Authors' response to referee's comments on "Unraveling the complex local-scale flows influencing ozone patterns in the southern Great Lakes of North America" by Levy et al

The authors thank Dr. Nielsen-Gammon for his compliments on the original manuscript and for his valuable comments and suggestions. The two main points raised by Dr. Nielsen-Gammon have been addressed in the revised manuscript: the font size of the text in some of the figures was increased and Section 3.3.4 (nighttime ozone oscillations) was extensively revised. Below are the authors' replies to all of Dr. Nielsen-Gammon's comments, marked by [AR] in blue font.
A revised version of the manuscript is attached as supplement, along with a version showing the changes done in track mode. Additional changes were made to the manuscript, mainly regarding minor corrections of style and grammar, but also for better clarity of the text and figures (e.g., Figure 10).

General Comments:
This paper provides a thorough synthesis and analysis of surface-based and airborne ozone and meteorological measurements during the BAQS-Met field campaign in 2007. Synthesis of complex and sometimes contradictory data in a region of complex topography is a difficult challenge, but this paper does it well. It provides a clear description of the different summertime meteorological regimes in the area during quiescent periods and how they affect ozone at the ground and aloft. The paper is a solid contribution to the literature. Only two aspects need fixing: the figure quality and the discussion of the nighttime oscillations. See my substantive comments below.

Substantive Comments:
Many of the figures use a character size that is unacceptably small. Someone printing the paper would be unable to read much of the figure text.
[AR] We agree with the comment regarding the quality of the figures and we have revised some of the figures accordingly (Figures 3, 5). Figures 7 and 10 were rearranged to fit one column width so as to make them larger. Other figures are expected to be larger in the final print version (i.e., two columns wide) and hopefully will not need larger text. However, changes to the text size will be done as necessary in the final stages of the submission.

19786, lines 21-22: I don't understand this sentence. The figure shows that temperature and ozone oscillate simultaneously, so clearly there's something happening in the atmosphere that's affecting them both. If the dew point changes are related to the oscillations in ozone, then they are also related to the oscillations in temperature. Periodic condensation of water vapor to the surface (and evaporation of water from the surface), with less water vapor (more condensation) when the temperature is colder, would imply that the dew point is related to the oscillations in temperature and ozone, so the two alternatives proposed by the sentence in the manuscript are in reality just a single alternative. This is true whether the authors envision periodic condensation and evaporation producing the oscillations or whether they envision surface condensation

establishing a vertical gradient of dew point, so that dew point varies with the up-and-down motion of the local atmosphere in the same way that temperature does.
[AR] The sentence is pointing to the different behavior of dewpoint at different times, with respect to the oscillations in ozone and temperature at the Leamington site. The sentence was removed and the behavior of the dewpoint is now explained in the manuscript more explicitly, i.e., at some times (e.g., 23:15) the dewpoint is correlated with the temperature and ozone, while at other times (e.g., 03:00-03:15) it is anti-correlated. At the other two sites where dewpoint was measured it shows no change corresponding the change in temperature (e.g., Lighthouse Cove between 23:00 and 02:00) or very little change but good correlation (e.g., Wheatley between 01:00-04:00).

19787, lines 8-11: It is not clear how the Huron breeze is supposed to create the circumstances for the oscillations. I can come up with two possibilities, but both are extremely unlikely. The first is that the lake breeze is so shallow (< 10 m) that the oscillations represent the top of the sea breeze inversion rising and falling past the sensors, but such a shallow lake breeze over such a large horizontal extent is impossible. The second is that the leading edge of the lake breeze moves back and forth periodically over the station location, but that is highly unlikely given the strong observed periodicity, its simultaneous occurrence at several stations, and the lack of observed horizontal wind oscillations farther inland to alter the speed of lake breeze advance. (see also 19788, lines 8-12).
[AR] The Lake Huron breeze was mentioned as one possible mechanism resulting in a vertical stratification (in addition to radiative cooling). Given this vertical structure it is hypothesized that wind shear at the inversion layer (e.g., due to low-level jets) would cause turbulence and inject warm and ozone-rich air to the surface. However, following this and other comments on this section, the possibility of Lake Huron breeze air arriving over SW Ontario and remaining as a distinct layer near the surface for the entire period that oscillations were observed at Wheatley, for example, is indeed unlikely and was omitted from the manuscript.

19787, lines 20-22: If the temperature inversion is generated by nocturnal radiational cooling of an initially well-mixed layer, the difference between the air masses at the surface and aloft would lie mainly in temperature and ozone (due to NOX titration and dry deposition). Unless the surface layer was cold enough to permit dew to form, there would be no mechanism to generate a dew point gradient between the two air masses and no dew point variations would be expected.
[AR] The sentence refers to the case where the temperature inversion is caused by the Lake Huron breeze air, in which case it is expected to have different water content than the air above it. However, following the previous comment the entire paragraph was rephrased and we believe it is clearer now.

19788, lines 15-22: It is difficult to see how buoyant adjustment of air in a shallow layer would bring warmer air to the surface. The tendency would be for warmer air to rise and be replaced laterally by cooler air. The lack of dew point oscillations, however, is not a problem with this explanation, since radiative cooling by itself does not alter the dew point.

[AR] We agree with this comment and have changed the text accordingly. Buoyancy is now mentioned as a possible cause for intermittent turbulence. The lateral replacement is mentioned as a caveat of this explanation and the lack of oscillations in dewpoint was removed from the text.

19788, lines 22-27: The front would be a single density current; injections of air from higher elevations from the surface would be caused by Kelvin-Helmholtz billows rather than additional density currents.

[AR] We agree and have included Kelvin-Helmholtz billows (induced by the front's density current) as a possible mechanism for the oscillations:

"Lastly, given the movements of the retreating Lake Erie breeze front and the advancing Lake Huron breeze front through the region on that night, as described in Sections 3.3.1 and 3.3.2, it is possible that these fronts generate shear-induced instabilities ahead and behind them that might result in periodic turbulence. Such Kelvin-Helmholtz billows induced by the front's density current could be a possible mechanism that injects air from higher elevations to the surface, as described by Sun et al. (2002). However, as with the first explanation, this mechanism would also result in short bursts of stronger winds measured at the surface, which are not observed in the measurements, but conceivably the shear-induced vertical mixing could occur upwind of the station and then horizontal advection could transport the ozone-enriched air over the station. In fact, if a number of billows overturned and collapsed, a number of near-surface horizontal "bands" of alternating ozone-rich and ozone-poor air could be created that could cause concentration oscillations at a fixed site if they were then advected over the site in succession."

19787-19788: It seems to me that intermittent turbulence, a common nocturnal phenomenon, could easily be responsible for the oscillatory features in the temperature and ozone. This possibility should at least be mentioned here and at the end of the final section.

[AR] We agree that intermittent turbulence can explain the observed oscillations, and indeed some of the explanations offered in the original manuscript may be the cause of it. Re-examination of the measurements showed some support for this explanation with the high ozone mixing ratios found by the aircraft over Lake Erie early in the morning (Figure 7a). Given the westerly flow during that night it is possible that the same air mass was present over SW Ontario during the night and was periodically brought to the surface by turbulence. This finding was inserted to the text.

Following the paper by Salmond and McKendry (2005) we now describe 5 possible causes for turbulence in the nocturnal boundary layer. Two of these (wind shear near the surface and land/lake breeze winds) are discarded because they require stronger winds than are observed, but the other three (low level jets, breaking gravity waves and density currents) are now discussed in the text in the context of intermittent turbulence. The manuscript was changed accordingly in Section 3.3.4, in the Conclusions, and in the Abstract.

19790, lines 24-26: I presume this passage is referring to Figure 4. If so, Figure 4 only shows a large reservoir of ozone centered over Lake Erie at 21:00 EDT. The term "large reservoir" is misleading because it implies that the ozone remains there for a while. The ozone pattern aloft at sunrise is much more relevant to ground-level ozone levels than the ozone pattern aloft in the evening. I do not know why the 21:00 EDT ozone pattern aloft is thought to be important enough to merit mention in the conclusions and the abstract.
[AR] We agree that the higher ozone aloft observed during the previous evening may have little effect on the daytime ozone levels. However we do believe that the presence of the nighttime reservoir layer of ozone is an important feature that should be included in the Conclusions and Abstract sections as it may have an effect on ground-level ozone during the night, e.g., by vertical transport as demonstrated by the oscillations in the case study. The adjective "large" was removed from the text, the nighttime reservoir is now emphasized less in the Abstract, and the following sentence was added to the Conclusions section:
"However, by early morning the vertical differences in ozone between over land and over lake are limited to a shallow layer of about 200 m a.g.l., suggesting that nighttime lake-land differences in surface ozone observed in this and previous studies have a limited effect on the overall ozone budget during the day."

Trivial Comments:
19765, line 7: The time-varying nature of the land-sea temperature difference is more important than the existence of a temperature difference itself, as it assures that the winds never come into gradient balance. Insert "time-varying" before "temperature".
[AR]: The sentence was changed as suggested.

19766, line 16: As written, the smallest change was 60 ppb and the largest change was 100 ppb. I think you meant to say that the "ozone levels ranged from 60 ppb to 100 ppb", so use that or similar language.
[AR]: The sentence was changed for clarity:
"ozone levels ranged from 60 ppbv to 100 ppbv over Lake Ontario"

19770, line 3: The AURAMS surface types do not have a 1:1 correspondence to the observation site types. Change "corresponding" to "various".
[AR]: Done

19774, lines 19-22: Another cause of the difference is the decreased vertical exchange of ozone over land at night.
[AR]: The manuscript was changed in this section and in the last sentence of Section 3.1 to mention the reduced vertical exchange of ozone at night.

19776, lines 26-27: The detailed analysis of the meteorological conditions is useful for showing the spatial extent of the different modes of transport, but the Harrow transport sequence described in the remainder of this sentence is deduceable exclusively from the station time series (Fig. 6a) with no detailed analysis required. Rephrase.
[AR] The sentence was changed to:

"…northeast, as can also be seen in the wind measurements at the Harrow site (Fig. 6a)."

Technical Corrections:
19765, line 23: Change "have" to "has".
[AR]: Done

19765, line 27: Change "models" to "model".
[AR]: Done

References:
Salmond, J. A. and McKendry, I. G.: A review of turbulence in the very stable nocturnal boundary layer and its implications for air quality, Progress in Physical Geography, 29(2), 171 -188, doi:10.1191/0309133305pp442ra, 2005.