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

Steven Cavallo
University of Oklahoma
School of Meteorology
120 David L. Boren Blvd. Suite 5900
Norman, OK 73072-7307
phone: (405) 325-2439 fax: (405) 325-7689 email: cavallo@ou.edu

William Skamarock
National Center for Atmospheric Research (NCAR)
NCAR Earth System Laboratory, Mesoscale and Microscale Meteorology Division
P.O. Box 3000 Boulder, CO, 80307-3000
phone: (303) 497-8161 fax: (303) 497-8171 email: skamaroc@ucar.edu

Award Number: N00014-121-0328

LONG-TERM GOALS

The long-term goal of this project is to gain knowledge of the role that tropopause polar vortices (TPVs) have in weather and climate prediction. We are addressing scientific issues regarding barriers that limit the capability of numerical models from accurately predicting extreme surface cyclones over the Arctic more than one week in advance. These issues involve the role that TPVs have with regard to extreme cyclones and rapid sea ice reductions over the Arctic during the summer, and the relationship that TPVs have with the Arctic Oscillation. Our study utilizes a new global, nonhydrostatic atmospheric model called the Model for the Prediction Across Scales (MPAS) to examine these multi-scale processes over the Arctic.

There is extensive knowledge of atmospheric dynamics in midlatitude regions, particularly surrounding the polar and subtropical jet streams, however there is relatively little knowledge of arctic dynamics and in particular TPVs. Although there is not much knowledge on the dynamics of TPVs, it is well-established that the atmospheric anomalies associated with them are necessary for the formation of extratropical cyclones at the surface (e.g., Kleinschmidt, 1950; Eliassen and Kleinschmidt, 1957; Petterssen and Smebye, 1971; Hoskins et al., 1985). Yet, TPVs are extremely common to the Arctic, and often have lifetimes on the order of months (e.g., Hakim and Canavan, 2005; Cavallo and Hakim, 2012). This is likely because of their relative position poleward of the polar jet stream where background flow is weaker, and because of the limited heat and moisture in their environments. These factors allow longwave radiative processes to dominate TPV intensity (Cavallo and Hakim, 2009, 2010, 2012, 2013). Although longwave radiative cooling rates are on the order of 1-2 K day$^{-1}$, such cooling rates within a TPV have a significant impact on net intensity on time scales greater than 5-7 days. Temperature anomalies in excess of 10 K imply that thermal gradients are significantly enhanced when
TPVs interact with jet streams. Thus we are working under the long-term hypothesis that TPVs are an important and active feature in atmospheric wave breaking, which is a prediction barrier in current numerical weather prediction (NWP) models on the time scales of about one week.

OBJECTIVES

Our primary objective in this project is to evaluate whether the capabilities of MPAS are beneficial for longer-term prediction of multi-scale features that include the prediction of TPVs, Arctic cyclones, sea ice, and atmospheric wave breaking. MPAS is a fully compressible, nonhydrostatic, global model that allows for local refinement of the horizontal grid to support a smooth transition in resolution from relatively coarse global mesh to finer mesh in regions of primary interest. MPAS’s smooth transition in horizontal resolution is designed to reduce complications that typically arise from traditional downscaling using nesting approaches (e.g., Ringler et al., 2011). MPAS does not require polar filtering and exhibits uniform performance over polar regions. Given these features, it is ideal for simulating multi-scale processes in a regional context. This study uses MPAS to perform simulations with several mesh configurations as depicted in Fig. 1. These different mesh configurations are designed to isolate the relative significance of resolving the different multi-scale features relevant to this project. We use these three mesh configurations, along with varying physical parameterizations to produce an ensemble that tests the predictive capability of MPAS with regard to our hypothesis. Our experimental setup is described in the following section.

Figure 1: Schematic of the MPAS C-grid horizontal discretizations that have been implemented for the current study. Comparisons are performed with (a) uniform mesh containing nearly equal cell spacing of ∼30-km globally, (b) a variable resolution mesh where cell spacing varies from ∼30-km over the Arctic Ocean to ∼60-km in lower latitudes, and (c) a variable resolution mesh where cell spacing varies from ∼30-km over midlatitude regions and ∼60-km over the Arctic region.

APPROACH

Our effort focuses on identifying the physical and dynamical processes that can improve predictability in the polar regions. Global prediction beyond one week most crucially depends on processes in polar regions (Jung et al., 2014), but these processes have yet to be identified. Our immediate hypothesis is that TPVs must be accurately resolved in order to accurately predict the extreme surface cyclones.
leading to rapid sea ice loss events. Rapid sea ice loss events are unpredictable, have been increasing in frequency, and sea ice extent during these years is often several standard deviations below what would otherwise occur from the trend of warming temperatures alone (e.g., Comiso et al., 2008; Stroeve et al., 2012, 2014). Furthermore, there is not good prediction of the extreme surface cyclones that develop just days before a rapid sea ice loss event, but prediction can be improved when assimilating upper-tropospheric observations near TPVs into the analyses used to initialize forecasts (Yamazaki et al., 2015). Minimum sea ice extent is important to predict, not just for navigational purposes, but also for subseasonal-to-seasonal prediction, because more open water increases the potential for the vertical transfer of heat and moisture from the ocean into atmosphere to change atmospheric circulation patterns during the autumn and early winter months (e.g., Budikova 2009; Deser et al. 2010; Jaiser et al. 2012; Francis and Vavrus 2012; Screen et al. 2013; Vavrus 2013).

Sea ice and TPVs are unique factors of significance in the north polar region, most critical to our understanding and likely to be co-dependent. The importance of synoptic-scale cyclones to the Earth’s climate system is well-established, particularly for their role in transporting heat, momentum and moisture from lower-latitudes to the extratropics (e.g., Trenberth and Stepaniak 2003; Eckhardt et al. 2004; Schneider et al. 2006; Boutle et al. 2011). Tropopause dynamics is important for the development of surface cyclones (e.g., Eliassen and Kleinschmidt 1957). TPVs are critical to improving predictability because they are always associated with an upper-level potential vorticity (PV) anomaly, which is a necessary feature for type B surface cyclogenesis (e.g., Petterssen and Smebye 1971), and recent observations of extreme surface cyclones have occurred in conjunction with rapid sea ice loss events (e.g., Simmonds and Rudeva 2012; Parkinson and Comiso 2013; Kriegsmann and Brümmer 2013; Zhang et al. 2013).

In order to study interactions between TPVs, sea ice, surface cyclones, and Rossby Waves, it is necessary to develop a tool capable of resolving multi-scale interactions between the Earth’s atmospheric, cryospheric, and oceanic components. A correct representation of the ocean and of sea ice is crucial during the warm season since energy fluxes between the atmosphere and ocean depend

![Figure 2: Time series of mean June, July, and August 500 hPa geopotential heights poleward of 60°N latitude (red) and March minus September sea ice extent (blue) from 1979-2014. Data are from ERA-interim reanalysis.](image)
strongly on the fractional coverage of sea ice, and thin sea ice is susceptible to forcings from the atmosphere (e.g., Rigor et al., 2002; Serreze et al., 2007). Our tool is the MPAS model, and we are ultimately seeking to add a sea ice and ocean model within the Community Earth System Model (CESM) framework. Once coupled, we expect this MPAS-CESM modeling system will have ability to capture atmosphere, ocean, and sea-ice feedbacks essential for accurate prediction on the order of weeks to months. We designed specific experiments to quantify the evolution, dynamics and predictability of Arctic surface pressure anomalies that are likely associated with the dynamics of tropopause polar vortices (TPVs). During the warm season, Arctic surface pressure anomalies correlate with the phase of the Arctic oscillation (AO) and the flow anomalies are significantly correlated to sea ice movement and extent (Fig. 2). We have chosen two contrasting years where September sea ice extent has varied drastically in order to study and identify mechanisms important for rapid sea ice loss.

Our study approaches this problem by systematically increasing model complexities through a hierarchy of couplings. The first phase began with MPAS atmosphere-only (MPAS-A) experiments, and we are currently transitioning to a second phase that culminates in fully coupled long-term numerical simulations with MPAS-CESM. We have chosen to evaluate the Arctic environment during the summer of 2006 and 2007, which is characterized by two strongly contrasting cyclonic and anticyclonic pressure and tropospheric circulation anomalies. Furthermore, we believe a long-lived TPV and an associated surface cyclone are important factors in the resulting large-scale atmospheric circulation pattern in the summer of 2006. These cases allow us to answer specific questions regarding the ability of MPAS 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 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.

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ctrl</td>
<td>Black</td>
<td>Control experiment</td>
</tr>
<tr>
<td>lev21</td>
<td>Cyan</td>
<td>21 vertical levels instead of 41</td>
</tr>
<tr>
<td>arctic</td>
<td>Blue</td>
<td>Refined mesh over Arctic</td>
</tr>
<tr>
<td>midLat</td>
<td>Red</td>
<td>Refined mesh over midlatitudes</td>
</tr>
<tr>
<td>60km</td>
<td>Green</td>
<td>Uniform 60-km cell spacing</td>
</tr>
<tr>
<td>kf</td>
<td>Long-dashed black</td>
<td>Kain-Fritsch convective parameterization</td>
</tr>
<tr>
<td>cam</td>
<td>Short-dashed black</td>
<td>CAM radiative parameterization</td>
</tr>
</tbody>
</table>

**Table 1: Summary of MPAS numerical modeling experiments.**

**WORK COMPLETED**

We have now performed our entire suite of MPAS-A experiments for 2006 and 2007. Month-long simulations were performed with three initialization dates for each experiment listed in Table 1: 00 UTC 01, 08, and 15 August. The control experiment consists of uniform cell spacing of $\Delta x = 30$ km, a model time step of $\Delta t = 2$ m, $(\Delta t_{\text{rad}}, \Delta t_{\text{mp}}) = (20$ m, $15$ s), 41 vertical levels, and a model top of 30 km. Physics parameterizations for the control simulation are Tiedtke convection (Zhang et al., 2011),
WSM6 microphysics (Lin et al., 1983; Hong et al., 2004; Dudhia et al., 2008), YSU planetary boundary layer (Hong and Pan, 1996), Monin-Obukhov surface layer (Paulson, 1970; Dyer and Hicks, 1970; Webb, 1970), NOAH land surface model (Chen and Dudhia, 2001), and RRTMG radiation (Mlawer et al., 1997) employing an upper-boundary longwave radiation correction (Cavallo et al., 2011). Initial conditions are from ERA-interim (Dee et al., 2011) and SST and sea ice updates are applied every 6 hours. Results will be summarized in the following section. We continue our efforts to develop a fully coupled MPAS-CESM configuration. Preliminary simulations have been performed, and we are currently analyzing our next steps. We plan to report on those results next year.

RESULTS

Figure 3: (a) Mean MPAS TPV track error (x-axis) vs. forecast lead time (y-axis) for each of the ensemble members. Spaghetti plot of 295 K and 340 K potential temperature contours on the tropopause for the (b) day 5 and (c) day 7 forecasts initialized 00 UTC 01 August 2006. See Table 1 for a description of the ensemble members.

Experiments indicate there is little track error for the 2006 TPV during the first 7 forecast days (Fig. 3a). However, as illustrated by the experiments for forecasts initialized 01 August, by forecast day 5, considerable differences in the amplitude of a developing Rossby wave are evident in the North Atlantic east of Greenland (Fig. 3b). These differences arise from slight variations in the strength of a surface cyclone off the southeastern Greenland coast. The strength of the surface cyclone affects the strength of the warm conveyor belt; thus a stronger surface cyclone results in a stronger upper-tropospheric ridge due to latent heating in the middle troposphere destroying PV near the tropopause. This ridge is strongest in the Arctic-refined mesh and in the 21-level mesh, and subsequently result in lower TPV track error as a result of the an earlier onset of the Rossby waves breaking in comparison to all other experiments (Fig. 3c). After the Rossby wave breaks, tracks diverge amongst the different experiments. This pattern of track error is consistent amongst the different initialization times, with the substantially lower track error in the Arctic refined and 21-level meshes at 2-week forecast lead times on average. Our analysis suggests that better resolving the TPV over the Arctic is important in order for the surface low pressures to intensify at the correct rates, and we believe
these differences arise from sensitivities in the distribution of water vapor and clouds near the TPV. Prediction on the 21-level mesh is also relatively accurate, but preliminary indications are that this solution is erroneous with regard to physical expectations and given what was observed.

We next analyze the summer of 2007, a year resulting in a record-low sea ice extent for that time. Our original expectation follows (Rigor et al., 2002), where a negative AO pattern with a large-scale anticyclone over the central Arctic Ocean is expected to prevent TPVs from entering the Arctic, and that sea ice reduction should then primarily be associated with the movement of sea ice out of the Arctic Ocean through the Fram Strait around the anticyclone. Our experiments show that while TPVs initially remain equatorward of the Arctic Ocean early in the summer, a long-lived TPV subsequently moves into the southern fringes of the Arctic Ocean later in the season by July (Fig. 4a,b). While this 2007 TPV contains a much shorter lifetime than the TPV of focus in 2006 (45 vs. 86 days, respectively), it moves into the Arctic Ocean after sea ice melt opened a wide channel north of the Siberian coast. This open water, adjacent to sea ice and land areas, increases low-level baroclinicity, which is a favorable environment for surface cyclone development if a TPV moves over that region. The tracks of the 2007 TPV show that this scenario did indeed occur (Fig. 4b).

Figure 4: Cyclonic (blue) and anticyclonic (red) TPV lifetimes, as a function of genesis time for (a) observed cases in 2006 and 2007 (red) and (c) numerically simulated cases of 2034 and 2032 from the CESM large ensemble. Cyclonic TPV tracks of the longest-lived (b) observed cases in 2006 (blue) and 2007 (red) and (d) numerically simulated cases of 2034 (blue) and 2032 (red) from the CESM large ensemble.

To further investigate the possible correlation between the TPV leading to surface cyclone development
over the Arctic Ocean, we examine the daily changes in sea ice concentration and find that there are several rapid, episodic sea ice loss events in late July and early August (Fig. 5a). In each of these episodic rapid sea ice loss events, there is a strengthening of a surface cyclone as this TPV moved near the edge of sea ice and open water. One of these events occurs on 4 August 2007, which we have shown in Fig. 5b for illustration. We believe that when a surface low forms near the edge of sea ice, and if the sea ice is sufficiently thin, that the surface stress induced by increasing low-level winds in association with the developing surface cyclone can drastically accelerate the break up of sea ice (e.g., Overeem et al., 2011; Asplin et al., 2012; Simmonds and Rudeva, 2012).

**Figure 5:** (a) Time series of sea ice extent (blue) and daily change in sea ice extent (red) from 1 July - 30 September 2007. (b) Change in sea ice concentration from 4-5 August 2007 (colors; blues = concentration decrease, reds = concentration increase) and tropopause potential temperature (gray contours for values $\leq 315$ K; contour interval = 5 K) and sea level pressure (black contours; contour interval = 4 hPa) on 4 August 2007 at 12 UTC. Sea ice concentrations are from National Snow and Ice Data Center (NSIDC) near-real-time Defense Meteorological Satellite Program Special Sensor Microwave Imager (DMSP SSM/I-SSMIS; 1987 to present) passive microwave data (Cavalieri et al., 1996) daily gridded data, and sea ice extent is the sum of the area over all grid points where sea ice concentration is $\geq 15\%$. These results emphasize the coupled nature of this problem. Given our current limitations in MPAS,
and until we have established a reliable coupled modeling system with it, further investigation of the mechanisms leading to ice breakup remain difficult. However, we then ask the question: Do analogous cases of 2006 and 2007 occur in a sophisticated climate model? To answer this, we use the CESM large ensemble (CESM-LE) (Kay et al., 2015). CESM-LE simulations use a single CMIP5 model (CESM with the Community Atmosphere Model, version 5). A 1000-year preindustrial control simulation is run until 1920, at which time 30 perturbations are applied to the atmospheric state that differ only by numerical roundoff error. Each ensemble member is then run from 1920-2005 using historic forcings, and then until 2100 with representative concentration pathway 8.5 (RCP8.5) external forcing.

We searched each ensemble member, looking for (1) years where anomalously low September sea occurred similar to 2007, and (2) whether the years in (1) occurred near years of an opposing anomaly like 2006. We found that there are many analogous years, and we now highlight the ensemble member that we found contained an illustrative analog. The member we illustrate is CESM-LE ensemble member 24, where its year 2032 contains an ice loss anomaly of $+1.6 \times 10^6$ km$^2$, analogous to the observed case in 2007. For clarity, when we refer to the CESM-LE simulated year, it will be followed by the year of the observed analog in brackets. For example, 2032 [2007] refers to CESM-LE analog year 2032 and observed year 2007. This ensemble member also contains an anomaly of opposing sign in 2034, with an ice loss anomaly of $-1.75 \times 10^6$ km$^2$, analogous to the observed case in 2006. A benefit of the CESM-LE is that comprehensive outputs are available for analysis, including many relevant daily fields. In our case, we would like to examine the sea ice budget to better understand how changes in sea ice occur in this model. This also provides us with a reference of comparison for when we perform MPAS experiments with CESM later.

We find long-lived TPVs in both analog cases of the CESM-LE member, with a longer-lived TPV in 2034 [2006] (Fig.4c). Although lifetimes are much shorter than those that are observed, the pattern is extremely similar with both years containing a single, relatively long-lived TPV that develop at roughly the same time. Furthermore, the tracks are strikingly similar between the CESM-LE and the observed cases, with a TPV track that is further equatorward in 2032 (similar to 2007) (Fig.4d).

The CESM large ensemble utilizes the Los Alamos Sea Ice Model (CICE). The change in sea ice concentration $a$ on a grid cell $i$ is

$$\frac{da_i}{dt} = \dot{a}_{i,d} + \dot{a}_{i,t}$$

where $\dot{a}_{i,d}$ are changes from dynamics, and $\dot{a}_{i,t}$ are changes from thermodynamics. The thermodynamic forcings are:

$$F_t = F_{\text{flocn}} + F_{\text{flat}} + F_{\text{sens}} + F_{\text{flw}} + F_{\text{fsw}}$$

where a positive sign implies the flux is downward. We now summarize results below:

- The dominant term in (1) in 2032 [2007] is the thermodynamic term. However, the dynamics term is comparable.
- A large-scale anticyclone develops in May in the CESM-LE year 2032 [2007]. However, this anticyclone weakens by the end of July, and is replaced by a cyclonic TPV. There is a substantial reduction in sea ice as this cyclonic TPV moves from the Barents Sea toward Greenland. This
**Figure 6**: Thermodynamic budgets from the CESM large ensemble member 24 Year 2032 minus Year 2034 for (a) July and (b) August. Images within the panels show the individual budget terms from (2), which are: (top left) flux from sea ice to ocean (top middle) latent heat flux (top right) downward longwave flux (bottom left) upward longwave flux (bottom middle) sensible heat flux (bottom right) shortwave flux. Saturated blues in the top left panel indicate areas where there is no sea ice in 2032 whereas there is sea ice in 2034 at the same time and location.
reduction appears to be associated with the dynamics term via sea ice loss out of the Arctic on the eastern side of Greenland.

- The thermodynamic budget reveals that there is strong downward shortwave/solar forcing with clear skies underneath the large-scale anticyclone through July (Fig. 6, bottom right panel). This precedes sea ice loss in August (Fig. 6, top left panel).

- Underneath cyclonic TPVs, the dynamics term in (1) dominates (Fig. 7).

Overall, these results indicate that a long-lived larger-scale anticyclone develops early in the season, consistent with the negative AO pattern. These results justify a new hypothesis as follows, which we intend to confirm or reject through additional cases in the future. The large-scale anticyclone promotes anomalous sea ice loss through thermodynamic processes related to fewer clouds, increased shortwave radiation reaching the surface, and warmer surface temperatures. The smaller-scale cyclonic TPVs remain outside of the Arctic Ocean during this time due to the blocking anticyclone over the Arctic Ocean. However, TPVs occasionally reach the Arctic coastline. This does not promote the generation of surface cyclones until open waters develop later in the season as a result of sea ice loss. Once surface cyclones begin forming over the Arctic, rapid, episodic sea ice loss events occur and the mean large-scale circulation transitions from anticyclonic to cyclonic.

IMPACT/APPLICATIONS

The MPAS modeling system will potentially be a useful tool 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.

REFERENCES


