ANALYSIS OF METEOROLOGICAL FACTORS AFFECTING A ROADWAY ACCIDENT DURING A FOG EVENT

Robert L. Buckley and Charles H. Hunter
Savannah River National Laboratory
Aiken, South Carolina 29808 (USA)

Abstract

The United States Forest Service-Savannah River (USFS-SR) 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 processing waste. 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 when poor visibility along a major roadway on the northern border of the SRS was determined to be the primary cause of an early-morning multi-car accident. This incident was significant because of concerns that the limited visibility was not due solely to the prevailing widespread fog, but that residual smoke from a prescribed burn conducted the previous day just to the northwest of the crash site had enhanced fog density, further reducing local visibility. Through the use of available meteorological information and detailed modeling, it was determined that most of the residual smoke would likely have been transported away from the roadway by the prevailing wind and, therefore, would not have contributed to additional degradation of visibility at the accident site. This event clearly illustrates the need for a careful examination of the characteristics of the fire site (e.g., proximity to roadway, topography, etc.), in conjunction with a forecast for the occurrence of overnight fog, when planning prescribed fires near major roadways.

Corresponding Author: Dr. Robert Buckley
Savannah River National Laboratory
773A, A1008, Savannah River Site, Aiken, South Carolina 29808
Email: robert.buckley@srnl.doe.gov

1. Introduction

The Savannah River Site (SRS) is a Department of Energy (DOE) reservation located in southwest South Carolina, 25 km 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 has existed since the mid 1970s. As part of this program, a network of towers was 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 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.
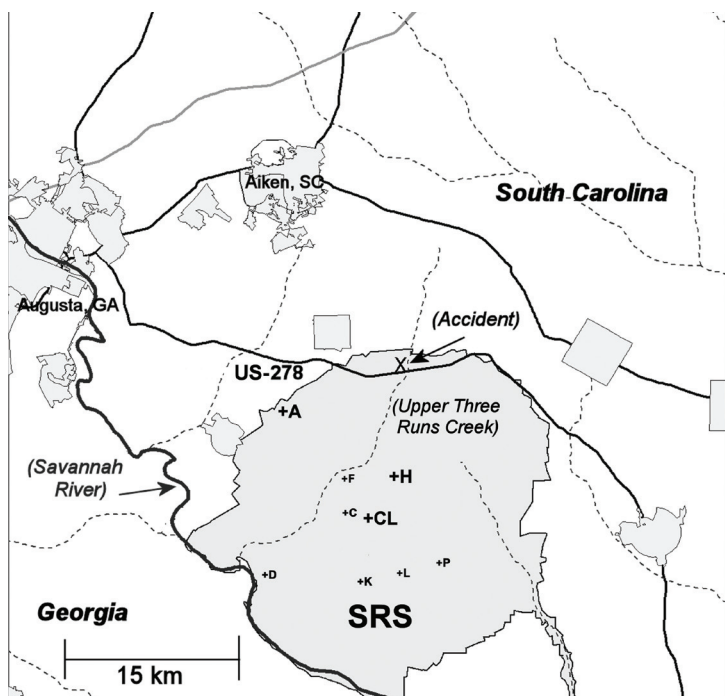
Fig. 1. Map indicating location of the accident in southwest South Carolina. The SRS is indicated by shading in the southern half of the map. Incorporated municipalities are also shaded. Roadways are given by solid lines, while smaller rivers or creeks are denoted by dashed lines. Meteorological towers are indicated with a "+", and those with larger font are discussed in the text.

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 weather 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 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 poor visibility. Shortly thereafter, several vehicles collided with 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 or excess moisture that could potentially enhance fog formation.

To assess possible impacts of the prescribed fire on fog density, prevailing synoptic conditions, available meteorological observations, and the results from a detailed numerical simulation of atmospheric conditions in the immediate vicinity of the prescribed fire, were examined. The meteorological observations consisted of data collected from the local SRS tower network, with supplemental information from a National Weather Service (NWS) sounding near Atlanta, Georgia. In addition, Geostationary Operational Environmental Satellite (GOES) imagery near the time of the accident was used to confirm the spatial extent of the fog. The detailed

numerical simulations were conducted with a nested grid configuration to as fine as 160 m using the Regional Atmospheric Modeling System (RAMS).

The results of this retrospective study are presented to underscore that effective planning and execution of prescribed fires near roadways require close coordination between operational weather forecasters and fire managers over the full life cycle of the fire, as potentially significant emissions of particulate matter and moisture occur from the fire site well after the active fire has been terminated. More specifically, forecasters must carefully consider the development of a stable atmospheric boundary layer and possibly dense fog during the overnight period following a prescribed fire, particularly in situations where the local topography supports the occurrence of microscale flows that could transport residual emissions from the fire site to the roadway.

2. Observations

Weather over the Southeast United States during 29 and 30 January 2002 was controlled by a strong ridge of high pressure centered off the Georgia/Florida coast producing generally southerly flow across the region. A synoptic map illustrating conditions at 0700 LST, 30 January is shown in Fig. 2 (NOAA 2002). An NWS sounding taken at 1900 LST on 29 January 2002 (0000 UTC 30 January) at Peachtree City, GA (not shown), 200 km west of the SRS, also indicates southwesterly winds and dry conditions through most of the troposphere. Data collected at 61 m above ground from two SRS meteorological towers, located within 10 km of 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 (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 m s⁻¹ from late morning through the afternoon of 29 January resulting in 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 on the day prior to the collision on US-278, with values ranging from roughly 7ºC on 28 January increasing to approximately 12 to 14ºC by 29 January (not shown). 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°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
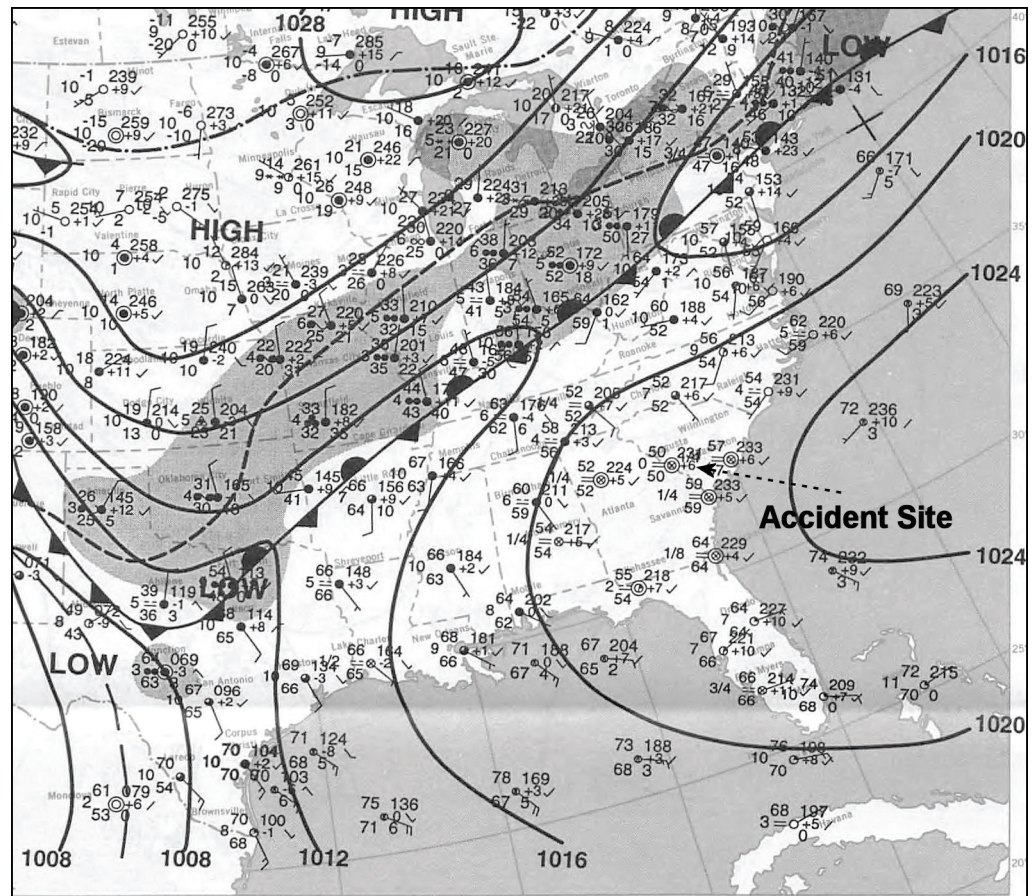

Fig. 2. Synoptic conditions at 0700 LST, 30 January (taken from NOAA 2002). Observations are shown in standard format.

Fig. 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.
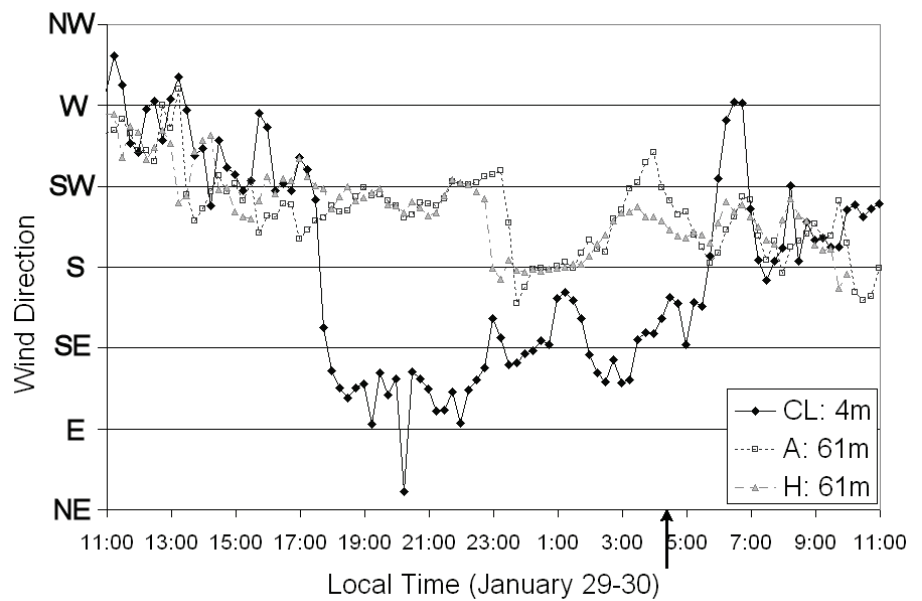
Fig. 3b. Wind speed measured at SRS A and H area towers (61-meter level) and Central Climatology Tower (4-m level) from 1100 LST 29 January through 1100 LST 30 January, 2002. The vertical arrow indicates the approximate time of the incident.
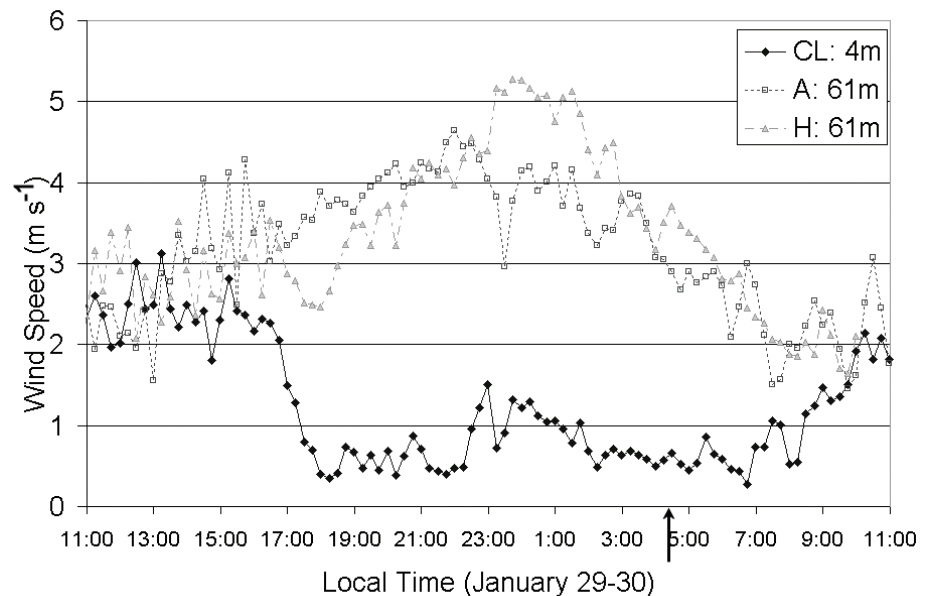
Fig. 3c. Temperature (61-m and 2-m) and dew point (2-m) measured at Central Climatology from 1400 LST 29 January through 1100 LST 30 January, 2002. The vertical arrow indicates the approximate time of the incident.
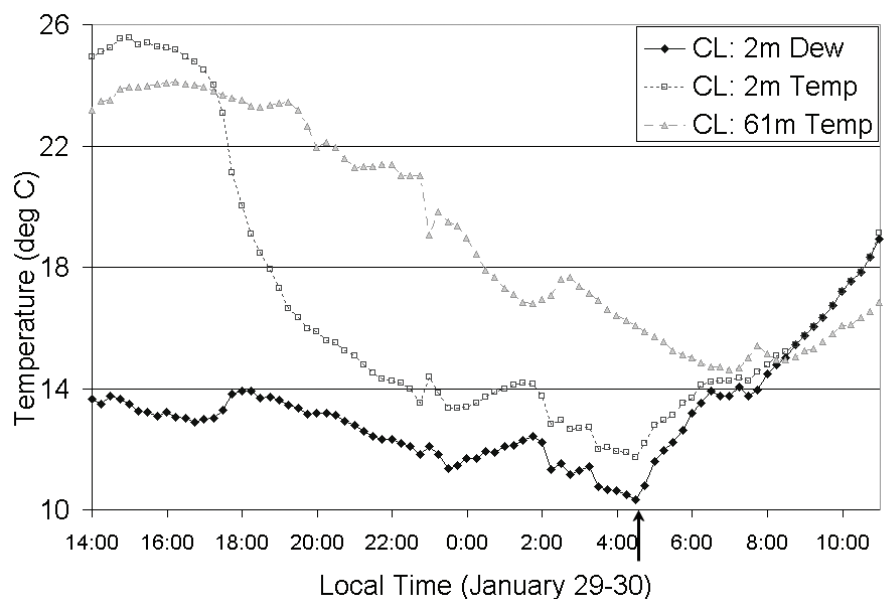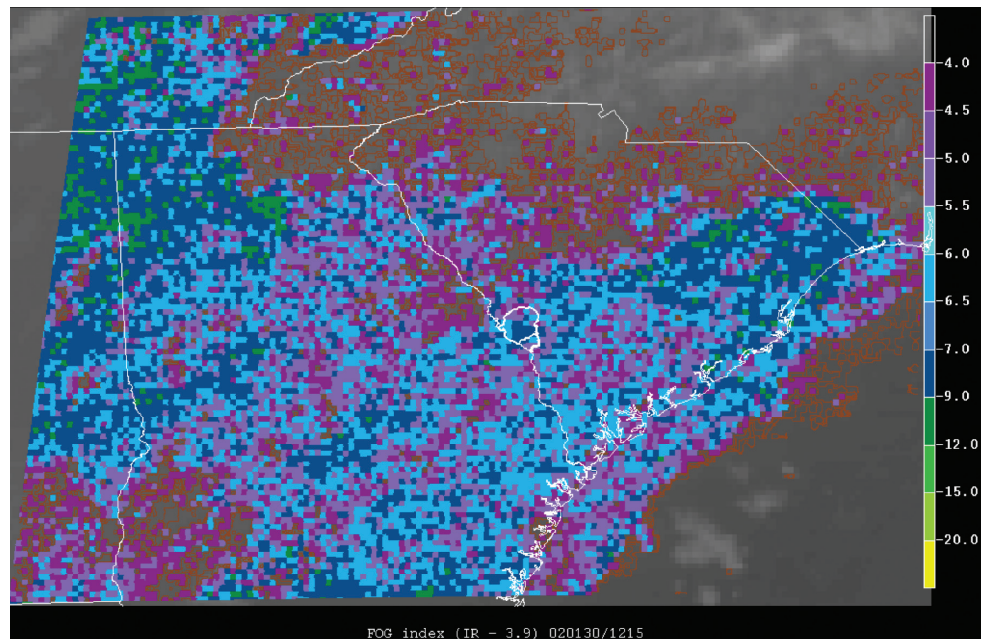
to affect surface transport winds.

By 2200 LST on 29 January, the ambient temperature at 2 m approached the dew point and both variables continued to decrease with time, suggesting air that was at or near saturation and the possible presence of fog. Five-minute METAR observations from the NWS observing station at the Augusta Regional Airport, approximately 18 km west of the accident site, indicate the development of fog with visibilities less than ¼ mile beginning at 2230 LST and persisting through the night. Between 0430 and 0630 LST on 30 January, the dew point suddenly increased nearly 4°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.

The considerable spatial extent of the fog during this event is illustrated in Fig. 4a, which shows an estimate of the fog density at 0715 LST derived from data at 4 km resolution using GOES-8 imagery. This fog index is obtained by taking the longwave (10.7-mm) infrared (IR) and subtracting the shortwave (3.9-mm) brightness values (Lee et al. 1997). It should be noted here that the product shown in Fig. 4a uses raw brightness values rather than a derived brightness temperature, implying that the sign of the subtraction is the opposite of the National Environmental Satellite, Data and Information Service (NESDIS) temperature category. This figure indicates fog covering much of Georgia, as well as the southern half of South Carolina, including the Savannah River Site. Visible imagery taken at 1000 LST (Fig. 4b) further reinforces the notion that the fog was widespread during this event.

Fig. 4a. Derived fog index from GOES at 0715 LST, 30 January 2002 after Lee et al. (1997). Colors in the legend indicate the difference in longwave infrared and shortwave brightness value. Larger differences (i.e. more negative) imply denser fog.
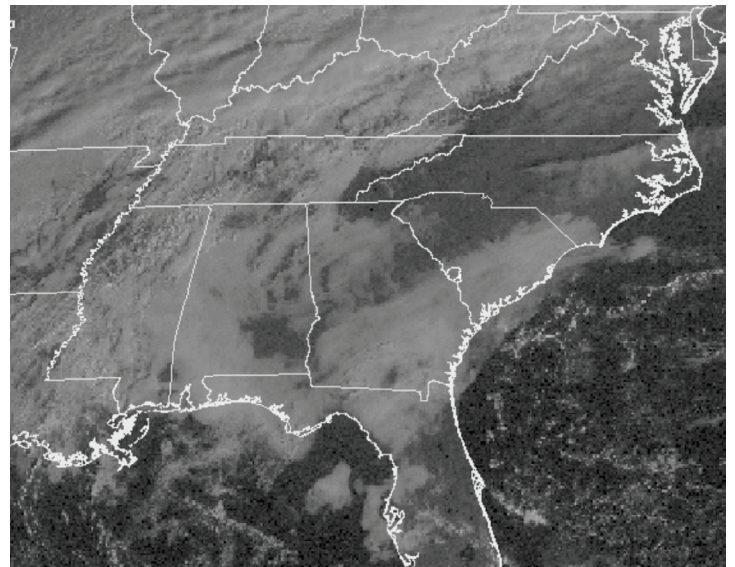
Fig. 4b. GOES visible satellite imagery from 1000 LST, 30 January 2002 for the southeastern United States.

not be able to detect drainage flows near the accident site, a numerical model simulation of airflow in this area was conducted with the 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,

3. Simulations

The topography of the Upper Three Runs River 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, resulting in the transport of residual smoke to the highway. Since available observations would

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 1976). 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. 5), in agreement with observations. The measurements at the CL tower indicated southwesterly to westerly flow at 18, 36, and 61 m above ground level (AGL) with speeds between 1 and 5 m s^{-1}, before shifting to southerly by early morning. Note that observed winds nearest the surface (4 m AGL) are south to southeast from late afternoon to early the next morning and quite light. 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 that surface conditions on a regional scale were well-represented by the model 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.
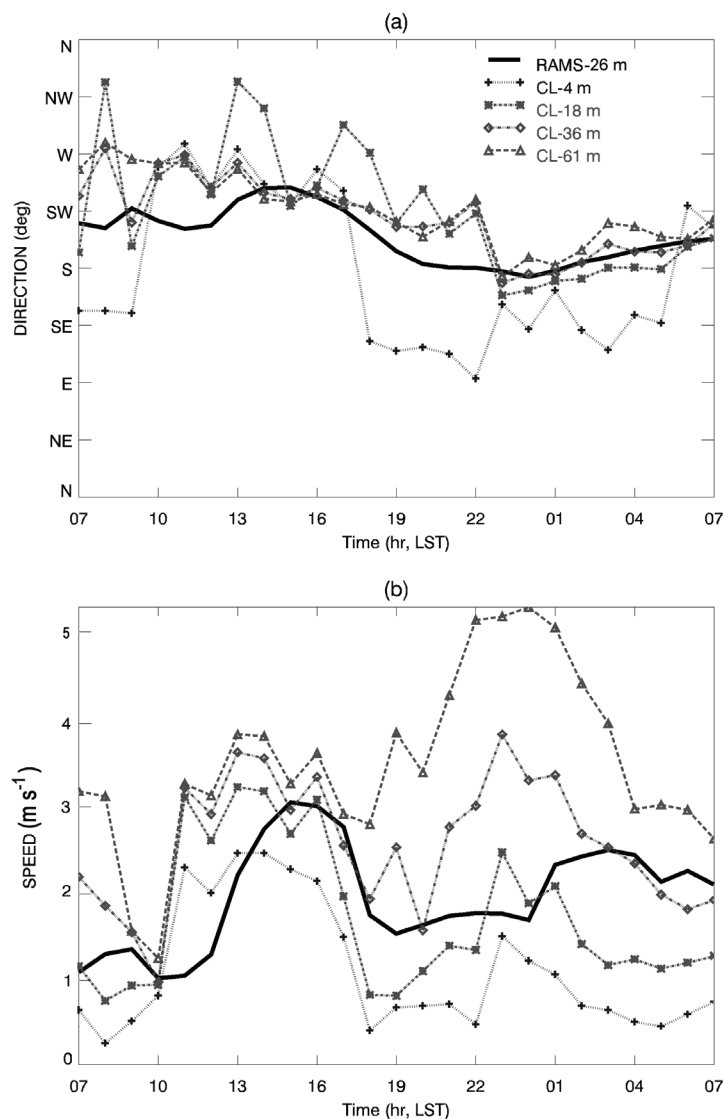
Fig. 5. Comparison of regional RAMS simulation with observations for the 24-hr period beginning 0700 LST 29 January, 2002. (a) Wind Direction, (b) Wind Speed.

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 the Upper Three Runs River Valley 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. 6. In addition, 23 vertical levels were used with the lowest level above ground at 10 m and the model top at 7100 m.

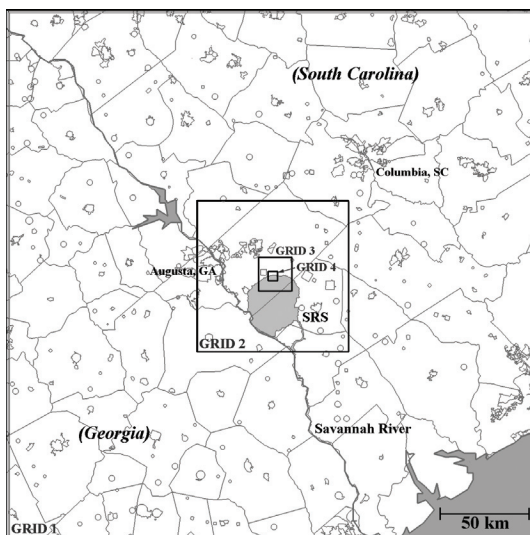| GRID	1	2	3	4
Horizontal Grid Spacing (m)	10240	2560	640	160
East-West Grid Points	30	34	30	34
North-South Grid Points	30	34	30	34
Topography Resolution (m)	10000	1000	500	90
Timestep (sec)	8	4	1	0.25

Table 1. Input characteristics used in RAMS.

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. 6). The simulation began at 0100 LST 29 January 2002. While the total simulation time was 30 hours (ending at 0700 LST 30 January 2002), only the final 18 hours were utilized in the analysis (beginning at 1300 LST 29 January 2002).
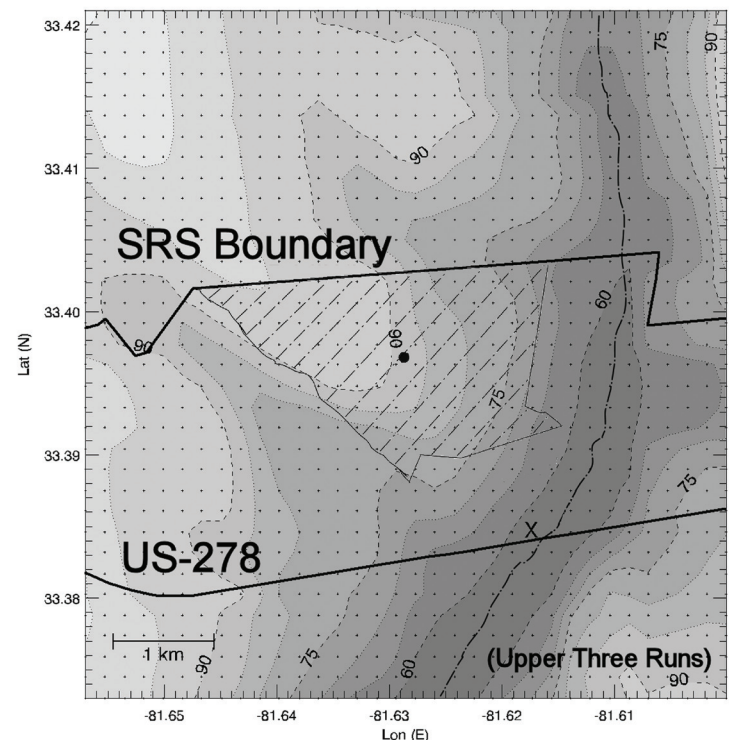
Further detail for the innermost grid topography (Dx = 160 m) is shown in Fig. 7. The circle in Fig. 7 indicates the central location of the USFS burn during the prior day, while the cross-hatched area denotes the spatial coverage. The 'X' denotes the approximate location of the traffic accident. Total 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. 8 for two times. At 0000 LST, the winds are somewhat uniform from the south, while at 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 9 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. 9 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.

Fig. 7. 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 extent of the USFS prescribed fire burn compartment is indicated by the cross-hatched area. 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.


Fig. 6. Region of interest for this modeling study. County and city outlines are also indicated. Grids denote domains used to generate meteorology during the event.
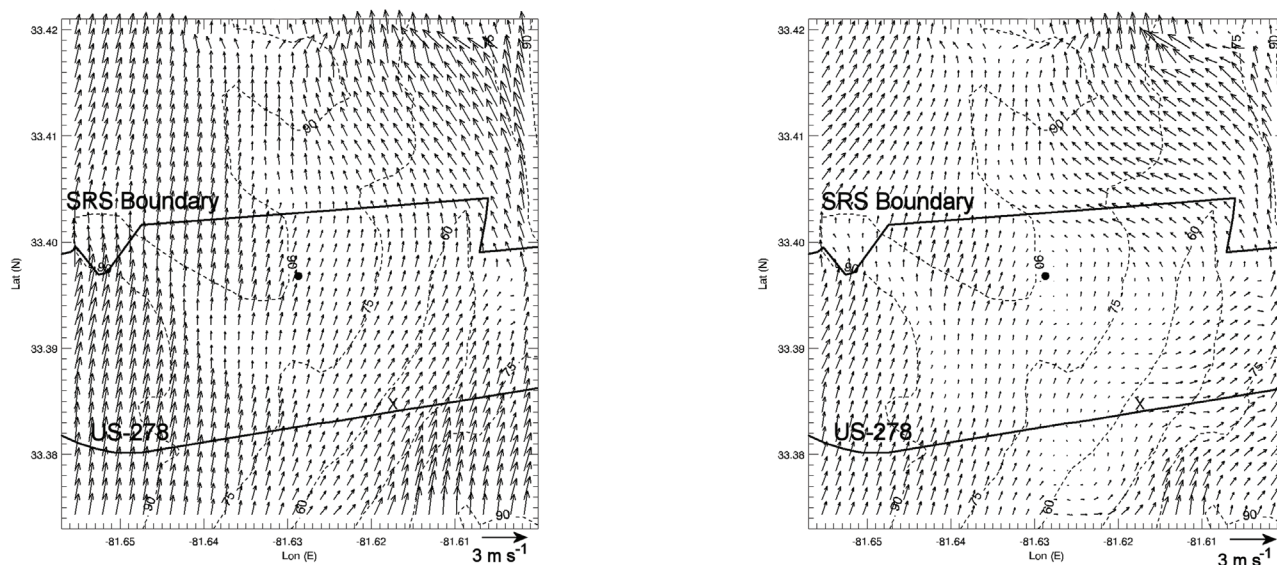
Fig. 8. Surface (10-m) winds as predicted using the innermost RAMS domain (Dx = 160 m) at (a) 0000 LST and (b) 0400 LST. The center of the USFS prescribed fire is given by the circle (●), while the approximate location of the traffic accident is given by the (X) along US-278.
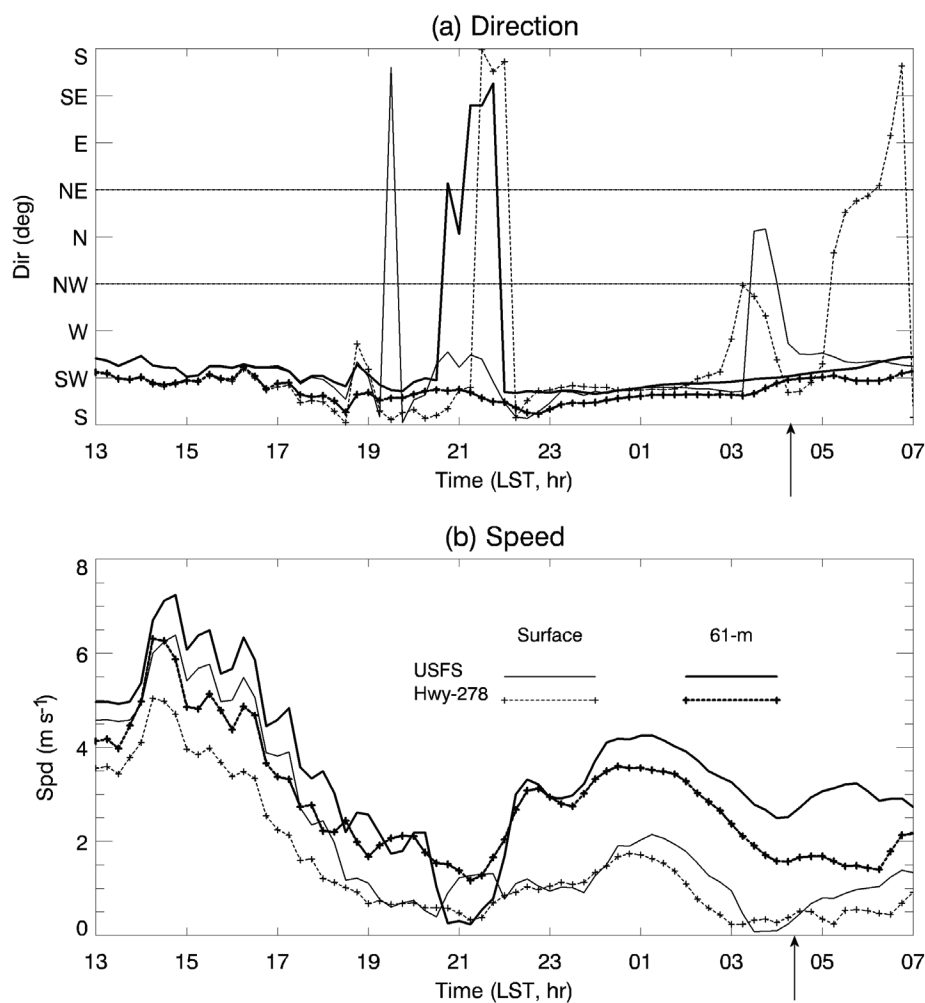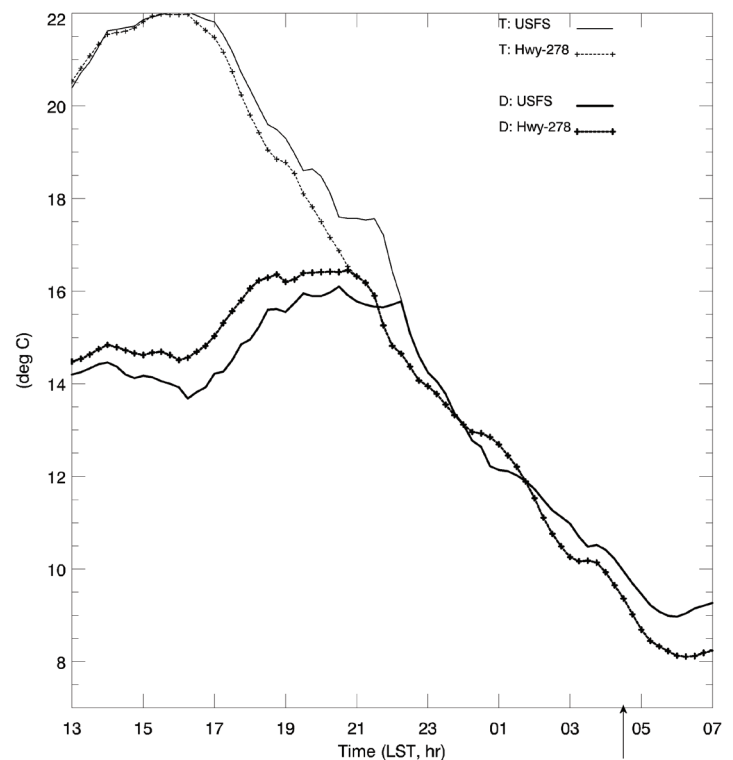

Fig. 9. Simulated winds from 1300 LST 29 January to 0700 LST 30 January, 2002 at 10 m AGL (thin lines) and 61 m AGL (thick lines) as interpolated on the innermost grid to the burn (USFS) and accident locations (Hwy-278). (a) Wind Direction, (b) Wind Speed. The vertical arrow indicates the approximate time of the incident.

For the near-surface conditions, wind speeds were very low after 1900 LST (<2 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. 9, 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 due to transport occurring during the brief period of light and variable winds. However, for 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. 10. The solid lines indicating the USFS burn site reveal saturated air near the surface by 2200 LST, while the dashed lines with markers 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).

The results provided in Figs. 8-10 represent results from a single simulation. An ensemble simulation set using the same grid structure as previously described was also performed to provide a measure of confidence in the results. A series of twelve different RAMS simulations was performed by using: (a) three options for the radiation parameterization, (b) two sets of minimum horizontal diffusion coefficients assumed for each grid, and (c) two weighting options for the Newtonian relaxation, affecting the strength of the lateral and internal nudging used during the model integration. An example of the results for wind direction at the scene of the accident along Highway 278 for the period 2000 LST, 29 January to 0600 LST, 30 January is shown in Fig. 11 for both the 10-m and 61-m levels (compare with Fig. 9a). The individual members are given by lighter lines, while the vector average is indicated by the bold lines. In three of the cases at the 10-m level, winds were predicted

Fig. 10. Simulated temperature (T) and dewpoint (D) from 1300 LST 29 January to 0700 LST 30 January, 2002 at 10m AGL as interpolated on the innermost grid to the burn and accident locations. The vertical arrow indicates the approximate time of the incident.
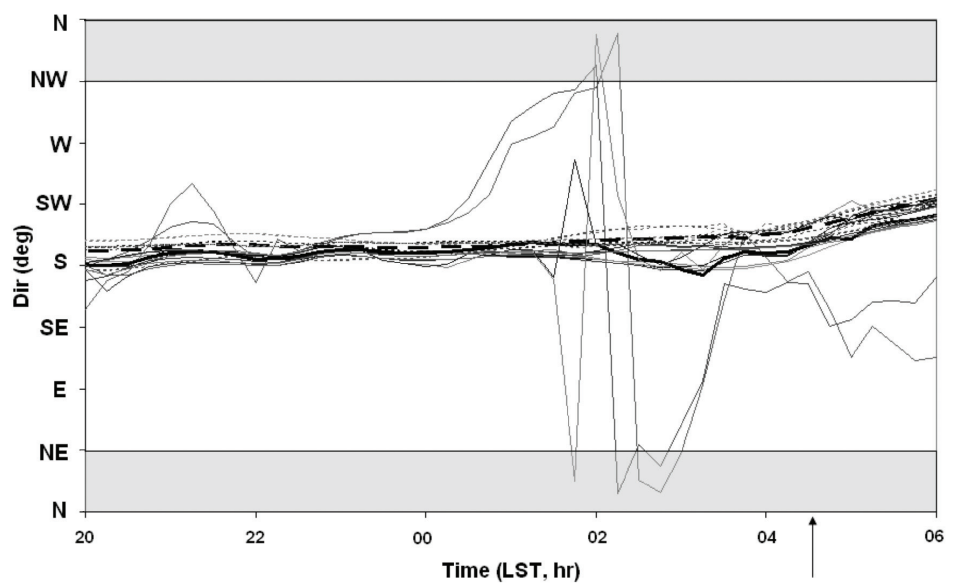
Fig. 11. Simulated wind direction for the ensemble RAMS simulation members from 2000 LST 29 January to 0600 LST 30 January, 2002 at 10 m AGL (solid lines) and 61 m AGL (dotted lines) as interpolated on the innermost grid to the accident locations. The bold lines indicate a vector mean of the ensemble results, while the vertical arrow indicates the approximate time of the incident.
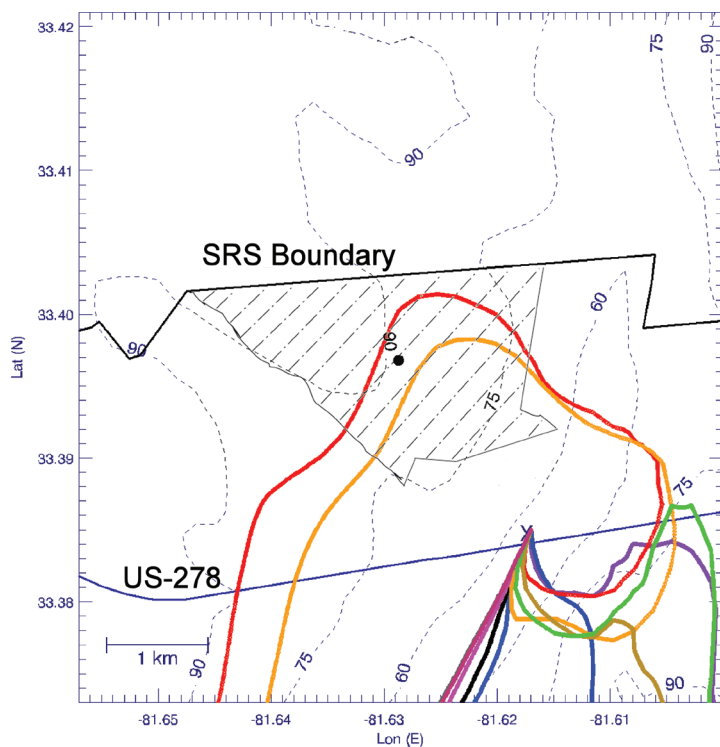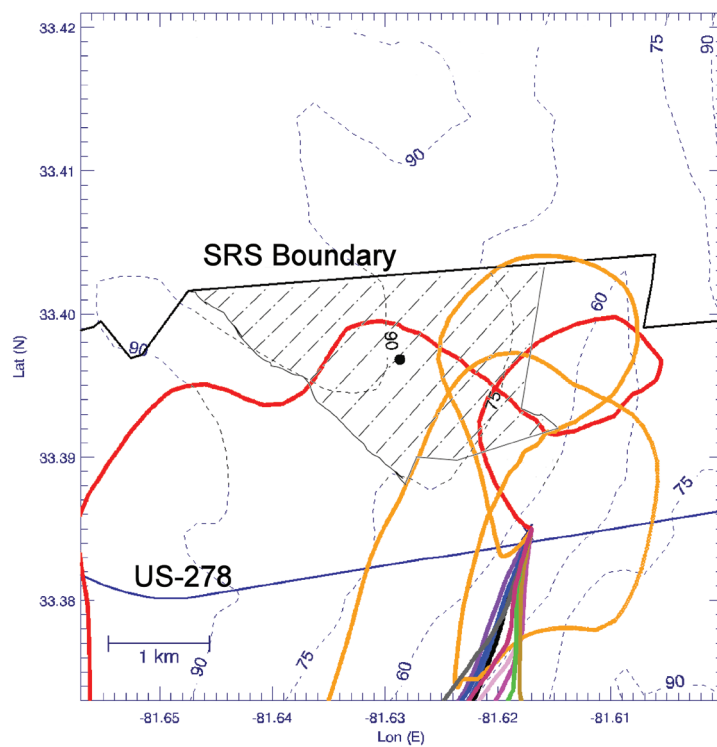
Fig. 12a. Simulated back-trajectories (thick colored lines) using RAMS meteorology from the innermost grid of the ensemble set starting at 0100 LST. Each trajectory represents use of a different ensemble member set. Topography is shown as dashed lines at 15-m intervals. The extent of the USFS prescribed 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.

Fig. 12b. Same as Fig.12a, except at 0315 LST.

to shift around to a direction between NW and NE, but this occurred between 0145 and 0300 LST, well over an hour before the accident. The speeds during these times for these realizations were relatively light (between 0.5 and 1.5 m s^{-1}, not shown). At the 61-m level, all of the simulations predict wind directions between S and SW for the entire overnight period. Similar analysis of ensemble winds at the burn location indicated even less variability in the ensemble members. This is by no means an exhaustive study of model perturbations that could have been performed. However, this exercise does illustrate the point that a strong consensus of the simulations does not support a sustained transport from the burn location to the accident site during the overnight period.

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 12 shows a map of the region (as in Fig. 7) with two back-trajectories indicated for times of 0100 and 0315 LST, using the results from the ensemble simulations. Note also the cross-hatched area indicating the burn compartment from the previous day. From Fig. 11, it is evident that winds along US-278 at 0100 LST were from the south-southwest at both 10-m and 61-m AGL for the majority of the simulations. As expected, the resulting trajectories shown in Fig. 12a trace an air-mass originating from the southwest in many of the ensemble members. Others indicate some transport coming from the south and east, while only two trace back to the burn compartment. On the other hand, for the back-trajectories beginning at 0315 LST (Fig. 12b), all but two of the ensemble members indicate strong transport originating from the southwest. The two simulations with potential transport from the burn compartment indicate a very circuitous route indicating lighter wind speeds in the vicinity of the burn area. The ensemble of trajectories confirms that wind directions generally do not support transport from the burn compartment to the crash site in the hours leading up to the accident. Based on these simulations, the only time in which direct transport from the burn compartment to the crash site is possible occurs at roughly 0200 LST (Fig. 11) from a small minority of the simulations.

4. Discussion and Conclusions

This case study clearly demonstrates that effective planning and execution of prescribed fires near roadways requires close coordination between operational weather forecasters and fire managers over the full life cycle of the fire. Previous studies have documented the hazards posed by the interaction of residual smoke, particulates, and excess moisture from a smoldering fire with fog. In this study, available observations and detailed numerical simulations were used to illustrate the potential contribution of local density-driven drainage flows as a mechanism for transporting these fog-enhancing residual emissions to a nearby roadway.

The USFS-SR 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 most of the visible smoke from the burn had dissipated. A multi-vehicle accident occurred the following morning at 0430 LST.

Observations from the SRS meteorological towers, GOES image products, and NWS surface observations and upper air soundings indicated 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 from the north or northwest (e.g., see Fig. 7) could, in principle, occur. However, the observational data and large-scale numerical simulations for the day of the accident also show that the mesoscale flow across the SRS was mainly from the south and southwest during and after the burn period. The base simulation conducted for this event, as well as all members of an ensemble of detailed simulations, reveals mainly southerly winds down to the surface, except for brief periods of light and variable flow roughly one to three hours before and after the accident occurred. Based on these simulations, back-trajectory calculations, and local wind measurements, the prevailing southwesterly winds likely inhibited drainage from the burn site down the Upper Three Runs River Valley to the intersection with US 278. The brief periods of northerly flow in the detailed simulation imply a possibility for transport of perhaps small amounts of residual 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 likely to have been noticeably enhanced due to an increased presence of condensation nuclei. Rather, a dense fog induced by the prevailing meteorological conditions, with some possible natural enhancement due to the presence of relatively cooler, moister air within the creek valley, is believed to be 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, the on-scene reports of a smell of smoke alone are not sufficient to preclude the results of this study.

Future work in this area would involve using a more detailed numerical simulation with activated microphysics together with visibility parameterizations (e.g., Gultepe et al. 2006). In this way, fog formation, development, and decay could be better documented and used for accident prevention as well as search and rescue operations (Gultepe et al. 2009).

Authors

Dr. Robert L. Buckley is a Fellow Engineer with the Savannah River National Laboratory (SRNL) operating at the Savannah River Site in Aiken, South Carolina. He received a Ph.D. in Mechanical/Aerospace Engineering from the University of Missouri-Columbia in 1993.

Charles H. Hunter is a Fellow Meteorologist and currently the Program Manager of the Atmospheric Technologies Group at the SRNL. He received his M.S. in Meteorology from Florida State University in 1979. Both authors have interests in the meteorological aspects of nuclear and non-nuclear emergency response.

References

Agency for Toxic Substances and Disease Registry, cited 2001: Medical management guidelines. [Available online at http://www.atsdr.cdc.gov/MMG/index.asp.]

Benjamin, S. G., K. J. Brundage, and L. L. Morone, 1994: The Rapid Update Cycle. Part I: Analysis/model description. NOAA Technical Procedures Bulletin No. 416, 16pp.

Buckley R. L., A. H. Weber, and J. H. Weber, 2004: Statistical comparison of Regional Atmospheric Modelling System forecasts with observations. *Meteorol. Appl.* 11, 67-82.

Davies, H. C., 1976: A lateral boundary formulation for multi-level prediction models. *Quart. J. Roy. Meteor. Soc.* 102, 405-418.

Dickinson, R. E., A. Henderson-Sellers, P. J. Kennedy, M. F. Wilson, 1986: Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. NCAR Tech Note NCAR/TN-275+ST, 69pp.

Gultepe, I., M. D. Müller, and Z. Boybeyi, 2006: A new visibility parameterization for warm fog applications in numerical weather prediction models. *J. Appl. Meteor.* 45, 1469-1480.

_____, G. Pearson, J. A. Milbrandt, B. Hansen, S. Platnick, P. Taylor, M. Gordon, J. P. Oakley, and S. G. Cober, 2009: The Fog Remote Sensing and Modeling Field Project. *Bull. Amer. Meteor. Soc.* 90, 341-359.

Hardy, C.C., R. D. Ottmar, J. L. Peterson, J. E. Core, and P. Seamon 2001: *Smoke Management Guide for Prescribed and Wildland Fire, 2001 Edition.* National Wildfire Coordinating Group, NFES 1279. 226pp. [Available online at http://www.nwcg.gov/pms/pubs/SMG/SMG-72.pdf].

Hunter, C. H., R. L. Buckley, R. L., and D. Shea, 2001: Operational weather support for fire management at the DOE's Savannah River Site. *Proc, Fourth Symposium on Fire and Forest Meteorology*, Reno, NV, 2001, Amer. Meteor. Soc., 189-194.

Lee, T. F., F. J. Turk, and K. Richardson, 1997: Stratus and fog products using *GOES-8-9* 3.9-*u*m Data. *Wea. Forecasting* 12, 664-677.

National Oceanic and Atmospheric Administration, cited 2002: Daily Weather Maps. [Available Online at http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html through the NOAA Central Library Data Imaging Project.] Accessed November 2011.

Pielke, R. A., 1984: *Mesoscale Meteorological Modeling.* Academic Press, Inc., 612 pp.

_____, W. R. Cotton, W. R., R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, N. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system—RAMS. *Meteor. Atmos. Phys.* 49, 69-91.

Sandberg, D. V., and F. N. Dost, 1990: Effects of prescribed fire on air quality and human health. *Natural and Prescribed Fire in Pacific Northwest Forests.* J. D. Walstad, S. R. Radosevich, D. V. Sandberg, Eds., Oregon State University Press, pp. 91-298.

Uliasz, M., 1993: The Atmospheric Mesoscale Dispersion Modeling System, *J. Appl. Meteor*. 32, 139-149.

Warner, T. T., R. A. Peterson, and R. E. Treadon, 1997: A tutorial on lateral boundary conditions as a basic and potentially serious limitation to regional numerical weather prediction. *Bull. Amer. Met. Soc.* 78, 2599-2617.