

Research Article

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# Coastal Sea-Ice Break-Up Events in Beringia

## Abstract

We quantify changes in break-up events of landfast ice in the transition from a perennial to a seasonal sea ice cover in the Arctic. A break-up event is defined as a time when coastal sea ice concentration drops below 95% after a minimum period of 10 days of stable ice conditions. To this end we analyze output diagnostics from the Community Earth System Model (Version 1) – Large Ensemble from 1920 to 2080, focusing on six coastal communities of Alaska, Chukotka, and the Kamchatka Peninsula: Utqiagvik, Point Hope, Gambell, Novoye Chaplino, Sireniki, and Pakhachi. Model results generally agree with the satellite record with open water formation along the coastline associated with sustained offshore winds, although the sensitivity of CESM1-LE is higher than that of observations due to the absence of a landfast ice parameterization in CESM1-LE. Specifically, we see a linear relationship between the magnitude of the opening and offshore surface wind stresses integrated over the 10 days prior to the opening event, ( $p$ -value < 0.01). While the break-up event frequency increases ( $5.53 \times 10^{-5}$  events/day/year for Utqiagvik) in the 21st century due to the thinning, or weakening, of the landfast ice cover, the total number of winter break-up events decreases due to a shortening of the winter season (mean of -5.3 days/decade).

## Introduction

The Arctic is home to approximately 4 million inhabitants<sup>1</sup>, spread out across seven countries. Landfast ice, defined as sea ice that is fastened to the shore or ocean floor, is an important part of Arctic coastal ecosystems<sup>2</sup>. Arctic communities often depend upon local landfast ice for daily activities such as hunting and fishing<sup>3</sup>, transportation, and recreational activities and thus have an intimate relationship with sea ice. While large-scale mean changes in Arctic sea ice have been studied extensively (e.g.<sup>4–8</sup> etc.), of more immediate use and concern to local peoples<sup>9</sup> are small-scale spatial and temporal changes, which have received less attention. Understanding the changes in the stability and predictability of landfast ice for instance<sup>10</sup>. The Arctic has had perennial ice cover since at least the mid Holocene Climactic Optimum<sup>11</sup>, and is expected to transition to seasonal cover before the mid 21st century<sup>4,5</sup>. It is therefore important to better understand this transition, which is likely too rapid for local communities to adapt to without severe social and economic stress.

Despite its name, landfast ice is very much a dynamic system, and understanding those dynamics is key to ensuring the safety and well-being of those who depend on it. In this study, we investigate break-up events<sup>10,12–14</sup>, which is the phenomenon where a portion of landfast ice breaks away from the coast during winter, forming an area of open water, followed by the closing of the pack ice several days later. These events are important to understand because they can create unsafe conditions for residents engaging in activities on the landfast ice, including becoming stranded on ice that has become a drifting floe. There has been some previous work investigating break-up events, sometimes named breakout events, but much of this work has either been focused on spring break-up rather than mid-winter events (e.g.<sup>15,16</sup>), or single events<sup>10,12–14</sup>, and mostly using a qualitative definition. While these studies characterized the general mechanisms behind break-up events such as wind forcing, ocean currents, and sea level change among other things, the overall understanding is by no means comprehensive. There has not been a study with the same goals as ours: exploring the use of models to study break-up events, and investigating future trends.

Few communities have local landfast ice monitoring systems in place (e.g. Utqiagvik, Alaska<sup>10</sup>), but such monitoring systems do not provide infor-

mation on future events or trends. In this study we look at decadal projections in the number of break-up events in coastal communities of Beringia (see Fig. 1), and at physical mechanisms responsible for break-up events. Models are an invaluable tool in climate science since they allow us to predict future trends, but some argue that the results involving landfast ice should be interpreted with caution<sup>17,18</sup> as landfast ice is difficult to model. However, since ground and satellite data on landfast ice is severely limited in terms of both spatial and temporal scale, the use of models is important to understand this phenomenon.

To this end, we analyse changes in simulated sea ice concentrations from the Community Earth System Model (Version 1) – Large Ensemble (CESM1-LE) and passive microwave observations.

## Data

### Passive Microwave Data

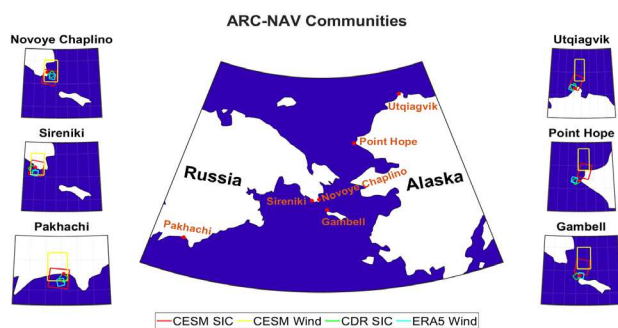
We use daily sea ice concentration (SIC) data from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration (CDR), Version 4<sup>19</sup>. The CDR database is based on the SICs from both the NASA Team algorithm<sup>20</sup>, and the NASA Bootstrap algorithm<sup>21</sup>. The database uses the NSIDC Polar Stereographic projection, which has a spatial resolution of 25 km × 25 km, and provides nearly continuous daily SIC estimates from October 25, 1978 to December 31, 2020. In the following, we omit 1978 and 2020 to have only complete years, and to be temporally consistent with ERA5 winds. Specific grid cells adjacent to the coast are chosen for analysis. We also use daily 10 m wind components from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5)<sup>22</sup>. ERA5 reanalysis, published by the ECMWF, provides hourly estimates of many Earth system components. We use 10 m wind components from the ECMWF ERA5 reanalysis interpolated on the Equal-Area Scalable Earth (EASE) Grid, at a spatial resolution of 25 km × 25 km. Grid cells located nearest to those chosen from the CDR dataset are used for analysis.

We use daily sea ice concentration, radiative surface temperature, and surface wind diagnostics from the Community Earth System Model Large Ensemble (CESM1-LE)<sup>23</sup>. CESM1-LE uses a rotated grid that puts the North Pole over Greenland with a nominal 1-degree latitude and longitude spatial resolution for the ocean and ice components. The atmospheric grid uses a standard spherical polar grid, also with a nominal 1-degree latitude and longitude spatial resolution. In this latitude band, 1-degree equates to approximately 50-100 km, which is large compared to a typical landfast ice extent in this region of approximately 20 km<sup>24</sup>, but still comparable. CESM1-LE is comprised of 5 individual components (atmosphere, ocean, land, sea ice, runoff), and a coupler to transfer the variables between the atmospheric and ocean/ice components. The model does not resolve, nor does it have a parameterization of, landfast ice, which makes the ice more susceptible to dynamical forcings, and is therefore less representative of reality. CESM1-LE has 40 ensemble members, each starting with slightly differing initial atmospheric conditions. For this study, only one Ensemble Member (EM2) is analyzed, from January 1, 1920, to December 31, 2080. The results are robust to the exact choice of member. All ensemble members are forced with historical carbon dioxide (CO<sub>2</sub>) emissions up to 2005, then follow the Representative Concentration Pathway 8.5 (RCP8.5) emissions scenario to the end of the simulation. RCP8.5 represents the scenario where current trends in population and economic growth continue in an absence of climate change policies, and has the highest greenhouse gas emissions of the RCPs<sup>25</sup>.

## Methodology

The analysis is conducted for communities in the Beringia region which are study sites of the Arctic Robust Communities Navigating Adaption to Variability (ARCNV) project (see Fig. 1). These include three communities in Alaska (USA) and three communities on the Kamchatka Peninsula (Russia): Utqiagvik (AK), Point Hope (AK), Gambell (AK), Novoye Chaplino (RU), Sireniki (RU), and Pakhachi (RU).

We identify the closest grid cell of each data set to each community's location to complete our landfast ice analysis (see Fig. 1). The grid cells from each of the CESM1-LE sea ice and atmosphere components are chosen to most closely match each other geographically, and likewise for the CDR and ERA5 datasets. Each grid cell is chosen based on its latitudinal and longitudinal proximity to its corresponding community in combination with minimal overlap with the land.



**Figure 1.** Map of Beringia (area comprising Alaska and Eastern Siberia) and locations of each key Arctic Robust Communities Navigating Adaption to Variability (ARCNV) community: Utqiagvik, Point Hope, Novoye Chaplino, Sireniki, Gambell, Pakhachi (red dots) with the closest grid cells for each data set used for analysis; CESM1-SEAICE (red), CESM1-ATMOSPHERE (yellow), CDR (green), and ERA5 (blue).

We define the start of the freeze season as the first day of a series of 10 days with a daily mean greater than 95% SIC and the start of the melt season as the first day of a series of 30 consecutive days with SIC below 95%. For some southern communities, these conditions are no longer met later in the 21<sup>st</sup> century, and the length of the winter season is set to zero. We define a break-up event as a period of at least 2 days with a mean SIC below 95%, following a period of 10 days with a mean SIC above 95%. We consider a 10-day period with a mean SIC  $\geq 95\%$  as a stable ice cover. Since a break-up event can last multiple days using this definition (up until the

stability condition is no longer met), the date on which the SIC of the event reaches a minimum is used for date-specific analysis. We choose a 95% SIC threshold for a break-up event because higher thresholds will trigger too many false events due to noise in the signal, and lower thresholds will fail to capture smaller-magnitude events. The exact number chosen is somewhat arbitrary, but thresholds in the range of 90%-98% show similar results (not shown). A different threshold may impact the number and average magnitude of events, but likely would not have a major effect on the qualitative properties of the observed trends. We therefore choose 95% SIC as our threshold, understanding that the trends are more important than exact values in this analysis.

## Results and Discussion

### Historical Record

We describe the general behaviour of the landfast ice cover and break-up events for a typical year in the mid 20<sup>th</sup> century in Utqiagvik (Fig. 2). The other communities follow the same pattern with the exception of Pakhachi, where winter sea ice cover rarely reaches stability. A qualitative analysis shows that most break-up events are preceded by a large spike in both wind speed perpendicular to the coastline, (meridional in Utqiagvik's case) and temperature.

While temperature is not explored further due to relative unimportance compared to wind forcing and lack of observational data, the relationship observed in Fig. 2 is explained by further analysis; Both CESM1-LE and CDR observations indicate that they often last a period of 3-10 days (see Fig. 3). The magnitude of a break-up event is weakly correlated with the 4-day integrated off-shore wind ( $\max. r^2 \approx 0.3$ ) (see Fig. 4) and the three to ten day timescale of break-up events points toward synoptic-scale ( $O \sim 1000$  km) weather phenomena, such as storms, that bring strong winds and relatively warm temperatures from the south. We infer that atmospheric forcings, specifically storms situated in a geographical position to apply off-shore wind stress, play an important role in causing and modulating the strength of break-up events.

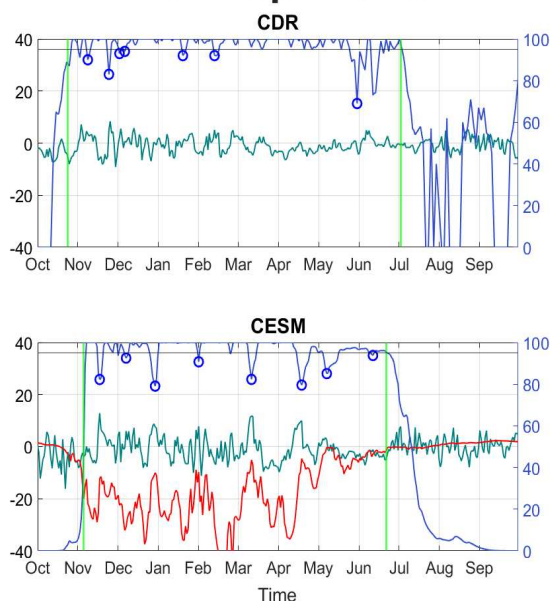
The model and satellite observations, however, do not always agree on the nature of the correlation (see Fig. 4). For instance, meridional (southerly) and zonal (easterly) wind anomalies have the largest impact on the magnitude of break-up events in Utqiagvik in the model and observations, respectively. In CESM1-LE, the sandspit on which Utqiagvik is located is not resolved, and the hamlet faces directly north to the Arctic Ocean, whereas in reality it faces north-west. All other communities considered, except Pakhachi, are located on geographical features (e.g. a peninsula) that are not resolved in the model. For example, Gambell is on an island that does not exist in CESM1-LE (i.e. Gambell is in open water instead of on land). In observations (Fig. 4), we find a wide range of zonal wind velocities for SIC  $\approx 95\%$  (i.e. near-stable landfast ice), reflecting differences in the internal ice stress and the presence of anchor points on the ocean floor on the shallow shelf<sup>2</sup>. In CESM1-LE, however, we see a much tighter SIC-meridional wind relationship even at near-stable SIC. This is likely due to the fact that CESM1-LE does not have a landfast ice parameterization (e.g.<sup>26</sup>), which causes it to be more susceptible to changes in wind forcing since there is no frictional force keeping the ice attached to shore, as well as a possible underestimation ice thickness near the shore due to a lack of an anchor point.

The addition of such a parameter, such as the one presented in [26], would improve the model's representation of reality, and would likely reduce both the number and magnitude of events observed in this study. Moreover, there is uncertainty associated with SIC measurements from passive microwave satellites near the coast due to land contamination<sup>27</sup>, where satellite have difficulty differentiating between sea ice and land snow. For this analysis we accepted that uncertainty since passive microwave satellite measurements are still the most consistent data source for SIC. ERA5 wind components have also been shown to be less reliable near coastlines, due mainly to the differences in surface roughness and solar irradiation<sup>28</sup>.

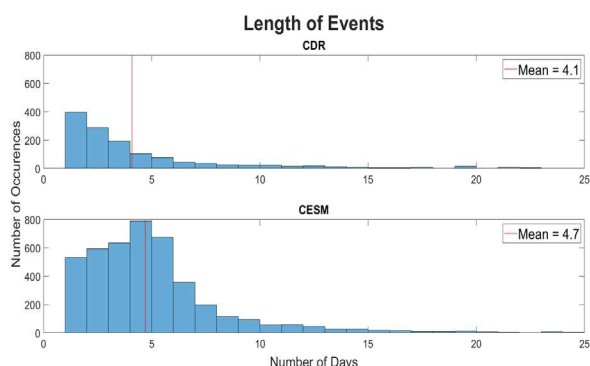
ERA5 is, as well, less reliable in areas of heterogeneous topography<sup>28</sup>, which could affect our results in Novoye Chaplino, Sireniki, and Pakhachi, as they are located near mountain ranges. Despite this, ERA5 has been found to be usable in Europe<sup>29</sup> and the South China Sea<sup>30</sup>, so we therefore believe ERA5 reasonably represents meteorological conditions in Beringia, within a degree of uncertainty.

Additionally, there could be an introduction of errors from downscaling the 1-degree model resolution for use at these locations, as the resolution is larger than the phenomena. For example, a break-up event could be detected in CESM1-LE that occurs far enough offshore to no longer be considered landfast ice. As a consequence of this, we expect CESM1-LE to overestimate break-up events. Despite these caveats, we find that CESM1-LE generally represents observed break-up events statistically well in terms of number, magnitude, length, frequency, and mechanisms of events. Based on these findings, we use CESM1-LE to predict long-term trends in break-up events.

## Break Up Events

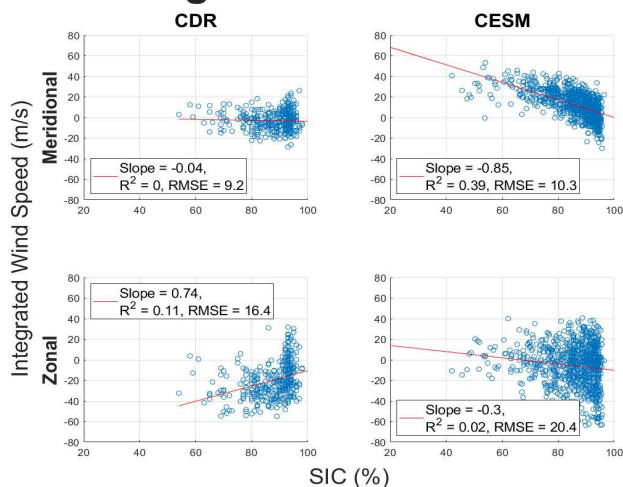


**Figure 2.** Sea-ice concentration (blue), surface ice temperature (red), and meridional wind speed (dark green) from the CDR, ERA5 and CESM1-LE EM 2 in Utqiagvik. The left-hand side vertical axis is both wind speed (m/s) and temperature (°C). Winter 1980 is shown for both CESM1-LE and CDR to represent typical mid-20th century years. A break-up event (blue circles) is defined as SIC falling below 95% following stable ice cover for 10 days. The start of the freeze season (green lines) is defined as the first day of a series of 10 days with a daily mean greater than 95% SIC, and the start of the melt season (green lines) is defined as the first day of a series of 30 consecutive days with SIC below 95% SIC.



**Figure 3.** Histogram of the length of all events for one grid cell offshore of each location from the CDR and CESM1-LE datasets. Pakhachi is not included as there are too few events to analyse. The mean of each distribution is included as a vertical red line.

## Integrated Wind and SIC



**Figure 4.** Scatter plot and linear regression of sea-ice break-up event magnitude, defined as minimum SIC of the event, and a four-day moving sum of meridional/zonal wind velocity preceding each event for one grid cell offshore Utqiagvik from the CDR, ERA5 databases and EM 2 of CESM1-LE.

## Projections

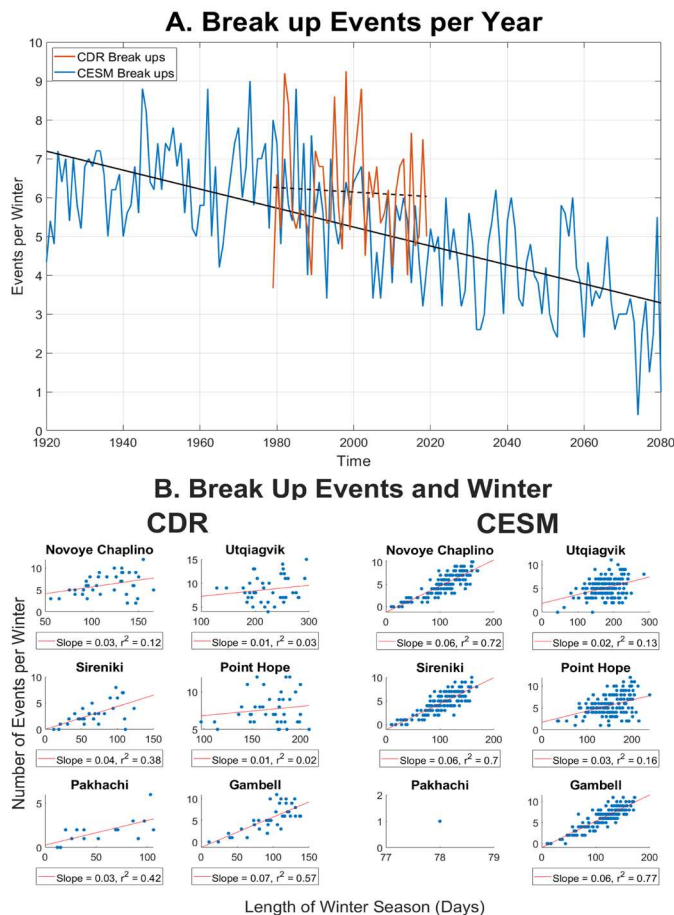
The number of break-up events in a season can be impacted by two opposing effects. The first effect is the shortening of the winter season, which reduces the number of break-up events by limiting the amount of time to produce them. The second effect is the thinning of the ice cover, which reduces the ice strength and increases the probability of a break-up event for a given wind forcing. Results show a negative trend in the mean number of break-up events per winter for all locations in both CDR (not significant) and CESM1-LE (p-value < 0.01) (see Fig. 5 A.). The negative trend is primarily the result of the decrease in the length of the winter season (see Fig. 6) as opposed to an increase in the time between events (results not shown).

In Utqiagvik and Point Hope, the model predicts a stable landfast ice cover being present until the end of the 21<sup>st</sup> century, contrary to the other four locations, in which the landfast ice cover becomes too unstable to meet our defined criteria at some point in the 21<sup>st</sup> century (see Fig. 6). In Gambell, Novoye Chaplino, Sireniki, and Pakhachi, we already see a complete absence of stable landfast ice cover, meaning no freeze date is identified, in the satellite record in 1, 2, 4, and 14 years at each location respectively. This is in accordance with the observational record which shows signs of a transition to a more unstable landfast ice coverage<sup>6,7,31</sup>. Primarily, the absence of a stable ice cover occurs late in the observational record (approximately 2015-2019). Whether this is due to long-term variability, or a trend, cannot be inferred from the short record. Nonetheless, it is consistent with model results.

The dominant effect changing the number of break-up events over the course of a winter (shortening of season versus thinning ice cover) depends on location (see Fig. 5 B.). In both the satellite observations and the model simulation, the more northern locations with a stable landfast ice regime (Utqiagvik and Point Hope) show almost no correlation between the number of events and the length of season; the more southern locations show a significant correlation with the length of the winter season. In CESM1-LE, we observe that Utqiagvik and Point Hope have positive slopes for break-up event frequency, which can be interpreted as 1 event every x days during the winter season (expressed in events per day per year), while Gambell, Novoye Chaplino, and Sireniki have negative slopes (all p-values < 0.01 and mean across 6 locations of  $-5.80 \times 10^{-5}$  events/day/year, p-value < 0.01) (results not shown). All locations have decreasing season length (mean of  $-5.3$  days/decade). The combination of these two measures results in negative slopes at all locations for break-up events per



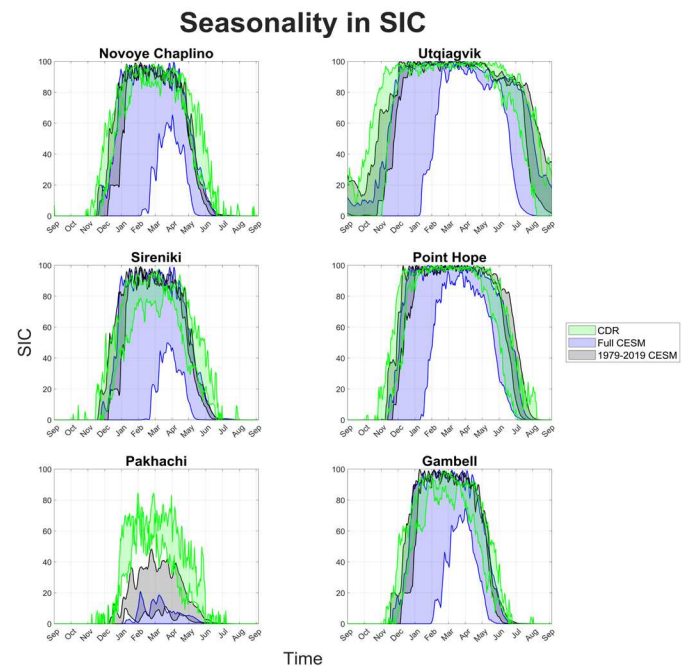
year (all p-values < 0.01, mean of  $-0.020$  events/year). In the CDR, we observe that Utqiagvik (p-value < 0.01), Point Hope (not significant), and Novoye Chaplino (p-value < 0.01) have positive slopes for break-up event frequency, Sireniki has a negative slope (p-value < 0.01), and Gambell has a slope of 0 (not significant) (mean of  $1.27 \times 10^{-4}$  events/day/year, not significant). In accordance with the model, all locations have decreasing season length (mean of  $-9.8$  days/decade, p-value < 0.01), resulting in non-significant slopes for break-up events per year at all locations, except for Gambell (p-value  $\approx 0.08$ ) and Sireniki (p-value < 0.01) with negative slopes (mean across 6 locations of  $-0.006$  events/year, not significant). In general, the number of events per year decreases significantly everywhere within the CESM1-LE, whereas in satellite observations, the trends are generally not significant, with the exception of winter season length, which decreases in both model and satellite observations significantly.



**Figure 5.** A. Mean Number of break-up events per year for the 6 considered locations identified from CDR (solid orange line) and CESM1-LE (solid blue line) with their linear regressions (black dotted and solid lines respectively). B. Scatter plot between the length of the winter season (days) and number of events (blue dots) with linear regressions (red lines). Pakhachi shows only one break-up event, and therefore a correlation is not possible. Model component is from ensemble member 2 of the CESM1-LE.

## Conclusions

The evolution of mid-winter coastal ice break-up events is an important factor to monitor for ensuring the safety of residents within coastal Arctic communities. An analysis of several Arctic communities with the CESM1-LE shows that its sea ice component, despite not having a landfast ice parameter, reasonably simulates break-up event magnitude and frequency. Moreover, in this analysis we demonstrate that these events are associated with synoptic-scale sustained offshore wind, and that their frequency under climate change depends on the two opposing effects of decreasing winter length, and decreasing ice stability. We show that the magnitude of each effect is associated with the minimum winter season length, which is approximated by latitude. This analysis also reveals that some communities have already begun a transition to a new, less stable sea ice regime,



**Figure 6.** Decadal mean SIC lost between the start and end of each dataset (shaded regions); CDR satellite observations (1979-88 & 2010-19, green), and CESM1-LE simulation (1920-29 & 2071-80, blue, and 1979-88 & 2010-19, black). The full CESM area does not cover the later 1979-2019 CESM area for Pakhachi because the first decade of its time series has anomalously low SIC.

where break-up events are more frequent, and the winter season shorter. Model simulations indicate that most coastal Alaskan communities will pass through such a transition in the 21<sup>st</sup> century. The transition will not be easily predicted from local observations, and is likely to present increased risk for residents making their livelihood on the ice. We hope that understanding these trends can augment local and indigenous knowledge and improve people's capacity to manage the risks.

## Acknowledgments

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