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El Niño Diversity and North American lake ice-out dates

Freezing Degree-day Thresholds and Lake Ice-out Dates: Understanding the Role of El Niño Conditions

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Submitted 16 April 2018

Supported by National Science Foundation Awards 0904155 and 1055934, and NOAA award NA14OAR4320158.

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ABSTRACT

In temperate lakes, the wintertime Accumulated Freezing Degree-Days (AFDD) modulate the thickness and phenology of winter ice-cover, which in turn influence lake ecosystem processes and functions across seasons. Empirical studies show that the El Niño-Southern Oscillation (ENSO)-winter AFDD relationship for North American regions depends on the location and amplitude of the winter ENSO-related sea surface temperature (SST) warming/cooling in the tropical Pacific (TP), and consequently changes in the magnitude and frequency of different ENSO patterns engender shifts and transitions in the North American lake ice regimes. For eight lakes located across North America, we found quasi-linear and nonlinear relationships between winter AFDDs and spring lake ice-out dates, and in some cases, existence of thresholds above and below which regression slopes are materially different, thus illuminating differential sensitivities. Conditional quantile functions for winter AFDDs that incorporate ENSO indices as covariates were developed to estimate the relative risk of early/late lake ice-out events for these lakes. For seven of the eight lakes, the canonical Eastern Tropical El Niño pattern increases likelihood of low winter AFDDs (associated with early ice-out dates in these lakes) by 1.5-2.8 times to that of the climatology (1951-2010 average), while the typical Central Pacific El Niño pattern corresponds to a decrease or no significant change in the occurrence probability of early ice-out dates in these Lakes. These results demonstrate that the conditional winter AFDD estimated based on a comprehensive characterization of ENSO allow for delineation of distinct local-to-regional patterns of elevated risk of early ice out and short lake ice-cover season for North American regions.

Keywords: El Niño flavours, North American lakes, Lake ice-out dates, Quantile Regression, Conditional Risk

1. Introduction

In temperate and polar regions of North America, where lakes freeze during winter, wintertime accumulated freezing degree-day (AFDD)—calculated as the sum of mean daily temperature departures below the freezing point (0°C or 32°F)—is an important cold season weather-climate variable. AFDD determines the amount of freezing energy available in the air to grow surgical ice on lakes, and consequently analytical studies often estimate the thickness of lake ice cover to be roughly proportional to the square root of the winter AFDD (Lepparanta, 2014). However, the impacts of wintertime AFDD variations on lakes may not be limited to the cold season. For example, springtime ice-out dates for Maine (USA) lakes are linked to wintertime AFDD thresholds (Beyene and Jain, 2015).

The prevailing winter climate, including the AFDD patterns over North America, has been shown to be sensitive to phases of El Niño-Southern Oscillation (ENSO), a coupled oceanic-atmospheric phenomenon in the tropical Pacific that affects weather and climate worldwide (e.g., Bonsal et al. 2001; Assel et al. 2004; Bai et al. 2012). For instance, during the 1997/98 El Niño event (warm phase of ENSO), northern US and southern

Canada recorded one of their lowest winter AFDDs such that it resulted in the least extensive ice-cover in the Great Lakes over the past century. However, the severity and spatial extent of the North American weather and climate anomaly patterns associated with El Niño events is neither alike nor is it linearly opposite to that of La Niña (cold phase of ENSO) events (e.g., Wyrtki, 1975; Hoerling and Kumar, 1997; Hoerling et al. 1997). Studies have shown that such discrepancies may arise from differences in the location and amplitude of their signature SST anomalies in the tropical Pacific as variations in the location of the warmest waters (SST>27.5C) in the tropical Pacific generate differential atmospheric wave trains responsible for climate variability worldwide (e.g., Barsugli and Sardeshmukh, 2002; Hoerling and Kumar, 1997). Furthermore, Beyene and Jain (2017) showed that the sensitivity of North American winter temperatures to diverse ENSO flavours is not uniform, both regionally and across different parts of the empirical probability density function (EPDF). In the present context, a salient question is: to what extent do distinct El Niño flavours affect North American lake ice-out dates through their differential effect on the (EPDF of) winter AFDD? Two aspects of current and future ENSO variability further motivate the above noted line of inquiry: (a) five-fold increase in the frequency of a "new variant" of ENSO is being projected under anthropogenic climate change (e.g. Yeh et al. 2009; Cai et al. 2014), (b) ENSO-based climate forecasts on seasonal and longer lead-times have proven to be reliable (Hoskins, 2013). To this end, this study aims to develop location specific risk functions for North American winter AFDD, that incorporate as covariates ENSO indices that capture the location and amplitude of tropical Pacific SST anomalies, in order to estimate ENSO-related changes in the relative occurrence probability of early/late lake ice out events in North America. In this study, the term occurrence probability is used interchangeably with risk and likelihood.

Past lake ice studies often assessed ENSO-induced changes in lake ice season by characterizing the response of local meteorological variables (relevant to lake ice evolution) to large-scale climate patterns using traditional statistical methods such as linear regression and averaging of sub-samples. However, analyses employing these methods offer limited insight, as they primarily measure the shift in the conditional mean and not the conditional tails of the distribution, where climate-related thresholds in lakes usually reside. This study thus employs quantile functions, first proposed by Koenker and Bassett (1978), to investigate the response of North American winter AFDD, across its variability range, to the amplitude and location of tropical Pacific SST warming/cooling, linked to ENSO events. This approach provides a functional framework to estimate the winter AFDD conditioned on ENSO indices with three important features: (a) no distributional assumption, (b) quantification of differential sensitivity across quantiles, and (c) resistance to outlier effects.

Beyene and Jain (2017) have shown that the change in the conditional risk of North American winter temperatures due to ENSO flavors varies both regionally and across different temperature quantiles. This study extends their work and aims to quantify ENSO related changes in North American lake ice out dates by characterizing its effect on winter AFDD variability. Two key tasks in this regard are as follows:

(1) Quantify the nature of relationships between lake ice and winter AFDD variability, based on observational records for a select group of lakes across North America.

(2) Estimate ENSO-related changes in the relative likelihood of early/late lake ice out events for eight North American lakes—location-specific risk functions for North American winter AFDD that incorporate ENSO indices as covariates are developed.

2. Data and Methods

Lake Ice-out (off) Dates: Lake ice-out date refers to the date when winter ice completely disappears from the lake surface. In this study, eight North American lakes (see Figure 1 for lake locations) that freeze during the winter were selected and their historical lake ice-out dates from 1950-2010 were downloaded from the following electronic databases: Global Lake and River Ice Phenology Database (at National Snow and Ice Data Center) and Lake Ice Clearance and Formation dataset (at Niwot Ridge Long Term Ecological Research Center). In Supplementary Table 1, geomorphological data and site of observation for ice out dates is provided for the eight selected lakes.

North American Winter AFDD: Time series of gridded, daily mean temperature data for North America from 1951-2010 were derived from HadGHCND dataset (Caesar et al.

2006), which provides station-based, daily observations of average temperature data on a 2.5°x3.75° grid resolution. The year-to-year winter AFDD for North American fields were then calculated as the daily degrees below freezing (0°C) summed over the total number of days from December to February that the daily average temperature was below freezing:

$$AFDD = \sum_{i=1}^{i=n} (T_0 - T_i)\Delta t, \quad T_0 > T_i, \tag{1}$$

where Δt is the time interval (Δt = 1 day), n is the number of days from December to February months (n = 90 or 91), T_i is the daily mean temperature (°C) and T_0 is the freezing temperature for water ($T_0 = 0$ *℃ or 32 ℉*). Lake ice occurs predominantly in regions with regular occurrence of sub-freezing temperatures and wintertime AFDD. Climatological winter AFDD patterns over North America (Figure 1a, b) indicate that regions with pole ward of 35°N show appreciable below-freezing temperatures; this region will be the focus of investigation in the remainder of this study.

Relationship between AFDD and lake ice thickness: Lake ice formation and growth results from the dynamical heat balance at lake surface. (Lepparanta 2014). Given that the surface air temperature strongly relates to major energy fluxes from lake to atmosphere, analytical studies often use the degree-day method— first derived by Stefan (1891) — to approximate the thickness of winter ice formed on lake surface. In general, in a degree-day model, ice growth (h) in inches, is modelled as a function of the square root of the accumulated freezing degree-days (*AFDD*)

$$h = C\sqrt{AFDD} \tag{2}$$

where C is a coefficient that accounts for local snow and atmospheric conditions and AFDD is in Degree-Day Fahrenheit (DDF) (e.g., Assur 1956). In Supplementary Analysis 2 section, we provide a detailed exposition of this physical basis of the relationship noted above.

ENSO Indices: The emergence, type and strength of El Niño /La Niña events are often based on areal averaged SST indices for four regions in the tropical Pacific: Niño 1+2, Niño 3, Niño 3.4 and Niño 4 (see supplementary Figure S1a). In this study, time series of monthly, spatially averaged SSTs for the four Niño regions from 1951-2010 were collected from a dataset prepared by NOAA's Climate Prediction Center, based on extended, reconstructed sea surface temperature (ERSST) V4 dataset. Time series of winter Niño SST indices from 1951-2010 were then computed by averaging the December to February SST index for each Niño region (see Supplementary Figure S1b).

Geographical distributions of ENSO-related tropical Pacific SST anomalies (warming or cooling relative to long-term averages) have been identified as important contributors to the spatial patterns and severity of climatic impacts in remote regions. Thus, it is critical to identify a small set of ENSO indices that best represent the detailed pattern of SST warming or cooling in the tropical Pacific. In this study, Principal Component

Analysis was performed on the time series of mean winter SST indices of the four Niño regions from 1951-2010 (see Supplementary Analysis 1). The resulting pair of indices (Principal Component 1 and 2, hereafter referred as PC1 and PC2) account for 99.8% of the total variance in the ENSO historical record (PC1 = 89% and PC2 =10.8%). While PC1 and PC2 time series comprehensively characterize the temporal variations in ENSO over the past six decades, the spatial loadings linked to these PCs offer helpful interpretation of the tropical Pacific warming and cooling patterns associated with ENSO events (see Supplementary Figure S2). PC1 loadings across the four Niño regions are of the same sign suggesting synchronous wintertime SST variation across all Niño regions (see Supplementary Table 2b and Supplementary Figure S2b). PC2 loadings are characterized by an east-west dipole pattern with the wintertime SSTs in Niño-1+2 (eastern Pacific) region varying out of phase with that of Niño-3.4 and Niño-4 (Central Pacific) regions (Supplementary Figure S2c). Beyene and Jain (2017) and others have showed that the joint indices of PC1 and PC2 allow characterization of the amplitude and location of maximum TP SST anomalies associated with diverse El Niño/La Niña events (see Supplementary Analysis 1). Therefore, PC1 and PC2 indices are used as covariates/predictors in the quantile regression pursued in this study. Finally, as noted in the previous section, recent improvements in the understanding on ENSO flavors imply distinct patterns of climatic impacts across North America, and projected trends for the 21st century reveal dramatic shifts in ENSO frequency—the associated risk to environmental variables such as lake ice remains unclear.

Quantile Regression: Historical winter AFDD variability at a particular location can be summarized based on a frequency distribution or probability density function (PDF). Characteristic AFDD values that correspond to specific quantiles (representing non-exceedance probability) can be obtained from the PDF. For instance, the AFDD value for the 0.25^{th} quantile is exceeded 75% of the time. An extension of this approach allows modelling of quantiles based on covariates or predictors (for example, ENSO conditions) that modulate the conditional quantile functions for the target variable (in our case, AFDD). In its general form, quantile regression (Koenker and Hallock 2001) affords conditional quantile estimates for each quantile, and as such, conditional PDF. These estimates are superior to ones from linear regression, wherein covariate effects are restricted to affect on the mean of the target variables. Example applications of quantile regression in lake studies include Bissinger et al. (2008), Fielding (2013), and Xu et al. (2015).

In this study, the quantile regression approach is used to model and predict the linear response of North American winter AFDDs, across all or selected quantiles, to ENSO indices (X_i). Mathematically, this can be expressed as

$$AFDD^{(\tau)} = \beta_0^{(\tau)} + \beta_1^{(\tau)} PC1 + \beta_2^{(\tau)} PC2 \qquad (3)$$

where $\beta_0^{(\tau)}$ is the intercept, and $\beta_1^{(\tau)}$ and $\beta_2^{(\tau)}$ are the slope coefficients for PC1 and PC2 patterns at τ^{th} quantile. The regression parameters $\beta^{(\tau)}$ are obtained by solving for minimization of the sum of weighted absolute residuals. The quantile regression implementation in the R computing environment (Koenker, 2017) is employed to provide the optimizing algorithm to estimate $\beta^{(\tau)}$ using linear programming techniques. Estimation of conditional winter AFDD quantiles requires fitting of curves across each quantile independently and as such generating multiple conditional winter AFDD quantile functions may yield quantile curves that cross or overlap, creating an invalid distribution. To alleviate the crossing problem in quantile regression, a procedure introduced by Bondell et al. (2010), which imposes a non-crossing constraint, is applied. The statistical significance for parameter estimates, $\beta^{(\tau)}$ in the conditional winter AFDD functions were assessed by constructing the confidence interval using the wild bootstrap method, an approach that is almost unaffected by residual heterogeneity (Feng et al. 2011).

3. Results

3.1 Winter AFDD and North American Spring Lake Ice-out Dates

Empirical and theoretical rationales are needed to establish the import of seasonal winter (December-February) AFDD on North American lake ice season. To this end, Supplementary Analysis 2 presents a synopsis of the theoretical-physical basis underlying AFDD-lake ice linkages. This section on the other hand, offers empirical findings by analyzing the observed response of spring lake ice-out dates to their antecedent winter AFDDs for eight North American lakes (see Figure 1a). Here, the efficacy of winter AFDD in conditioning the spring lake ice out dates was examined using non-parametric kernel regression approach, as the functional relationship between winter AFDD and spring ice-out dates is unknown and may vary across lakes. Kernel regression method (Silverman 1986) is based on a smoothing approach that is locally adaptive, thus allowing for the estimation of linear and nonlinear relationship from data. The degree of smoothing depends on the bandwidth, which is selected based on a minimization of integrated error (Bowman and Azzalini, 1999). In the context of ice-out and winter AFDD relationship, of particular interest is the diagnosis of nonlinearity and potential break points in the relationship (akin to thresholds).

Results of this analysis show that for all selected lakes, there is a positive (direct) relationship between winter AFDD and spring ice-out dates, which implies that winters with relatively low (high) winter AFDDs are generally related to earlier (later) than normal lake ice-out dates the following spring (see Figure 1c-j). However the degree of sensitivity of spring ice-out dates to winter AFDDs in these lakes varies both spatially and across different winter AFDD quantiles. For instance, contrasting the overall slope of the winter AFDD regression line across the eight lakes indicate that the response of spring ice-out dates to the antecedent winter AFDD variability is relatively stronger at Lake Superior (USA) and Damariscotta Lake (USA) as compared to those at Lake Albion (USA) and Long Lake (Canada). This implies that the strength of association between spring ice-out dates and the antecedent winter AFDDs for North American lakes shows geographical variation and locally, is also likely to be modulated by other factors such as morphometry, elevation, and continentality. On the other hand, examining the response of spring ice-out dates of the eight lakes across different winter AFDD quantities reveals that unusually low /high winter AFDDs are strongly related to early/late spring ice-out dates. For instance, for Damariscotta Lake, 5 of the 6 winters with AFDD less than 200 Degree Day Celsius (DDC) (τ d 0.30^{th}) are associated with ice-out dates earlier than April 3^{rd} (see figure 1H). Similarly for Lesser Slave Lake (Canada), 5 of the 6 winters with AFDD less than 2270 DDC (τ d 0.28^{th}) are linked to ice out dates that occurred prior to May 15^{th} (see figure 1D).

These findings on the presence of winter AFDD quantities that correspond to early/late spring ice-out dates for North American lakes is consistent with the findings reported in Beyene and Jain (2015). This implies that the efficacy of ENSO events in modulating the variability of ice-out dates in lakes depends on their effect on the occurrence of winter AFDDs associated with ice-out dates. Thus, characterization of ENSO-related change in risk of early/late ice dates requires an understanding of the relationship between different El Nino (or La Nina) events and winter AFDD at specific quantiles, as well across the entire winter AFDD distribution. It should be noted that for studied lakes, the degree of coherence between winter AFDD and spring ice-out dates can generally be assumed to be independent of spring temperature conditions, as there is no significant ($p < 0.1$) correlation between winter and spring AFDD for almost all North American regions (see Supplementary Figure S4).

3.2 ENSO Diversity and North American Winter AFDD Variability

Differences in the location of peak ENSO-related Sea Surface Temperature (SST) warming/cooling in the Tropical Pacific (TP) contribute to the observed variability in ENSO-related climate patterns in North America (e.g., Hoerling and Kumar, 1997). To illustrate this difference in the context of North American winter AFDD, five years were selected where by majority agreement of different ENSO identification methods (EP/CP method, Niño3/4 method, EMI method and regression-EOF method) have been determined as Central Pacific (CP) El Niño (1969, 1988, 1995, 2003, 2005, 2010), Eastern Pacific (EP) El Niño (1973, 1983, 1987, 1998, 2007) and La Niña events (1956, 1971,1974, 1976, 1989) (see Supplementary table 1). It should be noted that our use of EP and CP El Niño terminology in this study serves only to contrast the site of peak SST warming in TP between the two El Niño patterns, and is by no means implying that these patterns are distinct modes of El Niño. The composite TP winter SST anomaly (departure from the long-term average) pattern for the five CP El Niño events selected features peak SST warming confined in the central TP regions (Niño3.4 and Niño4 regions) flanked by cooler than normal SSTs on both sides of the equatorial Pacific (see Figure 2a bottom). While there is some inter-event differences, the pattern of North American winter AFDD variability pattern corresponding to CP El Niño events can broadly be characterized as southeast-northwest dipole pattern, where there is relatively strong increase in the seasonal winter AFDD (colder temperatures) over the Midwest and northeast US regions and decrease in winter AFDD (warmer temperatures) over western US and Canadian regions and northern edges of Canada (see Figure 2a top). In contrast, the location of maximum SST warming in the TP during EP El Niño winters is concentrated in eastern TP extending from the western coast of South America to the regions east of the dateline (Niño1+2 & Niño 3 regions) (see Figure 2b). Moreover, these events are associated with a significant decrease of winter AFDD over much of North America (except for the Pacific US regions and Baffin Island). These results illustrate that the location of maximum SST warming in the tropical Pacific has important implication on the impact of individual El Niño events on the winter AFDD over US and Canada. On the other hand, the composite TP winter SST anomaly pattern for the five La Niña events exhibits peak SST cooling over central-eastern equatorial Pacific (Niño3 and Niño4 regions). Moreover, the North American winter AFDD anomaly patterns related to these events generally features a northwest-southeast dipole pattern with a relatively strong increase in winter AFDD over western Canada and Alaska and decrease in winter AFDD over the Southeast US states. These results reveal the effect of La Niña events on the winter AFDD of various North American regions is not a mirror opposite to that of El Niño events. They also establish the significance of tropical Pacific in producing non-linearity in the response of North American winter AFDD to opposite phases of ENSO.

In summary, the above findings show that the ENSO-winter AFDD relationship for North America varies with the location of peak ENSO-related SST warming and/or cooling in the TP. In other words, the efficacy of El Nino (or La Nina) events in modulating the conditional winter AFDD distribution for North American regions shows spatial variation. Consequently, in the face of EP or CP El Niño/La Niña episodes, the likelihood associated with various AFDD magnitudes, including the ones that correspond to early/late spring ice-out dates in North American lakes, is marked by differential sensitivities. Quantile regression framework offers conditional risk estimates of AFDD at a location as well as regional scale.

3.3 ENSO Patterns and Lake Ice Season Risk Assessments

It was noted in earlier sections that there are winter AFDD quantities that correspond to early/late spring ice-out dates for North American lakes. The efficacy of quantile functions in generating AFDD quantiles conditioned on ENSO indices can thus offer usable risk estimates for unusually early/late ice-out events in these lakes. For instance, figure 3a shows that for Lake Superior, winters with AFDDs less than 820 Degree-day Celsius (DDC) ($\tau < 0.31^{th}$) are strongly associated with spring lake ice-out dates prior to March

30th, and according to the climatology, the occurrence probability of such "mild winters" is 0.30. Please note that the method used here for determining the winter AFDD threshold is highly subjective and as such serves only for illustrative purposes only. To estimate the change in the conditional risk of early lake ice-out dates at Lake Superior due to ENSO patterns, a set of quantile functions for winter AFDD (that incorporate ENSO indices as covariates) were fitted at $\tau = 0.01$ intervals over the quantile range ($0.01 < \tau < 0.99$) and these function were used to compute winter AFDDs at the respective quantiles for sample combination of PC1-PC2 indices. Figure 3b shows the resulting conditional winter AFDD distribution as well as conditional risk of winter AFDDs less than 820 DDC for archetypical ENSO flavors (derived as centroids of PC1-PC2 index for the five selected EP, CP El Niño and La Niña events mentioned in the first result section). From these, it can be observed that during archetypical EP El Niño events, the likelihood of mild winters that engender early ice-out dates at Lake Superior increases by 2.16 times relative to that of the climatology (probability = 0.31). During typical CP El Niño pattern however, there is no significant change in the occurrence probability of early ice out dates at Lake Superior relative to that of the climatology. Contrary to the traditional assumption, this result highlights that the effect of different El Niño flavors on North American lake ice-out dates are not alike. Figure 3c extend the results in figure 3b to depict the change in risk (relative to that of the climatology) of early ice-out dates for sample combinations of PC1 and PC2 indices. Broadly speaking, the conditional risk of early ice-out dates at Lake Superior increases from region of negative PC1 and positive PC2 to a region of positive PC1 and negative PC2. This means that strong EP El Niño patterns (PC1 > 2 & PC2 < 0) are related to an increase the relative likelihood of early ice-out dates at Lake Superior by 1.2 - 2.5 times that of the climatology, while strong CP El Niño events (PC1 > 1 & PC2 > 0) correspond to a rise in the relative risk of early ice out dates by 0.9-2.4 times. On the other hand, La Niña events (PC1 < -1.5 & PC2 < 0) reduce the relative occurrence probability of mild winters by 0.6-1.

Diversity in the influence of different ENSO patterns on North American lake ice-out dates can be illustrated by contrasting the change in the likelihood of mild winters that produce early ice-out dates, due to the three archetypical ENSO patterns, for the eight North American lakes. Results reveal that the effect of ENSO pattern on the timing of North American spring lake ice-out dates varies both spatially and for different ENSO events (see Figure 4). For seven of the eight lakes, the archetypical EP El Niño pattern increases the likelihood of mild winters that correspond to early ice-out dates, by 1.5-2.8 times to that of the climatology, while for Deadman's Pond the occurrence probability of such winters decreases by 0.63 times relative to the climatology. In contrast, at Damariscotta Lake and Deadman's Pond, typical CP El Niño pattern decreases the likelihood of mild winters that are associated with early ice out dates, by 0.4-0.8 times to that of the climatology, while for the other six lakes it has modest or no effect on the risk of such winters. On the other hand, for Lake Albion (Deadman's Pond), archetypical La Niña pattern reduces (increases) the occurrence probability of mild winters by 0.46 (1.2) times to that of the climatology, while for the other six lakes, it is associated with modest or no changes in risk of early ice out dates. These results taken together show that for North American lakes, (a) the effect of EP El Niño on the timing of ice-out dates is quite distinct to that of CP El Niño from local-to-regional scale, (b) El Niño related changes in the timing of spring ice-out dates is not a linear opposite to that of La Niña events. As discussed in earlier sections, these effects stem from the asymmetry in the regional AFDD patterns associated with El Niño/La Niña flavors and distinctness of AFDD thresholds for ice-out dates among local lakes. Supplementary figure S6-S10 depicts the wintertime AFDD quantities that correspond to early ice out date in lakes and the results of the conditional risk analysis for sample combinations of PC1 and PC2 for the seven other lakes.

4. Discussion and Summary

ENSO-related warming/cooling in the tropical Pacific sea surface temperatures cause systematic shifts in the North American wintertime Accumulated Freezing Degree-days (AFDD) patterns. Winter AFDD governs the thermal flux between lake and atmosphere to grow lake ice, and early/late spring ice-out dates have been sensitively linked to seasonal winter AFDD thresholds. Consequently, changes in the magnitude and frequency ENSO has the potential to cause shifts and transitions in the ice regime of North American lakes. Our analysis of the response of spring ice-out dates to winter AFDD for select North

American lakes reveals two important features. One is that for North American lakes, the relationship between winter AFDD and spring lake ice-out dates can be characterized from quasi-linear to highly non-linear. Second, in a number of these relationships, there are AFDDs (thresholds) that are strongly associated with specific ice out dates. Thus, the conditional quantile regression approach developed in this study allows a detailed characterization of quantile-specific ENSO-AFDD that can be readily used to estimate risk functions for AFDD and lake ice out conditioned on ENSO. Results for seven out of the eight North American lakes show that typical Eastern Pacific (EP) El Niño pattern is associated with an increase in the risk of low winter AFDDs (that produce early ice-out dates in these lakes) by 1.5-2.8 times to that of the climatology, while the typical Central Pacific (CP) El Niño pattern corresponds to a decrease or no significant change in the likelihood of early ice-out dates in these lakes. On the other hand, for Deadman's Pond (Lake Albion) the archetypical La Niña pattern induces an increase (decrease) the occurrence probability of early ice out dates by 1.2 (0.46) times relative to that of the climatology. To summarize: (a) the effect of CP and EP El Niño on the timing of spring ice-out dates of North American lakes is distinct from local-to-regional scale, (b) for North American lakes, the change in the timing of spring ice-out dates due to El Niño and La Niña patterns is not linearly opposite. In conclusion, we offer the following observations and discuss emerging research directions:

1. This work broadens current understanding of ENSO-related AFDD teleconnections for North America. In doing so, the relative contributions of ENSO flavors (delineated as the two leading pattern of tropical Pacific SSTs) in modulating AFDD distribution as a whole, and select AFDD thresholds (associated with lake ice-out dates) for North American regions was quantified.. Detection and evolution of ENSO events in the tropical Pacific is a well understood subject and as such, magnitudes of ENSO events are estimable up to 9 months in advance (e.g. Ramesh and Murtugudde, 2012; Hoskins, 2013). These imply that the ENSO-related conditional risk functions developed here pave the way for use of seasonal and longer-lead ENSO forecasts that can be profitably used to anticipate shifts in lake ice out dates.
2. The quantile regression risk framework advanced in this study, while specific to lake ice out, is applicable to other lake variables to assess climate-related risk and vulnerability. While a linear approach was taken here, nonlinear and non-parametric approach can be used to model complex relationships (for example, ones involving lake chemistry).

3. Changing weather/climate patterns reflect trends and inter-annual variability (for example, due to ENSO). Resulting seasonal temperatures can disrupt the lake phenology and linked processes, species dynamics and succession, and nutrient loading and mixing characteristics. For instance, for temperate and arctic North

American lakes, winter climate variability has directly or indirectly been shown to affect ice cover phenology and extent (e.g. Bai et al. 2012; Beyene and Jain 2015), water temperatures (e.g. Austin and Colman 2007), onset of stratification period (e.g. Winder and Schindler 2004), seasonal plankton composition, abundance and succession (e.g. Goldman et al. 1989; Hampton et al. 2017), fish population (e.g. Farmer et al. 2015) and seasonal geo-chemical dynamics (e.g. Joung et al. 2017; Powers et al. 2017). In a changing climate, successful conservation and restoration of lake ecosystems can benefit from climate-based risk framework presented here, thus affording pinpointed estimates of trends and transitions in lake variables. Finally, improved understanding and prediction of lake and river ice conditions has important environmental and socio-economic (e.g. recreational, hydro-power generation, cultural, commercial) implications, a point underscored in recent studies (e.g., Prowse et al. 2011; Durnford et al., 2017).

REFERENCES

Assel, R., S. Drobot, and T. E. Croley. 2004. Improving 30-Day Great Lakes Ice Cover Outlooks. *Journal of Hydrometeorology*, 5(4): 713-717.

Assur, A. 1956. Airfields on floating ice sheets for regular and emergency operations. Snow Ice and Permafrost Research Establishment, Report no. 36, U. S Army Corps of Engineers, Wilmette, Illinois, USA.

Austin, J.A., and S. M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophysical Research Letters* 34, L06604

Bai, Xuezhi, Jia Wang, Cynthia Sellinger, Anne Clites, and Raymond Assel. 2012. Inter-annual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research*: Oceans 117(C3).

Barsugli, J. J., & P. D. Sardeshmukh. 2002. Global atmospheric sensitivity to tropical SST anomalies throughout the Indo-Pacific basin. *Journal of Climate*, 15(23), 3427-3442.

Beyene, M. T., and S. Jain. 2015. Wintertime weather- climate variability and its links to early spring ice- out in Maine lakes. *Limnology and Oceanography*, 60(6): 1890-1905.

Beyene, M.T. and S. Jain. 2017. North American wintertime temperature anomalies: the role of El Niño diversity and differential teleconnections. *Climate Dynamics*: 1-13. https://doi.org/10.1007/s00382-017-3880-x

Bissinger, Jan E., David JS Montagnes, and David Atkinson. 2008. Predicting marine phytoplankton maximum growth rates from temperature: Improving on the Eppley curve using quantile regression. *Limnology and Oceanography* 53(2): 487-493.

Bondell, H. D., B. Reich, & H. Wang. 2010. Non-crossing quantile regression curve estimation. *Biometrika*, 97(4), 825-838.

Bonsal, B. R., X. Zhang, L. A. Vincent, and W. D. Hogg. 2001. Characteristics of daily and extreme temperatures over Canada. *Journal of Climate* 14(9): 1959-1976.

Bowman, Adrian W., and Adelchi Azzalini. 1997. *Applied smoothing techniques for data analysis: the kernel approach with S-Plus illustrations*. Vol. 18. OUP Oxford.

Caesar, J., L. Alexander, and R. Vose. 2006. Large‐scale changes in observed daily maximum and minimum temperatures: Creation and analysis of a new gridded data set. *Journal of Geophysical Research: Atmospheres*, 111, D5.

Cai, W., S. Borlace, M. Lengaigne, P. Van Rensch, M. Collins, G. Vecchi, and others. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2), 111-116.

Durnford, D., V. Fortin, G.C. Smith, B. Archambault, D. Deacu, F. Dupont, S. Dyck, Y. Martinez, E. Klyszejko, M. Mackay, L. Liu, P. Pellerin, A. Pietroniro, F. Roy, V. Vu, B. Winter, W. Yu, C. Spence, J. Bruxer, and J. Dickhout. 2017. Towards an operational water cycle prediction system for the Great Lakes and St. Lawrence River. *Bull. Amer. Meteor. Soc.,* https://doi.org/10.1175/BAMS-D-16-0155.1

Farmer, T.M., E.A. Marschall, K. Dabrowski and S.A. Ludsin. 2015. Short winters threaten temperate fish population. *Nature Communications* 6: 7724

Feng, Xingdong, Xuming He, and Jianhua Hu. 2011. Wild bootstrap for quantile regression. *Biometrika*, 98(4): 995.

Fielding, Samuel R. 2013. Emiliania huxleyi specific growth rate dependence on temperature. *Limnology and Oceanography* 58(2): 663-666.

Goldman, C.R., A. Jassby, and T. Powell. 1989. Interannual fluctuations in primary production: meteorological forcing at two subalpine lakes. Limnology and Oceanography 34(2) 310-323.

Hampton, S. E., A. Galloway, S. Powers, T. Ozersky, K. H. Woo, and others. 2017. Ecology under lake ice. *Ecology Letters*. 20: 98–111.

Hampton, S.E., A.W. Galloway, S.M. Powers, T. Ozersky, K.H. Woo, R.D. Batt, S.G. Labou et al. 2017. Ecology under ice. *Ecology Letters* 20(1) 98-111

Hoerling, M., A. Kumar, & M. Zhong. 1997. El Niño, La Niña, and the nonlinearity of their teleconnections. *Journal of Climate*, 10(8), 1769-1786.

Hoerling, M. P., & A. Kumar. 1997. Why do North American climate anomalies differ from one El Niño event to another? *Geophysical Research Letters*, 24(9), 1059-1062.

Hoskins, B. 2013. The potential for skill across the range of the seamless weather- climate prediction problem: a stimulus for our science. Quarterly *Journal of the Royal Meteorological Society*, 139(672): 573-584.

Joung, D., M. LeDuc, B. Ramcharitar, Y. Xu, P. Isles, J. D. Stockwell, G.K. Druschel, T. Manley and A. W. Schroth. 2017. Winter weather and lake-watershed physical configuration drive phosphorous, iron and manganese dynamics in water and sediment of ice covered lakes. Limnology and Oceanography 62(4) 1620-1635.

Koenker, R., & G. Bassett Jr. 1978. Regression quantiles. *Econometrica: journal of the Econometric Society*, 33-50.

Koenker, R. & K. Hallock. 2001. Quantile regression: An introduction. *Journal of Economic Perspectives*, 15(4), 43-56.

Koenker, R. (2017). quantreg: Quantile Regression. R package version 5.34. https://CRAN.R-project.org/package=quantreg

Leppäranta, M. 2014. *Freezing of lakes and the evolution of their ice cover*. Springer Science & Business Media

NCSU. 2010. URL: http://www4.stat.ncsu.edu/%7Ebondell/Software/NoCross/NoCrossQuant.R

Powers, S. M., & Stephanie E. Hampton. 2016. Winter Limnology as a New Frontier. *Limnology and Oceanography Bulletin*, 25(4): 103-108.

Powers, S.M., S.G. Labou, H.M. Baulch, R.J. Hunt, N.R. Lottig, S.E. Hampton, and E.H. Stanley. 2017. Ice duration driver winter nitrate accumulation in north temperate lakes. *Limnology and Oceanography* 2(5) 177-186

Preston, Daniel L., Nel Caine, Diane M. McKnight, Mark W. Williams, Katherina Hell, Matthew P. Miller, Sarah J. Hart, and Pieter TJ Johnson. 2016. Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. *Geophysical Research Letters* 43(10): 5353-5360.

Salonen, K., M. Leppäranta, M. Viljanen, & R. Gulati. 2009. Perspectives in winter limnology: closing the annual cycle of freezing lakes. *Aquatic Ecology* 43(3): 609-616.

Scheffer, M., D. Straile , E. van Nes, & H. Hosper. 2001. Climatic warming causes regime shifts in lake food webs. *Limnology and Oceanography*, 46(7): 1780-1783.

Silverman, Bernard W. 1986. *Density estimation for statistics and data analysis*. Vol. 26. CRC Press.

Wetzel, Robert G. 2001. *Limnology: lake and river ecosystems*. Gulf Professional Publishing.

Weyhenmeyer, Gesa A., David M. Livingstone, Markus Meili, Olaf Jensen, Barbara Benson, and John J. Magnuson. 2011. Large geographical differences in the sensitivity of ice‐covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology* 17(1): 268-275.

Winder, M., and D.E. Schindler. 2004. Climatic effects on the phenology of lake processes. *Global Change Biology* 10(11) 1844-1856

Wyrtki, Klaus. 1975. El Niño—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *Journal of Physical Oceanography* 5(4): 572-584.

Xu, Yaoyang, Andrew W. Schroth, and Donna M. Rizzo. 2015. Developing a 21st Century framework for lake‐specific eutrophication assessment using quantile regression. *Limnology and Oceanography: Methods* 13(5): 237-249.

Yeh, S. W., J. Kug, B. Dewitte, M. Kwon, B. Kirtman, & F. Jin. 2009. El Niño in a changing climate. *Nature*, 461(7263), 511-514.

ACKNOWLEDGEMENTS
NCEP Reanalysis data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/

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Table 1: Ratio of conditional likelihood of selected winter AFDDs over lakes due to ENSO events, to that of the unconditional. Results are computed using the same techniques as in figure 3b.

Table 1: Ratio of conditional likelihood of selected winter AFDDs over lakes due to ENSO events, to that of the unconditional. Results are computed using the same techniques as in figure 3b.

Lake	Ice out dates corresponding to winter AFDD		Unconditional probability of W* for the 1951-2010 period	Conditional risk relative to the Unconditional probability		
	Winter threshold (W*) in DDC units	Ice-out Date corresponding to W*		Eastern Pacific El Niño	Central Pacific El Niño	La Niña
Damariscotta	200	3-April	0.14	1.57	0.78	0.93
Superior[#]	820	31-March	0.31	2.16	1.06	0.83
Winnipeg	2015	13-May	0.26	3.3	0.43	1.06
Lesser Slave	2170	13-May	0.28	1.67	0.93	0.82
Dease	2170	28-May	0.1	1.7	1.2	0.5
Deadman's Pond	1735	3-May	0.3	0.63	0.7	1.2
Long	2730	26-May	0.2	2.5	0.85	0.7

AFDD- Accumulated Freezing Degree days
DDC- Degree-day Celsius

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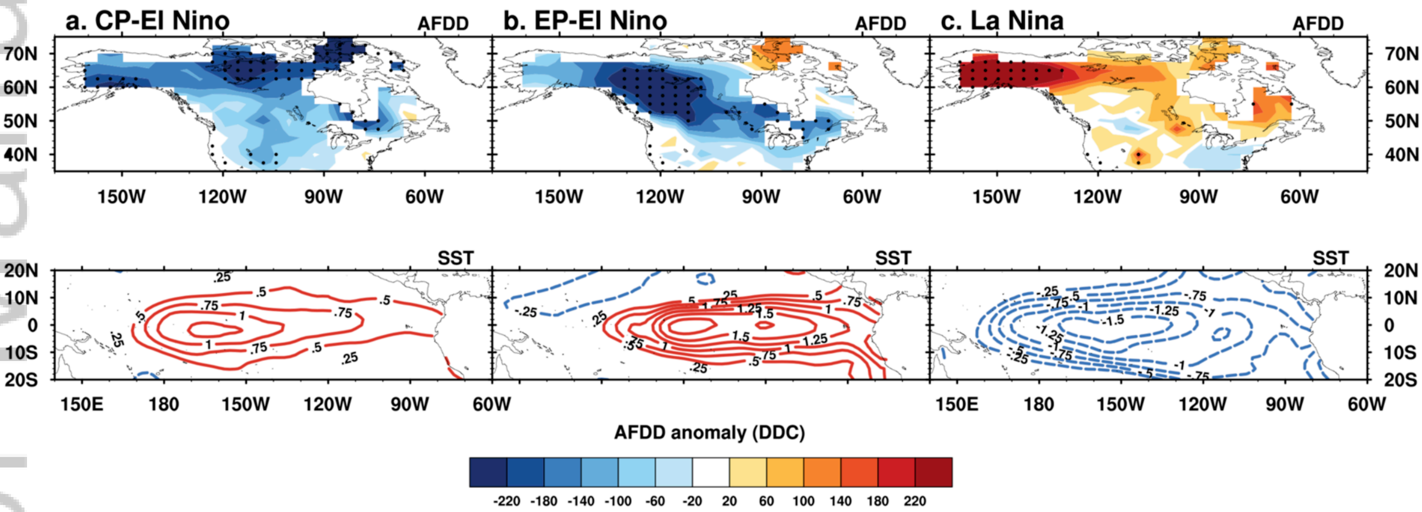
Figure 1: Climatology of winter Accumulated Freezing Degree Days (AFDD) over North America and its relationship with lake ice-out dates. North American map of the (a) mean, (b) standard deviation of winter AFDDs from 1951-2010. Contour intervals for the mean and standard deviation winter AFDD are set at 300 and 40 Degree-day Celsius (DDC) respectively. The red coloured polygons represent the location of the eight selected lakes. Plotting lake ice-out dates as a function of winter AFDD at (c) Dease Lake (d) Lesser Slave Lake (e) Lake Winnipeg (f) Lake Albion (g) Deadman's Pond (h) Damariscotta Lake (i) Lake Superior (j) Long Lake. The filled/unfilled polygons in each scatter plot represent the ice out date as a function of winter AFDD for each lake. The red line denotes locally averaged lake ice out date conditioned on the winter AFDD, and is computed using non-parametric kernel regression method. The blue shadings designate the 90% confidence band for a linear model.

Figure 2: Composite maps of tropical Pacific winter SST warming/cooling and associated North American winter Accumulated Freezing Degree-days (AFDD) anomalies for select five (a) Central Pacific (CP) El Niño (b) Eastern Pacific (EP) El Niño (c) La Niña events. These events were chosen by majority consensus across different identification methods in the literatures (see Supplementary Table 3). Anomalies are computed as departure from the 1951-2010 average and contour intervals for winter AFDD and SST anomalies are 40 Degree day Celsius (DDC) and 0.25° Celsius respectively. Stippled areas denote regions where the departure is significant at 90% confidence level based on two-tailed re-sampling tests.

Figure 3: Risk estimates for winter Accumulated Freezing Degree-day (AFDD) quantities, corresponding to spring ice-out dates earlier than April 1st at Lake Superior, conditioned on different El Niño /Southern Oscillation patterns. (a) Scatter plot for spring ice-out dates at Lake Superior as a function of the antecedent winter AFDD. The grey unfilled circles denote the winter AFDD associated with observed ice out dates. The purple line represents locally averaged lake ice-out dates conditioned on the winter AFDD, and is computed using non-parametric kernel regression method. The blue shadings denote the 90% confidence band for computed regression line. (b) Conditional winter AFDD distribution at Lake Superior associated with the three archetypical ENSO patterns: CP El Niño (blue), La Niña (green) and EP El Niño (red). The grey area represents part of the conditional distribution less or equal to 820 Degree-day Celsius (DDC),. The conditional winter AFDD distribution curves for typical ENSO patterns was constructed by generating conditional quantile functions for estimating winter AFDD at $\tau = 0.01$ intervals over the quantile range ($0.01 < \tau < 0.99$), followed by estimation of winter AFDD quantiles at the centroid of five selected samples of ENSO flavours in the PC1-PC2 phase space. (c) Contour surface plot of estimated conditional risk for winter AFDD at Lake Superior to be less or equal to 820 DDC, relative to the unconditional (climatology). The dark filled circles represent the PC1-

PC2 indices for the three archetypical ENSO patterns, while the grey polygon represents the convex hull – region containing observed PC1-PC2 values. The colour key for ratio of risk conditioned on PC1-PC2 values is given at the bottom.

Figure 4: Risk estimates for winter Accumulated Freezing Degree-days (AFDD) quantities (thresholds), corresponding to early ice-out dates for selected North American lakes, conditioned on three archetypical ENSO patterns. At each lake, the blue, green and red curves denote the conditional winter AFDD distribution associated with Central Pacific (CP) El Niño, La Niña and Eastern Pacific (EP) El Niño respectively, while the black curve represents the unconditional winter AFDD distribution for the 1951-2010 period. The steps by which the conditional distributions are generated are given in the caption for figure 3b. The grey area signifies part of the conditional distribution less or equal to specific AFDD threshold (broken black line). The confidence intervals for risk estimates was determined by computing the occurrence probability of each year conditioned on its PC1-PC2 index and determining the 5th and 95th percentile from the time series of risk estimates. Conditional non-exceedance probability (risk) estimates in bold are significant at 10% significance level.



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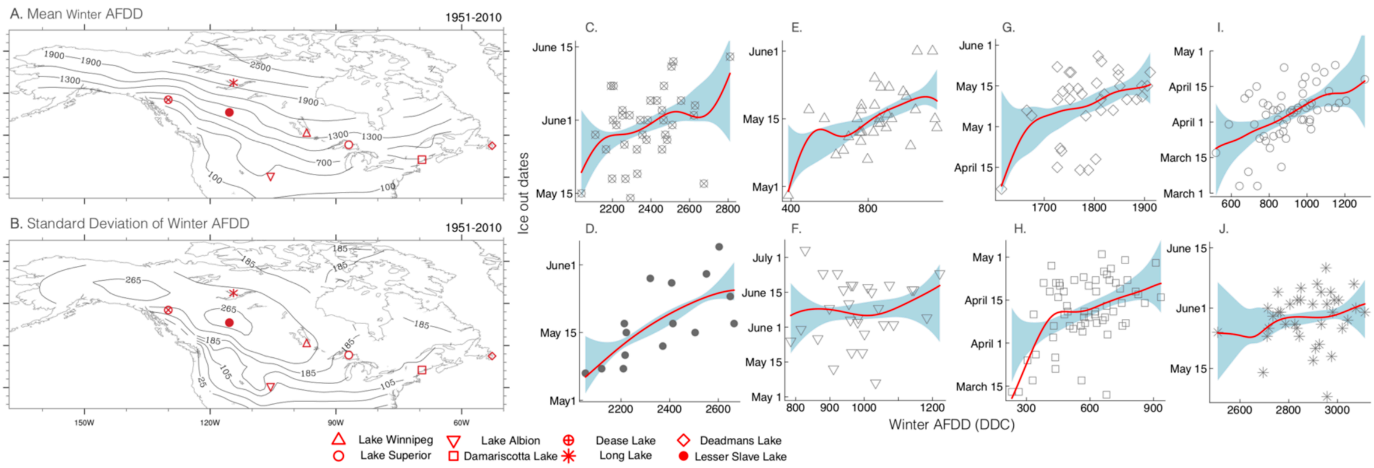

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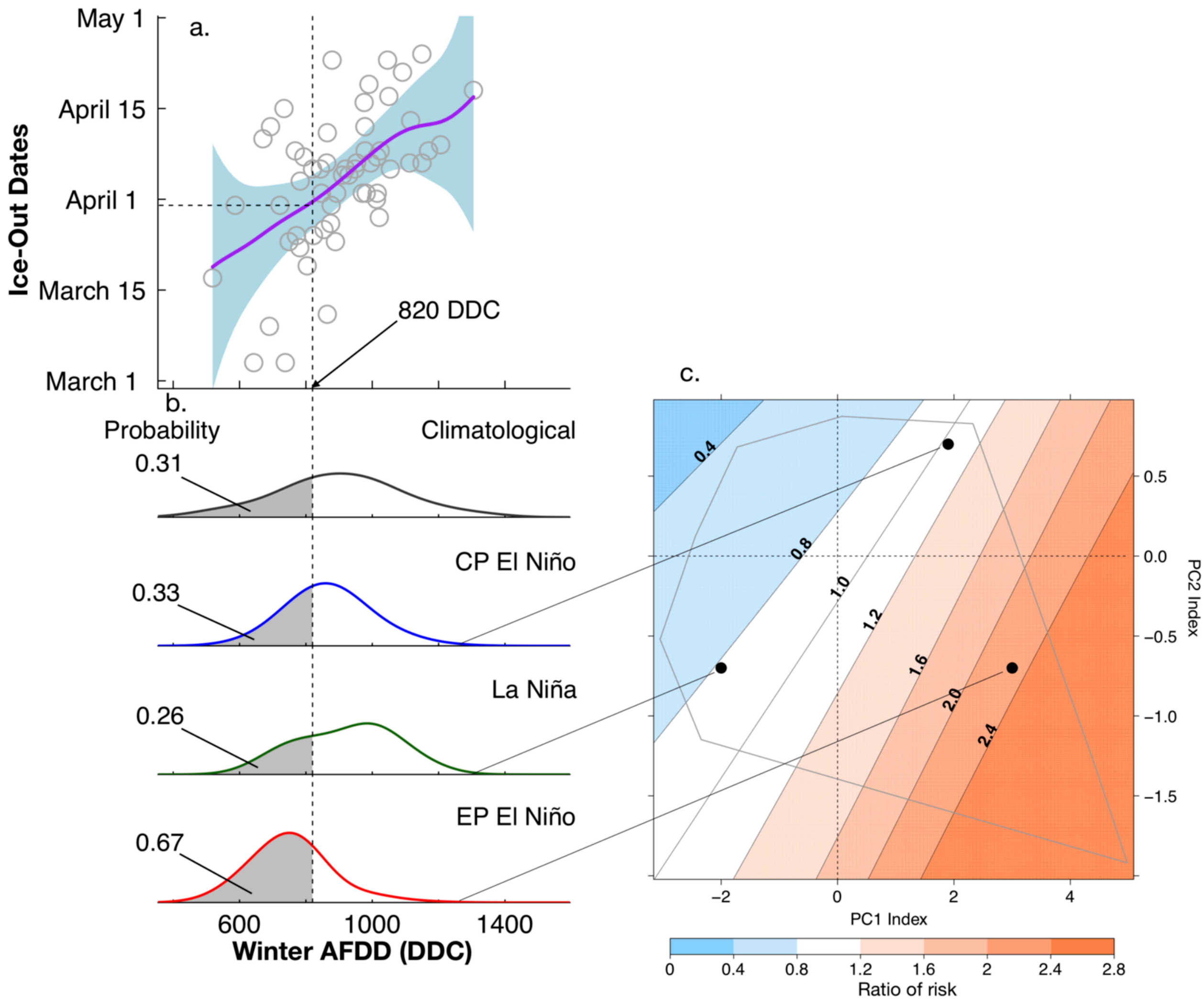

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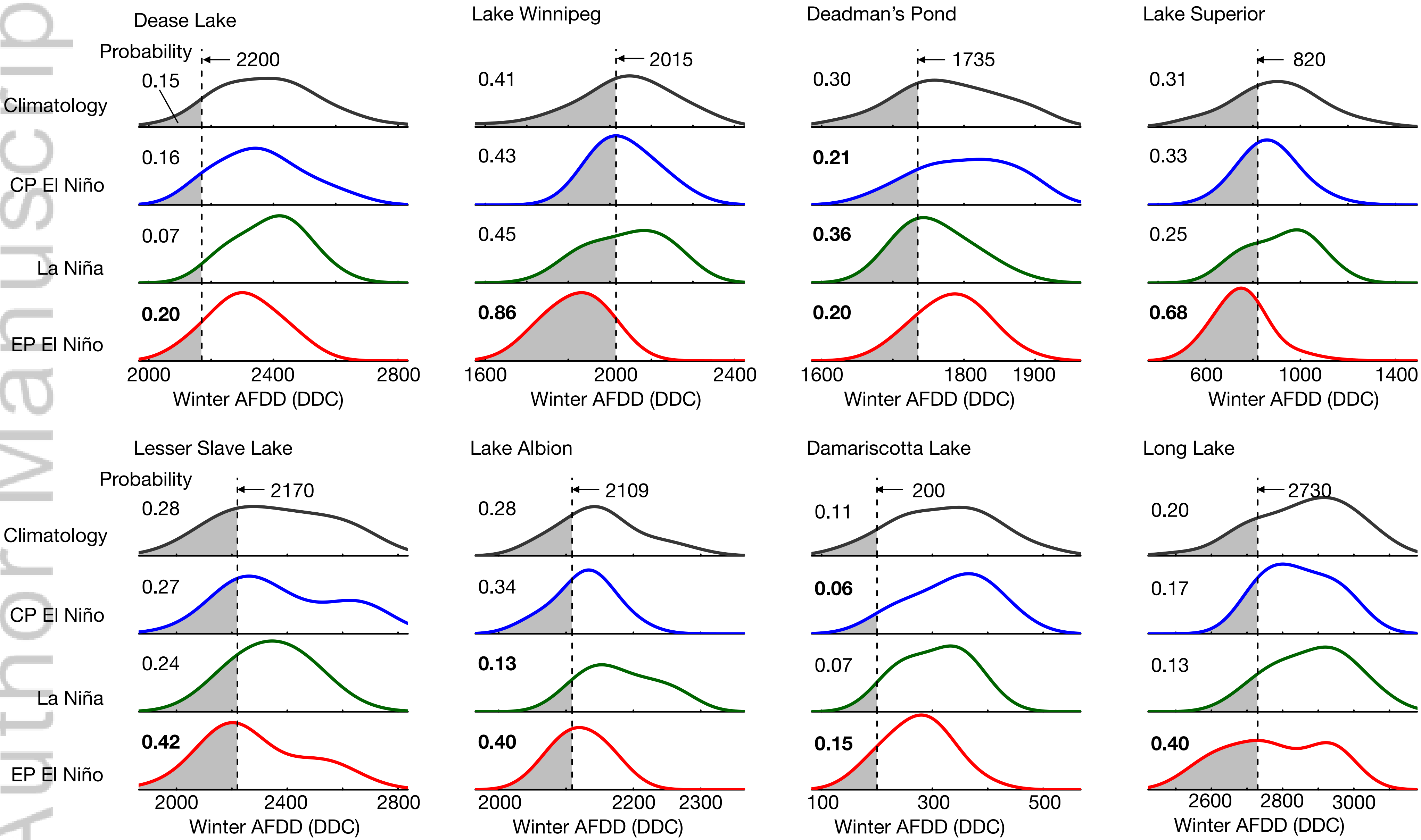
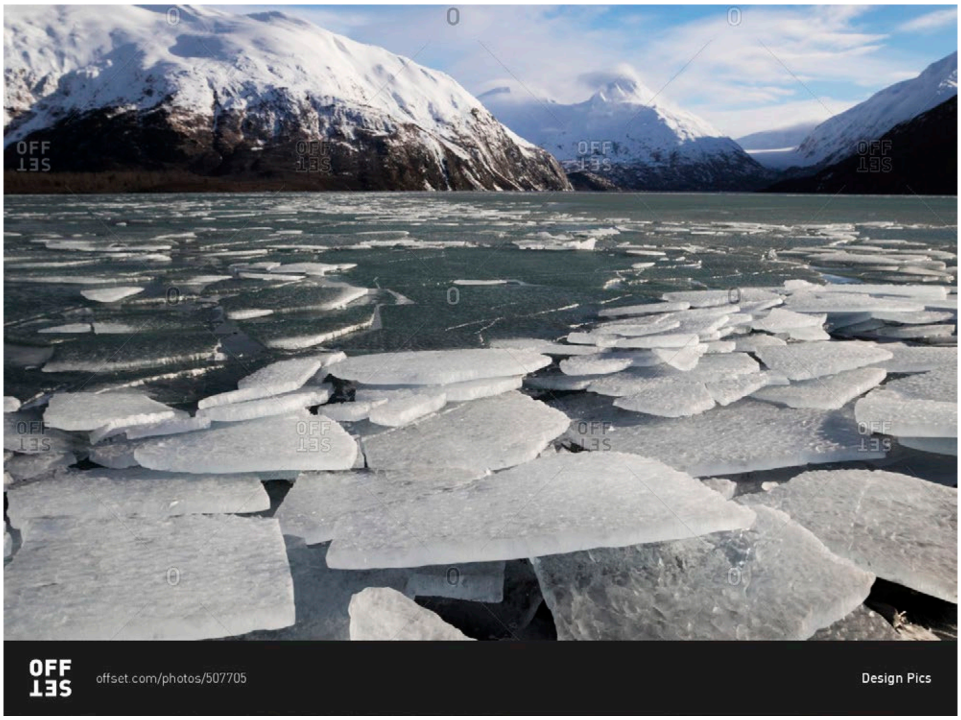
Figure 4


Dease Lake
Probability
2200
0.15
Climatology
0.16
CP El Niño
0.07
La Niña
0.20
EP El Niño
2000
2400
2800
Winter AFDD (DDC)
Lake Winnipeg
2015
0.41
0.43
0.45
0.86
1600
2000
2400
Winter AFDD (DDC)
Deadman's Pond
1735
0.30
0.21
0.36
0.20
1600
1800
1900
Winter AFDD (DDC)
Lake Superior
820
0.31
0.33
0.25
0.68
600
1000
1400
Winter AFDD (DDC)
Lesser Slave Lake
Probability
2170
0.28
Climatology
0.27
CP El Niño
0.24
La Niña
0.42
EP El Niño
2000
2400
2800
Winter AFDD (DDC)
Lake Albion
2109
0.28
0.34
0.13
0.40
2000
2200
2300
Winter AFDD (DDC)
Damariscotta Lake
200
0.11
0.06
0.07
0.15
100
300
500
Winter AFDD (DDC)
Long Lake
2730
0.20
0.17
0.13
0.40
2600
2800
3000
Winter AFDD (DDC)

Freezing Degree-day Thresholds and Lake Ice-out Dates: Understanding the Role of El Niño Conditions

Mussie T. Beyene* and Shaleen Jain



The timing of spring ice-out dates of lakes is sensitive to the prevailing winter Accumulated Freezing Degree Days (AFDD). Empirical studies show that the El Niño-Southern Oscillation (ENSO)-winter AFDD relationship for North American regions depends on the spatial patterns of ENSO-related sea surface temperature (SST) warming/cooling in the tropical Pacific (TP). Using conditional quantile functions for winter AFDDs that incorporate ENSO indices as covariates, we show that for North American lakes, (a) the effect of EP El Niño on the timing of ice-out dates is quite distinct to that of CP El Niño from local-to-regional scale, (b) El Niño related changes in the timing of spring ice-out dates is not a linear opposite to that of La Niña events.

Freezing Degree-day Thresholds and Lake Ice-out Dates: Understanding the Role of El Niño Conditions

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Submitted 31 March 2018

Supported by National Science Foundation Awards 0904155 and 1055934, and NOAA award NA14OAR4320158.

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ABSTRACT

In temperate lakes, the wintertime Accumulated Freezing Degree-Days (AFDD) modulate the thickness and phenology of winter ice-cover, which in turn influence lake ecosystem processes and functions across seasons. Empirical studies show that the El Niño-Southern Oscillation (ENSO)-winter AFDD relationship for North American regions depends on the location and amplitude of the winter ENSO-related sea surface temperature (SST) warming/cooling in the tropical Pacific (TP), and consequently changes in the magnitude and frequency of different ENSO patterns engender shifts and transitions in the North American lake ice regimes. For eight lakes located across North America, we found quasi-linear and nonlinear relationships between winter AFDDs and spring lake ice-out dates, and in some cases, existence of thresholds above and below which regression slopes are materially different, thus illuminating differential sensitivities. Conditional quantile functions for winter AFDDs that incorporate ENSO indices as covariates were developed to estimate the relative risk of early/late lake ice-out events for these lakes. For seven of the eight lakes, the canonical Eastern Tropical El Niño pattern increases likelihood of low winter AFDDs (associated with early ice-out dates in these lakes) by 1.5-2.8 times to that of the climatology (1951-2010 average), while the typical Central Pacific El Niño pattern corresponds to a decrease or no significant change in the occurrence probability of early ice-out dates in these Lakes. These results demonstrate that the conditional winter AFDD estimated based on a comprehensive characterization of ENSO allow for delineation of distinct local-to-regional patterns of elevated risk of early ice out and short lake ice-cover season for North American regions.

Keywords: El Niño flavours, North American lakes, Lake ice-out dates, Quantile Regression, Conditional Risk

1. Introduction

In temperate and polar regions of North America, where lakes freeze during winter, wintertime accumulated freezing degree-day (AFDD)—calculated as the sum of mean daily temperature departures below the freezing point (0°C or 32°F)—is an important cold season weather-climate variable. AFDD determines the amount of freezing energy available in the air to grow surgical ice on lakes, and consequently analytical studies often estimate the thickness of lake ice cover to be roughly proportional to the square root of the winter AFDD (Lepparanta, 2014). However, the impacts of wintertime AFDD variations on lakes may not be limited to the cold season. For example, springtime ice-out dates for Maine (USA) lakes are linked to wintertime AFDD thresholds (Beyene and Jain, 2015).

The prevailing winter climate, including the AFDD patterns over North America, has been shown to be sensitive to phases of El Niño-Southern Oscillation (ENSO), a coupled oceanic-atmospheric phenomenon in the tropical Pacific that affects weather and climate worldwide (e.g., Bonsal et al. 2001; Assel et al. 2004; Bai et al. 2012). For instance, during the 1997/98 El Niño event (warm phase of ENSO), northern US and southern Canada recorded one of their lowest winter AFDDs such that it resulted in the least extensive ice-cover in the Great Lakes over the past century. However, the severity and spatial extent of the North American weather and climate anomaly patterns associated with El Niño events is neither alike nor is it linearly opposite to that of La Niña (cold phase of ENSO) events (e.g., Wyrtki, 1975; Hoerling and Kumar, 1997; Hoerling et al. 1997). Studies have shown that such discrepancies may arise from differences in the location and amplitude of their signature SST anomalies in the tropical Pacific as variations in the location of the warmest waters (SST>27.5C) in the tropical Pacific generate differential atmospheric wave trains responsible for climate variability worldwide (e.g., Barsugli and Sardeshmukh, 2002; Hoerling and Kumar, 1997). Furthermore, Beyene and Jain (2017) showed that the sensitivity of North American winter temperatures to diverse ENSO flavours is not uniform, both regionally and across different parts of the empirical probability density function (EPDF). In the present context, a salient question is: to what extent do distinct El Niño flavours affect North American lake ice-out dates through their differential effect on the (EPDF of) winter AFDD? Two aspects of current and future ENSO variability further motivate the above noted line of inquiry: (a) five-fold increase in the frequency of a “new variant” of ENSO is being projected under anthropogenic climate change (e.g. Yeh et al. 2009; Cai et al. 2014), (b) ENSO-based climate forecasts on seasonal and longer lead-times have proven to be reliable (Hoskins, 2013). To this end, this study aims to develop location specific risk functions for North American winter AFDD, that incorporate as covariates ENSO indices that capture the location and amplitude of tropical Pacific SST anomalies, in order to estimate ENSO-related changes in the relative occurrence probability of early/late lake ice out events in North America. In this study, the term occurrence probability is used interchangeably with risk and likelihood.

Past lake ice studies often assessed ENSO-induced changes in lake ice season by characterizing the response of local meteorological variables (relevant to lake ice evolution) to large-scale climate patterns using traditional statistical methods such as linear regression and averaging of sub-samples. However, analyses employing these methods offer limited insight, as they primarily measure the shift in the conditional mean and not the conditional tails of the distribution, where climate-related thresholds in lakes usually reside. This study thus employs quantile functions, first proposed by Koenker and Bassett (1978), to investigate the response of North American winter AFDD, across its variability range, to the amplitude and location of tropical Pacific SST warming/cooling, linked to ENSO events. This approach provides a functional framework to estimate the winter AFDD conditioned on ENSO indices with three important features: (a) no distributional assumption, (b) quantification of differential sensitivity across quantiles, and (c) resistance to outlier effects.

Beyene and Jain (2017) have shown that the change in the conditional risk of North American winter temperatures due to ENSO flavors varies both regionally and across different temperature quantiles. This study extends their work and aims to quantify ENSO related changes in North American lake ice out dates by characterizing its effect on winter AFDD variability. Two key tasks in this regard are as follows:

(1) Quantify the nature of relationships between lake ice and winter AFDD variability, based on observational records for a select group of lakes across North America.
(2) Estimate ENSO-related changes in the relative likelihood of early/late lake ice out events for eight North American lakes—location-specific risk functions for North American winter AFDD that incorporate ENSO indices as covariates are developed.

2. Data and Methods

Lake Ice-out (off) Dates: Lake ice-out date refers to the date when winter ice completely disappears from the lake surface. In this study, eight North American lakes (see Figure 1 for lake locations) that freeze during the winter were selected and their historical lake ice-out dates from 1950-2010 were downloaded from the following electronic databases: Global Lake and River Ice Phenology Database (at National Snow and Ice Data Center) and Lake Ice Clearance and Formation dataset (at Niwot Ridge Long Term Ecological Research Center). In Supplementary Table 1, geomorphological data and site of observation for ice out dates is provided for the eight selected lakes.

North American Winter AFDD: Time series of gridded, daily mean temperature data for North America from 1951-2010 were derived from HadGHCND dataset (Caesar et al. 2006), which provides station-based, daily observations of average temperature data on a 2.5°x3.75° grid resolution. The year-to-year winter AFDD for North American fields were then calculated as the daily degrees below freezing (0°C) summed over the total number of days from December to February that the daily average temperature was below freezing:

$$AFDD = \sum_{i=1}^{i=n} (T_0 - T_i)\Delta t, \quad T_0 > T_i, \tag{1}$$

where Δt is the time interval (Δt = 1 day), n is the number of days from December to February months (n = 90 or 91), T_i is the daily mean temperature (°C) and T_0 is the freezing temperature for water ($T_0 = 0$ *℃ or 32℉*). Lake ice occurs predominantly in regions with regular occurrence of sub-freezing temperatures and wintertime AFDD. Climatological winter AFDD patterns over North America (Figure 1a, b) indicate that regions with pole ward of 35°N show appreciable below-freezing temperatures; this region will be the focus of investigation in the remainder of this study.

Relationship between AFDD and lake ice thickness: Lake ice formation and growth results from the dynamical heat balance at lake surface. (Lepparanta 2014). Given that the surface air temperature strongly relates to major energy fluxes from lake to atmosphere, analytical studies often use the degree-day method— first derived by Stefan (1891) — to approximate the thickness of winter ice formed on lake surface. In general, in a degree-day model, ice growth (h) in inches, is modelled as a function of the square root of the accumulated freezing degree-days ($AFDD$)

$$h = C\sqrt{AFDD} \quad (2)$$

where C is a coefficient that accounts for local snow and atmospheric conditions and AFDD is in Degree-Day Fahrenheit (DDF) (e.g., Assur 1956). In Supplementary Analysis 2 section, we provide a detailed exposition of this physical basis of the relationship noted above.

ENSO Indices: The emergence, type and strength of El Niño /La Niña events are often based on areal averaged SST indices for four regions in the tropical Pacific: Niño 1+2, Niño 3, Niño 3.4 and Niño 4 (see supplementary Figure S1a). In this study, time series of monthly, spatially averaged SSTs for the four Niño regions from 1951-2010 were collected from a dataset prepared by NOAA's Climate Prediction Center, based on extended, reconstructed sea surface temperature (ERSST) V4 dataset. Time series of winter Niño SST indices from 1951-2010 were then computed by averaging the December to February SST index for each Niño region (see Supplementary Figure S1b).

Geographical distributions of ENSO-related tropical Pacific SST anomalies (warming or cooling relative to long-term averages) have been identified as important contributors to the spatial patterns and severity of climatic impacts in remote regions. Thus, it is critical to identify a small set of ENSO indices that best represent the detailed pattern of SST warming or cooling in the tropical Pacific. In this study, Principal Component Analysis was performed on the time series of mean winter SST indices of the four Niño regions from 1951-2010 (see Supplementary Analysis 1). The resulting pair of indices (Principal Component 1 and 2, hereafter referred as PC1 and PC2) account for 99.8% of the total variance in the ENSO historical record (PC1 = 89% and PC2 =10.8%). While PC1 and PC2 time series comprehensively characterize the temporal variations in ENSO over the past six decades, the spatial loadings linked to these PCs offer helpful interpretation of the tropical Pacific warming and cooling patterns associated with ENSO events (see Supplementary Figure S2). PC1 loadings across the four Niño regions are of the same sign suggesting synchronous wintertime SST variation across all Niño regions (see Supplementary Table 2b and Supplementary Figure S2b). PC2 loadings are characterized by an east-west dipole pattern with the wintertime SSTs in Niño-1+2 (eastern Pacific) region varying out of phase with that of Niño-3.4 and Niño-4 (Central Pacific) regions (Supplementary Figure S2c). Beyene and Jain (2017) and others have showed that the joint indices of PC1 and PC2 allow characterization of the amplitude and location of maximum TP SST anomalies associated with diverse El Niño/La Niña events (see Supplementary Analysis 1). Therefore, PC1 and PC2 indices are used as covariates/predictors in the quantile regression pursued in this study. Finally, as noted in the previous section, recent improvements in the understanding on ENSO flavors imply distinct patterns of climatic impacts across North America, and projected trends for the 21st century reveal dramatic shifts in ENSO frequency—the associated risk to environmental variables such as lake ice remains unclear.

Quantile Regression: Historical winter AFDD variability at a particular location can be summarized based on a frequency distribution or probability density function (PDF). Characteristic AFDD values that correspond to specific quantiles (representing non-exceedance probability) can be obtained from the PDF. For instance, the AFDD value for the 0.25th quantile is exceeded 75% of the time. An extension of this approach allows modelling of quantiles based on covariates or predictors (for example, ENSO conditions) that modulate the conditional quantile functions for the target variable (in our case, AFDD). In its general form, quantile regression (Koenker and Hallock 2001) affords conditional quantile estimates for each quantile, and as such, conditional PDF. These estimates are superior to ones from linear regression, wherein covariate effects are restricted to affect on the mean of the target variables. Example applications of quantile regression in lake studies include Bissinger et al. (2008), Fielding (2013), and Xu et al. (2015).

In this study, the quantile regression approach is used to model and predict the linear response of North American winter AFDDs, across all or selected quantiles, to ENSO indices (X_i). Mathematically, this can be expressed as

$$AFDD^{(\tau)} = \beta_0{}^{(\tau)} + \beta_1{}^{(\tau)} PC1 + \beta_2{}^{(\tau)} PC2 \qquad (3)$$

where $\beta_0{}^{(\tau)}$ is the intercept, and $\beta_1{}^{(\tau)}$ and $\beta_2{}^{(\tau)}$ are the slope coefficients for PC1 and PC2 patterns at ι^{th} quantile. The regression parameters $\beta^{(\tau)}$ are obtained by solving for minimization of the sum of weighted absolute residuals. The quantile regression implementation in the R computing environment (Koenker, 2017) is employed to provide the optimizing algorithm to estimate $\beta^{(\tau)}$ using linear programming techniques.

Estimation of conditional winter AFDD quantiles requires fitting of curves across each quantile independently and as such generating multiple conditional winter AFDD quantile functions may yield quantile curves that cross or overlap, creating an invalid distribution. To alleviate the crossing problem in quantile regression, a procedure introduced by Bondell et al. (2010), which imposes a non-crossing constraint, is applied. The statistical significance for parameter estimates, $\beta^{(\tau)}$ in the conditional winter AFDD functions were assessed by constructing the confidence interval using the wild bootstrap method, an approach that is almost unaffected by residual heterogeneity (Feng et al. 2011).

3. Results

3.1 Winter AFDD and North American Spring Lake Ice-out Dates

Empirical and theoretical rationales are needed to establish the import of seasonal winter (December-February) AFDD on North American lake ice season. To this end, Supplementary Analysis 2 presents a synopsis of the theoretical-physical basis underlying AFDD-lake ice linkages. This section on the other hand, offers empirical findings by analyzing the observed response of spring lake ice-out dates to their antecedent winter AFDDs for eight North American lakes (see Figure 1a). Here, the efficacy of winter AFDD in conditioning the spring lake ice out dates was examined using non-parametric kernel regression approach, as the functional relationship between winter AFDD and spring ice-out dates is unknown and may vary across lakes. Kernel regression method (Silverman 1986) is based on a smoothing approach that is locally adaptive, thus allowing for the estimation of linear and nonlinear relationship from data. The degree of smoothing depends on the bandwidth, which is selected based on a minimization of integrated error (Bowman and Azzalini, 1999). In the context of ice-out and winter AFDD relationship, of particular interest is the diagnosis of nonlinearity and potential break points in the relationship (akin to thresholds).

Results of this analysis show that for all selected lakes, there is a positive (direct) relationship between winter AFDD and spring ice-out dates, which implies that winters with relatively low (high) winter AFDDs are generally related to earlier (later) than normal lake ice-out dates the following spring (see Figure 1c-j). However the degree of sensitivity of spring ice-out dates to winter AFDDs in these lakes varies both spatially and across different winter AFDD quantiles. For instance, contrasting the overall slope of the winter AFDD regression line across the eight lakes indicate that the response of spring ice-out dates to the antecedent winter AFDD variability is relatively stronger at Lake Superior (USA) and Damariscotta Lake (USA) as compared to those at Lake Albion (USA) and Long Lake (Canada). This implies that the strength of association between spring ice-out dates and the antecedent winter AFDDs for North American lakes shows geographical variation and locally, is also likely to be modulated by other factors such as morphometry, elevation, and continentality. On the other hand, examining the response of spring ice-out dates of the eight lakes across different winter AFDD quantities reveals that unusually low /high winter AFDDs are strongly related to early/late spring ice-out dates. For instance, for Damariscotta Lake, 5 of the 6 winters with AFDD less than 200 Degree Day Celsius (DDC) ($\tau \leq 0.30^{th}$) are associated with ice-out dates earlier than April 3rd (see figure 1H). Similarly for Lesser Slave Lake (Canada), 5 of the 6 winters with AFDD less than 2270 DDC ($\tau \leq 0.28^{th}$) are linked to ice out dates that occurred prior to May 15th (see figure 1D).

These findings on the presence of winter AFDD quantities that correspond to early/late spring ice-out dates for North American lakes is consistent with the findings reported in Beyene and Jain (2015). This implies that the efficacy of ENSO events in modulating the variability of ice-out dates in lakes depends on their effect on the occurrence of winter AFDDs associated with ice-out dates. Thus, characterization of ENSO-related change in risk of early/late ice dates requires an understanding of the relationship between different El Nino (or La Nina) events and winter AFDD at specific quantiles, as well across the entire winter AFDD distribution. It should be noted that for studied lakes, the degree of coherence between winter AFDD and spring ice-out dates can generally be assumed to be independent of spring temperature conditions, as there is no significant ($p < 0.1$) correlation between winter and spring AFDD for almost all North American regions (see Supplementary Figure S4).

3.2 ENSO Diversity and North American Winter AFDD Variability

Differences in the location of peak ENSO-related Sea Surface Temperature (SST) warming/cooling in the Tropical Pacific (TP) contribute to the observed variability in ENSO-related climate patterns in North America (e.g., Hoerling and Kumar, 1997). To illustrate this difference in the context of North American winter AFDD, five years were selected where by majority agreement of different ENSO identification methods (EP/CP method, Niño3/4 method, EMI method and regression-EOF method) have been determined as Central Pacific (CP) El Niño (1969, 1988, 1995, 2003, 2005, 2010), Eastern Pacific (EP)

El Niño (1973, 1983, 1987, 1998, 2007) and La Niña events (1956, 1971,1974, 1976, 1989) (see Supplementary table 1). It should be noted that our use of EP and CP El Niño terminology in this study serves only to contrast the site of peak SST warming in TP between the two El Niño patterns, and is by no means implying that these patterns are distinct modes of El Niño. The composite TP winter SST anomaly (departure from the long-term average) pattern for the five CP El Niño events selected features peak SST warming confined in the central TP regions (Niño3.4 and Niño4 regions) flanked by cooler than normal SSTs on both sides of the equatorial Pacific (see Figure 2a bottom). While there is some inter-event differences, the pattern of North American winter AFDD variability pattern corresponding to CP El Niño events can broadly be characterized as southeast-northwest dipole pattern, where there is relatively strong increase in the seasonal winter AFDD (colder temperatures) over the Midwest and northeast US regions and decrease in winter AFDD (warmer temperatures) over western US and Canadian regions and northern edges of Canada (see Figure 2a top). In contrast, the location of maximum SST warming in the TP during EP El Niño winters is concentrated in eastern TP extending from the western coast of South America to the regions east of the dateline (Niño1+2 & Niño 3 regions) (see Figure 2b). Moreover, these events are associated with a significant decrease of winter AFDD over much of North America (except for the Pacific US regions and Baffin Island). These results illustrate that the location of maximum SST warming in the tropical Pacific has important implication on the impact of individual El Niño events on the winter AFDD over US and Canada. On the other hand, the composite TP winter SST anomaly pattern for the five La Niña events exhibits peak SST cooling over central-eastern equatorial Pacific (Niño3 and Niño4 regions). Moreover, the North American winter AFDD anomaly patterns related to these events generally features a northwest-southeast dipole pattern with a relatively strong increase in winter AFDD over western Canada and Alaska and decrease in winter AFDD over the Southeast US states. These results reveal the effect of La Niña events on the winter AFDD of various North American regions is not a mirror opposite to that of El Niño events. They also establish the significance of tropical Pacific in producing non-linearity in the response of North American winter AFDD to opposite phases of ENSO.

In summary, the above findings show that the ENSO-winter AFDD relationship for North America varies with the location of peak ENSO-related SST warming and/or cooling in the TP. In other words, the efficacy of El Nino (or La Nina) events in modulating the conditional winter AFDD distribution for North American regions shows spatial variation. Consequently, in the face of EP or CP El Niño/La Niña episodes, the likelihood associated with various AFDD magnitudes, including the ones that correspond to early/late spring ice-out dates in North American lakes, is marked by differential sensitivities. Quantile regression framework offers conditional risk estimates of AFDD at a location as well as regional scale.

3.3 ENSO Patterns and Lake Ice Season Risk Assessments

It was noted in earlier sections that there are winter AFDD quantities that correspond to early/late spring ice-out dates for North American lakes. The efficacy of quantile functions in generating AFDD quantiles conditioned on ENSO indices can thus offer usable risk estimates for unusually early/late ice-out events in these lakes. For instance, figure 3a shows that for Lake Superior, winters with AFDDs less than 820 Degree-day Celsius

(DDC) ($\tau < 0.31^{th}$) are strongly associated with spring lake ice-out dates prior to March 30^{th}, and according to the climatology, the occurrence probability of such “mild winters” is 0.30. Please note that the method used here for determining the winter AFDD threshold is highly subjective and as such serves only for illustrative purposes only. To estimate the change in the conditional risk of early lake ice-out dates at Lake Superior due to ENSO patterns, a set of quantile functions for winter AFDD (that incorporate ENSO indices as covariates) were fitted at $\tau = 0.01$ intervals over the quantile range ($0.01 < \tau < 0.99$) and these function were used to compute winter AFDDs at the respective quantiles for sample combination of PC1-PC2 indices. Figure 3b shows the resulting conditional winter AFDD distribution as well as conditional risk of winter AFDDs less than 820 DDC for archetypical ENSO flavors (derived as centroids of PC1-PC2 index for the five selected EP, CP El Niño and La Niña events mentioned in the first result section). From these, it can be observed that during archetypical EP El Niño events, the likelihood of mild winters that engender early ice-out dates at Lake Superior increases by 2.16 times relative to that of the climatology (probability = 0.31). During typical CP El Niño pattern however, there is no significant change in the occurrence probability of early ice out dates at Lake Superior relative to that of the climatology. Contrary to the traditional assumption, this result highlights that the effect of different El Niño flavors on North American lake ice-out dates are not alike. Figure 3c extend the results in figure 3b to depict the change in risk (relative to that of the climatology) of early ice-out dates for sample combinations of PC1 and PC2 indices. Broadly speaking, the conditional risk of early ice-out dates at Lake Superior increases from region of negative PC1 and positive PC2 to a region of positive PC1 and negative PC2. This means that strong EP El Niño patterns (PC1 > 2 & PC2 < 0) are related to an increase the relative likelihood of early ice-out dates at Lake Superior by 1.2 - 2.5 times that of the climatology, while strong CP El Niño events (PC1 > 1 & PC2 > 0) correspond to a rise in the relative risk of early ice out dates by 0.9-2.4 times. On the other hand, La Niña events (PC1 < -1.5 & PC2 < 0) reduce the relative occurrence probability of mild winters by 0.6-1.

Diversity in the influence of different ENSO patterns on North American lake ice-out dates can be illustrated by contrasting the change in the likelihood of mild winters that produce early ice-out dates, due to the three archetypical ENSO patterns, for the eight North American lakes. Results reveal that the effect of ENSO pattern on the timing of North American spring lake ice-out dates varies both spatially and for different ENSO events (see Figure 4). For seven of the eight lakes, the archetypical EP El Niño pattern increases the likelihood of mild winters that correspond to early ice-out dates, by 1.5-2.8 times to that of the climatology, while for Deadman's Pond the occurrence probability of such winters decreases by 0.63 times relative to the climatology. In contrast, at Damariscotta Lake and Deadman's Pond, typical CP El Niño pattern decreases the likelihood of mild winters that are associated with early ice out dates, by 0.4-0.8 times to that of the climatology, while for the other six lakes it has modest or no effect on the risk of such winters. On the other hand, for Lake Albion (Deadman's Pond), archetypical La Niña pattern reduces (increases) the occurrence probability of mild winters by 0.46 (1.2) times to that of the climatology, while for the other six lakes, it is associated with modest or no changes in risk of early ice out dates. These results taken together show that for North American lakes, (a) the effect of EP El Niño on the timing of ice-out dates is quite distinct to that of CP El Niño from local-to-regional scale, (b) El Niño related changes in the timing of spring ice-out dates is not a linear opposite to that of La Niña events. As discussed in earlier sections, these effects stem from the asymmetry in the regional AFDD patterns associated with El Niño/La Niña flavors and distinctness of AFDD thresholds for ice-out dates among local lakes. Supplementary figure S6-S10 depicts the wintertime AFDD quantities that correspond to early ice out date in lakes and the results of the conditional risk analysis for sample combinations of PC1 and PC2 for the seven other lakes.

4. Discussion and Summary

ENSO-related warming/cooling in the tropical Pacific sea surface temperatures cause systematic shifts in the North American wintertime Accumulated Freezing Degree-days (AFDD) patterns. Winter AFDD governs the thermal flux between lake and atmosphere to grow lake ice, and early/late spring ice-out dates have been sensitively linked to seasonal winter AFDD thresholds. Consequently, changes in the magnitude and frequency ENSO has the potential to cause shifts and transitions in the ice regime of North American lakes. Our analysis of the response of spring ice-out dates to winter AFDD for select North American lakes reveals two important features. One is that for North American lakes, the relationship between winter AFDD and spring lake ice-out dates can be characterized from quasi-linear to highly non-linear. Second, in a number of these relationships, there are AFDDs (thresholds) that are strongly associated with specific ice out dates. Thus, the conditional quantile regression approach developed in this study allows a detailed characterization of quantile-specific ENSO-AFDD that can be readily used to estimate risk functions for AFDD and lake ice out conditioned on ENSO. Results for seven out of the eight North American lakes show that typical Eastern Pacific (EP) El Niño pattern is associated with an increase in the risk of low winter AFDDs (that produce early ice-out dates in these lakes) by 1.5-2.8 times to that of the climatology, while the typical Central Pacific (CP) El Niño pattern corresponds to a decrease or no significant change in the likelihood of early ice-out dates in these lakes. On the other hand, for Deadman's Pond (Lake Albion) the archetypical La Niña pattern induces an increase (decrease) the occurrence probability of early ice out dates by 1.2 (0.46) times relative to that of the climatology. To summarize: (a) the effect of CP and EP El Niño on the timing of spring ice-out dates of North American lakes is distinct from local-to-regional scale, (b) for North American lakes, the change in the timing of spring ice-out dates due to El Niño and La Niña patterns is not linearly opposite. In conclusion, we offer the following observations and discuss emerging research directions:

1. This work broadens current understanding of ENSO-related AFDD teleconnections for North America. In doing so, the relative contributions of ENSO flavors (delineated as the two leading pattern of tropical Pacific SSTs) in modulating AFDD distribution as a whole, and select AFDD thresholds (associated with lake ice-out dates) for North American regions was quantified.. Detection and evolution of ENSO events in the tropical Pacific is a well understood subject and as such, magnitudes of ENSO events are estimable up to 9 months in advance (e.g. Ramesh and Murtugudde, 2012; Hoskins, 2013). These imply that the ENSO-related conditional risk functions developed here pave the

way for use of seasonal and longer-lead ENSO forecasts that can be profitably used to anticipate shifts in lake ice out dates.

2. The quantile regression risk framework advanced in this study, while specific to lake ice out, is applicable to other lake variables to assess climate-related risk and vulnerability. While a linear approach was taken here, nonlinear and non-parametric approach can be used to model complex relationships (for example, ones involving lake chemistry).

3. Changing weather/climate patterns reflect trends and inter-annual variability (for example, due to ENSO). Resulting seasonal temperatures can disrupt the lake phenology and linked processes, species dynamics and succession, and nutrient loading and mixing characteristics. For instance, for temperate and arctic North American lakes, winter climate variability has directly or indirectly been shown to affect ice cover phenology and extent (e.g. Bai et al. 2012; Beyene and Jain 2015), water temperatures (e.g. Austin and Colman 2007), onset of stratification period (e.g. Winder and Schindler 2004), seasonal plankton composition, abundance and succession (e.g. Goldman et al. 1989; Hampton et al. 2017), fish population (e.g. Farmer et al. 2015) and seasonal geo-chemical dynamics (e.g. Joung et al. 2017; Powers et al. 2017). In a changing climate, successful conservation and restoration of lake ecosystems can benefit from climate-based risk framework presented here, thus affording pinpointed estimates of trends and transitions in lake variables. Finally, improved understanding and prediction of lake and river ice conditions has important environmental and socio-economic

(e.g. recreational, hydro-power generation, cultural, commercial) implications, a point underscored in recent studies (e.g., Prowse et al. 2011; Durnford et al., 2017).

REFERENCES

Assel, R., S. Drobot, and T. E. Croley. 2004. Improving 30-Day Great Lakes Ice Cover Outlooks. *Journal of Hydrometeorology*, 5(4): 713-717.

Assur, A. 1956. Airfields on floating ice sheets for regular and emergency operations. Snow Ice and Permafrost Research Establishment, Report no. 36, U. S Army Corps of Engineers, Wilmette, Illinois, USA.

Austin, J.A., and S. M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. *Geophysical Research Letters* 34, L06604

Bai, Xuezhi, Jia Wang, Cynthia Sellinger, Anne Clites, and Raymond Assel. 2012. Inter-annual variability of Great Lakes ice cover and its relationship to NAO and ENSO. *Journal of Geophysical Research*: Oceans 117(C3).

Barsugli, J. J., & P. D. Sardeshmukh. 2002. Global atmospheric sensitivity to tropical SST anomalies throughout the Indo-Pacific basin. *Journal of Climate*, 15(23), 3427-3442.

Beyene, M. T., and S. Jain. 2015. Wintertime weather-climate variability and its links to early spring ice-out in Maine lakes. *Limnology and Oceanography*, 60(6): 1890-1905.

Beyene, M.T. and S. Jain. 2017. North American wintertime temperature anomalies: the role of El Niño diversity and differential teleconnections. *Climate Dynamics*: 1-13. https://doi.org/10.1007/s00382-017-3880-x

Bissinger, Jan E., David JS Montagnes, and David Atkinson. 2008. Predicting marine phytoplankton maximum growth rates from temperature: Improving on the Eppley curve using quantile regression. *Limnology and Oceanography* 53(2): 487-493.

Bondell, H. D., B. Reich, & H. Wang. 2010. Non-crossing quantile regression curve estimation. *Biometrika*, 97(4), 825-838.

Bonsal, B. R., X. Zhang, L. A. Vincent, and W. D. Hogg. 2001. Characteristics of daily and extreme temperatures over Canada. *Journal of Climate* 14(9): 1959-1976.

Bowman, Adrian W., and Adelchi Azzalini. 1997. *Applied smoothing techniques for data analysis: the kernel approach with S-Plus illustrations*. Vol. 18. OUP Oxford.

Caesar, J., L. Alexander, and R. Vose. 2006. Large-scale changes in observed daily maximum and minimum temperatures: Creation and analysis of a new gridded data set. *Journal of Geophysical Research: Atmospheres*, 111, D5.

Cai, W., S. Borlace, M. Lengaigne, P. Van Rensch, M. Collins, G. Vecchi, and others. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2), 111-116.

Durnford, D., V. Fortin, G.C. Smith, B. Archambault, D. Deacu, F. Dupont, S. Dyck, Y. Martinez, E. Klyszejko, M. Mackay, L. Liu, P. Pellerin, A. Pietroniro, F. Roy, V. Vu, B. Winter, W. Yu, C. Spence, J. Bruxer, and J. Dickhout. 2017. Towards an operational water cycle prediction system for the Great Lakes and St. Lawrence River. *Bull. Amer. Meteor. Soc.,* https://doi.org/10.1175/BAMS-D-16-0155.1

Farmer, T.M., E.A. Marschall, K. Dabrowski and S.A. Ludsin. 2015. Short winters threaten temperate fish population. *Nature Communications* 6: 7724

Feng, Xingdong, Xuming He, and Jianhua Hu. 2011. Wild bootstrap for quantile regression. *Biometrika*, 98(4): 995.

Fielding, Samuel R. 2013. Emiliania huxleyi specific growth rate dependence on temperature. *Limnology and Oceanography* 58(2): 663-666.

Goldman, C.R., A. Jassby, and T. Powell. 1989. Interannual fluctuations in primary production: meteorological forcing at two subalpine lakes. Limnology and Oceanography 34(2) 310-323.

Hampton, S. E., A. Galloway, S. Powers, T. Ozersky, K. H. Woo, and others. 2017. Ecology under lake ice. *Ecology Letters*. 20: 98–111.

Hampton, S.E., A.W. Galloway, S.M. Powers, T. Ozersky, K.H. Woo, R.D. Batt, S.G. Labou et al. 2017. Ecology under ice. *Ecology Letters* 20(1) 98-111

Hoerling, M., A. Kumar, & M. Zhong. 1997. El Niño, La Niña, and the nonlinearity of their teleconnections. *Journal of Climate*, 10(8), 1769-1786.

Hoerling, M. P., & A. Kumar. 1997. Why do North American climate anomalies differ from one El Niño event to another? *Geophysical Research Letters*, 24(9), 1059-1062.

Hoskins, B. 2013. The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science. Quarterly *Journal of the Royal Meteorological Society*, 139(672): 573-584.

Joung, D., M. LeDuc, B. Ramcharitar, Y. Xu, P. Isles, J. D. Stockwell, G.K. Druschel, T. Manley and A. W. Schroth. 2017. Winter weather and lake-watershed physical configuration drive phosphorous, iron and manganese dynamics in water and sediment of ice covered lakes. Limnology and Oceanography 62(4) 1620-1635.

Koenker, R., & G. Bassett Jr. 1978. Regression quantiles. *Econometrica: journal of the Econometric Society*, 33-50.

Koenker, R. & K. Hallock. 2001. Quantile regression: An introduction. *Journal of Economic Perspectives*, 15(4), 43-56.

Koenker, R. (2017). quantreg: Quantile Regression. R package version 5.34. https://CRAN.R-project.org/package=quantreg

Leppäranta, M. 2014. *Freezing of lakes and the evolution of their ice cover*. Springer Science & Business Media

NCSU. 2010. URL: http://www4.stat.ncsu.edu/%7Ebondell/Software/NoCross/NoCrossQuant.R

Powers, S. M., & Stephanie E. Hampton. 2016. Winter Limnology as a New Frontier. *Limnology and Oceanography Bulletin*, 25(4): 103-108.

Powers, S.M., S.G. Labou, H.M. Baulch, R.J. Hunt, N.R. Lottig, S.E. Hampton, and E.H. Stanley. 2017. Ice duration driver winter nitrate accumulation in north temperate lakes. *Limnology and Oceanography* 2(5) 177-186

Preston, Daniel L., Nel Caine, Diane M. McKnight, Mark W. Williams, Katherina Hell, Matthew P. Miller, Sarah J. Hart, and Pieter TJ Johnson. 2016. Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. *Geophysical Research Letters* 43(10): 5353-5360.

Salonen, K., M. Leppäranta, M. Viljanen, & R. Gulati. 2009. Perspectives in winter limnology: closing the annual cycle of freezing lakes. *Aquatic Ecology* 43(3): 609-616.

Scheffer, M., D. Straile , E. van Nes, & H. Hosper. 2001. Climatic warming causes regime shifts in lake food webs. *Limnology and Oceanography*, 46(7): 1780-1783.

Silverman, Bernard W. 1986. *Density estimation for statistics and data analysis*. Vol. 26. CRC Press.

Wetzel, Robert G. 2001. *Limnology: lake and river ecosystems*. Gulf Professional Publishing.

Weyhenmeyer, Gesa A., David M. Livingstone, Markus Meili, Olaf Jensen, Barbara Benson, and John J. Magnuson. 2011. Large geographical differences in the sensitivity of ice‐covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology* 17(1): 268-275.

Winder, M., and D.E. Schindler. 2004. Climatic effects on the phenology of lake processes. *Global Change Biology* 10(11) 1844-1856

Wyrtki, Klaus. 1975. El Niño—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *Journal of Physical Oceanography* 5(4): 572-584.

Xu, Yaoyang, Andrew W. Schroth, and Donna M. Rizzo. 2015. Developing a 21st Century framework for lake‐specific eutrophication assessment using quantile regression. *Limnology and Oceanography: Methods* 13(5): 237-249.

Yeh, S. W., J. Kug, B. Dewitte, M. Kwon, B. Kirtman, & F. Jin. 2009. El Niño in a changing climate. *Nature*, 461(7263), 511-514.

ACKNOWLEDGEMENTS

NCEP Reanalysis data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/

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Table 1: Ratio of conditional likelihood of selected winter AFDDs over lakes due to ENSO events, to that of the unconditional. Results are computed using the same techniques as in figure 3b.

Table 1: Ratio of conditional likelihood of selected winter AFDDs over lakes due to ENSO events, to that of the unconditional. Results are computed using the same techniques as in figure 3b.

Lake	Ice out dates corresponding to winter AFDD		Unconditional probability of W* for the 1951-2010 period	Conditional risk relative to the Unconditional probability		
	Winter threshold (W*) in DDC units	Ice-out Date corresponding to W*		Eastern Pacific El Niño	Central Pacific El Niño	La Niña
Damariscotta	200	3-April	0.14	1.57	0.78	0.93
Superior[#]	820	31-March	0.31	2.16	1.06	0.83
Winnipeg	2015	13-May	0.26	3.3	0.43	1.06
Lesser Slave	2170	13-May	0.28	1.67	0.93	0.82
Dease	2170	28-May	0.1	1.7	1.2	0.5
Deadman's Pond	1735	3-May	0.3	0.63	0.7	1.2
Long	2730	26-May	0.2	2.5	0.85	0.7

AFDD- Accumulated Freezing Degree days

DDC- Degree-day Celsius

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Figure 1: Climatology of winter Accumulated Freezing Degree Days (AFDD) over North America and its relationship with lake ice-out dates. North American map of the (a) mean, (b) standard deviation of winter AFDDs from 1951-2010. Contour intervals for the mean and standard deviation winter AFDD are set at 300 and 40 Degree-day Celsius (DDC) respectively. The red coloured polygons represent the location of the eight selected lakes. Plotting lake ice-out dates as a function of winter AFDD at (c) Dease Lake (d) Lesser Slave Lake (e) Lake Winnipeg (f) Lake Albion (g) Deadman's Pond (h) Damariscotta Lake (i) Lake Superior (j) Long Lake. The filled/unfilled polygons in each scatter plot represent the ice out date as a function of winter AFDD for each lake. The red line denotes locally averaged lake ice out date conditioned on the winter AFDD, and is computed using non-parametric kernel regression method. The blue shadings designate the 90% confidence band for a linear model.

Figure 2: Composite maps of tropical Pacific winter SST warming/cooling and associated North American winter Accumulated Freezing Degree-days (AFDD) anomalies for select five (a) Central Pacific (CP) El Niño (b) Eastern Pacific (EP) El Niño (c) La Niña events. These events were chosen by majority consensus across different identification methods in the literatures (see Supplementary Table 3). Anomalies are computed as departure from the 1951-2010 average and contour intervals for winter AFDD and SST anomalies are 40 Degree day Celsius (DDC) and 0.25° Celsius respectively. Stippled areas denote regions where the departure is significant at 90% confidence level based on two-tailed re-sampling tests.

Figure 3: Risk estimates for winter Accumulated Freezing Degree-day (AFDD) quantities, corresponding to spring ice-out dates earlier than April 1st at Lake Superior, conditioned on different El Niño /Southern Oscillation patterns. (a) Scatter plot for spring ice-out dates at Lake Superior as a function of the antecedent winter AFDD. The grey unfilled circles denote the winter AFDD associated with observed ice out dates. The purple line represents

locally averaged lake ice-out dates conditioned on the winter AFDD, and is computed using non-parametric kernel regression method. The blue shadings denote the 90% confidence band for computed regression line. (b) Conditional winter AFDD distribution at Lake Superior associated with the three archetypical ENSO patterns: CP El Niño (blue), La Niña (green) and EP El Niño (red). The grey area represents part of the conditional distribution less or equal to 820 Degree-day Celsius (DDC),. The conditional winter AFDD distribution curves for typical ENSO patterns was constructed by generating conditional quantile functions for estimating winter AFDD at $\tau = 0.01$ intervals over the quantile range ($0.01 < \tau < 0.99$), followed by estimation of winter AFDD quantiles at the centroid of five selected samples of ENSO flavours in the PC1-PC2 phase space. (c) Contour surface plot of estimated conditional risk for winter AFDD at Lake Superior to be less or equal to 820 DDC, relative to the unconditional (climatology). The dark filled circles represent the PC1-PC2 indices for the three archetypical ENSO patterns, while the grey polygon represents the convex hull – region containing observed PC1-PC2 values. The colour key for ratio of risk conditioned on PC1-PC2 values is given at the bottom.

Figure 4: Risk estimates for winter Accumulated Freezing Degree-days (AFDD) quantities (thresholds), corresponding to early ice-out dates for selected North American lakes, conditioned on three archetypical ENSO patterns. At each lake, the blue, green and red curves denote the conditional winter AFDD distribution associated with Central Pacific (CP) El Niño, La Niña and Eastern Pacific (EP) El Niño respectively, while the black curve represents the unconditional winter AFDD distribution for the 1951-2010 period. The steps by which the conditional distributions are generated are given in the caption for figure 3b. The grey area signifies part of the conditional distribution less or equal to specific AFDD threshold (broken black line). The confidence intervals for risk estimates was determined by computing the occurrence probability of each year conditioned on its PC1-PC2 index and determining the 5^{th} and 95^{th} percentile from the time series of risk estimates. Conditional non-exceedance probability (risk) estimates in bold are significant at 10% significance level.