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Sea ice break-up and freeze-up indicators for users of the Arctic coastal environment

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Abstract

Arctic coastal waters are characterized by seasonal retreat and advance of sea ice. The timing of advance and retreat varies substantially from year to year. Various activities, ranging from marine transport to the use of sea ice as a platform for industrial activity or winter travel, are affected by variations in the timing of break-up and freeze-up, resulting in a need for indicators to document the regional and temporal variations in coastal areas. Here we develop indicators based on daily sea ice concentrations derived from satellite passive microwave measurements. The "day of year" indicators are designed to optimize value for users while building on past studies characterizing break-up and freeze-up dates in the open pack ice. Relative to indicators for broader adjacent seas, the coastal indicators show later break-up at sites known to have extensive landfast ice, for which break-up typically lags retreat of the adjacent, thinner drifting ice. The coastal indicators also show an earlier freeze-up at some sites in comparison with freeze-up for broader offshore regions, likely tied to earlier freezing of shallow water regions and areas affected by freshwater input from nearby streams and rivers. A factor analysis performed to synthesize the local indicator variations shows that the local break-up and freeze-up indicators have greater spatial variability than corresponding metrics based on regional ice coverage. However, the trends towards earlier break-up and later freeze-up are unmistakable over the post-1979 period in the synthesized metrics of the coastal break-up/freeze-up and their corresponding regional ice coverage. The findings imply that locally defined indicators can serve as key links between pan-Arctic or global indicators such as sea-ice extent or volume and local uses of sea ice, with the potential to inform community-scale adaptation and response.

Key words: sea ice, Arctic, break-up, freeze-up, ice concentration

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1. Introduction

Coastal sea ice impacts residents and other users of the offshore environment in various ways. Perhaps most obvious is the fact that non-ice strengthened vessels require ice-free waters for marine transport, which can serve purposes such as resupply of coastal communities, the transport of extracted resources (oil, liquefied natural gas, mined metals), migration of marine mammals (e.g., bowhead whales) and wintertime travel over the ice by coastal residents. Key metrics for offshore uses such as these are the timing of break-up (or ice retreat) in the spring and the timing of freeze-up (or ice advance) in the autumn or early winter.

Sea ice concentration is the basis of most metrics of the timing (dates) of sea ice break-up and freeze-up (Markus et al., 2009; Johnson and Eicken, 2016; Bliss and Anderson, 2018; Peng et al., 2018; Bliss et al., 2019; Smith and Jahn, 2019). An emerging tendency in these studies is the definition of break-up date as the date on which ice concentration drops below a prescribed threshold and remains below that threshold for a prescribed minimum duration (chosen to eliminate repeated crossings of the concentration threshold as a result of temperature- or wind-driven changes in ice coverage associated with transient weather events). A corresponding criterion is used for the freeze-up date.

Coastal regions present special challenges in the application of such criteria. First, shorefast or landfast ice (stationary sea ice held in place along the shoreline ~~through~~ as a result of grounding and/or confinement by the coast) is common in waters immediately offshore of the coast, especially in areas with shallow water. Shorefast ice provides especially important sea ice services because it offers a stable platform for offshore travel, serves as a critical habitat for marine mammals such as seals and polar bears (Dammann et al., 2018), and provides a buffer against coastal storms (Hosekova et al., 2021). Second, sea ice concentrations derived

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from passive microwave measurements are prone to contamination by microwave emissions from land in coastal grid cells. Finally, many parts of the Arctic coastline have inlets, river deltas and barrier islands that are not captured by the 25 km resolution of the passive microwave product.

A key aim of the current study is to contribute to efforts at the national and global scale to establish key sets of indicators that support sustained assessment of climate change and inform planning and decision-making for adaptation action (Kenney et al., 2016; IPCC, 2022). Both at the pan-Arctic and global, as well as the U.S. national level, indicators associated with the state of the sea ice cover so far have focused on the summer minimum and winter maximum extent and ice thickness (AMAP, 2017; Box et al., 2019; IPCC, 2022). As outlined by Box et al. (2019), this approach has been motivated by the objective of describing and tracking the state of key components of the global climate system. However, large-scale (pan-Arctic) measures of e.g., sea-ice extent or volume are of little value and relevance to those needing to adapt or respond to such change at the community or regional scale. Here, we examine the timing of sea-ice freeze-up and break-up as key constraints for a range of human activities and ecosystem functions in Arctic settings.

2. Data and methods

The primary data source used here is the archive of gridded daily sea ice concentrations derived from the SMMR, SSM/I and SSMIS sensors onboard the Nimbus-7 and various DMSP satellites dating back to November, 1978. The dataset, NSIDC-0051 of the National Snow and Ice Data Center (NSIDC), is the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration Version 3. In the construction of this dataset, the NASA Team algorithm (Cavalieri et al., 1984) and the NASA Bootstrap algorithm (Comiso et al.,

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1986) were used to process the microwave brightness temperatures into a consistent time series of daily sea ice concentrations. The data are on a polar stereographic grid projection with a grid cell size of 25 km x 25 km.

The daily sea ice concentrations are used to define the metrics of the start and end of break-up and freeze-up in each year of a 40-year period, 1979-2018. The definitions build on those used by Johnson and Eicken (2016), which were informed by Indigenous experts' observations of ice use and ice hazards in coastal Alaska, and relate to planning and decision-making at the community-scale (Eicken et al., 2014). Here, we expand the satellite data analysis with minor modifications of the break-up and freeze-up criteria to broaden the applicability to non-coastal areas. Examples include imposing maximum and minimum values for the thresholds computed from summary statistics of the daily sea ice concentration values of relevant periods. The revised definitions are presented in Table 1. Prior to applying these definitions, the data were processed with a linear interpolation to fill in missing daily values, followed by a spatial and then temporal smoothing to smooth out short (< 3 days) events.

A key objective of this work is to compare the various dates at nearshore locations with the corresponding metrics for broader areas of the Arctic Ocean and the subarctic seas. A set of ten locations was selected on the basis of their geographical distribution and the relevance of local sea ice to uses by communities, industry, military or other stakeholders. These locations are listed in Table 2, together with their geographic coordinates. For each of these locations, several passive microwave grid cells close to (but not adjacent to) the coastline were selected for calculation of the break-up and freeze-up metrics. Figure 1 shows geographical insets illustrating the proximity of the selected grid cells to the coastline.

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Table 1. Definition of the start and end of break-up and freeze-up.

Break-up start	The date of the last day for which the previous two weeks' ice concentration always exceeds a threshold computed as the maximum of (a) the winter (January-February) average minus two standard deviations and (b) 15%. Undefined if the average summer sea ice concentration (SIC) is greater than 40% or if the subsequent break-up end is not defined.
Break-up end	The first date after the break-up start date for which the following two weeks' ice concentration is less than a threshold computed as the maximum of (a) the summer (August-September) average plus one standard deviation and (b) 50%. Undefined if the daily SIC is less than the threshold for the entire summer or if break-up start is not defined.
Freeze-up start:	The date on which the ice concentration exceeds for the first time a threshold computed as the maximum of (a) the summer (August-September) average plus one standard deviation and (b) 15%. Undefined if the daily SIC never exceeds this threshold, if the mean summer SIC is greater than 25%, or if subsequent freeze-up end is not defined.
Freeze-up end:	The first date after the freeze-up start date for which the following two weeks' ice concentration exceeds a threshold computed as the maximum of (a) the average winter (January-February) ice concentration minus 10% and (b) 15%, and the minimum of this result and (c) 50%. Undefined if daily SIC exceeds this threshold for every day of the search period or if freeze-up start is not defined.

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Table 2. Near-coastal locations selected for calculation of break-up and freeze-up metrics

Sea	Location	Latitude, Longitude	Significance of location
Beaufort Sea	Prudhoe Bay	70.2N, 148.2W	oil facilities
Chukchi/Beaufort Seas	Utqiaġvik	71,3N, 156.8W	Indigenous community
Chukchi Sea	Bering Strait coast	69.6N, 170W	shipping route
Bering Sea	St. Lawrence Island	65.7N, 168.4W	Indigenous community
East Siberian Sea	Pevek	69.8N, 170.6E	port, mining facility
Laptev Sea	Tiksi	71.7N, 72.1E	research site, port
Kara Sea	Sabetta	71.3N, 72.1E	port, LNG facility
Greenland Sea	Mestersvig	72.2N, 23.9W	military base
Baffin Bay	Clyde River	70.3N, 68.3W	Indigenou community
Hudson Bay	Churchill	58.8N, 94.2W	port, tourism

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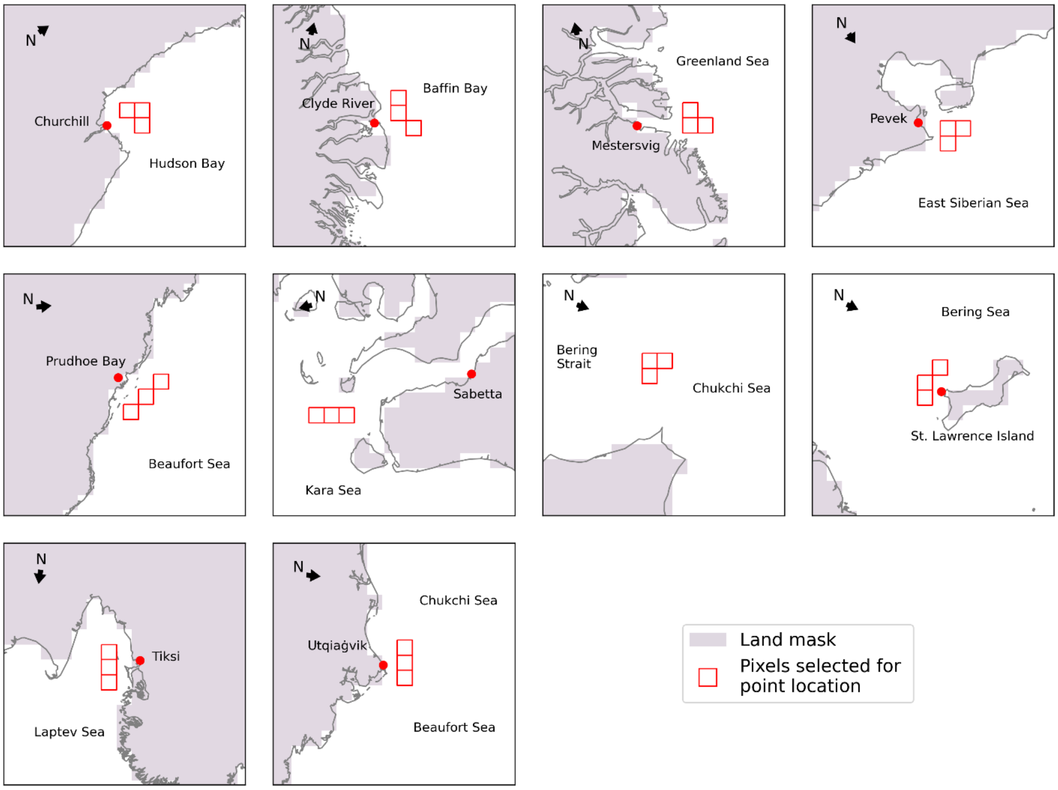

Figure 1. Grid cells used for sea ice indicator metrics corresponding to coastal locations (red dots).

Previous studies cited earlier have evaluated break-up and freeze-up metrics for subregions of the Arctic Ocean and the surrounding seas. For comparisons with similar regions, we utilize the MASIE (Multisensor Analyzed Sea Ice Extent) regionalization (https://nsidc.org/data/masie/browse_regions). Of the MASIE regions shown in Figure 1, we choose the following for computation of regionally averaged metrics of break-up and freeze-up: (1) Beaufort Sea, (2) Chukchi Sea, (3) East Siberian Sea, (4) Laptev Sea, (5) Kara Sea, (6) Barents Sea, (7) Greenland Sea, (8) Baffin Bay, (9) Canadian Archipelago, (10) Hudson Bay, (11) Central Arctic and (12) Bering Sea.

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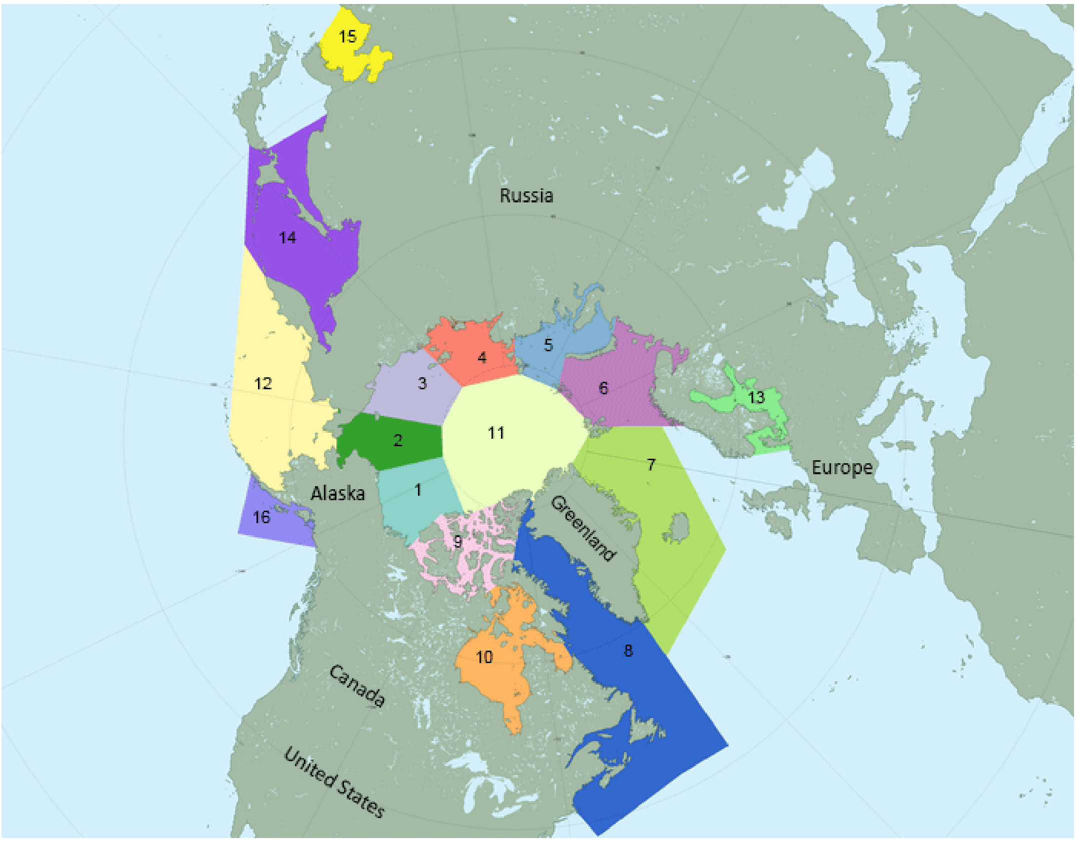

Figure 2. The MASIE subregions of the Arctic. Regions utilized in this study (see Table 2) include #s 1 (Beaufort Sea), 2 (Chukchi Sea), 3 (East Siberian Sea), 4 (Laptev Sea), 5 (Kara Sea), 7 (Greenland Sea), 8 (Baffin Bay), 10 (Hudson Bay) and 12 (Bering Sea).

The following section includes time series of the local indicators and, for comparison, time series of the corresponding regional indicators. In order to address the spatial coherence of the indicators, we performed a factor analysis on the different sets (break-up/freeze-up, start/end dates) of ten regional indicators. Factor analysis is a statistical method for

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quantifying relationships among a set of variables. The variability in the overall dataset is depicted by a set of factors. Each factor explains a percentage of the total variance in space and time. Each variable in each factor is given a loading (or weight) based on its contribution to the variance explained by that factor. The first factor can be viewed as the linear combination of the variables that maximizes the explained variance in the overall dataset. The second and each successive factor maximizes the variance unexplained by the preceding factors. Successive factors explain successively smaller fractions of the overall variance. Multiple variables can have strong loadings in the same factor, indicating they follow a similar pattern and are likely highly related. Factor analysis has a long history of applications to Arctic sea ice variability (Walsh and Johnson, 1982; Fang and Wallace, 1994; Deser et al., 2000; Fu et al., 2021). The factor analysis calculations used here were performed using the XLSAT software package run in Excel (https://www.xlstat.com/en/)

3. Results

With coastal ice retreat and onset of ice advance as this study's primary focus, we first demonstrate the applicability of the indicators evaluated here. The various metrics of sea ice break-up and freeze-up in Table 2 are not defined for all locations in the Arctic. For example, locations that remain ice-covered throughout a particular year will not be assigned dates for any of the indicators in that year, and the same is true of locations at which sea ice does not form during a particular year. Figure 3 shows the number of years in the 1979-2018 study period during which the break-up and freeze-up indicators are actually defined. It is apparent that the indicators are consistently defined in the seasonal sea ice zone spanning the subarctic seas. In particular, all ten coastal locations in Table 2 are in the yellow areas (>35 years out of 40 years defined) of Figure 3. Of note in Figure 3 is that the number of years with defined

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break-up indicators slightly exceeds (by one) the number of years with freeze-up indicators at some locations at the outer periphery of the seasonal sea ice zone. These are locations in which sea ice was present for some portion of the early years but not at the end of the study period, so in one of the years there was a break-up but no freeze-up.

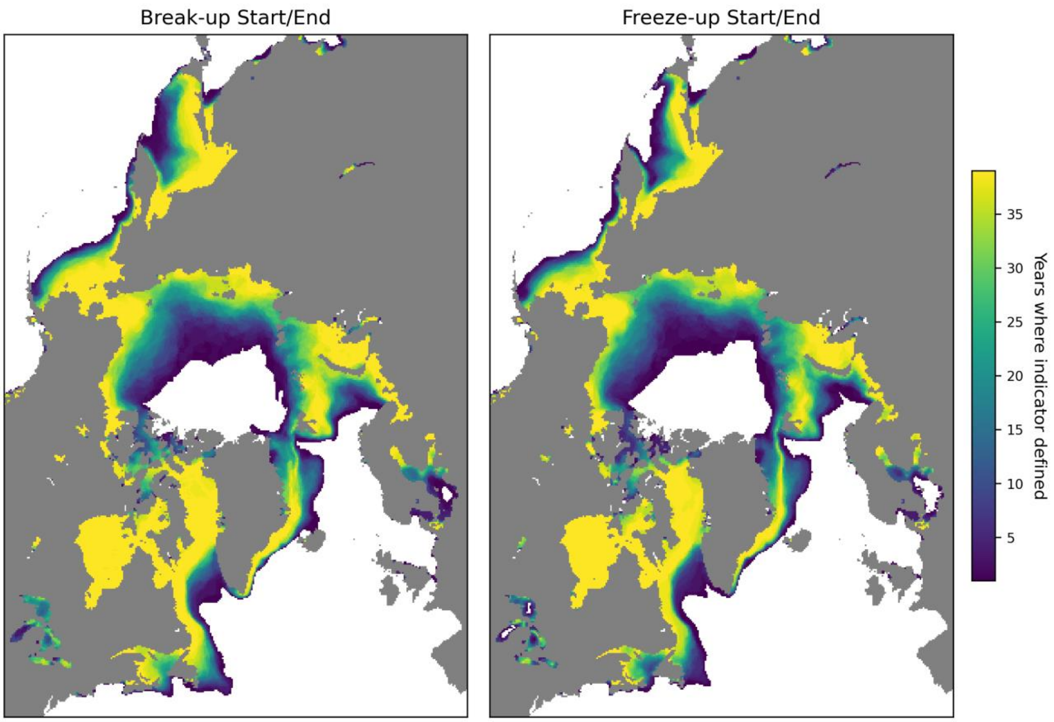

Figure 3. Number of years in the 1979-2018 study period in which the break-up and freeze-up indicators were defined.

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A key issue to be addressed is the degree to which the indicators utilized here differ from those of previous studies. The metrics of Bliss et al. (2019) or similar variants have been used in recent publications and provide natural points of comparison. While there are various differences between our metrics and those of Bliss et al., the most consequential for the computed dates is the use of departures from winter/summer averages concentrations in our criteria vs. Bliss et al.'s use of 15% and 80% concentrations as key thresholds.

The four indicators in this study are the dates of the start and end of break-up and freeze-up. The corresponding indicators used by Bliss et al. (2019) are the date of opening (defined as the last day on which the ice concentration drops below 80% before the summer minimum), the date of retreat (defined as the last day the ice concentration drops below 15% before the summer minimum), the date of advance (defined as the first day the ice concentration increases above 15% following the final summer minimum) and the date of closing (defined as the first day the ice concentration increases above 80% following the final summer minimum). Figure 4 shows that there are systematic differences between our metrics (based on Johnson and Eicken, 2016; hereafter denoted as J&E) and those of Bliss et al. when the two sets of metrics are evaluated for the MASIE regions. In particular, J&E's start and end of breakup generally occur earlier by up to several weeks than the corresponding dates of opening and retreat defined by Bliss et al. On the other hand, J&E's freeze-up dates are more closely aligned with those of Bliss et al., although J&E's end-of-freeze-up occurs later (by 1 to 3 weeks) than Bliss et al.'s closing date in most of the MASIE regions, especially the North Atlantic and Canadian regions.

The violin plots in Figure 4 show distributions but not the temporal variations that have been indicated by results of previous studies (Peng et al., 2018; Bliss et al., 2019). Figures 5 and 6

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provide the temporal perspective on the end dates of break-up (Day of retreat) and freeze-up (Day of closing), respectively. In each of the MASIE regions, the J&E criterion gives an earlier break-up date. The difference is typically two to three weeks, although it exceeds a month in the Greenland Sea and Baffin Bay. Despite the offsets, the trends are nearly the same in nearly all the regions. Exceptions are the Canadian Archipelago, where the J&E trend is weaker than the Bliss trend, and the Bering Sea, where the trends are opposite in sign. However, the trend in the Bering region is not statistically significant at the 99% level by either metric, in contrast to all other regions in which the trends are significant at this level. The main conclusion from Figure 5 is that, except for the Bering Sea, sea ice break-up is occurring earlier throughout the Arctic than several decades ago, no matter which metric is used.

In contrast to the trends towards earlier breakup, the J&E and Bliss metrics for the end of freeze-up both show significant trends towards later dates in most of the MASIE regions (Figure 6). In this case, even the Bering Sea shows a trend towards later freeze-up. Again, there is an offset towards a later date with the J&E metric, although the offset has a range among the region, from essentially zero in Hudson Bay to more than six weeks in the Greenland Sea. The trends, however, show less agreement in some regions than do the trends for break-up dates in Figure 5. The J&E trends are more strongly positive in the seas of the eastern Russian sector: the Chukchi, East Siberian and Laptev Seas. The same is true, although to a lesser degree, in the Barents Sea and the Canadian Archipelago. The main message from Figure 6 is that the freeze-up is ending later throughout the Arctic, although the magnitude of the trend is more sensitive to the criteria used for end-of-freeze-up than for end-of-break-up.

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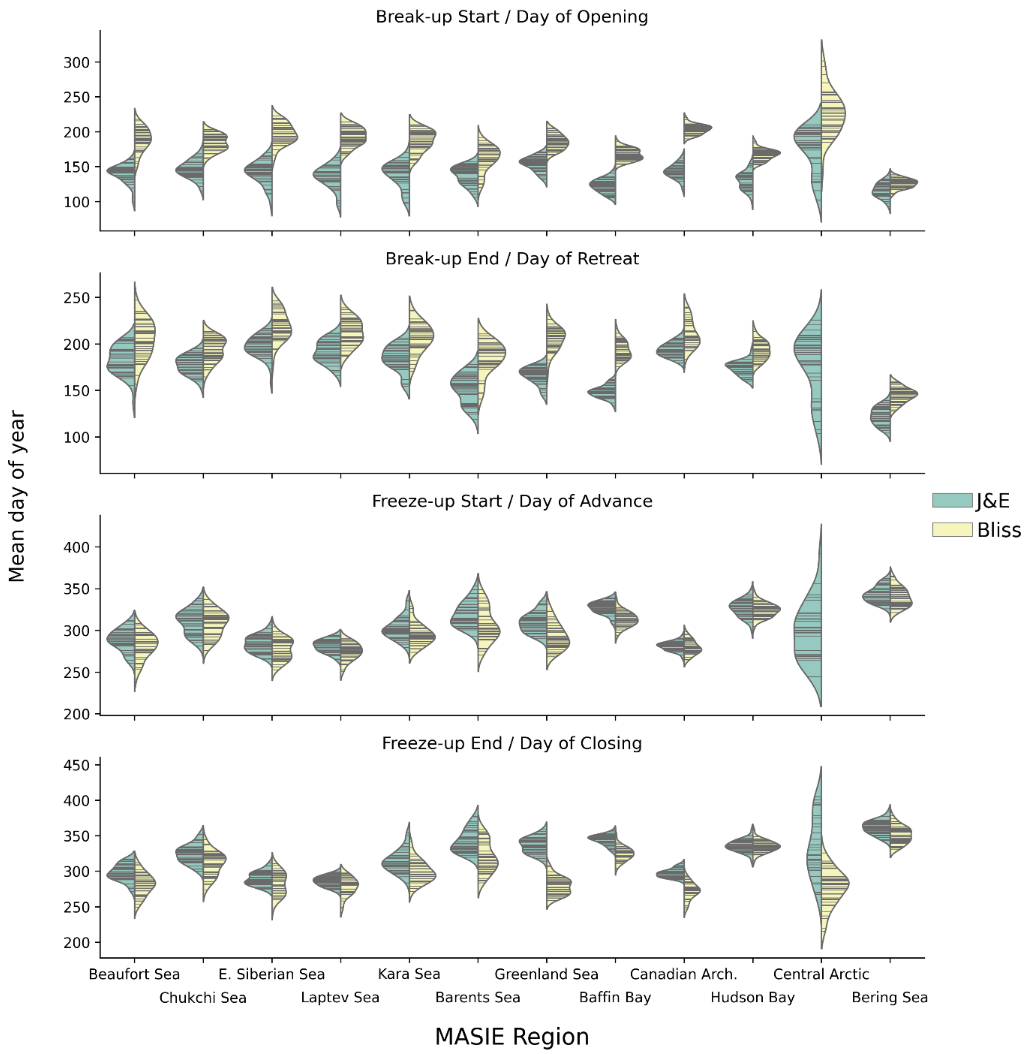

Figure 4. Violin plots of the Julian dates of the break-up/freeze-up metrics used in this study based on Johnson and Eicken (2016) (green shading) and the corresponding dates of ice opening, retreat, advance and closing as defined by Bliss et al. (2019).

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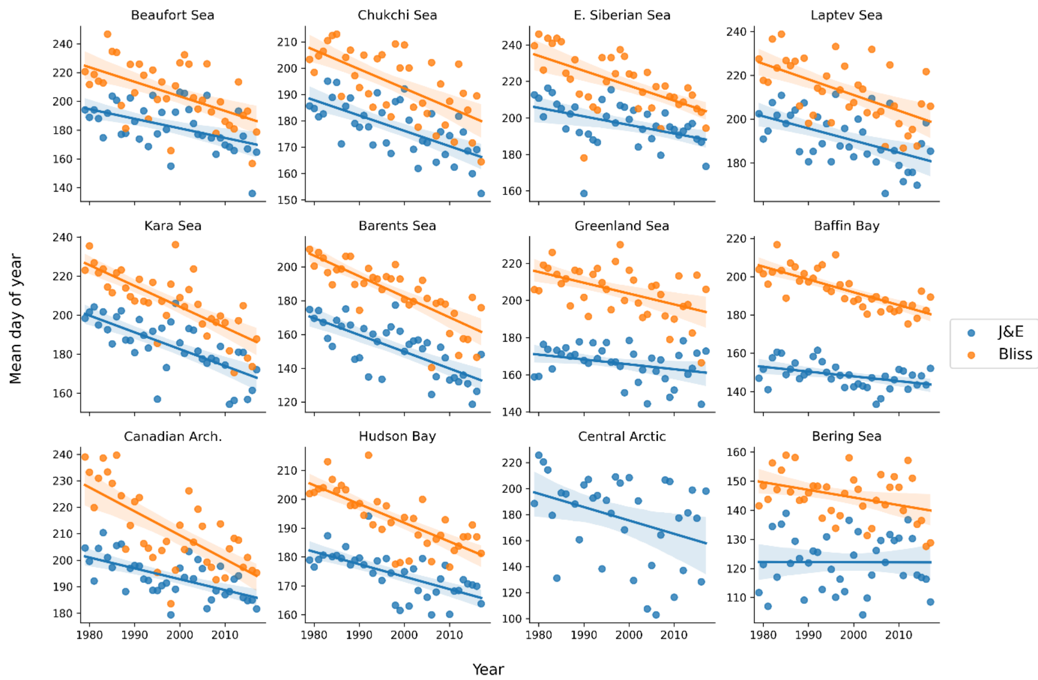

Figure 5. Yearly values of J&E's break-up end date (blue symbols) and the Bliss et al.'s (2019) Day of retreat (orange symbols) in the various MASIE regions. Corresponding trend lines are shown in each panel. (For the Central Arctic region, the Bliss metric (Day of retreat) was not defined for a sufficient number of years).

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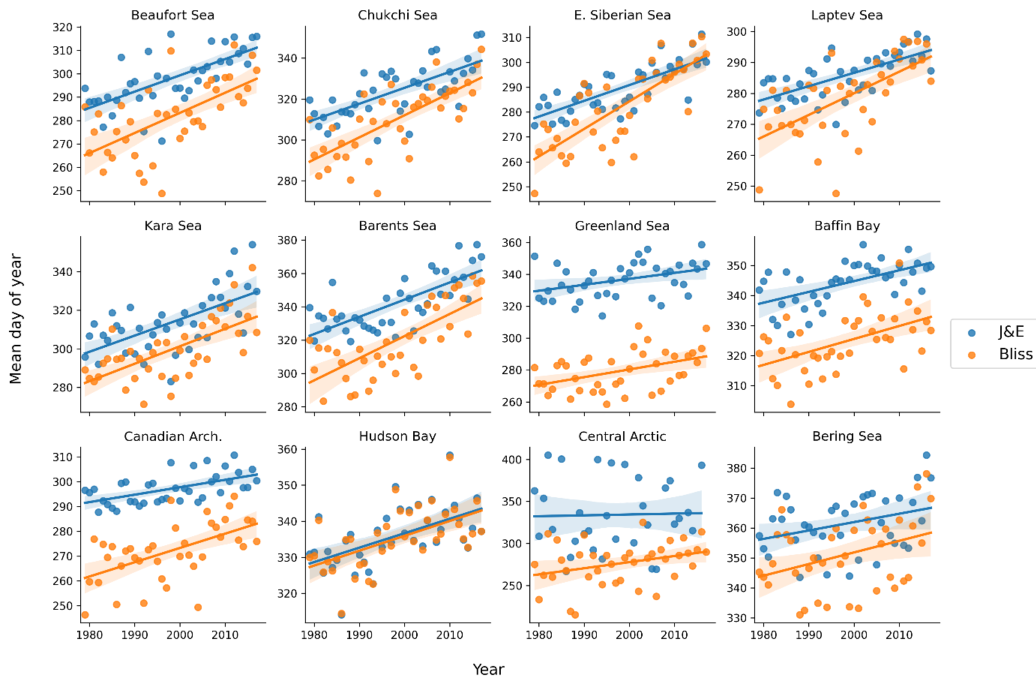

Figure 6. Yearly values of J&E's freeze-up end date (blue symbols) and the Bliss et al.'s (2019) Day of closing (orange symbols) in the various MASIE regions. Corresponding trend lines are shown in each panel. Y-axes labels are Julian dates.

A final comparison is presented in Figure 7, which shows the ice season lengths computed using the two sets of metrics. The ice season length is defined as the number of days between the end of freeze-up and the start of break-up. Consistent with J&E's earlier break-up (Figure 5) and later freeze-up (Figure 6), the ice season length is generally longer when computed from the J&E metrics. The differences in Figure 7 exceed a month in most of the Arctic except for the Bering Sea, Hudson Bay and the Canadian Archipelago. However, the negative trends of ice season length are similar in magnitude according to both sets of metrics over

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most of the Arctic. The trend maps are not shown here because they add little to the information conveyed in Figures 5 and 6.

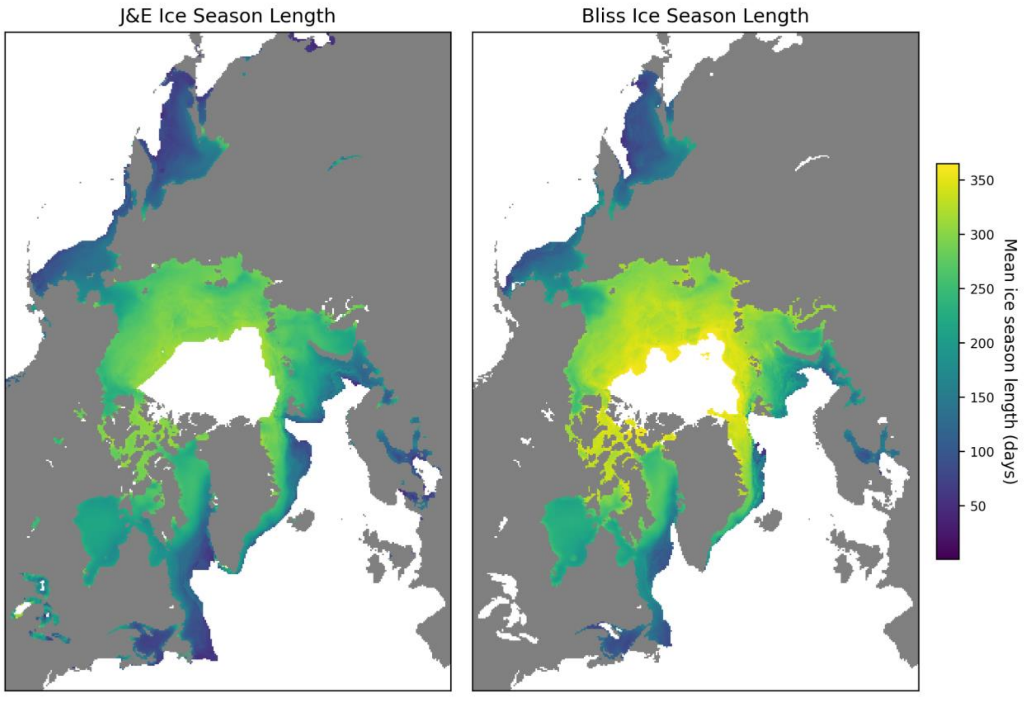

Figure 7. Mean ice season length based on the J&E metrics (left) and the Bliss et al. (2019) metrics (right). Metrics of break-up and freeze-up were not defined in a sufficient number of years in the white area near the North Pole.

The main focus of the present study is the relationship between the indicators for the coastal locations and those for the broader MASIE regions containing the coastal locations. Figures 8-11 provide these comparisons for all four metrics defined by the modified J&E algorithms. In all cases, the yearly values (and linear trend lines) for the ten coastal locations in Table 2

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are plotted for the 1979-2018 period, together with the values for the corresponding MASIE regions.

The break-up start dates (Figure 8) differ between the coastal locations and the broader MASIE regions in most of the ten cases, and in some cases the trends are notably different. With regard to systematic differences, not only the magnitude but also the sign of the offsets varies among the regions. The break-up start date at the coast is later than for the MASIE regions for Prudhoe (Beaufort Sea), Utqiaġvik (Chukchi Sea), Tiksi (Laptev Sea), and both Canadian locations: Churchill (Hudson Bay) and Clyde River (Baffin Bay). These sites are all Arctic coastal locations at which varying extents of landfast ice are present. By contrast, the coastal locations have earlier break-up start dates (relative to their corresponding MASIE regions) at St. Lawrence Island (Bering Sea), Mestersvig (Greenland Sea) and the Bering Strait (Chukchi Sea). These locations are less prone to experience a buildup of landfast ice during the winter. The results imply that landfast ice is a key determinant of the timing of the start of breakup relative at coastal locations relative to the broader sector of the seasonal sea ice zone.

While the general trend towards earlier break-up noted above (Figure 5) is apparent at most of the coastal locations, the magnitudes of the trends can differ between the coastal sites and the broader MASIE regions. Figure 8 shows that, in most cases, the trend towards an earlier start of break-up is stronger at the coastal location relative to the MASIE region at Churchill, Clyde River, Pevek and Sabetta. Only at Tiksi is the negative trend weaker at the coastal site. In the other regions the trends are nearly identical.

The break-up end dates (Figure 9) show differences similar to those in Figure 8 in most, but not all, cases. The break-up end date occurs earlier at Clyde River, Prudhoe and Utqiagvik

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relative to the MASIE regions, as is the case with the results in Figure 8. However, unlike the break-up start date, the break-up end date also occurs earlier at Mestersvig than for the Greenland Sea MASIE region. The opposite relationship is found in the Kara Sea (Sabetta) and the South Chukchi Sea (Bering Strait), where the MASIE region has the earlier break-up end date. The temporal trends in the break-up end dates are generally similar for the coastal locations and the MASIE regions, and there are no differences in sign. All coastal locations and all MASIE regions show negative trends, i.e., trends toward earlier break-up end dates in recent decades.

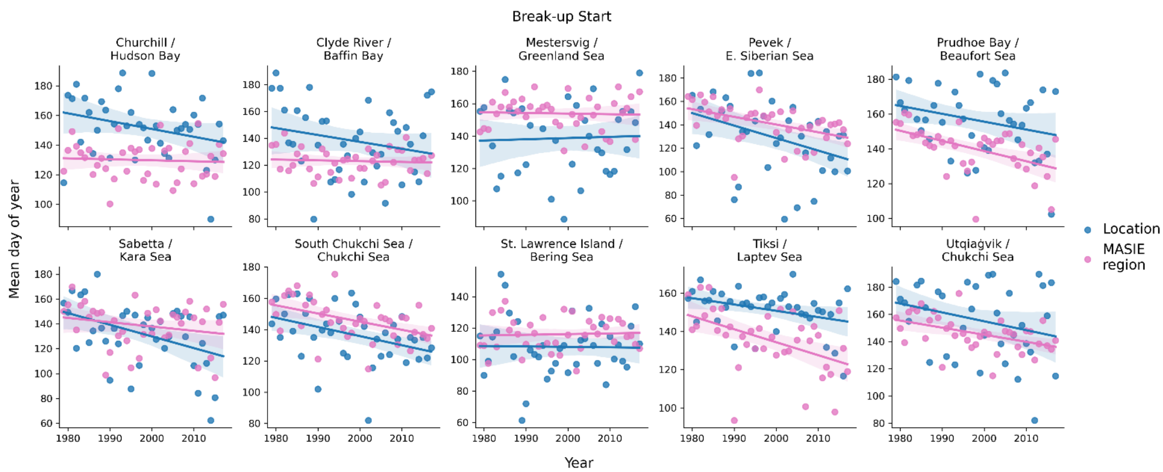

Figure 8. Yearly values (1979-2018) of the break-up start dates for the coastal locations (blue) and the corresponding MASIE regions (purple). Linear regression lines are shown with the same color coding. In each panel, the upper line of header identifies the coastal location and the lower line identifies the MASIE region. All values are based on the modified J&E algorithms.

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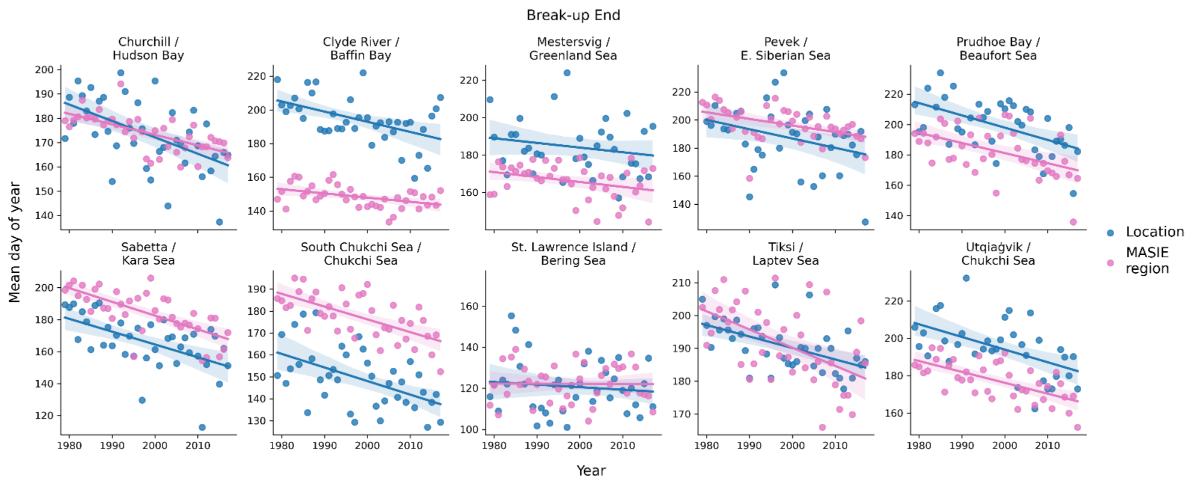

Figure 9. Same as Figure 8, but for the break-up end dates.

The freeze-up start dates are compared in Figure 10. Several regions show large offsets, most notably Clyde River (Baffin Bay) and Mestersvig (Greenland Sea), where the start of freeze-up occurs earlier at the coast by several weeks. Both Baffin Bay and the Greenland Sea are large MASIE regions (Figure 2), favoring the delay of freeze-up over a substantial portion of the seasonal sea ice zone within the respective MASIE regions. Freeze-up dates are also earlier than offshore at several other coastal locations: Churchill, Sabetta and Utqiaġvik. These are regions in which it is common for ice to form along the coast in autumn, with the ice edge advancing offshore to meet the expanding main ice pack as freeze-up progresses. By contrast, the southern Chukchi Sea location has a later freeze-up date than the Chukchi MASIE region, largely because the southern Chukchi grid cells are located in an area of relatively warm inflowing currents and are in the southern portion of the Chukchi MASIE

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region. As with the break-up end dates, all coastal locations and MASIE regions show trends of the same sign. In this case, the trends are all positive, indicating a later start to freeze-up.

Finally, Figure 11 compares the freeze-up end dates for the ten coastal sites and their MASIE regions. The results are quite similar to those for the freeze-up start dates in Figure 10. Relative to the MASIE regions as a whole, freeze-up ends earlier at both Canadian sites (Churchill and Clyde River), Mestersvig, Sabetta and Utqiaġvik. Again, the differences are especially large (more than a month) at Clyde River and Mestersvig, both of which are in large MASIE regions as noted above. The southern Chukchi Sea and, to a lesser extent in recent decades, Pevek (East Siberian Sea) show later freeze-ups near the coast than for the MASIE region. Once again, all trends are positive, pointing to a later end to freeze-up at coastal as well as offshore regions throughout the Arctic. The changes in the freeze-up dates over the 40-year period are especially large, exceeding one month, at Pevek (East Siberian Sea) and Prudhoe (Beaufort Sea). The changes are close to a month at Utqiaġvik (Chukchi Sea) and the Southern Chukchi Sea.

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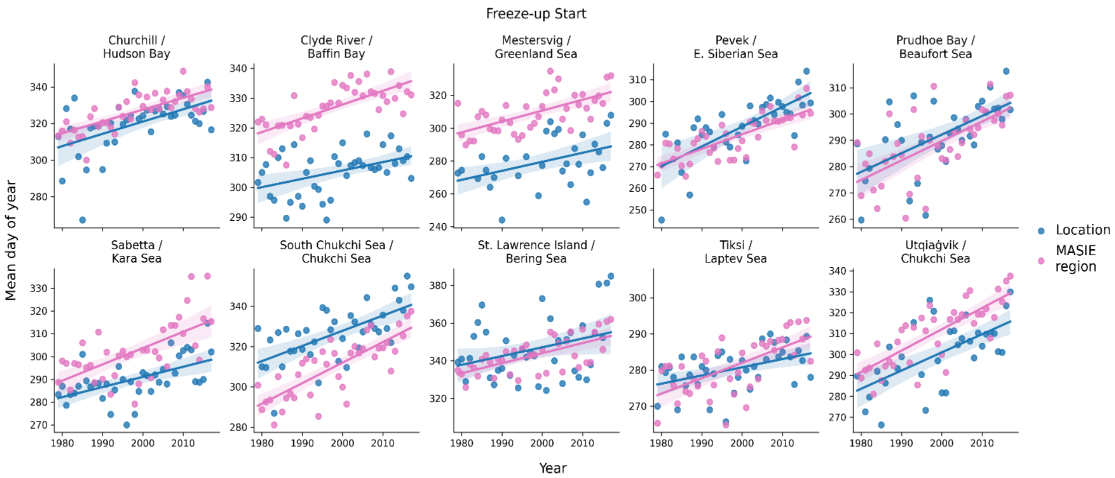

Figure 10. Same as Figure 8, but for the freeze-up start dates.

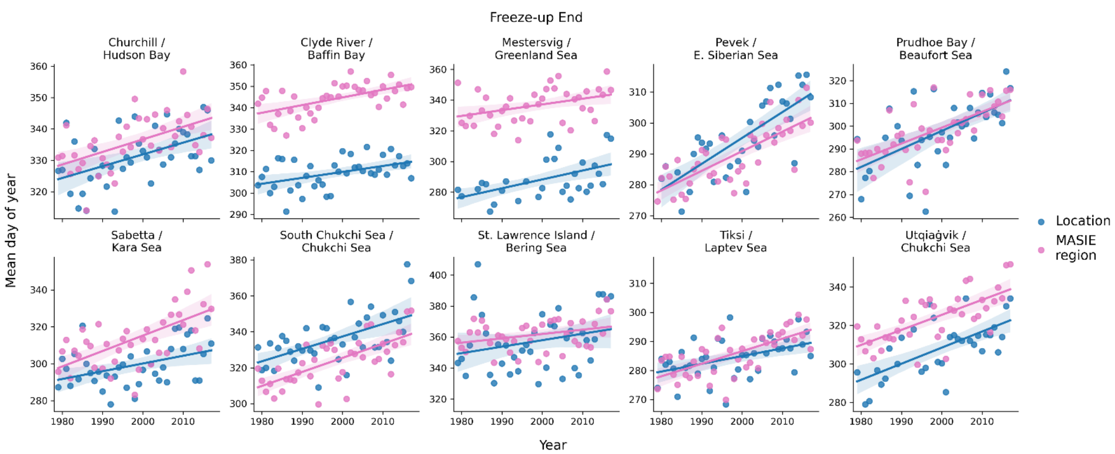

Figure 11. Same as Figure 8, but for the freeze-up end dates.

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In order to synthesize the information provided by the local indicators, we applied a factor analysis to each of the four local indicators described in Section 2. For the local indicators, each matrix was 10 (locations) x 40 (years). For comparison, we also applied the factor analysis to the corresponding regional sea ice areas from the MASIE database (National Snow and Ice Data Center dataset G02135_v3.0-4). Because the Chukchi Sea is the MASIE region for two of the local indicators (South Chukchi and Utqiagvik), the data matrix for the MASIE regional factor analysis contained 9 (regions) x 40 (years) entries. We performed the MASIE factors separately for middle months of the break-up and freeze-up seasons (June and November, respectively).

In all cases, the first factor contains loadings of the same sign for all locations/regions and is essentially a depiction of the temporal trends, which account for substantial percentages of the variance. The second factor consists of loadings of both signs, corresponding to positive departures from the mean at some locations negative departures at others. Figure 12 illustrates this behavior for (a) the break-up start dates and (b) the freeze-up end dates. While every one of the ten locations has a positive loading in Factor 1, the mixed signs of the Factor 2 loadings point to a regional clustering of the dates. For example, Figure 12a shows that the northern coastal sites in the Pacific hemisphere (Prudhoe Bay, Utqiagvik, Tiksi, Pevek) have a component of break-up start date variability that is out of phase with the locations in the western Atlantic/eastern Canada sector (Mestersvig, Churchill, Clyde River).

The interpretation of Factor 1 as a trend mode is supported by Figure 13, which shows the time series of the scores of Factor 1 for (a) the break-up start date and (b) freeze-up end dates. The trends towards an earlier start of break-up and a later end of freeze-up are clearly evident. Figure 12 also illustrates the tendency for occasional "outlier" years to be followed by a

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recovery in the following year. These plots and those for the other local indicators show that these extreme excursions and recoveries are superimposed on the strong underlying trends, resulting in new extremes when the sign of an extreme year is the same as the sign of the underlying trend.

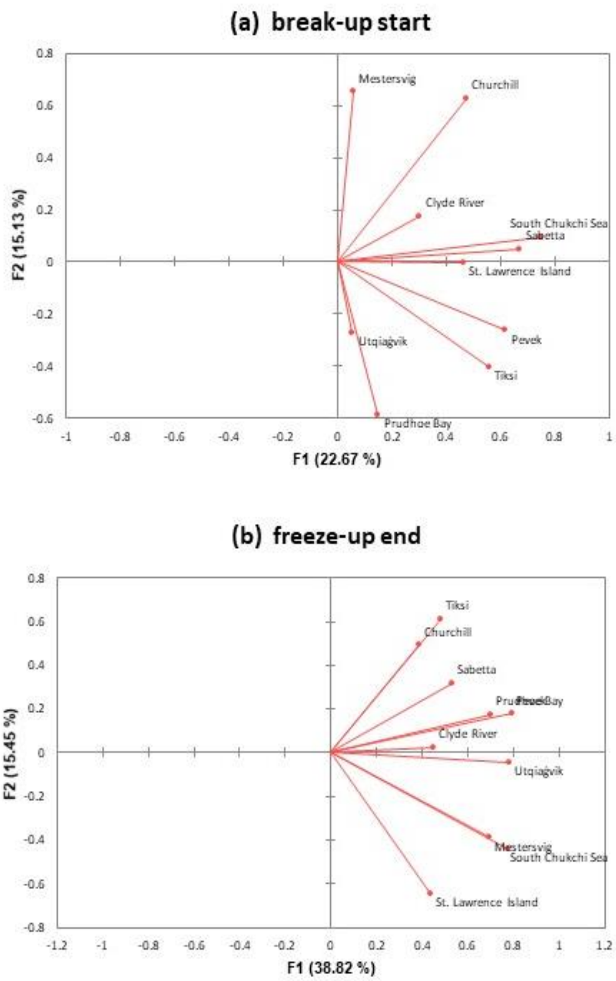

Figure 12. Loadings for Factor 1 (x-axis) and Factor 2 (y-axis) for (a) the start of break-up and (b) the end of freeze-up at the ten local coastal sites. Labels on vectors denote locations.

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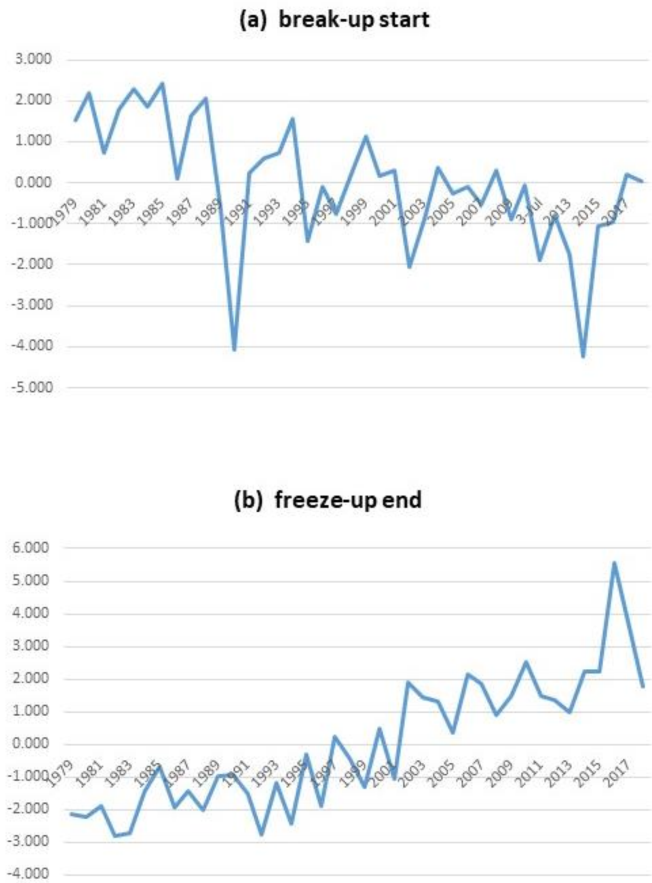

Figure 13. Scores (time series) for Factor 1 of (a) the start of break-up and (b) the end of freeze-up at the ten local coastal sites.

Table 3 shows that the first two factors explained more than half the variance for all local and MASIE indicators except the local break-up start date. The break-up start date is notable for the small percentages of variance explained by the first two factors. The implication is that

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local conditions play a relatively greater role in the timing of the start of break-up. These local factors can include landfast ice, inflow of water and heat from the adjacent land areas (including rivers), and possibly other effects related to local ocean currents or local weather conditions. The freeze-up start date has the most spatial coherence in the trend mode (55.7% of the explained variance). However, as shown by the last two lines of Table 3, the MASIE regional ice areas have even greater percentages of variance explained by the first two factors. In both the break-up and freeze-up seasons (June and November), the first two factors explain more than 60% of the variance (vs. 37.8%-55.7% for the local indicators). These differences again point to the importance of local conditions relative to the broader underlying trend in ice coverage, as Factor 1 (the trend) accounts for most of the differences between the local and regional results in Table 3.

Table 3. Percentages of variance explained by Factors 1 and 2. Numbers in parentheses are the contributions of the individual factors (Factor 1 + Factor 2).

Break-up start	37.8%	(22.7% + 15.1%)
Break-up end	50.9%	(37.6% + 13.3%)
Freeze-up start	55.7%	(40.1% + 15.6%)
Freeze-up end	54.3%	(38.8% + 15.5%)
MASIE ice areas: June	60.9%	(47.1% + 13.8%)
MASIE ice areas: November	64.1%	(48.7% + 15.4%)

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Finally, Figure 14 illustrates the tendency for tighter clustering in the regional indicators. For both the June and December results, the clustering in Figure 14 is clearly more distinct than in Figure 12, which is the corresponding figure for the local indicators. The clustering in Figure 14 is geographically coherent, e.g., the Pacific sector sites (Bering, Chukchi, East Siberian) are in a distinct cluster for the June (break-up), while subclusters for November include the Hudson and Baffin regions, the Kara and Laptev regions, and the Bering and Chukchi regions. The results imply that underlying trends and spatially coherent patterns of forcing will be more useful in explaining – and ultimately predicting – variations of regional sea ice cover. However, diagnosis and prediction of local indicators will require a greater reliance on additional information (local geography and local knowledge, including information from residents and other stakeholders who have had experience with break-up and freeze-up of sea ice in the immediate area.

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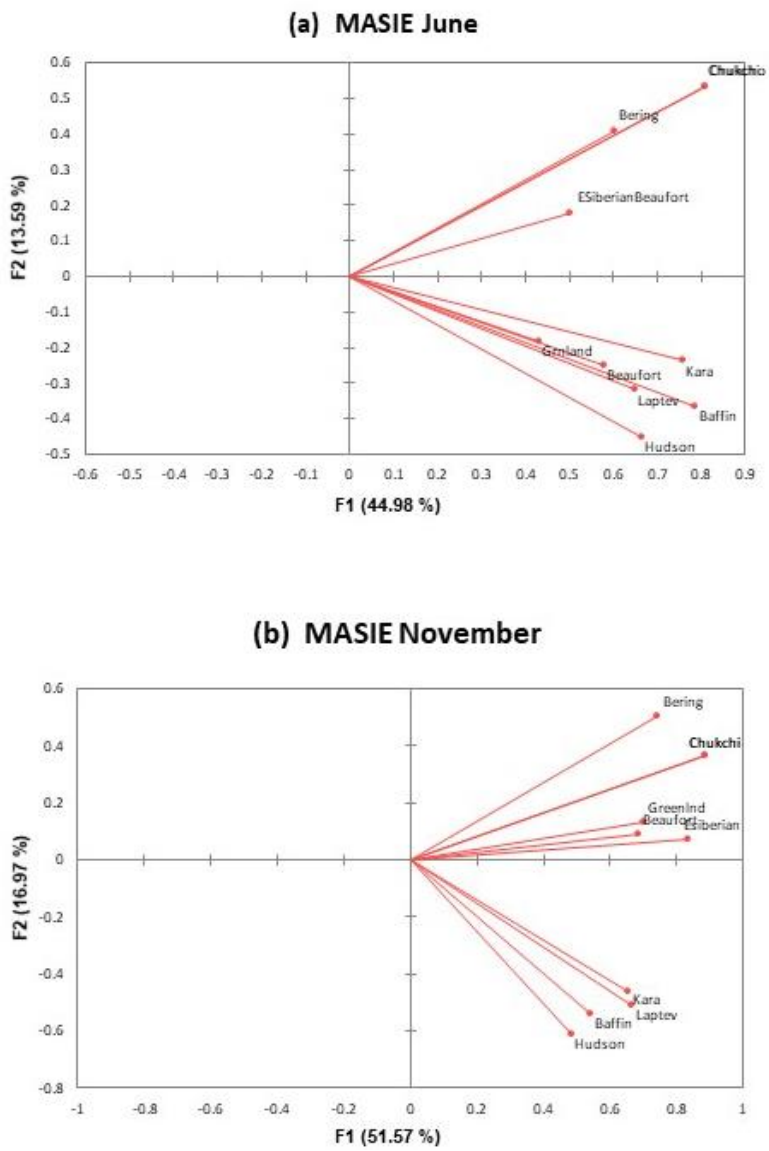

Figure 14. Loadings for Factor 1 (x-axis) and Factor 2 (y-axis) for the MASIE regional ice areas of (a) June and (b) November. Labels on vectors denote MASIE regiona.

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4. Conclusion

This study has utilized sea ice indicators based on local ice climatologies informed by community ice use (Johnson and Eicken, 2016; Eicken et al., 2014) rather than prescribed "universal" thresholds of ice concentration (e.g., 15%, 80%) used in other recent studies of sea ice break-up and freeze-up. Both types of indicators show similar trends and associated interannual variations, but the more locally-tailored indicators generally show earlier break-up and, in many instances, later freeze-up. The primary objective of this study was to use the locally-based indicators to construct indicators of break-up and freeze-up at near-coastal locations in which sea ice has high stakeholder relevance. A set of ten coastal locations distributed around the Arctic were selected for this purpose.

The trends and interannual variations of the local indicators of break-up and freeze-up at the ten nearshore are similar to the trends and variations of corresponding indicators for broader offshore regions, but the site-specific indicators often differ from the regional indicators by several days to several weeks. Relative to indicators for broader adjacent seas, the coastal indicators show later break-up at sites known to have extensive landfast ice, whose break-up typically lags retreat of the adjacent, thinner drifting ice. The coastal indicators also show an earlier freeze-up at some sites in comparison with freeze-up for broader offshore regions, likely tied to earlier freezing of shallow water regions and areas affected by freshwater input from nearby streams and rivers. However, the trends towards earlier break-up and later freeze-up are unmistakable over the post-1979 period at nearly all the coastal sites and their corresponding regional seas.

The differences between the coastal and offshore regional indicators matter greatly to local users whose harvesting of coastal resources and Indigenous culture are closely tied to the

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timing of key events in the seasonal ice cycle (Huntington et al., 2021; Eicken et al., 2014). These differences also matter from the perspective of maritime activities, where access to coastal locations for destinational traffic is a key factor (Brigham, 2017). These offsets vary considerably by region. In light of these findings, we view locally as well as regionally defined measures of sea-ice break-up and freeze-up as a key set of indicators linking pan-Arctic or global indicators such as sea-ice extent or volume to local and regional uses of sea ice, with the potential to inform community-scale adaptation and response.

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Data Availability

The daily grids of passive-microwave-derived sea ice concentrations are available from the National Snow and Ice Data Center as dataset NSIDC-0051, available at https://nsidc.org/data/nsidc-0051. Lists of the indicator dates for the coastal sites and the MASIE regions are available from the author on request.

Author contributions

JEW served the principal investigator for the study, led the drafting of the manuscript, and performed the factor analysis described in Section 4. HE supervised the implementation of the revised indicators for the coastal sites and the MASIE regions, and drafted parts of the text. KR performed the indicator calculations, produced Figures 1-11, and assisted in the preparation of the manuscript. MJ designed the original indicators, participated in the modification of the indicators, and contributed to the revision of the manuscript.

Competing interests

The authors declare that they have no conflict of interest

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