Large-Scale Climate Controls of Interior Alaska River Ice Breakup

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ABSTRACT

Frozen rivers in the Arctic serve as critical highways because of the lack of roads; therefore, it is important to understand the key mechanisms that control the timing of river ice breakup. The relationships between springtime Interior Alaska river ice breakup date and the large-scale climate are investigated for the Yukon, Tanana, Kuskokwim, and Chena Rivers for the 1949–2008 period. The most important climate factor that determines breakup is April–May surface air temperatures (SATs). Breakup tends to occur earlier when Alaska April–May SATs and river flow are above normal. Spring SATs are influenced by storms approaching the state from the Gulf of Alaska, which are part of large-scale climate anomalies that compare favorably with ENSO. During the warm phase of ENSO fewer storms travel into the Gulf of Alaska during the spring, resulting in a decrease of cloud cover over Alaska, which increases surface solar insolation. This results in warmer-than-average springtime SATs and an earlier breakup date. The opposite holds true for the cold phase of ENSO. Increased wintertime precipitation over Alaska has a secondary impact on earlier breakup by increasing spring river discharge. Improved springtime Alaska temperature predictions would enhance the ability to forecast the timing of river ice breakup.

1. Introduction

Because Alaska lacks roads in rural areas, rivers serve as critical highways—on ice in winter and on water in summer—but are impassable during breakup. In winter, rivers are used as ice roads to reach remote sites for oil and gas exploration and mining operations, as well as to reach the next village. The timing of ice-free conditions, which is dictated largely by the onset of breakup, signals the end of transportation on the ice and the ice roads. The breakup of river ice can also lead to ice jams and flooding in spring (Beltaos 2008) and occurs when broken ice stops moving, piles up, and restricts the flow of a river.

The date of river ice breakup (hereafter breakup) depends on a combination of river discharge and melting river ice; hence, breakup is the result of a balance between multiple forces. Breakup is initiated when the downstream forces of frictional river drag on the ice plus the forces associated with the momentum of moving ice from upstream overcomes the strength of the decaying stationary ice to resist movement. On the Yukon River at Dawson City, Canada, breakup is controlled by runoff from snowmelt at higher elevations and river flow characteristics (Carmack and Alford 1985). The exact date of breakup is somewhat subjective and tends to be defined as the passage of a breakup front at a given location, but the actual definition varies from observer to observer. The breakup date is most difficult to define in

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FIG. 1. Map of Alaska identifying locations of river breakup (gold stars), river discharge (blue triangles), and first-order climate station (red circles) data. River drainage basins are located in western and Interior Alaska.

years when sufficient ice decay occurs prior to a significant increase in river flow so that the ice begins to move along the length of the river without any significant ice run from upstream. Despite the seemingly vague definition of breakup, our results show that breakup is a robust measure in Alaska as multiple sites are highly correlated with one another.

The breakup date potentially integrates multiple climate parameters on both spatial and temporal scales into a single representative value. River parameters such as ice thickness have been used as proxies of the corresponding winter climate in the midlatitudes (Beltaos and Prowse 2002). Variability in ice conditions on Lake Baikal in Russia has been shown to be sensitive to multiple modes of climate variability across numerous seasons (Todd and Mackay 2003). Breakup trends on rivers and lakes throughout the Northern Hemisphere appear to be linked with observed climate variability (Magnuson et al. 2000). Anomalies in breakup on major rivers in Siberia and Canada have also been linked with the Pacific decadal oscillation (PDO; Pavelsky and Smith 2004), while ice jam activity has been linked with El Niño on the Yukon River (Jasek 1999). Since breakup integrates climate conditions spanning multiple seasons, it can also provide general information about the climate of Alaska and how it may relate to the large-scale climate.

The climate of Alaska has been linked with the largescale climate in the Pacific sector. The El Niño–Southern Oscillation (ENSO) plays a major role in controlling temperature throughout Alaska and winter air temperatures tend to be warmer on average during warm (El Niño) events (Papineau 2001). In addition, the positive phase of the North Pacific Oscillation/West Pacific Pattern (NPO/ WP) is characterized by increased storminess near Alaska that increases warm air advection into Alaska during the winter (Linkin and Nigam 2008).

While previous studies have primarily focused on the winter season, this work also explores climate and hydrological anomalies in spring. Through breakup we investigate the relationship between the large-scale (i.e., global or hemispheric scale) and local climate, toward the eventual goal of improving breakup forecasts. The novel aspects of our paper include the following: investigating the role of climate in Alaska breakup, identifying key climate–breakup physical linkages for Alaska, and proposing a plausible physical mechanism relating winter/ spring local and large-scale climate processes for Alaska.

2. Data and methods

a. Meteorological data

Station data of monthly average temperature and accumulated liquid precipitation from 1948 to 2008 were provided by the Alaska Climate Research Center (available online at http://climate.gi.alaska.edu/) for the firstorder stations located throughout Alaska (Fig. 1). The analysis was augmented with daily station observations, which include maximum and minimum daily temperature, sunrise to sunset average sky cover, and accumulated liquid precipitation for 1948–2008. The National Climatic Data Center provided the daily data (available online at http://www.ncdc.noaa.gov/oa/ncdc.html). The chosen stations have relatively long records of high-quality continuous observations since they are professionally operated and maintained by the National Weather Service and the Federal Aviation Administration. The stations are all located at relatively low elevations and represent various climate types ranging from Arctic for Barrow, Alaska, to continental in Interior Alaska, to coastal in western and southern Alaska (Shulski and Wendler 2007).

To investigate the relationship with the large-scale climate, standard gridded climate data were employed. Over the land, monthly average surface air temperature (SAT) from the University of East Anglia Climate Research Unit (CRU) TS3.0 dataset was used (available online at http://www.cru.uea.ac.uk/cru/data/). This data interpolates global station data to a $0.5^{\circ} \times 0.5^{\circ}$ grid over land only for 1901–2006 (Mitchell and Jones 2005). Over the oceans, monthly average sea surface temperature (SST) data from the National Oceanographic and Atmospheric Administration (NOAA) extended reconstructed SST data version 3 (see online at http://www.esrl.noaa.gov/psd/) were used. The SST data are provided on a $2^{\circ} \times 2^{\circ}$ grid spanning 1854–2009 and incorporates satellite data after 1985 (Smith et al. 2008).

Data representing the atmospheric circulation were provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis 1 (see online at http://www. esrl.noaa.gov/psd/). Variables investigated include monthly mean sea level pressure (SLP) and 500-hPa geopotential height (500-hPa height). The NCEP–NCAR reanalysis 1 assimilates observations using a weather forecast model and is provided on a $2.5^{\circ} \times 2.5^{\circ}$ grid spanning 1948–2008 (Kalnay et al. 1996).

The storm track data are based on the tracking algorithm of Zhang et al. (2004) and span 1948–2008. The tracking algorithm searches gridded 6-hourly SLP data to determine points of minimum pressure and then flags these as candidate cyclone (storm) centers. The candidate centers were then tracked through time and the individual storms were identified by a tracking criterion of minimum lifetime. Individual storms were identified and tracked in the Northern Hemisphere north of 30°N and were constructed from the NCEP– NCAR reanalysis.

Climate indices were used to complement the analysis. The Niño-3 index was obtained from the Earth System Research Laboratory Physical Science Division (see online at http://www.esrl.noaa.gov/psd/) and spans 1871–2008. The Pacific–North American (PNA) index was obtained from the Climate Prediction Center (see online at http://www.cpc.noaa.gov/) and covers 1950– 2008.

b. Hydrological data

Monthly average river discharge was provided by the U.S. Geological Survey (USGS), which maintains flow gauges on the rivers in Alaska (Fig. 1) where the breakup date is measured. Only a few flow gauges were collocated with the breakup observation locations, so proximal gauges on the same rivers were selected for the period 1948–2008.

Breakup date data were provided by the Alaska Pacific River Forecast Center (see online at http://aprfc. arh.noaa.gov/data/breakup.php) for the three locations (Fig. 1) on the Yukon, Tanana, and Kuskokwim Rivers in interior and western Alaska. The three breakup sites were chosen because of their location along major rivers, location in Interior Alaska, and their superior data quality relative to the other sites (only a few missing years). Bethel was initially selected to compare with the interior locations but it was significantly correlated with the interior sites; hence, it was grouped with the interior stations. Winter river ice thickness measurements contained temporal inconsistencies and extensive periods of missing data so they could not be used.

The term breakup refers to the time when a breakup front (i.e., the interface between the stationary and moving ice) reaches the location of the observer, which can be somewhat subjective. Despite the subjectivity involved in breakup observations, the three locations (Fig. 2a) all tend to have the same sign anomalies each year, which is evident from visual inspection of Fig. 2a. They display significant correlations ranging from 0.70 Dawson City and Bethel, to 0.80 between Bethel and Nenana, and 0.80 between Nenana and Dawson City. The average breakup (Fig. 2b) is employed in this study because of the covariability between measurement sites.

Breakup typically occurs in early May, beginning in upstream reaches and then moving downstream toward the coast. Bethel has the latest breakup date and Nenana the earliest (Table 1) with a standard deviation at each station of about 1 week. The extreme latest breakup date observed was 3 June 1964 at Bethel while the earliest was at Nenana on 24 April 1998. All three sites have a significant decreasing trend with breakup occurring 1.3 days earlier per decade.



FIG. 2. (a) Breakup date time series for Dawson City (Yukon River), Nenana (Tanana River), and Bethel (Kuskokwim River) are shown as a solid, gray dotted, and black dashed lines, respectively. (b) The gray line shows the 3-station average, while the 5-yr running mean of the station average is shown in black. The horizontal solid and dashed lines show the mean and standard deviation of the average breakup, respectively. Averaging the stations was justified since they were significantly correlated (>0.70).

c. Analysis methods

Standard statistical techniques for climate analysis were employed in this study to investigate the relationships between the various climate and hydro-climate parameters. Pearson correlation coefficients were calculated on linearly detrended (least squares method) time series since trends can be quite large in the Arctic. Linear regression coefficients were calculated using the least squares method. The correlation and regression analyses yielded similar results so only the regression analysis is presented. For ease of discussion, results were scaled by a factor of -1 as needed to reflect anomalies corresponding with early breakup. The statistical significance of correlations and regressions was assessed using a two-tailed t test at the 95% or greater level. Composite analysis was constructed by combining events larger than one standard deviation. As our datasets all have different record lengths, the analysis was conducted on the common period of 1948–2008.

Seasonal average analyses are presented in the paper for the sake of brevity. Winter in Alaska is a time of minimal solar radiation and snow cover, whereas in spring solar insolation leads to significant daytime heating. Snow however, remains on the ground until at least April for many areas of Alaska and controls the radiative properties of the surface because of its high albedo relative to bare ground. By grouping months with similar

TABLE 1. Average, standard deviation, record minimum and maximum, and trend for breakup observed at Dawson City, Nenana, Bethel, and the average breakup.

	Dawson	Nenana	Bethel	Avg
Avg (day of year)	128	124	133	128
Std dev (days)	5	6	8	6
Record min (day of year)	119	110	121	118
Record max (day of year)	149	141	155	148
Trend (days per decade)	-1.3	-1.3	-1.3	-1.3

physical processes we defined winter as December– March (DJFM) and spring as April–May (AM).

3. Results

a. Local controls of breakup

Station temperature was regressed on breakup (Fig. 3a) and indicated that breakup tends to occur 1 day earlier (later) when average AM temperatures are 0.2°-0.3°C warmer (cooler) in interior/western and northern Alaska. In southern Alaska the relationship between station temperature and breakup is weaker but still statistically significant. Springtime (AM) discharge regressed on breakup (Fig. 3b) suggests that breakup tends to occur earlier when river discharge is higher. Conversely breakup tends to occur later when river discharge is lower. The notable exception is the Chena River, which is a relatively small river. River discharge was normalized for all stations (excluding the Chena River) and then averaged to construct an interior river discharge time series. Regressions of DJFM precipitation on the AM-average-normalized river discharge (Fig. 3c) indicate that increased DJFM precipitation in interior and northern Alaska is associated with above-average AM discharge. However, wintertime (DJFM) temperature and precipitation were weakly related with breakup, with only a few stations having significant regression coefficients (not shown). When AM station temperature was regressed on the normalized spring discharge (Fig. 3d) it was found that increased spring discharge is related to warmer spring temperatures throughout Alaska.

In summary, warmer AM temperatures melt the snowpack, increase river discharge, and degrade the river ice leading to earlier thermal and mechanical forcing that breaks up river ice cover. Conversely, cooler AM temperatures maintain the snowpack, reduce river discharge, and maintain the river ice leading to later breakup. While breakup is related to runoff from the melting snowpack, winter precipitation was only weakly related to breakup. In conclusion, this suggests that AM surface air temperatures are the most important climate variable that determines breakup.



FIG. 3. Linear regression coefficients of (a) AM temperature, (b) AM river discharge on breakup date, (c) DJFM precipitation, and (d) AM temperature on AM normalized river discharge. Note that (a) and (b) have been scaled by -1. Regressions significant at the 95% or greater level are shown in bold. Breakup tends to occur earlier (later) when temperatures are warmer (cooler) and river discharge is higher (lower). Higher (lower) AM discharge occurs with increased (decreased) DJFM precipitation.

b. Large-scale controls of breakup

Winter (DJFM) and spring (AM) gridded climate data were regressed on breakup to investigate large-scale climate variability patterns particularly during the winter that could be exploited for breakup forecasting.

Regressions of wintertime (DJFM) surface temperatures (SAT over land and SST over oceans) on breakup (Fig. 4a) display significant negative values in the midlatitude Pacific and significant positive values along coastal North America and in the eastern equatorial Pacific. This DJFM regression pattern (Fig. 4a) in the Pacific compares favorably with the ENSO signal (Parker et al. 2007) and shows that during the positive phase of ENSO breakup is earlier than normal. The absence of significant regressions between breakup and DJFM SAT over Alaska is consistent with the analysis of local station data (section 3a) where also no significant coefficients were found in winter. Breakup was only weakly correlated with the DJFM Niño-3 index (not shown); however, composite analysis of DJFM SSTs (not shown) revealed that while the positive phase of ENSO tends to occur with early breakup, the negative phase is only weakly related to late breakup. This suggests a nonlinear relationship where the warm phase of ENSO has a larger impact than the cool phase in controlling breakup.

Winter (DJFM) SLP regressed on breakup (Fig. 4b) displays an area of significant negative coefficients in the eastern midlatitude Pacific, which suggests enhanced southerly flow into Alaska during earlier breakup. The regressions of 500-hPa height on breakup (Fig. 4c) display a pattern extending from the tropics with a high–low–high–low pattern that compares favorably with the positive phase of the PNA pattern. As the PNA is considered to be an atmospheric response to ENSO forcing (Horel and Wallace 1981), it is reasonable to conclude that the PNA-like regression pattern (Figs. 4b,c) is the atmospheric response to the ENSO structure (Fig. 4a). In



FIG. 4. Linear regression coefficients of DJFM (a) SST/SAT, (b) SLP, (c) 500-hPa height, and AM (d) SST/SAT, (e) SLP, (f) 500-hPa height on breakup. Note that (a)–(f) have been scaled by -1. Contour intervals (CI) are shown under the titles. Positive (negative) regressions significant at the 95% or greater level are shaded red (blue). DJFM and AM SAT/SST pattern resemble ENSO-related climate anomalies in Pacific. The warm phase of ENSO is associated with an earlier breakup.



FIG. 5. Time series of DJFM and AM GOA and Bering Sea storm counts shown by gray lines. Smoothed (5 yr) time series are shown by black lines. The plot limits vary, but the scale is the same for all line plots.

summary, local winter conditions in Alaska have a minimal direct impact on breakup, however, there may be an indirect relationship since the winter SST and circulation anomaly patterns persist into spring.

Regressions of springtime (AM) temperature on breakup (Fig. 4d) are similar to those during winter (see Fig. 4a). The notable difference between DJFM and AM is that in AM there are significant positive regressions over all of Alaska. As a result of the high degree of similarity of the SST patterns in the Pacific between Figs. 4a,d and the slow speed of ocean processes, Pacific spring and winter SST patterns are likely linked through seasonal anomaly development in the ocean. This is supported by the large pattern correlation (0.77) between the winter and spring regression patterns (Figs. 4a,d) over the ocean.

Regressions of spring SLP and 500-hPa height on breakup (Figs. 4e,f) display patterns that are similar to those during winter, except the magnitudes of spring regressions are generally larger and shifted westward. The



FIG. 6. Linear regression coefficients of DJFM precipitation on DJFM Bering Sea storm count. Storms that entered the outlined box were included in the storm count. Regressions significant at the 95% or greater level are shown in bold. Increased (decreased) storms result in more (less) precipitation in Interior Alaska in winter.

correlation between the AM PNA index and breakup was -0.47 (95% level significance), consistent with an earlier breakup during the positive phase of the PNA. In summary, breakup is impacted by ENSO- and PNA-related climate anomalies in the Pacific that begin to develop in DJFM and persist into AM.

c. Local to large-scale connection

Thus far, our results have shown that breakup is most closely linked with local AM temperature and with ENSOrelated climate anomalies on the large scale. Regression and composite analysis of storm tracks, with breakup and climate variables, are used to investigate a physical mechanism linking the local and large-scale climate anomalies.

Alaska is situated north of the major storm track in the Pacific (Klein 1957; Zhang et al. 2004; Mesquita et al. 2010) and storms primarily impact the state through the Gulf of Alaska with a secondary track through the Bering Sea for storms of more western origin (Klein 1957; Rodionov et al. 2007; Mesquita et al. 2010). In this analysis we investigated the relationship between breakup, storms approaching Alaska, and the large-scale climate. Storms entering the Gulf of Alaska (GOA; 55°-62°N, 137°–158°W, see box in Fig. 7a) and Bering Sea (Bering; 55°-70°N, 163°W-180°, see box in Fig. 6) were counted for DJFM and AM. The time series for the regional storm counts are shown in Fig. 5, with a 5-yr smoothing that highlights the decadal to multidecadal variability. The observed station data and gridded data were regressed on the GOA and Bering storm counts for DJFM and AM to evaluate their relationships.

During the winter (DJFM) only the Bering storm count had a significant relationship with accumulated precipitation in Interior Alaska at the seasonal scale (Fig. 6).



FIG. 7. Linear regression coefficients of AM (a) station temperature, (b) SST/SAT, (c) SLP, and (d) 500-hPa height on the AM GOA storm count. Note that (a)–(d) have been scaled by -1. Contour intervals shown above plots. In (a), regressions significant at the 95% or greater level are shown in bold. Positive (negative) regressions that are significant at the 95% or greater level are shaded red (blue). Storms that entered the outlined box in (a) were included in the storm count. Increased (decreased) GOA storm counts are associated with the cool (warm) phase of ENSO. Increased (decreased) storm counts result in cooler (warmer) temperature in Alaska.

More storms approaching Alaska from the Bering in DJFM results in increased DJFM precipitation, while, less storms approaching Alaska from the Bering in DJFM results in reduced DJFM precipitation. This finding is consistent with the self-organized map analysis of Cassano and Cassano (2009), which found that low pressure in the Bering Sea results in increased precipitation over the Yukon basin. Storms that approach Alaska through the Bering allow more moisture penetration and precipitation in Interior Alaska, since the topographic barriers are significantly smaller than for storms that approach from the Gulf of Alaska. GOA storms deposit most of their precipitation on the windward side of the Alaska range (Mock et al. 1998). Since breakup has a weak relationship with DJFM precipitation and AM river discharge is primarily controlled by AM temperatures, the role of precipitation from DJFM Bering storms is concluded to be of minor importance.

Gulf of Alaska storms play a prominent role during the spring and station temperature regressed on AM GOA counts (Fig. 7a) indicated that fewer storms occurring in the Gulf of Alaska resulted in warmer surface air temperatures and earlier breakup. Conversely, more storms entering the Gulf of Alaska resulted in cooler surface air temperatures and later breakup. In contrast, during winter GOA storms warm Interior Alaska from adiabatic warming from downslope southerly flow over the Alaska range. Bering storms did not have a significant relationship with temperature in the spring. Spring SST/SAT, SLP, and 500-hPa height regressions on AM GOA storm counts (Figs. 7b-d) display patterns that compare favorably with the corresponding panels shown in Figs. 4d-f for breakup. The frequency of storms occurring in the Gulf of Alaska during spring is linked to similar large-scale climate patterns as breakup, suggesting that GOA storms are a key control of breakup variability through their influence on temperature in Interior Alaska.

The results have shown that spring (AM) Gulf of Alaska storm counts are correlated with breakup and spring station temperature and all of these variables are related to similar large-scale climate patterns. Next we investigated how Gulf of Alaska (GOA) storms in spring (AM) control the local conditions (i.e., AM temperature) that lead to breakup.

Composites of accumulated thawing degree-days (the sum of temperatures above 0°C), accumulated sunrise to sunset cloud fraction, and accumulated precipitation were computed in relation to breakup date using the Fairbanks, Alaska, meteorological station data. Fairbanks was selected for this analysis as it had consistently high correlations with breakup and best illustrates the impact of GOA storms on the interior. Composite years for early breakup (1951, 1953, 1958, 1961, 1969, 1979, 1990, 1993, and 1998) and late breakup (1952, 1962, 1964, 1972, 1982, 1985, 1986, 1987, 1992, 2002, and 2006) were identified. The days in the composite were keyed to breakup and included 30 days before and 5 days after breakup, with breakup occurring on day 0. This was done to analyze the local weather conditions leading up to breakup and to facilitate a comparison with GOA storms.

Composites of maximum and minimum air temperatures for late and early breakup (Figs. 8a,b) indicate that temperatures tend to be warmer when breakup is earlier. Earlier breakup occurs when there is decreased cloud cover, reduced precipitation, and decreased numbers of storms occurring in the Gulf of Alaska (Figs. 8c–e). During spring, when solar radiation heats the surface, decreased cloud cover and precipitation help to raise surface air temperatures by increasing net solar radiation at the surface and is consistent with an earlier breakup. Conversely, more GOA storms, increased cloudiness, and enhanced precipitation lead to a later breakup by reducing the amount of solar radiation reaching the surface. A detailed analysis of the relationship between storms in the Gulf of Alaska and Pacific SSTs during DJFM and AM is beyond the scope of this study; however, published literature can provide insight on this topic. Using climate models and observations, Seager et al. (2010) found that there is a southward shift in the Pacific storm track during positive ENSO events. This is consistent with our findings that when storm counts decrease in the Gulf of Alaska there is an increased storm count into a box just to the south (not shown).

d. Low-frequency breakup signal

Visual inspection of the smoothed (5-yr running mean) breakup time series (Fig. 2b) suggests the presence of decadal variability, which accounts for 29% of the variance. This hypothesis was confirmed and quantified using singular spectrum, wavelet, and harmonic analysis on the unsmoothed breakup time series (not shown). The wavelet analysis also suggested that the decadal signal changes in frequency in the late 1980s. Closer examination of the low-frequency line in Fig. 2b indicated that there was a shift to earlier breakup between the mid-1980s to the mid-1990s. It has been noted that a shift in the leading mode of SST variability in the North Pacific in the early 1990s (Bond et al. 2003) from a PDO-like pattern to the North Pacific gyre oscillation (NPGO) pattern (Di Lorenzo et al. 2008) has occurred. The regression patterns of DJFM Pacific SSTs on breakup before and after 1989 are consistent with the empirical orthogonal function (EOF) analysis from Bond et al. (2003) and Di Lorenzo et al. (2008), which showed a shift from the first to the second mode in Pacific SST variability (not shown). In addition, Bourne et al. (2010) found that surface-based temperature inversion parameters in Alaska were more strongly correlated with the PDO before 1989 than afterward. While a shift to earlier breakup was observed from the 1980s to 1990s, the storm counts (see Fig. 5) do not display a corresponding shift. While a physical mechanism linking the changes in breakup to North Pacific SST variability is unknown, there is some indication that the change to lower-frequency variability in breakup since 1989 reflects the concurrent shift noted in the North Pacific.

4. Conclusions

A summary of the key processes that relate breakup to the large-scale climate is shown schematically in Fig. 9. Breakup is primarily controlled by local spring surface air temperatures and river discharge. Additionally, river discharge is strongly influenced by surface air temperatures, with warmer temperatures leading to higher discharge due



FIG. 8. Daily average composites for late, early, and average breakup of Fairbanks observed (a) accumulated thawing degree-day based on maximum temperature, (b) accumulated thawing degree-day based on minimum temperature, (c) accumulated cloud fraction, (d) accumulated precipitation, and (e) accumulated GOA daily storm count. The window starts 30 before and ends 5 days after breakup date, which is marked with a vertical line.

to runoff from the melting snowpack. Winter precipitation, despite providing the snowpack, influences breakup to a lesser extent since spring temperatures control the rate and timing of melt. Breakup is linked to ENSOrelated climate anomalies that persist from winter into spring, suggesting that breakup may have some degree of predictability prior to the spring.

The overall climate–breakup mechanism (Fig. 9) can be summarized as follows: during El Niño in spring (AM), fewer storms occur in the Gulf of Alaska reducing cloudiness, warming air temperatures, and leading to earlier interior river ice breakup. Although weaker than the influence of El Niño, during La Niña in spring (AM) more storms occur in the Gulf of Alaska increasing cloudiness, cooling temperatures, and resulting in later breakup.

The findings of this study expand on those of Papineau (2001), which linked winter temperatures in Alaska with ENSO. Our study indicated that ENSO-related climate anomalies influence Alaska springtime temperatures as



FIG. 9. Summary of the breakup–climate mechanism highlighted for early breakup. The primary mechanism is outlined within the boxes, with the secondary mechanism shown on the left. DJFM represents the December–March period while AM signifies April– May. Later breakup can be described by opposite sign anomalies.

well as the timing of breakup. Breakup was also found to contain a low-frequency climate signal when smoothed and a shift to earlier breakup after the 1980s was revealed that might reflect the shift in Pacific variability documented in 1989. This study shows that breakup in Alaska is sensitive to large-scale, low-frequency climate variability in the Pacific. The winter Pacific SST anomaly patterns, which persist into spring, may be potentially exploited to develop seasonal forecasts of springtime temperatures in Alaska. Consequently, seasonal predictions of spring temperatures in Alaska would help forecast river breakup date, breakup severity, and breakup-related flooding.

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