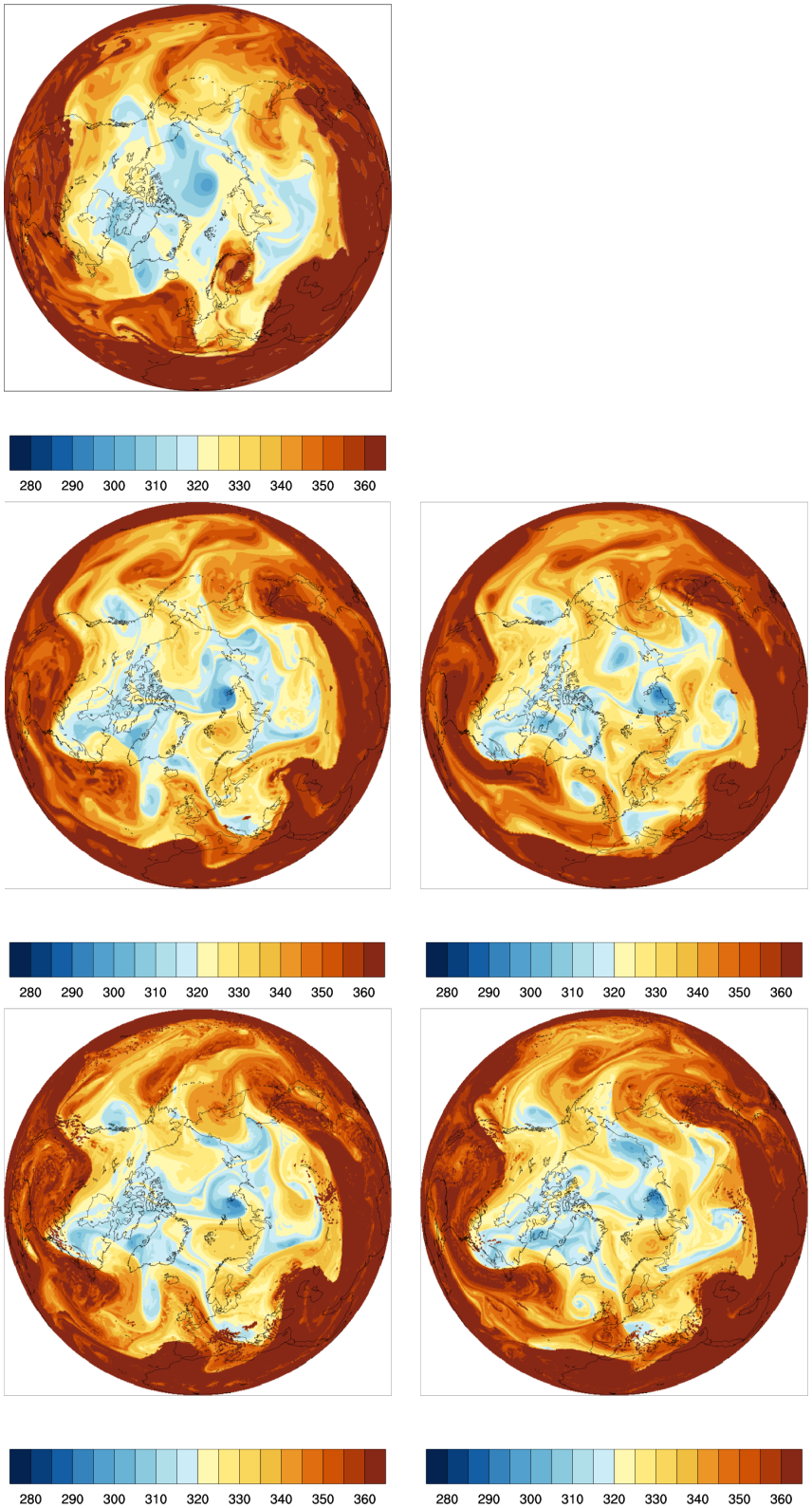

Figure 5: *Comparison of 7-day forecasts of tropopause potential temperature for forecasts initialized 1 August 2006 in (a) CFSR and in the MPAS experiments (b) x4_t, (c) x4_kf, (d) x7_t, and (e) x7_kf in units of Kelvin.*