ISEIS

Journal of Environmental Informatics 11(2) 45-50 (2008)

Journal of Environmental Informatics

www.iseis.org/jei

An Assessment of Meteorological Effects on Air Quality in Windsor, Ontario, Canada — Sensitivity to Temporal Modeling Resolution

A. Anastassopoulos, S. Nguyen, and X. Xu*

Department of Civil and Environmental Engineering, University of Windsor, Windsor, ON N9B 3P4, Canada

Received 31 October 2005; revised 23 March 2007; accepted 1 January 2008; published online 30 May 2008

ABSTRACT. The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model was used to study air quality in the City of Windsor (42.16° N, 82.58° W), Ontario, Canada. Two-day back trajectory simulations were conducted for the year of 2003 to investigate the regional transport of air pollutants. Trajectories were then characterized by air mass path direction and regions traversed, as dominant factors in regional transport of air pollutants, to assess meteorological effects on air quality in Windsor and provide initial identification of potential upwind pollution source regions. Statistical analysis was conducted to study whether the trajectory simulation results are sensitive to temporal modeling resolution of one, two, three and six simulations per week. It was found that HYSPLIT backward trajectory modeling can provide good quality and consistent results with a temporal resolution of two or three runs per week, comparable to a resolution of six runs per week. The HYSPLIT backward trajectory modeling and analysis methods presented can identify potential source regions of transboundary pollutants at practical temporal modeling resolutions. This is useful to communities and policy-makers developing public health policy.

Keywords: air quality, air mass, air pollution, environmental health, modeling, resolution, sensitivity, source-receptor relationship, transboundary air pollution

1. Introduction

Air quality models are widely used tools in studying the source-receptor relationships (Collett and Dyuyemi, 1997; Zannetti and Puckett, 2004). Among them, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT, Draxler and Hess, 1997, 1998) model is a commonly used air modeling program that can calculate air mass paths from one region to another and thus demonstrate whether the vector for air pollutant transport is indeed present (e.g. Perkauskas, 2000; Texas Natural Resource Conservation Commission, 2004). The HYSPLIT model is a complete system that is designed to support a wide range of simulations related to regional or long-range transport, dispersion, and deposition of air pollutants. The output of the HYSPLIT model can vary from simple air parcel trajectories to complex dispersion and deposition simulations (NOAA, 1999). HYSPLIT calculates advection and dispersion using either puff or particle approaches under a Lagrangian framework (Draxler and Hess, 1997). The transport and dispersion of a pollutant is calculated by release of a single puff with a particular distribution or the release of a number of dispersal particles. The trajectory calculation is achieved by the time integration of the position of an air parcel as it is transported by the 3-D winds (Draxler and Hess, 1997; Draxler, 2003). By moving backward in time, the resulting back trajectory indicates air masses arriving at a receptor at a particular time, thus identifying potential source regions.

The HYSPLIT model has been used in numerous air quality modeling applications (e.g. Poissant, 1999; Hsu et al., 2003). Appropriate analysis of HYSPLIT backward trajectory modeling can provide an important initial identification of potential upwind source provinces/states impacting a region's local air quality, and is therefore useful in transboundary air quality decision-making. This identification of potential source regions can then in turn serve as a resource for developing region-specific public community health policies.

The City of Windsor (42.16° N, 82.58° W), Ontario, Canada, is located downwind from Michigan, Ohio and other Midwestern states in the United States. As a result of local and transboundary air pollutants, the possible degraded air quality in Windsor is a cause of major concern to the local people, government agencies and public health professionals. Recently, Canada and the USA have adopted a joint strategy, known as the Border Air Quality Strategy, aimed at improving air quality in border communities and regions as well as addressing associated human health concerns. As part of efforts to investigate and improve ambient air quality in this region, Anastassopoulos et al. (2004) analyzed HYSPLIT trajectory model (Draxler and Rolph, 2003; Rolph, 2003) output for

* Corresponding author. Tel.: +1 519 2533000; fax: +1 519 9713686.
E-mail address: xxu@uwindsor.ca (X. H. Xu).

ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.200800110

Windsor in 2003. The results identified Ontario and neighbouring American states including Michigan, Ohio and Wisconsin as regions having greater influence on Windsor air quality, primarily due to the prevailing wind directions. They also found that HYSPLIT backward trajectory modeling can provide good quality results with a temporal modeling resolution of three runs per week, comparable to a resolution of six runs per week.

Most air pollution modeling remains a combination of human operator effort (e.g. manual model setup and input) and computer processing effort, making it time-intensive and resource-intensive. The analysis of graphical trajectory plots generated by HYSPLIT's trajectory module is a further manual operation. It is therefore of interest to investigate the modeling resolution (i.e. number of modeling runs) required to achieve satisfactory and statistically significant results, as a lower modeling resolution (i.e. fewer runs) translates directly into potential time and money savings. To achieve this, the project expanded the work of Anastassopoulos et al. (2004) by including additional temporal resolutions with more rigorous statistical analysis.

Figure 1. Location of Windsor, Ontario, Canada (adapted from www.nationalgeographic.com).

2. Methodology

2.1. Simulation Design and Modeling Results Characterization

The design of simulation and analysis of results largely followed that in Anastassopoulos et al. (2004) but included additional modeling resolutions. Briefly, an entire calendar year (2003) was modeled so that seasonal variations would be included in the analysis. Key model simulation parameters are summarized in Table 1. For each modeling run, a 48 hour HYSPLIT backward trajectory was modeled with Windsor Airport as the starting point.

Each modeling run (i.e. 48 hr back trajectory) yielded an aerial plot of a trajectory arriving at Windsor. A manual method was used to determine air mass path direction: for the 0-24 hr sub-trajectory, a 'compass graphic' was overlaid onto the aerial plot and the resulting direction was recorded for cumulative frequency analysis. An example is shown in Figure 2, where the wind direction for this example would be recorded as West.

Table 1. Model Parameters Set for All Simulation Runs

Model Parameter	Setting
Meteorological dataset	EDAS 80km, 2003
Trajectory direction	Backward
Total run time (trajectory duration)	48hr
Start point	Windsor Airport (42.16^{o}N, 82.58^{o}W)
Start time	19:00 UTC (2 pm EST)
Start height	500 m Above Ground Level

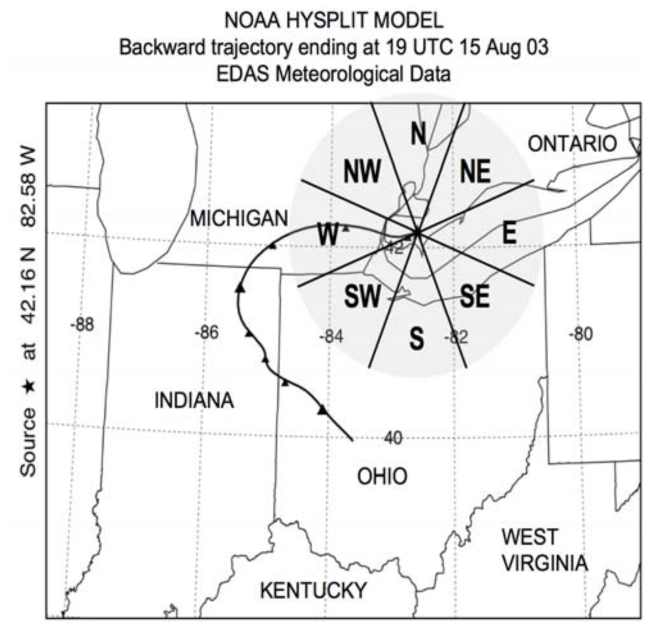

Figure 2. Sample use of manual compass graphic for sub-trajectory (0-24 hr) air mass direction and states/provinces that the air mass path traversed (each segment is 6 hr).

Incoming air mass path direction cannot alone characterize regional influence on Windsor air quality. Therefore, all states/provinces that an air mass path traversed during its entire 48 hr journey to Windsor were tabulated and the frequency distribution of states/provinces was calculated. For the example shown in Figure 2, the two-day trajectory traversed Ohio, Indiana and Michigan. Details on methodology of determining the air mass path and states/provinces traversed can be found in Anastassopoulos et al. (2004).

Table 2 illustrates the discretization of the week into modeling days for the selected temporal modeling resolutions. Analysis was conducted at four temporal resolutions, allowing the difference in modeling results to be assessed in terms of progressive savings in modeling time:

I. six runs per week (i.e. full resolution);

II. three runs per week;

III. two runs per week;

IV. one run per week.

For schedules II and III, only equal split configurations were included for uniform representation of days throughout the week (Table 2). Simulation was not conducted for Sundays in order to allow an even number of simulations in the full resolution (i.e. 6 runs/week, schedule I in Table 2).

Table 2. Temporal Modeling Resolutions and Schedules Used

Resolution Schedule	Days of the Week Modeled					
	a	b	c	d	e	f
I - 6 runs/wk (M, T, W, R, F, S)	-	-	-	-	-	-
II - 3 runs/wk (equal split)	M, W, F	T, R, S	-	-	-	-
III - 2 runs/wk (equal split)	M, R	T, F	W, S	-	-	-
IV - 1 run/wk	M	T	W	R	F	S

2.2. Modeling Resolution Analysis

The analysis of simulation results was conducted at the various temporal resolution schedules for: (1) eight wind directions and the total frequency of dominant wind directions (i.e. westerly = W, SW, NW); (2) regions of influence (i.e. the top seven state/province the air mass traversed).

In order to study the sensitivity of simulation results to temporal model resolution, the results of the various resolutions were compared with that of the full resolution (i.e., 6 runs/week). Wind directions and regions (i.e., state/province) were ranked based on their frequency of occurrence in the year-long simulation, as illustrated in Tables 3 and 6. When a tie occurred, the average rank of the tied obervations was used. Spearman’s rank-correlation coefficient (Johnson, 2005) was then calculated for the top seven states/provinces in the 6 runs /week simulation and all eight directions to assess the sensitivity of the results to model resolution.

3. Results and Discussion

3.1. Direction of Incoming Windsor Air Mass Paths

The ranked frequency of occurrence for the eight wind directions is shown in Table 3. For simplicity of presentation, the table compares the lowest resolution schedule IVa (i.e. 1 run/week, Monday) with the full resolution schedule I (i.e. 6 runs/week, Monday to Saturday). Results show that the ranking order of the four-highest ranked wind directions, which together represented at least 75% of the modeled year, was unchanged at the 1 run/week resolution. Differences in ranking between the 6 runs/week and 1 run/week resolutions were seen only for the least-frequently occurring directions; this was expected as the differences in the frequency of occurrence between these directions is very small (i.e., within 1% for 6 runs/week; within 2% for 1 run/week).

At all modeled resolutions, the westerly wind directions (i.e. W, SW, and NW) comprised the majority of air mass paths influencing the Windsor air quality. The variation of total frequency of westerly winds with changes in temporal resolution and resolution schedule (i.e., days of week selected for modeling) is tabulated in Table 4. Results for the 3 and 2 runs/week resolutions were within ±3% of the full 6 runs/week resolution. However, results for the 1 run/week resolution showed greater difference from the full 6 runs/week resolution, ranging from -11.9 to 8.3%.

Table 3. Air Mass Directions, Ranking Based on Frequency of Occurrence (Temporal Resolution Schedules I, IVa)

Direction	6 runs/week		1 run/wk (IVa)	
	Frequency	Rank	Frequency	Rank
SW	23.0%	1	28.8%	1
NW	21.4%	2	25.0%	2
W	18.5%	3	17.3%	3
N	12.1%	4	11.5%	4
NE	6.7%	5	3.8%	7
S	6.4%	6	3.8%	7
SE	6.1%	7	3.8%	7
E	5.8%	8	5.8%	5

Results for the 1 run/week resolution also exhibited greater variation depending on which day of the week was modeled. In the most extreme case, the westerly winds represented 71.2% of the modeled year at 1 run/week when Mondays or Tuesdays were modeled (i.e. schedules IVa, IVb), compared with only 51.0% when Fridays were modeled (i.e. schedule IVe).

Spearkman’s rank correlation coefficient was then calculated to compare the rankings of air mass path direction at each

Table 4. Total Frequency of Westerly (W, SW, and NW) Winds, Comparison of Different Temporal Resolution Schedules

Resolution Schedule	Frequency of Westerly Winds					
	a	b	c	d	e	f
I - 6 runs/week	62.9%	-	-	-	-	-
II - 3 runs/week (equal split)	61.8%	63.5%	-	-	-	-
III - 2 runs/week (equal split)	60.6%	65.7%	65.7%	-	-	-
IV - 1 run/week	71.2%	71.2%	64.2%	51.9%	51.0%	67.3%

Table 5. Rank Correlation of Air Mass Directions, Indicating Temporal Resolution vs. 6 Runs per Week

Resolution Schedule	Rank Correlation (r)						
	a	b	c	d	e	f	Mean (r)
II - 3 runs/wk - equal split	0.976	0.970	-	-	-	-	0.973
III - 2 runs/wk - equal split	0.929	0.929	0.929	-	-	-	0.929
IV - 1 run/wk	0.810	0.738	0.887	0.762	0.857	0.899	0.825

temporal modeling resolution against the full resolution (i.e. 6 runs/week), as shown in Table 5. To accommodate the temporal resolution schedule variations for each of the 3 runs/ week, 2 runs/week and 1 run/week resolutions, a mean rank correlation was calculated. As expected, mean rank correlation compared with the full 6 run/week resolution decreased with decreasing temporal resolution level. The mean rank correlation of the 3 runs/week resolution was 0.973, indicating a strong correlation to the ranking results of the full 6 runs/week. While mean rank correllation of the 2 runs/week was reduced to 0.929, it also indicated good correlation with the full 6 runs/ week resolution. However, the mean rank correlation dropped considerably for the 1 run/week resolution (i.e. 0.825), indicating a weaker correlation with the full 6 runs/week resolution.

It was also noted that the rank correlation did not vary greatly for the respective schedules of the 3 runs/week and 2 runs/week resolutions. For the 3 runs/week resolution, schedule IIa had a rank correlation of 0.976 while schedule IIb had a rank correlation of 0.970. Results for the 2 runs/week resolution showed similarly consistent rank correlations of 0.929 for all three schedules (i.e., IIIa, IIIb, and IIIc). In comparison, the rank correlation for the 1 run/week resolution varied considerably, from a weakest rank correlation value of 0.738 for schedule IVb to a strongest rank correlation value of 0.899 for schedule IVf.

3.2. Regions of Influence on Windsor Air Quality

Regions of significant influence were classified as those that influenced Windsor air quality for at least 15% of the total modeled days in 2003. By this criterion, a total of seven regions were obtained at the six runs per week modeling resolution. The ranked frequency of occurrence for the top regions traversed by the air mass paths is shown in Table 6. As an example, the table compares the lowest resolution schedule IVc (i.e. 1 run/week, Wednesday) with the full resolution schedule I (i.e. 6 runs/week, Monday to Saturday). Results show that Michigan, Ontario, Ohio, and Wisconsin were the top four ranked regions at both resolutions, with a ‘switch’ in ranking occurring for the third-ranked and fourth-ranked regions. Beyond the top four ranked regions, however, there is significant change in regions’ rankings.

Using the same method as described in section 3.1, rank correlation was then calculated to compare the rankings of the top seven regions at each modeling resolution against the full resolution (i.e. 6 runs/week), as shown in Table 7. Mean rank correlation with the 6 run/week resolution was observed to decrease for the lower resolution levels: ranking results of the 3 runs/week resolution had a strong correlation to the ranking results of the 6 runs/week resolution (mean rank correlation of 0.982); ranking results of the 2 runs/week resolution had a good correlation with the 6 runs/week resolution (mean rank correlation of 0.964); ranking results of the 1 run/week resosolution had a weaker correlation with the 6 runs/week resolution (mean rank correlation of 0.850).

Table 6. Ranking Based on Frequency of Occurrence, Top Seven States/Provinces Air Mass Traversed (Temporal Resolution Schedules I, IVc)

State/Province	6 runs/week		1 run/week (IVc)	
	Frequency	Rank	Frequency	Rank
Michigan	54.3%	1	61.5%	1
Ontario	42.8%	2	46.2%	2
Ohio	37.1%	3	26.9%	4
Wisconsin	28.1%	4	30.8%	3
Indiana	23.3%	5	15.4%	7
Illinois	21.4%	6	26.9%	5
Minnesota	16.0%	7	17.3%	6

Similar to air mass direction, the rank correlation of the top seven regions with the 6 runs/week schedule varied less for the 3 runs/week and 2 runs/week resolutions than it did for the 1 run/week resolution. Rank correlation for the 1 run/week resolution once again varied considerably, from the weakest rank correlation value of 0.710 for schedule IVd to the strongest rank correlation value of 0.964 for schedule IVe. Thus, while a strong rank correlation is possible for the 1 run/week resolution, it is highly dependent on the specific day of the week selected for modeling.

To further determine the modeling resolution (i.e. number of runs per week) needed to assure satisfactory and consistent results, a frequency plot of top ranking regions was used, providing ready visual comparison between results at each of the temporal modeling resolutions. This is shown in Figure 8 for the seven top ranked regions of influence. This plot shows, for example, that Michigan influenced Windsor approximately 54% of the time at the six runs/week temporal resolution while results varied for each of the 3 runs/week, 2 runs/week and 1 run/week schedules. This plot showed that the greatest difference (i.e. as much as 13%) in results from the 6 run/ week resolution occurred with the 1 run/week resolution. In comparison, results for the 3 runs/week resolution were typically within 3% and results for the 2 runs/week resolution

Table 7. Rank Correlation Coefficients of Top Seven State/Province, Indicating Temporal Resolution vs. 6 Runs/Week

Resolution Schedule	Rank Correlation (r)						
	a	b	c	d	e	f	Mean (r)
II - 3 runs/wk - equal split	0.964	1.00	-	-	-	-	0.982
III - 2 runs/wk - equal split	1.00	0.929	0.964	-	-	-	0.964
IV - 1 run/wk	0.853	0.795	0.857	0.710	0.964	0.920	0.850

were typically within 4%. These results suggest that the frequency of regional influence on Windsor air quality is comparable at any of the 6 runs/week, 3 runs/week and 2 runs/week temporal modeling resolutions. Based on this analysis, however, use of the 1 run/week resolution is not seen to provide comparable results to the higher temporal resolutions. Therefore, it is recommended to use a temporal modeling resolution of two or three runs per week.

It should be noted that HYSPLIT backward trajectory modeling is more useful for identifying potential source regions for pollutants associated with long range transport (e.g. fine particulate matter, SO_2). This can augment air quality studies performed at the intra-city scale. For example, recent air quality studies in the City of Windsor have characterized pollutant distributions at the intra-city scale using land use regression modeling. The land use regression modeling linked intra-city spatial distribution of several pollutants (i.e. NO_2, SO_2, volatile organic compounds, and particulate matter) to traffic and point sources (Wheeler et al., 2006; Luginaah et al., 2006). The HYSPLIT backward trajectory modeling and analysis presented in this paper for the City of Windsor identifies the potential source regions of transboundary pollutants.

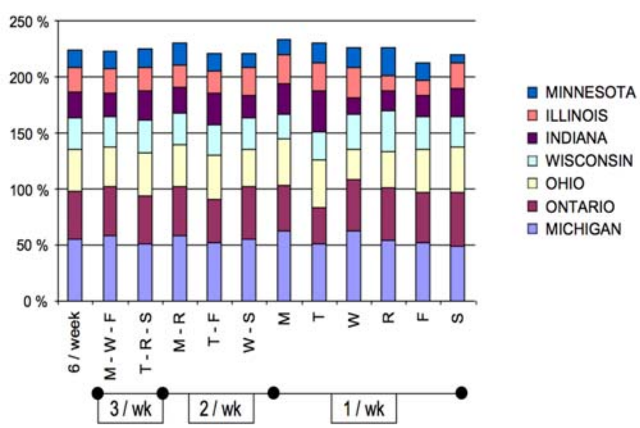

Figure 3. Comparison of the top seven regions influencing Windsor air quality by different temporal resolutions.

4. Conclusions

The HYSPLIT model was used to study air mass paths arriving at the City of Windsor, Ontario, Canada. The simulation results of different temporal resolutions (i.e. model runs per week) were analyzed to investigate the two dominant factors in regional transport of air pollutants: air mass path direction and regions traversed.

From this analysis, it was found that the HYSPLIT backward trajectory modeling can provide good quality and consistent results with a temporal resolution of two or three runs per week, generating results comparable to a temporal resolution of six runs per week. It was also found that, for temporal resolutions of two or more runs per week, modeling results are relatively insensitive to the specific days of the week selected for simulation. In comparison, greater variability in model results was observed for the one run per week simulations. Results demonstrated that significant time savings can be achieved by using a lower temporal modeling resolution, without compromising the statistical significance of results. Temporal resolution levels of 3 and 2 runs/week are recommended; representing half and two-third fewer model runs, respectively, in comparison with 6 runs/week. While a Lagrangian model (i.e. HYSPLIT) was used in this study, the appropriate temporal resolutions recommended here are expected to be applicable to other types of regional scale air quality models such as Gaussian and Eulerian models.

It should be noted that the recommended temporal resolution of two or three runs per week may not be adequate in some seasons when wind directions change frequently. Investigation of seasonal variability is beyond the scope of this study since only one year was modeled (i.e., 2003). An expanded model simulation of multiple calendar years would allow additional analysis of both seasonal variability and inter-annual variability. Furthermore, air quality data collected in the Windsor-Detroit airshed could be used to evaluate the predictive capacity of the simulation of air mass path direction and regions traversed.

The HYSPLIT backward trajectory modeling and analysis methods presented in this paper can be used to identify potential source regions of transboundary pollutants at practical temporal modeling resolutions. This is useful to communities and policy-makers seeking to develop public health policy.

Acknowledgments. The authors gratefully acknowledge 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.

References

Anastassopoulos, A., Nguyen, S. and Xu X. (2004). On the use of HYSPLIT model to study air quality in Windsor, Ontario, Canada, *Environmental Informatics Archives*, 2, 375-383.

Collett, R.S. and Dyuyemi, K. (1997). Air quality modeling: a technical review of mathematical approaches, *Meteorol. Appl.*, 4(3), 235-246, doi:10.1017/S1350482797000455.

Draxler, R.R. and Hess, G.D. (1997). Description of the Hysplit_4 modeling system, *NOAA Tech. Mem. ERL ARL-224*, pp. 24.

Draxler, R.R. and Hess, G.D. (1998). An Overview of the Hysplit_4 Modeling System for Trajectories, Dispersion, and Deposition, *Aust. Met. Mag.*, 47, 295-308.

Draxler, R.R. (2003). Evaluation of an ensemble dispersion calculation, *J. Appl. Meteorol.*, 42, 308-317, doi:10.1175/1520-0450(2003)042<0308:EOAEDC>2.0.CO;2.

Draxler, R.R. and Rolph G.D. (2003). HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website http://www.arl.noaa.gov/ready/hysplit4.html.

Hsu, Y., Holsen, T.M. and Hopke, P.K. (2003). Locating and Quantifying PCB Sources in Chicago: Receptor Modeling and Field Sampling, *Environ. Sci. and Technol.*, 37(4), 681-690, doi:10.1021/es025531x S0013-936X(02)05531-1.

Johnson, R.A. (2005). *Miller and Freund's Probability and Statistics for Engineers*, 7th edition, Pearson Education, Inc. London.

Luginaah, I., Xu, X., Fung, K., Grgicak-Mannion, A., Wintermute, J., Wheeler, A.J., Brook, J. (2006). Establishing the Spatial Variability of Ambient Nitrogen Dioxide in Windsor, Ontario, *Int. J. Environ. Stud.*, 63(4), 487-500, doi:10.1080/00207230600802122.

NOAA. (1999). NOAA Technical Memorandum ERL ARL-230, pp. 35.

Perkauskas, D. (2000). Evaluation of possible air pollution transport from the Ignalina nuclear power station in regional scale, *Proceedings of Millenium (24th) NATO/CCMS International Technical Meeting on Air Pollution Modeling and it's Application*, Boulder, Colorado, pp. 212-213.

Poissant, L. (1999). Potential sources of atmospheric total gaseous mercury in the St. Lawrence River valley, *Atmos. Environ.*, 33 (16), 2537-2547, doi:10.1016/S1352-2310(98)00207-6.

Rolph, G.D. (2003). Real-time Environmental Applications and Display System (READY) Website. http://www.arl.noaa.gov/ready/hysplit4.html.

Texas Natural Resource Conservation Commission (2004). Trajectories for Texas Locations. http://www.tnrcc.state.tx.us/updated/air/ monops/data/trajectories/maintraj.html.

Wheeler, A.J., Xu, X., Smith-Doiron, M., Gilbert, N. and Brook, J. (2006). Intra-urban variability of air pollution: monitoring and modelling of PM2.5, PM2.5-10, and NO2, *Epidemiology*, 17(6), S243.

Zannetti, P. and Puckett, K. (2004). Air Quality Modeling: Theories, Methodologies, Computational Techniques, and Available Databases and Software-Volume I-Fundamentals, *A&WMA and the EnviroComp Institute*, pp. 430.