Research & Technology Transfer

Alaska Department of Transportation & Public Facilities

Future Projections of Precipitation for Alaska Infrastructure

FINAL REPORT

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Neptune and Company, Inc.
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The goals of this project were to use the best available climate change models and data to create more accurate projections of the severity and frequency of extreme precipitation events, and to present these projections in useful, accessible, site-specific formats for hydrologic and engineering applications. Ultimately, the goal was to provide crucial information to assist in safe, efficient, cost-effective engineering solutions. The project used the best available modeled climate data and associated methodologies to calculate and provide downscaled, bias corrected projections of future liquid precipitation from now until 2100 in formats and appropriate summary intervals for the Department of Transportation and Public Facilities (DOT&PF) direct use in planning and design efforts and associated calculations. To facilitate direct integration into the DOT&PF's operations, the projected precipitation data products closely follow the format of the NOAA ATLAS 14 precipitation frequency estimates, providing outputs across the entire state of Alaska for a range of precipitations durations and probability-based return intervals. Data outputs show substantial increases in projected precipitation across regions, durations, return intervals, and future time periods. These changes have important ramifications for engineering and hydrological design in Alaska, now and in coming decades.

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
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ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
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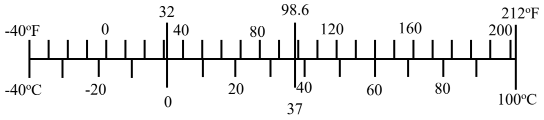
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC	ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm 2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements



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Executive Summary

The traditional method of determining design discharges for hydraulic structures in Alaska and elsewhere is to use historical data. However, Alaska now has a changing climate. Ongoing and projective future trends prevent historical data from being appropriately used to estimate future conditions. Alaska is projected to experience major changes in extreme weather during the twenty-first century.

The goals of this project were to use the best available climate change models and data to create more accurate projections of the severity and frequency of extreme precipitation events, and to present these projections in useful, accessible, site-specific formats for hydrologic and engineering applications. Ultimately, the goal was to provide crucial information to assist in safe, efficient, cost-effective engineering solutions.

The project used the best available modeled climate data and associated methodologies to calculate and provide downscaled, bias corrected projections of future liquid precipitation from now until 2100 in formats and appropriate summary intervals for the Department of Transportation and Public Facilities (DOT&PF) direct use in planning and design efforts and associated calculations. To facilitate direct integration into the DOT&PF's operations, the projected precipitation data products closely follow the format of the NOAA ATLAS 14 precipitation frequency estimates, providing outputs across the entire state of Alaska for a range of precipitations durations and probability-based return intervals.

A project overview is found here https://uaf-snap.org/project/future-projections-of-precipitation-for-alaska-infrastructure/. From this introductory page, the results of this effort are readily linked via a web tool to allow efficient delivery and use of the final gridded and tabular data products. This user-friendly interface, located at https://snap.uaf.edu/tools/future-alaska-precip, minimizes the complexities involved in applying multiple projections of future conditions, and allows ease of data access to end users. In addition, all data can be accessed directly for more technical uses via an online data portal, found here http://ckan.snap.uaf.edu/dataset/annual-maximum-precipitation-projections-for-alaska.

This project does not replicate all functions of the current NOAA ATLAS 14 website, although the online tools are very similar, to aid in familiarity and ease of use. It instead focuses on providing efficient access to datasets that concorporate and interpret the best available climate information and models. It includes six complete data options – two different models for each of three different future time periods -- thus representing the range of future projections associated with climate change.

Data outputs show substantial increases in projected precipitation across regions, durations, return intervals, and future time periods. These changes have important ramifications for engineering and hydrological design in Alaska, now and in coming decades.

Introduction

Problem Statement and Research Objective

The traditional method of determining design discharges for hydraulic structures in Alaska and elsewhere is to use historical data. However, Alaska now has a non-stationary climate, which means that current climate data are heterogeneous. Although thus far historical trends in total precipitation and extreme precipitation over Alaska are generally not significant (White et al., 2020, IJOC, Bieniek et al., 2017, IJOC), Alaska is projected to experience major changes in extreme weather during the twenty-first century. For example, in Alaska by the year 2100, the mean annual precipitation as well as the 1-day and 5-day precipitation is expected to increase by about 50% (Lader et al. 2017). These are statewide averages that cannot be used at any particular location. Thus, site-specific projected precipitation data were deemed necessary.

During project design, the Federal Highway Administration (FHWA) encourages consideration of climate change and risks due to extreme weather events. However, FHWA does not recommend using arbitrary increases of historical information to estimate design discharges. Rather, FHWA recommends using sound hydrologic methodologies and data. The current recommended methodologies are in Hydraulic Engineering Circular (HEC) No. 17, second edition by FHWA dated June 2016. Chapter 7 provides five levels to determine design discharges in the non-stationary climate that are increasingly more accurate but require increasingly more data and analysis. FHWA recommends that the method used to determine the design discharges is based on an evaluation of risk that includes the asset criticality, vulnerability, and cost, where Level 1 relies only on historical data, and is appropriate for projects with low failure risks and/or short lifespans. Level 2 uses historical discharges with confidence intervals but at some locations, the required data to use this method is not available, requires significant estimation, or is considered inadequate. For these locations it is desirable to determine design discharges using an analysis method recommended for Level 3 or higher, but this requires projected precipitation.

Scope of Study

This project proposed to calculate and provide downscaled, bias corrected projections of future liquid-equivalent precipitation from now until 2100 in formats and appropriate summary intervals for the Department of Transportation and Public Facilities (DOT&PF) direct use in planning and design efforts and associated calculations. This will allow DOT&PF to customize infrastructure design to better handle the projected and future precipitation levels and therefore extend infrastructure life cycles and reduce emergency events. To facilitate direct integration into the DOT&PF's operations, the projected precipitation data products closely follow the format of the NOAA ATLAS 14 precipitation frequency estimates.

As such, this final report explains the methodology applied, the uncertainties, and best practices associated with output data. The project will also provide training and outreach to interested audiences.

Research Approach

Methodology

High level overview of work

The workflow across the duration of the project, described in more detail below, can be briefly summarized as an effort to create downscaled future precipitation frequency (PF) estimates congruent with NOAA Atlas 14 estimates (Figure 1), using Weather Research and Forecasting (WRF) Reanalysis datasets. The steps in this process included first comparing WRF PF estimates with Atlas 14 PF estimates to confirm they were being calculated as expected. One-to-one matching was not expected, but it was necessary that overall patterns and extremes should be reasonably correlated.

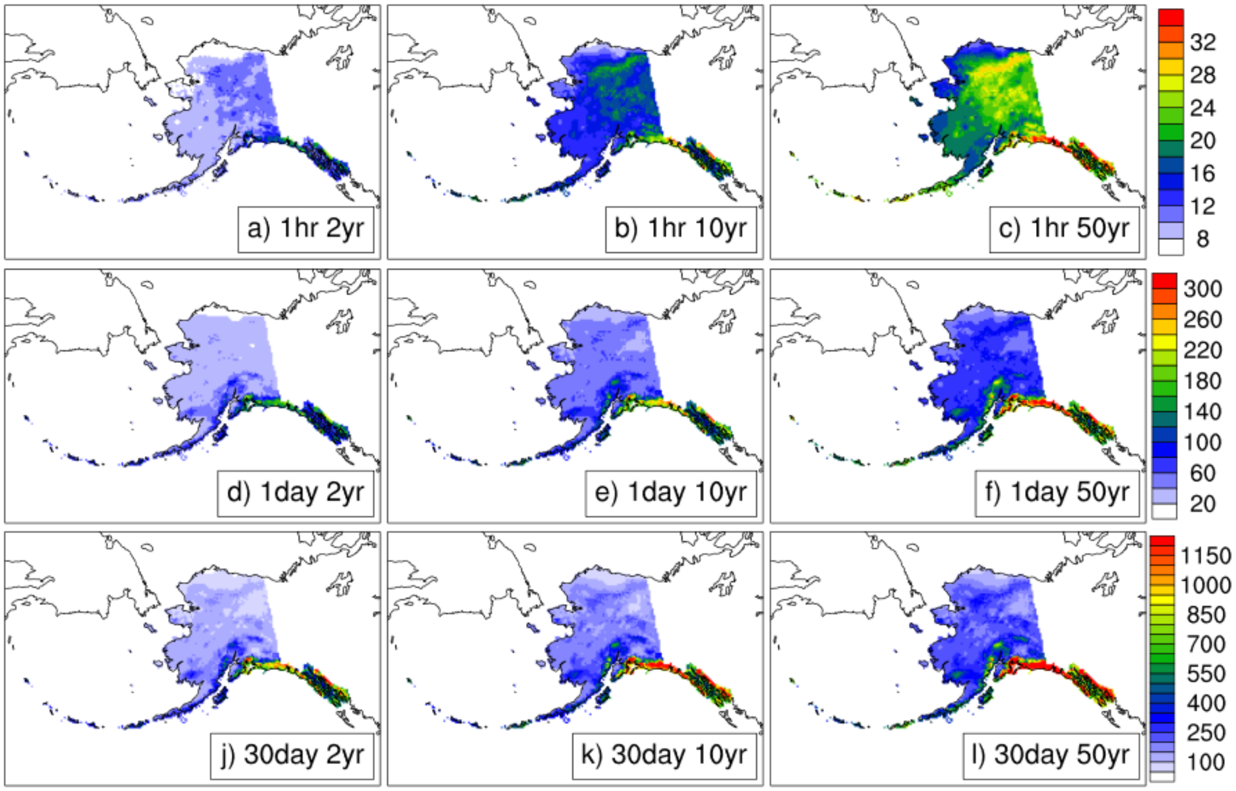


Figure 1: Atlas 14 data outputs represented in map format in order to highlight statewide variability across durations and return intervals. Units are shown in mm.

Once this was achieved, the next steps involved completing data generation using the Statistical Delta Downscaling Method (Figure 2). The Statistical Delta Downscaling Method can be described as a means by which one first calculates the change in climate (the delta) from some baseline time period according to a model of the future (GCM), next spatially interpolates those deltas to the higher resolution of the observed dataset (or, in this case, Atlas 14), and finally combines the deltas with the known higher resolution data. When working with precipitation, as in this case, we divide and then multiply. This keeps everything above 0. For reference, this link explains the delta method in the context of less complex monthly data: https://www.snap.uaf.edu/methods/downscaling.

This involved creating a PF Climatology across a baseline period; creating PF Deltas at every timestep at WRF 20km resolution; interpolating the Deltas to a spatial resolution of 1km; and combining PF Deltas with NOAA Atlas 14 PF estimates.

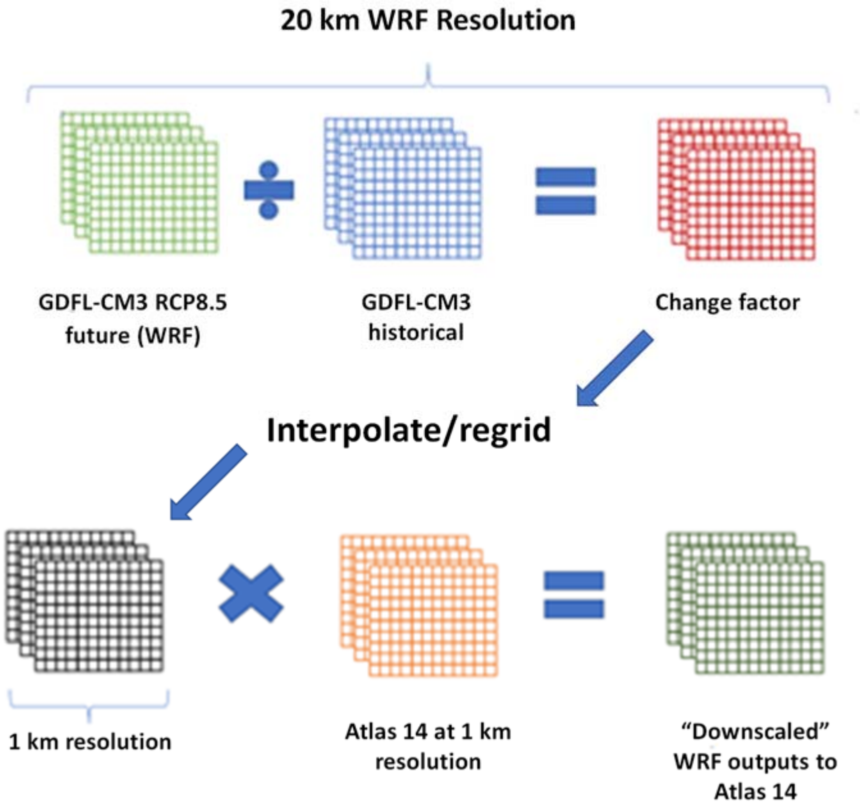


Figure 2: Schematic illustrating the Delta Downscaling approach.

Data Gathering

The first stage of project development involved obtaining the full catalog of NOAA ATLAS 14 point precipitation frequency estimates for the state of Alaska and preparing them for input into a downscaling and bias correction methodology. We communicated and coordinated with NOAA personnel to obtain the complete ATLAS 14 dataset and associated metadata. Data preparation included QA/QC and analysis to understand and explore trends and patterns in this historical dataset to understand how it would interact with the downscaling routine and to identify where adaptations in the existing methodology would be required.

During this stage, project team members also discussed and clarified optimal outputs and products. Because precipitation estimates are continuous across the entire state at 1km resolution, and because there is not an easy or useful way to put this into print form, it was determined that we would offer a simplified user interface that would refer to as an online repository. It was determined that the online repository would include many of the query features of the NOAA Atlas 14 site, such as the ability to click on a map and obtain the values for that pixel as well as the ability to identify pixels by precise input of latitude and longitude.

During the data gathering stage, we also performed additional literature review to identify and explore methods used by other researchers in similar projects, specifically with regard to temporal resolution. Cannon et al., 2019 contains the state of the art on the use of Generalized Extreme Value (GEV) theory for extrapolating information on precipitation extremes (duration-threshold-return periods). It is a reference on what a full-blown rigorous attempt to generate projections at sub-hourly thresholds would entail if the GEV approach were used. However, we determined that we did not have the resources or data required. Wang et al., 2014 offered other approaches, but the scaling factors have a location dependence that is not feasible or valid in Alaska, given data availability. Thus, it was determined that any attempt to create sub-hourly datasets would be spurious and statistically invalid.

Bias Correction

The next project stage involved development, testing, and debugging of downscaling and bias correction codebase. Delta downscaling methodologies were adapted to the higher temporal frequencies required for this application and adjusted for statewide application. We utilized existing WRF dynamically downscaled historical ERA-Interim data for the modeled historical data and 2 top performing Global Circulation Models (GFDL-CM3 and NCAR-CCSM4) under the future RCP 8.5 scenario for the modeled projected data. We utilized the NOAA ATLAS 14 data as the observed historical data. Processing included the calculation of frequency and recurrence intervals from the modeled historical and projected data at similar intervals as the ATLAS 14 historical data. However, we limited the shortest duration resolution to hourly as this is the finest temporal resolution at which the projected data is available. Next, the delta downscaling procedure was applied to both the historical and projected data, which spatially downscales the data and removes model bias, rooting the precipitation projections to real world expected values.

Determination and calculation of uncertainty metrics

Several uncertainty metrics were considered and then applied to give a reasonable range of possible future values. First, we used uncertainty metrics already included in Atlas 14, in the form of upper and lower bounds (confidence intervals) for each duration (from one hour to 60 days) and each return interval (from two years to a thousand years).

In addition to the uncertainty metrics used in Atlas 14, we added metrics specific to this project. One key metric was the choice to utilize two models of future climate, which allowed us to bracket the expected magnitude of changes. The two models are GFDL-CM3 and NCAR-CCSM4. Both are among the models used by SNAP, and were selected based on reliability and validity in the far north (Walsh et al. 2018, Lader et al. 2017). See also https://uaf-snap.org/methods-overview/model-selection/. These two were chosen because they represent the upper and lower ends of the range of Alaska climate change projected by their generation (CMIP5) of global climate models. They also provide lower and higher projected estimates, within the range of the five most preferred models used by SNAP (Walsh et al., 2018). Differences in outputs, including the underlying atmospheric drivers and variables within the models, are further discussed later in this report.

Over the course of the project, the team discussed at length the challenges associated with data limitations, both in terms of spatial resolution and temporal resolution. We noted the fact that although curves can be fitted to existing data with high precision within the bounds of measured return intervals, extrapolated data diverge at long return intervals, under a range of many possible extreme value distributions or lose precisions under a preferred GEV. Although partially resolved, as described under methods and results, this issue remains an inevitable source of some uncertainty, particularly for extremely long return intervals. Given that infrastructure planning does not generally occur at a timescale of hundreds or thousands of years, this uncertainty is more academic than practical.

One other decision pertaining to model uncertainty was the selection of the future timeframes to model. Initial runs were performed using decadal futures. However, test runs were also performed using two thirty-year future time periods (2020-2049 and 2050-2079) and a final twenty-year period (2080-2099), in order to compare the uncertainty (width of confidence intervals) between the two methods. The confidence intervals are indeed much narrower with these longer periods. There seemed to be minimal benefit in creating the type of granularity offered by providing decadal futures as opposed to coarser futures, from the point of view of end users. Moreover, single-decade time-slices have larger uncertainties arising from internal variability. The eventual decision, after discussion by the entire project team, was to evaluate three longer intervals to reap the benefits of reduced data uncertainty.

The team considered using rolling sums, as opposed to binning data for calculating duration series. (Figure 3). The benefits of this method are relatively minimal, in terms of reducing uncertainty, and it was decided that binning would be sufficient, because the code that calculated rolling sums generated so much more data that the system ran out of memory. In later stages of processing we revisited this option again, but found that lack of rolling sums was not causing uncertainty in model outputs. Thus, we retained the use of binned data.

Figure 3: Diagram illustrating the difference between binned data and rolling sums, demonstrating how the two methods can yield different maximum values for a given duration.

Pre-Processing of Data

We initiated an in-depth examination of the methods used in Atlas 14, so that these methods could, as far as is feasible, be applied to modeled current and future climate data at fine temporal scales -- where Weather Research and Forecasting (WRF) dynamically downscaled historical ERA-Interim data were to be used for the modeled historical data, and outputs from two Global Circulation Models (GFDL-CM3 and NCAR-CCSM4) under the future RCP 8.5 scenario are to be downscaled for the modeled projected data.

To this end, we also worked on WRF data processing. This included raw hourlies pre-processing -- generating the duration sums for each of the timing durations used in the Atlas14 app, and computing annual maximum series (AMS) by computing the maximum value for each pixel and for each year of the summed durations series.

We then looked at L-moments, computing L-moments using the AMS data fit to the Generalized Extreme Value (GEV) distribution. Using the fitted distribution and the return intervals we were able to estimate the values at each grid point for all of the intervals used in the app. In order to assess confidence intervals, we used a bootstrap procedure, pulling random values from that distribution over 5000 iterations and computed the 5/95 confidence intervals of this procedure, as used in Atlas 14.

In an effort to make sure our analysis/interpretation of the downscaled vs station precipitation variables were consistent, we created some plots for analysis and discussion. As an example, we pulled the precipitation data from the nearest grid point to the Fairbanks airport station from the downscaled ERA data and got the Fairbanks airport data from ACIS. For the station and downscaling we plotted the annual total precipitation and daily maximum precipitation each year for comparison. We also compared the yearly daily maximum precipitation for Anchorage vs. Fairbanks using only the station data. The team analyzed and discussed these plots.

Verification with Atlas 14 methodology

In order to verify our methods regarding the statistics behind calculating the original NOAA Atlas 14 return intervals, we contacted Dr. Sveta Stuefer, an Atlas-14 co-author. She offered useful information, but also suggested contacting Dr. Sanja Perica, the lead author for Atlas 14. We contacted Dr. Perica, and requested a meeting with all members of the project team, which she kindly granted. Prior to the meeting, we gave Dr. Perica an overview of the project and its goals, as well as an overview of processing methods. At the meeting, Dr. Perica confirmed that the pre-process methods being used by the SNAP team indeed matched the Atlas 14 methods. This validated the utility and parallel nature of much of the preceding work.

The group asked Dr. Perica specific questions about the statistical methods used in Atlas 14, including the use of regional L-moments computed for every station, the use of the GEV distribution that was used in the Atlas with regard to fit performance, and the use of a bootstrapping procedure for data processing.

Dr. Perica clarified that data for Atlas 14 relied on methods of weighting data from gauge stations, such that stations with finer temporal resolution or more years of data could weigh more heavily against stations with less data. She also confirmed concerns expressed by the team regarding tradeoffs in accuracy related to coarse (20km) spatial resolution and the need for fine (sub-daily) temporal resolution. She recommended using a ratio method to correct for scale, but cautioned that small sample sizes would still be problematic. In particular, Dr. Perica's advice shifted the group's focus toward using a ratio approach for informing an interpolation from 20km to 1km and using a frequency metric as opposed to annual maxima.

Data Processing Pipeline

The full pipeline by which data processing occurred is shown in Figure 4. It is described in detail below. After discussing methods with the full team and Dr. Perica, we wrote and ran the scripts that produced the precipitation frequencies across all durations and intervals for all pertinent datasets, including the GFDL-CM3 Historical, the GFDL-CM3 RCP85, the NCAR-CCSM4 Historical, and the NCAR-CCSM4 rcp85.

We also wrote scripts to stack all the NOAA Atlas 14 data to NetCDF4. This aided in analysis and code reduction. We then wrote scripts to stack the resulting precipitation frequency data to NetCDF4 to aid in development, and to make the data nimbler. Finally, we wrote a comparison script that compares the ERA-Interim data to the existing NOAA Atlas14. Based on this analysis, we did not need to use the ERA interim data in further steps, instead drawing directly from Atlas 14 data.

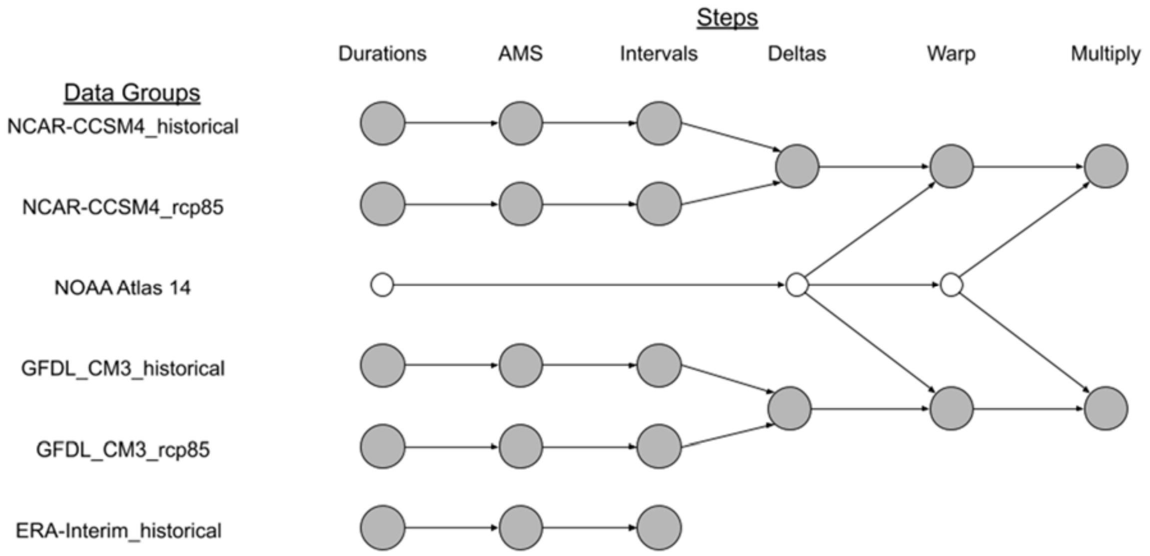


Figure 4: The data processing pipeline

Datasets included the following NOAA Atlas 14 Precipitation Frequency (PF) estimates for Alaska at 1km spatial resolution, for durations of minutes to 60 days, and WRF Dynamically downscaled precipitation data at 20x20km spatial resolution and hourly temporal resolution.

The WRF dataset has several versions. However, the data we used for this project were the WRF GCM Historical dataset and the WRF GCM Projections. The Historical WRF ran using GCM Historical run data as inputs (1979-2005) and includes WRF GFDL-CM3 historical and WRF NCAR-CCSM4 historical. The WRF Projections ran using GCM data as inputs (2006-2100) and includes WRF GFDL-CM3 RCP85 and WRF NCAR-CCSM4 RCP85. RCP85 references the 8.5 Representative Concentration Pathway used by the Intergovernmental Panel on Climate Change.

The two datasets above were used to statistically downscale (also called the delta method, as previously defined) the WRF Projections. Through this process, we also increased the spatial resolution of the WRF Projections. Because the WRF data are only available at an hourly temporal resolution, we will *not* be providing sub-hourly PF estimates (ie 5-min, 10-min, etc).

There are two data and time series types (depth and intensity, duration and maximum) in the NOAA Atlas. There are two types of displays available to users of the online tool for Atlas 14: 1) for various return intervals, a plot of the depth vs. duration; or 2) for various durations, a plot of the depth vs. return interval.

While the procedure used can produce "future" versions of each of these displays, changes in the maximum depth for each duration and return interval seemed sufficient to meet the planning needs of DOT&PF. Thus, we focused on 1) for which changes also seem more intuitive and easier to grasp by planners.

Deltas were calculated across all interval and recurrence periods. Using WRF GCM Historical, we calculated the average PF estimates across all durations and intervals across 1979-2005. This is a type of long-term PF climatology. We called this "WRF_PF_GCM_hist.clim". Using WRF GCM Projections runs, across both GCM models, we calculated PF estimates across all durations and intervals for each future decade (2020-2029, 2030-2039, ...2090-2099). This was later amended to two thirty-year periods and a final twenty-year period. We called this "WRF_PF_GCM_proj". Then we created the PF estimate deltas by dividing WRF_PF_GCM_proj by WRF_PF_GCM_hist.clim. We called these the "WRF_Deltas".

We spatially interpolated the WRF_Deltas to the higher resolution of the Atlas 14 dataset, 1x1km pixels, matched the projection grid of the NOAA Atlas 14 grid, and called these values "WRF_Deltas_Int". We then combined (multiplied) the deltas (WRF_Deltas_Int) with the known higher resolution NOAA Atlas 14 values. We called the final product "WRF_PF_Projections_1x1".

Technical Advisory Committee member Paul Janke had some initial comments on the sample data, first noting that they are in usable format. He asked that the return interval be changed to an annual exceedance probability (AEP), where AEP = 1/(return interval). We fulfilled this request; changing the return intervals to annual exceedance probabilities is a matter of changing how the units are presented and not a change in the underlying data. All other notes and requests at that time referenced changes or efforts already underway and have been fulfilled via the web application.

Data Testing Review (QA/QC)

As is to be expected in any complex project involving multiple datasets and code sources, problems were encountered and QA/QC efforts performed in development of the WRF-derived precipitation frequency (PF) estimates for this project. Initial QA/QC efforts involved expert review of early pipeline outputs, such as the comparison of WRF-based estimates with "observed" (Atlas 14) data. The first problems were discovered after review of the final PF estimates when the first pipeline run was completed. Code edits, new methods, and rerunning of the pipeline was necessary to iteratively correct all issues.

The following is a breakdown of the problems encountered during the iterative process of running the pipeline and reviewing/testing the outputs:

1) Some confidence intervals showed a lower bound greater than the estimate, and/or an upper bound less than the estimate. This was determined to be an artifact of the downscaling method, in which we had applied the delta method to the confidence bounds independent of the estimates. Instead, we recalculated the final confidence bounds from bound-estimate differences, in keeping with methods used in Atlas 14.

2) Some output estimates appeared logically inconsistent, as in cases where estimates at shorter durations or intervals were greater than those at longer durations or intervals. This was determined to be an artifact of the statistical methodology, due to statistical uncertainty and small input data, such that output estimates were not being smoothed based on input data for similar ("neighboring") intervals and durations. We adopted the 1.01% correction technique used by NOAA, thus mimicking Atlas 14 methodology.
3) A temporary inability to manually recreate data from durations step of the pipeline was found to be caused by incorrect legacy code file-reading optimization. It was quickly corrected via correct application of the optimization.
4) Preliminary outputs appeared to have unrealistically small confidence intervals. This was due to an incorrect scaling factor, which was corrected via application of correct scaling.
5) Preliminary confidence bounds also included negative values. These were corrected to zero.
6) Extremely large confidence bounds for 60 minute duration estimates were causes by a legacy code mix-up with file-reading; the code was fixed to read the correct files.

This process of re-running the pipeline and reviewing outputs aided the development of a data testing plan that described a series of automated tests that the final data had to pass completely to be considered production-ready. Essentially, this test plan consisted of testing all data (285 GB) for sensible values, and manually recreating and verifying each step of the pipeline for a small sample of locations. This plan also followed the application of SNAP's QA/QC checklist, which, aside from ensuring valid data, is designed to enhance usability and transparency. Exploring these problems and their solutions involved the use of Jupyter notebooks, which allowed for integration of plain language (ideas) and code execution, which can be viewed in the GitHub repository by anyone interested.

We ran the above tests to ensure that the final PF data matched expectations. Testing each step of the pipeline was implemented to verify that pipeline outputs matched what is expected from the objective of each pipeline step. The design of the interactive web app minimizes the chance of erroneous representation of the final PF data, as it is querying these data. The testing plan also has a focus on metadata, ensuring that final output files meet the structural requirements of the Climate Forecasting (CF) convention, which requires an extensive suite of information for describing the data therein.

Results

Data Outputs

The final dataset offers, for each location (pixel) in the state, six separate tables of precipitation frequency (PF) estimates associated with it, one for each GCM-Future (2 GCMs, three future time periods). Data outputs can be readily viewed via the online interface at https://snap.uaf.edu/tools/future-alaska-precip. The complete dataset is included in the web application. Thus, the application is similar to the NOAA Atlas 14 interface, but for each location, it has multiple options for each decadal PF estimate.

Data can also be downloaded in full from this data portal: http://ckan.snap.uaf.edu/dataset/annual-maximum-precipitation-projections-for-alaska. The details and functionality of these interfaces are discussed in further detail in the following sections.

In order to fully illustrate the following discussion of outputs, we created a set of regional maps illustrating the change from baseline for a range of precipitation variables. The full set of maps are included in Appendix C: Regional Maps. We created these additional maps (outside the scope of the project) in order to better display delta values (projected change in precipitation) at a statewide and regional level.

As an example, Figure 5 shows regional projected changes in maximum 60-minute precipitation (as compared to baseline WRF data) for two different models and three future time periods. This figure shows percentage changes in WRF data; to generate the final product, we essentially multiplied the data in this figure by the Atlas 14 data.

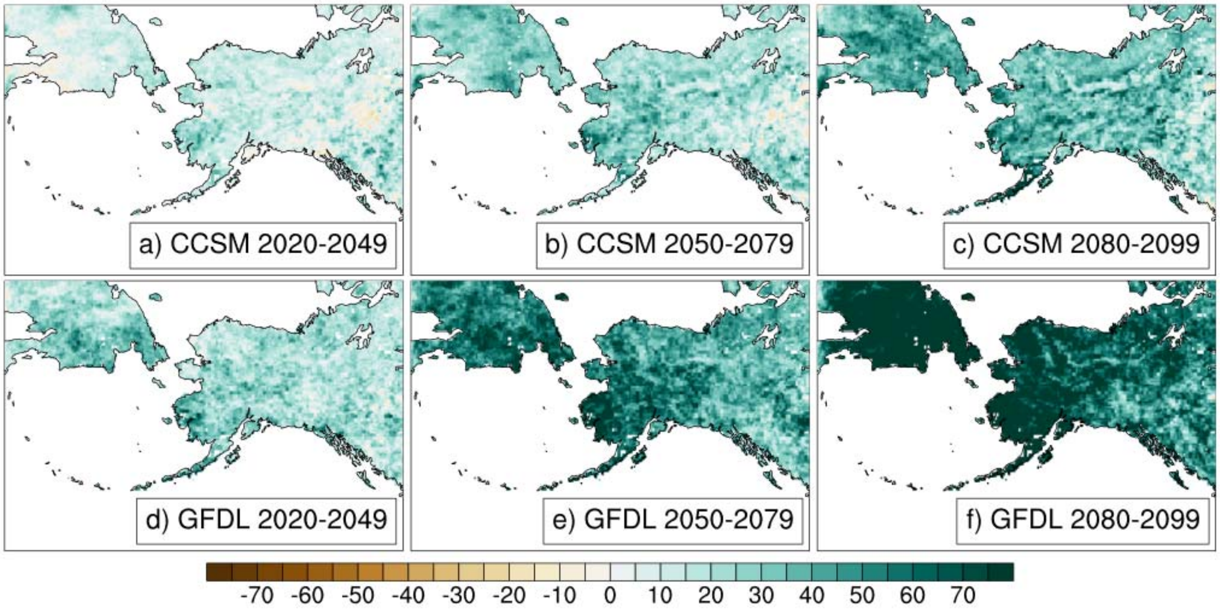


Figure 5: Projected percent change, as compared to baseline historical WRF data, for 60-minute maximum precipitation with a two year return interval (frequency estimate).

These maps clearly illustrate both the directionality of projected change and the uncertainty associated with it, based on the range of futures and models available. Note that although both GCMs clearly project increases in precipitation statewide, with increases becoming more pronounced later in the century, the CCSM model projects more modest shifts, while the GDFL model projects more extreme shifts, with increases of precipitation of 70% or more across large portions of the state. Regionally, both models show geographic variability based on topography, latitude, and longitude. In addition, both models include built-in variability typical to climate and weather. This uncertainty creates realistically wide ranges of possible precipitation scenarios within each model.

It is notable that the overall percentage increases tend to be higher for shorter durations (one hour), and lower for longer durations (one month), as seen in sample data from Nome (Table 1). Note that darker blue shading signals larger proportional increases, as compared to Atlas 14 data. (See also Appendix C: Regional Maps). In other words, extreme events of short duration are likely to change more than overall precipitation.

Table 1: Proportional projected increases in precipitation, as compared to Atlas 14 baseline, for the community of Nome.

Nome (64.501, -165.406)	**One hour maximum**			**One day maximum**			**One month max (30 day)**		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.30	1.68	2.12	0.90	1.02	1.14	1.28	1.48	1.41
GFDL-CM3, 2050-2079	1.64	2.11	2.88	1.30	1.38	1.63	1.44	1.58	1.42
GFDL-CM3, 2080-2099	2.10	2.51	2.89	1.57	1.84	2.31	1.93	1.86	1.52
NCAR-CCSM4, 2020-2049	1.11	1.52	1.93	1.02	1.15	1.17	0.94	1.05	1.19
NCAR-CCSM4, 2050-2079	1.22	1.62	1.80	1.27	1.43	1.37	1.07	1.31	1.56
NCAR-CCSM4, 2080-2099	1.49	1.60	1.45	1.23	1.56	1.73	1.08	1.34	1.54

Also of note is the fact that the CCSM model run does not have nearly as much convective precipitation as the GFDL model run, as compared to stratified precipitation. Convective precipitation, which derives from clouds that rise rapidly due to localized warm air, is generally more intense, and of shorter duration, than stratiform precipitation, which derived from stable stratified clouds. This is likely to be the reason GFDL has larger projected changes than the CCSM. However, the models suggest an increase in convective precipitation as the climate warms in the latter portion of this century. Overall, the greatest increases are seen in the most distant future time period (due to the greatest degree of climate change), the longest return intervals, the more pessimistic model (GFDL), and the shortest durations.

For the purposes of deeper analysis we also selected sample data outputs for eight selected communities (Fairbanks, Anchorage, Juneau, Utqiaġvik, Unalaska, Ketchikan, Nome, and Anaktuvuk Pass) for all three time periods (2020-2049, 2050-2079, 2080-2099), for both GCMs (GFDL-CM3 and NCAR-CCSM4), for three selected durations (one hour, one day, and one month), and for three selected return intervals (two years, ten years, and fifty years). These locations and communities were selected to represent the full range of geographic area and the full range of precipitation conditions for the state of Alaska, and are shown in Figure 6. These outputs are shown in their entirety in Appendix D: Community Data Examples, with associated tables, graphs, and comparisons to ATLAS 14 data.

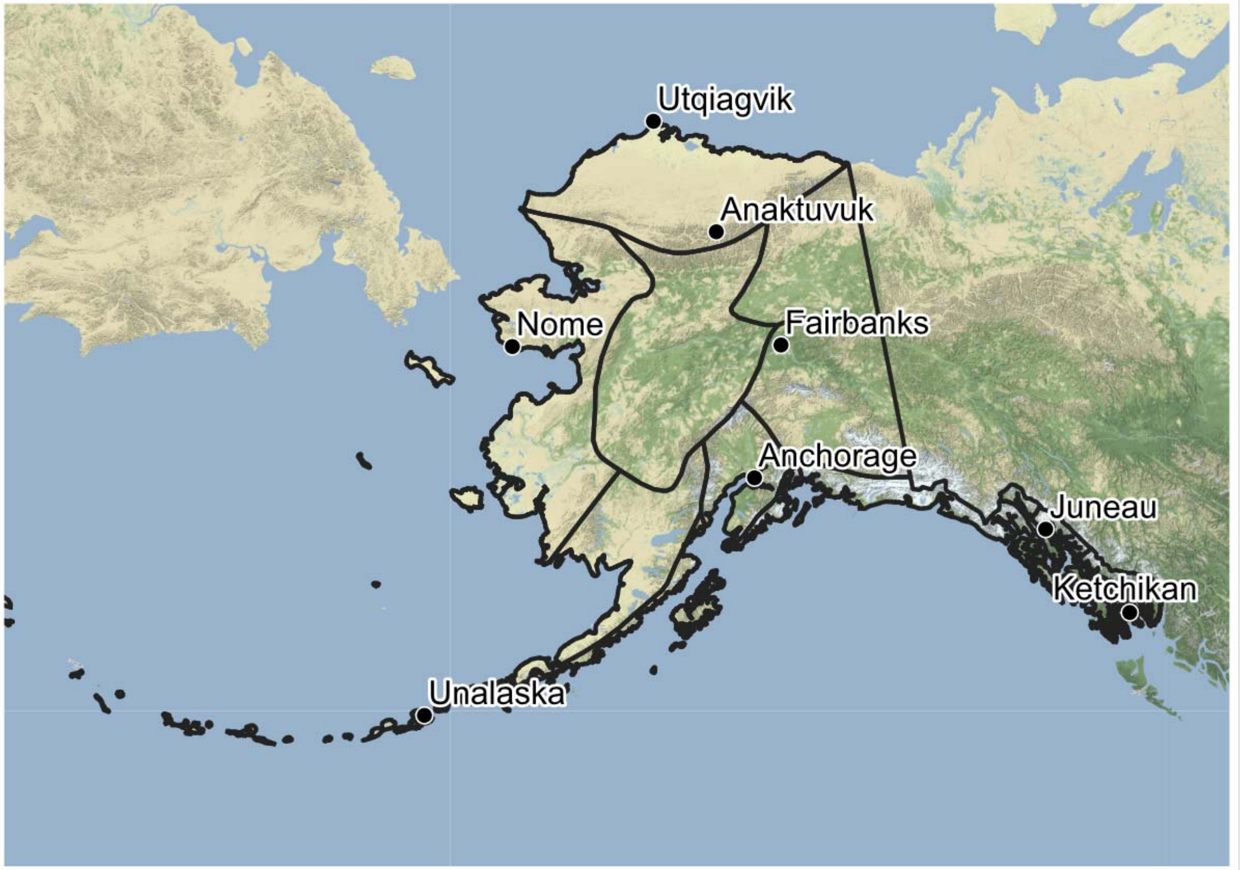


Figure 6: Map of selected community locations in Alaska, within NOAA climate division.

In general, modeled precipitation is greater than Atlas-14 data across all durations and return intervals. Table 2 shows data for all eight communities, with values denoting the ratio between projected data and Atlas 14 data. For example, the first table entry, "1.26", indicates that maximum hourly precipitation for Utqiagvik for a two-year return interval, based on downscaled GDFL-CM3 model data for the period from 2020 to 2049, is likely to be 1.26 times the value of Atlas 14 data for that same location, duration, and return interval.

Projected trends show generally wetter conditions for later in the century, based on ongoing climate change effects. Not surprisingly, trends are also toward greater precipitation during less-common events (longer return intervals) and longer events (greater duration). The GFDL-CM3 model shows notably wetter trends than the NCAR-CCSM4 model, although both are wetter than Atlas 14. Of the eight communities, Nome shows (overall) the greatest projected percentage increases in precipitation, and Ketchikan (already by far the wettest location) the least. As can be seen in the table, variability is relatively high, and specific projected values vary by model, future time period, duration, interval, and location. As will be discussed in Interpretation and Application, this can be attributed to inter-model, intra-model variability, and sparse weather data.

Table 2: Precipitation projections shown as factors of equivalent Atlas 14 data for eight selected communities, three durations, three returns intervals, two models, and three future time periods.. Darker shading denotes greater change, as compared to Atlas 14 data. Data are ratios (without units).

Utgiagvik 71.291 -156.789	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.26	1.39	1.62	1.11	1.20	1.26	1.00	1.06	1.13
GFDL-CM3, 2050-2079	1.38	1.70	2.11	1.27	1.34	1.49	1.27	1.23	1.10
GFDL-CM3, 2080-2099	1.49	1.77	2.25	1.40	1.63	2.08	1.35	1.38	1.31
NCAR-CCSM4, 2020-2049	0.86	1.16	1.67	1.00	1.28	1.51	0.98	1.05	1.06
NCAR-CCSM4, 2050-2079	0.98	1.12	1.20	0.98	1.09	1.12	1.07	0.95	0.79
NCAR-CCSM4, 2080-2099	1.26	1.50	1.81	1.20	1.61	1.93	1.25	1.06	1.01
Fairbanks (64.838, -147.716)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.18	1.20	1.25	1.15	1.21	1.31	1.14	1.33	1.48
GFDL-CM3, 2050-2079	1.43	1.49	1.56	1.43	1.58	1.81	1.47	1.63	1.72
GFDL-CM3, 2080-2099	1.79	2.05	2.31	1.62	1.51	1.37	1.43	1.75	2.08
NCAR-CCSM4, 2020-2049	1.04	1.10	0.98	0.95	1.11	1.18	0.97	1.24	1.50
NCAR-CCSM4, 2050-2079	1.26	1.20	0.94	1.02	1.07	1.08	1.17	1.19	1.13
NCAR-CCSM4, 2080-2099	1.34	1.18	0.85	1.08	1.12	1.16	1.13	1.18	1.14
Anaktuvuk (68.143, -151.736)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.03	1.11	1.19	1.10	1.18	1.20	1.17	1.28	1.23
GFDL-CM3, 2050-2079	1.36	1.60	1.88	1.36	1.56	1.78	1.41	1.38	1.25
GFDL-CM3, 2080-2099	1.65	2.05	2.36	1.45	1.58	1.61	1.57	1.84	1.91
NCAR-CCSM4, 2020-2049	0.88	0.88	0.72	0.94	1.06	1.10	1.01	1.03	0.95
NCAR-CCSM4, 2050-2079	1.05	1.08	0.91	1.05	1.30	1.46	1.15	1.13	0.97
NCAR-CCSM4, 2080-2099	1.26	1.71	1.88	1.14	1.51	1.88	1.15	1.26	1.21
Anchoarge 61.182, -149.993	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.01	1.13	1.31	1.12	0.97	0.76	1.11	1.16	1.09
GFDL-CM3, 2050-2079	1.34	1.55	1.68	1.30	1.21	1.02	1.27	1.27	1.10
GFDL-CM3, 2080-2099	1.60	2.10	2.69	1.50	1.57	1.52	1.43	1.48	1.36
NCAR-CCSM4, 2020-2049	1.14	1.28	1.25	1.01	1.14	1.12	1.02	1.23	1.31
NCAR-CCSM4, 2050-2079	1.14	1.22	1.17	0.99	1.16	1.35	1.02	1.22	1.44
NCAR-CCSM4, 2080-2099	1.18	1.28	1.32	1.06	1.13	1.10	1.09	1.28	1.39
Nome (64.501, -165.406)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.30	1.68	2.12	0.90	1.02	1.14	1.28	1.48	1.41
GFDL-CM3, 2050-2079	1.64	2.11	2.88	1.30	1.38	1.63	1.44	1.58	1.42
GFDL-CM3, 2080-2099	2.10	2.51	2.89	1.57	1.84	2.31	1.93	1.86	1.52
NCAR-CCSM4, 2020-2049	1.11	1.52	1.93	1.02	1.15	1.17	0.94	1.05	1.19
NCAR-CCSM4, 2050-2079	1.22	1.62	1.80	1.27	1.43	1.37	1.07	1.31	1.56
NCAR-CCSM4, 2080-2099	1.49	1.60	1.45	1.23	1.56	1.73	1.08	1.34	1.54
Unalaska (53.873, -166.533)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.22	1.13	1.05	0.92	1.00	1.09	0.94	1.12	1.25
GFDL-CM3, 2050-2079	1.56	1.47	1.43	1.08	1.38	1.78	1.06	1.16	1.22
GFDL-CM3, 2080-2099	1.72	1.62	1.51	1.32	1.71	2.17	1.23	1.38	1.49
NCAR-CCSM4, 2020-2049	0.97	0.98	0.89	0.99	1.18	1.27	0.93	1.07	1.11
NCAR-CCSM4, 2050-2079	1.20	1.37	1.43	1.13	1.29	1.26	0.98	1.10	1.11
NCAR-CCSM4, 2080-2099	1.13	1.33	1.48	1.15	1.35	1.54	1.01	1.11	1.14
Juneau (58.302, -134.42)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.21	1.41	1.60	1.08	1.29	1.56	1.09	1.10	0.99
GFDL-CM3, 2050-2079	1.38	1.58	1.81	1.25	1.36	1.56	1.23	1.30	1.27
GFDL-CM3, 2080-2099	1.60	1.91	2.23	1.43	1.47	1.53	1.40	1.56	1.57
NCAR-CCSM4, 2020-2049	1.09	1.15	1.04	0.67	1.21	1.27	0.94	1.00	1.06
NCAR-CCSM4, 2050-2079	1.15	1.24	1.17	1.11	1.22	1.15	1.13	1.14	1.06
NCAR-CCSM4, 2080-2099	1.31	1.44	1.48	1.21	1.36	1.26	1.14	1.21	1.20
Ketchikan (55.342, -131.636)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	1.13	1.10	1.05	1.19	1.20	1.25	1.08	1.06	0.98
GFDL-CM3, 2050-2079	1.27	1.34	1.48	1.22	1.27	1.37	1.19	1.11	1.03
GFDL-CM3, 2080-2099	1.44	1.46	1.48	1.34	1.42	1.57	1.35	1.36	1.28
NCAR-CCSM4, 2020-2049	1.11	1.16	1.16	0.89	0.97	1.02	0.93	0.92	0.92
NCAR-CCSM4, 2050-2079	1.15	1.29	1.48	1.05	1.25	1.39	1.08	1.15	1.16
NCAR-CCSM4, 2080-2099	1.27	1.30	1.31	1.15	1.18	1.14	1.15	1.15	1.10

A sub-sample of this community analysis is shown below, using Juneau (wet maritime climate) and Fairbanks (dry interior climate). A comparison between Atlas-14 data and data for each of the two models and three future time periods for the community of Juneau is shown in Table 3 and Figure 7, and for Fairbanks in Table 4 and Figure 8. In the figures, error bars (thin black lines on each colored bar) represent the range between the two models, while colored bars represent the mean of the two.

For example, for Juneau, using the GFDL model, maximum hourly precipitation events with a fifty year return interval are projected to increase from 22 mm to 35 mm using the 2020-2049 data, and to 48 mm using the 2080-2099 data. For the NCAR model, predicted changes are also positive, but more moderate.

Table 3: Comparison between projected (WRF downscaled) data and Atlas-14 data for two different models for Juneau. Units are mm of precipitation, rainwater equivalent.

Juneau (58.302, -134.42)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	15	24	35	96	156	243	505	644	691
GFDL-CM3, 2050-2079	17	26	39	110	164	242	567	763	883
GFDL-CM3, 2080-2099	20	32	48	127	177	237	648	916	1092
NCAR-CCSM4, 2020-2049	13	19	23	59	147	198	433	590	738
NCAR-CCSM4, 2050-2079	14	21	25	98	148	179	521	672	740
NCAR-CCSM4, 2080-2099	16	24	32	108	164	195	527	710	834
ATLAS 14	12	17	22	89	121	155	462	587	696

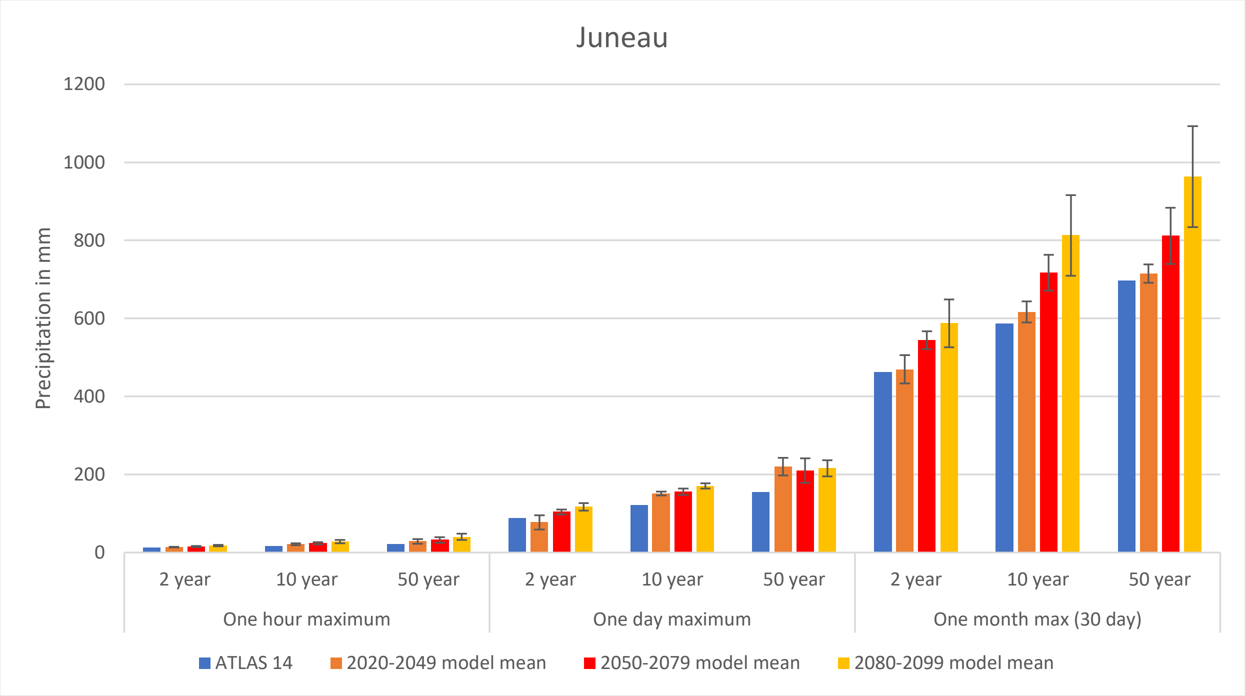


Figure 7: Comparison of model output data and ATLAS 14 data for Juneau. Data are shown for three different precipitation event durations (one hour, one day, and one month; for three different return intervals (two years, ten years, and fifty years) and four different time periods (historical Atlas 14 data versus three future time ranges of modeled data, which takes into account ongoing and projected climate change). Trends toward increasing precipitation can be seen across all variables.

In comparing Fairbanks data to Juneau data, it is interesting to note that the very different climates of these locations yield different patterns of precipitation. While hourly maxima for the two locations are quite similar, monthly maxima are much higher – roughly three times higher – in Juneau's wet climate. However, modeled data nonetheless project increases, with GFDL-CM3 again predicting more significant change than NCAR-CCSM4.

Table 4: Comparison between projected (WRF downscaled) data and Atlas-14 data for two different models for Fairbanks. Units are mm of precipitation, rainwater equivalent.

Fairbanks (68.838, -147.716)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	11	19	29	33	54	88	103	176	265
GFDL-CM3, 2050-2079	13	23	35	40	71	122	133	214	309
GFDL-CM3, 2080-2099	16	32	52	45	67	92	129	230	373
NCAR-CCSM4, 2020-2049	9	17	22	27	50	80	88	165	273
NCAR-CCSM4, 2050-2079	11	19	21	28	48	73	106	156	202
NCAR-CCSM4, 2080-2099	12	18	19	30	50	78	102	155	205
ATLAS 14	9	15	23	28	45	67	90	131	180

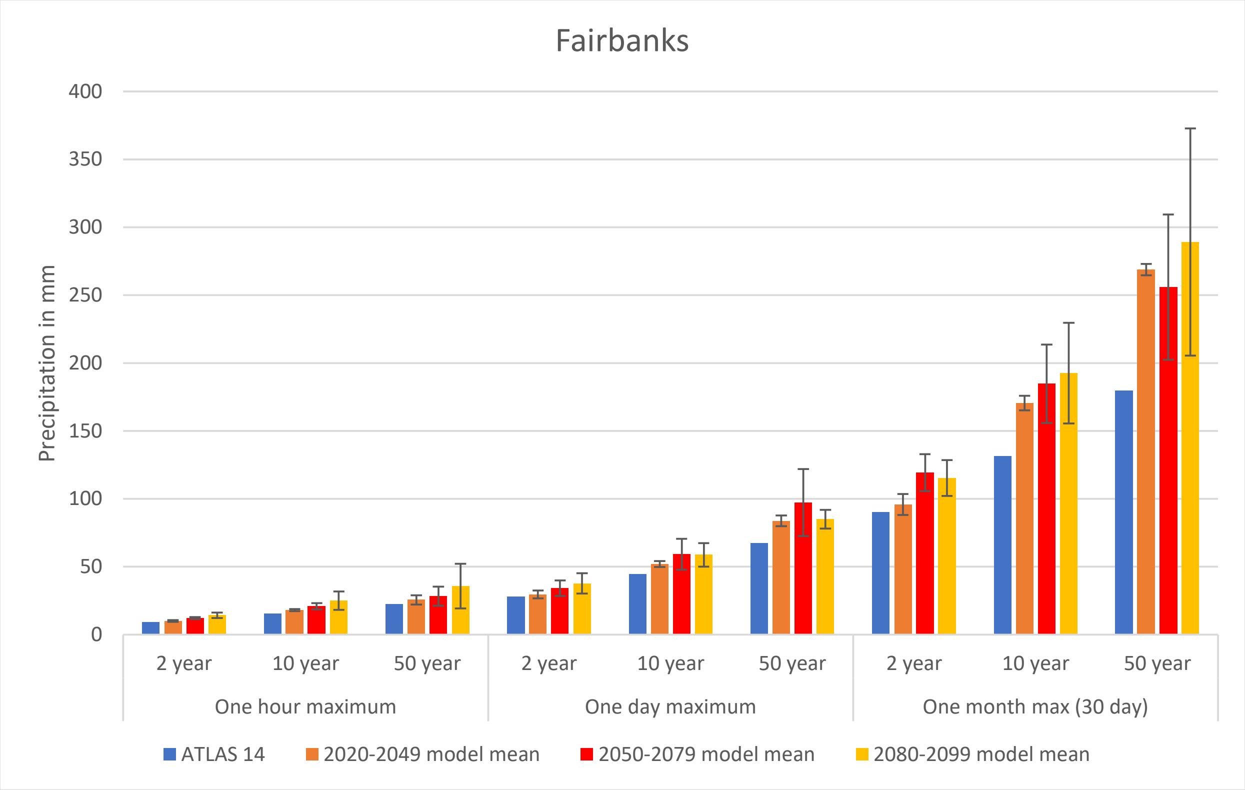


Figure 8: Comparison of model output data and Atlas 14 data for Fairbanks. Data are shown for three different precipitation event durations (one hour, one day, and one month; for three different return intervals (two years, ten years, and fifty years) and four different time periods (historical Atlas 14 data versus three future time ranges of modeled data, which takes into account ongoing and projected climate change). Trends toward increasing precipitation can be seen across all variables.

These datasets are in keeping with our general understanding of predicted changes in precipitation, in terms of temporal factors, spatial factors, and range of uncertainty between models. As noted, the two models selected represent, to the greatest degree possible, the full range of robust validated climate models in use by SNAP.

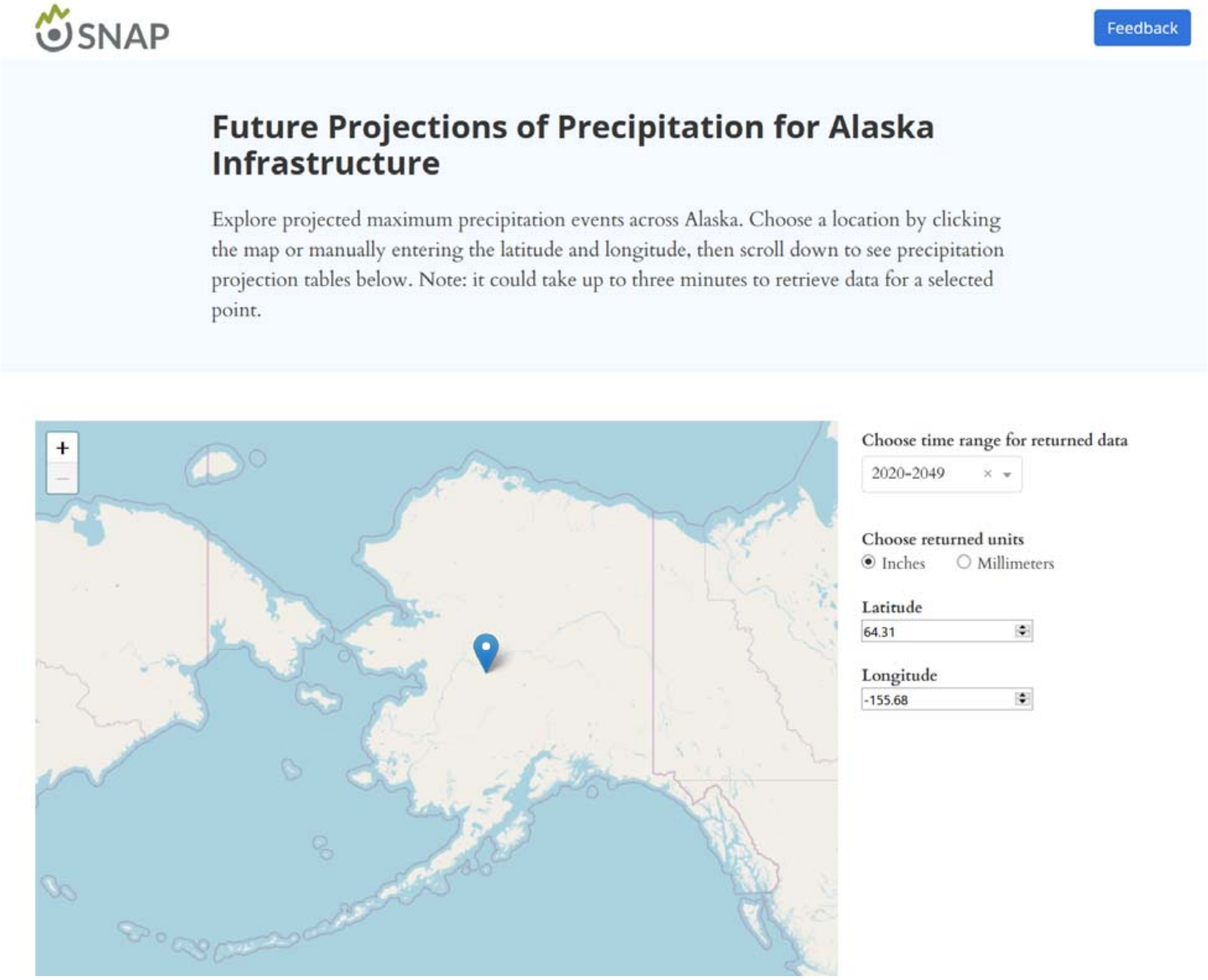
Users' Guide

Data Delivery Via Online Repository

The SNAP project team developed two different ways for users to access output data online, thereby allowing efficient delivery and use of the final gridded and tabular data products The first interface is a data portal offering the full dataset as NetCDF files for technical use: http://ckan.snap.uaf.edu/dataset/annual-maximum-precipitation-projections-for-alaska. The second is a user-friendly web tool for less technical data users, located at https://snap.uaf.edu/tools/future-alaska-precip. Each is discussed in further detail below. These repositories do not replicate all functions and data associated with the current NOAA Atlas 14 website, as that is outside the scope of this proposal. They instead focus on providing efficient access to tabular information. Both are intended to minimize the complexities involved in applying multiple projections of future conditions, while allowing ease of data access to end users. These data access pages are further linked via a project overview page, which is available here: https://uaf-snap.org/project/future-projections-of-precipitation-for-alaska-infrastructure/

Online interactive tool

Broadly, the goal of this app is to provide an easy-access interface similar to what is available on the existing NOAA application at https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_ak.html,but using output from this project. The app allows users to select the type of data they want (choice of two GCMs, three future time periods, Imperial/Metric units). It also allows spatial selection of a pixel by using an interactive zoomable map or entering lat/long (Figure 9). Results are shown in a tabular form (Figure 10) matching the Atlas 14 NOAA app, ensuring that the data are in a format that DOT&PF engineers are familiar with.



Future Projections of Precipitation for Alaska Infrastructure

Explore projected maximum precipitation events across Alaska. Choose a location by clicking the map or manually entering the latitude and longitude, then scroll down to see precipitation projection tables below. Note: it could take up to three minutes to retrieve data for a selected point.

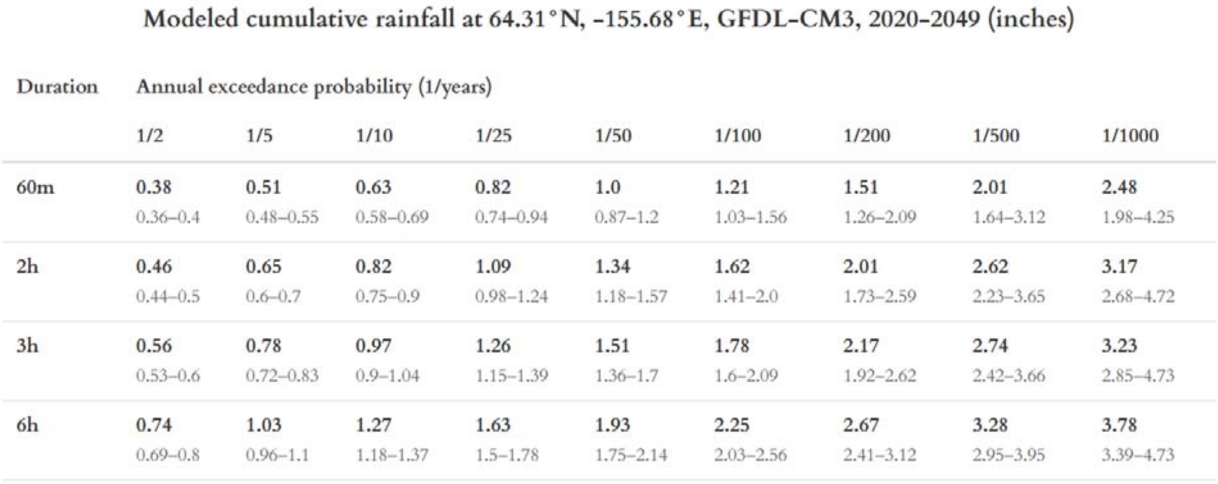
Choose time range for returned data: 2020-2049

Choose returned units: ● Inches ○ Millimeters

Latitude: 64.31

Longitude: -155.68

Figure 9: Sample screenshot of the input/request interface for the online data repository



Modeled cumulative rainfall at 64.31°N, -155.68°E, GFDL-CM3, 2020-2049 (inches)

Duration	Annual exceedance probability (1/years)								
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
60m	**0.38** 0.36–0.4	**0.51** 0.48–0.55	**0.63** 0.58–0.69	**0.82** 0.74–0.94	**1.0** 0.87–1.2	**1.21** 1.03–1.56	**1.51** 1.26–2.09	**2.01** 1.64–3.12	**2.48** 1.98–4.25
2h	**0.46** 0.44–0.5	**0.65** 0.6–0.7	**0.82** 0.75–0.9	**1.09** 0.98–1.24	**1.34** 1.18–1.57	**1.62** 1.41–2.0	**2.01** 1.73–2.59	**2.62** 2.23–3.65	**3.17** 2.68–4.72
3h	**0.56** 0.53–0.6	**0.78** 0.72–0.83	**0.97** 0.9–1.04	**1.26** 1.15–1.39	**1.51** 1.36–1.7	**1.78** 1.6–2.09	**2.17** 1.92–2.62	**2.74** 2.42–3.66	**3.23** 2.85–4.73
6h	**0.74** 0.69–0.8	**1.03** 0.96–1.1	**1.27** 1.18–1.37	**1.63** 1.5–1.78	**1.93** 1.75–2.14	**2.25** 2.03–2.56	**2.67** 2.41–3.12	**3.28** 2.95–3.95	**3.78** 3.39–4.73

Figure 10: Sample screenshot of data outputs (partial view) from online data repository

The user can select data using data selection controls. Selection can be made by lat/long or via a map. When a selection has been made, the data table is updated. Selection by lat/long allows the user to enter lat/long combos in decimal format. If the entry is valid, the map re-centers to that point. If the selection is outside the spatial domain of the data, the user is alerted in the data results section that the location is invalid.

Selection by map allows the user to zoom and pan and click to select a point. When the user clicks, lat/long are also updated in the text fields with decimal locations. The interface alerts the user in the data results section if the location is invalid. If there are no data for the selected point, a message is displayed to the user letting them know that the location isn't within the range of the dataset. A table containing the results of the query is displayed to the user.

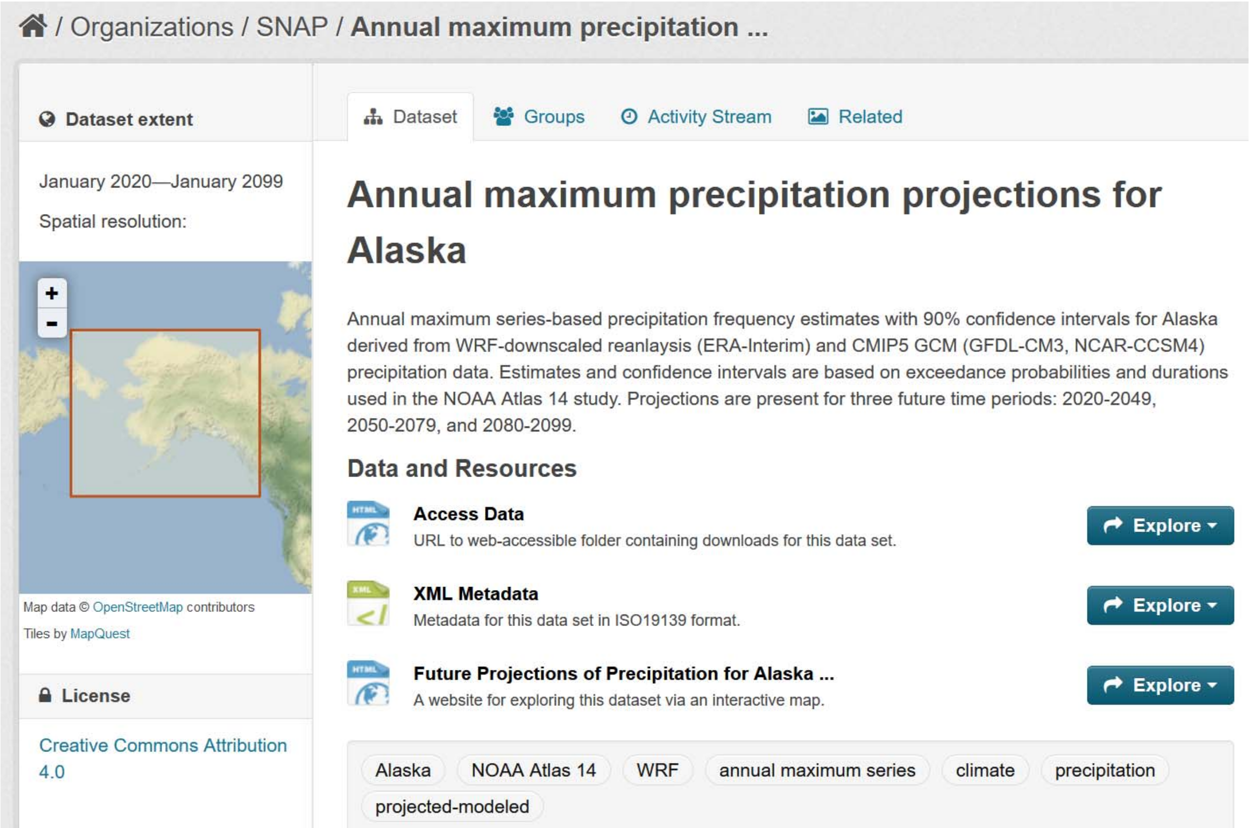
Table columns match the Atlas14 NOAA app: "Annual exceedance probability (1/years)", with 1/2, 1/5, 1/10, 1/25, 1/50, 1/100, 1/200, 1/500, and 1/1000 columns. These are equivalent to return intervals of the indicated number of years, and represent the expected frequency with which extreme precipitation events would be statistically predicted to occur. Rows mostly match the Atlas14 NOAA app: "Duration", but without sub-hour intervals. Thus, rows include 60 minute, 2 hour, 3 hour, 6 hour, 12 hour, 24 hour, 2 day, 3 day, 6 day, 7 day, 10 day, 20 day, 30 day, and 60 day durations. The table is in a suitable format for printing.

The online interface also includes explanatory help text describing the data output. This is similar to that used in the NOAA Atlas 14. However, we included additional plain-language explanatory text to make the interface more accessible to a wide range of users, some of whom may be less familiar with Atlas 14.

Data portal

We have served out these files as a bundle of NetCDF, which can be used in GIS applications. The data have an appropriate metadata record. The data are served through the SNAP CKAN portal, and can be found here: http://ckan.snap.uaf.edu/dataset/annual-maximum-precipitation-projections-for-alaska

The final data directory, entitled "Annual maximum precipitation projections for Alaska" includes links to the data, the metadata, and the web interface, as well as additional information. It includes summary text as seen in Figure 11.



January 2020—January 2099

Spatial resolution:

Creative Commons Attribution 4.0

Annual maximum precipitation projections for Alaska

Annual maximum series-based precipitation frequency estimates with 90% confidence intervals for Alaska derived from WRF-downscaled reanlaysis (ERA-Interim) and CMIP5 GCM (GFDL-CM3, NCAR-CCSM4) precipitation data. Estimates and confidence intervals are based on exceedance probabilities and durations used in the NOAA Atlas 14 study. Projections are present for three future time periods: 2020-2049, 2050-2079, and 2080-2099.

Data and Resources

Access Data
URL to web-accessible folder containing downloads for this data set.

XML Metadata
Metadata for this data set in ISO19139 format.

Future Projections of Precipitation for Alaska ...
A website for exploring this dataset via an interactive map.

Alaska | NOAA Atlas 14 | WRF | annual maximum series | climate | precipitation | projected-modeled

Figure 11: Screenshot showing the Data Portal interface for all project data and metadata.

Projections are present for three future time periods: 2020-2049, 2050-2079, and 2080-2099. The directory contains one NetCDF file for every duration period x decade (for projected data). With two models with three future time periods each and 14 duration periods, the total is (2 x 3 x 14) = 84 files. Each of these files is approximately 500MB (0.5 GB) in size, allowing for reasonable ease of access for downloading.

Every file has three coordinates: ‘xc,’yc’ and ‘interval’ and three variables: ‘pf’,’pf-lower’ and ‘pf-upper’ which represent the estimated precipitation along with the lower and upper confidence intervals. Essentially, each file represents a single row on the table in the NOAA app for every point.

Interpretation and Application

General Recommendations

Projected precipitation data are needed to design hydraulic structures, such as bridges and culverts, which must function effectively over time spans of decades or centuries. The effects of structural failure can be costly in terms of remediation and repair, or catastrophic in terms of human health and safety. Conversely, over-building can lead to significant budgetary inefficiency. Design discharges are currently estimated based on either (a) upper confidence intervals of discharges calculated from historical data or (b) other methods that use estimated precipitation data. Neither take into account the best available science as recommended by FHWA, which should include projected climate data for the lifespans of the hydraulic structures in question. Hence, current methods are not defensible, and are likely to result in hydraulic structures that are designed for discharges that are either too high or too low. Incorporating climate projections into design discharges, as we have done via this project, brings methodologies into compliance with FHWA recommendations. This effort will also increase long-term budgetary efficiency and reduce the long-term risk of catastrophic structural failure.

Data Use and Best Practices

Best practices with regard to the use of the data provided by this project depend, to a large degree, on a clear understanding of the sources of uncertainty associated with the climate models used. These uncertainties fall into several distinct categories:

1. Inherent spatial variability of precipitation
2. Inherent temporal variability of precipitation
3. Limited data records with which to validate modeled and mathematically fitted data
4. Long-term climate model uncertainty with regard to meteorological factors and drivers
5. Long-term climate model uncertainty with regard to future human behavior and greenhouse gas emissions.

The first three categories above are equally an issue for the new data generated for this report and the old Atlas 14 data. Given that these data can be viewed as an update to the existing NOAA Atlas 14 data, and given that our underlying methods were based on Atlas 14 methods, best practices with regard to the first three sources of uncertainty hinge on understanding the appropriate uses of that dataset. Atlas 14 is already in common use among Alaska DOT&PF hydrologists, engineers, and other stakeholders in the target audience for this project.

For further information relating to uncertainties already inherent to the Atlas 14 methods and data, please refer to NOAA Atlas 14 volume 7: https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume7.pdf The uncertainties explained in detail therein are mostly related to the necessity of fitting measured precipitation data to assumed distribution curves. The authors explain the mathematical challenges associated with modeling a phenomenon as inherently variable across time and space as precipitation, particularly given a paucity of real data for model validation, and they outline attempts to fit data to curves – including some failed attempts. They also note that, "One of the primary problems in precipitation frequency analysis is the need to provide estimates for average recurrence intervals that are significantly longer than available records." (p. 19). Of particular note is the fact that shorter durations in Atlas 14 (hourly and sub-hourly) were calculated using ratios and scaling factors, rather than directly from station-specific data: "Given the relatively little available data and after reviewing the ratios by region, it was decided that the final scaling factors would be calculated by taking averages of quality controlled ratios from all stations in the project area" (p. 25). Given the already high uncertainty for such data, if interpreted at the local level, and given the lack of sub-hourly outputs from SNAP's downscaled WRF data, SNAP project leaders, statisticians, and analysts agreed that sub-hourly data could not be updated in a mathematically meaningful manner.

The following analysis pertains to differences in data use and best practices unique to this new dataset. These are based on long-term climate model uncertainty with regard to meteorological factors, and drivers and long-term climate model uncertainty with regard to future human behavior and greenhouse gas emissions.

In order to address the issue of meteorological uncertainty within models, this project used two different GCMs, as already noted, that offer outputs that represent the upper and lower bounds of precipitation estimates within the range of models in the IPCC archives and regularly used by SNAP researchers. Interestingly, the CCSM model run does not have nearly as much convective precipitation as GFDL (Figure 12). This difference may be the reason why GFDL has larger projected changes in precipitation than CCSM. Regardless, the two models represent a range of possible precipitation futures for the state.

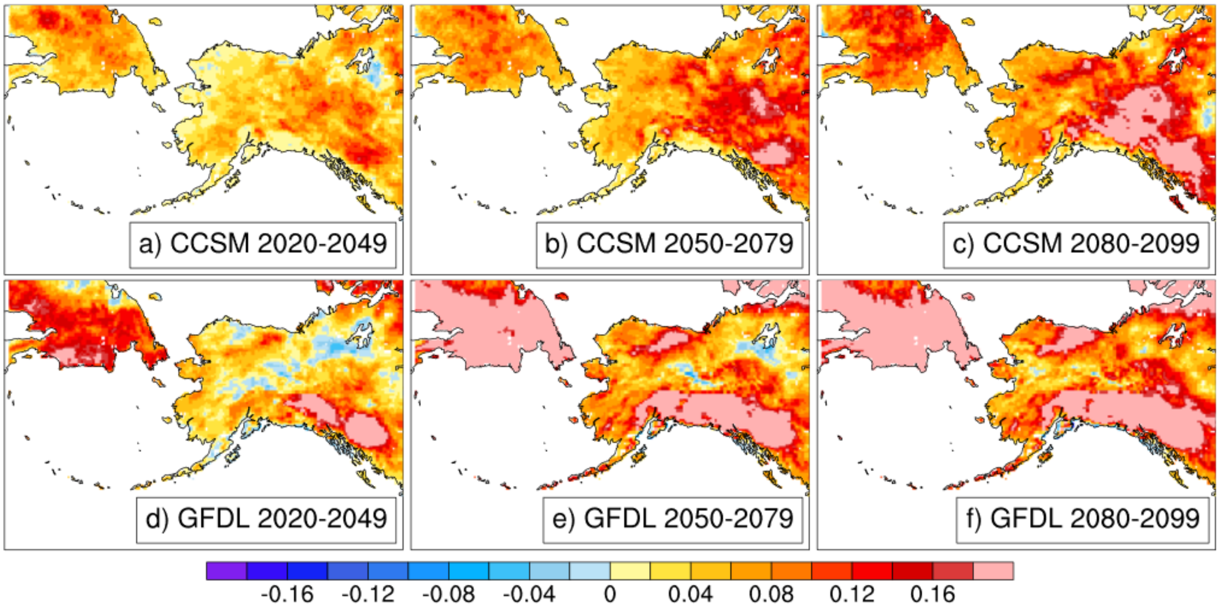


Figure 12: Difference (future-historical) in convective precipitation (expressed as fraction of total) for June and July.

Finally, the uncertainty of human behavior is an unavoidable aspect of any climate projections. However, in selecting the RCP8.5 future scenario, which seems the most likely currently global trajectory (albeit a slightly pessimistic one), we are offering the most useful and apt available picture of the future, from an engineering standpoint. For users interested in other emission scenarios (e.g., RCP 4.5), projected changes in temperature and precipitation show approximately linear relationships to the radiative forcing from anthropogenic sources (the RCP value). Evan in the latest (CMIP6) generation of models, the anthropogenic radiative forcing has the same RCP values (2.6, 4.5, 8.5) as in CMIP5, and there are no indications that the general proportionality between the atmospheric response and the RCP value has changed.

A final important point regarding uncertainty is the fact that while the outputs from Atlas 14 are fitted to frequency distributions (smooth curves), and while the new outputs in this project represent differences from these values (deltas), the deltas themselves are not fitted to curves, but rather derived directly from modeled data. Thus, it is to be expected that the outputs from this project show greater variability than those of Atlas 14 and appear less “smooth”. Although we could have performed additional mathematical and statistical smoothing, best practices dictated that we allow this level of model variability to be reflected in output data.

Regional and Site-specific Recommendations

Regional and site-specific recommendations can be drawn from the above discussion of uncertainty, and directly from the data, based on local projected increases in extreme precipitation events. The eight communities selected for and displayed under Results and in Appendix D: Community Data Examples offer a range of representative cases, as already discussed. Data users can select any location across the state in order to derive more specific case studies.

While precipitation is projected to increase statewide, patterns of increase do differ by location. For example, increases in return factors in Ketchikan (the wettest of the eight selected locations) are generally more modest than increases in other locations (Table 2). However, it should be noted that increases in actual precipitation amounts could nonetheless be greater at Ketchikan than at other locations, given that Ketchikan is an extremely wet location. For design purposes, changes in the actual amounts could be more important than changes in the return factors.

Of particular note, regionally, are the differences between increases in projected short-duration precipitation events (e.g. one hour maxima) versus changes in long-duration precipitation maxima (e.g. one month). Although precipitation is projected to increase across all durations and locations, increased in longer-duration maxima are less extreme. This suggests that engineering solutions designed to accommodate brief flooding events may require greater adjustments and alterations than those designed to accommodate longer-term conditions.

We hesitate to offer specific engineering advice to end users of these data, beyond advising that for purposes of site-specific design and construction best practices would suggest looking at data for both models and multiple future projected time periods. Depending upon design criteria, it might be advisable to use either the mean or these estimates or the most pessimistic or extreme estimate. In most cases this would presumably be the largest (wettest) value, although cases may occur where lack of extreme precipitation events might be a concern.

Links to Web Tool and Online Data Repository

These have been repeatedly referenced in this report, but are included here for convenience.

Web tool:
https://snap.uaf.edu/tools/future-alaska-precip

Online data repository:
http://ckan.snap.uaf.edu/dataset/annual-maximum-precipitation-projections-for-alaska

Limitations and Suggested update frequency

Although the completion of this project and the end date of the associated grant officially end the responsibilities of the grantees and sub-awardees, all data and data interfaces will be continuously maintained by SNAP beyond the completion date of the project and for the foreseeable future. The SNAP team at UAF plans to maintain both the web tool and the online data repository indefinitely, along with all other data sets and tools managed by SNAP. This includes all necessary technical updates to maintain data and metadata accessibility. It does not include creating new datasets or any additional work.

SNAP will contact key personnel at DOT&PF should it become advisable to update data or methods at some point in the future, and will recommend approximately when DOT&PF should request revised projected precipitation data in coordination with the current state of the modeling efforts at UAF. Should future climate projections differ greatly from the data currently available, DOT&PF might wish to enter into a new contract with UAF in order to update outputs. At the present time, outputs represent the best available data and methods.

Conclusions

The findings in this Final Report add to the understanding of the statistical probability of extreme precipitation events across all locations in Alaska, currently and in the future. These statistical ranges were calculated from projected climate data, and calibrated and validated using historical data. While uncertainty is inevitably associated with any modeled or projected data, the calculation methods used to derive these new data offer the most robust available information. Projected extreme precipitation events are directly correlated with extreme discharge.

As such, hydraulic structures such as bridges and culverts, if designed based on careful assessment and interpretation of the new datasets created in the course of this project, will better meet the standards for sound hydrologic methodologies and best available science, as recommended by FHWA.

Suggested Research

As noted in this report, data uncertainties with regard to precipitation are driven to a great degree by paucity of data. This can be remedied to some degree by mathematical modeling, but increased precipitation data collection across the state will improve model validation.

More broadly, issues of hydrology and water flow depend heavily on not just precipitation events, but also a wide range of other climate variables. Temperature plays a huge role in determining whether precipitation arrives as rain versus snow; when (and how rapidly) spring snowpack will melt; when river ice will form in the autumn and break up in the spring; meltwater flows from glaciers and high-elevation snowpack; and how much soil moisture will be lost to evapotranspiration. Formation of snowpack is also affected by wind and other variables. Better data gathering via remote sensing and on-site meteorological stations can inform improved modeling efforts.

Improved analysis and downscaling of GCMs and other climate models coupled with improved analysis of all the climate variables described above can improve predictive capacity. Future models might predict hydrologic events related to landscape level flows. Many future opportunities exist for collaborative research in these areas between SNAP/IARC, DOT&PF, and other partners.

Appendix A: Literature Review and Citations

Following are pertinent statements in the literature that help justify the need for the recommended research, support the methods and data selected, and/or highlight points brought out in the results or interpretation of results.

The initial review was compiled by both DOT&PF project collaborators from the Future Projections of Precipitation for Alaska Infrastructure research needs statement. It was updated by UAF personnel to include other relevant publications and science findings throughout the duration of the project.

It will continue to be updated for the final report.

Memo from John R. Baxter, Associate Administrator for Infrastructure, FHWA dated September 24, 2012

1. Consideration of extreme weather events, their impacts on highways and transportation systems, and development of adaptation strategies should be grounded in the best available scientific approaches.

Order 5520 by FHWA, December 15, 2014

1. Climate change and extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of the Nation's transportation infrastructure and operations.
2. It is FHWA's policy to strive to identify the risks of climate change and extreme weather events … promote preparedness and resilience; safeguard Federal investments; and ensure the safety, reliability, and sustainability of the Nation's transportation systems.
3. FHWA encourages State departments of transportation … to develop, prioritize, implement and evaluate risk-based and cost-effective strategies to minimize climate and extreme weather risks and protect critical infrastructure using the best available science, technology and information.
4. FHWA encourages consideration of climate change and extreme weather event risks, preparedness and resiliency in the delivery of programs.

Hydraulic Engineering Circular No. 17 by FHWA, June 2016
https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

1. Given the evolutionary nature of climate science, modeling, and data, FHWA recommends … designers consult with various organizations with expertise as needed to support project … design.
2. FHWA does not recommend using arbitrary increases in flows to estimate projected discharges from historical discharges. Rather, FHWA recommends using sound hydrologic methodologies and data.
3. HEC 17 presents the best available science.
4. HEC 17 present state-of-the-art methodologies.

Lader, R., J.E. Walsh, U.S. Bhatt, and P.A. Bieniek, 2017: Projections of Twenty-First-Century Climate Extremes for Alaska via Dynamical Downscaling and Quantile Mapping. J. Appl. Meteor. Climatol., 56, 2393–2409, https://doi.org/10.1175/JAMC-D-16-0415.1

1. Alaska is projected to experience major changes in extreme weather during the twenty-first century.

2. While global climate models generally replicate climate extremes, they also occasionally exhibit large errors owning to coarse resolution. Regional dynamical downscaling of the global models attempts to reduce these errors by providing gridded output at a much finer spatial and temporal resolution.
3. The average annual precipitation in Alaska is projected to increase 53% by the end of the century.
4. The average annual count of heavy precipitation days and very heavy precipitation days in Alaska is projected to increase 66% and 101%, respectively by the end of the century.
5. The average annual maximum 1-day and 5-day precipitation is projected to increase by 53% and 50%, respectively by the end of the century.

Synthesis of Approaches for Addressing Resilience in Project Development by FHWA, July 2017

1. For information on projected climate in Alaska, consult with Scenarios Network for Alaska & Arctic Planning (SNAP).
2. Changes in precipitation and the resultant changes in stream flows are the primary climate change stressors expected to impact transportation assets in the riverine environment.
3. Stationarity is a characteristic of time series data such that the data are homogeneous. There are no trends that would prevent historical data from being used to estimate future conditions.
4. Non-stationarity is a characteristic of time series data such that the data are heterogeneous. Trends over time prevent historical data from being used to estimate future conditions. Historic conditions or patterns may not be valid in the future.
5. The inclusion of historic precipitation in discharge regression equations, does not allow for consideration of non-stationarity.
6. Climate change refers to any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature or precipitation that occur over several decades or longer. Changes in climate may manifest as an increase in the frequency and magnitude of extreme weather events.
7. FHWA encourages State DOTs to develop, prioritize, implement, and evaluate risk-based cost-effective strategies to minimize climate and extreme weather risks and protect critical infrastructure using the best available science, technology, and information.
8. To incorporate non-stationarity into a design, climate modeling projections should be used.
9. Climate models produce projections at a coarse geographic resolution. This information is often too coarse to capture the site-specific conditions that are needed to inform asset-level analysis.
10. Historic precipitation has been used to predict future conditions, but this does not allow for consideration of the current non-stationary climate. Therefore, projected precipitation is needed.
11. The non-stationary climate should be incorporated into a design by using the best available science to estimate projected precipitation.

Berne, Alexis, Guy Delrieu, Jean-Dominique Creutin, and Charles Obled (2004). Temporal and spatial resolution of rainfall measurements required for urban hydrology. Journal of Hydrology. Volume 299, Issues 3–4, 1 December 2004, Pages 166-179.

Cannon, Alex, and Silvia Innocenti (2019). Nat Projected intensification of sub-daily and daily rainfall extremes in convection-permitting climate model simulations over North America: implications for future intensity– duration–frequency curves.. Hazards Earth Syst. Sci., 19, 421–440, 2019 https://doi.org/10.5194/nhess-19-421-2019

Hosking, J., & Wallis, J. (1997). *Regional Frequency Analysis: An Approach Based on L-Moments*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511529443

Perica, Sanja, Douglas Kane, Sarah Dietz, Kazungu Maitaria, Deborah Martin, Sandra Pavlovic, Ishani Roy, Svetlana Stuefer, Amy Tidwell,Carl Trypaluk,Dale Unru,Michael Yekta, Erica Betts, Geoffrey Bonnin, Sarah Heim, Lillian Hiner, Elizabeth Lilly, Jayashree Narayanan, Fenglin Yan, Tan Zhao. (2012). NOAA Atlas 14 Precipitation-Frequency Atlas of the United States Volume 7 Version 2.0: Alaska. NOAA. Silver Spring, Maryland, 2012

Walsh, John E., Uma S. Bhatt, Jeremy S. Littell, Matthew Leonawicz, Michael Lindgren, Thomas A. Kurkowski, Peter A. Bieniek, Richard Thoman, Stephen Gray, T. Scott Rupp. (2018). Downscaling of climate model output for Alaskan stakeholders, Environmental Modelling & Software, Volume 110, 2018, pages 38-51.

Wang, X., G. Huang, and J. Liu (2014), Projected increases in intensity and frequency of rainfall extremes through a regional climate modeling approach, J. Geophys. Res. Atmos., 119, 13,271–13,286, doi:10.1002/ 2014JD022564.

Wang, L-P., Ochoa-Rodriguez, S., Van Assel, J., Pina, R.D., Pessemier, M., Kroll, S.,Willems, P., Onof, C., Enhancement of radar rainfall estimates for urban hydrology through optical flow temporalinterpolation and Bayesian gauge-based adjustment, Journal of Hydrology (2015)

.

Appendix B: Codebase and Development

Complete information can be found on Github, here:

https://github.com/ua-snap/precip-dot

These data constitute an effort to update the NOAA Atlas 14 for Alaska using more recent historical observed climate information and adding in the effects of a changing climate. The goal is to produce a similar set of data as is displayed and served currently through the NOAA Atlas 14 Precipitation Frequency Web Interface, using the WRF Dynamically Downscaled Data for Alaska produced by researchers affiliated with the Alaska Climate Adaptation Science Center (AK-CASC). This work is funded by the Alaska Department of Transportation and Public Facilities (DOT&PF) to add climate futures data to existing workflows designing culverts and other engineering features of road construction.

The Data Pipeline

The data transformation in this project follows a pipeline with the following steps:
Starting point: WRF hourly precipitation data (can be obtained here), along with the NOAA Atlas 14 data. (See the scripts in here for help obtaining and pre-processing the NOAA Atlas 14 data).
Durations: Calculate duration series for various time periods.
AMS: Calculate **A**nnual **M**aximum **S**eries for all duration series.
Intervals: Calculate return intervals based off AMS.
Deltas: Calculate the difference, as a ratio, between the historical WRF data and the multiple decades of projected data.
Warp: Reinterpolate this grid of deltas to match the grid of the NOAA Atlas 14 data.
Multiply: Multiply the NOAA Atlas 14 data by the deltas to get the final precipitation estimates.
The WRF data includes 5 different models/data groups (listed below). The pipeline is repeated for every group:
NCAR-CCSM4_historical
NCAR-CCSM4_rcp85
ERA-Interim_historical
GFDL-CM3_historical
GFDL-CM3_rcp85

The diagram below outlines the relationship between the different data groups and their involvement in each step of the pipeline:

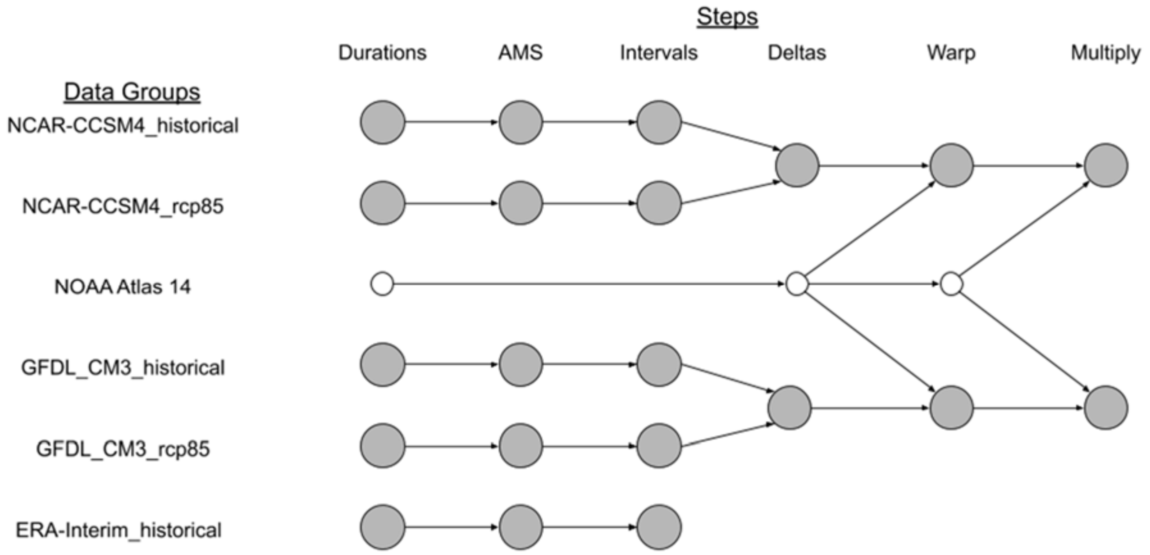


Figure 13: Schematic of data pipeline

The python scripts in the pipeline directory are used to execute different steps of the pipeline and the run-pipeline script is used to execute all or part of the entire pipeline.

Running the Pipeline

Setting Up

If you're running on SNAP's ATLAS server, then some of this has probably already been done for you.

Install Dependencies: Call `pip install -r requirements.txt` to install all of the necessary python packages (it is recommended that you do this inside a new virtual environment or conda environment). You may also need to install various libraries such as HDF5 and NetCDF to get the packages to install.

Set up Data Directory: Decide on the directory where you want to store all the data.

In that directory, create another directory called `pcpt` and download all of hourly precipitation WRF data into it. (The data can be found on S3 here).

Create another directory (in the main data directory) called `NOAA` which will store all the NOAA Atlas 14 data.

Executing the Pipeline

Simply calling `./run-pipeline` will execute the entire pipeline for all data sets with default options configured for running on SNAP's ATLAS server. However, the run-pipeline script is very powerful and through various command-line options, it can be customized to run just subsets of the pipeline, in different directories, with or without SLURM and more. Call `./run-pipeline --help` for more information.

Running the pipeline on ATLAS with SLURM:

You can call `run-pipeline` using the 'sbatch' command to run it with SLURM. Since this will copy the script to a temporary directory before running it, you will have to manually specify the script directory. You will also likely want to override the python executable to use whichever virtual environment you're in at the time. The command below will work to run the entire pipeline on SLURM.

```
sbatch ./run-pipeline -e $(which python3) --script-dir $(pwd)/pipeline/ -p 64
```

Running the pipeline on your own:

Running the pipeline by yourself is generally simpler, but you will have to override the default data directory.

```
./run-pipeline -d path/to/your/data/directory
```

Appendix C: Regional Maps

The following maps illustrate differences in projections between the two Global Circulation Models used in this study across future time periods and precipitation durations.

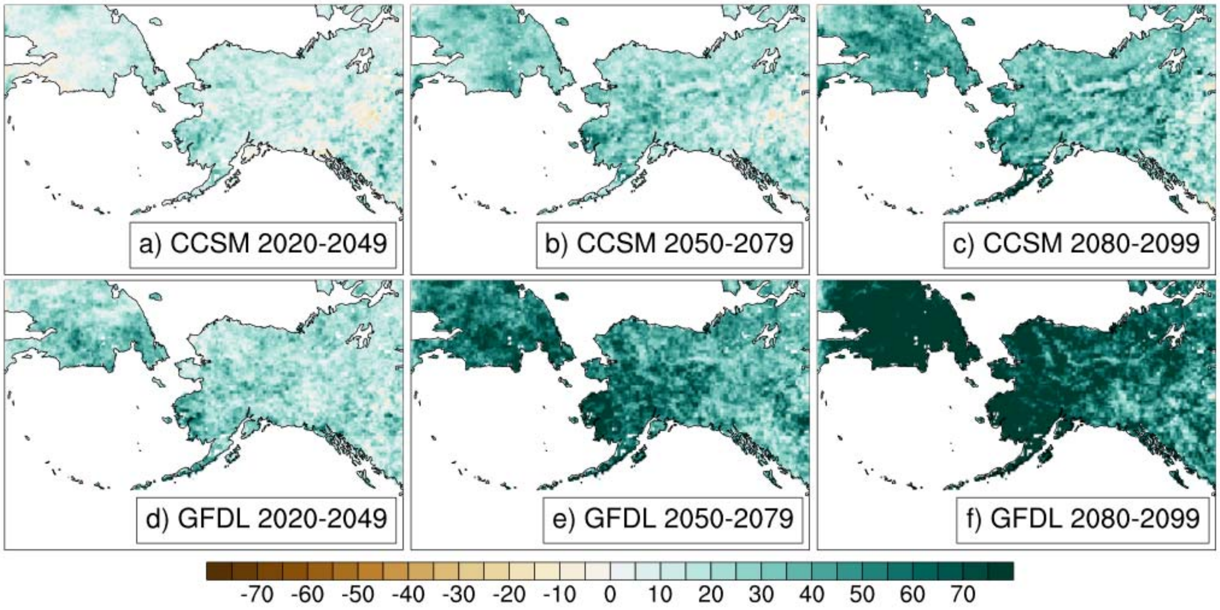


Figure 14: Projected percent change, as compared to baseline WRF data, for 60-minute maximum precipitation with a two year return interval (frequency estimate).

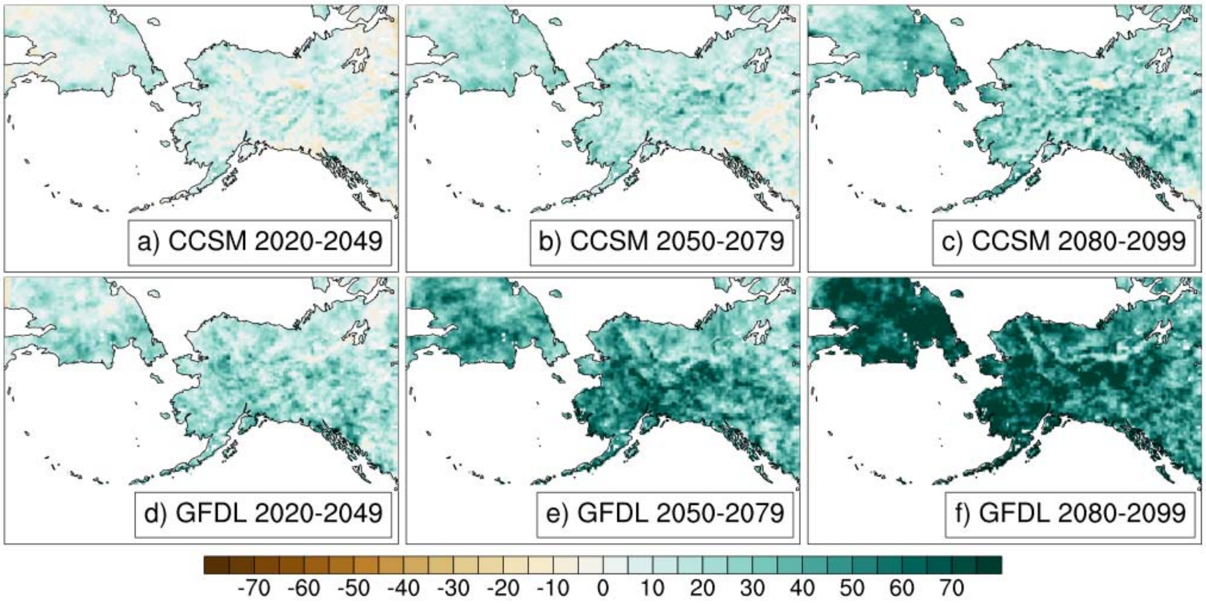


Figure 15: Projected percent change, as compared to baseline WRF data, for 24-hour maximum precipitation with a two year return interval (frequency estimate).

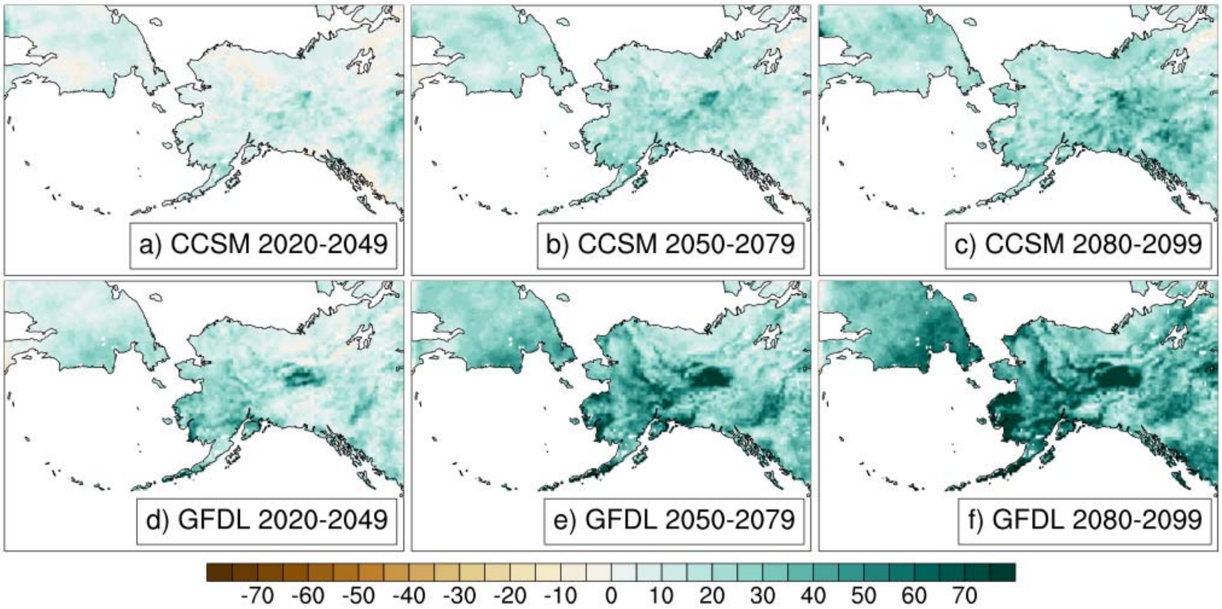


Figure 16: Projected percent change, as compared to baseline WRF data, for 30-day maximum precipitation with a two year return interval (frequency estimate).

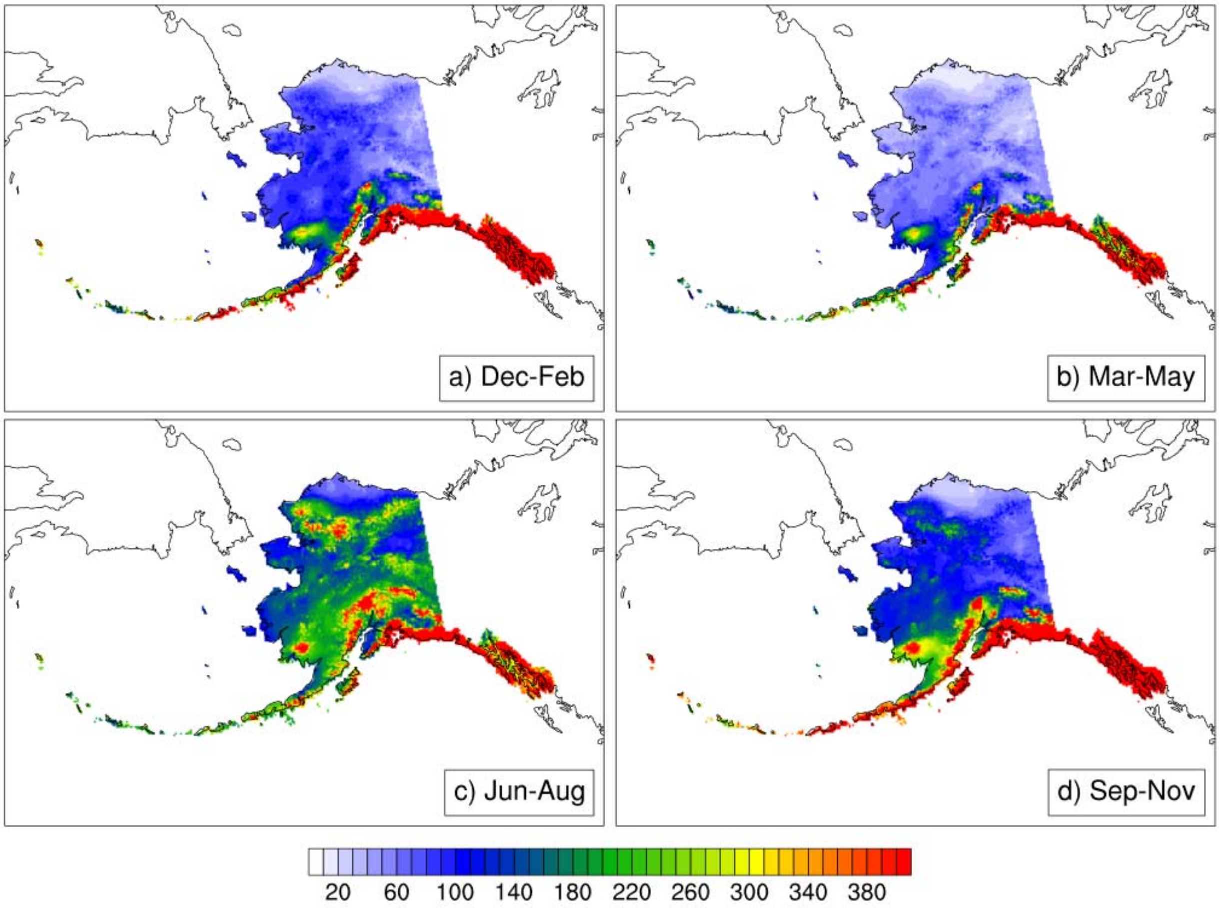


Figure 17: Differences in precipitation (mm) across seasons, based on PRISM baseline climate data for the state of Alaska

Appendix D: Community Data Examples

Table 5Following are sample data for Precipitation Frequency estimates for eight selected communities derived using the downscaling processes described in this report. All units are in millimeters.

Utgiagvik 71.291 -156.789	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	6	10	18	15	27	42	45	70	100
GFDL-CM3, 2050-2079	6	13	23	18	30	50	58	82	97
GFDL-CM3, 2080-2099	7	13	24	20	36	69	61	91	115
NCAR-CCSM4, 2020-2049	4	9	18	14	28	50	44	70	94
NCAR-CCSM4, 2050-2079	4	8	13	14	24	37	49	62	70
NCAR-CCSM4, 2080-2099	6	11	20	17	36	64	57	70	89
ATLAS 14	4	7	11	14	22	33	45	66	88
Fairbanks (68.838, -147.716)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	11	19	29	33	54	88	103	176	265
GFDL-CM3, 2050-2079	13	23	35	40	71	122	133	214	309
GFDL-CM3, 2080-2099	16	32	52	45	67	92	129	230	373
NCAR-CCSM4, 2020-2049	9	17	22	27	50	80	88	165	273
NCAR-CCSM4, 2050-2079	11	19	21	28	48	73	106	156	202
NCAR-CCSM4, 2080-2099	12	18	19	30	50	78	102	155	205
ATLAS 14	9	15	23	28	45	67	90	131	180
Anaktuvuk (68.143, -151.736)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	11	20	31	33	59	95	134	207	266
GFDL-CM3, 2050-2079	14	29	50	41	78	141	162	224	269
GFDL-CM3, 2080-2099	18	37	62	43	80	128	180	298	413
NCAR-CCSM4, 2020-2049	9	16	19	28	53	87	116	167	206
NCAR-CCSM4, 2050-2079	11	20	24	31	65	116	131	183	211
NCAR-CCSM4, 2080-2099	13	31	50	34	76	149	132	204	261
ATLAS 14	11	18	26	30	50	79	115	162	216
Anchoarge 61.182, -149.993	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	8	14	22	40	55	59	140	208	249
GFDL-CM3, 2050-2079	10	19	28	47	69	80	160	226	253
GFDL-CM3, 2080-2099	12	25	45	54	89	119	180	264	313
NCAR-CCSM4, 2020-2049	9	15	21	36	65	88	128	219	302
NCAR-CCSM4, 2050-2079	9	15	20	36	66	105	129	218	332
NCAR-CCSM4, 2080-2099	9	15	22	38	64	86	137	229	320
ATLAS 14	8	12	17	36	57	78	126	179	230
Nome (64.501, -165.406)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	9	17	29	29	49	75	163	268	337
GFDL-CM3, 2050-2079	11	21	39	42	67	107	182	287	339
GFDL-CM3, 2080-2099	14	25	40	50	89	151	245	337	363
NCAR-CCSM4, 2020-2049	7	15	26	33	56	76	119	191	285
NCAR-CCSM4, 2050-2079	8	16	25	41	69	90	135	237	373
NCAR-CCSM4, 2080-2099	10	16	20	39	75	114	137	243	367
ATLAS 14	7	10	14	32	48	66	127	181	239
Unalaska (53.873, -166.533)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	13	21	28	77	122	183	343	569	813
GFDL-CM3, 2050-2079	17	27	38	90	168	300	387	594	794
GFDL-CM3, 2080-2099	19	30	40	110	208	366	448	703	966
NCAR-CCSM4, 2020-2049	11	18	24	82	144	214	339	545	725
NCAR-CCSM4, 2050-2079	13	25	38	94	157	213	359	561	722
NCAR-CCSM4, 2080-2099	12	25	39	96	164	259	368	564	739
ATLAS 14	11	18	27	83	122	169	366	511	650
Juneau (58.302, -134.42)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	15	24	35	96	156	243	505	644	691
GFDL-CM3, 2050-2079	17	26	39	110	164	242	567	763	883
GFDL-CM3, 2080-2099	20	32	48	127	177	237	648	916	1092
NCAR-CCSM4, 2020-2049	13	19	23	59	147	198	433	590	738
NCAR-CCSM4, 2050-2079	14	21	25	98	148	179	521	672	740
NCAR-CCSM4, 2080-2099	16	24	32	108	164	195	527	710	834
ATLAS 14	12	17	22	89	121	155	462	587	696
Ketchikan (55.342, -131.636)	One hour maximum			One day maximum			One month max (30 day)		
Return interval -->	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**	**2 year**	**10 year**	**50 year**
GFDL-CM3, 2020-2049	21	27	33	179	241	322	866	1061	1185
GFDL-CM3, 2050-2079	23	33	46	183	254	351	949	1114	1249
GFDL-CM3, 2080-2099	26	35	46	201	285	403	1081	1362	1556
NCAR-CCSM4, 2020-2049	20	28	36	133	194	261	744	923	1117
NCAR-CCSM4, 2050-2079	21	31	46	157	251	356	865	1155	1409
NCAR-CCSM4, 2080-2099	23	31	41	173	236	292	921	1158	1340
ATLAS 14	18	24	31	150	201	257	800	1003	1214

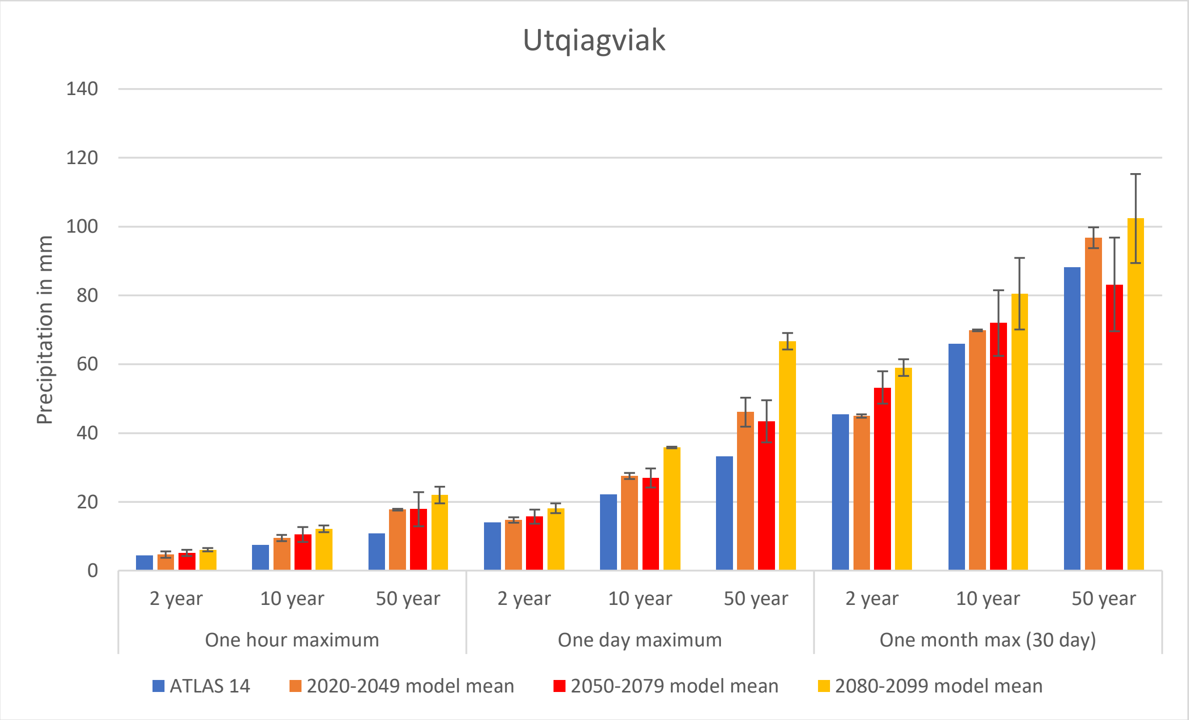


Figure 18: Comparison of model output data and Atlas 14 data for Utqiagvik. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

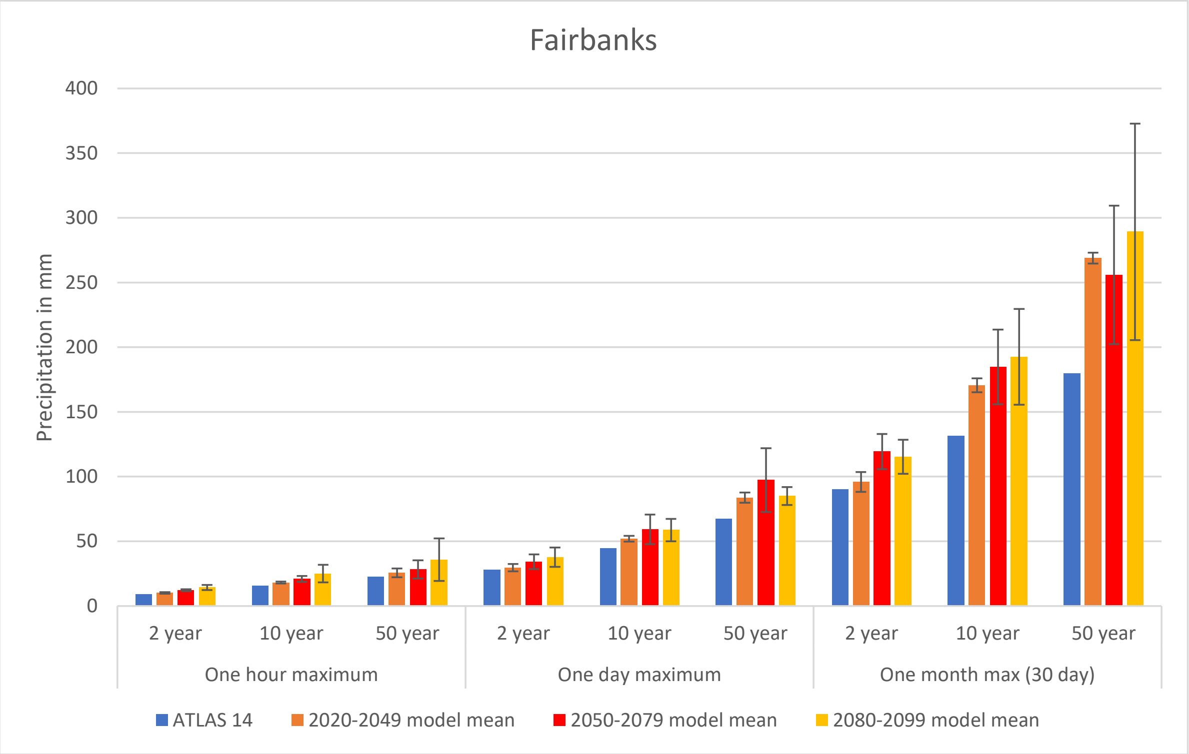


Figure 19: Comparison of model output data and Atlas 14 data for Fairbanks. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

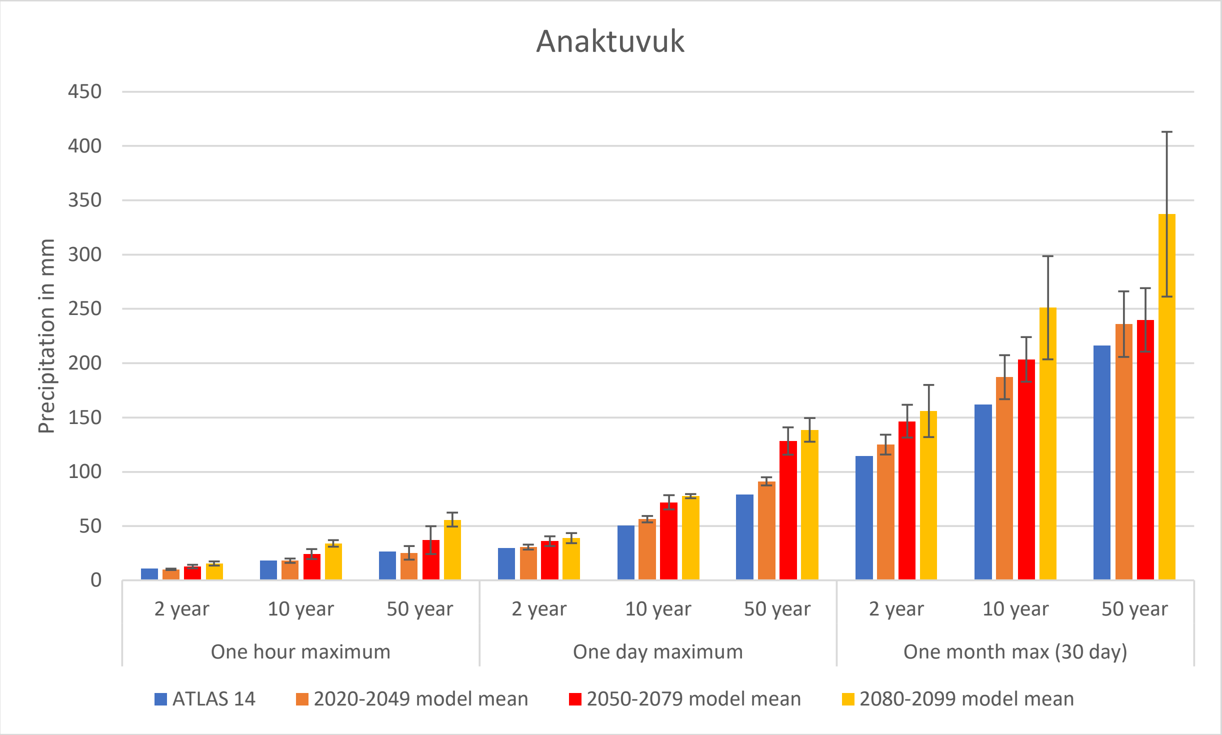


Figure 20: Comparison of model output data and Atlas 14 data for Anaktuvuk. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

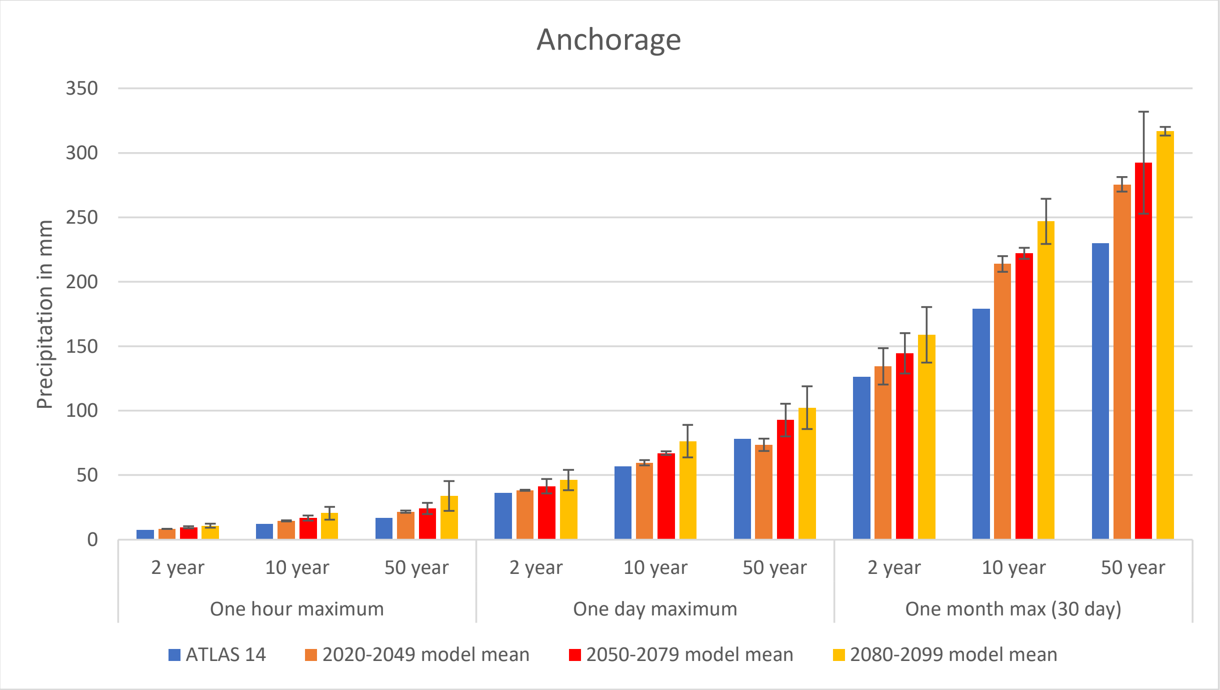


Figure 21: Comparison of model output data and Atlas 14 data for Anchorage. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

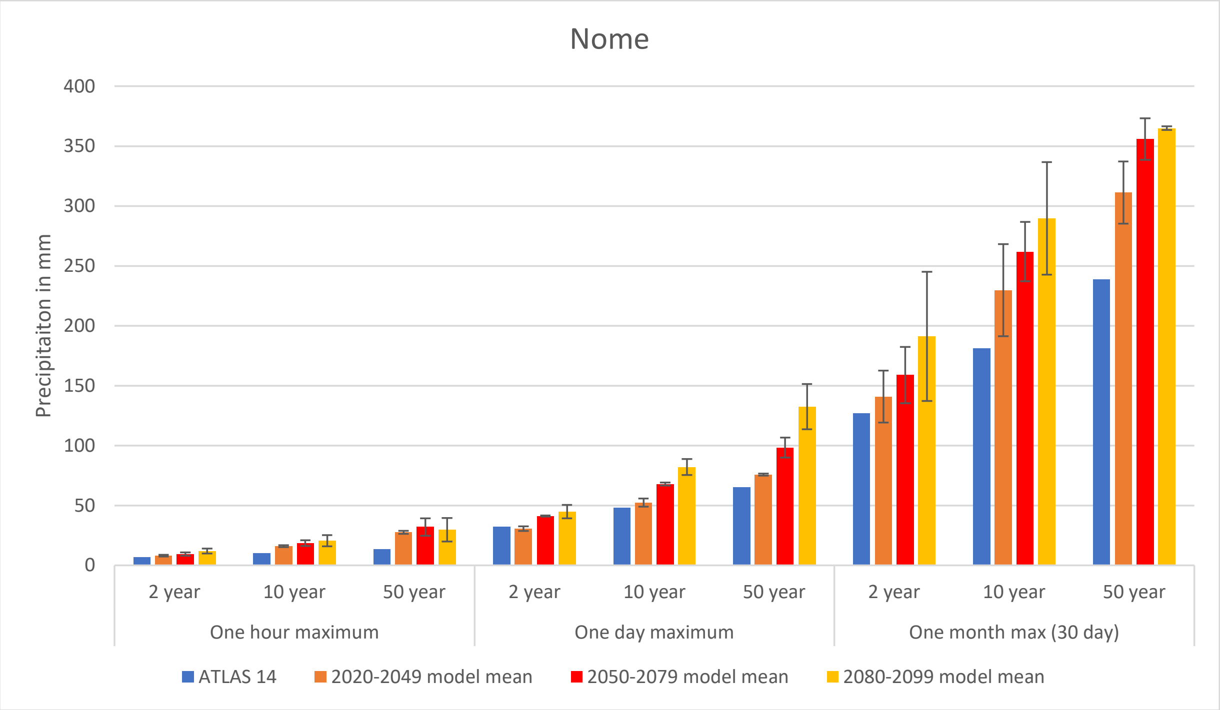


Figure 22: Comparison of model output data and Atlas 14 data for Nome. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

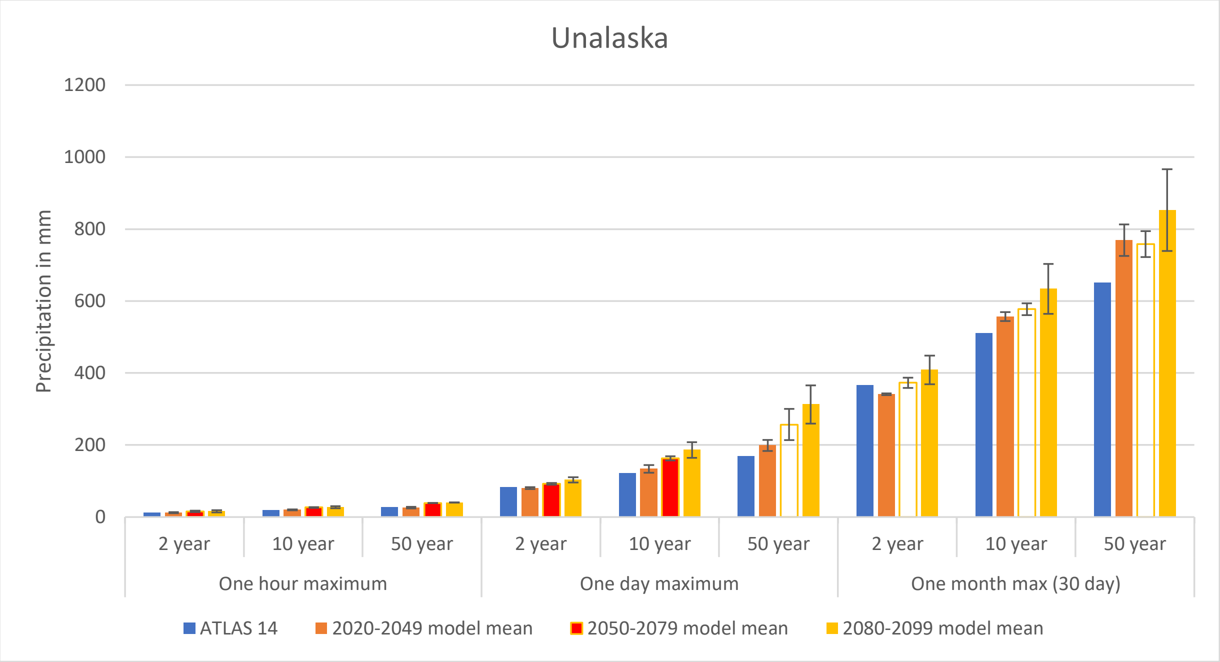


Figure 23: Comparison of model output data and Atlas 14 data for Unalaska. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

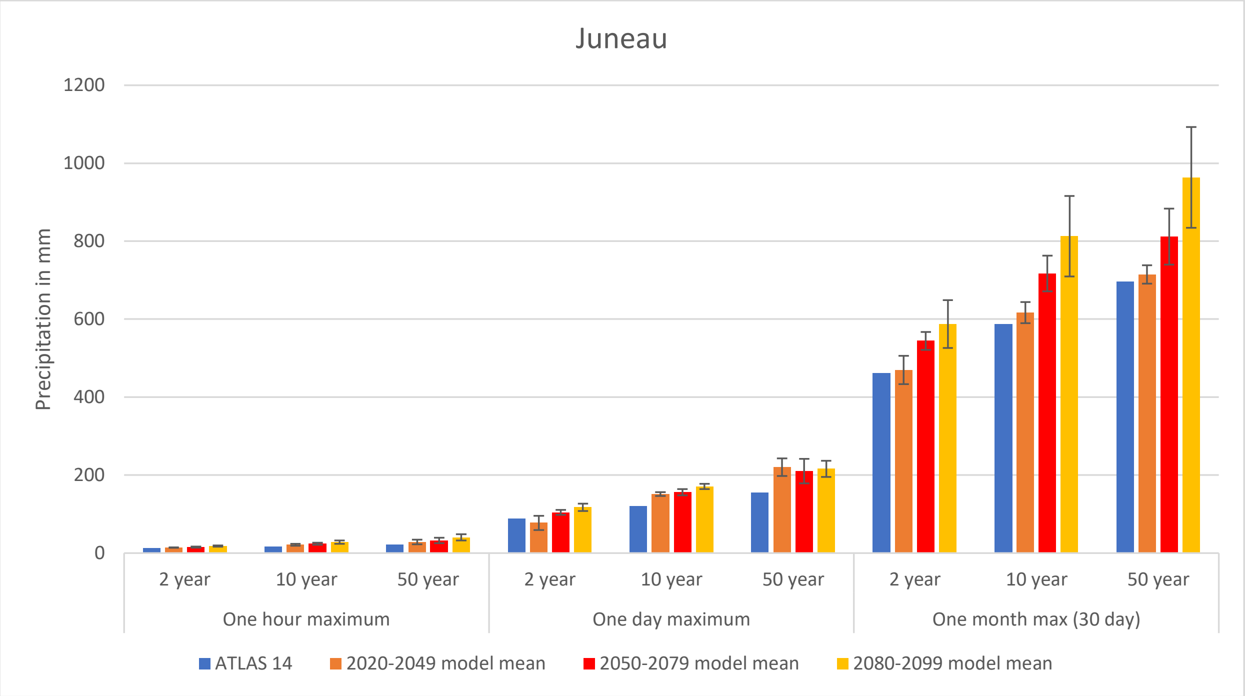


Figure 24: Comparison of model output data and Atlas 14 data for Juneau. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

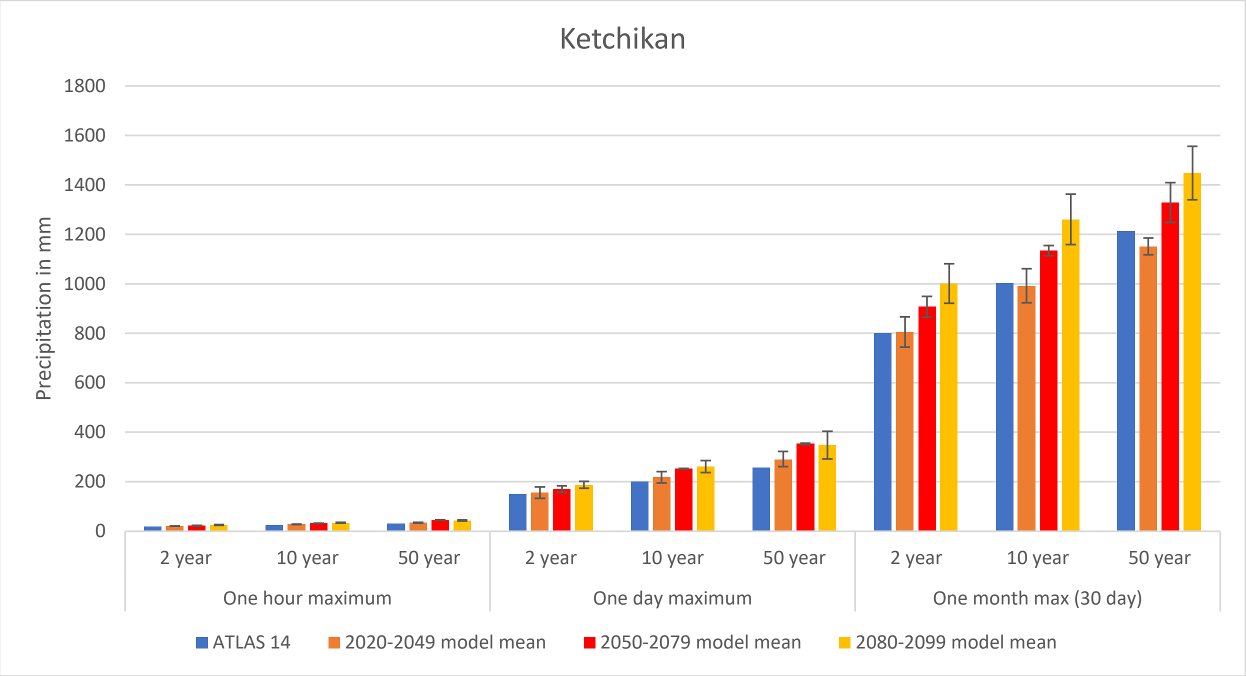


Figure 25: Comparison of model output data and Atlas 14 data for Ketchikan. Black lines represent the range between two models. Despite variability, trends show increases above baseline precipitation across all durations and return intervals.

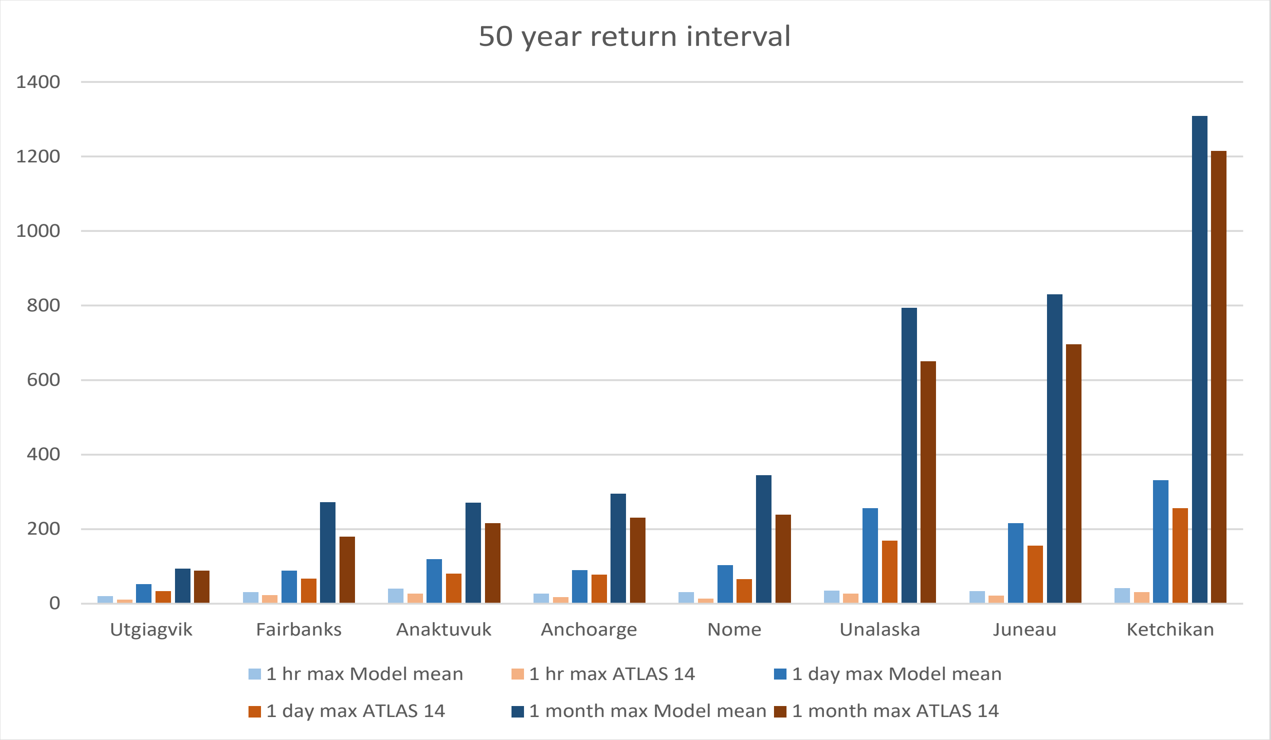


Figure 26: Comparison of maximum precipitation (mm) for model averages and Atlas 14 data across three durations, for eight communities

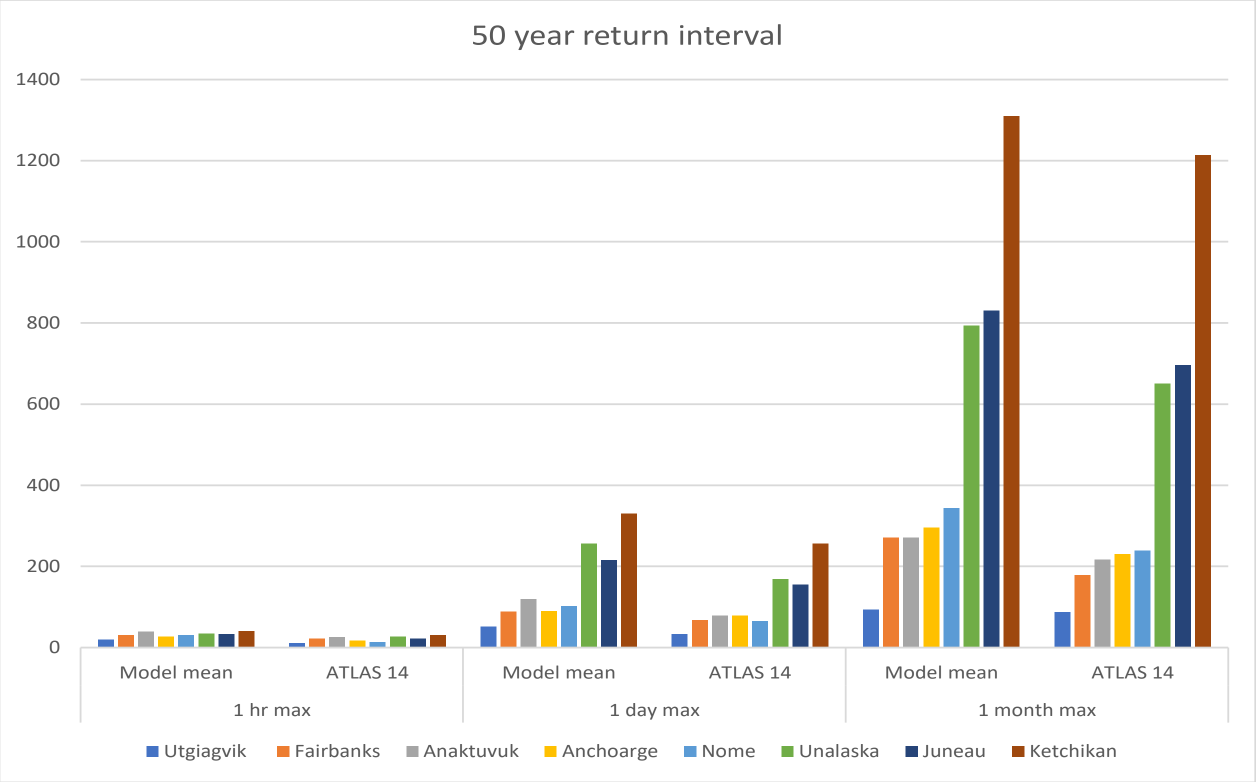


Figure 27: Comparison of maximum precipitation (mm) across three durations and eight communities, comparing model averages and Atlas 14 data