Alaska Daily Extreme Precipitation Processes in a Subset of CMIP5 Global Climate Models

Kevin M. Smalley  
*Iowa State University*

Justin M. Glisan  
*Iowa State University*

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

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

Part of the Atmospheric Sciences Commons, Climate Commons, and the Statistical Models Commons

The complete bibliographic information for this item can be found at https://lib.dr.iastate.edu/ge_at_pubs/281. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.

This Article is brought to you for free and open access by the Geological and Atmospheric Sciences at Iowa State University Digital Repository. It has been accepted for inclusion in Geological and Atmospheric Sciences Publications by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Alaska Daily Extreme Precipitation Processes in a Subset of CMIP5 Global Climate Models

Abstract
We analyze physical processes leading to daily wintertime (December, January, and February) extreme precipitation events in Alaska between 1986 and 2005. This is done by applying self-organizing maps to environmental conditions corresponding to National Centers for Environmental Information precipitation, using the European Centre for Medium-Range Weather Forecasts reanalysis (ERA-Interim) and Coupled Model Intercomparison Project 5 (CMIP5) global climate selected Global climate model (GCM; selected GCMs). We focus on widespread extreme events, defined as the top 0.1% of daily precipitation occurring on at least six grid boxes on the same day. The self-organizing maps methodology allows identifying large-scale circulations conducive to extreme events. This methodology identifies distinctive circulation patterns conducive to producing extreme events with a trough west of Alaska leading to south or southwest flow across the state. Extreme events occur along the windward (southern) side of the Alaska Range due to uplift by the mountains in the ERA-Interim and in all models. In the National Centers for Environmental Information observations, precipitation rates are greater than in any of the selected GCMs. Simulated extreme precipitation decreases as model resolution decreases, and our study suggests that the smoothness of model topography is a reason for the scaling between model precipitation rate and model resolution.

Disciplines
Atmospheric Sciences | Climate | Statistical Models

Comments

This article is available at Iowa State University Digital Repository: https://lib.dr.iastate.edu/ge_at_pubs/281
Key Points:

- Self-organizing maps help identify large-scale circulations conducive to precipitation extremes in a subset of Global Climate Models
- Global climate models can simulate large-scale processes conducive to daily precipitation extremes
- Global climate model topography can be too coarse to properly simulate orographically forced extreme precipitation

Citation:


1Department of Geological and Atmospheric Sciences, Iowa State University of Science and Technology, Ames, IA, USA, 2Department of Atmospheric Science, Texas A&M University, College Station, TX, USA

Abstract

We analyze physical processes leading to daily wintertime (December, January, and February) extreme precipitation events in Alaska between 1986 and 2005. This is done by applying self-organizing maps to environmental conditions corresponding to National Centers for Environmental Information precipitation, using the European Centre for Medium-Range Weather Forecasts reanalysis (ERA-Interim) and Coupled Model Intercomparison Project 5 (CMIP5) global climate selected Global climate model (GCM; selected GCMs). We focus on widespread extreme events, defined as the top 0.1% of daily precipitation occurring on at least six grid boxes on the same day. The self-organizing maps methodology allows identifying large-scale circulations conducive to extreme events. This methodology identifies distinctive circulation patterns conducive to producing extreme events with a trough west of Alaska leading to south or southwest flow across the state. Extreme events occur along the windward (southern) side of the Alaska Range due to uplift by the mountains in the ERA-Interim and in all models. In the National Centers for Environmental Information observations, precipitation rates are greater than in any of the selected GCMs. Simulated extreme precipitation decreases as model resolution decreases, and our study suggests that the smoothness of model topography is a reason for the scaling between model precipitation rate and model resolution.

1. Introduction

Melvin et al. (2016) recently reported that damages to infrastructure during the 21st century will cost Alaska between 1.3 and 5.5 billion dollars without any adaptation due to climate change. They find 45% of the total cost results from enhanced rainfall, with the largest source of damages being infrastructure degradation due to flooding. Over Alaska’s coastal regions, more frequent and intense precipitation events will also threaten shoreline, wetland, and coastal development due to enhanced erosion and freshwater runoff (Scavia et al., 2002). Across the state, station observations already show that total average precipitation has increased 17% since 1950 (Wendler et al., 2017); thus, adapting to both present and future challenges is critical to sustaining Alaska’s economy.

During the last 30 years, the Arctic has warmed approximately four times more than the tropics (Pithan & Mauritsen, 2014) and faster than any other region on Earth. This suggests that Alaska is much more sensitive to a warming climate than other lower-latitude regions. Sea ice and snow loss drive the amplification in surface warming (e.g., Screen, 2014; Serreze & Francis, 2006; Screen & Simmonds, 2010; Serreze et al., 2009). By reducing sea ice and snow cover, the amount of solar radiation absorbed by the surface increases, reducing surface albedo and further accelerating warming (Pistone et al., 2014). By increasing surface evaporation, a warmer surface and open waters will provide more moisture to the lower atmosphere (Bintanja & Selten, 2014). This will likely result in more intense precipitation due to enhanced low-level moisture (e.g., Trenberth et al., 2003). Bintanja and Selten (2014) found average precipitation over the Arctic to be approximately twice as sensitive to warming than the global average. This identifies a possible mechanism responsible for flood damage risk identified by Melvin et al. (2016).

Satellite and ground observations show a pronounced seasonal cycle in Alaska precipitation (Adler et al., 2003; Wendler et al., 2017), with maximum precipitation occurring during the winter. Temperature contrasts are largest between the warm Gulf of Alaska and the mostly ice covered Bering Sea and Arctic Ocean during the winter, and they fuel successive low-pressure systems that track south of Alaska and advect moisture northward (e.g., Rodionov et al., 2007; Zhu et al., 2007). Additionally, the loss of sea ice combined...
with increasing surface temperature leads to enhanced surface evaporation and moistening the lower atmosphere. Bintanja and Selten (2014) concluded that these factors are most prominent during the winter, resulting in enhanced precipitation. Across Alaska, this suggests that a warming climate that will result in more frequent extreme precipitation events will be more common, especially during the winter.

Alaska is one of the most topographically diverse regions of North America, with extensive coastlines, mountain ranges, and volcanoes. The topographic uplift of humid air advected from the northern Pacific can result in more intense precipitation over southern Alaska. Recent studies have found this to be an issue in observations, reanalysis, and climate models (e.g., Bieniek et al., 2016). Different methodologies have been used to mitigate precipitation bias due to elevation, including downscaling observations (Lader et al., 2017). In this context, it is necessary to understand not only the seasonal influence on intense Alaska precipitation events but also the topographic influences.

Global climate models (GCMs) tend to underpredict increases in precipitation frequency and intensity than would be expected from observations (Allan & Soden, 2008). This demonstrates that model bias can undermine confidence in projected changes of extreme precipitation event frequency and intensity. To quantify extreme precipitation uncertainty in GCM output, previous studies have compared historical GCM output to observations (e.g., Bennett & Walsh, 2014; Chen, 2013; Gutowski et al., 2003, 2007; Kawazoe & Gutowski, 2013; Mass et al., 2011; Tehaldi et al., 2006). Woldemeskel et al. (2016) found that GCM uncertainties are largest over regions that typically receive heavy rainfall and regions with complex terrain. This suggests that Alaska's variable topography may introduce a large amount of uncertainty into precipitation predicted by GCMs. To correctly capture both the magnitude and variability of extreme precipitation events, GCMs must be able to realistically replicate behaviors, including relevant circulation patterns and topographic effect, yielding extremes in observations.

In this work, we examine high-intensity precipitation events produced by a set of selected GCMs for Alaska, focusing on extremes occurring simultaneously in multiple grid boxes, so-called “widespread extremes” (e.g., Glisan & Gutowski, 2014; Kawazoe & Gutowski, 2013). We then evaluate synoptic-scale circulation and processes responsible for widespread extreme precipitation events. The ultimate goal of this study is to determine physical processes contributing to widespread extreme precipitation events in Alaska and analyze how well the selected GCMs replicate observed behavior. Section 2 covers the data sources used in the analysis and the analysis methodology. Section 3 details our results, while section 4 summarizes the results and gives our conclusions.

2. Data Sources and Methodology

2.1. Data Sources

This study focuses on Alaska (Figure 1) during (December–February) DJF from 1986 to 2005. This corresponds to the contemporary period used in the Intergovernmental Panel on Climate Change's Fifth Assessment Report from Working Group 1 (e.g., Collins et al., 2013). We are building on previously published work that used the season DJF, so that results here can be directly compared with previous analysis discussed in Glisan and Gutowski (2014) and Glisan et al. (2016).

For observed precipitation, we utilize the National Centers for Environmental Information (NCEI) Global Summary of the Day daily observations (Table 1; National Centers for Environmental Information, 2018). For other diagnostic fields, including 500-hPa geopotential heights, we use the European Centre for Medium-Range Weather Forecast's European Reanalysis (ERA-Interim; Dee et al., 2011) to represent observed behavior. This study does not consider ERA-Interim precipitation because it is not constrained by observations and tends to underestimate precipitation in mountainous regions (Lu et al., 2012). The ERA-Interim fields we use represent key synoptic features occurring during the development of extreme events.

We use output from six selected GCMs that provided output to the Coupled Model Intercomparison Project 5 (CMIP5) data set (Taylor et al., 2012): ACCESS1-0, HadGEM2-CC, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, and the MPI-ESM-LR (Table 1). We analyze these selected GCMs because they simulate well the evolution of the annual cycle in late twentieth century Arctic sea ice (Wang & Overland, 2012). In this region, this suggests that any large-scale circulation behavior coupled to ocean-atmosphere interactions will not be highly skewed relative to ERA-Interim. The selected GCMs also provided to the CMIP5 archive all the fields examined here (precipitation, 500-hPa geopotential heights, 500-hPa vertical wind
speed, and near-surface-specific humidity), except that HadGEM2-CC and HadGEM2-ES did not provide 500-hPa vertical velocities.

### 2.2. Precipitation Analysis

We define a daily precipitation event as an observation or selected GCM grid box amount exceeding 2.5 mm/day; this threshold is used because NCEI stations do not accurately represent light precipitation (Goodison et al., 2013; Yang et al., 2005). NCEI stations must contain no more than four missing days per month to be included in this study. Between 1986 and 2005, only 21 stations meet this criterion. McAfee et al. (2013), studying precipitation trends using Alaska NCEI observations, found only 29 stations that consistently record observations. They note that inconsistent observations introduce bias into Alaska’s precipitation record, and we acknowledge that this may be an issue with our study as well. We consider extreme precipitation as the top 0.1% of all daily precipitation events occurring collectively among a GCM’s grid boxes falling within our analysis region. We then determine what we term widespread extreme events by identifying extreme events occurring in multiple adjacent grid boxes on the same day.

### Table 1

**Characteristics of Precipitation Data Sources**

<table>
<thead>
<tr>
<th>Data source</th>
<th>Grid (° lat × lon)</th>
<th>Equivalent 1° grid boxes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEI</td>
<td>N/A</td>
<td>19.33</td>
<td>National Centers for Environmental Information (2018)</td>
</tr>
<tr>
<td>ACCESS1-0</td>
<td>1.25 × 1.88</td>
<td>2.34</td>
<td>Dix et al. (2012)</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>1.25 × 1.88</td>
<td>2.34</td>
<td>Martin et al. (2011)</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>1.25 × 1.88</td>
<td>2.34</td>
<td>Martin et al. (2011)</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>1.85 × 1.86</td>
<td>3.47</td>
<td>Giorgetta et al. (2013)</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td>2.79 × 2.81</td>
<td>7.84</td>
<td>Watanabe et al. (2011)</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>2.79 × 2.81</td>
<td>7.84</td>
<td>Watanabe et al. (2011)</td>
</tr>
</tbody>
</table>

*Note.* NCEI = National Centers for Environmental Information; N/A = not applicable.
The native NCEI precipitation data are not gridded, but we attempted to grid daily precipitation to each selected GCM’s resolution to properly compare biases between models. Due to rapidly changing elevation throughout our analysis region, we recognize that including orographic effects might increase the station-based precipitation values. We attempted to use a thin-plate spline (e.g., Arowolo et al., 2017; Boer et al., 2001; Hutchinson, 1995, 1998; Tait et al., 2006) to interpolate observations to the spatial resolution of each selected GCM (Table 1). Unfortunately, there are not enough observations to accurately estimate the gradient in precipitation rate with elevation (Kane & Stuefer, 2013), and we obtained unrealistic precipitation intensities by interpolating the observations. We will see that a key issue here is undersimulation of extreme precipitation events by the selected GCMs. This is irrespective of whether or not orography is included in the gridded observations.

The same methodology used to identify observational extreme precipitation events is used to identify extreme events output by the selected GCMs. However, some GCM grid points in our domain occur over ocean, and, to not bias our results, we remove ocean point precipitation data from our analysis. Unfortunately, the selected GCMs do not have the same resolution, which can influence our diagnosis of the spatial extent of their extreme events. When assessing the spatial extent of possible widespread events, we measure the size of GCM grid boxes in terms of equivalent 1° × 1° latitude-longitude grid boxes (Kawazoe & Gutowski, 2013). Table 1 shows the equivalent grid boxes for the observations and models. We make a similar estimate for the NCEI stations, though one must recognize that they are not evenly distributed across our analysis region. For example, the MIROC-ESM has 2.8° × 2.8° grid boxes, meaning that one MIROC-ESM grid box contains 7.8 equivalent 1° grid boxes. We define a widespread extreme as one with extreme daily precipitation occurring simultaneously on six or more equivalent 1° grid boxes. This definition emerges from a consideration of the frequency of simultaneous events (see below). For at least the higher-resolution models, these events are likely to be the outcome of resolved behavior (e.g., Kawazoe & Gutowski, 2013). Note that for the coarsest models, MIROC-ESM and MIROC-ESM-CHEM, a widespread event can occur with just one grid box experiencing an extreme event.

2.3. Self-Organizing Maps

Self-organizing maps (SOMs; Hewitson & Crane, 2002; Kohonen, 2001; Sheridan & Lee, 2011) have been used in the past to analyze the impact of large-scale circulation on synoptic-scale processes; they then can be used to develop a synoptic climatology of the large-scale circulation patterns associated with extreme events (e.g., Cassano et al., 2015). As a result, previous studies have used SOMs to analyze the variability in extreme events within several different geographic regions (e.g., Agel et al., 2018; Alexander et al., 2009; Cavazos, 1999, 2000; Horton et al., 2015; Lee et al., 2017; Ramseyer & Mote, 2017). Within Alaska, Glisan et al. (2016) used SOMs to study topographically forced widespread precipitation extremes, and they found this type of analysis tool to be effective. This provides us a basis to use SOMs for the analysis of uncertainties in extreme precipitation events simulated by the selected GCMs.

In this study, SOMs are used to evaluate reanalysis and simulated 500-hPa geopotential height fields. The SOM methodology utilizes a neural network that generates a two-dimensional array of maps spanning the pattern space of the ERA-Interim and selected GCM daily 500-hPa geopotential height fields. In the SOM array, an individual map, or node, is considered a representative spatial pattern of the input maps. From a user-designated array size, the nodes are initialized using random values with no assumptions made about the spatial pattern distribution (Hewitson & Crane, 2002). A training procedure, described by Sheridan and Lee (2011), then yields a two-dimensional self-organized array of maps. During our study period, we apply the SOM training to all daily DJF 500-hPa geopotential height fields simulated by ERA-Interim and the selected GCMs. To do this, we regrid the ERA-Interim and the selected GCM 500-hPa geopotential height fields to a common 1° × 1° grid. Note that the regridded 500-hPa geopotential height fields still retain the underlying, coarser resolution of each model.

Following considerations given by Cassano et al. (2015), we create a 7 × 5 array of maps. After obtaining the SOM array, a climatology of large-scale circulation patterns associated with both total precipitation and widespread extreme precipitation events is determined. By mapping individual daily widespread extreme precipitation events to the widespread extreme precipitation climatology, we can compute the frequency of occurrence on each SOM node. The frequency distributions highlight several features, the degree to which specific large-scale circulation patterns produce widespread extreme precipitation, the clustering of patterns
in the SOM array that yield widespread extreme precipitation, and the degree of agreement between ERA-Interim and the selected GCMs.

3. Results
3.1. Extreme Precipitation
By examining the frequency distribution of precipitation events with varying intensities, Figure 2 shows the observations and selected GCMs generally agree up to about 10 mm/day. For more intense precipitation events, the observations occur at a higher frequency (>10 mm/day; hereby high-intensity precipitation events) than any of the selected GCMs. By comparing Weather Research and Forecasting Model output to NCEI observations, Glisan and Gutowski (2014) found that even when using a much higher-resolution model, high-intensity precipitation events still occur more often in observations than model output. None of the selected GCMs produce precipitation intensities at or exceeding the observation maximum intensity, with maximum model intensities approaching 40 mm/day, while observations approach 60 mm/day. The lowest-resolution models, MIROC-ESM and MIROC-ESM-CHEM, produce the lowest frequency of high-intensity precipitation events, whereas the highest-resolution models, ACCESS1-0, HadGEM2-CC, and HadGEM2-ES, produce the highest occurrence of high-intensity precipitation events. Table 2 shows that the 99.9th percentile of the observations is higher than any of the selected GCMs at 62.77 mm/day. The 99.9th percentile of selected GCMs ranges between 20 and 30 mm/day. Considering that none of the selected GCMs

### Table 2

<table>
<thead>
<tr>
<th>Data source</th>
<th>99.9th percentile precipitation (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEI</td>
<td>62.77</td>
</tr>
<tr>
<td>ACCESS1-0</td>
<td>27.81</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>27.96</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>26.07</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>26.55</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td>22.55</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>22.70</td>
</tr>
</tbody>
</table>

*Note: NCEI = National Centers for Environmental Information; GCM = global climate model.*
produce precipitation intensities at or near to the NCEI observations, these results suggest that precipitation intensity is linked to model resolution, consistent with Kawazoe and Gutowski (2013).

Figure 3 contains the distribution of days with extreme events occurring simultaneously on one or more grid boxes. All observational extreme events are considered widespread due to a lack of stations and resulting in an effective resolution equivalent to 19.33° grid boxes (Table 1). All selected GCMs have very few simultaneous extreme events occurring on 30 or more equivalent grid boxes, and the number of events tends to decrease rapidly as the spatial scale (number of equivalent grid boxes) increases. This suggests that the spatial scales of NCEI extreme events are larger than any events simulated by the selected GCMs. For wintertime precipitation, this apparent deficiency in spatial scale of events for the selected GCMs is similar in character to deficiencies found by Glisan and Gutowski (2014). Among the selected GCMs, Figure 3 also shows that the spatial scale of extreme events decreases about twice as slow for ACCESS0-1, MPI-ESM-LR, and MIROC-ESM-CHEM than the other selected GCMs. In contrast to precipitation intensity, this suggests that the spatial scale of extreme precipitation events simulated by each selected GCM does not appear to have any dependence on resolution.

3.2. Self-Organizing Maps Behavior

Figure 4 shows the SOM array produced using daily 500-hPa heights for DJF during 1986–2005 from ERA-Interim and all six models. The key features in Figure 4 are as follows:

- Low 500-hPa heights west of Alaska and high heights in eastern Alaska for maps in the upper left corner of the array,
- Low heights in northern Alaska and high heights in the Gulf of Alaska for maps in the upper right corner of the array,
- Low heights both southwest and northeast of Alaska and high heights both northwest and southeast of Alaska in the lower left, and
- Low heights southeast of Alaska and high heights southwest of Alaska for maps in the lower-right corner of the SOM array.

Figure 5 shows the climatological frequencies of 500-hPa geopotential height patterns for the ERA-Interim (Figure 5a) and the selected GCMs. If the occurrence of different 500-hPa geopotential height patterns were the same, climatological frequencies of each SOM node would be 2.86%. The actual frequency distributions are relatively smooth, and 60% or more of the frequencies are in the range 1.86–3.86%, for ERA-Interim
Figure 4. The 7 × 5 500-hPa geopotential height domain self-organizing map representing the synoptic circulation patterns for ERA-Interim and all selected global climate models during December, January, and February. Shaded contours change every 20 m.

and all the selected GCMs. However, there are differences in detail between the distributions. ERA-Interim 500-hPa patterns have the highest frequencies on the left side of the SOM array. From Figure 4, we see that most observed precipitation events are associated with a 500-hPa low-pressure system west of Alaska. This 500-hPa geopotential height pattern would result in moisture advection off the north Pacific and Gulf of Alaska, providing region with the moisture necessary to produce precipitation. ACCESS1-0 (Figure 5b) 500-hPa geopotential height patterns tend to occur with a distribution similar to the ERA-Interim. Even though Hadley Centre and ACCESS models all use the HadGEM2 atmosphere (Knutti et al., 2013), the HadGEM2-CC (Figure 5c) and HadGEM2-ES (Figure 5d) distributions differ from those of the ERA-Interim, with concentrations in the middle columns of the SOM array. Over this portion of the SOM array, Figure 4 shows a much broader 500-hPa trough in the middle of the SOM array. This suggests that precipitation events simulated by HadGEM2-CC and HadGEM2-ES are associated with more zonal flow and weaker large-scale forcing. The MIROC-ESM (Figure 5f) has a relatively uniform distribution, while MIROC-ESM-CHEM (Figure 5g) clusters 500-hPa geopotential height pattern on the left edge of the SOM array thus resulting in precipitation for similar reasons as ERA-Interim. Whereas, MPI-ESM-LR (Figure 5e) clusters precipitations along the right edge of the SOM array. The 500-hPa geopotential height patterns associated with MPI-ESM-LR precipitation events are a 500-hPa low-pressure system over eastern Alaska and a 500-hPa high-pressure system over western Alaska. Unlike ERA-Interim and the other selected GCMs, this type of synoptic setup would result in precipitation events most likely located over northwestern Alaska. In this
Figure 5. (a–g) The climatological frequency of precipitation events associated with 500-hPa geopotential height patterns occurring on a given node for the full 7 × 5 self-organizing map domain. The boxes relate directly to the nodes shown in Figure 4.

Despite the differences in the climatological distributions, Figure 6 shows ERA-Interim (Figure 6a) and each of the selected GCMs clusters extreme events in relatively small portions of the SOM array, generally toward the upper rows of SOM space, between nodes (2,1) and (5,1). Within this part of the SOM array, a strong 500-hPa low-pressure system is west of Alaska, and a strong 500-hPa high-pressure system is east of Alaska (Figure 4). However, this type of pattern is most apparent on nodes (2,1) and (3,1). For nodes (4,1) and (5,1) the 500-hPa low-pressure system weakens, and 500-hPa high-pressure system becomes the dominant feature. Both of these types of patterns are conducive to heavy precipitation by providing both strong large-scale forcing and moisture to sustain precipitation events. Using mean sea level pressure instead of 500-hPa geopotential height to classify the environment, Glisan et al. (2016) performed a similar analysis by comparing 50-km resolution Weather Research and Forecasting output to ERA-Interim. Similar to these
results, they found that extreme precipitation events are associated with a strong low-pressure system east and a high-pressure system west of Alaska. HadGEM2-CC (Figure 6c), HadGEM2-ES (Figure 6d), and the MPI-ESM-LR (Figure 6e) cluster all extreme events on a small number of nodes (i.e., (2,1), (3,1), (4,1), and (5,1)) along the top two rows of the SOM array, while ERA-Interim, ACCESS1-0 (Figure 6b), MIROC-ESM (Figure 6f), and MIROC-ESM-CHEM (Figure 6g) show low-frequency events also occurring in other quadrants of the SOM array, primarily the lower left quadrant. This pattern results in the 500-hPa cutoff low southwest of Alaska and a 500-hPa high-pressure ridge southeast of Alaska. However, both the 500-hPa low- and high-pressure systems are not as strong and would not provide as much synoptic-scale support to produce intense precipitation.

### 3.3. Synoptic Setup for an Extreme Event
The ERA-Interim and all selected GCMs have some of their extreme events on a common node (4,1). As shown in Figure 7, the typical synoptic setup for such an extreme event is a 500-hPa low-pressure system west of Alaska and, especially, a 500-hPa high-pressure system east of Alaska. This pattern results in southerly flow bringing moisture from the Gulf of Alaska north, and the interaction between the relatively...
Figure 7. (a–g) The average 500-hPa geopotential height patterns (contours) during widespread extreme (99.9th) precipitation events occurring on node (4,1) from Figure 4. The location of National Centers for Environmental Information (a) and selected global climate model (b–g) extreme events are depicted using white pluses. humid air and the southern Alaska terrain results in widespread extreme precipitation events. Given the strength of the 500-hPa ridge, this behavior also suggests that a blocking pattern may exist over southeastern Alaska. This suggests that during widespread extreme precipitation events, the 500-hPa low-pressure system west of Alaska becomes quasi-stationary. This would result in a steady supply of moisture from the Gulf of Alaska over a prolonged period of time, similar to findings by Glisan et al. (2016) over southern Alaska and Gutowski et al. (2008) over the central United States. The lowest 500-hPa geopotential heights are similar in magnitude among both ERA-Interim (Figure 7a) and selected GCMs west of Alaska. However, east of Alaska, the ridge simulated by MIROC-ESM (Figure 7f) and MIROC-ESM-CHEM (Figure 7g) is closest to that in ERA-Interim. As a result, we expect a slower moving trough in ERA-Interim, MIROC-ESM, and MIROC-ESM-CHEM and sustained moisture to result in the most intense precipitation. This relationship holds for ERA-Interim; however, MIROC-ESM and MIROC-ESM-CHEM produce the least intense extreme events among models. Over southern Alaska, the combination of moisture from the Gulf of Alaska and the potential of the 500-hPa low-pressure system slowing down would increase the likelihood of widespread extreme precipitation. However, none of the selected GCMs produce extreme precipitation events with similar intensities to NCEI observations (Figure 2). This suggests that other processes are impacting precipitation intensity. As will be shown later, the ability of each model to resolve topography has a significant impact on extreme precipitation events.
Figure 8. The average near-surface-specific humidity patterns (contours) during widespread extreme (99.9th) precipitation events occurring on node (4,1) from Figure 4. The location of National Centers for Environmental Information (a) and selected global climate model (b–g) extreme events are depicted using white pluses. Regions north of 60°N contoured in white have near-surface-specific humidity values below 1 g kg$^{-1}$.

In ERA-Interim and models, Figure 8 shows near-surface-specific humidity anomalies of greater than 4 g/kg just south of Alaska. The similarity of specific humidity fields among ERA-Interim and the selected GCMs (Figure 8) does not indicate a substantial humidity bias in the large-scale fields of the selected GCMs, and indirectly suggests there is no large-scale temperature bias. ERA-Interim (Figure 8a), MIROC-ESM (Figure 8f), and MIROC-ESM-CHEM (Figure 8g) all simulate the largest near-surface-specific humidity anomalies, with values greater than 6 g/kg just south of Alaska. Similar to 500-hPa geopotential heights shown in Figure 7, the selected GCMs simulating the most moisture being transported into southern Alaska are the selected GCMs producing the least intense extreme precipitation. Again, this suggests that processes other than large-scale dynamics are also impacting extreme precipitation intensity.

Examining upward motion associated with extreme precipitation events, Figure 9 shows a region of 500-hPa vertical velocities greater than 3 cm/s in the ERA-Interim (Figure 9a) reanalysis and some of the selected GCMs (note again that the CMIP5 archive did not have vertical velocities from either HadGEM2-CC [Figure 9c] or HadGEM2-ES [Figure 9d]). As resolution decreases, maximum 500-hPa vertical velocity both decreases and broadens spatially over southern Alaska. Additionally, in ERA-Interim and the selected GCMs, most extreme events occur within the region of maximum 500-hPa vertical velocity and the magnitude of extreme events scale with 500-hPa vertical velocity. Based on upward motion alone, the relationship
The average 500-hPa vertical velocity patterns (contours) during widespread extreme (99.9th) precipitation events occurring on node (4,1) from Figure 4. The location of National Centers for Environmental Information (a) and selected global climate model (b–g) extreme events are depicted using black pluses. This study notes that 500-hPa vertical velocity from HadGEM2-CC and HadGEM2-ES was not available in the Coupled Model Intercomparison Project 5 repository.

shown between 500-hPa vertical velocity and magnitude of extreme precipitation intensity is not surprising. Even though the finest-resolution selected GCM, ACCESS-1 (Figure 9b), has the strongest vertical motion, it is still approximately 3 times smaller than ERA-Interim. Thus, an important issue then is why the vertical motions from the selected GCMs are much lower than those in ERA-Interim.

3.4. Topographic Effects
As shown in Figures 7–9, widespread extreme precipitation events occur over southern Alaska. Specifically, Figure 10 shows that extreme events are concentrated south of the Alaska Range. It is evident that selected GCMs that resolve topography most similar to ERA-Interim simulate the most intense extreme widespread precipitation events. This suggests that as the topography becomes smoother due to decreasing model resolution, the strength of upward motion decreases and results in the selected GCMs producing less intense precipitation. This is consistent with results shown in Figure 9; however, other factors including the parameterization of clouds (Lim & Hong, 2010; Morrison, Curry, & Khvorostyanov, 2005; Morrison, Curry, Shupe, et al. 2005) and aerosols (Girard & Blanchet, 2001) may also be hampering simulated precipitation intensity.

Given the large-scale flow patterns indicated by Figure 7 and also suggested by Figures 4 and 6, our results suggest that topographic lift is the primary forcing mechanism responsible for extreme events. By
Figure 10. Topography resolved by ERA-Interim (a) on a 0.75° × 0.75° grid and the selected global climate model (b–g) on their native resolutions (Table 1 are contoured. The location of National Centers for Environmental Information (a) and selected global climate model (b–g) widespread extreme (99.9th) precipitation events are depicted using red pluses. Regions of white are areas where ERA-Interim and selected global climate model topography are <0 m.

Figure 11 shows differences in model topography in comparison to actual topography. Figure 11 suggests that weaker precipitation intensity in the selected GCMs is due to the substantial smoothing of the complex terrain in southern Alaska by the GCMs’ grids. All of the selected GCMs do show extreme precipitation in response to topographic uplift in southern Alaska, but the smoothness of their topography limits their ability to properly simulate extreme precipitation intensity. While it is likely that the representation of terrain in the selected GCMs is not the only factor responsible for the undersimulation of extreme precipitation events, these results suggest that the proper representation of topography is key to properly simulating precipitation intensity over southern Alaska.

4. Conclusions

As Arctic warming continues to accelerate in response to sea ice and snow loss, it is essential that GCMs are able to accurately predict both the frequency and magnitude of changes in extreme events. In particular, Alaska’s infrastructure is highly vulnerable to changes in the frequency and intensity of precipitation events. This study focuses on understanding the processes responsible for widespread extreme precipitation events in a set of GCMs. To accomplish this, we compare wintertime (DJF) NCEI-observed precipitation to output provided to the CMIP5 archive by a selected group of GCMs from 1986 to 2005. The SOM
methodology is then used to identify 500-hPa geopotential height patterns associated with widespread extreme precipitation events and determine the processes responsible for these extreme events. Our approach allows insight into not only the processes responsible for widespread extreme precipitation over Alaska but also processes limiting each GCMs’ ability to properly predict widespread extreme precipitation events in a warming climate.

By comparing NCEI observations to the selected GCMs, we show that the selected GCMs undersimulate extreme precipitation events. Considering that the highest-resolution GCMs simulate the most frequent and intense extreme precipitation events, we suspect that the discrepancy between NCEI observations and the selected GCMs is likely a function of GCM resolution.

We find that the spatial scale of NCEI widespread extreme precipitation events is larger than any event produced by the selected GCMs. This study also shows that the spatial scale of widespread extreme events does not change faster or slower for the higher-resolution selected GCMs. This suggests that, unlike precipitation intensity, there is no dependence among the selected GCMs on resolution.

The SOM methodology provides insight into the synoptic patterns responsible for widespread extreme precipitation events occurring over Alaska. By analyzing the frequency at which a widespread extreme precipitation event occurs on a given SOM node, this study shows that ERA-Interim and all the selected GCMs effectively cluster extreme events within a relatively small portion of the 500-hPa geopotential height pattern space. The ACCESS1-0, HadGEM2-CC, HadGEM2-ES, and MPI-ESM-LR all cluster extreme events within the upper two rows of SOM space. This part of SOM space is associated with a 500-hPa low-pressure system west and a 500-hPa low-pressure system east of Alaska. This type of setup would supply both the necessary moisture and large-scale forcing needed for widespread extreme precipitation events to occur. While ERA-Interim, MIROC-ESM, and MIROC-ESM-CHEM cluster the majority of extreme events in the upper two rows, a few events cluster in the lower left portion of SOM space. The 500-hPa geopotential height pattern associated with this region of SOM space is a 500-hPa cutoff low-pressure system southwest of Alaska and a 500-hPa ridge southeast of Alaska. While this type of synoptic setup is similar to that occurring along the upper row of SOM space, the synoptic-scale support for precipitation events would not be as strong. As a result, extreme events would be less frequent.

ERA-Interim and all the selected GCMs shared a common node (4,1) that widespread extreme precipitation events occurred on. To determine the quality of selected GCMs interpretation of processes responsible for extreme events, this study analyzed the average 500-hPa geopotential height field, near-surface-specific humidity field, and 500-hPa vertical velocity field responsible for these events. The typical synoptic setup
responsible for extreme events is a 500-hPa trough west of Alaska supplying moisture from the Gulf of Alaska north. Due to the interaction between the incoming moisture and Alaska’s terrain, this results in intense precipitation over southern Alaska. Additionally, our results show that the 500-hPa ridge east of Alaska is especially strong. Potentially, this would result in a blocking pattern and slow the forward progress of the 500-hPa trough, resulting in sustained precipitation over a longer time period.

Both the 500-hPa geopotential height and near-surface-specific humidity patterns support the occurrence of widespread extreme precipitation in the selected GCMs. However, there are large differences between ERA-Interim and the selected GCM vertical velocity fields, with ERA-Interim maximum vertical velocity approximately 3 times larger than the nearest GCM. This may explain why extreme precipitation intensities in the selected GCMs are much smaller than NCEI observations. Due to GCM resolution, we determine that the topographic forcing over southern Alaska is not sufficiently supplementing the upper-level support for widespread extreme precipitation, consistent with Glisan and Gutowski (2014) and Glisan et al. (2016).

It is encouraging that our results show that the selected GCMs are properly simulating the large-scale patterns responsible for widespread extreme precipitation events. However, given the complexity of southern Alaska’s terrain, our results suggest that GCMs are unable to fully capture extreme events. Unless GCMs can explicitly capture the rapidly changing topography over southern Alaska, or effectively parameterize topography, there is little likelihood that any GCM will be able to appropriately capture extreme precipitation intensity in the future.

Acknowledgments
This work was supported by NSF grant ARC-1023639, with additional support from the U.S. Department of Energy grants DEFG0207ER44643 and DESC0016438. The ERA-Interim reanalysis was accessed through the ECWMF data servers (http://apps.ecmwf.int/datasets/data/interim-full-daily/). CMIP5 GCM data were downloaded from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) data server (https://cmip.llnl.gov/cmip5/data.portal.html) at the Lawrence Livermore National Laboratory. The 2-min gridded global relief data (2-min DEM) data were downloaded from the NOAA global relief data (https://cmip.llnl.gov/cmip5/data_portal.html). We are grateful to the three anonymous reviewers who provided us with valuable feedback that helped strengthen and improve our paper’s quality.

References


