**Lake-Effect Snowfall Within the Laurentian Great Lakes Region in the Context of Anthropogenic Climate Change**

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**Abstract**

This review seeks to achieve a more comprehensive understanding of how climate change may influence seasonal lake-effect snowfall occurrences within the Great Lakes region. Evidence suggests that climate change is already influencing the climate of this region. The enormity and thermal capacity of the Great Lakes, projected increases in global surface temperatures, combined with a relatively large population residing in the area make this a valuable case study in terms of the possible implications that altered lake-effect snowfall trends may pose for the region in the future.

**Introduction**

 In the age of the Anthropocene, human activities are regarded as a relevant and important influence in shaping Earth’s physical climate processes, including the progression of anthropogenic climate change. Therefore, as physical climate processes occur at various spatial and temporal scales, humans have the capacity to influence these processes on a number of dimensions. Seasonal lake-effect snowfall events within the Laurentian Great Lakes region of North America, for instance, embody an important physical climate process on a regional scale. Lake-effect snowfall events result from the interaction between relatively cold and dry continental air masses and relatively warm water bodies over which air masses are advected (Thompson, 2014). This advection will lead to unstable conditions through the exchange of moisture and energy fluxes (Baijnath-Rodino et al., 2018). Moist air will then rise and cool sufficiently enough that it freezes and later falls as snow on nearby land surfaces; this is due to the continued influence of advective processes (Baijnath-Rodino et al., 2018; Thompson, 2014). Notably, the thermal capacity and sheer size of the Great Lakes indicate that they have the capacity to generate significant amounts of snowfall that is lake-induced (Burnett et al, 2003). Additionally, lake-effect snowfall tends to occur in the leeward (downwind) settings of the lakes, giving rise to differential climate-related impacts across communities within this region (Burnett et al., 2003).Though transient at local scales, lake-effect snowfall may encompass the majority of snowfall totals for several communities nearby to the Great Lakes. Significant seasonal snowfall totals brought about by lake-effect snowfall can hold important economic implications for

communities in this region, particularly as it concerns agriculture and recreational activities (Notaro et al., 2015). The economic impacts of lake-effect snow can be positive (for instance, through local revenue generated from ski resorts), or impacts can be negative (for instance, through hazardous driving conditions or infrastructure damage). Evidently, the occurrence of lake-effect snowfall can play a significant role in shaping the daily activities of particular locales. As a result, one may hypothesize that prolonged alterations to lake-effect snowfall trends may significantly impact local economies and livelihoods. One may also wonder where lake-effect snowfall in this region stands as it relates to the processes of climate change.

 Due to the enormity of the Great Lakes and the large quantities of water that they hold collectively, the role of the lakes in influencing regional climate and weather characteristics through modulation of the local surface energy budget, hydrological budget, and atmospheric circulation patterns cannot be overlooked or underestimated (Baijnath-Rodino et al., 2018). The significant regional climate influences of the Great Lakes in addition to the relatively large population living in close proximity to them make this a valuable case study given projected increases in global temperatures as a result of climate change (Burnett et al., 2003). Furthermore, the progression of climate change over the next century will be coupled with not only a rise in global temperatures, but also notable regional variability in the alterations to these temperatures and in precipitation levels (Albritton et al., 2001, as cited in Burnett et al., 2003). Appropriately, the key motive of this paper is to offer a more comprehensive understanding of how climate change may influence seasonal lake-effect snowfall occurrences within the Great Lakes region currently and in the future. Alterations to characteristic snowfall trends could significantly impact the climate characteristics of the region such that its associated economic activities will be profoundly affected (Notaro et al., 2015). Importantly, in order to generate meaningful predictions for the future, linkages must first be established between past and current snowfall trends within the Laurentian Great Lakes Basin and the possible influence climate change may already have on these trends. Trends can refer to snowfall intensities and annual snow accumulation levels.

**Methods**

 In the literature, analyses of atmosphere and surface predictor variables were conducted (such as lake surface temperatures and ice cover) in an attempt to evaluate long-term climatological trends, as witnessed in a study conducted by Baijnath-Rodino and colleagues (2018). Other methods included the utilization of a regional climate model that is run from the mesoscale level, as utilized in the work of Notaro et al. (2015). Burnett et al. (2003) placed heavy analysis on the collection of historical snowfall data from local weather stations in an effort to shed light on snowfall trends in the data records that were deemed as statistically significant.

**Results and discussion**

 Prior to discussions of findings from literature sources, an important consideration must be made as it concerns the behaviour of lake-effect snowfall events and their relation to surrounding climate characteristics. Such a consideration will enlighten the meaningfulness of the findings from the literature, which will be discussed thereafter.
 Significant decreases in ice cover fraction have been observed across the Great Lakes in recent years, suggesting that the effects of climate change have already begun to take hold in this region (Baijnath-Rodino et al., 2018). For a given winter season, this will mean delayed freezing and/or premature thawing of seasonal ice cover. Thus, lakes will oftentimes not have the capacity to freeze over completely within the timeframe of a winter season, and in turn will exhibit a prolonged ‘lake-effect snowfall season’ (Thompson, 2014).

 Importantly, whether a lake is ice free or ice covered holds important implications for lake-effect snowfall events due to their heavy reliance on open (rather than capped) waters for their production. As lakes become cooler and begin to freeze over during the course of a season, latent heat fluxes diminish as ice begins to act as a cap for the transfers of significant energy and moisture between the water and the atmosphere (Baijnath-Rodino et al., 2018). This process can therefore shed light as to why lake-effect snowfall events tend to be more persistent in the earlier portion rather than the latter portion of winter seasons.

 Investigations conducted by Burnett et al. (2003) are suggestive of increasing trends in snowfall totals amongst lake-effect sites since the year 1931. As this group sought to enlighten possible links between various regional snowfall totals and possible global warming processes, they stratified their locations of investigation for sites that exhibit lake-effect snowfall and those that do not. The team found statistically significant linear upward trends in snowfall totals in lake-effect sites, but not in non-lake effect settings (Burnett et al., 2003). The researchers suggested that increased lake-effect snowfall was reflective of records of air temperature, water temperature, and lake ice cover (Burnett et al., 2003). They hypothesized that the observed increases in lake-effect snowfall totals are related to alterations in the thermal conditions that drive lake-effect precipitation events; specifically, warmer waters coupled with decreased ice cover (Burnett et al., 2003). Indeed, investigations conducted by Burnett et al. (2003) into historical ice cover data revealed the trend of an increasingly later onset and earlier conclusion of seasonal Great Lakes ice cover since the 1850s, consistent with overall northern hemispheric warming trends of air and water surfaces in recent years (Burnett et al., 2003). In non-lake effect snowfall settings, by contrast, where snowfall accumulation is not attributable to the influences of nearby water bodies, snowfall totals remained relatively stable over time (Burnett et al., 2003). These findings illustrate the critical role large bodies of water play in shaping the climates of surrounding regions, and that as the Great Lakes continue to warm through climate change, the climate of its surrounding regions can be impacted.

 As it concerns lake-effect snowfall accumulation in the future, Burnett et al. (2003) stressed that continued general warming trends may lead to an increase in lake-effect snowfall events in this region over time, but only to the extent that temperatures remain favourable for the development of snow (Burnett et al., 2003). This means that at the conclusion of the 21st century, warming could reduce the frequency of below-freezing days in this region to the extent that lake-effect snowfall is no longer a significant climate process (Burnett et al., 2003). The authors suggest that the remainder of lake-effect snowfall may perhaps be restricted to the region’s most northerly areas by this point in time (Burnett et al., 2003). This hypothesized warming process is supported by the projections of the IPCC of a 1.4-5.8 degrees Celsius warming in global surface temperatures over the course of the 21st century (Albritton et al., 2001, as cited in Burnett et al., 2003). In the meantime, however, such a warming trend would favour the continued development and persistency of lake-effect snowfall events in this region in the coming years.

 Baijnath-Rodino and colleagues (2018) also conducted a pursuit on this topic, particularly from a Canadian context. Results from their investigation indicated significant decreases in precipitation, including snowfall accumulation, in the leeward locales of Lake Superior and Lake Huron/Georgian Bay over a 36-year period, particularly for the latter (Baijnath-Rodino et al., 2018). Therefore, despite an assumption that warming lakes generate elevated evaporation rates, and in turn, elevated precipitation rates, a reduction of annual precipitation rates (including that generated from lake-effect snowfall events) was observed. To support this finding, Baijnath-Rodino and colleagues eluded to the fact that there are other complicated processes to consider as they influence lake-effect snowfall events. Such complications can include inefficient moisture recycling and increased moisture storage within warmer air masses; such processes can be exacerbated through climate change (Baijnath-Rodino et al., 2018). The increased moisture storage of warmer air masses is particularly important in the context of climate change and its influences on lake-effect snowfall events. The enhanced moisture storages of these air masses may potentially lead to a reduction in lake-effect precipitation for locales immediate to the lakes, particularly for leeward areas (Baijnath-Rodino et al., 2018). This illustrates the fact that what is evaporated in one lake might not necessarily be deposited as precipitation in the immediate (leeward) area next to the lake. Moist air parcels can travel distantly before impacting particular regions as precipitation due to advection and over-lake fetch processes, and as directed by particular wind patterns (Baijnath-Rodino et al., 2018; “The Importance of Wind Direction in Forecasting Lake Effect Snow,” 2015). Recent destructive lake-effect snowfall events in 2006 and in 2014 in the city of Buffalo, NY, could serve as an interesting case study as it relates to this phenomenon (Baijnath-Rodino et al., 2018). Because the city is located leeward of more than one body of water that generates lake-effect moisture, perhaps it is susceptible to more intense snowfall accumulation following the advection of moist air across multiple lakes. Ultimately, however, an online article published by the National Weather Service in 2015 indicates that the particulars of where lake-effect snowfall accumulates as precipitation likely depend predominantly on wind patterns (“The Importance of Wind Direction in Forecasting Lake Effect Snow,” 2015). Ultimately, findings from Baijnath-Rodino and colleagues (2018) are meaningful in that they are indicative of decreasing lake-effect precipitation accumulation at Canadian locations, but not necessarily for locales in parts of the United States such as Buffalo, NY as observed in this study, or Syracuse, NY as observed by Burnett and colleagues in 2003.

 Notaro and colleagues (2015) sought to project changes in lake-effect snowfall for the middle to the end of the 21st century. Their modelled projections implied that an overall reduction in heavy lake-effect snowstorms will occur over the course of the twenty-first century, except with increases around Lake Superior by the mid-century where temperatures will remain low enough for heavy lake-effect snow to continue to form (Notaro et al., 2015). The study noted the important role that reduced ice cover and greater dynamically induced wind fetch play in shaping and strengthening lake evaporation processes, and in turn, total lake-effect precipitation (Notaro et al., 2015). Therefore, conclusions from this study are similar to those previously discussed: the progression of climate change may drive increases in the duration and intensity of lake-effect snowfall events before they eventually deteriorate significantly late in the 21st century from a reduced frequency of sharp cold air outbreaks from the Canadian north (Notaro et al., 2015). As influxes of cold air to the Great Lakes are crucial for the formation of lake-effect snow, a reduction in such would significantly alter the regional climate of the Great Lakes basin.

**Conclusions**

 The purpose of this review was to explore how climate change may influence the regional climate mechanisms responsible for the formation and character of lake-effect snowfall events within the Great Lakes basin. Given projections of future climate change as well as an understanding of the role of climate change as it concerns the stability of regional lake-effect snowfall trends, hypotheses can be made with respect to how lake-effect snowfall in this region may be altered by climate change in the future.

 A general acknowledgment exists across the literature that the role of climate change in elevating lake surface temperatures should increase the seasonal duration and intensity of lake-effect snowfall events. However, two important exceptions to this trend must be made. First, that the changing behaviour of wind patterns and advection of air masses can generate differential impacts across locales, which can shed light on statistically significant trends previously observed. Second, that elevated lake-effect snowfall will only last as long as climate change will allow it to. If global temperatures rise sufficiently enough by the end of the 21st century, the formation and accumulation of lake-effect snow may become sparse in this region, especially in its southernmost areas. Given global surface temperature projections, the eventual sparsity of lake-effect snow is quite possible for a large portion of this region.

 An improved understanding of the relationship between climate change and lake-effect snowfall events can be achieved through a more extensive analysis of historical snowfall trends across longer timescales and additional locales of interest. Additionally, and as previously observed by Baijnath-Rodino and colleagues, investigations into this matter have predominantly originated from south of the border. As the Great Lakes span into both Canada and the United States, so too should future investigations pertaining to the lakes’ profound influences on regional climates. Conducting additional studies from a Canadian context may provide further insight into the peculiar nature of lake-effect snowfall in this region as it concerns observed differential impacts.

**References**

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