WRF winter extreme daily precipitation over the North American CORDEX Arctic

Justin M. Glisan
Iowa State University, glisanj@iastate.edu

William J. Gutowski Jr.
Iowa State University, gutowski@iastate.edu

Follow this and additional works at: http://lib.dr.iastate.edu/ge_at_pubs

Part of the Climate Commons

The complete bibliographic information for this item can be found at http://lib.dr.iastate.edu/ge_at_pubs/87. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
WRF winter extreme daily precipitation over the North American CORDEX Arctic

Abstract
We analyze daily extremes of precipitation produced by a six-member ensemble of Pan-Arctic Weather Research and Forecasting that simulated 19 years on the Coordinated Regional Downscaling Experiment Arctic domain. Analysis focuses on four North American regions defined using climatological records, regional weather patterns, and geographical/topographical features. We compare simulated extremes for the winter season with those occurring at corresponding observing stations in the U.S. National Climate Data Center’s Global Summary of the Day. We define winter as the 3 month period leading up to and including the climatological sea ice maximum: January-February-March (JFM). Our analysis focuses on winter variations in features of extremes such as magnitudes, spatial scales, and temporal regimes. Using composites of extreme events, we also analyze the processes producing winter season extremes. We compare circulation, pressure, temperature, and humidity fields from the ERA-Interim reanalysis and the model output. Although the model produces lower amounts of extreme precipitation compared to observation, the model is simulating the physical forcing that is found during observed extreme events. Specifically, the model and reanalysis highlight the importance of low-level moisture advection and its interaction with topography. The analysis establishes the physical credibility of the simulations for extreme precipitation events in JFM and their associated atmospheric circulations, laying a foundation for examining projected changes in extreme precipitation.

Keywords
Precipitation extremes, Regional climate modeling, North American Arctic, Topographical forcing

Disciplines
Climate

Comments
RESEARCH ARTICLE
10.1002/2014JD021676

Key Points:
- Simulations give insight into the nature of extremes in select Arctic regions.
- Establishes the physical credibility of WRF simulations for extreme behavior.
- Impact of topography on creating widespread precipitation extremes.

Correspondence to:
J. M. Glisan,
glisanj@iastate.edu

Citation:

Received 22 FEB 2014
Accepted 29 AUG 2014
Accepted article online 4 SEP 2014
Published online 24 SEP 2014

WRF winter extreme daily precipitation over the North American CORDEX Arctic

Justin M. Glisan1 and William J. Gutowski Jr.1

1Department of Geological and Atmospheric Sciences, Iowa State University of Science and Technology, Ames, Iowa, USA

Abstract We analyze daily extremes of precipitation produced by a six-member ensemble of Pan-Arctic Weather Research and Forecasting that simulated 19 years on the Coordinated Regional Downscaling Experiment Arctic domain. Analysis focuses on four North American regions defined using climatological records, regional weather patterns, and geographical/topographical features. We compare simulated extremes for the winter season with those occurring at corresponding observing stations in the U.S. National Climate Data Center's Global Summary of the Day. We define winter as the 3 month period leading up to and including the climatological sea ice maximum: January-February-March (JFM). Our analysis focuses on winter variations in features of extremes such as magnitudes, spatial scales, and temporal regimes. Using composites of extreme events, we also analyze the processes producing winter season extremes. We compare circulation, pressure, temperature, and humidity fields from the ERA-Interim reanalysis and the model output. Although the model produces lower amounts of extreme precipitation compared to observation, the model is simulating the physical forcing that is found during observed extreme events. Specifically, the model and reanalysis highlight the importance of low-level moisture advection and its interaction with topography. The analysis establishes the physical credibility of the simulations for extreme precipitation events in JFM and their associated atmospheric circulations, laying a foundation for examining projected changes in extreme precipitation.

1. Introduction

Extreme precipitation events in the Arctic can have substantial impact on both human and natural systems. The character of Arctic precipitation can change between winter and summer because of the large annual cycle of temperature, which leads to substantial liquid precipitation in summer but frozen precipitation in winter. Here we follow on an analysis of Arctic summer precipitation extremes from Glisan and Gutowski [2014] with a complementary analysis of winter extreme precipitation. In this paper, we focus on the winter season (January-February-March (JFM)) from the same 16 year ensemble simulation for analysis. Whereas smaller-scale circulation features (both spatial and temporal) may be important in summer, large-scale synoptic and topographical forcings are more likely responsible for a majority of winter precipitation events.

Substantial climate change is occurring in the Arctic, including sea ice depletion and stronger, more frequent cyclone activity [Zhang et al., 2004; Cassano et al., 2006; Zhang and Walsh, 2006; Serreze et al., 2009]. The Arctic is also projected to experience enhanced warming as much as twice as fast as the rest of the planets in the future [Randall et al., 2007; Serreze et al., 2009; Flato et al., 2013]. Tebaldi et al. [2006] showed that this enhanced Arctic warming should be a clear motivation for understanding how extremes will change in the future climate system, specifically their expected increased occurrences. In response to the increased warming, models studies from Kunkel [2003] indicate that extreme precipitation will also increase in the Arctic.

Our domain encompasses the Arctic where certain geographical features and circulation regimes are conducive to extreme precipitation events. For example, proximity to ocean bodies can provide substantial moisture, and topographical forcing can have significant impact on the production and maintenance of transient synoptic rainfall processes. Semipermanent pressure features (e.g., the Aleutian low, the Icelandic low, and the Canadian high) will also affect circulation characteristics within our analysis regions. The paper is organized as follows: Section 2 describes the Pan-Arctic Weather Research and Forecasting (WRF) model and analysis methodology. Section 3 describes our results, and section 4 gives our conclusions.
2. Analysis Methods

2.1. Simulations

We ran version 3.1.1 of the Weather Research and Forecasting-Advanced Research WRF [Skamarock et al., 2008], using parameterization choices discussed in Glisan and Gutowski [2014]. These included the subgrid cumulus scheme of Grell and Devenyi [2002] and the Goddard Cumulus Ensemble microphysical scheme [Tao and Simpson, 1993], the Mellor-Yamada-Janic planetary boundary layer scheme parameterization [Janjić, 1990, 1996, 2002], atmospheric radiation computed using the NCAR Community Atmospheric Model spectral band scheme [Mlawer et al., 1997; Collins et al., 2004], and the four-layer Noah land surface model [Chen and Dudhia, 2001] as modified for the polar regions by Hines et al. [2011].

Simulations used the Arctic domain specified by the Coordinated Regional Downscaling Experiment (CORDEX) [Giorgi et al., 2009]. The domain (Figure 1) contains most of the Northern Hemisphere’s sea ice cover and encompasses most of the Arctic drainage system. The Pan-Arctic WRF (PAW) used the standard CORDEX horizontal resolution of 50 km. The model also used 40 unequally spaced sigma levels for vertical resolution, with the model top at 0.5 hPa and the lowest level at 12.5 m above ground level.

We used the European Centre for Medium-Range Weather Forecasts ERA-Interim (EI) reanalysis [Dee et al., 2011] for lateral boundary conditions and sea surface temperature. Sea ice extent and fraction were specified from the Defense Meteorological Satellite Program Special Sensor Microwave Imager passive microwave satellite observations, which is available at the National Snow and Ice Data Center (NSIDC) [Comiso, 2008]. PAW produced a six-member ensemble for a period covering 1989–2007, which is an appropriate-sized ensemble for diagnosing Arctic climatology [Taschetto and England, 2008]. To produce the ensemble members, we chose a 24 h staggered start. Glisan et al. [2013] showed that this method allows the ensemble to develop adequate ensemble spread due to the model’s nonlinear internal variability. We discarded the first 3 years of the simulation since they were used to spin-up land surface processes.

![Figure 1](https://example.com/image1.png)

**Figure 1.** CORDEX Arctic 50 km domain with the North American analysis regions: Alaska North (AN), Alaska South (AS), Canada East (CE), and Canada West (CW). Individual analysis regions denoted by colored boxes. Coloring on the land portions of the plot represent topography height. Black dots represent NCDC stations.
2.2. Precipitation Analysis

In our study, we use the four North American analysis regions developed in Glisan and Gutowski [2014, Figure 1]; these regions are denoted Canada East, Canada West, Alaska North, and Alaska South and are described below:

1. Canada East: The Canadian Archipelago—Stations within this box are located on islands making up the archipelago. Nearly a quarter of these stations are north of the Arctic Circle.

2. Canada West: East of the Canadian Rockies—Stations here are in the Canadian interior, spanning the sub-Arctic Canadian plains.

3. Alaska North: North of the Brooks Range, plus Arctic Sea stations—Stations here all reside north of the Arctic Circle and are thus highly influenced by the Arctic Ocean (including sea ice processes and the circumpolar vortex).

4. Alaska South: South of the Brooks Range and west of the Canadian Rockies—Stations here are influenced by the North Pacific storm track.

Extreme precipitation events are extracted from each region using procedures presented in Gutowski et al. [2007]. Specifically, for each grid point in an analysis region, we pooled the daily precipitation during JFM from the multimodel ensemble and extracted the 99th percentile. We analyzed the spatial scale of extreme precipitation events and used a threshold of 25 or more concurrent grid point events to define what we term widespread events. Given the number of National Climate Data Center (NCDC) stations for each analysis region, 25 grid points is a good approximation of the spatial scale of extremes events. We used the National Climate Data Center’s (NCDC) Global Summary of the Day [National Climate Data Center, 2011], which provides surface observations of precipitation and air temperature. Within our simulation domain, there are over 150 stations available, some dating back to the 1940s. Even though NCDC performs quality control on the station observations, we require no more than four missing days per month for an acceptable station. If a station does not meet this threshold, it is excluded from the analysis; a total of 125 stations are used. Further analysis focused on these widespread extreme events.

For each analysis region, we divided the total number of model grid points by the total number of NCDC stations. This gave us a scaling factor for which we were able to determine observational widespread extreme event. One NCDC represents 14 and 16 model grid points for Alaska North and Alaska South, respectively; for Canada East and Canada West, 43 and 24 grid points, respectively.

2.3. Circulation Diagnostics

We are also interested in whether the long-term PAW simulations are producing behavior that is physically consistent with observations. To aid our investigation, we used seasonal mean plots of model bias in surface and upper level variables with respect to the reanalysis, using 16 year JFM averages. These biases allowed us to better understand areas that were more difficult to model in the winter season, such as over sea ice and within the circumpolar vortex, which is more isolated from the lateral boundaries than other parts of the domain. Relevant circulation features and dynamics for widespread extreme precipitation were diagnosed using composited fields of several WRF variables and compared against EI composites.

Using the widespread extreme criterion, we extracted the relevant days from the ensemble members and pooled them together. The pooled days were then averaged to create the composites. For observational comparison, we used the same steps for the NCDC stations to extract equivalent widespread extremes. Once we determined the relevant days, we used the EI reanalysis to produce composited fields. We also produced plots of anomalies with respect to the 16 year average of fields that were relevant for winter season extremes.

3. Results

3.1. Spatial Climatology Bias

The mean sea level pressure (MSLP) has its largest negative bias over topographical features (Figure 2a). This appears to be due to differences between the reanalysis and the model in how each data source computes MSLP in regions of high topography. Fox [2010] showed MSLP variability for the Canadian Arctic of up to 15 hPa during the cold season. Figure 2b shows differences in 500 hPa geopotential heights, ranging over ±20 geopotential meters (gpm). Wei et al. [2002] showed a daily variability in the 500 hPa heights of...
around 100 gpm. In terms of specific humidity, the most prominent biases are positive and occur over open ocean, including the Gulf of Alaska, which is a source region for moisture advection into Alaska South and Canada West (Figure 2c). Large cold biases for winter surface air temperature occur over sea ice and snow-covered land and collocated with the negative moisture biases (Figure 2d); Wei et al. [2002] found cold bias of as much as 10°C. These results suggest that PAW is systematically simulating colder and drier conditions over certain regions. Compared to the temporal variability of these fields in our analysis regions, the overall biases are relatively small.

### 3.2. Precipitation Frequency Versus Intensity

Figure 3 shows the pooled 16 year JFM daily precipitation’s frequency versus intensity for the four analysis regions. A fairly consistent behavior is evident: Pan-Arctic WRF underestimates extreme precipitation amounts. We have also placed arrows indicating the 95th and 99th percentiles for PAW and the NCDC observations. In general, the model is producing lower intensity extreme events when compared to NCDC. This is especially evident at the 99th percentile, where observed extremes are at least twice as intense as those produced in PAW.

Figure 4 shows the number of days having at least $N$ grid points exceeding the 99th percentile for each analysis region. PAW ensemble members and the NCDC observations are plotted separately. The plotted relationship indicates the frequency of events at different spatial scales. As we discussed in section 2.2, we use 25 model grid points to define a widespread extreme event. Figure 4 shows that this is about the place on the simultaneity plot where the ensemble members begin to diverge; at about 40 grid points, they completely diverge for three of the regions; Alaska North shows greater spread among ensemble members, with separation of curves from individual members occurring at $N = 10$ grid points. Note that this is the smallest of our analysis regions, and so the number of samples from each realization is less, a factor that might contribute to greater spread in the results.
Most important, the observations show fair agreement with the simulated curves; the model and observed curves differ by less than 10% on the log-linear scale used on the plots. The only exception can be found in Alaska South; here we find that the observed spatial extent for a given number of event days is somewhat larger when compared to PAW than in other regions. Otherwise, we find that the spatial scale for simulated extreme events is roughly the same as the observed scale, despite the weaker precipitation extremes in the simulations.

3.3. Interannual Variability of Daily Precipitation Extremes

Figure 5 shows the time series of winter seasonal frequency of widespread extreme events for Alaska South, as an example. The plots for each analysis region show that ensemble members agree most with each other in years with either very many or very few simulated extreme events; individual members showed greater disagreement in the interim years. Although there can be substantial spread among the ensemble members, the simulation is able to capture the observational variability well; the magnitude of interannual variability in the model is approximately the same as observed. Other regions also show similar variability behavior.

The analysis regions are in the higher latitudes, suggesting possible influence of the Arctic Oscillation (AO) on interannual variability. The AO involves fluctuations in surface pressure that affect storm tracks in the higher midlatitudes [Thompson and Wallace, 1998, 2001]. A positive (negative) phase indicates negative (positive) pressure anomalies over the Arctic region, with the opposite pressure anomaly equatorward. We compared the simulated and observed interannual variability to the Arctic Oscillation index. We found that the most positive AO index tended to coincide with years of high occurrences of precipitation extremes and years with negative AO index tended to be years with relatively few extremes. Our plots show a connection between years of increased precipitation extremes (1992, 1995, 1998, 2001, and 2003) and the positive phase of the AO; the positive phase suggests a poleward movement of storm tracks. Matsuo and Heki [2012] show that a positive phase of the AO produced increased precipitation in the high latitude. Sea level pressure composites for widespread extreme days show systematic low pressure over the eastern Arctic Ocean for all analysis regions.
Figure 4. Number of days having at least $N$ grid points with precipitation exceeding the 99th percentile in the Pan-Arctic WRF ensemble and NCDC station observations for (a) Canada East, (b) Canada West, (c) Alaska North and (d) Alaska South. The simulation ensemble members are denoted A–F. One NCDC station represents 43 grid points in Canada East, 24 in Canada West, 14 in Alaska North, and 16 in Alaska South.

Figure 5. The interannual variability of daily widespread extreme precipitation occurrences (%) in the Alaska South analysis region. The Pan-Arctic WRF ensemble mean is plotted in light blue. Whiskers showing the spread of the ensemble have also been plotted in light blue to show the ensemble member spread, which is shaded for emphasis. NCDC observations are plotted in red and the Arctic Oscillation (AO) Index is plotted in blue. The AO Index has been scaled by a factor of 5 in order to compare with PAW and NCDC.
These findings suggested that the AO is a contributing physical process to mechanisms governing the frequency of widespread extreme precipitation events. We found a modest correlation of 0.40 at a statistical significance of 95% between the PAW ensemble mean frequency and the AO index. However, the correlation is stronger in summer (62%) [Glisan and Gutowski, 2014]. There were not enough observational samples to obtain a statistically significant correlation.

When we cross correlate individual ensemble members for their annual time series of the number of widespread events, the amount of variance in one member’s time series that is explained by the other’s range from 4% to 75%, with typical values less that 50%. This suggests that the simulations are responding to common forcing, but only to a degree, as the variability of one member only partially explains the variability of the others. However, the spread of the PAW ensemble in the years with the most or fewest extreme events suggests that there are processes in the model controlling ensemble behavior. These results indicate that the occurrence of extremes in PAW may be related to the model’s internal variability, which was shown in Glisan and Gutowski [2014]. Thus, it is possible that the AO may be a contributing factor affecting the physical behavior during extreme precipitation events. The pattern of the AO may also explain the close connection exhibited between PAW and NCDC, suggesting that important aspects of the AO are being captured by the model.

3.4. Spatial Extent of Widespread Extreme Precipitation Events

Here we calculate the percent occurrence of widespread extreme events that occur at a given grid point within an analysis region. This gives us the ability to find favored locations for extreme events and then examine the pertinent physical mechanisms. Figure 6 was produced with this method and also includes composites of widespread daily averaged extreme precipitation.

Figure 6a shows that higher intensity daily extreme events occur on the eastern coast of Baffin Island (greater than 50% of the time). In terms of the highest widespread occurrence location, two focal regions appear—northern Ellesmere Island and eastern Baffin Island. However, the location of greatest widespread occurrence is over Ellesmere Island and not Baffin Island, where the highest-intensity events occur.

Locations with the highest-frequency widespread extremes do not have to occur in the same locations receiving the highest amounts of composited extreme precipitation. For example, a location with only a few widespread extremes could have substantial outlier precipitation (much greater than the typical extreme event) on days when it does have extreme precipitation.
However, each of the remaining regions has high-intensity precipitation collocated with the highest percentage of widespread events. This region was over the eastern stretch of the Canadian Rockies in Canada West (Figure 6b). In Alaska North, the northwestern section of the Brooks Range is the focal point (Figure 6c). In Alaska South, nearly 60% of extreme precipitation occurs in the coastal mountain ranges adjacent to the Gulf of Alaska (Figure 6d). This is consistent with orographic forcing, among other factors, influencing the event frequency.

3.5. Upper Level Circulation Features

To diagnose the circulations patterns associated with extreme precipitation events in the four analysis regions, we use various fields composited for the event days from both PAW and EI. In general, the composites exhibit approximately the same large-scale circulation pattern for each of the four analysis regions (not shown). For each region, composite 500 hPa circulation in the ERA-Interim reanalysis on days with widespread extremes shows a cutoff low situated between the Canadian Archipelago and Greenland. We also find a trough across the Arctic basin; Figure 7 is shown as an example of this behavior for Alaska South. The observed upper level circulation can be conducive for a poleward advection of midlatitude air. Similar behavior appears for widespread extremes in the PAW simulations. Overall, when we compare composites from each region, the large-scale patterns are similar. Glisan [2012] performed additional analysis of the large-scale composite patterns; while similar circulations were found for each analysis region, different synoptic signals were not being averaged together. Such a composite would not be representative of individual extreme events.

We also compared the event days between regions to determine how many of these days were shared among the analysis regions. We found that while a few days were shared with at most three regions, a vast majority were unique to one analysis box. This implies that although large-scale patterns had similarity across composites for each region, local responses to pattern details may be important for determining whether or not a given precipitation event is extreme and widespread.

3.6. Low-Level Moisture Convergence

We calculated the vertically integrated moisture flux vectors to determine whether moisture was pooling in areas collocated with extreme precipitation events (Figure 8). Each analysis region exhibits similar behavior in that vectors are flowing onshore from the adjacent ocean bodies and converging over land. The strongest implied convergence is also occurring within the same areas of the highest composited daily precipitation (e.g., Figure 6), thus creating a possible link between extreme precipitation and low-level moisture sources. The strongest implied moisture convergence is found in Alaska South analysis (Figure 8d). These results indicate that moisture flow into the analysis regions is impeded by high topography; such behavior induces orographically forced extreme precipitation. Additionally, the pattern of moisture convergence is similar across all analysis regions, which is what we also found for the large-scale circulations.
4. Conclusions

We have analyzed a 19 year CORDEX Arctic simulation produced by a polar-modified version of the WRF model to assess the capability of the Pan-Arctic WRF for producing winter (JFM) widespread extreme precipitation events. The simulation used a six-member ensemble and was forced with the ERA-Interim reanalysis and NSIDC sea ice concentrations. We discarded the first 3 years for spin-up and focused on output for winter.

We used the 99th percentile as our definition of an extreme precipitation event. Our analysis was restricted to daily widespread events in which 25 or more grid points in a region had an extreme precipitation. We used the analysis regions developed in Glisan and Gutowski [2014] to determine whether the temporal and spatial distribution of extreme events varied as a function of geography. We also extracted time steps matching the widespread criterion to create seasonal composite fields of pertinent variables for each analysis.

Figure 8. Vertically integrated moisture flux vectors (kg kg$^{-1}$ m s$^{-1}$) during extreme event days from (top) ERA-Interim and (bottom) Pan-Arctic WRF for (a) Canada East, (b) Canada West, (c) Alaska North, and (d) Alaska South.
region. Analysis of these composites along with the climatological deviation allowed us to develop an understanding of the physical mechanisms and associated circulations responsible for producing extreme behaviors. For comparison and validation, we used the same analysis procedure on EI output and NCDC station precipitation. Composites of observed surface and atmospheric fields allowed us to determine whether the simulated circulation features were consistent with real world processes producing extreme precipitation events.

To establish the utility of the simulations for extremes analysis, we first compared observed and simulated winter climatologies for several fields. As we showed in Glisan and Gutowski [2014] for summer, PAW and EI are in general agreement in their winter surface and atmospheric climatologies. We found the largest simulation departures from the EI in the surface temperature fields. This suggested a systematic PAW winter cold bias, mostly contained within the central Arctic and adjacent land regions, which appeared to be related to how PAW treats sea ice. In particular, PAW uses the standard WRF prescription for sea ice thickness of 2 m, which is likely too thick, thus limiting the amount of heat flux from the ocean to the atmosphere. Consistent with this cold bias, PAW also produced less low-level moisture over land than observed. The model did have a positive moisture bias over the Gulf of Alaska; this region was a source for moisture fetch into Alaska South and Canada West.

Using frequency versus intensity histograms, we found that PAW consistently underestimated extreme precipitation amounts compared to the NCDC station observations. We did find that simulation and observations agree at the lower end of the intensity spectrum, suggesting that the model was reproducing low precipitation events well. Moreover, the spread among ensemble members in JFM was much larger when compared previous results for JAS [Glisan and Gutowski, 2014].

The interannual variability of simulated widespread precipitation extremes was similar to the NCDC station observations. In general, years with very high or very low occurrences of observed extreme events were encompassed by the simulation ensemble. These results suggested that simulated extremes may be a function of PAW’s unforced internal variability. However, partial agreement among ensemble members during years with very high or very low occurrences suggested that a large-scale process may be a controlling factor, with the positive phase of the Arctic Oscillation showing some correlation with widespread extreme event interannual variability.

Across the four analysis regions, a consistent synoptic pattern was present during widespread extreme days. At the surface, a large area of high pressure extended westward from central Canada into Siberia with a region of lower pressure flanking this region. Combined with a cutoff low in the 500 hPa heights, we diagnosed a poleward advection of warmer air from the upper midlatitudes. In addition, we found low-level flow from adjacent ocean bodies into each region.

We constructed composite fields for the days with widespread extreme precipitation. This allowed us to analyze physical processes responsible for the events’ creation and maintenance. We found that regions of the highest-intensity daily extreme events were collocated with favored regions for widespread extreme events, except in Eastern Canada. Moreover, these regions are found over higher topographical features. Combined with the synoptic setup, flow over these features supports orographic precipitation, which appears to be the dominant mechanism for extreme event production.

The analysis shows that PAW simulates too few high-intensity events, consistent with the summer season [Glisan and Gutowski, 2014]. However, composite fields indicate that PAW simulates well atmospheric conditions responsible for precipitation events. Along with the NCDC station precipitation and EI reanalysis, Pan-Arctic WRF output has given us better insight into the nature of precipitation extremes in the four analysis regions; moisture fetch from adjacent bodies of water and orographic processes are important in the production of extreme events. This suggests synoptic circulation features supporting orographic precipitation may be the most important factor for widespread winter precipitation extremes in this part of the Arctic. Overall, the model is simulating physical processes leading to daily precipitation extremes well enough that they can be used to analyze changes in conditions producing extremes events in the future climate.

Acknowledgments
This research was supported by U.S. Department of Energy grant DEFG0207ER64463 and National Science Foundation grant ARC1023369. Computer support was provided by the University of Alaska Arctic Region Supercomputing Center (ARSC).

References