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Impact of lake breezes on ozone and nitrogen oxides in the Greater Toronto Area

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HIGHLIGHTS

- Impacts of lake breezes on air quality is investigated in the Greater Toronto Area.
- Lake Ontario breezes form on 74% of summer (May–September) days.
- O_3 is 42–49% (13–15 ppb) higher when a lake breeze is present.
- Only sites within the circulation exhibit enhanced O_3.

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ABSTRACT

Meteorological and air quality datasets from summertime (May to September, 2010–2012) were analysed in order to assess the influence of lake-breeze circulations on pollutant levels in the Greater Toronto Area (GTA). While previous estimates of the frequency of summer days experiencing lake breezes range between 25 and 32 % for the GTA, a simple algorithm using surface meteorological observations suggested Lake Ontario breezes occurred on 56% of summer days, whereas a more reliable multiplatform approach yielded a frequency of 74%. Data from five air quality stations across the GTA were used to compare air quality on days during which a lake-breeze circulation formed (“lake breeze days”) versus days when one did not (“non-lake breeze days”). Average daytime O_3 maxima were 13.6–14.8 ppb higher on lake breeze days relative to non-lake breeze days. Furthermore, the Ontario Ambient Air Quality Criteria (AAQC) for 1-h average O_3 (80 ppb) and 8-h average O_3 (65 ppb) were exceeded only on lake breeze days and occurred on a total of 30 and 54 days throughout the study period, respectively. A causal link between lake-breeze circulations and enhanced O_3 was identified by examining several days in which only some of the air quality sites were inside the lake-breeze circulation. O_3 mixing ratios at sites located within the circulation were at least 30 ppb higher than sites outside the circulation, despite similar temperatures, cloud conditions and synoptic regimes across the region. Rapid O_3 increases were concurrent with the arrival of the lake-breeze front, suggesting O_3-rich air from over the lake is being advected inland throughout the day. Lake-breeze circulations were found to have less impact on nitrogen oxide (NO_x) levels. Morning NO_x was greater on lake breeze days, probably due to the stagnant conditions favourable for lake breeze formation. During the late afternoon, only inland sites experience increased NO_x on lake breeze days, likely as a result of being downwind from near-shore city centres.

1. Introduction

1.1. Air quality and the Greater Toronto Area (GTA)

Highly populated urban areas often experience poor air quality and photochemical smog as a result of large emissions of pollutants from industrial activities and transport. Tropospheric ozone (O_3) can be a major constituent of smog and has adverse health effects for both humans and vegetation (Seinfeld and Pandis, 2006). Ozone is produced in the troposphere through a series of complex, non-linear reactions that depend on two main precursors: volatile organic compounds (VOCs) and nitrogen oxides (NO_x). Meteorology also exerts a strong control on O_3 levels, with clear skies, high temperatures and stagnant conditions generally favouring higher concentrations. The behaviour of these pollutants and their

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precursors is heavily influenced by meteorology and local topography. For instance, Lu and Turco (1995) found sea breezes and mountain-induced flows in the Los Angeles Basin to be a key contributing factor to poor air quality in Los Angeles.

In this context, we explore air quality in Toronto, Canada (43°40′N, 79°23′E), which is situated along the north-western shore of Lake Ontario. The Greater Toronto Area (GTA) has a population of roughly 5.5 million and encompasses 7000 km^2. It is one of the most populated and industrialized regions in Canada and is frequently afflicted with poor air quality. A report released by the Ontario Medical Association (OMA) estimated that the annual economic burden of air pollution in Ontario in 2015 will be CAD $9.8 billion (OMA, 2005). Establishing the major determinants of air quality in the GTA will help in the development of more accurate air quality forecasts (including smog alerts) and of more effective mitigation strategies. Previous studies have looked at the impact of meteorology and/or reduction of VOC and NO_x emissions on O_3 (Geddes et al., 2009; Pugliese et al., 2014) in the GTA. However, the influence of lake-breeze circulations on these pollutants has not been well characterized in the GTA.

1.2. Lake-breeze circulations

Lake (and sea) breezes are mesoscale meteorological phenomena that result from a pressure difference triggered by preferential heating of land relative to water, and typically develop a few hours after sunrise and persist until sunset (Physick, 1980; Crosman and Horel, 2010). The positive land-lake temperature difference is more pronounced in summer; hence most lake-breeze circulations develop from May to September in the Northern hemisphere. Fig. 1 shows a vertical cross-section of an idealized lake-breeze circulation under light synoptic winds. As the sun rises the land will heat up faster than the water, which results in the air over land becoming warmer than the air over water. This thermal contrast results in a pressure differential that causes cooler, higher pressure air from over the lake to flow inland. As the air mass penetrates inland it warms up and the shallow thermal internal boundary layer (TIBL) deepens. A narrow updraft region, called the lake-breeze front, forms and progresses inland throughout the day. Subsiding air in the return flow completes the lake-breeze circulation and creates a very shallow capping inversion over the lake. The capping inversion helps to suppress cloud formation behind the lake-breeze front, whereas the updraft region can promote a narrow band of clouds along the front (Segal et al., 1997). As a result, defining features of a lake-breeze circulation are high solar insolation, shallow inflow boundary layer, and the entrainment of pollutants in a circulating pattern. Some lake-breeze fronts penetrate as far inland as 200 km; however, most stay within tens of kilometres of the shoreline (Sills et al., 2011). Land breezes are analogous phenomena that occur at night-time due to a negative land-lake air temperature difference and result in an offshore flow. Extensive reviews of the lake breeze phenomenon are prevalent in the literature (e.g. Simpson, 1994; Crosman and Horel, 2010).

Numerous studies have explored the effect of lake (and sea) breezes on air quality in coastal environments, and several have focused on impacts to O_3 in the Great Lakes region of North America (e.g. Biggs and Graves, 1962; Sills, 1998; Hastie et al., 1999; Lennartson and Schwartz, 2002; Hayden et al., 2011). These studies conclude that O_3 concentrations at inland locations are generally higher during the presence of a lake-breeze circulation, which may be a result of: (1) increased solar insolation, (2) decreased mixing height, and/or (3) recirculation of pollutants. However, the conditions most favourable for lake breeze formation (clear skies, light winds, warm air temperature) are also conducive to rapid O_3 production (Seinfeld and Pandis, 2006). Hence, it is difficult to establish whether a cause-and-effect relationship exists between lake-breeze circulations and enhanced O_3, or whether the relationship is merely a correlation. Other investigations have examined the behaviour of other pollutants in lake (and sea) breeze circulations, such as $PM_{2.5}$ (Harris and Kotamarthi, 2005; Hayden et al., 2011), PM_{10} (Papanastasiou and Melas, 2009), and NO_x (Reid et al., 1996; Hastie et al., 1999). However, these studies are less prevalent and the role(s) lake breezes play in modifying the levels of these pollutants is much less clear. This present study investigates the impact lake-breeze circulations have on air quality in the GTA using a representative (season-long), multi-year approach. To our knowledge, this is the first attempt to ascertain the impact of Lake Ontario breezes on O_3 and NO_x across the GTA using complete, multiyear datasets. The specific goals of this paper are to:

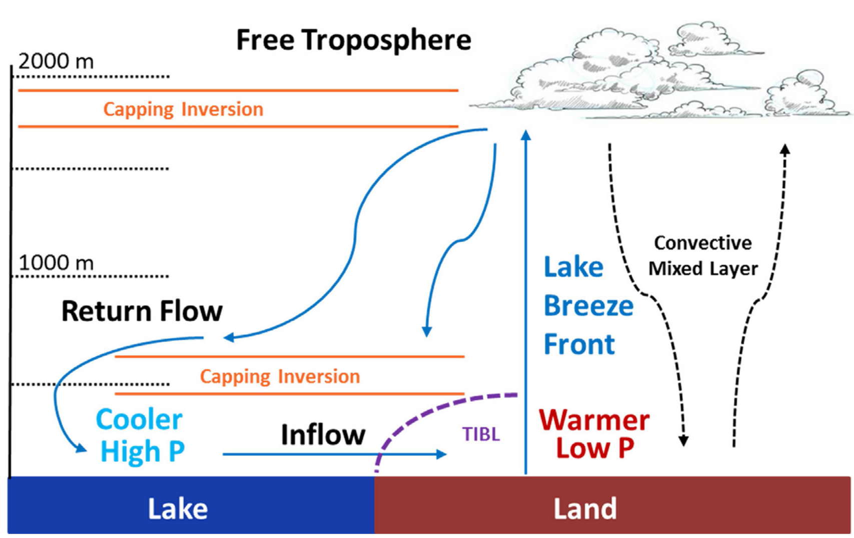

Fig. 1. Vertical cross-section of a typical lake breeze under light synoptic winds. Arrows depict motions of air masses both inside and outside the lake-breeze circulation. A thermal internal boundary layer (TIBL) is shown in purple and grows in height with distance inland until it reaches the height of the convective mixed layer. The lake-breeze front is denoted by the vertical blue arrow and the orange lines represent capping inversions. This figure is adapted from Sills et al. (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)