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Arctic daily temperature and precipitation extremes:
Observed and simulated physical behavior

By

Justin Michael Glisan

A dissertation submitted to the graduated faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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2012

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Simulations using a six-member ensemble of Pan-Arctic WRF (PAW) were produced on two Arctic domains with 50-km resolution to analyze precipitation and temperature extremes for various periods. The first study used a domain developed for the Regional Arctic Climate Model (RACM). Initial simulations revealed deep atmospheric circulation biases over the northern Pacific Ocean, manifested in pressure, geopotential height, and temperature fields. Possible remedies to correct these large biases, such as modifying the physical domain or using different initial/boundary conditions, were unsuccessful.

Spectral (interior) nudging was introduced as a way of constraining the model to be more consistent with observed behavior. However, such control over numerical model behavior raises concerns over how much nudging may affect unforced variability and extremes. Strong nudging may reduce or filter out extreme events, since the nudging pushes the model toward a relatively smooth, large-scale state. The question then becomes - what is the minimum spectral nudging needed to correct biases while not limiting the simulation of extreme events? To determine this, we use varying degrees of spectral nudging, using WRF’s standard nudging as a reference point during January and July 2007. Results suggest that there is a marked lack of sensitivity to varying degrees of nudging. Moreover, given that nudging is an artificial forcing applied in the model, an important outcome of this work is that nudging strength apparently can be considerably smaller than WRF’s standard strength and still produce reliable simulations.

In the remaining studies, we used the same PAW setup to analyze daily precipitation extremes simulated over a 19-year period on the CORDEX Arctic domain for winter and
summer. We defined these seasons as the three-month period leading up to and including the climatological sea ice maximum and minimum, respectively. Analysis focused on four North American regions defined using climatological records, regional weather patterns, and geographical/topographical features. We compared simulated extremes with those occurring at corresponding observing stations in the U.S. National Climate Data Center’s (NCDC’s) Global Summary of the Day. Our analysis focused on variations in features of the extremes such as magnitudes, spatial scales, and temporal regimes. Using composites of extreme events, we also analyzed the processes producing these extremes, comparing circulation, pressure, temperature and humidity fields from the ERA-Interim reanalysis and the model output. The analysis revealed the importance of atmospheric convection in the Arctic for some extreme precipitation events and the overall importance of topographic precipitation. The analysis established the physical credibility of the simulations for extreme behavior, laying a foundation for examining projected changes in extreme precipitation. It also highlighted the utility of the model for extracting behavior that one cannot discern directly from the observations, such as summer convective precipitation.
CHAPTER 1: GENERAL INTRODUCTION

1. Introduction

According to Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), the Arctic is expected to experience significant changes due to anthropogenic global warming. Of particular note, the Arctic has experienced twice the warming as the rest of the Earth over the last several decades (IPCC 2007). As the planet warms, various modeling studies have indicated that extreme temperature and precipitation events will also increase. Over North America, for example, extremes occurring every 20 years in the contemporary climate will occur twice as often in a warmer climate (Zhang et al. 2001). A general goal of this thesis is to understand Arctic extreme temperature and precipitation events and their simulation, setting a foundation for understanding how they may change in the future.

The increase in average temperature has already produced noticeable impact on the environment and ecology. Spatially widespread precipitation events not only increase freshwater run-off into the Arctic basin, but also exacerbate surface flooding via river ice damming in the cold season (Schindler and Smol, 2006). Additionally, permafrost melting has produced changes in the growth cycle of native tundra plants, many of which are vital in the food chains of Arctic birds and mammals (Romanovsky et al., 2002). This study also points to the impacts of permafrost melt on runoff, drainage, and groundwater, not to mention infrastructure constructed on top of these areas.
Since the Arctic is an integral part of the climate system, it greatly influences surface energy and moisture fluxes, as well as oceanic and atmospheric circulations. Studies of the Arctic confirm its vast importance to Earth’s climate including physical mechanisms that have the capability of producing or initiating abrupt climate changes (Clark et al. 1996; Foley 2005; Lindsey and Zhang 2005). Of particular note in the polar region is perennial sea ice, the ice that remains at the end of the summer minimum ice cover. Sea ice in the Arctic Ocean influences planetary climate system variability in two important ways. First, air-sea fluxes of heat, momentum, and moisture are affected by perennial Arctic sea ice (Maykut 1978). Second, perennial ice cover strongly influences the Earth’s ability to absorb incoming shortwave radiation, thus contributing to the ice-albedo feedback (e.g., Rind et al. 1995). This interaction is arguably the most important coupling between the global climate system and the Arctic (Curry et al. 1995).

The changes in the Arctic climate system suggest that we can expect substantial changes in extreme behavior in the coming decades. To ensure that we project these changes reliably, we need to understand first the nature of Arctic temperature and precipitation extremes and how well we can simulate them and their underlying processes.

2. Arctic Regional Climate Modeling for Extreme Events

It is important to establish the capability of regional climate models (RCMs) in producing temperature and precipitation events well. Compared to global climate models (GCMs), RCMs use higher horizontal and vertical resolutions. Over the polar region, typical GCM resolutions of 150-200 km may lack the ability to sufficiently capture atmospheric
processes responsible for the production of extreme events. This is especially pertinent in the summer season, since these processes are often produced by small-scale circulations that GCMs and even RCMs may not resolve (e.g. mesoscale convective events).

Nonetheless, even though RCMs have finer spatial resolution, there is still a need to establish how well they can replicate observed extremes and, even more important, the processes producing extremes. RCMs offer the opportunity to explore physical connections of the surface to the atmosphere. When studying the mechanisms responsible for precipitation, the resolutions provided by RCMs improve the simulated representations of significant topographical features. Mountain ranges and bodies of water, for example, can create regional circulations that are conducive to precipitation events. Furthermore, understanding the capabilities of RCMs to produce extremes lays an important foundation for assessing confidence in their ability to indicate future changes in extremes.

3. Dissertation Organization

The underlying theme of the dissertation is the analysis of extreme and spatially widespread temperature and precipitation events using Arctic climate simulations produced by the Pan-Arctic WRF (PAW). We have produced a set of short-term and long-term simulations of the Arctic as a means of exploring how extreme events are produced in our model and how they compare with observations. Moreover, we want to determine how the processes producing simulated extremes compare with those discerned from observations. For example, are these simulated extremes produced under certain atmospheric circulation regimes? Moreover, do these extremes occur under the same model conditions as what is observed?
As a means of answering these questions, we developed three studies to determine the validity of PAW in producing extremes correctly. Each paper also contains a discussion on literature that is pertinent to the case study.

a. Effects of Spectral Nudging on Temperature and Precipitation Simulations

Our initial analysis of PAW simulations indicated that a substantial circulation bias developed in the northern Pacific storm track region of our domain. This bias was manifested in mean sea-level pressure (MSLP), layer temperatures, and 500-hPa geopotential height fields. When we re-ran the initial simulation with WRF’s standard form of spectral nudging, we found that it substantially reduced the biases. Since spectral nudging is an artificial control over model behavior, we have concerns over how much it may affect unforced variability and extremes. Strong nudging may reduce or filter out extreme events, since the nudging pushes the model toward a relatively smooth, large-scale state.

The basis for Paper one is determining what minimum strength of spectral nudging is needed to minimize biases occurring on the RACM domain while not limiting PAW simulation of extreme events. We use eight spectral nudging strengths ranging from 2 to 1/128 times the default WRF value. Our study uses January and July 2007 as representative months for the winter and summer seasons. For winter, the PAW ensembles were initialized one day apart from 13-18 December 2006 and run through 01 February 2007. December PAW output was discarded, as the first two weeks of the run were used as spin-up. For the summer study, the ensembles were initialized one day apart from 13-18 June 2007 and run through 01 August
2007. June PAW output discarded, as the first two weeks of the run again were used as spin-up.

The analysis determines how changing spectral nudging strength impacts temperature and precipitation extremes. The maximum and minimum temperatures at each point from among the ensemble members are examined, on the 95\textsuperscript{th} and 99\textsuperscript{th} confidence intervals. The maximums and minimums over the simulation period are considered. Additionally, we use the National Climate Data Center’s (NCDC) Global Summary of the Day (NCDC 2011) to determine if the simulated processes producing precipitation extremes are consistent with observational processes. We also use the ERA-Interim Reanalysis (ECMWF 2009) for analysis of pertinent atmospheric fields.

\textit{b. WRF Summer Extreme Daily Precipitation over the CORDEX Arctic}

In paper two, we analyze precipitation extremes produced in 19-year ensemble PAW simulations over the Coordinated Regional Climate Downscaling Experiment (CORDEX) Arctic domain (Giorgi et al. 2009). We collect both individual grid point extremes and spatially widespread extremes for analysis. We are interested in the atmospheric circulations responsible for the creation of extreme events and how they are affected by seasonality and geography. Paper two covers the summer season, defined here as July-August-September, which are the three months leading up to and including the minimum in sea-ice cover. We use NCDC station data and the ERA-Interim reanalysis to determine if our simulations are producing observationally consistent results.
Within the study domain, stations are segregated into four geographical analysis boxes based on climatological records, regional weather patterns, and geographical/topographical features. Each station is considered an individual realization within their parent analysis box; hence each realization has a large number of samples, adding many degrees of freedom for statistical analysis. Observations are ordered and ranked by precipitation amount or temperature. We then find the extreme event threshold using both the 95th and 99th percentiles. We also use composites of diagnostic fields to find the spatial and temporal extent of the extreme events. Doing so will give us a greater understanding of the circulation mechanisms and scale dynamics responsible for the production of these extremes.

c. **WRF Winter Extreme Daily Precipitation over the CORDEX Arctic**

This study follows the same methodology as paper two, but focuses on Arctic winter, defined here as January-February-March. JFM are the three months leading up to and including the climatological maximum in sea-ice cover. In part because of differences in ice and snow cover, the characteristics and physical behavior of extreme events may differ between JAS and JFM, thus the basis for examining JFM separately.

This dissertation concludes with a final section in which the general results of the three studies are summarized. Additionally, the findings will be synthesized in a manner that allows us to outline future studies and shed light on possible broader-scale conclusions concerning Arctic-based extreme events and their production mechanisms.
4. References


CHAPTER 2: EFFECTS OF SPECTRAL NUDGING ON TEMPERATURE AND PRECIPITATION SIMULATIONS

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1. Abstract

Pan-Arctic WRF (PAW) simulations produced using a 50-km domain developed for the fully-coupled Regional Arctic Climate Model (RACM) were found to produce deep atmospheric circulation biases over the northern Pacific Ocean, manifested in pressure, geopotential height, and temperature fields. Possible remedies to correct these large biases, such as modifying the physical domain or using different initial/boundary conditions, were unsuccessful.

Spectral (interior) nudging was introduced as a way of constraining the model to be more consistent with observed behavior. However, such control over numerical model behavior raises concerns over how much nudging may affect unforced variability and extremes. Strong nudging may reduce or filter out extreme events, since the nudging pushes the model toward a relatively smooth, large-scale state. The question then becomes - what is the minimum spectral nudging needed to correct biases while not limiting the simulation of
extreme events? To determine this, we performed case studies using a six-member PAW ensemble on the RACM grid with varying spectral nudging strength, using WRF’s standard nudging as a reference point. We simulated two periods, one in a cold season (January 2007) and one in a warm season (July 2007).

Precipitation and 2-meter temperature fields were extracted from the output and analyzed to determine how changing spectral nudging strength impacts both temporal and spatial temperature and precipitation extremes. Temperature and precipitation maximums and minimums over the simulation period were also examined. Results suggest that there is a marked lack of sensitivity to varying degrees of nudging. Moreover, given that nudging is an artificial forcing applied in the model, an important outcome of this work is that nudging strength apparently can be considerably smaller than WRF’s standard strength and still produce reliable simulations.
2. Introduction

Limited area models for climate simulation pose an issue of how one ingests time-varying lateral boundary conditions. Davies (1979) introduced the concept of a “sponge zone” as a means of reducing spurious features such as reflections at the lateral boundaries. These reflections would appear as transient waves and act to produce anomalous behavior within the domain. In the sponge zone, the model solution is damped towards a specified external data set with the damping becoming progressively stronger as one moves towards the edge of the domain. However, substantial bias may still develop within the interior of the domain.

Waldron et al. (1996) introduced the concept of spectral or interior nudging as a means of reducing anomalous behavior in regional simulations driven by global reanalyses. This additional damping towards the external data set is weaker and focused on the interior of the domain. This forcing allows simulated large-scale fields advecting across the domain to remain consistent with the external data set at the boundaries.

Miguez-Macho et al. (2004) provide greater detail on the interaction of regional model solutions with external boundaries. The most prevalent effect of this interaction is the alteration of the large-scale circulation. Circulation modification results from the incompatibility between the boundary conditions and model solution. This produces a domain-wide interaction between the lateral boundaries and model dynamics. As noted, the sponge zone helps promote smooth transition from the lateral boundaries to the interior. Miguez-Macho et al. (2004) also show that various domain sizes yield differing degrees of model drift as well as different precipitation values. Including spectral nudging effectively corrects the precipitation biases.
The internal forcing introduced by spectral nudging occurs by adding terms to certain model equations, such as horizontal momentum and thermodynamics equations (von Storch et al. 2000; Alexandru et al. 2009). These terms nudge model fields toward the externally specified driving fields. Since these are artificial terms added to the governing equations, care is needed to avoid introducing more error into the simulation. Also, the strength of the nudging can vary with height and field. Von Storch et al. (2000) suggests that since the large-scales tend to be rather deep, these nudging terms should be confined to levels away from the surface, allowing the smaller-scales near the surface freedom to respond to local processes.

Spectral nudging can also be limited by which wavelengths are nudged. This is determined in part by how well the boundary-conditions data set can reliably resolve a given wavelength. While there have been several studies on the subject of spectral nudging, there appears to be little analysis on the sensitivity of simulations to the strength of the nudging in regional climate simulation. Von Storch et al. (2000) did give some consideration to impacts of strength of the nudging in a one-month run, but suggested more comprehensive study is necessary. Various other studies have found spectral nudging may improve precipitation simulations (Cha and Lee, 2009; Tang et al., 2009; Colin et al., 2010; Song et al., 2011) or have a neutral effect (Yhang and Hong, 2011).

Alexandru et al. (2009) performed a series of experiments using the Canadian Regional Climate Model to determine benefits and drawbacks to altering degrees of freedom in regional climate simulation via spectral nudging. Three case studies involved changing the level at which the nudging was turned on. A fourth case doubled the nudging while making it constant throughout all levels. Their results indicated an inverse relationship between
nudging strength and internal variability. Furthermore, a marked decrease in extreme precipitation occurred as nudging increased.

In this study, we use a polar-optimized version of the Weather Research and Forecasting (WRF) model to produce a six-member ensemble simulation for two case studies, January and July 2007, over a 50 km pan-Arctic domain. The use of interior nudging is especially important in our domain, because it includes the circumpolar vortex. Because the circumpolar vortex is contained within the model, there is much less flow across lateral boundaries compared to mid-latitude simulation, so the influence of the lateral boundary conditions inside this region is weaker.

The analysis focuses on four regions in our simulation domain to diagnose the effect of varying spectral nudging on mean and extreme 2-m temperature and daily precipitation fields. Of particular interest is determining a possible optimal nudging strength for minimizing large-scale, systematic circulation errors, while also minimizing errors in mean and extreme fields. The question then becomes - what is the minimum spectral nudging needed to correct the biases occurring on the RACM domain while not limiting the model’s ability to produce extreme events?

The paper is organized as follows: Section 2 describes the Pan-Arctic WRF model. Section 3 describes the simulation setup as well as the data used to force the model. Section 4 details the evaluation methodology for analysis. Section 5 presents the results of nudging strength on 2-meter temperature and precipitation as a function of season and analysis region. Section 6 summarizes the results and gives our conclusions.
3. Pan-Arctic WRF (PAW)

We use version 3.1.1 of the Weather Research and Forecasting – Advanced Research WRF (WRF-ARW), (Shamrock et al., 2008). Selection of Arctic-appropriate physical parameterizations was an important consideration for our model simulations. This parameterization set is similar to the choices developed by Cassano et al. (2011) for Arctic simulation, with further modifications based on work by M. Seefeldt (unpublished data, 2010). We use the sub-grid cumulus scheme developed in Grell and Devenyi (2000) and the Goddard Cumulus Ensemble (GCE) models (Tao and Simpson, 1993) microphysical scheme, with three categories of ice-phase. From Janic (2001) we used the Mellor-Yamada-Janic (MYJ scheme) for the planetary boundary layer (PBL), which is based on similarity theory from Monin and Obukhov (1954). Short and longwave radiation was parameterized by the NCAR Community Atmospheric Model (CAM 3.0) spectral-band scheme (Collins et al., 2004; Mlawer et al., 1997). A polar-specified land surface model (LSM) was also an important addition to our simulations; we used the 4-layer Noah LSM (Chen and Dudhia, 2001) as modified in Hines et al., (2011). Additionally, the sea ice albedo and emissivity were set at 0.80 and 0.98, respectively.
4. Simulations and data preparation

a. Pan-Arctic WRF simulations

Pan-Arctic WRF (PAW) was designed to produce simulations on a domain developed for the Regional Arctic Climate Model (RACM) Project (Maslowski et al. 2007). This modified polar domain includes 205 (275) south-north (west-east) points with 50-km grid spacing (Fig. 2.1). The RACM domain contains all of the Northern Hemisphere’s sea ice cover as well as all of the Arctic river-drainage system. Moreover, it contains critical inter-ocean exchange and transport features, such as horizontal advection of warm ocean water into and under sea ice cover from the Pacific and Atlantic (Stroeve and Maslowski, 2007). Taken together, these processes are important for regional climate modeling. Vertical resolution uses 40 model levels, with the model top at 0.5-hPa and the lowest level at 12.5 meters above ground level.

Initial long and short-term simulations from the uncoupled PAW showed a systematic, strong low-pressure bias co-located with the North Pacific storm track. The bias appeared in surface fields (MSLP, 2m-T) and throughout the depth of the atmosphere in geopotential heights and layer temperatures. The bias occurred throughout the year, despite different choices in forcing data set, length of simulation, location of lateral boundaries, and changes in physical parameterizations.

Spectral nudging emerged as a method to minimize the bias. However, concern arose that for sufficiently strong nudging, weather extremes would be suppressed. Also, since spectral nudging introduces an artificial forcing into the model, minimizing such forcing is
important. Hence, we explore here the sensitivity of mean and extreme model behavior to nudging strength.

\textit{b. Experimental design}

In the study simulations, the strength of the nudging varies about the default WRF value of $3.33 \times 10^{-4}$ s$^{-1}$ (50 minutes), ranging from $2 - 1/128$ times the default. The various coefficients and associated nudging times can be found in Table 2.1. The model applies nudging with equal strength to four fields: The zonal and meridional wind components, temperature, and perturbation geopotential height. The default implementation has no nudging below 500-hPa, and varies with height at higher levels according to nudging equation as introduced in Miguez-Macho et al. (2004) and implemented in the version of WRF:

\[
\frac{dQ}{dt} = L(Q) - \sum_{|n| \leq N} \sum_{|m| \leq M} K_{mn} \cdot (Q_{mn} - Q_{omn}) e^{ik_{mx}} e^{ik_{ny}}
\]

(1)

$Q$ represents the prognostic variable being nudged, $L$ is the model operator, and $Q_o$ is the driving field variable. $Q_{mn}$ and $Q_{omn}$ represent the spectral coefficients of $Q$ and $Q_o$. $K_{mn}$ is the nudging coefficient that can vary with $m$ and $n$ (wavenumbers in the $x$ and $y$ direction, respectively) as well as height. $K_m$ and $k_n$ then represent the wave vector and are dependent on the domain size, $D_x$ and $D_y$, given by:

\[
k_m = \frac{2\pi \cdot m}{D_x}; \quad k_n = \frac{2\pi \cdot n}{D_y}
\]

(2)
We retain this vertical nudging profile throughout our experiments as well as the same domain (Fig. 2.1). We also nudge the first two horizontal wavelengths. Part of the analysis determines how the magnitude of nudging impacts daily average temperature and precipitation. In addition, we examine in each of our analysis regions the warmest and coolest 1% and 5% values of temperature and the strongest 1% and 5% values of daily precipitation from among the ensemble members. We look at these extremes for four sub-regions within the domain. We also examine the difference between time means in each realization and observations to assess the sensitivity of mean fields to nudging.

c. Boundary conditions

Forcing data for PAW uses two input data sets. For initial conditions, simulations use the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (ECMWF 2009). The ERA-Interim output is available on a reduced Gaussian grid with a uniform, approximately 79-km horizontal grid spacing and sixty vertical levels, up to 0.1-hPa. The ERA-Interim fields are available every six hours, starting from 1989 through 2007. The model also uses the Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I satellite sensors (Comiso 2008) archived at the U.S. National Snow and Ice Data Center. The native grid for the ice concentration data is the SSM/I polar stereographic grid, with 25-km grid spacing.
d. Validation data

Model validation compares the output against two data sets. We use the National Climate Data Center’s (NCDC’s) Global Summary of the Day (NCDC 2011), which provides both temperature and precipitation observations. Within the RACM domain there are nearly 150 stations with available observations, some of which date back to the 1940s. While NCDC does perform quality control on the station data, to ensure data continuity, our analysis requires that an acceptable station have no more than four missing days in any month.

The second data set is the ERA-Interim reanalysis (ECMWF 2009), which provides output for atmospheric fields (e.g. MSLP, humidity, level temperatures, 500-hPa heights) and statistical analysis. We do not use ERA-Interim precipitation because it is a model product that is not constrained by precipitation observations.

5. Evaluation Methodology

We are interested in how well PAW produces observationally consistent mean and extreme behavior in the Arctic as well as how both are affected by various degrees of spectral nudging. To determine sensitivity to nudging strength and ultimately an optimum choice, we devised a standardized experimental design for two case studies: one winter month and one summer month. Each case study uses eight spectral nudging strengths, and each nudging strength in turn uses a six-member ensemble, thus producing six months of simulation for each nudging coefficient. Overall, each seasonal case has 48 months of simulation.
   a. Ensemble members were initialized one day apart from 13-18 December 2006 and run through 01 February 2007
   b. December PAW output discarded, as the first two weeks of the run were used as spin-up

2. Summer Case: June – July 2007
   a. Ensemble members were initialized one day apart from 13-18 June 2007 and run through 01 August 2007
   b. June PAW output discarded, as the first two weeks of the run were used as spin-up

   a. Analysis regions

To analyze the influence of nudging on mean and extreme behavior, we selected sub-regions within the domain for more detailed analysis. Of particular interest were regions in proximity to the northern Pacific bias region as well as the North American land mass contained in the RACM domain that was downstream from the strong bias. We focused on four regions:
1. Alaska: This region is downstream of the strong bias region and contains topographical features that interact with the large-scale flow.

2. North America: This is the largest of the analysis regions. Its importance here occurs because it contains a large portion of Arctic drainage basins. Also, it is downstream of the bias region and adjacent to the circumpolar vortex flow that potentially brings into the region heat and moisture from the bias region.

3. Northern Pacific: This is the region where the largest model bias occurs when there is no nudging.

4. Siberia: This is poleward and upstream of the bias region. This analysis region also contains important topographical features and Asian-Arctic drainage basins

\[b. \text{ Differencing and statistical analysis}\]

We show the effectiveness of spectral nudging in minimizing the northern Pacific bias using monthly time-averaged bias plots for selected variables; these fields will aid in our understanding of how nudging affects the mean state. Another important analysis is the relationship between simulations using different nudging coefficients. This is necessary to determine how the mean and extreme behaviors are modified via nudging and which coefficient(s) is the optimum for retaining observationally valid mean model behavior. More
important, we ask the question: how sensitive are temperature and precipitation extremes to nudging strength and can some ranges of nudging produce similar results (suggesting model insensitivity, for example)?

Our analysis involves a number of steps. We calculate ensemble means and percentiles for each nudging strength and compute the sensitivity of model behavior to changes in the nudging strength using the Tukey Honestly Significance Test (HSD; Ott 2001). The Tukey test also includes an Analysis of Variance (ANOVA) for assessing the significance of changes as the strength of the nudging is changed.

The power of the Tukey HSD is that it compares the means of all possible pairs from the group pool. Here, the pool is the output from the eight nudging coefficients plus the applicable observations. This procedure assumes that all tested samples are independent and have equal variation – a condition known as homoscedasticity. In essence, Tukey HSD calculates how large the mean difference among group members must be for any two individual members to be significantly related. The formula for the Tukey HSD is as follows:

\[ HSD = \frac{Y_{\text{max}} - Y_{\text{min}}}{SE} \] (3)

where \( Y_{\text{max}} \) (\( Y_{\text{min}} \)) is the largest (smallest) of the pair-wise means being compared and SE is the Standard Error of the group pool.

After segregating the PAW output into the sub-regions, we used a ranking process for the daily extremes of temperature and precipitation. Ranking the Tukey-analyzed extreme values allows a better determination of the effects of nudging on extreme behaviors. Nudging
strengths that are significantly related are grouped together, thus giving us an understanding of the degree of model sensitivity to changes in nudging. The ranking procedure followed these steps:

1. Perform Tukey analysis on each RACM sub-region separately for mean temperature and precipitation
   a. Daily precipitation included eight SN coefficients and NCDC observations (N = 9 available values)
   b. Daily temperature included eight SN coefficients, ERA-Interim, and NCDC observations (N = 10 available values)
2. Create an N x N grid, with x-axis = rank order, y-axis = nudging strength
3. Follow same procedure for each percentile
   a. Daily precipitation: 95th and 99th
   b. Daily temperature: 1st, 5th, 95th, 99th

For each case study, we created rank matrices for each analysis region. Some analysis regions showed similar behavior, so we placed them on the same ranking matrix (e.g. Fig. 2.2). Each cell in the rank matrix was then sub-divided so that each set of percentiles could be plotted together. For temperature, we plotted the cold (warm) percentile using blue (red) symbols with the 50th percentile plotted as black. In instances where the rank of the cold and warm percentiles coincided, purple was used. Since precipitation only contains three percentiles, gray-scale shading was used, with black as the mean.
More importantly, the patterns among the percentiles show how the mean and extreme behaviors are related. Comparing ranking matrices for different fields and percentiles can reveal common patterns of nudging sensitivity. While this ranking procedure is important in determining an optimal nudging strength, the magnitude of change among the nudging coefficients compliments the ranking analysis. We plot individual percentile values for the nudging coefficients and observations to show the magnitude spread among the group members (e.g. Fig. 2.10). Specifically, a measure of the magnitude of change (within a percentile) as nudging strength changes will give us an idea of the behavior of a region over and above the statistical ranking. Thus we supplement the matrix presentation with information showing the sensitivity of results to nudging strength.

6. Results

a. PAW – Era-Interim time-average bias

We analyzed monthly spatial mean fields of MSLP, two-meter temperature, 500-hPa geopotential heights and layer temperatures in order to determine the pre and post-nudging PAW biases versus ERA-Interim output. Table 2.2 shows biases in these fields for each of our target regions with no nudging and with WRF’s standard nudging strength. As mentioned in Section 3, the initial simulation on the RACM domain produced large, time-average bias within the North Pacific storm track. In our analysis sub-regions, the largest biases occurred in the ocean analysis region followed by the Alaska sub-region. Spectral nudging substantially reduced the bias for nearly all fields in Table 2.2. The exception was 2-m temperature, which
would already have relatively small bias because the model uses specified sea-surface

temperature. There also appears to be a seasonal pattern in that the January case produces

much higher biases than the July case.

Spectral nudging proves extremely beneficial in correcting the biases in all of the state

and diagnostic fields for both case months. We find an interesting feature when comparing

each set of monthly mean field plots (not shown) corresponding to the nudging coefficients,

with each other. While minor differences can are found, in general, the amount of correction

for any given nudging coefficient is not significantly different from any other coefficient. This

suggests that for monthly spatial means, spectral nudging at any strength aids in the

minimization of the initial anomalous behavior. In other words, Pan-Arctic WRF appears to

be insensitive to the amount of prescribed nudging.


When analyzing the Tukey HSD output with respect to the most extreme values of
daily precipitation over the four sub-regions, a very noticeable pattern emerges (Fig. 2.2). As

the nudging strength decreases in PAW, the extreme values also decrease in rank - the

stronger the nudging, the larger the extreme values. This pattern is somewhat more

pronounced when considering the 50\textsuperscript{th} percentile behaviors. In comparison with the NCDC

station data, the higher values of nudging coefficients show closest agreement with the

observations.

When considering only PAW output plotted in figure 2.2, the standard and half

coefficients yield the most extreme daily precipitation values. A notable outlier is present in
that the Siberian sub-region exhibits a reverse behavior (Fig. 2.3). When the nudging strength is increased, the extreme values decrease.

The NCDC observations yield the largest mean values across all percentiles (50th, 95th and 99th percentiles) for the land sub-regions. This is consistent with what we found in the analysis of extremes. In comparison the largest means produced by our simulations correspond to the strongest spectral coefficients, namely full and half. Thus, when considering the mean behavior across all percentiles, the general behavior indicates that a decrease in nudging strength produces a decrease in the mean values.

Siberia exhibits a consistent reversal in behavior as detailed in the extreme analysis. When we compared the slope of the Tukey ranks, an interesting feature was found. Around the lower end of the spectral nudging strength, an intersection point was found between Siberia (negative rank slope) and the other land sub-regions (positive rank slope) around the 1/8th and 1/16th coefficients. This suggests that a lower nudging strength may be appropriate for all regions, especially when compared to the NCDC observations.

c. Daily precipitation Tukey analysis – July 2007

When we analyzed the July results for extreme values, the general behavior discussed in the January case is reversed (Fig. 2.4). As the nudging increases, the extreme values of precipitation decrease. However, as in the January case, the NCDC observations have the highest extremes in the Alaska and North America sub-regions. One departure is found in the Ocean and Siberian locations, though (Fig. 2.5). The highest extreme values occur using the
1/8th spectral nudging coefficient. Moreover, these two sub-regions show very irregular behavior when ranked, making a determination of rank slope somewhat difficult.

In contrast to the January Tukey group means, all land sub-regions exhibit a decrease in behavior of the 50th percentile as the nudging strength is increased. We found that the Ocean region exhibits an opposing mean behavior; the highest mean values across the full field and extreme percentiles are found at the high end of the nudging spectrum.

Siberia stands out as a sub-region because its Tukey ranking is noisier when compared to the other regions. This suggests the model’s insensitivity to changes in the nudging strength. When the mean results are taken all together, the weakest nudging produces the mean behaviors in closest agreement with the NCDC observations.


We examined the high and low extremes for all four sub-regions during a specific month. Tukey HSD analysis of the 1st, 5th, 95th, and 99th temperature percentiles provides information on how model behavior varies given nudging strength.

During the January 2007 case, the lowest (coldest) temperature extreme values for the land sub-regions occur in the ERA-Interim output, followed by the NCDC data (Fig. 2.6). For the model output, the 1/128th coefficient produced an extreme value closest to the observations. Therefore, the weakest nudging produced results that are more akin to those temperature extremes produced in the Arctic.

The Siberian and Ocean regions are noisier than the other sub-regions and their Tukey rankings varied strongly about the axis of general behavior (Fig. 2.7). The rank pattern
indicates that weaker nudging generated colder extreme temperatures. This is the same pattern we find in the January precipitation extremes. The full and half coefficients produce the warmest January temperature extremes in the simulations. The Tukey ranking is consistent with what was observed in the January extremes.

The mean behavior found in the Tukey analysis for the 1st, 5th, and 50th percentiles suggests weaker coefficients produced warmer means. When compared to observations, the 50th percentile is still warmer; weaker nudging produces mean temperatures closest to the observed.

e. Daily two-meter temperature Tukey analysis – July 2007

The coldest extremes for the summertime occur in the ERA Interim and NCDC data. In all previous analyses presented here, the relationship between nudging and extremes was linear. For July, we find that the ranking was much noisier (Fig. 2.8 and 2.9). It also appears as if there were two axes of behavior. Positive (increasing nudging strength creates cooler extremes) between the 1st and 5th rank groups and negative (increasing nudging creates warmer extremes) from the 6th to the 10th rank groups.

For the warmest summer extremes, we find a consistent pattern, as seen in the precipitation fields, that decreasing the nudging strength decreases extreme values; extremes become warmer as nudging becomes stronger.

The mean values for the 50th, 95th and 99th percentiles show PAW produces the warmest temperatures when nudged with one of the three strongest coefficients. These three strengths represent the closest model realizations to the ERA-Interim reanalysis and NCDC
station observations. The Tukey ranking, in agreement with the precipitation analysis, indicates that stronger nudging yields warmer median temperatures in the model simulation.

\( f. \) **Magnitude spread among spectral nudging coefficients within a percentile**

The mean behavior for all sub-regions and in both case studies produced the smallest spread among the nudging coefficients while the highest extremes in rainfall produced the largest spread. This behavior was responsible for the greatest sensitivity to the nudging strength (Fig. 2.10). Alaska and Oceana had the largest spreads while Siberia and North America showed the smallest. The NCDC observations were not used in the precipitation plots as they are appreciably larger than the model output.

In Figure 2.11, both model output and observations were used for the daily temperature. For the land regions, we found a relatively small difference in the spread among all percentiles, averaging on the order of 5°C. Oceana showed little, if any, spread as sea surface temperatures modulate the air temperature above the surface. In terms of observations, both data sets were generally warmer in all sub-regions, with the exception of Oceana. However, there was good agreement with PAW output.

This then implies that an important thing to consider when assessing “optimum” choices for spectral nudging coefficients is how the magnitude of spread for a given percentile is related to its rank matrix. If the amount of spread is negligible, then the ranking results are not as important. Such results indicate that the model is insensitive to nudging strength. On the other hand, if a large degree of spread occurs, the rank matrix gives a better indication of the coefficient (or range of coefficients) that produces the most realistic results.
7. Discussion and Conclusions

Spectral nudging can constrain a model to be more consistent with the observations. However, since nudging is an added artificial forcing on model behavior, inappropriate nudging can smooth extreme events even while yielding realistic mean behavior. Thus, this study was developed to analyze how changing the strength of the interior nudging would affect the circulation biases observed in the non-nudged PAW runs. Daily two-meter temperature and total precipitation extremes were analyzed during two periods, January 2007 (cold season case) and July 2007 (warm season case) for eight spectral nudging strengths.

Monthly time-averaged plots of biases for several diagnostic variables showed the extent to which nudging minimized anomalous regions of behavior in non-nudged PAW. When comparing different degrees of bias among the varying strengths, we found the differences between the coefficients were negligible. This suggests that the mean behavior as produced by PAW is not sensitive to changes in nudging.

Using statistical analysis, each of the eight nudging strengths were compared against each other and the observations, using Tukey Honestly Significant Difference (HSD) for each sub-region and case month. Ranking the mean and extreme behaviors together in matrix format allowed for a better understanding of how specific nudging strengths affect individual sub-regions. Furthermore, grouping sub-regions by similar behavior gave us a clearer picture of which nudging strength(s) were most efficient, i.e. the range of strengths that produced the most observationally realistic mean and extreme model performance.

Precipitation ranking indicated that in both January and July cases, the NCDC station observations ranked first in all percentiles with the largest magnitude extremes. This suggests
that PAW is under-producing extreme precipitation. When comparing the nudging coefficients in January, we found that a decrease in nudging leads to a decrease in the mean and extreme precipitation behavior in the North American and Alaska regions. A noticeable inverse relationship was found in Siberia as the behavior is opposite of the other land regions. At least in the cold season, Oceana exhibited a pattern consistent with North America and Alaska.

In July, the pattern of percentile ranking reverses from the January case in all three land regions. As nudging decreases, we found a general increase in values for each percentile. For Oceana, the general behavior of all percentile rankings was instead a decrease. The implications of these results are clarified further when coupled with the change of magnitude plots (Fig. 2.10). The spread among the nudging coefficients indicates that there is sensitivity in the model behavior to nudging. Moreover these results indicate that nudging less than the WRF default produces model output more consistent with the observations.

NCDC observations and the ERA Interim reanalysis were used in the temperature analysis and always had the highest rank, i.e., their extremes had greater magnitude. The temperature distribution was normal (not shown) so we analyzed the cold and warm extremes on either side of the 50th percentile. The North American and Alaskan regions exhibited a dual behavior in the ranking. When nudging was increased, the 1st and 5th percentiles decreased while the 95th and 99th percentiles increased. This result implied the lowest nudging ranges produce results on the order of the observations for the cold extremes, while stronger nudging may yield warm extremes more in-line with the observations. Siberian and Oceana rankings were much noisier, but their patterns were consistent with the larger sub-regions.

The July analysis for Alaska and North America showed a more consolidated behavior
for all percentiles. As nudging was increased, percentile means increased, indicating that stronger nudging may be more beneficial in driving the model towards observations. Again it is important to look at the magnitude of change plots for an indication of how differences in nudging affect the magnitude of precipitation extremes (Fig. 2.11). A larger (smaller) spread suggests more (less) sensitivity to nudging. The spread among the nudging strengths was much smaller than the precipitation spread implying that the rank procedure may not have as much power. Indeed, when looking at North America and Oceana, negligible changes are seen; Alaska and Siberia show larger spreads.

8. Synthesis

The analysis in our paper suggests that the nudging necessary to decrease the amount of model bias can vary seasonally and geographically. We also show that this holds true for specific atmospheric fields – namely precipitation and temperature.

Our analysis of daily precipitation shows that stronger nudging, on the order of full to half the WRF default, produces mean and extremes consistent with observations. For the summer season, our results show weaker nudging is more in line with the NCDC stations. Interestingly, we find the opposite behavior when evaluating the surface temperature fields. Weaker (stronger) nudging produces observationally realistic model output in January (July).

When we consider the original circulation biases in the non-nudged cases, we show that winter bias was larger than in summer. Further evidence is found in the percentile magnitude spread. Magnitude plots show a much larger range of values for the January mean
and extreme percentiles. These features indicate that the winter season is more sensitive to changes in nudging strength.

Because we find multiple nudging outcomes due to seasonality, geography, and atmospheric fields, we believe our statistical analysis points to an optimal nudging range for pan-Arctic based simulations. Considering the Tukey HSD ranking and magnitudes spreads for precipitation, we recommend choosing a nudging strength in the range of 1/8th to 1/16th the WRF default value. Of course, the ultimate goal of climate simulations should be to improve the modeling sufficiently that nudging is no longer a necessary step in producing observationally realistic output.
9. References


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Table 2.1: Spectral nudging strengths $[s^{-1}]$ and associated time $[s]$.

<table>
<thead>
<tr>
<th>Coefficient Name</th>
<th>Nudging Strength $(s^{-1})$</th>
<th>Nudging Time (days)</th>
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</thead>
<tbody>
<tr>
<td>Double</td>
<td>0.00066</td>
<td>0.02</td>
</tr>
<tr>
<td>Full*</td>
<td>0.00033</td>
<td>0.04</td>
</tr>
<tr>
<td>Half</td>
<td>0.000165</td>
<td>0.07</td>
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<tr>
<td>Quarter</td>
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<tr>
<td>Eighth</td>
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</tr>
<tr>
<td>Sixteenth</td>
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<td>0.56</td>
</tr>
<tr>
<td>128th</td>
<td>0.000002578</td>
<td>4.5</td>
</tr>
<tr>
<td>Zero</td>
<td>0.00</td>
<td>--</td>
</tr>
</tbody>
</table>

* denotes the WRF default spectral nudging value
Table 2.2: Selected diagnostic field biases pre and post nudging over the RACM domain. The left column under each month represents the bias between the non-nudged model (Pan-Arctic WRF; PAW) and observations (ERA-Interim; EI). The right column under each month represents the bias between the nudged model and observations. The right most column represents the analysis region.

<table>
<thead>
<tr>
<th></th>
<th>January 2007</th>
<th>July 2007</th>
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<tbody>
<tr>
<td></td>
<td>PAW/EI</td>
<td>SN PAW/EI</td>
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<tr>
<td>MSLP (mb)</td>
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<tr>
<td></td>
<td>12</td>
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<td></td>
<td>10</td>
<td>4</td>
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<td></td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Z500 (gpm)</td>
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<td>175</td>
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CHAPTER 3: WRF SUMMER EXTREME DAILY PRECIPITATION OVER THE CORDEX ARCTIC

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1. Abstract

We analyze daily precipitation extremes produced by a six-member ensemble of the Pan-Arctic WRF that simulated 19 years on the CORDEX Arctic domain for the Arctic summer. Analysis focuses on four North American analysis regions defined using climatological records, regional weather patterns and geographical/topographical features. We compare simulated extremes with those occurring at corresponding observing stations in the U.S. National Climate Data Center’s (NCDC’s) Global Summary of the Day. Our analysis focuses on variations in features of the extremes such as magnitudes, spatial scales and temporal regimes. Using composites of extreme events, we also analyze the processes producing these extremes, comparing circulation, pressure, temperature and humidity fields from the ERA-Interim reanalysis and the model output. The analysis establishes the physical credibility of the simulations for extreme behavior. It also highlights the utility of the model for extracting behavior that one cannot discern directly from the observations such as convective precipitation.
2. Introduction

Extreme precipitation events can affect both human and natural systems. If these events are spatially widespread, both systems can experience substantial impacts, such as flooding and land erosion. Run-off from land-based extreme precipitation events also contributes to the Arctic Ocean’s relatively fresh surface waters (Barry and Serreze 2000), which strongly influence growth and maintenance of sea ice (Cassano et al. 2007). The Arctic is experiencing substantial climate change (Serreze et al. 2009) and is expected to experience greater change in the future than most of the planet (IPCC 2007), motivating a need to understand how climate change will affect extremes.

With increased warming in the Arctic, model studies indicate that extreme precipitation events will also increase. For example, Zhang et al. (2000) show that North American extremes usually occurring every 20 years in contemporary climate are projected to occur in half that time in a warmer climate. Canada would also undergo an average increase in extreme precipitation events of 14% when compared to the last decade of the 20th century. Thus, extreme events are likely to have an increasingly strong impact on human and natural processes as the Arctic warms.

Establishing the capability of regional climate models (RCMs) to produce precipitation events well is important. Global climate models (GCMs) with typical resolutions over polar land areas of 150-200 km may lack sufficient resolution to capture precipitation extremes and, equally important, their causal processes. At these resolutions, Arctic processes such as surface-based physical responses to sea ice and snow cover and the highly stable polar inversion are difficult to simulate (Dethloff et al. 1996). Development of
Arctic-focused RCMs is thus an important step in understanding polar extremes and their underlying processes (Matthes et al. 2010).

Of particular interest are precipitation and temperature regimes associated with topographical features that occur at resolutions finer than in GCMs (Dethloff et al. 1996). Simulations with 50-km resolution can give an adequate representation of daily precipitation extremes (e.g. Gutowski et al. 2007). Thus, finer grid spacing than is typical in current GCMs may give a better rendition of physical mechanisms responsible for daily extreme precipitation events in the Arctic. In turn, RCMs that can produce real world physical processes responsible for extremes are then an important tool in the evaluation of potential future changes in extreme precipitation. Here we examine the ability of a polar-optimized RCM to produce observationally consistent mean and extreme model behavior. We also evaluate the ability of the model to produce the physical processes responsible for extreme precipitation events.

Our simulations use the Arctic domain developed for the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al. 2009), and our analysis focuses on four Arctic analysis regions. We concentrate on extreme daily precipitation events occurring in the summer from 1992 through 2007. The paper is organized as follows: Section 2 describes the Pan-Arctic WRF model and simulations. Section 3 details the evaluation methodology for analysis. Section 4 describes our results and section 5 gives our conclusions.
3. Model and Simulations

a. Pan-Arctic WRF (PAW)

We used version 3.1.1 of the Weather Research and Forecasting – Advanced Research WRF (Shamrock et. al, 2008). Selection of Arctic-appropriate physical parameterizations was an important consideration for our model simulations. We used parameterization choices discussed in Cassano et al. (2011) with further modifications based on work by M. Seefeldt (unpublished data, 2010).

For water condensation, we used the sub-grid cumulus scheme of Grell and Devenyi (2000) and the Goddard Cumulus Ensemble models microphysical scheme (Tao and Simpson, 1993) using three categories of ice-phase. For the planetary boundary layer, we used the Mellor-Yamada-Janic scheme (Janic 2001), which is based on eta surface sensitivity theory (Monin and Obukhov, 1954). Shortwave and longwave radiation used the NCAR Community Atmospheric Model spectral-band scheme (Collins et al., 2004; Mlawer et al., 1997). A polar-specified land surface model (LSM) was also an important part of our simulations; we used the 4-layer Noah LSM (Chen and Dudhia, 2001) as modified by Hines et al. (2011). Guided by Cassano et al. (2011), we set the sea ice albedo and emissivity at 0.80 and 0.98, respectively.
b. Model domain and simulation

We used the Arctic domain specified by CORDEX. The domain (Fig. 3.1) contains all of the Northern Hemisphere’s sea ice cover and encompasses most of the Arctic drainage system. Moreover, it contains critical inter-ocean exchange and transport circulations important for regional climate modeling. We used the standard CORDEX horizontal resolution of 50 km. The model used 40 unequally spaced sigma levels for vertical resolution, with the model top at 0.5 hPa and the lowest level at 12.5 meters AGL.

c. Initial and boundary conditions

Initial and boundary conditions for PAW used two distinct data sets. For initial conditions, simulations used the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (EI) reanalysis. The ERA-Interim output is available on a reduced Gaussian grid with a uniform, approximately 79-km horizontal grid spacing and sixty vertical levels, up to 0.1 hPa. The ERA-Interim fields are available every six hours, starting from 1989 through 2007. The model also used the Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I satellite sensors (Comiso 2008) archived at the U.S. National Snow and Ice Data Center. The native grid format for the ice concentration data is the SSM/I polar stereographic grid (25 x 25 km).
d. Simulations

Our simulations produced a six-member PAW ensemble on the CORDEX-Arctic domain covering the period of 1989 – 2007. To produce the ensembles, we chose a 24-hour staggered start. Glisan et al. (2012) showed that this method allows the ensemble to develop adequate ensemble spread due to the model’s nonlinear internal variability. We discarded the first three years of the simulation since they were used to spin-up land-surface processes.

We focus on the summer season, which is defined by the sea ice cycle. Specifically, we choose the months July, August, and September, the period leading to the minimum Arctic sea ice extent. In summer, smaller-scale (e.g., mesoscale) processes may be of greater significance than in winter for the production of precipitation events. The smaller-scale circulation dynamics may present some difficulties, as these circulations can be sub-grid scale even at our resolution.

4. Analysis Methods

a. Observational data

Model validation compares the model output against two data sets. The ERA-Interim reanalysis provides output for composite, observation-based fields and model bias analysis. We do not use ERA-Interim precipitation because it is a model product that is not constrained by precipitation observations.
The second data set is the National Climate Data Center’s (NCDC) Global Summary of the Day (NCDC 2011), which provides both temperature and precipitation observations. Within the CORDEX-Arctic domain there are nearly 150 stations with available observations, some of which date back to the 1940s. While NCDC does perform quality control on the station data, to ensure data continuity, our analysis requires that an acceptable station have no more than four missing days in any month.

\[b. \textit{Analysis regions}\]

To analyze extreme precipitation and causal processes, we focused on four analysis regions (Fig. 3.2). We used climatological records and regional weather patterns to help define these regions. We also found that the NCDC stations were located near higher-populated areas or airports and in geographical regions more conducive for station maintenance. These features aided us in producing the analysis regions because of “natural” breaks in stations across Alaska and Canada:

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.

c. Simulation bias

To assess how well our simulations produced observationally consistent output, we used seasonal mean plots of PAW-EI bias for surface and various pressure-level fields. We analyzed the 16-year seasonal mean bias from the model and reanalysis for sea level pressure, surface and pressure level temperatures, surface specific humidity, and 500-hPa geopotential heights.

d. Precipitation extremes

We extracted extreme precipitation events using procedures presented in Gutowski et al. (2007). Daily events were defined as a single grid point or NCDC station having precipitation greater than 2.5 mm. We chose this threshold since the NCDC stations cannot measure precipitation below 2.5 mm. We pooled all events in an analysis region for further study.
We constructed two sets of plots to aid in our analysis of precipitation extremes. The first set was frequency versus precipitation histograms. We used the Wilks (1995) criterion to avoid excessively coarse or fine bin widths. We normalized the histograms by dividing each bin’s count of events by the total number of events tallied from a data source. Using these diagrams, we defined extreme events as those occurring at the 99th percentile or higher. The second set of plots gave the number of extreme events occurring on at least N grid points simultaneously (i.e., on the same day). The simultaneity plots gave an indication of the spatial scale of extreme events. While each ensemble member had the same number of grid points, (and approximately the same number of events) the number of observation points (stations) was smaller than the number of grid points. Thus, we used a normalization procedure to account approximately for the differences in spatial resolution of the simulations and the observation stations. In each analysis region, we divided the total number of model grid points by the total number of NCDC stations. This value was then used to estimate the number of model grid points represented by an observation point. We use the simultaneity plots to define “widespread extremes”, which here were daily extremes occurring simultaneously over 25 or more grid points within an analysis region.

e. Circulation diagnostics

To understand how well the long-term PAW simulations produce observationally consistent behavior, we used seasonal mean bias plots of surface and upper-level variables. These biases allowed us to discern better the areas within the domain that are more difficult to model.
We diagnosed the relevant circulation and related features and dynamics of widespread extreme precipitation using composited fields of several diagnosed variables. Using the widespread extreme criterion, we extract the days with widespread extremes from the ensemble and composite their fields. We performed this procedure separately for each analysis region. For observational comparison, we used the same steps for the NCDC stations to extract widespread extremes in the observations. Once the relevant days were extracted, we used the ERA-Interim reanalysis to produce composited fields, as the NCDC observations did not include upper-air observations.

We also produced anomaly plots, calculated from the difference between extracted extreme time steps and the seasonal climatology, for each analysis region. The anomalies showed how extreme events depart from mean atmospheric behavior.

Since portions of our analysis regions were within the higher mid-latitudes, convective processes might have been present during the summer. To further understand the role of convection in the production of extreme precipitation events, we calculated the simulation’s convective contribution to the total rainfall on widespread extreme days. With this information, we were able to determine which analysis regions were candidates for further convective analysis. This analysis included composite plots of various indices used to diagnose convective behavior.
5. Results

a. Spatial climatology bias

PAW – EI mean biases shows that simulated behavior agrees well with observations. The mean sea level pressure (MSLP) has its largest absolute bias over topographic features (Fig. 3.3). These features appear to be systematic negative pressure biases that are connected to the model’s ability to resolve higher elevation topography (finer topography) and also to differences between the reanalysis and the model in how each data source computes MSLP in regions of high topography. We also note a 4-hPa positive bias within the Arctic basin. In addition, we observe that simulated temperatures at 850-hPa and 500-hPa show PAW producing a cold bias. Figure 3.4 shows differences in 500-hPa geopotential heights ranging from -10 to +40 gpms. Near-surface atmospheric humidity bias has its largest values over land. These results suggest PAW is systematically simulating drier conditions in the warm season (Fig. 3.5). Fisel et al. (2011) showed that biases like these are relatively small compared to the models’ year-to-year variability.

b. Precipitation frequency versus intensity

Figure 3.6 shows daily precipitation’s pooled 16-year frequency versus intensity for each analysis region. The model consistently underestimates extreme precipitation amounts. We find best agreement at the lower intensity end of the spectrum. The figure shows that the 95th and 99th percentile levels are substantially higher in the observations. We also note that
there is not a substantial amount of spread between the ensemble members. For further work, we define extreme precipitation as daily amounts at the 99\textsuperscript{th} percentile or higher, recognizing the difference between observed and simulated values.

Figure 3.7 shows the number of days having at least N grid points with precipitation exceeding the 99\textsuperscript{th} percentile, for each analysis region. All ensemble members are plotted individually, with the NCDC observations scale as discussed earlier. All analysis regions display nearly identical behavior. We define “widespread events” as those occurring simultaneously on 25 or more model grid points (or a comparable number of scaled observation points). This choice balances a goal of having a moderately large number of samples to analyze against an assumption that widespread extremes are governed by resolved fields in the simulations.

The curves for each of the ensemble members tend to group together for N values up to about 50, for three of the regions. The Alaska North box shows greater spread among ensemble members, with separation of curves from individual members occurring at around N=10 grid points. This behavior is likely tied to the relative smallness of the analysis region. More important, the simulation curves show fair agreement with the observation curves. This suggests that the spatial scale for simulated extreme events is roughly the same as the observed scale, despite the weaker precipitation extremes in the simulations.

c. Interannual variability of daily precipitation extremes

To understand the interannual variability of widespread precipitation events during the simulation period, we have plotted the percentage of extreme events occurring in each year for
PAW ensemble members and NCDC observations. Figure 3.8 shows the South Alaska results as an example. The general behavior of the ensemble members and their mean captures the behavior of the NCDC observations. The plots for the remaining analysis regions (not shown) show similar behavior.

Since our analysis regions are in the higher latitudes, we were also interested in whether the Arctic Oscillation (AO) has any control over interannual variability. The AO is a pattern of pressure fluctuations that affect the path of storm systems in the higher latitudes. A positive (negative) phase has negative (positive) pressure anomaly over the Arctic, with the opposite anomaly equatorward. Our plots show a connection between years of increased precipitation extremes (1993-1994, 1996-1997, and 2000) and the negative phase of the AO. This signal was especially evident in Southern Alaska, where a negative AO phase could explain the increase in widespread extreme precipitation events found in the land regions adjacent to the Gulf of Alaska. We will see later that the locations where the highest percentages of widespread extreme events occur are collocated with higher daily precipitation rates near the Gulf.

Taken together, these results suggest that the occurrence of extremes in PAW may be partly an outcome of the model’s unforced internal variability. However, the behavior of the observed and simulated extreme event frequencies in years with either very many or very few extreme events suggests that there is some process at least partly governing this behavior, as the spread between members and between simulations and observations is smaller than in other years. The AO may be one of the factors affecting the frequency of extreme precipitation events. The AO pattern may also explain the close connection between the ensemble members and NCDC observations during the years with very many or very few
widespread extremes, suggesting the model is capturing important aspects of the Arctic Oscillation behavior.

\[d. \text{ Spatial extent of widespread extreme precipitation events} \]

Before we discuss the physical behaviors that contribute to widespread extreme precipitation, we examine the spatial extent of these events. In Fig. 3.9, we plot composites of precipitation of days with widespread extreme events. In addition, we have plotted the frequency of occurrence of precipitation exceeding the 99th percentile during widespread extreme events on a gridpoint-by-gridpoint basis. This plot shows the favored locations for these events in an analysis region. With this information, we can examine surface and atmospheric fields in specific parts of the analysis region for dominant physical processes. We also split the analysis regions into two groups, as we found evidence that the Western Canadian region has substantial convective precipitation during extreme events, whereas the others do not. We discuss Western Canada convection (Fig. 3.10) in Section 4h.

Figure 3.9 (a) shows that while higher overall precipitation fell on the eastern side of Baffin Island in the Eastern Canadian analysis region, the concentration of widespread extremes occurred on the western side. Alaska North exhibited somewhat different behavior in that the highest daily values of extreme precipitation were collocated with the favored location of widespread extremes (Fig. 3.9b). Like Alaska North, Alaska South had higher overall precipitation in regions favoring widespread events, such as the Alaska Range and coastal mountains adjacent to Prince William Sound (Fig. 3.9c). These results indicate that orographic forcing produces extreme precipitation in these regions.
To diagnose processes associated with extreme precipitation events in our analysis regions, we use fields of various variables composited on the days of the event occurrence. The 500-hPa circulation associated with precipitation extremes, as seen in the ERA-Interim reanalysis, shows a cut-off low/trough over the Arctic basin (Fig. 3.11). The 500-hPa composites do not differ substantially between analysis regions, even though they were composited for each region’s specific widespread events. Taken together, the observed upper-level circulation indicates a poleward advection of moisture from the mid-latitudes.

When we compare the PAW fields to the reanalysis composites, we find our results match observations well. While the cut-off low and trough features are not as deep as found in the EI, the spatial extent and strengths are comparable. Thus, PAW and EI are in general agreement in their 500-hPa circulations during extreme events.

We find that the composited 850-hPa horizontal winds (Fig. 3.11) blow on-shore from adjacent oceans into individual analysis regions. This type of flow suggests advection of moisture into the analysis regions. In comparison to the EI, PAW shows some difficulty in replicating the strength and, in some cases, direction of the 850-hPa winds.

Our composites of simulated and observed two-meter specific humidity anomalies show nearly identical spatial extent and amounts across all analysis regions (Fig. 3.12). The figures also show that anomalous surface pooling of specific humidity was always collocated.
with regions of extreme precipitation. This behavior is consistent with the surface advection of moist air from adjacent ocean bodies, as indicated by the MSLP’s low-level circulation and the 10-m wind fields (Fig. 3.13). Simulated surface winds generally agree with observed winds. We find that flow is mostly onshore into regions of positive moisture anomalies and where moisture flux vectors imply moisture convergence. With the exception of Western Canada, where convective processes are important, flow into the analysis regions appears to be impeded by higher topographical features; This suggests that the Alaskan and Eastern Canadian regions are experiencing extreme precipitation induced by orography.

\[ g. \text{ Vertically integrated moisture flux vectors} \]

Extreme precipitation events may be located in regions in which there is convergence of low-level moisture. Here, we have calculated the vertically integrated moisture flux vector for our analysis regions (Fig 3.13). In each region, we find a consistent feature in that onshore flow from adjacent ocean bodies is transporting moisture inland. Moreover, flux vectors place the strongest implied moisture convergence within regional areas of anomalous surface moisture and favored locations for widespread extremes.

\[ h. \text{ Convective contribution to total precipitation} \]

To understand better the possible contribution by convection to widespread extreme events, we present for Western Canada events composites of various convective diagnostics: the Lifting Condensation Level (LCL), the Level of Free Convection (LFC) and Convective
Available Potential Energy (CAPE). These fields help us determine whether or not conditions are favorable for convection within the analysis region. The LCL gives the level at which a mechanically lifted surface air parcel reaches condensation. A finite LFC indicates a level where surface air parcels have positive buoyancy, thus indicating a potential convective instability. CAPE indicates the amount of buoyant energy a surface air parcel can have. Lower LCL and LFC heights, in conjunction with larger CAPE, indicate more conducive conditions for convection.

Figure 3.14 shows Western Canada LCL anomalies for the EI and PAW. The simulated LCL anomalies agree well with the reanalysis anomalies, especially over interior land regions. The largest departures from the observations occur over the interior of the Arctic basin, outside of the analysis region.

While lower LCL anomalies appeared in other regions during their widespread extreme events (not shown), LFC and CAPE values consistent with convection appeared only in Western Canada (Fig. 3.15). For this region, we found that the simulated convective contribution on widespread extreme days was nearly 60%. Compared to PAW climatology (Fig. 3.12), this was an increase of nearly 10%. Moreover, the region of anomalously higher convection was collocated with the largest occurrence of widespread extreme precipitation. Finally, the most intense daily-average values for extreme event days were also in the same location.
i. **Concurrent precipitation and temperature extremes**

We also analyze possible connections between extreme precipitation and temperature events, to determine if conditions responsible for precipitation extremes are also favorable for temperature extremes in the same region. We define an extreme warm temperature event using the same threshold percentile (99%) as an extreme precipitation event.

We find that the simulated spatial distribution of surface temperatures anomalies is comparable to observations (Fig. 3.12). However, in comparison with EI, the simulated surface temperature anomalies on widespread extreme days are more negative. In each analysis region, EI has a positive temperature anomaly collocated with extreme summer precipitation (Fig 3.9). There is good simulation versus reanalysis agreement in the Eastern Canada and Northern Alaska analysis regions; PAW fails to capture the positive anomalies in the remaining analysis regions.

6. **Discussion and Conclusions**

In this paper, we have analyzed a 19-year CORDEX Arctic simulation produced by a polar-modified version of the WRF model. The simulation was created using a six-member ensemble, forced with the ERA-Interim reanalysis and sea ice concentration from the National Snow and Ice Data Center. We discarded the first three years for model spin up and analyzed output for a summer season (July-August- September) based on the sea ice cycle.

We used the 99th percentile as our definition of an extreme precipitation event. We further restricted our analysis to widespread events in which 25 or more grid points had an
extreme precipitation on the same day. We defined four analysis regions over North America to determine whether the temporal and spatial distribution of extreme events varied as a function of geography, and proximity to ocean bodies. We also used days of widespread extreme precipitation to create seasonal composite fields for each analysis region. Analysis of these composites along with the deviation from climatology (anomaly plots) allowed us to develop an understanding of the physical mechanism and associated circulations responsible for producing extreme precipitation. For comparison and validation, we used the same analysis procedure on the EI and NCDC station observations. 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 model’s simulation credibility, we showed that the model and observations were in general agreement using seasonally averaged plots of surface and atmospheric fields.

Using frequency versus intensity histograms, we showed that PAW consistently underestimates extreme precipitation amounts compared to the NCDC station observation. We did find that simulation and observations come into agreement at the lower end of the intensity spectrum, suggesting that the model is reproducing lower intensity events well. The PAW spatial scales for widespread extreme events are roughly equivalent to the observed scales.

The interannual variability of widespread extremes showed similarity to the observed variability. In general, years with the highest and lowest occurrences of observed extreme events were simulated well by the model. However, the spread among the PAW ensemble members tended to be more variable during the interim periods. These results suggest that the occurrence of extremes is partly a function of model internal variability. Agreement among
ensemble members during favored years suggests a controlling factor imposed on the simulation, with the Arctic Oscillation showing some correlation with the interannual variability of widespread extreme events.

In order to locate regions within our analysis boxes where widespread extremes were more likely to occur, we calculated a gridpoint-by-gridpoint occurrence frequency. Along with the frequency, we also produced plots of daily average precipitation during extreme event days. Analysis of these plots allowed us to focus on locations that were responsible for the greatest occurrences of widespread events.

We used composites of MSLP, 10-m winds, 850-hPa winds, and 500-hPa geopotential heights to diagnose the behavior of the atmosphere during widespread extreme precipitation events in both simulations and observations. Using composites of convection diagnostics, we found that the Western Canadian analysis region had a significant contribution to widespread extreme events from atmospheric convection. We performed additional analysis on the convective contribution to total extreme precipitation amounts in this region. We discovered that a 10% increase in convection occurred during widespread extreme days. Additionally, the highest intensity extreme daily precipitation fell in the region collocated with the highest occurrence of widespread extremes. These results indicate that atmospheric convection is the primary mechanism for widespread extreme precipitation events in Western Canada during summer.

The remaining analysis regions did not exhibit a significant convective contribution to extreme precipitation events. Composite plots of surface and upper-level fields for widespread events in each region showed that the large-scale circulation was similar for each region. We also found low-level flow into each region from adjacent ocean bodies. Moreover,
convergence in the moisture flux field gave conditions conducive for precipitation in the locations of widespread extreme events.

With the exception of Eastern Canada, the location of highest overall precipitation was always found in the region favored for widespread extreme events. Moreover, these regions were located over higher topography and thus indicated a significant orographic contribution to the extreme events. In Eastern Canada, we found the highest overall precipitation over eastern Baffin Island. The most favored region of widespread extremes, however, was found over western Baffin Island and the Melville Peninsula. Even though these regions were not collocated, orographic precipitation still appeared to be the dominant process for widespread extreme events.

Even though PAW simulated fewer high intensity precipitation events than seen in the observations, the composite results showed that the model is reproducing well the atmospheric features conducive for the events. The seasonal circulations for widespread extreme events were generally the same for each analysis region. Coupled with the observed precipitation and the reanalysis, the model output has given us insight into the nature of precipitation extremes in these regions. In addition, for the Western Canada region, the model’s distinction between convective and non-convective precipitation helped guide the analysis. Overall, the model appears to produce the physical behavior of extreme daily precipitation well enough that it can be used for analysis of changes in extreme events in future climate.
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Figure 3.1: CORDEX Arctic 50-km domain
Figure 3.2: North American analysis regions. Individual analysis regions denoted by colored boxes and labels.
Figure 3.3: Pan-Arctic WRF – ERA Interim Reanalysis 16-year JAS mean sea level pressure bias [hPa].
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CHAPTER 4: WRF WINTER EXTREME DAILY PRECIPITATION OVER THE CORDEX ARCTIC

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1. Abstract

We analyze daily extremes of precipitation produced by a six-member ensemble of Pan-Arctic WRF that simulated 19 years on the CORDEX 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 (NCDC’s) Global Summary of the Day. We define winter as the three-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. 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.
2. 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 Chapter 3 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 forcing are more likely responsible for a majority of winter precipitation events.

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. Semi-permanent pressure features (e.g. the Aleutian low, the Icelandic low, and the Canadian high) will also affect circulation characteristics within our analysis regions.
3. Analysis Methods

a. Simulations

We ran version 3.1.1 of the Weather Research and Forecasting – Advanced Research WRF (WRF-ARW), (Shamrock et. al, 2008), using parameterization choices discussed in Glisan and Gutowski (2012b). These included the sub-grid cumulus scheme of Grell and Devenyi (2000) and the Goddard Cumulus Ensemble microphysical scheme (Tao and Simpson, 1993), the Mellor-Yamada-Janic planetary boundary layer parameterization (Janic 2001), atmospheric radiation computed using the NCAR Community Atmospheric Model spectral-band scheme (Collins et al., 2004; Mlawer et al., 1997), and the 4-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 (Fig. 4.1) contains all 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 meters AGL.

Using the ERA-Interim reanalysis for boundary conditions, PAW produced a six-member ensemble for a period covering 1989-2007. To produce the ensembles, we chose a 24-hour staggered start. Glisan et al. (2012) showed that this method allows the ensemble to
develop adequate ensemble spread due to the model’s nonlinear internal variability. We discarded the first three years of the simulation since they were used to spin-up land-surface processes.

\textbf{b. Precipitation analysis}

In our study, extreme precipitation events are extracted using procedures presented in Gutowski et al. (2007). We use the four North American analysis regions developed in Chapter 3 (Fig. 4.2). Specifically, for each grid point in an analysis region, we pooled the daily precipitation during JFM from the multi-model ensemble and extracted the 99\textsuperscript{th} 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. As in Glisan and Gutowski (2012a), we also constructed various types of plots to aid in our analysis of precipitation extremes.

\textbf{c. Circulation diagnostics}

We are also interested in whether the long-term PAW simulations are producing observationally consistent behavior. To aid in our investigation, we used seasonal mean bias plots of surface and upper-level variables. The bias plots were calculated from the model and reanalysis JFM 16-year 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 compositied fields of several variables. Using the widespread extreme criterion, we extract the relevant days from the ensemble members and pool them together. The pooled days are then averaged to create the composite. For observational comparison, we use the same steps for the NCDC stations. Once we extracted the relevant days, we used the ERA-Interim reanalysis to produce compositied fields, as the NCDC observations did not include upper-air observations important in the diagnosis of circulation characteristics. We also produced anomaly plots of fields that were relevant for winter season extremes.

4. Results

a. Spatial climatology bias

The mean sea level pressure (MSLP) has its largest negative bias over topographical features (Fig. 4.3). 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. We also note a 4-hPa positive departure in both seasons within the Arctic basin. Large cold biases for winter surface air temperature occur over sea ice and snow-covered land. We also find that simulated layer temperatures at 850-hPa and 500-hPa also show PAW producing a cold bias. Figure 4.4 shows differences in 500-hPa geopotential heights, ranging over ± 20 gpms. Surface specific humidity bias has its largest values over land (Fig. 4.5). These results
suggest PAW is systematically simulating drier conditions that are consistent with PAW’s cold bias as shown in Chapter 3.

\( b. \ Precipitation \ frequency \ versus \ intensity \)

Figure 4.6 show daily precipitation’s pooled 16-year frequency versus intensity for each analysis region. In terms of overall precipitation accumulation, a fairly constant behavior is evident in three regions. Pan-Arctic WRF consistently underestimates extreme precipitation amounts. Southern Alaska is an exception. We find good agreement at the lower end of the intensity spectrum. We have also placed arrows indicating the 95th and 99th percentiles for PAW and the ERA-Interim reanalysis. 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 4.7 shows the number of days having at least N grid points exceeding the 99th percentile for each analysis region. All ensemble members are plotted separately, along with the NCDC observations. The ensemble members tend to group together until N=40 for three of the regions. The Alaska North box shows greater spread among ensemble members, with separation of curves from individual members occurring at N=10 grid points. This behavior may be tied to the relative smallness of the analysis region.

Most important, the observations show fair agreement with the simulated curves. The only exception can be found in the Southern Alaska region; here we find that the observed spatial extent 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.

c. *Interannual Variability of Daily Precipitation Extremes*

Figure 4.8 shows the time series of annual frequency of extreme widespread events for North Alaska, as an example. The plots for each analysis region show that ensemble members agree most in years with either very many or very few extreme events; individual members showed greater disagreement in the interim years. While the spread of ensembles members is larger than the NCDC observations, the simulation is able to capture the observational variability well. 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 mid-latitudes. A positive (negative) phase indicates negative (positive) pressure anomalies over the Arctic region, with the opposite pressure pattern equatorward. Our plots show a connection between years of increased precipitation extremes (1995, 2001, and 2003) and the positive phase of the AO; the positive phase suggests a poleward movement of storm tracks. Sea level pressure composites for widespread extreme days show systematic low pressure over the eastern Arctic Ocean for all analysis regions.

As shown in Chapter 3 these results suggest that the occurrence of extremes in PAW may be related to the model’s internal variability. However, the spread of the PAW ensemble in the years with the most or least extreme events years suggest that there are
processes in the model controlling ensemble behavior. 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.

\[d. \quad \textit{Spatial extent of widespread extreme precipitation events}\]

In Chapter 3, we outlined a method of calculating the percent occurrence of widespread extreme events within an analysis region. This gave us the ability to find favored locations for extreme events and then examine the pertinent physical mechanisms. Figure 4.9 was produced with this method and also includes composites of widespread daily-averaged extreme precipitation.

Figure 4.9 (a) shows that higher intensity daily extreme events occur on the eastern coast of Baffin Island. 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.

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 (Fig. 4.9 b). In Alaska North, the northwestern reaches of the Brooks Range are the focal point (Fig. 4.9 c). In Alaska North, nearly 60% of extreme precipitation occurs in the coastal mountain ranges adjacent to the Gulf of Alaska (Fig. 4.9 d).
e. 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. In general the composites exhibit the same pattern and circulation processes across the four analysis regions. 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.

For each region, composite 500-hPa circulation in the ERA-Interim reanalysis on days with widespread extremes shows a cut-off low situated between the Canadian Archipelago and Greenland for (Fig. 4.10). We also find a trough across the Arctic basin. The observed upper-level circulation can be conducive for a poleward advection of mid-latitude air. When we compare the reanalysis output to the simulated PAW fields, we find our results match observations well. While these upper level features are not as deep as found in the EI, the spatial extent is comparable. Thus, PAW and EI are in general agreement in their circulation conditions present during periods of extreme precipitation.

We find that the 850-hPa horizontal winds are blowing on-shore from the ocean bodies adjacent to individual regions. This behavior suggests advection of moisture into the analysis regions. We note in Chapter 3 that PAW has difficulty simulating the strength and direction of the 850-hPa flow in JAS; we find similar results here.


\textit{f. Surface-based features}

The winter El Niño MSLP composited on days with widespread extremes shows an area of high pressure extending from central Canada westward into central Siberia (Fig. 4.10). We also note an areas of low pressure in the southern portion the analysis regions. This surface circulation pattern, combined with the 500-hPa features indicates that low-level mid-latitude flow is advecting poleward (equatorward) over extreme western Canada and Alaska (Eastern Canada). The general spatial extent and magnitude of simulated MSLP fields agree with the features in the reanalysis.

Composited anomalies of simulated and observed two-meter specific humidity show differences in both spatial extent and magnitudes across the analysis regions (Fig. 4.11). Pan-Arctic WRF simulates relatively dry surface specific humidity compared to the ERA-Interim. This is especially true in the West Canadian and North Alaskan analysis regions where negative anomalies or neutral conditions reign. The more pronounced difference is found in the spatial distribution of the anomalies. The simulated fields show a larger spatial distribution of anomalies, while the observed anomalies are more localized. Fields composited for the previous day show the presence of positive moisture anomalies (not shown). This may suggest that the surface moisture was expended during the physical processes creating widespread extreme precipitation events.

The presence of negative temperature and moisture anomalies (Fig. 4.11b) in Western Canada is perplexing; for extreme days, it appears that saturation is achieved by the air becoming cooler. Considering the topography then, stronger orographic uplift appears to be the dominant forcing for extreme precipitation in Western Canada.
While some regions do not have anomalous pooled surface moisture, compositied vertical profiles from widespread extreme days show a nearly saturated atmosphere below 800-hPa for all analysis regions. For example, Figure 4.12 shows simulated and observed vertical profiles for Western Canada. PAW and EI sampling locations were within regions where widespread events occurred regularly. The simulated vertical profiles show good agreement with the observed profiles.

g. Vertically integrated moisture flux vector

We calculated the vertically integrated moisture flux vectors to determine whether moisture was pooling in areas collocated with extreme precipitation events. 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 positive surface specific humidity anomalies (Fig. 4.11) and highest composited daily precipitation (Fig. 4.9), thus creating a possible link between extreme precipitation and anomalous low-level moisture sources. The strongest implied moisture convergence is found in the Southern Alaskan analysis region (Fig. 4.13d).

h. Concurrent precipitation and temperature extremes

The connection between extreme precipitation and temperature events was also of interest in this study. Here, we analyze seasonal temperature fields to determine if the conditions responsible for precipitation extremes are also favorable for temperature extremes
in the same region. We define an extreme temperature at the same percentile as a precipitation event.

We find good agreement between positive temperature and moisture anomalies in the Eastern Canada and North Alaska analysis regions (Fig. 4.11). In comparison with the composited extreme precipitation plots, these positive anomalies are found within the same location. As for the Western Canada, both PAW and EI show cold events concurrent with precipitation events.

5. Discussion and Conclusions

In this paper, we have analyzed a 19-year CORDEX Arctic simulation produced by a polar-modified version of the WRF model. The simulation was created using a six-member ensemble, forced with the ERA-Interim reanalysis and sea ice concentration from NSIDC. We discarded the first three years for spin-up and focused on output for winter.

We used the 99th percentile as our definition of an extreme precipitation event. We further restricted our analysis to widespread events in which 25 or more grid points in a region had an extreme precipitation event on the same day. We defined four analysis regions over North America 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 region. Analysis of these composites along with the deviation from climatology (composite anomaly plots) 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 ERA-Interim 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 Chapter 3, PAW and EI are in general agreement in their seasonal 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. This appeared to be related to how PAW treats sea ice. In particular, PAW uses the standard WRF prescription for sea-ice thickness of two meters, 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 than observed.

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 (Chapter 3).

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 simulated well by the model. However,
ensemble spread tended to be greater during the neutral periods. These results suggested that simulated extremes may be a function of PAW’s internal variability. However, agreement among ensemble members during years with very high or very low occurrences suggested that a model process may be a controlling factor.

We compared the simulated and observed interannual variability to the Arctic Oscillation index. We found that the negative AO phase tended to coincide with years of high occurrences of precipitation extremes. These findings suggested that the AO is a contributing physical process to mechanisms governing the frequency of widespread extreme precipitation events.

We constructed composite fields for individual days in which 25 or more grid points had an extreme precipitation event. This allowed us to analyze physical processes responsible for the events’ creation and maintenance. As in JAS, we used plots of MSLP, 850-hPa winds, and 500-hPa geopotential heights to determine whether PAW was simulating observationally consistent circulations that were present during widespread extreme precipitation events.

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 cut-off low in the 500-hPa heights, we diagnosed a poleward advection of warmer air from the upper mid-latitudes. In addition, we found low-level flow from adjacent ocean bodies into each region. In terms of available moisture, all regions with the exception of Western Canada have a positive surface anomaly indicating pooled moisture. Vertical profiles also show high relative humidity values below 800-hPa in all regions.
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 summer results found in Chapter 3. However, composite fields indicate that PAW simulates well atmospheric conditions responsible for precipitation events. Along with the NCDC station precipitation and ERA-Interim reanalysis, Pan-Arctic WRF output has given us better insight into the nature of precipitation extremes in the four analysis regions. 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.
6. References


Figure 4.1: CORDEX Arctic 50-km domain
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CHAPTER 5: GENERAL CONCLUSIONS

This dissertation is comprised of three papers, all of which deal with the analysis of extreme temperature or precipitation events. We use a six-member ensemble of a polar-optimized version of the WRF model over two Arctic domains. We are interested in how the Pan-Arctic WRF (PAW) produces extreme events and how they compare with the two observational data sets. In addition, we address the question - are the simulated dynamical mechanisms and circulation features comparable to what is seen in the observations? Finally, we study the seasonality of extremes and how they are produced in various analysis regions.

1. General Results

In Chapter Two, we use a method called “spectral nudging” to minimize systematic circulation bias in the Pacific storm track located within the lateral boundaries of our larger Arctic domain. Spectral nudging imposes an artificial damping on various model variables, thereby constraining the simulations to be more consistent with observations. Excessive damping, however, can smooth extreme events while leaving the mean behavior intact. Thus, this study explores a range of eight nudging coefficients, based on the WRF default value, as a means of determining an optimal range of nudging strengths for general pan-Arctic simulations. For case study months, we use January and July 2007 as representations of the winter and summer seasons. We also analyze daily precipitation and temperature events at the 95th and 99th percentiles over four smaller analysis regions. Our simulations indicate that
changing the strength of nudging can have differing seasonal and geographical impacts on mean and extreme events.

Monthly mean bias plots of sea level pressure, temperature, and 500-hPa geopotential heights indicate that winter is more sensitive to changes in nudging than summer. Statistical analysis of the 50th, 95th, and 99th percentile precipitation events show that stronger (weaker) nudging produces results analogous to NCDC station observations for January (July). We analyzed the 1st, 5th, 50th, 95th, and 99th percentiles for temperature and find that weaker (stronger) nudging produces more realistic percentile behavior in January (July). Taken together, these results indicate that an optimal nudging range for pan-Arctic simulations lies within 1/8th to 1/16th (0.000021 - 0.000041 s⁻¹) WRF’s default value.

Chapter Three gives an analysis of a 19-year simulation over the CORDEX-Arctic domain using Pan-Arctic WRF. Since the lateral boundaries of the CORDEX Arctic region are well within the high-latitudes, the biases that interfered with our pan-Arctic simulations in Chapter Two were minimal and required no spectral nudging. We define July-August-September (JAS) as the summer season, using the climatological sea ice minimum. We then analyze JAS daily extreme precipitation events with an eye towards temporal and spatial extents. In addition, we construct composite plots from extreme event days to determine the physical mechanisms responsible for extreme events. As in Chapter Two, we use the NCDC station data and ERA-Interim reanalysis to establish if the simulated mechanisms responsible for extreme precipitation events are consistent with observations.

Within the simulation domain, we create four smaller analysis regions based on geography and climatology. This method provides the opportunity to study the local
processes and regional circulations associated with unique features in the analysis regions, e.g. topography and proximity to moisture sources. With this information we are then able to study how extremes are produced in each analysis region.

Composited fields of MSLP and 500-hPa geopotential heights show that on days of extreme widespread events, a uniform pressure field exists at the surface along with an upper level trough extending from the Canadian Archipelago across the Arctic basin. These features are found in both PAW and ERA-Interim composites for each analysis region, except for a slightly higher pressure region over the middle of the domain for North Alaska. Specific humidity and implied moisture convergence composites show that anomalous pooling and convergence of moisture is always collocated with composite extreme precipitation. Low-level flow off of adjacent ocean bodies into the analysis regions is also a consistent feature. Additionally, three of the four regions have the highest intensity extreme events concurrent with favored regions for widespread events.

To determine whether the analysis regions had a significant convective contribution to extreme precipitation, we analyze the convective component of the total precipitation during extreme event days. We also use anomaly composites of convective diagnostics including Lifting Condensation Level (LCL), Level of Free Convection (LFC), and Convective Available Potential Energy (CAPE) for further evidence. While we did find anomalously lower LCLs in all regions, West Canada is the only region exhibiting dominant convective behavior. In fact, we find a 10% increase in convection during extreme events. Furthermore, CAPE and LFC anomalies in Western Canada show the atmosphere is convectively unstable during extreme event days. In regions where convection is not
significant, orographic forcing over higher topography is the dominant process creating extreme precipitation events.

Chapter Four gives a complimentary analysis focusing on the Arctic winter using the same methodology presented in Chapter Three. We use the climatological sea ice maximum to define winter as January-February-March (JFM). Since there are differences in the sea ice and snow cover between JFM and JAS, we hypothesize that the physical behavior and characteristics of extreme precipitation events may also differ. This includes spatial scales over which events may occur and circulation features conducive for extremes.

We use the Arctic winter climatology to establish the utility of the model for extreme analysis in winter. We find that the model and observations are in general agreement. The largest differences between PAW and ERA-Interim occur with surface temperature, showing a systematic PAW cold bias. This bias is contained within the Arctic basin and adjacent land regions. We believe this bias is a function of how sea ice is treated in PAW - prescribed thickness is two-meters, which is likely too thick to allow for oceanic heat flux into the atmosphere. Consistent with the cold bias is the fact that PAW underestimates surface moisture.

MSLP composites for all regions show a high pressure feature extending from central Canada into the eastern Arctic basin; areas of lower pressure flank this feature. The gradients of the MSLP field indicate that synoptic systems may be important for extreme events in JFM. Both PAW and ERA-Interim are in good agreement with this surface arrangement. Co-located with the surface feature is a 500-hPa geopotential trough. We also note the presence of geopotential ridging in the Gulf of Alaska. Coupled with the implied surface flow, these
conditions suggest a poleward advection of warmer, moister air into the Alaskan analysis regions. We also find onshore flow into Western Canada from both the Gulf of Alaska and Beaufort Sea, while Eastern Canada is under the influence of a weak northwest flow from the Beaufort Sea. This synoptic setup is conducive for moist low-level onshore flow into the analysis regions. This resultant flow orographically interacts with higher topography, creating widespread extreme precipitation events.

As we showed in JAS, positive specific humidity anomalies are always present and co-located with areas of moisture convergence. Examination of the extreme precipitation composites for each analysis region points to events occurring in regions of pooled low-level moisture. With the exception of East Canada, the highest intensity daily events are also found in the region favored for widespread extreme events. East Canada has two favored location for widespread events; the lower percent occurrence location over Baffin Island is collocated with the highest intensity precipitation region.

Our results show that PAW consistently underestimates extreme precipitation amounts compared to observations. PAW and NCDC stations do agree when we consider lower intensity events. When dealing with widespread extremes, the simulated and observed spatial scales are roughly equivalent. We also note a smaller (larger) spread among the ensemble members in JAS (JFM). Furthermore, we find that the observed and simulated interannual variability of extremes in JAS (JFM) may be related to the negative (positive) phase of the Arctic Oscillation (AO). This suggests that the AO may be a contributing factor affecting the frequency of widespread extreme precipitation events. Coupled with the NCDC station observations and ERA-Interim reanalysis, Pan-Arctic WRF simulations have given us
greater insight into the nature of widespread extreme precipitation in the four analysis regions. We have also gained a better understanding of the causal physical mechanisms creating these events during different seasons.

2. Future Work

The utility of spectral nudging has been shown in the results outline in Chapter Two. However, longer simulations would provide greater basis for determining the optimal value of nudging for general Arctic simulations. Additionally, the use of Self Organizing Maps (SOMs; Kohonen 1995) would aid in the diagnoses of seasonally dominant circulation features. SOMs use an artificial neural network algorithm to find patterns in input data and then map these features on a user-defined array of nodes. Through an iterative process, the nodes are clustered in regions where higher data densities are present. Hewitson and Crane (2002) showed that SOMs can be a valuable tool in the creation and analysis of synoptic climatologies.

The study of causal mechanisms and circulation features for extreme precipitation events over the CORDEX-Arctic can be expanded to include temperature extremes as well as the shoulder seasons (Fall and Spring). While the relationship between concurrent temperature and precipitation extremes was broached in Chapters Three and Four, a more in-depth examination of the 16-year simulations would give us a better understanding of the connections between warm and cold extremes and precipitation events.

Also of interest are quasi-persistent high and low pressure systems that can produce widespread extreme events such as heat waves and droughts. Quasi-persistent high pressures,
also known as blocking, can impose changes on a region for multiple seasons. Locations
downstream of the block can also experience precipitation and temperature extremes. The
use of Lyapunov exponents has been shown to be a valuable indicator of block stability and
hence predictability (Glisan and Lupo, 2010).

Verifying that PAW can successfully produce extreme precipitation and temperature
events in short and long simulations gives us a powerful tool when it comes to the study of
regional climate change. Because we are now able to determine the casual circulations and
dynamics of extreme events in the contemporary climate, we can now use this RCM to
simulate future climate. In so doing, we can determine whether the processes producing
extreme events now are also present in future climates and if not, how they have evolved in a
warming climate.

Comparison of the reanalysis-driven PAW simulations with those of simulations
produced by WRF initialized with GCM boundary conditions will also be important in future
work. GCM-driven WRF will aid in the determination of how GCM boundary conditions
alter extreme event simulations. They will also reveal how projected changes in the future
climate will affect the factors responsible for extreme event production.
3. References

Glisan, J.M. and A.R. Lupo, 2010: Two cases of extreme atmospheric blocking over Western Europe and Alaska. *In progress.*


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