1.11 THE INFLUENCE OF METEOROLOGICAL PHENOMENA ON MIDWEST $PM_{2.5}$ CONCENTRATIONS: A CASE STUDY ANALYSIS

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1. INTRODUCTION

Fine particulate matter ($PM_{2.5}$) forecasting has become an increasingly important part of air quality public outreach programs designed to inform the public about air quality conditions, protect public health, and encourage the public to reduce activities that contribute to air pollution. Starting in January 2003, current- and next-day forecasts for $PM_{2.5}$ were issued for cities throughout the United States, including a number of cities in the Midwest: Columbus, Cleveland, and Cincinnati, Ohio; Chicago, Illinois; and Detroit, Michigan. Through daily forecasts, it became clear that certain atmospheric phenomena and their impact on $PM_{2.5}$ concentrations needed more analysis to better understand the atmospheric mechanics that influence $PM_{2.5}$ episodes in the Midwest. As a result, a case study of meteorological and air quality conditions was performed for the period of September 9 through September 15, 2003.

The improved understanding gained from this case study provides forecasters with information to more accurately predict $PM_{2.5}$ concentrations during similar episodes occurring in the future. This case study also demonstrates the complexity of the processes that influence $PM_{2.5}$ concentrations, which tend to make accurate $PM_{2.5}$ forecasting more difficult compared to ozone.

1.1 Overview of the Episode

From September 9 through 15, 2003, $PM_{2.5}$ levels were high throughout the midwestern United States. During the episode, widespread $PM_{2.5}$ levels reaching Moderate on the Air Quality Index (AQI) occurred, and several cities reached the Unhealthy for Sensitive Groups level (as high as 77 µg/m^3). In addition to the presence of high $PM_{2.5}$ concentrations, this episode was marked by complex atmospheric conditions that made it difficult for forecasters to predict such concentrations. At various times during the episode, a number of atmospheric phenomena impacted regional air quality and are investigated in this case study, including

1. Development and motion of weather features including planetary-scale waves, synoptic-scale waves, frontal boundaries, and surface low-pressure centers (Section 2).
2. Surface weather features including surface-wind stagnation, a stalled frontal boundary, and surface cyclogenesis (Section 3).
3. Interactions among the behaviors of $PM_{2.5}$ concentrations before, during, and after a frontal passage (Section 4).

2. PLANETARY-SCALE WEATHER

Planetary-scale weather features strongly influence regional and local weather. Figure 1 shows the 500-mb height pattern on September 10, 2003 and illustrates the planetary-scale weather features important to the Midwest $PM_{2.5}$ episode. The figure shows two high-amplitude troughs and a high-amplitude ridge (HAR) in place over North America and the North Atlantic. The high-amplitude ridge also had an upper-level low-pressure trough to its south (signified by a trough in the 590-dm height contour south of the ridge). This pattern, called a rex block, persisted for several days because the upper-level flow split the high-low couplet.

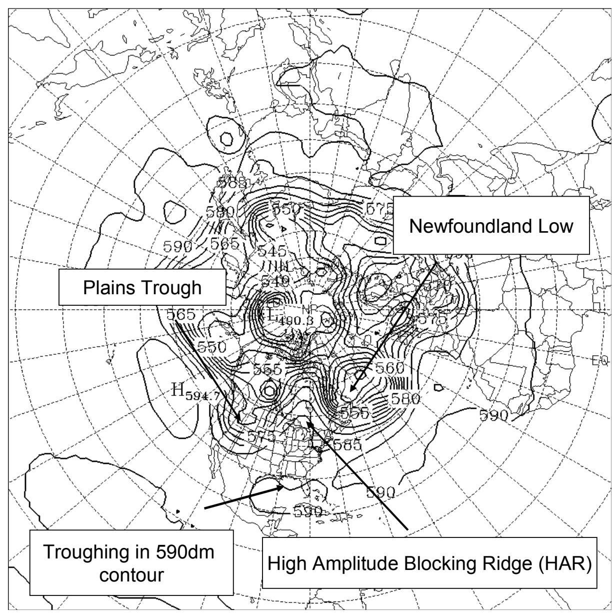

Figure 1. 500-mb geopotential height analysis for the northern hemisphere at 0600 CST on September 10, 2003.

In addition, the high-amplitude trough over Newfoundland and Southern Greenland (Newfoundland Low) helped maintain the position of the upper-level ridge over the Midwest by blocking the easterly progression of the ridge. The high-amplitude trough over the western Great Plains (Plains trough) was eventually responsible for the end of this event. Although its movement was initially blocked by the high amplitude ridge during the first part of the episode, once the ridge began to move east, the motion of the Plains trough was strongly affected by smaller-scale atmospheric waves (short waves) traveling along the longer wave pattern.

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In addition to planetary-scale features, daily weather and local $PM_{2.5}$ concentrations were influenced by smaller-scale weather features, including short-wave troughs and ridges and their associated dynamics (e.g., vorticity advection and rising motion). These features influenced $PM_{2.5}$ concentrations by controlling the formation of the surface cyclone and frontal movement.

To understand the interaction between upper-level features and surface weather features, weather patterns were examined in chronological order. A surface-pressure analysis and 500-mb height fields are presented for each day of the episode. Each surface and upper-level feature is marked so that they may be tracked throughout the event. The position of short-wave troughs and ridges were ascertained using 500-mb absolute vorticity. The axis of each wave is designated by a letter on the 500-mb height field. An example of the charts used to determine short-wave positions is shown in Figure 2. Short-wave troughs can be seen as areas of increased absolute vorticity and enhanced curvature in the 500-mb height lines; the axis of one of the short-wave troughs in this event is marked by the black line.

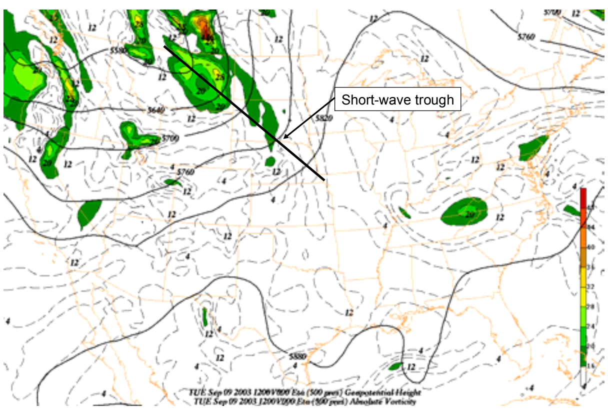

Figure 2. Example of 500-mb geopotential height field (dm) and absolute vorticity (s-1) used to determine short-wave trough and ridge position. Analysis for 0600 CST September 9, 2003. Green to red shading indicates regions of increasing positive vorticity.

2.1 September 9-10, 2003—Atmospheric Blocking and Surface Stagnation

The driving atmospheric force over the Midwest during the first two days of this case study was the high amplitude ridge depicted in Figure 1. Figures 3(a) and 3(b) show that the ridge (marked HAR) remained centered over the Midwest on September 9-10. This caused reduced vertical mixing and strong surface-temperature inversions throughout the Midwest. In addition, Figures 3(c) and 3(d) show the associated surface high-pressure center (marked SH) located in the Midwest. This surface high resulted in light winds and surface stagnation throughout the Midwest. Although the surface high moved toward the northeast on September 10, shown in Figure 3(d), its influence remained strong in the Midwest both days. The persistence of the surface and aloft high pressure during this period was a result of the high-amplitude pattern and blocking effect of the Newfoundland Low that was illustrated in Figure 1.

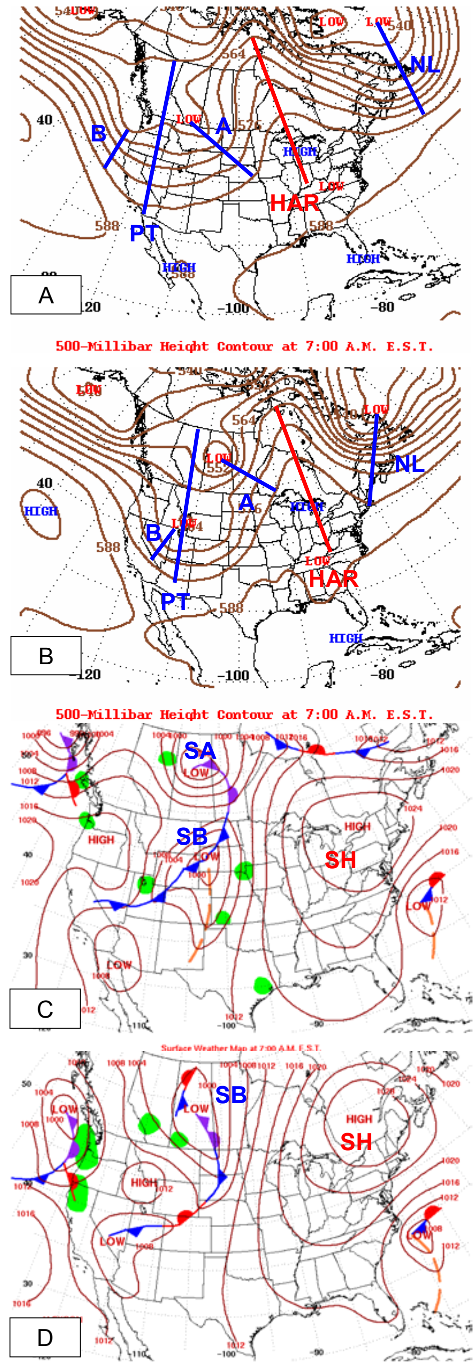

Figure 3. 500-mb and surface weather maps: (a) 500-mb geopotential height for September 9; (b) 500-mb geopotential height for September 10; (c) surface pressure analysis for September 9; and (d) surface pressure analysis for September 10. Location of ridges (red) and troughs (blue) are shown on the 500-mb maps.

2.2 September 11-12, 2003—Pattern Progression

On September 11, the Plains long-wave trough began to move eastward. The eastward movement of the trough can be seen by comparing the position of the trough's axis (PT) on September 10 in Figure 3(b), and on September 11 in Figure 4(b). However, by midday on September 11, the Plains trough was blocked by the high amplitude ridge over the eastern Midwest. In addition to upper-level blocking, the high-amplitude ridge also effectively blocked the surface cyclone and frontal boundary that was moving in conjunction with the Plains trough. This surface blocking can be seen in Figure 4(c). As the front (FA) and surface cyclone (SB) encountered the persistent surface high (SH) associated with the high-amplitude ridge, the surface cyclone began to dissipate and the front slowed.

On September 12, the Newfoundland Low (NL) (Figure 1) shifted east, allowing the high-amplitude ridge that was resident over the Midwest to progress over the Northeast as seen by the motion of its axis (HAR) from September 12 in Figure 4(a) to September 13 in Figure 4(b). This marked a change in the overall pattern. At this point, atmospheric blocking became less important to the progression of the upper-level pattern, and short-wave/long-wave interactions within the Plains trough became more significant. In addition to a change in the upper-level pattern, the surface pattern changed significantly on September 12. The position of an upper-level short-wave trough (B) in Figure 4(b) resulted in surface cyclogenesis in central Manitoba. A new low-pressure center (SC) developed in that region behind the existing frontal boundary shown in Figure 4(d). The developing surface low (SC) produced warm air advection and southerly flow throughout the central Midwest, which became an important factor in the position of the frontal boundary (FA) the following day.

2.3 September 13, 2003—The Frontal Stall

With the high amplitude-blocking ridge progressing eastward and the frontal boundary (FA) in western Wisconsin the previous day, conditions on September 13 seemed to suggest that the front (FA) would move through the Midwest during the day. However, by the end of the day, the front had hardly moved and the central Midwest remained under southerly winds. Figure 4(b) shows a short-wave ridge (R) moving through the Plains trough over the border between North and South Dakota and a short-wave trough over the northern Rockies (C) at 0600 CST on September 12. Figure 5(a) shows that, by 0600 CST on September 13, the short-wave ridge forced the geopotential height gradient over the Midwest toward the Northwest. In addition, the development of a cut-off low-pressure system at 500 mb (D) shown in Figure 5(a) helped push the Plains trough farther northwest. As a result, the best upper-level support for surface cyclogenesis was located over central Manitoba. This resulted in intensification of the surface low-pressure center (SC) shown in Figure 5(c). The intensification of the surface low caused warm-air advection throughout the central Midwest. This caused the frontal boundary (FA) to move northwest and join a new frontal boundary (FB) that moved in from the Great Plains to form a single frontal boundary (FAB) by 0600 CST on September 13. In fact, surface winds changed from northerly to southerly in Duluth and Minneapolis on September 13 as the front (FA) retrogressed and merged into a single front (FAB).

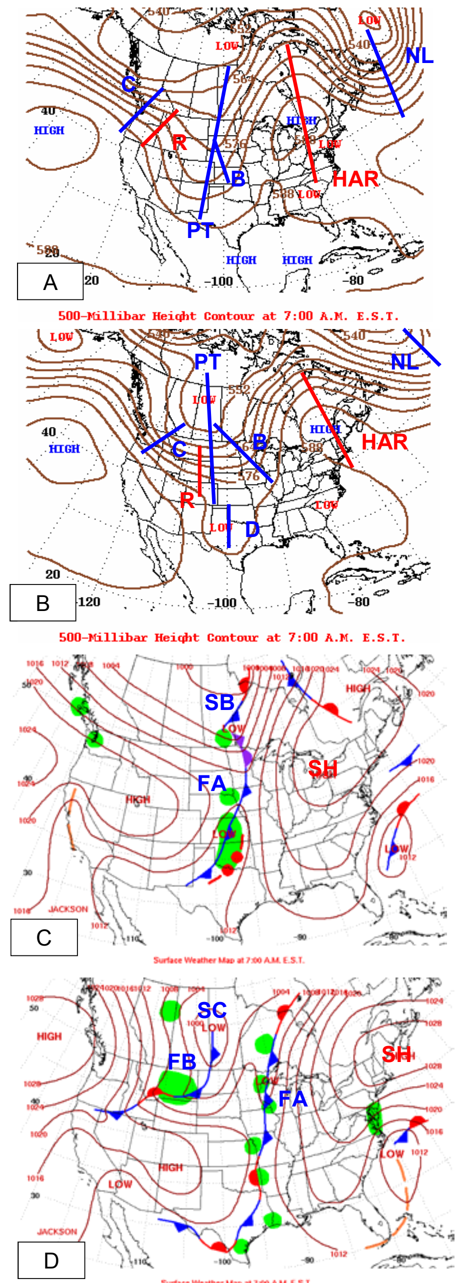

Figure 4. 500-mb and surface weather maps: (a) 500-mb geopotential height for September 11; (b) 500-mb geopotential height for September 12; (c) surface pressure analysis for September 11; and (d) surface pressure analysis for September 12. Location of ridges (red) and troughs (blue) are shown on the 500-mb maps.

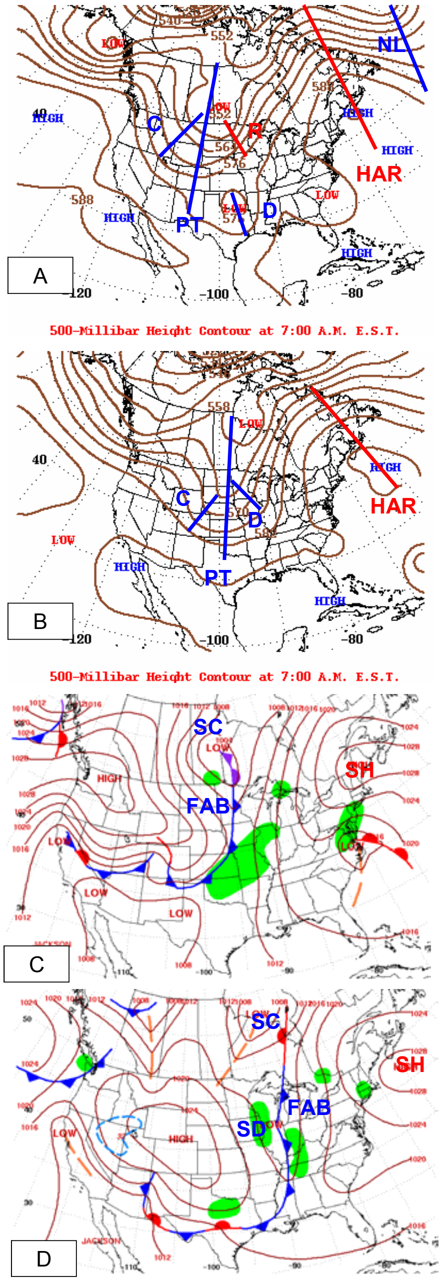

Figure 5. 500-mb and surface weather maps: (a) 500-mb geopotential height for September 13; (b) 500-mb geopotential height for September 14; (c) surface pressure analysis for September 13; and (d) surface pressure analysis for September 14. Location of ridges (red) and troughs (blue) are shown on the 500-mb maps.

2.4 September 14, 2003—Short-wave Intensification

Figure 5(b) shows that, by 0600 CST on September 14, the Plains trough (PT) had intensified over the western Midwest as the short-wave trough (C), over the Rockies the previous day, moved into the Midwest. As the Plains trough intensified, it also drew the cut-off low (D) that was resident over the Mississippi Delta into the large-scale flow, further intensifying the Plains trough (PT). As the Plains trough intensified, it resulted in enhanced upper-level dynamics (vorticity advection and vertical motion) over the central Midwest and western Quebec. This caused the surface low-pressure center located over central Manitoba (SC) to move northeast, finally dragging the cold front (FAB) through the central Midwest. In addition, an area of enhanced upper-level forcing that resulted from the cut-off low (D) moved over northern Illinois during the morning of September 14, intensifying a surface low-pressure center (SD) in northern Illinois that further strengthened the frontal boundary (FAB).

2.5 September 15, 2003—Final Clean-Out Day

By September 15, the high-amplitude ridge from the beginning of the event moved offshore. The axis (HAR) can be seen over Newfoundland and the northern Atlantic in Figure 6(a). This allowed the newly intensified trough (a combination of the original high amplitude Plains trough, the cut-off low [D], and another short-wave trough [C]) to progress unencumbered across the Midwest on September 15. The progression of the upper-level dynamics associated with the trough quickly drove the surface cyclone (SD) and frontal boundary (FAB) across the Midwest, resulting in an airmass change for the entire region. Figure 6(b) shows that, as of 0600 CST on September 15, the surface front (FAB) had moved through all but the extreme eastern Midwest.

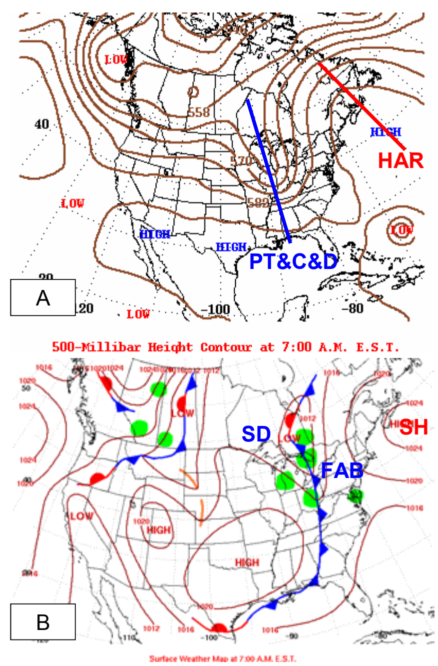

Figure 6. 500-mb and surface weather maps: (a) 500-mb geopotential height for September 15; and (b) surface pressure analysis for September 15. Location of ridges (red) and troughs (blue) are shown on the 500-mb maps.

This episode illustrates complex meteorology. Predicting this type of pattern is aided by diagnosing

1. the planetary wave pattern—whether it is progressive or blocking and if there are blocking patterns;
2. areas with favorable dynamics for surface cyclone intensification, including vorticity advection and enhanced vertical motion; and
3. frontal motion by examining surface cyclogenesis and its influence on frontal development.

3. REGIONAL WEATHER AND $PM_{2.5}$ CONCENTRATIONS

Planetary weather patterns influence regional weather, which has a large impact on $PM_{2.5}$ concentrations. The three important regional-scale weather phenomena that influenced this episode include

1. stagnation associated with the high-amplitude ridge and surface high pressure;
2. regional transport associated with southerly winds east of the stalled frontal boundary; and
3. a decrease in $PM_{2.5}$ concentrations associated with the frontal passage.

3.1 Surface Stagnation

On September 9 and 10, regional $PM_{2.5}$ concentrations increased throughout the Midwest because of surface stagnation and reduced vertical motion caused by the high-amplitude ridge centered over the Midwest. $PM_{2.5}$ concentrations began to increase in the stagnant regional airmass shown in Figure 7.

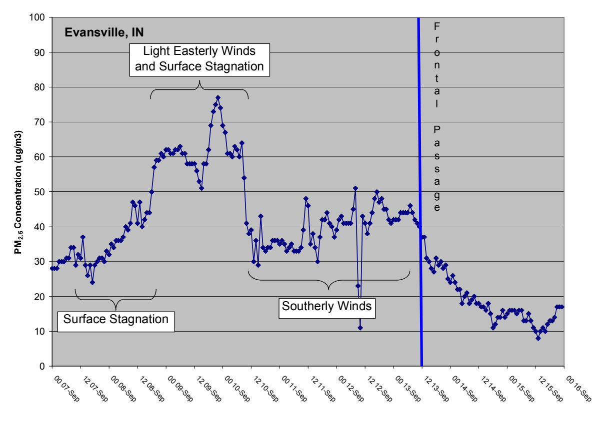

Figure 7. Hourly $PM_{2.5}$ measurements for Evansville, Indiana, September 7-15. Timing of the frontal passage is marked by a blue line and wind directions are indicated when relevant.

3.2 Frontal Stalling and Transport

After the initial regional buildup of $PM_{2.5}$, the most prominent feature on a regional scale was the motion and impact of the first cold front (FA). During the early part of the episode, the surface front progressed into the northwestern Midwest. Figure 4(c) shows the front (FA) that moved through most of Minnesota by the morning of September 11. The front was well-defined on surface weather maps as it moved though Minneapolis and Duluth, Minnesota, on September 11. Figures 8 and 9 show a new airmass ushered in by the front, causing an abrupt decrease in the $PM_{2.5}$ concentrations in both cities.

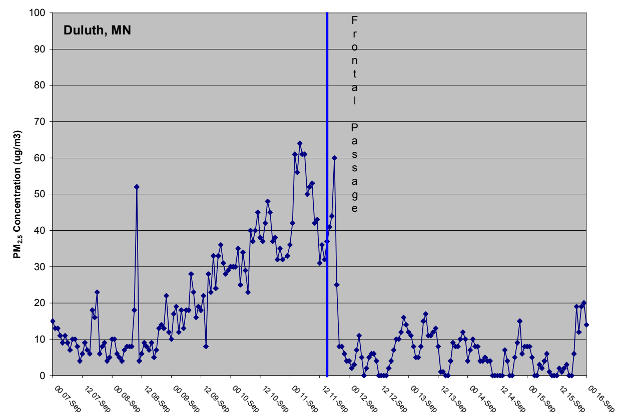

Figure 8. Average hourly $PM_{2.5}$ measurements for Duluth, Minnesota, from September 7 to September 16. The timing of the frontal passage is marked by a blue line.

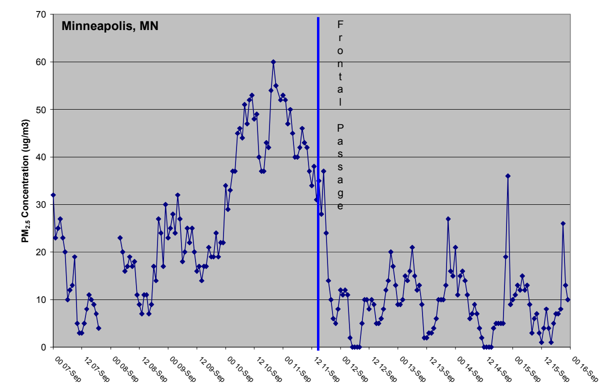

Figure 9. Average hourly $PM_{2.5}$ measurements for Minneapolis, Minnesota, from September 7 to 16. The timing of the frontal passage is marked by a blue line.

After the front (FA) passed through Minnesota, it began to stall. Figure 10 shows regional $PM_{2.5}$ concentrations that indicate the stalled front continued to separate into two vastly different airmasses.

By September 13, the cold front (FA) became diffuse as the second cold front (FB) associated with the developing surface cyclone (SC) moved into the area. The building surface cyclone (SC) caused winds in the central Midwest to shift direction from southeasterly to southerly. Figure 11 shows the wind shift indicated by the change in direction of the backward trajectories for Chicago for September 11 and 13. The impact of this wind shift on Chicago's $PM_{2.5}$ concentrations is depicted in Figure 12, with the $PM_{2.5}$ concentrations falling after the winds shifted southerly. Although $PM_{2.5}$ concentrations did not fall into the Good category, the wind shift seemed to mark the introduction of a different airmass (transport) into the Chicago region. A similar reduction in $PM_{2.5}$ concentrations, shown in Figure 7, occurred at Evansville, Indiana on September 10, when winds in that area shifted from easterly to southerly, illustrated in Figure 13.

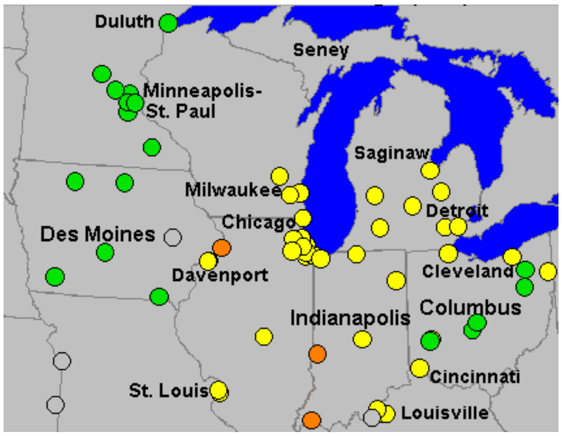

Figure 10. $PM_{2.5}$ 24-hr peak concentrations and the position of the surface cold front at 0600 CST on September 12. Colors are determined by the $PM_{2.5}$ category of the 24-hr peak $PM_{2.5}$ concentration based on the AQI. Green is Good AQI, yellow is Moderate AQI, and light orange is Unhealthy for Sensitive Groups.

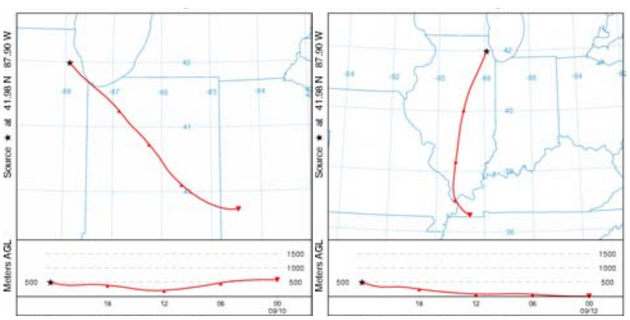

Figure 11. 24-hr backward trajectory ending in Chicago, Illinois at 0600 CST on September 11 and 13. Trajectories were calculated by the HYSPLIT model using Eta Data Assimilation System (EDAS) data and represent an air parcel starting at 500 m agl.

3.3 Frontal Passage

The biggest change in $PM_{2.5}$ concentrations occurred when the cold front (FAB) passed through the Midwest on September 14. A large decrease in $PM_{2.5}$ concentrations occurred in conjunction with the frontal passage at all locations throughout the region. A few examples of this reduction can be seen in Figures 12, 14, and 15. The first and second frontal boundaries (FA and FB) separated two airmasses that had different levels of $PM_{2.5}$ concentrations. As a result, the progression of the front (FAB) through each area marked a change in airmass and subsequent reduction in $PM_{2.5}$ concentration. Diagnosing and accurately predicting the timing of the front's motion is key to issuing accurate $PM_{2.5}$ forecasts.

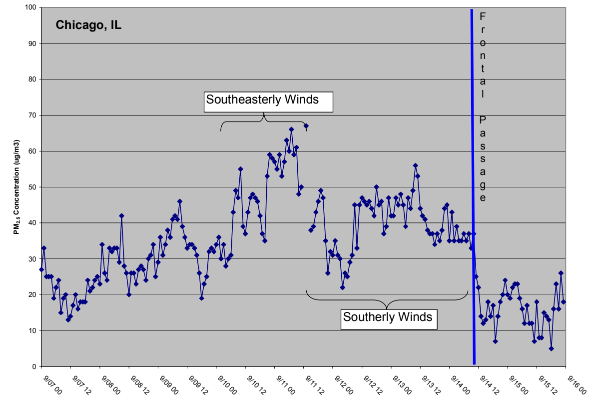

Figure 12. Average hourly $PM_{2.5}$ measurements for Chicago, September 7 to 16. Timing of the frontal passage is marked by a blue line, and wind directions are indicated when relevant.

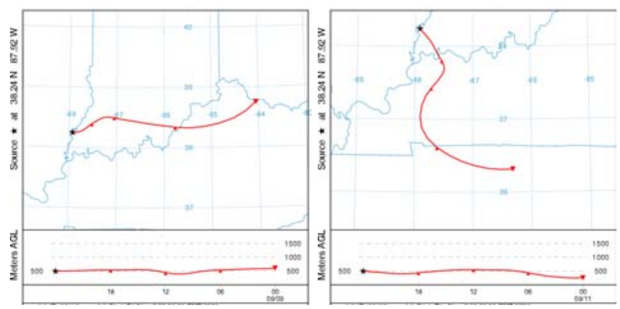

Figure 13. 24-hr backward trajectory ending in Evansville, Indiana, at 0600 CST on September 10 and 12. Trajectories were calculated by the HYSPLIT model using EDAS data and represent an air parcel starting at 500-m agl.

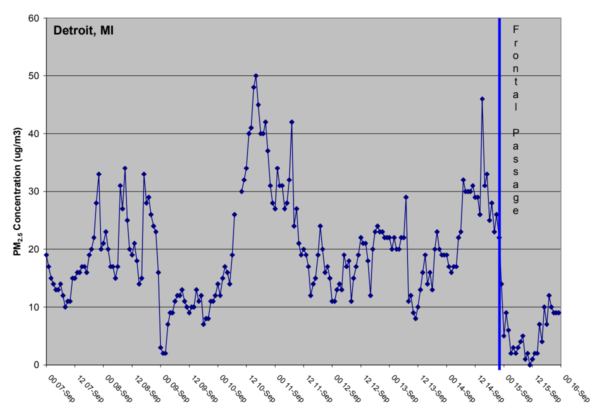

Figure 14. Average hourly $PM_{2.5}$ measurements for Detroit, Michigan, from September 7 to 16. The timing of the frontal passage is marked by a blue line.

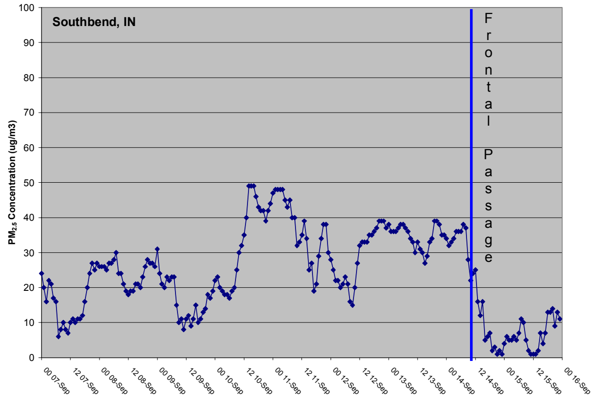

Figure 15. Average hourly $PM_{2.5}$ measurements for South Bend, Indiana, from September 7 to 16. The timing of the frontal passage is marked by a blue line.

4. LOCAL $PM_{2.5}$ CHARACTERISTICS NEAR FRONTS

Fronts have a significant effect on $PM_{2.5}$ concentrations; thus, it is important to understand fine-scale changes in $PM_{2.5}$ that occur within the frontal zone. To understand how $PM_{2.5}$ changes before, during, and after the front, hourly $PM_{2.5}$ measurements were plotted relative to the frontal passage for 11 states. Figure 16 shows that $PM_{2.5}$ concentrations fell concurrently with frontal passage, consistent with the change in airmass. The tendency for $PM_{2.5}$ concentrations to fall a few hours before the front moved through each area suggests that a pre-frontal mechanism that reduced $PM_{2.5}$ concentrations was an influence separate from the airmass change.

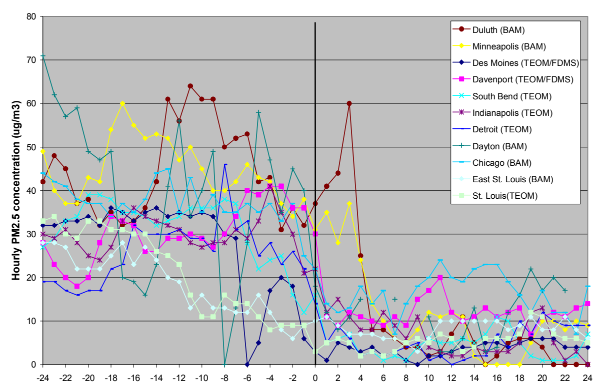

Figure 16. Front-relative $PM_{2.5}$ hourly concentrations for 11 Midwestern cities for 24 hours preceding and following the frontal passage. The types of instruments are identified; BAMs and TEOMs are present in the graph.

To examine the pre-frontal reduction in $PM_{2.5}$ concentrations, pre-frontal surface meteorological data in northern Indiana (South Bend) were analyzed, but phenomena that caused $PM_{2.5}$ concentrations to decrease could not be identified.

Figure 16 indicates that a large reduction in $PM_{2.5}$ concentrations occurred between six and eight hours pre-frontal in Des Moines, Iowa, and Dayton, Ohio. This large reduction did not occur in the other cities. The surface meteorological observations were analyzed for both cities. In both cases, when pre-frontal $PM_{2.5}$ concentrations were lowest (six hours pre-frontal in Des Moines and eight hours pre-frontal in Dayton), moderate to heavy precipitation was observed. This pre-frontal precipitation and enhanced vertical motion helped reduce the $PM_{2.5}$ concentrations during the periods of precipitation.

Figure 16 shows that $PM_{2.5}$ concentrations at two sites in Minnesota did not rapidly decrease after the front passed, as they did in the other cities. At both sites, $PM_{2.5}$ concentrations actually increased during the hour after the front passed through. An examination of monitoring types found in the Midwest indicated that Minnesota is one of the few states in the region that uses beta-attenuation monitors (BAMs) for measuring $PM_{2.5}$ concentrations. To investigate this issue, two other regional BAMs and tapered oscillating element monitors (TEOMs) that were situated outside Minnesota were examined to identify whether the observation may have been related to the type of instrument. Figure 17 shows monitors located in Dayton, Chicago, South Bend, and Indianapolis. None of the monitors in this comparison exhibited the same lag in data values near the time of frontal passage, suggesting a probable systematic cause (time stamp or instrument setting). In addition, we found no meteorological cause for such a lag in Minnesota. In general, the data suggest little difference in the reporting by the two monitor types as it relates to frontal passage.

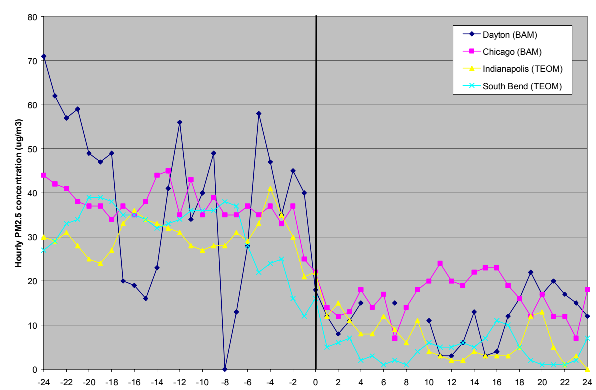

Figure 17. Front-relative $PM_{2.5}$ hourly concentrations for Dayton, Ohio; Chicago, Illinois; and Indianapolis and South Bend, Indiana, for the 24 hours preceding and following the frontal passage.

3. CONCLUSIONS

The analyses described in Sections 2 through 4 of this case study lead to several conclusions and applications for the air quality and meteorological community.

Section 2, an overview of synoptic weather during the case study episode, suggests the following conclusions:

1. Large-scale atmospheric features including atmospheric blocking should be analyzed to accurately forecast the timing of regional weather features that influence local weather and air quality.
2. Upper-level dynamics have a strong influence on the development and motion of surface weather features; in order to accurately forecast surface features, the progression of upper-level dynamics should be evaluated.
3. Surface cyclogenesis can cause large variations in frontal motion; in order to analyze and accurately predict surface frontal motion, surface cyclogenesis should be taken into account.

Section 3, the relationship of regional weather and $PM_{2.5}$ concentrations, suggests the following conclusions:

1. Accurate evaluation of frontal passage is the most critical factor in an accurate forecast of $PM_{2.5}$ due to the significant impact that the change of airmass associated with a frontal passage has on $PM_{2.5}$ concentrations.
2. Frontal stagnation can cause regional $PM_{2.5}$ concentrations to remain high for extended periods, and reduction of $PM_{2.5}$ concentrations is largely dependent on the progression of the frontal boundary.
3. Regional stagnation associated with surface and aloft high pressure tends to produce the best conditions for regional build-up of $PM_{2.5}$ concentrations as well as provide conditions that favor the highest $PM_{2.5}$ concentrations during an event.

Section 4, $PM_{2.5}$ characteristics near fronts, suggests the following conclusions:

1. Rapid reduction in $PM_{2.5}$ concentrations occurs during or a few hours before frontal passage.
2. There is little difference in the manner in which BAMs and TEOMs react to the passage of a frontal boundary.

4. ACKNOWLEDGMENTS

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