International Journal of Environment and Climate Change

9(1): 29-43, 2019; Article no.IJECC.2019.003
Previously known as British Journal of Environment & Climate Change
ISSN: 2231–4784

Explaining the Non-significant Changes in Ice-off Date over Six Decades at Lake of Bays and Lake Nipissing, South-Central Ontario

Huaxia Yao[1*] and Congsheng Fu[2]

[1]Dorset Environmental Science Centre, Ontario Ministry of Environment, Conservation and Parks, 1026 Bellwood Acres Road, Dorset, Ontario, P0A 1E0, Canada.
[2]Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, P. R. China.

Authors' contributions

This work was carried out in collaboration between both authors. Author HY conceived the idea, prepared datasets, conducted most analysis and calculation. Author CF conducted the MRA analysis. Both authors wrote the manuscripts. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2019/v9i130095

Received 07 November 2018
Accepted 19 January 2019
Published 01 April 2019

Original Research Article

ABSTRACT

The phenomenon of non-significant trends in ice-off date under a warming climate was quantitatively explained by three efforts: exploring possible driving factors where possible and defining new factors to represent snow conditions, identifying the contributing factors through correlation and trend tests, and evaluating relative contributions through partial Mann-Kendall method. Why the ice-off became only slightly earlier over 62 years at Lake of Bays has been satisfactorily assessed: the increased winter temperature, increased total rain and decreased days of snow on ground acted as three promoting drivers to earlier ice-off date, but their promoting functions were effectively offset by adverse changes in four other factors (snowfall slope, precipitation slope, snowpack slope, and last day of snow). The ice-off date at Lake Nipissing did not have a significant trend over 58 years, although there were five factors contributing to the ice-off decline without sufficient offsetting, suggesting that the ice-off of this lake may not be sensitive, or basically elastic, to the climatic variation stressor. Relative contributions of drivers as calculated helped explain how much they contributed to ice-off trends or how much they offset the influences.

Keywords: Ice-off date; non-significant trend; drivers; offsetting; relative contribution; Central Ontario.

**Corresponding author: E-mail: huaxia.yao@ontario.ca;*

1. INTRODUCTION

Ice phenology (ice-on and ice-off dates, ice cover duration) has been monitored, researched and analyzed at multiple temporal and spatial scales, either being served as a proxy for climate changes, or being used as an indicator of freshwater health condition, infrastructure (like winter road) and recreation purposes. Ice phenology studies are summarized in a few reports [1,2,3,4,5,6,7,8]. It is important for environmental and biological sciences to fully understand the variations in ice dynamics and phenology, especially for climate changed related researches such as global glaciers [9], global patterns of lake ice [10], effective sentinels of climate change [11], projection of climate change impacts [12], thermal regime and water level [13], and lake-climate interactions [14].

A generalized and consistent impact has been formulated for the ice-on date (or formation date): becoming later or delayed over long-term period (>50 years) at lakes and rivers around the world due to climate warming or change, with the changing trend being significant at most places. The impacts regarding ice-off date (or breakup date) are not as clear and consistent as for ice-on. Apart from a number of reports saying that lake ice-off has occurred earlier temporally across various regions [5], there are a few reports of long-term ice-off records that indicated no significant changing trends or even becoming oppositely delayed (e.g. [2,8]). For example, ice-off records from the south-central Ontario region (east of Georgian Bay, Lake Huron) indicated weak or undetectable changes. The 35-year data at Dickie Lake of this region showed a non-significant trend in ice-off [8]; a possible reason being that the increased air temperature was offset by increased snowfall, reduced wind was mentioned but not detailed. The trends and periodic changes in ice-off dates at ten inland lakes of the same region [2] indicated that none of them showed a significant changing trend (*P* value > 0.18), with five records indicating a tendency of ice-off advancing (appeared earlier), and another five indicating a tendency of ice-off delaying (appeared later). Six climatic variables reflecting temperature and snow condition were identified as possible drivers to the ice-off changes. However, how they determined or contributed to the non-significant ice-off trends was not explained.

Under a general trend of global climate warming over last century, ice-off would have followed a trend of appearing earlier as the majority of reports have reported. But some lakes or regions showed a different story. A few possibilities or reasons have been proposed/mentioned regarding the non-significance in ice-off date: changes in climatic variables other than air temperature (such as snowfall, precipitation, wind speed, snowpack features like days of snow-on-ground, etc.) may contribute to or affect the ice growth and decaying process, and thus offset or reduce the driving force of climatic warming [2,8]. However, the phenomenon of non-significant changes in ice-off has not been well explained.

It is necessary to explain the phenomenon of non-significant changes in ice-off date, as some key drivers or reasons might have been over-looked in previous studies, and a predictive model/relationship of ice-off would not provide sound future predictions if the full range of drivers were not considered. So, we looked into the ice and climate data from two sites of the south-central Ontario region: Lake of Bays over 62 years of 1955 to 2016 and Lake Nipissing over 58 years of 1955 to 2012, and tried to explain the phenomenon using both old and new drivers and from new perspectives. We focused on three hypotheses or questions. (a) The influential or driving factors to the ice-off changing trend are multiple and should be identified where possible. (b) Ice-off change may not be sensitive, or may even be quite elastic, to climate change stressors within certain regions, such as south-central Ontario; the changed climate in 1955-2016 may not be strong enough to make a significant response in the ice-off trend. (c) There are offsetting (contradicting) factors, which may be the reason for the non-significance in ice-off change, or may help to explain the non-significance.

2. MATERIALS AND METHODS

2.1 Lake of Bays

Lake of Bays is a medium-sized lake in the District Municipality of Muskoka in south-central Ontario, Canada (Fig. 1). The lake is fed by Oxtongue River, as well as other smaller rivers and creeks flowing from the north-east. Its outflow is the Southern Branch of Muskoka River. Lake of Bays is a deep, cold, infertile lake which forms an important part of the Muskoka watershed and eventually drains into Georgian Bay of Lake Huron. The water is clear, and the maximum secchi disc reading obtained was 8 m.

The surface layer varies in temperature throughout the year. In the summer months of July and August, the surface layer can have an average temperature approaching 21°C, while the top few metres can warm to extremes of about 26.5°C. Below the top layer, the summer temperature drops rapidly to around 7°C.

The lake surface area is 70.53 km^2, with an average depth of 22.25 m and maximum depth of 70.10 m. Its water volume is 1,567,519,824 m^3 or 1.568 km^3, with a shore length of 170.59 km, and its surface elevation is 315.5 meters. The ice-off date was observed and recorded by a local family and their parents/grandparents, at Haystack Bay (the central bay area of the lake, marked by a red circle in the figure), from 1908 up to the present year. They used common sense to judge when the ice is gone from the bay area by observing from their home or the shore, it is an ice-off date.

Daily climate data of maximum, minimum and mean temperature, snowfall, rainfall and precipitation in a day, and snowpack depth on the ground are available from Environment Canada and Climate Change weather stations in the Muskoka region. The Huntsville station, located about 15 km northwest of the lake, is the main station used for the study. Missing data are infilled by the data at two other weather stations: Beatrice which is 25 km west of Lake of Bays, and Muskoka Airport which is 20 km southwest of the lake. Climate data for temperature and precipitation are available since 1879, however snow depth on ground data was not started until 1955. For this reason we chose 1955-2016 to be our study period.

2.2 Lake Nipissing

Located to the east of upper Georgian Bay, Lake Nipissing is the third-largest lake in Ontario, excluding the Great Lakes, with an area of 873 km^2, a volume of 3.8 km^3, and an elevation of 196 m. It is shallow with a mean depth of 4.5 m and maximum depth of 52 m. Its drainage streams are distributed mainly on the eastern and northern sides, and outflows through the French River to the west into Georgian Bay.

The ice-off date was recorded by local communities since 1901 and posted for public (i.e. newspaper Nugget, http://www.nugget.ca/2015/05/05/ice-off-lake-nipissing). Daily climate data of the same parameters were obtained from the Environment Canada and Climate Change station located at North Bay Airport which is close to the lake. Climate data for temperature and precipitation started from 1939, but data of snow depth on ground started from 1955 and lasted to 2012. So we used 1955-2012 as the analysis period for Lake Nipissing case.

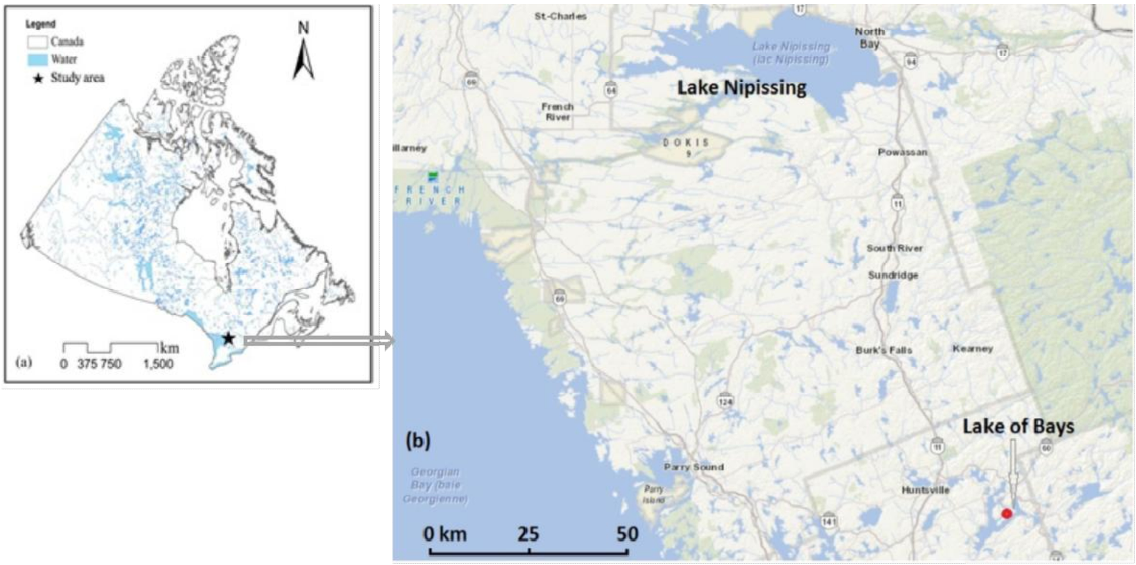

Fig. 1. Study area and lakes

(a) Location of study area (marked by the star) in Canada; (b) Lake Nipissing and Lake of Bays

2.3 Evaluation Methods

According to past experience and reports, significantly increased winter temperature would force or drive the ice-off to appear significantly earlier, or in other words, a clear trend in air temperature over a long time would cause a clear trend in ice-off date. If such a clear trend in ice-off is not evident, it is indicated there are other contributing factors related to ice-off adversely affecting its trend, offsetting the effect of the increase in temperature. Ice-off dates at Lake of Bays have a nearly flat linear trend line over 1908-2016, appearing slightly earlier by 2.96 days per 100 years, which is not statistically significant (Mann-Kendal *P* value is 0.458). It has a weak and non-significant decline trend over 1955-2016 (P=0.33), appearing 0.86 days earlier per decade. The ice-off records at Lake Nipissing have a flat linear trend line over 1901-2015, showing a slight increasing (delaying ice-off) tendency of 1.4 days per 100 years. It has a weak and non-significant decline trend over 1955-2012, appearing 0.89 days earlier per decade. Every possible driving factor or explanatory variable should be checked and considered to explain this phenomenon of less-than-expected ice-off changes.

2.3.1 Factors to consider: especially new factors

Air temperature has been identified as the most determinable or sometimes the single driver to analyze ice-off data series (e.g. [2,8,15, 16,17,18]). Apart from the temperature, possible explanatory factors mentioned in literature include: snowfall or rainfall amount during a season, snowpack depth, days of snow-on-ground during the season, and last day of snow-on-ground, which are mostly associated with snow conditions (e.g. [2,3]).

The dual-sided or two opposite functions of snowfall or snowpack on the ice-off (or ice dynamics) were noted [8,19]. A layer of snow over the ice can act as a heat insulation media and reduce the cold delivering from ambient airmass to the ice body, and therefore reduce the speed of ice growth throughout the winter, which may lead to earlier melting of the thinner ice body. On the other hand, the heat insulation of snowpack may reduce the heat delivering from the warm air to the ice body during ice melting days, which may lead to slower ice melting. This feature of snowpack influence has not been explicitly expressed or explored in a statistical analysis of ice phenology, to our best knowledge of ice date researches.

We propose that the timely distribution of snowfall or snowpack within a winter season may play an important role in determining ice-off date, probably even more important than the snowfall amount (or snowpack depth) itself. This distribution can partly reflect or represent the above-mentioned dual-sided functions of snowpack. If the snowfall happens more in an early stage like December to February, the accumulated snowpack will help insulate cold air from lake ice body and reduce the ice growth rate, and the less snowpack remaining in late stage (March, April; thinner than at its early stage) will not substantially block the warm air from melting the ice. The composite result of such a snowfall distribution within a season is a thinner ice layer and faster ice melting, thus promoting an earlier ice-off date. To the contrast, if the snowfall happens more in a late stage (more snows in later months than earlier months), the less snowpack in the early stage will promote greater ice growth, and the more snowpack in the late stage will insulate more heat from melting the ice, eventually producing a delayed ice-off.

To express this concept of timely distribution, four new explanatory factors are defined and designed as the tilting (or leaning) slope of distribution of monthly amount within a winter season. Considering the fact that lake ice exists mostly in December throughout April, monthly snowfall during the five months are used to calculate a factor named “slope of snowfall”. Fig. 2a shows the factor “slope_snowfall”: the blue dots indicate monthly snowfall amount for a winter (year 1984) with early snowfall, its distribution in the winter produces a largely negative tilting slope (-48.8 mm/month). The red dots in Fig. 2a indicate a quite even distribution of monthly snowfall in a different winter (year 2004) and produces a much flatter tilting slope (-7.4 mm/month). Similarly, the factor “slope_precipitation” is defined for precipitation based on monthly precipitation data (Fig. 2b), and “slope_snowpack” is defined for snowpack depth (Fig. 2c). The fourth factor “slope_rain” is not shown in the figure. They are used to express how the variable is distributed over the five months.

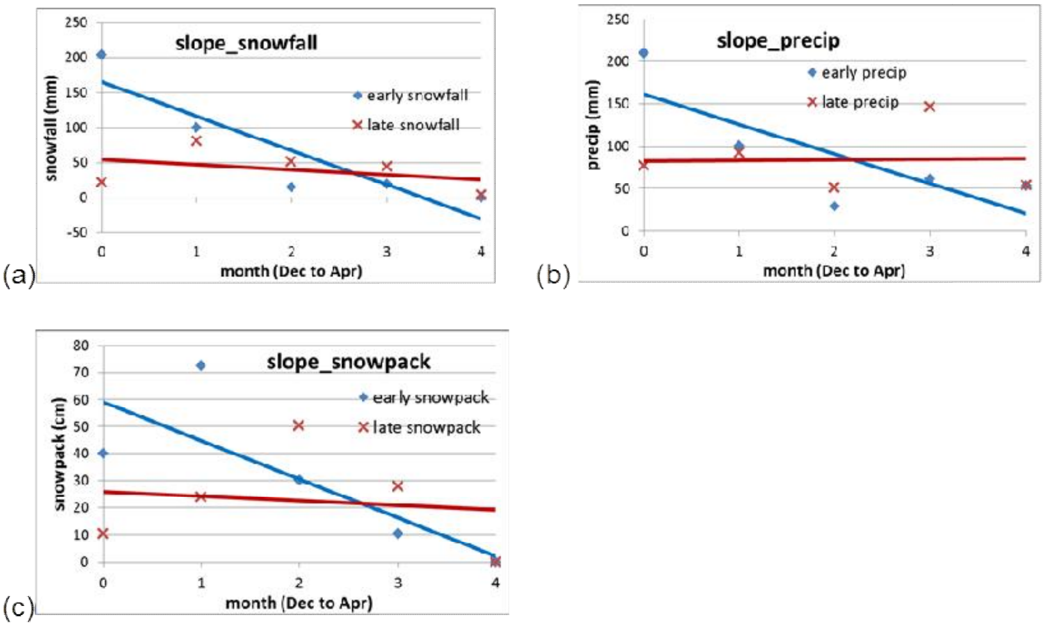

Fig. 2. Factors of tilting slope

2.3.2 The period for analyses and potential factors

Because the available data of snowpack on ground started from 1955, we consider the study period of 1955-2016 for conducting our analysis at Lake of Bays, and the period of 1955-2012 at Lake Nipissing. All ten possible factors are checked where possible, including: air temperature, slope_rain, slope_snowfall, slope_precipitation, slope_snowpack, total snowfall, total rainfall, mean snowpack depth, days of snow-on-ground, last day of snow-on-ground.

The objective or responsive variable is ice-off date. The air temperature is the mean of daily-mean temperature over five months (Dec to Apr). Slope_rain, slope_snowfall, slope_precipitation and slope_snowpack are defined as above, having a number for an individual season. The slope_snowpack is the tilting slope for snowpack depth, similarly defined as the slope_snowfall. These four explanatory factors are associated with timely distributions in a winter season. The total snowfall or total rainfall is the sum of monthly snowfall or rainfall, over the same five months; the mean snowpack depth is the average of daily snowpack depth over five months; the days of snow-on-ground is the total number of days with snow on the ground; and the last day of snow-on-ground is the Julian date for the last day with snow on the ground. The four slope factors are newly proposed and considered. The other six factors were once considered in previous reports [2], but their contributions to the non-significant trend in ice-off have not been clarified.

2.3.3 Judgement criterion for contribution

Whether or not a factor made a contribution to the changes in ice-off date is judged by the Pearson correlation coefficient (R) and the trend as detected by a Mann-Kendall test. If the correlation between ice-off and any factor passes a significance threshold of 0.1 (used for our study here), or if the M-K trend of this factor is significant ($P < 0.1$), it is identified as a contributing factor, otherwise it is omitted out. Whenever a factor does not have a significant correlation or a trend, it is not a contributing factor.

What kind of contribution a contributing factor made to the ice-off is identified by the sign of the correlation coefficient R and the strength or significance of the trend in that factor. A positive sign in correlation R means a positive contribution: a trend of increase in the factor contributes to increase the ice-off (becoming later), and a trend of decrease in the factor contributes to decrease the ice-off (becoming earlier). A negative sign in R means a negative or opposite contribution: a trend of increase (e.g.

air temperature) contributes to decrease the ice-off (becoming earlier).

There could be three kinds of contribution strength or situation. (i) When the contributing factor has a strong or significant changing trend over time (i.e. its $P < 0.1$), it usually makes a strong contribution to the trend in ice-off. (ii) When the factor has a weak and non-significant trend, its contribution to ice-off trend must also be weak, but it is not neglected. A combined influence of several factors with weak contribution may have caused enough power to offset the influence of another factor with strong contribution (details in the results section). (iii) When the factor has a very weak trend or simply no trend, its contribution to ice-off should not be simply ignored either, because the no-trend feature in the factor could assist in stabilize the ice-off date, contributing to its non-trend phenomenon. By synthesizing the different, probably offsetting or opposite contributions of multiple factors, the non-significant trend in ice-off under a climate warming background can be explained.

2.3.4 Nonlinear trends

Wavelet analysis is a powerful tool of analyzing long-term time series in the Earth sciences [20]. By implementing the discrete wavelet transform (DWT) in the pyramid algorithm [21], the multi-resolution analysis (MRA) can decompose the time series or signal into approximation (A) and detail (D) components by successively translating and convolving the elements of a high-pass filter and low-pass scaling filter associated with the mother wavelet [22]. MRA decomposes a time series based on frequency/periodicity. For example, if a time series includes periodicities of 2–32 years, MRA first decomposes the time series into an approximation component including periodicities of 4–32 years (A1) and a detail component including periodicities of 2–4 years (D1); then the approximation component A1 is decomposed into an approximation component including periodicities of 8–32 years (A2) and a detail component including periodicities of 4–8 years (D2), and so on.

In the present study, multidecadal trends obtained using MRA are used. The multidecadal trends for MRA are obtained by subtracting the detail components with periodicities ≤ 20 years from the original time series. The nonlinear, multidecadal trends in ice-off and contributing drivers are compared to indicate their response features: the driver being promoting or offsetting the ice-off trend.

2.3.5 Relative contributions

To assess relative contributions of individual drivers to a given response variable, the Partial Mann-Kendall trend test is utilized [23,24]. The long-term trend in observed data of ice-off date (response variable) is detected first by a regular Mann-Kendall test, giving a Mann-Kendall statistic Z which indicates the direction and strength of the trend. A positive (or negative) statistic value means an increase (or decrease) trend, and its absolute magnitude value means the trend strength (the larger the stronger). At the same time, a M-K P value determines the significance of the trend (threshold 0.1 is used here).

Contributing drivers to ice-off date (judged or identified by the Pearson correlation coefficient R and the M-K trend as mentioned above) have their individual influence on the dynamics of ice-off. By treating each driver as a covariate and running a Partial M-K test for the same ice-off data, a new value of M-K statistic, Zi (i is the i-th driver), is obtained with the influence of this driver on the ice-off trend being “removed” statistically [23]. In another word, the difference ($Zi - Z$) indicates how large the influence would be: a big difference means a big influence, otherwise a small influence. Similarly conducting the Partial M-K test to all other drivers separately and removing their individual influence, the differences (or changes) in the M-K statistic index are obtained, named as Di. The relative or percent contribution of each driver to the ice-off trend is defined as:

$$Cont = Di / \text{Sum}(Di) * 100 \qquad (1)$$

Note that the Di can be both positive and negative and their sum can be less than the sum of absolute values of Di. As a result, a percent contribution of one driver may be larger than 100%, which means to compensate for the opposite contribution of another driver with negative contribution percentage.

3. RESULTS

3.1 Lake of Bays

3.1.1 Time series of variables and their trends

Annual time series of ice-off date and ten potential factors showed different changing trends (Fig. 3). Ice-off did not have a significant trend (*P*=0.33; Table 1), only showing a weak decline tendency of 0.86 days per decade. Among the ten factors, the air temperature had a significant trend of increase: 0.16 ^{0}C per decade (*P*=0.083; Table 1). The total rain in a season had a significant increasing trend (*P*<0.001) although it did not have significant correlation with ice-off (*P*=0.928). All other factors did not have any significant trends (Table 1; Fig. 3).

Based on calculated correlation coefficients of ice-off and any of the factors (Table 1), six factors were identified as contributing ones (their *P* <0.1): air temperature, slope_snowfall, slope_precipitation, slope_snowpack, days of snow-on-ground, and last day of snow-on-ground. Together considering the significance of trends, totally seven factors were identified as "contributing" drivers (adding the total rain).

3.1.2 Contributions and offsetting

Among seven contributing drivers, the air temperature was strongly correlated to ice-off and had a strong increasing trend (Table 1), therefore it was the major driver to shape a tendency of earlier ice-off. But the ice-off trend was not as strong as the temperature, and several other factors should have played an adverse or offsetting role. Any individual slope factor for snowfall, precipitation and snowpack depth did not have a high correlation to the ice-off and not have a clear trend, but they all had a tendency of increase. An increase in these slopes meant relatively more snow covering in the later stage (Feb to Apr) than in the earlier stage (Dec to Feb), which could help to delay ice-off. Most probably, just one of these offsetting factors would not function sufficiently or remarkably to compensate for the influence of increased air temperature. However, their combined power could lead to a sufficient or accountable compensation and produce a non-significant trend in the ice-off.

The last two factors, the days of snow and last day of snow, had both high correlations with ice-off, without a clear long-term trend. The increasing trend (or delaying) in the last day of snow on ground could also contribute to delay the ice-off and formulate the non-significance in ice-off. Therefore, it is possible that the four factors (snowfall_slope, precipitation_slope, snowpack_slope, last day of snow) have worked together to offset the driving effect of increased air temperature, causing only a weak change in ice-off under a strong warming background.

It is noted that the correlation *R* with snowfall slope or snowpack slope is larger than the correlation with total snowfall, which meant that the timely distribution of snow covering in a season could play a greater role in offsetting the ice-off trend than did the total snowfall of the season. Only knowing whether the snowfall has changed does not fully explain the specific ice-off change; knowing the change in snowfall distribution over a winter season is also needed. The functioning mechanism of total rainfall change on ice-off has not been well understood. It was negatively correlated to ice-off and had a strong trend of increase over time, as a result its change could help to push the ice-off earlier.

Table 1. Correlations and trends in ten drivers at Lake of Bays (1955-2016)

	Correlation of ice-off and a driver R	**Significance level of the correlation P**	**MK trend and its p-value [trend, P]**
Temperature	-0.552	**<0.001**	**[+, 0.083]**
Rain slope	0.111	0.39	[+, 0.725]
Snowfall slope	0.221	**0.084**	[+, 0.851]
Precipitation slope	0.260	**0.041**	[+, 0.365]
Snowpack slope	0.265	**0.037**	[+, 0.894]
Total snowfall	0.125	0.332	[+, 0.927]
Total rain	-0.012	0.928	**[+, 0.0001]**
Snowpack depth	0.206	0.108	[-, 0.693]
Days of snow	0.514	**<0.001**	[-, 0.976]
Last day of snow	0.669	**<0.001**	[+, 0.697]
Ice-off			[-, 0.33]

Note: the bold font in the first column indicates a contributing factor. The sign for a R value in the second column indicates a positive or negative correlation. The bolded P values in the third column indicate a significant correlation. The sign for a trend in the fourth column indicates an increase or decrease trend, and the bolded values indicate a significant trend

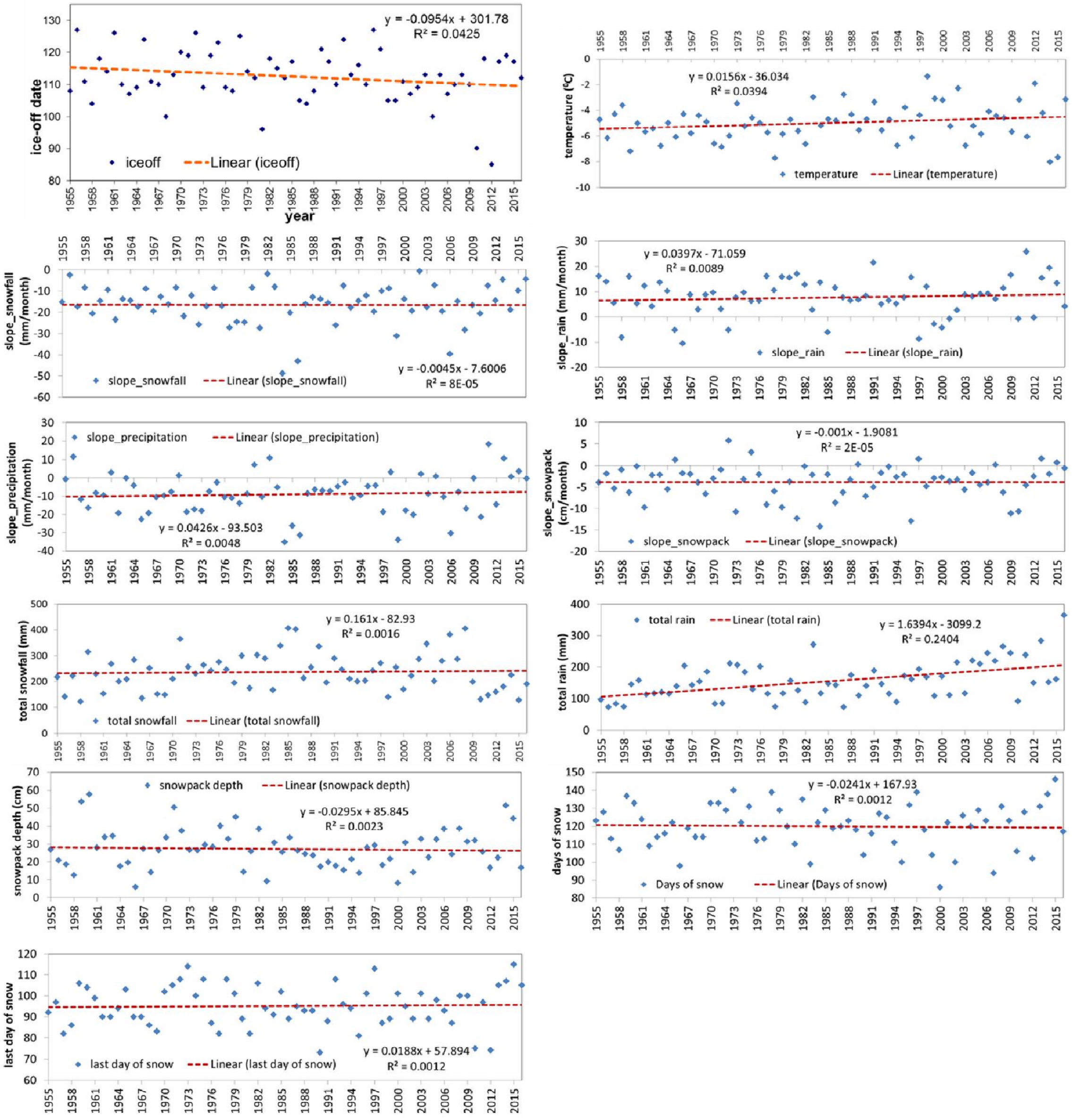

Fig. 3. Annual series of ice-off and ten potential factors at Lake of Bays

3.1.3 Confirmation of various influences of drivers on ice-off trend

The non-linear trends as detected and expressed by the Multi-Resolution-Analysis (MRA) method are showed in Fig. 4, with each sub-figure comparing the ice-off trend and the trend of one driving factor. Contributing features (either promoting or offsetting the ice-off decline trend) need to be judged by the physical relationship (or functioning mechanism) between two of them. Increased air temperature caused earlier ice-off, acting as a main promoting driver (Fig. 4a). Increasing slope of rain placed more rainfall in late winter and should help push earlier ice-off (promoting the ice-off decline trend), although it actually did not play an accountable role (Fig. 4b, Table 1). The increases in slope of snowfall, slope of precipitation and slope of snowpack depth all placed increased snows in the late winter period, causing ice-off delaying or offsetting the ice-off decline trend (Fig. 4c, d, e). Total snowfall volume and total rainfall had opposite contribution: the increasing snowfall offset ice-off decline (Fig. 4f), whereas the increasing rainfall promoted ice-off decline

(Fig. 4g). The decreased snowpack depth promoted ice-off decline (Fig. 4h), although its role was very limited. The changes in days of snow on ground promoted ice-off decline (Fig. 4i), while the changes in last day of snow on ground offset ice-off decline (Fig. 4j). All of these comparisons confirmed what have been found in above section, in terms of promoting and offsetting drivers.

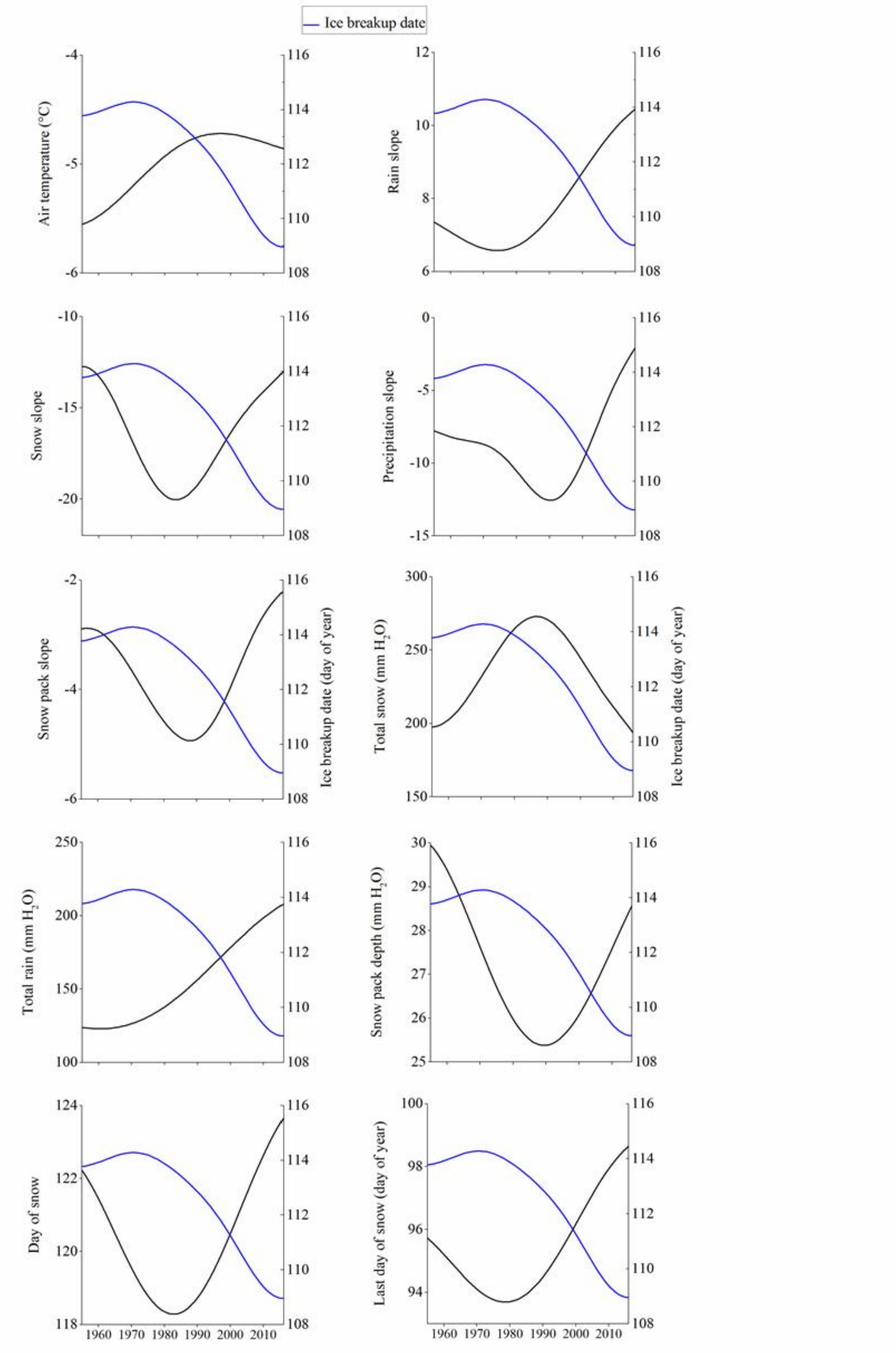

Fig. 4. Comparison of nonlinear trends between ice-off and each driving factor

3.1.4 Relative contributions to ice-off decline

The correlations between ice-off and individual drivers (Table 1), temporal trends (Fig. 3) and comparison of trends (Fig. 4) indicated or revealed how these drivers had acted/contributed to the ice-off trend, by telling their; promoting, offsetting or no contribution factor. But a quantitative evaluation of the contributions was not yet provided. The 62-year ice-off dates had an M-K statistic of -160.0, with a *P*=0.33. Contributing drivers were identified as seven: air-temperature, snowfall_slope, precipitation_slope, snowpack_slope, total rain, days of snow-on-ground and last day of snow-on-ground. The partial M-K statistic of ice-off series, when each of the seven drivers was treated as a covariate, was listed in Table 2. By removing the influence of air temperature, the ice-off trend statistic downsized to -7.0 and had a huge difference (153 as of -7.0 – (-160.0)) compared to the original statistic of -160, which produced a +178.7% contribution (promoting the decline ice-off trend) against the difference sum of 85.6 (referring Equ.1). The days of snow-on-ground had a promoting contribution too, but very limited (2.9%). The total rain made an obvious difference in the statistics (23.3) and gave a promoting contribution of 27.2% to the ice-off decline.

The other four drivers: snowfall_slope, precipitation_slope, snowpack_slope and last day of snow-on-ground, had offsetting contributions (i.e. negative percentage), with varying contributing rate: -7.2%, -43.5%, -7.6% and -51.1% respectfully. It is seen like this: these four drivers tend to make a later ice-off (with a combined contributing power of -109.4%), while the temperature, total rain and days of snow tend to produce an earlier ice-off (with a combined contributing power of 209.3%); the promoting power had to compensate for the offsetting power, and they jointly resulted an observed ice-off trend that was not significant. Without those offsetting drivers, ice-off could have a significant decline. For example, if the offsetting influence of the last day of snow-on-ground were removed by using the partial M-K trend analysis, the declining trend in ice-off would become significant with a *P*=0.09 (< 0.1), much stronger than its original trend of *P*=0.33 (> 0.1).

3.2 Lake Nipissing

Similar data processing and analyses were conducted for Lake Nipissing. Obtained results were both similar to and different from that of Lake of Bays. Similarly a total of seven factors were identified as contributing explanatory drivers (Table 3) as they were significantly correlated to the ice-off or had a significant trend over 58 years, but the drivers' composition and their contributing features were partially different from the case of Lake of Bays. The seven drivers at Lake of Bays are indicated too in Table 3 for a convenient comparison between the two lakes. Five drivers were commonly identified at both sites (temperature, snowpack slope, total rain, days of snow, last day of snow). The remaining two drivers were different.

The winter temperature correlated strongly with ice-off (*P*<0.001) and increased strongly over time (*P*=0.044), acting as the major promoting driver to a declined ice-off (*P*=0.177). Among the four slope factors, only the slope of snowpack was chosen as a driver as it was highly correlated to ice-off (P<0.001), but the other three slopes did not play an accountable role. The snowpack slope was positively correlated to ice-off and had an increasing tendency, so its change acted to delay the ice-off or offset the ice-off decline trend. Similar to the snowpack slope, the total snowfall was strongly correlated to ice-off and its weak increasing tendency acted to offset ice-off decline. The increase in total rain still played a promoting role to the ice-off decline as happened at Lake of Bays. The snowpack depth and days of snow had a decreasing trend, and acted to promote the ice-off decline. However, the last day of snow decreased over time and promoted the ice-off decline, opposite to its increasing trend and offsetting role at Lake of Bays.

The temporal trends at Lake Nipissing are basically similar to Lake of Bays (Fig. 5, Table 3), except for the last two factors. Ice-off became 0.89 days earlier per decade on average, very close to the 0.86 days per decade at Lake of Bays. Lake Nipissing saw an increase in winter temperature of 0.29°C per decade, stronger than the 0.16°C per decade at Lake of Bays. The four slopes did not show any clear or significant trend, similar to Lake of Bays. Total snowfall had no trend, while total rain had a strong increase trend. Mean snowpack depth seemed to have more decrease tendency than at Lake of Bays. The days of snow and last day of snow had significant decreases at Lake Nipissing, but no clear trend at Lake of Bays.

The relative contributions of seven drivers, as evaluated by using the partial M-K test, are quite different from that for Lake of Bays (Table 4).

Apart from two offsetting drivers (snowpack slope and total snowfall) whose changes made slight contributions of -1.2% and -2.0% respectively, the other five drivers acted to promote the ice-off decline: the changes in temperature, days of snow and last day of snow contributed roughly the same percentage (25.7, 30.2, 30.3%), and the increased total rain and decreased snowpack depth contributed the remaining 9.9% and 7.0%. The relative contributions of temperature and total rain were very high at Lake of Bays (178.7%, 27.2%) as they had to compensate for the substantial offsetting influence from a few drivers (e.g. precipitation slope -43.5%, last day of snow -51.1%). But the relative contributions of promoting drivers at Lake Nipissing were much smaller, as there was no strong offsetting driver to be compensated for. It is also noted that the contribution of last day of snow was completely opposite between two sites: an offsetting influence of -51.1% at Lake of Bays versus a promoting influence of 30.3% at Lake Nipissing.

Table 2. Differences of M-K statistic for seven drivers at Lake of Bays

Driver or covariate	**Partial M-K statistic of ice-off**	***P* of modified iceoff trend**	**Difference in statistic**	**Relative contribution (%)**
Air-temperature	-7.0	0.96	153.0	178.7
Snowfall_slope	-166.2	0.302	-6.2	-7.2
Precipitation_slope	-197.2	0.215	-37.2	-43.5
Snowpack_slope	-166.5	0.289	-6.5	-7.6
Total rain	-136.7	0.405	23.3	27.2
Days of snow	-157.1	0.242	2.9	3.4
Last day of snow	-203.7	0.09	-43.7	-51.1
			Sum: 85.6	

Table 3. Correlations and trends in ten factors at Lake Nipissing (1955-2012)

	Correlation of ice-off and a driver R	**Significance level of the correlation P**	**MK trend and its p-value [trend, P]**	**Drivers at Lake of Bays**
Temperature	-0.665	**<0.001**	**[+, 0.044]**	√
Rain slope	-0.184	0.168	[+, 0.542]	
Snowfall slope	-0.084	0.533	[+, 0.457]	√
Precipitation slope	-0.128	0.337	[+, 0.321]	√
Snowpack slope	0.453	**<0.001**	[+, 0.899]	√
Total snowfall	0.406	**0.002**	[+, 0.758]	
Total rain	-0.089	0.504	**[+, 0.0007]**	√
Snowpack depth	0.366	**0.005**	[-, 0.235]	
Days of snow	0.728	**<0.001**	**[-, 0.045]**	√
Last day of snow	0.816	**<0.001**	**[-, 0.055]**	√
Ice-off			[-, 0.177]	

Table 4. Differences of M-K statistic for seven drivers at Lake Nipissing (its M-K statistic is -201.0)

Driver or covariate	**Partial M-K statistic of ice-off**	**P of modified iceoff trend**	**Difference in statistic**	**Relative contribution (%)**	**Relative contribution at L. of B.**
Air-temperature	-8.1	0.944	192.9	25.7	178.7
Snowpack slope	-209.7	0.113	-8.7	-1.2	-7.6
Total snowfall	-215.8	0.126	-14.8	-2.0	NA
Total rain	-126.7	0.389	74.3	9.9	27.2
Snowpack depth	-148.8	0.296	52.2	7.0	NA
Days of snow	25.7	0.791	226.7	30.2	3.4
Last day of snow	26.4	0.77	227.4	30.3	-51.1
			Sum: 750		

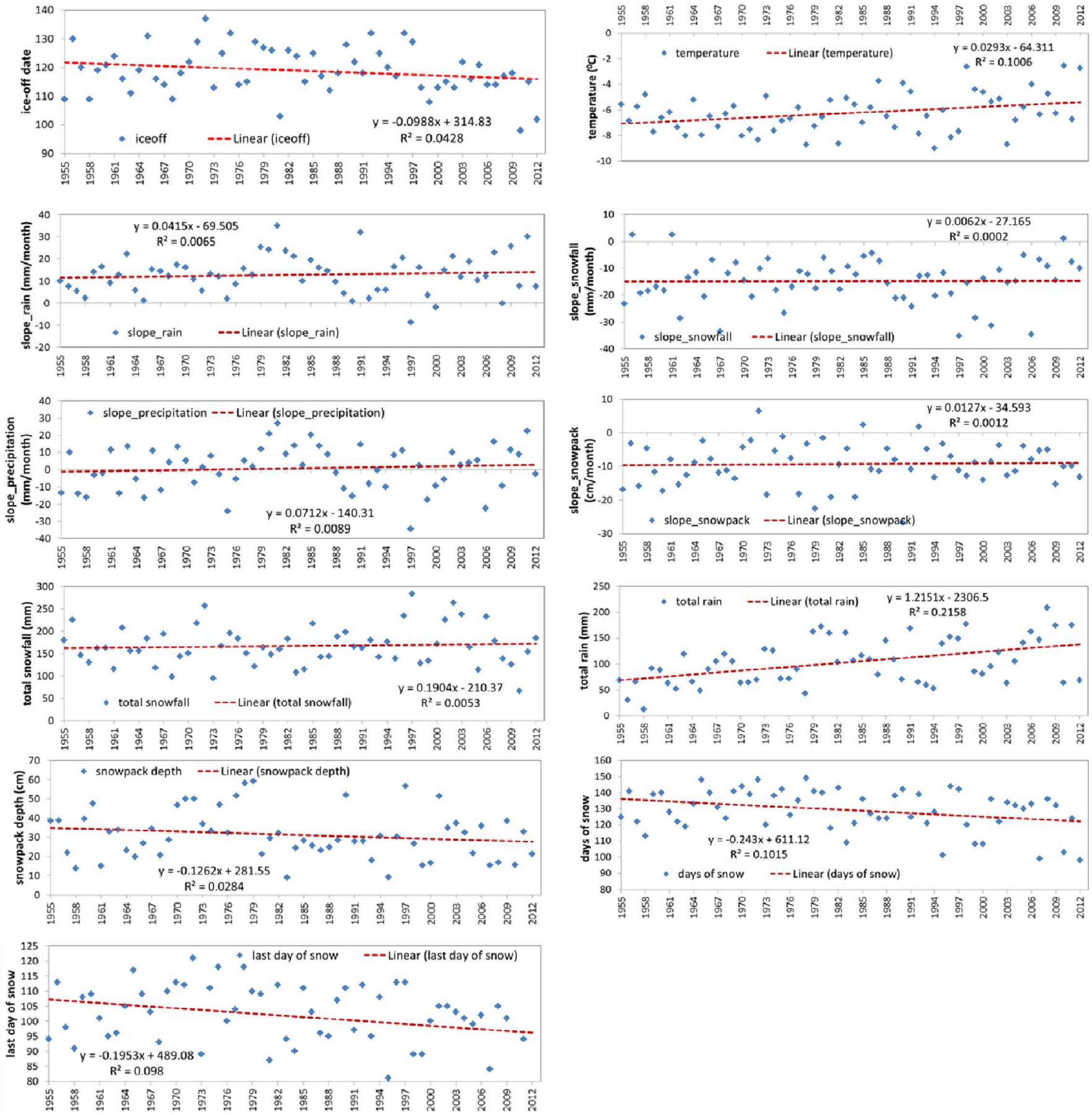

Fig. 5. Annual series of ice-off and ten potential factors at Lake Nipissing

It is interesting and still not well understood that the ice-off did not turn out to have a significant decline at Lake Nipissing although there were five promoting drivers.

4. DISCUSSION

Two types of possibilities are seen regarding the non-significance in ice-off in the south-central Ontario region. First, like what has happened at Lake of Bays, the promoting drivers could have produced a significant change in ice-off (if without those offsetting drivers in place), but those offsetting drivers have been in place, dragging or softening the ice-off changes, and the promoting functions had to compensate for the offsetting influences, therefore eventually they together did not produce a significant change in ice-off. Therefore the non-significance in ice-off trend was caused by the contradiction and offsetting between three promoting drivers (air temperature, total rain, days of snow-on-ground) and four offsetting drivers (slopes of snowfall, precipitation and snowpack depth and last day of snow).

Second, like what happened at Lake Nipissing, the promoting drivers were the majority in all factors, and the offsetting drivers were few. But the promoting drivers were not powerful enough (for some physical reason not well understood) to force a significant change in ice-off, even the offsetting influence was minimal. The changes in five promoting drivers (temperature, total rain, snowpack slope, days of snow and last day of snow) could not produce a significant change in ice-off date. It seems that the lake itself was quite elastic or resistant to having a changing trend in ice-off under multiple stressors.

Of course, a significant change in ice-off at many other lakes may be thought to be one of two opposite situations (opposite to our study lakes): the promoting drivers are powerful enough to produce a significant change in ice-off, even though some offsetting drivers are in place; or there are few offsetting drivers, and the promoting drivers are powerful enough to produce the ice-off change.

The contributing drivers behind ice-off changes can be quite site-specific and different. Lake of Bays and Lake Nipissing are 160 km away; among ten potential factors five common drivers were identified for both lakes: temperature, snowpack slope, total rain, days of snow and last day of snow. But two other drivers were different: slope of snowfall and slope of precipitation for Lake of Bays, whereas total snowfall and snowpack depth for Lake Nipissing. Furthermore, the contributing effects of those chosen drivers were quite different between lakes: a driver may be a promoting one for both sites, but its contribution power or percentage is different (e.g. the temperature contributed 178.7% and 25.7% respectively); a driver may be an offsetting one for both sites, but its contribution power is different (e.g. the snowpack slope contributed -7.6% and -1.2% respectively); or a driver's contribution may be opposite between two sites (e.g. the last day of snow offset the ice-off change by 51.1% at Lake of Bays but promoted it by 30.3% at Lake Nipissing).

The evaluation method of relative contributions for drivers, based on the partial M-K test, is an initial trial. Modification may be achieved, or other methods may be proposed. So far, this method, together with the correlation analysis and trend detection, provided a comparatively easy way to explain the non-significance phenomenon in ice-off in certain regions. Especially the presented percent contributions of all explanatory drivers should help to understand why the phenomenon occurs.

The strong relation between ice-off date and air temperature was utilized to project future ice-off response under future climate (e.g. [8,15,16]). However, considering the complex promoting and offsetting relationships between ice-off and multiple climatic drivers as illustrated in present study, and also considering the possible insensitive response as shown in our study area, it is reminded that a future projection would need to also include the changes in all possible drivers other than air temperature. A projection trial for ice-off change without considering snow condition changes might lead to substantial uncertainty or bias.

Possible teleconnection between ice-off change and global-scale oceanic oscillations was mentioned in a few studies [2,10,25,26]. A strong correlation or influence of El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) on the ice-off was not identified by a study for the Dickie Lake [8] which is close to the Lake of Bays. Therefore the teleconnection of these oscillation factors were not included in our present study. Also, the possible effects of long-term changes in solar radiation and wind speed on ice-off trend were not considered due to the data unavailability for studied period.

5. CONCLUSION

We analyzed and explained the non-significant changes in ice-off dates at two lakes in the south-central Ontario region using lake ice and climate data: Lake of Bays over 62 years and Lake Nipissing over 58 years, identified both promoting and offsetting drivers leading to the insignificant ice-off changes, and evaluated drivers' relative contributions. We confirmed that: (a) the driving factors to ice-off change trend (or its non-significance phenomenon) are multiple and should be found out as much as possible; (b) ice-off change may be not sensitive, or even quite elastic, to climate change stressors at certain regions such as south-central Ontario; the changed climate in 1955-2016 may not be strong enough to make a significant response in ice-off; and (c) there are some offsetting (contradicting) factors, which may reduce the promoting effects of other drivers, causing a non-significance in ice-off change.

ACKNOWLEDGEMENT

Brian Tapley and newspaper Nugget are thanked for providing lake ice-off data. Environment Canada and Climate Change is thanked for providing climatic data. Tim Field provided a final proofreading.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Duguay CR, et al. Recent trends in Canadian lake ice cover. Hydrol. Process. 2006;20:781-801.
2. Fu C, Yao H. Trends of ice breakup date in south-central Ontario. J. Geophys. Res. Atmos. 2015;120:9220-9236.
3. Jensen OP, et al. Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. Limnol. Oceanogr. 2007; 52:2013-2026.
4. Keller W. Implications of climate warming for Boreal Shield lakes: A review and synthesis. Environ. Rev. 2007;15:99-112.
5. Magnuson JJ, et al. Historical trends in lake and river ice cover in the Northern Hemisphere. Science. 2000;289:1743-746.
6. Sharma SJ, Magnuson JJ, Mendoza G, Carpenter SR. Influence of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905-2004. Clim. Change. 2013;118:857-870.
7. Weyhenmeyer GA, et al. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. Global Chang. Biol. 2011;17: 268-275.
8. Yao H, et al. The interplay of local and regional factors in generating temporal changes in the ice phenology of Dickie Lake, South-Central Ontario, Canada. Inland Waters. 2013;3:1-14.
9. Kjar KH. Is the ice burning? Aktuel Naturvidenskab. 2009;18-21.
10. Walsh SE, Vavrus SJ, Foley JA, Fisher VA, Wynne RH, Lenters JD. Global patterns of lake ice phenology and climate model simulations and observations. Journal of Geophysical Research. 1998;103:28,825-28,837.
11. Adrian R, O'Reilly CM, Zagarese H, Baines SB, Hessen DO, Keller W, David M, Livingstone DM, Sommaruga R, Straile D, Donk EV, Weyhenmeyer GA, Winder M. Lakes as sentinels of climate change. Limnol Oceanogr. 2009;54:2283–2297.
12. Minns CK, Brian J, Shuter BJ, Fung S. Regional projections of climate change effects on ice cover and open-water duration for Ontario lakes. Climate Change Research Report CCRR-27 of Ontario Ministry of Natural Resources. 2012;19.
13. Hamilton DP, Magee MR, Wu CH, Kratz TK. Ice cover and thermal regime in a dimictic seepage lake under climate change. Inland Waters. 2018;8:381-398.
14. Brown LC, Duguay CR. The response and role of ice cover in lake-climate interactions. Progress in Physical Geography: Earth and Environment. 2010;34:671-704.
15. Crossman J, Eimers MC, Kerr JG, Yao H. Sensitivity of physical lake processes to climate change within a large Precambrian Shield catchment. Hydrol. Process. 2016; 30:4353-4366.
16. Yao H, et al. Comparing ice and temperature simulations by four dynamic lake models in Harp Lake: Past performance and future predictions. Hydrol. Process. 2014;28:4587-4601.
17. Sharma S, et al. Direct observations of ice seasonality reveal changes in climate over the past 320–570 years. Scientific Reports. 2016;6. Article number 25061.
18. Williams SG, Stefan HG. Modeling of lake ice characteristics in North America using climate, geography, and lake bathymetry. J. Cold Reg. Eng. 2006;20:140-167.
19. Brown LC, Duguay CR. The response and role of ice cover in lake-climate interactions. Prog. Phys. Geog. 2010;34:671-703.
20. Labat D. Cross wavelet analysis of annual continental freshwater discharge and selected climate indices. J. Hydrol. 2010; 385:269–278.
21. Mallat SG. A theory for multiresolution signal decomposition: The wavelet representation. IEEE Trans. Pattern Anal. Mach. Intell. 1989;117:674–693.
22. Martinez B, Gilabert MA. Vegetation dynamics from NDVI time series analysis using the wavelet transform. Remote Sens. Environ. 2009;113:1823–1842.
23. Yao H, et al. Relative contributions of stream concentration, stream discharge and shoreline load to base cation trends in Red Chalk and Harp lakes, South-Central Ontario, Canada. Hydrol. Process. 2016; 30:858-872.
24. Libiseller C, Grimvall A. Performance of partial Mann-Kendall tests for trend

detection in the presence of covariates. Environmetrics. 2002;13:71-84.

25. Anderson WL, Robertson DM, Magnuson JJ. Evidence of recent warming and El Nino-related variation in ice breakup of Wisconsin lakes. Limnol. Oceanogr. 1996; 41:815-821.

26. Robertson DM, Ragotzkie RA, Magnuson JJ. Lake ice records used to detect historical and future climatic changes. Clim. Change. 1992;21:407-427.
