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A Brief Overview of Mesoscale Numerical Modeling for the Earth's Polar Regions as of 2018

by Robert E Dumais Jr

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This report is an attempt to provide a quick review of the current state of mesoscale numerical weather prediction modeling over polar regions of the Earth. These areas are notoriously difficult for both models and human forecasters due to their complexities of terrain, energy budget, ice-albedo feedback, and cloud microphysics (to name just a few). Although both global and mesoscale numerical weather prediction models have become increasingly sophisticated over the last several decades and in step with phenomenal increases in computational power, unique modifications still have had to be developed for their proper application to polar regions of the globe. Even in lieu of these improvements and specialized modifications, there remain a number of challenges and deficiencies to be addressed for more skillful use over polar regions, including for short-range forecasting and nowcasting purposes (which are of great interest to the US Army and other US Armed Forces).

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1. Introduction

The Earth's polar regions, both the Arctic and Antarctic, have been of increasing interest to the US and international communities since at least the 1950s. An abundance of natural resources, strategic interest from a military perspective, and a recognition of having a pivotal role in driving the Earth's climate system have all made these regions a focus of increasing research efforts for the last half century. Over the past 25 years, due to the growing interest and concerns over anthropogenic contributions to climate change, these regions have also become a growing focus of meteorological and climate field research and modeling efforts.

Numerical weather prediction (NWP) over polar regions can be challenging. A study by Jung and Matsueda (2016) compared the performance of many operational global forecast systems through a 7-year period (2006–2012) generated from the THORPEX Interactive Grand Global Ensemble (TIGGE). This study focused on both the Arctic and Antarctic regions, and specifically on model performance of 500-hPa geopotential height (Z500) and 2-m above ground level (AGL) temperature (T2M). The study examined both deterministic and probabilistic (ensemble) model forecasts from each of the selected operational modeling systems. For short-to-medium range forecasts, they found that the year-to-year variability of deterministic skill was lower in the midlatitudes than in the Arctic, and that the skill in the most predictable winters was comparable between the midlatitudes and the Arctic. They also concluded that year-to-year differences in deterministic forecast skill of Z500 in the Arctic was primarily due to flow-dependent perturbation growth rather than individual forecast system development. For the ensemble forecasts, the study found that differences in the performance across the various systems appeared larger for the probabilistic versus deterministic forecasts. These differences were presumed due to differences in the quality of the individual methods of each system used for representing the initial condition and model uncertainties, although as for the deterministic scores, large year-to-year variability in predictive skill was found once again. Curiously, winters that showed more predictability in the deterministic forecasts tended to show less in the probabilistic perspective, and some potential ideas for this were posited. Finally, the T2M forecasts over the Arctic exhibited less skill than those for Z500, and this was largely thought to be due to the more poorly handled state of the Arctic lower boundary (whereas Z500 skill is linked more to the better handled planetary/ synoptic processes).

Although global models seem to perform comparably in the polar regions versus across other parts of the Earth, various studies have shown that mesoscale features (usually unresolved at global forecast model resolutions) are critical to forecasting short-range weather conditions in both the Arctic and Antarctic. Typically, these mesoscale phenomena are resolved through application of a regional scale limited-area mesoscale NWP model, nested inside the forecast solution provided by a current global model. Because it is more computationally tractable to provide higher model resolution (both horizontal and vertical) across a limited area domain, the mesoscale model can apply the higher resolution (including in both the terrain and land use) necessary to explicitly capture many of the important features left unresolved by the global models. Although this is a reasonable approach, at times even small initial condition spatial displacement, orientation, or phase errors from the global model prediction of the synoptic scale weather features can be problematic to the short-range prediction of the mesoscale model (Stensrud and Fritsch 1991). Lateral boundary condition sweeping in strong synoptic flow can also pose problems to limited-area mesoscale models (Warner et al. 1997). Important (and sometimes even less important) synoptic weather features need to be captured well by global models in order for short-range mesoscale models to maximize their advantages. For example, in the Arctic these synoptic systems would include inverted troughs, barrier jets, upper tropospheric shortwaves, cold lows, and polar lows.

While higher resolution can be obtained over focused subregions of the globe by applying limited-area mesoscale models, another approach is to develop global modeling systems with adaptive grid meshing strategies. Systems such as the National Centers for Environmental Prediction (NCEP)-selected next-generation US global prediction system called the Finite-Volume Cubed-Sphere Dynamical Core (FV3; Lin S-J et al. 2016) and the National Center for Atmospheric Research (NCAR) experimental Model for Prediction Across Scales (MPAS; Judt 2018) are currently under active research and development, and in the case of FV3, planned for operational status over the next few years. However, their full benefits may take longer to recognize since the improved dynamical cores still outpace the modifications required in the physics packages (due to a need for physics parameterizations that can span across all scales) and in the couplings to land surface and ocean modeling components.

This report attempts to summarize the current state of numerical modeling with an emphasis over the polar regions of the globe. Those areas still prove especially challenging to modeling efforts using present state-of-the-art NWP modeling systems. The focus is aimed more at limited-area mesoscale modeling systems, and although relatively agnostic in terms of mesoscale model, much of the discussion comes from knowledge compiled through operational application and research studies using a few of the more established polar modeling systems. Both the mesoscale models and their approaches to data assimilation are given a general overview within this report.

2. The Ability of Mesoscale Models to Resolve Important Polar Meteorological Phenomena

In polar regions, wherever complex terrain coexists with a nearby coastline and an extensive coverage of elevated snow and ice fields, very strong katabatic and persistent winds at the surface are likely. Katabatic winds are a special case of downslope winds that carry high-density air from higher elevations downslope under the force of gravity. The air undergoes strong radiational cooling at higher elevations, particularly over large snow and ice fields, and due to density considerations and gravity will flow downslope. If the flow is funneled through narrow coastal valleys of polar regions, extremely strong winds can occur. The prolonged polar darkness during winter and permanence of elevated ice fields can lead to almost continuous katabatic wind conditions for very long stretches. Greenland and Antarctica are particularly known for such winds (DuVivier and Cassano 2015). In order to accurately generate numerical weather forecasts of katabatic winds in such areas, high-resolution topography is needed to resolve the small-scale features such as coastal valleys and fjords that contribute to katabatic winds and can add to their intensity. Global models, due to their coarser grid spacing and resolution of the topography, cannot capture such important local enhancements to the larger-scale katabatic flow system. This is one meteorological phenomena of the polar regions by which running a high-resolution limited-area mesoscale model is advantageous to short-range forecasting. Discussions pertaining to the complex challenges of modeling at high resolution including forecasting high-speed katabatic wind events, along with the potential need for near-kilometer or even sub-kilometer model grid resolutions, can be found in Sun (1995), Bromwich et al. (2001), Mass et al. (2002), Zangl (2002), Morton and Molders (2007), Arnold et al. (2012), Bryan (2014), Dudhia and Wang (2014), Moore (2016), Wille et al. (2017), and Yang (2018).

During the winter season, regions near the poles receive very little incoming solar shortwave radiation. In addition, the wide coverage of snow and ice provides surfaces of high albedo to reflect away what little solar energy does reach the surface. This leads to a long-lasting regime of high static stability within the atmospheric boundary layer, highlighted by a large surface temperature inversion due to the strong radiative flux divergence. Under such conditions, any boundary layer turbulence tends to be suppressed. However, there are additional energy transfer pathways that are known to exist within stable boundary layers (Nappo

1991), although numerical weather models (even at high resolution) have a rather difficult time reproducing them (Fernando et al. 2015; Vercauteren et al. 2016). For example, Galperin et al. (2007) note that within very stable stratified boundary layers, turbulence can survive and a nonlaminar flow condition can remain at critical Richardson number values much greater than unity. This may be due, in part, to complex and poorly resolved stable boundary layer interactions between internal gravity waves and turbulence, as well as other phenomena like shallow drainage flows, which produce anisotropization. These processes can contribute to negative consequences in short-range model forecasts since they can modulate boundary layer profiles of temperature, wind, and moisture—particularly in polar regions. Monin-Obukhov Similarity Theory (MOST) functions to compute profiles of temperature, moisture, and momentum in the surface "constant flux" layer may also need to be recast for very stable conditions (Tastula et al. 2015). As computational breakthroughs begin allowing mesoscale NWP models to routinely apply grid nesting to almost large eddy simulation resolution (~500-m horizontal grid spacing) and allow the continued increase in vertical resolution, it might be anticipated that complex features of stable stratification would start getting resolved explicitly. On the other hand, new boundary layer turbulence parameterizations are showing promise in dealing with scale-dependent subgrid complex features found under stable stratification. For example, the relatively new Quasi-Normal Scale Elimination (QNSE) spectral theory offers a non- Reynold's-Averaged Navier-Stokes (RANS) approach, which employs gradual coarsening of the resolved domain by successively eliminating small shells of unresolved scales. Each shell that is removed will contribute to the eddy viscosity and eddy diffusivity and is allowed to differ in vertical and horizontal directions—flow anisotropization. This process can thus introduce contributions from internal gravity waves (Sukoriansky et al. 2005). This scheme has been tested with some success (Sukoriansky et al. 2005; Tastula et al. 2016) in both the High Resolution Limited Area Model (HIRLAM; Unden et al. 2002) and Weather Research and Forecasting (WRF; Skamarock et al. 2005) mesoscale models.

Over both polar regions, particularly the Arctic in the summer and early autumn seasons, cloud fractions can be as high as 85% over extended stretches (Intrieri et al. 2002). The majority of such clouds are of the low stratus variety, and a strong relationship exists between these stratus clouds and low-level stability. Low clouds in the Arctic are typically persistent (and often nonprecipitating) and tend to develop due to processes subgrid to most operational mesoscale model grid spacing (Fan et al. 2011; Hines et al. 2011; Bromwich et al. 2017). Recent studies have indicated that in polar regions, these clouds are underrepresented by current operational models (Bromwich et al. 2013; Hines and Bromwich 2017). The clouds have serious implications in terms of modeling the surface shortwave solar and downwelling longwave radiative fluxes, with an overall tendency in current operational models during the summer/autumn to predict excessive incident shortwave radiation and insufficient downwelled longwave radiation at the surface (Bromwich et al. 2013; Hines and Bromwich 2017). The difficulties in predicting the polar low stratus within current mesoscale models has much to do with complex interactions involving sea ice coverage, melt, peat wetlands, surface albedo, radiation, and mixed phase microphysics (supercooled liquid water vs. ice; Koralev et al. 2017), as well as turbulent mixing and nucleation/aerosol processes (Shupe et al. 2015). Interestingly, Yurova et al. (2014) find that proper treatment of the lower boundary conditions over the peat moss wetlands of Siberia can be an important consideration for NWP over that region. Microphysics schemes such as Lin et al. (1983), Hong et al. (2004), Morrison et al. (2009), and Tao et al. (2014) have been used for polar mesoscale real-time and research modeling efforts, an example being the Ohio State University Byrd Polar Meteorology Center's (PMC) Antarctic Mesoscale Prediction System (AMPS; a variant of Polar-WRF [Wilson et al. 2012]) discussed in Powers et al. (2003), Cassano et al. (2011), and Bromwich et al. (2013). In addition, PMC also runs a different variant of Polar-WRF for the NASA Arctic Radiation – Ice Bridge Sea and Ice Experiment (ARISE) centered over Alaska. In the ARISE version, an altered version of the Morrison et al. (2009) scheme is used where an option has been added for reduced cloud liquid droplet concentration. A reduced droplet concentration from 250 per cm cubed to 50 per cm cubed can now be used, which tends to produce fewer, larger liquid cloud droplets—resulting in precipitation being easily produced and less forecast cloud liquid water. Tests show better transmission of solar radiation to the surface with this change (Listowski and Lachlan-Cope 2017).

A variety of new bulk and spectral bin microphysics schemes (e.g., Milbrandt and Yau 2005; Khain et al. 2010; Lin and Colle 2011; Morrison and Milbrandt 2015), some even aerosol aware (e.g., Thompson and Eidhammer 2014), have become available in newer versions of modeling systems such as the WRF. A number of these are compared in the papers of Naeger et al. (2017) and Listowski and Lachlan-Cope (2017). One or more of these may prove valuable to improving the treatment of microphysical processes of low cloud production and maintenance in the polar regions, and so are open candidates for future testing and research. As for precipitation forecasting, in Polar-WRF (Bromwich et al. 2009b) there is a clear tendency to overpredict precipitation during the summer season when convective processes dominate (Wilson et al. 2012; Bromwich et al. 2013). A possible explanation for this is that Polar-WRF produces excessive evaporation over land surfaces in the summer, making too much low-level boundary layer moisture available for the convective parameterizations (Wilson et al. 2012). Hines et al. (2011) also point to positive biases in soil moisture initial conditions as well as sources from the land surface model as being other contributors to the summer precipitation positive bias. On the other hand, vigorous convection that occurs over open ocean when air masses arrive from the sea-ice or cold land are still cited as major challenges for Arctic atmospheric reanalysis systems (Schyberg 2016).

Improved short-range prediction of surface fluxes and clouds in the polar areas also requires a better set of initial conditions for the lower boundary, as well as an increasingly complex treatment of oceanic and land surface processes. As an example, the Polar-WRF model currently runs coupled to a “polar-modified” version of the Noah (Tewari et al. 2004) land surface model (LSM). To help alleviate systematic positive biases in surface winds produced by the European nonhydrostatic HARMONIE-AROME modeling system (Bengtsson et al. 2017, Muller et al. 2017), which have been observed in verification against scatterometer data and buoys (Suld et al. 2015), a two-way coupling with the WAM wave model (The WAMDI Group 1988) has been incorporated over an Arctic domain used in operations by Met-Norway (Bengtsson et al. 2017). Mahura et al. (2016) illustrate other challenges and shortcomings of arctic near-surface temperature and moisture forecasting in both the mesoscale HARMONIE-AROME (Seity et al. 2011; Bengtsson et al. 2017) and HIRLAM-ALADIN (Bengtsson et al. 2017) modeling systems. The studies of Wilson et al. (2011, 2012) discuss near-surface forecast biases found in the Polar-WRF, such as an annually averaged cold bias in surface temperature and overprediction of daily surface temperature range. Another report (Norman et al. 2014) compares surface model biases of both the WRF and the HIRHAM (HIRLAM+ECHAM; Christensen et al. 1996) models over Greenland, and find HIRHAM had negative moisture bias opposed to the WRF positive moisture bias. The importance of treatment of sea ice for polar forecasting is discussed in detail by Hines et al. (2015). In both the AMPS and ARISE variants of PMC’s Polar-WRF model, important modifications have recently been made (including within the Noah LSM) to more accurately treat the polar lower boundary conditions that are critical to short-range forecasting and nowcasting. It is hoped these changes will help with the cloud and near-surface mesoscale model biases that have been noted in the past over polar regions. Improved treatments have been implemented to better handle surface energy balance and heat transfer in the Noah LSM over both sea ice and permanent ice surfaces, as well as a change to allow specified sea ice fractions and the land mask associated with sea ice to update within a simulation (Bromwich et al. 2000). In addition, in the AMPS version, the sea ice albedo now offers an option that forecasts the sea-ice albedo based on temperature and snow depth, snow fraction can be used in calculating surface fluxes of latent heat and sensible heat, snow cover depth and sea ice thickness can be allowed to vary in a simulation, and modified surface emissivity and thermal conductivity can be used for ice sheets. Initial values for snow cover, vegetation fraction, and albedo all come from satellite, and the fractional sea-ice implementation involves the surface-layer scheme being called twice: first for completely frozen conditions, then for completely open water conditions. The results of these two calls are weighted by the sea-ice fraction to determine surface fluxes and other terms. Further details of recent modifications to Polar-WRF are available at http://polarmet.osu.edu/PWRF/ and http://polarmet.osu.edu/AMOMFW_2016/0606_1530_Bromwich.pdf .

3. Data Assimilation Approaches for Polar Mesoscale Modeling

Data assimilation in the polar regions remains a great challenge for NWP modeling (Bromwich et al. 2009a). A significant issue in polar mesoscale modeling (particularly operationally) is the relative dearth of direct and in situ weather observations poleward of about 70° latitude; this is especially true for upper air observations and over the arctic expanse of ocean and ice. In some instances, special surface and radiosonde networks have been deployed on a limited research basis (Inoue et al. 2013; ECMWF 2018). Due to the lack of in situ weather observations in polar regions, the ability to leverage indirect observations from orbiting weather satellites (atmospheric motion vector winds, GPS water vapor, and radiances) is very important in this region. A number of techniques of various levels of complexity have been developed (and continue to be developed) for assimilating satellite (along with other remotely sensed sources of indirect weather observations like radar/lidar) measurements into NWP models. The level of complexity can vary based on the resources of the operational (or research) entity, the purpose of the NWP model (longer-range global forecasts vs. shorter-range mesoscale "nowcasts"), and the types of observations most likely to support the modeling system. The global modeling systems (which by their nature also include polar regions) now use a variety of different hybrid ensemble Kalman filter (EnKF)-4-D variational (4DVAR) strategies, which are extensively described in the literature (Yang et al. 2009; Lorenc et al. 2015; Bannister 2017). These techniques are particularly useful for synoptic scale modeling where initial condition errors grow over several days, but are increasingly being applied at mesoscales (Ancell and Mass 2006; Liu et al. 2009; Jirak et al. 2012; Sun et al. 2014; Schwartz et al. 2015; Simonin et al. 2017). In global models, large forecast improvements have been realized through the effective assimilation of satellite observations (Barker 2017). These include models such as the European Centre for Medium-Range Weather Forecasts (ECMWF; https://software.ecmwf.int/wiki/display/FUG/1+Introduction), United Kingdom

Met Office (UKMO; https://cpo.noaa.gov/sites/cpo/MAPP/Webinars/2017/09-29-16/Walters.pdf), Global Forecast System (GFS; http://www.emc.ncep.noaa.gov/GFS/doc.php), Japan Meteorological Agency (JMA; http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/nwp-top.htm), and Global Environmental Multiscale model (GEM; http://collaboration.cmc.ec.gc.ca/science/rpn/gef_html_public/index.html). Most of these global models now push to the 10–20 km grid spacing realm. For very short range (km-scale) NWP-based nowcasting systems, which may have to run on more modest computer hardware assets and in places where observations may be sparse, there remain cheaper and effective alternatives for data assimilation (Hu et al. 2006a, 2006b; Weygandt et al. 2006; Zhao et al. 2006; Stauffer et al. 2007; Shaw et al. 2008; Stephan et al. 2008; Liu et al. 2009; Xie et al. 2011; Lei et al. 2012; Reen et al. 2017). Out of these alternatives, 3-D variational (3DVAR) and nudging methods are computationally the easiest and cheapest to implement for short nowcasting windows, although for the polar regions a variational approach will be necessary if satellite radiance is deemed as a critical polar observation for model improvement. One of the main disadvantages of nudging is that the method can only handle observations of variables that are prognostic within the model. Weather observations of nonprognostic variables, such as satellite radiances, must be assimilated differently. Satellite atmospheric motion vectors, on the other hand, are straightforward to ingest into the 4-D data assimilation nudging scheme of WRF.

Outside of the US-based Polar-WRF variants (AMPS and ARISE) being run by the PMC, the Applications of Research to Operations at Mesoscale (AROME)-Arctic (based on HARMONIE-AROME) operational system run by the Norwegian Meteorological Institute (Muller et al. 2017) is also available. In addition, the Danish Meteorological Institute is also running operational high-resolution (2.5-km grid spacing) windows using their own implementation of the mesoscale AROME-HARMONIE model for different regions of Greenland (Bengtsson et al. 2017). Tables 1 and 2 provide the data assimilation methodologies for the AMPS and the AROME-Arctic systems, as well as all other pertinent details of their respective model configurations. Figures 1–4 show various output from recent operational forecasts generated through public online user interfaces for these models.

Table 1 AMPS configuration of Polar-WRF for the Antarctic as maintained and operated by Ohio State University PWC

Horizontal nesting grid spacing and dimensionality	24 km (413×535), 8 km (835×787), 2.67 km (676×1036), 0.89 km (769×901)
Vertical levels	61
PBL and surface layer	Mellor–Yamada–Janjic (MYJ; Janjic 1994) with Eta Monin-Obukhov (Janjic 2002)
Shortwave radiation	Goddard (Chou et al. 2001)
Longwave radiation	RRTMG (Iacono et al. 2008)
Microphysics	WSM 5-Class (Hong et al. 2004)
Deep cumulus parameterization	Kain-Fritsch (includes shallow cumulus) only on 24- and 8-km nests (Kain 2004)
Land surface model	Noah (Tewari et al. 2004)
Data assimilation	WRFDA 3DVAR (Barker et al. 2012) with a hybrid EnKF-3DVAR option available
Observations	Surface (METAR, SYNOP, SHIP, BUOY, AWS), upper (RAOB, PIBAL), aircraft (MDCRS, AMDAR, PIREP, AIREP), satellite (SATOB, SATEM, MODIS, GPS radio occultations, GEOAMV, PolarAMV, AMSU-A radiances)
Lateral boundary conditions for 24-km nest	0.25° GFS
WRF version based upon	3.9.1

Table 2 AROME-ARCTIC, Norwegian Meteorological Institute: current model configuration over the Arctic

Horizontal nesting grid space and dimensionality	2.5 km (739×949)
Vertical levels	65
PBL and surface layer	Prognostic TKE with diagnostic mixing length (Bougeault and Lacarrere 1989; Cuxart et al. 2000) and surface layer (Masson and Seity 2009)
Shortwave radiation	6-spectral band scheme (Fouquart and Bonnel 1980)
Longwave radiation	RRTM (Mlawer et al. 1997)
Microphysics	3-Class ice or ICE3 (Pinty and Jabouille 1998) coupled to Kessler scheme for warm processes.
Deep cumulus parameterization	Explicit, but scheme of Pergaud et al. (2009) handles subgrid shallow convection.
Land surface model	SURFEX (Best et al. 2004)
Forecast cycles	4 times daily out to 66 h
Data assimilation	3DVAR (Brousseau et al. 2011) with 3-h DA cycling
Observations	Surface
Lateral boundary conditions	ECMWF

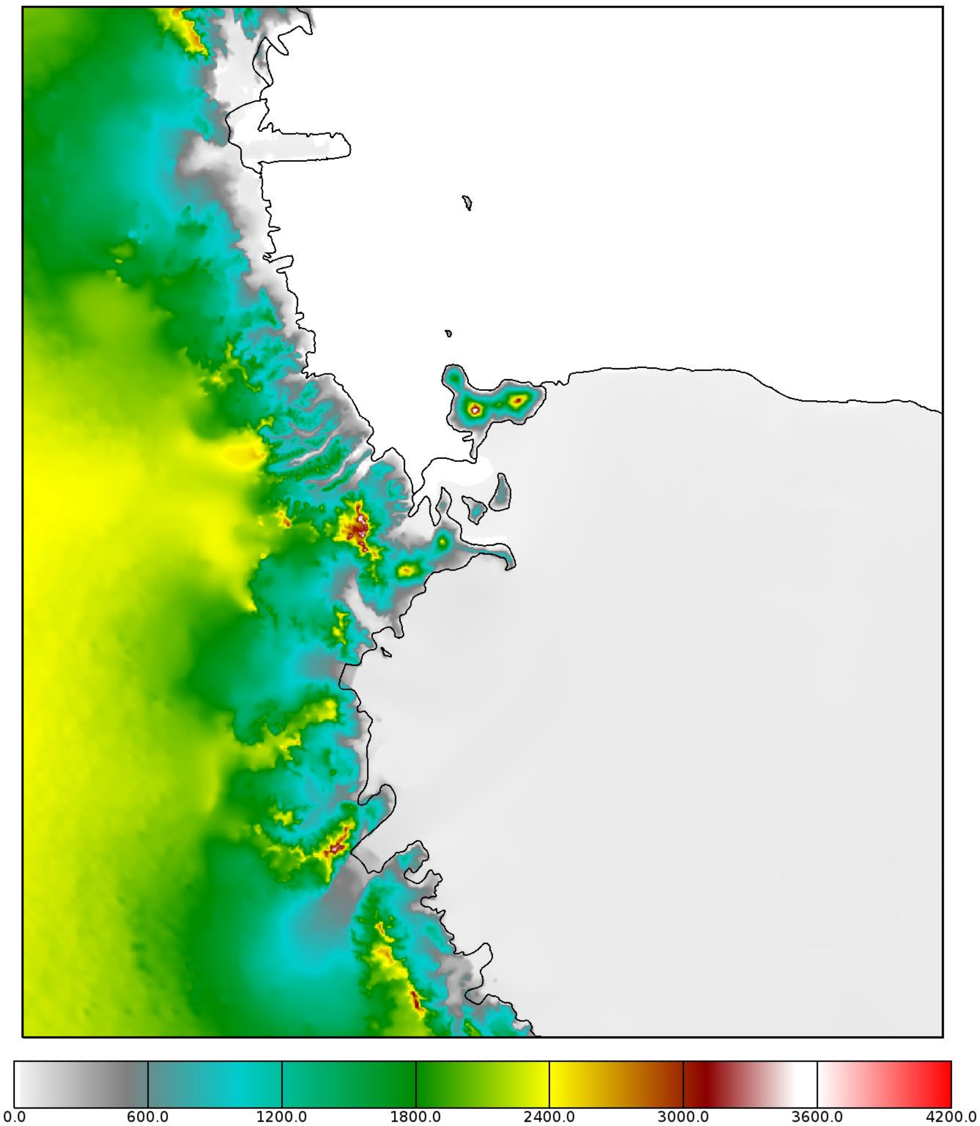

Fig. 1 High-resolution terrain (m) for the high-resolution (0.89-km grid spacing) Polar-WRF AMPS nest near Cape McMurdo in Antarctica. Figure generated at http://www2.mmm.ucar.edu/rt/amps/information/configuration/maps_2017101012/maps.html.

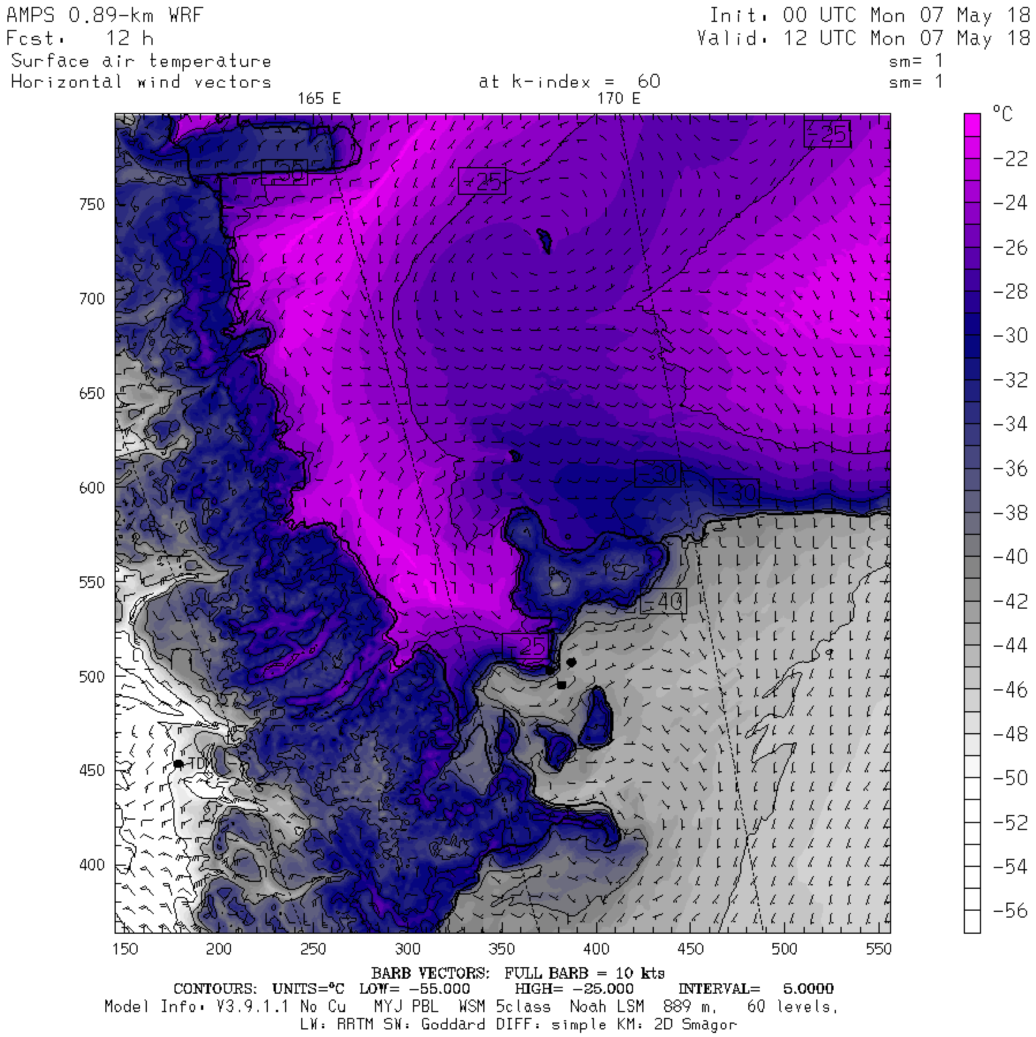

Fig. 2 Surface wind and temperature forecast for the AMPS 0.89-km nest of Polar-WRF near Cape McMurdo in Antarctica. Figure generated at http://www2.mmm.ucar.edu/rt/amps/.

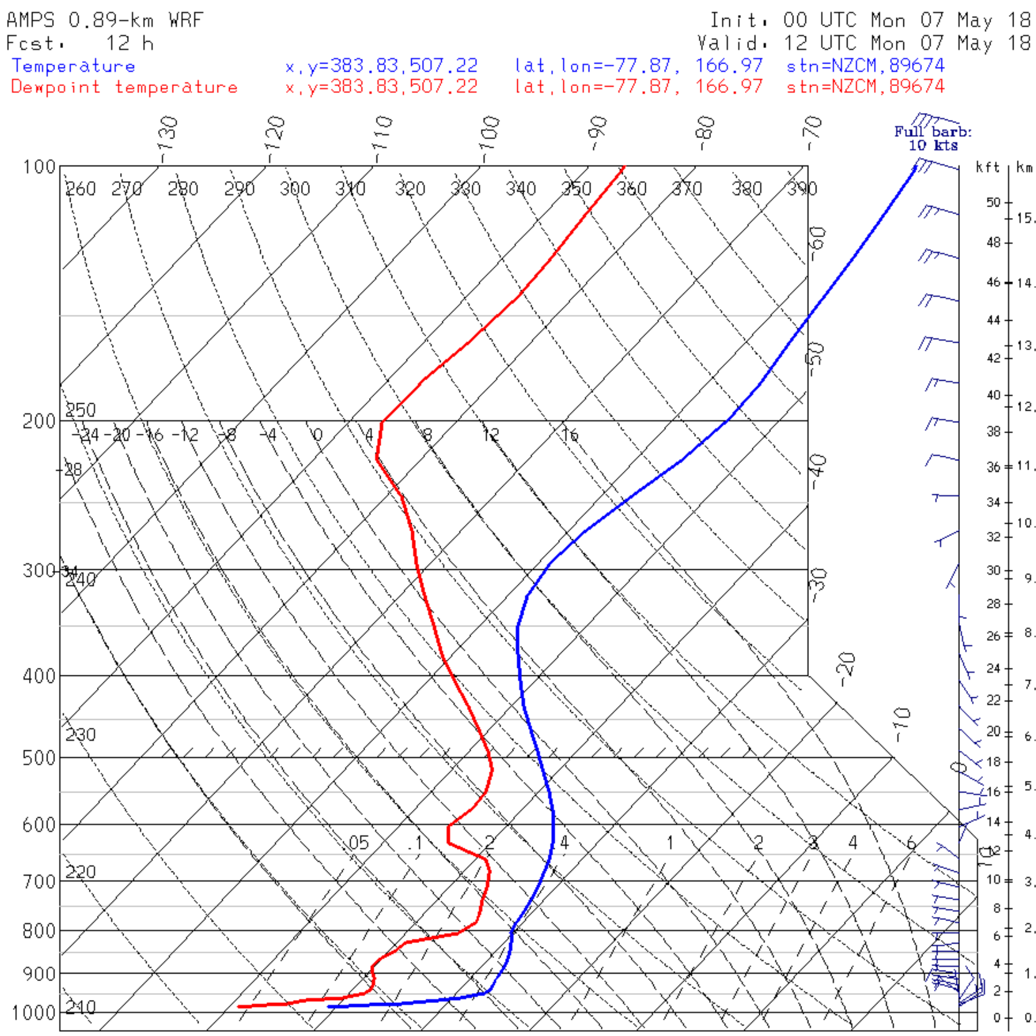

Fig. 3 SkewT-LogP generated from a forecast from the AMPS 0.89-km nest of Polar-WRF near Cape McMurdo in Antarctica. Figure generated at http://www2.mmm.ucar.edu/rt/amps/.

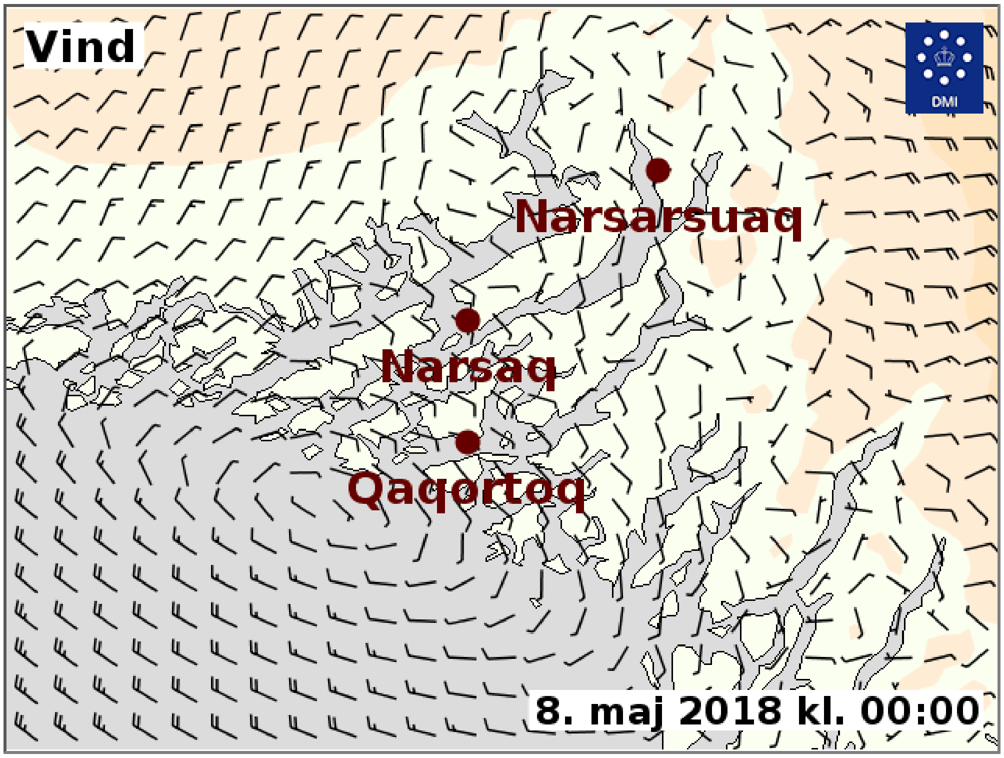

Fig. 4 Surface wind forecast for a region of SW Greenland from the 2.5-km HARMONIE-AROME model run by the Danish Meteorological Institute. Figure generated at https://www.dmi.dk/en/groenland/vejret/vind/.

4. Conclusion and Summary Discussion

This report provides a thorough, but clearly inexhaustive, review of the current state of mesoscale NWP modeling over polar regions. Although this report mostly focused on two or three US and European mesoscale modeling systems currently operational for polar regions, there are certainly others that can and have been applied, such as the US Navy Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Tjernström et al. 2004) and the German Weather Service's Consortium for Small-scale Modeling (COSMO)—also run over the Arctic by the Russian Hydrometeorology Service (Schroder et al. 2011). The last decade or two of expanding interest in the polar regions due to climate change has resulted in a growing number of international centers, initiatives, and field programs aimed at developing a better understanding of the physics and modeling of these regions. Examples include efforts such as the Arctic Climate Impact Assessment (https://www.amap.no/arctic-climate-impact-assessment-acia), Arctic System Reanalysis (Bromwich et al. 2018), Arctic Radiation–IceBridge Sea and Ice Experiment (Smith et al. 2017), Arctic Summer Cloud Ocean Study (Tjernström et al. 2014), United States Antarctic Program (https://www.usap.gov/), Arctic System

Science Program (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13426), Arctic Research Consortium of the United States (https://www.arcus.org/), and the Surface Heat Budget of the Arctic Ocean (Uttal et al. 2002). In addition, a number of international workshops have also been established to encourage collaboration and information exchange between researchers and modelers focused on this part of the Earth: Workshop on Antarctic Meteorology and Climate, Antarctic Meteorological Observation, Modeling and Forecasting Workshop, International Symposium on Polar Sciences, and NOAA's Science Challenge Workshop "Predicting Arctic Weather and Climate and Related Impacts: Status and Requirements for Progress". Clearly these represent only a fraction of those workshops and conferences that have focused on arctic and Antarctic meteorology and climate over the last 20 or so years, but they do provide a good sampling of the activities that have been occurring. Special academic centers have also been established across the United States, Europe, and elsewhere to focus on polar meteorology—for example, the Byrd Polar and Climate Research Center at Ohio State University, the Cooperative Institute for Arctic Research at the University of Alaska-Fairbanks, the University of the Arctic, the Arctic Five Partnership, and EU-Polarnet, to name only a small few.

It is clear from the literature that although global NWP models have significantly increased spatial resolutions (now near 10-km grid spacing in some instances) and significantly improved physics over the last few decades, simple statistical downscaling approaches of the global model forecast output will still inadequately account for numerous microscale-to-mesoscale boundary layer and surface processes critical to forecasting short-range weather in the polar regions. These forecasts are critical for a variety of civilian commercial, research, government, and military interests that either operate or may need to operate in the future in these regions. Dynamical downcasting of the global NWP forecasts through use of high-resolution, limited-area mesoscale NWP models appears to be the cheaper and more effective approach into the near future, although consistent biases and errors identified in these models over the past decade or two still need to be addressed for them to fully provide their promised benefits. This is especially true when the models are pushed below 1-km grid spacing, as many are being required to do now given the advancements in computing, since many existing parameterizations designed to estimate contributions of subgrid physics processes (turbulence, cumulus convection, microphysics, radiation, etc.) begin to violate underlying assumptions that were acceptable at coarser grid spacing (Wyngaard 2004). Some newer scale-aware physics packages are beginning to address some of these issues (Grell and Freitas 2014; Shin and Hong 2015). In addition, new multiscale modeling systems such as MPAS and FV3 may offer alternative approaches to address such very fine resolution for focused regions.

In addition to the meteorological models themselves, continued improvements to polar atmospheric observation networks, treatment of land surface processes (particularly ice and snow, including their summer melt), data assimilation, and even multi-system coupling (atmosphere, ocean, hydrological, etc.) will become more important to fully capture the full range of atmospheric and oceanic processes over and near the poles. In addition to a heavy use of satellite technologies, it would be expected that a growing need for incorporating radar will be important toward improving knowledge and modeling in the polar regions of important cloud microphysical processes so critical to short-range forecasting (Intrieri et al. 2002; Oue et al. 2018). Parameterization and treatment of surface fluxes, turbulent fluxes, and cloud microphysics are still areas that need further improvement within mesoscale (and global) models over the polar regions (Birch et al. 2009; Koralev et al. 2017). The US Army Weather Running Estimate-Nowcast (WRE-N) is a short-range nowcasting implementation of the WRF model with data assimilation designed for nesting to 1 km or even finer grid spacing (Dumais et al. 2014). In a tactical deployment, dynamic downscaling in a rapid refresh cycling mode (with assimilation of locally available weather observation assets) could be achieved within either the high-resolution global model (Global Air-Land Weather Exploitation Model [GALWEM]; Stoffler 2017) forecasts generated by the 557th Weather Wing (WW) of the US Air Force, or from 557th WW forecasts produced several times daily from a high-resolution limited-area mesoscale nest applied within the global model (perhaps to 1.5-km grid spacing). If WRE-N were tailored more towards polar applications (for example, by leveraging or improving upon the selected physics options now used in Polar-WRF), it could be applied as a nowcast modeling tool in polar regions, which could prove to be of great value to both Army and Air Force forward area operations in polar regions.

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List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
3DVAR	3-D variational
4-D	4-dimensional
4DVAR	4-D variational
AGL	above ground level
ALADIN	Aire Limitée Adaptation Dynamique Développement International
AMPS	Antarctic Mesoscale Prediction System
ARISE	Arctic Radiation – Ice Bridge Sea and Ice Experiment
AROME	Applications of Research to Operations at Mesoscale
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
COSMO	Consortium for Small-scale Modeling
ECMWF	European Centre for Medium-Range Weather Forecasts
EnKF	ensemble Kalman filter
FV3	Finite-Volume Cubed-Sphere Dynamical Core
GALWEM	Global Air-Land Weather Exploitation Model
GEM	Global Environmental Multiscale model
GFS	Global Forecast System
GPS	global positioning system
HARMONIE	Research on Mesoscale Operational NWP in Euromed
HIRHAM	HIRLAM+ECHAM
HIRLAM	High Resolution Limited Area Model
JMA	Japan Meteorological Agency
LSM	land surface model
MOST	Monin-Obukhov Similarity Theory
MPAS	Model for Prediction Across Scales
MYJ	Mellor–Yamada–Janjic

NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
PMC	Polar Meteorology Center
QNSE	Quasi-Normal Scale Elimination
RANS	Reynold's-Averaged Navier-Stokes
T2M	2-m air temperature
TIGGE	THORPEX Interactive Grand Global Ensemble
UKMO	United Kingdom Met Office
WRE-N	Weather Running Estimate-Nowcast
WRF	Weather Research and Forecasting
WW	Weather Wing
Z500	500-hPa geopotential height

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