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Analysis of Climatic and Riverine Factors Influencing Peace River Ice Jam Flood Frequency in the Peace-Athabasca Delta: From History to Future Climate Implications

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Abstract

The Peace-Athabasca Delta (PAD) of northeastern Alberta is one of the largest inland freshwater deltas in the world, lying at the confluence of the Peace and Athabasca Rivers. Periodic ice jam flooding from both rivers promotes biological production and diversity by replenishing water in numerous lakes. A key question for the future ecological productivity of the PAD is which climatic and riverine factors best predict ice jam flood occurrence, and how climate change may affect flood frequency. In this paper, we first present an exploratory data analysis of climatic and river regulation factors that may affect flood occurrence, and then develop a logistic regression model to predict large Peace River ice jam floods across history. Using the available data, we find that historical large ice jam floods are best explained by a model containing accumulated winter precipitation and temperature as explanatory variables. Models that included river flow during the Nov./Dec. freeze-up period and/or freeze-up river elevation had smaller and statistically insignificant effects after accounting for these climatic factors. Thus, it is unlikely that river regulation has reduced large Peace River ice jam floods in the PAD. These results are supported by physical understanding of ice jam formation in the PAD, as winter precipitation affects the break-up flow and degree-days freezing affects the ice thickness (which is generally unobservable across the spatial domain). Finally, we examine climate projections of the precipitation and temperature factors to draw insights about the likelihood of ice jam flooding to 2100. The climate models we evaluated agree that by about 2050, regional warming is likely to result in conditions warmer than any large ice jam flood on record.

1. Introduction

The Peace-Athabasca Delta (PAD) is located in northeastern Alberta about 1200 km downstream from the Bennett and Peace Canyon Dams in British Columbia (Figure 1). It is a very large, predominantly wetland area bound to the south by the Athabasca River Delta, Lake Claire to the west, Lake Athabasca to the east and the Peace River that flows along its northern boundary. Periodic flooding from ice jams along the Peace and Athabasca Rivers are deemed beneficial to ecology of the PAD because they are the primary source of recharge to perched basins (Peterson, 1992; Prowse and Lalonde, 1996; Timoney, 2002). There have been perceived changes in the PAD since the 1970s (Peterson, 1992), including to ice jam flood (IJF) frequency on the Peace River since the construction of the Bennett Dam that coincides with regional drying (Timoney, 2002) and warming (Section 3.3.2). This has led to a debate among scientists on the possible primary causes of flooding, and whether or not a change in flood frequency has actually occurred (Beltaos, 2017; Timoney et al., 2018; Hall et al., 2018). Lamontagne et al. (in revision) provides further detail and discussion on these topics.

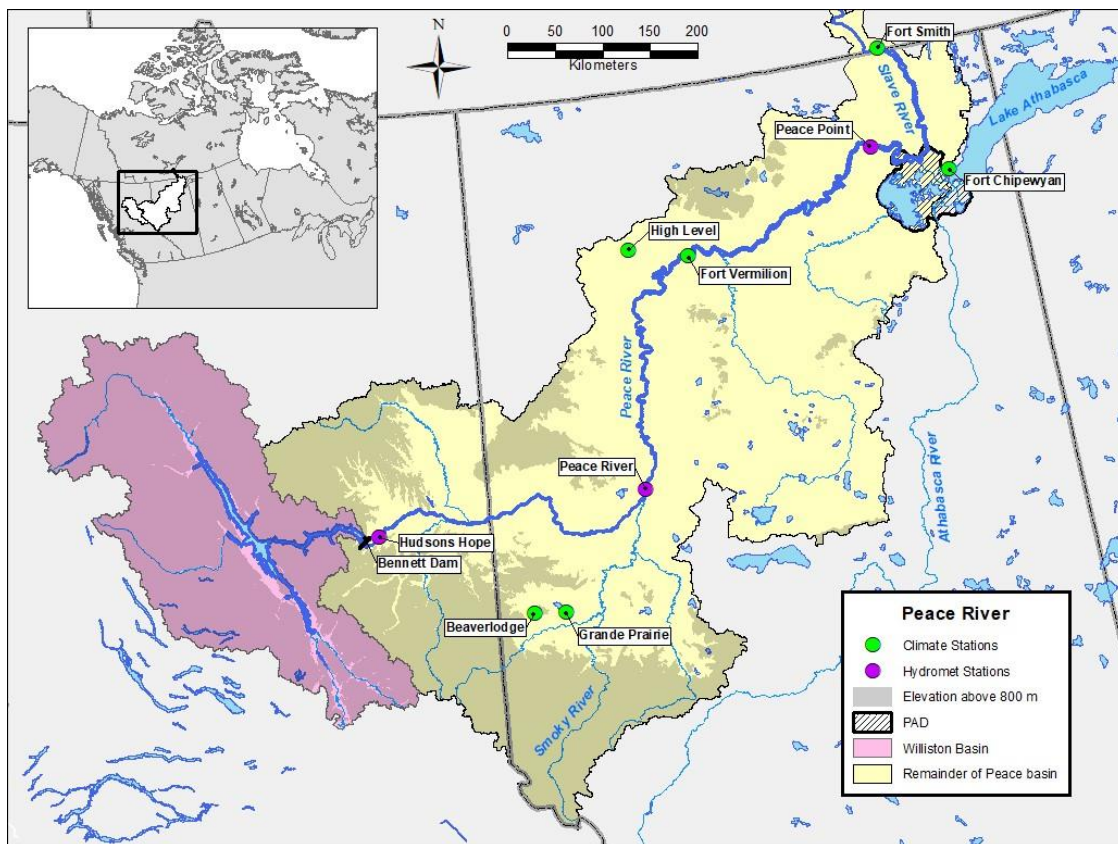


Figure 1: Map of the Peace River Drainage Area and the Peace-Athabasca Delta (PAD). Also shown are meteorological and hydrometric stations from which data were used in the analysis. Most of the snowmelt that drives breakup comes from the lower elevation (unshaded yellow) portion of the basin. The pink portion represents the drainage area that is regulated by the Bennett Dam and is mostly at high elevation (shaded pink). Adapted from Lamontagne et al. (in revision).

The aim of this study was to perform an exploratory data analysis of variables (or their proxies) to determine which climatic and riverine factors are most predictive of large Peace River ice jam flooding of the PAD. This paper presents a more detailed discussion of the following factors, in support of the analysis completed by Lamontagne et al. (in revision).

Many authors have hypothesized that higher post-regulation winter river flows have resulted in higher freeze-up elevations that reduce IJF frequency (Prowse and Conly, 1998; Beltaos, Prowse and Carter, 2006; Beltaos, 2014; 2017). Thus, we evaluate riverine factors including freeze-up elevations at Peace Point (upstream of the PAD) and winter discharges at three gauges along the Peace River. We also evaluate climatic factors, including winter air temperatures in the PAD and upstream of the PAD as proxies for ice thickness, and winter precipitation in the Grande Prairie area in the heart of the Smoky River Basin where much of the spring freshet originates that drives dynamic breakup on the Peace River.

In this study, as in Lamontagne et al. (in revision), the factors that are most predictive of large IJFs over the historical record are determined by logistic regression. Section 2 of this paper provides an introduction to estimating the likelihood of a large IJF using a relatively short historical flood record, and conditional probability (conditional on the evaluated factors). Section 3 presents the exploratory data analysis of all factors, and Section 4 presents the best logistic regression model for predicting large IJFs over history. For these most predictive variables, Section 5 presents values for future climate projections that were obtained from GCMs and examined to derive insights about the future occurrence of large IJFs on the Peace River in the PAD. The resulting figures and discussion provide support to the estimation of IJF probabilities presented in Lamontagne et al. (in revision).

2. What Can History Tell Us About Ice Jam Flood Probability?

Based on the historical flood record in the PAD (Timoney, 2009), there is good evidence that the frequency of ice jam floods may change over time, possibly as a function of a number of climatic and/or river regulatory related factors. As part of the debate over whether changes in flood frequency are occurring and what factors may be causing changes, it is important to highlight why it is so hard to speak authoritatively about the PAD's IJF frequency (past, present, or future). To do so, we begin with a grounding in probability theory as distinct from statistics. Probability theory begins with a specific population from which a sample is drawn and describes the likelihood that some event may occur: it requires no data. Statistics involves inferring, as best one can, the characteristics of the population from observed events: good data are critical. Most engineers and scientists conduct statistical analyses because the true population of events is rarely known. Yet probabilistic analyses, like Monte Carlo trials, can be instructive as thought experiments. Probability theory allows us to play the role of an omniscient being in a world of our own construction to test just how far our observed events may deviate from the unknown truth: it lets us assess how wrong we may be in real life.

As an example, consider a simplified probabilistic model of PAD ice jam flood arrivals in which floods are independent from year to year and the probability of a flood is fixed at $p_{flood} = \frac{1}{7}$. Here $\frac{1}{7}$ is selected for purely illustrative purposes, though this is roughly the average probability of a

large Peace River flood over the last 120 years. With this probability model, we can simulate any number of synthetic flood histories, H , of arbitrary length, L , by generating sequences of Bernoulli distributed random variates. Each of these synthetic histories are alternatives that could arise from the stochastic IJF generating process described by an annual probability of p_{flood} . Again, for illustrative purposes we generate $H = 1,000,000$ synthetic timeseries with $L = 60$ years: 60 years being roughly the length of reliable flood magnitude record in this study. In each of the 1,000,000 synthetic records, we compute the average probability of an ice jam flood:

$$\hat{p}_{flood} = \frac{n_{flood}}{60}$$

and plot the distribution of results in Figure 2a. The true value that we selected, p_{flood} is plotted in orange. We see clearly that \hat{p}_{flood} is a random variable, with its own distribution, and that realizations can vary substantially even though the underlying stochastic process is the same in all synthetic histories. 95% of the simulated \hat{p}_{flood} values range between [0.06, 0.23], or return periods of between 17 and 4.3 years. So just by random chance, in a simple world with the same probability of a flood in every year, our observed frequency may reasonably vary in excess of a decade.

In practice, our dilemma is that we only experience one history and in general $p_{flood} \neq \hat{p}_{flood}$, as evident in Figure 2a. This is where statistical analyses enter to provide us some indication of how far the truth, p_{flood} , may be from our best estimator, \hat{p}_{flood} . It is an interesting and worrisome exercise to imagine how far our best estimate may be from the truth. Let us assume that our world is Realization 4, which experienced 6 floods for a $\hat{p}_{flood} = 0.1$. Although 0.1 is not far from p_{flood} , Realization 4's 95% confidence interval for p_{flood} is [0.033, 0.183]. This includes the true p_{flood} of our synthetic world, $\frac{1}{7}$, but the range corresponds to return periods ranging from 5.45 to 30 years. That is, an analyst residing in Realization 4 cannot be very confident how far they may be from the truth: an issue of a relatively short 60-year flood record.

Would a 20-year gap in ice jam floods seem unusual to an analyst in Realization 4? Here we employ the geometric distribution, with our best guess of $\hat{p}_{flood} = 0.1$, and find that a wait of at least 20 years could emerge with probability 12.1% purely from chance. The analyst in Realization 4 may conclude that 20 years is a bit longer than one would expect, but not terribly so. If, however, the analyst had perfect knowledge of the true $p_{flood} = \frac{1}{7}$, they would conclude that a wait of at least 20 years would emerge by chance about 4.6% of the time. The analyst would be more likely to conclude that the wait was unusually long. Of course, the analyst in Realization 4 has no way of knowing p_{flood} , just as we have no way of knowing the true probability of an ice jam flood in the PAD. The distinction between the observed \hat{p}_{flood} and the true p_{flood} is critically important for communicating what we do or do not know for sure. As a result, we should always provide estimates of the uncertainty distribution of the probability of a flood, \hat{p}_{flood} . We revisit this point later in this section.

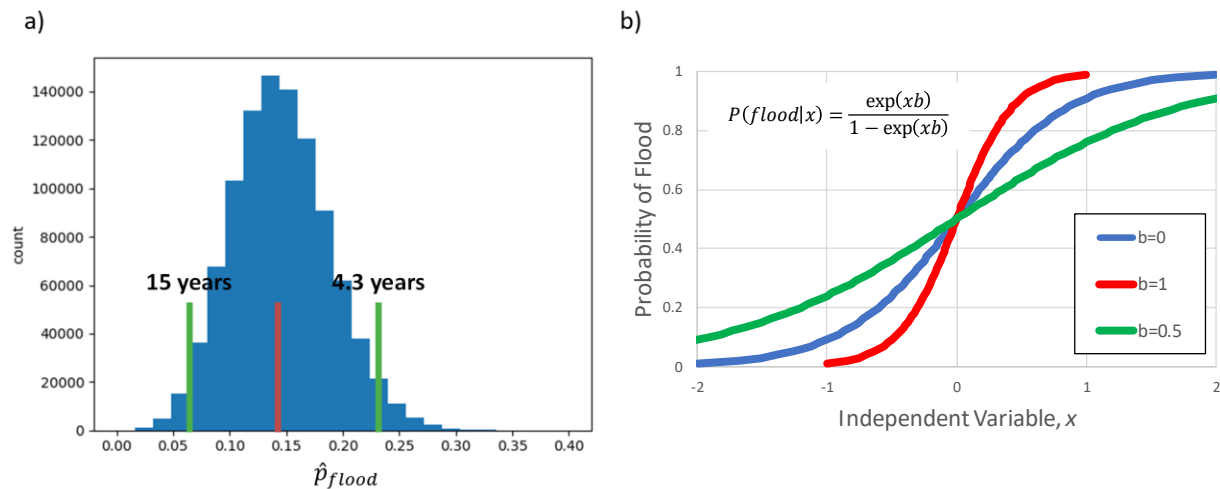


Figure 2 a) Distribution of \hat{p}_{flood} across 1,000,000 Monte Carlo samples. The true $p_{flood} = \frac{1}{7}$ is plotted in orange. Green lines indicate 5th and 95th quantiles from the 1,000,000 samples. Associated return periods for floods are reported. b) The logistic function.

Of course, this thought experiment is much simpler than the real world. Ice jam floods tend to be correlated from year to year, necessitating more complicated analyses than the independence assumption used above. Ice jam floods tend to occur near other ice jam floods in the historical record, and so the timeseries has autocorrelation. That is not to say that ice jam floods in one year cause ice jam floods in following years. Instead, it is more likely that ice jam floods are correlated due to the correlation in climatic factors that cause ice jam floods to occur, such as consecutive years with cold winters and high snowpack related to global climate cycles. The results of our conditional probability analysis support that climatic factors are dominant explanatory factors for the observed clustering of floods in the historical record.

As a result of climate change, there is good reason to suspect that, in the long run, the probability of an ice jam flood is nonstationary. Additionally, from year-to-year, conditions that favor ice jam flood formation may vary in severity, such that even if the most important drivers of ice jam floods are stationary over time, the annual probability of an ice jam flood may vary from the long-term average. We can model such variability in annual conditions, X , using conditional probability:

$$P(flood|X = x) = \frac{P(flood \cap x)}{P(x)}$$

where X is some factor impacting flood occurrence, x is a realization of that factor, $P(x)$ is the probability of that realization's value arising, $P(flood \cap x)$ is the probability of a flood and realization x jointly arising, and $P(flood|x)$ is the conditional probability of a flood given factor $X = x$.

For instance, imagine that X is winter temperature or Degree Days Freezing, and we are interested in the probability of a flood for a year in which X is less than the historical average. Let us assume that ice jam floods in the historical record only occur when the winter is colder than average, and that the average probability of an ice jam flood estimated from the historical record is 0.13. Then the probability of a large ice jam flood and being colder than average is also $P(flood \cap cold) =$

0.13. Let us also assume that it is colder than average about half the time (i.e. $P(cold) = 0.52$). We can then revise our probability of an ice jam flood from 0.13 to a conditional probability that considers that we are in a colder than average winter:

$$P(flood|cold) = \frac{P(flood \cap cold)}{P(cold)} = \frac{0.13}{0.52} = 0.25$$

Thus, because the winter is cold, the probability of a large ice jam flood is increased from the simple average based on the observed flood frequency. Of course, nature rarely exhibits such firm threshold effects. One way to model conditional probability as a smooth function of some condition (independent variable) is with logistic regression. Logistic regression models the relationship between the binary dependent variable (i.e. flood or no flood) and some independent variable with the logistic function (see Figure 2b). For a detailed description of logistic regression, see Lamontagne et al. [2021]. In addition to providing a predictive model for ice jam floods, logistic regression software packages provide estimates of the strength of any hypothesized association. That is, it indicates which variables may be most predictive of floods, the direction of that association, and how likely the hypothesized association may have arisen from chance.

Logistic regression is particularly useful for analyses of PAD IJF frequency, which is complicated by coincident changes in regulation and climate factors that confound superficial analyses. This is a common problem across many fields including economics, medicine, public health, and sports. For instance, it may not be clear what factors most predict the salaries of hockey players, and it may be hypothesized that it is primarily a function of team, league, years in the league, or position. Standard regression could answer the question of which factor is individually most important, but could also disentangle factors that may be related (by chance or design). So, if goalies on the New York Islanders get paid a lot, is it because they are goalies or is it that the Islanders pay well, or is it that the Islanders pay goalies particularly well? One could disentangle this with standard regression techniques by controlling for one factor and looking for the additional effect of a second.

In our case, our independent variable is binary (flood or no flood) but in principle we can use the same idea. Logistic regression allows us to remove the effect of climate factors, like temperature, and ask whether regulation effects have additional impact. Importantly, we can also ask how uncertain we are in those effects. Standard statistical software provides estimates of significance (p-values), but these make strong parametric assumptions. One approach to characterizing uncertainty that makes fewer parametric assumptions is to employ a bootstrap. In bootstrapping, the observed sample is re-sampled with replacement many times, the statistic of interest (in our case the logistic regression parameter values) are computed each time, and from this we can estimate uncertainty information in both the regression model parameters and in the resulting predicted probability of a flood.

For instance, if the analyst in Realization 4 wanted to quantify the uncertainty in \hat{p}_{flood} , they could generate many (hundreds to thousands) of bootstrap 60-year records by repeatedly sampling and replacing the flood record. If they were concerned that autocorrelation in the flood record may render a standard geometric test incorrect, they could block bootstrap, in which blocks of consecutive years are sampled and replaced rather than individual years (see Timoney et al., 2018). This test could distinguish between a record in which all six floods occur sequentially, followed by 54 years of no floods and one in which floods occur exactly once every ten years. In the context of the former, 20 year gaps seem quite normal. In the context of the latter they would appear

unusual. A more preferable way to account for such correlation directly through the forcing (i.e. to capture correlation in the factors that explain ice jam flood occurrence, see Lamontagne et al. [2021]). This requires the assumption that the correct model relating the factors, X, to the outcome, Y, is known, but parametric uncertainty in the effect of X on Y persists. This method is used in Section 4 to estimate the distribution of \hat{p} for every year in the historical record, conditional on factors, X, that are described in Section 3.

3. Quantifying a PAD IJF conceptual model – exploratory data analysis

(Jasek, 2019ab) constructed a conceptual model of ice breakup drivers and resistors based on detailed observations of the 2014 and 2018 breakups.

1. Discharge potential for breakup: snowpack and regulated releases
2. Sustained warm-up: duration and rapidity of spring thaw
3. Breakup ice resistance upstream of the PAD
4. Breakup ice resistance in the PAD and upper Slave River

The study proposed that high discharge potential, a rapid spring warming, a lower breakup resistance upstream of the PAD and a higher ice resistance within the PAD were conducive to the formation and sustained ice jams in the PAD that produced large scale flooding. Although, high breakup resistance in both upstream and downstream of the PAD still had the potential to produce large IJFs.

Knowledge of these factors is useful to inform predictive models; however, none of these factors can be measured directly across the PAD and Peace River watershed, so proxy data are needed. This section describes the environmental data that were used to evaluate the breakup drivers and resistors that form the basis of the statistical analysis for Lamontagne et. (in review) as well as this paper.

3.1 Discharge potential for breakup

Discharge potential has two sources for the PAD: regulated Peace River flows from the Bennett and Peace Canyon Dams about 1200km upstream of the PAD, and unregulated inflows from lower elevation tributaries (spring freshet).

3.1.1. Regulated releases at breakup

Flow regulation on the Peace River started in 1972, and filling of the Williston Reservoir impacted flows from 1968-1971. The average winter flows have changed as a result of regulation (Figure 6) ($p < 0.001$ for mean of the average monthly November and December flows at Hudson's Hope and Peace River); however, at the time of ice breakup in spring, unregulated inflows from snowmelt make up the overwhelming majority of Peace River flows (75-90%) and regulated flows have a relatively minor contribution. Additionally, regulated flow at the time of breakup increases the natural river flow on average and remains unchanged at the time of PAD ice jam flooding (Beltaos and Peters, 2019). From a purely available discharge perspective, there is no reason to suspect that regulation reduces the chance to initiate an IJF or reduce its first week of flood volume.

Instead, we expect that the snowpack must be sufficient to produce the streamflows needed to initiate and sustain a dynamic breakup that can lead to large IJFs.

3.1.2. Snowpack or winter precipitation

From decades of observations and published river flows, it is known that the bulk of the spring runoff that drives dynamic breakups on the Peace River comes from the lower-lying plains portion of the Smoky River Basin and other hydrologically and climatically similar basins and terrain between Hudson's Hope and the Town of Peace River, Alberta (Figure 1). Therefore, historical data that represented the snowpack at the end of the winter in this region were investigated. The familiar trade-off between a long temporal record at few sites versus a shorter record with greater spatial coverage was encountered; this being the cumulative winter precipitation in the Grande Prairie area going back more than 100 years, versus the Alberta plains snow survey network going back several decades. Due to the relative rarity of large PAD IJFs, we opted to use the longer and less spatially representative record in order to maximize the number of IJFs for this analysis. If the snowpack is an important predictor of large IJFs, future work can consider the value of using the snow survey network using methods to account for missing data at each survey site.

The longest and most continuous climatic record exists in the heart of an agricultural area in the Grande Prairie region. Two locations provided the longest records: Beaverlodge from 1913 – 1996, and Grande Prairie from 1943 – present.

Cumulative winter precipitation from daily data was calculated in order to come up with a proxy for the snowpack that was available for melt in the spring to drive a dynamic breakup. Cumulative degree-days of freezing (DDF) at Grande Prairie or Beaverlodge were used to distinguish rainfall from snowfall in late fall/early winter. Precipitation was only counted if the DDF remained negative. If the DDF went back to zero following a snowy-freezing period it was assumed that the snow had melted, and the precipitation summation started again from zero once freezing temperatures returned. Any snowmelt due to short mid-winter warm spells that did not bring the DDF back to zero were assumed to not cause a substantial loss of water that would be available to drive breakup in the spring, assuming the top layer of the snowpack melts and just refreezes in the lower layers (Bengston, 1982). There may be some water loss to ground for longer duration warm spells but it was assumed that it would freeze to the ground surface and would still be available for run-off in the spring, or at least add to the soil moisture to allow the remaining snowmelt to runoff more efficiently. Using this DDF method to compute cumulative winter snowfall is especially important in future climate scenarios where the snow accumulation may start later in the year under a warmer climate rather than considering an arbitrary period like November through April.

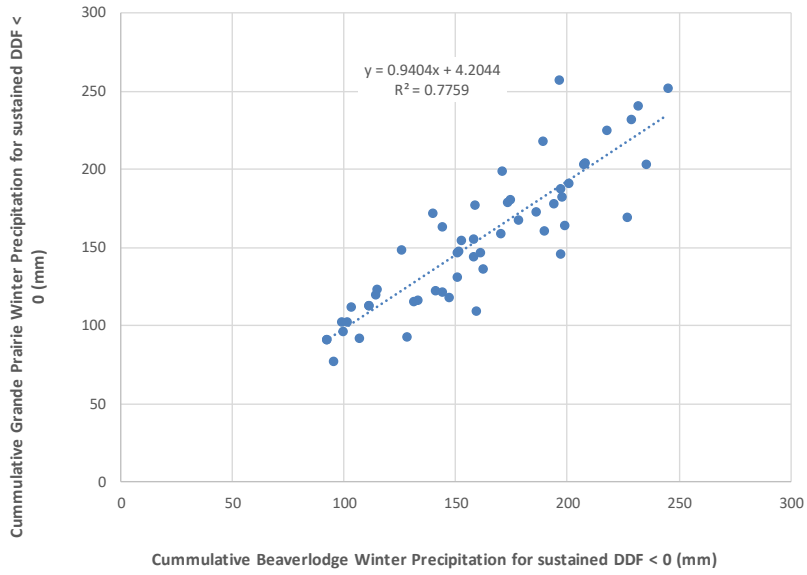


Figure 3. Good correlation ($R^2 = 0.78$) between Beaverlodge and Grande Prairie winter precipitation with a slope close to one and the intercept close to zero.

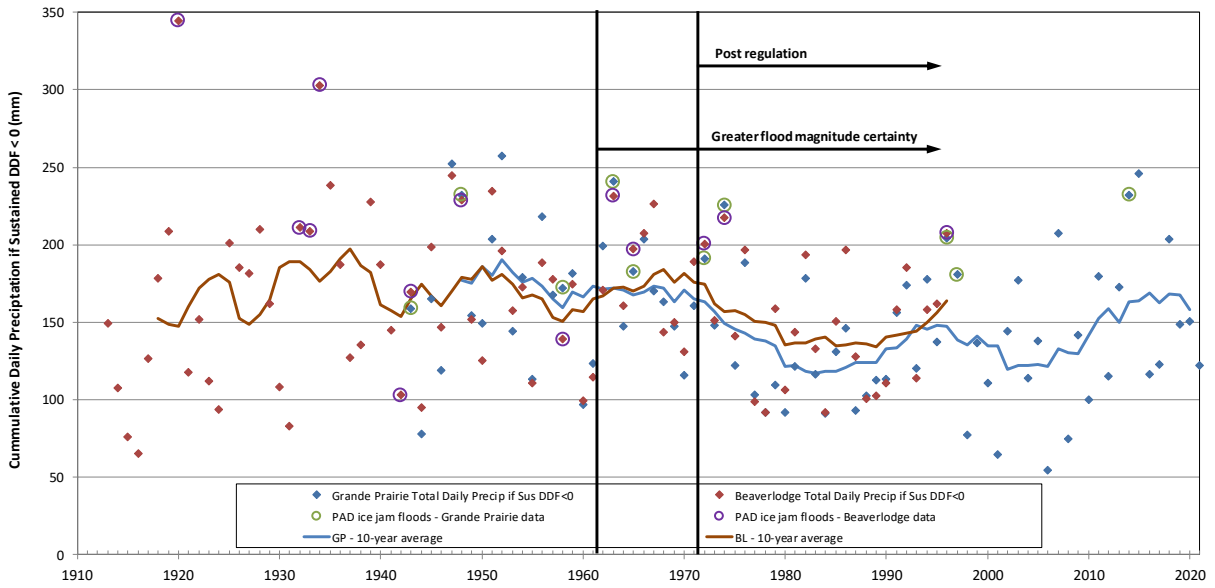


Figure 4. Total winter precipitation for sustained degree-days of freezing at Grande Prairie and Beaverlodge, AB. Large PAD IJF years are circled. Note that large IJF year data are taken from Timoney (2009) and some years are uncertain before ~1962.

Grande Prairie and Beaverlodge are 36 km apart and at a similar elevation. The overlapping period 1943 – 1996 shows that there is a good correlation between the two sites (Figure 3). We opted to make a single continuous record by substituting data from the other station, when necessary. Again, a method that accounts for missing data at each site could be evaluated in future studies.

Figure 4 shows the winter precipitation for both Grande Prairie and Beaverlodge for the period of record. Large ice jam flood years were taken from the Timoney (2009) classification with the exception of also including the year 1948 as a large flood (classified as a moderate flood by Timoney (2009) but as a large flood by Peterson (1994). The Peterson reference indicated that in 1948, there was flooding around Egg Lake in addition to Rocky Point in the PAD. Observations in 2014 indicated that it took many days for the water to reach Egg Lake after the ice jam was in place through Rocky Point, and we know that 2014 was a large flood. This observation was not available to Timoney in 2009 but the differences in classification indicates the subjectivity of classifying the size of some of the older floods where water level gauge data, aerial and satellite monitoring were not available. This is the reason why the subsequent statistical analysis considered data only back to 1962. Extending the record to 1915 by considering the uncertainty in flood magnitudes from 1915-1962 is left for a future, ongoing study.

The circled data representing large ice jam floods in Figure 3 show preference for larger winter precipitation. 10-year centered running average lines shown in Figure 3 indicate a reduction in annual snowpacks coincidentally after regulation and substantial dry periods in the late 1970s, 1980s and 2000s compared to the decades preceding regulation. These dry post-regulation periods contained no large ice jam floods. Wetter periods in the late 1990s and 2000s were responsible for three large PAD ice jam floods. Note that 1942 is a low outlier and will be discussed later.

In general, the cumulative winter precipitation at Grande Prairie/Beaverlodge appears to be a good proxy for the water available to create a large ice jam flood, so was evaluated by way of logistic regression in the subsequent analysis.

3.2. Rate of warming in the spring

This proxy aimed to differentiate between rapid and slow warming that drives snowmelt. Various combinations based on Cumulative Degree-C-days of Thaw (DDT) were tried and referred to as “Melt Tests”. This was based on examining known dynamic break-up dates at the Town of Peace River and also the PAD and their corresponding DDT’s at Grande Prairie. The former ranged from 33 to 65 DDT and the latter ranged from 65 to 139 DDT. It was not enough to just have a certain number of degree days but the cumulative DD threshold needed to be exceeded in a shorter duration for a better chance of a large IJF. The first set of Melt Tests were based on temperature during a DDT range:

Melt Test 1: The maximum 5-day running average temperature 1 to 5 days ago during period when $50 > \text{DDT} > 150$.

Melt Test 2: The maximum 5-day running average temperature 1 to 5 days ago during period when $50 > \text{DDT} > 100$.

Melt Test 3: The maximum 5-day running average temperature 2 to 6 days ago during period when $50 > \text{DDT} > 100$.

Melt Test 4: The maximum 5-day running average temperature 3 to 7 days ago during period when $50 > \text{DDT} > 100$.

Melt Test 5: The maximum 5-day running average temperature 4 to 8 days ago during period when $50 > \text{DDT} > 100$.

For the above tests, a higher average temperature indicates a more rapid snow melt. The variation in the number of days ago, was to try and get at the basin snowmelt response time that best reflected when the snow melted and showed up at the dynamic break-up location on the Peace River. The best results for this series of tests was Melt Test 1.

A second set of melt tests was tried with a different type of formulation based on days to accumulate a certain DDT amount:

Melt Test 6: Number of days to go from 40 DDT to 100 DDT.

Melt Test 7: Number of days to go from 10 DDT to 70 DDT.

Melt Test 8: Number of days to go from 40 DDT to 150 DDT.

Melt Test 9: Number of days to go from 0 DDT to 50 DDT.

For the above tests, a smaller number of days indicate a more rapid snow melt. The best one was Melt Test 8 and was better than Melt Test 1. Melt Test 8 Grande Prairie data were expanded to include the Beaverlodge data back to 1913 and the results remained consistent. Figure 5 shows the data for Melt Test 8 with large PAD flood years identified with most flood years occurring Melt Test 8 ≤ 18 days but as high as 22. What can be concluded from this figure is that in most years it warms up fast enough for Melt Test 8 to be satisfied. The consequences of this fact to be discussed later.

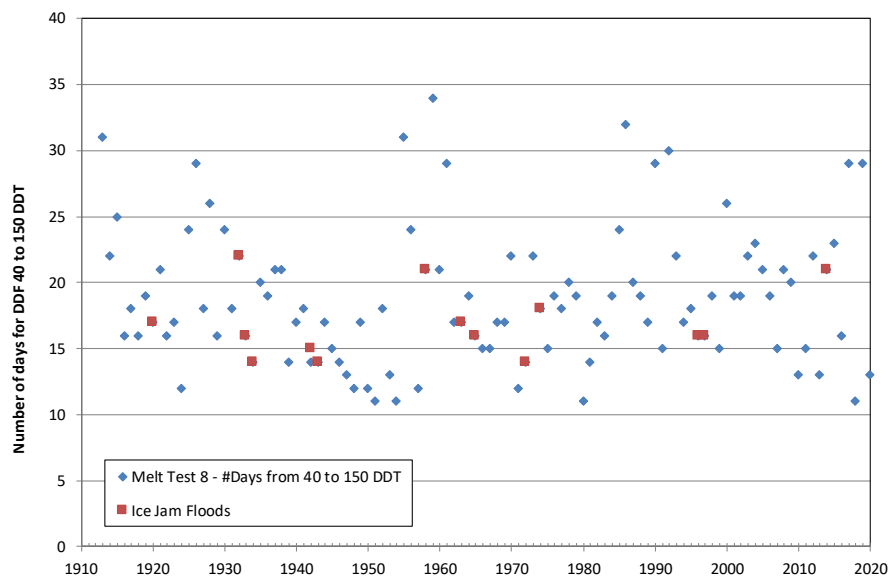


Figure 5. Number of days for degree-day of thaw (DDT) at Grande Prairie to go from 40 DDT to 150 DDT. Note that large IJF year data are taken from Timoney (2009) and some years are uncertain before ~1962

3.3 Breakup ice resistance

The resistance of the ice cover to breaking up can be relegated to two categories: geometry constraints to movement, and ice sheet fracture resistance. For geometry, one can ask the question how much room there is for the ice sheet to start moving due to its width and thickness in getting around channel bends and channel narrows? For strength one can ask the question how easy is it for the ice to fracture due to loads on the ice cover? In the latter, once the ice is sufficiently fractured, it can get around bends and narrows easily.

For geometry, it has been theorized that a higher freeze-up elevation creates a wider ice cover which is therefore more difficult to move around channel bends and narrows at breakup. Some previous studies (Prowse and Conly, 1998; Beltaos et al., 2006) have theorized that because Peace River winter discharges are higher post-regulation, which causes higher freeze-up ice elevations, that this higher ice level requires greater discharge in the spring to create a dynamic break-up (Beltaos et al., 2006), thereby causing the frequency of ice jams to decrease post-regulation (Beltaos 2014; 2017). Although this is recently under debate (Timoney et al., 2018; Hall et al., 2018; Beltaos, 2019; Lamontagne et al., in revision).

There are many more factors that determine the breakup resistance from the ice sheet fracture resistance perspective. The resistance to fracturing has two components, the ice thickness and the strengths of the ice cover to resist fracture (measured in force per unit area, and are different in compression and tension and thus failure modes are important).

The thickness of the ice cover prior to breakup is determined by:

- 1) how cold the winter is
- 2) how much snow falls on the ice cover and the timing of the snow falls as snow insulates the ice cover from freezing temperatures
- 3) the timing of freeze-up when thermal ice growth begins
- 4) if the ice is growing into water or frazil slush underneath it (it will grow faster into slush as part of the substrate is already frozen)
- 5) how wind effects the snow depth on the ice cover thereby effecting the insulation
- 6) how the snow settles or densifies on the ice cover (denser snow provides less insulation than lighter snow)
- 7) how much snow melts or sublimates from the ice cover
- 8) formation of snow-ice on the top of the ice cover (occurs when the snow on the ice cover is sufficient in mass to submerge the ice cover and freeze the wet snow to the top of the ice cover.
- 9) friction from water flow underneath reduces the rate of ice cover growth during cold air temperatures and can thin the ice cover when air temperatures are above freezing
- 10) above freezing water temperatures thin the ice cover from underneath (Most of the winter the water under the ice cover is at the freezing point, but open leads in the spring along the banks due to rising flows can create areas were solar radiation heats this water that makes its way under the ice cover.

The strength of the ice cover prior to breakup is determined by:

- 1) warm air temperatures and mostly solar radiation (due to its more penetrative properties) in the spring can degrade the strength of the ice cover by melting the ice crystal boundaries where impurities act as antifreeze. From this it follows that the albedo and cloud cover are important factors.
- 2) Albedo is a function of how much snow is left on the ice cover and how quickly it is melting as once the snow has completely melted the river ice surface albedo dramatically increases and the rate of ice strength degradation increases correspondingly.
- 3) Snow ice, and thermal ice that freezes into frazil slush has a higher albedo than clear ice. The ice strength in these “white ice” types degrades slower than that of clear ice because of the scattering and reflectiveness of the smaller ice crystals.

Data are not available to describe most of these physical factors, especially along an 800 km long ice cover like on the Peace River. However, the climatic factors that we evaluate are likely correlated with some of these, and we expect that their effects may be captured by our analysis to some degree.

3.3.1 Discharges at freeze-up and freeze-up elevation (geometric constraint)

To test the impact of regulation at the time of river ice freeze-up (geometry constraint to breakup resistance in above section), we evaluate early winter regulated river flows and the river’s freeze-up elevation at Peace Point as possible predictors of IJFs in the statistical analysis.

The previous November and December flows in the Peace River mainstem can be examined to quantify the regulated flows in the Peace River. Three gauging locations are examined: Hudson’s Hope, located 28 km downstream of the Bennet Dam, 2) Town of Peace River, about 397 km downstream, and 3) Peace Point, about 1136 km downstream and 62 to 107 km upstream of the PAD (Figure 1). This flow data is shown in Figure 6.

Figure 6 shows that since the Bennet Dam was constructed, regulation has caused a step change in typical flows in these months. If previous fall/winter river flows are a significant predictor of spring IJFs, then there would be reason to suspect that a change in flow caused by the Bennet Dam could impact IJF frequency. However, examining Figure 6 shows that large ice jam floods in the PAD have occurred for both higher and lower November and December discharges.

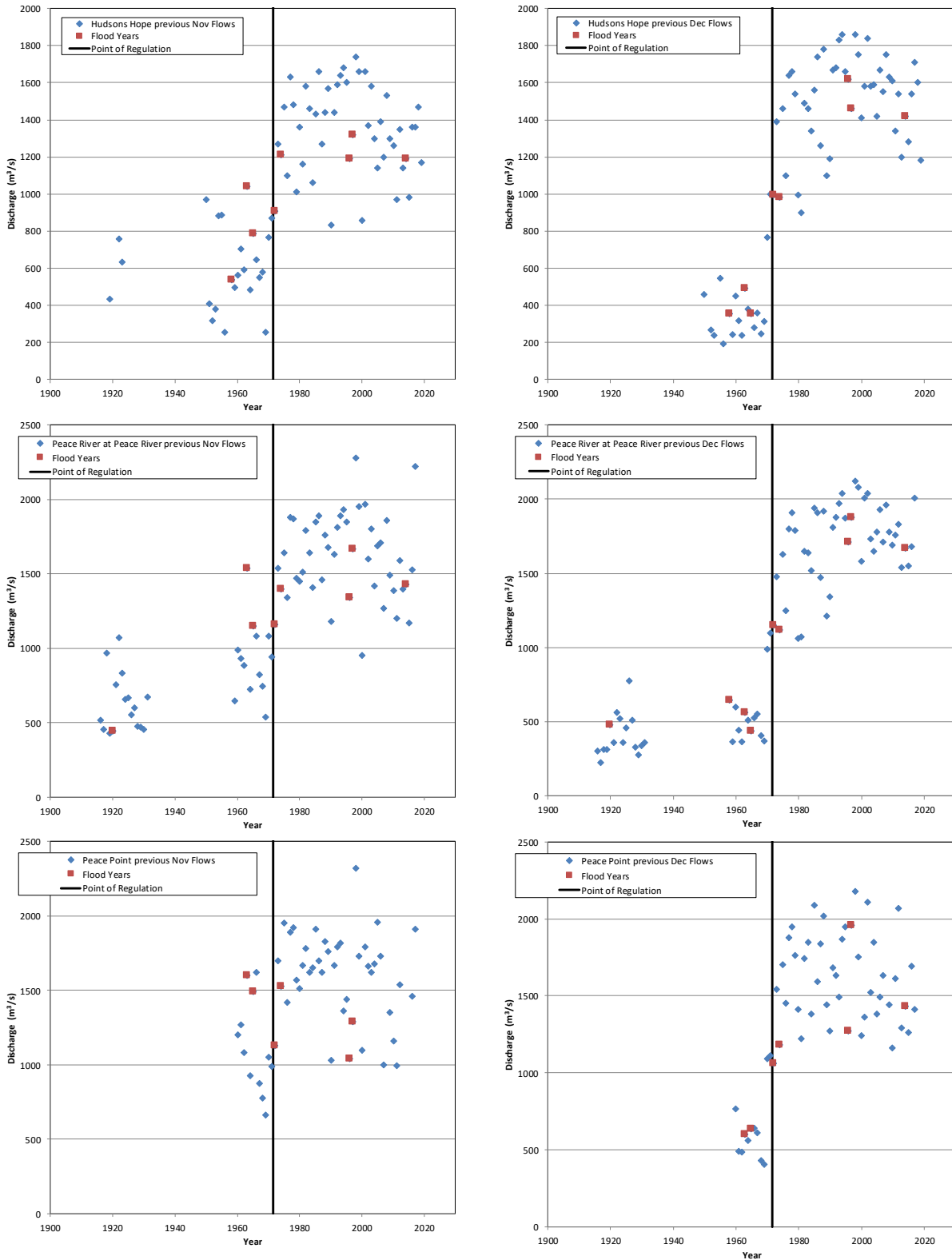


Figure 6. Peace River mainstem monthly average discharges the previous fall/winter with large PAD IJFs indicated. Note that large IJF year data are taken from Timoney (2009) and some years are uncertain before ~1962.

Next we plot the previous fall/winter freeze-up elevation data from Beltaos (2014) and supplemental data at Peace Point for each breakup year and note the large flood years (Figure 7). There are only 10 years of data prior to regulation with only two large floods and floods have occurred post-regulation with higher freeze-up stages. With so few floods both pre and post regulation, it is difficult to obtain statistical confidence about the role of freeze-up stage, especially in light of the climatic factors like decreased snowpack, already discussed, and winter air temperatures discussed in the next section, both going much further back in history.

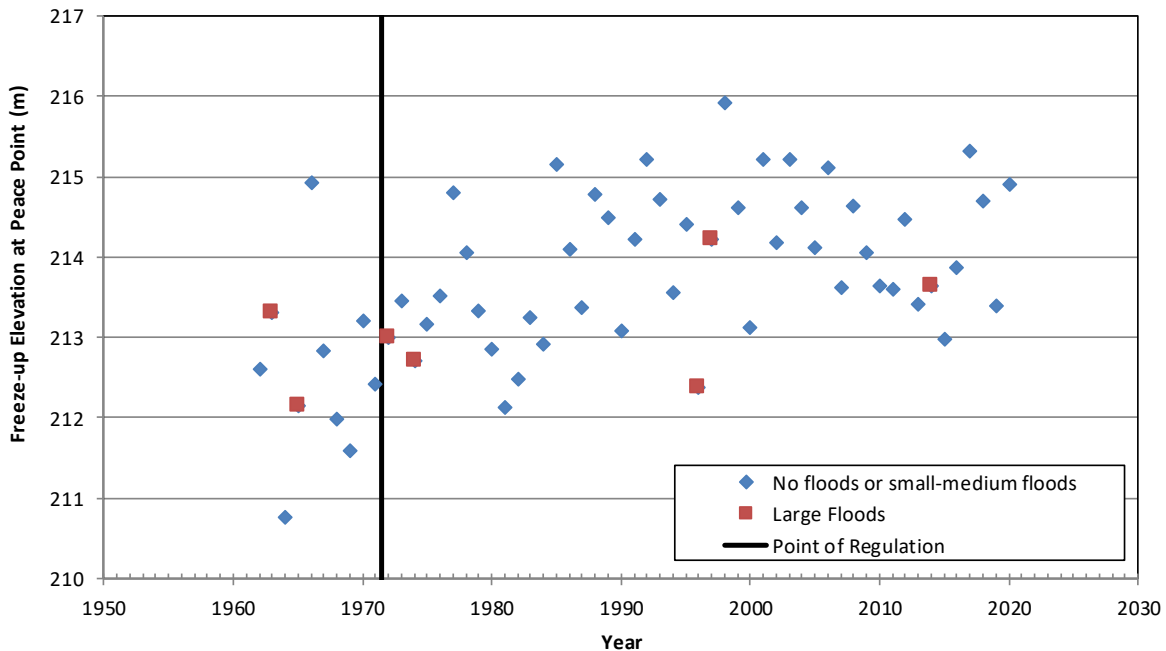


Figure 7. Freeze-up elevation at Peace Point.

3.3.2 Ice sheet fracture resistance at breakup

The next proxy that was needed was some measure of the ice sheet fracture resistance at the PAD and also upstream of the PAD. This by far is the most challenging proxy because of all the unknowns that are not easily measured or recorded historically nor are they available over the spatial extent that is needed that go into determining break-up resistance (numbered lists in Section 3.3).

The simplest and most readily available parameter are historic air temperatures throughout the winter. This parameter at least is the main driver of thermal ice growth and one can use cumulative degree-days of freezing (DDF) for the entire winter as a proxy for the end of the winter ice thickness before degradation from warmer weather prior to breakup begins. It does not account for the many other snow cover related factors that determine the end of the winter ice thickness, but it is a good start.

Both DDF at Fort Chipewyan and Fort Vermilion were explored with Fort Smith Data and High Level Data used to fill in missing data at the two locations respectively (See Figure 1 for locations). Missing data was filled using an offset based on the average monthly divergence of air temperatures between the two stations. This allowed for the computation of DDFs at the two sites back to 1915 with only one year of missing at Fort Chipewyan (1938) and five years at Fort Vermilion (1938, 1942, 1948, 1993, 1994), with 1942 and 1948 being flood years.

Although ice thickness is proportional to the square root of DDF, subsequent statistical analysis showed that it made little difference to statistical significance, so the original units were preferred for simplicity.

Figure 8a,b show historical DDF for Fort Vermilion and Fort Chipewyan respectively with a longer record at the latter. Large ice jam flood years are also indicated. The 10-year centered moving average at both sites shows a warming trend since the early 1900s at Fort Vermilion and since the early 1970s at Fort Chipewyan. The ice jam flood years shown in both DDF plots indicate that large PAD ice jam floods tend to occur after colder winters (thicker ice thickness). The figures also show that ever since about the point of regulation, the climate warming has increased substantially enough that there has been a dramatic decrease number of years of DDF for which large PAD ice jam floods have occurred prior to regulation.

Figure 8c shows a ratio of Fort Chipewyan over Fort Vermilion DDFs to examine if a stronger ice cover at the PAD than upstream of the PAD is conducive for large ice jam floods. This is not apparent in the data. However, it does show that generally, the winters are colder further east and closer to the PAD, probably due to being closer to the winter Hudson Bay low pressure area that frequently draws Arctic air southward into the interior of the continent. The ratio is less than one in the early 1900s (with the exception of the first two years) and then increases gradually. It has been left to further study if there could be a climatological explanation for this or perhaps a data measurement bias in the early part of the record at one of the stations.

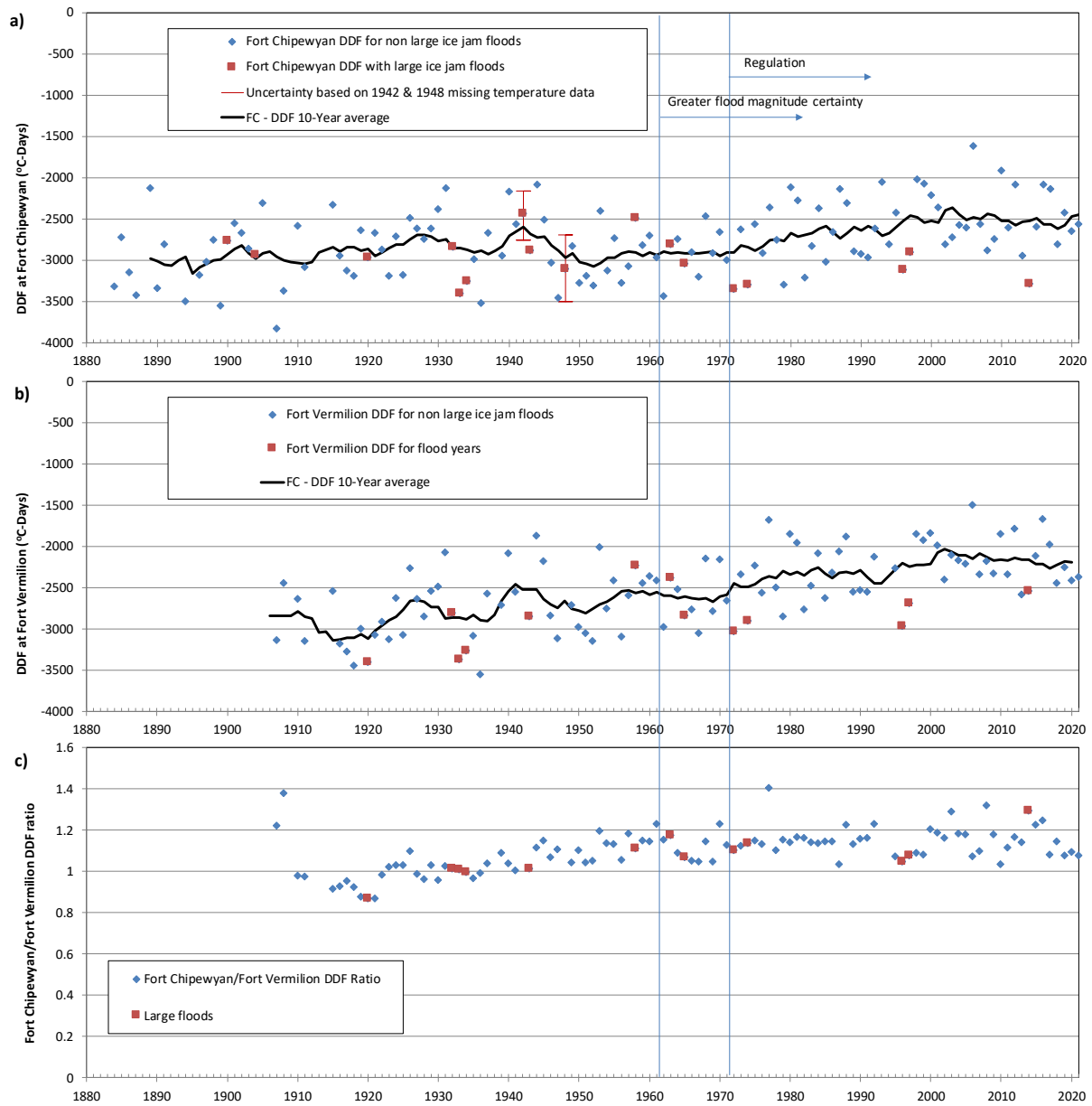


Figure 8. Historical DDF for a) Fort Chipewyan, b) Fort Vermilion, and c) the ratio of the two. The large flood years 1942 and 1948 for Fort Vermilion temperature data is missing. For Fort Chipewyan these years contain error bars based on 20 and 16 consecutive days of missing data at that station. The range determined by the warmest and coldest historical DDF sequences for these days substituted. Note that large IJF year data are taken from Timoney (2009) and some years are uncertain before ~1962

3.4 Comparison of snowpack and winter severity

In the previous sections, plots of proxies for winter precipitation in the Smoky River Basin and ice breakup resistance at the PAD and upstream of it have shown some promise of being predictive of large ice jam floods at the PAD. Therefore, we look at plotting these variables together in Figure 9.

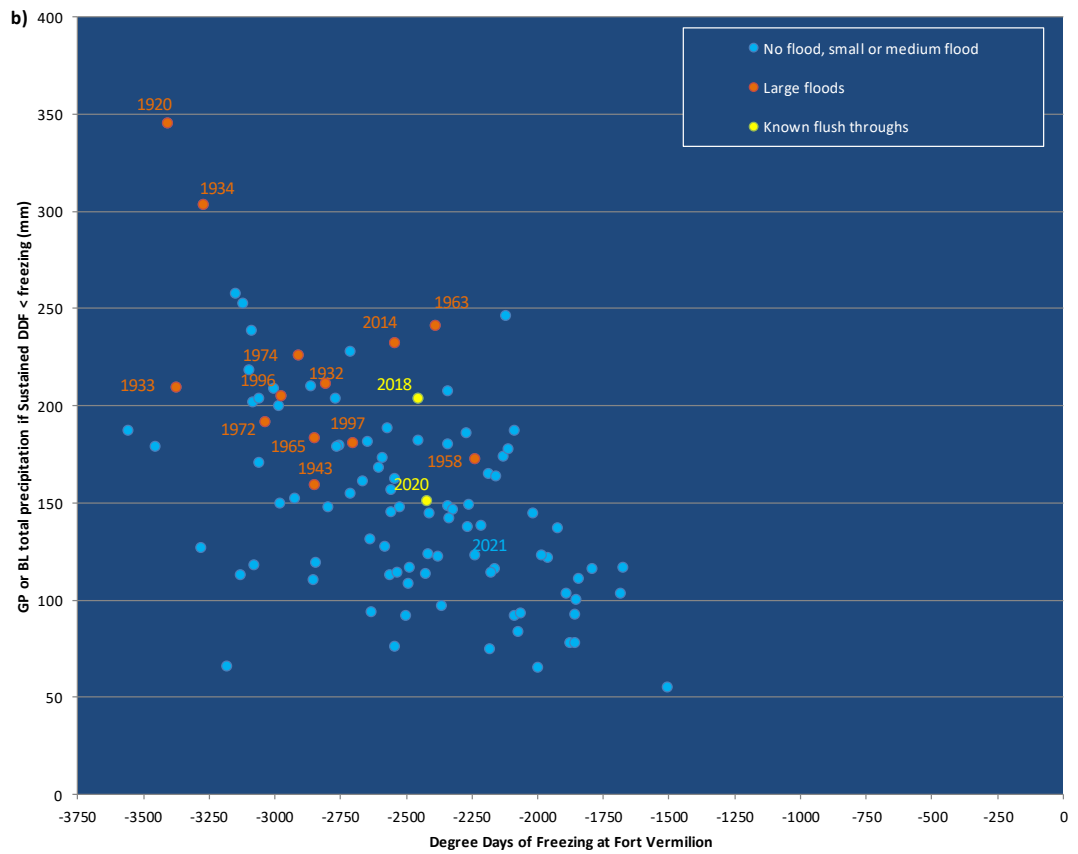
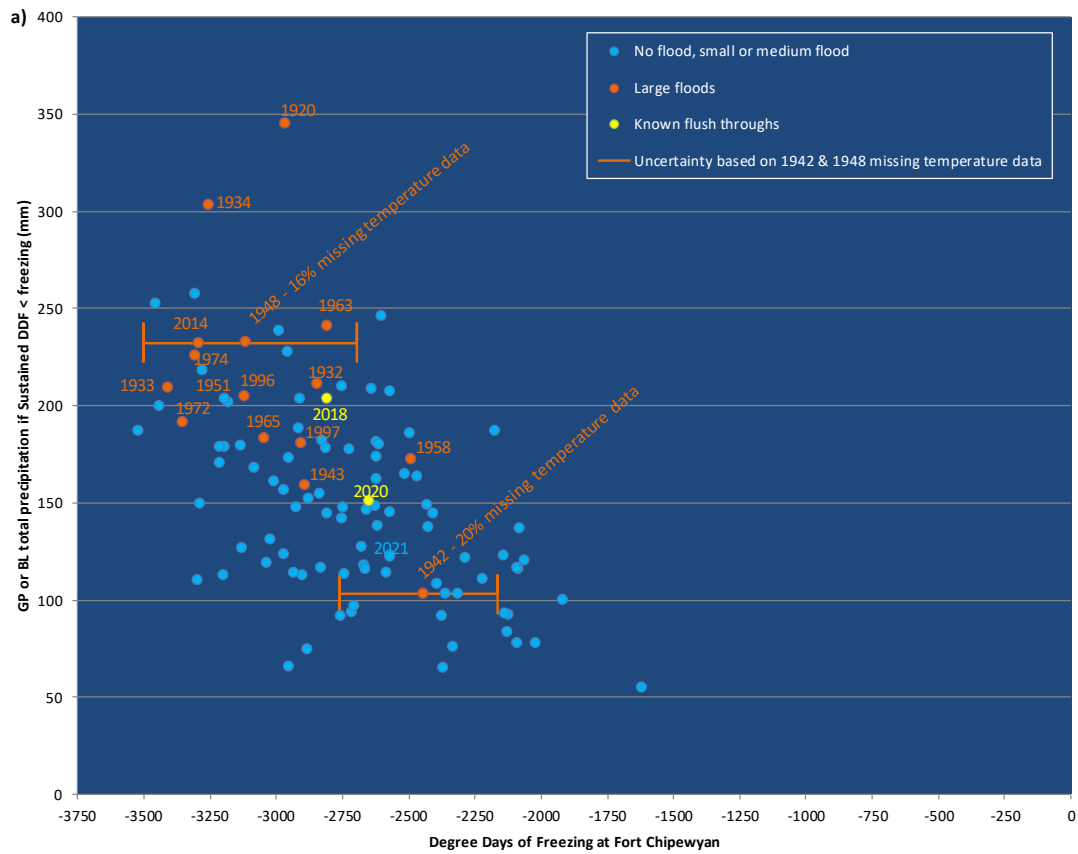
Figure 9a shows cumulative winter precipitation at Grande Prairie or Beaverlodge against DDF at Fort Chipewyan and Figure 9b against DDF at Fort Vermilion. Both figures show that large ice jam flood year points congregate in the top left of their distributions; they represent cold winters in the north part of the basin near the PAD and high snowpacks in the south. It is evident that not all high snowpacks combined with cold years guarantee a large flood but roughly about 40% of the points that plot in this quadrant are large floods.

Also plotted in Figures 9a,b are two recent breakups (2018 and 2020) where the dynamic breakup was observed to flush through the PAD (not stop and create an ice jam) despite high snowpacks in the south. These two points in yellow plot on the lower right extent of the orange points indicating that this area may be on the margin of producing ice jam floods where the ice breakup resistance (smaller DDF) may not be high enough to stop breakup at the PAD.

The year 1942 designated as large flood in Timoney (2009) and also 1948 had a significant amount of missing temperatures for Fort Chipewyan and were entirely missing for Fort Vermilion. These years contain error bars in Figure 9a based on 20 and 16 consecutive days of missing data at this station for those years respectively. The range determined by the warmest and coldest historical DDF sequences for these days substituted. This indicates that the year 1942 stands out as an anomalous flood with a low snowpack and likely warmer winter than most large flood years. Some readers will be familiar with the most recent breakup in 2021 where there was no indication of large discharges or dynamic breakup behavior. This 2021 datapoint is labeled in Figure 9a and it shows a slightly higher snowpack proxy and likely a slightly colder winter than 1942 so the validity of 1942 being a large flood comes into question. It may be that the run-off came from elsewhere in the basin than the Grande Prairie area but a preliminary look at cumulative precipitation at other stations (Elmworth, Dunvegan and Fairview, AB) were also at the lower end of their distributions in 1942.

In Section 3.1.2 we discussed the uncertainty around the magnitude of the 1948 flood but include it here as large flood year in the plots discussed.

Figure 9c plots DDF at Fort Chipewyan vs. DDF at Fort Vermilion. Most points and all floods with one exception plot below the 1:1 line indicating Fort Chipewyan is almost always colder than Fort Vermilion but there is no indication that a larger DDF at the PAD compared to upstream of the PAD in general promotes large ice jam floods. It may be there is not enough data to make this distinction or other factors that govern the deterioration of breakup resistance during the spring warming overwhelm the building of ice over the winter.



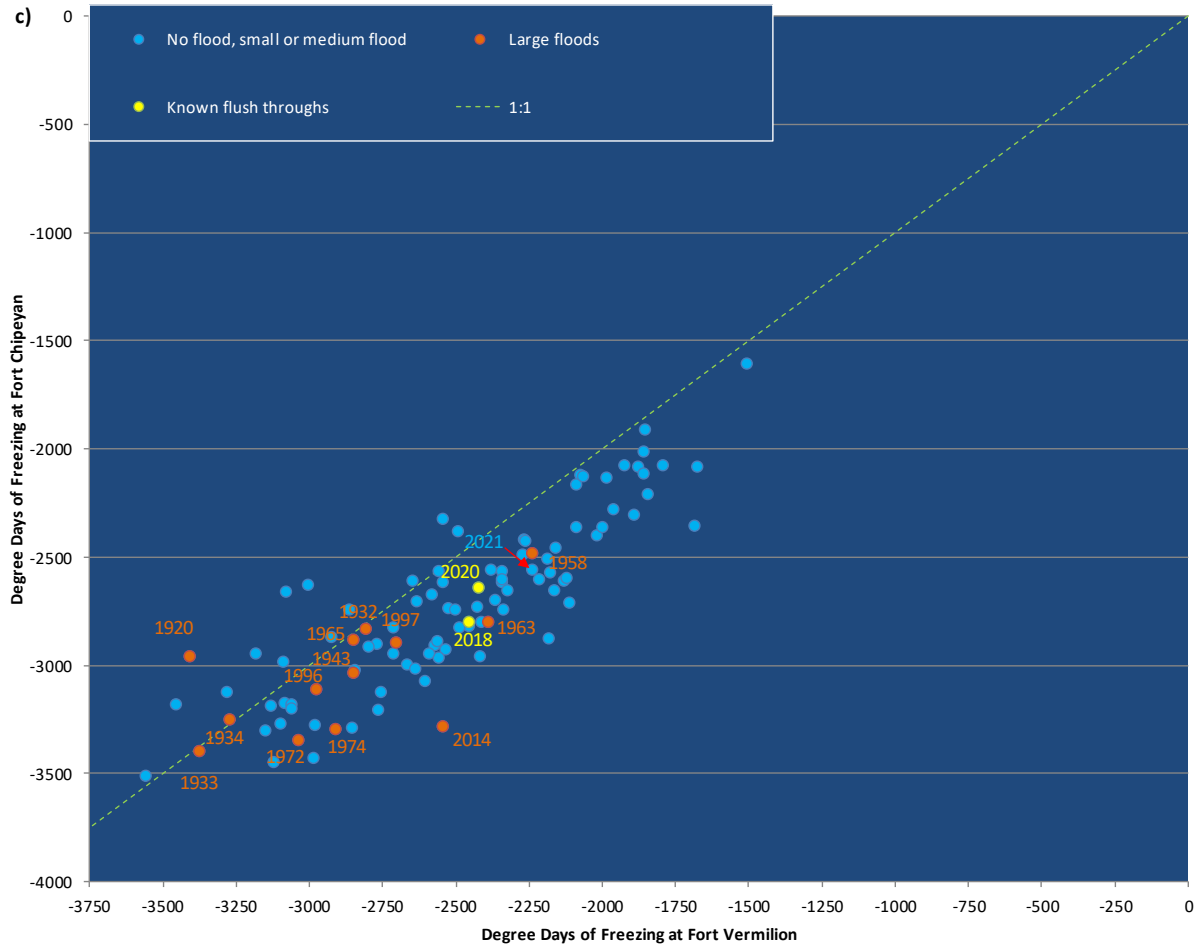


Figure 9. Grande Prairie-Beaverlodge total winter precipitation vs. a) DDF at Fort Chipewyan. b) vs. DDF at Fort Vermilion. c) DDF at Fort Chipewyan vs. DDF at Fort Vermilion. Note that large IJF year data are taken from Timoney (2009) and some years are uncertain before ~1962

Based on the specific examples of the uncertainty of assigning flood magnitudes for some of the older data discussed above and the difficulty of assigning flood magnitudes to the older PAD floods in general (Wolfe et al. 2020), it was thought best to use data only as far back as the hydrometric record (1962) for the statistical analysis for the companion study (Lamontagne et al, in revision) described next in this paper. This is not to say that data prior to 1962 does not contain useful information, only that a different statistical approach will be needed to incorporate this data, which has been relegated to future work.

4. Predictive model development using logistic regression

The factors we explored in the previous section were used to build the “best” possible logistic regression model for predicting the 1962-2020 historical flood record. Here, as in Lamontagne et al. (in revision), we define the best model as the one that minimizes the Akaike Information Criterion (AIC), corrected to second-order to be more accurate for the small size of our dataset (AICc). Table 1 presents the best model consisting of 0 to 4 explanatory variables. In the right

column of Table 1, we force the first explanatory variable to be freeze-up elevation as a way to compare the performance of a model with and without freeze-up included. The preferred model is the one for which the AICc is smallest while the parameter coefficients are also large and statistically significant at the 5% level. Based on those criteria, the model consisting of accumulated winter precipitation at Grande Prairie / Beaverlodge and Fort Vermillion DDF is preferred. Adding a third explanatory variable, Hudson’s Hope November flows in this case, results in a slightly lower AICc, but the effect of HH flows is not statistically significant, and the practical significance is also low (0.66). Models containing freeze-up elevation are larger in AICc and generally have smaller parameter significance. Of note is that spring warming as approximated by Melt Test 8 was also not found to be significant after accounting for winter precipitation and temperature factors. This is likely because there are relatively few years where Melt Test8 is not satisfied while there was also favorable DDF and winter precipitation; only two years may have been thwarted since 1962 and only seven years since 1913. For this factor and all others, statistical insignificance could be a function of a short record length and does not have to indicate that a factor is physically unimportant. This and other possible limitations of this analysis are explored further in Lamontagne et al. (in revision). From this analysis, we can conclude that climatic factors are most predictive of large Peace River IJFs in the PAD, and river regulation factors are less predictive.

Table 1: Best logistic regression models for 1962 – 2020. * indicates significant coefficients at the 5% level. “HH Nov. Flows” is the average monthly flow on the Peace River at Hudson’s Hope the November prior to breakup. Adapted from Lamontagne et al. (in revision).

Number of Explanatory Variables	Best Model			Best Model Including Freeze-up		
	Variables	$\hat{\beta}$	AICc	Variables	$\hat{\beta}$	AICc
0	Constant*	-1.86	42.17	Constant*	-1.86	42.17
1	Constant* GP Precip.*	-3.04 1.99	26.90	Constant* Freeze-up	-2.06 -0.80	38.11
2	Constant* GP Precip.* Fort Verm. DDF*	-4.84 2.37 -1.68	22.24	Constant* Freeze-up GP Precip.*	-3.17 -0.70 1.86	25.93
3	Constant* GP. Precip.* Fort Verm. DDF* HH Nov. Flows	-5.46 2.84 -2.26 0.66	22.23	Constant* Freeze-up GP Precip.* Fort Verm. DDF	-4.40 -0.30 2.10 -1.42	23.65
4 (same model)	Constant* GP. Precip.* Fort Verm. DDF HH Nov. Flows Freeze-up	-4.95 2.56 -1.97 0.57 -0.19	23.96	Constant* Freeze-up GP Precip.* Fort Verm. DDF HH Nov. Flows	-4.95 -0.19 2.56 -1.97 0.57	23.96

The uncertainties in the parameter values for the best model were evaluated through fitting the model to all of the bootstrapped alternative histories, as described in Section 2. The resulting parameter distributions for the constant (intercept), Fort Vermillion DDF, and Grande Prairie precipitation are provided in Figure 10. The marginal distributions along the diagonal confirm that the parameter values tend to be much different than 0, and visually support the statistical significance reported in Table 1. The off-diagonal joint distributions reveal correlations in parameter values. All distributions are skewed, and their tail parameter values are correlated.

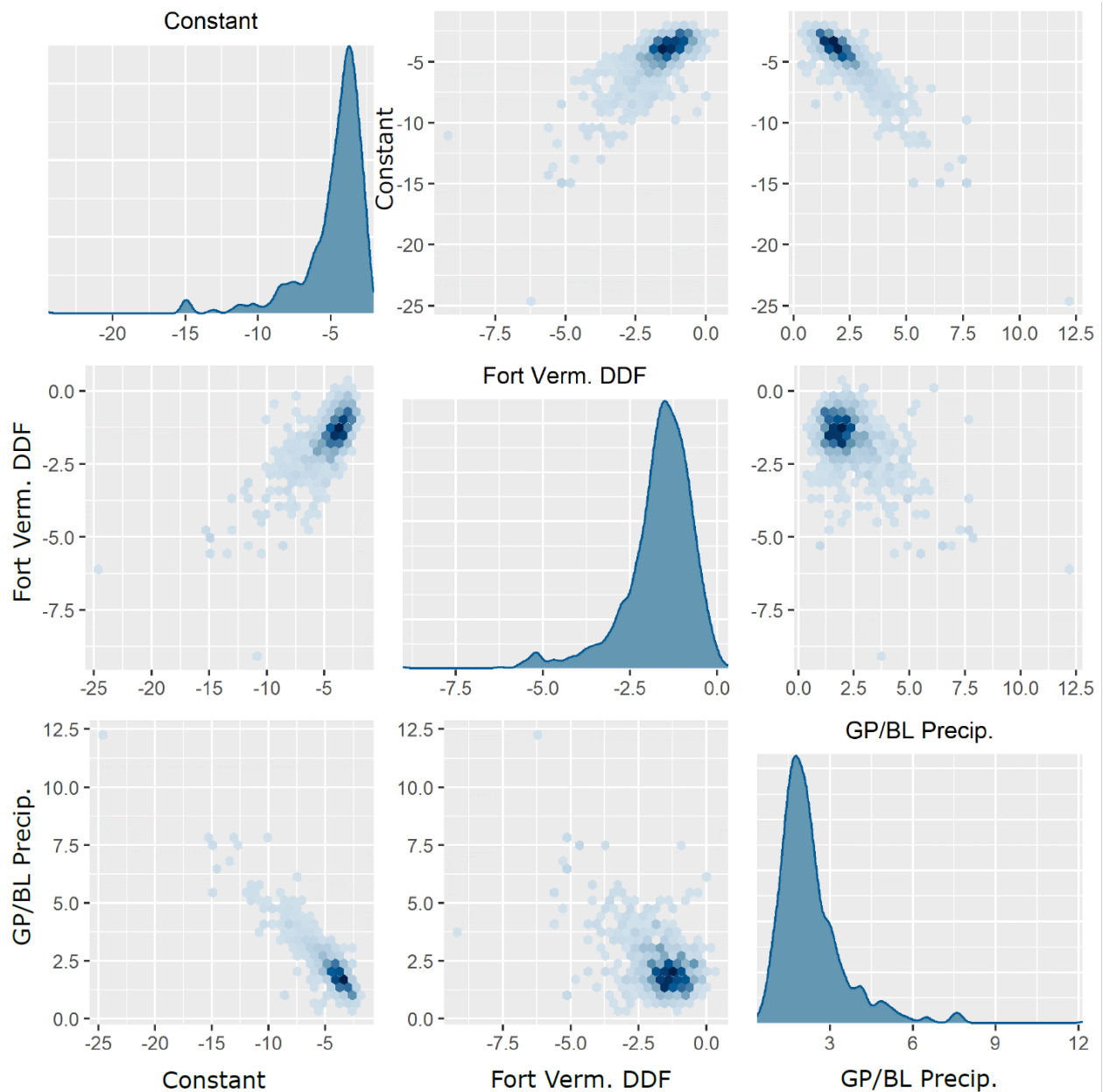


Figure 10. Marginal and joint distributions of logistical regression coefficients (parameter values) based on the bootstrapping exercise. The joint distributions have a density shading, wherein darker colors indicate there is a higher concentration of data points than lighter colors. The single dimensional plots (upper-left to lower-right diagonal) are frequency plots and the y-axes do not have meaningful units but the area under the graphs is approximately equal to one.

We used the bootstrapped parameter values to estimate the probability of a large Peace River IJF in every year of the historical record. This resulted in a distribution of probability for each year. We then used a 10-year moving window to capture decadal trends, as shown in Figure 11. The confidence intervals from our model predictions have similar trends as the observed data, and contain the observed data well, which gives support to climatic factors being the primary drivers of large IJF occurrence in the PAD. Given this finding, the following section focuses on how DDF and precipitation may change in future climates, and presents implications for IJF frequency.

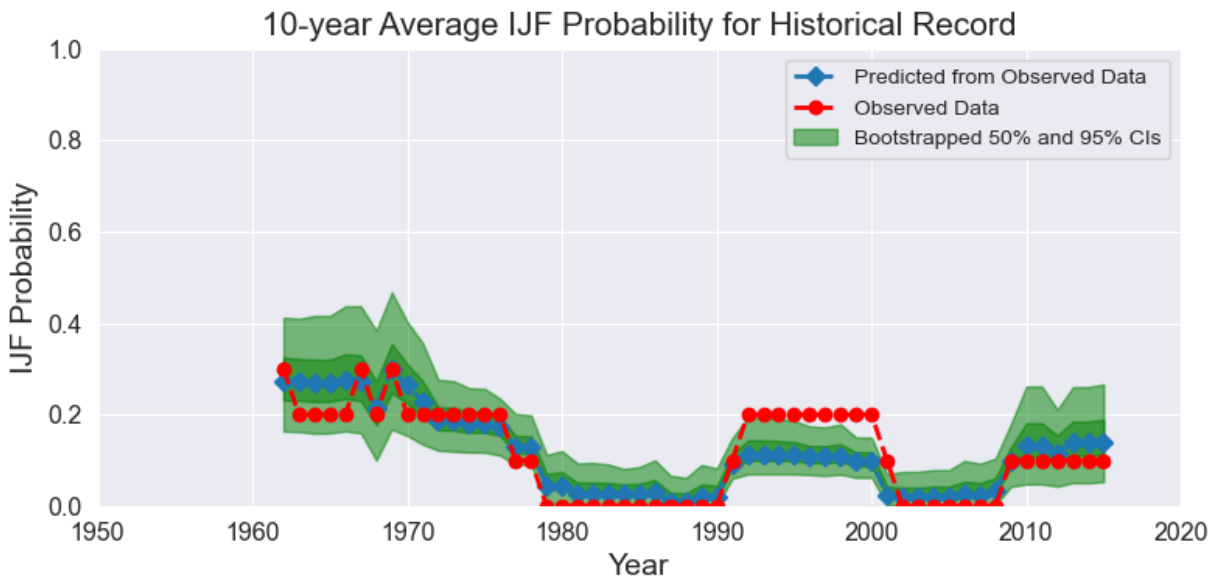


Figure 11. Observed and predicted large ice jam flood probabilities over the historical record, averaged over a 10-year centered window. The blue line corresponds to the most likely parameter values, while the green corridors correspond to the bootstrapped distribution. Adapted from Lamontagne et al. (in revision).

5. GCM data

To look at a wide range of climate scenarios, GCM output from two emissions scenarios (RCP 45 and RCP 85), van Vuuren et al. (2011)) and six climate models (HadGEM2, ACCESS, CanESM, CCSM4, CNRM-CM5, and MPI-ESM-LR) were considered. The GCM data were downscaled and bias corrected (Cannon, Sobie and Murdock, 2015; Werner and Cannon, 2016) to the meteorological stations comprising the best model presented in Section 4 (Grande Prairie for precipitation and Fort vermilion for DDF).

To distinguish snowfall from rainfall, total cumulative winter precipitation data were computed from downscaled daily GCM output in the same manner as historical data described in Section 3.1.2. DDFs for each year were computed by summation of daily values, in the same manner as historical data.

Figure 12 shows winter precipitation for Grande Prairie from the six GCMs and 2 RCPs along with historically observed precipitation data with ice jam flood years identified. The overlap from 1946 to 2021 between GCM data and historical data appears to have roughly the same mean with extreme precipitation values slightly underrepresented by the GCM models. The best model representing extreme values appears to be CNRM-CM5.

The precipitation as snow generally has about the same mean and range of values going into the future to 2100. However, one must remember that the accompanying temperature increasing trends (Figure 13) indicate that in order for the snowpack to be about the same in the future climate as the past, it must snow more intensely to make up for the shorter winter. This could have further implications on diminishing thermal ice growth by insulating the ice cover and this is not considered in our model.

Overall, Figure 12 shows that all the GCM projections show that there still should continue to be, in some years at least, a sufficient snowpack to drive a dynamic breakup during freshet.

Winter DDF GCM projections into the future representing ice thickness indicate a different story, with all GCM projections indicating values for which large ice jam floods have occurred historically to no longer occur, even for future cold extreme winters. Historical DDFs at Fort Vermilion ranged from -1500 to -3500 with ice jam floods occurring in the -2300 to -3500 range. By the mid 21st Century, all GCM projections indicate that all the winters will be warmer than the warmest winters that were coincident with large ice jam floods in the past.

The readers are encouraged to read Lamontagne et al. (in revision) where the logistic regression model presented in Section 4 is applied to the GCM data presented here, and the probability of future IJFs and the waiting time between floods are estimated.

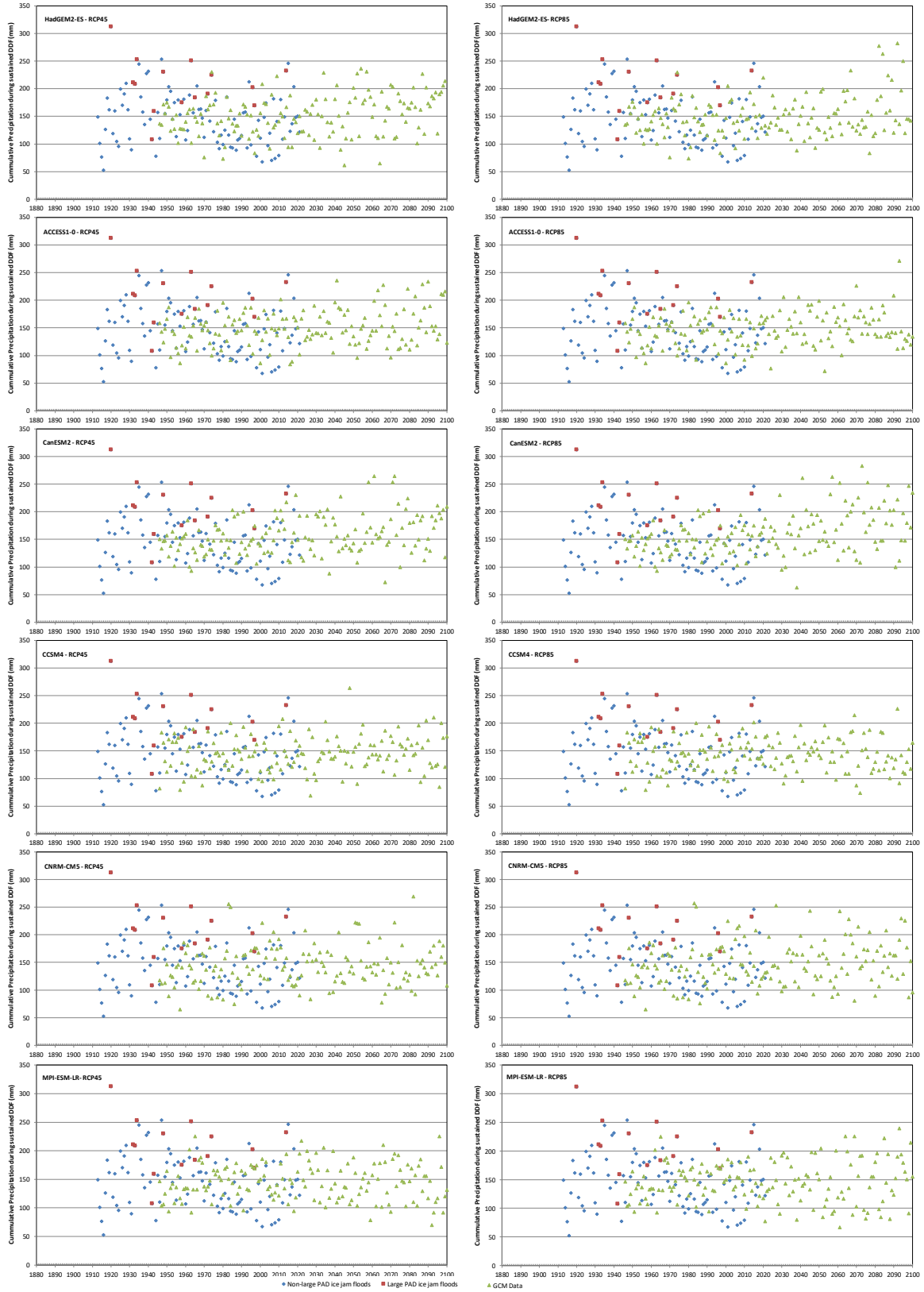


Figure 12. Observed winter precipitation at Grande Prairie with large flood years indicated compared to the 12 GCM scenarios to 2100.

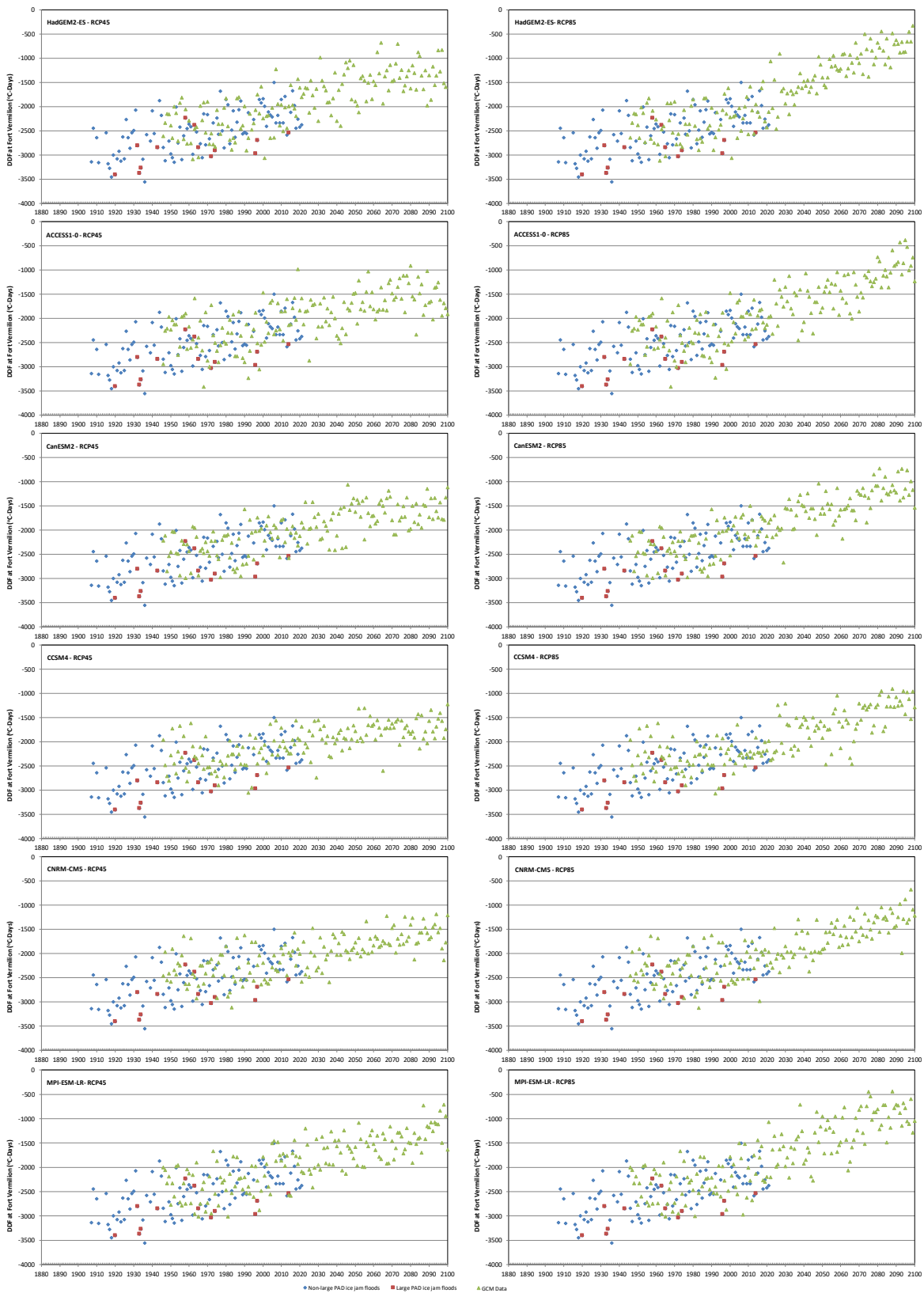


Figure 13. Observed DDF at Fort Vermilion with large flood years indicated compared to the 12 GCM scenarios to 2100.

6. Discussion

We evaluated the effect of regulation on large IJFs by including regulated river flows and freeze-up elevation as potential predictors in the logistic regression. An advantage of the logistic regression approach to evaluate the effect of river regulation is that it first removes the effects of the most explanatory climatic variables, which are accumulated winter precipitation and DDF in this study. We found that freeze-up elevation and streamflows in early winter (Nov. and Dec.) are generally not significant predictors of large IJFs even before removing these climatic effects. After removing climatic effects, they remain insignificant at the 5% confidence level. Thus, while we can say that the mean of the average monthly flows in November and December has changed as a result of regulation, we find that river flows in Nov. and Dec. are not significant predictors of large IJFs. With the available data, climatic factors describing winter conditions are the primary predictors of whether or not a large IJF will occur the following spring.

However, we see from our regression model results that climatic factors are not perfect predictors of large IJFs. The following subsections discuss limitations of our modeling approach, present some physical justifications on findings, and propose a possible missing explanatory factor.

6.1 Stochastic nature of ice jam floods: relevance to regression model predictability

This section discusses by way of example why in some years all of the conditions for a large ice jam flood appear to be good and yet a large flood does not occur. To say it in another way, we present a reason for why ice jam floods are not entirely a deterministic process but rather have a significant stochastic component.

Dynamic break-up especially has a large stochastic component since rapidly changing downstream forces from unsteady flow conditions are interacting with rapidly varying spatially and temporarily unique break-up resistances. This is perhaps best demonstrated by way of two hypothetical examples, one where a large PAD flood occurs (like in 2014) and one where the break-up flushes through the PAD, such as occurred in 2018 and 2020. In both examples, suppose a dynamic break-up is travelling towards the PAD with sufficient river discharge behind it to produce a large ice jam flood if an ice jam in the PAD were to form. To simplify the example, let's use river discharge as a surrogate for downstream forces. One can think the downstream resistance in terms of break-up initiating discharge (BID) that is a function of space due to changing river geometry, initially ice resistance parameters (strength and thickness) and time due to the deterioration of the ice cover from air temperature, water temperature and solar radiation. Also important is the fact that there is a short duration peak discharge at the front of the break-up front associated with the channel storage release. So, in the first example let's say that this peak discharge is $5000 \text{ m}^3/\text{s}$ and there is a particularly narrow point in the river upstream of the PAD that has a BID of $4900 \text{ m}^3/\text{s}$ and the PAD reach has a BID of $5500 \text{ m}^3/\text{s}$ that is decreasing by $200 \text{ m}^3/\text{s}$ per day due to the action of solar radiation and ice melt and it takes about a day for the dynamic break-up to travel to the PAD. So in this case where the peak flow would be $5000 \text{ m}^3/\text{s}$ and the BID a day later would be $5300 \text{ m}^3/\text{s}$ the dynamic break-up would be arrested in the PAD reach and cause flooding of the PAD. Now, let's look at the second example that is only slightly different. Let's presume that the BID of the narrow constriction upstream of the PAD is $5100 \text{ m}^3/\text{s}$ so it would arrest the dynamic break-up because the peak flow was $5000 \text{ m}^3/\text{s}$. Following the arrest, the peak flow associated with the dynamics of the channel storage release would decrease to say $4000 \text{ m}^3/\text{s}$. Suppose there is more

water coming from snowmelt raising the discharge by 100 m³/s per day while at the same time the BID is decreasing at the constriction and the PAD by 200 m³/s per day, it follows then that the ice jam would release in about 3 to 4 days at a discharge of about 4400 m³/s. Once it releases it would gain channel storage flow increasing the flow back up to its previous value of 5000 m³/s. With an additional travel time of a day the BID at the PAD would have decreased from 5500 to 4700 m³/s. With the dynamic break-up peak of 5000 m³/s and the PAD BID of 4700 m³/s the dynamic break-up would pass through the PAD reach producing only moderately high-water levels for a much briefer period than if an ice jam would have formed. This explains, why the historical data in some years where the pre-conditions are so similar there can be a large PAD ice flood in one of those years and not the other with only a minuscule difference in peak dynamic break-up flow of 100 m³/s or 2% of 5000 m³/s.

As demonstrated in the above example, this may be one reason why large floods occur only about 40% of the time when the main explanatory variables (winter precipitation and temperature) are met.

6.2 Likely reasons why freeze-up elevation is not significant and DDF is significant in the case of the Peace River.

Freeze-up elevation is a proxy for bank resistance to the ice sheet linked to the geometry of the ice sheet getting around bends and through narrow openings while DDF is one of many (but apparently significant in this study) proxies for the ice resistance to fracture at the time of break-up. In the latter case, the ice sheet does not have to be narrow enough to get around bends for a dynamic break-up to continue downstream but just weak enough to crack into pieces that are small enough to get around bends and narrows. Cracks can form quickly from point loads from islands and river bank planform irregularities as driving forces (water flow and gravity) push the ice sheet downstream. The Peace River is a wider river than most, so it is likely that ice resistance, rather than bank resistance plays a more dominant role since the wider the ice sheet compared to its thickness, the more likely weak spots will allow crack propagation from point loads.

Another important consideration is the ice bending strength. This is what causes the arrests of dynamic break-ups that lead to ice jam formation and flooding. Strong bending strength is needed to allow resistance to further breakage from the buoyancy of the accumulation of ice rubble under the ice cover at the break-up front (Andres et al., 2005). If the ice cover is strong enough in bending large quantities of ice rubble underneath can reach the river bed providing anchor points from the river bed causing the arrest of the dynamic break-up leading to ice jam formation and flooding. Freeze-up elevation does not play as direct a role to thickness and strength of the ice sheet as does DDF in this mechanism.

6.3 Possible role of Lake Athabasca water levels and outlet water temperatures on the ice thickness in the PAD reach and resulting effects on IJF probability

New insights obtained from the 2018 and 2020 breakup observations as well as winter ice cover conditions on the Des Rochers channel leading from Lake Athabasca to the Peace-Slave Confluence indicates that a totally unrelated factor not considered in this and previous studies may be playing a role in reducing ice jam flooding in the PAD. It appeared that in these two years, the

ice melted/thinned in the Slave River prior to the main dynamic break-up on the Peace River. This occurred because warm water was flowing from the Lake Athabasca down the Des Rochers channel into the Slave River. In 2020, the ice escaped not down the Slave River but south down into the ice free Des Rochers and flowed back into Lake Athabasca, unable to form an ice jam. Could this have been a factor in other historical years? It is doubtful that the variables we examined thus far in this study would be proxies for Lake Athabasca water temperature and outflow magnitude as limnology, inflows from the Athabasca River and summer air temperatures (in addition to winter air temperatures that we examined) could dominate that process. It is possible that some historical potential ice jam flood years with high snowpack and cold winters were thwarted by warm water coming out of Lake Athabasca. It is also more likely that a warming climate could produce these conditions more often.

7. Conclusions

We used exploratory data analysis and statistical regression to determine which climatic and river regulation factors best explain the occurrence of large Peace River ice jam flooding of the PAD over the last six decades. We found that accumulated winter precipitation and temperature provided the best model with our available dataset. Although there is large uncertainty in the exact effect that each of these climate variables has on ice jam flood frequency, the resulting model predictions match trends in the observed data well. After accounting for the effects of these climate variables, statistically insignificant effects were found for river freeze-up elevation and the streamflows in the winter months coinciding with freeze-up. Therefore, we conclude that climatic factors are the primary drivers of large Peace River ice jam flooding of the PAD, and factors related to river regulation do not have a significant role. Based on these findings, we explore winter precipitation and temperature in future climate projections. It is likely that by mid-century the winter temperatures (degree-days freezing) will be warmer than the warmest historical years that experienced large ice jam floods.

8. Acknowledgments

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