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Projected Changes in Extreme Event Indices for Alaska

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Abstract

As climate has warmed in recent decades, Alaska has experienced a variety of high-impact extreme events that include heat waves, wildfires, coastal storms and freezing rain. Because the warming is projected to continue, it is essential to consider future changes when planning adaptation actions and building resilience. In this study, we synthesize information on future changes in extreme events in Alaska from an ensemble of regional climate model simulations performed as part of Arctic-CORDEX (Coordinated Regional Climate Downscaling Experiment). A set of 13 extreme event indices, based on those developed by the World Climate Research Programme's Expert Team on Climate Change Detection and Indices (ETCCDI), are evaluated from the Arctic-CORDEX output for Alaska. Of the 13 indices, six pertain to temperature, five to total precipitation, one to wind and one to snow. The results for locations in seven different climate zones of Alaska include large increases (5˚C - 10˚C) in the temperature thresholds for the five hottest and coldest days of the year, and large increases in warm spell duration and decreases in cold spell duration. Changes in the cold day temperature threshold are generally larger than the changes in the hot day temperature threshold, consistent with the projections of a stronger warming in winter than in summer in Alaska yearly maximum 1-day and 5-day precipitation amounts as well as the yearly number of consecutive wet days are projected to increase at all locations. The indices for heavy snow days and high-wind days show mixed changes, although the results indicate increases in heavy snow days at the more northern locations and increases in windy days at coastal locations. The changes in the extreme event indices continue through 2100 under the higher-emission (RCP 8.5) emission scenario, while the changes generally stabilize under the lower-emission (RCP 4.5) scenario.

Keywords

Extreme Events, Temperature, Precipitation, Alaska Climate

1. Introduction

Extreme climate and weather events, especially changes in extremes, often have greater impacts on ecosystems [1], infrastructure [2] and humans [3] than changes in climate averages. Moreover, extreme events can trigger exceedances of thresholds for impacts and for abrupt changes in the environment. While a general lack of studies of extreme events in the Arctic has been noted in previous Arctic assessment reports (e.g., [4] [5]), such events have begun to receive attention by the research community. This increased attention has been especially apparent in Alaska, where recent warming has been accompanied by severe wildfire seasons, a shortened snow season on land and reduced sea ice coverage in adjacent waters, as well as highly impactful flooding in coastal and inland areas [6].

As noted by the Intergovernmental Panel on Climate Change (IPCC) [7], the identification and definition of extreme weather and climate events that are relevant from an impact perspective are complex and depend on the stakeholders involved. The weather and climate literature has tended to define an extreme weather or climate event in terms of the occurrence of a value of a weather or climate variable above or below a threshold within the range of observed values of the variable (p. 116 in [7]). The choices of thresholds vary and are sometimes based on percentiles or standard deviations from normal. Absolute thresholds (rather than these relative thresholds based on the range of observed values of a variable) can also be used to identify extreme events. Even for a given approach to extreme event definition, the criteria will vary from place to place in an absolute sense (e.g., the threshold temperature for a hot day in the Arctic will be different from the tropics). Acknowledging the absence of universal definitions of extreme events, we frame this evaluation of extreme events in Alaska on a commonly used set of metrics developed by the World Climate Research Programme's Expert Team on Climate Change Detection and Indices (ETCCDI). The development of these metrics, which emphasize moderate climate extremes for which recurrence times are a year or less, is summarized by Karl and Easterling [8] and Klein Tank *et al.* [9]. The metrics have been applied to historical data and global climate model output by Sillmann *et al.* [10] [11] among others.

The Intergovernmental Panel on Climate Change [7] has also addressed the causes of changes on weather and climate extremes. In the case of temperature, changes in extremes can result from either a simple warming-driven shift of the temperature distribution or from a change in the shape of the distribution. In the latter case, changes in wind patterns or cloudiness can confound the effects of greenhouse gases on the change in the distribution of temperature. With regard to precipitation, changes in thresholds and frequencies of heavy precipitation events result in part from the increase of the atmosphere's moisture capacity as temperature increases. While this association is a manifestation of the Clausius-Clapeyron relationship, it is part of a general intensification of the hydrologic cycle shown by global climate models under all scenarios of increased greenhouse gas emissions [4] [7]. Changes in extreme snowfall are more complex, as they result from competing factors: increased precipitation (favoring more snowfall) and higher temperatures (favoring less snowfall because of a transition from snow to rain).

In this study we evaluate a set of 13 indices of extreme events over Alaska in a suite of regional climate model simulations. For seven regions of Alaska, the indices are evaluated as decadal means for the period 1980-2100 under two scenarios of greenhouse gas emissions. The across-model spread of the decadal means is used as a measure of the signal of the future change in each index at each location.

2. Data and Methods

The climate model output used here is from a suite of Arctic regional climate simulations performed under the auspices of the World Climate Research Programme's CORDEX (COordinated Regional Downscaling EXperiment). **Table 1** lists the combinations of global climate models (GCMs) and regional climate models (RCMs) used in the Arctic-CORDEX simulations. This list includes simulations by the same regional climate model (e.g., RCA4_v1, UQAM-CRCM5)

Table 1. Climate model simulations used in evaluation of extreme event indices.

Modeling Center	Global Model	Regional Model	Historical	RCP 4.5	RCP 8.5
SMHI	CanESM2_r1i1p1	RCA4_v1	1951-2005	2006-2100	2006-2100
SMHI	EC-EARTH_r12i1p1	RCA4_v1	1951-2005	2006-2100	2006-2100
SMHI	MPI-ESM-LR_r1i1p1	RCA4_v1	1951-2005	2006-2100	2006-2100
SMHI	NorESM1-M_r1i1p1	RCA4_v1	1951-2005	2006-2100	2006-2100
SMHI	EC-EARTH_r12i1p1	RCA4_SN1	1951-2005	N/A	2006-2100
SMHI	MPI-ESM-LR_r1i1p1	RCA4_SN1	1951-2005	N/A	2006-2100
CCCma	CanESM2_r1i1p1	CanRCM4_r2	1951-2005	2006-2100	2006-2100
UQAM	CanESM2_r1i1p1	UQAM-CRCM5_v1	1951-2005	N/A	2006-2100
UQAM	MPI-ESM-MR_r1i1p1	UQAM-CRCM5_v1	1951-2005	N/A	2006-2100
DMI	EC-EARTH_r3i1p1	HIRHAM5_v1	1951-2005	2006-2100	2006-2100
MGO	MPI-ESM-LR_r1i1p1	RRCM_v1	1951-2005	N/A	2006-2100

driven by several global models as well as several global climate models (e.g., EC-EARTH, CanESM2) driving more than one regional climate model. A similar set of models was used by Reader and Steiner [12] in their evaluation of trends of temperature and precipitation over the Arctic Ocean. The spatial resolution of the regional climate models ranges from 0.22 to 0.44 degrees. The final two columns in **Table 1** show the availability of simulations run under RCP 4.5 (lower emission) and RCP 8.5 (higher emission) future

For validation and bias-correction of the RCM simulations, we use the ERA5 reanalysis which has a 31 km (0.25˚) spatial and hourly temporal resolution [13]. Relative to its predecessor reanalysis (ERA-Interim), ERA5 is characterized by an increase in assimilated data with time, especially from satellite radiances, and recent advances in terrestrial, oceanic, and atmospheric data assimilation methods; such improvements and an overview of newly added data are provided by Hersbach *et al.* [13]. While ERA5 covers the period 1950-present, we utilized only the output through 2005 for bias-adjustment of the CORDEX historical simulations.

The ERA5 reanalysis has been used in recent Arctic climate assessments [5] [14] and has been shown to compare well against observations over Arctic land and marine areas with reduced air temperature biases relative to other modern atmospheric renalyses [15] [16]. ERA5 has also been shown to perform well in capturing boreal high-latitude trends of near-surface air temperature and precipitation, including rainfall and snowfall [17] [18] [19] [20] More specific to Alaska, recent studies have shown that ERA5 is also robust against observations and therefore represents a valid gridded product for the assessment of statewide precipitation trends [21] and extremes [22].

The variables listed in **Table 2** were retrieved from the CORDEX model simulations. While the CORDEX simulations cover a broad pan-Arctic domain (**Figure 1**), we retrieved the CORDEX output variables for a cropped Alaska subdomain in order to reduce data storage requirements. The cropped domain is shown in the right panel of **Figure 1**.

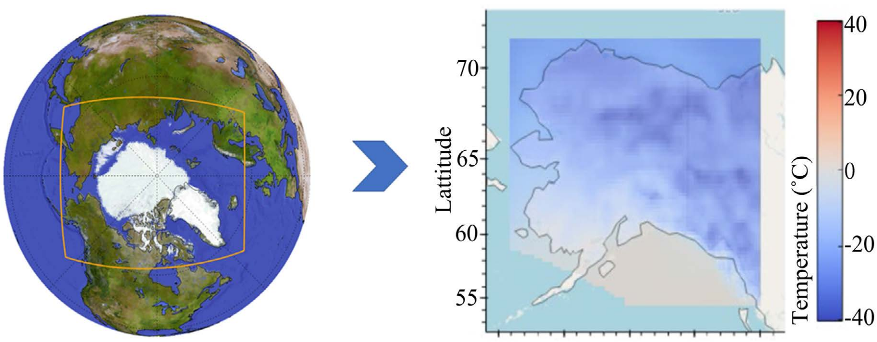

Figure 1. The CORDEX-Arctic domain (left panel) and the Alaska subdomain (right panel) for which the daily output variables in **Table 2** were retrieved. Colored shading in right panel shows near-surface air temperatures (˚C) from one model for a day in January.

Table 2. Variables retrieved from the CORDEX model simulations in **Table 1**.

Daily mean near-surface air temperature
Daily maximum near-surface air temperature
Daily minimum near-surface air temperature
Daily total precipitation
Daily total snowfall
Daily mean surface wind speed (eastward and northward components)

The variables in **Table 1** were then regridded to the 0.25˚ × 0.25˚ grid of the ERA5 reanalysis using a bilinear interpolation routine implemented using the Climate Data Operator software [23]. The use of a common grid for all the models (and ERA5) facilitated the bias-correction, following the quantile delta mapping procedure outlined by Cannon *et al.* [24]. Specifically, for each grid cell in the Alaska domain, the daily values within a sliding 31-day window of each variable from each model were binned into 20 quantiles. The corresponding daily ERA5 values were similarly binned into 20 quantiles. For each quantile, a "delta" (the ERA5 value minus the model value) was added to all model values in the quantile of the temperature variables. In the case of wind and the precipitation variables, the model's value was adjusted by a multiplier, *i.e.*, the ratio of the ERA5 value to the model value for each quantile. This procedure has the advantage of adjusting for model biases that vary among the distribution (e.g., seasonally). Prior to bias correction, values below a threshold of 0.01 mm/d were replaced with a uniform random noise to avoid very large correction factors when very small amounts of precipitation are observed. To maintain realistic relative minimum and maximum temperature values through the bias correction (*i.e.*, to ensure the maximum is greater than the minimum), we apply a multiplicative bias correction to the diurnal temperature range (the difference between maximum and minimum daily temperatures), then subtract it from the maximum daily temperature to estimate the minimum daily air temperature [25] [26].

While other applications of quantile mapping have utilized separate quantiles for each value in distributions of monthly data (e.g., [27] [28]), we have found that the use of "binned" quantiles effectively preserve the adjustment while minimizing effects of outlier values when the procedure is applied to daily distributions of ~10,000 values as is in this study. The bias correction was applied using the open source *xclim* software [29].

The bias-adjusted values of the CORDEX models were then used to compute a set of 13 extreme-event indices. These indices are based largely on the ETCCDI metrics, although we have modified several of the thresholds (e.g., "Summer Day" and "Deep Winter Day" temperatures) to align with Alaska's high-latitude climate.

3. Results

In this section we first present a sample of the results to illustrate the character of the changes in the extreme events. We selected seven locations in different climate regions of Alaska in order to illustrate the spatiotemporal variations of the indices. Each location is near a particular community in Alaska that is (and will be) impacted by the changes in extreme events. Each of these communities has also indicated an interest in the results of this study because of their vulnerability to extreme events. The seven Alaska climate regions and communities are listed in **Table 3**. The locations of the communities are shown on the map in **Figure 2**.

For each location, the yearly and decadal means of each index were calculated from the daily output of each model. The decadal means and the across-model spread were evaluated for both scenarios (RCP 4.5 and RCP 8.5), and a decade of "signal emergence" was defined as the first decade in which the historical mean for the 1980-2005 period lies completely outside the across-model range for that decade. It should be noted that the across-model spread includes the effect of internal variations, so this criterion for "signal emergence" takes into account more than simply the across-model differences.

Figure 2. The Alaska locations for which the extremes indicators have been evaluated.

Table 3. Alaska climate regions and representative communities used in this study.

Aleutians	Nelson Lagoon
Southwest Coast	Levelock
Southwest Interior	Igiugik Village
Southern Coast	Eyak
Southeast	Ketchikan
Northeast Interior	Stevens Village
Northern Coast	Kaktovik

Bar plots of the decadal means for 1980-2099 were created for each of the thirteen indices and each of the seven locations. The projections for the post-2005 period were plotted for both the RCP 4.5 and RCP 8.5 scenarios. The bar plots summarize the multi-model results for each of the 13 indices and the two RCP scenarios. In the following, we step through the results for each index in Table 4, providing a summary of the results for that index together with an illustrative example in most cases.

Figure 3 provides an illustration of the projected changes and the "signal emergence" of the HD (Hot Day) threshold by showing the decadal means and across-model spread for Nelson Lagoon in the Aleutians. The Hot Day threshold (5 occurrences per year) increases through the simulation period, with increases by 2090 (2080-2099) of 2.9˚C and 5.1˚C in the RCP 4.5 and 8.5 scenarios, respectively. In this case, the decade of "signal emergence" is the 2030s for both RCP scenarios. However, as is typical of most of the indices that undergo changes in the 21st century, the change continues to increase through 2100 under RCP 8.5, while the change under RCP 4.5 diminishes to near-zero by mid-to-late century, as indicated by the leveling off of the blur bars in Figure 3. The across-model range also tends to be larger in RCP 8.5 than in RCP 4.5, especially in the late 21st century, although this difference is at least partly attributable to the fact that there are more RCP 8.5 simulations (11) than RCP 4.5 simulations (6), as shown in Table 1.

The changes in Figure 3 are typical of those at the other sites. In all cases, the increases weaken under RCP 4.5 in the second half of the 21st century. The seven-site mean increase under RCP 4.5 is 2.4˚C by the mid-term (2050-2069) but only 2.7˚C by the long-term (2080-2099), while the corresponding increases for RCP 8.5 are 2.8˚C and 5.1˚C.

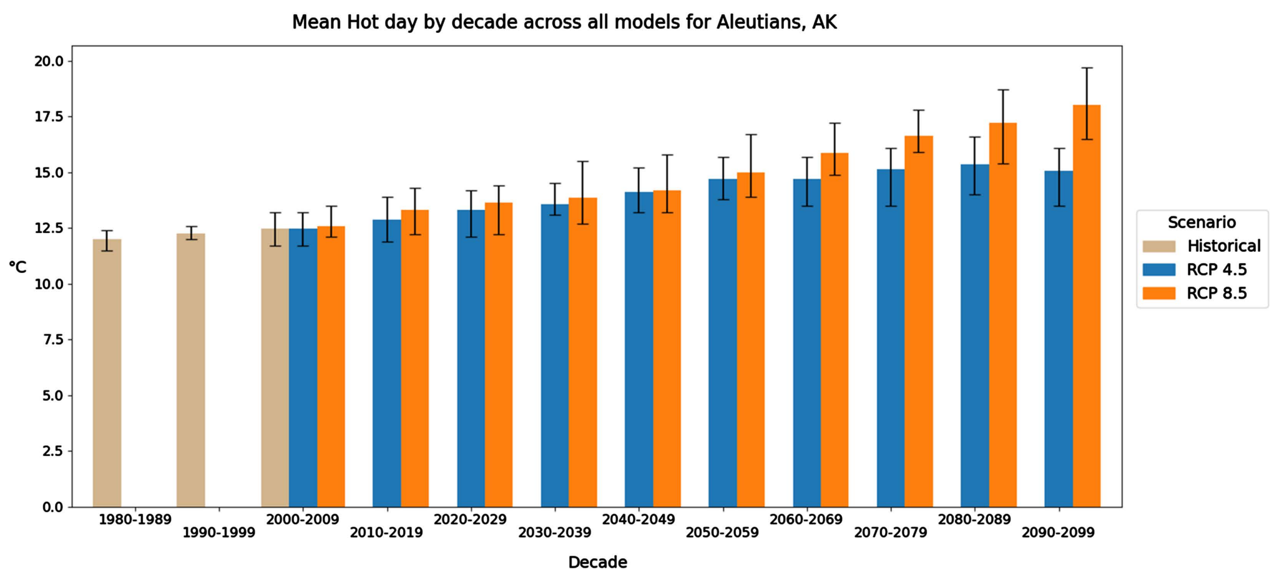

Figure 3. Decadal means of the HD (Hot Day) temperature thresholds (˚C) at Nelson Lagoon in the Aleutian region of Alaska. Results are shown for historical simulations (tan bars), RCP 4.5 projections (blue bars) and RCP 8.5 projections (orange bars). Whiskers denote across-model ranges.

Table 4. The extremes indicators evaluated from the CORDEX model output.

HD	"Hot Day" threshold	the highest observed daily Tmax such that there are 5 other observations equal to or higher than this value
CD	"Cold Day" threshold	the lowest observed daily Tmin such that there are 5 other observations equal to or lower than this value
SUD	Summer Days	Annual number of days with Tmax above 25˚C
DWD	Deep Winter Days	Annual number of days with Tmin below −30˚C
WSDI	Warm Spell Duration Index	Annual count of occurrences of at least 5 consecutive days with daily mean T above 90th percentile of historical values for the date
CSDI	Cold Spell Duration Index	Same as WDSI, but for daily mean T below 10th percentile
Rx1day	Maximum 1-day precipitation in a year	Largest single-day precipitation amount in a calendar year
Rx5day	Maximum 1-day precipitation in a year	Largest amount of precipitation over a period of five consecutive days in a calendar year
R10mm	Number of heavy precipitation days	Annual count of days with precipitation > 10 mm
CWD	Consecutive Wet Days	Annual count of days with precipitation > 10 mm
CDD	Consecutive Dry Days	Same as CWD, but for days with precipitation < 1 mm
HSD	Heavy Snow Days	The mean of the snow totals for the 5 snowiest days of a year
WNDD	Windy Days	Yearly number of days with mean wind speed > 10 m/sec

While the Hot Day threshold increases substantially, the corresponding upward trends in Cold Day (CD) thresholds are even more striking. **Figure 4** shows the decadal values of the CD index for Stevens Village in the Northeastern Interior of Alaska. In this case, the long-term (2080s-2090s) increase of the CD threshold is 9.5˚C under RCP 4.5 and a remarkable 14.2˚C under RCP 8.5. In the latter case, the Cold Day threshold undergoes a moderation from −38.2˚C to −24.0˚C. The increases under RCP 8.5 are even larger at 15.3˚C on the Southwest Coast (Levelock) and 15.4˚C in the Southwest Interior (Igiugik Village). The seven-site mean increases by the 2080s-2090s are 6.8˚C under RCP 4.5˚C and 12.2˚C under RCP 8.5. As with HD, the rate of increase decelerates sharply under RCP 4.5 in the second half of the 21st century while it shows a relatively steady increase throughout the century under RCP 8.5, as illustrated by the example in **Figure 4**.

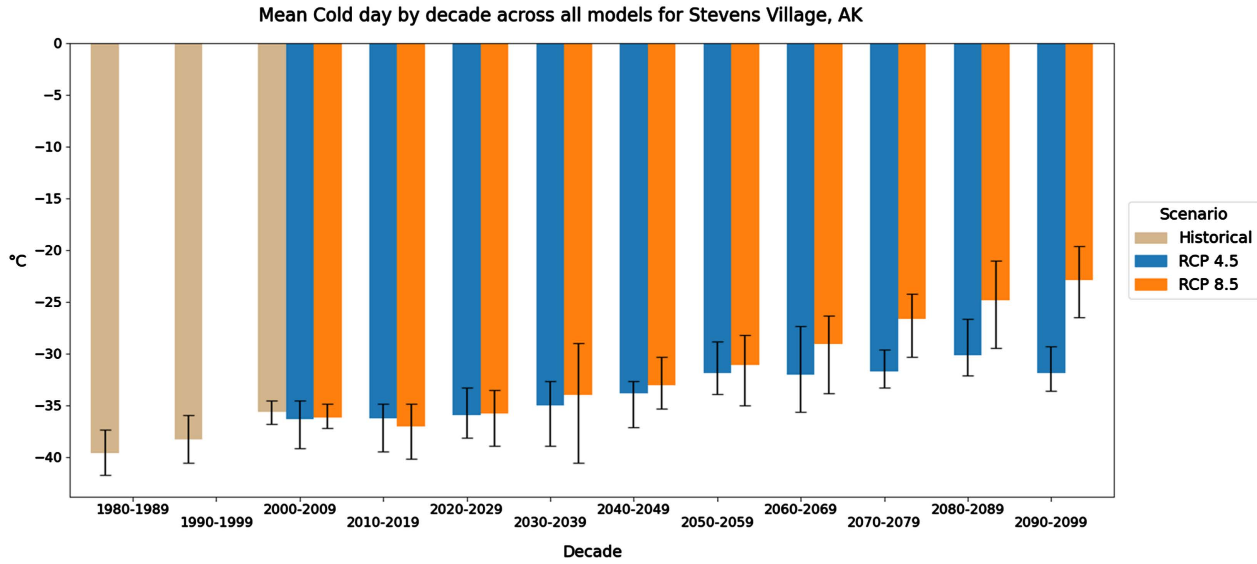

Figure 4. As in **Figure 3**, but for the CD (Cold Day) threshold (˚C) at Stevens Village in the Northern Interior of Alaska.

While **Figure 3** and **Figure 4** depict time-varying threshold temperatures, the metrics SUD (SUmmer Days) and DWD (Deep Winter Days) represent time-varying frequencies of occurrences of extreme warm (Tmax > 25˚C) and extreme cold (Tmin < −30˚C) days. Historically, only one of the seven locations that regularly experiences Summer Days is the Northeastern Interior community of Stevens Village, where typically about ten Summer Days per year occurred from the 1980s through the early 2000s. As shown in **Figure 5**, this number is projected to increase substantially by the late century to about 25 days per year under RCP 4.5 and about 40 days per year under RCP 8.5. The decade of signal emergence under both scenarios is the 2020s. Because 25˚C is approximately the temperature at which the interiors of buildings become uncomfortably warm and because few buildings in Interior Alaska have air conditioning, this change has implications for the comfort and health of village residents [30]. The cooler locations do not experience 25˚C Summer Days even under the RCP 8.5 scenario, although several locations (Southern Coast, Southwest Interior, Southwest Coast) are projected to experience several such days per year by the end of the 21st century under the RCP 8.5 scenario.

Corresponding to the increase in Summer Days is a precipitous decline in the number of DWD (Deep Winter Days) at all locations. **Figure 6** shows this decline for the Northern Coast community of Kaktovik, where the late-20th century value of about 25 days per year decreases to 1-to-2 days per year by the late 21st century under RCP 4.5 and to essentially zero under RCP 8.5. In this case, the decade of signal emergence is the 2010s. The only other site with more than 3 DWD per year in the historical period is Stevens Village in the Northeast Interior, where the annual number of DWD decreases from 26 days historically to about 8 days under RCP 4.5 and fewer than 2 under RCP 8.5 by 2080-2099. The more moderate coastal sites have no DWD occurrences in either the historical or the (projected) future period.

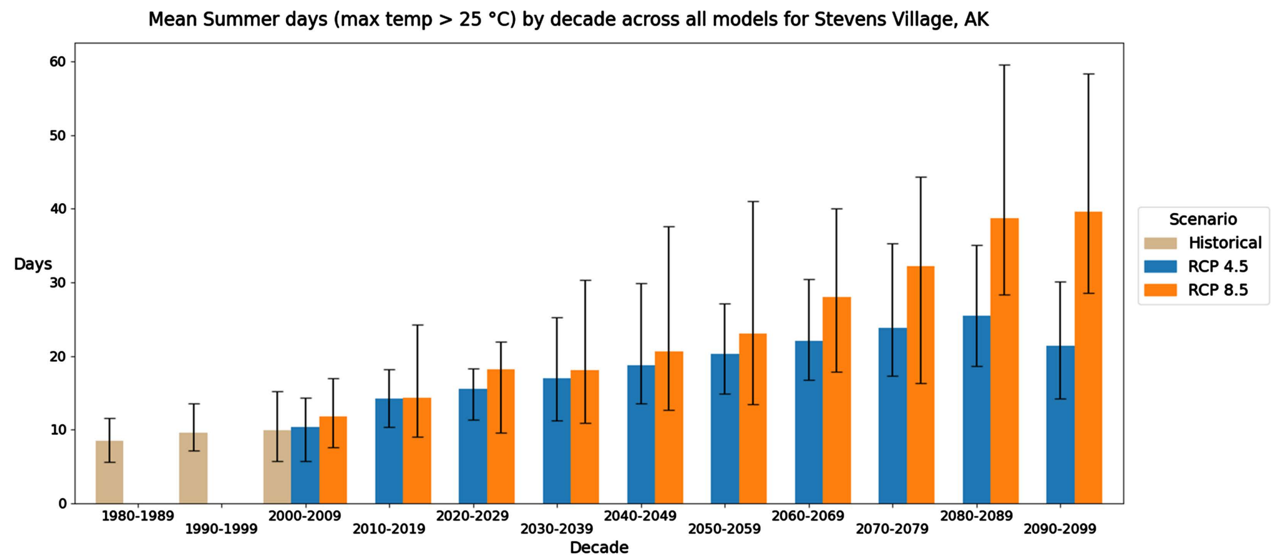

Figure 5. As in **Figure 3**, but for the SUD (SUmmer Days) index at Stevens Village in the Northern Interior of Alaska.

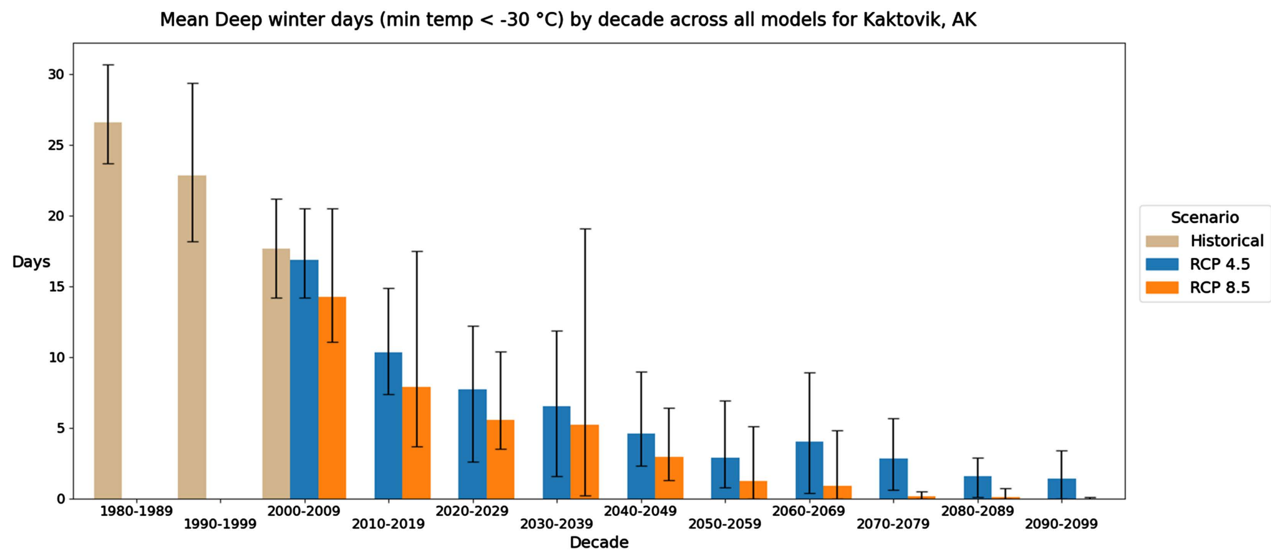

Figure 6. As in **Figure 3**, but for the DWD (Deep Winter Days) index at Kaktovik on Alaska's Northern Coast.

Of all the indicators considered here, the Warm Spell Duration Index (WDSI) undergoes some of the most striking changes. The increases by the late 21st century range from 43 to 224 days per year under RCP 4.5, and from 138 to 308 days per year under RCP 8.5. (Because this index is defined as the number of 5-day periods with temperatures in the historical upper 10 percentiles, there is overlap in the 5-day periods that are counted). These changes imply a large increase in the frequency of days with mean temperatures in the upper 10 percentiles of the historical distributions. The increases are largest in the Aleutians (Nelson Lagoon), where the maritime climate results in relatively narrow historical distributions of daily mean temperatures. **Figure 7** shows the sequence of decadal values for the Southern Coast location (Eyak), for which the changes are in the middle of the seven-region range. In this case, the decade of signal emergence is the 2020s, with values increasing from 10 in the historical period to approximately 100 by late century under RCP 4.5 and to more than 200 by late century under RCP 8.5. If the projections are correct, the majority of the days at Eyak will be within warm spells defined by the historical 5-day/10-percentile criterion by late century under RCP 8.5. The same is true for all the locations except the Northeastern Interior (Stevens Village).

The corresponding Cold Spell Duration Index (CSDI) shows similar tendencies in the opposite direction. In this case, the changes are large as percentages (ranging from 90% - 100% by late-century) but are smaller in terms of the number of days because the "floor" of zero occurrences is reached. The decade of signal emergence ranges from the 2010s to the 2050s, with the 2020s and 2040s the most common. Because the RCP 4.5 and RCP 8.5 scenarios do not diverge widely until after 2050, the decade of signal emergence is the same under the two scenarios at most of the sites. Collectively, the WSDI and CSDI results indicate that the warming will result in major changes in the tails of the distributions of the daily temperatures at all locations.

While the temperature indicators are generally projected to undergo major changes by the late 21st century, changes in precipitation are more modest but still strong enough to produce a signal by the criterion used here. The yearly maximum 1-day precipitation (Rx1day), for example, increases by 8% to 38% by late century under RCP 4.4 and by 25% to 55% under RCP 8.5. A representative example (Eyak on the South Coast) is shown in Figure 8. In this case, the signal emerges in the 2030s under RCP 8.5 and in the 2040s under RCP 4.5. As with the temperature metrics, there is little change after 2050 under RCP 4.5, but the increase continues to 2100 under RCP 8.5.

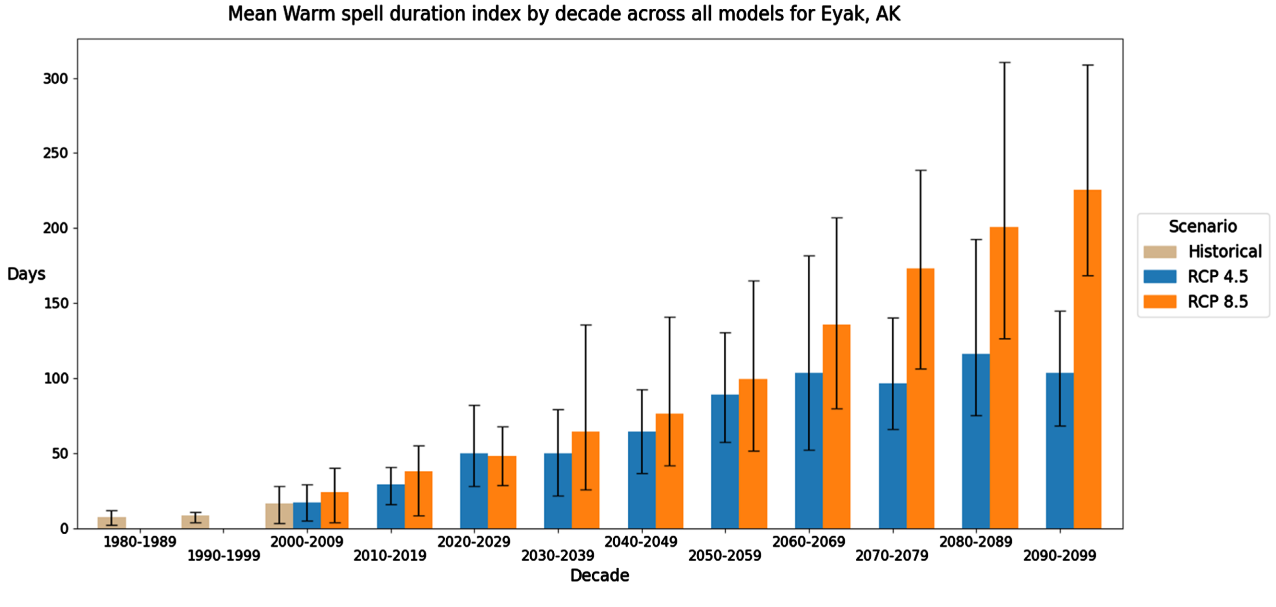

Figure 7. As in Figure 3, but for the WSDI (Warm Spell Duration Index) at the southern coastal location of Eyak.

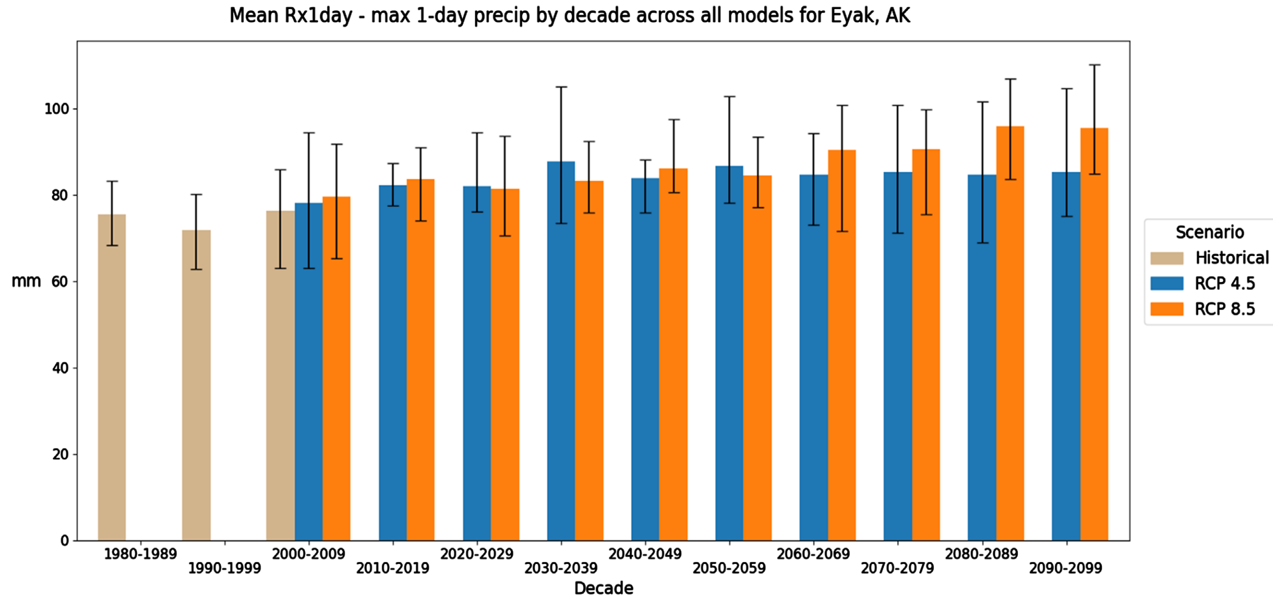

Figure 8. As in **Figure 3**, but for the Rx1day (yearly maximum 1-day precipitation) at the Southern Coast location of Eyak.

The yearly maximum 5-day precipitation (Rx5day) are quite similar to those of Rx1day. However, the increases in Rx5day are potentially more consequential because the actual historical amounts (and hence the increases) are much larger than for Rx1day, increasing the potential for increased runoff and flooding.

For the frequency of heavy precipitation events, R10mm is the more appropriate metric. All sites show increases in R10mm, although the percentage increases vary widely because the historical frequencies range from 2 and 4 days at the northern sites to 47 and 90 days at the southeastern and southern coastal sites. An example is shown in **Figure 9** for Stevens Village in the Northeast Interior. In this case, R10mm nearly doubles by late century under RCP 8.5 and increases by about 70% under RCP 4.5. The signal emergence in the 2030s (RCP 8.5) and 2040s (RCP 4.5) is typical of the other sites with the exception of Eyak (Southern Coast), where R10mm's historical value is already large at 90 days.

The two other precipitation indices, Consecutive Wet Days (CWD) and Consecutive Dry Days (CDD), show less coherent changes and, in most cases, do not show an emergent signal even by 2100. An exception is Kaktovik on the Northern Coast, where the CWD indicator increases by 17% under RCP 4.5% and 50% under RCP 8.5 (**Figure 10**). The corresponding decades of signal emergence are the 2070s and 2040s, respectively. The majority of the other CWD changes are positive and the majority of the CDD changes are negative, consistent with the background increase of precipitation, but even the late-century values for the other sites fall within the range of the historical variability.

The Heavy Snow Day (HSD) index shows a decrease at most of the sites, consistent with a transition of precipitation from snow to rain. However, HSD is a rather volatile metric because the historical amounts are small at most stations. Across-model variability is also large, as shown in the example for Kaktovik on the Northern Coast (Figure 11). Kaktovik shows a modest increase in the HSD metric, +11% under RCP 4.5 and +12% under RCP 8.5 by late-century, but the across-model variability precludes the emergence of a signal. The Northeast Interior location of Stevens Village also shows a slight increase. The tendency for heavy snowfall events to increase at the colder locations, while the warmer southern locations generally show decreases, agrees with the broader pattern of snowfall increases in cold Arctic locations and decreases in warmer subarctic locations [31]. For the sites examined here, the only signals to emerge by the across-model-range criterion are the decreases at the warmer southern locations (Eyak, Igiugik Village and Levelock).

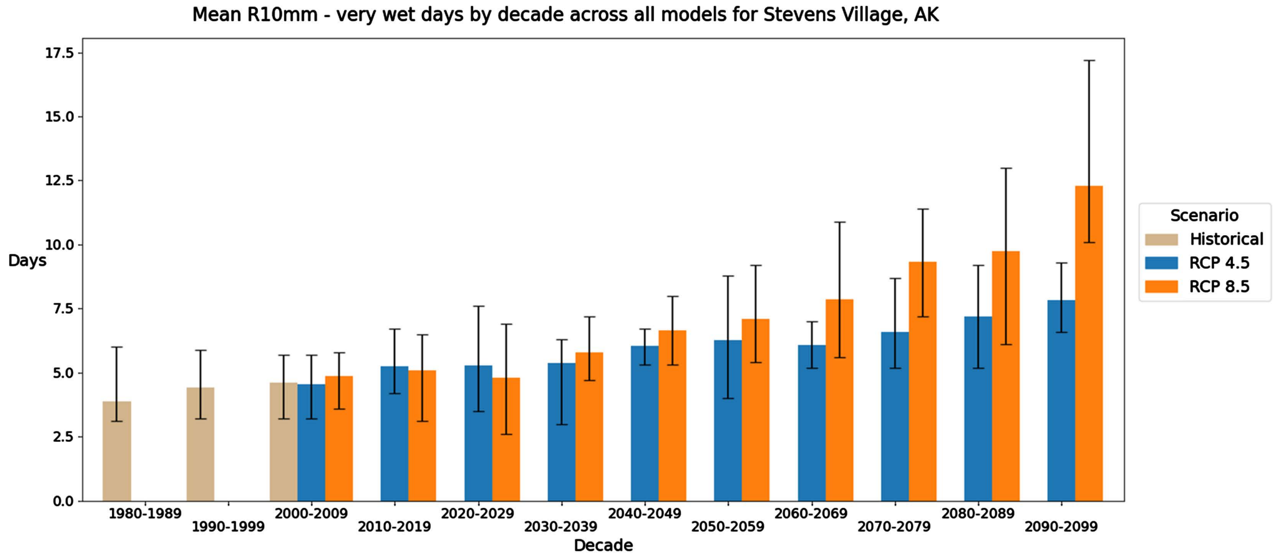

Figure 9. As in Figure 3, but for R10mm (number of very wet days) at the Northeastern Interior location of Stevens Village.

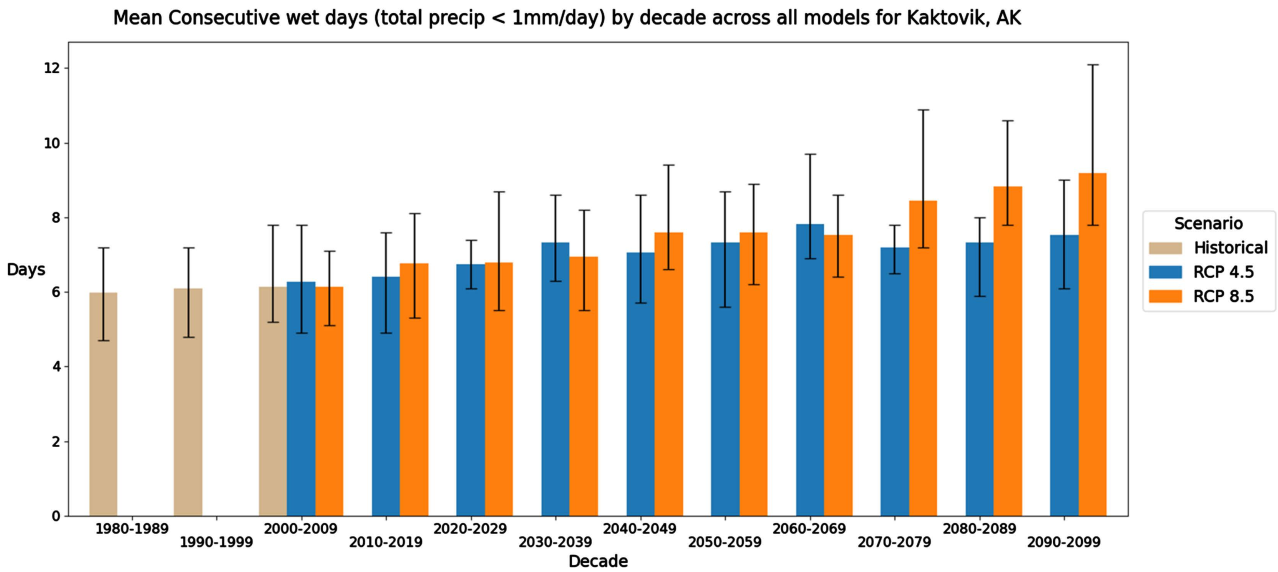

Figure 10. As in Figure 3, but for CWD (yearly maximum number of consecutive wet days) at the Northern Coastal location of Kaktovik.

The WNDD (Windy Days) indicator varies widely among the seven locations in the historical data, with historical values ranging from less than one day per year at Stevens Village and Eyak to 37 days on the Northern Coast (Kaktovik), 72 days in the Aleutians (Nelson Lagoon) and 82 days in the Southeast (Ketchikan). As with the Heavy Snow Days, the projected changes in Windy Days are mixed in sign and generally insignificant. Only the changes in the Aleutians (Nelson Lagoon) have an emergent signal (**Figure 12**), and even this signal does not emerge until the 2080s (RCP 8.5) and 2090s (RCP 4.5). On the Northern Coast, Kaktovik has increases of 14% (RCP 4.5) and 27% (RCP 8.5) by 2080-2099, although the across-model variability dominates the signal.

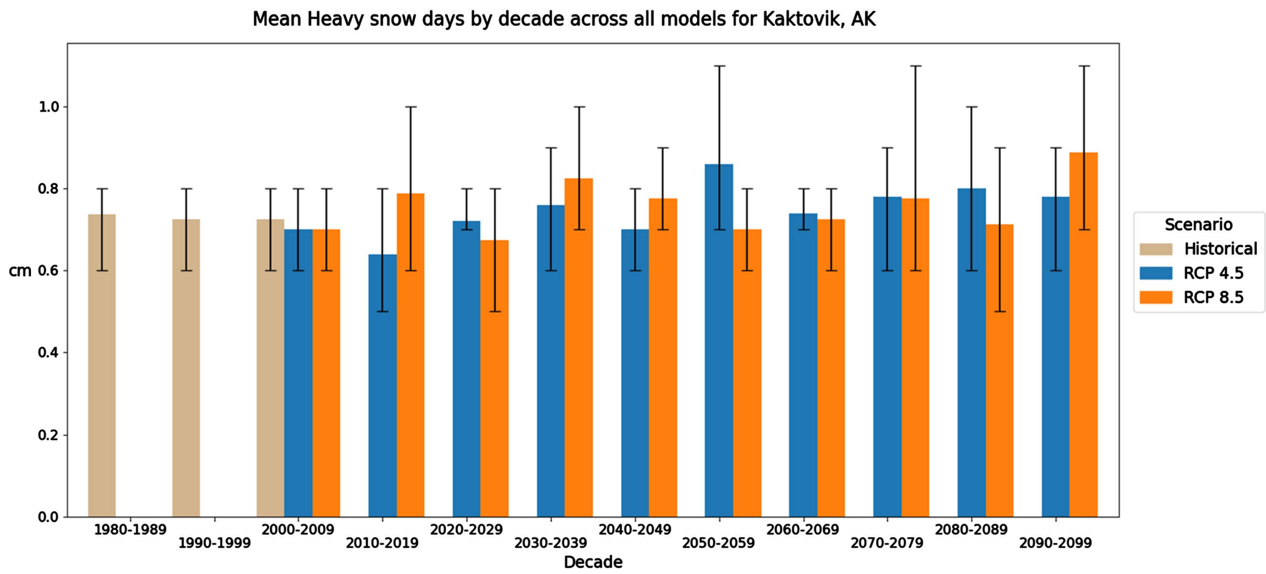

Figure 11. As in **Figure 3**, but for HSD (snowfall on Heavy Snow Days)) at the Northern Coast location of Kaktovik.

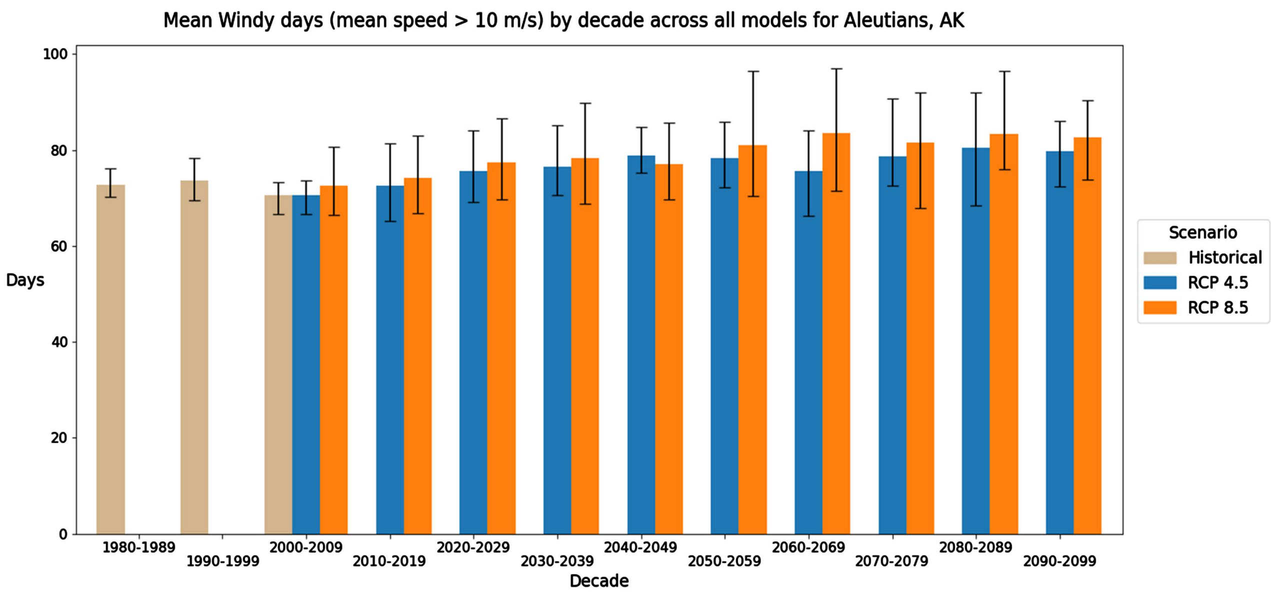

Figure 12. As in **Figure 3**, but for WNDD (annual number of Windy Days) in the Aleutians (Nelson Lagoon).

4. Discussion

The results in the preceding section show that Alaska's climate is on a trajectory towards substantial changes in extremes of temperature, consistent with a background warming that is occurring at a faster rate than in middle and lower latitudes [4] [5] [32] [33]. For most of the temperature indices, the change "signal", defined here as the first decade in which the across-model range no longer includes the historical mean, has already emerged or will emerge by mid-century. Changes in the occurrences of the outermost 10 percentiles of the temperature distributions are sufficiently large that the Warm Spell Duration Index and the Cold Spell Duration Index are both projected to undergo especially large changes by the end of the 21st century. By mid-century, the changes in the Cold Day temperature thresholds are notably larger than the projected changes in the mean temperatures in the CMIP6 model simulations. The projected changes mean temperature changes averaged over Alaska are approximately 4˚C under SSP2-4.5 and 6˚C under SSP5-8.5 (cf. Figure 3.5 in [5]).

The changes in extreme precipitation are also consistent with the increase in mean precipitation amounts associated with a warmer climate via the nonlinear increase in saturation vapor pressure. However, precipitation is known for its heterogeneous spatial distribution, especially during the warm season and in areas with significant topography, so it is not surprising that the increases in extreme precipitation do not present as strong a signal as the changes in extreme temperature. For the precipitation intensity thresholds (Rx1day, Rx5day) and heavy precipitation event frequencies (R10mm), the signals generally emerge in the mid-21st century, several decades later than the early-21st century emergence of many of the temperature indices. However, extreme precipitation events such as the heavier Rx5day events can be highly consequential for flooding in rural as well as urban communities. We also note that the Consecutive Wet and Dry Day indicators (CWD, CDD) generally show only small changes at most locations, implying that increased flood risk will be due to heavier events rather than prolonged events.

With regard to the changes in wind speed, it is notable that Nelson Lagoon and Kaktovik are coastal locations and therefore vulnerable to flooding and erosion from high-wind events. Moreover, the western and northern coasts are among the few regions of Alaska for which there are indications of increasing frequencies of high-wind events in the historical station reports [34]. More generally, future projections of storminess in the Arctic show a spatially heterogeneous pattern in the IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report (Figure 4.27a in [35]), although the Bering Sea is one of the few regions with a storminess increase projected by most (>80%) of the CMIP6 models summarized by the IPCC. However, even if storm activity does not change, surface wind speeds can be expected to increase in coastal areas where sea ice is lost because static stability and surface roughness are reduced over open water relative to sea ice [12] [36] [37].

The indices for heavy snow days (HSD) and high-wind days (WNDD) do not show systematic changes, although the results in Section 3 do include increases in heavy snow days at the more northern locations and increases in windy days at coastal locations. These changes of snowfall are potentially consequential for rural communities that rely on overland travel for subsistence and other activities, while the changes in high-wind events in coastal areas have serious implications for the frequency of coastal flooding and erosion events that are already threatening Alaska coastal communities.

For most of the projected changes discussed here, recent studies cited in Sections 1 and 3 provide evidence that the changes in the background variables are already apparent as trends in the means. Because changes in mean values will generally be associated with changes in the tails of distributions, the results obtained here provide specificity and added credibility to future expectations.

5. Conclusions

Extreme events are the most consequential manifestations of climate change, so the results imply that adaptation and mitigation will be increasingly required to respond to the risks posed by extreme events in regions such as Alaska. In this regard, it is especially notable that nearly all the extremes indicators continue to increase through 2100 under the higher-emission RCP 8.5 scenario, while they generally stabilize in the second half of the 21st century under the lower-emission RCP 4.5 scenario. The results presented here therefore provide further motivation for reductions in the emissions of greenhouse gases.

The results obtained here imply the need for proactive planning in anticipation of changes in extreme events, particularly those of temperature and precipitation. More frequent high temperatures and new thresholds of maximum temperatures will require measures to alleviate human discomfort during warm spells. Whether the response will be in the form of increased ventilation or air conditioning will depend on the baseline climate (e.g., warm at Stevens Village, cold at Kaktovik). A reduction of occurrences of extreme cold will change the vegetation hardiness zonation as well as the susceptibility to cold-sensitive invasive species. Shifts in vegetation zones will lead to ecosystem changes that impact wildlife and hydrology, which in turn will impact food and water security in remote villages such as those in this study. Perhaps the greatest risk is from flooding associated with increased frequencies of heavy precipitation events as well as unprecedented precipitation amounts in a short period. The placement of infrastructure and the design of drainage systems should take into account the likely increase of heavy precipitation events that are consistently apparent in climate model projections for many regions, including Alaska.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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