Using Variable-Resolution Grids to Model Precipitation from Atmospheric Rivers around the Greenland Ice Sheet

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Using Variable-Resolution Grids to Model Precipitation from Atmospheric Rivers around the Greenland Ice Sheet

By

Annelise Waling

BS, Clemson University, 2021

Thesis

Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Earth Sciences – Hydrology

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Dedication

To my mom and dad, whose love and support have guided me to where I am today, and to wherever in the world I will go.
Acknowledgments

Thank you to my committee members for your guidance and expertise over the past two years, I couldn’t have done it without each of you. Dr. Elizabeth Burakowski, for seeing my potential and bringing me on as one of her first graduate students, Dr. Adam Herrington, for providing me with the coding skills and simulations necessary for this project, Dr. Katharine Duderstadt, for continually supporting me in both words and in opportunities, and Dr. Jack Dibb for his expansive knowledge regarding Greenland and for always making sure that us modelers stay focused in reality.

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Abstract

Atmospheric rivers (ARs) are synoptic-scale features that transport moisture poleward and have been shown to cause short duration, high-volume melt events in the Greenland ice sheet (GrIS). This project supports the effectiveness of variable-resolution (VR) grids in modeling ARs and their subsequent precipitation around the GrIS using a study period of 1 January 1979 to 31 December 1998. VR simulations from the Community Earth System Model (CESM2) bridge the gap between limitations of global climate models and regional climate models while maximizing computational efficiency. VR grids improve the representation of ARs, in part by resolving small-scale processes. ARs are identified in the CESM2 using three grid types (VR, latitude-longitude, and quasi-uniform) of varying resolutions and comparison to output of the observation-based reanalysis product, ERA5. The VR grids produce a smaller areal extent than latitude-longitude and quasi-uniform grids, as well as lower integrated precipitation. We hypothesize that the smaller areal extents in VR grids are produced by the refined topography resolved in these grids. Due to the coarser resolution in latitude-longitude and quasi-uniform grids, smoothing occurs therefore allowing ARs to penetrate further inland into the GrIS. This areal extent also likely causes the lower area-integrated cumulative precipitation occurring in the VR grids, as the area-average cumulative precipitation is similar for VR, latitude-longitude, and quasi-uniform grids. The VR grids behave the most similarly to ERA5 in these two metrics, therefore suggesting that they describe AR behavior and subsequent precipitation the most accurately among the three grid configurations included in this study.
Chapter I

Introduction

Atmospheric rivers (ARs) are large filamentary structures within the atmosphere that contain concentrated amounts of water vapor (Fig. 1.1). ARs originate in the subtropics from the interaction between an extratropical cyclone and a low-level jet (Sodemann et al., 2020), and subsequently travel poleward. Nearly 90% of total annual polar moisture transport is attributed to ARs (Payne et al., 2020). In size, ARs are generally around several thousand km long and only a few hundred km wide (Newell et al., 1992), though their exact geometries can vary storm by storm or during the lifespan of an individual event.

In addition to bringing large amounts of water vapor to the poles, ARs often bring warm temperatures (Mattingly et al., 2020). Polar regions are already sensitive to feedbacks and warming induced melting and ARs can exacerbate these extreme melting events (Payne et al., 2020). For example, in July 2012 the Greenland ice sheet (GrIS) experienced a short-duration, high-volume melt event in association with an AR (Fig. 1.2), which caused substantial mass loss (Bonne et al., 2015). Bonne et al. (2015) found that during this event surface mass balance (SMB) fell three standard deviations below the average value during this time of year and surface melt covered 97% of the GrIS.
ARs have been shown to cause significant and complicated melt and surface mass balance changes to the GrIS (Bonne et al., 2015; Mattingly et al., 2018; Neff et al., 2018; Box et al. 2022). During the winter, ARs can contribute to increasing surface mass balance. During the summer, however, melt and mass loss can be high. In addition to season, the intensity of each AR factors into its impact on the GrIS. Strong ARs (those in the top 85th percentile of integrated vapor transport (IVT)) have been shown to cause exponentially higher melt than medium size ARs. Location of landfall also plays a role in melt and the mechanisms by which melt occurs (Mattingly et al., 2020).
In addition to degrading the polar ice sheets, ARs also impact sea ice in these regions (Kapsch et al., 2013; Boisvert et al., 2016; Hegyi and Taylor, 2018; Zhang et al., 2023). A study from Hegyi and Taylor (2018) highlights the effects that ARs have on the radiative forcings during the wintertime, a period when sea ice usually regrows after a summertime of ablation. By increasing the downwelling longwave radiation and reducing the cooling efficiency of the surface and atmosphere, ARs reduce sea-ice regrowth. Along with these radiative fluxes impacting sea ice regrowth, Zhang et al. (2023) noted that precipitation can melt new, thin ice before it has time to thicken.
As climate change progresses, researchers have found that ARs are increasing in both frequency and intensity and are expected to continue to do so (Lavers et al., 2015; Hagos et al., 2016; Espinoza et al., 2018; Curry et al., 2019; Gershunov et al., 2019; Huang et al., 2020; Zhang et al., 2021; Zhang et al., 2023). This could mean that ARs which impact the GrIS surface mass balance in a substantial way, such as the July 2012 event, could increase in frequency. Already in 2022, the GrIS experienced another major event in mid-August which caused rainfall atop Summit (Box et al., 2022).

In addition to affecting Arctic landscapes, these ARs also cause large precipitation events in other parts of the world. For example, ARs are a critical process bringing much needed moisture to the western US (Dettinger, 2013; Wang et al., 2017; Rhoades et al., 2020), though sometimes bringing such heavy precipitation it that causes more harm than good (Hatchett et al., 2017; Waliser and Guan, 2017; Huang and Swain 2022). For example, during the winter of 2023 California was impacted by at least 12 separate ARs (Fawcett, 2023). Negative effects from these ARs in California include massive and widespread flooding, sinkholes, and landslides. ARs that impact one location in such a short amount of time, such as those recently impacting California, have been termed AR families (Fish et al., 2019; Fish et al., 2022). As expected, the occurrence of AR families often leads to more negative impacts than a single AR due to the large amount of precipitation which occurs during a sequence of these events (Fish et al., 2022).

Despite their current widespread impacts, the study of ARs is an emerging field, appearing in the scientific literature only within recent decades (Newell et al., 1992; Zhu and Newell, 1998; Gimeno et al., 2014; Bonne et al., 2015; Mattingly et al., 2020; Payne et al., 2020; Shields et al.,
While they are qualitatively defined as channels within the atmosphere carrying high moisture, specific quantitative metrics that define the shape (e.g., length or width of the channel) or moisture thresholds for an AR are still being developed (Shields et al., 2018; Lora et al., 2020; Reid et al., 2020; Shields et al., 2023). In addition, ARs themselves are also constantly changing. As they travel through the atmosphere, their geometries evolve in response to local convergence and evaporation (Payne et al., 2020). Due to both the ongoing debate on AR detection and their impacts in the Arctic and elsewhere, accurately modeling ARs is a relevant and necessary field of study.

The AR Tracking Method Intercomparison Project (ARTMIP) was created to compare AR tracking algorithms (Shields et al., 2018). During the first stage of ARTMIP, various tracking algorithms were run on the same dataset and analyzed to see how they vary based on AR geometry, threshold, and temporal requirements. After simply comparing the results of this first stage, the well-performing trackers were used to investigate larger scientific questions (Shields et al., 2023). One key finding from this study was an inverse relationship between spatial footprint and intensity. This may indicate that smaller ARs can produce more precipitation when making landfall with an area. This could be especially important when considering a family of small ARs making landfall with a region over a short amount of time.

As ARTMIP focused on AR representation using various tracking algorithms, research on how ARs vary based on grid configuration is still developing (Herrington et al. 2022). Within the larger modeling community there has been a shift in preferred grid configurations to rectify the “polar problem”, namely that finite-volume grids are standard latitude-longitude grids (hereafter
referred to as “lat-lon” grids), and thus grid size decreases towards the poles. As this decrease occurs, the numerics within the climate model become unstable, manifesting as the “polar problem”, and a dampening polar filter is necessary to prevent any numerical instability. The effect of such filters reduces some of the benefit of increased resolution towards the poles, though not entirely. Some modelers have recently been shifting towards quasi-uniform unstructured grids, e.g., the spectral-element (SE) dynamical core (Lauritzen et al., 2018). While these grids eliminate the need for a polar filter and allow for increased computing efficiency, they have coarser spatial resolution in polar regions. Variable-resolution grids may alleviate some of the negative effects of lat-lon schemes while enabling fine spatial resolution in polar regions, though this comes at a higher computation cost.

Another important consideration regarding grid configuration is the model representation of GrIS topography, as coarser grids result in topographical smoothing so as to not excite grid-scale modes, which are numerically inaccurate. Figure 2.1 shows the differences in topography based on grid configurations used in this study. The coarser resolution grids (f19, ne30pg2) result in poorer representation of the steep dome in the middle of the GrIS. The finest resolution grids (ARCTIC, ARCTICGRIS) offer the most realistic representation of topography (Herrington et al., 2022) and match the fifth European Weather Center for Medium-Range Forecasts atmospheric reanalysis (ERA5; Hersbach et al., 2020) topography dataset extremely well (Figure 2.1).

Given the complexity of temporal, spatial, and mechanistic variations in melt due to ARs and the relatively recent emergence of methods for identifying and studying ARs, there are many
opportunities to improve models. This study specifically focuses on AR-related precipitation as produced by different grid configurations rather than broader understanding of the underlying mechanisms causing melt in the GrIS. Clarifying the differences in precipitation amongst grid configurations can inform future modeling experiments seeking to understand melt in the GrIS.

I used variable-resolution grids with the Community Earth System Model (VR-CESM; Zarzycki and Jablonowski, 2015; Zarzycki et al., 2015) to model ARs around the GrIS using a set of simulations produced by Herrington et al. (2022). VR grids employ static mesh refinement dynamical downscaling in order to yield enhanced resolution around our area of interest, Greenland. We evaluated the VR-CESM model simulations with two quasi-uniform unstructured grid and two latitude-longitude grid simulations (Table 2.1). We hypothesize that the VR grids portray ARs more accurately than the uniform resolution grids through better resolution of finer-scale physical processes and topography. Specifically, we suggest that the improved representation of topography in the VR-CESM grids contributes to the differences in GrIS-wide integrated precipitation among the models. The model output from all simulations was compared to ARs detected in ERA5 as in other studies involving simulated ARs (Marquardt Collow et al., 2022).

This thesis compares precipitation produced from latitude-longitude, quasi-uniform, and variable-resolution grids in CESM2.2. Chapter 2 describes the detection algorithm, grid configurations, validation method, and remapping workflow used in this study. Chapter 3 consists of a manuscript that will be submitted to the peer-reviewed Journal of Advances in Modeling Earth Systems (JAMES) documenting our findings. Chapter 3 also contains the main
results and their implications. Chapter 4 describes more extensive conclusions from our work and directions for future research.
Chapter II

Methods

2.1 Detecting Atmospheric Rivers

Synoptic storms were tracked using TempestExtremes v2.1 atmospheric feature detection software (Ullrich et al., 2021). This algorithm was chosen to detect ARs due to its usage of the Laplacian of the integrated water vapor transport (IVT) rather than IVT alone. The gradients identified by the Laplacian method can detect ARs more accurately because there will still be a steep gradient between the AR itself and any surrounding moist area, thus better constraining the boundaries of the AR (McClenny et al., 2022).

Two TempestExtremes v2.1 package algorithms were used to detect and track ARs: DetectBlobs and StitchBlobs. These algorithms are executables that identify ARs using IVT. DetectBlobs searches the global extent for ARs meeting parameters: Laplacian of IVT $<-30,000$ kg m$^{-2}$ s$^{-1}$ rad$^{-2}$, $>20$ degrees latitude, and areal extent 566,666 km$^2$. The Laplacian IVT threshold was chosen based off a study from Ullrich et al. (2021), in which they chose an IVT of -20,000 kg m$^{-2}$ s$^{-1}$ rad$^{-2}$. In comparison, our threshold is stricter and requires a larger gradient. The areal extent was chosen conservatively as 2/3 the area of an average AR, which is 850,000 km$^2$ (A. Rhoades, 2022, personal communication). IVT is defined by,

$$ IVT = \sqrt{uIVT^2 + vIVT^2} \quad \text{eq. 1} $$
where uIVT and vIVT are pointwise vertically integrated meridional and zonal vapor transport, respectively.

The output of DetectBlobs provides a binary mask outlining candidate ARs. The StitchBlobs algorithm is then used to connect the binary masks from DetectBlobs in time, providing each AR its own unique identification number. The unique ARs produced in a given model simulation are totaled, then pared down to the ARs that intersect with the Greenland Ice Sheet. StitchBlobs takes all ARs detected by DetectBlobs and unifies them together as the same uniquely identified AR as it varies by timestep, and also rejecting candidate blobs that are not continuous in time. Using these two algorithms together, we track a single AR across its entire lifespan, from its origin in the mid-latitude regions and eventual transport and dissipation.

We ran StitchBlobs based on optimizations from A. Rhoades (personal communication, 2020).

2.2 Ensemble description and validation

This study uses model output from the simulations described in Herrington et al. (2022). These simulations used CESM2.2 (Danabasoglu et al., 2020), a CMIP6-class (Coupled Model Intercomparison Project Phase 6; Eyring et al., 2016) Earth System Model. The simulations were configured using the Atmospheric Model Intercomparison Project (AMIP) protocols, which prescribe monthly sea-surface temperature and sea ice following Hurrell et al. (2008).

Herrington et al. (2022) ran simulations using CESM at six different grid resolutions (Table 2.1, Fig. 2.2) from 1 January 1979 to 31 December 1998. These include two latitude-longitude (lat-
lon) grids, two uniform quasi-uniform grids, and two variable resolution (VR) grids (Figure 2.2). Lat-lon grid configurations use the finite-volume (FV) dynamical core (hereafter referred to as dycore), using a flux-form Lagrangian scheme (Lin and Rood, 1997) in the horizontal direction and semi-Lagrangian discretization in the vertical (Lin 2014). In contrast to the lat-lon grids, the quasi-uniform dycores use the Galerkin spectral finite element (SE) method (Fournier et al., 2004). These dynamics are solved using high-degree piecewise polynomials, and therefore have improved numerical accuracy in the horizontal compared with the FV core. SE dycores use the same semi-Lagrangian vertical discretization as the FV dycore. SE cores are used for high resolution modeling for improved computational efficiency on massively parallel systems, as well as including the effects of condensates that can greatly influence the dynamics of a system at high resolution (Baumeister et al., 2012; Lauritzen et al., 2018). With their high computational efficiency, SE dycores also support variable-resolution grids, including the two used in our study (Table 2.1).

### Table 2.1. Grid configurations used in this study.

<table>
<thead>
<tr>
<th>grid name</th>
<th>dynamical core</th>
<th>$\Delta x_{eq}$ a (km)</th>
<th>$\Delta x_{refine}$ b (km)</th>
<th>remappings c</th>
</tr>
</thead>
<tbody>
<tr>
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<td>FV</td>
<td>278</td>
<td>-</td>
<td>ESMF-pg2, TR-pg2</td>
</tr>
<tr>
<td>f09</td>
<td>FV</td>
<td>139</td>
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<tr>
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<td>SE</td>
<td>111</td>
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<td>ARCTICGRIS</td>
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<tr>
<td>ERA5</td>
<td>-</td>
<td>27</td>
<td>-</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
</tbody>
</table>

a Average equatorial grid spacing.
b Grid refinement for variable resolution grids.
c Remappings performed which were included in final ensemble. ESMF-f19/TR-f19 and ESMF-pg2/TR-pg2 refer to ESMF and TempestRemap methods which transformed native grids to f19 and ne30pg2, respectively. Note that f19 and ne30pg2 grids were not remapped to themselves, their native grid configurations were used.
The atmosphere simulations used the Community Atmosphere Model 6.3 (CAM6; Gettelman et al., 2019) with data recorded at six-hourly intervals. The Community Land Model 5.0 (CLM5; Lawrence et al., 2019) was coupled to CAM6 and produced daily averages. The variables used from these models were convective precipitation rate (PRECC) and large-scale stable precipitation rate (PRECL), which were summed to reach the total atmospheric precipitation (PRECT). The IVT field from CAM6 was used for AR detection. We remapped each grid configuration to both the coarsest lat-lon grid (f19) and the coarsest quasi-uniform grid (ne30pg2) using two remapping methods, thus resulting in four ensemble members. The two remapping methods were ESMF (Mahadevan et al., 2022) and TempestRemap (Ullrich and Taylor, 2015). The usage of f19 and ne30pg2 was a conservative choice in order to favor down-scaling instead of up-scaling. For each simulation, the tracker was run four times, one for each ensemble member.

Reanalysis data from ERA5 were used to validate the ensemble generated AR variables. ERA5 is the fifth reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). Reanalysis data combines observational data from various sites and then integrates observational data from various sites with a numerical atmosphere model to gap fill spatially and temporally. ERA5 data used in this study were originally recorded with single-hourly resolution, though they were downscaled to six-hourly to compare to our data. ERA5 was chosen to use as validation for this study based on previous research in the field choosing this dataset (Marquardt Collow et al., 2022).
Figure 2.1 shows the impact of grid configuration on the resolution of the topography in Greenland. We see that within the coarser grid configurations (lat-lon, quasi-uniform), the gradient from the low elevations to high is not well represented. In addition to this, the high elevation in the middle of the GrIS is smoothed in the coarser grids. We see that the VR ARCTIC and ARCTICGRIS grids are the most similar to ERA5. The modeled topography in CESM2.2 is based on the BedMachine v3 (Morlighem et al., 2017) and ERA5 on Byrd Polar Research Center data (Howat et al., 2014), both of which are originally at 1 km spacing.

Figure 2.1 Topography of each grid configuration used in this study (top) and comparisons to ERA5 (bottom).
2.3 Remapping

Remapping is a common practice to make direct comparisons between simulations with different grid configurations. For example, the volume of each cell in a 25 x 25 km grid is 1/16th the cell volume in 100 x 100 km grid (assuming fixed cell height). To compare the two directly and quantitatively, we would take sixteen of the 25 km x 25 km grid cells and find the average across them to estimate the variable being studied over the same volume as the larger grid cell.

Furthermore, VR-grid configurations resolve more spatially tight changes in IVT than the other ensemble members. In lat-lon and quasi-uniform grids, these IVT changes would be smoother as
there are not as many grid cells, therefore yielding lower gradients. As the Laplacian calculates
the divergence of the gradient of a function, TempestExtremes would detect much higher
Laplacian magnitudes within the native VR grids. These high values would result in ARs being
detected in a different way for the VR grids than the uniform lat-lon and quasi-uniform grids,
therefore not allowing for equal comparisons between the grid configurations without
remapping.

Remapping was conducted using the ncremap algorithm in the netCDF Operator open-source
geospatial data analysis software (NCO; Zender, 2008) and relevant weight files. These weight
files describe the transformation from one grid configuration to either f19 or ne30pg2 depending
on the desired grid. In most cases, transforms are performed from fine resolution to coarser
resolution, though when from ne30pg2 to f19 up-scaling is taking place.

The Earth System Modeling Framework (ESMF) algorithms are overlay-mesh-based operators
which provide bilinear and conservative remapping methods (Mahadevan et al., 2022). In this
study, conservative first-order (ESMF) was used, and a second-order (ESMF2) method was
considered. ESMF computes the function from the source to target grid by using a weighted
average. This works well, but it assumes a constant value for the entirety of the target grid cell.
ESMF2 uses a more complicated approach by incorporating the gradients within each
neighboring source cell into the computed target cell (Jones, 1999). This allows for a
comparatively more realistic interpretation of the source cell when comparing ESMF and
ESMF2. As noted by Jones (1999), when downscaling the second-order approach does not yield
a large increase in accuracy when comparing the first- and second-order methods. After verifying
that the AR statistics are insensitive to which method, we chose to only include ESMF, not ESMF2, in our ensemble.

The TempestRemap remapping algorithm is also overlay-mesh-based (Mahadevan et al., 2022) but performs high-order conservative, consistent, and monotone linear remappings (Ullrich and Taylor, 2015). TempestRemap finds all areas from the source mesh which overlap with parts of the target mesh. Conservation refers to the global mass of all fields being maintained and consistency to the constant field being maintained. Following this projection, monotonicity is maintained by altering coefficients of the operators performing the operation. Monotonicity refers to the prohibition of uncharacteristic extrema occurring.

The number of ARs detected by ESMF and TempestRemap varied based on whether the remapping was performed to the lat-lon f19 grid or the quasi-uniform ne30pg2 grid (Table 2.2). The spread between ARs intersecting the GrIS remapped to f19 and ne30pg2 in TempestRemap allows for a larger amount of diversity in our ensemble.

Table 2.2. Total number of ARs intersecting the GrIS using ESMF and TempestRemap remapping methods.

<table>
<thead>
<tr>
<th>grid name</th>
<th>ESMF</th>
<th>TempestRemap</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f19</td>
<td>ne30pg2</td>
<td>Δd</td>
</tr>
<tr>
<td>f19</td>
<td>381</td>
<td>339</td>
<td>42</td>
</tr>
<tr>
<td>f09</td>
<td>431</td>
<td>420</td>
<td>11</td>
</tr>
<tr>
<td>ne30pg2</td>
<td>474</td>
<td>485</td>
<td>11</td>
</tr>
<tr>
<td>ne30pg3</td>
<td>483</td>
<td>447</td>
<td>36</td>
</tr>
<tr>
<td>ARCTIC</td>
<td>441</td>
<td>404</td>
<td>37</td>
</tr>
<tr>
<td>ARCTICGRIS</td>
<td>397</td>
<td>359</td>
<td>38</td>
</tr>
<tr>
<td>ERA5</td>
<td>426</td>
<td>374</td>
<td>52</td>
</tr>
</tbody>
</table>

Six grid configurations used in study (a) were remapped to f19 and ne30pg2 using ESMF (b) and TempestRemap (c). Difference between f19 and ne30pg2 detected ARs intersecting GrIS for each remapping method is calculated (d). Average (e) takes into account ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, and TempestRemap-ne30pg2.
2.4 Compositing storms

To analyze the effects of ARs on precipitation within CESM, we first found all ARs that intersect the GrIS (Fig. 2.3). We counted all ARs which touch the “Glacier” land units of Greenland in CLM. Along with the time and location of maximal overlap with the ice sheet, we created composite masks as the union of the spatial extent of each AR during its path over the GrIS (Fig. 2.3). The composite masks are used to represent areas of the GrIS where precipitation is caused by ARs. We ran this AR characterization process over each of the four ensemble members (ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, TempestRemap-ne30pg2) and took the average of each variable over the entire ensemble (Table 2.3). Each grid configuration was then compared to the ERA5 ARs and AR impacts. We discuss an alternate method to analyzing the effects of ARs on the GrIS in section 3.2.3.3.

![Figure 2.3](image.png)

**Figure 2.3.** Schematic illustrating how the DetectBlobs algorithm identifies ARs intersecting GrIS and creates a composite mask. This schematic shows a single AR making landfall with the GrIS over eight timesteps (t1-t8). The AR intersects the GrIS at timesteps t3-t5. Small regions of the GrIS where ARs have touched are shown in red in t3-t5 and composite mask is the union of these overlapping regions. The point of maximum intersection is shown at t4.
### Table 2.3. Variables used to study effects of ARs on GrIS.

<table>
<thead>
<tr>
<th>variable name&lt;sup&gt;a&lt;/sup&gt;</th>
<th>description</th>
<th>model&lt;sup&gt;b&lt;/sup&gt;</th>
<th>temporal resolution</th>
<th>ERA5 equivalent&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRECT</td>
<td>Convective precipitation rate (liquid &amp; ice; PRECC) + Large-scale (stable) precipitation rate (liquid &amp; ice; PRECL)</td>
<td>CAM</td>
<td>6-hourly instantaneous sample</td>
<td>PRECT</td>
</tr>
<tr>
<td>RAIN ICE (SNOW ICE)</td>
<td>atmospheric rain (snow) after rain (snow) repartitioning based on temperature (ice landunits only)</td>
<td>CLM</td>
<td>daily average</td>
<td>PRECT</td>
</tr>
</tbody>
</table>

<sup>a</sup>Model variable name in CESM2.
<sup>b</sup>Model within CESM from which variable is derived.
Chapter III

Using variable-resolution grids to model precipitation from atmospheric rivers around the Greenland ice sheet

Paper to be submitted to *Journal of Advances in Modeling Earth Systems*

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Abstract

Atmospheric rivers (ARs) are synoptic-scale features that transport moisture poleward and have been shown to cause short duration, high-volume melt events in the Greenland ice sheet (GrIS). This project supports the effectiveness of variable-resolution (VR) grids in modeling ARs and their subsequent precipitation around the GrIS using a study period of 1 January 1979 to 31 December 1998. VR simulations from the Community Earth System Model (CESM2) bridge the gap between limitations of global climate models and regional climate models while maximizing computational efficiency. VR grids improve the representation of ARs, in part by resolving small-scale processes. ARs are identified in the CESM2 using three grid types (VR, latitude-longitude, and quasi-uniform) of varying resolutions and comparison to output of the observation-based reanalysis product, ERA5. The VR grids produce a smaller areal extent than
latitude-longitude and quasi-uniform grids, as well as lower integrated precipitation. We hypothesize that the smaller areal extents in VR grids are produced by the refined topography resolved in these grids. Due to the coarser resolution in latitude-longitude and quasi-uniform grids, smoothing occurs therefore allowing ARs to penetrate further inland into the GrIS. This areal extent also likely causes the lower area-integrated cumulative precipitation occurring in the VR grids, as the area-average cumulative precipitation is similar for VR, latitude-longitude, and quasi-uniform grids. The VR grids behave the most similarly to ERA5 in these two metrics, therefore suggesting that they describe AR behavior and subsequent precipitation the most accurately among the three grid configurations included in this study.

3.1. Introduction

Atmospheric rivers (ARs) are large filamentary structures within the atmosphere that contain concentrated amounts of water vapor. ARs originate in the subtropics and subsequently travel poleward. Nearly 90% of total annual polar moisture transport is attributed to ARs (Payne et al., 2020). In addition to bringing large amounts of water vapor to the poles, ARs often bring warm temperatures and cause melt (Bonne et al., 2015; Mattingly et al., 2018; Neff et al., 2018; Mattingly et al., 2020; Box et al. 2022, Mattingly et al., 2023). Polar regions are sensitive to feedbacks and warming induced melting and ARs can exacerbate extreme melting events (Payne et al., 2020). For example, in July 2012 the Greenland ice sheet (GrIS) experienced a short-duration, high-volume melt event in association with an AR, which caused substantial mass loss. Bonne et al. (2015) found that during this event, surface mass balance (SMB) fell three standard
deviations below the average value during this time of year and surface melt covered 97% of the
GrIS.

As climate change progresses, researchers have found that ARs are increasing in both frequency
and intensity and are predicted to continue doing so (Lavers et al., 2015; Hagos et al., 2016;
Espinoza et al., 2018; Curry et al., 2019; Gershunov et al., 2019; Huang et al., 2020; Zhang et al.,
2021; Zhang et al., 2023). This could mean that ARs which impact the GrIS SMB in a substantial
way, such as the July 2012 event, will increase in frequency. The GrIS has already experienced
another major event in mid-August 2021 which caused rainfall at Summit Station (Box et al.,
2022).

Studies have been conducted regarding the effects of tracking algorithms on AR detection
(Shields et al., 2018; Shields et al., 2023), but little has been published on the effect of grid
configuration choice. Within the modeling community there has been a shift in preferred grid
configurations to rectify the “polar problem” where grid size in standard latitude-longitude grids
(also referred to herein as lat-lon grids) decreases towards the poles. As this decrease occurs, the
numerics within the climate model become unstable and a dampening polar filter is necessary to
prevent any numerical instability. Implementing such filters reduces some of the benefit of
increased resolution towards the poles, though not entirely. Some modelers have recently been
shifting towards quasi-uniform unstructured grids, e.g., the spectral-element (SE) grid dynamical
core (Lauritzen et al., 2018). While these grids eliminate the need for a polar filter and allow for
increased computing efficiency, they have coarser spatial resolution in polar regions. Variable-
resolution grids may alleviate some of the negative effects of lat-lon schemes while enabling high spatial resolution in polar regions, though this comes at a higher computation cost. We use variable-resolution grids with the Community Earth System Model (VR-CESM; Zarzycki and Jablonowski, 2015; Zarzycki et al., 2015) to model ARs around the GrIS (Herrington et al., 2022). VR grids employ static mesh refinement dynamical downscaling in order to yield enhanced resolution around our area of interest, Greenland. VR-CESM model results are compared to two quasi-uniform unstructured grid and two latitude-longitude grid simulations (Table 3.1). We hypothesize that the VR grids will portray ARs more accurately than the uniform resolution grids through better resolution of finer-scale physical processes and topography. The model output is compared to ARs detected in ERA5 as in other studies involving simulated ARs (Marquardt Collow et al., 2022).

This study compares precipitation produced from latitude-longitude, quasi-uniform, and variable-resolution grids in CESM2.2. Section 3.2 describes the ensemble, remapping workflow, AR detection method, and validation dataset used in this study. Section 3.3 contains the main results and analyses performed in this project. Section 3.4 discusses the implications of these results. Section 3.5 summarizes main conclusions from our work and provides directions for future research.
3.2. Data and Methods

3.2.1 Ensemble description

This study uses model output from the simulations described in Herrington et al. (2022). These simulations used CESM2.2 (Danabasoglu et al., 2020), a CMIP6-class (Coupled Model Intercomparison Project Phase 6; Eyring et al., 2016) Earth System Model. The simulations were configured using the Atmospheric Model Intercomparison Project (AMIP) protocols, which prescribe monthly sea-surface temperature and sea ice following Hurrell et al. (2008).

Herrington et al. (2022) ran simulations using CESM at six different grid resolutions (Table 3.1, Fig. 3.1) from 1 January 1979 to 31 December 1998. These include two uniform latitude-longitude (lat-lon) grids, two quasi-uniform grids, and two variable-resolution (VR) grids. Lat-lon grid configurations use the finite-volume (FV) dynamical core (hereafter referred to as dycore), using a flux-form Lagrangian scheme (Lin and Rood, 1997) in the horizontal direction and semi-Lagrangian discretization in the vertical (Lin, 2014). The quasi-uniform grids use spectral-element (SE) dycores and the Galerkin spectral finite element method (Fournier et al., 2004). These dynamics are solved using high-degree piecewise polynomials, and therefore have improved numerical accuracy in the horizontal compared with the FV core. SE uses the same semi-Lagrangian vertical discretization as the FV dycore. SE cores are used for high resolution modeling for improved computational efficiency on massively parallel systems, as well as including the effects of condensates that can greatly influence the dynamics of a system at high resolution (Bacmeister et al., 2012; Lauritzen et al., 2018). With their high computational
efficiency, SE dycores also support variable-resolution grids, including the two used in our study (Table 3.1).

**Table 3.1.** Grid configurations used in this study.

<table>
<thead>
<tr>
<th>grid name</th>
<th>dynamical core</th>
<th>$\Delta x_{eq}^a$ (km)</th>
<th>$\Delta x_{refine}^b$ (km)</th>
<th>remappings$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>f19</td>
<td>FV</td>
<td>278</td>
<td>-</td>
<td>ESMF-pg2, TR-pg2</td>
</tr>
<tr>
<td>f09</td>
<td>FV</td>
<td>139</td>
<td>-</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
<tr>
<td>ne30pg2</td>
<td>SE-CLSAM</td>
<td>167</td>
<td>-</td>
<td>ESMF-f19, TR-f19</td>
</tr>
<tr>
<td>ne30pg3</td>
<td>SE-CLSAM</td>
<td>111</td>
<td>-</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
<tr>
<td>ARCTIC</td>
<td>SE</td>
<td>111</td>
<td>28</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
<tr>
<td>ARCTICGRIS</td>
<td>SE</td>
<td>111</td>
<td>14</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
<tr>
<td>ERA5</td>
<td>-</td>
<td>27</td>
<td>-</td>
<td>ESMF-f19, ESMF-pg2, TR-f19, TR-pg2</td>
</tr>
</tbody>
</table>

$^a$ Average equatorial grid spacing.  
$^b$ Grid refinement for variable resolution grids.  
$^c$ Remappings performed which were included in final ensemble. ESMF-f19/TR-f19 and ESMF-pg2/TR-pg2 refer to ESMF and TempestRemap methods which transformed native grids to f19 and ne30pg2, respectively. Note that f19 and ne30pg2 grids were not remapped to themselves, their native grid configurations were used.

The atmosphere simulations used the Community Atmosphere Model 6.3 (CAM6; Gettelman et al., 2019) with data recorded at six-hourly intervals. The Community Land Model 5.0 (CLM5; Lawrence et al., 2019) was coupled to CAM6. The variables used from these models were convective precipitation rate (PRECC) and large-scale stable precipitation rate (PRECL), which were summed to reach the total atmospheric precipitation (PRECT). The IVT field used in AR detection also came from CAM6.

Figure 3.2 shows the impact of grid configuration on the resolution of the topography in Greenland. We see that within the coarser grid configurations (latitude-longitude, quasi-uniform), the gradient from low to high elevations is not well represented. In addition to this, the
high elevation in the middle of the GrIS is smoothed in the coarser grids. We see that the VR ARCTIC and ARCTICGRIS grids are the most similar to ERA5. The modeled topography in CESM2.2 is based on the BedMachine v3 (Morlighem et al., 2017) and ERA5 on Byrd Polar Research Center data (Howat et al., 2014), both of which are originally at 1 km spacing.

Figure 3.1. Grids used in this study. A-b show latitude-longitude (a- f19, b- f09) grids, c-d quasi-uniform (c- ne30pg2, d- ne30pg3), and e-f variable-resolution (e- ARCTIC, f- ARCTICGRIS). VR grids are shown with insets focusing on Greenland to show resolution. Lower resolution grids are shown on top row and high resolution on bottom row. Adapted from Herrington et al., (2022).
3.2.2 Remapping

Remapping was conducted using the ncremap algorithm in the netCDF Operator open-source geospatial data analysis software (NCO; Zender, 2008) and relevant weight files. These weight files describe the transformation from one grid configuration to either f19 or ne30pg2. In most cases, transforms are performed from fine resolution to coarser resolution, though when mapping from ne30pg2 to f19 up-scaling is taking place.

We remapped each grid configuration to the coarsest lat-lon grid (f19) and the coarsest quasi-uniform grid (ne30pg2) using two remapping methods, thus resulting in four ensemble members. The two remapping methods were ESMF (Mahadevan et al., 2022) and TempestRemap (Ullrich and Taylor, 2015). This was a conservative choice in order to favor down-scaling instead of up-
scaling. For each simulation, the tracker described below was run four times, once for each ensemble member.

### 3.2.3 Detecting Atmospheric Rivers

#### 3.2.3.1 Global Distribution of ARs

Synoptic storms were tracked using TempestExtremes v2.1 atmospheric feature detection software (Ullrich et al., 2021). This algorithm was chosen to detect ARs due to its usage of the Laplacian of the integrated water vapor transport (IVT) rather than IVT alone. The gradients identified by the Laplacian method can detect ARs more accurately because there will still be a steep gradient between the AR itself and any surrounding moist area, thus better constraining the AR (McClenny et al., 2022).

Two TempestExtremes v2.1 package algorithms were used to detect and track ARs: DetectBlobs and StitchBlobs. These algorithms are executables that identify ARs using integrated vapor transport (IVT). DetectBlobs searches the global extent for ARs meeting parameters: Laplacian of IVT < -30,000 kg m$^{-2}$ s$^{-1}$ rad$^{-2}$, > 20 degrees latitude, and areal extent 566,666 km$^2$. The Laplacian IVT threshold was chosen based on Ullrich et al. (2021). They chose an IVT of -20,000 kg m$^{-2}$ s$^{-1}$ rad$^{-2}$, our threshold is stricter and requires a larger gradient. The areal extent was chosen conservatively as 2/3 the area of an average AR, which is 850,000 km$^2$ (A. Rhoades, 2022, personal communication). IVT is defined by,

$$IVT = \sqrt{uIVT^2 + vIVT^2}$$  \hspace{1cm} \text{eq. 1}
where \(u_{IVT}\) and \(v_{IVT}\) are pointwise vertically integrated meridional and zonal vapor transport, respectively.

The output of DetectBlobs is a binary mask outlining candidate ARs and StitchBlobs algorithm is used to connect the blobs in time, providing each AR its own unique identification number. StitchBlobs takes all ARs detected by DetectBlobs and unifies them together as the same AR as it varies by timestep, and also rejecting candidate blobs that are not continuous in time. Using these two algorithms together, we track a single AR across its entire lifespan, from its origin in the mid-latitude regions and eventual transport and dissipation northward. We chose to run StitchBlobs using standard default settings based on optimizations from A. Rhoades (personal communication, 2020). The number of ARs varied based on whether the native grid was remapped to f19 or ne30pg2 and on the remapping method (Table 3.2). The spread between ARs intersecting the GrIS remapped to f19 and ne30pg2 in TempestRemap allows for a larger amount of diversity in our ensemble.

### Table 3.2. Total number of ARs intersecting the GrIS using ESMF and TempestRemap remapping methods.

<table>
<thead>
<tr>
<th>grid name(^a)</th>
<th>(E_{SMF})(^b)</th>
<th>(\Delta)(^d)</th>
<th>(E_{TempestRemap})(^b)</th>
<th>(\Delta)(^d)</th>
<th>average(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f19</td>
<td>381</td>
<td>339</td>
<td>42</td>
<td>381</td>
<td>281</td>
</tr>
<tr>
<td>f09</td>
<td>431</td>
<td>420</td>
<td>11</td>
<td>510</td>
<td>356</td>
</tr>
<tr>
<td>ne30pg2</td>
<td>474</td>
<td>485</td>
<td>11</td>
<td>632</td>
<td>405</td>
</tr>
<tr>
<td>ne30pg3</td>
<td>483</td>
<td>447</td>
<td>36</td>
<td>596</td>
<td>458</td>
</tr>
<tr>
<td>ARCTIC</td>
<td>441</td>
<td>404</td>
<td>37</td>
<td>572</td>
<td>405</td>
</tr>
<tr>
<td>ARCTICGRIS</td>
<td>397</td>
<td>359</td>
<td>38</td>
<td>520</td>
<td>359</td>
</tr>
<tr>
<td>ERA5</td>
<td>426</td>
<td>374</td>
<td>52</td>
<td>411</td>
<td>376</td>
</tr>
</tbody>
</table>

Six grid configurations used in study (a) were remapped to f19 and ne30pg2 using ESMF (b) and TempestRemap (c). Difference between f19 and ne30pg2 detected ARs intersecting GrIS for each remapping method is calculated (d). Average (e) takes into account ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, and TempestRemap-ne30pg2.
3.2.3.2 Composite mask method. To analyze the effects of ARs on precipitation within CESM, we first found all ARs that intersect the GrIS at some point in their lifetimes (Fig. 3.3). We counted all ARs which touch the “Glacier” land units of Greenland in CLM. Along with the time and location of maximal overlap with the ice sheet, we created composite masks as the union of the spatial extent of each AR during its path over the GrIS (Fig. 3.3). The composite masks are used to represent areas of the GrIS where precipitation is caused by ARs. We ran this AR characterization process over each of the four ensemble members (ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, TempestRemap-ne30pg2) and took the average of each variable over the entire ensemble (Table 3.3).

3.2.3.3 Individual storm mask method. To analyze the effects of ARs on precipitation within CESM, we first found all ARs that intersect the GrIS at some point in their lifetimes (Fig. 3.3). We counted all ARs which touch the “Glacier” land units of Greenland in CLM. After finding these ARs, we looked at each individual timestep over which the AR overlapped Greenland and found the overlapping area. The precipitation occurring in Greenland was then counted if it fell within this overlapping area. This method was used over each timestep of the ARs landfalling, therefore counting all precipitation which was occurring under the AR during its lifespan. We ran this AR characterization process over each of the four ensemble members (ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, TempestRemap-ne30pg2) and took the average of each variable over the entire ensemble (Table 3.3).
3.2.4 Validation

Reanalysis data from ERA5 were used to validate the ensemble generated AR variables. ERA5 is the fifth reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). Reanalysis data combines observational data from various sites and then integrates observational data from various sites with a numerical atmosphere model to gap fill spatially and temporally. ERA5 data has horizontal spatial resolution of roughly 27 km and the variables chosen for this study have hourly resolution, though we downscaled this to 6-hourly to match the other variables. ERA5 was chosen to use as validation for this study based on previous research in the field choosing this dataset (Marquardt Collow et al., 2022).

Figure 3.3. Schematic illustrating how the DetectBlobs algorithm identifies ARs intersecting GrIS and creates a composite mask. This schematic shows a single AR making landfall with the GrIS over eight timesteps (t1-t8). The AR intersects the GrIS at timesteps t3-t5. Small regions of the GrIS where ARs have touched are shown in red in t3-t5 and composite mask is the union of these overlapping regions. The point of maximum intersection is shown at t4.
Table 3.3. Variables used to study effects of ARs on GrIS.

<table>
<thead>
<tr>
<th>variable name\textsuperscript{a}</th>
<th>description</th>
<th>model\textsuperscript{b}</th>
<th>temporal resolution</th>
<th>ERA5 equivalent\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRECT</td>
<td>Convective precipitation rate (liquid &amp; ice; PRECC) + Large-scale (stable) precipitation rate (liquid &amp; ice; PRECL)</td>
<td>CAM</td>
<td>6-hourly instantaneous sample</td>
<td>PRECT</td>
</tr>
<tr>
<td>RAIN_ICE (SNOW_ICE)</td>
<td>atmospheric rain (snow) after rain (snow) repartitioning based on temperature (ice landunits only)</td>
<td>CLM</td>
<td>daily average</td>
<td>PRECT</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Model variable name in CESM.
\textsuperscript{b}Model within CESM from which variable is derived.

3.3. Results

3.3.1 Frequency and Areal Extent of Atmospheric Rivers

Between 7500 and 9800 ARs were detected globally across the six model configurations and ERA5 between the years 1979-1998 (Fig. 3.4). ERA5 resolved the highest number of ARs at 9763 and f19 the lowest at 7514. We used the number of ARs intersecting the GrIS (Table 3.2) and ARs detected globally to calculate the percentage of ARs intersecting the ice sheet. This metric only varied from 4.0% to 5.3%, with ERA5 showing the lowest percentage of ARs reaching GrIS.
Figure 3.4. Average number of ARs in the Northern Hemisphere among ensemble (left axis, blue). Average percentage of ARs intersecting GrIS among ensemble (right axis, green) normalized by total ARs was calculated using data available in Table 3.2. Global ARs and percentages based on ensemble average.

The annual number of ARs intersecting the Greenland ice sheet ranged from 10-37 depending on grid-configuration and specific year (Fig. 3.5). There are large variations from year to year among the grid configurations, as is expected. ERA5 produces annual variations which are similar to the spread of modeled simulations, therefore suggesting that the models are producing ARs within or close to the bounds of reality.
Seasonal distribution of ARs indicates that winter and spring generally have fewer ARs than summer and fall (Fig. 3.6). In comparing the grid configurations, ERA5 produces the lowest number of all ARs in all seasons except for winter. One or both VR grids produce the same median values as ERA5 in all seasons except for summer. The quasi-uniform grids produce the largest number of outliers of the grid configurations. In every season, the lat-lon grid f19 produces the smallest spread. In comparing the median values of boxes seasonally, fall produces the most similar median number of ARs among the simulated outputs compared to ERA5. Summer produces the largest spread in ARs among the four seasons.

Few significant trends in the number of ARs annually or within the different seasons were predicted by CESM regardless of grid or in ERA5. The quasi-uniform ne30pg3 and lat-lon f19 showed increasing numbers of ARs during spring between the start and end of the study period ($p = 0.0291$ and $0.0247$, respectively) and ERA5 showed decreasing numbers occurring during
summer (p = 0.0330). Over the full year, only ne30pg3 showed a significant increasing trend (p = 0.00384).

![Figure 3.6](image)

**Figure 3.6.** Seasonal number of ARs intersecting the Greenland ice sheet. Winter was characterized as December through February, spring as March through May, summer as June through August, and fall as September through November. Seasonal distributions consider 19 years of data (1979-1998) using values from each of the four remapped ensemble members (N=76). Orange line in the center of each box signifies median value and box lower/upper boundaries describe the 25% and 75% quartiles, respectively. The whiskers on each box describe the minimum and maximum daily values and floater points indicate outliers.

Compared to ERA5, all model configurations simulate a larger AR footprint on the GrIS (Table 3.4). The lower resolution lat-lon and VR grids have smaller footprints compared to their higher resolution pairs, while the quasi-uniform simulations show the opposite relationship. The VR simulations have the smallest footprints of the different configurations.

In nearly all cases remapping to the quasi-uniform ne30pg2 grid yields smaller footprints than remapping to f19. The sole exception is for the ARCTIC VR grid, where there is a difference of
about 10,000 km², though this is only a difference of around 1.5% therefore perhaps not being significant.

Table 3.4. Areal extent km² of ARs depending on grid configuration.

<table>
<thead>
<tr>
<th>grid name</th>
<th>f19 areal extent (km²)</th>
<th>ne30pg2 areal extent (km²)</th>
<th>average areal extent (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f19</td>
<td>1.09x10⁶</td>
<td>9.37x10⁵</td>
<td>1.01x10⁶</td>
</tr>
<tr>
<td>f09</td>
<td>1.25x10⁶</td>
<td>1.17x10⁶</td>
<td>1.21x10⁶</td>
</tr>
<tr>
<td>ne30pg2</td>
<td>1.33x10⁶</td>
<td>1.18x10⁶</td>
<td>1.25x10⁶</td>
</tr>
<tr>
<td>ne30pg3</td>
<td>1.05x10⁶</td>
<td>9.82x10⁵</td>
<td>1.02x10⁶</td>
</tr>
<tr>
<td>ARCTIC</td>
<td>8.55x10⁵</td>
<td>8.67x10⁵</td>
<td>8.61x10⁵</td>
</tr>
<tr>
<td>ARCTICGRIS</td>
<td>9.80x10⁵</td>
<td>8.46x10⁵</td>
<td>9.13x10⁵</td>
</tr>
<tr>
<td>ERA5</td>
<td>6.07x10⁵</td>
<td>5.11x10⁵</td>
<td>5.59x10⁵</td>
</tr>
</tbody>
</table>

Average areal extent values are the mean of each of the four ensemble members (ESMF-f19, ESMF-ne30pg2, TempestRemap-f19, TempestRemap-ne30pg2), f19 areal extent the mean of the two f19 ensemble members (ESMF-f19, TempestRemap-f19), and ne30pg2 areal extent the mean of the two ne30pg2 ensemble members (ESMF-ne30pg2, TempestRemap-ne30pg2). All columns approximate the total area of the GrIS covered by ARs based on included ensemble members.

The variation of footprint size is mainly due to the spatial distribution of ARs across the GrIS (Fig. 3.7). ARs are most frequently making landfall with the southwestern and southeastern margins of the GrIS, and this amount gradually declines moving inland for all configurations. ARs modeled with lat-lon and quasi-uniform grid configurations travel further inland than in the VR grids and ERA5. It should also be noted that fewer ARs make landfall in the northern portions of the GrIS in ERA5 than any of the other configurations.
3.3.2 Precipitation

Precipitation rates over the GrIS vary based on grid configuration and precipitation sampling time. We examine the effects of grid choice on the precipitation variables in CAM (PRECT) and CLM (RAIN_ICE+SNOW_ICE) from the community land model (CLM). Both variables describe the sum of solid and liquid precipitation from the same precipitation schemes; that is, precipitation coming from CAM is simply passed through CESM to CLM. They differ based on sampling time, as the output from CAM is in the form of six-hourly instantaneous samples, whereas CLM gives daily averages.

Figure 3.8 describes the number of ARs intersecting the GrIS based on days relative to maximum overlap, and the lifecycle of these intersecting ARs before and after the maximum overlap time. Based on this, we chose to analyze the ARs over the course of five days. The peak storm count at
maximum overlap in Figure 3.8 is equal to the ensemble average of storm counts in Table 3.2. Similar to that table, the quasi-uniform grids produce more ARs than the rest, with the lat-lon and variable-resolution in the middle, and ERA5 producing the least. All models produce ARs which eventually intersect the GrIS at an increasing rate around two to three days before maximum overlap and then these ARs decrease in number. Notably, ERA5 produces an extremely large spread of ARs. Figure 3.8 shows that the majority of ARs pass over Greenland in two days, so the choice of a five-day analysis interval captures all relevant data.

Five days before the point of maximum overlap roughly 20-25% of the landfalling ARs have formed (Figure 3.8). This number of ARs increases until the point of maximum overlap, with the largest increase from five days to two days before the point of maximum overlap. After the point of maximum overlap, the number of ARs decreases for all grid configurations and ERA5. The number of ARs one day after the point of maximum overlap is 25-50% lower than the number of ARs during maximum overlap. This means that many of the ARs rapidly dissipate, indicating that a large amount of moisture is being transferred from the ARs to the GrIS, although some ARs do continue evolving until around five days past maximum overlap.
Figure 3.8. Number of ARs intersecting the GrIS through time (top) and existence of these intersecting ARs before time of maximum overlap ($t = 0$). Lifespan of landfalling ARs on the GrIS. Total number of ARs intersecting GrIS at time $t = 0$ is equal to average number of intersecting ARs for each grid configuration in Table 3.2. Shaded regions in total ARs overlapping GrIS show spread across ensemble. The bottom figure shows the existence of the ARs which eventually intersect the GrIS through time. For example, at $t = -5$, only around 1/5 of the ARs that eventually intersect the GrIS have formed.

Many ARs affecting Greenland make landfall on the west coast and travel eastward until they reach the steepest portion of the GrIS (Fig. 3.9). At this point, much of the moisture deposits as precipitation and the storm dissipates. Figure 3.9 shows the average precipitation of ARs as they travel over their storm path for one particular grid configuration and remapping scenario. The main difference between configurations comes from how far inland ARs can penetrate.
Figure 3.9 CLM precipitation rate (RAIN_ICE) over the GrIS during landfalling ARs. Rate considers each landfalling AR and finds average of all storms. Cumulative precipitation is integrated over area and time. In the case of this configuration (ARCTICGRIS mapped to f19 using TempestRemap), 520 ARs made landfall with the GrIS; this figure shows the average precipitation rate of all 520 ARs. Time t indicates the point at which the AR is maximally overlapping the GrIS and time is projected into the past and future.

Figure 3.10 shows the average water equivalent depth per grid cell from CAM and CLM. Depth simulated by both CLM and CAM rapidly increases up to the time of maximum AR overlap of the GrIS and more slowly later (Fig. 3.10). For the CLM precipitation, there is a maximum difference of around 10 mm of accumulated precipitation among the grid configurations and ERA5. After the five-day period, ERA5 has the deepest deposited precipitation and ARCTICGRIS has the smallest. For CAM, there is a smaller difference at the end of the five days; ERA5 still produces the highest average precipitation depth but f09 has the smallest. However, when taking the full spread into account, the CAM and CLM variables produce a similar range of average precipitation amounts. The main trends in precipitation depth increase are also similar among both models; the GrIS experiences the highest rate of increase during the day preceding maximum overlap, where the rate then slows over the course of the day following maximum overlap.
Figure 3.10 also compares the area-integrated precipitation, showing variation among model grids as well as between CLM daily mean and CAM 6-hour instantaneous values. CLM and CAM area-integrated precipitation are more similar regarding spread and grid configuration ordering than the accumulated precipitation depth. Both models simulate the most precipitation in ne30pg2, followed closely by the other spectral element grid and the lat-lon grids. The two VR grids simulate less and ERA5 the least. There is a difference of about 4 Gt between the ERA5 and VR integrated precipitation in CLM. For CAM, this difference is about 7 Gt. The spread between highest and lowest integrated precipitation is about 23 Gt for both CLM and CAM. The trends in rate of increase of area-integrated precipitation are similar to those seen in the average cumulative depth of precipitation; the highest rate of increase is during the day preceding maximum overlap, after which it begins to slow.

**Figure 3.10.** Area-average precipitation (top) and area-integrated cumulative precipitation (bottom) over GrIS during landfalling ARs. Area-average precipitation considers each landfalling AR and finds average of all storms. Cumulative precipitation is integrated over area and time. Time \( t \) indicates the point at which the AR is maximally overlapping the GrIS. CLM precipitation (left) uses variable PRECT from ERA5 downscaled to daily average of 6-hourly samples and CLM RAIN_ICE for all modeled simulations. CAM precipitation (right) uses PRECT from ERA5 at 6-hourly samples and CAM PRECC + PRECL for all modeled simulations.
### 3.3.3 Size of Atmospheric Rivers and Overlap with the Greenland ice sheet

During their lifespans, ARs are constantly evolving and subsequently changing in size and geometry, and there is little agreement among the grid configurations regarding the area of ARs intersecting with the GrIS during the two to five days before point of maximum overlap (Fig. 3.11). Beginning at the second day before maximum overlap, we see a consistent and smooth increase in size of AR in all grid configurations and ERA5. This increase continues until around one day before maximum overlap. During the day before maximum overlap all configurations simulate a sharp decrease. This sharp decrease is due to a rapid reduction of moisture within the AR, and therefore a reduction in size. After time of maximum overlap all the simulations and ERA5 show ARs slowly increasing in size again, though not at a consistent rate.

The quasi-uniform configurations produce the largest ARs for almost the entire study period. After the day of maximum overlap, there is some interchanging of position with f19, but they remain high. ERA5 produces the smallest AR areas, though there is again some fluctuation during the days after maximum overlap, especially after day four.

The amount of an AR overlapping with the GrIS also varies during its lifespan (Fig. 3.11). In general only a very small portion of any AR overlaps with the GrIS. Average AR areas range from 140-200x10^10 m^2 but less than 5.0x10^10 m^2 of any AR is overlapping with the GrIS even during its time of maximum overlap. The f19 simulations have the largest area of overlap during the time of maximum extent and onward. Before the day of maximum extent, there are large fluctuations among the grid configurations in terms of which has the highest overlap amount, though ERA5 and the VR grids are consistently on the lower ends and f19 is on the higher.
While the quasi-uniform grids produce the largest ARs, they don’t have the largest overlap area with the GrIS.

![Graph of AR area and overlap with GrIS](image)

**Figure 3.11.** Evolution of AR area through time (top) and overlap with the GrIS (bottom). AR overlap is constrained to two days before and after time t=0 as most ARs finish landfalling in this period. Shaded regions show spread among the ensemble.
3.4. Discussion

The difference in areal extent based on grid configuration may be due to how well each grid resolves topography of the GrIS (Figure 3.2). In the lat-lon and quasi-uniform grids, smoothing occurs on the margin around the topographical high in the middle of the GrIS. The lat-lon f19 grid has the lowest elevations and it also has the largest AR overlap area. We hypothesize that the different representation of topography among the model configurations explains much of the difference in GrIS-wide integrated precipitation. We hypothesize that greater smoothing of topography allows for ARs to penetrate much further into the interior of the ice sheet, avoiding extreme orographic lifting that would otherwise drain the ARs of their moisture and cause them to dissipate. In contrast, the topographical highs are better represented in the VR grids and ERA5, which we speculate prevents ARs from penetrating as far inland as the lat-lon and quasi-uniform grids. There is very little difference between the topography in ERA5 and the VR grids (Figure 3.2). Even the lower resolution VR grid, ARCTIC, has similar topography to ERA5 as its resolution is 28 km compared to 27 km in ERA5. The agreement between the highest resolution grid, ARCTICGRIS at 14 km, and ERA5 suggests that 27 km resolves the topography of the GrIS reasonably well.

In ERA5, there are very few ARs which intersect the northern regions of the GrIS. The VR grids, in comparison, have many ARs making landfall there. These geographic landfall variations likely explain the difference in areal extent between the VR grids and ERA5. As ERA5 exhibits smaller ARs, their lack of penetration into the northern GrIS could be due to quicker dissipation. As
ERA5 also produced fewer ARs compared to the CESM2.2 simulations (Table 3.2), this could also affect the total span of areal extent (Table 3.4). If there are fewer ARs to begin with, it can be argued that there is less opportunity for reaching far northern portions of the GrIS. We hypothesize that the differences in area-integrated cumulative precipitation among grid configurations is due to the areal extent of ARs impacting GrIS simulated using the different grids (Fig. 3.10). As the differences between average precipitation depth among grid configuration is small simulations which cover a larger areal extent of the GrIS deposit more total precipitation. To understand whether the grid configurations vary in IVT, further analysis needs to be conducted looking at AR intensity. This could help inform whether one grid configuration precipitates more readily than the others.

CLM simulates average precipitation depth magnitudes which are more similar across grid configuration than in CAM. As CAM rates are based on six-hourly instantaneous sampling of the precipitation, there is likely some sampling bias, with CLM daily means more representative of the actual precipitation occurring. Additionally, the CLM precipitation is directly used to compute the surface mass balance of the GrIS in CESM, so the strong agreement in CLM is important for future modeling efforts.

Despite the differences in average precipitation depth between CLM and CAM, the area-integrated cumulative precipitation in both schemes agrees well (Fig. 3.10). As the area-integrated precipitation is largely controlled by area and not the depth of precipitation falling per grid cell, this explains why there are not large differences between CLM and CAM. ERA5 produces the smallest integrated precipitation which is then closely followed by both VR grids.
Following the VR grids are the lat-lon and quasi-uniform grids, in very similar orderings in both CLM and CAM.

We also get a sense of the lifespan of modeled ARs from the cumulative area-integrated precipitation in CLM (Fig. 3.10). There are small increases in precipitation in the days preceding maximum overlap of the AR. About one day before maximum overlap, the precipitation begins to increase at a faster rate. This increasing rate continues until around one day after the AR is at maximum extent, when the rate then slows, suggesting that precipitation is most critical during the days directly preceding and following the maximum extent. Near the point of maximum overlap the AR is likely reaching the high topography in GrIS. As an AR approaches this high topography orographic uplift would cause most remaining precipitable water to drop and the AR would dissipate.

The higher resolution VR grids and ERA5 produce smaller AR sizes (Fig. 3.11). This is not surprising, as the higher resolution allows for more precision in atmospheric moisture tracking. Though f19 produces the highest amount of overlap with the GrIS, ARs simulated with this configuration do not have the largest area sizes before intersecting GrIS. This speaks to the topographical smoothing occurring in f19 and is the most direct evidence put forward to support our hypothesis. We envision a mechanism where greater smoothing of topography allows for ARs to penetrate much further into the interior of the ice sheet, avoiding any orographic lifting that would otherwise drain the ARs of their moisture and dissipate. The other lat-lon grid and the quasi-uniform grids also produce higher amounts of area-integrated precipitation than the variable-resolution grids and ERA5 and have correspondingly larger AR overlaps. The
resolution of topography in grids with different resolutions and the resulting AR overlap areas likely describe much of the differences in precipitation occurring among grid configurations.

We believe that the differences seen among grid configurations due to topography is significant, but our methodology to investigate precipitation likely causes us to over-predict the amount of precipitation occurring due to an AR. The composite mask which we created is the union of all portions of the Greenland ice sheet that are touched by an individual AR during its lifespan. We use this entire composite mask during the five-day period to sum the amount of precipitation during an AR. Due to the fact that an AR is not actually occurring over the entire composite mask, yet we are attributing that whole area to precipitation deposited from an AR, our area-integrated precipitation amounts are too large. We are developing an algorithm that sums the precipitation of the AR area which is overlapping the ice sheet at each timestep rather than the composite approach which will lead to more accurate precipitation magnitudes. This being said, we expect our findings regarding the VR grids and ERA5 producing lower magnitudes of precipitation to hold true with this new method.

In order to resolve ARs the most accurately using the VR grids, one may consider the extension of the spatial domain of the grids. Rhoades et al. (2020) investigated the effects of increasing the domain of a VR grid focusing on the western US to include more of the Pacific Ocean and found that when more the ocean was included, IVT and precipitation was generally lower than on the smaller spatial domains. Stansfield et al. (2020) found similar results regarding precipitation from extratropical thresholds in the eastern US. For this study, we consistently found that the simulations were producing more ARs and precipitation than ERA5, so perhaps extending the
domain further southward could be efficient at getting the simulated outputs closer to ERA5. This being said, Rhoades et al. (2020) also found that despite these differences in IVT, AR characteristics and impacts on snowpack were similar among the simulations using different spatial extents. Therefore, if resolving precipitation is the goal, increasing the spatial domain to include more of the ocean could be of use but otherwise it would likely not make a significant difference on the AR impacts to Greenland surface mass balance.

3.5. Conclusions

Latitude-longitude, quasi-uniform, and variable resolution grids produce differing numbers and sizes of ARs. These grid configurations produce ARs which interact with the GrIS in different ways. For example, the lat-lon and quasi-uniform grids produce ARs yielding a larger areal extent and area-integrated precipitation than the variable-resolution and ERA5. Due to these differences, the impact of precipitation from ARs on the GrIS varies in magnitude among grid configurations.

We find that the topography resolved within each of the grid configurations likely constrains AR penetration into the GrIS. In lower resolution grids, there is greater smoothing of the topography of the GrIS and therefore ARs can travel further inland. As the precipitation per grid cell does not vary greatly across the different configurations, we suggest that the overlap extent of ARs largely controls the simulated amount of precipitation falling onto the GrIS.
We find that the variable-resolution grids produce AR areal extents, cumulative integrated precipitation, and AR size that are most similar to ERA5. However, all simulations produce higher values for all three metrics than ERA5. As there is little difference in the topography between the variable-resolution grids and ERA5, we suggest that there is an additional factor causing ERA5 to produce smaller areal extents, less precipitation, and fewer ARs than the models. This likely has to do with the northern region of the GrIS not being touched by ARs in ERA5, though more investigation is needed. This could be elucidated by studying the frequency of ARs as a function of latitude to see if there are a similar number of northern ARs in ERA5, meaning they just aren’t penetrating as far inland. Despite the differences between the outputs of the variable-resolution grids and ERA5, the similarities between them suggest that increased resolution is important in modeling ARs and precipitation around Greenland.

In addition to the findings regarding the performance of our models, we see strong trends elucidating AR behavior and lifespan around the GrIS. In the CESM simulations and in ERA5, most ARs only intersect the GrIS for three days at most. Before the point of intersection, ARs experience a period of increasing intensity leading up to the day of maximum overlap of the GrIS. One day before maximum overlap, the AR is likely already intersecting the GrIS and at this point the ARs experience a “draining period” in which they decrease in size. This reduction in size is likely due to orographic uplift occurring from landfalling in which the AR can no longer support its moisture content. This is supported by simulated rates of precipitation. The largest increase in precipitation occurs shortly before the point of maximum overlap with the GrIS and around one day after, consistent with drainage of the AR due to orographic uplift.
There are multiple opportunities for future work, including the lack of ARs in northern Greenland as resolved by ERA5. Though we hypothesize that this is due to the size of ARs produced by ERA5, ground-truthing with meteorological data would ensure that ERA5 is the best possible dataset to compare with model simulations. Another area for future work relates to the intensity of ARs as produced by CESM2.2. As VR grids support higher gradients on their native grids, it is plausible that despite regridding, VR resolved ARs carry more moisture than lat-lon and quasi-uniform grids. CESM results should be compared to observation or reanalysis data to see whether non-VR grids are producing ARs which are not as intense as reality. We also encourage studies focusing on the evolution of intensity of ARs during their time over the GrIS. Our results showing AR size decreasing during the day before maximum overlap, likely associated with depletion of moisture by precipitation, could be further supported by intensity evolution studies.

Finally, the methodology in this study can be applied to study modeled variables outside of precipitation. As snowmelt is available both in CESM2.2 and ERA5, this would be an ideal variable to pursue to better understand how GrIS mass balance is affected by ARs. In addition to this, the differences in radiative fluxes among grid configurations could be studied to better understand the mechanics of snowmelt on the GrIS as caused by ARs.
Chapter IV

Conclusions and Future Work

Latitude-longitude, quasi-uniform, and variable resolution grids produce differing numbers and sizes of ARs. These grid configurations produce ARs which interact with the GrIS in different ways. For example, the lat-lon and quasi-uniform grids produce ARs yielding a larger areal extent and area-integrated precipitation than the variable-resolution. Due to these differences, the impact of precipitation from ARs on the GrIS varies in magnitude among grid configurations.

We find that the topography resolved within each of the grid configurations likely constrains AR penetration into the GrIS. In lower resolution grids, there is greater smoothing of the topography of the GrIS and therefore ARs can travel further inland. As the precipitation per grid cell does not vary greatly across the different configurations, we suggest that the overlap extent of ARs largely controls the amount of precipitation falling onto the GrIS. In addition to this, we do not believe that size of ARs is the main factor controlling precipitation in the GrIS as only a small portion of the large ARs are actually making landfall and, more importantly, the grids resolving the largest ARs do not have the maximum overlap amounts.

We find that the variable-resolution grids produce AR areal extents, cumulative integrated precipitation, and AR size that are most similar to ERA5. However, all simulations produce higher values for all three metrics than ERA5. As there is little to no difference in the topography
of the variable-resolution grids and ERA5, we suggest that there is an additional factor causing ERA5 to produce smaller areal extents, less precipitation, and fewer ARs than the models. This likely has to do with the northern region of the GrIS not being touched by ARs in ERA5, though more investigation is needed. This could be elucidated by studying the frequency of ARs as a function of latitude to see if there are a similar number of northern ARs in ERA5, meaning they just aren’t penetrating as far inland. Despite the differences between the outputs of the variable-resolution grids and ERA5, the similarities between them suggest that increased resolution is important in modeling ARs and precipitation around Greenland.

In addition to the findings regarding the performance of our models, we see strong trends elucidating AR behavior and lifespan around the GrIS. In the CESM simulations and in ERA5, most ARs only intersect the GrIS for three days at most. Before the point of intersection, ARs experience a period of increasing intensity leading up to the day of maximum overlap of the GrIS. One day before maximum overlap, the AR is likely already intersecting the GrIS and at this point the ARs experience a “draining period” in which they decrease in size. This reduction in size is likely due to orographic uplift occurring from landfalling in which the AR can no longer support its moisture content. This agrees with simulated rates of precipitation. The largest increase in precipitation occurs shortly before the point of maximum overlap with the GrIS and around one day after, consistent with drainage of the AR due to orographic uplift.

There are multiple opportunities for future work, and the first step towards improving this project should be the implementation of the new precipitation analysis method. As previously discussed,
precipitation is likely overestimated in our current composite mask method. By using a new individual timestep precipitation summing method, our precipitation estimates will be improved. Additionally, we hope to further investigate the lack of ARs in northern Greenland as resolved by ERA5. Though we hypothesize that this is due to the size of ARs produced by ERA5, ground-truthing with meteorological data would ensure that ERA5 is the best possible dataset to compare with model simulations. A study from Mattingly et al. (2023) uses the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2; GMAO, 2015) reanalysis as their validation dataset in studying ARs. In MERRA2, ARs made landfall with northern Greenland much more than we found in ERA5. We used a different tracking method in this study which could account for some difference, but this could be validated by running our tracker on MERRA2 as well. Both of these items should be completed prior to submission of to a peer-reviewed journal.

Another area for future work relates to the intensity of ARs as produced by CESM2.2. As VR grids support higher gradients on their native grids, it is plausible that despite regridding, VR resolved ARs carry more moisture than lat-lon and quasi-uniform grids. CESM results should be compared to observation or reanalysis data to see whether non-VR grids are producing ARs which are not as intense as reality. We also encourage studies focusing on the evolution of intensity of ARs during their time over the GrIS. Our results showing AR size decreasing during the day before maximum overlap, likely associated with depletion of moisture by precipitation, could be further supported by intensity evolution studies. Additionally, rating the ARs based on the Ralph et al. (2019) intensity-scale would help compare GrIS ARs to those occurring around
the world. This would also allow for a comparison of AR intensity over time as climate change progresses.

Finally, the methodology in this study can be applied to study modeled variables outside of precipitation. As snowmelt is available both in CESM2.2 and ERA5, this would be an ideal variable to pursue to better understand how GrIS mass balance is affected by ARs. In addition to this, the differences in radiative fluxes among grid configurations could be studied to better understand the mechanics of snowmelt on the GrIS as caused by ARs.
Chapter V

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