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The Alaskan Arctic regime shift since 2017: A harbinger of years to come?

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Abstract

Recent fingerprints of Alaskan Arctic climate change include new weather patterns whose impacts propagate through the Alaskan marine ecosystem. Multiple lines of observational evidence draw attention to the last five years (2017-2021) as a remarkable period of change. Bering Sea winter and spring ice coverage was remarkably low in 2018 and 2019 associated with a shifted Aleutian Low (AL) into the western Bering Sea, and ridging of the overlying polar jet stream (PJS) that supported southerly winds and reduced ice growth. The climatological Beaufort High and associated Beaufort Gyre saw multiple winter-long collapses (2017 and 2020), the only two such events of the modern reanalysis era. In contrast, from 2012-2016 the AL and PJS were located southeastward across the Gulf of Alaska, which supported sea ice growth. The recent collocation of the exposed ocean surface and atmospheric anomalies supports the emergence of a regional atmospheric circulation response to sea-ice loss. We propose that the regional system shift after 2017 foreshadows the beginning of a period with an increasing frequency of major sea-ice loss events and associated impacts – floods, delayed spring blooms, and marine food chain disruptions – which is sooner than projected by climate models.

Keywords: Alaska, Aleutian Low, Beaufort High, Polar jet stream, Regime shift

1. The Alaskan Arctic climate in recent years

The Alaskan Arctic (**Fig. 1**) is one of the most responsive northern high-latitude regions to climatic forcing. Within the past decade warming across the ocean-atmosphere interface has been associated with unprecedented sea-ice change, along with enhanced interannual atmospheric variability. The Beaufort High (BH) and associated Beaufort Gyre, critical features in the pan-Arctic sea ice mass budget and transport, unexpectedly vanished for much of winter 2017 and 2020 amidst stormy weather patterns (Moore et al., 2018; Ballinger et al., 2021). Meanwhile, adjacent first-year ice formation and southward advance tend to be common, wintertime phenomena in the northern Bering Sea, but extreme Bering and Chukchi ice loss took place in winter 2018 *and unexpectedly again* during winter of 2019 with impacts on marine species and subsistence activities (Stabeno and Bell, 2019; Hauser et al., 2021). The absence of cold-season sea-ice cover effectively removes the turbulent heat exchange buffer between the ocean and the atmosphere and can affect synoptic processes. For example, upper-ocean heat transfer aloft to the atmosphere can raise the local air pressure, and provide additional energy to intermittent overlying ridges of high pressure in the polar jet stream. The amplification of these waves aloft are linked to wind patterns that advect frigid Arctic air southward into the lower-latitudes of downstream North America. The confluence of such surface-atmosphere interactions in the Alaskan Arctic has been associated with hemispheric-scale dynamical and thermal anomalies, such as the eastern North American cold winter of 2017-2018 (Tachibana et al., 2019; Iida et al., 2020). Winter ice loss has also been associated with a number of important factors, such as increased upward, turbulent heat exchange, decreased static stability, and increased horizontal wind shear, that can intensify cyclones within the Arctic environment (Crawford et al., 2022).

41 Several synthesis efforts documenting Alaskan Arctic climate change and various local
42 system-level impacts have been published in recent years (e.g., Ballinger and Rogers, 2013;
43 Wood et al. 2013; Overland et al., 2018; Danielson et al., 2020; Huntington et al., 2020). Short-
44 term atmospheric variability has been a key factor associated with such previous sub-decadal
45 warm and cold events of the historical record (Overland et al., 2012). A warm pattern emerged in
46 2014 over the ocean and adjacent terrestrial Alaska (Overland et al., 2018) with the 2014-2018
47 period marked by dramatically warmer upper ocean and lower tropospheric temperatures than
48 the respective climatological means (Thoman and Walsh, 2019; Danielson et al., 2020). This
49 recent Alaskan Arctic warming period has been connected to local atmospheric patterns and
50 processes. Danielson et al. (2020) noted strengthening of the region's ocean-ice-atmosphere
51 feedback loop and thus its memory evident in consistent physical processes since 2014. For
52 example, reduced spring sea ice has led to enhanced summer solar radiation absorption that
53 increased upper-ocean temperatures and induced elevated ocean-to-atmosphere heat fluxes and
54 amplification of autumn Pacific Arctic air temperatures with possible effects on regional cyclone
55 activity. More recently, observations suggest such an array of processes have persisted through
56 the climatological freeze period and winter season, precluding south-central Bering Sea ice
57 formation in 2018 and 2019. The unprecedented inertia of mechanisms that span the annual cycle
58 have brought about a plethora of consequences that emanate through the region's socio-
59 ecological system (Huntington et al., 2020; Hauser et al., 2021).
60 Multiple extreme events have taken place in the Alaskan Arctic during recent years
61 signaling that a regional climatic regime shift may be underway. In this paper, we turn attention
62 toward the 2017-2021 abrupt cold season changes that have occurred by evaluating atmospheric
63 observations and documenting the magnitude of these shifts relative to sub-decadal changes

64 documented in previous reports. We focus on recent winter (January – March) variability of key
65 climatological features compared with historical observations, particularly the Aleutian Low
66 (AL), BH, the pressure gradient defined by their co-variability, and the overlying polar jet stream
67 (PJS). Our goal is to offer atmospheric context and identify regional-scale climatic linkages
68 underpinning recent changes within the Alaskan Arctic system.

69 *2. A possible recent regime change in the Bering Sea*

70 An unparalleled lack of sea ice occurred in the Bering Sea during winter 2018. This event
71 cascaded to major impacts: flooding due to longer open-water fetch, delays in the spring blooms,
72 and bottom-to-top ecosystem changes from the food supply for the normally large fishery to lack
73 of sea ice habitat for walrus and ice-dependent seals (Duffy-Anderson et al., 2019; Hauser et al.,
74 2021; Mahoney et al., 2021). Winter 2018 was followed by a similar sea-ice-free event in 2019.
75 One sea-ice loss event was rare, but back-to-back events were statistically unexpected; it is
76 difficult to maintain that the second event was climatologically random.

77 For comparison to winters 2017-2021, sea-level pressure (SLP) fields averaged for
78 winters 2012-2016 (**Fig. 2a**) show the climatological atmospheric Arctic pressure gradient front
79 that supports a north–south thermal barrier north of the Bering Strait (Overland et al., 2018).
80 Associated with this pattern are strong, cold northeasterly winds that grow and advect sea ice
81 southward over the central Bering Sea. The AL center is well to the south and extends west to
82 east along the Aleutian Island chain, and the BH is well-established north of Alaska. In contrast,
83 for the recent winters (2017-2021) the AL is centered over the northwestern Bering Sea
84 supporting southerly winds over the eastern Bering Sea (**Fig. 2b**). The center of the BH is weak
85 and located further east, north of the US-Canadian border. Winters 2020 and 2021 were in fact

most similar to 2018 and 2019 in their position for the AL, but with a stronger north-south pressure gradient north of Bering Strait.

Recent sea ice extents reflect southerly wind patterns (**Fig. 3**). The two lowest winters (**Fig 3a**) and annual cycles of sea-ice extent occurred in 2017-2018 and 2018-2019 (**Fig. 3b**). During these winters, sea-ice extent dipped 101% and 75%, respectively, below the climatological mean and continued the recent period of abrupt ice loss. The dashed blue line representing 2020-2021 shows that the recent year's sea ice growth slowed after January (**Fig. 3b**). The southern Bering Sea was under the influence of the AL while the northern Bering Sea behaved more like a typical winter. Growth of sea ice in winter 2019-2020 also started slowly and retreated in March.

One cause of the transition before and after 2017 is seen in the steering-level winds at 500 hPa (**Fig. 4**). For 2012-2016 (**Fig. 4a**), the jet stream is located well south of the Bering Sea and to the east over southeastern Alaska. Geopotential height gradients are weak over the Bering Sea allowing the strong climatological surface high pressure to develop. In contrast, for 2017-2021 (**Fig. 4b**) the jet stream is located southward from Bering Strait. Surface low pressure in the northwestern Bering Sea is supported at 500 hPa by the lobe of low geopotential heights over Kamchatka. The large-scale, pan-Arctic atmospheric circulation pattern does not shift over the 2010-2021 period with the centers of both the tropospheric PJS (500 hPa) and the stratospheric polar vortex (100 hPa, not shown) shifted off of the pole toward central Asia, with a lobe of low geopotential heights toward the Sea of Okhotsk.

What is to be made of 2018 and subsequent events? Winter 2018 was certainly unexpected, followed by its impact on the ecosystem and human populations, both local (coastal communities) and distant (fisheries). Even less expected were the back-to-back 2018 and 2019

winter events given the large year-to-year variability of regional weather systems. Winter 2021, and to a lesser extent 2020, had physical features reminiscent of winter 2018 with less sea ice and a westward shifted AL. Contrasting 500 hPa height fields gives some indication of a shift over the Bering Sea to a more northerly-located jet stream. Less Bering Sea ice and warmer ocean temperatures could help to increase the geopotential thickness and thus disrupt the orientation of the wind pattern akin to documented mechanisms of the Barents Sea region (Sorokina et al., 2016). Over the record of hydrographic profiles beginning in 1966 on the Bering Sea shelf, 2020 likely marked the seventh consecutive year of positive water column temperature anomalies in the region (Danielson et al., 2020; Danielson, personal communication, 2021). That there are no shifts in the large-scale weather pattern *beyond this region* supports the Bering Sea events as having local thermodynamic causes. Given the history of winters 2017-2021, one can expect a future increase in the frequency of such events and their impacts. Early winter 2021-2022 shows an example of a southern location of the PJS and the earliest Chukchi sea ice advance since 2012 (Thoman, personal communication, 2021); it highlights the continuing importance of large-scale atmospheric interannual variability to the region.

3. Unprecedented Beaufort High variability in recent years

The BH pattern is a key, year-round feature in the surface pressure field of the Alaskan Arctic (Ballinger and Sheridan, 2014). However, recent years have seen a decline in both BH occurrence and extremes (**Fig. 5**). Winter uncharacteristically stands out in part due to BH collapse in 2017 when the pressure pattern and its associated anticyclonic winds and ice motion over the west Arctic were absent perhaps for the first time (in the reanalysis record) through the duration of the season (Moore et al., 2018). A follow-up winter BH collapse occurred in 2020, marked by the lowest March SLP (~1009 hPa) on record (Ballinger et al. 2021). Increased storm

activity at the expense of BH patterns in the Alaskan Arctic was a common thread across the anomalous winters of 2017 and 2020. Enhanced cyclone occurrence into the region was aided by the aforementioned PJS configuration and southerly wind regime across the Bering Sea.

Additional historical context to the BH pattern over the 2017-2021 period is provided in **Fig. 5**. The two anomalous winter cases in 2017 and 2020 are defined by at least 20 fewer BH days (i.e., days where SLP>1013 hPa) and 10 fewer BH extremes (i.e., days where SLP $\geq 1\sigma$ above the 1981-2010 mean and standard deviation; **Fig. 5a,c**) than climatology. Winter 2018 saw a return to above-normal occurrence of BH days (+12d) followed by a sharp reduction in 2019 (-13d), and both years had below-normal occurrences of BH extremes. In 2018, the southerly surface winds along the west flank of the BH supported poleward warm air advection through the Bering Strait and low ice cover. In 2019, decreased BH presence coupled with the westward-displaced AL promoted southerly flow that propagated storms into the Alaskan Arctic, allowing low Bering ice cover to once again persist. BH hallmark collapse winters in 2017 and 2020 followed by anticyclone re-emergence in 2018 and 2021 collectively encompasses a sub-decadal 5-year period of unprecedented BH variability within the reanalysis record (**Fig. 5b,d**).

4. Changes in the Beaufort and Bering Seas reflected in the regional pressure gradient

A synergistic relationship exists between the AL and BH variability at weather-to-climate timescale scales (Cox et al., 2019). Mechanistically, when the AL is shifted westward and the BH is simultaneously centered over the Beaufort Sea, weakened, or even absent as in much of winter 2017 and 2020, southerly winds supported by these configurations allow relatively warm, moist flow and storm systems to propagate across the Bering Sea and into the Alaskan Arctic. Conversely, if the AL is present in the western Bering Sea but the BH is shifted west over the Chukchi Sea, the resulting poleward air transport through Bering Strait is blocked from entering

155 the Alaskan Arctic as in winter 2021. The covariability of these weather patterns affect processes
156 such as sea-ice melt rates and timing as well as snowmelt over terrestrial western Alaska (Cox et
157 al., 2019). In preceding sections, we showed that a change in AL position and BH occurrence
158 were both anomalous with regards to the recent string of winter seasons. The co-variability of
159 these features are further investigated by analyzing the region's winter pressure gradient across
160 the latitudinally intersecting Arctic front at three atmospheric levels: the surface (i.e., SLP), mid-
161 troposphere/PJS level (i.e., 500 hPa/z500), and lower stratosphere polar vortex level (i.e., 100
162 hPa/z100). A simple approach defines these gradients, modified from Cox et al. (2019), by
163 taking the difference of a level-specific gridpoint value within the climatological BH domain
164 (P1: 75°N, 170°W) from that in the AL domain (P2: 50°N, 170°W; as referenced in **Fig. 1**).
165 The pressure gradient analyses in **Fig. 6** support the recent regime changes with regards
166 to the AL and BH. The SLP gradient in recent years is remarkably weak reaching a 5-year
167 minima in 2017-2021 highlighted by little difference in pressure between the Beaufort and
168 Bering Seas in 2020 when the BH collapsed (**Fig. 6a**). The upper-air and surface pressure
169 gradients exhibit co-variability as z500 and z100 winter minima also occurred in 2020 with
170 record or near-record 2017-2021 means (lowest and 5rd lowest 5-year means, respectively; **Fig.**
171 **6b,c**). Through time, the SLP gradient is more tightly coupled with the PJS ($r=0.92$, $p<0.05$) than
172 the lower stratosphere ($r=0.65$, $p<0.05$). Though the recent structure and intensity of the
173 stratospheric polar vortex is linked with negative (positive) surface pressure anomalies and BH
174 collapse (amplification) in 2020 and 2021, respectively (Lawrence et al., 2020; Mallett et al.,
175 2021), the long-term association points toward tropospheric dominance of the PJS on the large-
176 scale AL and BH pattern. The stronger linkage of the surface with the middle troposphere
177 relative to the stratospheric polar vortex across time suggests that the recent Alaskan Arctic

178 regime shift, characterized by anomalous atmospheric conditions in 2017-2021, is closely tied to
179 a potential ocean-atmosphere feedback between the warm ocean/thin ice, southerly atmospheric
180 circulation pattern, and associated storm activity.

181 *5. What to make of the present Alaska Arctic regime and what it may imply in the near term*

182 Studies have noted sub-decadal shifts in the Alaskan Arctic climate through the 20th and
183 into the 21st century independent of the phasing of low-frequency, large-scale climate modes
184 such as the Pacific Decadal Oscillation (Overland et al., 2012). However, the broader question
185 has been left relatively open-ended as to whether these climate shifts in regional atmospheric
186 pressure anomalies associated with AL and BH dynamics and their interactions were/are a
187 product of random internal weather variability, a limited-memory red-noise process, ongoing
188 Arctic change, or some combination. In recent years, unusual synoptic activity categorizes 2017-
189 2021 as a climatic shift relative to previous cases. As evidence, the position and magnitude of
190 atmospheric and sea ice anomalies, including westward-displaced AL patterns and low pressure
191 permeating across the Alaskan Arctic that subsumed the climatological BH and thus typical ice
192 motion in the Beaufort Gyre in 2017 and 2020, stand as unprecedented in the reanalysis record.

193 Freeze-up evaded much of south-central Bering Sea in winter 2017-18 and 2018-19, and
194 anomalous open water areas and southern ice edge positions exceeded even 2030-2044 ensemble
195 mean freeze projections from phase 5 of the Coupled Model Intercomparison Project (Wang et
196 al., 2018). These future projections of ice loss were mainly attributed to thermodynamic
197 processes with wind-driven forcing playing a secondary role. Warm ocean conditions and low
198 Bering ice coverage in 2016-17 to 2018-19 coincided with more frequent and persistent periods
199 of southerly flow (Stabeno and Bell, 2019). We suggest that continued Alaskan Arctic ice loss
200 through the winters of 2020 and 2021 was linked to the confluence of these relatively localized

ocean-atmosphere conditions. While not accounted for in our analyses, other factors such as a diminished Bering cold pool and increased northward heat flux of Pacific water were also important contributors to this recent regime shift (Danielson et al., 2020; Polyakov et al., 2020; Stabeno and Bell, 2019).

Atmospheric extremes underscore the anomalous 2017-2021 period in the Alaskan Arctic. However, as the Arctic continues to rapidly change, a related, open question is to what extent that low ice coverage impacts the strength of the winds and associated atmospheric heat transports into this region? Alkama et al. (2020) applied a causality approach to reanalysis data (1979-2018) and found a linkage whereby winds robustly influence sea-ice loss, but the ice loss also enhances Pacific Arctic winds at a lag of four months. However, recent, rapid sea-loss losses may be reducing such purported lagged effects on the overlying winds. In their examination of future model projections (2071-2100) from the Community Earth System Model Large Ensemble, Mioduszewski et al. (2018) attributed a poleward-shifted storm track, deepened winter SLP, and increased 10-m winds across the Alaskan Arctic to diminished coverage of attendant local sea ice (see their Fig. 5 and 10). Observational evidence suggests that atmospheric changes associated with changing Alaskan Arctic winter ice conditions that were thought to be decades away may now be common features of the current climate regime. As this manuscript is written, early winter 2021-22 provides another case of the regional impact of large-scale PJS variability with a southward displaced North Pacific jet allowing northerly winds to advect and grow sea ice more rapidly in the Chukchi and northern Bering Seas. This PJS configuration, with analogous cases during years prior to 2017, underscores the key role of synoptic wind patterns when local forcings (i.e., above-freezing sea surface temperatures and a retreated ice edge) are not dominant. Despite the importance of large-scale winds in modulating

Arctic surface-atmosphere interactions, meridional PJS features tend to be underestimated in climate model hindcasts, limiting the portrayal of such phenomena in the future under accelerated Arctic change (Smith et al., 2020).

In summary, we propose that an era of new and prolonged extremes is underway in the Alaskan Arctic. Accelerated open water and thin ice areas flanking the region's southern pack ice boundary since 2017, thought to be decades away, is already impacting the magnitude and persistence of regional weather/climate regimes, including southerly winds and storm systems. Complex ocean-atmosphere interactions, largely attributed to internal variability, have been linked to regional extremes through 2018 (e.g., Overland et al. 2018; Tachibana et al., 2019; Danielson et al., 2020). Since then, unparalleled atmospheric, oceanic and sea-ice extremes have continued to transpire, signaling a new Alaskan Arctic weather regime with an increase in the interannual frequency of warm events that will be ongoing over the next decade and propagate through the region's physical-ecological-human system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

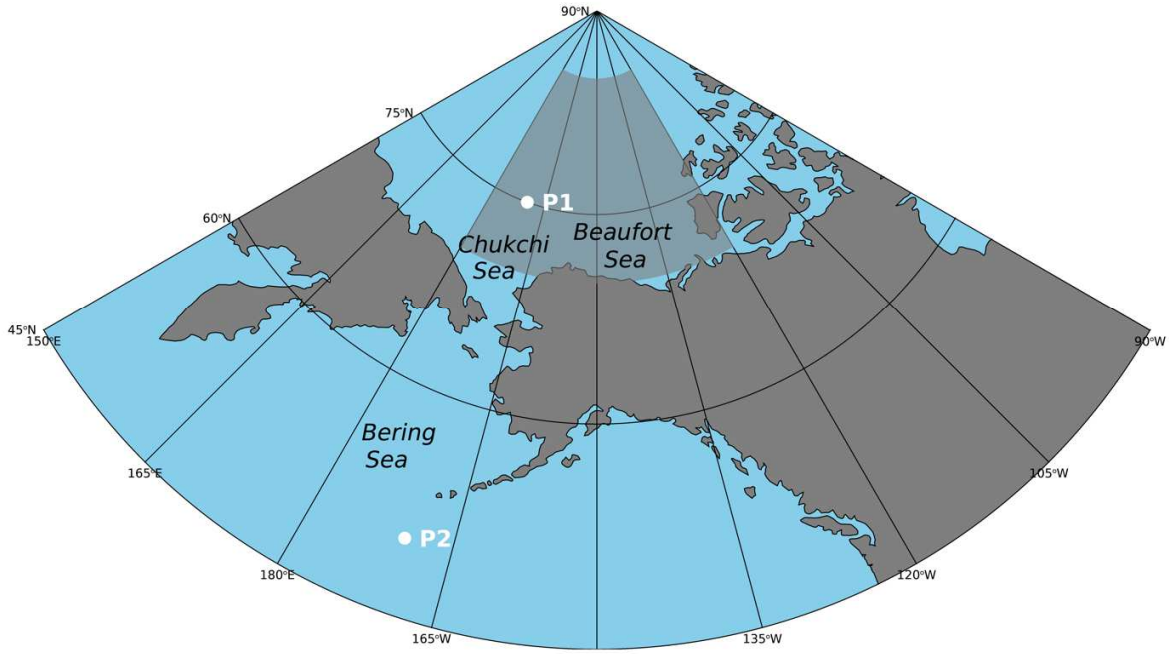

Fig. 1. Map centered on the Alaskan Arctic study area. The main focus regions are labeled as are the Beaufort High analysis domain (light gray shaded polygon) and SLP grid points (white dots labeled P1 and P2) for which analyses are presented in **Fig. 5 and 6**, respectively.

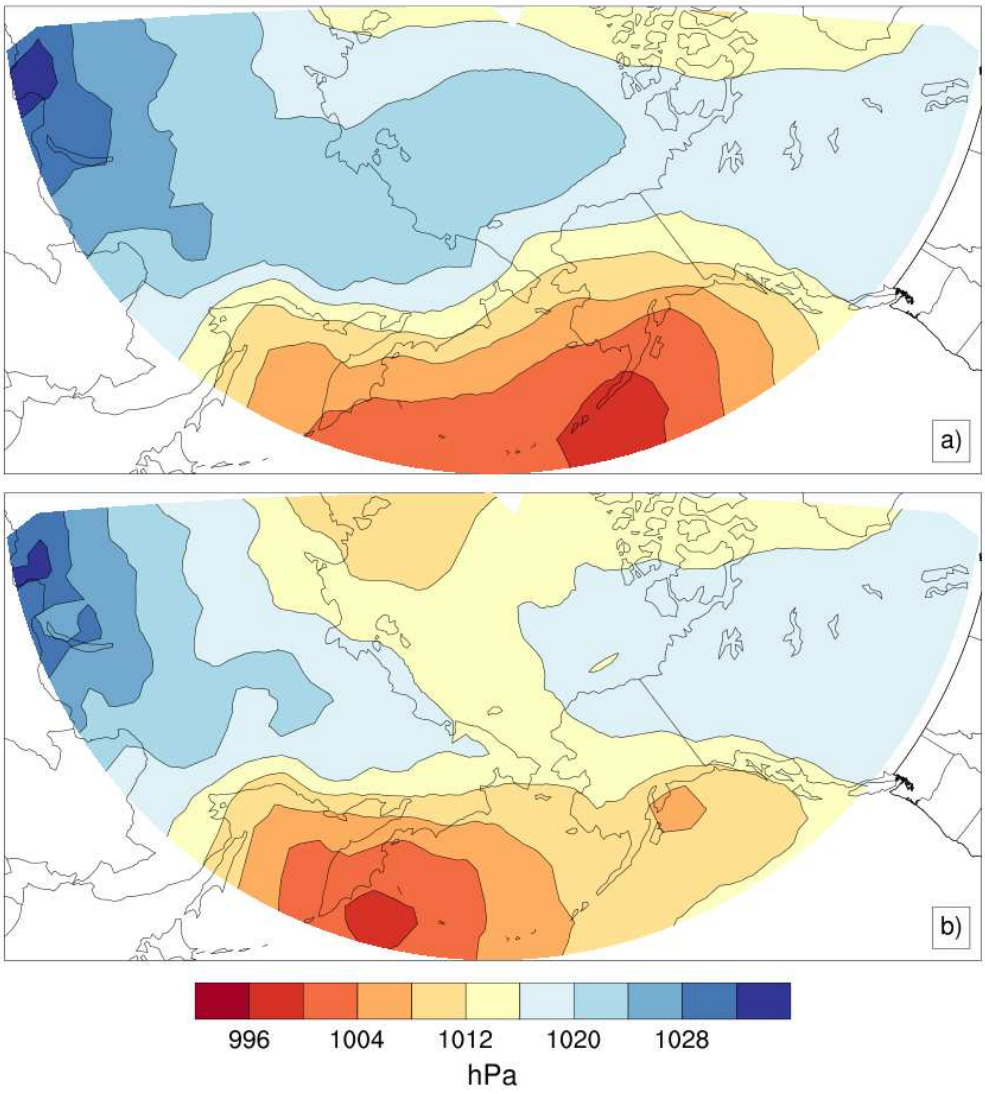

Fig. 2. Mean sea-level pressure (SLP) fields for two distinctly different atmospheric regimes. Winter (January – March; JFM) SLP is shown for 2012-2016 in a), and for 2017-2021 in b). Note the westward shift of the Aleutian Low in the more recent period. SLP data are from NCEP/NCAR reanalysis (Kalnay et al., 1996).

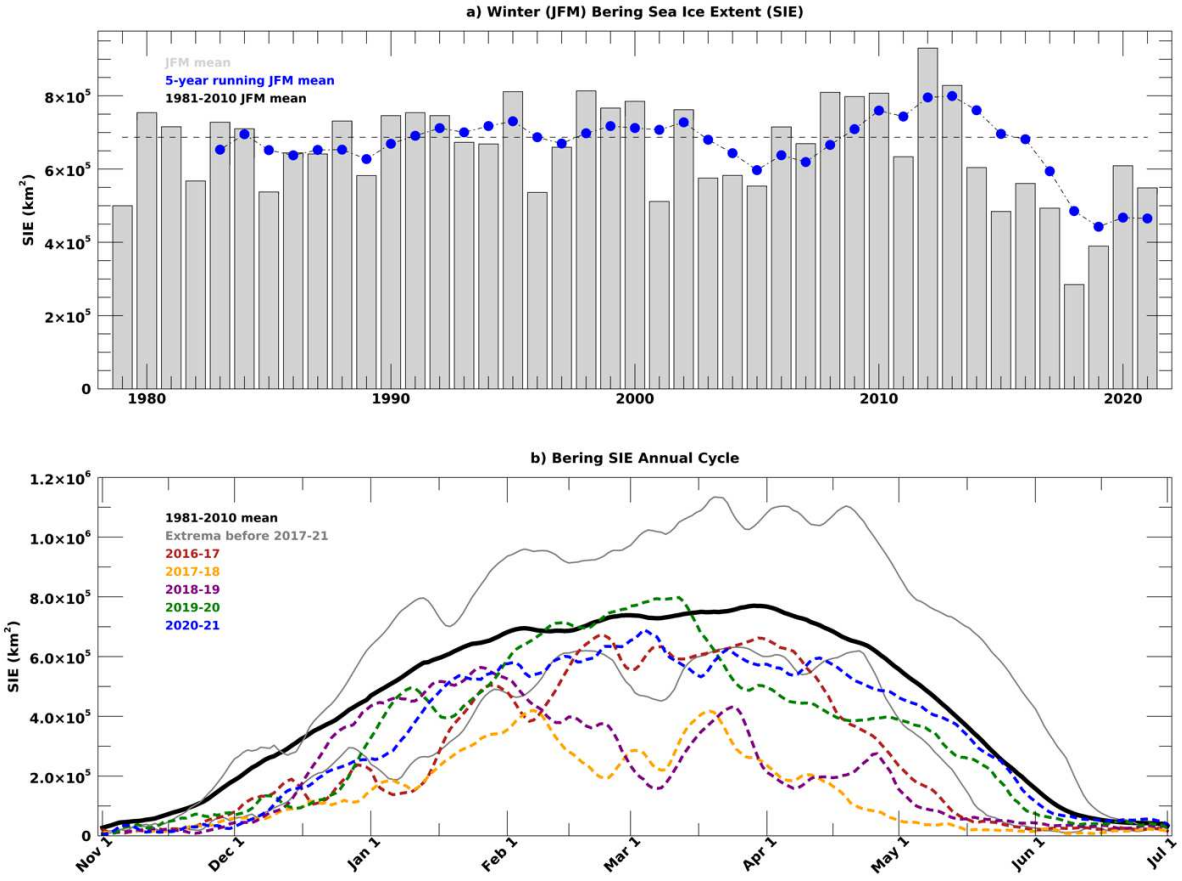

Fig. 3. Bering Sea ice extent (SIE; in km^2) from 1979-2021. In a) winter (JFM) SIE is shown with the running five-year mean and 1981-2010 climatology overlaid. The Bering SIE annual cycle is presented in b) for the 1981-2010 mean, winter extrema before 2017-21 (i.e., highest (lowest) JFM mean SIE in 2011-12 (2014-15)), and the last five annual cycles, 2016-17 to 2020-21. Data are from the Sea Ice Index obtained from the National Snow and Ice Data Center (Fetterer et al., 2017, updated daily).

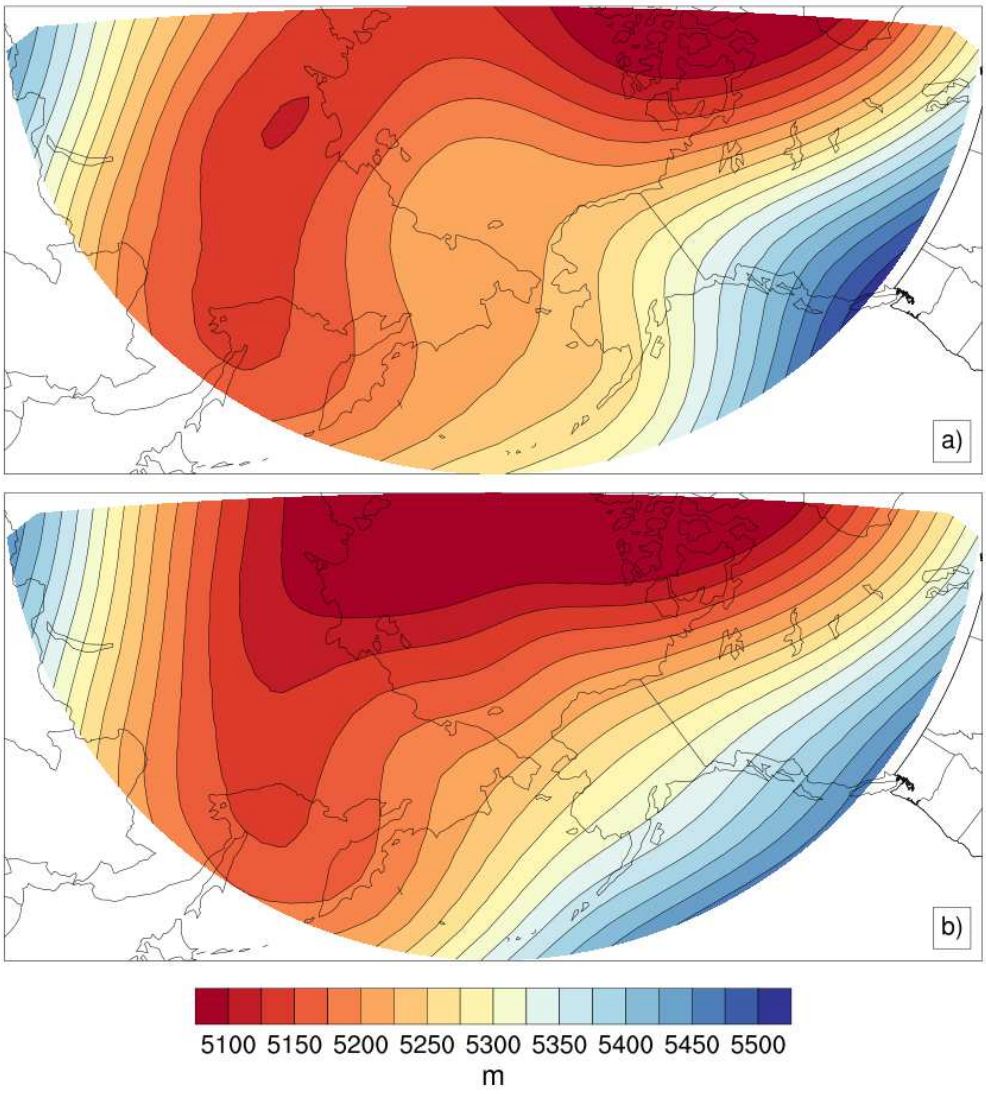

Fig. 4. Mean 500 hPa geopotential height fields (i.e., z500; in meters (m)) for the same periods isolated in **Fig. 1**. The winter (JFM) z500 field is shown from 2012-2016 in a), and for 2017-2021 in b). Geopotential height data are from NCEP/NCAR reanalysis.

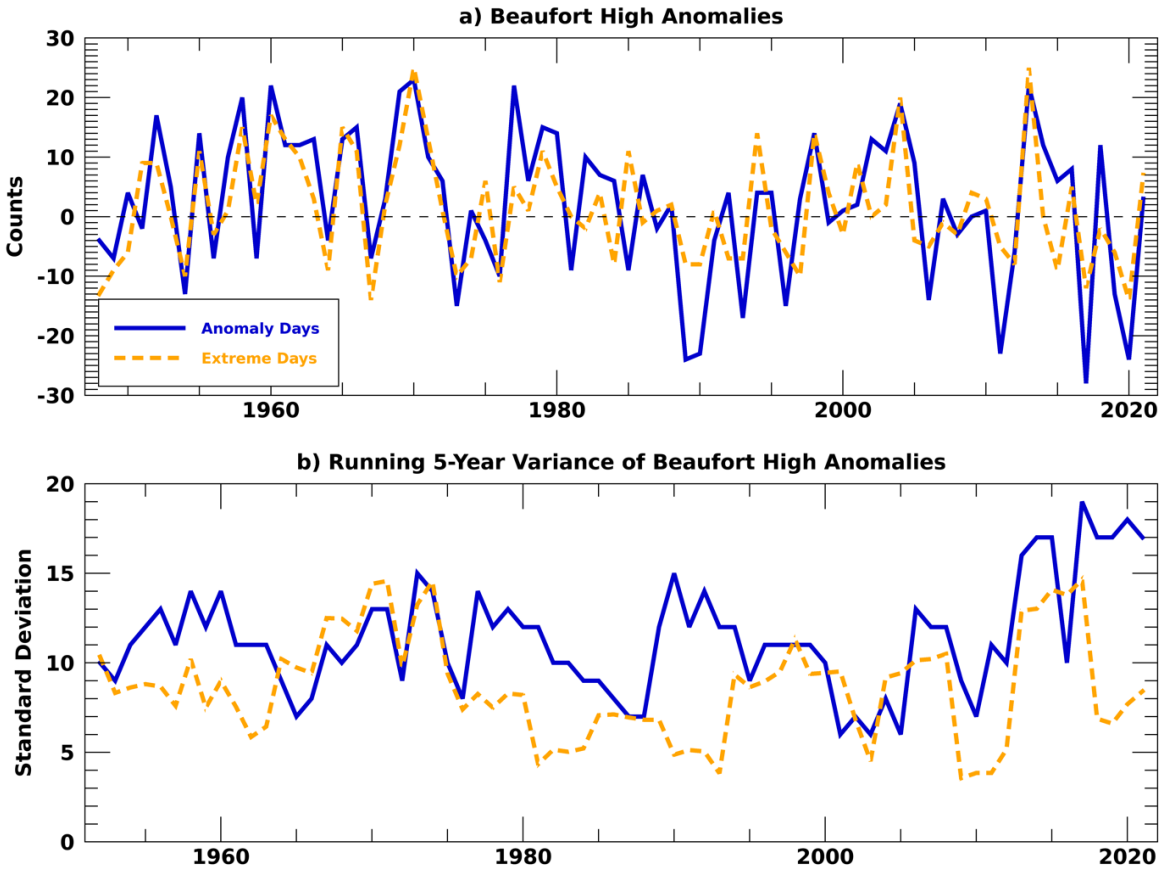

Fig. 5. Winter (JFM) Beaufort High Anomaly and Extreme Day counts and variability. Statistics are calculated for SLP data aggregated across the gray shaded area in **Fig. 1**. In a), counts are shown for Beaufort High (BH) Anomaly Days (blue line) and for BH Extreme Days (dashed orange line). A BH Anomaly Day is defined as such when daily SLP > 1013 hPa, while a BH Extreme Day is determined when daily SLP is ≥1σ from the 1981-2010 daily mean. These days are summed across the winter season, and both time series are presented with respect to the 1981-2010 seasonal mean counts. In b), a running five-year standard deviation is applied to each time series in a). For example, the 1952 values represent the running variance from 1948-1952 and the 2021 values are similarly calculated for the 2017-2021 period. Data are from the NCEP/NCAR reanalysis.

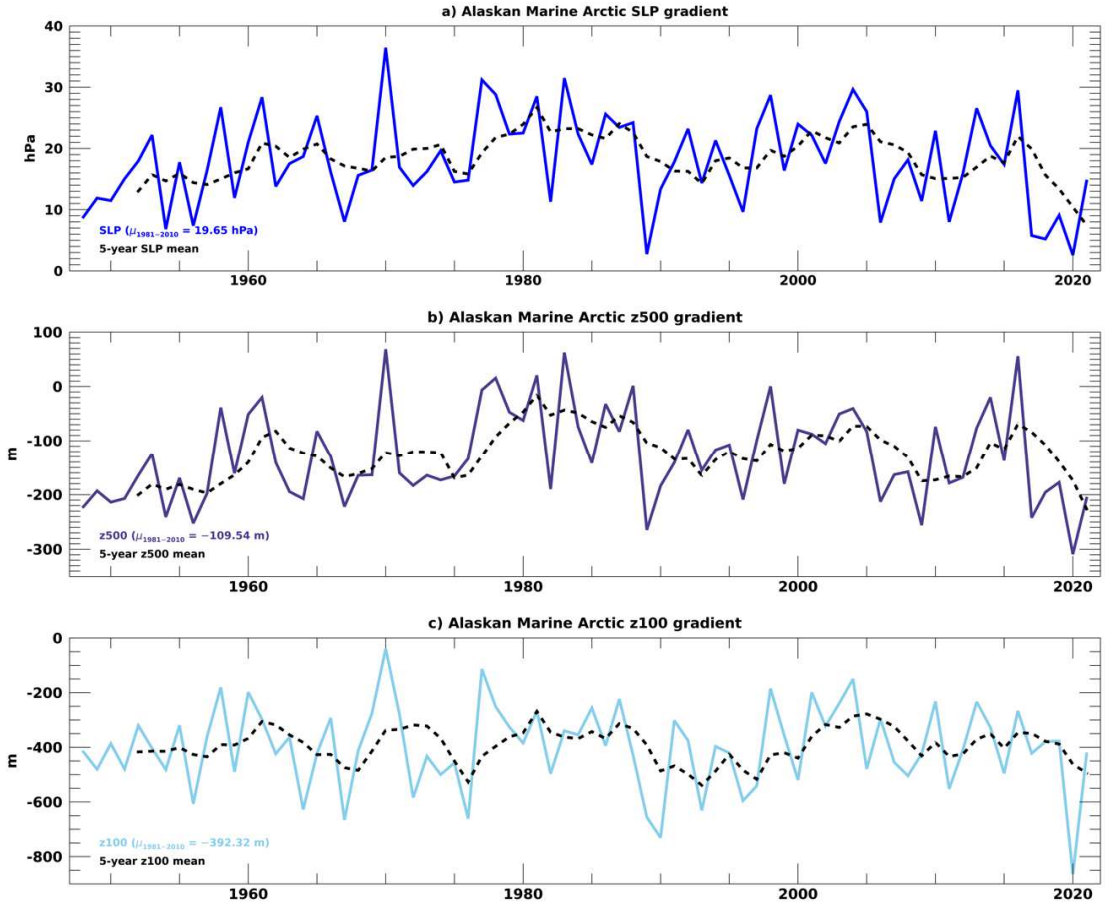

Fig. 6. Winter (JFM) pressure gradients across the Alaskan Arctic. The gradients (solid lines) and corresponding 5-year running means (dashed lines) are shown across the Alaskan Arctic at three pressure levels: a) surface (i.e., SLP), b) 500 hPa (i.e., z500), and c) 100 hPa (i.e., z100). These gradients are calculated from P1 – P2 as shown in **Fig. 1**. Notice the pressure decrease in all three time series to record or near-record minima in the 2017-2021 era. The 1981-2010 climatological mean (μ) gradient for each level is listed in each plot for reference. Data are from the NCEP/NCAR reanalysis.