







PRIMER

Forecasting lake-/sea-effect snowstorms, advancement, and challenges

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Abstract

Lake-/sea-effect snow forms typically from late fall to winter when a cold air mass moves over the warmer, large water surface. The resulting intense snowfall has many societal impacts on communities living in downwind areas; hence, accurate forecasts of lake-/sea-effect snow are essential for safety and preparedness. Forecasting lake-/sea-effect snow is extremely challenging, but over the past decades the advancement of numerical forecast models and the expansion of observational networks have incrementally improved the forecasting capability. The recent advancement includes numerical forecast models with high spatiotemporal resolutions that allow simulating vigorous snowstorms at the kilometer-scale and the frequent inclusion of radar observations in the model. This combination of more accurate weather prediction models as well as ground-based and remotely sensed observations has aided operational forecasters to make better lake-/sea-effect snow forecasts. A remaining challenge is that many observations of precipitation, surface meteorology, evaporation, and heat supply from the water surface are still limited to being land-based and the information over the water, particularly offshore, remains a gap. This primer overviews the basic mechanisms for lake-/sea-effect snow formation, evolution of forecast techniques, and challenges to be addressed in the future.

This article is categorized under:

- Science of Water > Water Extremes
- Science of Water > Water and Environmental Change
- Science of Water > Methods

KEYWORDS

extreme weather, lake-effect snow, numerical model, sea-effect snow, weather forecast

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1 | INTRODUCTION

Lake-/sea-effect snow is a common occurrence in the late fall and winter downwind of large water surfaces in mid-to-high latitudes. It forms when cold air flows over the relatively warm water, absorbs significant amounts of heat and moisture from the water surface, and can result in significant amounts of snow downwind (Hjelmfelt, 1990; Niziol, 1987; Niziol et al., 1995; Olsson et al., 2020; Steenburgh & Nakai, 2020).

Driven by similar lake/sea-to-atmosphere processes, the phenomena can consistently be found in different parts of the world, including North America (e.g., the North American “Great Lakes” or the Great Salt Lake, Atlantic Canada), Europe (e.g., Baltic Sea, Caspian Sea, Black Sea), and East Asia (e.g., Sea of Japan, Yellow Sea). Occurrence in the Southern Hemisphere is rarely reported. Among these examples, the Great Lakes, the Great Salt Lake, and the Sea of Japan are the most well-documented regions with respect to the formation mechanisms of lake-/sea-effect snow bands and forecasting techniques (Alcott et al., 2012; Ballentine et al., 1998; Carpenter, 1993; Fujisaki-Manome et al., 2020; Minder et al., 2020; Nakai et al., 2012; Niziol, 1987; Niziol et al., 1995; Steenburgh & Nakai, 2020) as well as field campaigns (Kristovich et al., 2003, 2016; Murakami, 2019). This is also reflected in the number of recent online articles on the Web of Science (Table 1).

In the mid-latitudes of the Northern Hemisphere, lake-/sea-effect snow occurs over a 3- to 4-month period from October to February. In the subarctic lakes, its period is limited to early winter (e.g., Lake Baikal, Great Bear Lake, Great Slave Lake). Once stable ice cover forms over these lakes, the supply of heat and moisture from the water surface is shut down and lake-effect snow no longer occurs. For example, in the Great Bear Lake and Great Slave Lake in the Northwest Territories of Canada, the lakes generally start to freeze by mid-November (Howell et al., 2009), after which lake-effect snow occurrence is very limited.

In downstream populated areas, lake-/sea-effect snow impacts a wide range of socioeconomic activities. Intense snowfall in a short duration increases the risk of stalled traffic and accidents (Ayon, 2017; Juga et al., 2014), hinders safe navigation (Valdez Banda et al., 2014; Lake Carriers' Association, 2019) and aviation, causes damage to trees and roofs, and makes snow removal logistics challenging (Heimbürger, 2018; Nakai et al., 2012). Precautionary planning for such extreme weather conditions should also be taken into account at shore-located nuclear power plants (Jylhä et al., 2018; Nuclear Energy Institute, 2018; Olsson et al., 2020). The American Highway Users Alliance and IHS Global Insight (2010) reported that a major snowstorm over North America could cost 300–700 million US dollars per day in some states both directly and indirectly because of impassable roads. As another example, cost for removal of the debris from a lake-effect snow storm downwind of Lake Erie in October 2006 was estimated to be over \$150 million US dollars (National Weather Service, 2006). However, such cost estimates do not account for other losses such as fatalities, injuries, accidents, agriculture loss, and power outages. Comprehensive assessment of socioeconomic impacts from lake-/sea-effect snow is still rare. Lake-/sea-effect snow is also impacted by climate change. However, the involved processes are complicated. The overall warming trend indicates that rainfall can gradually replace snowfall in total precipitation, but at the same time, reduced ice cover can increase evaporation from the water surface, which may result in a net

TABLE 1 Number of research and review articles in the Meteorology, Atmospheric Sciences category found in Web of Science^a

Geographical names used for refined search (right) initial search criteria (below)	“Great Lakes,” “Lake Superior,” “Lake Huron,” “Lake Michigan,” “Lake Erie,” or “Lake Ontario”	“Great Salt Lake”	“Sea of Japan”	“Black Sea”	“Caspian Sea”	“Baltic Sea”	“Yellow Sea”
“Lake-effect,” “sea-effect,” or “ocean-effect” anywhere and “snow” anywhere. Total 159 found	102	20	8	4	4	3	1
“Snow” in title or abstract. Total 8259 found	168	16	64	12	11	35	10

Note: The initial search criteria are in the leftmost column and the results were refined using each geographical name. Note that in the third row, articles may be on snow research but may not necessarily be on lake-/sea-effect snow. Similarly, articles found under a geographical name used in the refined search may not be entirely on the geographical domain (e.g., the geographical name can be mentioned in the introductory text).

^aOther geographical names used for refined search are “Gulf of St. Lawrence,” “Lake Baikal,” “North Sea,” and “Great Bear Lake.” No article was found for the primary search criteria in the second row.

increase of lake-/sea-effect precipitation and therefore, of snowfall. The historical trend suggests a mixture. Burnett et al. (2003) and Kunkel et al. (2009) showed an increasing trend in lake-effect snowfall over the US portion of the Great Lakes domain over the 20th century. On the other hand, Baijnath-Rodino et al. (2018) showed a significant decrease in total snowfall along the Ontario snow belts (Canadian side downwind of the Great Lakes) over the period from 1980 to 2015. Near the Arctic, Bailey et al. (2021) showed significant increases in maximum snowfall over northern Europe from 1979 to 2020 associated with the sea ice decline in the Barents Sea. In other parts of the world, the downwind areas of the Sea of Japan experienced a decline of annual maximum snow depth at low-elevation coastal cities from 1962 to 2017 but no significant trend at high-elevation sites (Japan Meteorological Agency, 2018; Steenburgh & Nakai, 2020). Bao and Ren (2018) showed the increasing trend in sea-effect snowfall over the Shandong Peninsula of Northern China in the period of 1962–2021. In future model, projections that follow the international “Coupled Model Intercomparison Project” (CMIP) protocol, regional climate model simulations over the Great Lakes indicated a general reduction in the frequency of heavy lake-effect snowstorms through the end of the 21st century under a high greenhouse gas emission scenario (the so-called representative concentration pathway 8.5). The exception was an increase around Lake Superior by the mid-century when local air temperatures remain low enough for wintertime precipitation to largely fall in the form of snow (Notaro et al., 2015). In another model study, Sasai et al. (2019) showed that snowfall over Japan decreased in coastal areas but no significant trend is apparent in the mountain areas for future warming scenarios. Using global climate model outputs, Sharma et al. (2019) projected a northward migration of lakes with intermittent winter ice cover (i.e., lakes that do not consistently freeze every year) in the northern hemisphere. This implies a possible occurrence of lake-effect snow over these lakes that are projected to have intermittent winter ice cover. Global climate model output suggests that the warming trend accompanies significant inter-annual variability (IPCC AR6, 2021) including more frequent extreme winter precipitation events, and it will be paramount to prepare for these in the foreseeable future. Therefore, techniques to forecast lake-/sea-effect snowfall continue to be critical for the preparedness and safety of the communities that live in areas impacted by lake-/sea-effect snow.

With this background, this primer overviews the basic mechanisms of lake-/sea-effect snow occurrence including morphologies of snow band formation (Section 2), evolution of forecast techniques including numerical models (Section 3), and their challenges to be addressed in the future (Section 4).

2 | FORMATION PROCESSES

2.1 | Basic recipes and morphologies

Lake-/sea-effect snowfall forms when cold, continental air moves over relatively warmer water and reaches downstream land areas. The lake-/sea-effect is often triggered by the passage of a synoptic-scale front or storm system which transports cold air over the region. Such scenarios are typically accompanied by northerly to westerly wind across the affected regions in North America, the Sea of Japan, and the Yellow Sea. In the Baltic Sea region, easterly winds also initiate post-frontal scenarios due to the cold air outbreaks from the northeastern continent (Jeworrek et al., 2017; Mazon et al., 2015; Rutgersson et al., 2022). When a cold air mass moves over the water surface, the difference in temperature at the air–water interface results in evaporation and heat supply from the water surface into the overlying air mass. This evaporation and heat supply helps to warm and moisten the air mass near the surface and destabilize it, creating vertical motion, cloud cover, and the potential for precipitation. For the Great Lakes region, the typical threshold needed to produce lake-effect precipitation is a temperature difference greater than 13°C from the lake surface to a height of about 1.5 km above the lake surface (Holroyd, 1971). In other regions, it was found that lake-effect precipitation can occur at a slightly smaller air–water temperature difference in the Great Salt Lake located in the western United States (Alcott et al., 2012) while it can be larger in the Black Sea in northern Turkey (Baltaci et al., 2021). These temperature changes with height approximately reflect the rate at which a dry air parcel cools as it is lifted in the atmosphere, or the dry-adiabatic lapse rate. Through several different processes, discussed later in this section, vertical motion can occur in conjunction with the destabilization which results in the formation of clouds and precipitation. While in most cases, the overlying air mass is sufficiently cold resulting in precipitation falling as snow, there are times when rainfall can occur.

For the most intense snow bands, the wind direction often aligns with the long axis of the water body because it allows the air parcel to move over a greater fetch. A well-aligned wind direction with height from the surface through

1–3 km height results in better organized snow bands. A change in wind direction with height results in less intense, spread out, or broken band structure (Niziol, 1987). Optimal wind speeds for lake-/sea-effect snow formation vary with morphologies and likely the shape and size of water bodies. Laird et al. (2003) classified morphologies using the ratio of wind speed to maximum fetch distance based on the results from an idealized numerical model representing the Great Lakes.

Four predominant cloud formation types that occur due to this interaction are described: (1) widespread, wind-parallel bands; (2) shoreline or mid-lake bands; (3) mesoscale vortices; and (4) transverse or T-mode snow bands. A number of studies have looked at the frequency of formation of these types of bands over different regions (Alcott et al., 2012; Kelly, 1986; Laird et al., 2003, 2017; Murakami, 2019; Steenburgh et al., 2000; Yavuz, Deniz, Özdemir, Kolay, et al., 2021) and have used differing classifications based upon the needs of the study—oftentimes distinguishing the differences between shoreline and mid-lake bands. The four morphologies presented here represent the main dynamical formation present in these types of events.

2.1.1 | Widespread wind-parallel bands

This type of morphology (see Figure 1a) is described as an area of widespread coverage of cloud cover and snowfall. Typically, bands in the snowfall can occur parallel to the wind flow, similar to an elongated version of a Rayleigh–Bernard circulation (Peace & Sykes, 1966). This type of morphology predominantly comes from having short fetch over the water, usually along the minor axis of the lake.

Wind parallel bands are favored by relatively strong winds rather than shoreline bands and mesoscale vortices. The spatial and vertical scale of these types of bands is usually small, with horizontal scales less than 5 km wide and remaining within the lowest 2 km of the atmosphere (Kelly, 1986). Most of the precipitation that occurs from these bands remains close to the shore. This morphology is most common in the Great Lakes region and is captured by satellite images in other places such as the Caspian Sea (Figure 2a; Ghafarian et al., 2021), Black Sea (Kindap, 2010; Yavuz, Deniz, Özdemir, Kolay, et al., 2021) and Baltic Sea (Andersson & Nilsson, 1990; Jeworrek et al., 2017). In the Sea of Japan, a typical longitudinal snow band is referred to as “L-mode” bands (Figure 2b; Yamada et al. 2010) and can be considered as an analogue to the widespread, wind-parallel bands. However, snowfall from L-mode bands can penetrate into inland mountain areas partly influenced by orographic effects (Steenburgh & Nakai, 2020).

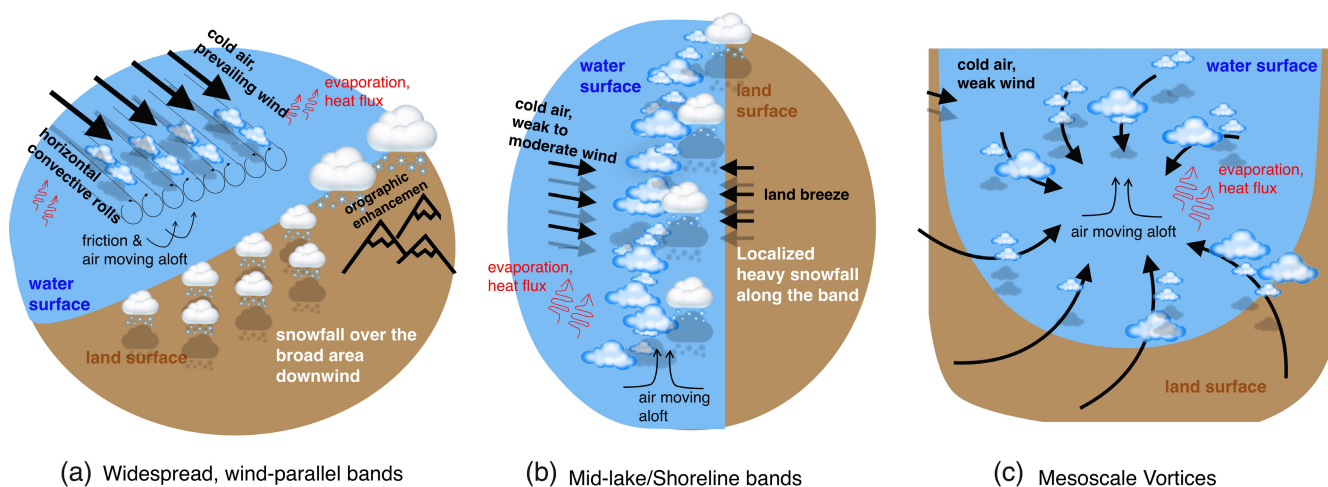


FIGURE 1 Schematic diagrams for morphologies of lake-/sea-effect snow bands. (a) Widespread, wind-parallel bands occur under prevailing wind, accompany horizontal convection rolls, and impact a broad area downwind of a lake. Orographic enhancement due to elevated terrains (e.g., mountains) is also illustrated. (b) Mid-lake/shoreline bands occur under weak-to-moderate wind in combination with land breeze and cause intense snowfall over a localized area. (c) Mesoscale vortices are less common and occur under weak wind and large air–lake temperature differences. A mesoscale vortex can migrate to the shoreline due to the synoptic scale wind and/or can be embedded in a shoreline/mid-lake band

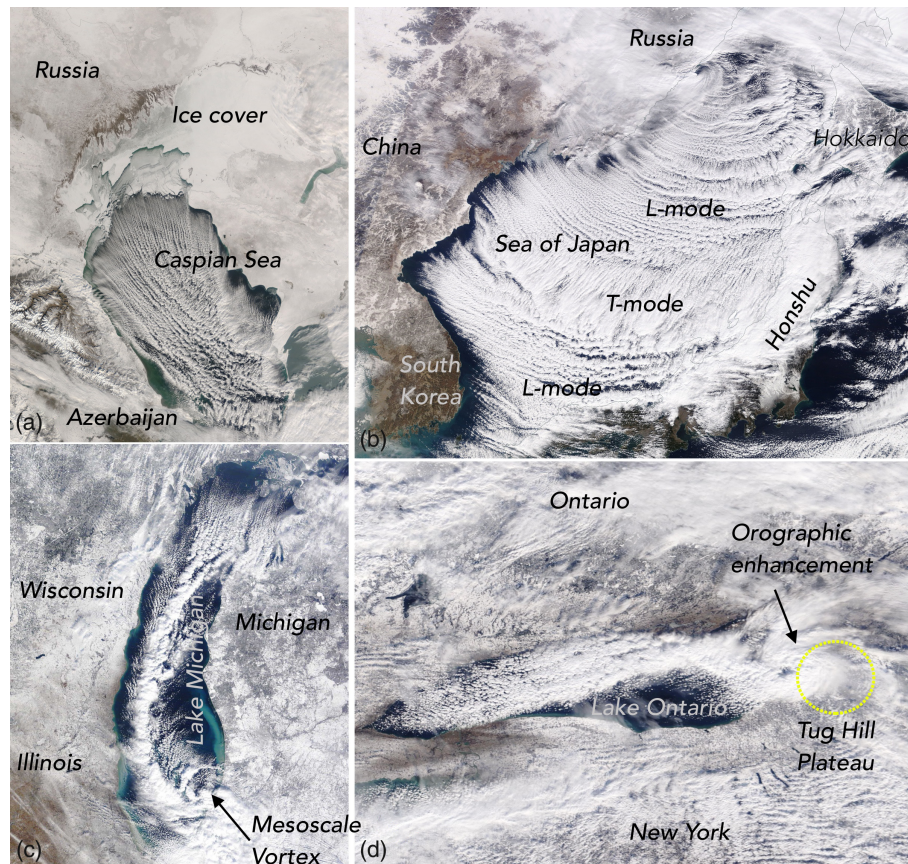


FIGURE 2 Satellite imagery of lake-/sea-effect snow bands. (a) Wide-spread, wind-parallel bands over the Caspian Sea originating along the edge of lake ice cover on January 10, 2008. (b) Sea-effect snow bands over Sea of Japan on January 23, 2018. In addition to the wide-spread, wind-parallel bands in the northern and southern regions, transversal snow bands that are oriented perpendicular to the north-westerly wind (T-mode) are found in between. (c) Mesoscale vortex in the south of Lake Michigan embedded in a mid-lake band oriented along the long axis of the lake on January 8, 2011. (d) Orographic enhancement at Tug Hill Plateau on December 12, 2013. The images are from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and adapted from the NASA Earth Observatory (a,d), the NASA WorldView (b), and the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Great Lakes node (c)

2.1.2 | Mid-lake/shoreline bands

Mid-lake bands and shoreline bands (see Figures 1b and 2c) are significantly larger in both distance as well as horizontal scale than the wind-parallel bands. These bands can be tens of kilometers wide and extend deeper vertically than the wind-parallel bands (Braham, 1983). Mid-lake bands form over the major axis of a lake, allowing for significant fetches over open waters and thus, higher precipitation amounts. The predominant interaction to produce a mid-lake band comes from a convergence of low-level air from equal-strength land breezes from both shores of the lake. The land breezes form in an environment with weaker background/synoptic scale flow or flow predominantly along the long axis of the lake which allows for local circulations to form due to the air temperature difference over the lake and over land. This temperature difference induces flow from the land to the water region, eventually creating a convergence zone over the water and enhanced vertical motion over the convergence zone.

Shoreline bands typically form parallel to the long axis of the lake, but closer to a shore rather than over the central part of a lake. Here, with surface frictional drag changes between open water and land along with land breezes, convergence can occur to help aid in the vertical ascent of the air. Shoreline bands can occur with wind speeds lower than 5 m/s (Niziol et al., 1995), usually when the convergence of the wind occurs along the shoreline from the synoptic circulation or a land breeze from the upwind shore (i.e., the other side of a lake) and a land breeze from the downwind shore.

Both of these types of bands have the potential to produce significant snowfall amounts over areas downwind of the lake. In November 2014, a band produced over 1.5 m of snowfall downwind of Lake Erie over a 2-day period (National Weather Service, 2014a, 2014b). Vortices on the order of 10 km or less can also be observed embedded within larger

mid-lake and lakeshore bands (Mulholland et al., 2017; Steiger et al., 2013), adding to the complex dynamics present within these snowbands.

2.1.3 | Mesoscale vortices

Mesoscale vortices form relatively close to the center of the open water during times of very calm wind speeds (see Figures 1c and 2b). Usually formed from a convergence of several land breezes, this type of structure has several distinct bands and clear cyclonic rotation associated with the horizontal scale of about 100 km and upwards of 5.5 km above the surface (Forbes & Merritt, 1984; Hjelmfelt, 1990; Kristovich & Steve, 1995). This type can easily move onto shore producing snowfall or can transition into other band morphologies with either an increase in background flow, increased differences in land breeze strengths, or interactions with the frictional difference induced by a shoreline. This type of morphology is not as frequent as the other two but has been shown to occur a few times per winter season over Lake Michigan in the United States (Forbes & Merritt, 1984), as well as in the Black Sea (Yavuz, Deniz, & Özdemir, 2021; Yavuz, Deniz, Özdemir, Kolay, et al., 2021).

The previously listed morphologies are not mutually exclusive, as during snowfall events the cloud formations may take on more than one distinct morphology across the event due to changes in the environment or multiple morphologies simultaneously. For example, wind-parallel bands may transition to a shoreline band due to a change in wind direction and fetch across the open water.

2.1.4 | T-mode

In the Sea of Japan, in addition to the wind-parallel bands (see Section 2.1.1), snow bands perpendicular to the wind direction are often observed. The snow bands are called the transverse-mode, or T-mode and typically observed in between the longitudinal, wind-parallel bands (L-mode) north and south (Figure 2b). T-mode bands are frequently observed in the Sea of Japan but rarely reported in the Great Lakes (Steenburgh & Nakai, 2020). The formation mechanism of T-mode snow band formation is not entirely understood (Murakami, 2019). Based on satellite imageries, radar and aero-logical data, Yagi et al. (1985) reported that for most L-mode and T-mode snow bands over the Sea of Japan, the convective rolls tended to develop preferentially with their axes oriented parallel to the vertical shear vector of the horizontal wind within a cloud layer. This was consistent with the relationship pointed out by Asai (1972) based on the perturbation analysis. However, Yamada (2005) reported that the orientation of snow bands was tilted from the vertical shear vector of horizontal wind based on Radiosonde data, aircraft observations, and dual Doppler radar observations. Eito et al. (2010) reported that there can be a transition from L-mode to T-mode snowbands near the Japan Sea polar air mass Convergence Zone (JPCZ), which forms because the cold air mass from the north divides near the high mountains in the Korean Peninsula and rejoins near the base of the Korean Peninsula (Eito et al., 2010; Hozumi & Magono, 1984; Nagata, 1991; Nakai et al., 2005).

2.2 | Other factors

The formation of these features is not only strongly dependent on synoptic-scale setups and the air-water temperature difference, but also on ice cover and upstream water bodies. Ice cover on the water changes the over-water environment in a number of ways, including changing the intensity of evaporation and heat supply off the water (Gerbush et al., 2008). As the evaporation and heat supply declines, the occurrence of lake-/sea-effect snowfall can be significantly reduced or altered (Cordeira & Laird, 2008). Wright et al. (2013) noted that the removal of ice and increase in water temperature saw not only shifts in the snowfall placement but also increased snowfall intensity in the Great Lakes. Upwind lakes can also influence the development of snowfall bands over downwind lakes, if located in relatively close proximity to one another as in the Great Lakes region (Laird et al., 2017; Lang et al., 2018; Mann et al., 2002; Rodriguez et al., 2007; Sousounis & Mann, 2000). The boundary layer can interact with upwind lakes, potentially producing snowfall or cloud cover, while helping to increase the boundary layer height through convective mixing. This in turn helps to prime the atmosphere for additional heat and moisture supply from downwind lakes, allowing for either a preferential setup of bands to form with this environment or deeper convection to occur over the downwind lake and thus increasing snowfall intensity.

Interactions with the downwind shoreline can also help to increase snowfall amounts, due in large part to orographic lift (Figure 4b). Wind interacting with the shoreline is slowed down when traveling from water to land regions

BOX 1 Historic lake-effect snowfall downwind from Lake Erie

The lake-effect snow event over Buffalo, NY, in November 2014 was an historic example of mid-lake snow bands. The elongated shape of Lake Erie and the wind blowing along its long axis further enhanced the single band formation. With massive evaporation and heat supply from the lake surface (Figure A), more than 1.5 m (5 feet) of snowfall fell over a localized area of the city in just 2 days, but only a few centimeters fell a few miles away to the north (National Weather Service, 2014b). With only a break of a few hours, the second storm arrived on the evening of the next day (19th), with additional 0.9 m (3 feet) of snow (National Weather Service, 2014a). The severe snowfall severely impacted the local community. There were 14 fatalities reported, thousands of stranded motorists, power outages, and food and supply shortages. The downwind area from Lake Erie is known as a snowbelt, but this record intense snowfall was the first occurrence since 1945.



FIGURE A Evaporation from Lake Erie and resulting lake-effect snow band, a view from the City Hall of Buffalo, NY, November 18, 2014 (Derek Gee/Buffalo News)

due to changes in surface friction drag, which in turn can help create vertical motion through convergence. Vertical motion can also be induced through interactions with orography, such as the mountain range in Japan (Steenburgh & Nakai, 2020) and the Tug Hill Plateau located to the east of Lake Ontario in the Great Lakes Region (Minder et al., 2015, 2020; Veals et al., 2018; Veals & James Steenburgh, 2015) (Box 1).

3 | EVOLUTION OF FORECAST METHODS

Forecasting methods have evolved substantially; from primarily observation-based techniques during the mid-20th century to now greater reliance on highly sophisticated numerical weather prediction (NWP) models that attempt to explicitly simulate convective storms (Figure 3). In practice, the full spectrum of methods is still employed, as numerical models insufficiently represent the extreme physical response. There are many lessons from the early work of Wiggin (1950) and Rothrock (1969), based on the increased understanding of the factors that could lead to heavy snowfall, that continue to serve as a basis for conceptual models. Niziol (1987) summarized the decision tree for lake-effect snow potential which was used for operational forecasting over western New York. The key variables used in the decision tree are (1) whether lake surface temperature is warmer than air temperature at 850 mb by 13°C or not, (2) wind direction from the near surface through 700 mb, (3) change in wind direction with height between the near-surface and 700 mb, and (4) whether and what height the low-level inversion exists.

Additional understanding through emerging technological tools in early NWP (Lavoie, 1972) and maturing operational NWP (Niziol et al., 1995) certainly assisted forecasters in the United States to better anticipate small-scale convective snowstorms. As numerical guidance has progressed into the current generation of high-resolution models that allow

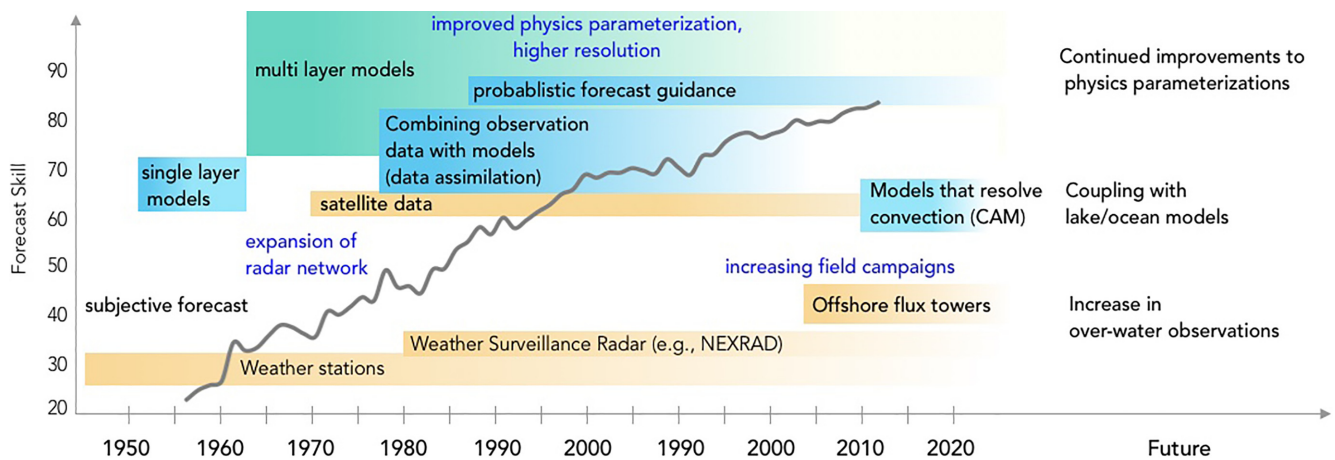


FIGURE 3 Evolution and accumulation of numerical models and observations that have been used to make decisions in lake-effect snow forecasts over the Great Lakes region. Gray line indicates the 36-ho forecast skill of the Global Forecast System at the National Centers for Environmental Prediction. The skill (S1) ranges from 0 to 100 (perfect forecast) and is based on the mean error of the 500 mb heights in the forecasts relative to radiosonde measurements over North America. The data are digitized from figure 2.1 of National Academies of Sciences, Engineering, and Medicine (2016)

representation of convections (so-called Convection Allowing Models or CAMs), greater detail of convective storm behavior can at least be partially represented, which can help forecasters communicate event specifics (Benjamin et al., 2016; Dowell et al., 2022; Olsson et al., 2018). Furthermore, available computational resources are now sufficient to support multiple simulations for a forecast cycle using such a high-resolution model in an operational environment. Such a set of multiple simulations is called an ensemble system, where multiple simulations generate a range of possible weather conditions and thus offer capabilities of probabilistic guidance to assist forecasters and end users in decision-making.

Remotely sensed observations either via radar or satellite have been a linchpin in short-term forecast operations. Advancements in satellite observation platforms (e.g., GOES-R, Himawari) have been vital in understanding the complicated behavior of convective cloud structures—especially in locations where radar horizon issues limit the ability to observe the rather shallow snow squall precipitation structures. The intense snow squalls can severely impact transportation, including the loss of life in multi-vehicle collisions. Therefore, combining an environmental understanding of convective squall maintenance with high-spatial and temporal observations from satellite and radar enables forecasters to communicate the imminent hazards.

As previously mentioned, the forecast process has accumulated methods rather than migrating from one approach to the next. Moreover, many of the early forecasting techniques have been adapted to interpreting modern prediction tools such as models. For instance, forecasters routinely leverage model soundings and environmental parameters, some of which are listed earlier in this section from Niziol (1987), from the full suite of NWP to make forecast decisions. Because many times the explicit NWP representation of the snow squalls is incomplete, forecasters must leverage probabilistic guidance from ensemble systems and conceptual models to produce the final forecast.

4 | CHALLENGES FOR FORECASTING

4.1 | Accuracy in timing, location, and intensity

A major challenge in forecasting lake-/sea-effect snowfall is to provide enough accuracy in the timing, location, and intensity of snowfall for the local community to prepare for it on a real-time basis. Such detailed information cannot be provided by projections from low-resolution models that cannot represent mesoscale events adequately. For example, climate models can inform overall trends under a given scenario, such as whether snowfall would increase or decrease over a relatively large region in the future decades (Notaro et al., 2015; Sasai et al., 2019). However, when it comes down to how much snow local areas (e.g., municipalities) would get in the next several hours, the information from climate models is not helpful. Such details are indeed required by real-time decision-making of a local community and should be covered by high-resolution weather forecast models. As numerical models advanced and forecasting tools

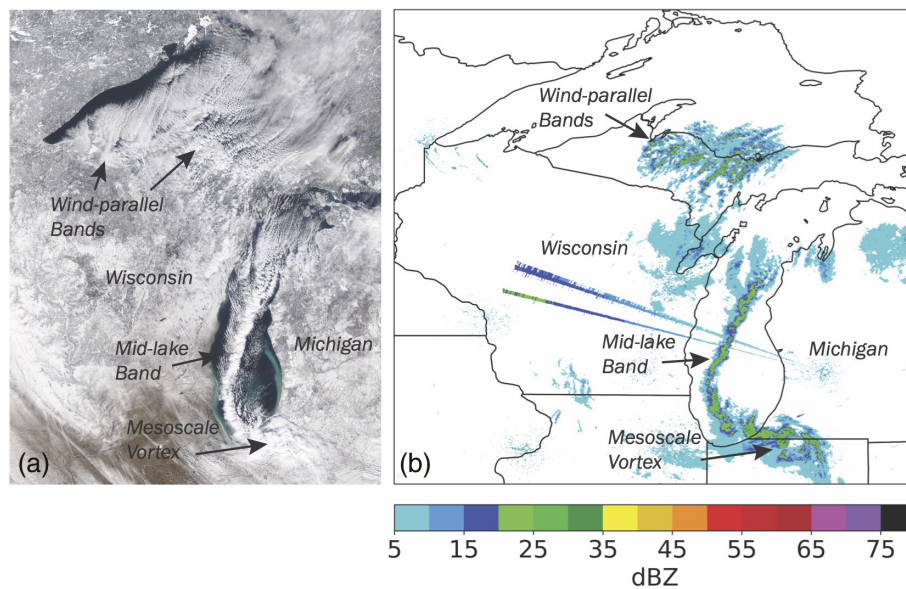


FIGURE 4 Comparison between satellite (a) and ground-based radar observations (b) for a mesoscale vortex embedded in a mid-lake band and wind-parallel bands on January 8, 2011, at 1840 UTC. The satellite image is from the Moderate-Resolution Imaging Spectroradiometer (MODIS) from the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Great Lakes node (a) and the radar observations are adapted from the Iowa Environmental Mesonet (IEM) NEXRAD Mosaic Archive. Note the radar returns extending from Wisconsin to Michigan (b) are artifacts of the radar retrieval and do not represent areas of active precipitation

diversified, the accuracy of lake-/snow-effect snow forecasts have substantially improved (see Section 3). However, observational and modeling gaps, as detailed in the following subsections, need to be addressed for further advancements

4.2 | Insufficient observational data over the water surface

The development and validation of numerical weather and water forecast models is dependent in part on the availability of routine and dense observations. Radar networks have grown in many places over the world (e.g., The Operational Weather Radar in Europe, The Next-Generation Weather Radar [NEXRAD], system in the United States) and have greatly benefited numerical models in improvement and verification as well as forecast decision-making. The coast-based radar observations were used in multiple lake-/sea-effect snowfall case studies, including those in the Caspian Sea (Ghafarian et al., 2021), Black Sea (Kindap, 2010), Baltic Sea (Olsson et al., 2018), the Sea of Japan (Nakai et al., 2005), and the Great Lakes (Minder et al., 2015). Although these radar stations provide coverage near the coast and radar location, there are still challenges in coverage over larger bodies of water. Due to the shallow vertical structure of the snowfall bands, the radar beam can overshoot the top of the snowfall bands at long distances from the radar (Figure 4). This lack of ground-based coverage further emphasizes the need for both satellite and ground-based observations of these snowfall bands to determine location, intensity, morphology, and evolution.

In addition to limited coverage from radar, over-water measurements are significantly limited compared to land-based networks, and often coastal stations are used to provide upwind or downwind verification of model forecasts. In particular, in situ over-water observations of evaporation and heat supply from the water surface are exceedingly rare compared with land-based observations despite the importance in lake-/sea-effect snow formation (Conrick et al., 2015; Fujisaki-Manome et al., 2017). Exceptions to this come from buoy observations or other offshore platforms (e.g., lighthouses), which provide measurements of surface meteorological conditions, water temperature, waves, and at times measurements of evaporation and heat supply (Blanken et al., 2011; Spence et al., 2011). Yet, these observations are often not available year-round. For example, in the Great Lakes, buoys are removed in the fall each year before the onset of lake ice, which hinders buoy measurements, and then redeployed in the following spring. In this case, over-water in situ measurements are unavailable for roughly half of the year and often during peak times for lake-/sea-effect snow.

On the other hand, satellite-derived products during late fall and winter are limited by cloud cover and as a result, composite analyses of surface water temperature and ice cover from these products often rely on data from previous days and do not necessarily represent up-to-date information. Recent studies achieved some level of success in removal of cloud cover from optical remote sensing imageries (Chen et al., 2020; Gao et al., 2020; Meraner et al., 2020), which may aid the initialization of numerical forecast models in the future. However, even if the present information of lake surface conditions is precise, water surface temperature can be cooled rapidly over the course of large lake-/sea-effect snow episodes. For example, Fujisaki-Manome et al. (2020) reported a cooling rate of 0.16–0.55°C/day during the lake-effect snow event over the Great Lakes in November 2014, which is notably larger than a climatological cooling rate of 0.07–0.21°C/day (Fichot et al., 2019). Such near-future cooling cannot be provided by observations but can be provided by water forecast models (Anderson et al., 2018) and greatly benefits weather forecast models.

4.3 | Computational limitations

Simulations of lake-/sea-effect snowfall require immense computational resources to accurately represent the processes necessary to develop the snowbands. Each flow characteristic, from lake surface conditions to near surface winds and the placement of the cold air outbreak acts on different spatial and temporal scales to produce the snowfall. This makes it difficult to accurately represent them in a single modeling framework. In most operational settings, at the time of writing, the highest resolution models are using an approximately 3 km horizontal grid (Benjamin et al., 2016; Dowell et al., 2022). The Warn-on-Forecast methods developed by the National Oceanic and Atmospheric Administration (NOAA) even utilize 1 km grid spacing over selected domains and short forecast periods of a few hours. With some of the finer-scale snow bands being less than 5 km wide, this grid spacing challenges numerical model's ability to simulate the updraft size and strength of the band. Today, high-resolution models (~3 km) that can capture convective storms (CAM) and ensemble systems are becoming increasingly used in operational settings to depict spread and uncertainty in forecasted outcomes. However, these ensemble systems, where a set of multiple simulations is run for a forecast cycle, still have limitations from horizontal grid spacing and the representation of the lake/sea surface characteristics in each member of multiple simulations.

One approach to improve lake-/sea-effect simulations is to couple atmospheric, hydrodynamic, and cryospheric (ice) models. The coupling of an atmospheric model to computationally inexpensive 1D lake models is a widely used approach. These mimic the vertical water mixing processes and the ice cover with various degrees of complexity (see Xiao et al., 2016) and are often adequate for the representation of small lakes. However, 1D lake models fail to capture the evolution of the lake surface temperature and ice conditions for large water bodies, such as the Great Lakes, due to the missing horizontal transport processes in the lakes (Notaro, Holman, et al. 2013; Notaro, Zarrin, et al. 2013). These complex lake conditions, specifically changes in the spatial distributions of evaporation and heat supply generated by evolving water temperature and ice cover, are provided when an atmospheric weather model is coupled to a 3D lake model to improve the representation of lake–air interactions and thereby improve the forecasts of these snowfall events.

The full coupling allows each system to interact and evolve more naturally in time but comes at the cost of computational resources needed to run each system simultaneously. There are instances of fully coupled modeling frameworks for sea-effect snow from the Baltic Sea (Gustafsson et al., 1997; Jeworrek et al., 2017) and Yellow Sea (Heo et al., 2010), but such an implementation in an operational framework is resource demanding, particularly for high-resolution models that can represent convection. Operational forecast models run multiple times every day (e.g., every hour as the “High-Resolution Rapid Refresh weather model”; or every 6 h as the “Great Lakes Operational Forecast System”). Each system needs to finish its forecast cycle in a much shorter timeframe than these intervals. If two models are fully coupled, computing times sum up, further add coupling overhead, and could easily reach the computational capacity in an operational environment.

One novel approach has been developed by Fujisaki-Manome et al. (2020) who asynchronously coupled an atmospheric and 3D hydrodynamic model for the Great Lakes in an operational NOAA environment. This allowed for physics-based, time-evolving lake surface temperature and ice conditions to exist in the atmospheric model and improved the forecasts for lake-effect snowfall. This style of lagged coupling also has the advantage of leveraging computational resources distributed at different research centers rather than needing the resources to be collocated as would be needed in a fully coupled system.

4.4 | Research coordination across different geographical areas

Coordination of the lake-/sea-effect snow research across the different geographical areas is very limited, and would benefit from further research advancements in the future. For example, Steenburgh and Nakai (2020) pointed out the lack of awareness of the snow climate over the west coast of Japan by North American meteorologists. They also underscored the importance of cross-regional collaborations in comparing the characteristics of lake-/sea-effect systems in various regions of the world to understand the fundamental processes that control the mode of the systems and their influence on the intensity and distribution of precipitation.

Most of the literature on lake-/sea-effect snow found in the Web of Science search is from the Great Lakes, the Great Salt Lake, and the Sea of Japan (Table 1). For other regions, fewer publications were discovered in the search. This can be partly due to the search criteria we used. For example, “Lake effect” is most used for the Great Lakes. Some publications essentially discuss lake-/sea-effect snow mechanisms in other regions even though they do not necessarily use the terms “lake effect,” “sea effect,” or “ocean effect.” For example, Cha et al. (2011) and Yoshizaki et al. (2004) studied wind-parallel bands due to the sea effect in Yellow Sea and the Sea of Japan respectively, but never used “sea effect” or “ocean effect” in their texts. Nakai et al. (2005) classified snow bands originating from the Sea of Japan but never mentioned these terms. On the other hand, even if the initial search criterion is loosened to “snow” only, the number of articles is still fewer for Black Sea, Caspian Sea, and Yellow Sea (Table 1). Research advancement and a broadened literature base for these geographical areas may contribute to more diverse knowledge in lake-/sea-effect snow formation mechanism, morphologies, and better forecasting.

5 | CONCLUSION

Although driven by common ingredients of warmer water surface, colder air moving over it, and land surface downwind, lake-/sea-effect snowfall can take various forms with a range of severity and impacts on local communities. A number of modeling and observational studies have contributed to revealing the distinct morphologies of the associated snowfall. In addition to the most common wide-spread, wind-parallel bands (or cloud streets), some morphologies are more frequently observed in the Great Lakes (mid-lake/shoreline band) or the Sea of Japan (T-mode). There are other morphology classifications reported in the literature, but those tend to be based upon the dynamics of the four main types presented here in this paper.

The evolution of lake-/sea-effect forecasts has benefited from the cumulative experience of operational forecasters, satellite measurements, expanding observational networks, and numerical forecast guidance. In particular, there have been marked advancements in the techniques around numerical weather and lake forecast models in the recent decades, including high-resolution models that can capture convective storms, probabilistic forecast based on ensemble systems, and iterative one-way coupling with a hydrodynamic-ice model. Operational forecasters employ the full spectrum methods in forecast decision-making (e.g., warning issuance) to inform local communities about expected hazardous conditions. Many challenges remain toward more accurate forecasts of lake-/sea-effect snow. Among these is the large observational gap that over-water observations during winter are very limited. While year-round offshore observations have increased in the Great Lakes (e.g., measurements at offshore lighthouses), such observations are still challenging especially in deep water. Another challenge is that computational resources are still limited in order to resolve the physics of lake-/sea-effect snow band formation, particularly in an operational environment, which has practical limitations concerning the allowable computational time for a forecast. Immediate demands for a numerical weather forecast model include a higher spatial resolution and full coupling with a hydrodynamic-ice model, the latter of which becomes critical when the water surface conditions change rapidly over the lake-/sea-effect snow storm duration. Finally, lake-/sea-effect snow research articles to date are concentrated on the Great Lakes, the Great Salt Lake, and the Sea of Japan. There are not as many in the other geographical areas. Coordination of the lake-/sea-effect snow research across the different geographical areas would benefit further research advancements in the future.

The warming trend will continue in the next decades and this will have implications for the lake-/sea-effect snowfall occurrence over the globe, including potential northern migration of their occurrence (e.g., the northern lakes may possibly experience prolonged lake-effect snow periods). Numerical forecast models will continue to provide an advanced understanding of the fundamental lake-effect snow processes and thereby continue to serve the local communities which are impacted by lake-/sea-effect systems in all parts of the world.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Ayumi Fujisaki-Manome: Conceptualization (lead); funding acquisition (supporting); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **David M. Wright:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (supporting). **Greg E. Mann:** Conceptualization (equal); funding acquisition (supporting); project administration (supporting); writing – original draft (equal); writing – review and editing (supporting). **Eric J. Anderson:** Conceptualization (equal); funding acquisition (supporting); project administration (supporting); writing – original draft (equal); writing – review and editing (supporting). **Philip Chu:** Conceptualization (equal); funding acquisition (lead); project administration (equal); writing – review and editing (supporting). **Christiane Jablonowski:** Conceptualization (equal); funding acquisition (lead); project administration (equal); writing – review and editing (supporting). **Stanley Benjamin:** Conceptualization (supporting); funding acquisition (supporting); project administration (supporting); writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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