Abstract

The annual spring river ice breakup has vast consequences for northern ecosystems as well as significant economic implications for Arctic industry and transportation. River ice breakup research is restricted by the sparse distribution of hydrological stations in the Arctic. A trend towards earlier ice breakup has been noted across the Arctic region, yet the specific climatic drivers of these trends are complex and can vary both regionally and within river systems. Consequently, understanding the response of river ice processes to a warming Arctic requires examination of both spatial and temporal trends in breakup timing. In this paper, I describe an automated algorithm for detecting the timing of river ice breakup using MODIS imagery that enables identification of spatial and temporal breakup patterns at whole-river scales and present an analysis of breakup timing on the Mackenzie, Lena, Ob and Yenisey rivers. Through splitting the rivers into 10 km segments and classifying each river pixel as snow, ice, mixed ice/water or open water, I am able to determine the dates of breakup from 2000-2014 with a mean uncertainty of around +/- 1.5 days. Where temporal trends are statistically significant, they are consistently negative, indicating an overall shift towards earlier breakup. Considerable variability in the statistical significance and magnitude of trends along each river suggests changing climatic drivers are impacting breakup patterns. Trends detected on the lower Mackenzie confirm previously observed weakening ice resistance and earlier breakup timing near the Mackenzie delta. In Siberia, the increased magnitude of trends upstream and strong correlation between breakup initiation and whole-river breakup patterns suggests that upstream discharge may play the dominant role in determining breakup timing. Exploratory analysis demonstrates that this method may in the future also be used to examine types of breakup events and assess event severity.

1. Introduction

River ice formation and breakup are major events for the ecosystem and economy of the pan-Arctic region. The spring ice breakup can lead to up to $250 million of damage in North America and more than $100 million in Russia every year (Beltaos & Prowse, 2009). Ice breakup severely impacts regional transportation dependent on river ice, and corresponding ice jam floods can be devastating to bridge, dam and hydropower infrastructure. Peak flow usually occurs around the time of ice breakup, and this high velocity flow is very erosive to the surrounding landscape (Prowse, 2001a). Despite the damage erosive flow can cause, heavy spring flow is also an integral part of Arctic ecosystems, and the resultant flooding is critical to the recharge of water to wetlands and ponds located near these rivers (Prowse, 2001b). This flow also mobilizes and transports large amounts of sediment and nutrients vital to the riparian life of the region.

Fundamentally, river ice breakup is controlled by the balance between the driving force (upstream discharge) and the resisting force (downstream ice cover) (Beltaos & Prowse, 2009). Breakup events can generally be described through two extremes: mechanical and thermal. Mechanical breakup events are characterized by high discharge and limited downstream melting, often causing high severity events and significant ice-jam flooding. In contrast, thermal breakup events are produced by decreased discharge and weak downstream resistance. While surface air temperature has been shown to have a large effect on breakup timing, other factors such as discharge, precipitation and ice thickness additionally impact breakup. Due to ongoing warming and intensification of the Arctic hydrological cycle, several studies have observed trends towards earlier ice breakup over the past 50-100 years across the pan-Arctic region (Magnuson et al., 2000; Shiklomanov & Lammers, 2014; Smith, 2000) and identified predicted shifts towards more thermal (less severe) breakup events (Prowse et al., 2010). Possible drivers of these trends vary both along river and between different regions. Increasing discharge in Eurasia (Peterson et al., 2002) can increase the driving force upstream whereas a decreasing temperature gradient (Prowse et al., 2010) may weaken downstream resistance. However, these studies all rely on point-based station data, preventing observation of changes in breakup processes and limiting understanding of spatial patterns in these trends. Without observation of river ice processes at whole river scales, it is difficult to understand how a warming climate impacts river ice breakup.

This paper presents an automated algorithm for detecting river ice breakup over the entire lengths of large northern rivers using daily time series of moderate resolution imaging spectrometer (MODIS) data. Using this surface reflectance imagery, I determine breakup dates in 10 km segments over the four largest pan-Arctic rivers from 2000-2014. The goals of this research are threefold. First, I aim to create an efficient and consistent method of detecting breakup timing over large spatial scales. Second, I seek to use this method to develop a comprehensive dataset of breakup timing for four large northern rivers over the past 15 years. Finally, I analyze spatial and temporal trends in breakup timing using this dataset and examine how the spatial distribution of trends at whole river scales compares to previous point-based studies.

2. Background

2.1 Summary of river ice processes

Breakup events generally coincide with the annual spring flood that is associated with increased discharge due to melting of the snowpack. Hydroclimatic conditions during the fall and winter control the freezing level of the river, the ice thickness and the snowpack, setting the initial conditions for the breakup season (Prowse et al., 2007). The meteorological conditions during the spring melt season generally play the most dominant role in controlling breakup dynamics (Goulding et al., 2009). Breakup does not always progress linearly; channel geometry and confluences with other rivers also influence breakup timing. In particular, the presence of thick downstream ice can lead to an ice jam and resulting heavy flooding (Beltaos, 2003).

The dynamics and severity of river ice breakup can be described through two extremes: mechanical and thermal. Dynamic breakup events are characterized by lower freeze-up levels, thicker ice and a large snowpack (Beltaos, 2003). In mechanical breakup events, the rapid melting of the snowpack increases discharge levels upstream before the downstream regions have begun to melt significantly. This high flow encounters significant resistance due to thicker ice downstream, often leading to severe ice jam flooding (Beltaos & Prowse, 2009). In contrast, thermal breakup events generally occur when there is a smaller winter snowpack or decreased spring melt, allowing downstream ice to ablate substantially before the arrival of the spring flood wave (Beltaos, 2003). The lower strength of the downstream ice cover leads to less severe breakup events and therefore decreased flooding. Thermal events can also be characterized by a decreased temperature gradient along the river (Prowse et al., 2010). Given the complexity of hydrometeorological forcings during the breakup season, most ice breakup events fall somewhere along this spectrum from mechanical to thermal, creating a broad range of event severity even within singular river basins (Beltaos & Prowse, 2009). Due to the current preferential warming of northern latitudes and increasing surface air temperatures, a shift from mechanical to thermal breakup events has been predicted (Prowse et al., 2010).

The timing of river and lake ice breakup is dependent on several climatic drivers and thus can be used to infer northern hemisphere climate variability. Numerous studies have noted a general trend in earlier ice breakup dates over the past 20 to 100 years (e.g. Magnuson et al., 2000; T. Prowse et al., 2007). Despite the general agreement regarding a trend towards decreasing length of ice conditions, the specific drivers of these changes are debated. Warming temperatures are hypothesized to lead to earlier initiation of melt and decreased water level peaks through thinning of downstream ice (reduced resistance) and higher discharge (increased forcing). While winter surface air temperature affects the initial conditions of the river basin system, numerous studies note a stronger correlation between spring air temperature and onset of breakup (Bieniek et al., 2011; Goulding et al., 2009; Shiklomanov & Lammers, 2014; Smith, 2000). Due to the observed increase in river discharge over the past 80 years for large northern rivers (Peterson et al., 2002), discharge has also been examined as a possible cause of earlier breakup. Though there is a strong correlation between the timing of peak discharge and the timing of river ice breakup, inconclusive and conflicting studies suggest the relationship between discharge and breakup timing is both location dependent and poorly understood (Bieniek et al., 2011; Goulding et al., 2009; Lesack, et al., 2014). Precipitation and snowpack depth, while related to discharge, may also impact breakup timing as separate factors. Changing spatial and temporal patterns in precipitation may lead to increased runoff and higher discharge in Eurasia (Shiklomanov & Lammers, 2009), while a decreasing snowpack may limit runoff and cause earlier breakup in Canada (Lesack et al., 2014). Natural variability and the influence of interannual, decadal and multidecadal climate oscillations such as the PDO and ENSO can also affect breakup and obscure trends (Bonsal et al., 2006; Prowse et al., 2007).

Though there is general agreement on the existence of trends towards earlier ice breakup, the magnitude and statistical significance of these trends vary across the Arctic region. A trend towards earlier spring breakup of 1-2 days per decade over the past 30 years has been identified in the Mackenzie River Delta (de Rham et al., 2008; Goulding et al., 2009; Lesack et al., 2014), but little conclusive research exists on trends in breakup timing in the central Mackenzie. Studies utilizing Russian point-based hydrologic data generally note earlier melt onset and decreasing duration of ice conditions (Ginzburg et al., 1992; Shiklomanov & Lammers, 2014; Smith, 2000; Vuglinsky, 2006; Vuglinsky, 2002). In his analysis of Russian hydrologic station data, Vuglinsky (2006) finds decreases in duration of ice conditions of 3-7 days from 1980-2000 for Siberian rivers. Similarly, Shiklomanov and Lammers (2014) observe decreases between 7 and 20 days over the period 1955-2012. It is important to note that these studies all rely on the assumption that point-based breakup dates can be used to infer whole river-scale variability and trends. Though previous work demonstrates that this assumption is reasonable (Pavelsky & Smith, 2004), there exists little research on how trends may vary spatially within an entire river system.

2.2 Review of Remote Sensing of River and Lake Ice

Obtaining high spatial and temporal resolution hydrologic data is vital to further research on trends in river ice breakup. Considering the remote location and large scale of major Arctic rivers, most studies are forced to rely on sparsely distributed hydrologic station data, preventing observation of spatial patterns in breakup at basin-wide scales. Furthermore, ground hydrologic river observations are decreasing across much of Siberia, meaning it may become increasingly difficult to obtain these types of data (Shiklomanov et al., 2002). Although remote sensing allows for study of river ice breakup at whole river scales, satellite imagery remains generally underutilized in river ice breakup research (Duguay et al., 2015; Jeffries et al., 2005).

Satellite imagery used for remote sensing of river ice must balance three main requirements. First, it must be possible to easily differentiate between ice, mixed ice/water and open water. Second, the imagery must be of sufficiently high resolution that one can distinguish lakes and rivers from the surrounding landscape. Third, the time between repeat imagery must be adequately small to allow for determination of breakup timing within a reasonable window of error. Past studies have utilized active and passive sensors in several wavelengths and from a variety of platforms to study river and lake ice. The majority of current remote sensing river and lake ice research focuses on assessing the capabilities of satellite imagery and/or economic applications such as locating ice jams or real-time ice detection. Only a handful of studies use remote sensing to study temporal trends in ice phenology (Latifovic & Pouliot, 2007; Pavelsky & Smith, 2004).

Due to its high spatial resolution and ability to distinguish different ice types, synthetic aperture radar (SAR) is commonly used to study river and lake ice. SAR operates in the microwave range of the electromagnetic spectrum, obtaining imagery at both day and night and under varied atmospheric conditions. The primary benefits of SAR are its relatively high spatial resolution and insusceptibility to cloud cover. However, the low temporal resolution means detected breakup dates generally have a larger window of uncertainty. Additionally, the complexity of SAR imagery can lead to some difficulty in distinguishing between ice and water, particularly when open water pools on the surface of the ice (Jeffries et al., 2005). As water is a specular reflector, calm open water appears dark in SAR imagery. The appearance of ice in SAR images depends on both surface and volume scattering due to factors such as the surface smoothness, dielectric constant and water content (Unterschultz et al., 2009). Ice will appear bright if the surface is rough, whereas wet and smooth ice can act a specular reflector and thus have a dark appearance similar to open water. Because the appearance of ice in SAR imagery is dependent on both the surface and the internal structure of the ice, SAR can be used to determine ice properties such as water content, thickness and whether the ice is frozen to the bed (Duguay et al., 2015). As a result, SAR is particularly well suited to identifying ice jams and categorizing river ice types through visual and automated classification methods (Bernier & Gauthier, 2006; Sobiech & Dierking, 2013; Weber et al., 2003).

Applications of SAR specific to river ice breakup are less common, and most studies focus on economic applications rather than identifying trends over significant time scales. Unterschultz et al., (2009) find that SAR can be used to determine river ice type and breakup timing over a relatively short stretch of the Athabasca River. Similarly, Floyd et al. (2014) utilize a time series analysis of SAR images over the Kuparuk River in Alaska, observing that variance in brightness is the most reliable indicator of the onset of breakup. A few studies have also explored the applicability of synthetic aperture radar interferometry (InSAR) to ice breakup research, finding that InSAR can be used to detect river ice motion and predict locations of mechanical breakup (Smith, 2002; Vincent et al., 2004).

Optical satellite sensors commonly provide imagery of snow and ice at global scales and are thus useful for detection of river and lake ice. High-resolution images from satellites such as Landsat (30 m) can be used to map ice extent on small rivers and lakes (Gatto, 1990) and can provide a helpful baseline reference in SAR research (Cook & Bradley, 2010; Nolan et al., 2002). However, the low temporal resolution and small size of Landsat scenes reduces their utility for large scale breakup research. Medium spatial resolution (0.25-1 km) and high temporal resolution optical imagery from sensors such as the advanced very high resolution radiometer (AVHRR) and the moderate resolution imaging spectrometer (MODIS) has several advantages for ice breakup study. Ice is easily distinguishable from water in near-infrared bands, and the daily coverage allows for high temporal precision. The coarser resolution restricts their use to major rivers and lakes, however, and cloud-obscured imagery limits temporal accuracy, particularly in the cloudy sub-Arctic region. Early research using moderate resolution optical imagery generally involves visual interpretation of VHRR and AVHRR data to determine river and lake ice breakup timing over relatively short time periods (Dey et al., 1977; Maslanik & Barry, 1987; Wynne & Lillesand, 1993).

More recent studies use time series of MODIS/AVHRR to examine river and lake ice phenology. Pavelsky and Smith (2004) determine the date of ice breakup at basin scales for four large northern rivers through visual examination of MODIS and AVHRR satellite imagery. Their results demonstrate that MODIS imagery is valuable in examining breakup at large scales, and they find breakup dates determined from remote sensing to be highly correlated to Russian hydrologic station data. Latifovic and Pouliot (2007) develop a method that detects the timing of breakup and freeze-up using time series of surface reflectance and brightness values from AVHRR data for 42 Canadian lakes, also noting a strong correlation between AVHRR analysis and in situ data. Similarly, Kropácek et al. (2012) examine patterns in ice phenology of lakes on the Tibetan Plateau using MODIS 8-day composite imagery. Other studies focus on real-time ice detection and economic applications for industrial areas. Chaouch et al. (2014) present an automated method of mapping ice extent using MODIS data on the Susquehanna River in Pennsylvania. While their study employs a similar approach to the method described in this paper, the primary goal of their algorithm is to assist in real time ice detection for economic purposes.

3. Methods

3.1 Study Area

I examine the four largest rivers draining into the Arctic Ocean: The Mackenzie in northwest Canada, and the Yenisey, Ob and Lena in Siberia (Fig. 1). These four rivers play important roles in the Arctic hydrologic system and are generally ice-covered for six months of the year or more (Bennett & Prowse, 2010). Discharge and corresponding freshwater input to the Arctic ocean are increasing for all four rivers as part of the intensifying hydrological cycle and rapid climate changes occurring in the Arctic region (Déry et al., 2009; Peterson et al., 2002). Several studies have examined breakup patterns in these rivers using point-based station data, remote sensing or a combination of methods (e.g. de Rham et al., 2008; Lesack et al., 2014; Pavelsky & Smith, 2004; Shiklomanov & Lammers, 2014). I determine breakup dates over the entire reach for the Yenisey and Mackenzie (1880 km and 1580 km respectively). For the Lena and Ob, I study 2800 and 2460 km respectively, cutting off when the river is less than 500 m wide and no longer distinguishable in the 250 m pixel MODIS imagery. I examine breakup timing for the full extent of the MODIS record, from 2000-2014.

3.2 MODIS imagery

I use MODIS data for this analysis due to the high temporal resolution and adequate

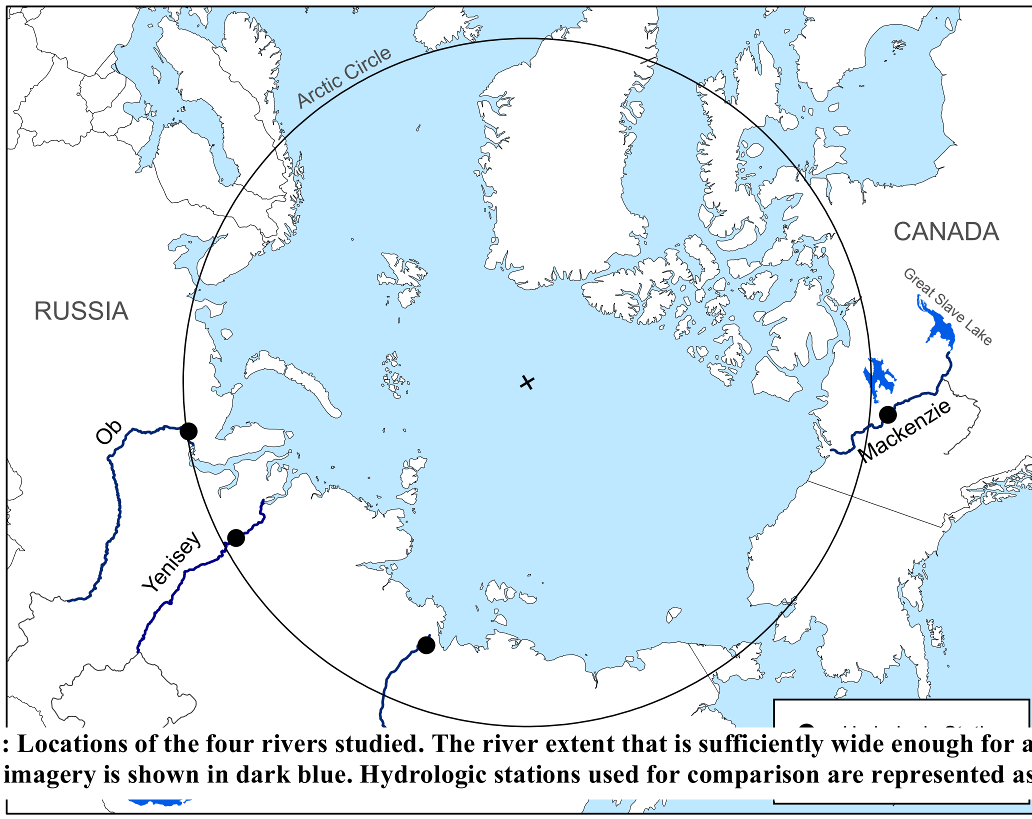

Figure 1: Locations of the four rivers studied. The river extent that is sufficiently wide enough for analysis using MODIS imagery is shown in dark blue. Hydrologic stations used for comparison are represented as circles.

spatial resolution of the imagery. The principal advantage of MODIS is its daily imagery, allowing for breakup detection at high temporal resolution. I utilize band 2 surface reflectance (841-876 nm) primarily due to its 250 m resolution and the simplicity of distinguishing between ice, mixed ice/water and open water in the near-infrared. The 250 m resolution is sufficient for breakup detection on rivers of greater than 500 m width, making it suitable for the large-scale analysis of major rivers presented here. Other MODIS bands and snow/ice products potentially useful in river ice detection exist; however, including more bands in this algorithm did not significantly increase the ability to distinguish between ice and water and thus did not outweigh the decreased efficiency. For cloud detection, I use MOD35_L2, the MODIS cloud mask product, gridded to 1 km resolution. For a summary of the MODIS Cloud Mask product and a description of the bitwise flags used for analysis, see Ackerman et al. (2010).

3.3 Algorithm

This algorithm is fully automated and takes between 1.5 to 3 hours to determine breakup dates over the complete 15-year time series for each river. The MATLAB codes used for this algorithm can be found in the Appendix.

1. I download daily MODIS band 2 surface reflectance imagery and cloud mask over the entire breakup season (approximately April 1st to July 1st) for each scene for each river from 2000-2014. I compile five cloud-free ice-covered images and five open water images from different years. I compute the normalized difference between these images and use it to create a binary river mask.
2. Using a river centerline, I split the river into segments of approximately 10 km length. I then split the river mask into 10 km segments by linearly interpolating the centerline groups over the mask, yielding river segments equal in length but not necessarily equal in river surface area.
3. I apply the river mask to each image such that the algorithm ignores all non-river pixels. I then classify each river pixel as ice, mixed ice/water or open water (Table 1). The thresholds use for these classifications were determined through frequency analysis of river surface reflectance values. This classification is performed over every scene of the entire breakup season.

	Ice	**Mixed Ice/Water**	**Open Water**
Band 2 Reflectance	>0.5	0.1 – 0.5	<0.1

Table 1: Threshold reflectance values used for classifying river surface

4. Using the MOD35_L2 Cloud Mask, I determine the number of cloudy and clear pixels in each river segment for each day of the breakup season. If more than 50% of the pixels in the river segment are cloudy, the river segment is classified as cloudy (Table 2).
5. I utilize the daily classified river images and the cloud mask to determine how the river surface changes over the breakup season. For each clear river segment, I sum the total number of pixels classified as water. I then determine the first day where 75% of

the pixels in the river segment are classified as open water, which I define as the detected date of breakup.

6. Using the cloud mask, I determine the number of days prior to the date of breakup where the river segment was cloud-obscured, meaning the algorithm could not detect breakup. If there is more than one cloudy day before the date of breakup, I consider the corrected date of breakup to be the midpoint of the cloudy period. The window of uncertainty around each breakup date is then plus or minus the number of days between this midpoint and the detected date of breakup.

3.4 Error Analysis

By far the largest source of error is cloud-obscured imagery, a common problem in optical remote sensing. Using the MODIS Cloud Mask product, I employ a 50% cloud tolerance to ensure that I am able to obtain accurate river surface reflectance data for each segment classified as clear. The relatively coarse resolution (1 km) of the MODIS cloud detection methodology as compared to the surface area of each 10 km river segment (between 5 and 40 km) means changing the algorithm's percent cloud tolerance has little impact on the number of segments classified as cloudy. Due to the differing climatic conditions governing western Canada versus central and eastern Siberia, the percent of river segments classified as clear varies amongst the four rivers, ranging from 40.2% for the Yenisey to 50.8% for the Mackenzie (Table 2). The average window of uncertainty for each breakup date also varies by river and by year (Table 2). Despite the significant amount of cloud-obscured imagery, for all four rivers examined, I am able to detect breakup within a window of +/- 1 day for the majority of river segments.

	Mackenzie	**Lena**	**Ob**	**Yenisey**
Percent clear segments	50.83	42.78	40.78	40.20
Mean breakup window (+/- days)	0.91	1.33	1.24	1.62

Table 2: Percent clear segments and mean breakup window due to cloud uncertainty

Another smaller source of error derives from the river masks used to distinguish between land and water pixels. For simplicity and consistency, I build the binary river masks from MODIS reflectance imagery by using the difference in surface reflectance values between ice-covered and open water imagery, averaged over five different years. Pixels with a normalized difference of greater than 0.75 are considered water, and the mask is corrected to only examine river pixels. For major rivers such as the four studied here, the location and extent of the river generally does not vary significantly from year to year. The only exception occurs in some especially flat and braided sections of the Ob where changing inundation levels can affect the river's location and extent. If the deviation from the mean river location is significant, it can result in the algorithm never detecting breakup for a particular segment because too many of the pixels in that segment are not water-covered during the breakup season in that given year. Due to the significant inefficiency of having to create individual masks for every Ob scene for all 15 years, I choose to ignore the segments of the Ob where the river never detects breakup in data smoothing and analysis. The number of segments removed is small, averaging fewer than 1 segment removed per 100 km, and does not impact the overall results.

3.5 Data Smoothing

10 km segments are used for breakup detection because the small area allows for examination of relatively small-scale breakup processes such as the discontinuous breakup that often occurs in mechanically driven breakup events. Utilizing shorter river segments would decrease the number of river pixels needed to meet the various thresholds involved in breakup detection. Fewer pixels per segment increases error due to variability in river extent and location, particularly in narrow or braided segments. When detected at 10 km segments, there is substantial noise present in the breakup dates (Fig. 2). Though some of this variability is a natural signal caused by confluences with other rivers or mechanical breakup events, much of the noise is likely due to cloud-obscured imagery. Sensitivity analyses of the various reflectance and cloud thresholds used in the algorithm also demonstrate that the thresholds used in the algorithm are likely not responsible for this noise. To reduce the impact of cloud error, I smooth the

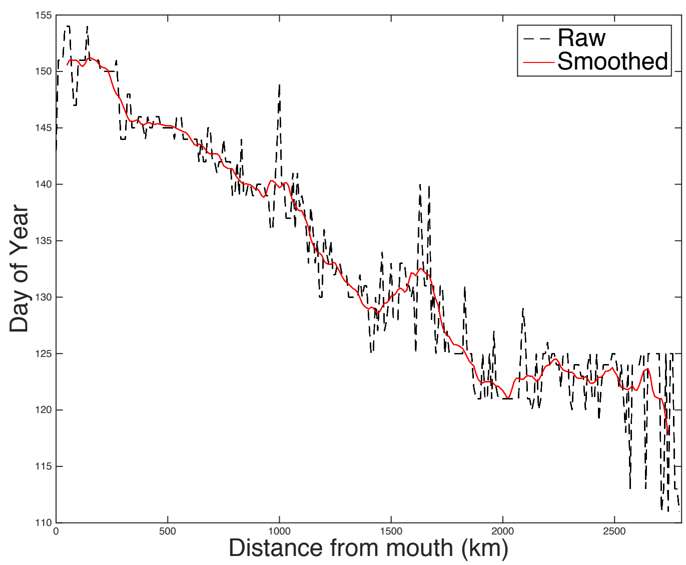

Figure 2: Raw breakup dates (black, dashed) and smoothed breakup dates using a 10-point moving average filter (red) for the Lena in 2014 plotted by distance from mouth (km)

breakup dates using a 10-point (100 km) moving average filter (Fig. 2). In employing this filter, the overall natural signals are maintained while making it easier to distinguish spatial and temporal patterns in breakup timing.

3.6 Additional Data

I utilize Water Survey of Canada (WSC) hydrometric records for the Mackenzie and Russian ice phenology records for the three Siberian rivers (Shiklomanov & Lammers, 2014) to compare the satellite breakup dates determined from the algorithm to ground data. WSC hydrometric data includes the 'Last B Date', the last day where ice conditions are assumed to impact the river's flow in the vicinity of the station (de Rham et al., 2008). It is important to note that WSC stations do not record visual observations of actual breakup dates of the river; rather the 'Last B Date' is generally an estimate from available data. The Russian data notes the conclusion date of ice events, considered to be the date of ice disappearance (Smith, 2000). Since the timing of the peak flood is commonly highly correlated with the timing of ice breakup, I also examine discharge data. For the Mackenzie, the date of peak discharge is determined using WSC discharge records. For the Siberian rivers, discharge data is available from ArcticRIMS, a data repository at the University of New Hampshire (Shiklomanov & Lammers, 2014). I do not examine peak discharge data for the Ob due to the extensive impact of dam regulation on discharge.

3.7 Trend and Correlation Calculation

To determine trends in breakup timing over the 15-year period, I use the nonparametric Mann-Kendall test (Helsel & Hirsch, 1992) that is commonly used in similar hydrological studies (e.g. Goulding et al., 2009; Lesack et al., 2014; Shiklomanov & Lammers, 2014; Smith, 2000). A least squares linear regression is then applied to the 15-year time series for each 10 km segment and to whole river averages of breakup timing. I consider trends to be statistically significant at the 90% level; however, in figures I also include trends significant at the 85% level. The Pearson correlation coefficient is used to examine correlations between various time series of breakup processes.

4. Results

4.1 Spatial Patterns in Breakup

Using the method described, dates of breakup are determined in 10 km segments from 2000-2014 for the entire reaches studied in each of the four rivers. I plot breakup dates for each year over a river centerline to illustrate the general breakup progression and the continuity and large spatial scale of the data (Fig. 3). By also plotting dates by distance from mouth, I am able to discern spatial patterns in breakup (Fig. 4). For each river, breakup progresses mainly linearly northward and downstream. There is considerable variability from year to year in the timing and length of breakup, but the overall spatial patterns remain similar. All four rivers show evidence of discontinuous breakup, where a section may breakup several days or more after the surrounding river segments. These later breakup events are generally caused by tributaries and channel morphology; however, their locations are not always consistent from year to year.

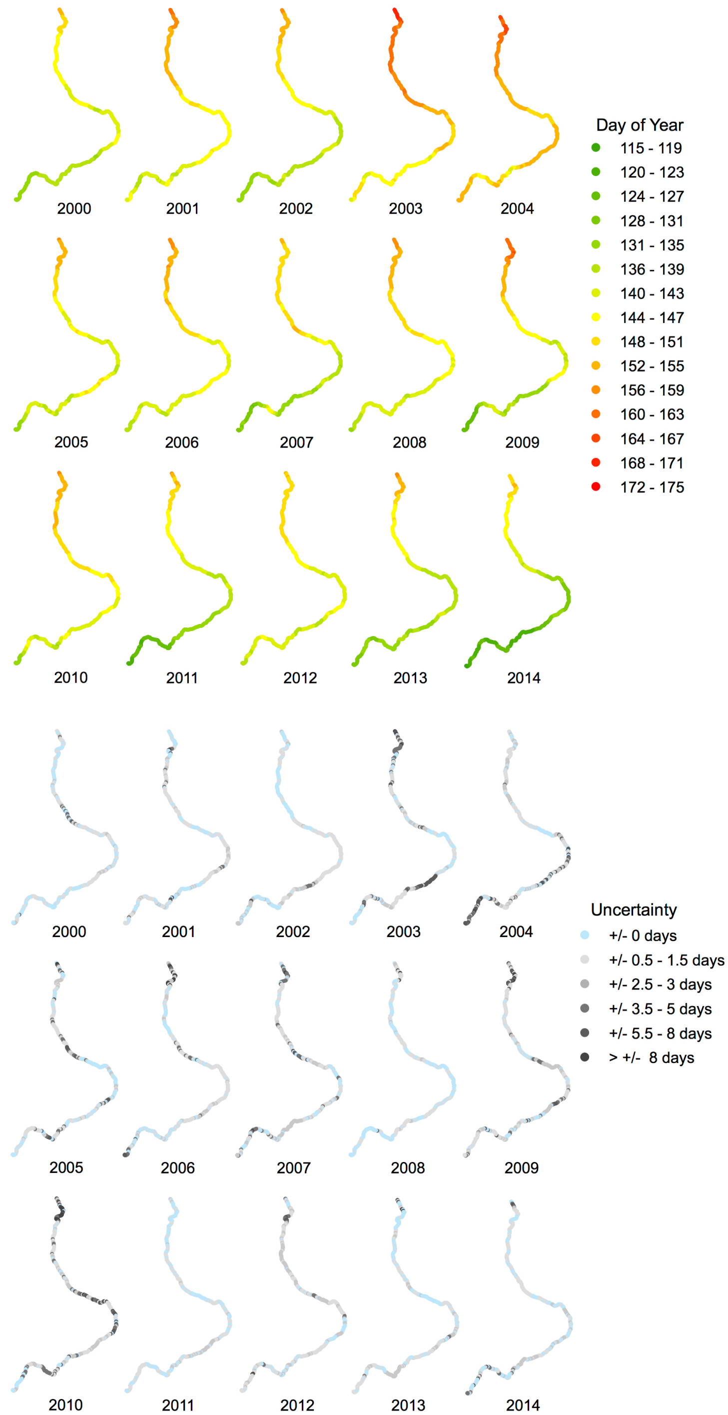

Figure 3: Breakup timing (upper) and cloud uncertainty (lower) for the Lena from 2000-2014

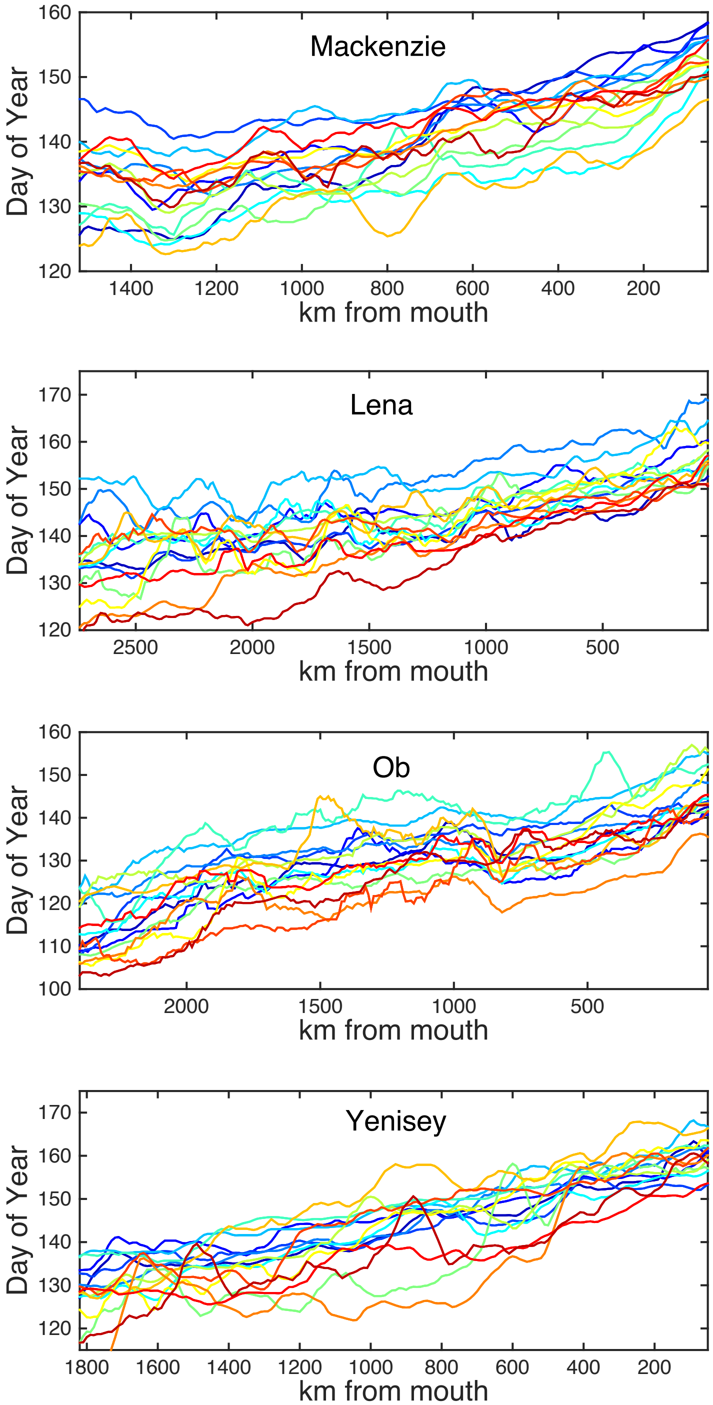

Figure 4: Breakup dates plotted by km from mouth

Distinct patterns in each river emerge upon closer examination of the data. On the Mackenzie, breakup generally occurs earlier moving downstream for the first few hundred kilometers. This pattern is likely due to the influence of Great Slave Lake, source of the Mackenzie and generally ice-covered until after the main stem of the Mackenzie has broken up. I observe significant spatial and temporal variability in the upstream portions of the Lena and relatively smooth breakup downstream. The transition into smoother breakup occurs near the confluence of the Lena and the Angara rivers at 1260 km from the mouth, suggesting that the addition of the Angara moderates breakup timing in the lower Lena. On the Ob, the northward and downstream progression of breakup slightly reverses between approximately 1300 and 900 km from the mouth. This section of the river is associated with a change in the direction of the along-river temperature gradient (Prowse et al., 2010). As the river moves westward towards European Russia, the surface air temperatures actually increase downstream until the river again turns northward and eastward, likely explaining the observed non-linearity in breakup timing.

The mean date and length of breakup vary significantly both between rivers and from year to year. While ice breakup does not progress downstream completely linearly, in general, breakup advances more rapidly on the Lena and the Ob, the longer, more braided rivers, at average speeds of 79.8 km/day and 57.2 km/day respectively. On the shorter and straighter Yenisey and Mackenzie rivers, breakup moves at average speeds of 50.5 km/day and 41.7 km/day respectively. The range of breakup speeds observed also varies significantly by river and by year, with a maximum speed of 100 km/day on the Lena and minimum of 37.1 km/day on the Mackenzie.

4.2 Ground Comparison

I find breakup dates to be highly correlated with ground observations of ice breakup (Fig. 5) for the Mackenzie, Lena and Ob rivers. There is not a strong correlation between the detected dates and ground data for the Yenisey; however, the ground breakup dates for the Yenisey over the period 2000-2012 are extremely variable and I question their accuracy. Additionally, though available discharge data only overlaps with the MODIS time series from 2000-2005, breakup dates on the Yenisey are correlated with the timing of peak discharge. A strong correlation between breakup timing and peak discharge is also found on the Lena and Mackenzie. The strong correlations between detected breakup, ground observations and the timing of peak discharge are consistent with scientific understanding of river ice processes and point to the accuracy of this algorithm.

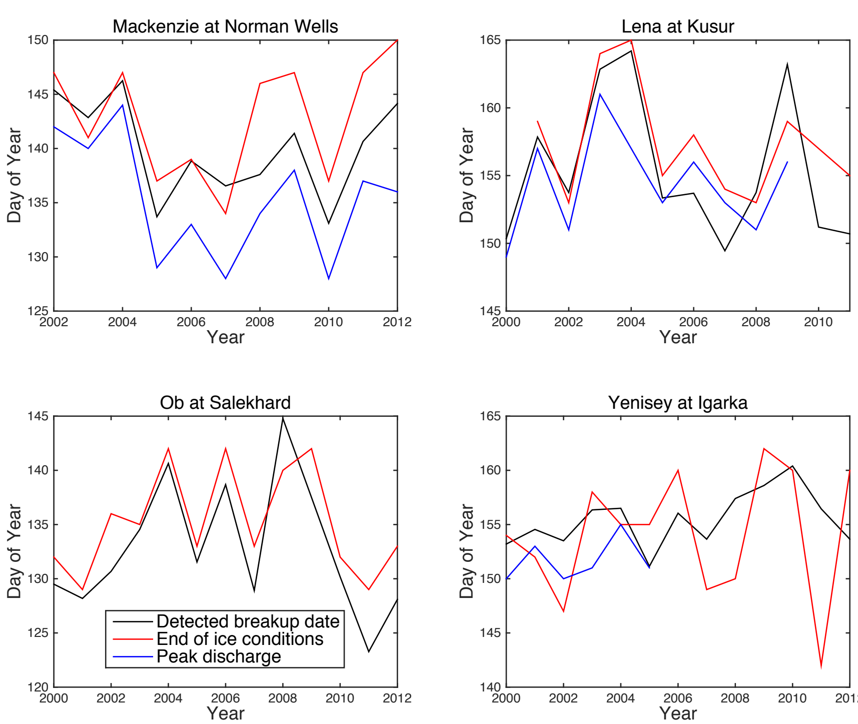

Figure 5: Comparison of satellite-derived breakup date, ground breakup date and date of peak discharge for the Mackenzie at Norman Wells, the Lena at Kusur, the Ob at Salekhard and the Yenisey at Igarka

4.3 Temporal Patterns in Breakup

To examine how the spatial distribution and patterns of breakup are changing, I calculate trends in breakup timing over the past 15 years for each 10 km segment of the four rivers. Where trends are statistically significant, they are consistently negative and indicate breakup is occurring earlier with trends between -0.25 and -1.25 days per year. However, the magnitude and statistical significance of the trends vary considerably along each river (Fig. 6). For the Lena, I find statistically significant trends across nearly the entire river, with the magnitude of the trends increasing moving upstream. The Mackenzie displays a strong trend towards earlier breakup near the delta, but no statistically significant trend is present over the middle and upper reaches. Trends on the Yenisey and the Ob also only occur in distinct sections; strong trends are found in the upper Yenisey and the middle to upper Ob.

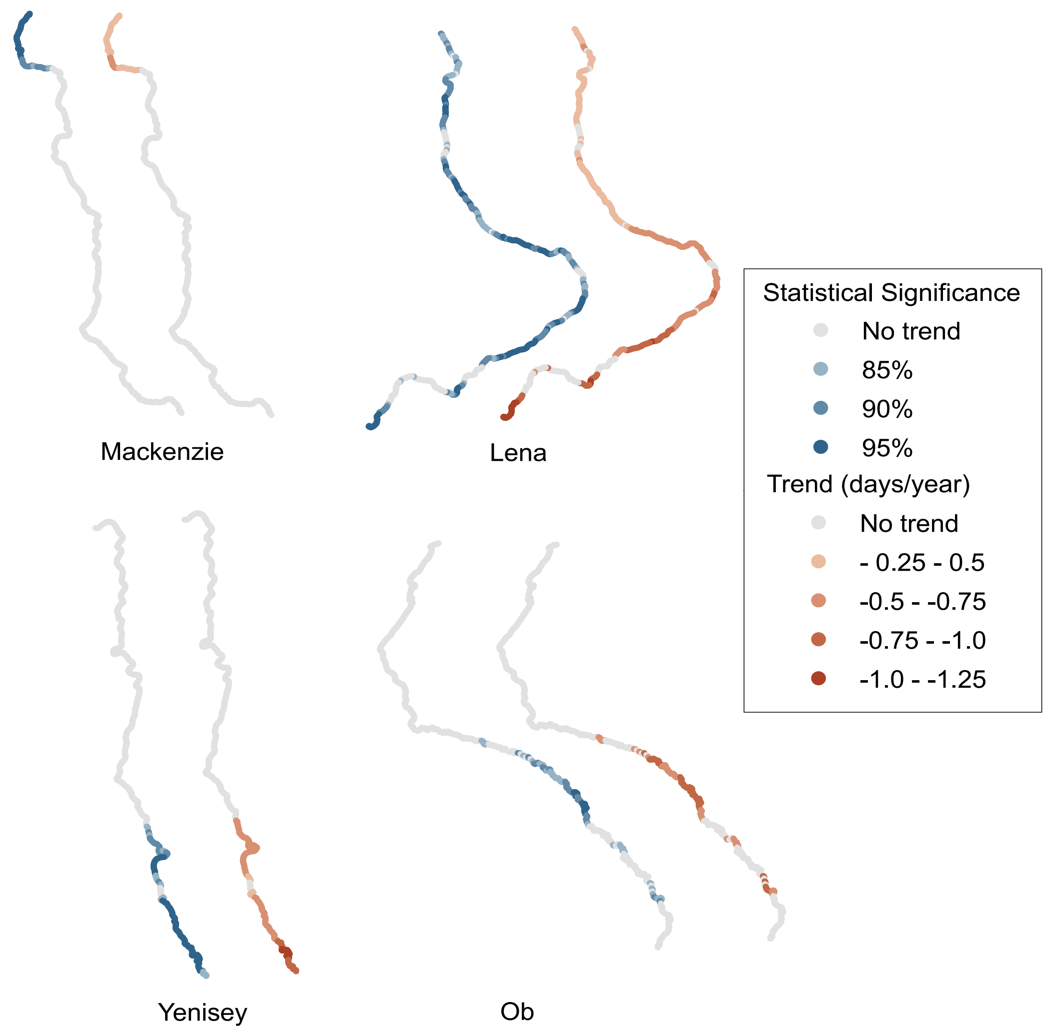

Figure 7: Locations of trends in breakup timing from 2000-2014. Statistical significance is shown in blue on the left, and trend magnitude is shown on the right in red

When examining whole river averages, I find breakup timing to be highly correlated between the three Siberian rivers but observe very little correlation between the Russian rivers and the Mackenzie (Fig. 7). Only the Lena has a statistically significant trend towards earlier breakup averaged over the whole river. I also examine patterns in the timing of the initiation of breakup, the end of breakup and the length of breakup (Fig. 7). There is a statistically significant trend indicating earlier initiation of breakup for the Lena, whereas for the Mackenzie, I find trends towards earlier breakup completion and decreasing breakup length. Despite clear patterns towards earlier breakup in the middle and upper sections of the rivers, there are no overall trends in either the Ob or Yenisey rivers.

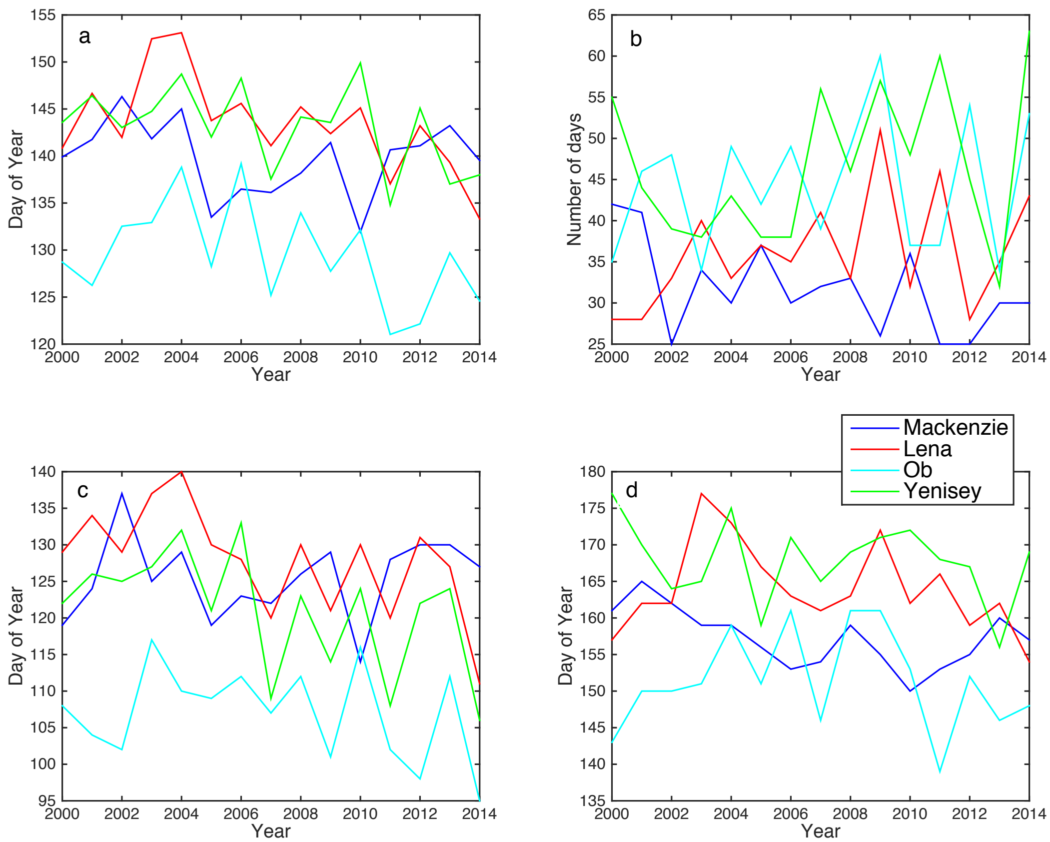

Figure 7: Time series of mean breakup date (a), length of breakup (b), earliest date of breakup (c) and final date of breakup (d) for each of the four rivers from 2000-2014.

To better understand the relationship between spatial variations in trends and overall breakup timing, I examine correlations between the first and last dates of breakup, the mean date of breakup for the uppermost and lowermost sections of the river, the length of breakup and the whole river-averaged date of breakup (Table 3). In general, upstream processes seem to be strongly related to overall breakup timing. On the Lena, Mackenzie and Yenisey, the timing of breakup initiation and the mean breakup date in the uppermost river section are more strongly correlated to both the whole-river mean breakup date and the breakup length.

	Mackenzie	Lena	Ob	Yenisey
Beginning of breakup – mean breakup date	0.92	0.91	0.80	0.82
End of breakup – mean breakup date	0.67	0.77	0.82	0.64
Beginning of breakup – breakup length	-0.78	-0.72	-0.47	-0.85
End of breakup – breakup length	0.27	0.22	0.37	0.34
Mean upstream breakup – breakup length	-0.64	-0.53	-0.30	-0.55
Mean downstream breakup – breakup length	0.08	0.08	0.41	0.26

Table 3: Correlation coefficients between the first and last dates of breakup and the mean breakup date in the uppermost and lowermost fourths of the river and the overall mean breakup date and mean breakup length.

5. Discussion

5.1 Analysis of Algorithm

The described results indicate that this algorithm can be used to detect breakup dates from MODIS imagery within a reasonable window of error and demonstrate the utility of this algorithm for further ice breakup research. The first notable advantage of this method is the ability to determine whole-river spatial trends in breakup timing. Ground-based research is inherently limited by the remoteness and inaccessibility of these major Arctic rivers and thus forces researchers to rely on single point-based data often many hundreds of kilometers apart. Considering the current interest in understanding how climate warming and the intensification of the Arctic hydrologic cycle impact river ice breakup, several studies have cited a need for improved research on whole river spatial processes (e.g. Beltaos & Prowse, 2009). The continuous along-river breakup dates determined through this method enable examination of not only temporal trends but also allow for study of spatial variability which is vital to improving understanding of breakup mechanisms.

Another significant advantage of this algorithm is the consistency in breakup detection. Comparison of trends in river ice phenology between rivers using ground-based data is challenging because hydrologic stations often use different definitions of critical river-ice characteristics (e.g. Catchpole & Moodie, 1974). In their study of breakup timing using station data in the Mackenzie River Basin, de Rham et al. (2008) choose to primarily use breakup indices determined from hydrographs, finding that the last 'b' dates (end of ice conditions) are not sufficiently reliable for their basin-scale comparisons and analysis. Additionally, most previous studies using optical satellite remote sensing data rely on visual examination, meaning their breakup dates are dependent on manual interpretation of imagery. The algorithm described in this paper, while only currently applicable to the 15-year time series of MODIS data, uses one standard breakup metric, defining breakup in each 10 km segment as the first date when 75% of river pixels are open water. This consistency allows for trend analysis and comparison not only within singular river basins but also across the entire Arctic region. Considering also the current decline in Arctic river ice observations (e.g. Shiklomanov et al., 2002), this method clearly provides a needed method of observing recent trends in breakup timing.

As with many optical remote sensing studies, a significant disadvantage of this algorithm is cloud-obscured imagery. However, while cloud-obscured imagery limits the accuracy to an average window of around +/- 1.5 days, the temporal accuracy is still higher than would be possible using many other types of satellite imagery. Another disadvantage derives from the relatively coarse 250 m resolution of MODIS imagery. It is not possible to distinguish very small-scale breakup processes, and breakup detection is generally not suggested for segments of less than 10 km except on the widest parts of the rivers. Additionally, the algorithm is only practical for examination of major northern rivers.

5.2 Spatiotemporal Trends in Breakup Timing

The temporal trends observed in this analysis, where statistically significant, consistently reflect a shift towards earlier breakup timing. The general agreement in direction of trends suggests that at large scales, point-based trend analyses (e.g. Magnuson et al., 2000) can be used to infer regional climate variability. However, the considerable variability in the magnitude and significance of trends along each river indicates that point-based trends do not necessarily reflect spatial patterns in breakup and smaller-scale processes.

While Arctic warming is expected to cause earlier breakup timing, the net impact of warming temperatures on spatial patterns in river ice breakup for northward-flowing rivers is very complex and difficult to predict. For the purposes of this discussion, I will examine two possible hypotheses regarding future changes in breakup processes. In one possibility, warmer spring temperatures would lead to a decrease in the mechanical strength of the ice cover and thus weaker resistance downstream. Combined with a thinning of the ice cover and a protraction of the spring freshet due to warmer winter temperatures, one would expect to observe a shift towards breakup events controlled by weakening downstream resistance, perhaps leading to more thermal breakup events (Prowse et al., 2010). In the second hypothesis, a projected increase in precipitation and snow water equivalents at northern latitudes due to an intensifying Arctic hydrological cycle (Brown & Mote, 2009; Déry et al., 2009; Rawlins et al., 2010) would lead to increasing discharge levels upstream. Additionally, earlier occurrences of breakup, meaning lower amounts of shortwave radiation, would limit reductions in downstream resistance due to the dependence of ice strength on internal melting and shortwave radiation absorption (Hicks et al., 2008). Consequently, a greater driving force from rising precipitation and discharge could increasingly govern breakup processes. While somewhat of a simplification, here I will consider these two different hypotheses for changing whole-river scale breakup processes due to warming temperatures as either resistance/downstream-driven (decreasing ice strength) or forcing/upstream-driven (increasing discharge).

The spatial analysis of temporal trends determined here can provide some insight into possible changes in breakup processes. On the Mackenzie, I detect a strong trend in the downstream reach of the river with no corresponding trend in the main stem. Several previous studies have found similar statistically significant trends in the Mackenzie River Delta region (de Rham et al., 2008; Goulding et al., 2009; L. Lesack et al., 2014). Lesack et al. (2014) attribute the earlier breakup trend in the delta to reductions in ice strength during the breakup season caused by local spring warming, finding no correlation between peak discharge levels and breakup timing. Considering the preferential warming of the downstream region, the absence of a trend in the main stem of the Mackenzie is consistent with their conclusions that a decreasing resisting force is a primary driver of the trend towards earlier breakup in the delta. Additionally, I identify a corresponding decreasing trend in breakup length on the Mackenzie, suggesting that the warming temperatures in the delta are leading to a shift towards a shorter breakup season caused by weakening downstream resistance. This observation supports the notion that identifiable shifts in breakup timing are largely due to decreasing resisting forces.

The patterns observed for the Siberian rivers are somewhat more complex and less conclusive. In general, there exists significantly less research on breakup timing in the Siberian rivers, and nearly all studies rely on single point-based research from stations near the mouth of each river (e.g. Shiklomanov & Lammers, 2014; Smith, 2000; Vuglinsky, 2006). As a result, it is more difficult to understand how the observed spatial patterns compare to previous studies. Unlike on the Mackenzie, the magnitude of trends generally increases upstream on the Lena and the Yenisey (Fig. 5), and I observe earlier initiation of the breakup season. However, the earlier beginning of breakup is not coupled to a statistically significant trend in the length of the breakup season. The trends identified are contrary to the conception that the largest changes in river ice processes will be found closer to the mouth due to weakening ice strength and a decreasing downstream temperature gradient. Considering also the stronger correlations between the mean timing and length of breakup and upstream breakup patterns on the Lena and Yenisey (Table ?), these results suggest that upstream breakup initiation is a dominant driver of breakup processes. Since breakup initiation is related to the onset of the spring freshet from a melting snowpack, upstream-driven breakup implies that a warming climate leads to earlier breakup through increasing discharge.

On the Ob, a statistically significant trend towards earlier breakup is found where the river shifts towards westward flow (Fig. 5). This section corresponds to the beginning of the temperature gradient reversal on the Ob, and the non-linearity in those breakup dates is evident in the spatial patterns of breakup timing observed. The trend towards earlier breakup found solely in this portion of the river suggests that possible changes in this gradient are impacting breakup processes. The anomalous correlations between upstream processes and mean breakup timing for the Ob are perhaps also due to the effects of the temperature gradient reversal.

The results of this spatial analysis point towards the second of the two hypotheses: a shift towards discharge-driven breakup, especially in Siberia. Substantial evidence demonstrates that increasing precipitation in a warming climate due to the water vapor feedback (Rawlins et al., 2010) and increasing discharge for Eurasian rivers (Peterson et al., 2002) are both significant components of the intensifying Arctic hydrological cycle, providing a necessary background for the conclusion that earlier breakup may be produced by an increasing upstream driving force in Siberia. However, the literature on the relationships between discharge, precipitation and breakup timing is largely inconclusive (e.g. Lesack et al., 2013; Shiklomanov & Lammers, 2014). For the Mackenzie, these relationships are perhaps more complex. The trend towards a shorter breakup season is consistent with a decreasing temperature gradient and a weaker resisting force, yet I still observe a stronger correlation between initiation of breakup and overall breakup trends.

Without corresponding along-river discharge and temperature data, these conclusions are only speculative. Given the complexity of the various factors impacting breakup, it is likely that the observed patterns are the result of a combination of processes. Considering also the substantial effect of channel morphology of individual river sections on breakup timing, it can be difficult to generalize breakup drivers amongst different rivers. The complex patterns observed demonstrate a need for continued analysis of spatial trends in breakup processes combined with field observations.

5.3 Possible future applications

The results presented in this paper represent only an initial analysis of data that can be obtained through this method. Of particular interest in current river ice research is moving beyond simple detection of breakup timing and towards examination of breakup mechanisms and event severity (Prowse et al., 2007). To this end, one possible related application of this method is classification of breakup types. Several studies have indicated a predicted trend towards more thermal breakup events and a corresponding decrease in event severity, yet more observations of breakup events are needed to confirm this result (Prowse et al., 2010).

To assess the applicability of this method for classification of breakup types, I identify and discuss the appearance of three primary types of breakup evident in the imagery: thermal, mechanical and braided. Thermal breakup is characterized by a decreased resisting force due to ice cover ablation, and generally involves little-to-no jamming and ice flooding (low severity). In MODIS imagery, thermal breakup appears as a slowly ablating ice surface (decreasing surface reflectance) where the transition from ice to mixed ice/water to open water occurs over a period of several days to weeks (Fig. 8a). The shift from ice to water is predominantly smooth and linear both in time and along the river.

In contrast, mechanical breakup is caused by a strong upstream force encountering significant downstream ice cover, often leading to ice jams and flooding (high severity). During mechanical breakup events, the ice cover is in motion and breakup can be very non-linear and discontinuous, often leading to reaches of open water in between ice-covered segments. Mechanical breakup viewed in MODIS imagery is distinguished by a fast transition from ice to water and discontinuous segments of ice-cover and open water (Fig 8b). Unlike in thermal

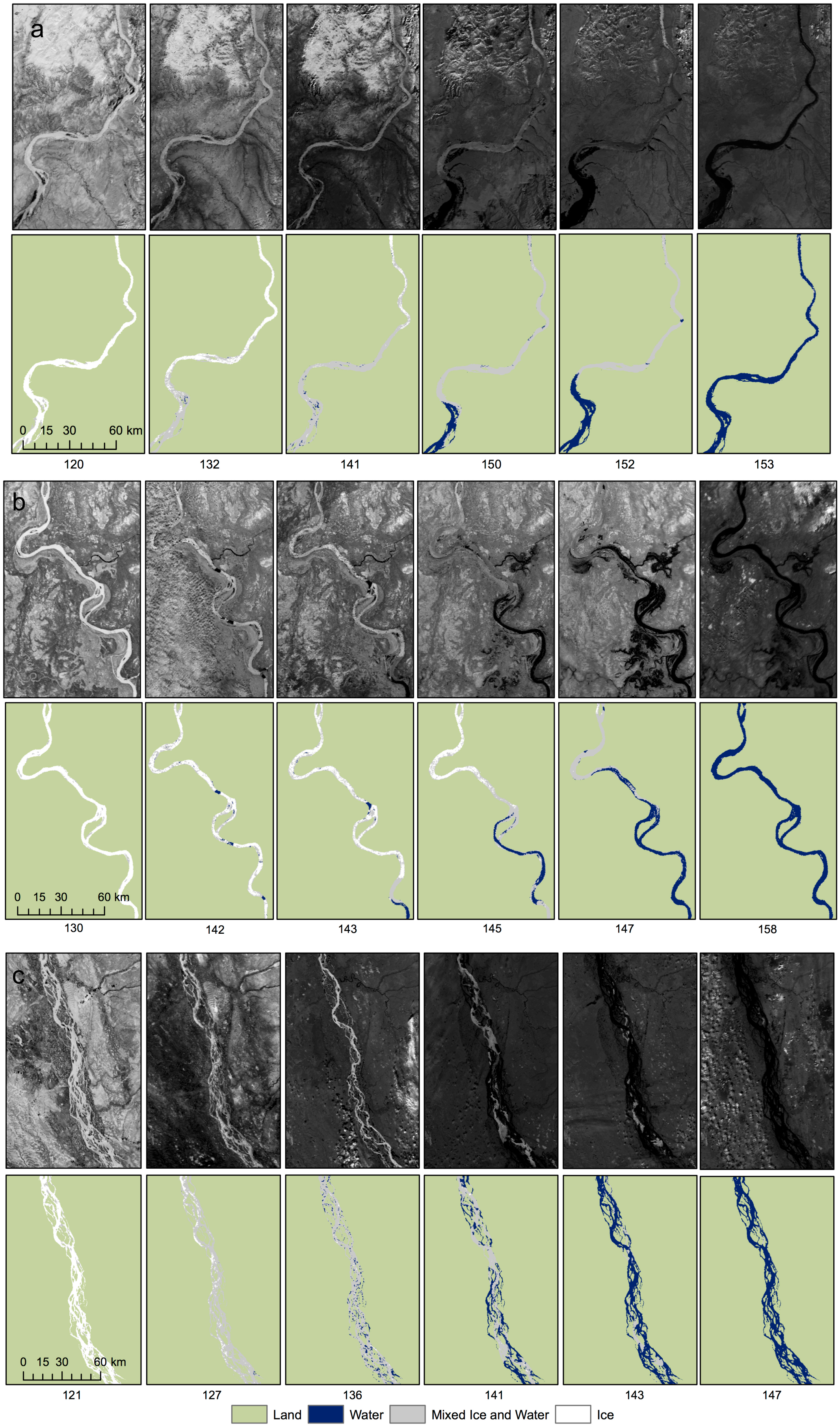

Figure 9: Examples of a thermal breakup event (a) on the Lena in 2011, a mechanical breakup event (b) on the Yenisey in 2009 and a braided breakup event on the Lena (c) in 2009. The top rows shows the original MODIS band 2 imagery; the bottom row is the classified version of the image. Green is land, blue is water, gray is mixed ice and water and white is ice and snow.

breakup events, relatively high reflectance (non-melted) ice may be in contact with open water, and the location of open water reaches can vary from day to day.

Breakup progression in especially braided river sections combines aspects of both mechanical and thermal breakups due to the differing channel morphology governing flow (Fig. 8c). First, there is generally an overall decrease in reflectance, indicating surface ice melting. This ablation is followed by breakup on the narrowest braids of the river while the main branches remain ice-covered. Eventually, the main branches begin to break up, leading to discontinuous stretches of mixed ice/water and open water. At some point, water can flow through the open branches unimpeded by the presence of ice, meaning small areas of ice cover on outer braids can remain after most of the segment has broken up.

The classifications and figures described demonstrate that a similar approach could be used to determine breakup type and event severity. A thorough examination of trends in breakup mechanisms would also require fieldwork to confirm this assessment of the appearance of mechanical and thermal breakup events on large, remote northern rivers. As a result, I do not specifically examine patterns in types of breakup and suggest this as a future application of this method.

6. Summary and Conclusions

The breakup detection algorithm presented in this paper provides a useful new method of studying breakup at large scales and is sufficiently precise for robust analyses of spatial patterns in breakup timing. In just an initial analysis of spatiotemporal trends in breakup, I identify several interesting patterns that given a longer time series and more ground data could help clarify breakup processes. The results of this study confirm previously identified changes in the Mackenzie Delta and suggest that upstream processes have a large impact on breakup trends and timing in Siberia. The complexity of the patterns observed emphasizes the need for further analysis of relationships between discharge, precipitation and breakup timing continuously along river. In the future, given the required ancillary datasets as well as a longer time series of MODIS imagery, this algorithm would be well suited for larger studies seeking to better understanding breakup mechanisms and the causes of observed trends towards earlier breakup. This method could also be used to assess breakup event type and severity, allowing for further research on projected shifts towards more thermal breakup events. Additionally, while the field of river ice modeling remains relatively undeveloped, combining these spatial analyses with both hydrological and climate modeling approaches could further improve the understanding of the response of river ice to a warming Arctic.

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