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Future Climate Change in the Northern Bering Sea

James E. Overland[1] | Muyin Wang[1,2]

[1]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA | [2]Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, Washington, USA

Correspondence: James E. Overland (james.e.overland@noaa.gov)

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Keywords: Alaska | Aleutian low | Arctic | Bering Sea | climate change | ecosystem shift

ABSTRACT

The Bering Sea is undergoing major changes from increasing winter temperatures to the north, extreme minimum sea-ice years in 2018 and 2019, through to an ecosystem reorganisation and negative impacts on communities' economic and subsistence food resources. These events have emerged under a global warming background, with positive feedback processes through a weakened atmospheric Alaskan Arctic Front (AAF) that promotes a self-reinforcing process of sea-ice loss, warmer air and sea temperatures, a wavy jet stream, and southerly winds. Interannual variability is still important: during 2021–2024 the Aleutian Low-pressure system was regionally dominant in supporting a strong AAF, and sea-ice conditions were observed close to the climatological mean. Before 2017, the AAF, consisting of cold dry air mass to the north and moist relatively warm air mass to the south, was a barrier to northward movement of storms, keeping the northern Bering/Chukchi seas with a cold Arctic climate. That historical situation is ending. Of critical importance is the probable reoccurrence of low Bering Sea sea-ice years over the next decades and related ecosystem impacts. We propose that radically low sea ice will have a frequency of one to three 2018-like low sea-ice events per decade in the coming two decades, based on a historical meteorological analysis and ensemble climate model projections. Arctic temperatures to the north are increasing, weakening their contribution to the AAF. A weakened AAF and low sea-ice years needs the winter Aleutian low pressure system to be far to the west of its average position, with southerly rather than northeasterly winds, warm years and low sea-ice extent. From 1948 to 2024 meteorological records, this western location occurred with a range of zero to three times per decade. Communities need to plan for a response to intermittent occurrence of 2018-like extreme sea-ice loss and their ecosystem impacts over the coming decades.

1 | Introduction

The Arctic continues to have extreme events such as wildfires, permafrost thaw, and sea-ice and glacier melt (Moon et al. 2019; Walsh et al. 2020; Overland 2022). Landrum and Holland (2020) conclude that the Arctic is transitioning from a stable cryosphere toward a different climate. In the northern Bering Sea, major oceanographic extreme events occurred during the low sea-ice winters of 2018 and 2019 with ecosystem impacts observed through 2021 (Siddon 2022; Hunt et al. 2022). There were connections from Arctic warming through record low sea ice, to a marine ecological reorganisation due to predatory fish moving northward, and to coastal communities' societal impacts (Overland et al. 2024). The occurrence of major sea-ice loss during 2018 and 2019 were extreme events relative to reconstructions back to 1850 (Walsh et al. 2017), and were earlier than projected by climate models (Wang et al. 2018). We propose that the climate of northern Bering and Chukchi Seas is now a combination of global warming and large interannual variability, with an increased frequency of extreme events over the next two decades. Because of the relevance to Bering Sea fisheries, Alaska economic development, and coastal communities, given future uncertainties, can we be semi-quantitative about future conditions of the northern Bering and Chukchi seas?

We take two independent approaches to project future minimum sea-ice years over the next decades. A first approach is based on historical meteorological data, specifically historical patterns of the Aleutian low-pressure system. We investigate the proximate cause for the record sea-ice minimums in 2018, concentrating on the importance of the weakening of the atmospheric Alaskan Arctic Front (AAF) (Polyakov et al. 2024). Sea ice in the Bering Sea historically is present from November through May through freezing and transport of sea ice southward by cold northly winds (Overland, Mofjeld, and Pease 1984). Such a pattern was interrupted during extended winter (January through March) 2018 and 2019. Stabeno and Bell (2019) and Thoman et al. (2020) discuss the ocean and sea-ice physics of these events. They note ocean warmth, late ice-cover development, and frequent atmospheric storminess were important factors.

The winter (January–February) AAF has been historically located in a west–east orientation near Bering Strait (Barry 1967) and is indicated by strong north–south gradients in temperature and sea level pressure (SLP). Before 2017, the winter AAF, consisting of cold dry air mass to the north and moist relatively warm air mass to the south, was a barrier to northward movement of storms, keeping the northern Bering/Chukchi seas with a cold Arctic climate (Serreze, Lynch, and Clark 2001). To assess recent minimum sea-ice events and potential frequency of a future weakening of the AAF, we investigate the variability and thus the uncertainty of Aleutian Low conditions from 1948 to 2024, noting when the center of the Aleutian Low is far to the west that would support southerly winds, warm temperatures, and low sea-ice extents (Serreze, Lynch, and Clark 2001). Data sources are NSIDC sea-ice analyses and standard atmospheric reanalysis products, that is NCEP/NCAR Reanalysis. See Data Sources at the end of the article.

The second independent approach is based on climate model results following Thoman et al. (2020) A major modelling advancement is the availability of multiple large ensemble simulations that provide for probability outlooks, accounting for inter-annual and internal atmospheric variability through small, but different, perturbations of their initial conditions (Kay et al. 2015; Thoman et al. 2020). After comparing these two approaches, we summarise applications.

2 | Results: Historical Analysis of the Northern Bering Sea Atmospheric Alaskan Arctic Front

A key northern Bering Sea climate variable is sea-ice extent that provides a barrier to heat loss in winter, ocean stratification in spring, and timing for many species and community activities. The Bering Sea is a location for a self-reinforcing process of joint sea-ice loss, warmer air and sea temperatures, a wavy jet stream, and southerly winds. Average sea-ice extent for the months of January–February is calculated from the monthly NSIDC analysis of satellite derived sea-ice indices south of Bering Strait, emphasising 2018 (Figure 1). Sea-ice extent was low in February and March for 2019. Note a maximum sea-ice year in 2012 and near the long-term average in 2022.

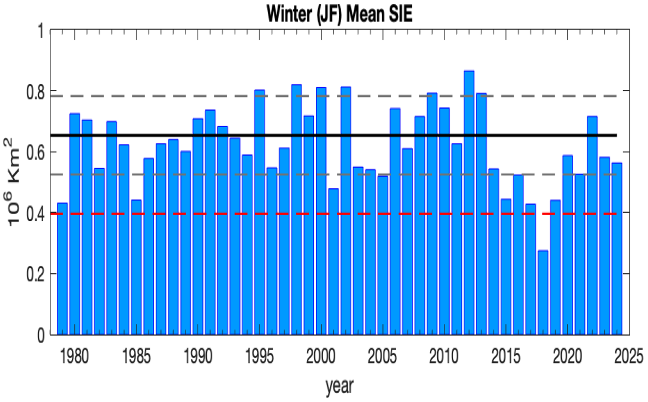

FIGURE 1 | Bering Sea winter (January and February) mean sea-ice extent (SIE in million km^2) from 1979 though 2024 during satellite era. The black heavy horizontal solid line indicates 1981–2010 period mean, the grey dashed lines indicate one standard deviation, and the red dashed line indicates two standard deviations away from the mean. Reliable estimates began in 1979 with the availability of satellite estimates. Data from NSIDC sea-ice extent monthly analysis.

An important meteorological feature for the Bering Sea region is the AAF. Lynch, Slater, and Serreze (2001) have multiple definitions for the AAF. We use the simple definition that uses sea-level pressure at a Beaufort Sea site (P1: 75° N, 170° W) minus those at an Aleutian low site (P2: 50° N, 170° W) following (Ballinger and Overland 2022; Overland, Wang, and Ballinger 2018; Cox et al. 2019; Overland et al. 2024). The proximate cause of low winter sea ice was the weakening of the AAF during 2017–2020, that is a weaker Beaufort High and a western Aleutian low position; there was reduced north–south gradient in SLP near Bering Strait (Figure 2A) and warmer winter Beaufort Sea temperatures (Figure 2B) (Ballinger and Overland 2022; Overland, Wang, and Ballinger 2018; Overland et al. 2024). Overland et al. (2024) show the strong correlation between AAF strength and Bering Strait winds.

The Aleutian low-pressure system can be described as the area enclosed by the 1000 hPa contour in the SLP field. Figure 3A shows the typical historical location of the Aleutian Low where the Aleutian Low center occupies both east and west of the international date line (180°). During the 2018 and 2019 low sea-ice years the Aleutian low center moved to the west of the date line (Figure 3B), in contrast to the long-term average SLP pattern (Figure 3A). Figure 3C shows winter 2020 and later with the return to an Aleutian Low-pressure region (dark purple) extending in a southern and eastern location along the Aleutian Island chain into Alaska and a north/south gradient near Bering Strait, similar to Figure 3A, typical of historical examples. This

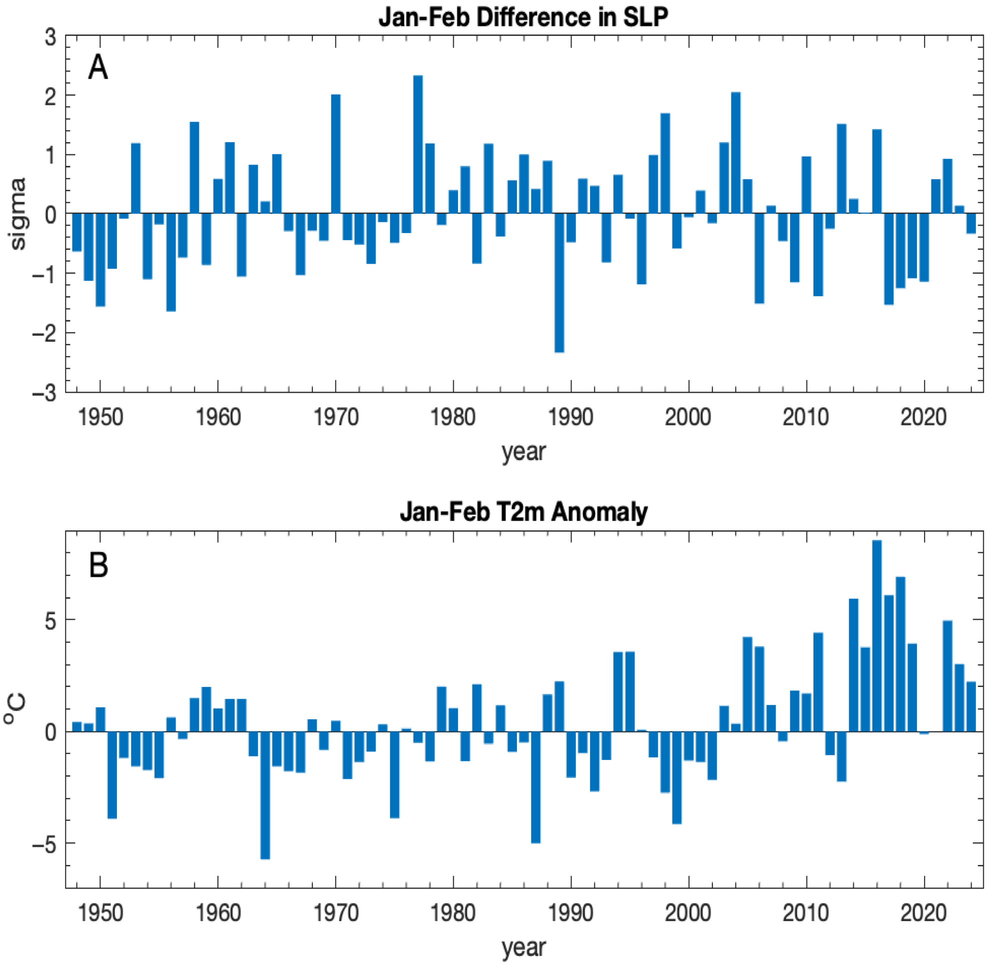

FIGURE 2 | (A) Winter (January and February) sea level pressure difference between a Beaufort High location (P1: 75° N, 170° W) and the Aleutian low domain (P2: 50° N, 170° W), shown as values normalised by the standard deviation. (B) Winter average Arctic surface temperature anomaly near the center of the Beaufort High pressure region. A dominate warming signal is obvious since 2004. Data based on NCEP/NCAR (NNR) reanalysis.

is reflected in the above SLP difference plot in Figure 2. Beaufort Sea temperatures and SLP were also greater in 2022–2024. Data in Figure 3A,B contrast in two ways. There continues to be a weaker Beaufort high-pressure region to the north. In 2018 and 2019 the Aleutian low was located well to the northwest, promoting a combination of southerly and southeasterly winds, warmer sea and air temperatures, and low sea-ice extents in the eastern Bering Sea. Our conclusions for the relative connection of the AAF to changes in the Beaufort High and Aleutian Low are further confirmed by Polyakov et al. (2024).

Looking forward in time what can be expected? Winter western Arctic warming is suggested to continue based on Arctic amplification in response to global warming (Figure 2B). Return to normal AAF years of 2021–2024 depended on the shifting southeastern position of the Aleutian Low (Figure 3C). Our analysis investigates meteorological analogues for the western location of the Aleutian low in the Bering Sea. The Aleutian Low can have a western center, be extended eastward, or split (Overland, Adams, and Bond 1999). Rodionov, Overland, and Bond (2005) demonstrates that warmer Bering Sea temperatures are primarily dependent on the west location of the Aleutian low center rather than on the intensity of central pressure or regional climate proxy indices such as the Pacific North American pattern (PNA). Additional authors have noted the importance of the western location of the Aleutian Low in the Being Sea on eastern Bering Sea wind patterns and temperatures (Niebauer 1998; Sasaki and Minobe 2005; Wang, Jing, and Guo 2023).

We start with an updated analysis of the winter (January and February) longitude of the low-pressure center of the Aleutian Low derived from the NCEP/NCAR reanalysis beginning in 1948 (Figure 4). Following Rodionov, Overland, and Bond (2005), cases with the Aleutian central pressure center south of 51°N are removed, that is those that have a more zonal wind pattern.

A west Aleutian low location criterion is set that the winter average (January and February) Aleutian Low central SLP location is centered to the west of 180° W (negative values in Figure 4). This is a stronger criterion than the warm Bering pattern (W1) of Rodionov, Overland, and Bond (2005) with their cut off for a west location of 173°W. There are eight major cases of the Aleutian Low center location west of 170°E (< -10 in Figure 4): 1949, 1969, 1973, 1989, 1999, 2011, 2018, 2019, out of the 18 cases

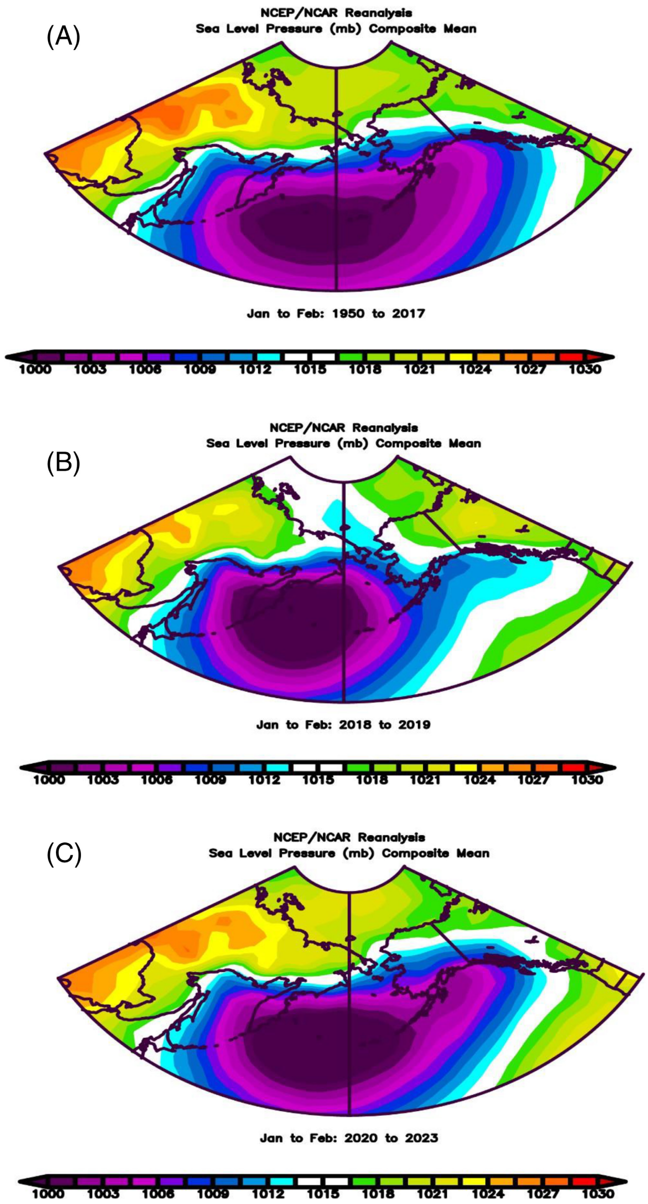

FIGURE 3 | Winter (January and February) sea level pressure pattern for (A) the historical period (1950–2017), (B) extreme low sea-ice years (2018, 2019) and (C) recent years (2020–2023) that show the contrast of center locations of Aleutian Low in different periods. Data are based on NCEP/NCAR reanalysis, using the plotting tool of NOAA Physical Sciences Laboratory.

west of the date line at 180°. Inspection of the timeseries shows that the contribution from a western location of the Aleutian low can be generalised to a range of zero to three cases per decade with no cyclic character.

Recent Arctic data (Figure 2B) suggests that the Beaufort High pressure region is not now a major factor for maintaining the AAF in most years due to a warmer Arctic (Polyakov et al. 2024). The more recent normal Bering Sea sea-ice years of 2022–2024 suggest that interannual variability is still important going forward for future projections. The years of 2022 has a southern Aleutian Low position and 2024 has an eastern position. Given the limited record of decadal events, numeration is a reasonable statistic to use. Overland et al. (2012) examined the 95-year air temperature record from St. Paul Island on the Bering Sea shelf and determined that sub-decadal warm and cold events are of a stochastic nature, consistent with a red noise model of climate variability. Based on historical analogues and interannual variability of the Aleutian Low Bering Sea cases, the best that can be done is to forward project a range of decadal Aleutian Low and resulting sea-ice extreme events: one to three cases per decade into the late 2020s and 2030s.

3 | Results: Climate Model Ensemble Calculations

An alternate approach is based on a review of modelling literature. Thoman et al. (2020) showed the probability that the 2018 sea-ice minimum will be exceeded is essentially zero through the 1990s, but increases to a 29% per year chance of occurrence in the 2030s, based on 40 simulations from CESM Large Ensemble (CESM-LENS) runs. To evaluate the attribution of climate change relative to the 2018 Bering Sea ice extreme anomaly, Thoman et al. (2020) employed monthly gridded sea-ice concentration from the CESM_LENS runs. CESM-LENS features fully coupled simulations with 40 ensemble members reflecting projected (2005–2100; RCP8.5) climate forcing. CESM-LENS sea-ice extent (Jahn et al. 2016) and sea-ice thickness (Labe, Magnusdottir, and Stern 2018) have shown fidelity to satellite observations post 1978. There are small differences between results for different greenhouse gas forcing scenarios over the next two decades (Kay et al. 2015). The number of contributing low sea-ice events from individual ensemble members ranged from zero to seven 2018-like occurrences during 2003 to 2033. The probability over all 40 CESM-LENS simulations is that the 2018 minimum will be exceeded in each decade was essentially zero per year through the 1990s, after which it increases to 6% in the 2010s, 14% in the 2020s, 29% in the 2030s, 52% in the 2040s, and 94% by the 2060s (Thoman et al. 2020). We add to the analyses by assuming that the ensemble fractions are yearly probabilities of occurrence over an entire decade and that each year is independent; calculating the cumulative binomial, one has a probability of 42% of two or more 2018-like events during the decade of 2020s and 83% during the 2030s (Binomial Distribution Probability Calculator; stattrek.com). Thoman et al. (2020) notes that the 2018 extreme event may become the mean Bering Sea sea-ice extent by the 2040s. Iida, Sugimoto, and Suga (2020) and Vavarus (2023, personal communication) also projected sea-ice free Bering Sea years in the next decades based on climate model results.

4 | Discussion

The future is inherently unpredictable, especially after rare events that are beyond previous records such as 2018 sea ice, and one should proceed with caution. Nevertheless, rational guidance, noting limitations, is relevant to decision making. We followed two independent paths. The first is based on an in situ climate: a continuing warming Arctic, historical analogues, interannual variability of the Aleutian Low, and Bering Sea sea-ice minimum cases. A second and independent modelling approach

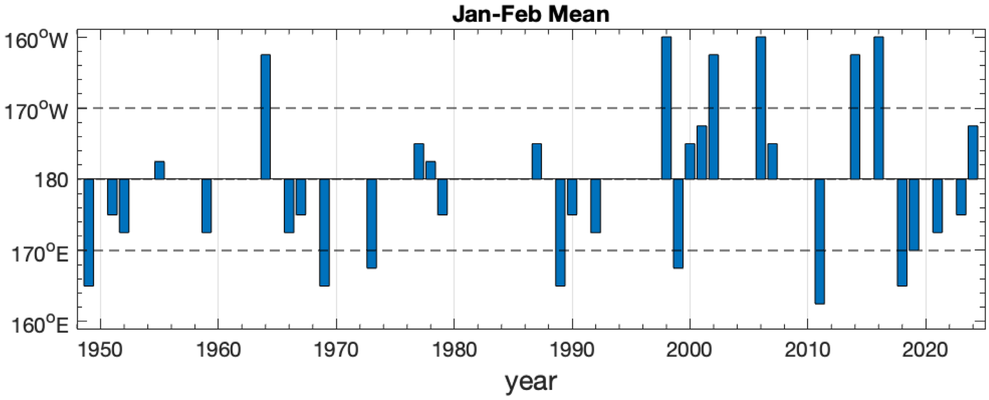

FIGURE 4 | Longitude of the winter (January and February) Aleutian Low central pressure location relative to the dateline (180°). Blank years show years when either the low center was located south of 51°N or the central pressure was above 1000 hPa. SLP data are based on NCEP/NCAR Reanalysis.

notes future large-ensemble climate model probabilities. Both approaches reasonably support a forward projection of one to three events of low sea-ice extremes per decade into the 2030s. The historical analogs have the shortcoming of assuming stationarity for forward decadal projection. It depends on the ongoing large contribution of internal atmospheric dynamics to the development of the Aleutian Low. Using the output of a model are subject to potential model deficiencies such as resolution of regional storm dynamics. We take positive support that both approaches confirm that sea-ice extreme events will not occur every year in the coming decades and that they both project that several events are probable.

Even given these rather limited *ad hoc* methods, one can conclude that coastal Alaskan Arctic communities should prepare for extreme intermittent events. Through scenario building (Shepherd 2021; Huntington et al. 2022) one can identify critical impacts and apply a sense of how these factors have interacted using models and the limited data from the past and might interact in the present and future. This approach depends on understanding and application of physical and ecosystem processes. Planners should adopt strategies and policies that are robust to alternative futures. Reduced sea ice allows higher storm surges to reach shore, and thawing permafrost makes the shoreline vulnerable to erosion. Delayed sea-ice freeze up during November is occurring during the period of fall storms. During a major fall storm in 2022, Typhoon Merbok had extensive flooding at Nome, Alaska, and adjacent coastlines. Emerging threats from warmer temperatures such as avian influenza and harmful algal blooms put in jeopardy subsistence practices of marine harvests of bird eggs, clams and seals. There is documentation of toxic algae in pinniped and cetaceans of the northern Bering Sea at levels that indicate potential health concerns/impacts (Lefebvre et al. 2022). Ecosystem reorganisation can have multi-year impacts following single year extremes, affecting fisheries (Hollowed et al. 2012; Stevenson and Lauth 2019; Wiese and Nelson 2022). One cannot wait for perfect knowledge to act. We suggest that 2018-type sea-ice minimum years and their ecosystem impacts will return within the next two decades, but will not occur every year. Part of the way forward is the collection of ocean, atmospheric, fisheries, biological, and societal data every year to further understanding of individual events.

Author Contributions

James E. Overland: conceptualization, formal analysis, writing – original draft, methodology, investigation, supervision, writing – review and editing, funding acquisition. **Muyin Wang:** conceptualization, data curation, formal analysis, visualization, writing – original draft, methodology, investigation, writing – review and editing, software.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Sea ice extent: NSIDC analyses: [https://noaadata.apps.nsidc.org/NOAA/G02135/north/monthly/]. Meteorological variables: NCEP/NCAR Reanalysis. [https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html]. For modelling data from CESM simulations refer to Thoman et al. (2020) and Kay et al. (2015).

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