Multiyear Model Evaluation over Lake Michigan Region

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1. Introduction and Motivation

Elevated ozone levels remain a concern for the Midwestern states. Similar to other regions in the eastern U.S., ozone episodes in this region are often under high temperatures, clear or hazy skies, low wind speeds, high solar radiation, and winds with a south-westerly component that are associated with slow-moving high pressure systems. In particular, high levels of ozone along the shores of Lake Michigan have been a recurring theme over the last 40 years. Previous field studies over Lake Michigan have indicated that the transport of ozone precursors from urban centers to areas over the lake allows ozone production and accumulation within the shallow boundary layer over the water. Subsequently, a return flow, due to Lake Breeze, brings the elevated ozone back onshore and over the population centers (Koerber et al. 1991, Dye et al, 1995; Lyons et al. 1995).

Despite this conceptual understanding, models continue to have difficulty in replicating ozone behavior in the region. It appears that the air quality models overestimate ozone concentrations over Lake Michigan (Cleary et al., 2015). Indeed, there could be inaccuracies in the timing and extent of the onshore flow during the day. Furthermore, the complex meteorological setting of the relatively cold lake in the summer ozone season limits the ability of the physical model to replicate this environment and may contribute to air quality modeling errors. The representation of the stable boundary layer in the model and/or errors in lake and land temperatures that define the strength of lake/land breezes are other factors impacting model performance.

In the current study, the average summertime behavior of flow field and chemistry over Lake Michigan is analyzed. The results from air quality simulations for summers of 2009, 2011, and 2013 are used to ascertain the key factors impacting ozone production and accumulation over the lake.

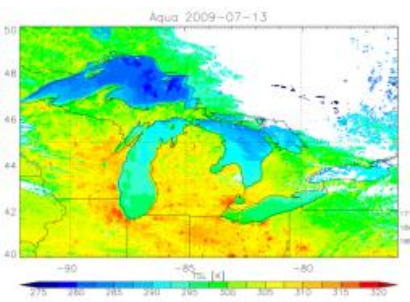
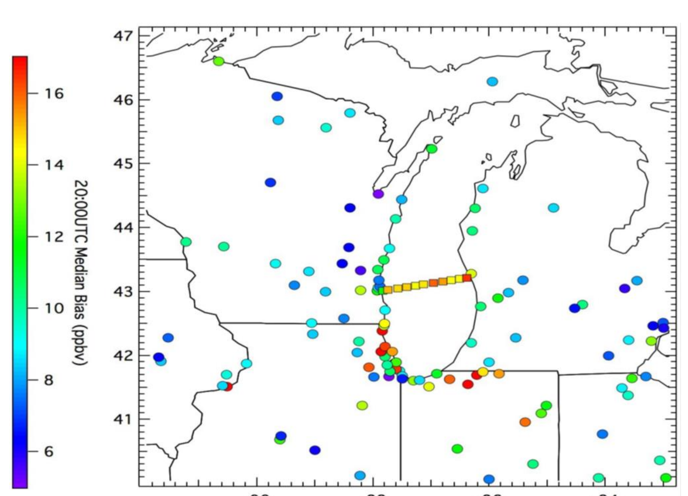


Figure 1. Satellite-retrieved skin temperature for July 13, 2009, shows the sharp contrast between the cold lake temperatures next to the hot land surfaces. The spatial temperature gradient plays a significant role in the timing and the strength of the sea/land breeze.

2. Background



Comparing NOAA Air Quality Forecast to Observations over the Summer of 2009

Figure 2. The figure, adapted from Cleary et al. 2015, shows CMAQ's ozone bias in the Lake Michigan region for the summer of 2009. Model predictions were compared to ferry and land sites' observations. Model consistently over-predicts ozone along the ferry path (over the lake). EPA monitor biases are calculated at 20:00 UTC (15:00 CDT), and the data have been windowed for only those days when Lake Express ferry data are available. The Lake Express ferry data are from the 12:30 to 15:00 CDT transect statistics.

Schematic of Lake Michigan Lake Breeze Systems

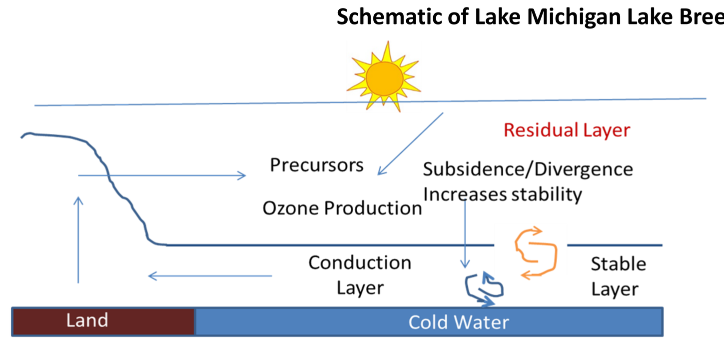


Figure 3. The daytime lake breeze circulation. After Foley et al (2011) and Adamski (2003).

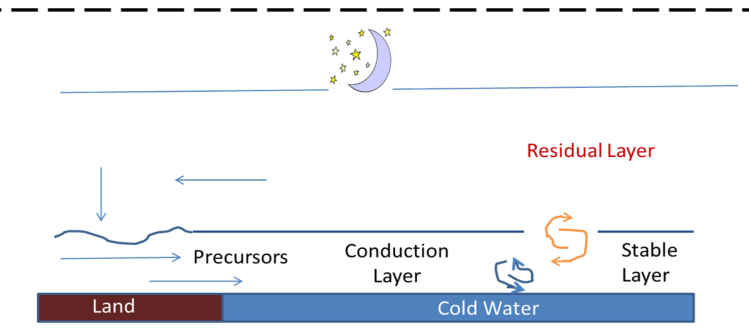


Figure 4. The nighttime/early morning land breeze circulation. After Foley et al (2011) and Adamski (2003).

3. Model Simulations

WRF/CMAQ results from 2009, 2011, and 2013 simulations were used in this study. There are differences in model configurations for different years. 2009 results are from the NOAA operational air quality forecast system using NAM-12/CMAQ, and the Yonsei University (YSU) PBL coupled with the NOAH land surface scheme. 2011 and 2013 simulations used ACM2 PBL coupled with Pleim-Xiu land surface scheme. The simulations covered the summer season. However, due to the similarities in the seasonal and monthly average characteristics, July-August averages are presented here.

4. Results

Average July-August Wind Field and Surface Ozone at 09:00 Local Time for 2009, 2011, and 2013

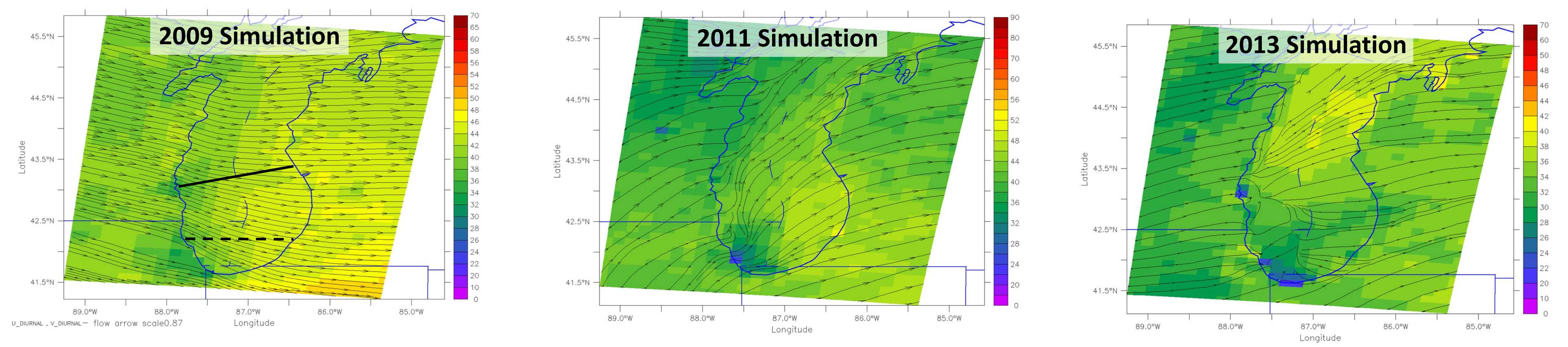


Figure 5. Average streamlines and surface ozone indicate the predominant westerly flow at 09:00 local time. For all three years, 9:00-10:00 am is the onset of lake breeze and a reversal in the surface flow field. The nighttime flow is mainly dominated with the synoptic flow with little modification by the land breeze circulation. For 2009, the modification to the flow field due to the formation of lake breeze started later in the day, while for 2011 and 2013, at 09:00 the lake breeze has already started initiating a divergence over the southwestern part of the Lake Michigan. Surface deposition and consumption of ozone by fresh NO over land results in low ozone concentrations in the south/southwest part of the lake. The low ozone over the lake indicates the transport during land breeze and agrees well with the schematic in Figure 4. *On the top left figure, solid line shows ferry crossing and the dashed line indicates the Southern Lake Michigan traverse.*

Average July-August Wind Field and Surface Ozone at 13:00 Local Time for 2009, 2011, and 2013

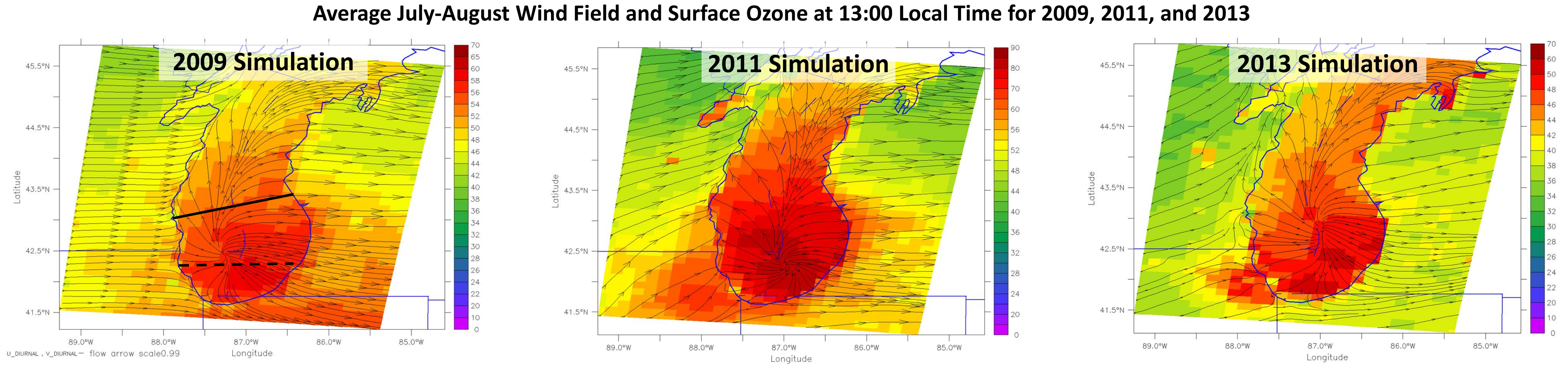
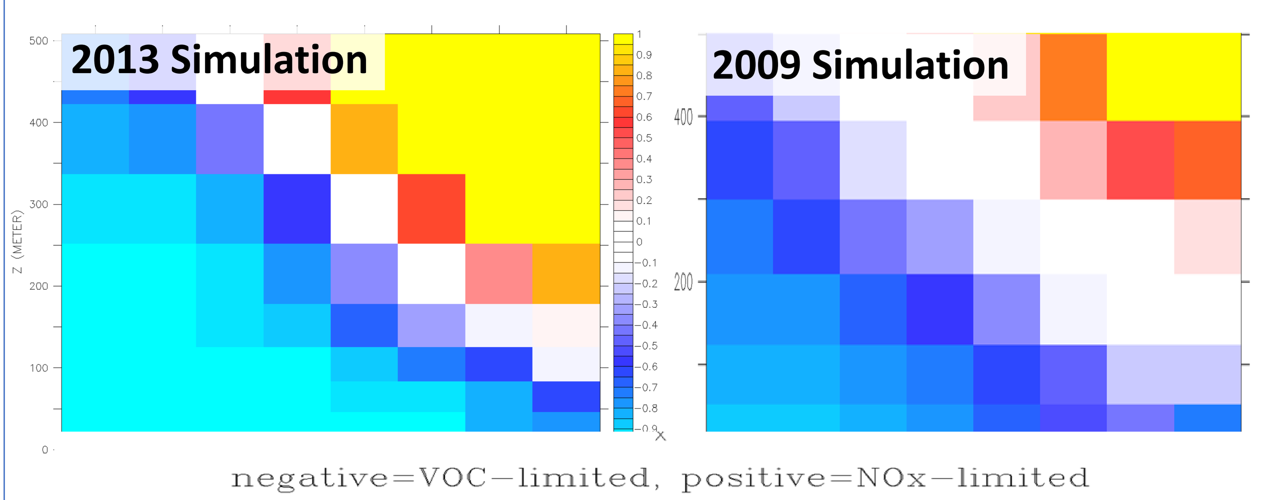


Figure 6. Average streamlines and surface ozone indicate that at 13:00 local time the predominant westerly/southwesterly flow is completely modified by lake breeze circulation. The similarities between the average flow and ozone concentration for all three years suggest the strong impact of meteorological factors on ozone concentration. Note that while the predominant flow for 2009 is from west and for 2011, 2013 from southwest, there is little change in the flow field over the lake. The location of maximum ozone remains to be to the east of the divergence zone. The flow from the center of divergence zone transports the air with higher ozone production potential toward the shores and also toward the northern part of the lake. Most of the ozone production takes place in the southern part of the lake. The results overall agree well with the schematic in Figure 3. However, it seems that the ozone production potential is controlled by the availability of ozone precursors at the center of divergence zone. Also note that while the pattern in 2011 is the same as other years, the magnitude of concentration is higher. *On the top left figure, solid line shows ferry crossing and the dashed line indicates the Southern Lake Michigan traverse.*



Identifying the Location of Maximum Ozone Production Efficiency

Figure 7. The air mass above the southern part of Lake Michigan (dashed lines in Figures 5 and 6) shows a distinct contrast from west to east. The air mass to the west is VOC limited, while the air from the east is NOx limited. The transition between these two air masses creates a mixture that is conducive to ozone production. Thus, the mixing of the VOC rich air to the lake surface may control the surface ozone concentration.

The figure is based on the average concentrations at 9:00 am local time. An enhanced functional form of VOC/NOx ratio was constructed to indicate VOC- vs Nox-limited regimes. The function normalizes (Isoprene+HCHO)/NOx ratio, with a threshold of 1.2 indicating the maximum production efficiency.

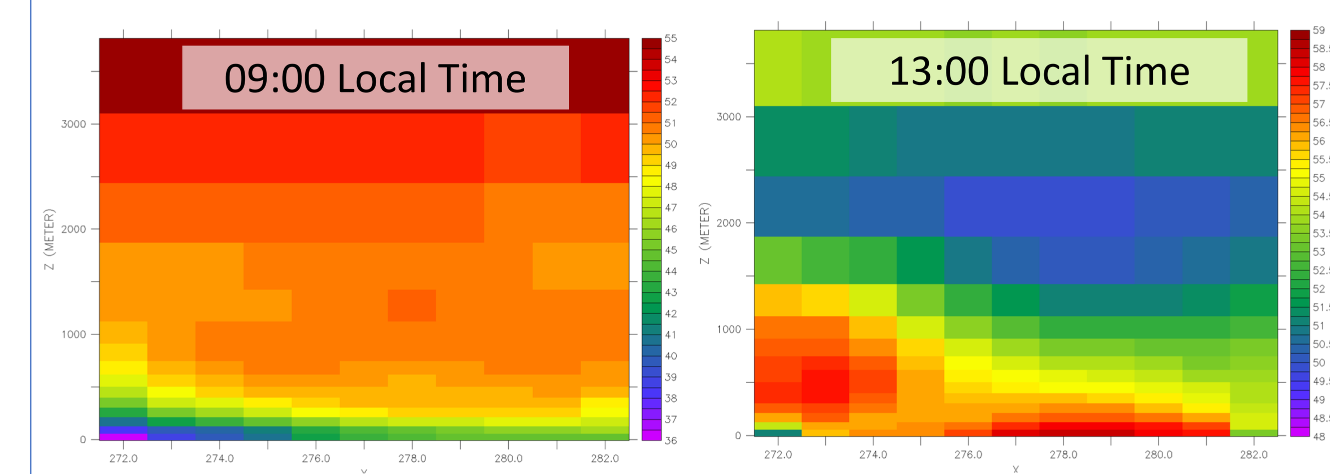


Figure 8. Average East-West cross section of ozone to the **south of ferry transect** for 0900 and 1300 local time. The transect is indicated by dashed line in Figures 5 and 6. The vertical gradients agree well with the ozone production efficiency presented in Figure 7.

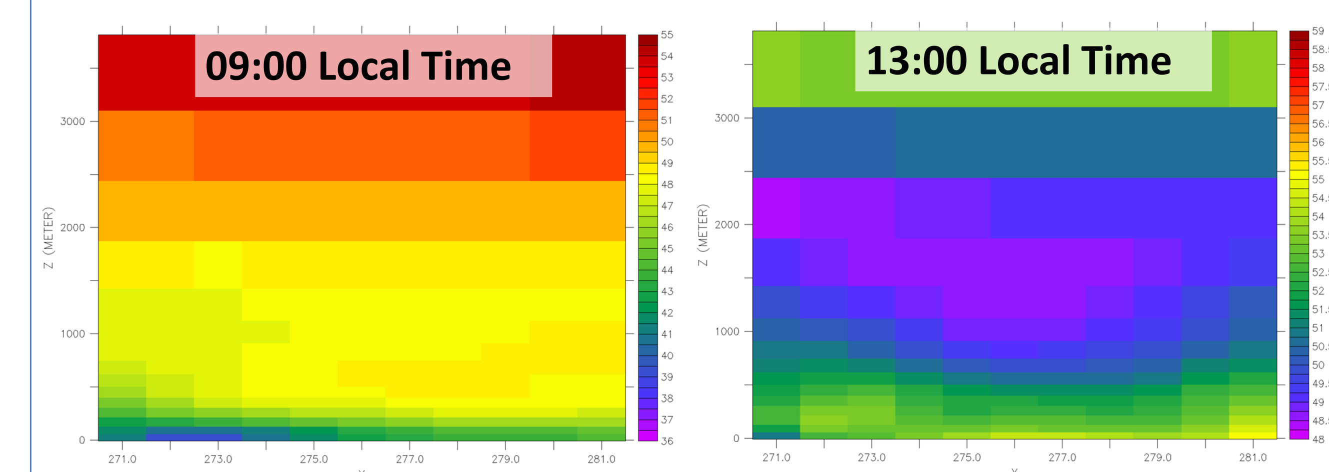


Figure 9. Average East-West cross section of ozone at **ferry transect** for 0900 and 1300 local time. The transect is indicated by solid line in Figures 5 and 6.

5. Conclusion

The results indicate that while there are pronounced similarities in the average flow field and spatial variation of ozone over Lake Michigan, the strength of the predominant westerlies, land/water temperature contrast, and the curvature of the shoreline determine the onset of sea-breeze and the location of a divergence zone at the lake surface that is prone to high ozone production. This divergence zone starts forming in the southwestern part of the lake. Furthermore, model vertical mixing impacts the delicate balance of ozone precursors within the air-mass and can lead to inaccurate prediction of ozone concentration over the lake.

The summertime average concentration fields along with the average flow field elucidate physical/chemical processes responsible for model predictions. Early in the day, before the onset of the sea-breeze, boundary layer growth over land mixes ozone precursors in a deeper atmospheric layer. At the onset of the sea-breeze, the return flow brings together the high NOx air from the west and VOC rich air from the east toward the southern part of the lake. The mixed air is transported to the lake surface and creates a strong divergence field in the southern part of the lake. Strong stable layer over the lake inhibits any further vertical mixing in the onshore and the southerly flow over the lake surface. The representation of strength of this stable layer in the model determines the ozone concentration over the lake surface. Perhaps future field experiments sampling the air over the southern part of the lake will provide the necessary information for validating the model performance.

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