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Modeling Dispersion from Chemicals Released after a Train Collision in Graniteville, South Carolina

by

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ABSTRACT

The Savannah River National Laboratory's (SRNL) Weather INformation and Display (WIND) System was used to provide meteorological and atmospheric modeling/consequence assessment support to state and local agencies following the collision of two Norfolk Southern freight trains on the morning of January 6, 2005. This collision resulted in the release of several toxic chemicals to the environment, including chlorine. The dense and highly toxic cloud of chlorine gas that formed in the vicinity of the accident was responsible for nine fatalities, and caused injuries to more than five hundred others. Transport model results depicting the forecast path of the ongoing release were made available to emergency managers in the county's Unified Command Center shortly after SRNL received a request for assistance. Support continued over the ensuing two days of the active response. The SRNL also provided weather briefings and transport/consequence assessment model results to responders from South Carolina Department of Health and Environmental Control (SCDHEC), the Savannah River Site's (SRS) Emergency Operations Center (EOC), Department of Energy Headquarters, and hazmat teams dispatched from the SRS.

Although model-generated forecast winds used in consequence assessments conducted during the incident were provided at 2-km horizontal grid spacing during the accident response, a high-resolution Regional Atmospheric Modeling System (RAMS, version 4.3.0) simulation was later performed to examine potential influences of local topography on plume migration. The detailed RAMS simulation was used to determine meteorology using multiple grids with an innermost grid spacing of 125 meters. Results from the two simulations are shown to generally agree with meteorological observations at the time; consequently, local topography did not significantly affect wind in the area. Use of a dense gas dispersion model to simulate localized plume behavior using the higher resolution winds indicated agreement with fatalities in the immediate area and visible damage to vegetation.

INTRODUCTION

The Savannah River Site (SRS) is an 800 km^2 (310 mile^2) nuclear facility owned by the U.S. Department of Energy and operated by the Washington Savannah River Company. SRS is located in western South Carolina, approximately 20 kilometers south of Aiken, bordered on the west by the Savannah River (Figure 1). Established in 1950, SRS produced radionuclides in support of the Nation's defense. Activities related to nuclear and chemical processing operations conducted over the years have required meteorological support.

The meteorological program at SRS is operated by the Atmospheric Technologies Group (ATG) of the Savannah River National Laboratory (SRNL), and supports site operations, emergency response, employee and public health and safety, environmental compliance programs, facility design engineering, future SRS missions, and work for other federal government agencies. The meteorological program includes a comprehensive tower-based atmospheric measurement program[1] or mesonet, a fully equipped weather forecast center, which provides access to local and world-wide weather data, advanced atmospheric modeling capabilities that provide operational numerical weather forecasts and atmospheric consequence assessments for emergency response and nonproliferation. Local meteorological data and consequence assessment support is also provided to several local county emergency management agencies through a mutual aid agreement. The focus of this paper is on the response to an atmospheric chemical release in the nearby town of Graniteville.

The town of Graniteville is located in west-central South Carolina a few kilometers (km) west of Aiken, SC and approximately 20 km north of the SRS and the SRNL. On January 6, 2005 at approximately 2:40 a.m., a moving Norfolk Southern freight train collided with a parked freight train on an industrial rail spur in Graniteville, South Carolina, resulting in the rupture of rail cars transporting liquefied chlorine and other industrial chemicals. The subsequent rapid discharge of up to 70 tons of chlorine quickly produced a dense airborne cloud of toxic gas and aerosols that spread throughout property occupied by a textile mill and into adjacent areas of Graniteville, resulting in the deaths of nine individuals, mainly mill workers, and injuries to more than 500 others[2]. The threat of a rupture to additional tankers of chlorine that were damaged in the accident resulted in closure of businesses and the relocation of more than 5000 residents for up to nine days, as crews worked to dispose of the remaining inventories. Hundreds of emergency workers from local volunteer fire departments, Aiken County sheriff and emergency management offices, the SRS, and state and Federal agencies responded to the event. This paper discusses the emergency response and advanced modeling components of the SRNL meteorological support in support of this train accident.

BACKGROUND

The SRNL's Weather INformation and Display (WIND) System[3] provides a comprehensive, automated resource for conducting consequence assessment modeling during emergency response. The WIND System accesses a variety of real-time sources of local, national, and international meteorological information. Meteorological data collected from the local tower network (mesonet) operated by SRNL are available in real-time. A continuous satellite-based feed from a private sector service is used to obtain regional, national, and international data from the National Weather Service (NWS) and other government agencies.

The backbone of the WIND System is a cluster of UNIX workstations located in a well-maintained onsite computer facility that gather local and regional data from the mesonet and satellite feed, and archives these data in a relational database. Meteorological observations are extracted from the database every 15 minutes and downloaded, along with forecast data from operational runs of a prognostic mesoscale model, to desktop computers. A suite of consequence assessment models residing locally on these computers can then be run with a combination of the local observations and forecasts to generate the real-time predictions of plume transport and associated hazards.

In 1996, the SRNL established mutual aid agreements with five counties surrounding the SRS[4], including Aiken County, SC. These agreements delineated three areas of collaboration through which WIND System resources could be leveraged to enhance regional emergency response programs: (1) assistance from SRNL in establishing meteorological monitoring stations in critical areas of need; (2) custom WIND System software for use by county officials in conducting local consequence assessments using observations from the local meteorological mesonet; and (3) providing technical assistance to the county's emergency management team during a real-time response to significant events such as the Graniteville accident.

WIND System Components

Meteorological Measurements. The mesonet of meteorological monitoring stations currently incorporated into WIND System operation is illustrated in Figure 1. Towers located adjacent to each of the SRS's eight major operational areas are instrumented to measure winds, turbulence, temperature, and moisture at an elevation of 61 meters above ground level. A ninth tower located near the center of the SRS collects similar data at four levels through a height of 61 meters. The ATG also operates instrumentation on a television tower facility located near the SRS which provides measurements of wind, temperature, and moisture at three levels: 30, 61, and 304 meters. Every 15 minutes, field observations are transmitted to the UNIX workstation cluster and archived, as noted above. The mutual aid agreements of 1996 led to the installation of an additional four monitoring stations in Augusta, Georgia. Measurements of wind and temperature at these four sites are collected at a single level with heights ranging from 10 to 60 meters above ground. Measurements from the regional mesonet are supplemented by Southeastern U.S. surface observations and upper-air soundings from the NWS..

Meteorological Forecasts. The ATG has configured a prognostic atmospheric model, the Regional Atmospheric Modeling System[5] (RAMS), to generate routine three-dimensional forecasts of meteorological conditions throughout the Central Savannah River Area (CSRA) of Georgia and South Carolina and much of the Southeast United States. Detailed 6-hour forecasts of wind speed, direction, turbulence and other meteorological variables are generated locally every 3 hours for a region encompassing the CSRA with an inner horizontal grid spacing of 2 km; 36-hour forecasts on a regional basis for an area that includes much of Georgia and South Carolina are produced every 12 hours.

For the local simulations used during the train accident, the initial conditions were provided by National Weather Service's Rapid Update Cycle (RUC) model[6]. The modeling of surface conditions requires land-use features such as topography, vegetation type, and soil type. Variable input soil moisture conditions are also used. The model's lowest atmospheric level is at 20 meters above ground. This grid system is designed for emergency response needs at the SRS (centered at 33.256ºN, 81.750ºW), located to the south-southeast of Graniteville by ~30 km (Figure 2). Graniteville is located within the inner domain.

Atmospheric Transport and Consequence Assessment Models. ATG maintains a suite of transport and dispersion models available for assessing consequences of hazardous materials released to the environment. These models are tailored to support a broad range of assessment needs during the early and intermediate phase of response. Two of these models were used during the Graniteville response, while another externally obtained model was used during the post-analysis.

Puff/Plume[7] is a segmented trajectory Gaussian dispersion model that provides an initial, reasonably conservative estimate of potential downwind hazards from a chemical or radiological release. Puff or plume release trajectories are constructed for up to 12 hours of observed and forecast winds with results available in less than a minute. Output can also be exported for use with geographic information system software.

The *Lagrangian Particle Dispersion Model*[8] *(LPDM)* provides highly refined transport and dispersion analyses on local to regional scales. LPDM utilizes a three-dimensional winds forecast by RAMS to account for complex wind patterns due to the effects of terrain or other mesoscale phenomena. Although primarily configured to calculate dose and deposition for radiological releases, LPDM can be used to simulate dispersion of any passive contaminant such as gases.

The *Hazard Prediction and Assessment Capability (HPAC)* is a software package developed by the Defense Threat Reduction Agency[9]. HPAC is actually a suite of models that allows for various modes of release of radiological, chemical and biological agents. HPAC generates interpolated meteorological data fields based on inputted meteorology, and transports the material using a tested transport and diffusion model (SCIPUFF[10, 11]). The primary reason for using HPAC in this scenario is its capability to model dense gas releases. This is particularly important when dealing with chlorine gas. HPAC was not used in this incident during the initial response, but only for the post-analysis phase.

INCIDENT

As previously stated, this unfortunate accident (as detailed in a report by the National Transportation Safety Board[2]) involving two trains in Graniteville, South Carolina during the early morning of January 6, 2005 resulted in nine fatalities. A stationary train sitting on a siding rail (spur) servicing a textile mill was impacted by another train carrying a variety of hazardous chemicals, including liquid chlorine (Cl_2). The switching mechanism was inadvertently set to send trains to the spur, rather than to the main track northward and out of town. The accident occurred at 2:40 a.m. and resulted in the derailment and catastrophic breach to one of several 90-ton cars containing the pressurized liquid Cl_2. Upon contact with the atmosphere, the liquid chlorine vaporized and became an airborne threat to the immediate vicinity. A detailed United States Geographic Survey (USGS) map of Graniteville is shown in Figure 3, while a photograph of the damage at the time of the incident is shown in Figure 4. It is clear that there were a significant number of residences very near to the site of the collision.

Table 1 provides a summary of meteorological conditions observed from the WIND System regional mesonet at the time of the accident. The south to southwest wind that was observed throughout the mesonet and at NWS stations across the region was the result of clockwise flow around a surface high pressure system centered off the southeast United States coast. Several aspects of the meteorological observations at the time of the accident through the remaining pre-dawn hours were believed to be very significant, indicating potential for transport of a significant portion of the Cl_2 release cloud away from the accident scene rather than persistent gravitational settling.

The uniform nature of observed wind direction and speed across all stations in the mesonet suggested that synoptic scale pressure gradients generally were sufficient to overcome possible microscale flows driven by local terrain. Surface wind speeds and turbulence were more pronounced than is often observed in winter during the early morning hours when very stable conditions are likely. In fact, measured values of turbulence intensity suggested an atmospheric stability based on the Pasquill-Gifford (P-G) index that varied between neutral and weakly stable. This provided the SRNL response team greater confidence that the regional wind observations were reasonably representative of conditions in the Graniteville area.

These meteorological conditions are believed to have been sufficient to cause some turbulent mixing and steady erosion of contaminant along the periphery of the dense cloud that formed immediately after the crash and tank rupture, with subsequent passive transport of chlorine gas toward slightly higher terrain and less populated areas to the north-northeast of Graniteville. Visual reports from television broadcasts shortly after dawn support this scenario, indicating that most of the initially compact dense cloud had been flushed from the shallow valley in which Graniteville is located. The turbulent transport and dispersion of this nighttime cloud likely reduced airborne concentrations of Cl_2 over the longer term (minutes to hours) and quite possibly could have reduced the number of casualties resulting from the accident.

Roughly one month after the incident occurred, two of the authors surveyed vegetation damage in the area. Vegetation is known to develop symptoms to exposure to chlorine concentrations of 0.1 to 5 ppm for 2 hours or more[12]. Visible damage to vegetation in the area is noted to have covered an area roughly oriented north-south along the shallow valley. The main vegetative damage occurred with pine trees and juniper bushes[13]. Photographs such as the ones shown in Figure 5 indicate bleaching of the pine trees. The pine tree shown in Figure 5a died shortly after this photograph was taken and has since been removed. Such visual evidence can be used to infer the spatial extent of the plume. In particular, Figure 5b shows that the tops of these pine trees appear not to be impacted by the chlorine plume, while the lower portions are affected. This vertical extent of bleaching suggests that the highest concentrations of Cl_2 only extended a few 10s of meters into the atmosphere.

SUPPORT DURING INCIDENT

Real-Time Support

Consultations with Aiken County Emergency Management Agency (EMA) began around 7:00 a.m. on the morning of January 6. Initially, the most significant challenge for the SRNL response team was the development of a source term that would provide an adequate basis for assessing protective action measures. Aiken County officials reported that the accident resulted in breaches to rail cars containing chlorine, sodium hydroxide, and cresol. The chlorine was recognized as by far the most volatile and significant of the three substances with respect to potential airborne hazards. Hence, all subsequent assessments then focused on the chlorine release. Furthermore, based on reports of injuries and possible fatalities occurring during the pre-dawn hours, the breach of the chlorine tanker was believed to have resulted in a rapid initial discharge of most of the contents, followed by an ongoing residual release. These assumptions were supported by television reports from the scene which showed no significant venting or reductions in visibility. The initial source term was based on a “default” estimate of an ongoing release of 0.454 kg/sec (60 lbs/min) for a chlorine tanker. Although the level of confidence associated with this default value is relatively low, this preliminary source term was believed to be conservative and enabled ATG to begin examining areas of concern for downwind transport based on real-time meteorological data. Such uncertainty in initial source terms is relatively common in such accidents and thoughtful, conservative estimates have to be used.

The first Puff/Plume transport model calculation, shown as Figure 6, was posted to an external web site for access by officials at Aiken County’s Unified Command Center around 8:00 a.m. Results showed that predicted downwind concentrations greater than the Emergency Response Planning Guide Level 2 (ERPG-2) threshold of 3 parts per million (ppm) extended no more than 1.6 km (1 mile) downwind of the accident site. The ERPG levels for chemicals are developed by the American Industrial Hygiene Association[14]. The ERPG-2 values are the consensus standard for implementing measures to protect industrial workers and the public.

Discussions continued through the morning with Aiken County EMA and with representatives from the South Carolina Department of Health and Environmental Control (DHEC) to begin evaluating the accuracy of the initial calculation and refine the assumptions on source term. Unsubstantiated reports by motorists along Interstate 20, approximately 20 km north of the incident, indicated odors had been noted; however, SC-DHEC reported no evidence of detectable levels of chlorine in areas downwind of the immediate incident scene after daylight. This provided the SRNL assessment team increased confidence that the chosen default release rate was reasonably conservative.

By 9:00 a.m., results were available from an LPDM simulation of downwind transport using RAMS forecasts of local winds. The RAMS forecasts for the Graniteville area showed winds that were consistent with the regional observations and indicated persistence of the south-southwest wind throughout the day (Figure 7). NWS and SRNL tower observations of winds during the day verified this RAMS forecast. Animation of LPDM results based on the RAMS forecast showed a corresponding north-northeast transport of the residual chlorine release that remained west of more densely populated areas near the city of Aiken, South Carolina.

The SRNL team continued to provide ongoing support as follows:

- Updates of Puff/Plume consequence assessment model output using current meteorological conditions, posted to the external web site for use by Aiken County and SC-DHEC approximately every 2 hours.
- Briefings for local and state officials on consequence modeling results and forecasts of meteorological conditions expected for the upcoming 12-24 hour period.
- Puff/Plume model results to core staff in the SRS Emergency Operations Center (EOC), DOE Headquarters EOC, and the DOE liaison with the Department of Homeland Security.

By midday on January 7, responders at the incident scene began to plan recovery actions for the ruptured tanker as well as for at least one additional chlorine tanker that had been damaged during the collision. One disposition alternative being considered was to physically lift the damaged tankers from the wreckage and remove them from the scene. Due to concern that such actions could result in an additional catastrophic rupture, Aiken County requested SRNL to estimate possible downwind consequences resulting from the postulated release of the entire contents of the tanker.

Puff/Plume results for this scenario, using meteorological conditions anticipated for that afternoon, showed an area of potentially life threatening effects (greater than the ERPG-3 concentration of 20 ppm) to a distance of 5 km from the crash site and potentially irreversible severe effects (greater than the ERPG-2 concentration of 3 ppm) to a distance of more than 20 km from the site (Figure 8). Furthermore, winds had shifted to a direction that would transport the contaminant more toward the city of Aiken and impact a nearby hospital and other sensitive facilities. ATG also forecasted stable conditions to occur during the following night and such conditions would have led to higher airborne concentrations of Cl_2 in the immediate vicinity over greater periods of time. Model results for this scenario were posted to the external web site and provided to Aiken County as a geographic information system (GIS) layer for display on the Unified Command Center mapping system. These results led to a decision to defer recovery actions involving movement of the damaged tankers. Eventually, teams were able to reach the tanker and siphon the remaining chlorine inventory onto undamaged tankers that were brought to the scene.

Post-Analysis

Since the train collision occurred in a valley and involved a dense gas release to the atmosphere, it was decided to run a much higher resolution RAMS simulation in an attempt to capture the near-surface wind fields very near the crash site. The original two-grid system (Figure 2) was modified to incorporate a third and fourth nested grid at 500 and 125-m horizontal grid spacing, respectively. In addition, the vertical grid spacing was reduced such that the lowest vertical level above ground for the two outer grids was ~ 15 m AGL, while for the inner two grids it was ~7 m AGL (resulting in 14 atmospheric levels below 300 m).

Analyzed RUC data at three-hour intervals beginning at 1:00 p.m., January 5, 2005 was used to create initial and lateral boundary conditions in RAMS. Fine resolution topography (~100 m) from digital elevation maps was used for topography. Figure 9 shows the topographic heights for the 500 and 125-m horizontal grids used in the simulations. The feature of particular interest is the valley where the accident occurred and the steeper terrain located just to the east. The northwestern part of the city of Aiken is located just to the east and southeast of this feature.

There were no meteorological observations taken in the vicinity of the crash site. The closest near-surface measurements were taken at a tower located on the SRS complex, and two National Weather Service (NWS) sites located at Daniel (DNL) and Bush Field (AGS) airports in Augusta, Georgia. Unfortunately, none of these is totally representative of actual wind conditions in the valley at the time of the incident but are valuable for understanding the synoptic flow of the region. Pertinent locations are given in Table 2 and also noted in Figure 2.

The detailed simulation indicated relatively light (< 2 m/sec) surface winds near the crash site and channeling through the valleys of Graniteville at the time of the accident. Wind speeds increased to ~2.5 m/sec by sunrise (7:00 a.m.) and to ~4 m/sec by mid-afternoon (3:00 p.m.). The direction was generally from the SSW or SW during the entire period.

Vertical cross-sections of various meteorological variables (vertical velocity [m/sec], turbulent kinetic energy [m^2/sec^2], potential temperature [K], and relative humidity [%]) over the lowest 600-m of the atmosphere along a west-to-east orientation intersecting the train collision location are shown in Figure 10 for a time of 3:00 a.m. The location of the train accident is indicated by the arrow. Vertical velocities were very light near the crash site with low turbulence levels. Potential temperature profiles indicated a weakly stratified atmosphere and humidity levels were very high (near 100%). For the dense gas behaving chlorine cloud, light wind conditions coupled with slightly downward air motion near the surface would support gravity driven flow.

Surface wind speeds increased by sunrise, and the depth of the boundary layer began to grow (Figure 11). By 11:00 a.m., vertical velocity was simulated to be upward at the crash site, and the boundary layer depth had grown to between 300 and 400 m. The atmospheric moisture content had also begun to drop. This would also support assertions that the cloud had dispersed by this time.

Time-series plots of wind speed and direction were generated for the period 2:30 a.m., 06 January to 7:00 p.m. and interpolated to the observation locations discussed previously. In addition, simulated wind speed and direction as interpolated to the surface level (10 m AGL) in Graniteville at the crash site are also plotted. All simulated values (except Graniteville) were taken from meteorology generated on Grid 2. Comparisons of wind direction and wind speed are given in Figure 12.

At the time of the collision, all three observation sites indicated winds from the SSW to SW, although DNL was closer to 225º, while the other stations were closer to 200º. Directions were generally uniform throughout the period, with veering to 240º by late day (~5:00 p.m.). Simulated values were generally within 20º to 40º of the observations, although early morning values at SRS indicate a southerly component. As expected, simulated values at Graniteville lie within values obtained from all of the measurement sites.

Observed wind speeds (Figure 12b) were all ~ 3 m/sec at the time of the accident, before peaking at ~8 m/sec by late afternoon. The simulated trends follow along these lines, although values between 2:30 and 7:00 a.m. at the airports were < 2 m/sec. Simulated wind speeds at Graniteville steadily rose from 1 m/sec at the time of the crash, to a maximum of 4.5 m/sec by 2:00 p.m., before tailing off later in the afternoon.

HPAC was used to simulate the effects of the dense gas very near the release location. An industrial transport accident was assumed for a tanker containing ~20,000 gallons of liquid chlorine. A major leakage was assumed to occur expelling over 62,000 kg of chlorine gas in both vapor and aerosol phase. This source term is consistent with the NTSB estimate of a release of approximately 70 tons. Dense gas calculations were made within HPAC, and appropriate median lethal (LCt) and incapacitating (ICt) concentration levels as well as ERPG levels were then determined. Figure 13 illustrates the plume footprint one hour after the crash using the 500 meter resolution RAMS winds, with detailed road overlays and the approximate location of deaths that occurred as a result of the accident. Since terrain near the site is actually lower to the southwest of the crash site, the relatively light winds coupled with gravity-driven spreading of the dense gas explains why several deaths occurred southwest of the wreck, even though winds were simulated to be blowing weakly from the southwest toward the northeast at the time of the crash.

The simulations appear to be reasonable in one other way. Also shown in Figure 13 (dark bold line) is an approximate outline of visible damage to vegetation in the area described earlier. The resulting footprint compares favorably with both vegetation damage and the locations of deaths that occurred as a result of the incident.

CONCLUSIONS

The SRNL's WIND System, a real-time consequence assessment resource for emergency response, performed as designed to provide timely support to Aiken County and State of South Carolina officials responding to the Norfolk Southern rail accident in Graniteville, SC. Results were used to reassess the appropriateness of initial protective actions for the surrounding community and to plan incident scene recovery actions. The value of SRNL's support to local emergency managers was noted in subsequent newspaper reports[15].

Furthermore, experience gained from the Graniteville response clearly demonstrates that local/regional consequence assessment assets can play a valuable role during hazardous material incidents of local and even national significance by providing nearly full-time, customized support targeted directly to local decision makers.

Detailed numerical simulations of meteorology during the Graniteville train collision were generated using the mesoscale RAMS model nested with 4 grids of horizontal spacing 8, 2, 0.5, and 0.125 km. The lowest vertical level above ground was 7 m. Simulated fields compare well with nearby observations, with transport for the first day indicating a plume directed between north and northeast.

Interestingly, even though the chlorine cloud was more dense than air, the synoptic winds were strong enough at the time of the accident (~3:00 a.m.), to greatly minimize the gravity driven flow into the upwind, shallow valley. In addition, turbulent mixing was sufficient to cause significant transport of the plume over slightly higher terrain to the north and northeast. Use of a dense gas model to simulate localized effects indicates agreement with fatalities in the immediate area and visible damage to vegetation.

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Table 1. Synopsis of meteorological conditions observed from the SRNL mesonet (between 3:00 and 6:00 a.m., January 6, 2005)

Variable	**Values**
Wind direction (from):	South-southwest
Wind speed (61 m):	3.2 to 4.5 m/sec (7 to 10 mph)
Wind speed (surface)	0.9 to 1.8 m/sec (2 to 4 mph)
Temperature:	11^{o}C to 13^{o}C (52^{o}F to 56^{o}F)
Relative humidity:	92% to 98%
Atmospheric stability (as determined by turbulence intensities):	P-G Class E and D
Cloudiness at AGS:	Partly cloudy

Table 2. Observation information

Observation location	**Latitude (ºN)**	**Longitude (ºW)**	**Elevation (m ASL)**	**Height (m AGL)**	***d***† **(km)**
AGS	33.37	81.97	40	10	26
DNL	33.47	82.03	134	10	24
SRS-Climatology	33.25	81.65	90	18	40
Graniteville	33.56	81.81	68	10	—

†Approximate distance from crash site to observation location.

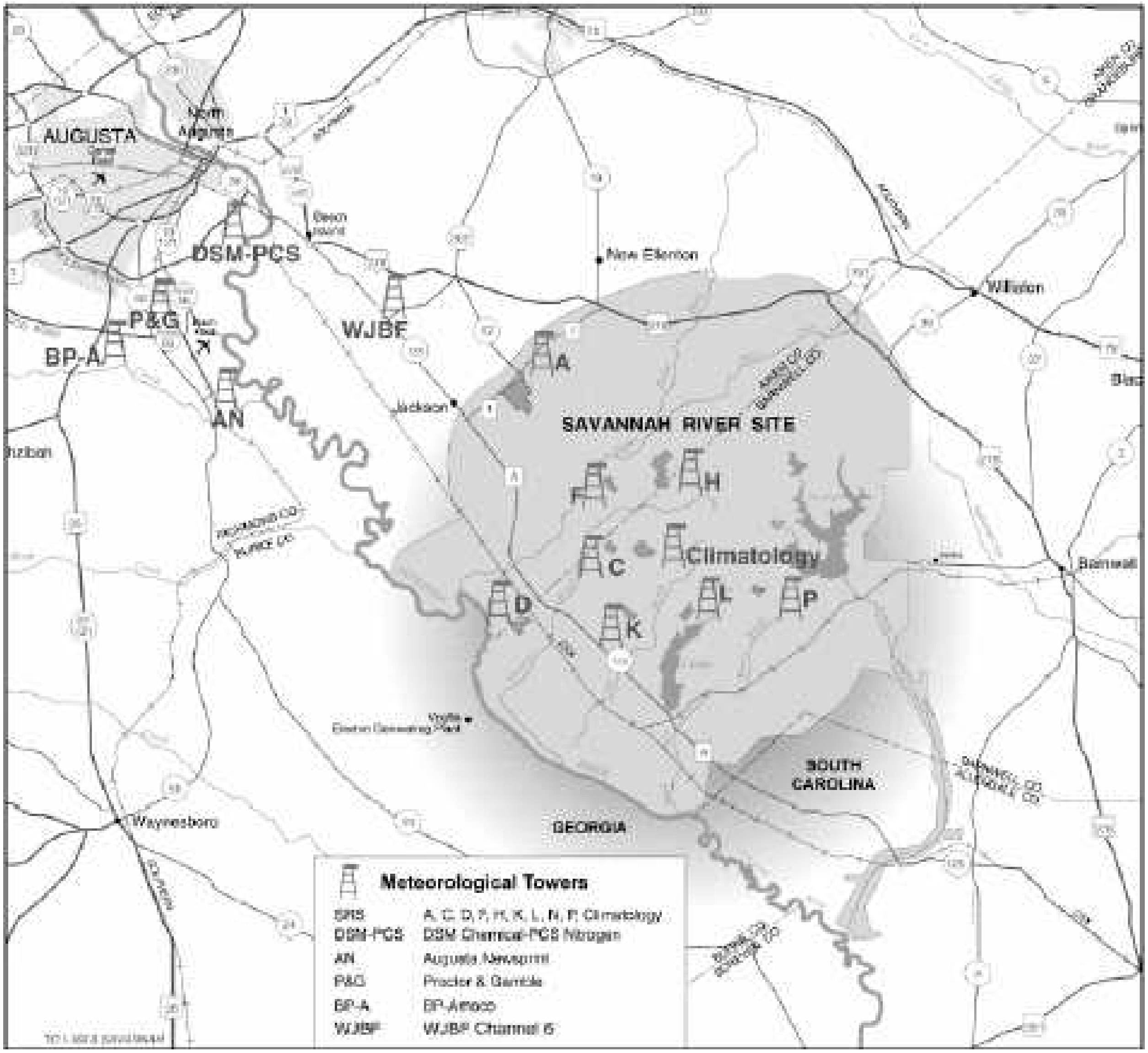


Figure 1: SRS regional monitoring network and surrounding features.

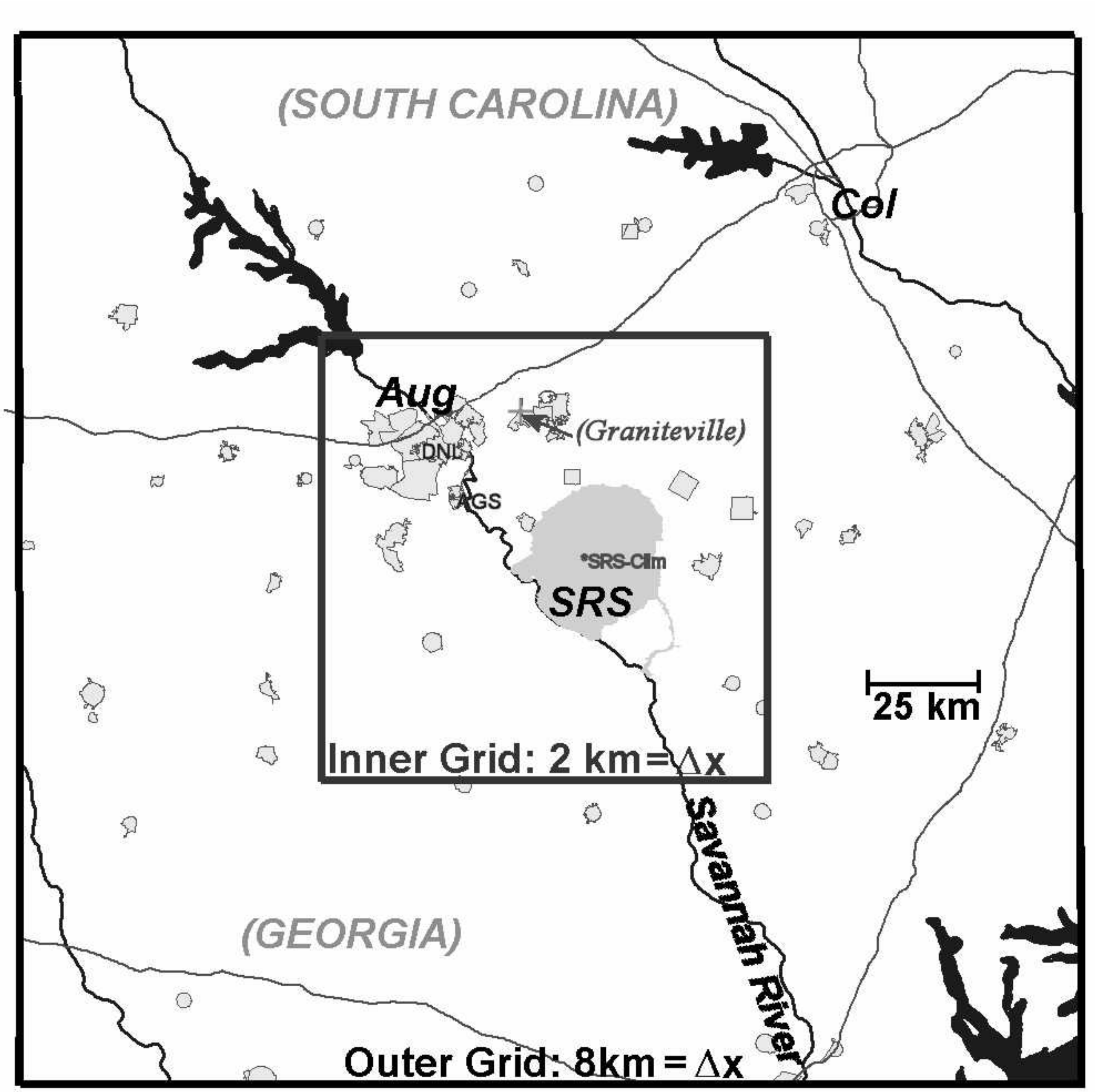


Figure 2: Standard local grid configuration used by the SRNL for generating mesoscale atmospheric conditions. Also shown are nearby cities including Augusta, Georgia (Aug) and Columbia, South Caroline (Col), along with interstate highways (light lines), rivers (dark lines), populated places (shaded areas) and NWS stations.

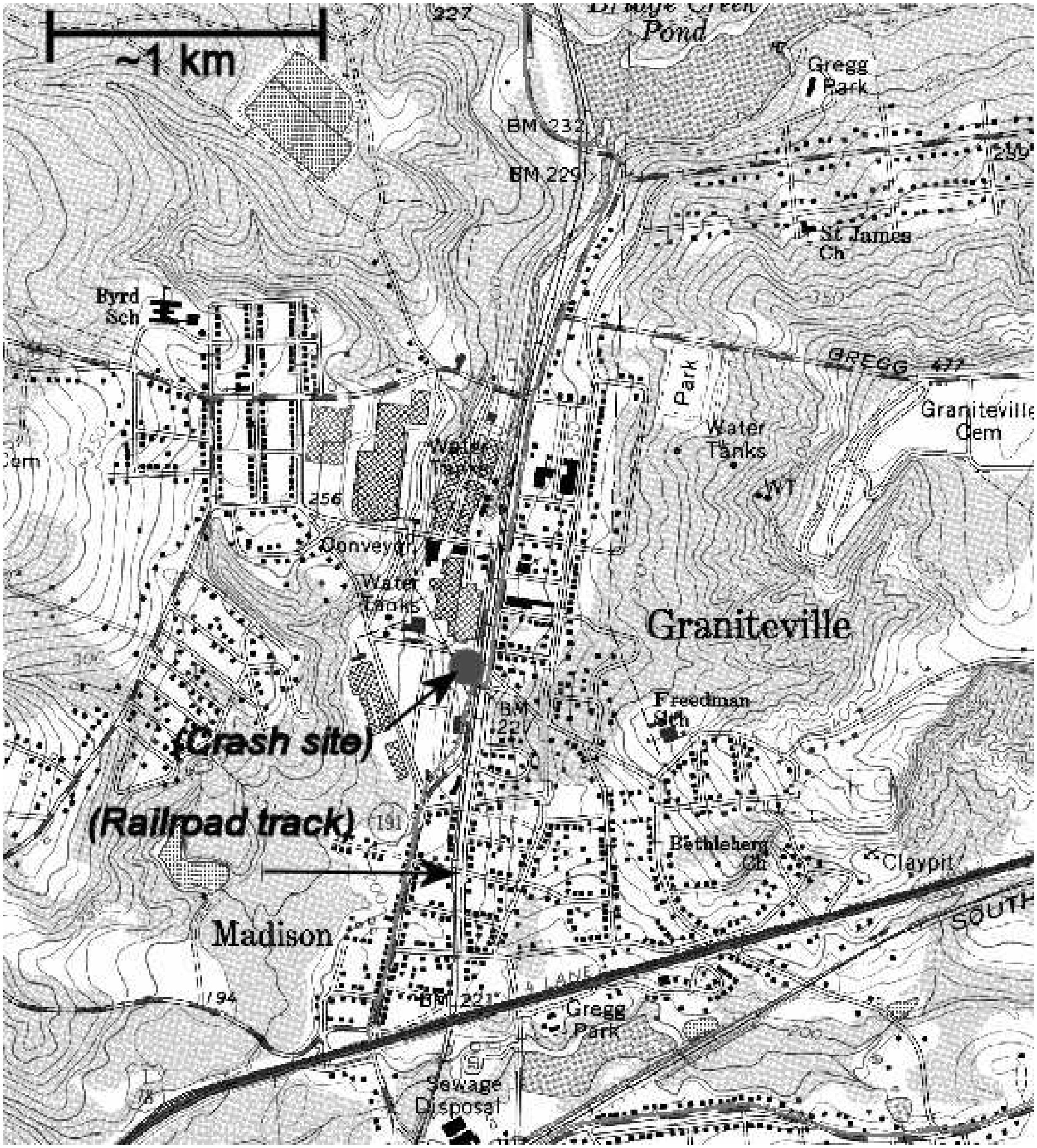


Figure 3: Detailed USGS map of Graniteville, showing the location of the train collision. The thin lines indicate topography relief at 10-foot intervals, while the black dots represent individual residences. Terrain in the immediate crash area is seen to be sloped slightly upward from north to south, with steeper sections at further distances to the east and west forming a broad, shallow valley around the accident site. The moving train was traveling northward at the time of the collision.

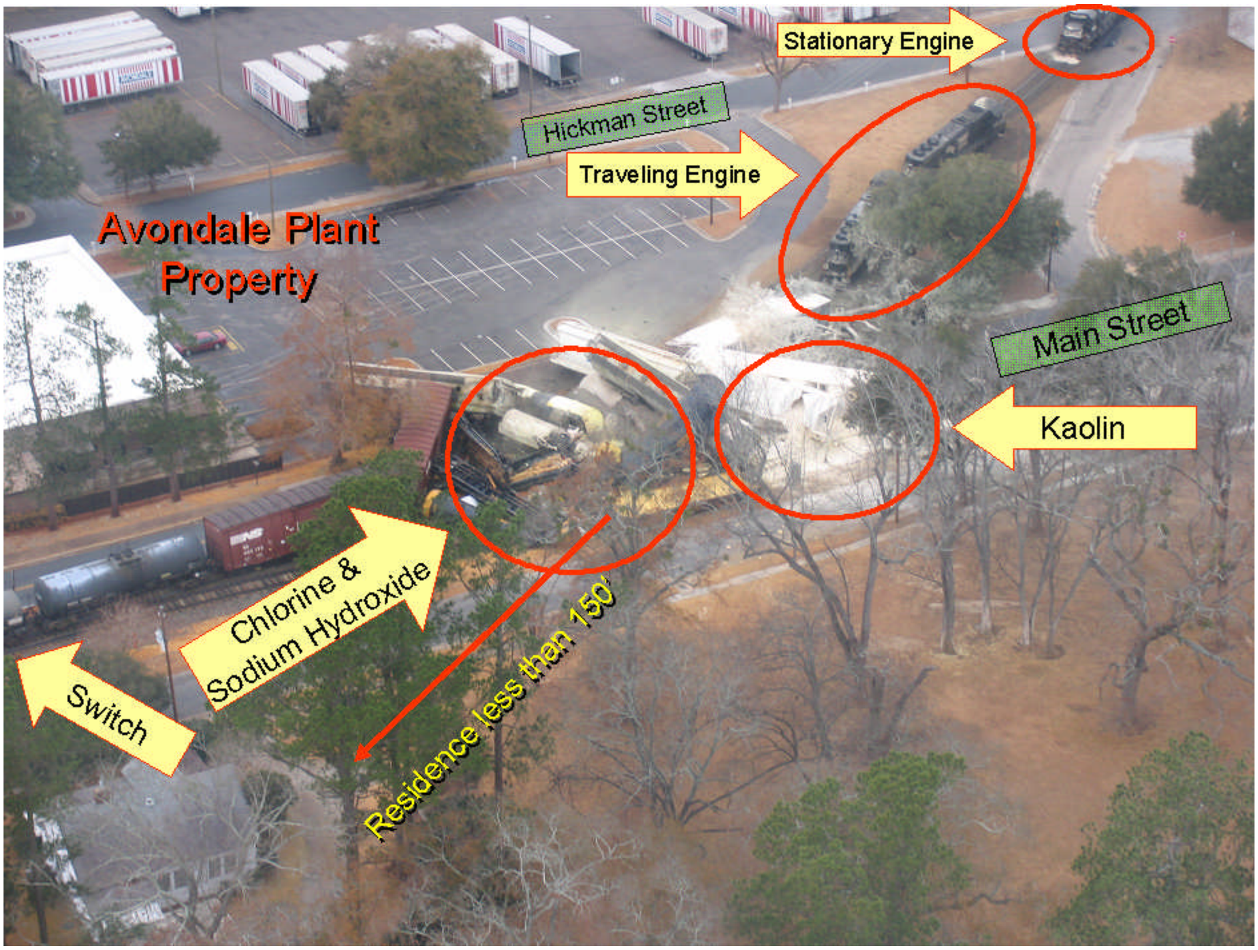


Figure 4: Train collision in Graniteville, South Carolina with details relating to chemicals released and nearby buildings. The picture is oriented such that north is directed to the right (photo courtesy of *Augusta Chronicle*).

(a)

(b)

Figure 5: Photographs of vegetative damage near the crash site. (a) Pine tree located south of the crash site ~30 m. (b) Pine trees located northwest of the crash site ~100 m. Note browning of the pine trees below the very tops which remained green in this photo.

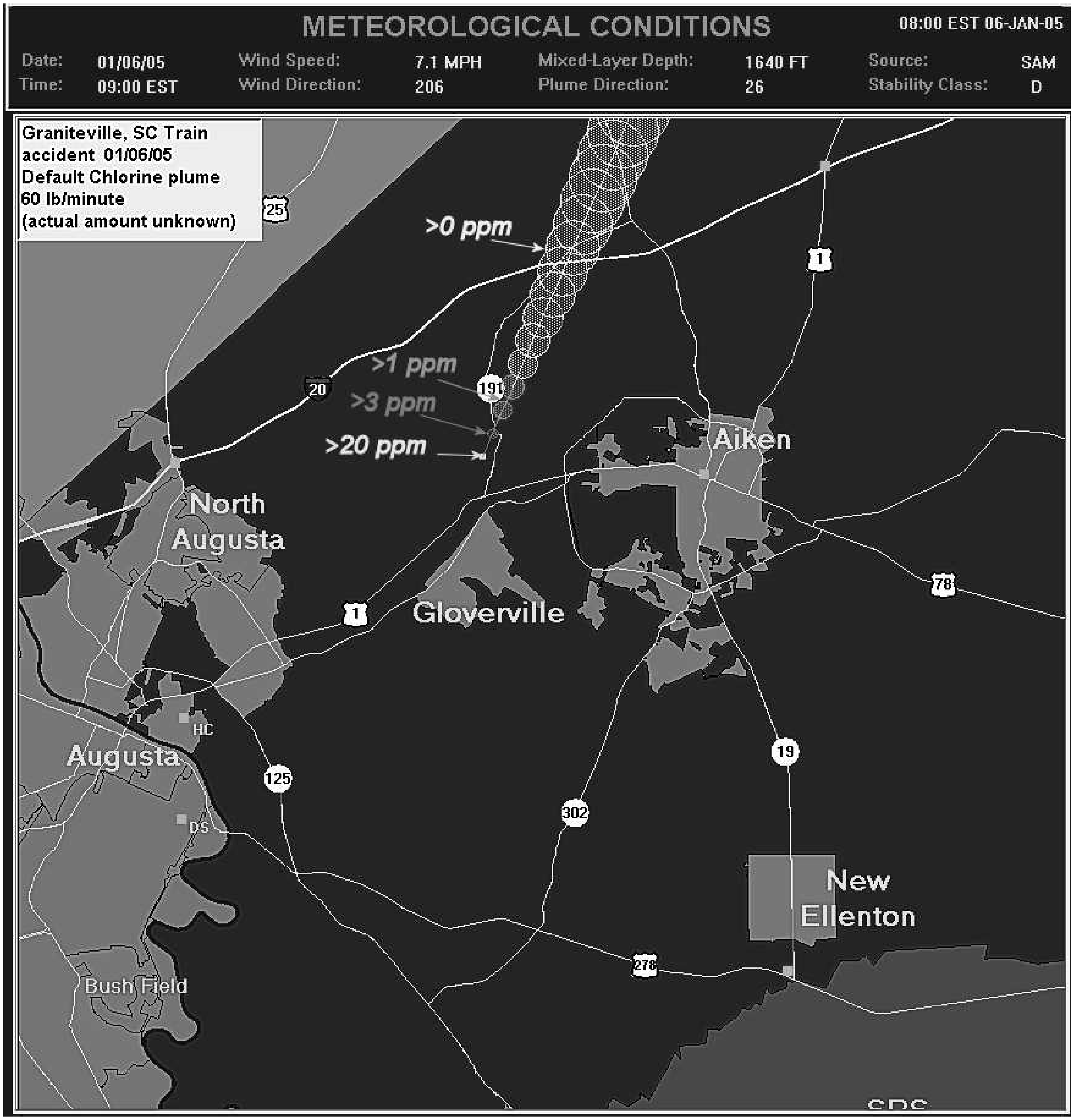


Figure 6: Initial Puff/Plume prediction provided to the Aiken County EMA and South Carolina DHEC for the ongoing residual release of chlorine from the Graniteville site. Values for the different shadings of dose (ERPG levels) are indicated on the figure.

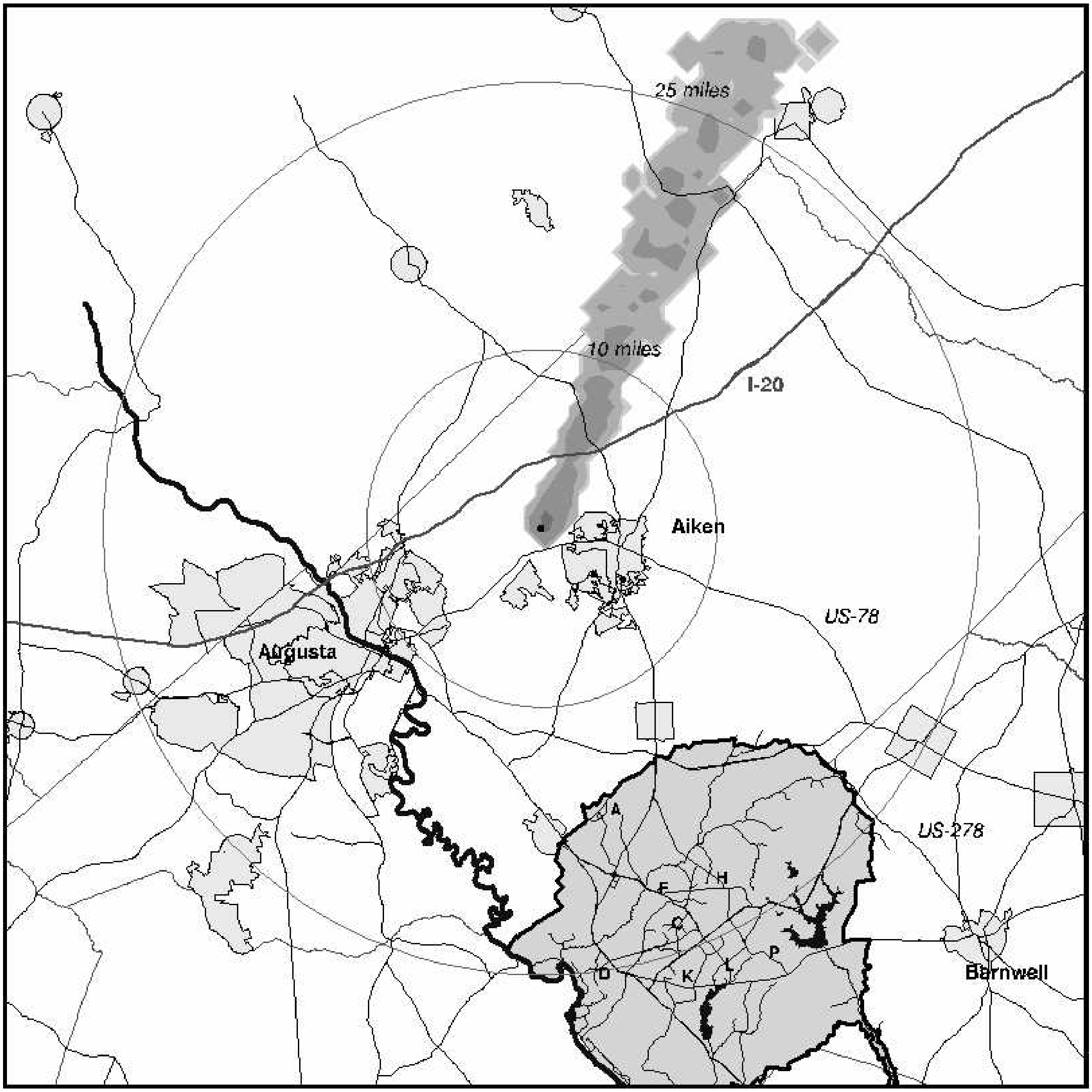


Figure 7: Forecasted concentration field from RAMS using the standard 2-grid simulation domain at 12:00 p.m. where different shading of the plume denotes orders of magnitude change (assuming a continuous unit release).

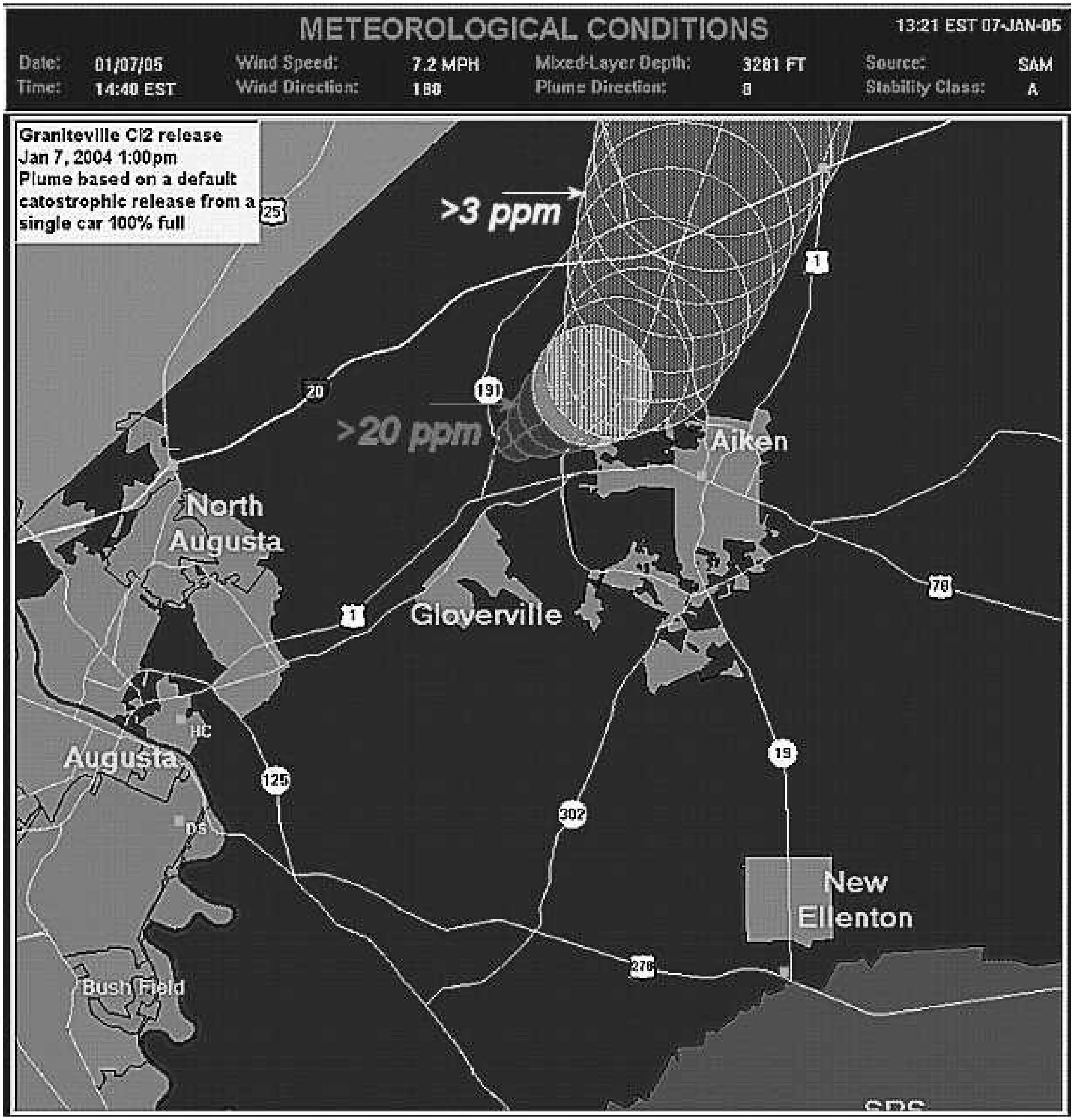


Figure 8: Puff/Plume prediction provided to the Aiken County EMA and South Carolina DHEC for a potential catastrophic rupture of a second tanker on January 7. Values for the different shadings of dose (ERPG levels) are indicated on the figure.

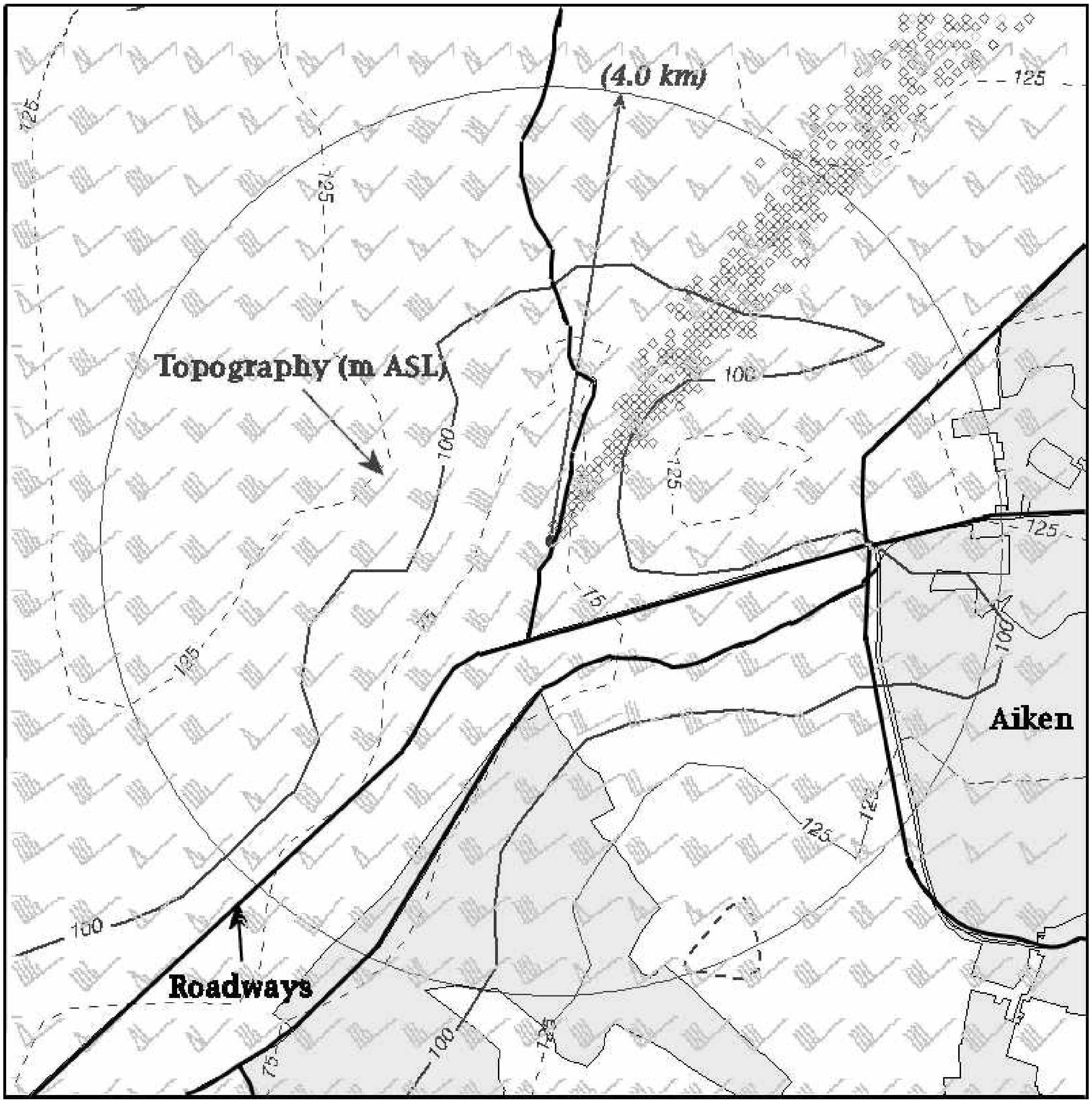


Figure 9: Post-accident assessment showing a detailed view of the Graniteville crash site (indicated by the large dot in the center of the picture) with topographic contours indicated, as well as nearby roads (bold lines) and population centers. Smaller dots indicate a simulated plume transported from the crash site at 3:00 p.m., while wind barbs are from the 500-m RAMS grid at 7 m AGL.

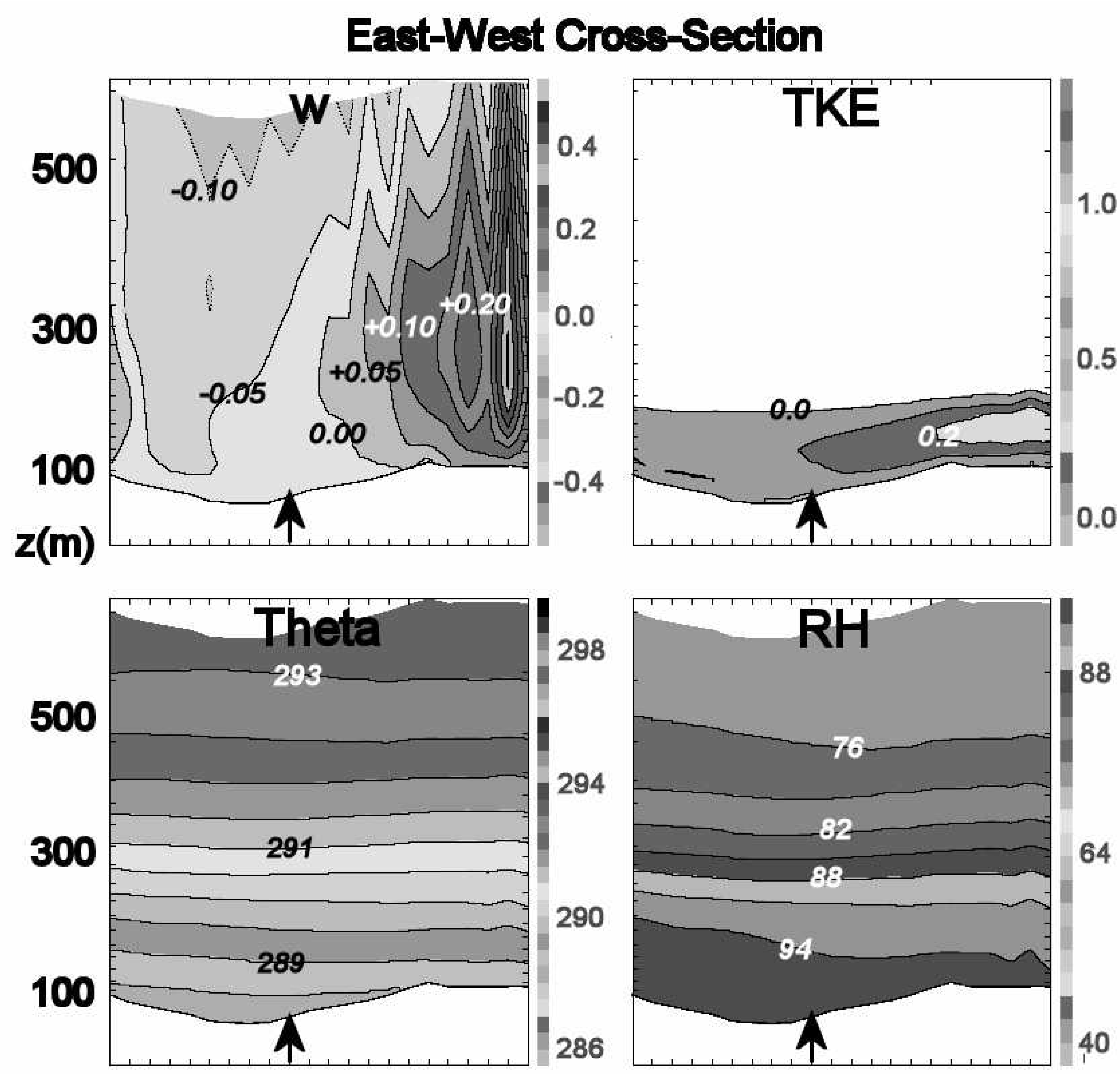


Figure 10: Vertical cross-section along the inner grid along the latitude of the crash site (indicated by the vertical arrow). Plots of meteorological variables (vertical velocity [w, m/sec], turbulent kinetic energy [TKE, m^2/sec^2], potential temperature [Theta, K], and relative humidity [RH, %]) are for 3:00 a.m.

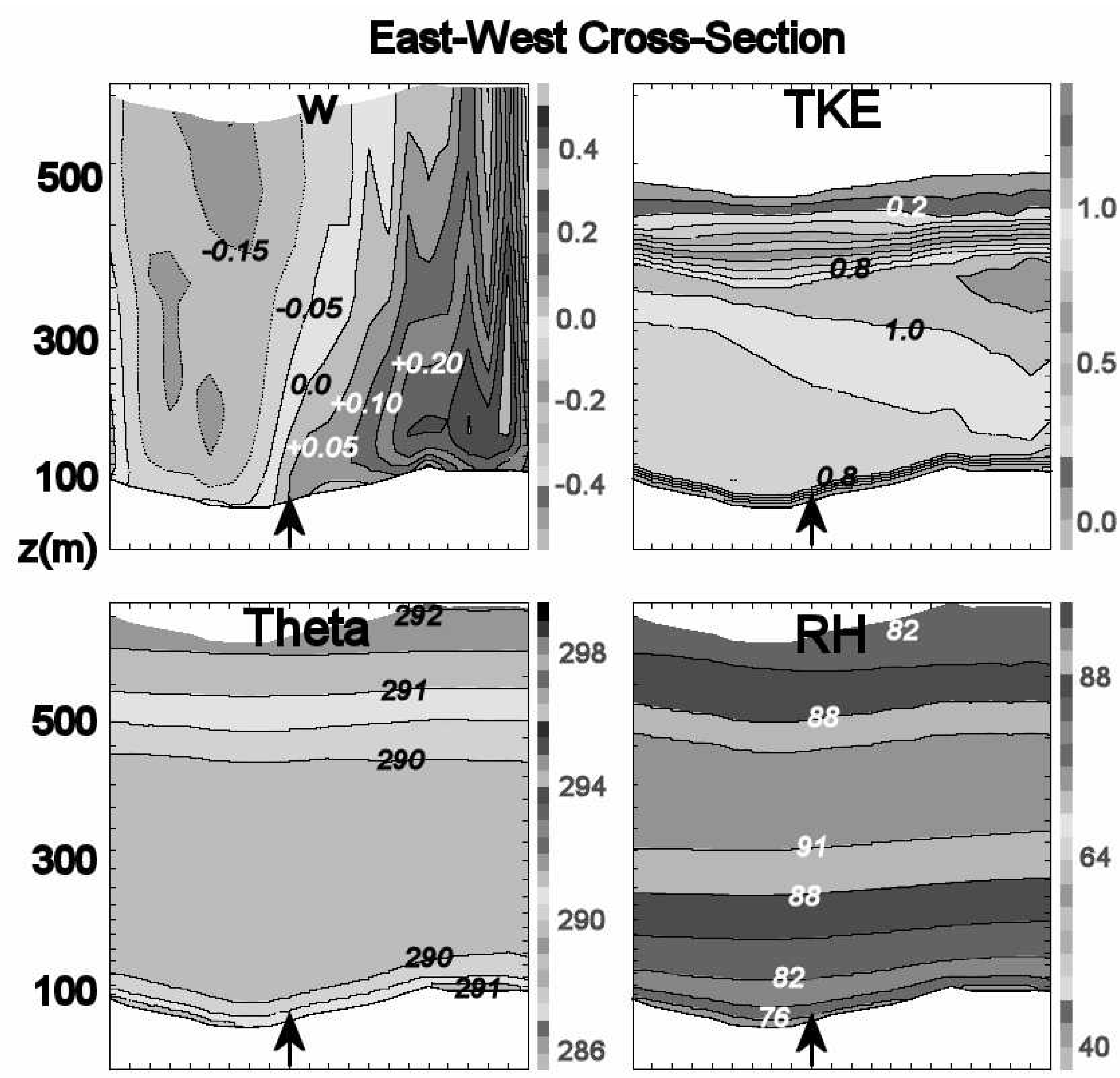
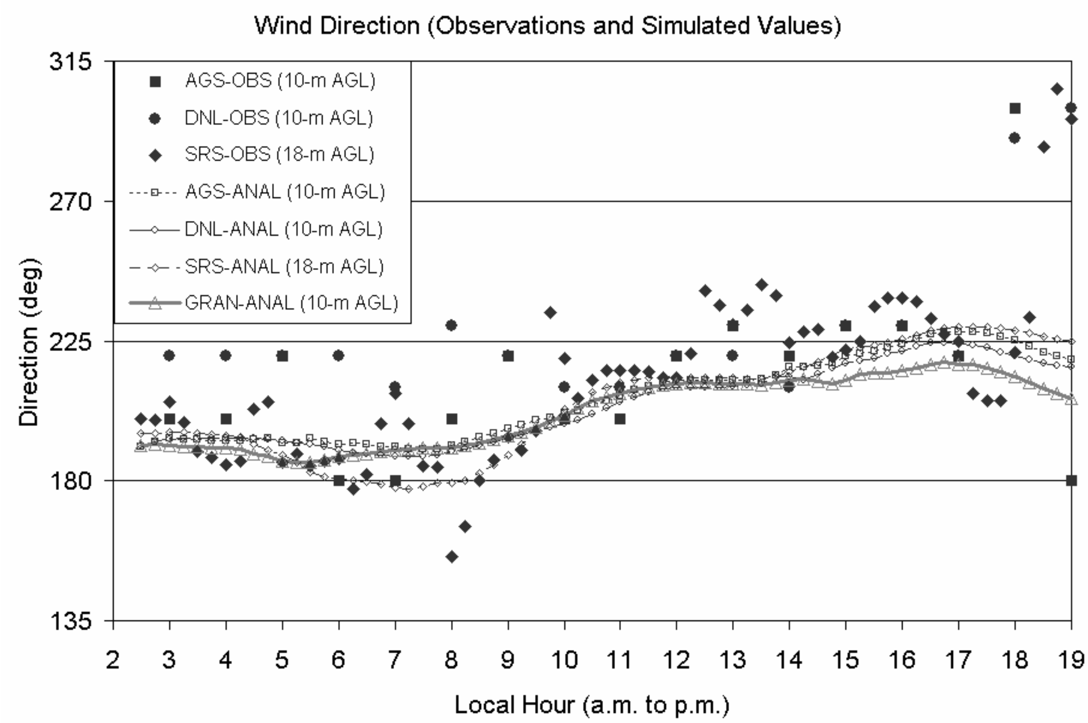


Figure 11: Vertical cross-section along the inner grid along the latitude of the crash site (indicated by the vertical arrow). Plots of meteorological variables (vertical velocity [w, m/sec], turbulent kinetic energy [TKE, m^2/sec^2], potential temperature [Theta, K], and relative humidity [RH, %]) are for 11:00 a.m.

(a)



(b)

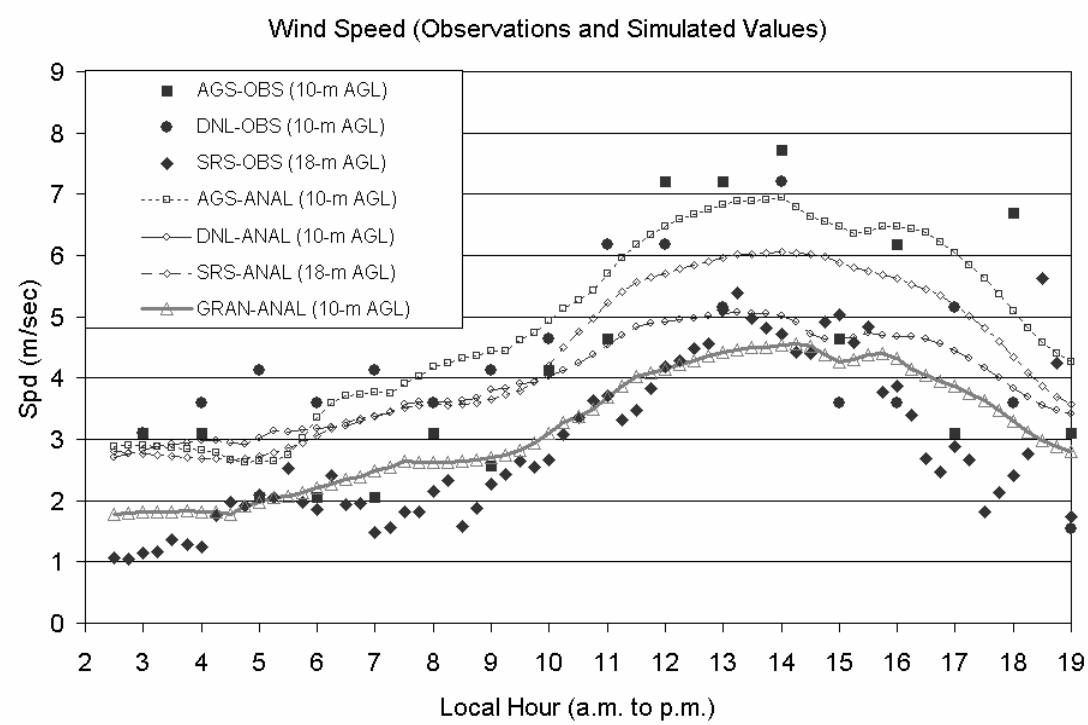


Figure 12: (a) Comparison of observed wind direction from various locations (isolated markers) and simulated values using RAMS (lines) as a function of local time from the beginning of the incident on January 6, 2005. The bolder line indicates model results from Graniteville, where no observations of wind direction were taken. (b) Comparison of wind speeds.

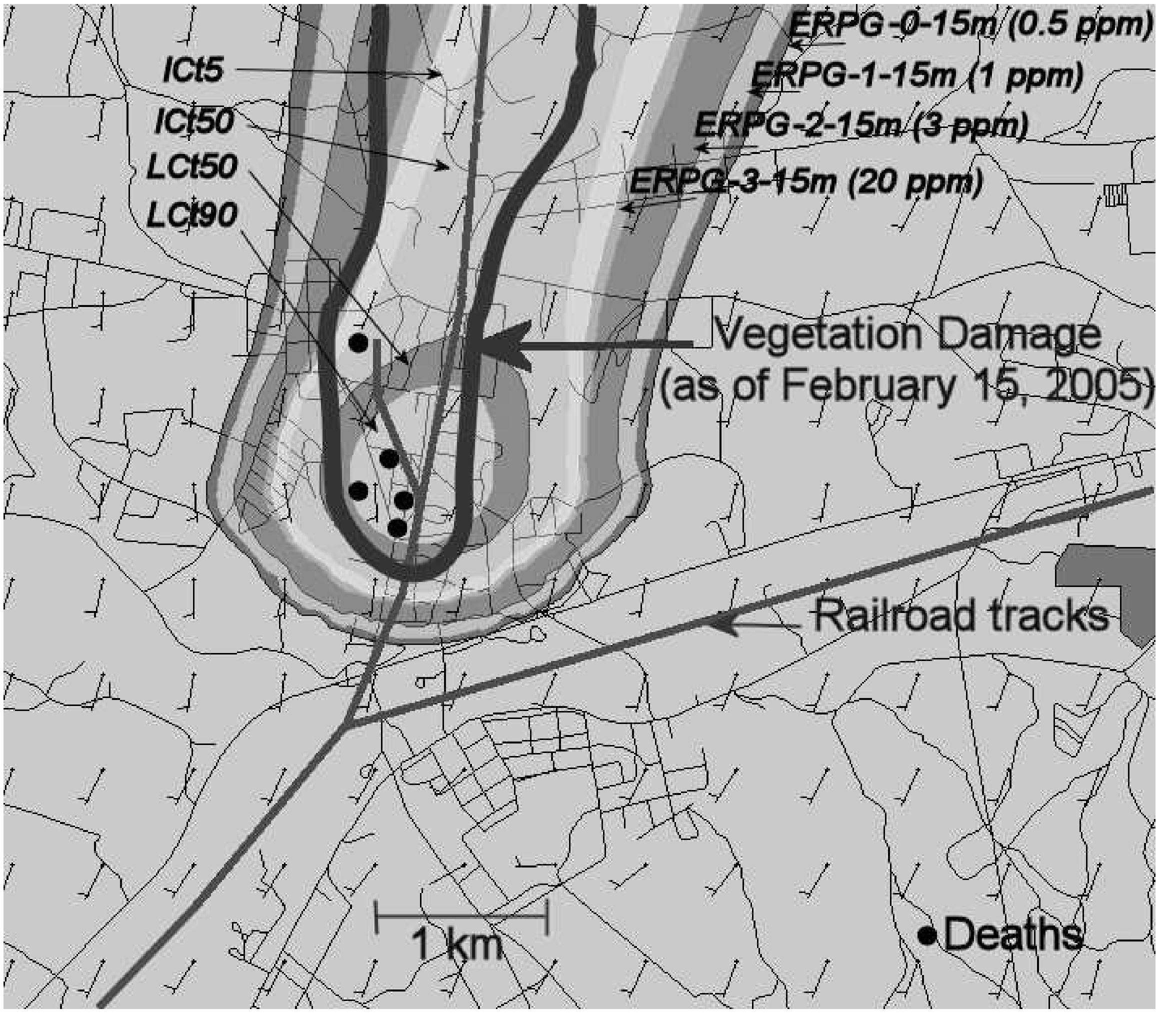


Figure 13: Plume showing transport of liquid chlorine vapor as simulated by HPAC using RAMS meteorology (shown as wind barbs) at ~3:40 a.m. Different isopleths indicate varying median lethal (LCt) and incapacitating (ICt) concentration levels, as well as ERPG levels. The thick straight lines indicate railroad tracks, the thin lines indicate roads, and the large dots show the location of deaths that occurred from the accident. In addition, the thickest line denotes the visible extent of vegetation damage roughly one month after the incident. (Note that dose levels for isopleth levels correspond to 83000, 19000, 3000, 1400, 870, 130.5, 43.5, and 21.75 mg min/m^3).