J2.1 A WIND PROFILER TRAJECTORY TOOL FOR AIR QUALITY TRANSPORT APPLICATIONS

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1. INTRODUCTION

Lagrangian based particle trajectory models are useful for studying the transport of atmospheric constituents such as aerosols, ozone, and water vapor. Several model-based trajectory tools already exist. The HYSPLIT model developed by the NOAA Air Resources Laboratory (http://www.arl.noaa.gov/ready/hysplit4.html) and the FLEXPART model developed by the Norwegian Institute of Air Research (http://zardoz. nilu.no/~andreas/flextra+flexpart.html) are two commonly used approaches.

The NOAA Earth System Research Laboratory (NOAA/ESRL) has developed an observationally-based trajectory tool that uses data from wind profiler networks to calculate forward or backward particle trajectories. The tool is purely observationally based, i.e., there are no model physics or parameterizations involved. The trajectory algorithm applies an inverse distance squared weighting function to the observations from profiler networks in order to determine the hourly position of the trajectories.

2. WIND PROFILERS

Wind profilers are Doppler radars that operate most often in the UHF or VHF frequency bands. Three primary types of wind profilers were in operation in the U.S. at the time of this publication. The NOAA Profiler Network (NPN) profilers are fixed radars that operate at a frequency of 404 MHz (Chadwick, 1988). A smaller, transportable, commercially available wind profiler used by NOAA research and other agencies is the 915-MHz boundary layer wind profiler (Carter et al. 1995). The 404-MHz profilers provide the deepest coverage of the atmosphere, but lack coverage in the planetary boundary layer (PBL). The 915-MHz profilers provide the best coverage of winds in the PBL, but they lack height coverage much above the PBL. A third type of wind profiler that operates at 449 MHz combines the best sampling attributes of the other two systems. The U.S. Air Force has recently installed several of these radars along the southern U.S. border.

Wind profilers transmit pulses of electromagnetic radiation vertically and in at least two slightly off-vertical (~75 degree elevation) directions in order to resolve the three-dimensional vector wind. A small amount of the energy transmitted in each direction is reflected or backscattered to the radar. The backscatter returns are Doppler shifted by the motion of the scattering media. Profilers receive backscatter returns from atmospheric features (turbulence, clouds, precipitation) and non-atmospheric features (insects, birds, trees, airplanes, radio frequency interference). The challenge in signal processing is to avoid the returns from non-atmospheric scattering targets and focus on the atmospheric returns. To do this, profilers sample thousands of consecutive transmitted pulses to boost the signal-to-noise ratio of the atmospheric returns, a process known as coherent integration.

The return signals are sampled at discrete intervals called range gates. The size of the range gates is determined by the length of the transmitted pulse, which is usually on the order of hundreds to thousands of nanoseconds (ns). For example, a 700 ns pulse translates into a range resolution of 105 m. Once the range-gated Doppler shifts from a set of beams have been determined, a wind profile is calculated. This process usually occurs over an observing period of 30 to 90 s. The wind profiles measured within a specified averaging period (15 min to 60 min) are averaged together using a consensus routine.

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The consensus routine filters outliers using threshold and acceptance windows. The consensus wind profiles are archived on site and transmitted back to a data hub in Boulder, Colorado via phone lines or, in remote areas, via satellite communications.

3. WIND PROFILER TRAJECTORY TOOL

The wind profiler data arriving from field sites are converted to a common format and placed in a database for use by the trajectory tool. The tool can be used in post experiment analysis activities, and beginning with the Texas Air Quality Study (TEXAQS-II) in 2005, in near real-time to support mission planning activities and NWS forecast operations. The user has the option of calculating forward or backward trajectories and specifies the start/end point location and the period over which to calculate the trajectories. Other options include specifying multiple altitude ranges and the number of profilers to use or exclude in the calculations. For locations over water, the user may also request surface trajectories that are produced from available buoy and shoreline wind observations (see Fig. 1).

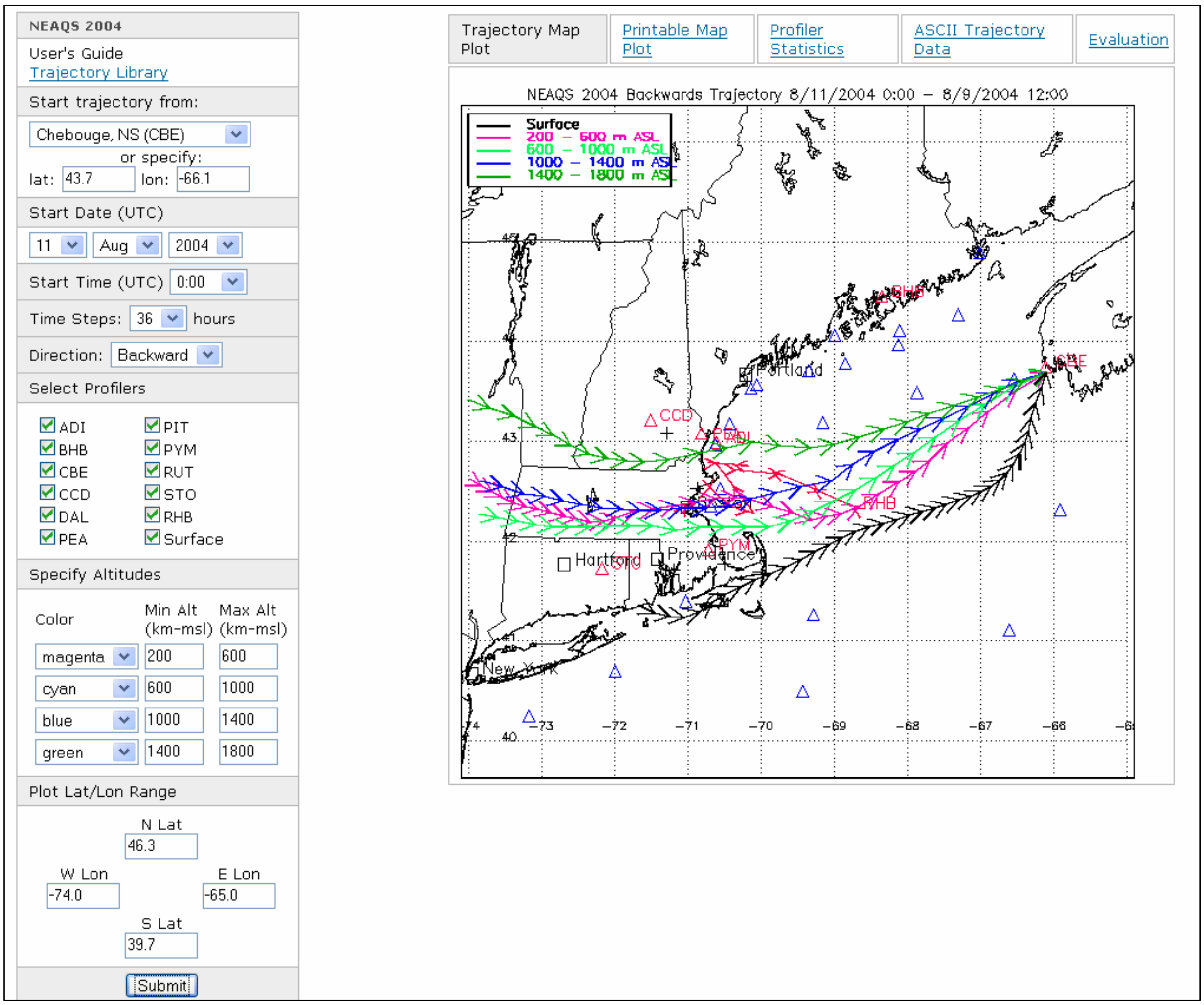


Figure 1. The NOAA/ESRL wind profiler trajectory tool web interface. The user sets input parameters on the left panel. Trajectory output is displayed on the map in the right panel. Arrowheads denote the position along each trajectory at hourly intervals. The red line shows the track of the NOAA research vessel Ronald H. Brown during the requested period. The locations of the profilers in the display domain are indicated by red triangles. The locations of buoy and shoreline observing stations are indicated by blue triangles. These maritime datasets were provided by NOAA's National Data Buoy Center, the Gulf of Maine Ocean Observing System, and the University of Maine.

The trajectory tool uses only the horizontal winds measured by the profiler network. Wind profilers are not capable of resolving synoptic-scale vertical motions measured on an hourly time scale, for example. As such, the profiler trajectories do not adhere to mass balance considerations and, therefore, may differ substantially from trajectories based on full three-dimensional simulations provided by numerical models. However, we believe the continuous nature of the profiler data, especially during active weather patterns, provides a more important benefit for the trajectory calculations. In the future, the most accurate trajectories may be produced by properly assimilating wind profiler data into a mesoscale model. The profiler trajectories are also only reliable within regions where there are profiler networks. This limits their general application compared to model-based trajectories and, more specifically, it limits the time scale over which the profiler trajectories are valid.

For each hour in the requested trajectory period, the NOAA/ESRL trajectory algorithm uses all available profilers in the network. The algorithm computes the distance from the trajectory start point to all requested profiler locations, calculates the average wind speed and direction using an inverse distance squared weighting function, and calculates the trajectory for the first hour. Profiler data at altitudes that fall into each of the user-specified altitude bins are averaged together. Then this process is repeated for the remaining hours of the trajectory period using the trajectory end point of the previous hour as reference point for the distance calculation. If data from one of the requested profilers is not available at any given hour during the trajectory period, the weighted average will be computed form the remaining profilers. If the same profiler provides useable data at a later point in time during the trajectory period it is again included in the average. If all selected profilers have a data outage at the same time then the trajectory calculation is stopped at the hourly time step preceding the outage. No interpolation across data gaps is performed. Therefore, a one-hour data gap in all selected profilers truncates the trajectory.

Once the trajectory output has been plotted on the map, the user has the option of getting a printable version of the trajectory map, creating statistics of which profilers were included along each trajectory (see Fig. 2), retrieving ASCII text of the trajectory output (see Fig. 3), and filling out an evaluation form (see Fig. 4) to let us know if the tool has been useful and/or to provide suggestions for how to improve the tool.

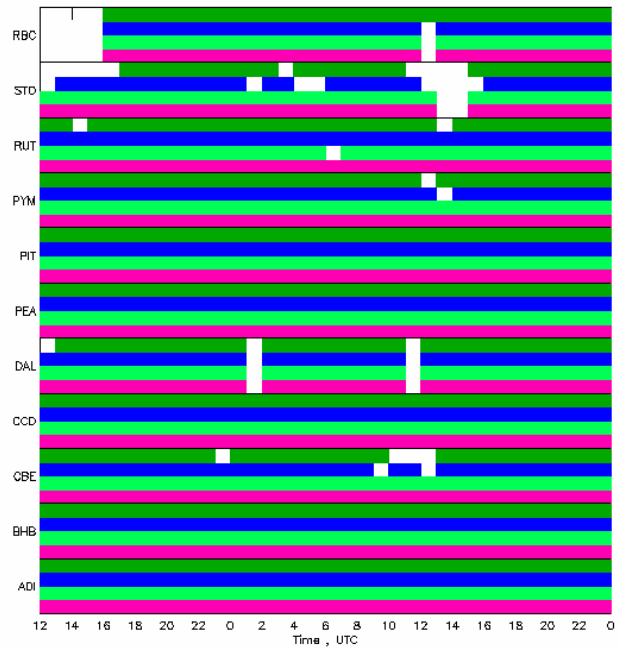
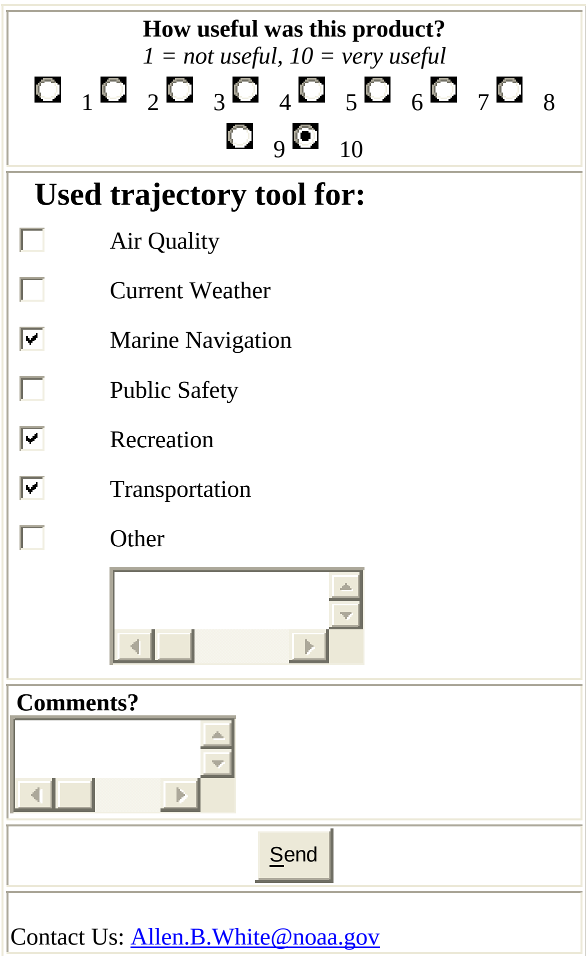


Figure 2. Sample profiler statistics output from the NOAA/ESRL trajectory tool. The x-axis displays the time along the trajectory in hours. The y-axis displays the three letter identifiers for the profilers selected in Fig. 1. RBC refers to a combined dataset that merges data from the Ronald H. Brown ship-based wind profiler and the ship-based Doppler lidar that provided high resolution wind profiles in clear sky and/or below cloud base via the VAD technique. The colored bars correspond to when profiler data was available for the trajectory analysis. Each color corresponds to one of the altitude ranges specified in Fig. 1. White space appears when data from a particular profiler at a particular altitude range was not available.

Date	Time UTC	Surface		200 - 600 m MSL		600 - 1000 m MSL		1000 - 1400 m MSL		1400 - 1800 m MSL	
08/10/2004	20:00	43.1076	-66.3455	42.9921	-67.4520	43.0528	-67.6138	43.2360	-67.5094	43.3682	-67.3652
08/10/2004	21:00	43.2375	-66.3124	43.1442	-67.1701	43.2119	-67.2963	43.3583	-67.1684	43.4513	-67.0362
08/10/2004	22:00	43.3866	-66.2444	43.3081	-66.8967	43.3825	-66.9409	43.4860	-66.8202	43.5282	-66.7103
08/10/2004	23:00	43.5414	-66.1585	43.5087	-66.5248	43.5545	-66.5299	43.6110	-66.4689	43.6165	-66.4073
08/11/2004	00:00	43.7000	-66.1000	43.7000	-66.1000	43.7000	-66.1000	43.7000	-66.1000	43.7000	-66.1000

New England Air Quality Study 2004 Backward trajectories

Figure 3. Sample ASCII output from the NOAA/ESRL wind profiler trajectory tool. The position data correspond to the positions indicated by the arrowheads in Fig. 1.



How useful was this product?

1 = not useful, 10 = very useful

1 2 3 4 5 6 7 8 9 10

Used trajectory tool for:

- [ ] Air Quality
- [ ] Current Weather
- [x] Marine Navigation
- [ ] Public Safety
- [x] Recreation
- [x] Transportation
- [ ] Other

Comments?

Send

Contact Us: Allen.B.White@noaa.gov

Figure 4. Evaluation form used to collect user feedback on the NOAA/ESRL wind profiler trajectory tool.

4. CASE STUDY

To demonstrate the value of incorporating hourly-resolution winds in a trajectory analysis, a case study from the 2004 New England Air Quality Study (NEAQS-04) is presented. The synoptic weather pattern for this case is shown in Fig. 5. The wind profiler data from Chebogue Pt. Nova Scotia (CBE) are shown in Fig. 6. Changes in wind direction in the lower troposphere associated with passing synoptic features are clearly indicated early on in the profiler data. The passage of the trough axis at approximately 0300 UTC on August 10 is indicated by a change from westerly to northwesterly flow. The subsequent passage of the ridge axis is indicated by the shift from northwesterly to weak westerly flow at 1500 UTC, which changes rapidly to southwesterly flow by 1800 UTC. Because the primary source of operational, upper-air wind data in NOAA's observing system is the rawinsonde network, trajectory models that are based on numerical model initialization fields have access to updated upper-air observations only every 12 hours, corresponding to the frequency of rawinsonde launches. Key changes in the synoptic conditions affecting the lower tropospheric winds observed in this case evolved between soundings, which will cause important discrepancies in the trajectories produced by the two methods.

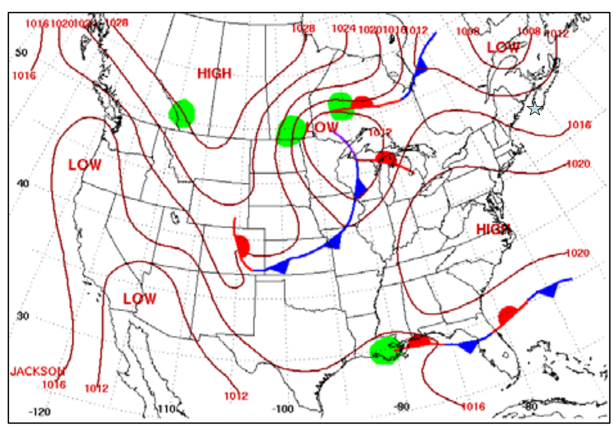


Figure 5. Surface weather map for 1200 UTC on August 9, 2004. The Chebogue Pt., Nova Scotia observing site (CBE) is indicated by the blue star. Map courtesy of NOAA's Hydrometeorological Prediction Center.

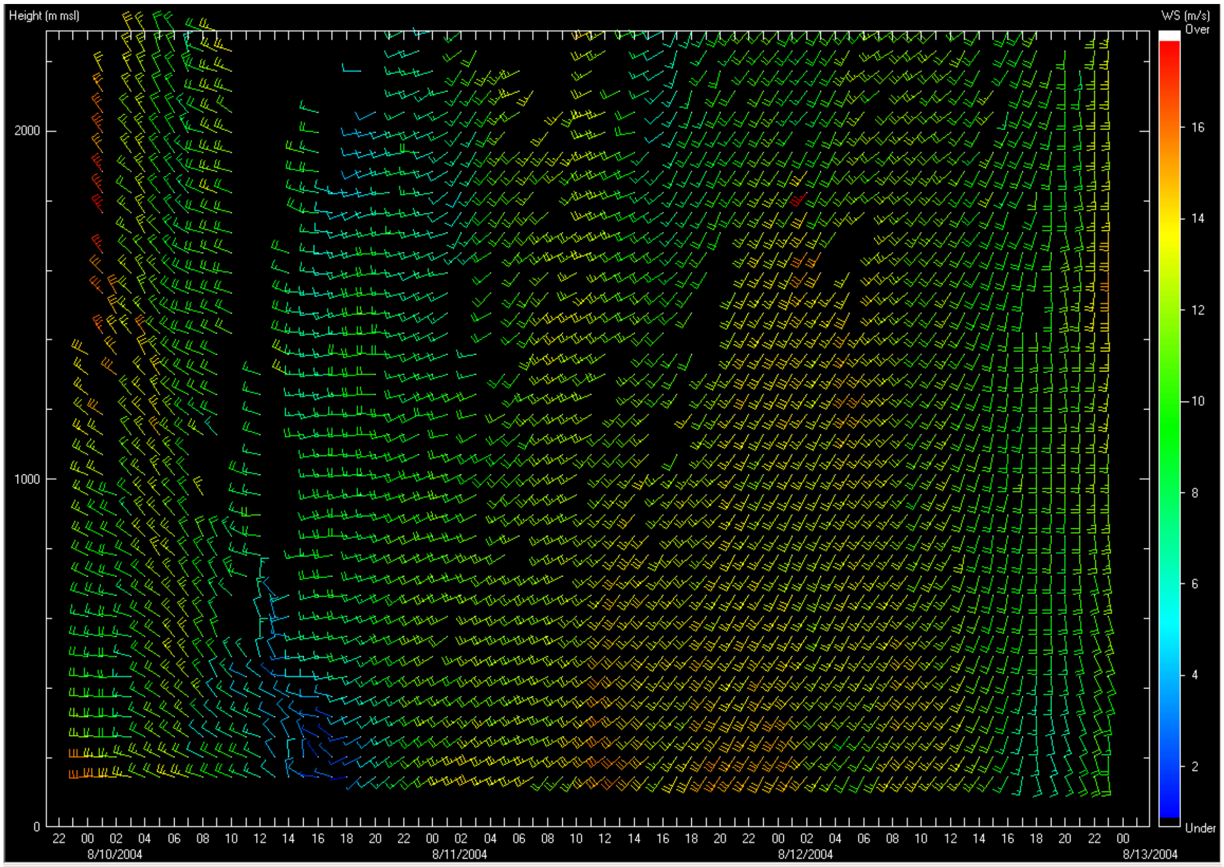


Figure 6. Time series of wind profiler data from Chebogue Pt., Nova Scotia (CBE) for the period indicated along the bottom axis. The vertical axes indicate altitude in m above mean sea level (msl). Each full barb represents a wind speed increment of 5 m s^{-1}. Wind speed is also color coded to the vertical scale on the right. Trough axis passage is shown by a shift from westerly to northwesterly flow near 0300 UTC on August 10. Ridge axis passage is shown by a rotation to westerly flow near 1500 UTC and a rapid shift to southwesterly flow near 1800 UTC on August 10. The overall transition from northwesterly flow to southwesterly flow occurs between 1200 UTC August 10 and 0000 UTC August 11, the times at which updated upper-air wind observations are available from the rawinsonde network.

Figure 7 compares back trajectories computed using the NOAA/ESRL wind profiler trajectory tool and the NOAA/ARL HYSPLIT trajectory model ending at 1500 UTC on August 10. For this comparison and the comparison that follows, the HYSPLIT model was run in its isobaric mode to allow for a more direct comparison with the constant altitude wind profiler trajectories. The input data for the HYSPLIT model was the 40 km resolution gridded data from the Eta Data Assimilation System (EDAS). The discrete altitudes of the three HYSPLIT trajectories match roughly the middle of the altitude ranges used for the upper three profiler-based trajectories. The two methods agree remarkably well at this time, only three hours after the wind field had been updated with rawinsonde data. Eight hours later, after the synoptic pattern had changed significantly, the agreement is not as good (Fig. 8). The back trajectories based on the hourly wind profiler data have shifted well to the south of the model-based trajectories. The HYSPLIT model trajectories have not had the benefit of an additional sounding, so the orientation of these trajectories has not changed substantially from their 1500 UTC orientation.

During NEAQS-04, the University of California at Berkeley ran an aerosol sampler at the Chebogue Pt. observing station with the goal of collecting aerosol data for certain marker compounds that could be used to characterize the source of the aerosol. A factor analysis was carried out on the aerosol time series to determine

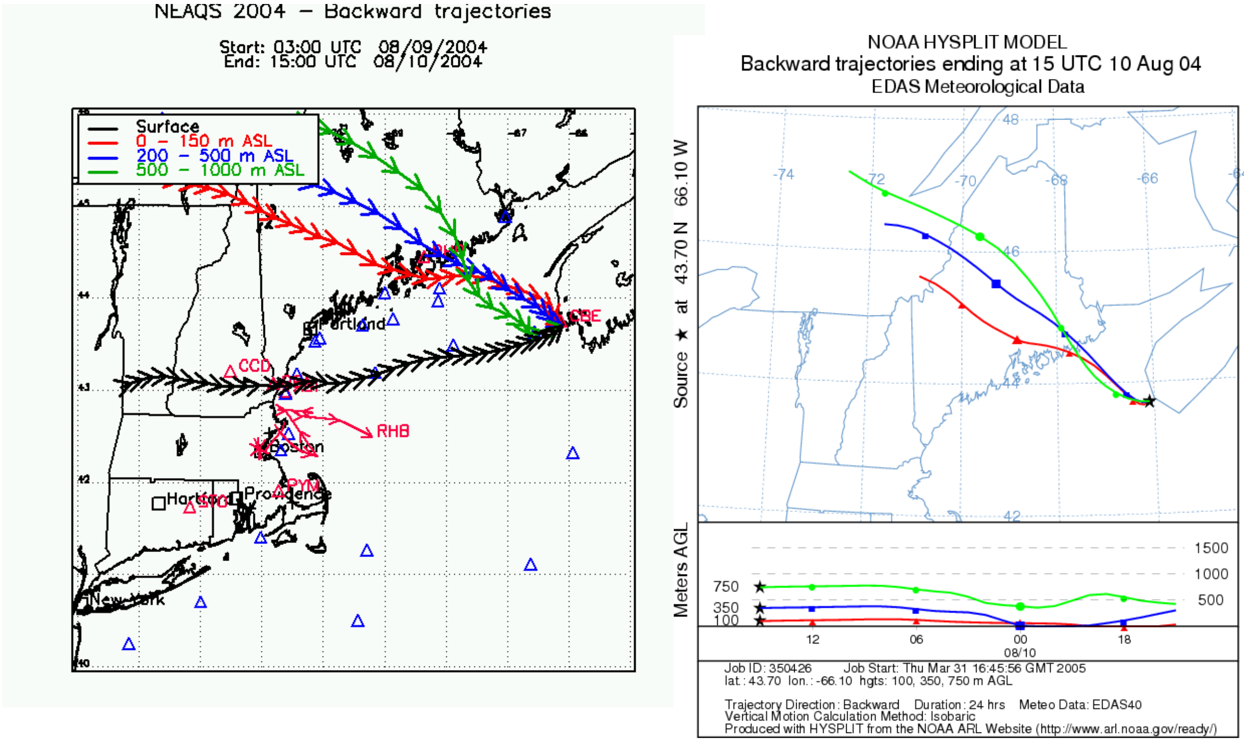


Figure 7. 36-hour back trajectories ending at 1500 UTC on August 10, 2004. The right panel shows the results from the NOAA/ARL HYSPLIT model. The left panel shows the results from the NOAA/ESRL wind profiler trajectory tool.

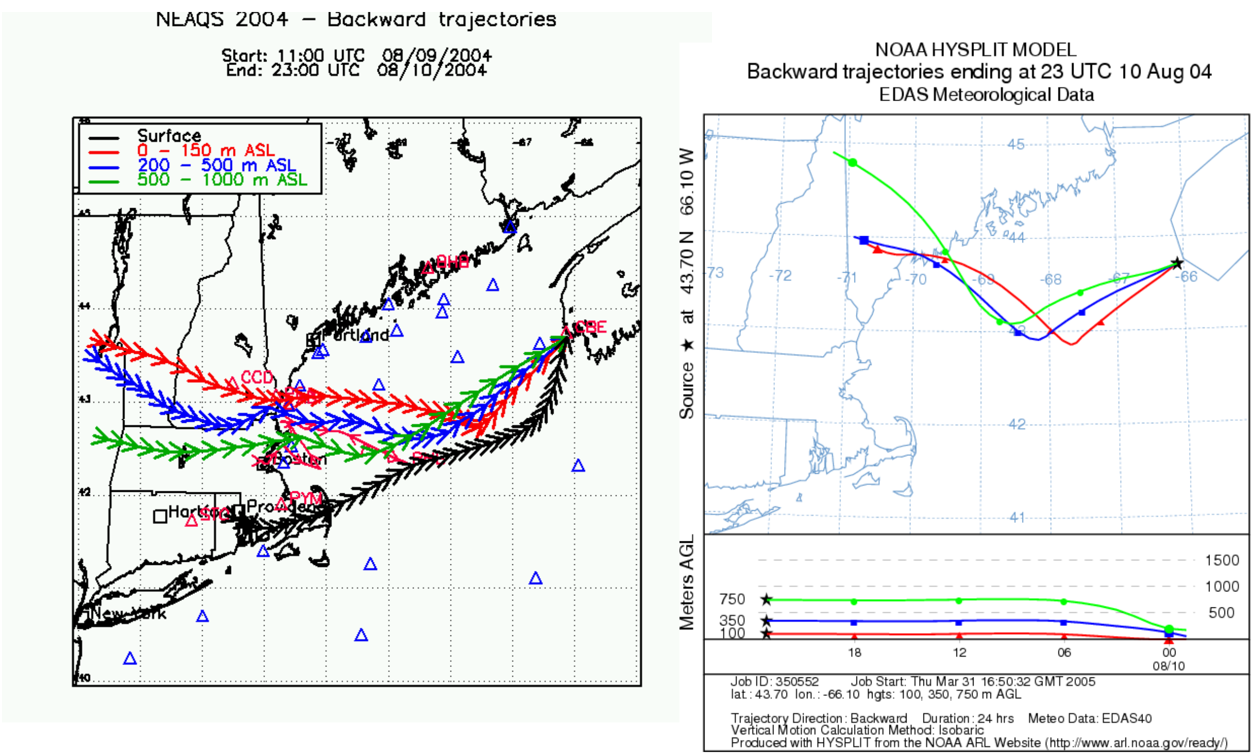


Figure 8. As in Fig. 7, except ending at 2300 UTC on August 10.

which compounds were likely to exist in a sample at the same time. One of the factors was attributed to pollution sources in the U.S. and consisted of a high concentration of organic aerosol and $S0_4$, indicating a contribution from coal-fired power plant plumes. This was the only factor that included sulfate, and it peaked in intensity at its highest value for the field study (not shown; Williams et al. 2005) at the same time as the endpoint of the back trajectories shown in Fig. 8. It is unlikely that a pollution plume with high $S0_4$ content originated in northern New England, as indicated by the HYSPLIT trajectories, because there are only a few small coal-fired power plants located there. It is more likely that the pollution originated further south, as indicated by the profiler-based trajectories, where a higher concentration of large coal-fired power plants exists (see Fig. 9).

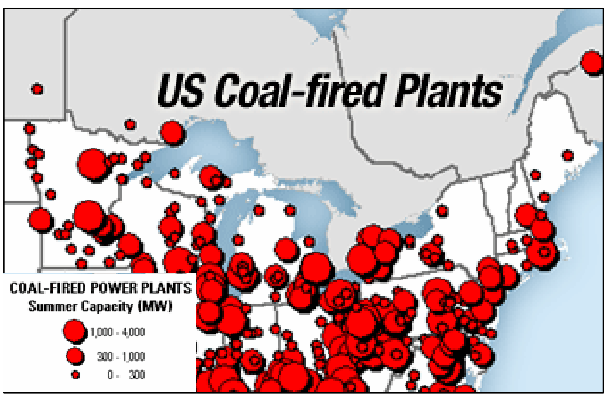


Figure 9. The distribution of coal-fired power plants in the United States as of 2004. The size of the circles marking the locations of the plants indicates the summer generating capacity in Megawatts (MW). Reprinted with permission from Platts, a division of McGraw-Hill Companies, Inc.

5. SUMMARY AND DISCUSSION

Particle trajectory models are useful for investigating atmospheric pollutant transport. However, as demonstrated by the case study presented, the winds in the lower troposphere that transport pollutants regionally are not measured with sufficient temporal resolution to capture important changes associated with mesoscale and synoptic weather. NOAA/ESRL has developed a wind profiler trajectory tool that is purely observationally based. The web-based application can be used in post-analysis mode for the New England Air Quality Studies in 2002 and 2004 and in real time, beginning in 2005, for the Texas Air Quality Study. The wind fields for this tool are derived primarily from networks of wind profilers that provide continuous, hourly, height-resolved observations of wind speed and direction. Over the Gulf of Maine and the Gulf of Mexico, surface trajectories can be computed using surface observations from NOAA and cooperative agency buoy and shoreline stations.

The backbone of the nation's operational, all-weather, upper-air wind observing system is still the rawinsonde, which provides wind profiles throughout the atmospheric column at 12-hour intervals. Unfortunately, the dense profiler networks that provide continuous winds for documenting regional transport are generally only available in specialized research field campaigns, and there is still work that needs to be done to improve real-time instrument performance, especially with regard to removing interfering signals that lead to erroneous wind measurements (e.g., radio frequency interference, ground clutter, migrating birds). Once these problems are solved, it is our hope that the observing gap for atmospheric transport will be addressed in future upgrades to the nation's upper-air observing system.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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