Earth-Science Reviews 209 (2020) 103324

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Extreme weather and climate events in northern areas: A review

John E. Walsh[a,*], Thomas J. Ballinger[a], Eugénie S. Euskirchen[b], Edward Hanna[c], Johanna Mård[d], James E. Overland[e], Helge Tangen[f], Timo Vihma[g,h]

[a] *International Arctic Research Center, University of Alaska, Fairbanks, Alaska, USA*
[b] *Institute of Arctic Biology, University of Alaska, Fairbanks, Alaska, USA*
[c] *School of Geography and Lincoln Center for Water and Planetary Health, University of Lincoln, Lincoln, UK*
[d] *Department of Earth Science, Uppsala University, Uppsala, Sweden*
[e] *NOAA Pacific Marine Environmental Laboratory, Seattle, Washington, USA*
[f] *Norwegian Meteorological Institute, Oslo, Norway*
[g] *Finnish Meteorological Institute, Helsinki, Finland*
[h] *The University Centre in Svalbard, Longyearbyen, Norway*

ARTICLE INFO

Keywords:
Climate
Weather
Extremes
Storms
Northern regions

ABSTRACT

The greatest impacts of climate change on ecosystems, wildlife and humans often arise from extreme events rather than changes in climatic means. Northern high latitudes, including the Arctic, experience a variety of climate-related extreme events, yet there has been little attempt to synthesize information on extreme events in this region. This review surveys work on various types of extreme events in northern high latitudes, addressing (1) the evidence for variations and changes based on analyses of recent historical data and (2) projected changes based primarily on studies utilizing global climate models. The survey of extreme weather and climate events includes temperature, precipitation, snow, freezing rain, atmospheric blocking, cyclones, and wind. The survey also includes cryospheric and biophysical impacts: sea ice rapid loss events, Greenland Ice Sheet melt, floods, drought, wildfire, coastal erosion, terrestrial ecosystems, and marine ecosystems. Temperature and sea ice rank at the high end of the spectra of evidence for change and confidence in future change, while drought, flooding and cyclones rank at the lower end. Research priorities identified on the basis of this review include greater use of high-resolution models and observing system enhancements that target extreme events. There is also a need for further work on attribution, impacts on ecosystems and humans, and thresholds or tipping points that may be triggered by extreme events in high latitudes.

1. Introduction

Extreme climate and weather events, especially changes in extremes, often have greater impacts on ecosystems (Ummenhofer & Meehl, 2017), infrastructure (Pregnolato et al., 2016) and humans (Curtis et al., 2017) than changes in climate averages. It follows that information on extreme events is needed by decision- and policy-makers charged with planning in various climate-sensitive sectors, especially if events previously considered extreme become increasingly routine in a changing climate (Landrum & Holland, 2020). While a general lack of studies of extreme events in the northern high latitudes has been noted in previous assessment reports (e.g., (AMAP, 2011)), such events have begun to receive attention by the research community. However, the studies to date of extreme events in northern regions are largely uncoordinated. The present paper represents a survey of recent work on extreme events in high northern latitudes as a step towards a synthesis and an identification of gaps and priorities.

There are linkages between the high latitudes and the rest of the global system, and these linkages may involve extreme events in lower latitudes. The subject of Arctic-midlatitude linkages is an active topic of research that has its own evolving literature (e.g., Cohen et al., 2020). The present review is distinguished by its focus on extreme climate and weather events in the Arctic and adjacent northern regions. We do not include the Antarctic in this review despite some parallels such as the prominence of the cryosphere and the relative absence of studies of extreme events in the Antarctic. We do, however, use recent global assessments of changes in extreme events (IPCC, 2012; IPCC, 2013; IPCC, 2019) to provide context for variations and trends in some of the types of extreme events addressed here.

While 2-5 years of sequential of extremes (sea ice, regional

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[*] Corresponding author at: International Arctic Research Center, University of Alaska, Fairbanks AK 99775, USA.
E-mail address: jewalsh@alaska.edu (J.E. Walsh).

https://doi.org/10.1016/j.earscirev.2020.103324
Received 25 December 2019; Received in revised form 15 July 2020; Accepted 6 August 2020

temperatures, precipitation) are not long enough to rule out the possibility of internal variability (Overland et al., 2012) and may be due to random events relative to a 40-year observational record, one is not sure how to interpret events that are beyond previous experience. Is it part of a previous climatology where observations have a Gaussian distribution, or a newly evolving one based on unique feedbacks that provide new outlying events (black swans)? The latter interpretation can be reinforced if the change is accompanied by additional information. For example, one can note supporting mechanisms such as sea ice/wind feedbacks and ecosystem shifts, and there may also be major concomitant changes in northern regions (Box et al., 2019). The changes surveyed here include various examples of concomitant changes in extreme weather and climate events.

From chaos theory, increases in extremes of both positive and negative values could be a precursor for change, especially if thresholds are inherent in a system. Rather than projecting a smooth trajectory for climate change in northern high latitudes over the next 50 years as often simulated in climate models (Bathiany et al., 2016; Cai et al., 2018), current conditions do not rule out a more rapid transition within the next decades (Landrum & Holland, 2020; Screen & Deser, 2019). The timing of abrupt transitions by their non-linear nature is impossible to predict; in this sense they are unknowable. Current multiple environmental signs imply that an abrupt high-latitude change may be more approachable compared to 30 years ago when thick sea ice provided a multi-year climate buffer to vigorous ocean-atmosphere interactions and large excursions from the mean.

In Section 2, we survey recent work on extremes of high-latitude temperature, precipitation, snow, freezing rain, atmospheric blocking, cyclones, and wind. Section 3 then surveys the impacts of these extreme events. The impacts include rapid losses of sea ice, Greenland Ice Sheet melt, flooding, drought, wildfire, coastal erosion, and terrestrial and marine ecosystems. While the extreme events in Section 2 are atmospheric, the impacts in Section 3 are not. For each topic, we review past work on historical trends and future projections. The historical reviews will be based primarily on observational studies (including those based on reanalysis products), while the survey of projected changes will draw primarily on model-based studies. The timescales of the extreme events will generally range from daily to annual. While daily-timescale events can be characterized as “weather” rather than climate, changes in climate can alter the characteristics (frequency, intensity, duration) of high-impact extreme weather events.

The spatial domain of this review is broadly defined as northern high latitudes. This domain includes the Arctic, for which there is no universal definition. Definitions of the Arctic range from the area north of the Arctic Circle (66.5°N) to the region poleward of the boreal forest to broader definitions that encompass the entirety of the watersheds of the major rivers draining into the Arctic Ocean. These watersheds extend equatorward of 45°N in some cases. Our choice of “northern high latitudes” is intended to include the Arctic and adjacent regions that are affected by the same weather systems, climate variations, and ocean anomalies. A key feature of the domain is the prominence of the cryosphere: sea ice, seasonal snow cover, perennially or seasonally frozen ground, and land ice. The latter includes the Greenland Ice Sheet.

This review addresses physical and ecological impacts of the various types of extreme events. However, it does not include economic or social impacts. An assessment of the socioeconomic implications of climate and weather in northern regions is an imminent activity of the Arctic Monitoring and Assessment Programme (AMAP) and its Climate Expert Group.

2. Recent and projected changes of extremes events in northern latitudes

While extreme values of a distribution of a weather or climate variable can be evaluated if the period of record and timescale (daily, monthly, yearly) are specified, the definition of extreme events is more problematic. The IPCC’s Special Report on extreme events and disasters defines an extreme event as “the occurrence of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends (tails) of the range of observed values of the variable ((IPCC, 2012), p. 111). Complicating factors in assessing extreme events are that impacts are often determined by the compounding of different types of extreme events or by the accumulations of a particular type of event, especially if impacts are related to threshold exceedances. The choice of thresholds in a distribution is somewhat arbitrary (e.g., two standard deviations, 99th percentile, or frequency of exceedances of a value such as 0°C, gale-force wind speed,…). A choice of thresholds based on impacts further complicates the definition of extreme events. A variety of such choices have been made in the published literature surveyed here. Accordingly, we retain a flexible definition of extreme events. Acknowledging that this approach introduces the risk of “apples vs. oranges” comparisons, we specify, when possible, the different criteria used in the wide variety of investigations summarized in this review.

2.1. Temperature

Several timescales of high-latitude temperature extremes can be distinguished, ranging from daily to monthly, seasonal and yearly. There is evidence that warm extremes are increasing on all of these timescales. At the longer end of the time range, the occurrence of extreme yearly temperatures is a striking indication of the impact of the background warming. For the land areas poleward of 60°N, the four warmest years since 1900 have been the most recent four years, 2016-2019 (Fig. 1). The two warmest years were 2016 and 2019. The spread between the high-latitude and global mean temperature departures from their 1981-2010 means was also greater in 2016 and 2019, indicating that these two years showed extremes of “Arctic Amplification”. According to the IPCC (IPCC, 2019), the record warmth of the high northern latitudes in 2016 would not have been possible without anthropogenic forcing (see also (Kam et al., 2018)).

Monthly and seasonal temperatures in northern regions have also set new records in the past several years. Alaska experienced its warmest spring of the post-1925 period of record in 2016, only to exceed that record in 2019 (https://www.ncdc.noaa.gov/cag/statewide/time-series). Alaska’s four warmest winters and two warmest autumns have occurred since 2000. Finland, Norway and Svalbard all recorded their warmest spring months on record in May of 2018; in all cases, periods of record extend back to approximately 1900 (Overland et al., 2018). The record heat continued into the summer of 2018, with many parts of Fennoscandia setting records for summer heat. Finland, for example, broke its record for the hottest July (and any calendar month) in 2018. Major heat waves over Europe in the summer of 2019 contributed to the advection of anomalously warm air over Greenland,

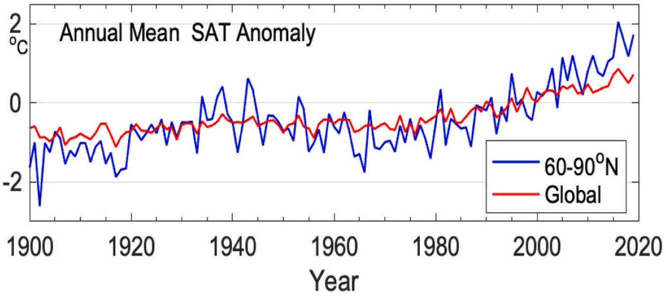

Fig. 1. Global (red line) and high-latitude (land stations north of 60° N; blue line) yearly land surface air temperature (SAT) anomalies (°C) for the period 1900-2019 relative to the 1981-2010 mean value. Source: NOAA (2019), based on CRUTEM4 dataset (www.cru.uea.ac.uk/cru/data/temperature/)

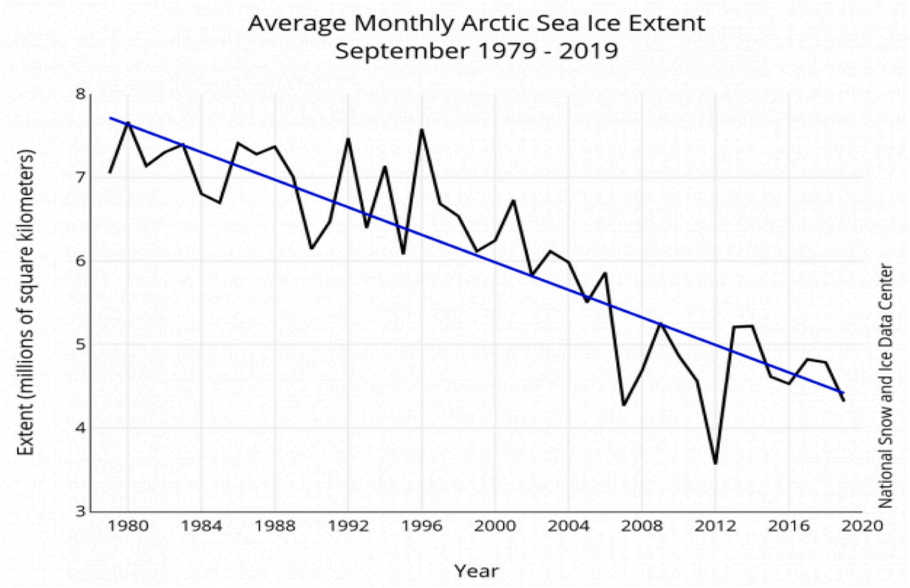

Fig. 2. September sea ice extent in the Arctic for each year, 1979-2019. Source: National Snow and Ice Data Center.

which experienced extreme summer melt discussed later in this review. The following winter of 2019-2020 was the warmest on record for Europe, northern Asia (especially Siberia) and Japan (https://public.wmo.int/en/media/news/europe-has-warmest-winter-record). Notably absent from the monthly and seasonal anomalies of the past several years are records for extreme cold.

While observational syntheses of monthly and seasonal temperature records in northern regions are generally lacking, there have been several evaluations of statistics of daily temperature extremes. In some cases these evaluations have made use of the indices developed by the World Climate Research Program's Expert Team on Climate Change Detection and Indices (ETCCDI), often referred to as the CLIMDEX (Climate Data Extremes) with processing enabled by the CLIMDEX analysis software (e.g., (Sillmann et al., 2013a)). Indices include exceedances of the 10th percentile and 90th percentile values of the daily high and low temperatures for a calendar month. Exceedances of these thresholds are termed "cold days" and "cold nights" (for the 10th-percentiles), and "warm days" and "warm nights" (for the 90th percentiles). Such metrics were mapped for land areas globally by the IPCC (2013, their Fig. 2.32), showing that there have been statistically significant changes since 1950 in all four metrics of extreme temperature over all northern land areas: occurrences of cold days and cold nights have decreased significantly, while occurrences of warm days and warm nights have increased significantly throughout the area. The actual magnitudes of the changes (days per decade) are larger for the night-time metrics, consistent with greater nighttime warming than daytime warming.

In a study focused on the Arctic, Graham et al. (2017) provide statistics of winter warming events over the central Arctic Ocean, where these events are associated with cyclone systems originating from the Atlantic and Pacific Oceans. The loss of winter sea ice reduces the over-ice trajectory of warmer maritime air during these events, favoring extreme winter warming such as the December 2015 event that raised temperatures above 0°C at the North Pole (Moore, 2016). Moore (2016) found that the frequencies of winter air temperatures above -5°C have been increasing by 4.25 days per decade in the North Pole region and by 1.16 days per decade in the Pacific sector of the Arctic Ocean. The same study also showed that the warmest midwinter temperatures at the North Pole have been increasing at twice the rate of warming of the mean midwinter temperatures near the Pole. A complementary synthesis of recent trends in daily temperature extremes over high-latitude land areas was performed by Matthes et al. (2015), who evaluated trends in extreme cold spells and extreme warm spells during winter and summer. The results showed widespread decreases in extreme cold spells over northern land areas during 1979-2013, although there were small areas of statistically significant increases in cold spells in Siberia. Long cold spells (cold events lasting more than 15 days) have almost completely disappeared since 2000. Similarly, the Northern Hemisphere's coldest airmasses, which are generally found over the far northern land areas, have shown a significant moderation over the past six decades (Kanno et al., 2019). This warming of the coldest airmasses is consistent with Screen et al.'s (2015a) model-derived conclusion that warming of Arctic airmasses will ultimately outweigh the effects of changes in the frequency of cold air outbreaks, thereby reducing the risks of cold extremes in middle latitudes of North America beyond the next few decades.

A more recent study of the CLIMDEX metrics over the 1979-2015 period partitioned the changes for the winter months into four northern subregions: Northwest Eurasia, Northeast Eurasia, Alaska, and Canada (Siu et al., 2017). While the trends were not statistically significant for all metrics in all subregions, the Canadian sector showed especially large and statistically significant decreases in cold nights and cold days, while Northwest Eurasia showed especially large and statistically significant increases in warm nights and warm days. The annual occurrences of both cold nights and cold days was found to have decreased by at least 30 days over the 37-year study period in all four subregions. Significant abrupt changes were identified in cold nights over Canada (in 1998) and in warm nights over northwestern Eurasia (in 1988). An analysis of data for Svalbard over the 1975-2014 period showed that all four extreme temperature metrics (cold days, cold nights, warm days, warm nights) show trends consistent with the background warming in both winter and summer (Wei et al., 2016). For the Alaska region, several studies show that new high temperature records are occurring far more frequently than new low temperature records on both daily and monthly time scales (Bieniek & Walsh, 2017; Thoman & Walsh, 2019). However, winter cold extremes in Alaska are decreasing much more rapidly than summer warm extremes are increasing (Sulikowska et al., 2019).

The changes in the extreme temperatures summarized above are consistent with a background warming together with the internal variability of the atmospheric circulation. Siu et al. (2017), for example, found that reduced sea ice extent associated with atmospheric warming has contributed to the decrease in the number of cold days and cold nights, especially during autumn. However, the abrupt changes noted above were associated with increased frequencies of south winds and warm advection, which are known to have contributed to extreme warming events in the central Arctic Ocean in recent years (Overland et al., 2018). Internal variability plays a role in at least the timing of these events. Similarly, Walsh et al. (2017) showed that the record warmth of the 2015-16 winter in Alaska was attributable to a combination of atmospheric circulation anomalies and the background warming.

Observations suggest that the Polar Front jet stream has become more meandering during recent decades (Cattiaux et al., 2016; Vavrus et al., 2017). This favors the occurrence of meridional circulation patterns with strong poleward transport of heat and moisture, resulting in warm extremes in high northern latitudes (Messori et al., 2018; Vihma, 2017). Among others, Overland et al. (2014) concluded that a high-amplitude jet stream was responsible for the warm extremes of the 2014 winter in Alaska. Also, the extremely high air temperatures at the North Pole in December 2015 were associated with a strongly meandering jet stream (Moore, 2016). These events are often associated with atmospheric blocking, which is discussed in Section 2.5.

Consistent with the ongoing and projected high-latitude warming, climate models project changes in extreme temperature occurrences over northern land areas. By 2081-2100 under the RCP 8.5 scenario, the coldest daily minimum temperature of the year is projected to be 10-12°C warmer than during the 1980-2000 reference period, while the highest daily maximum temperature of the year is projected to be 5-7°C warmer during 2081-2100 than during 1980-2000 ((Collins et al., 2013), their Fig. 12.13). This seasonality conforms to the broader global pattern in which extreme minimum temperatures are projected to increase more than extreme maximum temperatures (Sillmann et al., 2013b). Saha et al. (2006) highlight this asymmetric increase of minimum relative to maximum temperatures in the projected warming for the Eurasian subarctic, while Bennett and Walsh (2015) and Lader et al. (2017) do so for Alaska in the North American subarctic.

According to Screen et al. (2015b), the increase in new extremes of maximum temperature and the decrease in new extremes of minimum temperatures is driven by the background global warming but amplified by the loss of sea ice in the Arctic. The sea-ice-driven changes in projected temperature extremes are especially large in the North American sector ((Screen et al., 2015a,b), their Fig. 3). In addition to the effects of sea ice loss, the changes in the occurrence of temperature extremes in northern areas are also affected by all other factors that contribute to the amplified Arctic warming. These include the lapse rate and Planck feedbacks (Pithan & Mauritsen, 2014), cloud feedback (Graversen & Wang, 2009), and snow/ice albedo feedback (Flanner et al., 2011).

2.2. Precipitation

The assessment of trends in extremes of precipitation in northern high latitudes regions presents challenges because (a) precipitation amounts often vary substantially over small scales, especially in the warm season, (b) the precipitation gauge network in high latitudes is sparse and biased towards low elevations, and (c) gauge undercatch is known to be a problem in cold windy environments (Yang et al., 2005). Partly for these reasons, model-based studies, including atmospheric reanalyses, have played a greater role in evaluations of trends of Arctic precipitation and their extremes. However, studies based on atmospheric reanalyses include major uncertainties, as estimates of Arctic precipitation may differ by more than 50% between various reanalyses (Boisvert et al., 2018). Assessments of trends in extreme precipitation in northern high latitudes regions are further complicated by the use of several different metrics to quantify precipitation extremes (Vihma et al., 2016).

In an early evaluation of changes in intense precipitation, Groisman et al. (2005) showed that the northern land areas were among the regions in which there had been disproportionate changes in heavy precipitation relative to changes in annual and seasonal mean precipitation. On the other hand, station data show no significant trends in annual daily maximum 1-day and 5-day precipitation amounts over northern land areas during the second half of the 20th century ((Min et al., 2011), their Fig. 1). For the 2000-2016 period, Boisvert et al. (2018) surveyed total precipitation in the Central Arctic in eight atmospheric reanalyses and noted significant increasing trends (1.4 – 8.2 mm yr^{-1}) in just three of the products. The most recent IPCC report (AR5) presented global land surface maps of trends of heavy precipitation. The number of days when precipitation exceeded the 95th percentile (R95p) showed significant increases over Finland and northwestern Russia, but inadequacies in the station data precluded assessments in other high-latitude regions (Hartmann et al., 2013). Increases in daily precipitation intensity were statistically significant over a much larger area of the subarctic, including northeastern Canada and much of northern Russia as well as Finland and northern Sweden.

On a regional basis, the number of days with heavy precipitation has shown significant increasing trends in large parts of the northern land area (Alexander et al., 2006; Borzenkova & Shmakin, 2012; Donat et al., 2013; Vincent & Mekis, 2006) but decreasing trends in western Canada (Alexander et al., 2006). Daily precipitation intensity has increased in northern Canada (Donat et al., 2013; Peterson et al., 2008; Vincent & Mekis, 2006) and Eurasia (Donat et al., 2013) but decreased in southern Canada (Donat et al., 2013; Peterson et al., 2008; Vincent & Mekis, 2006) and coastal northern Russia (Donat et al., 2013). Extreme precipitation events were found to show no systematic temporal trend at Svalbard from 1979 through the early 2000s (Serreze et al., 2015), and there is similarly no trend in heavy precipitation events in Alaskan station data over 1949-2012 (Bieniek & Walsh, 2017). Lader et al. (2017) also evaluated the frequency of extreme precipitation days in Alaska using both station data and five different atmospheric reanalyses; no notable trends were found over the 1979-2009 period ((Lader et al., 2017), their Fig. 10). On the other hand, the most recent U.S. National Climate Assessment shows that the percentage of precipitation falling in the heaviest percentile of precipitation events over Alaska increased by 11% during the 1958-2012 period, although the trend is not statistically significant ((USGCRP, 2014), their Fig. 2.17). The regional trends reported above are very sensitive to the study period.

In contrast to the general lack of observational evidence for spatially coherent trends in extreme precipitation over northern high latitudes, projections of high-latitude precipitation point to increased intensities and/or shorter return periods for heavy precipitation events. When expressed as percentage changes, the heaviest precipitation amounts generally increases more than the annual mean precipitation (Kharin et al., 2013). The CMIP5 models project increases of 20-30% for the maximum 5-day precipitation amounts within a year over most northern land areas by 2081-2100 under the RCP 8.5 scenario ((Collins et al., 2013), p. 1083-1086). These increases are consistent with projections for much of the Northern Hemisphere and with the 7% increase of saturation vapor pressure per °C of warming (Clausius-Clapeyron equation).

As far back as the CMIP3 era, regional climate models projected more frequent and more intense precipitation events in the Eurasian subarctic under climate warming (Saha et al., 2006). Bennett and Walsh (2015) found an increase in the heaviest monthly and seasonal precipitation occurring over Alaska in CMIP5 global model projections through 2100. More recently, Kusunoki et al. (2015) examined changes in precipitation intensity projected for the Arctic by a high-resolution (60 km) global climate model. Monotonic increases in the late 21st century were found in the Arctic's (67.5-90°N) annual mean precipitation, a daily precipitation intensity index, and maximum 5-day precipitation totals (R5d) averaged over the Arctic. However, a precipitation efficiency metric (conversion of water vapor to precipitation per °C of warming) changed less for extreme precipitation (R5d) than for average precipitation, in contrast to mid-latitude and tropical regions. Kusunoki et al. (2015) attributed the increase of extreme precipitation events primarily to reinforced penetration of transient cyclones far into the Arctic. However, the link between the moisture transport and precipitation is not necessarily straightforward (Gimeno-Sotelo et al., 2018).

An aggregation of results from eight selected CMIP5 models suggests that the 50-year return level of daily precipitation will increase in high latitudes (Toreti et al., 2013). The regions with consistent results from the eight models include northern Eurasia in winter and the Arctic Ocean in summer. Based on the CMIP5 results, increases are also projected for the 20-year return level of daily precipitation in northern high latitudes, particularly in winter (Kharin et al., 2013). Very-wet-day precipitation, maximum 5-day precipitation, and the number of days with heavy precipitation are also projected to increase (Sillmann et al., 2013b).

In addition to changes in the return periods and intensities of precipitation events of various thresholds, changes of phase of precipitation present challenges in the northern high latitudes. Freezing rain is a high-impact weather phenomenon in northern regions, and its trends and changes are discussed in Section 2.4. More generally, changes associated with the transition from snow to rain in a warming climate can shorten the snow season to the extent that snow season lengths previously considered extremely short may become the norm in the future. Landrum and Holland (2020) show that, while a statistically significant signal of this change from snow to rain has not yet emerged in the Arctic, it is likely to emerge in the mid-to-late 21st Century and impact the hydrologic regime of the Arctic.

2.3. Snow

Several recent studies have documented variations in the extent and duration of snow cover in the northern high latitudes (Brown et al., 2017; Mudryk et al., 2019). The variations and trends identified in these studies provide a backdrop for the occurrence of extreme events. Consistent with the recent climate warming, there is a general trend towards a shorter snow season and reduced snow extent, especially in the spring months of April-June. Post-1967 decreases of snow extent during May and June are apparent over the northern land areas of both North America and Eurasia ((Mudryk et al., 2019), their Fig. 5.19). New extremes of negative anomalies have occurred in both regions in the past several years. An important caveat is that interannual variability is large, and the April snow extent over Eurasia was actually a new extreme maximum in 2019 (Mudryk et al., 2020).

The general decreases of snow extent and duration are projected to continue through the remainder of the 21st century across much of the northern land areas (Brown et al., 2017; Landrum & Holland, 2020), consistent with larger fractions of winter precipitation falling as rain as climate warms. However, increases of snowfall are projected for the northernmost areas, where subfreezing conditions predominate during winter even under warming scenarios (Krasting et al., 2013). Similarly, the annual maximum snow water equivalent is projected to increase over much of northeastern Asia and northern Canada ((Brown et al., 2017), Fig. 3.18), even under the RCP 8.5 scenario, pointing to a likely increase of heavy snow events during the shortened cold season. The increase in heavy snowfalls near the Arctic Ocean should be enhanced by the increased fluxes of latent and sensible heat resulting from the reduction of the sea ice cover (Liu et al., 2012). The combination of a shorter snow season but greater water equivalents is consistent with O'Gorman's (2014) conclusion that, for the coldest climates, the occurrence of extreme snowfalls should increase with warming due to increasing atmospheric water vapor, while for warmer climates it should decrease because subfreezing temperatures will be less frequent.

Few studies have addressed extreme events of snowfall or other snow metrics in the northern high latitudes or other regions (NAS, 2016). Among the exceptions are several studies documenting the impacts of aggregate snowfall events that have impacted wildlife populations (Schmidt et al., 2019). While this study demonstrates negative impacts of heavy snow events on wildlife, other environmental factors (e.g., icing, temperature, vegetative disturbance by fire and insects) as well as population density can also be major determinants of the impacts.

2.4. Freezing rain

A type of extreme event with major impacts in northern areas is freezing rain, often referred to as rain-on-snow events. Because ice layers can persist for weeks or even months in the Arctic, freezing rain is a major hazard to surface transportation and to foraging wildlife (Hansen et al., 2011) and it may also increase the risk of avalanches (Conway & Raymond, 1993). Examples of impacts of freezing rain on wildlife populations are presented in Section 3.7 (Terrestrial Ecosystems).

In one of the few systematic evaluations of freezing rain occurrences, Groisman et al. (2016) show that freezing rain frequencies in northern North America increased by about one day per year in the 2005-2014 decade relative to the three previous decades. Substantial increases were detected over northern Norway, while somewhat less coherent patterns of increase were found over Siberia and European Russia. A similar hemispheric-scale analysis by Cohen et al. (2015) based on two atmospheric reanalysis products (MERRA and ERA-Interim) showed little coherence in winter trends of rain-on-snow events on the continental scale, although the MERRA reanalysis showed decreases in frequency during autumn and winter over western Scandinavia and southwestern Alaska. Cohen et al.'s noted decrease over Norway contrasts with Groisman et al.'s (2016) results, pointing to the challenges in identifying freezing rain events in reanalysis products as well as to the potentially important distinction between freezing rain events documented by Groisman et al. (2016) and rain-on-snow events documented by Cohen et al. (2015). Focusing on Svalbard, Peeters et al. (2019) found that, in Ny Ålesund (data since 1969) and Svalbard Airport (data since 1957), every third to fourth winter during the earlier decades was essentially rain-free, but in 1998 the climatic regime shifted so that some rain occurred in virtually every winter.

With regard to future changes, Hansen et al. (2014) examined the temperature-dependence of historical freezing rain events in Svalbard and concluded that the frequency of rain-on-snow events is likely to increase in northern regions. On the basis of output from 37 CMIP5 (Coupled Model Intercomparison Project, phase 5) climate models, Bintanja and Andry (2017) calculated that during this century in the Arctic (70-90°N), the average annual snowfall will decrease but rain will increase. The increase of rain will be strongest in summer and autumn but will also occur in winter, which will result in increasing occurrence of rain on snow events. On the basis of regional climate model simulations, Bieniek et al. (2018) showed that rain-on-snow events are projected to increase in frequency over much of Alaska but are expected to decline over southwestern/southern Alaska. The increases in frequency are the result of more frequent winter rainfall, while the decrease of freezing rain in southwestern Alaska is attributable to the rise of temperatures above the freezing threshold. Based on associations derived from remote sensing products over a shorter period (2003-2016), Pan et al. (2018) also concluded that rain-on-snow events will increase in frequency and extent over much of Alaska in the future. This increase is consistent with a broader projected increase of 40% in the total hemispheric rain-on-snow area by 2080-2089 (Rennert et al., 2008).

2.5. Atmospheric blocking

High-latitude blocking often represents persistent, quasi-stationary anticyclonic conditions that divert the zonal path of the polar jet steam equatorward and tend to yield more meridional transport of storms into and out of the northern high latitudes (Woollings et al., 2018). As with analyses of high-latitude storminess (see ***Cyclones***, Section 2.6), there are varied findings related to blocking trends. Blocking variability and temporal changes have been shown to be sensitive to the definition and index applied (Woollings et al., 2018) and to the time period of analysis (Barnes et al., 2014). Using three distinct blocking indices, Barnes et al. (2014) did not find increases in Northern Hemispheric blocking frequency at the seasonal scale over the 1980/1990-2012 period(s). However, the authors noted substantial spatiotemporal variability and an increasing summer (JJA) regional trend over 1980-2012 in the North Atlantic sector blocking based on an index identifying persistent 500 hPa geopotential height reversals. Davini et al. (2012) found a decreasing trend in winter (DJF) blocking events over 1951-2010, including over the Canadian Archipelago and northern Siberia, while Luo et al. (2019) found increases in winter high-latitude European and Ural blocking events from 1979-2015 under low (versus high) sea ice conditions. Yao et al. (2018) similarly applied a composite framework and found statistically significant increases in Greenland, Ural, western Pacific, and eastern Pacific blocking based on low versus high marginal sea ice conditions proximate to regions of anticyclonic circulation anomalies.

Regional metrics and assessments have been developed for blocking hotspots using domain-averaged geopotential height fields, including for sectors centered on Greenland, (e.g., (e.g., Hanna et al., 2016; McLeod & Mote, 2016) and Alaska (McLeod et al., 2018). McLeod et al. (2018) identified statistically significant increases in Alaskan Blocking Index (ABI) values over annual and summer periods during 1981-2010. During summer, composite differences of summer ABI extremes (i.e. high “minus” low values) revealed two-meter air temperature anomalies of at least 1-2°C (2-3°C) across the central and north (northwest) areas of Alaska and negative sea ice anomalies in the nearby Chukchi and Beaufort Seas. Downstream, Hanna et al. (2016) constructed a long-term (1851-2015) Greenland Blocking Index (GBI) and found a statistically significant increase in the index across all seasons, most notably a trend during summer from 1981-2010 that exceeded changes in previous epochs. In complementary daily analyses, Hanna et al. (2018a) noted that the number of GBI days exceeding 1 and 2 standard deviations from the mean had increased since 1990 during summer, winter, and on the annual time scale. Remarkably, over the aforementioned time period, there was a statistically significant increase of about 43 days in the annual number of days with GBI values > 1; this trend reflects a clear change toward increasing frequency of northwest Atlantic extreme high-pressure patterns with consequences for the region’s cryosphere (see ***Greenland Ice Sheet,*** Section 3.2). Assessing 7-year periods since 1958, McLeod and Mote (2016) found a consistent increase in the annual number of Greenland extreme blocking days from 1986-1992 to 2007-2013, with an increase in blocking duration as well as frequency over the recent period of accelerating high-latitude change.

Despite historical changes in high-latitude blocking characteristics, atmosphere (e.g. AMIP) and coupled (e.g. CMIP) climate model simulations have generally failed to capture such changes. Relative to previous generations of coupled models, Davini and D’Andrea (2016) noted improvement for the winter season in the CMIP5 ensemble mean in depicting retrospective Pacific blocking frequency, but little advancement for the Greenland region. For summer, Hanna et al. (2018b) similarly found that all CMIP5 models, under RCP4.5 and RCP8.5 scenarios, greatly underestimated the observed magnitude of Greenland blocking increases over the 1996-2015 period. Comparing twenty-first and twentieth century differences in the CMIP5 multimodel mean, Masato et al. (2013) found an increase (decrease) in West Arctic (Greenland) blocking in winter and a strong decrease in summer frequency across both regions. Given global climate model shortcomings in capturing recently observed high-latitude blocking frequency and intensity changes, future projections must be interpreted with caution.

2.6. *Cyclones*

Analyses of observational data have produced mixed results on trends of high-latitude cyclones and storminess. Several studies, mostly based on atmospheric reanalyses and cyclone detection algorithms, have indicated increased cyclone activity in the northern high latitudes. Zhang et al. (Zhang et al., 2004) found an increase of cyclone activity in the circumpolar Arctic and subarctic during 1948-2002. Trigo (2006), Zhang et al. (2004), Sorteberg and Walsh (2008), and Sepp and Jaagus (2011) detected an increase in the number of cyclones entering the Arctic. Sepp and Jaagus (2011) noted that during 1948-2002 the increase in cyclones entering the high latitudes was strongest in the Pacific sector, but there was no increase in cyclogenesis north of 68^{o}N. Increases in Arctic cyclone activity were also detected by Rudeva and Simmonds (2015) for the period 1979-2013 and by Zahn et al. (2018) for the period 1981-2010. Rinke et al. (2017) found that the frequency of extreme cyclone events in the subarctic North Atlantic has increased at a rate of 6 events per decade over 1979-2015. This trend is dominated by large increases in November and December, consistent with a diminished sea ice cover (Moore, 2016) and changes in atmospheric blocking patterns in the North Atlantic sector (Section 2.5). For the period 1979-2016, Wickström et al. (2019) detected an increase in the occurrence of winter (DJF) cyclones around Svalbard and the northwestern Barents Sea, while Koyama et al. (2017) reported an increase in the occurrence of extreme cyclones in the Svalbard region.

In most of the above-mentioned studies, the increase in high-latitude cyclone activity has been associated with a northward shift of storm tracks. In addition, McCabe et al. (2001) reported such a shift over the Northern Hemisphere during the last several decades of the 20th century. Wang et al. (2006) detected a northward shift of cyclone activity, primarily during winter, over Canada during 1953–2002, and this meridional shift was confirmed more generally in a more recent study by the same group (Wang et al., 2013). The Third U.S. National Climate Assessment (USGCRP, 2014) points to a poleward shift of storm tracks over North America during recent decades. Further, Tamarin-Brodsky and Kaspi (2017) suggested that cyclones propagate further north under externally forced (anthropogenic) climate change.

In contrast to the findings summarized above, other studies suggest little or no increase in cyclone activity. Mesquita et al. (2010) found that temporal trends of cyclones in the North Pacific Ocean have generally been weak over the 60-year period ending 2008. Walsh et al. (2011a; 2011b) concluded that storminess had increased in parts of the North American Arctic since 1960s, but not in the circumpolar Arctic as an average. Koyama et al. (2017) detected an increase in baroclinicity in the northern high latitudes but not in the occurrence of cyclones except for extreme cyclones in the Svalbard region (see above). In contrast to their results for the Svalbard region, Wickström et al. (2019) detected a decrease in cyclone occurrence in the southeastern Barents Sea during 1979-2016, associated with an increase in the Scandinavian blocking pattern.

The most comprehensive model-based assessment of Arctic cyclone activity is Akperov et al.'s (2018) evaluation based on ensembles of reanalyses and regional Arctic model simulations. Akperov et al. defined the Arctic as 65-90°N. Over the historical period, neither the reanalyses nor the models showed consistent historical changes of cyclone frequency, although the reanalyses showed significant winter increases and summer decreases in the frequency of deep cyclones. Trends in cyclone intensity and size showed a similar seasonality. The regional models generally did not capture these significant trends. Consistent with Akperov et al.’s results, Vessey et al. (2020) found no trend in storms travelling north of 65°N during 1980-2017.

The discrepancies among the above-mentioned findings may arise in part from differences in the cyclone tracking algorithms applied, especially with respect to the choice of sea level pressure or 850 hPa vorticity as the key metric (Vessey et al., 2020). Some papers have focused on changes in storm activity, excluding the weak and moderate cyclones. We should keep in mind that the trends may also be affected by changes in the availability of *in situ* and remote sensing data.

Some of the most intense high-latitude cyclones are mesoscale low pressure systems, often referred to as “polar lows” (Rasmussen & Turner, 2009; Kolstad, 2011; Stoll et al., 2018). While they can occur in all subpolar seas when cold air flows over open water equatorward of the sea ice edge, they are most common in the high latitudes of the North Atlantic, especially the Nordic Seas (Noer et al., 2011; Rojo et al., 2019). Global reanalyses and climate models generally lack the spatial resolution to capture these mesoscale systems. Condron et al. (2006) and Condron and Renfrew (2013) have shown that this under-representation is especially problematic in the subarctic North Atlantic. Because of the difficulties in resolving polar lows and documenting their occurrences, there is little available pan-Arctic information on historical trends or projections of future changes in polar low activity. In regional studies, Zahn and von Storch (2008) found little evidence of historical trends in North Atlantic polar lows, while Zahn and von Storch (2010) found that the frequency of occurrence of polar lows in the North Atlantic is projected to decrease because of a projected increase of the static stability of the air over the North Atlantic. Further, using marine cold-air outbreaks as a proxy for the occurrence of polar lows, Kolstad and Bracegirdle (2008) projected a northward migration of polar lows, following the retreating sea ice margin.

With regard to future changes in high-latitude cyclones, the published literature does not reveal a consistent signal. In a study focused on the central Arctic (65-90°N), Akperov et al. (2019) found that most of a set of six Arctic climate models showed an increase of cyclone frequency in winter and a decrease in summer by the end of the 21st century, although there was considerable regional variation within the polar cap. Some of the models indicated trends towards weaker and smaller cyclones in winter but deeper and larger cyclones in summer, contrary to the historical changes reported by Akperov et al. (2018). Based on CMIP5 simulations forced by the RCP4.5 scenario, Zappa et al. (2013) found a general decrease in future cyclone activity over the North Atlantic Ocean, except for a projected increase in the cyclone track density near the southern tip of Greenland in summer. On the broader hemispheric scale, projected changes in the frequency of extratropical cyclones are generally small in the aggregate of the CMIP5 models. There are some hints of a northward shift in the storm tracks, but overall the Northern Hemisphere shows a weaker and much less spatially coherent poleward shift of storm tracks than is apparent in the projections for the Southern Hemisphere ((Collins et al., 2013), Fig. 12.20).

2.7. Wind

Extreme wind events are generally associated with strong cyclones or orographic effects. While temperature and precipitation events have been the subjects of various studies, there are relatively few analyses of high-wind events in the northern areas, especially in the context of climate change. However, extreme winds are common in high latitudes. According to ERA-Interim based global climatology (Kumar et al., 2015), the mean of the annual maximum wind speed is largest in Antarctica, Greenland and other Arctic islands, as well as coastal regions of Siberia, with increasing trends in eastern Greenland. The studies to date of high-wind events have drawn upon a variety of sources of wind information. For example, Lynch et al. (2004) made use of wind observations from Barrow in northern Alaska to assess the impacts of extreme wind events at a single location. Hughes and Cassano (2015) used winds obtained from several reanalysis products and a regional climate model to map the median and 99th percentile wind speeds across the Arctic, with an emphasis on the comparison between the regional model simulations and the reanalyses. Redilla et al. (2019) have recently shown that high-wind events in the Alaska region are associated with synoptic-scale cyclones, with strong anticyclones often in close proximity to enhance the pressure gradient.

The occurrence and strength of extreme winds is sensitive to orographic effects (Jonassen et al., 2020). These effects include downslope wind storms (Oltmanns et al., 2014), tip jets (Renfrew et al., 2009), and barrier winds (DuVivier et al., 2017; Harden et al., 2011). Climatologies of the occurrence of orographically-forced strong winds have been calculated for the Greenland region (Harden et al., 2011), for the tip jet south of Spitsbergen (Reeve & Kolstad, 2011), for winds over Novaya Zemlya (Moore, 2013), and for high-latitude low-level jets (Tuononen et al., 2015). Downscaling methods have been developed to estimate the high-resolution spatial distribution of strong winds in northern areas, for example to evaluate the damage they cause to forests in northern Finland (Venäläinen et al., 2017). However, there have been relatively few attempts to assess climatological trends in extreme winds, either historically or in the future. One example is Mölders et al.’s (2016) downscaling of winds for a near-future (2016-2032) time slice in a case study targeting wind energy at a site near Juneau. Alaska.

Several regional studies have pointed to future increases of wind speeds on the northern flanks of present-day storm tracks. Ruosteenoja et al. (2019) analyzed the output of 21 CMIP5 models in the European-North Atlantic sector covering latitudes from 30° to 85°N. Comparing the periods 1971-2000 and 2070-2099 under the RCP8.5 emission scenario, they found that in all seasons the 99th percentile of the near-surface wind speed will increase most in the northernmost part of the study region. The largest increases were found over the Arctic Ocean north of Greenland and Ellesmere Island in autumn (> 10% relative increase) and over the Barents and Kara Seas in winter (5-10%). Over Greenland the 99th percentile near-surface wind speeds are projected to mostly decrease, especially in winter (Ruosteenoja et al., 2019).

In a study for the Pacific subarctic, Redilla et al. (2019) synthesized observational data and bias-corrected model output to evaluate the frequencies of occurrence of historical and projected (future) changes at coastal locations around Alaska. High-wind events over the 1980-2014 historical period were found to be most common during autumn and winter, with increasing frequencies in northern and western Alaska and decreases in the southeast. For the future, a regional climate model forced by output from two global climate models projected an increase of high-wind events in the northern and western Alaska coastal regions, which are precisely the regions in which the protective sea ice cover has decreased (and is projected to decrease further), pointing to increased risks of coastal flooding and erosion (Rolph et al., 2018)..

3. Impacts of extreme weather and climate events

3.1. Sea ice: rapid ice loss events

The trajectory of northern hemisphere sea ice towards record minima in recent years has received widespread attention in the context of global change. The IPCC (2019), for example, concludes that the record minima of winter/spring 2016 would not have been possible without anthropogenic forcing, but that the relative roles of preconditioning, interannually varying atmosphere/ocean forcing and storm activity in determining the evolution of sea ice are still highly uncertain (Petty et al., 2018).

On the interannual to decadal timescales, the decrease of summer Arctic sea ice has been characterized by years of extreme ice loss, often followed by a year or two in which the sea ice extent increases but not to its prior level (Fig. 2). In the post-2000 period, 2007 and 2012 stand out as such years, as do 1985, 1990, and 1995. Holland et al. (2006; 2008) examined rapid ice loss events (RILEs), which were defined as periods when the loss of September sea ice extent over a five-period exceeded 0.5 million km^2. These events, defined by various similar criteria, have been addressed further in the context of interannual-to-decadal changes by Döscher and Koenigk (2013) and Rogers et al. (2015), among others. RILEs have accounted for most of the reduction of Arctic sea ice extent over the past several decades, and model simulations suggest that they will continue to do so in the future (Holland et al., 2006; Paquin et al., 2013).

Much less attention has been paid to extreme sea ice losses over shorter timescales, i.e., several days. The work that has been done on these timescales has generally focused on storm events. The thinning and reduction of extent of sea ice can make the ice cover more vulnerable to the wind-forcing and associated ocean mixing. Indeed, the record minimum of sea ice extent in September 2012 (lower by 0.67 million km^2 than any other year on record through 2019) has been attributed partially to the occurrence of a strong cyclone in August 2012 (Parkinson & Comiso, 2013). However, while the 2012 Arctic cyclone was indeed extreme (Simmonds & Rudeva, 2012), another study (Zhang et al., 2013) concluded that the storm accounted for only 0.15 million km^2 of sea ice loss.

Wang et al. (2019) identified Large Daily Sea Ice Loss (LDSIL) events both regionally and on a pan-Arctic basis. LDSIL events in most regions show significant associations with poleward moisture transport into the region and with column water vapor in the immediate vicinity. Central Arctic LDSIL events are associated with inflow from the North Atlantic but not the North Pacific. Signatures of atmospheric river events are apparent in regional LDSIL events from the Greenland Sea through the Russian subarctic to the Beaufort/Chukchi/East Siberian Seas. Pan-Arctic LDSIL events show no such signature. The number of LDSIL days is significantly correlated with September ice extent on the pan-Arctic scale and in several subregions, including the central Arctic.

Global climate models are unanimous in projecting further losses of sea ice in the Arctic (IPCC, 2013; IPCC, 2019). While the consensus of the models is that the Arctic will begin to experience ice-free (ice extent < 1 million km^2) by the 2030s or 2040s, the timing varies considerably among external forcing scenarios and among models (Notz & Stroeve, 2018; Peng et al., 2020).

3.2. Greenland Ice Sheet: extreme melt events

The Greenland Ice Sheet (GrIS) has experienced record melt in recent years, including 2012 and 2019 (Fig. 3). These extreme summer melt years are part of an ongoing trend towards increased melt, runoff and mass loss from the GrIS (IPCC, 2019, their Section 3.3; Hanna et al., 2020a), and reflect significant Greenland warming that, as part of Arctic Amplification, averaged around 1.7 °C in summer from 1991-2019 (Hanna et al., 2020b). The increase in melt is non-linear, and recent melt levels in central-west Greenland have not been seen for at least 7000 years (Trusel et al., 2018).

While oceanic drivers including the Atlantic Multidecadal Oscillation (AMO) are increasingly recognized as playing a role in recent mass losses, atmospheric factors contributing to this trend include a background warming and a general decrease in the magnitude of the North Atlantic Oscillation (NAO) since 1990 with more frequent and higher intensity blocking weather patterns over Greenland (Hanna et al., 2015; Hanna et al., 2016; Hanna et al., 2018b; Tedesco et al., 2013), decreased summer cloud cover/increased shortwave insolation (Hofer et al., 2017), and surface albedo feedbacks (Box et al., 2012; Cook et al., 2019). These factors combine to produce extreme melt events such as those of 2012 (Hanna et al., 2014) and 2019 (Hanna et al., 2020b).

Although the summers of 2012 and 2019 both had extreme high values of Greenland Blocking (see *Atmospheric Blocking*, Section 2.5), their synoptic characteristics were somewhat different. The mid-July 2012 melt peak involved advection of relatively warm air from the southwest up over the western flank of the Ice Sheet, which is the more conventional direction of airflow seen in most other recent warm summers. By contrast, the 2019 extreme melt in late July/early August was driven by a plume of warm air originating from record-breaking heat over Europe, from where this airmass was transported westwards over Greenland and warmed adiabatically as it descended the west side of the ice sheet (Hanna et al., 2020b; NSIDC, 2019). As a result, Summit at the top/center of the GrIS (3200-m elevation) experienced its highest temperature on record (1.2°C) on 31 July 2019, while Danmarkshavn (northeast Greenland coast) recorded a new record maximum August temperature of 19.7°C. The 2019 warmth/melt was most extreme in far northern Greenland, somewhat following the pattern of 2015, which was another high Greenland melt year (Tedesco et al., 2016). This may reflect northward recession of sea-ice earlier in the melt season, as well as a systematic shift in the North Atlantic atmospheric circulation towards a more negative summer NAO and increased (decreased) cloud coverage over northern (southern) Greenland since the 1990s (Noël et al., 2019). Because the GrIS is already relatively warm around its margins in summer, more frequent and extreme melt events occur with only modest (~1°C) additional temperature rises; this is also a function of the gently-sloping surface topography at and above elevations of ~1500-2000 m (around the level of the current equilibrium line altitude), which exposes much greater areas of the GrIS to surface melt as it gets warmer (Hanna et al., 2020a).

Quantification of GrIS melt extremes also depends on the metrics used. Välisuo et al. (2018) found that interannual variations in the

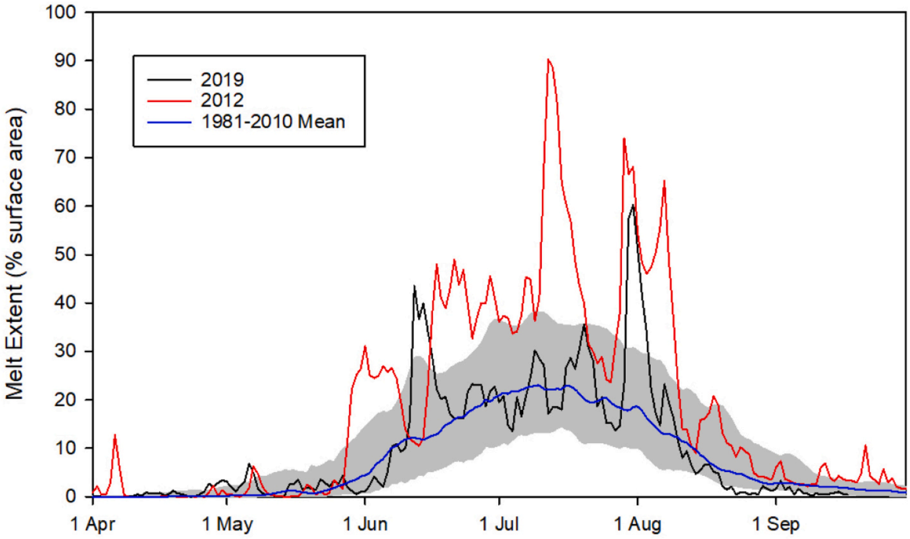

Fig. 3. Seasonal evolution of the melt area of the Greenland Ice Sheet during 2012 (red line) and 2019 (black line). Climatology (1981-2010) and range are shown by blue line and shading. Source: Thomas L. Mote, University of Georgia.

maximum melt extent differed from those in the number of melt days, cumulative melt extent, and modeled melt amount. During years 2000 to 2014, total column water was the forcing factor most strongly correlated with inter-annual variations in the number of melt days (r^2 = 0.83), cumulative melt extent (0.84), and modeled melt amount (0.82). According to Välisuo et al. (2018), the maximum melt extent was most strongly (negatively) correlated with the occurrence of air-masses of northeasterly origin on the high plateau.

Greenland melt projections from a regional climate model driven by several initially-available Coupled Model Intercomparison Project 6 (CMIP6) simulations suggest a range of 4.0-6.6°C of additional summer warming over Greenland if we follow the SSP-585 (high-emissions) emissions scenario: the resulting surface melt could contribute at least 10-13 cm to global sea-level rise (Hanna et al., 2020b). Under that scenario, surface melt events covering nearly the entire GrIS, as occurred in 2012, could become commonplace well before 2050. Also, such events contribute significantly to yearly GrIS mass loss values (NSIDC, 2019). It is therefore crucial to improve climate-model projections, which generally fail to capture the recent increase in summer blocking over Greenland that is evident from the atmospheric reanalysis record (Hanna et al., 2018b).

Mass losses from GrIS outlet glaciers are also important, and are particularly affected by changes in ocean circulation, but are likely to be overtaken by melt and surface mass losses from the main ice sheet in an increasingly warm climate (Hanna et al., 2020a). However, estimates of the relative mass loss contributions from GrIS surface mass balance and dynamics vary and – due to limitations of ice-sheet models and verification data – there remains a significant lack of understanding of the interaction between these processes (Hanna et al., 2020b).

3.3. Flooding

Extreme flooding events in northern high latitude regions fall into two primary categories, coastal and river flooding. Coastal floods generally result from wind-driven waves, often associated with coastal storms, and are often exacerbated by elevated sea level resulting from low atmospheric pressure (the inverse barometer effect), high tides, and the slow background rise of sea level driven by climate change. In interior regions, heavy rainfall events are key drivers of floods, although compounding factors in high latitudes include the springtime snow melt and ice jams on rivers. The presence of permafrost in Arctic catchments may further promote flooding of wetland areas due to reduced infiltration. Examples of recent high-latitude floods in which springtime snow melt and ice jams played key roles include the major flood disasters in Edeytsy on the Lena River and Galena on the Yukon River in the spring of 2013 (Kontar et al., 2018). Fig. 4 shows the Galena flood. A recent flood event caused by heavy rains occurred in the Irkutsk region, southeastern Siberia, starting in June 2019. Over 6000 homes were inundated and the floods affected more than 30,000 people (Floodlist, 2019a). The area was hit by another flood in the end of July, which lead to another 2,300 people being affected (Floodlist, 2019b).

Arheimer and Lindström, 2015) used data from 69 gauging sites in Sweden to conclude there has been no significant trend in the annual maximum daily river discharge over the past 100 years. Their results were qualitatively in agreement with those of Shiklomanov et al. (Shiklomanov et al., 2007), who analyzed data on floods in Russia, where flooding causes more damage than any other type of natural hazard related disaster. While Shiklomanov et al. (2007) found a significant shift to earlier spring discharge, there was no evidence of widespread trends of maximum-discharge events over the Russian Arctic, leading the authors to question the validity of hypotheses that the risks of extreme floods are increasing. However, Shevnina et al. (2017) compared flood data for 1930-1980 with projections for 2010-2039, and identified large regions in the Russian Arctic where the spring flood depth of runoff is projected to increase by more than 30%. Their study was based on a probabilistic hydrological model, which used climate model projections as input. Finally, Burn et al. (2016) studied flood regimes over the past 50-80 years in Canadian watersheds using a peak-over-threshold (POT) approach. Their results imply that there are smaller-magnitude snowmelt events, but increased number of POT events over the study period. They also noticed a shift in flood regimes from snowmelt events towards snow-and-rainfall and rainfall events. Vormoor et al. (2016) arrived at a similar conclusion for floods in Norway, where increasing flood frequencies in southern and western Norway were found to be due to positive trends in the frequency of rainfall-dominated events. By contrast, northern Norway has experienced a decrease in flood frequencies because of negative trends in snowmelt-dominated flooding. In an analysis of a pan-Nordic dataset of streamflow records, Wilson et al. (2010) found that temperature signals dominated precipitation signals in streamflow changes, which indicated a trend towards earlier snowmelt flooding.

Several studies have addressed future changes in high-latitude flooding. Hirabayashi et al. (2013) found that, during the 21st century, the projected return period of the 100-year flood decreases in most of the river basins included in their global analyses. Considering the largest rivers in the northern regions, the return period is expected to decrease for the Yukon, Mackenzie, Yenisei, and Lena basins, where the peak of spring snowmelt will decrease, as is the case for smaller rivers in northern Europe. This finding is consistent with the results of Archeimer and Lindström (2015) for Sweden and Olsson et al. (2015) for Finland. According to Archeimer and Lindström (2015), high-resolution climate model projections suggest a future decrease of the annual maximum daily river discharge by approximately 1% per decade, driven mostly by a decrease of spring snowmelt. On the other hand, the autumnal maximum daily river discharge may increase by 3% per decade, driven by more intense precipitation. Further, the boundary zone between snow- and rain-driven floods in Sweden is projected to move northwards. According to Olsson et al. (2015), spring floods in Finland will occur earlier and become weaker towards the end of the century, also yielding mostly negative trends in annual high flows. Olsson et al. (2015) stressed the importance of bias correction in climate models, in particular for extreme events such as floods. Finally, Lehner et al. (2006) show that, even if spring floods may become weaker in Fennoscandia, the frequency of extended floods (during the entire year) may increase.

Glacial melt during the warm season can trigger floods in some areas of the Arctic. Dahlke et al. (2012) examined trends in flooding in northern Sweden, focusing on two sub-Arctic catchments with contrasting glacier coverage. Both catchments experienced warming but little change in precipitation over the study period (1985-2009), but the glacierized catchment showed a statistically significant increase in flood magnitudes while the non-glacierized catchment showed a significant decrease. Drainage of ice-dammed lakes, or glacial outburst floods, occur when a moraine is breached or an ice-dam fails (e.g., Emmer, 2017) in various northern regions, including Alaska, Canada and the Himalayas. However, there has been little work on temporal trends in glacial outburst floods.

3.4. Drought

Droughts are largely the results of precipitation deficits, often exacerbated by high temperatures and low humidities that favor enhanced evapotranspiration. For this reason, extreme drought events are closely related to persistent negative anomalies of precipitation. The increasing frequency of severe wildfire seasons (see following section) suggests that the effect of longer and warmer summers may favor summer drying in the Arctic even if precipitation increases, although wildfire season severity is also complicated by the important role of lightning as an ignition source (Veraverbeke et al., 2017). However, droughts in the northern land areas, especially the Arctic, have received little attention by the climate research community. There are several likely reasons for the absence of more comprehensive assessments of

Fig. 4. Ice-jam flooding in Galena, Alaska during May, 2013. Yukon River is in left portion of photo. Source: E. Plumb, NOAA/ National Weather Service.

drought in high northern latitudes: (1) precipitation over much of the region is climatologically low in comparison with middle latitudes, (2) uncertainties in trends and variations are greater for high-latitude precipitation than for temperature, and (3) much of the land surface is underlain by permafrost.

Notable droughts have occurred in other northern countries in recent years (e.g., Fennoscandia in 2018, western Canada in 2015, southeastern Alaska in 2018-19). Another example, is the 2010 drought in Russia, which was intense and covered a large area, resulting in environmental degradation, large economic losses and impacts on human health (Kogan & Guo, 2016). This drought together with an intensive heatwave also triggered numerous wildfires, which resulted in up to 2 million hectares burned area (García-Lázaro et al., 2018). In one of the few studies to provide a temporal perspective on high-latitude drought, Wilson et al. (2010) found a tendency towards more severe summer droughts in southern and eastern Norway over the 20th century. More recently, Ryazanova and Nadeshda (2017) calculated a reanalysis-based aridity index for southern Siberia (50-65°N, 60-120°E), where the mountain areas in the eastern portion of the domain were found to have become increasingly arid over the 1979-2010 period.

In view of the general increase of high-latitude precipitation in recent decades (Min et al., 2008) and projections of continued increases in the future (Bintanja & Selton, 2014; Flato & Ananicheva, 2017), one would expect drought occurrences in the Arctic to decrease. Indeed, a synthesis of global climate model output shows a projected reduction by 5-10 days in the yearly maximum number of consecutive dry days over Arctic land areas (Collins, 2013, their Fig. 12.26d). However, regional variations can be expected. For example, Wong et al. (2011) used downscaled climate model output to drive a precipitation-runoff model for Norway. Hydrologic summer drought duration and area were projected to increase in southern Norway because of reduced precipitation and in northernmost Norway because of increased temperature (Wong et al., 2011).

A recent study of paleoclimatic data has suggested links between Arctic warming and drought in middle latitudes (Routson et al., 2019). Cvijanovic et al. (2017) arrive at a similar conclusion based on climate model sensitivities to sea ice loss. In view of these potential linkages and the relative absence of comprehensive assessments of droughts in high latitudes, drought in northern land areas appears to be an under-researched type of extreme event, especially in the context of climate change

3.5. Wildfire

Wildfire in northern regions has major impacts on terrestrial ecosystems, carbon release, and air quality. Recent severe fire outbreaks in Russia and Fennoscandia during 2018 and 2020 and Alaska during 2015 and 2019 have highlighted these impacts. Data for monitoring wildfire activity on a year-to-year basis and for detecting trends over time exist mainly for Alaska and Canada, while comparable data for Siberia are less available. As shown in Fig. 5, the frequency of extreme wildfire years in Alaska has increased. Of the 20 years with more than a million acres burned since 1950, seven occurred in the first half of the record and thirteen in the second half. For Canada, any analogous trend is threshold-dependent (http://cwfis.cfs.nrcan.gc.ca/ha/nfdb?wbdisable=true), precluding definitive statements about trends in extreme fire years in Canada. Wildfire frequency and burned area have increased in Siberian forests between 1996 and 2015, where frequency is correlated with air temperature anomalies and the drought index SPEI (Standardized Precipitation Evapotranspiration Index) (Kharuk & Ponomarev, 2017; Ponomarev et al., 2016). On the century timescale,

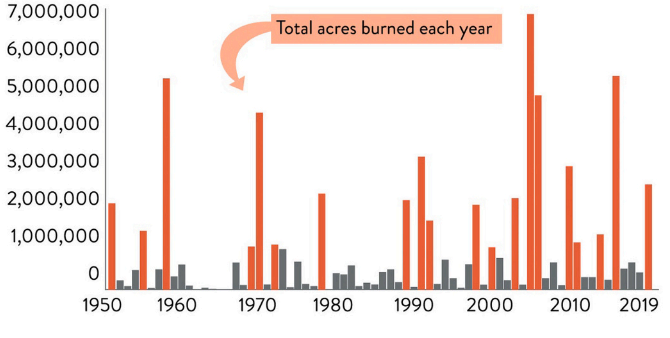

Fig. 5. Yearly numbers of acres burned by wildfires in Alaska, 1950-2019. Source: Thoman and Walsh (2019)..

however, wildfires have strongly decreased since 1900 in Fennoscandian forests, as they are actively monitored and fought due to the economic importance of forestry (Aakala, 2018).

Recent research has shown that lightning is a major driver of recent severe fire years in North America's boreal forests. Veraverbeke et al. (2017) found that lightning ignitions have increased since 1975 and that the extreme fire years of 2014 (Canada) and 2015 (Alaska) coincided with record numbers of lightning ignitions. Using convective precipitation as a proxy for lightning, Veraverbeke et al. obtained projected increases of lightning-driven burn areas of 29-35% for Canada's Northwest Territories and 46-55% for Interior Alaska by the late 21st century ((Veraverbeke et al., 2017), their Table 2). A similar approach was used by Bieniek et al. (2020), who dynamically downscaled two global climate model projections to obtain estimates of a doubling of lightning strikes over Interior Alaska by the end of the 21st century.

Finally, while wildfires are much less common in tundra areas than in the boreal forest, there are indications that tundra wildfires may be increasing. An unusually large wildfire in the tundra of western Greenland in August 2017 was part of Greenland's most extensive wildfire season since the beginning of the satellite record (NOAA, 2017). Alaska has also seen large tundra fires in recent years, including the massive Anaktuvuk River fire of 2007 (Hu et al., 2010). The Noatak River basin in northwestern Alaska experienced around 40 wildfire events in 2010 (Hu et al., 2015). On the circumpolar scale during 2001-2015, Masrur et al. (2018) showed that warm and dry weather in late spring to mid-summer has favored tundra wildfire occurrence and fire intensity. Negative anomalies in precipitation and soil moisture in winter and spring were also found to be related to fire intensity.

3.6. Coastal erosion

Coastal erosion is one of the more visible manifestations of extreme weather and climate events in the northern regions. Coastal erosion rates in the Arctic are indeed among the largest on the earth, with average rates of retreat of several meters per year along much of the Russian and Alaskan coasts (Fig. 6). Various studies have pointed to a doubling (and even more) of coastal erosion rates in the Arctic in recent decades (Arp et al., 2010; Jones et al., 2009; Overeem et al., 2011; Frederick et al., 2016).

Because much of the Arctic coastline is permafrost, thermal as well as dynamical processes play a role in the retreat of far northern coasts. While climate warming would by itself result in increased rates of coastal erosion in the Arctic, coastal retreat has been accelerated by the recent loss of sea ice (Section 3.1) in combination with Arctic storm activity (Section 2.6). The combination of a longer open water season, increased fetch for wave build-up during storms, and warmer water and air temperatures complicates the distinction between thermal (melt-driven) and dynamical (wave-driven) erosion of Arctic coastlines.

Barnhart et al. (2014) showed how the lengthening of the open water season by factors of 1.5 to 3.0 has increased the open-water fetch for autumn storms along much of the Arctic Ocean's coastline. The same authors illustrate the linkage between increased fetch and extreme values of water-level setup at Drew Point, Alaska, where the erosion rates exceed 4.5 m yr^{-1} (Fig. 6). Rolph et al. (2018) showed that, over the period 1979-2014, there was an approximate tripling of the number of wind events during open water conditions at Utqiagvik (Barrow), Alaska. Most of the increase was attributable to the increased open water season length, although the frequency of storm-related high-wind events has also shown an increase in this region (Rolph et al., 2018, their FIg. 8;, their Fig. 10). The U.S. Global Change Research Program (Karl et al., 2009) has used the northern Alaskan coast to illustrate the risks of flooding and coastal erosion. Since the open water season offshore of northern Alaska has lengthened by 1 to 3 months in recent decades (Stroeve & Notz, 2018; Thoman & Walsh, 2019), this region highlights the fact that storms in coastal areas of the Arctic pose increasing risks regardless of whether storm activity is changing.

Kostopoulos et al. (2018) used coastal engineering models to relate open water fetch to wave height, coastal erosion and sediment transport, all of which will impact Arctic operations, infrastructure and human activities. As the open water area of the Arctic Ocean expands in a warming climate, wind-waves as well as swell will increase. Swell from distant storms can further increase the wave energy reaching the Arctic coastline (Frederick et al., 2016).

In summary, the recent increase in coastal erosion results from a combination of the background climate change (increasing water temperatures, longer ice-free season) and extreme weather events (storm-driven waves and swell). While a continuation of changes in the background climate, including the loss of sea ice and the warming of coastal waters, is relatively certain, there is less confidence in the future changes of storminess in the high-latitude coastal areas (Section 2.6).

3.7. Terrestrial ecosystems

Across the northern land areas, ecosystems are responding to gradual warming over recent decades (e.g., Elmendorf et al., 2012).

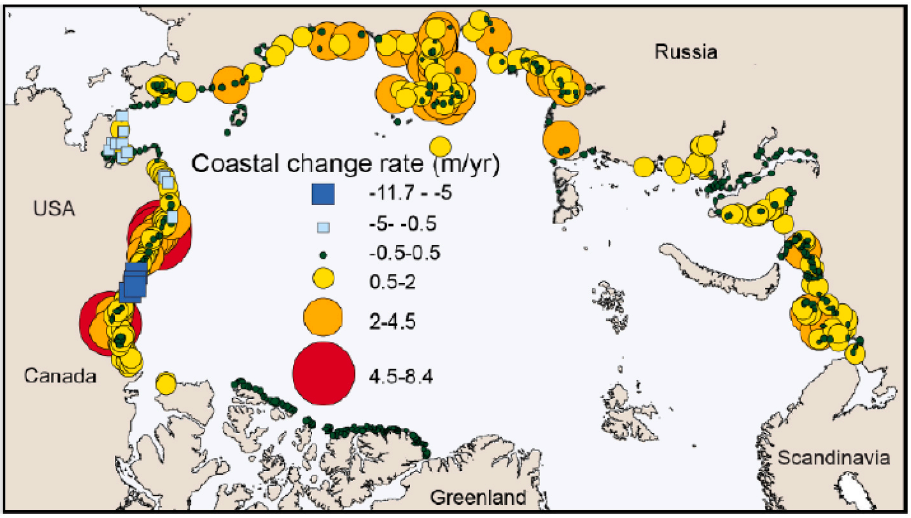

Fig. 6. Coastal erosion rates along the Arctic. The highest erosion rates are seen along the U.S. and Canadian Beaufort Sea coast. .From Frederick et al. (Frederick et al., 2016), adapted from Barnhart et al. (Barnhart et al., 2014); Lantuit et al. (Lantuit et al., 2012).

However, at more local scales, ecosystems are also responding to an increasing frequency in stochastic climate events, such as extreme winter or summer warming, rain-on-snow events, drought conditions, and extreme rainfall or snowfall. These localized extreme events may have a substantial impact on ecosystem processes in Arctic terrestrial ecosystems. Here we provide examples of ecosystem impacts associated with various types of the extreme events summarized in Section 2, while acknowledging that background changes in climate can affect ecosystem vulnerability to extreme events. Changes in the background climate can also change a system's proximity to thresholds that may be exceeded during extreme events. The 0°C temperature threshold is one such example.

A number of studies have documented the impacts of extreme events on northern plant communities (Bokhorst et al., 2018; Orsenigo et al., 2014; Phoenix & Bjerke, 2016; Treharne et al., 2018). Both extreme summer and winter warming may cause plant mortality, or 'browning' (Bokhorst et al., 2018; Zona et al., 2014). Some plants, such as evergreens, may be more vulnerable to extreme winter warming compared to grasses and deciduous shrubs, possibly due to the ability of grass species to modify fatty acid composition in their tissues (Bokhorst et al., 2018). Extreme summer warmth may also impact plant communities, including desiccation of mosses (Zona et al., 2014). Extreme snowfall that results in a delay of snowmelt may inhibit leaf-out and plant growth during the growing season (Schmidt et al., 2019). Fig. 7 shows the impacts of the late melt of an extremely deep snow pack at Zackenberg, Greenland. Alternatively, extreme warming that results in a lack of snow cover, possibly combined with winter rainfall, causes a loss of ground insulation or icing, with plant population dieback (Bjerke et al., 2017; Bokhorst et al., 2011), and reduced rates of decomposition (Kreyling et al., 2013). These impacts on plant population growth may be widespread, such as in one study showing the impacts of a hard frost without a protective snow cover resulting in damage along ~1000 km of coastal Norway (Parmentier et al., 2018). Cumulatively, these studies point towards increases in plant mortality with extreme climatic events in both winter and summer, and are counter to the tundra greening and plant growth occurring with longer-term warming trends in the Arctic (Phoenix & Bjerke, 2016).

The measurements at Zackenberg have also enabled documentation of the impacts of extreme events on carbon dioxide and methane exchanges between the surface and the atmosphere. Christensen et al. (2020) showed that an intensive 9-day rain event in August 2015 reduced the CO_2 uptake by an amount comparable to the typical annual carbon budget in Arctic tundra. The reduction in solar radiation was a key factor in the decrease of CO_2 uptake. Farther south in a peatlands ecosystem of Sweden, Lund et al. (2012) found that drought changed a nutrient-poor peatland from a CO_2 sink to a CO_2 source

The extreme snow melt season at Zackenberg ((Schmidt et al., 2019); Fig. 7 below) led to thermokarst gullies that transformed the ecosystem from an annual CO_2 sink to a CO_2 source and that triggered highly elevated methane releases. Increased precipitation has also been found to drive mega-slump development and the destabilization of permafrost terrain in northern Canada (Kokelj et al., 2015). The extreme snow melt at Zackenberg in 2018 was also accompanied by large increases in riverine transport of organic carbon to the coast. These responses have major implications for tundra ecosystems and their coupling to the atmosphere and ocean as extreme precipitation events

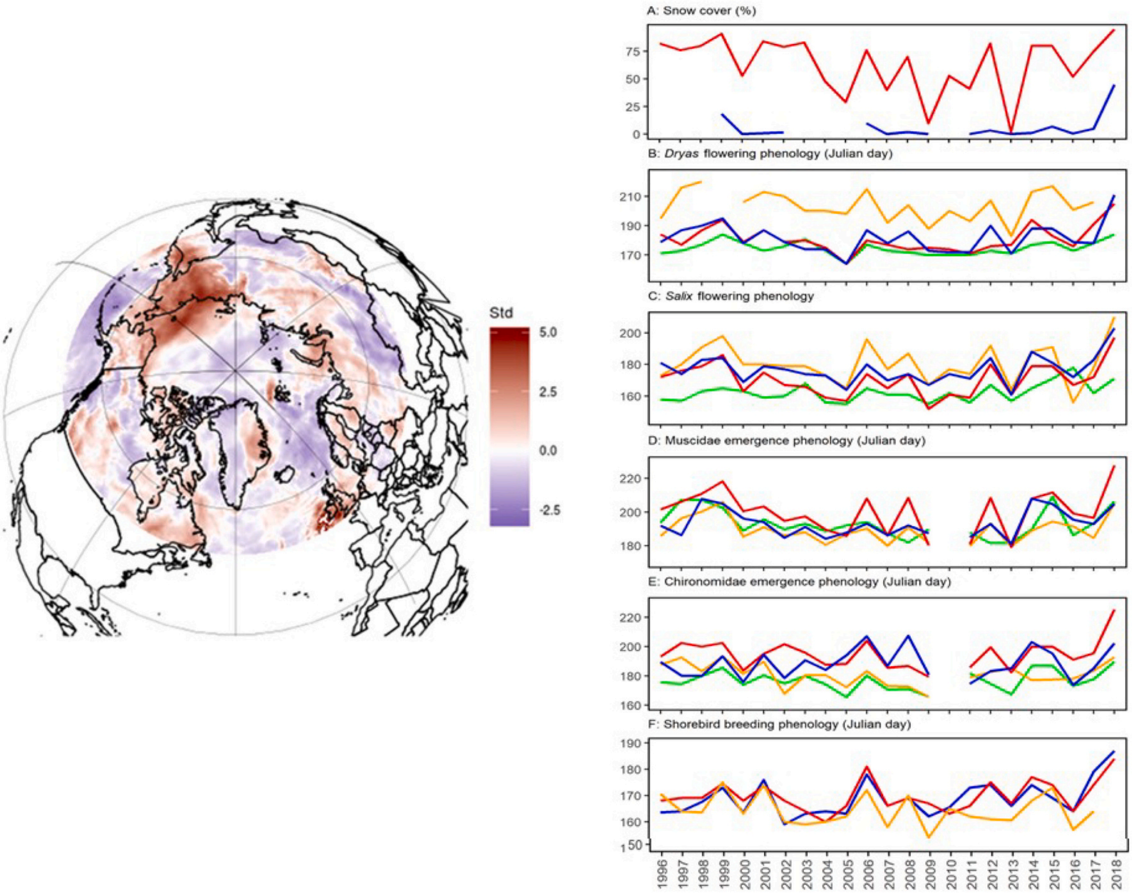

Fig. 7. Left panel: The 2018 snow cover anomalies (standard deviations) in the Arctic (from Schmidt et al., 2019, their Fig. 1). Right panel: Ecological time series on phenology from Zackenberg in northeast Greenland: (A) snow cover in second week of June (red) and third week of July (blue); (B)-(E) Julian dates of 50% flowering of Dryas sp., Salix arctica, Muscidae emergence, and Chironomidae emergence; (F) median date for nest initiation of three shorebird species. In (B)-(E), different colors represent different measurement sites around the Zackenberg field station. (Adapted from (Schmidt et al., 2019), their Fig. 2)/

become more common in the future (Section 2.2).

Coupled with the impacts of extreme events on arctic plant communities are the impacts on animal populations. These impacts occur across multiple trophic levels in the highly interconnected food webs of northern regions (Hansen et al., 2013). Rain-on-snow events that cause ice layer formation, winter warm spells, and extreme snowfall may lead to winter food shortages for arctic herbivores (Loe et al., 2016; Hansen et al., 2011) or arriving spring migratory birds in years when extreme snow cover extends late in the season (Krause et al., 2016). Notable examples of impacts of a rain-on-snow event include the massive reindeer mortality events of 2006 and 2013 on Russia's Yamal Peninsula (Forbes et al., 2016). Food shortages result in reduced overall body mass and condition, leading to higher mortality rates in less mobile species, such as musk oxen (Reynolds, 1998; Schmidt et al., 2016). These negative impacts on arctic herbivores and their forage availability may then influence the population dynamics of predators or secondary consumers, such as the arctic fox (Hansen et al., 2013). However, counterintuitively, negative effects on herbivores may also be buffered in highly mobile species that are able to locate better forage conditions, such as caribou, resulting in lower mortality rates and higher fecundity (Loe et al., 2016). Furthermore, recent work suggests that as some extreme events become more common, such as rain-on-snow events, herbivore populations may trend towards more resilient age classes, reducing population crashes during future rain-on-snow events (Hansen et al., 2019).

Extreme events may also impact animal populations and biogeochemistry in northern freshwater ecosystems. This includes cold events during winters that can impact freshwater fish populations. For example, smaller streams with little snow cover insulation can freeze to the bottom during cold events, killing eggs, parr and overwintering spawners, e.g., brown trout (Borgstrøm & Museth, 2005). While increasing temperatures may favor recruitment of native fish and lead to overpopulation, extreme temperatures in aquatic ecosystems during extremely dry and warm summers can lead to lethal conditions (Borgstrøm & Museth, 2005). Freshwater ecosystems may also experience changes in the production, mobilization, and export of dissolved organic carbon (DOC) following extreme precipitation events in northern streams (Tiwari et al., 2019). Extreme drought impacts on northern rivers can promote increased water residence time, resulting in biogeochemical shifts and poor water quality (Gómez-Gener et al., 2020).

The distribution of ecological measurements in the high-latitudes is concentrated at long-running field stations and sparse elsewhere (Metcalfe et al., 2018). Because extreme events are highly infrequent and their ecological effects often localized, ecological impacts of extreme events represent an observational challenge. An expansion of *in situ* monitoring networks could provide more comprehensive documentation of the impacts of extreme events on high-latitude ecosystems (e.g. (Mahecha et al., 2017)) and provide ecological context for remotely sensed long-term greening and browning trends (e.g., Epstein et al., 2018). Metrics derived from remote sensing approaches may also facilitate the identification of the impacts of extreme events on arctic ecosystems, particularly those associated with extreme events that cause browning (Treharne, 2020). Overall, changes in the variability of the high-latitude climate appear to have just as important ecological consequences as long-term warming trends.

3.8. Marine ecosystems

The warming of ocean waters introduces the potential for cascading effects in marine ecosystems. However, because ocean variations generally have longer timescales than atmospheric events, one must acknowledge the challenges in distinguishing effects of climate change and extreme events. Here we consider marine ecosystem impacts that have occurred on timescales of a season to several years. While these timescales exceed those addressed in previous sections, they admittedly overlap with those of short-term climate variations. With this caveat, we review several notable marine ecosystem impacts of recent seasonal and interannual extremes in atmospheric and oceanic drivers. The presence or absence of sea ice is a key driver of marine biogeochemistry, so the rapid sea ice loss events described in Section 3.1 take on added importance in the context of marine ecosystem changes.

The background warming of the atmosphere and ocean has led to increased likelihoods of marine heat waves, such as the 2015-2016 event in the Bering Sea (Walsh et al., 2018). The ecological impacts of such events are complex but unequivocal. The 2015-16 event was associated with one of the largest harmful algal blooms to reach the Arctic coast (Peterson et al., 2016) and changes in copepod abundance, which in turn affected the food sources for higher trophic levels such as forage fish (Kintisch, 2015). Other impacts included major mortality events in seabird species and increased incidence of diseases, including sea star wasting disease.

While this 2015-16 event was associated with the anomalous North Pacific "blob" of warm sea surface temperature anomalies (Peterson et al., 2016), similar extreme temperatures have recurred in Alaskan coastal waters in more recent years. The warmth of the waters contributed to unprecedented low sea ice extent in the Bering Sea during the winters of 2017-18 and 2018-19. The 2017-18 event included a weakened water column stratification, delayed spring bloom, and low abundance of large crustacean zooplankton, even in the northern Bering Sea where ecosystem effects of sea ice variations are normally not observed (Duffy-Anderson et al., 2019). The "cold pool" of temperatures close to 0°C near the Bering Sea floor has historically served as a barrier to northward migration of fish species, but the cold pool was nearly absent during these two years (Stabeno, 2019). In particular, fish species such as Alaska pollock and Pacific cod previously associated with the northern Bering Sea shelf have shifted northward by 2018, and their former habitat is now occupied by southern shelf species (Thorson et al., 2020). While these recent marine events may be regarded as extreme in the historical context, longer-duration ecosystem shifts must be considered plausible if the extreme marine conditions of the past 4-5 years in the Pacific sector of the Arctic become a "new normal".

In the subarctic North Atlantic, recent extreme events have included extensive (millions of square kilometers) phytoplankton blooms in the Barents Sea, which may reduce the marine carbon sink (Kondrik et al., 2018). Fish communities of the Barents Sea shifted rapidly from 2004 to 2012 but have remained relatively stable since 2012. However, the northward shift included increased abundance and expanded distribution of large-bodied feeders (Atlantic cod, haddock) taking advantage of more favorable conditions in the Barents Sea, while many Arctic species retracted to smaller areas to the northeast and have not recovered to their previous distributions (Thorson et al., 2020). Little information is available on higher trophic levels in the Russian shelf seas. However, studies based on remote sensing show that the reduction of sea ice cover has led to increases of 40-70% in the frequency of autumn/secondary algal blooms in the Russian Arctic seas (Ardyna et al., 2014).

Marine ecological impacts of extreme events are also manifest at the higher trophic levels, including marine mammals such as seals, walrus, whales and polar bears. Extreme events such as the Bering Sea shift of the early 2000s and the recent loss of ice in the Bering/Chukchi sector have had impacts such as increased detections of toxins in marine mammals (Thoman & Walsh, 2019), unusual gray whale mortality (McFarland et al., 2020), and walrus haul-outs on shorelines that had previously provided walrus with access to sea ice (Fig. 8).

The effects of extreme events in the marine ecosystem will accelerate the impacts of more gradual Arctic changes impacting sea ice, ocean temperatures, water column stability, and nutrient availability. As an example of the effects of more gradual changes on marine mammals, Moore and Huntington (Moore & Huntington, 2008) have distinguished the effects of an altered sea ice regime on ice-obligate species (polar bears, walrus, bearded and ringed seals), ice-associated species (narwhal, bowhead whale, several types of seals), and

Fig. 8. Walrus have historically hauled out on sea ice for feeding and resting between dives to the floor of the shallow shelf seas (left panel). When sea ice recedes beyond the shelf break, haul-outs on land become more common (right panel). Source: NOAA.

seasonally migrant species (most whale types). Because sea ice has undergone rapid changes in response to recent atmospheric and oceanic forcing (Section 3.1), it enables weather and climate events to exert strong leverage on marine ecosystems in high latitudes. In this respect, sea ice loss is arguably a consequential "extreme event" in terms of its impacts on the marine ecology of northern regions.

4. Summary and recommendations

The preceding review has surveyed a variety of types of extreme events in northern regions and has highlighted the impacts on land, sea and the cryosphere. The review has encompassed studies that range from systematic analyses to somewhat subjective selection of events for analysis. While the published literature uses a diverse mix of criteria to identify extreme events, the review enables some conclusions about the state of knowledge of extreme events in northern areas, including recent trends and projected changes. In an attempt to synthesize the review, we provide the following assessment of ongoing (recent) and expected (future) changes in the occurrences of each of the 14 types of events surveyed here.

In Table 1, the evidence for ongoing changes is grouped into four categories: high, medium, low, and none. The confidence in future changes is grouped into three similar categories: high, medium, and low. While ratings assigned here represent "expert judgment", we believe that the reviews in the previous sections provide at least a qualitative (and in some cases quantitative) justification for the ratings. The table of ratings is provided in the spirit of a similar ranking by the NAS (NAS, 2016) of extreme events globally in a context of attribution.

Table 1
Assessment of evidence for recent trends or changes in extreme event types and impacts based primarily on observational evidence, and confidence in future changes based primarily on model projections. One, two and three dots denote low, medium and high levels of evidence (confidence), respectively. Absence of dots indicates that there is no consistent evidence for change.

	Evidence for change	Confidence in future change
Temperature	●●●	●●●
Precipitation	●	●●●
Snow	●●	●●
Freezing rain	-	●●
Atmospheric blocking	●	●
Cyclones	●	●
Wind	●	●
Impacts		
Sea ice (rapid loss events)	●●●	●●●
Greenland ice sheet (melt events)	●●	●●●
Flooding	-	●
Drought	-	●
Wildfire	●●	●●
Coastal erosion	●●●	●●●
Terrestrial ecosystems	●	●●●
Marine ecosystems	●	●●●

The review presented here has been limited to published studies that have utilized observational data and model simulations to evaluate variations and trends in various types of extreme events and impacts. The assessment of historical variations and trends has emphasized documentation rather than attribution, although the discussions of future projections were based on climate models driven by changing external (anthropogenic) forcing. Attribution studies of the historical variations are a priority in order to place the projected changes into a framework of reality checks. However, such studies–and indeed the evidence and confidence levels in Table 1–are subject to the limitations of the available observational datasets and climate models.

The observational datasets, among which we include reanalyses and other data assimilation products, often fail to capture local scale extreme events. Polar lows (Section 2.6), heavy accumulations of freezing rain (Section 2.4), and localized high-wind events (Section 2.7) are examples of extreme events that often "fall between the cracks" in today's in situ observing systems. Remote sensing offers substantial advantages for the identification of polar lows, but the details of the precipitation and wind distributions in these systems are not readily derivable from remote sensing. Even extreme temperature events are not reliably captured by today's observational products. The network of surface stations is sparse in high latitudes, so the most extreme cold and warm temperatures are unlikely to be directly measured. Moreover, reanalyses have been shown to have notable warm biases in their depiction of extreme cold events (Graham et al., 2019). The warm bias arises from the reanalysis models' inadequate vertical resolution of near-surface inversions that are often strong in cold stable airmasses, even in the most recent higher-resolution reanalyses such as ERA5 and the Arctic System Reanalysis (Graham et al., 2019). Limitations imposed by resolution are even greater in global climate models, which are used in many attribution studies. It follows that continued work on high-resolution multi-model assessments is essential, especially in the context of attribution and local-scale impacts of extreme events.

While higher-resolution models are a priority for understanding and attribution of high-impact local events, there is also a need for greater observational coverage. Increasing reliance on reanalysis products requires observations for not only routine assimilation, but also for benchmarking the accuracy of the reanalysis products. Moreover, observations required to assess ecosystem changes and impacts are seriously deficient, as the existing information comes from a relatively small number of intensive ecological observing sites, from occasional field programs, and from anecdotal evidence provided by residents. Many ecosystem impacts are sufficiently small-scale that they are not detected by existing observing networks. The surveys of nearly every type of extreme event and impact in Sections 2 and 3 were limited by the sparseness of direct observations, pointing to the need to factor extreme event detection into the design of high-latitude observing systems.

The reviews in the preceding sections have been absent of discussions of thresholds and tipping points. This absence reflects the general absence of studies of thresholds in the high-latitude system, including both its physical and ecological components. Potential thresholds and tipping points for abrupt changes in the Arctic have been highlighted in general surveys by Lenton (2012) and Duarte et al. (2012), but the linkages between extreme events and threshold exceedances have received little attention. Given the potential for high-impact thresholds to be reached during extreme events, the topic of thresholds in northern regions is emerging as another research priority.

Finally, the impacts of extreme events in the Arctic remain under-researched. As far back as the Arctic Climate Impact Assessment (ACIA, 2005), high-latitude changes and their impacts have tended to be discussed largely in terms of climatic averages. This tendency is especially apparent in future projections of change. By contrast, it is extreme events rather than changes in averages that often have the greatest impacts on ecosystems and humans in northern regions. In this regard, the topic of ecosystem impacts can serve as a convenient bridge between extreme events, thresholds, and their implications for vegetation, wildlife and humans. More generally, documentation of the impacts of extreme events on ecosystems and humans can serve to guide the priorities for further evaluation of changes in northern high-latitude extreme events.

Declaration of Competing Interest

None.

Acknowledgments

This review was prepared under the auspices of the Arctic Monitoring and Assessment Programme. Support for JW was provided by the National Oceanic and Atmospheric Administration through Grant NA17OAR4310160 and the National Science Foundation through Grant ARC-1602720, and for TV by the Academy of Finland through Grant 317999.

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