Lake-Effect Freezing Drizzle: A Case-Study Analysis

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ABSTRACT

A series of lake-effect freezing drizzle events occurred southeast of Lake Michigan during the 2009–2010 cool season. These events occurred under an anomalous flow pattern, were not anticipated by forecasters, and in more than one case, led to the issuance of advisories for slick travel conditions and ice accrual. Given the potential impacts of such events on the public and aviation communities—as well as limited previous research on lake-effect freezing precipitation—two case studies are performed.

Despite their rarity, a common synoptic and mesoscale evolution is found in these freezing drizzle cases. Whereas the thermodynamic environment initially is supportive for lake-effect snow, a lowering capping inversion and a loss of moisture above this level diminishes the potential production of cloud ice. While this typically results in the end of lake-effect precipitation, these cases transitioned to freezing drizzle and are hypothesized to have resulted from a lack of cloud condensation nuclei in the air mass arriving from the lakes. Mesoscale model soundings projected the evolution of the thermodynamic environment. A conceptual summary of these events is presented that, given suggestive model guidance, includes tools to help forecasters better anticipate future similar events.

1. Introduction

Lake-effect snow (LES) is a phenomenon most well-known for causing extreme snowfall rates and highly variable weather conditions over short distances (e.g., Wiggin 1950; Hill 1971). LES typically forms as a continental polar or arctic air mass moves over the warmer waters of a lake, with the resulting sensible and latent heat fluxes from the water into the air assisting cloud and precipitation development (e.g., Niziol et al. 1995). Holroyd (1971) determined that the development of LES was favored when the lake-to-850-hPa temperature difference was $\geq 13^{\circ}\text{C}$, with lake-enhanced snows occurring with this temperature difference as low as $8\text{--}10^{\circ}\text{C}$ (Eichenlaub 1970; Dockus 1985) in the presence of synoptic-scale moisture and forcing for ascent. Because of the high-impact nature of LES bands, numerous studies have examined snowband formation and movement (e.g., Wiggin 1950; Holroyd 1971; Niziol 1987), snowband characteristics and types (e.g., Niziol et al. 1995), and the ability of meso-

scale models to simulate snowbands in advance of their occurrence (e.g., Hill 1971; Ballentine et al. 1998; Arnott 2010). Much less research has documented lake-induced precipitation occurring under environmental conditions unsupportive of snow.

Freezing drizzle (FZDZ) is of particular interest because of its impacts on ground and aviation transportation. FZDZ typically results from the collision-coalescence process in clouds where temperatures are $\geq -10^{\circ}\text{C}$ (and thus more likely void of substantial quantities of activated ice nuclei) and surface temperatures $\leq 0^{\circ}\text{C}$ (e.g., Mason and Howorth 1952; Bocchieri 1980). Cortinas et al. (2004) performed a comprehensive climatology of freezing rain, FZDZ, and sleet across the United States and Canada. They found that FZDZ occurred most often east of the Rocky Mountains with an increase in events at higher latitudes. In another study on freezing rain, Cortinas (2000) noted a relative minimum in freezing rain frequency downwind of the Great Lakes and hypothesized that this was due to the moderating influence of the lakes.

Bernstein et al. (2004) performed an analysis of aircraft data in cool-season Great Lakes clouds, describing environments conducive to supercooled large drop (SLD) production, and thus the implied potential for drizzle and FZDZ. They found that SLD production was directly related to the interplay between cloud liquid water content and drop concentrations. SLD production was favored in cases where liquid water content was high in the presence of low drop concentrations [due to lower concentrations of cloud condensation nuclei (CCN)]. This was found to occur often in cases where a cloud layer beneath a capping inversion was located above a stable layer, which acted to isolate the cloud layer from the boundary layer (and typically higher CCN concentrations). This result also suggests “cleaner” source regions for developing clouds (that would result in lower drop concentrations) would favor greater SLD production.

Some support for the preferential occurrence of FZDZ downwind of bodies of water is presented in Bernstein (2000), where an onshore wind trajectory was favored for FZDZ formation at Green Bay, Wisconsin, and Erie, Pennsylvania. It was suggested that the “clean environment” necessary for FZDZ production was produced by upstream or coincident snowfall, which acted to scavenge CCN. Bernstein (2000) also suggested a potential influence of lake/sea ice on downstream FZDZ production, but did not investigate it specifically in the study.

Three lake-effect FZDZ events occurred southeast of Lake Michigan during January and February of 2010. A review of the previous three winters during this period in this region found that none of the 14 FZDZ events that occurred at South Bend, Indiana (KSBN), were associated with lake-effect precipitation. In fact, the majority were associated with warm advection, suggestive of the stable boundary layer profile shown by Bernstein et al. (2004) to be favorable for drizzle production. The 2010 FZDZ events are of particular interest to operational meteorologists because 1) the events occurred under an anomalous flow pattern, 2) the events were not anticipated, and 3) in two cases, FZDZ was of sufficient significance to prompt winter weather advisories or warnings from the northern Indiana National Weather Service (NWS) Forecast Office (IWX) for slick travel conditions and ice accrual. Interestingly, seasoned forecasters at IWX (some with more than 20 years working in the area) could not recall the occurrence of lake-effect FZDZ. Given the apparent forecast challenge, as well as the limited amount of previous research on this topic, an

analysis of two of these events was undertaken. The goal of this analysis was to determine the common synoptic and mesoscale characteristics of these events, allowing for improved forecasts of lake-effect FZDZ.

A description of data used is in section 2. The anomalous nature of the flow pattern is presented in section 3, followed by detailed case study analyses of the two events in section 4. A conceptual summary of the findings, and the conclusions, follow in section 5.

2. Data

Observational and numerical guidance available to forecasters, both leading up to and during the events, were examined. Upper-air data were retrieved from the NWS Storm Prediction Center (www.spc.noaa.gov/obswx/maps/) and University of Wyoming (weather.uwyo.edu/upperair/sounding.html). Tropospheric Airborne Meteorological Data Reporting (TAMDAR) flight soundings were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (www.esrl.noaa.gov). Surface data were gathered from the Hydrometeorological Prediction Center (www.hpc.ncep.noaa.gov/html/sfc_archive.shtml). The historical data used to examine past FZDZ events at KSBN were gathered from the National Climatic Data Center (www.ncdc.noaa.gov). Backward trajectories from the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPPLIT) model were obtained from the Air Resources Laboratory website (ready.arl.noaa.gov/HYSPLIT.php). The online radar archive available from the University Corporation for Atmospheric Research (locust.mmm.ucar.edu/imagearchive) and images from the College of DuPage (weather.cod.edu) were employed to view archived regional radar images. Satellite images were obtained from the National Center for Atmospheric Research (weather.rap.ucar.edu/satellite). Vertical profiles of temperature, dewpoint, and wind in binary universal form for the representation of meteorological data (BUFR) format from operational deterministic model simulations were examined using the BUFKIT software (Mahoney and Niziol 1997). Finally, Lake Michigan water temperatures were obtained from the Michigan Sea Grant Coastwatch (www.coastwatch.msu.edu).

3. Large-scale pattern surrounding the events

A composite analysis [using National Centers for Environmental Prediction/National Corporation for Atmospheric Research (NCEP/NCAR) reanalysis data;

Kalnay et al. 1996] of the upper-air conditions surrounding these events is shown in Fig. 1. At 500 hPa, the pattern featured strong blocking per the anomalous ridging throughout southern Greenland along with a cutoff low over maritime Canada (Figs. 1a,b). At 850 hPa (Fig. 1c), a cyclonic gyre was located across the northwestern Atlantic. This resulted in maritime polar air flow from the northwestern Atlantic into much of northeastern North America, including the Great Lakes region.

To further identify the various source regions for the component air masses for the lake-effect FZDZ events, 1-week backward trajectories were performed (again using NCEP/NCAR reanalysis data) for parcels arriving at 100 m and 1500 m over KSNB at 0000 UTC 6 January 2010 and 0000 UTC 18 February 2010 (Fig. 2). The 1500-m trajectory clearly shows the maritime origin of the air mass at this level while the near-surface trajectory shows a history over the land mass (or ice covered waters) of interior Canada. This implies the juxtaposition of a relatively warm air mass in the cloud layer with relatively cold surface temperatures, supporting a potential FZDZ scenario as described in more detail below.

4. Case studies

a. Case study 1: 5–6 January 2010

1) SYNOPTIC AND MESOSCALE EVOLUTION

At 1200 UTC 5 January 2010, upper-air analyses (Fig. 3) showed north-northwesterly flow over Lake Michigan. The 850-hPa analysis (Fig. 3a) showed temperatures near -10°C , which when combined with lake temperatures around 2°C (not shown), indicates an environment with lapse rates marginally supportive for pure lake-effect precipitation (Holroyd 1971). This is consistent with regional radar images that showed a narrow “rope” of very light returns downwind of Lake Michigan at 1226 UTC 5 January 2010 (red oval in Fig. 4a). Also shown in Fig. 4b is a $3.9\text{ }\mu\text{m} - 11\text{ }\mu\text{m}$ satellite image that has been found to assist in assessing cloud particle sizes and, therefore, the potential for drizzle when clouds contain supercooled drops (e.g., Lee et al. 1997). Note the relatively bright area (black oval in Fig. 4b, implying large particle sizes before dawn) in the region of the reflectivity band seen in Fig. 4a. If corroborating data can show that the cloud is predominately composed of supercooled liquid, then the potential for SLD and FZDZ would be implied by these images. Of final note in the regional radar im-

Figure 1. NCEP/NCAR reanalysis of the 500-hPa height a) mean composite and b) anomaly, and c) 850-hPa vector wind composite for the period 5–6 January 2010 and 17–18 February 2010 compared to a 1980–2010 climatology. Click image for an external version; this applies to all figures hereafter.

Figure 2. One-week backward trajectories for two parcels arriving at 100 m (red) and 1500 m (blue) AGL at South Bend, Indiana, at a) 0000 UTC 6 January 2010 and b) 0000 UTC 18 February 2010. Top panel indicates parcel location while the bottom panel indicates parcel altitude. Trajectories are based on the NCEP/NCAR reanalysis dataset and use a time step of 1 h.

ages in Fig. 4a is a band of light-to-moderate returns that extend from central Lower Michigan into Lake Erie. This is at the leading edge of a short-wave trough in the 500-hPa flow (Fig. 3c).

Precipitation either mixed with or changed to FZDZ during the morning of 5 January at KSBN and Fort Wayne, Indiana (KFWA; see Fig. 4a for locations). Absence of glaciation in the cloud is suggested by TAMDAR soundings just before 1200 UTC 5 January 2010 (Fig. 5) that show saturation from near the surface up to -12°C . The KFWA sounding (Fig. 5b) is much colder and stable in the low levels, likely due to its greater distance from the lake and low-level westerly flow having a colder overland trajectory. When compared to the work of Bernstein et al. (2004), the KFWA sounding has a more classic drizzle signature with the stable low levels helping preclude CCN introduction from the boundary layer. The KSBN profile is not as favorable (given more low-level instability), but suggests that given the occurrence of precipitation at the ground, the liquid water content was sufficient to overcome potentially larger concentrations of CCN and produce SLD.

After a lull during the early afternoon, precipitation redeveloped during mid-afternoon as all snow at KSBN and KFWA. At this time the regional radar images (not shown) revealed echoes associated with

the approaching midlevel short-wave trough intersecting ongoing lake-induced returns over northern Indiana. It is hypothesized that the transition back to all snow was caused by a “seeder-feeder” mechanism (Braham 1967; Hall and Pruppacher 1976; Reinking and Boatman 1986) where ice crystals originating at midlevels seed supercooled clouds at lower levels, causing these clouds to glaciate and produce snow. Midlevel clouds also were noted on regional infrared satellite images (not shown), corroborating this idea.

This short-wave trough moved southeast of the region by 0000 UTC 6 January 2010. With ongoing cyclonic northwesterly flow through the vertical column, very light precipitation continued from 0000 to 1200 UTC 6 January 2010 (not shown). Given the loss of midlevel moisture associated with the departing short-wave trough, precipitation at both KSBN and KFWA changed back to FZDZ, with occasional FZDZ and/or snow continuing through the morning. Continued backing of the low-level flow in response to the departing northeastern United States trough, along with continued warming at 850 hPa, brought an end to the light precipitation on 6 January.

2) FORECAST PERFORMANCE

The last public forecast issued by IWX (the NWS office responsible for both KSBN and KFWA) pre-

Figure 3. Objective upper-air analysis for 1200 UTC 5 January 2010 at a) 850 hPa, b) 700 hPa, and c) 500 hPa using available observations and a 6-h forecast from the 0600 UTC NAM for the first-guess background field. Dashed line in c) denotes a short-wave trough described in the text.

ceding the first FZDZ report came at 0245 UTC 5 January 2010. Even though LES warnings and advisories were in effect for areas downwind of Lake Michigan, the emphasis was on snowfall with no men-

tion of FZDZ in the forecast. The forecast was updated at 0837 UTC 5 January 2010 with “patchy freezing drizzle” wording. The Terminal Aerodrome Forecasts (TAFs) for KSBN and KFWA also did not include any mention of FZDZ before it occurred.

Plan-view model forecasts from the North American Mesoscale (NAM) model were examined and found to adequately replicate the evolution of synoptic and mesoscale features throughout the event (not shown). Model forecast soundings were examined in BUFKIT to determine if the possibility of FZDZ could be detected in advance. Vertical profiles were examined for the NAM and Global Forecast System (GFS) models at KSBN and KFWA from the cycle initialized at 1200 UTC 4 January 2010 and the NAM, GFS, and Rapid Update Cycle (RUC) models initialized at 0000 UTC 5 January 2010. In every instance, substantial drying above 850 hPa was noted during the morning of 5 January. An example model sounding evolution is shown from the NAM in Fig. 6 that, at 1200 UTC, compares quite favorably with the TAMDAR sounding shown in Fig. 5b.

b. Case study 2: 17–18 February 2010

1) SYNOPTIC AND MESOSCALE EVOLUTION

A deep upper-level low was located over the northeastern United States at 0000 UTC 17 February 2010 (Fig. 7). At this time, thermal profiles at Gaylord, Michigan, and White Lake, Michigan, supported snow given saturation at temperatures $< -12^{\circ}\text{C}$ (Figs. 8a,b). As the closed upper low lifted northeast, however, the capping inversion lowered with drying in the middle and upper troposphere (Figs. 8c,d). By 1400 UTC 17 February 2010 this led to the top of the cloud layer having temperatures $> -10^{\circ}\text{C}$ (not shown). It was at this time that precipitation began to mix with or change to FZDZ given surface temperatures $< 0^{\circ}\text{C}$. Radar returns diminished substantially during the morning of 17 February, with very light returns indicative of drizzle or FZDZ (red oval in Fig. 9a). By 1500 UTC 17 February 2010, FZDZ was reported at both KSBN and KFWA. TAMDAR and RUC soundings confirmed a saturated layer below midlevel drying, with temperatures in the saturated layer generally $> -12^{\circ}\text{C}$. With these data suggesting a cloud layer void of ice crystals, satellite images (Fig. 9b) can then be examined to determine if the clouds consisted of SLD (see Fig 9b; the dark area within the black oval over northern Indiana implies large particle sizes during

Figure 4. a) Regional radar composite for 1226 UTC 5 January 2010. b) Regional multispectral ($3.9\ \mu\text{m} - 11\ \mu\text{m}$) satellite image for 1215 UTC 5 January 2010. Locations of South Bend (KSBN) and Fort Wayne (KFWA), IN, are indicated in white in a). Black oval in b) indicates brighter area, implying large particle sizes during predawn.

Figure 5. TAMDAR soundings from a) flight descending into KSBN at 1153 UTC 5 January 2010 and b) flight ascending from KFWA at 1133 UTC.

the daytime), and thus would be more likely to produce FZDZ at the surface.

A secondary trough rotating around the periphery of the northeastern United States upper low supported weak midlevel ascent as well as low-level warm advection from the north (not shown). This midlevel ascent, combined with a brief increase in moisture aloft (apparent in infrared satellite images, not shown), supported the transition back to snow as observed at KSBN and KFWA from 2100 to 2300 UTC 17 February 2010, again suggesting “seeder-feeder” processes. FZDZ returned to KSBN after this trough departed, indicated by the 2338 UTC 17 February 2010 surface observation, as northerly flow over Lake Michigan continued. The upper low and associated surface low over the northeastern United States continued to move northeast, with warm advection ongoing over the southern Great Lakes. This warm advection, combined with a lowering capping inversion, caused the saturated portion of the sounding to lower to where all areas were $>-10^{\circ}\text{C}$, as indicated in regional TAMDAR and radiosonde observations (Fig. 10). FZDZ ceased at KSBN by 2346 UTC 17 February 2010, with drizzle falling between 1200 and 1600 UTC 18 February 2010 as surface temperatures rose

Figure 6. NAM BUFR forecast soundings for KSBN from the 0000 UTC 5 January 2010 cycle verifying at a) 0600 UTC, b) 1200 UTC, c) 1800 UTC, and d) 0000 UTC 6 January 2010.

Figure 7. Objective 500-hPa analysis from 0000 UTC 17 February 2010 using available observations and a 6-h forecast from the 1800 UTC NAM for the first-guess background field.

above freezing. At KFWA, FZDZ was briefly observed again from 1530 to 1620 UTC 18 February 2010. Eventually, advection of much drier air into the region (not shown)—combined with a declining lake response (due in part to warming profiles and backing low-level flow supporting a much shorter fetch)—ended all precipitation as surface ridging commenced.

2) FORECAST PERFORMANCE

The public forecast from IWX first included FZDZ at 0854 UTC 17 February 2010. Although this was before the first FZDZ was observed at KSBN and KFWA, the area forecast discussion, issued along with the public forecast, indicated that FZDZ had *already* been observed at the forecast office, suggesting the forecast change was in *reaction* to observations rather than in *anticipation* of them. This argument is corroborated by the fact that the TAFs for KSBN and KFWA

Figure 8. Upper-air soundings from White Lake and Gaylord, MI, for 0000 UTC 17 February 2010 (a and b, respectively) and 1200 UTC 17 February 2010 (c and d, respectively).

Figure 9. a) Regional radar composite for 1455 UTC 5 January 2010. b) Regional multispectral (3.9 μm – 11 μm) satellite image for 1445 UTC 5 January 2010. Dark area within the black oval over northern Indiana implies large particle sizes during the daytime.

Figure 10. a) TAMDAR sounding from a flight leaving KFWA at 0351 UTC 18 February 2010 and b) upper-air sounding from White Lake, MI, at 0000 UTC 18 February 2010.

failed to anticipate FZDZ before it occurred. An updated public forecast was issued at 1035 UTC 17 February 2010 with the inclusion of a winter weather advisory for slick travel conditions and light ice accretal.

Plan-view model forecasts from the NAM indicated the model did a reasonable job capturing the primary synoptic and mesoscale features responsible for lake-effect precipitation. Forecast soundings from the 0000 UTC 16 February 2010 and 0000 UTC 17 February 2010 NAM and GFS cycles all indicated drying above 700 hPa, as well as warming below this level, resulting in cloud top temperatures becoming $>-12^{\circ}\text{C}$. Figure 11 shows an example evolution from the NAM at KSBN and compares favorably to the sounding evolution shown in Figs. 8 and 10.

5. Conceptual summary and conclusions

This study highlighted two cases of lake-effect FZDZ that were not expected by forecasters, with a goal of understanding the meteorological factors, and thus to provide forecasters with tools to help better anticipate future events.

The evolution in the forecast soundings shown in Figs. 6 and 11 is common during the later portions of LES events, and based on TAMDAR observations, appears to be a reasonable representation of what actually occurred during the events. This evolution features a strengthening and lowering capping inversion, which results from mid- and upper tropospheric troughing that departs the Great Lakes region, usually ending LES. However, in these events, FZDZ occurred instead. Therefore, simply following the evolution implied by Figs. 6 and 11 is not sufficient to produce lake-effect FZDZ, which likely is a key reason why these events were not foreseen. Another contributing factor was the lack of forecaster experience with such events, given their rarity.

Is it possible for forecasters to anticipate these events? We hypothesize that the anomalous mid- and upper-level flow across eastern North America and the northwestern Atlantic likely played a role in conditioning the atmosphere to produce lake-effect FZDZ. Recall the composite flow pattern in Fig. 1c, which reveals a cyclonic gyre at 850 hPa that transported maritime polar air into the Great Lakes region. In addition to this air mass likely being substantially warmer than is typical for this flow direction, the maritime origin (and subsequent passage over snow-covered ground and the Great Lakes) suggested it also was void of substantial quantities of CCN. This air mass would therefore be more likely to support a transition from snow to FZDZ (given sufficient liquid water content) versus snow to non-precipitating clouds (e.g., Bernstein et al. 2004).

In addition to the hypothesis above, the occurrence of lake-effect FZDZ also depends on the atmospheric temperature profile. There is a requirement for 1) surface temperatures below freezing, 2) temperatures at the base of the capping inversion to be $>-10^{\circ}\text{C}$ ($>-12^{\circ}\text{C}$ for the cases examined here) to minimize ice crystal production in the clouds, and 3) lake-to-850-hPa temperature differences to be near 13°C for the lake contribution to any downstream mesoscale circulation to provide sufficient lift to produce drizzle. Together, these factors suggest that 850-hPa temperatures

Figure 11. NAM BUFR forecast soundings for KSNB from the 0000 UTC 17 February 2010 cycle verifying at a) 0600 UTC, b) 1200 UTC, c) 1800 UTC, and d) 0000 UTC 18 February 2010.

near -12°C may be a good indicator of the potential for the progression of events seen here.

Finally, an important caveat to the above evolution is the presence of additional sources of lift and mid- to upper-level moisture, such as midlevel short-wave troughs. As shown in both of the case studies in section 4, such features can provide a seeding mechanism that helps to glaciate cloud water into cloud ice in the lake-induced precipitation band, thus changing the precipitation type to snow.

In summary, this study has shown tools to heighten awareness for the potential of lake-effect FZDZ. Trajectory analysis can provide foreknowledge of potential characteristics of the air mass over the Great

Lakes region, including source regions and implied CCN concentrations. From this information, forecasters can have a heightened awareness for the potential changeover from snow to FZDZ. This depends on the microphysical properties of the specific event, with the balance between liquid water content and CCN concentration key to the production of drizzle. Although there may be environmental clues to the likelihood of this transition (via multispectral satellite images or the known existence of stable low-level profiles from TAMDAR soundings), forecasters should also pay close attention to spotter reports as well as the occurrence of very light radar returns (best seen in clear-air mode) suggestive of a snow to FZDZ transi-

tion rather than a snow to cessation of precipitation. Once FZDZ develops, it can continue given moist, cyclonic low-level flow with a contribution from the lake, given that lake-to-850-hPa temperature differences are near 13°C. Finally, as boundary layer temperatures increase with further lowering of the capping inversion, the thinning lake-induced cloud becomes unable to support continued drizzle production, and the lake-effect FZDZ comes to an end.

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