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ATMOSPHERIC MODELING IN SUPPORT OF A ROADWAY ACCIDENT

by

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Abstract
The United States Forest Service-Savannah River (USFS) routinely performs prescribed fires at the Savannah River Site (SRS), a Department of Energy (DOE) facility located in southwest South Carolina. This facility covers ~800 square kilometers and is mainly wooded except for scattered industrial areas containing facilities used in managing nuclear materials for national defense and waste processing. Prescribed fires of forest undergrowth are necessary to reduce the risk of inadvertent wild fires which have the potential to destroy large areas and threaten nuclear facility operations. This paper discusses meteorological observations and numerical model simulations from a period in early 2002 of an incident involving an early-morning multi-car accident caused by poor visibility along a major roadway on the northern border of the SRS. At the time of the accident, it was not clear if the limited visibility was due solely to fog or whether smoke from a prescribed burn conducted the previous day just to the northwest of the crash site had contributed to the visibility. Through use of available meteorological information and detailed modeling, it was determined that the primary reason for the low visibility on this night was fog induced by meteorological conditions.

1. Introduction

The Savannah River Site (SRS) is a Department of Energy (DOE) reservation located in south central South Carolina, 25 kilometers southeast of Augusta, Georgia (Fig. 1). For many years, the primary mission of the SRS was the production of nuclear materials for national defense. This mission required operation of a complex of facilities to fabricate, irradiate, and process nuclear fuel and target elements. With the end of the cold war, the production-related activities declined and were replaced with management and disposition of nuclear waste, and environmental restoration.

Comprehensive meteorological monitoring in support of SRS operations have existed since the mid 1970s. As part of this program, a network of towers were erected across the SRS with instrumentation to measure wind speed, direction, temperature and dew point at 61-m above ground (to match process facility stack height). A ninth tower near the geographic center of the SRS is instrumented with wind, temperature, and dewpoint sensors at four levels (4, 18, 36, and 61 m). (Note that the temperature and dew-point sensors nearest the surface are actually at 2 m). This area, known as Central Climatology (CL), is also equipped with other ground-based instruments, including a rain gauge and barometric pressure sensor. Tower locations are shown in Fig. 1. Data loggers record measurements continuously and provide a 15-minute average and standard deviation of the meteorological variables at all tower locations. The results are stored in an oracle database running a central computer cluster and are available for operational applications.

Since most of the SRS is forested, a fire and forest management program is run by the United States Forest Service-Savannah River (USFS). Prescribed burn activities are performed for many reasons, including the reduction of wildfire hazard fuels, improvement of wildlife habitat, and improvements in access to various site facilities. Prescribed fires must comply with smoke management guidelines as coordinated with the South Carolina Forestry Commission since such burns can obviously affect visibility along roadways, as well as impact the health of personnel working within the industrial areas. The USFS has access to the SRS meteorological data, as well as forecast products tailored specifically for their use when considering a prescribed burn with specific focus on items such as surface winds, temperature inversions, humidity, and atmospheric boundary layer heights (Hunter et al. 2001).

A multi-vehicle accident occurred on U.S. Highway 278 (US-278) within the northernmost part of the Savannah River Site (SRS) near the base of a shallow river valley traversed by Upper Three Runs Creek early on the morning (0430 LST) of 30 January 2002 (Fig. 1). A tractor-trailer traveling west-bound on US-278 descended to the bottom of the valley and stopped due to a lack of visibility. Shortly thereafter, several more vehicles impacted the tractor-trailer. It was reported at the scene of the accident that the fog was very dense, and that a smoke odor was evident. A prescribed fire had been conducted the prior day by the USFS on 645 acres just *northwest* of the crash site and extinguished by mid-afternoon. At the time of the accident the following morning, it was not clear whether residual smoke from this burn or perhaps some other source of smoke could have contributed to the poor visibility, either as an additional obscurant or as a source of condensation nuclei that could potentially enhance fog formation.

This paper first discusses meteorological observations taken from the local SRS tower network, with supplemental information from a National Weather Service (NWS) sounding near Atlanta, Georgia. Detailed numerical simulations of the atmospheric conditions with a nested grid configuration to as fine as 160 m using the Regional Atmospheric Modeling System (RAMS) are then discussed in relation to the accident.

2. Observations

Weather over the Southeast United States during 29 and 30 January was controlled by a strong ridge of high pressure centered off the Georgia/Florida coast. A synoptic map illustrating conditions at 0700 LST, 30 January is shown in Fig. 2 (NOAA, 2002). Winds across the region were generally southwesterly with dry conditions present through most of the troposphere, as evidenced from an NWS sounding at Peachtree City, GA, 200 km west of the SRS (not shown) taken at 1900 LST on 29 January 2002 (0000 UTC 30 January). Data collected at 61-meters (m) above ground from the two SRS meteorological towers nearest the burn site (A and H areas shown in Fig. 1) show winds from the west-southwest at the start of the prescribed fire shifting to southwesterly during the afternoon (see Fig. 3a). Winds continued from the southwest during the early evening, then shifted to southerly after midnight on 30 January. Concurrent wind speed data from these towers (Fig. 3b) show moderate speeds of 3 to 4 meters per second (m s^{-1}) from late morning through the afternoon of 29 January resulting in good dilution, and favorable transport of smoke emitted from the fire area into a well-mixed atmospheric boundary layer. Wind speeds at this level increased to 4 to 5 m s^{-1} overnight.

Dew point temperature measured at the 2-m level on the CL tower shows a pronounced increase in surface layer moisture just prior to the collision on US-278 on 30 January, with values ranging from roughly 7ºC on 28 January to approximately 12 to 14ºC by 29 January. With dry air aloft, strong radiational cooling of this relatively moist surface layer began immediately after sunset on 29 January. Temperature data from CL (Fig. 3c) indicate that a strong surface-based temperature inversion began to develop around 1730 LST. The inversion intensified through the evening, with the temperature difference between the 2-m and 61-m levels reaching 7^{o}C by 2200 LST. As this moist, stable surface layer began to decouple from the regional flow, winds near the surface became very light. Average wind speeds at the Central Climatology 4-m level (Fig. 3b) decreased considerably from daytime values, averaging less than 1 m s^{-1} throughout the night. In addition, the 4-m wind direction (Fig. 3a) became southeasterly, indicating microscale factors, such as local terrain, were beginning to affect surface transport winds.

By 2200 LST on 29 January, the ambient temperature at 2 m approached the dew point and both variables began to show an identical response (primarily decrease) with time, suggesting air that was near saturation and the possible presence of fog. Between 0430 and 0630 LST on 30 January, the dew point suddenly increased nearly 4^{o}C. The rapid increase in near-surface moisture may explain development of the very dense fog that was observed throughout much of the area during the early morning. The cause of this sudden influx of moisture into the surface layer is not apparent. The ground-based inversion began to break around 0800 LST 30 January as sunshine warmed the surface layer. The fog persisted through 1100 LST when drier air aloft began to mix downward.

3. Simulations

The topography of the Upper Three Runs valley in the vicinity of US-278 suggests that local terrain-following 'drainage' flows were possible during the highly stable conditions that were present in the early morning hours of 30 January, possibly resulting in transport of smoke to the highway. To test this hypothesis, a numerical model simulation of airflow in this area was conducted with the Regional Atmospheric Modeling System (RAMS, Pielke et al. 1992).

a. *Model Configuration*

RAMS is a three-dimensional, finite-difference numerical model used to study a wide variety of atmospheric motions ranging in size from synoptic scale phenomena such as cyclones and hurricanes (100's of km), to large eddy simulations (100's of m). Basic features of the model include the use of non-hydrostatic, quasi-compressible equations and a terrain-following coordinate system with variable vertical resolution. This model is used routinely at the SRS in a prognostic mode to provide forecasts on both regional and local scales. The regional simulation provides a 36-hour forecast covering the two-state region of Georgia and South Carolina with a horizontal grid spacing of 20 km. Information from these simulations is made available to the USFS twice daily to aid them in planning prescribed fires (Hunter et al. 2001). Large-scale analyses obtained from the National Centers for Environmental Prediction (NCEP) are used in an isentropic analysis package within RAMS to create three-dimensional dynamic and thermodynamic fields. Lateral boundary conditions are also provided at various time increments (i.e. 3, 6, or 12 hours) using a Newtonian relaxation scheme to drive (nudge) the prognostic variables toward the forecasted large-scale values (Davies 1983). It is important to keep the outermost boundaries of a limited-area model such as RAMS far from the region of interest to avoid contamination of the results due to the nudging application (Warner et al. 1997). A soil model with 11 levels to 50 cm below ground is used to predict sensible and latent heat fluxes which are enhanced through a vegetation parameterization using the biosphere-atmosphere transfer scheme (BATS, Dickinson et al. 1986). The vegetation data used are defined at 1 km horizontal resolution. Finally, sea surface temperatures are obtained from the latest data at 1° horizontal grid resolution.

b. *Model Results*

1) Meteorological Simulations

The operational forecasts that were produced by RAMS (Buckley et al. 2004) over the 24-hour period beginning at 0700 LST 29 January indicated basically southerly and southwesterly flow throughout the period (Fig. 4), in agreement with observations. The measurements at the CL tower at varying levels indicated southwesterly to westerly flow at 18, 36, and 61 m AGL with speeds between 1 and 5 m s^{-1}, before shifting to southerly by early morning. The bold solid line indicates the RAMS simulation at the 20-km horizontal grid spacing and interpolated to this location at 26 m AGL (the lowest model level above ground). This indicates the model represented surface conditions on a regional scale well for this night. With the coarse grid resolution of the operational RAMS simulations, fine-scale features such as drainage flow from the Upper Three Runs river valley would not be simulated.

In order to examine possible terrain-induced drainage flow, a much finer grid was used, especially in the local vicinity of the prescribed fire. It is important to have at least 4 grid points covering a geographical feature in order to simulate it with a finite-difference model (Pielke 1984). Since the basin of Upper Three Runs Creek at the scene of the accident is roughly 1500 m in length, it was decided that a grid spacing of 160 m for the innermost grid was adequate to capture the spatial features.

For this study, the NCEP Rapid Update Cycle (RUC, Benjamin et al. 1994) data at 60-km horizontal grid spacing were used to supply the boundary conditions. A four-grid simulation was used to generate atmospheric conditions during the burn; the main features of the grid configuration are given in Table 1 and illustrated in Fig. 5. In addition, 23 vertical levels were used with the lowest level above ground at 10 m and the model top at 7100 m.

The coarse grid is large enough to keep lateral conditions from influencing the results on the innermost domain, but not so large as to be computationally prohibitive (Fig. 5). The simulation began at 0100 LST 29 January. While the total simulation time was 30 hours (ending at 0700 LST 30 January), only the final 18 hours were utilized in the analysis (beginning at 1300 LST 29 January).

Further detail for the innermost grid topography ($\Delta x = 160$ m) is shown in Fig. 6. The circle in Fig. 6 indicates the central location of the USFS burn during the prior day, while the 'X' denotes the approximate location of the traffic accident. Total elevation difference between the two points is roughly 30 m. It is evident from the elevation relief that the tendency for drainage flows during calm conditions with no external forcing and strong radiational cooling would be from the northwest toward the southeast, and then southward along the axis of the Upper Three Runs river valley.

An indication of surface wind flow is given in Fig. 7 for two times. For the first time (0000 LST), winds are somewhat uniform from the south, while for the second time (0400 LST), more terrain-induced variation in wind flow patterns are evident. As discussed, the prevailing regional flow was from the southwest to south for the 18-hr period of study. Figure 8 shows a time-series of simulated wind speed and direction at 61 m AGL and very near-surface (10 m AGL) for both the center of the USFS burn, and the accident location. For the 61-m simulated winds, Fig. 8 indicates that except for a brief time around 2100 LST in which winds became light and variable as wind speeds dropped to near calm, the winds were mainly from the south to southwest. During the remainder of the night, speeds were between 1.5 and 4 m s^{-1}, with the speeds over the river valley location being slightly lower.

For the near-surface conditions, wind speeds were very low after 1900 LST (<1 m s^{-1}) for both locations. There was more variability in wind direction, but mainly after 0300 LST and associated with very light wind conditions. As indicated in Fig. 8, predicted winds at the burn location were light and variable after 0300 LST. Wind directions at the accident site were southwesterly at the time of the accident (0430 LST), but did shift to northwesterly, northerly, and northeasterly for a time between 0500 and 0600 LST, although wind speeds were also quite low at this time. These results suggest that persons at the site of the accident may have smelled smoke from the burn the day before during the brief period of light and variable winds. However, the majority of the time during (day of 29 January) and after the burn (night of 29-30 January), winds were from the south or southwest.

It is also of interest to note the model simulated thermodynamic conditions during the event. Time series of temperature and dewpoint temperature for the two locations are plotted in Fig. 9. The bold lines indicating the USFS burn site reveal saturated air near the surface by 2200 LST, while the lighter lines representing the road location show saturated conditions occurring roughly one hour earlier. This would indicate the presence of fog for a majority of the night. This generally agrees with observations from CL (Fig. 3c).

2) Dispersion Simulations

The fine-scale meteorology was also used in a Lagrangian particle dispersion model (Uliasz 1993) to determine back-trajectories at 15-minute intervals from 2200 LST to 0415 LST just prior to the accident to investigate the origin of the air mass at the scene of the accident. Figure 10 shows a map of the region (as in Fig. 6) with two back-trajectories indicated for times of 0100 and 0315 LST. Note also the cross-hatched area indicating the burn compartment from the previous day. From Fig. 8, it is evident that winds along US-278 at 0100 LST were from the southwest at both the surface and at 61-m AGL. As expected, the resulting trajectory shown in Fig. 10 traces an air-mass originating from a path back toward the southwest. On the other hand, for the back-trajectory beginning at 0315 LST, winds were simulated to be from the northwest along US-278, so the resulting trajectory is seen to traverse a semi-circular route first toward the northwest, before turning back to the southeast, and finally toward the southwest. Note that wind speeds were also lighter during this period. None of the trajectories (including those not shown here) are simulated to come from near the center of the original burn location. The 0315 LST trajectory represents the most extreme northern-oriented position (roughly 500 m from the burn compartment), with trajectories close to the accident time (after 0400 LST) resembling the 0100 LST trajectory.

4. Discussion and Conclusions

The work described here clearly indicates the importance of using available observations and detailed numerical simulations in ascertaining the causes and effects of certain accidents related to environmental factors. The USFS conducted a prescribed fire on the northern boundary of the SRS on 29 January 2002. Forest Service logs indicated that the burn was completed by 1515 LST; subsequent aerial reconnaissance conducted around 1630 LST reported that 95% of the smoke from the burn had dissipated. A multi-vehicle accident occurred the following morning at 0430 LST.

Observations from the SRS meteorological towers and NWS soundings indicate that moderate surface layer moisture along with dry conditions aloft led to the development of a strong temperature inversion and widespread heavy fog during the night of the accident. Terrain in the vicinity of the accident implies that on nights when regional flow is weak, drainage flows could indeed be from the north or northwest (e.g. see Fig. 6). However, the observational data and large-scale numerical simulations also show that the mesoscale flow across the SRS was mainly from the south and southwest during and after the burn period. Detailed simulations reveal mainly southerly winds down to the surface, except for one brief period of light and variable flow roughly one hour before and after the accident occurred. Based on this simulation, back-trajectory calculations, and local wind measurements, the prevailing southwesterly winds likely inhibited drainage from the burn site down the Upper Three Runs valley to the intersection with US 278. The brief periods of northerly flow in the detailed simulation could imply the transport of smoke to the incident scene and the production of an odor. This implies that poor driving conditions on this night were not likely due to smoke from the prescribed fire, nor was fog formation enhanced due to increased condensation nuclei. Rather, fog induced by the prevailing meteorological conditions was the primary contributor to poor visibility.

Finally, an examination of smoke odor thresholds was undertaken. For a typical prescribed fire, the toxins of most concern are carbon monoxide (odorless), respirable particulates, acrolein, benzene, and formaldehyde (NWCG, 2001). Data taken from the Agency for Toxic Substances and Disease Registry (ATSDR, 2001) indicates odor thresholds for combustion products from a wildland fire are as low as 0.16 ppm (acrolein). Sandberg and Dost (1990) note that acrolein (and to some extent formaldehyde) may rapidly cause eye and nose irritation. Consequently, scene reports of a smell of smoke infer the advection of only minute amounts of smoke during periods of light and variable winds.

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Figure Captions:

Figure 1: Map indicating location of the accident in southwest South Carolina. The SRS is indicated in shading in the southern half of the map. Corporate locations are also shaded. Roadways are given by solid lines, while smaller rivers or creeks are denoted by dashed lines. Meteorological towers are indicated with a "+", and those with larger font are discussed in the text.

Figure 2: Synoptic conditions at 0700 LST, 30 January (taken from NOAA, 2002).

Figure 3a: Wind direction measured at SRS A and H area towers (61-meter level) and Central Climatology tower (4-m level) from 1100 LST 29 January through 1100 LST 30 January, 2002. The vertical arrow indicates the approximate time of the incident.

Figure 3b: Wind speed measured at SRS A and H area towers (61-meter level) and Central Climatology tower (4-m level) from 1100 LST 29 January through 1100 LST 30 January, 2002. The vertical arrow indicates the approximate time of the incident.

Figure 3c: Temperature (61-m and 2-m) and dew point (2-m) measured at Central Climatology from 1400 LST 29 January through 1100 LST 30 January, 2002. The vertical arrow indicates the approximate time of the incident.

Figure 4: Comparison of regional RAMS simulation with observations for the 24-hr period beginning 0700 LST 29 January, 2002. (a) Wind direction, (b) wind speed.

Figure 5: Region of interest for this modeling study. County and city outlines are also indicated. Grids denote domains used to generate meteorology during the event.

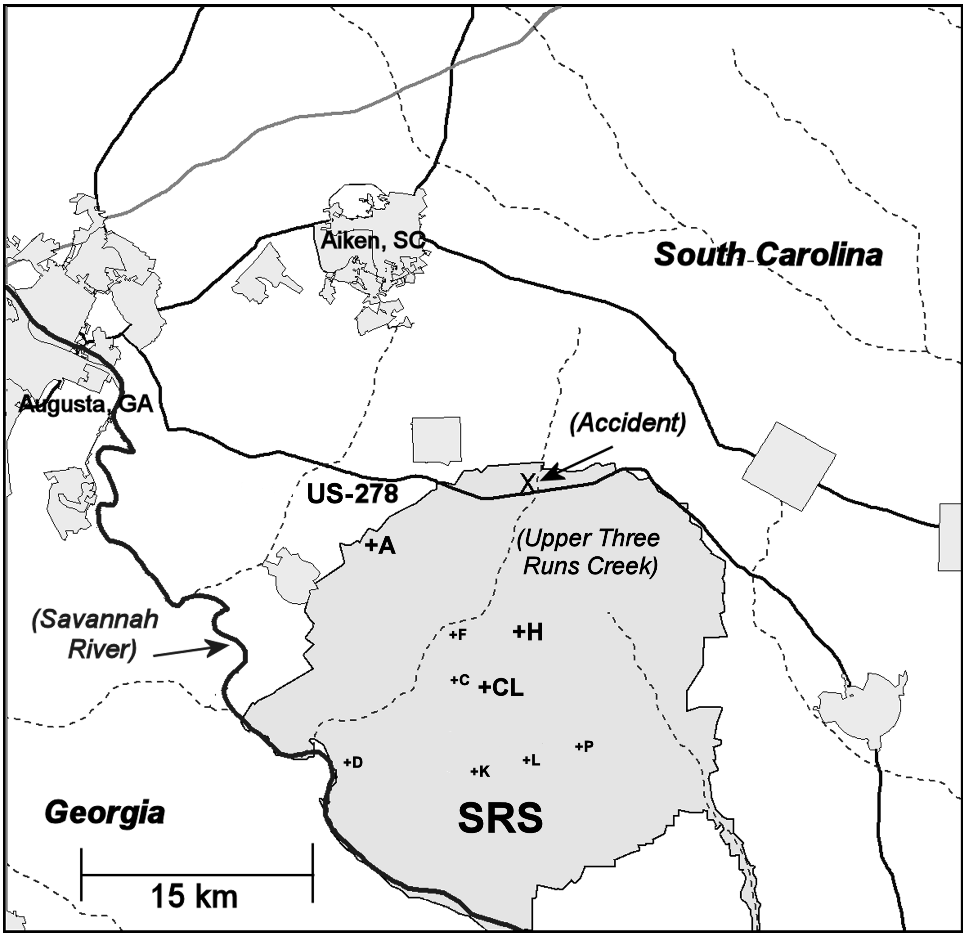
Figure 6: Innermost RAMS domain topography (contour interval of 5 m) with some features for the area denoted. The center of the USFS prescribed fire is given by the circle (●), while the approximate location of the traffic accident is given by the (X) at the intersection of US-278 and Upper Three Runs Creek. The small markers indicate grid points used in the modeling.

Figure 7: Surface (10-m) winds as predicted using the innermost RAMS domain ($\Delta x = 160$ m) at (a) 0000 LST, and (b) 0400 LST. The center of the USFS prescribed fire is given by the circle (●), while the approximate location of the traffic accident is given by the (X) along US-278.

Figure 8: Simulated winds from 1300 LST 29 January to 0700 LST 30 January, 2002 at 10 m AGL (thin lines) and 61 m AGL (thick lines) as interpolated on the innermost grid to the burn and accident locations. (a) Wind direction, (b) Wind speed. The vertical arrow indicates the approximate time of the incident.

Figure 9: Simulated temperature and dewpoint from 1300 LST 29 January to 0700 LST 30 January, 2002 at 10 m AGL as interpolated on the innermost grid to the burn and accident locations. The vertical arrow indicates the approximate time of the incident.

Figure 10: Simulated back-trajectories using RAMS meteorology from the innermost grid. Topography shown as dashed lines at 15-m intervals. The extent of the USFS prescribed fire burn compartment is indicated by the cross-hatched area, the center of the fire is given by the circle (●), while the approximate location of the traffic accident is given by the (X) along US-278. Two trajectories are shown starting at 0100 and 0315 LST.



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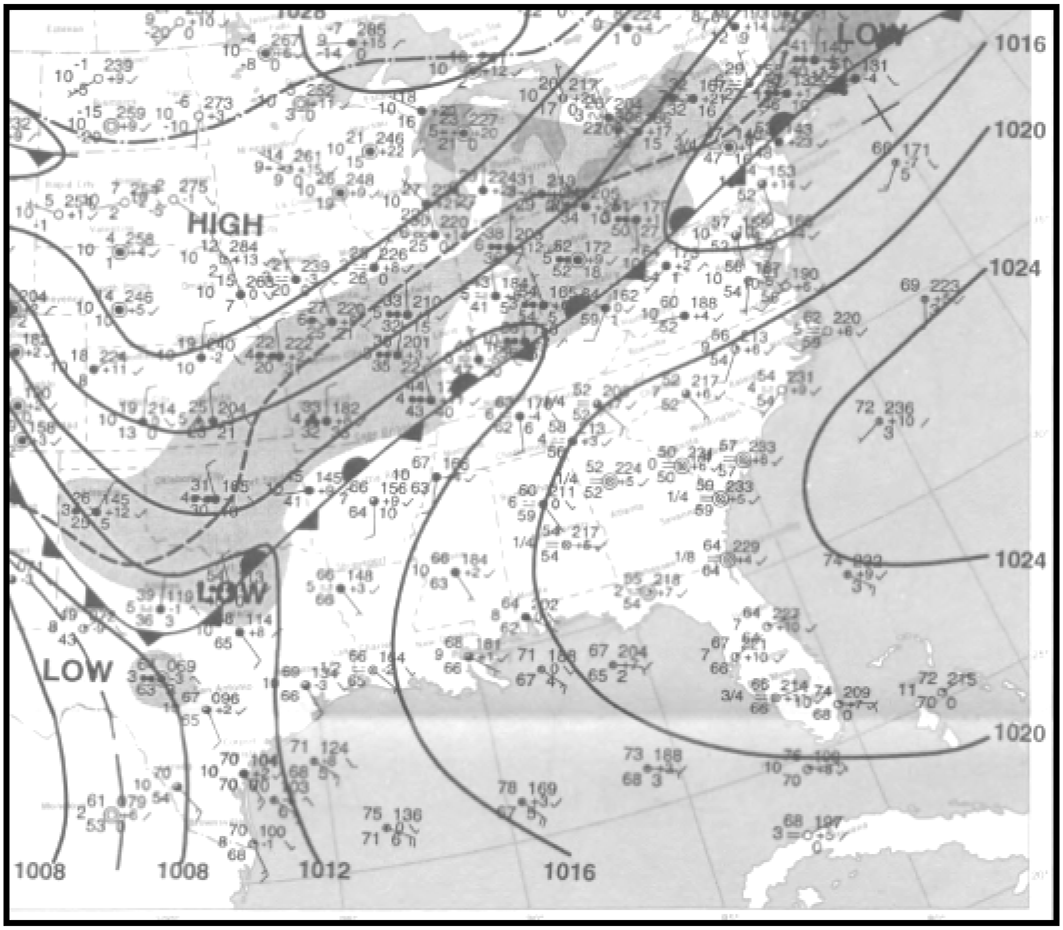

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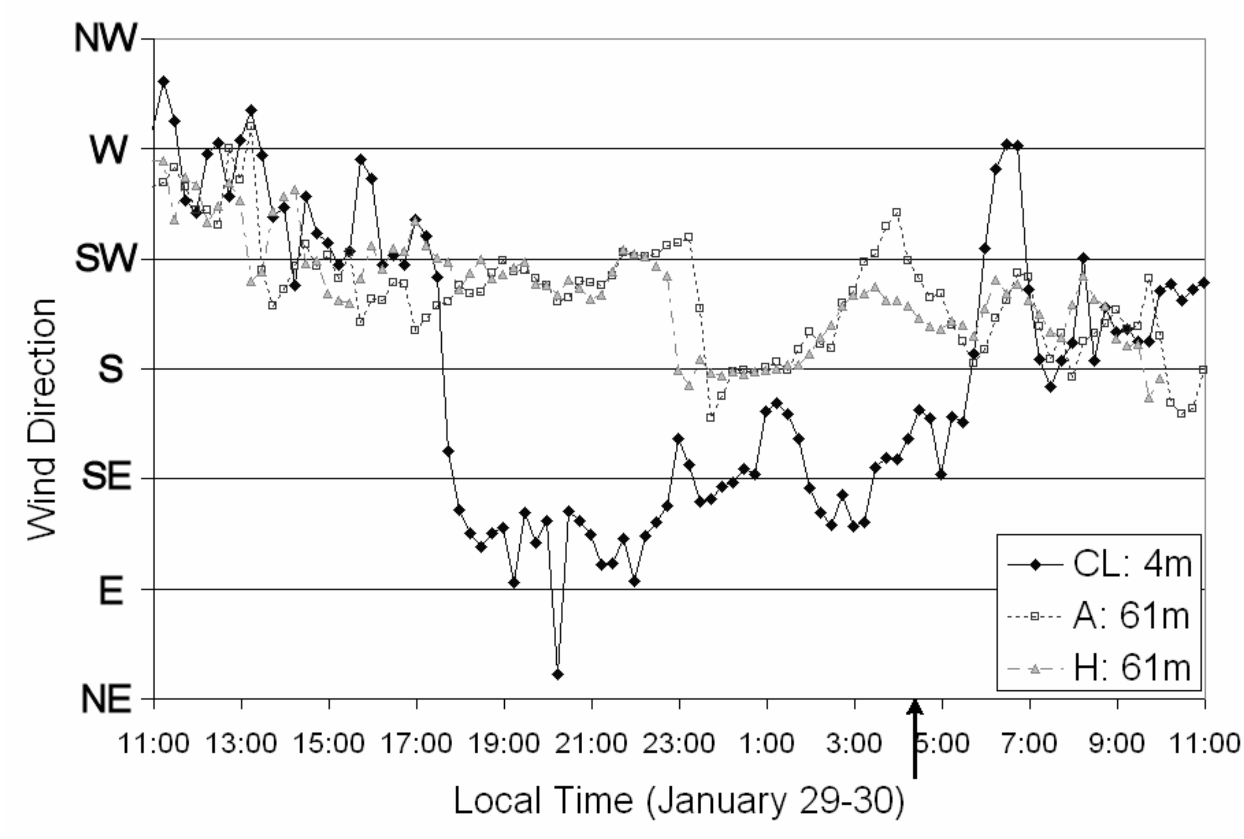

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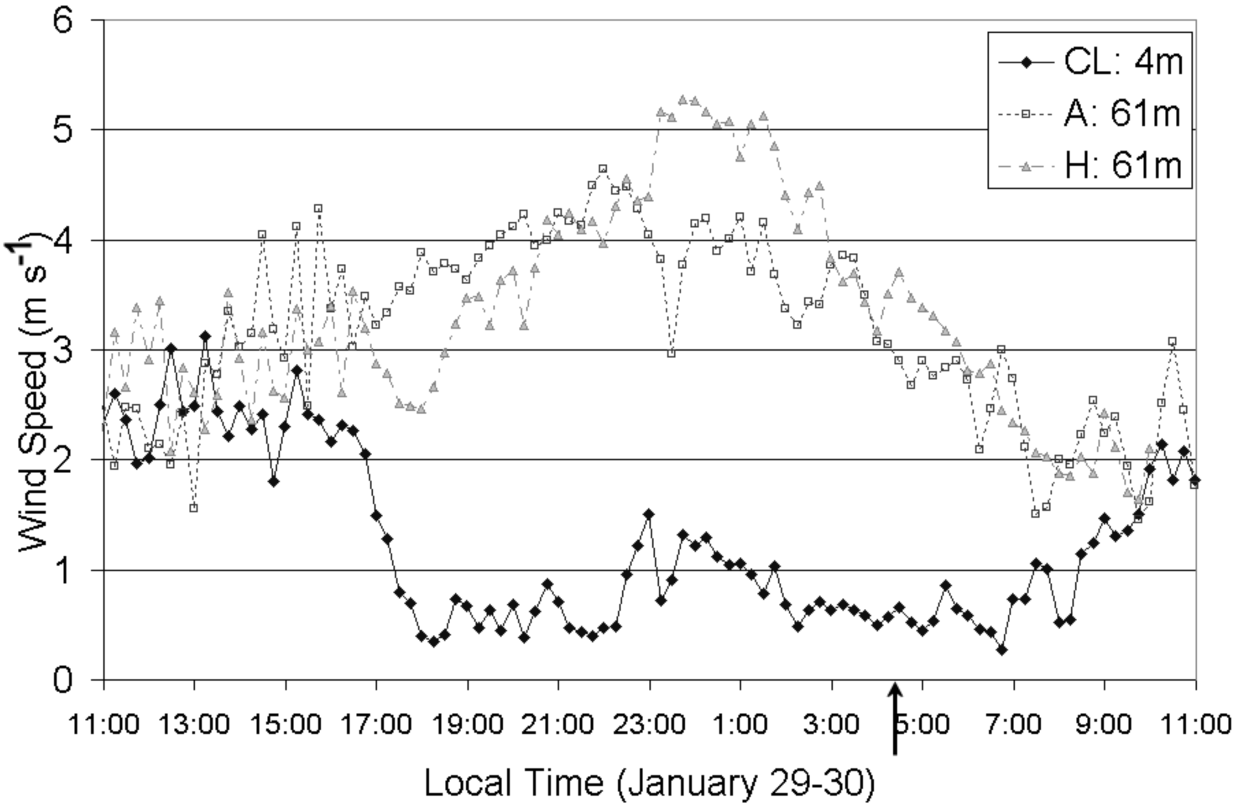

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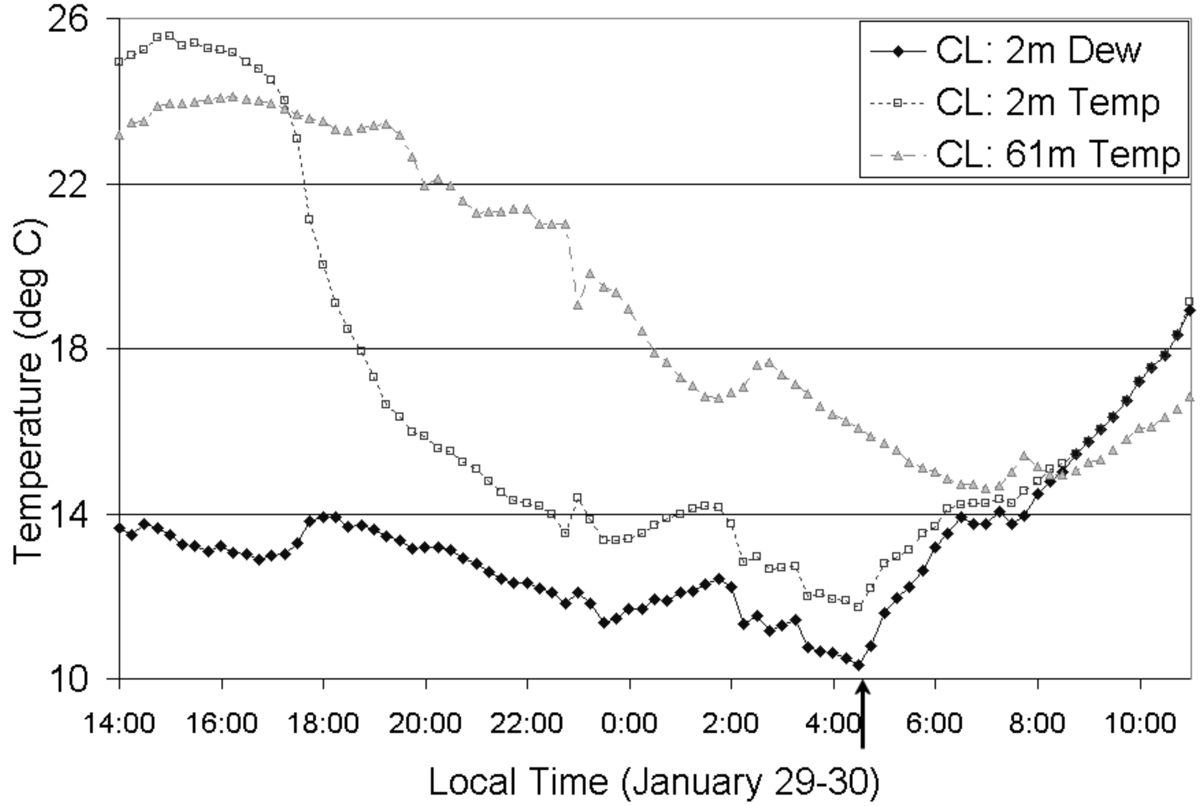

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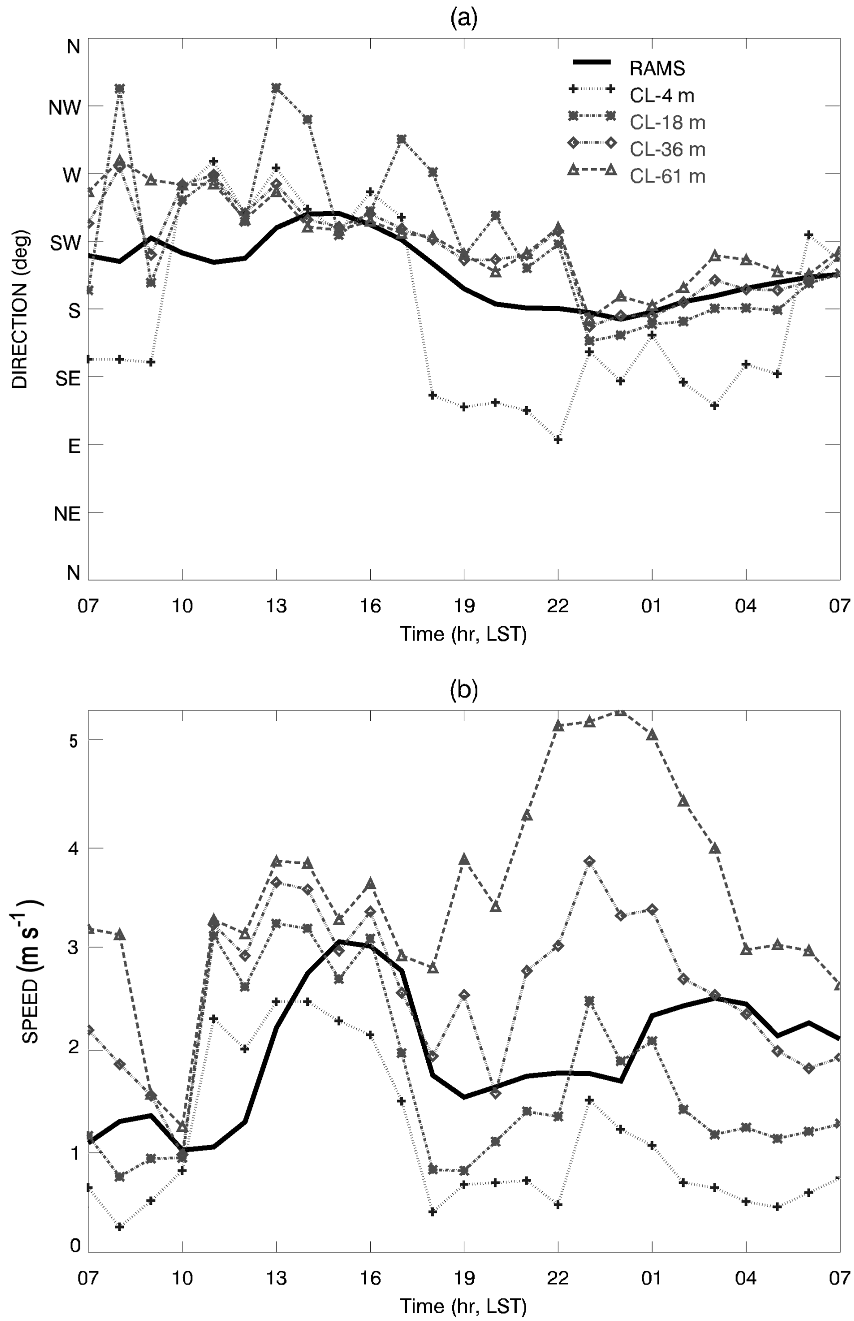

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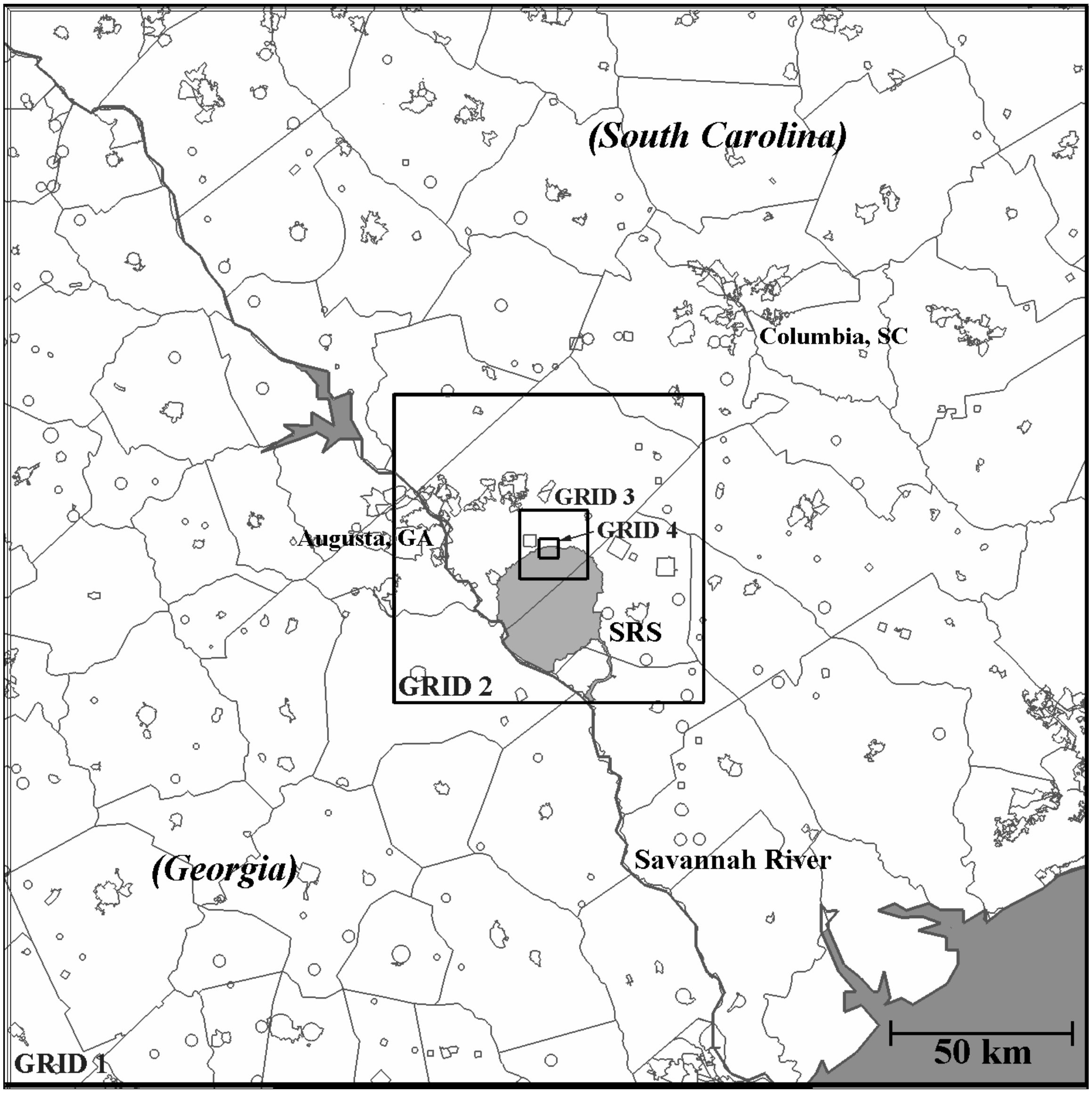

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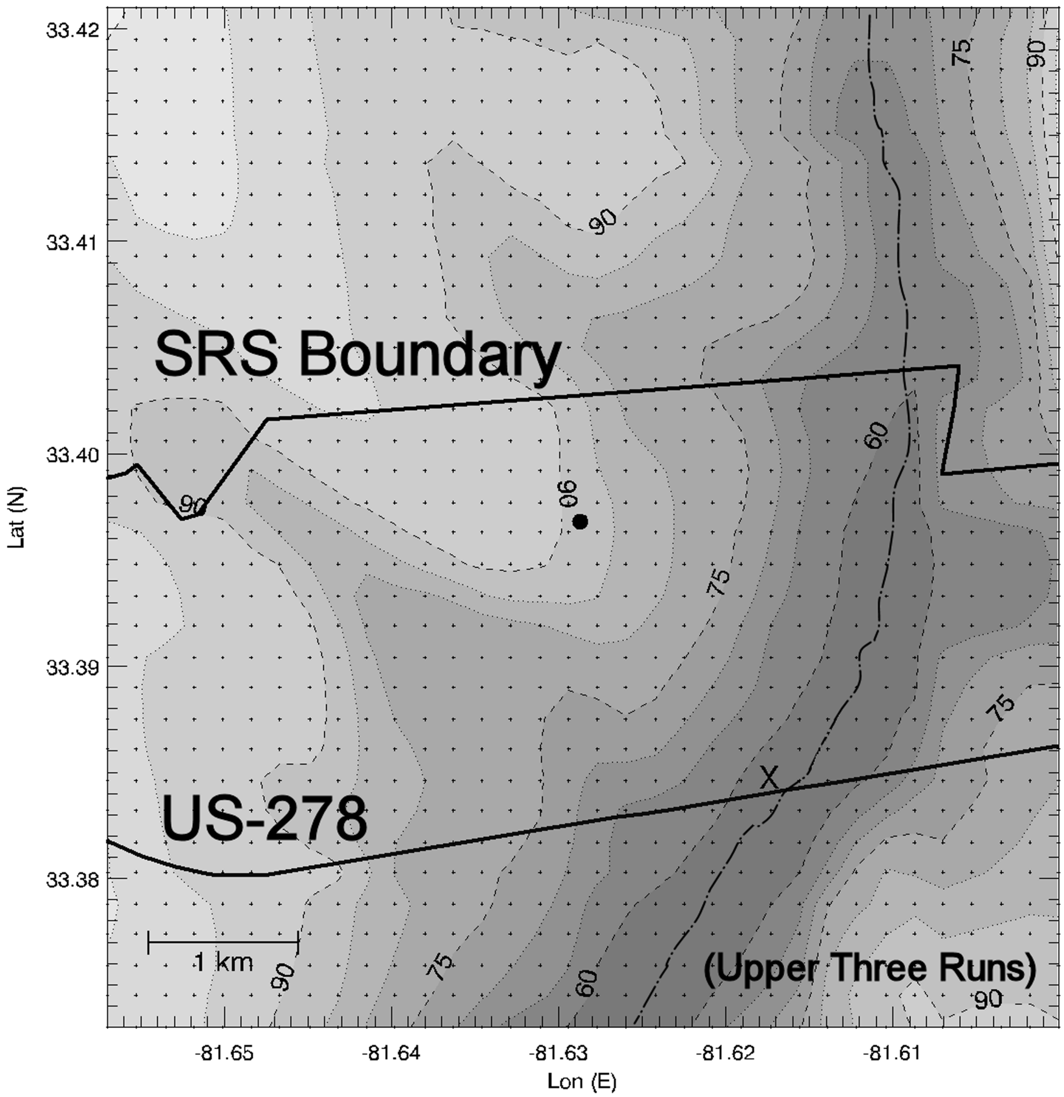

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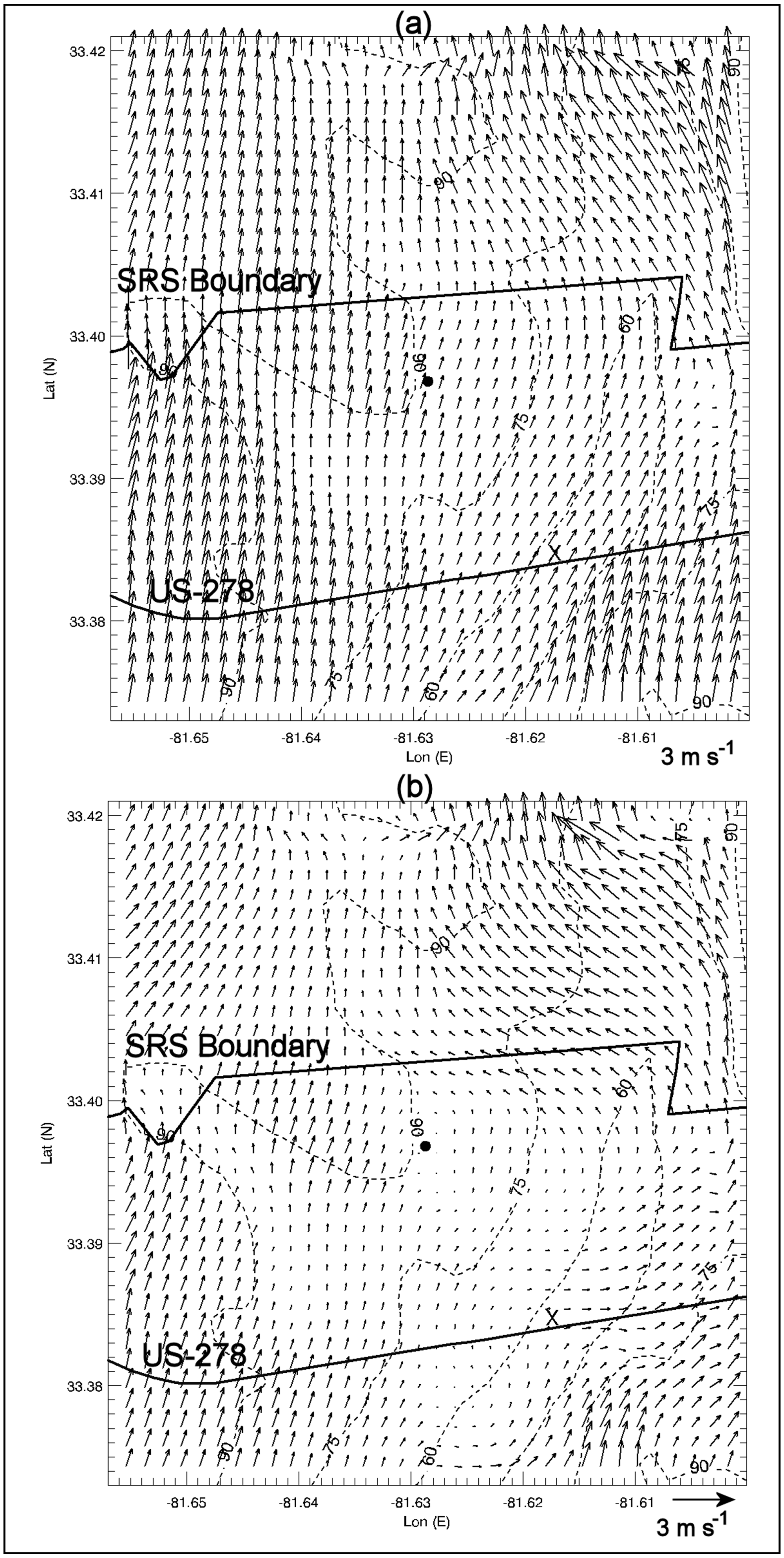

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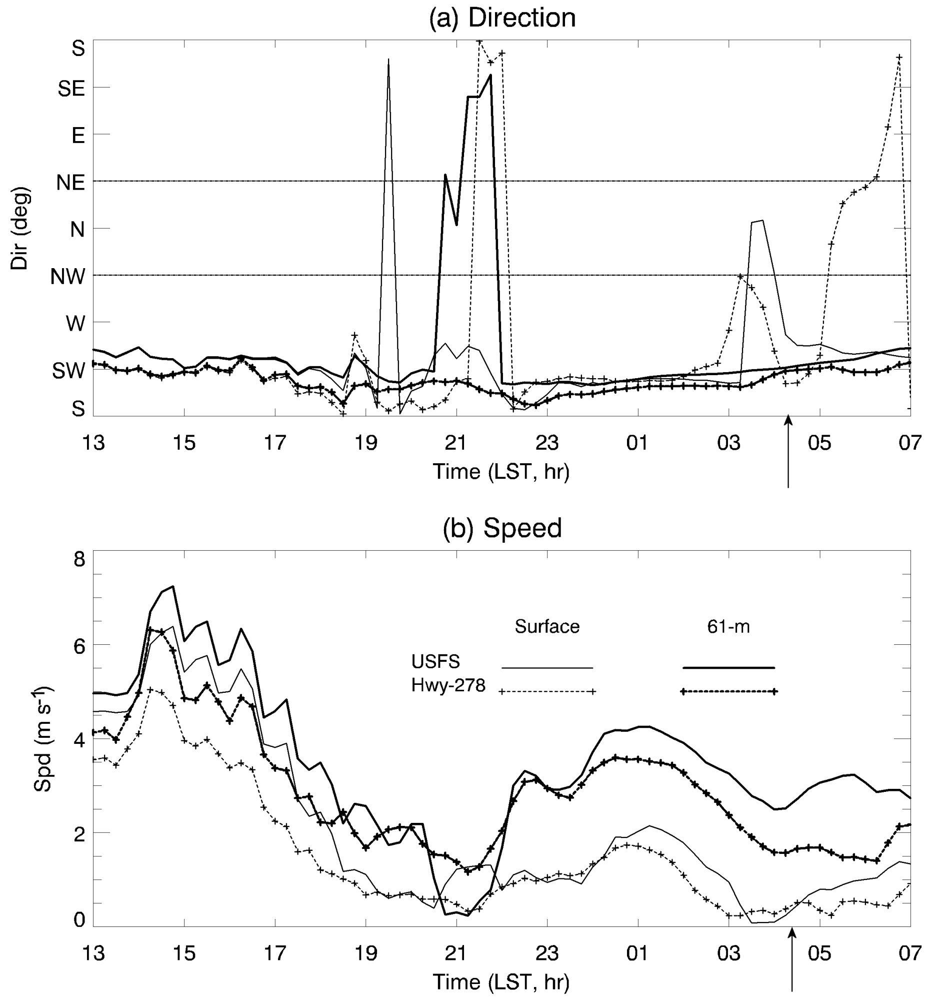

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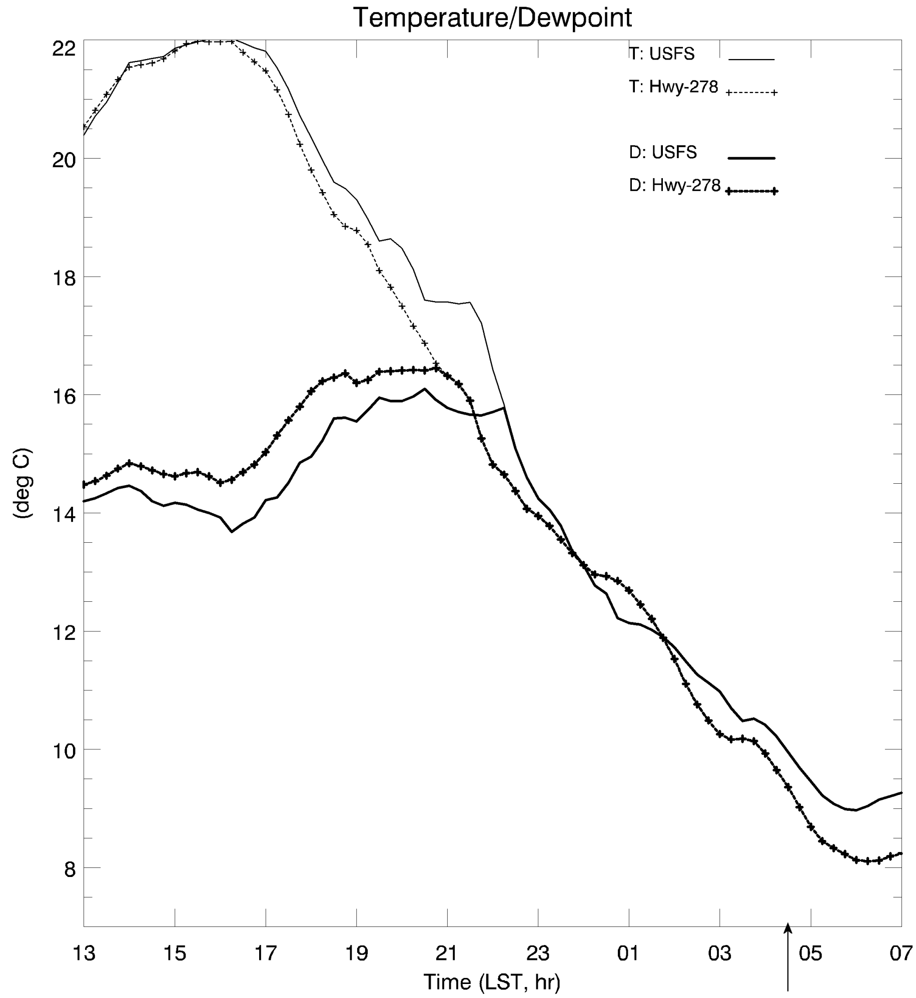

Figure 9: Simulated temperature and dewpoint from 1300 LST 29 January to 0700 LST 30 January, 2002 at 10 m AGL as interpolated on the innermost grid to the burn and accident locations. The vertical arrow indicates the approximate time of the incident.

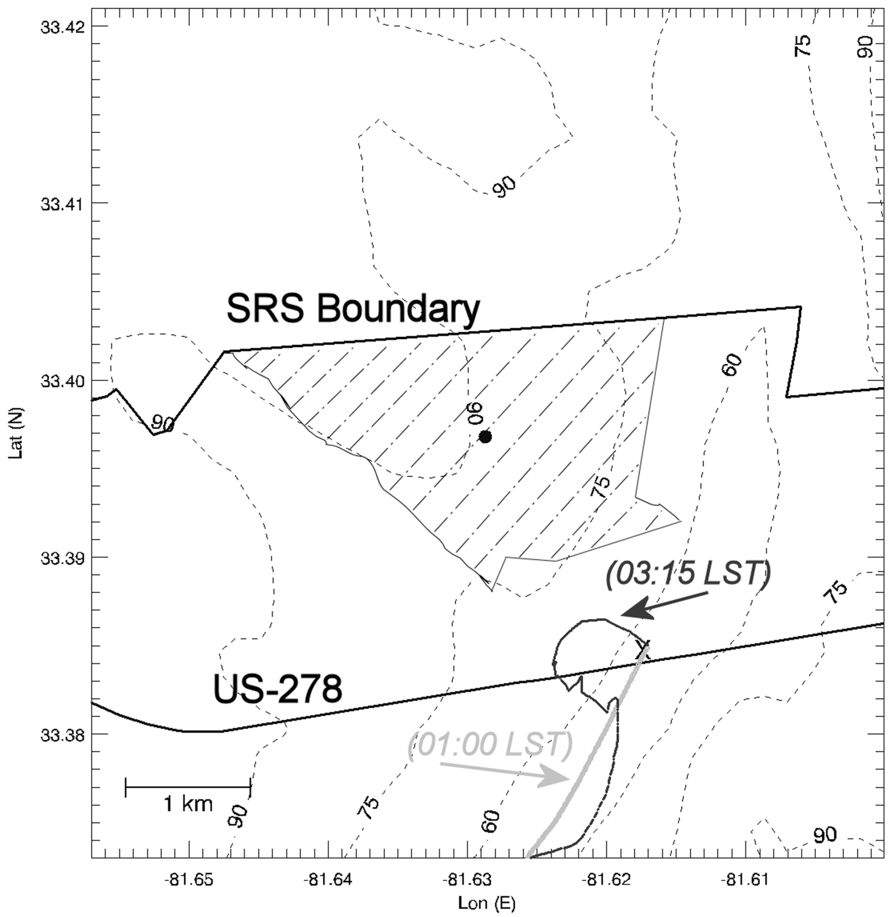

Figure 10: Simulated back-trajectories using RAMS meteorology from the innermost grid. Topography shown as dashed lines at 15-m intervals. The extent of the USFS prescribed fire burn compartment is indicated by the cross-hatched area, the center of the fire is given by the circle (●), while the approximate location of the traffic accident is given by the (X) along US-278. Two trajectories are shown starting at 0100 and 0315 LST.

Table 1 RAMS Input Characteristics

GRID	1	2	3	4
Horizontal Grid Spacing (m)	10240	2560	640	160
East-West Grid Points	30	34	30	34
North-South Grid Points	30	34	30	34
Topography Resolution (m)	10000	1000	500	90
Timestep (sec)	8	4	1	0.25