Trans-boundary air pollution in Windsor, Ontario (Canada)

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Abstract

Windsor (Ontario) is located on the Canada-US border. Some believe that the heavy industrial facilities such as power generation and automobile production in the neighbouring regions of US greatly affect Windsor’s air quality. This study investigates the frequency of air mass exchange between Windsor and the neighbouring US states. Two-day (48-hr) and one-day (24-hr) back trajectories were run using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Windsor Airport (42.27° N, 82.96° W) was the starting point. The model resolution was three days a week. Two calendar years, 2008 and 2009, were modeled thus seasonal and inter-annual variations could be observed. It was found that the fraction of air mass parallel to the border is small. When considering the 48-hr trajectories on an annual basis, 53-55% of air masses arriving Windsor were from the US, whereas the 24-hr trajectories showed a much higher percentage (81-82%). The inter-annual variability between 2008 and 2009 was small. In both years, winter had higher frequency of US to Canada transport than Canada to US. In the other three seasons (spring, summer and fall), one year had more frequent US to Canada transport while the other year had less. It was concluded that overall the US-Canada transport had a higher frequency. However, this alone is inadequate to support the claim of air masses coming from US greatly affect Windsor air quality. Further analyses using state and province wide emission densities and ambient concentrations were conducted for a two-week period during each year to quantitatively assess the trans-boundary movement of air pollutants. Statistical analyses showed no consistent, significant correlations between the travel path of the air mass prior to arrival and the measured NO2 or PM2.5 concentrations at the receptor.

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Keywords: Air pollution; Emission; HYSPLIT; Long-range transport; Trajectory; Trans-boundary

1. Introduction

Air pollution in a particular city is not only influenced by local emission sources but also by sources in the region around the city as air movement does not respect any geo-political boundaries. Air mass movement is influenced by meteorological conditions and the geography of the region. Analysis of frequency distribution of air mass movements provides useful insights about the effect of non-local emissions on local air quality.

Windsor (Ontario) is located on the Canada-US border (Figure 1a). Some believe that the heavy industrial facilities such as power generation and automobile production in the neighbouring regions of US greatly affect
Windsor’s air quality. This study examines the 48-hr and 24-hr back trajectories over two years using the Hybrid Single-Particle Langrangian Integrated Trajectory (HYSPLIT) model [1]. HYSPLIT has been used in previously published research as a means to investigate the impact of long range transport of pollutants [2, 3]. Observation of the source locations and directions of air masses arriving at a receptor may suggest influences of neighbouring regions on the local air quality, but it does not necessarily mean that a particular region is the ‘culprit’ for bad local air quality. Several other factors are involved such as the presence of emission sources along the air mass trajectory, the time it takes for the air mass to reach the receptor and the height of air mass when it approaches the receptor.

To further analyze whether the travel path of the air mass influences the measured concentration at the receptor, the emission densities of the pollutants of interest and the ambient concentrations of these pollutants along the pathway was investigated to determine whether significant correlations exist. This analysis was performed for a two-week sample period during each year and the pollutants considered are nitrogen dioxide (NO$_2$) and particulate matter less than 2.5 microns (PM$_{2.5}$). This expanded analysis should provide a better understanding of whether or not the origin and the pathway of an air mass and the strength of the sources encountered along the path can be expected to influence the measured concentrations at the receptor.

2. Methods

2.1 Modeling

The backward trajectories were modelled using Hybrid Single-Particle Langrangian Intergrated (Trajectory HYSPLIT) Model 4[1]. Two calendar years, 2008 and 2009, were modeled thus, seasonal and inter-annual variations would be observed. Modeling resolution was three days a week, i.e. Tuesday, Thursday and Saturday. Two-day (48-hr) and one-day (24-hr) HYSPLIT back trajectories were run using Windsor Airport as the starting point. The simulation parameters are shown in Table 1.

Table 1. Parameters used for all modeling runs

| Model parameter                        | Setting                                      |
|----------------------------------------|----------------------------------------------|
| Meteorological dataset                 | EDAS 40km, 2004-Present                      |
| Trajectory direction                   | Backward                                     |
| Total run time (trajectory duration)   | 48hr & 24hr                                  |
| Start point                            | Windsor Airport (42.27° N, 82.96° W)         |
| Start time                             | 00:00 UTC (7 pm EST)                         |
| Start height                           | 500m AGL                                     |
2.2 Origins and Directions of Air Mass

The back trajectories obtained from the modeling simulation were categorized based on the origin of the 48-hr or 24-hr air mass, the direction of the 24-hr air mass (N, E etc) just before entry into Windsor, and trans-boundary movement of air mass: Windsor-Detroit, Detroit-Windsor or parallel to the border. For this purpose, eight directions were chosen with a 45 degree tolerance band for each direction. A picture of the compass divided into eight directions was overlaid on the trajectory image to precisely determine the direction of air mass movement. Figure 1b shows an example 48-hr trajectory with origin in the US and direction of entry into Windsor as southwest. In discussion concerning seasonal variability, the seasons were defined as follows, spring: March, April, May; summer: June, July, August; fall: September, October, November; winter: December, January, February.

Fig. 1. (a) Map of study area; (b) Sample trajectory with compass image overlay. Air mass source is US and direction of entry in Windsor is southwest.
2.3 Correlations between concentration at receptor and trajectory pathway

In order to investigate whether the origin or pathway of an air mass is correlated with the measured concentration at the receptor, two sample periods were subjected to further analysis. The sample periods were each two weeks in length; September 5th-20th, 2008 and May 29th-June 13th, 2009. The measures that were investigated were the emissions encountered along the air mass pathway, and the ambient annual average concentrations encountered along the air mass pathway.

The 24-hr backward air mass trajectories for each day during the study periods were analyzed to determine which regions they passed through before arriving at the receptor site (Windsor, Ontario). Once the regions for all dates were identified, the total NO\textsubscript{2} and PM\textsubscript{2.5} emissions for these states/provinces were calculated by consulting the US Environmental Protection Agency [4] and the Environment Canada [5] online emission inventories and were then normalized based on the square kilometers of the state or province. If an air mass passed through more than one state or province a weighted average emission rate value was calculated based on the travelled path and the approximate time spent in each region.

The average ambient concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} for each state/province were determined by consulting the US EPA [4] and the Ontario Ministry of Environment websites [6]. Using the same weighted average method, an ambient concentration value for each pollutant was assigned to the air mass on each day based on the time spent in each region.

Using scatter plots and Pearson correlation, analyses were performed to determine if there were any correlations between the path of the trajectory and the level of NO\textsubscript{2} and PM\textsubscript{2.5} concentration measured at the National Air Pollution Surveillance [7] Windsor West site [8] on a given day.

3. Results and Discussion

3.1 Origins of Air Masses

Table 2 shows the percentage of air mass movement between the two countries for 2008 and 2009 based on the 48-hr and 24-hr trajectories. When considering the 48-hr trajectories, a slightly higher proportion of air masses originated in the US for both 2008 and 2009. However, when considering the 24-hr trajectories, this difference is much more pronounced with over 80% of air masses originating in the US.

The variability between the two years is very small. When considering both the 48-hr and 24-hr trajectories, the variability between 2008 and 2009 does not exceed two percent. This suggests that the movement of air masses between the two countries is consistent on an annual basis.

|          | 48-hr  | 24-hr  | 48-hr  | 24-hr  |
|----------|--------|--------|--------|--------|
|          | 2008   | 2009   | 2008   | 2009   |
| Canada   | 45%    | 47%    | 18%    | 19%    |
| US       | 55%    | 53%    | 82%    | 81%    |

Figure 2 shows that a higher percentage of air masses entering Windsor during the winter season of both 2008 (64%) and 2009 (58%) were from US. In the other three seasons of 2009 the percentage of air mass coming from Canada and US were almost equal. In contrast, in 2008 summer and fall have different patterns with 72% of air masses originating from US in summer and 38% in fall. Figure 3 shows that regardless of season and year a higher percentage of air masses arriving in Windsor were originated in the US when considering the 24-hr trajectories, especially during winter.
Figure 4 shows the direction of air mass movement with respect to the Windsor-Detroit border. In all four seasons of both years a higher percentage of air masses entering Windsor were from the US, especially during summer 2009. On average, 30% of the air masses entering Windsor were parallel to the border during 2008 followed by 20% during 2009. A much lower percentage of air masses entering parallel to the border was observed in summer and winter 2009 due to the lower frequency of south and south-westerly air flows during that time.
3.2 Directions of Air masses

Figure 5 shows the direction of air mass entry into Windsor. For both 2008 and 2009, westerly flow is the most frequent. The combined flow from the southwest, west, and northwest directions accounted for 61% in 2008 and 55% in 2009.

![Figure 5. Percentage of occurrence of air mass path direction.](image)

Seasonal comparison of air mass flow directions for 2008 and 2009 is shown in Figure 6. In 2008, the most common air mass flow direction during spring, summer, and winter was from the southwest. In fall, the percentage of air mass flow direction for both southwest and northwest was equal. In 2009, the most common air mass flow directions during each season were as follows, spring and fall: southwest, summer: northwest, and winter: west. These seasonal trends corroborate the annual observations by showing that the most frequent directions of air mass entry to Windsor are the ones entering from the direction of the US.

3.3 Air Mass Pathways for Sample Periods

Reverse geo-coding and examination of the 24-hr backward trajectories for each day during the two weeks sample periods were used to determine the origin of the trajectories as well as the regions that the passed prior to arrival at the receptor. Air masses arrived from as far away as Missouri and travelled through as many as four states/provinces prior to arrival in Windsor. From the models, a total of eight states and one province were predicted to have possibly affected the measured pollutant concentrations during the study period. Results suggest that Windsor is exposed to trans-boundary air pollution on nearly a daily basis (13/16 days during the 2008 sample period and 12/16 days for 2009).
3.4 Effect of Emission Densities Encountered along Air Mass Pathway

Annual emissions of NO2 and PM2.5 for each state/province were determined by consulting the US EPA (US States) and the EC (Ontario) websites. The most recent year in which data was available for the US was 2005, whereas for Ontario 2007 data was available (2005 data was not available for Ontario). The annual emissions from all sources were then divided by the area of each region in order to obtain an emissions/area value, reported in tons/km² of NO2 or PM2.5. An emissions/square kilometer value was calculated for each day in the sample period based on the 24-hr air mass trajectory for that day. On days where the air mass passed through more than one region, a weighted average was taken. This was carried out as a means of finding a rough estimate of the emissions that a given air mass was exposed to prior to arriving at the receptor site.

Fig. 6. Seasonal variation of air mass flow directions.
Scatter plots and Pearson correlation analysis revealed that there was no observable correlation between the projected emissions encountered along the pathway of an air mass and the measured concentration at the receptor. An exception to this was the Pearson correlation between the average air mass exposure to PM$_{2.5}$ and the concentration at the receptor during the 2008 sample period ($r = 0.44$, $p<0.05$). Since this trend was not observed during the 2009 sample period, further analysis, including longer sampling periods may be required in order to determine whether or not a significant correlation exists between the two measures. Scatter plots did not reveal any significant relationships. An example of the scatter plots for 2008 (24-hr trajectories) is shown Figure 7.

Fig. 7. Observed concentrations vs. weighted average air emissions density for the 24-hr trajectories for (a) NO$_2$, (b) PM2.5.

### 3.5 Effect of Ambient Concentrations along Air Mass Pathway

The annual average ambient concentrations of NO$_2$ and PM$_{2.5}$ for each area are shown in Table 3. Similar to the previous analysis, scatter plots between the annual ambient concentration of the pollutants in the regions that the air mass has travelled through and the measured concentrations at the Windsor West NAPS site on a given day were not seen to be significant. Pearson correlation analysis confirmed the lack of correlation between these measures for both sampling periods. This is likely due to the large area and long timeframe over which the concentrations have been averaged. For example, in Michigan there are 31 PM$_{2.5}$ monitors with ambient annual concentrations ranging from 6.59 µg/m$^3$ to 15.54 µg/m$^3$. Once these values are averaged over the entire state the concentration obtained is 11.29 µg/m$^3$. An air mass may have passed through an area where the concentration was higher (lower) than the average but this would not be reflected in the correlation.

| State/Province | NO$_2$ (ppb) | PM$_{2.5}$ (µg/m$^3$) |
|----------------|--------------|-----------------------|
| Ontario        | 11           | 7.00                  |
| Michigan       | 12           | 11.29                 |
| Ohio           | 13           | 12.46                 |
| Illinois       | 18.5         | 11.58                 |
| Indiana        | 9.2          | 11.71                 |
| Missouri       | 9.3          | 12.22                 |
| Kentucky       | 8.3          | 12.08                 |
| Wisconsin      | 7.5          | 10.06                 |
| Pennsylvania   | 11.2         | 13.90                 |
4. Conclusions

Observation of 48-hr backward air mass trajectories during both 2008 and 2009 reveal that although a higher percentage of backward trajectories originate from US, the difference is not significant when compared with the percentage of trajectories originating from Canada. However, the results of the 24-hr trajectories showed a much higher percentage of US to Canada air movement. The time period over which the air mass movement is modelled is a significant factor which points to further research into which time period (24-hr or 48-hr) is the most relevant when considering the movement of pollutants. For both trajectory time periods the inter-annual variability in air mass movement was small.

Analysis of the air mass directions supports the 24-hr trajectory results. In all four seasons of both years a higher percentage of air masses entering Windsor were from the US. Most of the air masses flow is from the southwest, west and northwest. These are the directions in which the industrialized US states are located around Windsor.

Windsor is located on the border and these air masses entering Windsor may potentially bring pollutants from the US. The direction of air mass flow just before entering Windsor may be more important than the origin of the air mass trajectory. An air mass may originate in Canada, but enter Windsor after passing through US. Such an air mass can still bring pollutants from the US.

When the 24-hr trajectories for the two sample periods were broken down by how many regions they passed through and by the time spent in each region, it was seen that an air mass arriving in Windsor may be a result of emissions occurring as far away as Missouri and may have had emissions from as many as four states/provinces contributing to the measured concentrations. The emissions/km² values for each trajectory were compared to the concentrations obtained at the receptor site for each day. Results from this analysis suggest a moderate positive correlation between the PM$_{2.5}$ emissions encountered along the path of the air mass trajectory and the measured PM$_{2.5}$ concentration at the receptor for 2008, however similar correlations were not observed during 2009. Therefore, further investigation over longer sample periods is required in order to make a conclusion. Strong correlations between emission densities and measured concentrations were not observed for NO$_2$ during either year. When comparing the annual ambient concentrations along the pathway of an air mass to the concentrations obtained at the receptor site no significant correlations were observed during both sample periods for either pollutant.

In conclusion, although the backward air mass trajectory origins as well as the analysis of the direction from which the air masses enter suggests that Windsor is frequently exposed to air mass arriving from the US, this alone does not suggest that the air quality in Windsor is in fact a result of this air mass movement. Analysis considering emission density and ambient concentrations did not show strong and consistent correlations. Further research is required to investigate whether or not the pathway of an air mass has a considerable effect on the measured concentration at the receptor.

An important future consideration would be to further break down the areas into smaller segments, allowing for more accurate determination of emissions density and ambient concentrations. Additionally, future investigations should consider longer sample periods and possibly more pollutants. Thorough consideration of weather patterns and their relationship to long range transport of pollutants should also be further explored.

Acknowledgments

The author gratefully acknowledges the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (http://www.arl.noaa.gov/ready.html) used in this publication. Special thanks to Marsha Pereira at University of Windsor for editorial assistance.

References

[1] Draxler RR, Rolph GD (2003). HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory). Model access via NOAA ARL READY Website. <http://www.arl.noaa.gov/HYSPLIT.php>. NOAA Air Resources Laboratory, Silver Spring, MD. Accessed February, 2010.
[2] Karaca F, Anil I, Alagha O. Long-range potential source contributions of episodic aerosol events to PM10 profile of a megacity. Atmospheric Environment 2009; 43: 5713–5722.
[3] Davis, R.E., Normale, C.P., Sitka, L., Hondula, D.M., Knight, D.B., Gawtry, S.P., Stenger, P.J. A comparison of trajectory and air mass approaches to examine ozone variability. *Atmospheric Environment* 2010; 44: 64–74.

[4] Environmental Protection Agency (EPA). Emissions Inventory. http://www.epa.gov/cgi-in/broker?_service=data&_debug=0&_program=dataprog.dw_do_all_emis_2005_saa&pol=227&stfips=29. Accessed February, 2010.

[5] Environment Canada (EC). Emissions Inventory. http://www.ec.gc.ca/pdb/websol/eeidm/ees_result_e.cfm?year=2007&substance=nox&location=ON&sector=all&submit=Search. Accessed February, 2010.

[6] Ontario Ministry of Environment (MOE), Air Quality in Ontario-2007 Report. 2008. http://www.ene.gov.on.ca/publications/6930e.pdf. Accessed June, 2010.

[7] National Air Pollution Surveillance Network (NAPS). http://www.etc-ete.ec.gc.ca/naps/index_e.html. Accessed February, 2010.

[8] Ontario Ministry of Environment (MOE), Historical Air Quality Pollutant Data. http://www.airqualityontario.com/history/. Accessed June, 2010.