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Lake breezes in the southern Great Lakes region and their influence during BAQS-Met 2007

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Abstract

Mesoscale observations from the BAQS-Met field experiment during the summer of 2007 were integrated and manually analyzed in order to identify and characterize lake breezes in the southern Great Lakes region of North America, and assess their potential impact on air quality. Lake breezes were found to occur on 90% of study days, often occurring in conditions previously thought to impede their development. They affected all parts of the study region, including southwestern Ontario and nearby portions of southeast Michigan and northern Ohio, occasionally penetrating inland from 100 km to over 200 km. Occurrence rates and penetration distances were found to be higher than previously reported in the literature. This more accurate depiction of observed lake breezes allows a better understanding of their influence on the production and transport of pollutants in this region.

The observational analyses were compared with output from subsequent runs of a high-resolution numerical weather prediction model. The model accurately predicted lake breeze occurrence in a variety of synoptic wind regimes, but selected cases showed substantial differences in the detailed timing and location of lake-breeze fronts, and with the initiation of deep moist convection. Knowledge of such strengths and weaknesses will assist with interpretation of results from air quality modelling driven by this meteorological model.

1 Introduction

The Border Air Quality and Meteorology Study (BAQS-Met) was conducted during the summer of 2007 in the southern Great Lakes region of North America to investigate the impacts of mesoscale boundary-layer phenomena, particularly lake-breeze circulations, on local air quality and the regional transport of pollutants. A mesoscale monitoring network operated from 1 June to 31 August while a measurement-intensive field campaign was carried out from 20 June to 10 July.

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The monitoring network comprised existing meteorological and air chemistry stations plus a number of special surface stations for collecting data with high temporal and spatial resolution. During the intensive observation period (IOP), a variety of additional meteorological and air chemistry measurements were made by aircraft, via vehicle-based laboratories, and at three “supersites”. The study domain and monitoring network are shown in Fig. 1.

The BAQS-Met study builds upon previous work in southern Ontario and southeast Michigan on lake-breeze circulations and their impacts on both air quality and severe summer storms. Field studies were conducted in 1992-93 (SONTOS/SEMOS – Reid et al., 1996; Wolff and Korsog, 1996; Sills, 1998; Hastie et al., 1999), in 1997 (ELBOW 97 – King and Sills, 1998; Sills, 1998), and in 2001 (ELBOW 2001 – Sills et al., 2002). Outstanding questions from these and other studies led to the development of a number of scientific hypotheses to be tested during the BAQS-Met experiment (see Brook et al., 2011). This article addresses two of them:

1) Local meteorological processes such as lake-breeze circulations exert a considerable influence on air quality in the study region, and

2) Current numerical models adequately represent both meteorological and chemical processes that lead to elevated O_3 and $PM_{2.5}$ events in the study region.

Previous studies have identified the conditions under which air quality in and near the study region can be influenced by large-scale meteorological features and the long-range transport of pollutants (e.g., Yap et al., 1988). However, under what conditions is air quality influenced by local or regional meteorological phenomena? This is addressed here by reviewing the significant impacts that lake-breeze circulations are known to have on local and regional air quality, and then demonstrating the frequency and spatial influence of lake-breeze circulations in the study region. Lake breeze characteristics such as occurrence frequency, start/end time intervals, response to various synoptic wind regimes, and inland penetration distance are examined using an approach that integrates complementary observations, providing what we believe to be an improved depiction of Great Lakes lake breeze behaviour.

Air quality models that are used for air quality research, regulation, and forecasting are typically driven by numerical weather prediction (NWP) models. The NWP models must be accurate in order to properly simulate the production and transport of pollutants. In this study, we assess the ability of a high-resolution NWP model used at Environment Canada for air quality research to generate lake-breeze circulations matching those observed during the IOP. Only meteorological processes are examined in this study. However, other studies investigating chemical processes and their relation to lake breezes during BAQS-Met (Hayden et al., 2011; Levy et al., 2010; Makar et al., 2010a) will be discussed.

After reviewing past research on lake breezes and impacts on air quality (Sect. 2) and the data and methodology used for this study (Sect. 3), this paper examines lake breeze characteristics observed during the entire BAQS-Met study (Sect. 4) and compares simulated and observed lake breezes during the BAQS-Met intensive period, including three case studies (Sect. 5). Results will be discussed in Sect. 6 and conclusions will be presented in Sect. 7.

2 Background

2.1 Lake breezes

Lake breezes, like sea breezes, are driven by the difference in pressure between warmer air over land and cooler air over water. Such temperature contrasts are the result of differences in heat flux for land and water surfaces. Lake-breeze circulations usually develop a few hours after sunrise and dissipate near sunset. Where present, the circulations strongly influence the meteorology through the lowest layers of the atmosphere. Figure 2 shows a schematic diagram of a typical lake-breeze circulation.

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Physick (1976) found by numerical simulation that, for gulfs and lakes roughly the size of the Great Lakes or smaller, circulations on each shore should not occur independently but interact to form a mesoscale high-pressure area with associated subsidence over the water. This result has been confirmed by Estoque (1981) and Comer and McKendry (1993), among others, and probably represents the most significant difference between lake breeze dynamics and the dynamics of sea breezes associated with much larger bodies of water.

The leading edge of the lake breeze, known as the lake-breeze front, is a narrow convergence zone with enhanced upward vertical velocity and moisture depth. Lift at the front can rapidly transport pollutants, and act to trigger the development of thunderstorms in a conditionally unstable environment (especially where lake-breeze fronts merge or intersect). The arrival of the lake-breeze front is frequently associated with a sharp decrease in temperature, a sharp increase in dew point, and a shift to onshore winds. However, the arrival signature in the temperature and dew point data typically becomes more subtle with increasing inland distance due to the rapid modification of the marine air mass over land (Lyons, 1972).

The inland penetration of the lake-breeze front is influenced by a number of factors, including lake-land temperature difference, orography, and even soil moisture (Physick, 1980). However, the factor having the greatest influence on inland penetration is the strength and direction of the synoptic wind[1] relative to the lake shore (Estoque, 1962; Bechtold et al., 1991; Arritt, 1993; Comer and McKendry, 1993; Simpson, 1994; King et al., 2003). A light to moderate onshore synoptic flow can increase the inland penetration of the lake-breeze front, but the formation of a front can be prevented if onshore flow is too strong. An offshore synoptic wind can impede the inland progress of the lake-breeze front considerably, in some cases preventing it from moving onshore at all. Observed sea breeze penetration distances have been reported in previous studies at

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[1] For this study, the 850 hPa wind is used to represent the large-scale synoptic wind and is categorized as follows: light (0.5–4.9 $\mathrm{m\,s^{-1}}$), moderate (5–9.9 $\mathrm{m\,s^{-1}}$) and strong (>=10 $\mathrm{m\,s^{-1}}$). A synoptic wind less than 0.5 $\mathrm{m\,s^{-1}}$ is considered calm.

up to 100 km in the US and the UK, and to nearly 300 km in Australia (see Simpson, 1994). Observed Great Lakes lake breeze penetration distances have ranged from 15 km to 45 km (e.g., Moroz, 1967; Lyons, 1972; Estoque et al., 1976; Ryznar and Touma, 1981), though more recently Sills (1998) reported penetration distances up to 120 km. Though not explicitly stated, distances approaching 100 km were also suggested in the analyses of lake breezes by Comer and McKendry (1993) and King et al. (2003).

2.2 Impacts on air quality

The exacerbation of air pollution problems in coastal environments is well known. One of the commonly occurring effects related to the onshore flow of relatively cool marine air is fumigation of pollutants downwind of the shoreline. Effluent from a smokestack at the shore blown inland by onshore winds may be confined to a plume in the stably stratified marine air. However, as this plume intersects the convective mixed layer inland, pollutants can be mixed down to the surface (Lyons and Cole, 1973).

Another commonly occurring effect in coastal areas is plume trapping. Stably stratified marine air moving onshore can have a mean mixing depth that is 10% of that existing away from the influence of the lake (Lyons and Cole, 1973). Thus, effluent that is emitted into this layer is effectively trapped and high concentrations of pollutants can subsequently reach the surface and persist. In addition, under such conditions, high concentrations of precursors and secondary pollutants can be sustained for longer times and over larger transport distances. This can influence chemical reactions and result in the formation of a greater quantity of ozone, for example.

Fumigation and plume trapping often occur in association with lake breezes. However, lake breezes introduce their own unique problems. The first is the ability of lake breezes to transport pollutants in three dimensions. Lake breezes are quasi-closed circulations and pollutants emitted into them can be recirculated over the near-shore area (Lyons, 1972; Lyons et al., 1995; Harris and Kotamarthi, 2005; Levy et al., 2008). That is, pollutants emitted into the inflow layer get lofted in the frontal region and disperse into the return flow aloft. A fraction of these pollutants may be forced into the inflow layer again by the descending branch of the circulation. Remaining pollutants reside in the residual layer aloft (see Fig. 2). Lyons and Olsson (1973) observed a helical trajectory within a lake-breeze circulation and suggested that the motion of pollutants might include an along-coast component in addition to the cross-coast components. Lyons et al. (1995) successfully simulated this three-dimensional behaviour using a numerical model.

Another effect on air pollution often occurring with lake breezes involves the increased production of ground-level ozone or "photochemical smog". The ingredients for deleterious ground-level ozone concentrations include an abundant supply of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x), strong insolation, relatively high air temperatures, light wind speeds, and limited mixing depths (Lyons and Cole, 1976). Three of these ingredients – strong insolation, relatively high temperatures over land, and light winds – are also conditions associated with the development of vigorous lake breezes. When a lake breeze occurs, cloudless skies and enhanced insolation are common over the lake and at inland locations behind the lake-breeze front, and can result in increased ozone production there given the availability of precursors. This ozone can then be advected inland by the lake breeze, as has been shown by Hastie et al. (1999).

Though a strong relationship between sea/lake breezes and photochemical smog has been demonstrated by Gusten et al. (1988), among others, there are also situations when the sea/lake breeze delivers relatively clean air to a region experiencing photochemical pollution (e.g. Hayden et al., 2011; Levy et al., 2010).

3 Data and methodology

3.1 Observational data

A number of observational data sets from the BAQS-Met mesoscale network were utilized for this study, including surface weather station data, GOES-8 visible channel satellite imagery, and weather radar imagery. There were a total of 54 surface weather stations operating in the BAQS-Met study region during the June to August period. Thirty-eight of those were existing stations operated by various agencies such as Environment Canada, the US National Weather Service, and the Ontario Ministry of the Environment, and these provided data hourly. The remaining 16 surface stations were installed for the BAQS-Met project, including 12 from Environment Canada (with a buoy in each of Lake Erie and Lake St. Clair) and four from York University (see Fig. 1). Data from these stations were recorded as 1 min averages.

The bulk of these stations made measurements at World Meteorological Organization standard heights of 10 m for wind and 1.5 m for temperature and dew point. Pressure, solar radiation, and precipitation were also measured at a number of sites. Data from these fixed surface stations were supplemented by mobile observations over land and ship observations over the lakes when available.

All available GOES-8 visible and infrared channel satellite imagery was collected, mainly at 15 min intervals. Lake surface temperature data based on infrared measurements from the NOAA POES polar-orbiting satellite were obtained from the Great Lakes Environmental Research Laboratory (GLERL) Great Lakes Surface Environmental Analysis (GLSEA) dataset (Schwab et al., 1992).

Weather radar data from the Environment Canada 5-cm wavelength Doppler radar at Exeter and from NOAA 10-cm wavelength Doppler radars in Detroit and Cleveland (see Fig. 1 for locations) were used at time intervals between 4.5 min and 10 min. The lowest-level reflectivity scans were used to identify instances of precipitation and radar “fine lines” in the study region. Fine lines indicate enhanced concentrations of insects along narrow regions of lift in the convective mixed layer (Wilson et al., 1994; Russell and Wilson, 1997). Sharp gradients in the lowest-level radial velocity data were also used to help identify mesoscale boundaries.

Finally, to determine synoptic wind regime characteristics during the study period, the 850 hPa wind at 20:00 local time (20:00 LT, equivalent to 00:00 UTC) from the closest rawinsonde station (DTX) northwest of Detroit, Michigan, was used (see Fig. 1 for location). In cases where 850 hPa winds were not available at 20:00 LT, or precipitation was falling at DTX in the hour preceding 20:00 LT, the 08:00 LT (12:00 UTC) sounding was used. In addition, DTX data were not available for the last few days of the study, so 20:00 LT data from the BUF rawinsonde station near Buffalo, New York, to the east of the study region were used instead.

3.2 High-resolution numerical model output

The Global Environmental Multiscale (GEM) model, described by Côté et al. (1998), is a numerical weather prediction model used for operational forecasting by Environment Canada. A limited-area version of this model, having approx. 2.5 km horizontal grid spacing and 58 hybrid-coordinate levels increasing monotonically with height from the Earth's surface to 10 hPa (hereafter referred to as GEM-LAM-2.5), was used to simulate the meteorological conditions observed during the BAQS-Met IOP. These meteorological fields were also used to drive a regional air pollution modeling system known as AURAMS (A Unified Regional Air-quality Modeling System, see Makar et al., 2010a,b). Most of the initial and boundary conditions for these high-resolution runs were provided by a global variable-resolution version of the GEM model using approximately 15 km horizontal grid spacing in the core region and the same vertical coordinates as the high-resolution simulation. High-resolution geophysical fields, and high-resolution lake surface temperatures based on climatological values, were exceptions. Initial and boundary conditions for the coarse grid model runs were provided by operational data assimilated analyses. See Makar et al. (2010b) for more details.

3.3 Identification of lake breezes in observational data

Since ancient times, one of the most widely recorded features of sea and land breezes has been the diurnal reversal of wind direction near the shore (Pielke and Segal, 1986; Steyn and Kallos, 1992; Simpson, 1994). Lake breeze identification in the Great Lakes region, however, has focused on detection of the lake-breeze front (e.g. Moroz, 1967; Lyons, 1972; Estoque et al., 1976; Ryznar and Touma, 1981; Laird et al., 2001). Accordingly, a lake-breeze front identification procedure was used to generate statistics describing lake breeze behaviour during the BAQS-Met study period.

Mesoscale meteorological analyses were generated for each day of the study using the Aurora workstation (Greaves et al., 2001). Surface weather station data, GOES-8 satellite visible channel imagery, and low-level radar reflectivity/radial velocity data were displayed simultaneously and visually inspected, both at hourly intervals and via animations. For days during the IOP, the estimated positions of identified lake-breeze fronts were incorporated into the hourly analysis, as were synoptic-scale front positions obtained from operational weather analyses. As an example, Fig. 3 is a mesoscale meteorological analysis plot valid at 15:00 LT on 6 July 2007 that includes the estimated positions of lake-breeze fronts. Animations of hourly mesoscale analyses for each day of the IOP are available at http://tinyurl.com/SillsBAQS-MetAnimations.

Table 1 lists the criteria used to identify lake-breeze fronts. Positive factors were those that gave clear evidence of a lake-breeze front, such as a line of cumulus clouds and/or radar fine line quasi-parallel to the shore moving gradually inland (but not associated with a thunderstorm gust front or synoptic-scale front). Negative factors, such as the absence of onshore flow evident in the surface data, were used to reject the case for a lake-breeze front. In addition, evidence for a lake-breeze front from a single observation platform could sometimes be ambiguous, such as there being no cloud present on visible satellite. In such cases, more weight was placed on evidence from the other observational platforms.

In situations where the passage of a lake-breeze front could not be confirmed via the mesoscale analysis, time series of 1 min data from individual surface stations were examined for rapid changes in wind, temperature and/or dew point not associated with thunderstorm gust fronts or synoptic-scale fronts. A similar factor-based methodology was used to identify other mesoscale boundaries such as land-breeze fronts and thunderstorm gust fronts. These were added to hourly mesoscale analyses when present during the IOP.

Errors in the analyzed positions of lake-breeze fronts at the surface depended on data type and density. In periods/regions with only low-density surface data available for identification, the error might be as large as ±10 km. When visible satellite imagery was used for identification, factors such as cloud line displacement relative to the front and parallax due to the nearly 45° satellite viewing angle resulted in errors estimated to be as large as ±5 km. Radar fine lines resulted in the most accurate analyzed lake-breeze front positions, estimated to be within ±1 km. However, fine lines were not visible on all days and were usually confined to within 100 km of a radar when present. The ability to integrate data from each of these platforms in space and time using the Aurora workstation often helped to reduce overall positional error considerably.

The manual lake breeze identification process described above is labor intensive and relies on human pattern recognition skills. However, there are numerous examples of this type of mesoscale boundary analysis undertaken in both in a research setting (e.g., Purdom, 1976; Wilson and Schreiber, 1986; Hastie et al., 1999; Sills et al., 2004; Wilson and Roberts, 2006) and a real-time setting (e.g., Wilson et al., 2004, 2010; Sills and Taylor, 2008). We believe that its use here has resulted in more accurate estimates of lake breeze frequency than could be obtained using the more stringent criteria (and in some cases, the automated approach) employed in other studies of Great Lakes lake breezes (this is discussed in greater detail in Sect. 4). The results should be replicable given substantial knowledge of and experience with meteorological data analysis.

Lastly, for days during the IOP, lake-breeze front inland penetration distances were calculated for each hour. For each lake, the distance selected was the furthest extent of the lake-breeze front from the lake, measured to the closest point along the shoreline. Values rounded to the nearest 5 km are reported.

3.4 Identification of lake breezes in GEM-LAM-2.5 output

GEM-LAM-2.5 output was examined using the Unidata Integrated Data Viewer (IDV) (Murray et al., 2003). As with the observational data, identification of a lake breeze mainly involved locating a lake-breeze front. Lake-breeze fronts were identified by superimposing 390 m vertical motion on the surface wind field. Elongated regions parallel to lake shores that had upward vertical velocity greater than 0.1 m s^{-1} at 390 m and surface wind convergence (not related to convective downdrafts and synoptic-scale fronts) were determined to be lake-breeze fronts. Typically, a lake-breeze front was detected via evidence of an abrupt surface wind shift to onshore winds. Animations of the wind and vertical velocity fields in IDV often made identification of lake-breeze fronts straightforward.

Figure 4 shows an example plot used for lake-breeze front identification valid at 15:00 LT on 6 July 2007. It includes the estimated positions of lake-breeze fronts derived from the model data. Errors in the analysis of model lake-breeze front positions at the surface were overall less than that for observations and depended mainly on the possible displacement between the surface convergence and the lift at 390 m, resulting in an estimated error up to ±2 km. Note that this represents analysis error and does not account for model error, which can be much larger.

The model daily penetration distance for each lake was calculated for the hour showing the maximum inland penetration of the lake-breeze front. The distance selected was the furthest extent of the lake-breeze front from the lake, measured to the closest point along the shoreline. Values rounded to the nearest 5 km are reported.

4 Results from the June–August period

A number of observed lake breeze characteristics are derived and compared in this section, covering the months of June 2007 through August 2007. They include lake breeze occurrence frequency, start/end time intervals, and the influence of the synoptic wind. Each of these is important for gaining a better understanding of the behaviour of summer lake breezes in the study region and determining their potential influence on air quality, as discussed in the Sect. 2. Derived data for each day are provided in the Supplement, Table S1.

4.1 Observed occurrence frequency

Table 2 shows lake breeze occurrence frequencies grouped by lakeshore for 90 of 92 days (data were not properly archived for two days – 18–19 August). Note that the lakeshores as defined here consist only of the lakeshore segments that are located in and near the study region.

Lake breezes associated with at least one lake in the study region were identified on 90% of study days. Each of the individual lakes generated a lake breeze on between 82% and 84% of days. On 76% of days, lake breezes were generated simultaneously by all of the lakes. Between 4 June and 4 August, inclusive, there was only one day without a lake breeze somewhere in the study region. In addition, there were three periods with lake breezes on all lakes occurring over 11 consecutive days or more (8 June–18 June, 20 June–10 July, 21 July–4 August) with the longest being 21 days (fortuitously, the BAQS-Met IOP was during this period). The Lake Huron shore had 24 consecutive lake breeze days between 20 June and 13 July. Remarkably, this is twice the highest number of consecutive lake breeze days previously reported in the Great Lakes region (12 days on the Lake Michigan shore; Eichenlaub, 1979).

The lake breeze frequencies found here for individual shorelines are much higher than those reported by other researchers in the Great Lakes region for June through August: 13% to 41% for eastern Lake Michigan (Laird et al., 2001; Ryznar and Touma, 1981; Lyons, 1972), 19% to 45% for Western Lake Michigan (Laird et al., 2001; Lyons, 1972), and 17% to 30% for Lake Erie (Biggs and Graves, 1962). Comer and McKendry (1993) estimated a 30% lake breeze frequency for Lake Ontario, but over a period from April to September, inclusive.

A check was also performed to see if this large difference in observed lake breeze frequency could be explained by weather conditions during the summer of 2007 being particularly conducive to the development of lake breezes. It was found that the average mean temperature, maximum temperature and minimum temperature for the June through August period at the Windsor Airport climate station were all 1.2 °C to 1.4 °C higher than the 1971–2000 climate normals, while the number of days with rainfall was 30.0 compared to the normal of 31.2 (see Table 3). The slightly higher temperatures and slightly lower number of days with rainfall might lead one to believe that lake breeze activity was slightly higher than normal during summer 2007. However, during July, the month with the greatest overall lake breeze occurrence during BAQS-Met, temperatures were nearly exactly normal and the number of days with rain was only about 10% below normal. This appears to show that larger-scale conditions during summer 2007 are not responsible for the large difference between the lake breeze occurrence during the summer months of 2007 and that stated in the literature.

The difference may be partly due to the fact that the observational datasets being used in this study are in some cases superior to those used in previous studies. It is also possible that some of the differences could be explained by regional influences on lake breeze occurrence, perhaps related to the orientation of the shoreline with respect to the prevailing synoptic wind. However, we believe that much of the difference can be explained by the use of more stringent lake breeze identification criteria in past studies. These studies employed one or more of the following criteria to identify days with lake breezes:

- no synoptic-scale frontal passages in the region of interest (Biggs and Graves, 1962; Comer and McKendry, 1993; Ryznar and Touma, 1981; Laird et al., 2001),

- synoptic wind not onshore (Biggs and Graves, 1962; Ryznar and Touma, 1981),
- presence of a return flow above the surface inflow (Lyons, 1972), and
- sky clear or partly cloudy during daylight hours (Comer and McKendry, 1993; Ryznar and Touma, 1981).

Each of the above selection criteria appears to be more restrictive than necessary. Lake breezes were observed to occur in the presence of a synoptic-scale front in the domain on 18 days (there were 24 days with fronts in the study domain during daytime hours, 18 with lake breezes). On 24 days, lake-breeze fronts were detected moving inland from the shoreline under light to moderate onshore synoptic winds up to 7.7 m s^{-1}. During intensive observations when data above the lake-breeze inflow layer could be sampled by aircraft, it was found that a return flow was often very difficult to discern (see Hayden et al., 2011). This is likely true in most cases with a moderate to strong synoptic wind. Finally, on 42 days, lake breezes were experienced in areas with more than three hours of mostly cloudy or overcast conditions (as revealed by visible satellite imagery). This cloud was often associated with arriving or departing precipitation, or a thin or broken deck of mid- or upper-level cloud. Occasionally the cloudy conditions were produced by convective showers and thunderstorms (hereafter referred to as deep moist convection, or DMC) initiated at the lake-breeze fronts themselves.

Given the above, the use of the aforementioned criteria (i.e., those used in earlier studies for the Great Lakes region) when identifying lake breeze days appears to incorrectly eliminate a considerable fraction of lake breeze occurrences and therefore lower the occurrence frequency.

4.2 Start and end time intervals

Lake breeze start and end time intervals observed during the study are values combining observations from all of the three lakeshores. One-hour intervals were used since the mesoscale analyses were only available every hour. On a day with lake breezes on all shores, for example, the hour interval over which lake breezes could first be observed on all shores would be the start time interval, and the first hour interval over which lake breezes could no longer be observed on all shores would be the end time interval. There are often small differences in start and end times for each lake but an analysis of this type was not undertaken. It should also be noted that lake breeze start and end times can vary widely depending on weather conditions. For example, lake breezes may begin late as cloud associated with a low-pressure system moves out, or may end early if cloud and downdrafts associated with DMC begin to dominate.

Using the above methodology, the median lake breeze *start* time interval for the period June to August 2007 was 10:00–11:00 LT, with a range from 09:00-10:00 LT to 19:00-20:00 LT. The median start time interval of 10:00–11:00 LT is the same as the most frequent interval found by Lyons (1972) on the Western Lake Michigan shore. The median end time interval during this period was 20:00–21:00 LT, with a range from 16:00–17:00 LT to 02:00–03:00 LT (the next day). The median lake breeze duration was calculated to be 10 h, with a range from 2 h to 16 h.

4.3 The synoptic wind and its influence

The frequencies of synoptic wind directions and speeds during the BAQS-Met study period are shown in Fig. 5. Synoptic winds from the western quadrant (southwest to northwest) were by far the most frequent. Northwest synoptic winds occurred on 19% of study days. In contrast, there were no cases with a synoptic wind from the east-northeast, east, or south-southeast. As shown in Fig. 5, synoptic winds with light to moderate winds were observed from most directions, but strong synoptic winds occurred only from the SSW through NW.

Lake breezes occurred in synoptic winds from each observed direction, and with synoptic wind speeds up to 22.6 m s^{-1}. The strength of the synoptic wind appeared to limit the occurrence of lake breezes only when there was a weak lake-land temperature difference, or if the synoptic wind was moderate to strong *and* onshore. Instead, the greatest limiting factor for lake breeze occurrence was the presence of thick clouds and precipitation, typically associated with a passing low-pressure system.

The lake-breeze circulation is deformed by the synoptic wind, with the degree of deformation depending mainly on the synoptic wind speed. Three distinct types of lake breeze deformation were identified during the BAQS-Met study period: low deformation (LD), moderate deformation (MD), and high deformation (HD). These lake breeze types are illustrated in an idealized fashion in Fig. 6. LD lake-breeze circulations are most similar to the classic "textbook" description of the lake or sea breeze with lake-breeze fronts observed around the entire perimeter of the lake under a light synoptic wind regime. The front on the upwind lakeshore may be strengthened due to the opposing synoptic wind increasing the convergence and the frontal gradient. The front on the downwind shore may be weakened due to the onshore synoptic wind reducing the frontal gradient, making it difficult to detect in the observational network. For this study, if a lake-breeze front was positively identified on at least one of the downwind shores of the lakes in the study area, then the lake-breeze circulations on that day were considered LD.

With MD lake-breeze circulations, fronts are observed around the perimeter of the lake except on the downwind side. There, a moderate to strong onshore synoptic wind prevents even a weak front from forming. The front on the upwind lakeshore is usually strengthened. For HD lake-breeze circulations, fronts are typically observed inland from lake shorelines parallel to the synoptic wind, but the strong synoptic wind prevents the development of fronts on both the upwind and downwind lakeshores.

Though the occurrence of each of the three types appears to depend primarily on the strength of the synoptic wind, the relationship is not always obvious. In several cases, HD lake breezes occurred under what appeared to be "moderate" synoptic wind regimes with 850 hPa winds as low as 5.7 $\mathrm{m\,s^{-1}}$. There is also one example where LD lake breezes occurred in a "strong" synoptic wind regime with an 850 hPa wind of 10.3 $\mathrm{m\,s^{-1}}$ (see Supplement, Table S1). This could point to problems with the representativeness of the available rawinsonde data, but also suggests that other factors may be important. Verifying the factors associated with lake breeze deformation and determining their importance is an area for future research and beyond the scope of this paper.

Table 4 shows the relative occurrence rate for each lake breeze type, with MD lake breezes having occurred the majority of the time during the BAQS-Met study period. To further illustrate the differences between them, one case of each type will be discussed in detail later in Sect. 5.3 (selected cases).

5 Results from the intensive period

The BAQS-Met IOP ran from 20 June to 10 July 2007. As mentioned earlier, this period was remarkable due to lake breezes being observed on all lakeshores in the study region on each day – a period of 21 straight days (see Supplement, Table S1). In this section, observed and GEM-LAM-2.5 simulated lake breeze characteristics are derived and compared for the IOP, and for three selected cases. The goal is to assess the ability of the GEM-LAM-2.5 to simulate the lake-breeze circulations observed, and to assess the accuracy of the meteorological fields that have been used to drive the AURAMS air quality modeling system. Daily details of the lake breezes generated by the GEM-LAM-2.5 are provided in the Supplement, Table S2.

5.1 General comparisons

GEM-LAM-2.5 successfully simulated the development of lake breezes for each lakeshore in the study region on each of the IOP days. In addition, GEM-LAM-2.5 accurately captured the lake breeze type for all days except 4 July, when a higher model synoptic wind speed resulted in HD lake-breeze circulations rather than the observed MD circulations.

Over the IOP, the observed median lake breeze start interval was 10:00–11:00 LT and the median end interval was 20:00–21:00 LT, with a median duration of 10 h. These values are the same as those for the entire BAQS-Met study period. For the GEM-

LAM-2.5 simulations over the IOP, the median start interval was 09:00–10:00 LT, the median end interval was 00:00–01:00 LT, and the median duration was 15 h. Part of the reason for the earlier median start time interval and later median end time interval from the model is that, with high spatial/temporal resolution and data at all locations, lake breeze fronts are less difficult to detect than with observational platforms that have spatial/temporal limitations (e.g., no visible satellite imagery at night).

5.2 Inland penetration of lake breezes

5.2.1 Observations

During the IOP, all parts of southwestern Ontario, plus nearby portions of southeast Michigan and northern Ohio, were affected by lake-breeze circulations. The observed median inland penetration distances for Lakes Huron, Erie and St. Clair were 75 km, 45 km and 50 km, respectively, while observed maxima were 215 km, 185 km and 100 km, respectively. These values, particularly for Lake Huron, are higher than those found in previous lake breeze studies (see Sect. 2), and suggest that the potential for lake breeze impacts on air quality in the Great Lakes region extends much farther inland than previously thought.

Each of the penetration distance maxima were recorded when a component of the synoptic wind was onshore. In general, lake breezes tended to penetrate farther inland in these regimes.

5.2.2 GEM-LAM-2.5 output

For days during the IOP, the GEM-LAM-2.5 simulated median inland penetration distances for Lakes Huron, Erie and St. Clair were 120 km, 65 km and 75 km, respectively, while maxima were 245 km, 160 km and 125 km, respectively. These values are generally higher than those observed during the IOP, owing to the fact that it becomes more difficult to identify lake-breeze fronts after sunset using observations, particularly visible satellite imagery.

To resolve this problem and objectively evaluate the model results, maximum inland penetration distances at or before 17:00 LT were obtained for both observed and simulated lake breezes (Supplement, Table S3). The penetration distance statistics are compared using a box-and-whiskers format in Fig. 7. The graph shows that simulated Lake Huron lake breezes, like their observed counterparts, penetrate farther inland on average than Lakes Erie and St. Clair lake breezes.

Median distances between 30 km and 50 km are shown for both observed and simulated lake breezes for Lakes Erie and St. Clair. For Lake Huron, however, there is a more clear difference between observed and simulated lake breeze penetration distances, with the median distance for GEM-LAM-2.5 lake-breeze fronts being 20 km farther inland than observed. In fact, the observed median is below the 25th percentile value for the simulated distances.

5.3 Selected cases

In this section, three cases from the IOP will be examined in greater detail. The cases were chosen to represent LD, MD, and HD lake-breeze circulation types, as well as a variety of air quality conditions and levels of DMC activity. In each case, the observed evolution of the lake-breeze circulation, and in particular the movement of lake-breeze fronts, is qualitatively compared to the evolution from the GEM-LAM-2.5 model output at three-hour intervals beginning at 11:00 LT and ending at 20:00 LT. Observed and modeled lake breeze interactions are also noted.

5.3.1 23 June 2007 LD lake breezes

The centre of a high-pressure system was located over southwestern Ontario in the morning and drifted southeast through the day. While little in the way of low-level cumulus cloud developed over the study region (even along lake-breeze fronts), there was a persistent deck of broken upper-level cirroform clouds, especially over the southwestern half. The synoptic wind was light, with the 850 hPa wind from the DTX 23 June 20:00 LT rawinsonde being 180° at only 3.6 m s^{-1}. Inland maximum temperatures ranged between 24 °C and 25 °C, while lake surface temperatures ranged from 13 °C in parts of southern Lake Huron to 24 °C in parts of western Lake Erie. BAQS-Met measurements on this day indicated good to moderate air quality across southwestern Ontario (daytime maximum ozone in the 30–60 ppbv range).

The observed and modeled evolutions of lake breezes on this day are shown in Fig. 8. For both observations and GEM-LAM-2.5 output, lake breezes developed on all lakes and moved inland from all shores, indicating that LD lake-breeze circulations were present. No DMC was observed, or simulated in the model.

The observed lake-breeze fronts from Lake Erie and Lake St. Clair penetrated approximately 100 km and 90 km inland, respectively, toward the northwest by 20:00 LT (Fig. 8d). By this time, nearly all of the study region was under the influence of lake-breeze circulations, thus having a large influence on boundary-layer characteristics, and pollutant interactions and transport in the area.

The GEM-LAM-2.5 850 hPa wind at 20:00 LT on 23 June was 149° at 1.9 m s^{-1}, so 31° farther east and 1.7 m s^{-1} less than the observed wind. The GEM-LAM-2.5 was more aggressive with the inland penetration of the Lake Erie lake breeze early in the simulation. The GEM-LAM-2.5 was also more aggressive with the inland penetration of the Lake Huron lake breeze toward the southeast, penetrating almost 50 km farther inland than observed by 17:00 LT. The lower speed of the opposing synoptic wind in the model likely allowed this increased penetration of the Lake Huron lake breeze.

Both observations and model output indicate that the Lake Erie and Lake St. Clair lake-breeze fronts merged south of Lake St. Clair (marked by “A” in Fig. 8b), and that the Lake Huron and Lake St. Clair lake-breeze fronts merged north of Lake St. Clair (marked by “B” in Fig. 8c). However, only the model output indicated the merger of the Lake Huron and Lake Erie lake-breeze fronts late in the day (marked by “C” in Fig. 8d).

5.3.2 26 June 2007 MD lake breezes

On this day, the study region was under the influence of a large "Bermuda High" pressure system with an approaching low-pressure system located over Southern Manitoba. Clear skies in the morning gave way to shallow low-level cumulus clouds at inland locations, deepening cumulus clouds along lake-breeze fronts, and isolated DMC late in the afternoon mainly south and west of Lake Erie. The 850 hPa wind from the DTX 26 June 20:00 LT rawinsonde was 235° at 6.7 m s^{-1}. Inland maximum temperatures ranged between 29 °C and 35 °C, while lake surface temperatures ranged from 15 °C in parts of southern Lake Huron to 24 °C in parts of western Lake Erie. BAQS-Met measurements on this day indicated poor air quality across southwestern Ontario (daytime maximum ozone in the 70–100 ppbv range) – the second day in row with such conditions.

The observed and modeled evolutions of lake breezes on this day are shown in Fig. 9. The observed lake-breeze fronts from Lake Erie and Lake St. Clair penetrated approximately 80 km and 70 km inland, respectively, toward the northeast by 17:00 LT. They moved even farther inland by 19:00 LT (not shown) but became undetectable by 20:00 LT (Fig. 9d). By that time, however, lake-breeze circulations had affected the boundary layer over the entire study region.

The GEM-LAM-2.5 850 hPa wind at 20:00 LT on 26 June was 214° at 6.9 m s^{-1}, so 21° farther east and 0.2 m s^{-1} more than the observed wind. The GEM-LAM-2.5 lake-breeze front positions are very similar to observations, except that in some areas they were affected by model DMC. In observations and model output, lake-breeze fronts penetrated well inland along the lateral edges of the lakes and were present on the upwind side of each of the lakes (relative to the synoptic wind). However, no lake-breeze fronts were present on the downwind side, indicating that these were MD lake-breeze circulations.

The development of DMC was both observed and simulated by the model south and west of Lake Erie (though the model developed storms several hours earlier than observed). However, in other areas, the model generated many more storms than were observed, with thunderstorm downdrafts dominating much of the western half of the study area by 17:00 LT. The estimated positions of thunderstorm gust fronts are included in Fig. 9.

Both observations and model output show that the Lake St. Clair and Lake Huron lake-breeze fronts intersected northwest of Sarnia by 14:00 LT (marked by “A” and “B” in Fig. 9b). However, only the observations indicated the intersection of the Lake Erie and St. St. Clair lake-breeze fronts by 17:00 LT (at two points marked by “C” and “D” in Fig. 9c).

5.3.3 8 July 2007 HD lake breezes

For this case, the study region was located in the warm sector of a low-pressure system whose centre was moving across the northern Great Lakes. Warm and cold fronts were positioned to the northeast and northwest of the study region, respectively. Shallow low-level cumulus clouds developed over northern Ohio and southeast Michigan but not over or downwind from Lakes Erie and St. Clair. Over the northeast part of the study region, there was a persistent area of broken mid- to high-level clouds associated with warm frontal DMC farther northeast. This cloud prevented a Lake Huron lake-breeze front from being detected until late afternoon. However, lake breezes were eventually detected on all lakeshores.

Inland maximum temperatures ranged between 33 °C and 36 °C, while lake surface temperatures ranged from 16 °C in parts of southeastern Lake Huron to 26 °C in parts of southwestern Lake Erie. BAQS-Met measurements on this day indicated poor air quality across southwestern Ontario (daytime maximum ozone in the 70–95 ppbv range) – a continuation of a string poor air quality days that began intermittently on 4 July and became more persistent from July 6 onwards. The 850 hPa wind from the 8 July 20:00 LT DTX rawinsonde was 260° at 12.9 $\mathrm{m\,s^{-1}}$. The GEM-LAM-2.5 850 hPa wind at 20:00 LT on 8 July was 233° at 13.7 $\mathrm{m\,s^{-1}}$, so 27° farther east and 0.8 $\mathrm{m\,s^{-1}}$ more than observed.

The observed and modeled evolutions of lake breezes on this day are shown in Fig. 10. The positions of both sets of lake-breeze fronts on the north shore of Lakes Erie and St. Clair are similar in orientation and location, but depart through the day with the observed fronts penetrating approximately 50 km farther inland toward the north. Also, a Lake Huron lake breeze existed in the model output at 11:00 LT (Fig. 10a) and 14:00 LT (Fig. 10b), while the observed Lake Huron lake breeze was not detected in the study region until 15:00 LT (not shown). In both cases, lake-breeze fronts penetrated well inland along the lateral shores of the lakes while no lake-breeze fronts were present upwind or downwind of the lake. Therefore, these were HD lake-breeze circulations.

Model output suggests an intersection between the Lakes Huron and St. Clair lake-breeze fronts (marked by “A” in Fig. 10b). However, the observations indicated that no lake-breeze front interactions took place.

6 Discussion

Accurate knowledge of the occurrence frequency and degree of spatial influence of lake-breeze circulations is needed in order to understand and anticipate their impacts on local and regional air quality. As was discussed in Sect. 2, lake breezes dominate boundary-layer flow when and where they occur and therefore dictate the transport and dispersion of pollutants. They can also enhance the production of secondary pollutants such as ozone by sustaining precursor concentrations over long durations and distances, and by increasing the insolation available for photochemical reactions.

Observations from a moderately dense network of 54 surface stations (many with 1 min data), high-resolution visible satellite imagery, and data from multiple Doppler radars were used in a complementary manner to manually identify lake-breeze fronts during the BAQS-Met study. This integrated data approach yielded much higher lake breeze occurrence rates than have been previously reported in the literature for the Great Lakes region, rates that we believe more accurately represent the actual occurrence.

In addition, lake-breeze fronts and other low-level convergence boundaries were identified and tracked on an hourly basis during the 21 day IOP using the high-resolution observational data set. The resulting mesoscale analyses provide a comprehensive depiction of the often complex meteorology in the region, including multiple interacting lake-breeze circulations, the deformation of lake-breeze circulations, inland penetration distances (in some cases more than 200 km), interactions between lake-breeze fronts and other low-level convergence boundaries, and evidence for the source regions of the air arriving at stations within each lake-breeze circulation. Such mesoscale analyses could not be obtained using data at just one lake shore, or using current methods of automated lake breeze detection.

These hourly mesoscale analyses have been used by a number of BAQS-Met air quality researchers to determine whether changes in the concentrations of both primary and secondary pollutants are due to meteorological or photochemical processes, and to determine the most likely source of emissions into the lake breeze air arriving at an air quality station. Using the hourly mesoscale analyses, Levy et al. (2010) demonstrated the complexity of the flow at one location in the study region where multiple lake-breeze front passages were recorded and four different air masses were sampled in one day, each with different chemical composition and photochemical age.

Hayden et al. (2011) used the hourly mesoscale analyses to help identify lake-breeze fronts in the Twin Otter aircraft data, and then compared these frontal boundaries to the locations of concentration changes in various pollutants. They presented evidence that, on a day during the IOP, pollutants emitted into the convective mixed layer from the Detroit-Windsor area were transported both vertically and horizontally along the Lake St. Clair lake-breeze front. By late afternoon, only low pollutant concentrations remained as the Lake Erie and Lake St. Clair lake-breeze fronts merged.

Makar et al. (2010b), using the GEM-LAM-2.5 to drive the AURAMS model, showed that ozone and its precursors can be carried hundreds of kilometers from a source region in a narrow band along a HD-type lake-breeze front, creating local ozone enhancements on the order of 20 ppbv above the regional ozone levels. The hourly mesoanalyses were used to help confirm that these modelled features matched observations and were not due to spurious model results.

Makar et al. (2010b) also found that the location of local emission sources in relation to the average location of lake-breeze fronts has a substantial impact on ozone production in those regions. Thus, an accurate assessment of the locations for lake-breeze fronts could be used in a policy sense to ensure that emitters are not located in those zones in the future.

It is critically important for air quality modelers to understand the strengths and weaknesses of the meteorological input that drives their air quality models. The GEM-LAM-2.5 evaluation against observations for IOP days has demonstrated that the GEM-LAM-2.5 can successfully predict lake breeze occurrence and type (LD, MD or HD). GEM-LAM-2.5 also showed some ability to predict the inland penetration of lake breezes observed, though the detailed timing and location of simulated lake-breeze fronts often did not match observations in the three cases examined. Such differences can result in lake-breeze front interactions that were not observed, and/or interactions that were observed but not simulated. Much of these differences may be attributed to inaccurate initial and boundary conditions. For instance, an incorrect synoptic wind can result in differences in penetration distances and a degree of deformation to lake-breeze circulations that was not observed. So, though a meteorological process may be represented in the model output, the timing and location may not be correct. Such errors then go on to affect the chemical processes in the air quality model.

The GEM-LAM-2.5 comparison to observations also indicates that there can be large differences in the generation of DMC. This was seen in the case study for 26 June, and for a number of other days during the IOP. It is well known that DMC serves to convectively overturn the atmosphere, with pollutants near the surface lofted into the upper troposphere and relatively clean air from above the convective mixed layer accompanying convective downdrafts to regions near the surface (Dickerson et al., 1987; Kong and Qin, 1993). In areas of DMC, surface pollutant concentrations can also be affected by wet deposition (e.g. rain out, wash out) and decreased photochemical production due to rapidly increasing convective cloud cover. Therefore, when observed and simulated DMC have large differences, model output should be used with caution when driving an air quality modeling simulation.

The results suggest that complex patterns in pollutant concentrations are not solely the result of variations in emissions and atmospheric chemistry. Rather, complex flows related to lake-breeze circulations will have a significant influence on the movement of, the accumulation of, and the chemical reactions among pollutants that occur over the southern Great Lakes region.

In order to accurately predict these flows, model grid-spacing (both horizontal and vertical) should be chosen in such a way that lake-breeze fronts are adequately resolved. In addition, any attempt to compute back or forward trajectories in this region should be made using output from such high-resolution simulations, as has been done in several of the papers in this special issue (e.g., Hayden et al., 2011; Slowik et al., 2010).

Lastly, the detection of lake-breeze fronts was a key component of this study. During the BAQS-Met study, high-resolution data were collected in the vicinity of lake-breeze fronts, both from surface-based and aircraft platforms. Future work will include analysis of these data, including horizontal gradients and vertical velocities, and further comparison to high-resolution model output. The goals would be to better understand the dynamics of lake-breeze fronts and their role in pollutant transport, and to assess the ability of NWP models to simulate them accurately.

7 Conclusions

Through analyses of mesoscale observations from the BAQS-Met field experiment in southwestern Ontario during the summer of 2007, and comparison with output from subsequent high-resolution numerical modelling, the following were found:

- Using a manual identification methodology integrating data from various modern observational platforms, lake breezes were identified in the study region on 90% of study days, even in conditions previously thought to impede their development such as with onshore winds, under cloudy skies, and in the presence of synoptic-scale fronts.
- Lake breeze occurrence for each lake shore was found to be 82–84% which is much higher than reported in past studies in the Great Lakes region.
- Inland penetration distances were generally higher than reported in past studies, with distances occasionally reaching over 100 km and in a few instances over 200 km.
- All parts of the study region, including southwestern Ontario and nearby portions of southeast Michigan and northern Ohio, were found to be affected by lake breezes.
- This improved knowledge of the observed occurrence and spatial influence of lake breezes facilitates a better understanding of their impacts on the production and transport of pollutants in this region.
- GEM-LAM-2.5 model accurately predicted lake breeze occurrence and type (low, moderate, and high deformation), and supported observations of occasional inland penetration distances greater than 200 km.
- Daily penetration distances predicted by the GEM-LAM-2.5 were comparable to observed values, except for Lake Huron lake breezes where model values were considerably higher than observed.
- Selected cases showed some substantial differences between modelled and observed lake breezes, especially with respect to the detailed timing and location of lake-breeze fronts and the development of deep moist convection.

- Since output from the GEM-LAM-2.5 is used to drive the AURAMS air quality model, knowledge of the strengths and weaknesses of GEM-LAM-2.5 simulations will aid in the interpretation and evaluation of AURAMS results.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/11/3579/2011/ acpd-11-3579-2011-supplement.pdf.

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Table 1. Lake-breeze front identification criteria based on three different observation platforms, including positive, negative, and ambiguous factors.

Platform	Positive factors	Negative factors	Ambiguous
Satellite (visible)	– Line of cumulus clouds or sharp gradient in cumulus cloudiness quasi-parallel to shoreline – Gradual inland penetration of above, or quasi-stationary	– Persistent thick cloudiness over most or all of lake area – Gradual change in the depth of cumulus clouds inland from lake (gradually deepening CBL)	– No cloud visible thin cirrostratus or broken mid-level clouds prevents seeing cumulus clouds
Radar (LogZ, Vr)	– Fine line or sharp gradient in clear-air echoes quasi-parallel to shoreline – Shift in radial velocity along fine line – Gradual inland penetration of above, or quasi-stationary	– Large area of persistent precipitation over region	– No clear air echoes – Fine line or gradient in clear-air echoes not well defined
Surface (Stn plots, time series)	– Rapid shift in wind direction to onshore wind (may be accompanied by rapid change in wind speed, sharp decrease in temperature and dew point within 20 km of shore) – Gradual inland penetration of onshore winds – Elongated area of convergence quasi-parallel to shoreline – Gradual inland penetration of above, or quasi-stationary	– No onshore winds	– Often very subtle surface gradients at boundaries in moderate/high synoptic wind regimes – An area of broad divergence over the lake and the adjacent shore often indicates that a lake-breeze circulation is present and may be used to support the presence of a lake-breeze front

Table 2. The number and percentage of days per month with observed lake breeze circulations, plus the total number and percentage for all study days. Values are grouped by lakeshore categories.

	June 2007		July 2007		August 2007		Total	
	Days	%	Days	%	Days	%	Days	%
Huron	28	93%	29	94%	19	66%	76	84%
Erie	27	90%	27	87%	20	69%	74	82%
St. Clair	26	87%	29	94%	20	69%	75	83%
All lakes	26	87%	26	84%	16	55%	68	76%
Any lakes	29	97%	30	97%	22	76%	81	90%

Table 3. Temperature (T) and rainfall averages for June, July and August 2007 compared to climatological normals. Data are from Environment Canada's historical weather web portal found at http://www.climate.weatheroffice.gc.ca.

	June		July		August		June–August	
	2007	Normal	2007	Normal	2007	Normal	2007	Normal
Max T	27.7	25.4	27.9	27.9	27.7	26.6	27.8	26.6
Min T	16.5	14.7	17.5	17.4	18.7	16.6	17.6	16.2
Mean T	22.1	20.1	22.7	22.7	23.3	21.6	22.7	21.5
Extreme max T	34.5	40.2	35.6	38.3	34.1	37.7	34.7	38.7
Days with rainfall	9.0	11.0	9.0	10.2	12.0	10.0	30.0	31.2
Rainfall	65.2	89.8	113.8	81.8	159.4	79.7	112.8	83.8

Table 4. Number of days and occurrence rate for each lake breeze deformation type over the entire BAQS-Met study period.

	June 2007		July 2007		August 2007		Total	
	Days	%	Days	%	Days	%	Days	%
LD	8	28.6%	6	20.0%	5	22.7%	19	23.8%
MD	13	46.4%	18	60.0%	15	68.2%	46	57.5%
HD	7	25.0%	6	20.0%	2	9.1%	15	18.8%

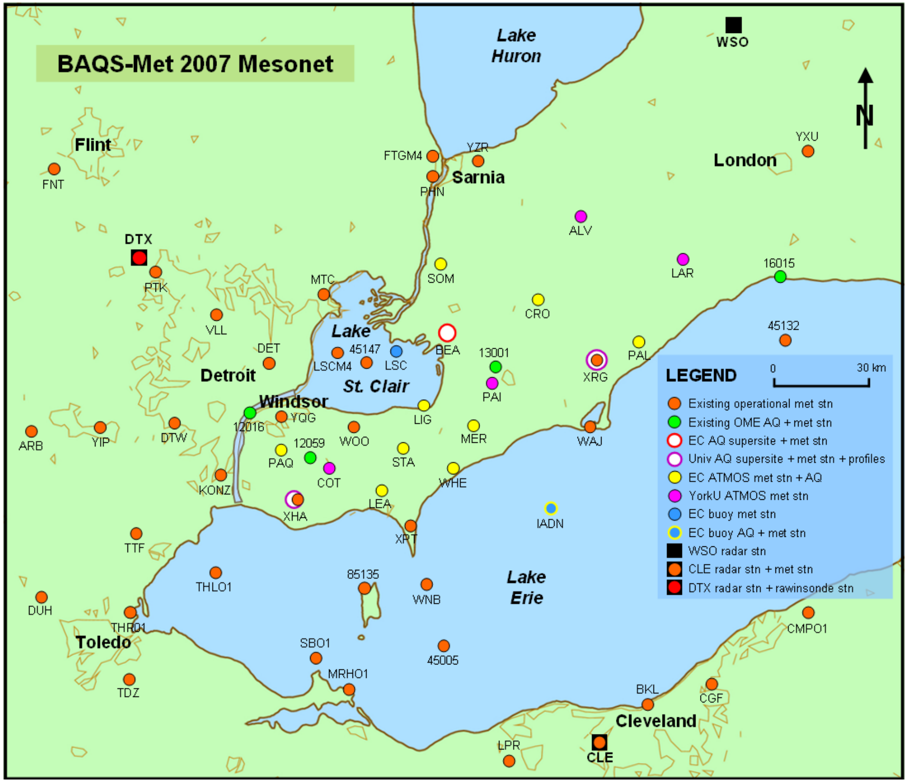

Fig. 1. Map showing the primary study domain and the fixed monitoring network used for this study. Light brown lines indicate urban boundaries. The terrain is generally flat to gently rolling and land use is predominantly agricultural with the exception of large urban/industrial areas (e.g. Detroit and Cleveland).

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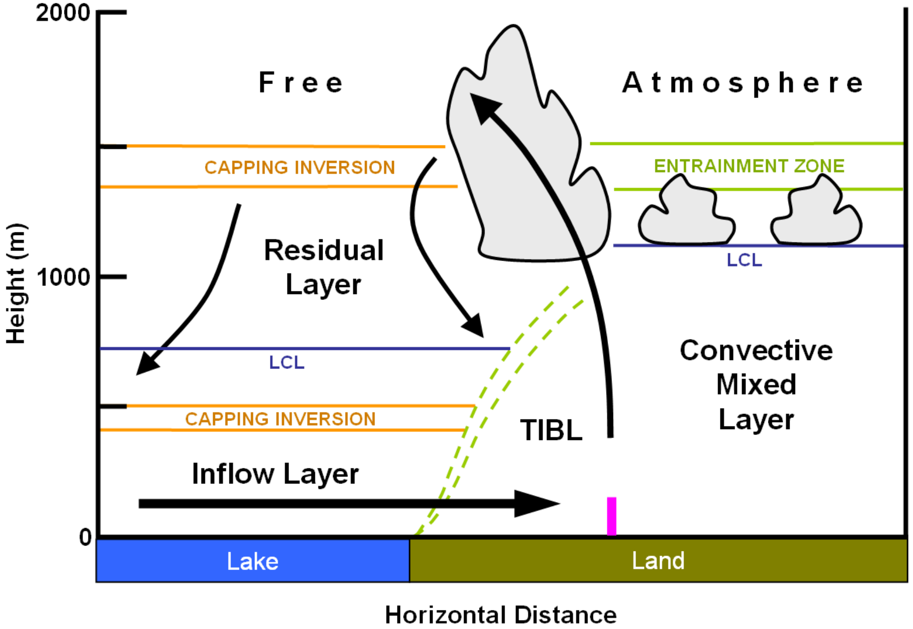

Fig. 2. Vertical cross-section diagram showing a typical lake-breeze circulation as it penetrates inland. Arrows show air motions within the circulation including the inflow, the frontal updraft, and the return flow. The surface location of the lake-breeze front is shown in magenta. Blue lines indicate the lifting condensation level (LCL), green outlines indicate entrainment zones, and orange outlines indicate capping inversions. Diagram modeled after Stull (1988, Fig. 1.7). The vertical scale is exaggerated to better show the diagram details.

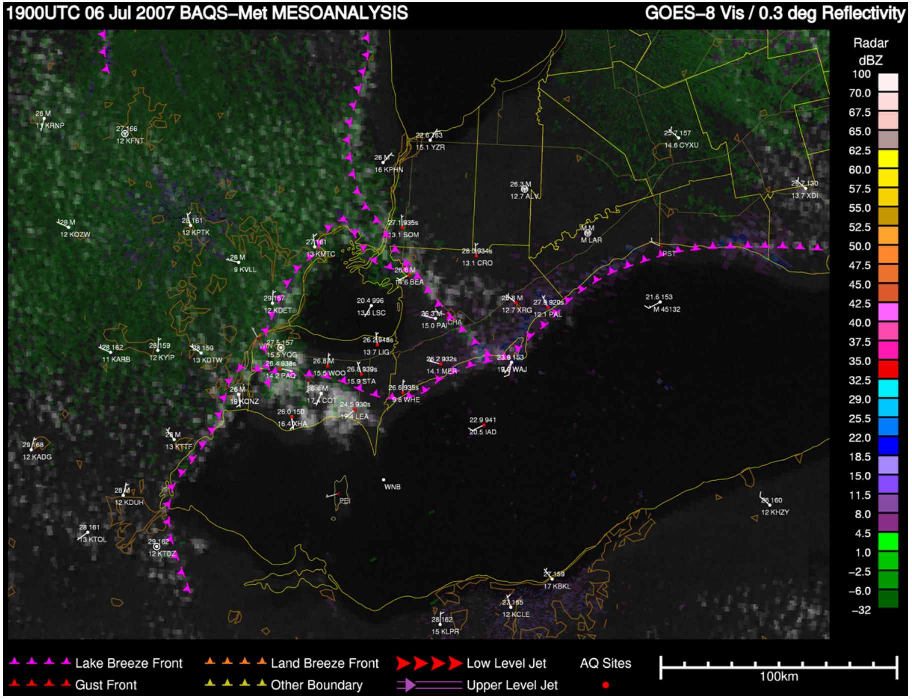

Fig. 3. Mesoscale analysis showing low-level radar echoes (mainly green), visible satellite imagery, surface observations, and the positions of lake-breeze fronts (broken magenta lines) for 15:00 LT on 6 July 2007. Long wind barbs are 5 m s^{-1}, short barbs are 2.5 m s^{-1}.

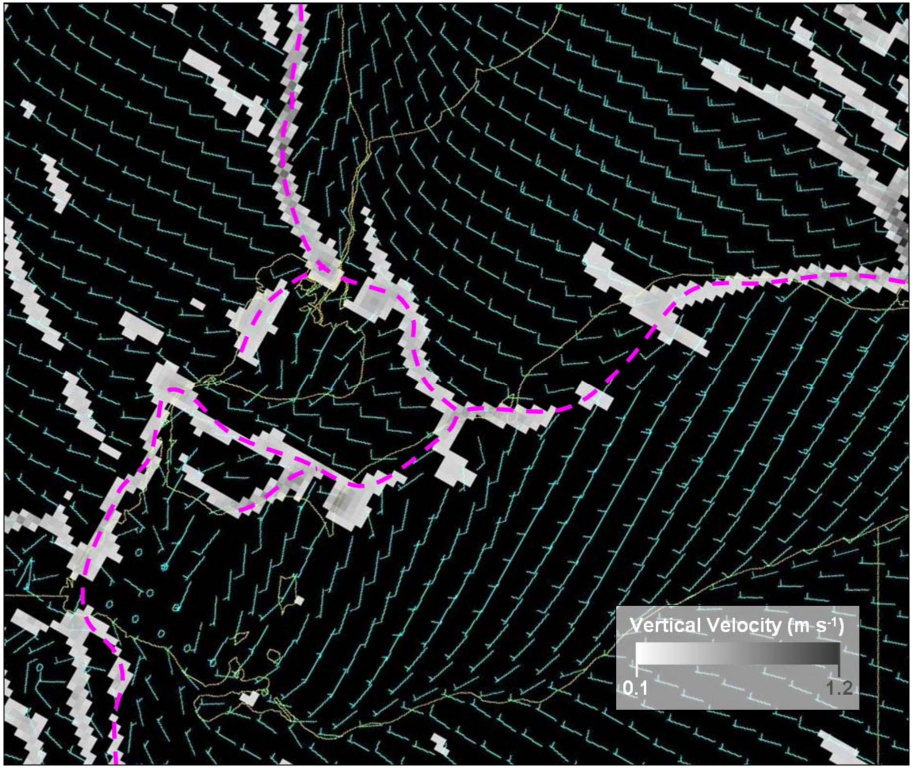

Fig. 4. GEM-LAM-2.5 surface winds (long barb=5 m s^{-1}, short barb=2.5 m s^{-1}), upward vertical velocities, and estimated positions of lake-breeze fronts (broken magenta lines) for 15:00 LT on 6 July 2007. The GEM-LAM-2.5 lake-breeze front positions are very similar to those estimated using observations, shown in Fig. 3.

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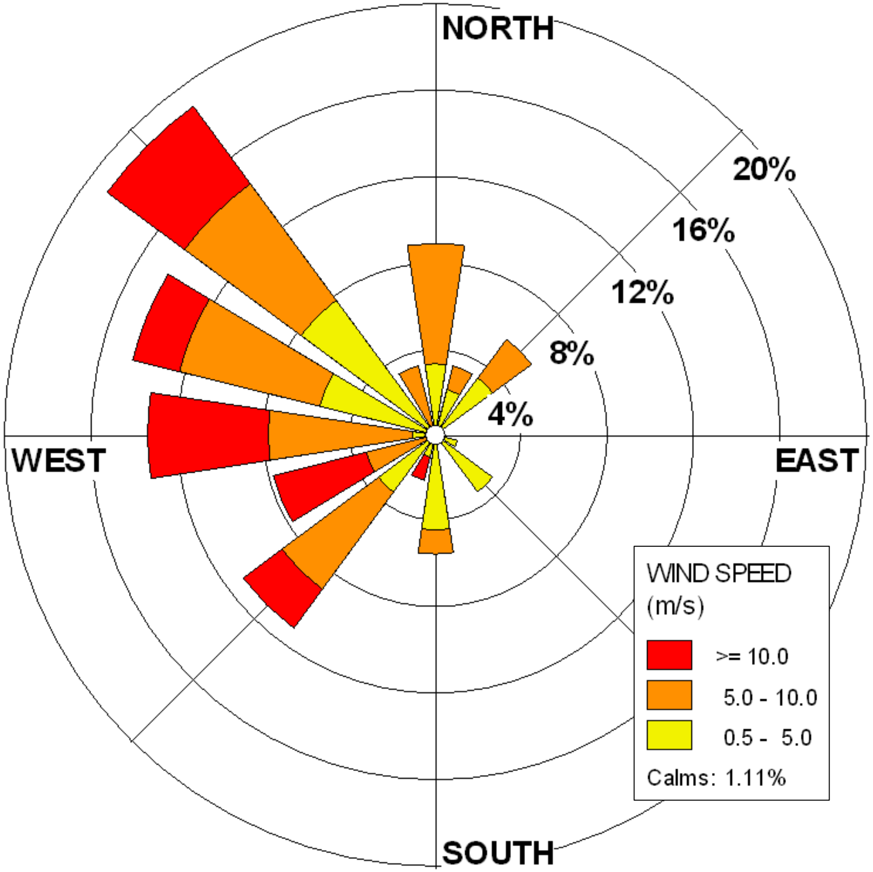

Fig. 5. Wind rose diagram showing the percent frequency of rawinsonde-derived 850 hPa wind directions (16 bins) and wind speeds (light=yellow, moderate=orange, and strong=red) for 90 days during BAQS-Met. Note that on one day the synoptic wind was calm and that there were no occurrences from the ENE, E or SSE.

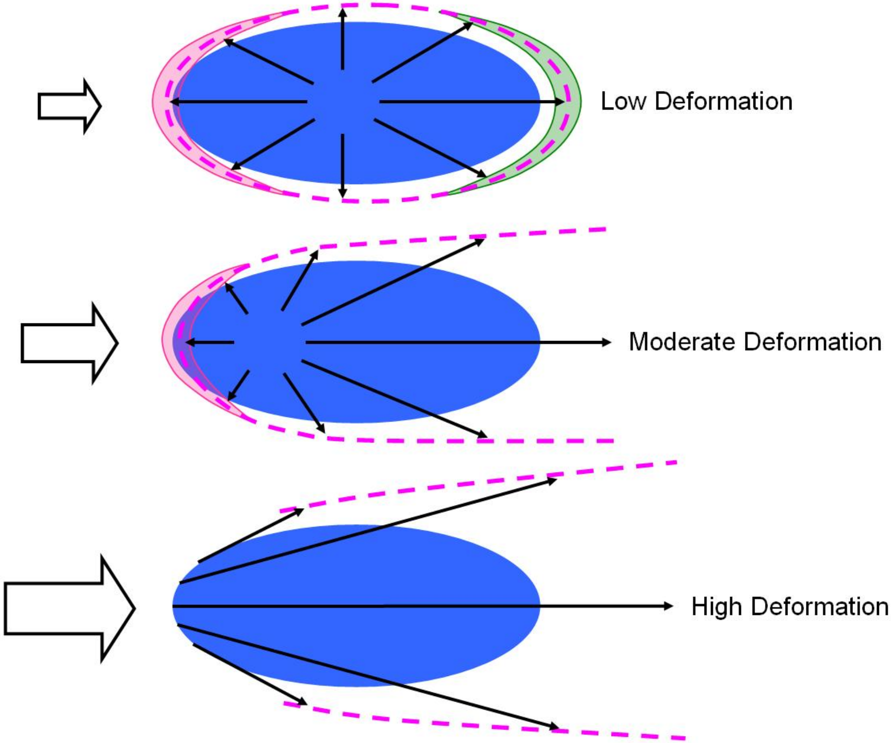

Fig. 6. Diagrams showing low, moderate and high deformation lake-breeze circulations in plan view. Black arrows are streamlines. Broken magenta lines are lake-breeze fronts. Large arrows at left represent the synoptic wind increasing from top to bottom. The synoptic wind results in a stronger front in magenta-shaded areas, and a weaker front in green-shaded areas.

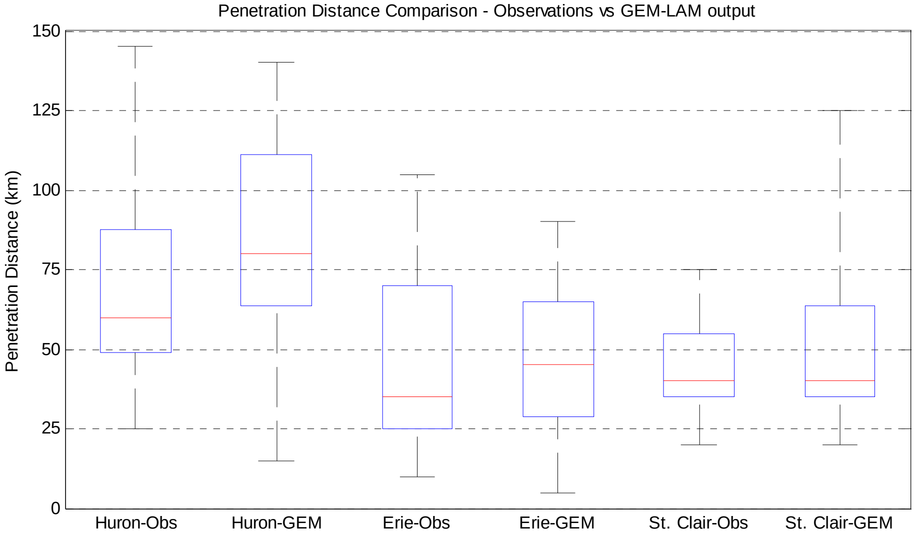

Fig. 7. Box and whiskers diagram comparing observed and GEM-LAM-2.5 maximum penetration distances at or before 17:00 LT. On each box, the red central mark is the median, the top and bottom of the box are the upper and lower quartiles, respectively, and the whiskers extend to the most extreme data points.

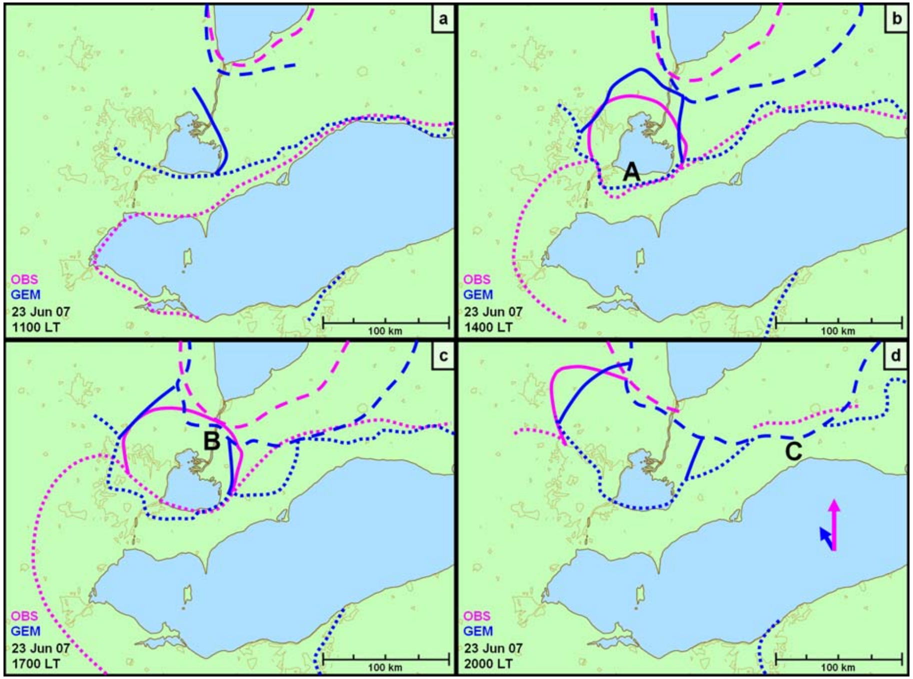

Fig. 8. Observed (magenta) and GEM-LAM-2.5 modeled (blue) features at four different times on 23 June 2007. Solid lines mark Lake St. Clair lake-breeze fronts, dotted lines Lake Erie lake-breeze fronts, and dashed lines Lake Huron lake-breeze fronts. Arrows on panel d show synoptic wind directions and relative synoptic winds speeds for the day. Locations A–C are discussed in the text.

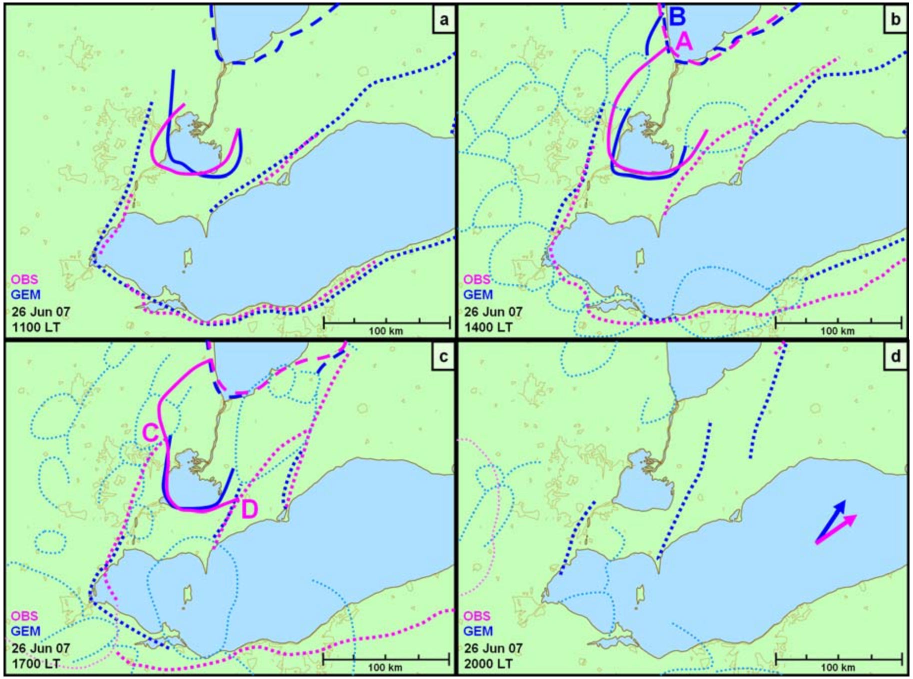

Fig. 9. Same as in Fig. 8 but for 26 June 2007. Dotted lines mark surface gust fronts due to deep moist convection (light magenta for observations and light blue for modeled). Locations A–D are discussed in the text.

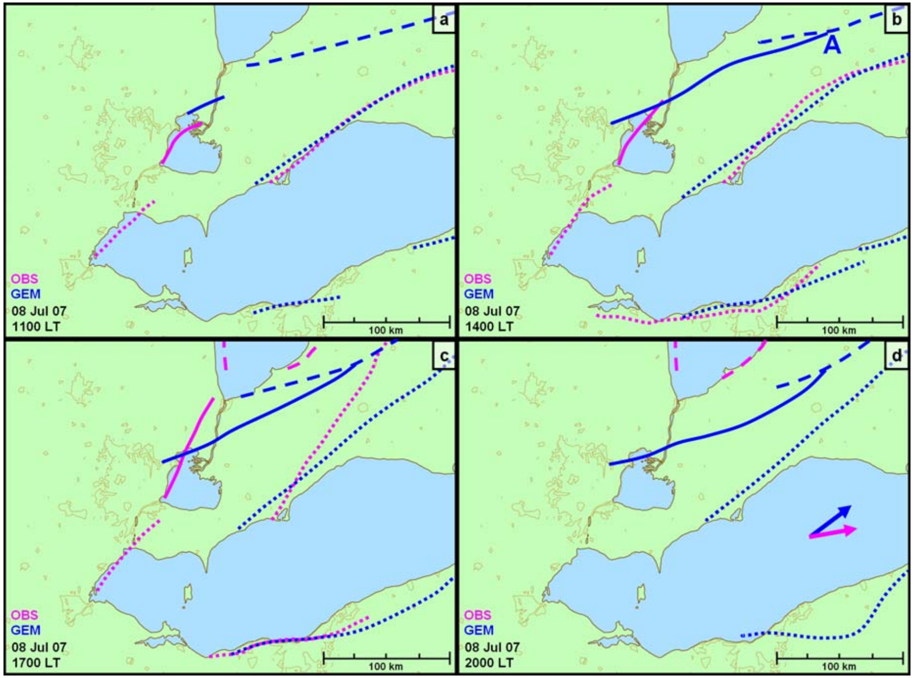

Fig. 10. Same as in Fig. 8 but for 8 July 2007. Location A is referred to in the text.