# 6.3 TRENDS IN ESTIMATED MIXING DEPTH DAILY MAXIMUMS

R. L. Buckley*[§], A. DuPont[†], R. J. Kurzeja[§], and M. J. Parker[§]
[§]Savannah River National Laboratory
[†]South Carolina Universities Research and Education Foundation (SCUREF)

## 1. INTRODUCTION

Mixing depth is an important quantity in the determination of air pollution concentrations. Fire-weather forecasts depend strongly on estimates of the mixing depth as a means of determining the altitude and dilution (ventilation rates) of smoke plumes. The Savannah River United States Forest Service (USFS) routinely conducts prescribed fires at the Savannah River Site (SRS), a heavily wooded Department of Energy (DOE) facility located in southwest South Carolina. For many years, the Savannah River National Laboratory (SRNL) has provided forecasts of weather conditions in support of the fire program, including an estimated mixing depth using potential temperature and turbulence change with height at a given location.

This paper examines trends in the average estimated mixing depth daily maximum at the SRS over an extended period of time (4.75 years) derived from numerical atmospheric simulations using two versions of the Regional Atmospheric Modeling System (RAMS). This allows for differences to be seen between the model versions, as well as trends on a multi-year time frame. In addition, comparisons of predicted mixing depth for individual days in which special balloon soundings were released are also discussed.

## 2. BACKGROUND

Two versions of a prognostic model are considered in this study. The Regional Atmospheric Modeling System (RAMS, versions 3a and 4.3) (Pielke et al., 1992; Cotton et al., 2003) is a three-dimensional, finite-difference numerical model used to study a wide variety of atmospheric motions. Referral to these models will be denoted by R3a and R43 throughout the remainder of this paper. Basic features of the model include the use of non-hydrostatic, quasi-compressible equations and a terrain-following coordinate system with variable vertical resolution. The prognostic model is used routinely at the SRS to provide forecasts on both regional and local scales (Fig. 1). The RAMS model is capable of simulating a wide range of atmospheric motions due to the use of a nested grid system. Other features are discussed in the references. Improvements in the newer version (R43) include the use of a new land-surface scheme, as well as parallel computing options.

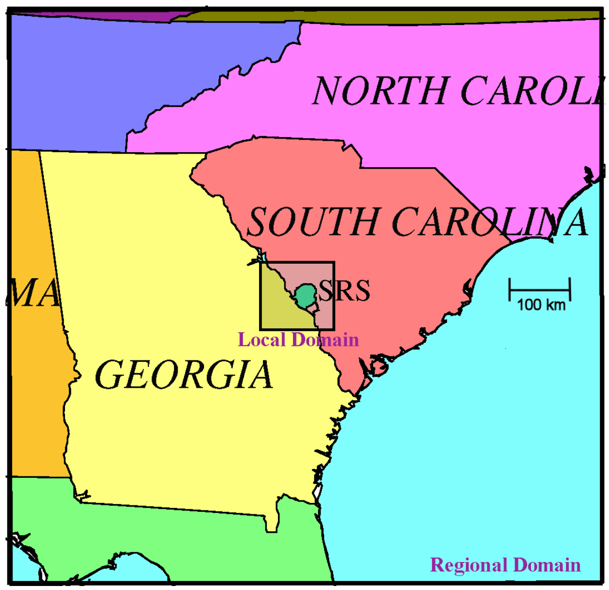


*Figure 1: Modeling domains used operationally at SRNL.*

Large-scale data are available in real time from a variety of sources, although the data used in this application is from the National Oceanic and Atmospheric Administration (NOAA). These larger-scale data are used to generate initialization files in RAMS containing the three-dimensional larger-scale observational data interpolated to the RAMS (polar-stereographic) model grid. The initialization file in RAMS corresponding to the starting time in the simulation is then used to create an initial condition for the entire three-dimensional RAMS model grid. Lateral boundary conditions are also provided at various time increments using a Newtonian relaxation scheme to drive (nudge) the

**Corresponding author address*: R. L. Buckley, Savannah River National Laboratory, Savannah River Site, Aiken, SC 29808 (USA); e-mail: robert.buckley@srnl.doe.gov

prognostic variables toward the forecasted large-scale values using linear interpolation in time (Davies, 1976). The model is allowed to 'spin-up' a realistic atmospheric boundary layer for the first 12 hours of a 48-hr simulation. Thus, the final 36 hours of simulation are used in the forecasts.

In this application, the regional domain utilizes 20-km horizontal grid spacing to generate forecasts of meteorological conditions over the two-state region covering Georgia and South Carolina (Fig. 1). There are over 30 vertical levels in the model telescoping from ~50 m at the surface to one kilometer at the model top. The lowest model level is ~25 m above ground level (AGL).

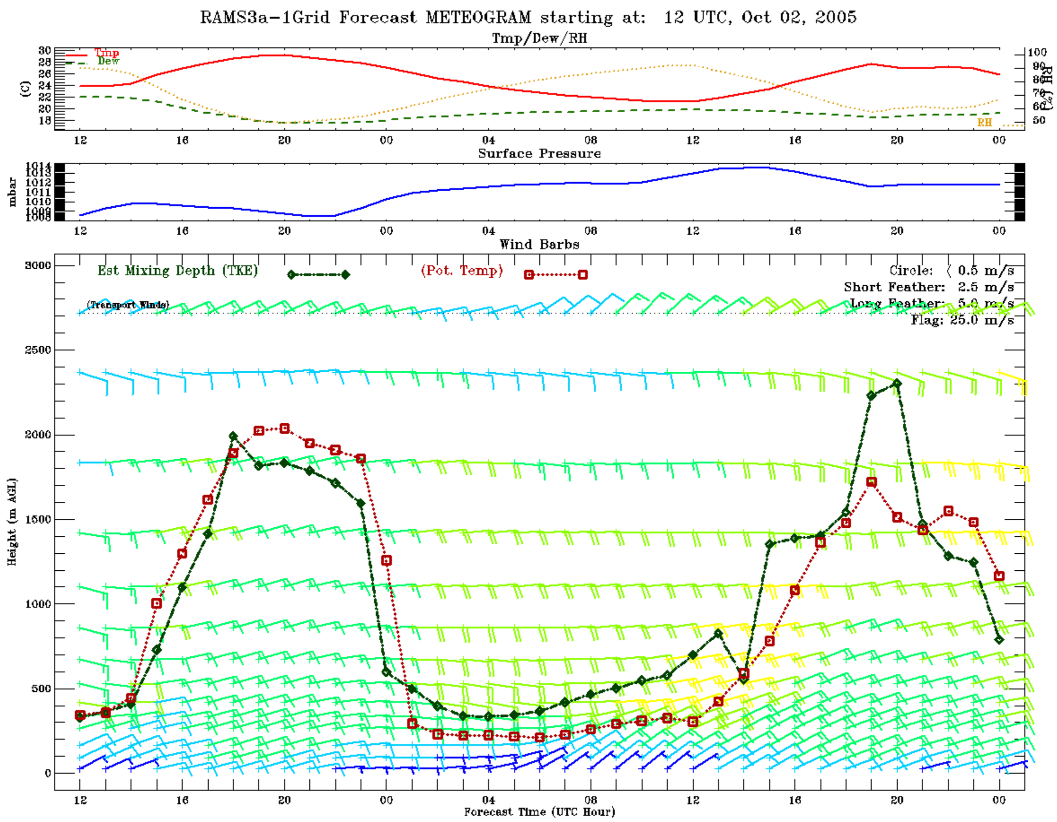


*Figure 2: Example meteogram from 02 October, 2005 generated from RAMS operational output. Wind barbs along the topmost line represent 'transport wind', i.e., the average speed and direction through the mixing depth.*

Fire-weather forecasts are provided to the USFS on a twice-daily basis in support of smoke management practices. Guidance for developing the detailed forecast includes a custom fire-weather meteogram of simulated conditions using RAMS for a nominal, central SRS location over a 36-hr forecast period. The example shown in Fig. 2 provides a time-series of near-surface temperature, relative humidity, dew point and pressure. Also shown are variations of wind speed and direction over the lowest 2500 m of the atmosphere, with estimates of the mixing height superimposed over the wind profiles. The estimates of the mixing depth are derived from the vertical gradient of turbulent kinetic energy (TKE) and potential temperature gradient.

## 3. RESULTS

### 3.1 *Trends*

An archive of RAMS-derived meteogram forecasts is maintained by SRNL for the past several years. Trends in the maximum estimated mixing depth were generated using the potential temperature gradient assumption (i.e. the red dotted line in Fig. 2). In addition, since USFS prescribed fires are conducted only during the daytime at SRS, and because forecasts are updated twice per day (i.e. using 00 UTC and 12 UTC analysis cycles), it was decided to limit the maximum chosen mixing depth to the earliest 12-hr time period starting at 12 UTC (7 or 8 AM LST). Thus, for a 00 UTC analysis cycle, this corresponds to forecast hours 12 to 24, while for a 12 UTC analysis cycle, this corresponds to forecast hours 24 to 36. Finally, days where RAMS did not run properly, or when windy and overcast or foggy conditions were predicted, were not considered in the trends.

Average maximum mixing depths at SRS were calculated on a monthly basis using forecast meteograms beginning on 01 January 2003. For the example shown in Fig. 2, the maximum estimated mixing depth is 2100 m at 20 UTC (16 EDT). This was done for R3a and R43 for both 00 UTC and 12 UTC cycles. (Note that 2005 R43 data were not available for analysis).

The results for the period January 2003 to September 2007 are given in Fig. 3. This figure shows results for R3a (blue and green lines) and R43 output (red and brown lines). In addition, dashed lines denote a 00 UTC (Z) cycle start time, while solid lines denote a 12 UTC (Z) cycle start time. Note that over 1700 simulations are factored into each line shown in Fig. 3.

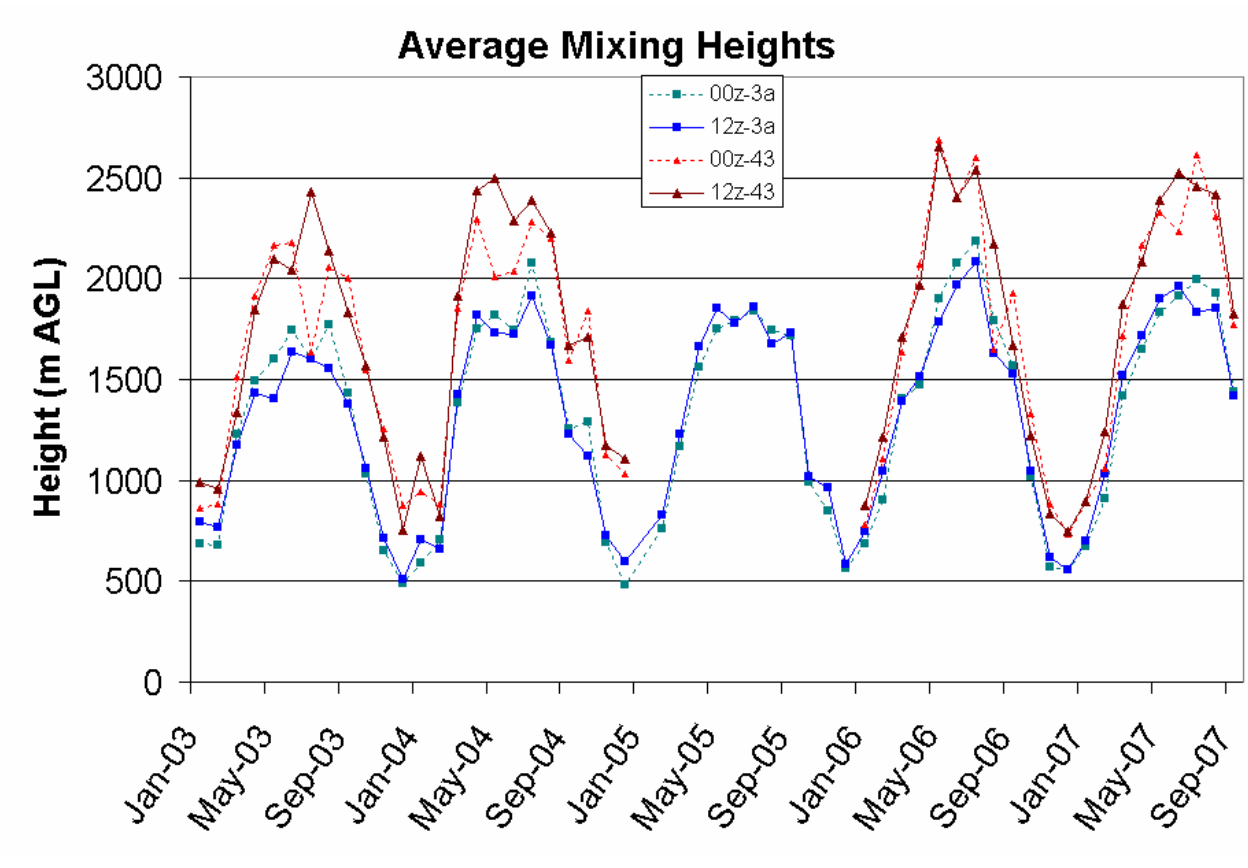


*Figure 3: Average monthly mixing depth as generated using RAMS (R3a and R43) for the period January 2003 to September 2007.*

It is readily apparent that maximum mixing depth values for R3a are lower than for R43 at almost all times. Inspection of daily maximum temperatures from each model reveals that R43 tends to predict higher daytime maximums, which in turn would lead to higher estimated mixing depths. This discrepancy between the models is likely related to the surface parameterization differences. In R43, the Land Ecosystem-Atmosphere Feedback (LEAF-2) model is used to describe the surface boundary conditions (Walko et al, 2000). A key difference from R3a is that patches are used in LEAF-2 to allow for finer-scale variations in surface characteristics (i.e. vegetation type, terrain slope, water bodies), allowing for differing responses based on fractional coverage within a given cell. In addition, modifications to a hydrology model allows for lateral transport of water within saturated regions of the soil. These differences lead to changes in subsequent heat and moisture fluxes to the atmosphere, thus altering surface temperatures between R3a and R43.

Figure 3 also indicates that the maximum average mixing depth was lower during the summer of 2003 than in more recent summers. Comparison with local meteorological observations at SRS support the lower overall mixing depth estimates during 2003. Table I shows several variables measured during the period May to September for the five years considered in this study. Total precipitation measured at SRNL for each of the 5 years indicates significantly more rain fell in 2003 than in later years. In addition, solar radiation (as averaged over each 15-minute period between 12 and 00 UTC) is lower in 2003, along with the average surface temperature. These are all indicative of increased cloud cover and a reduced average mixing depth. The heat stress (*HS*) is a parameter derived for worker safety that is a function of the wet bulb globe temperature (WBGT). The WBGT can be estimated using standard meteorological measurements including temperature, humidity, incoming solar radiation, and wind speed (Hunter and Minyard, 2000). Values of heat stress range from 0 (no effect) to 5 (maximum heat stress). For these comparisons, a total count of the number of occurrences of stress at least 3 ($HS_3$) was determined for each year. As expected, there are fewer occurrences of the more dangerous heat stress categories in 2003.

| Year | $P$ (mm) | $S$ (W/m$^2$) | $T_{avg}$ (°C) | $HS_3$ |
|---|---|---|---|---|
| 2003 | 813.6 | 430.2 | 26.3 | 1300 |
| 2004 | 694.2 | 458.1 | 27.5 | 1402 |
| 2005 | 481.8 | 445.2 | 27.1 | 1722 |
| 2006 | 416.3 | 479.0 | 27.6 | 1453 |
| 2007 | 455.9 | 476.0 | 27.8 | 1609 |

*Table 1: Observed meteorological variables at SRS (May to September)*

$P$: Total precipitation
$S$: Average solar radiation per 15-min period as determined from 12:00 UTC to 23:45 UTC
$T_{avg}$: Average temperature (2 m AGL) as determined from 12:00 UTC to 23:45 UTC
$HS_3$: Number of occurrences (15-min period) with Heat Stress at least category 3

### 3.2 *Specific Soundings*

Almost fifty separate balloon-borne sonde derived soundings have been collected at SRNL since 2003. These data are used to assess the accuracy of the forecasted mixing depth from RAMS. A previous study by Hanna and Yang (2001) examined a variety of mesoscale model output parameters, including estimates of mixing depth, and found that model simulations of daytime mixing depths were often within ±20% of the observations. Table 2 shows the date and time of the soundings, along with the observed mixing depth (to the nearest fifty meters). The mixing depth was determined from discontinuities in the vertical gradients of temperature and dewpoint. In some cases the vertical variations of wind speed and direction were examined by were often inconclusive. The uncertainty in the observed mixing depth is estimated to be ~100 meters. Also shown in the table are simulated values of mixing depth at the time of the observation for both RAMS versions (R3a, R43) and for different cycle start times. (Simulations which are missing are indicated by an 'x'). Estimates within ±20% of the observations are additionally indicated in bold font.

Considering both models and all forecast lead times, roughly 40% of all simulated mixing depths are within ±20% of the measured value. However, it is evident that the newer version of RAMS (R43) tends to agree more closely with the observed mixing depth. Roughly one-third of the simulated mixing depths using R3a, and one-half of the R43 simulated mixing depths were within ±20% of the measurements. For comparison, Hanna and Yang found RAMS to agree roughly 60% of the time for this threshold. The lower agreement in this study is possibly to due to coarser grid resolution. The prior study used a nested grid with an inner horizontal grid spacing of 4.5 km (as opposed to 20 km here) and a vertical grid spacing of ~10 m near the surface (as opposed to ~25 m here). Nonetheless, the improved surface parameterizations utilized in R43 have resulted in better simulation of mixing depth. It is also worth noting that the tendency is to underestimate the mixing depth using R3a and R43.

| | Time | Mixing Depth (m) | | | | |
|---|---|---|---|---|---|---|
| Date | EST | *OBS* | R3a: 00 | R3a: 12 | R43: 00 | R43: 12 |
| 24-Feb-03 | 10:00 | *400* | 100 | 50 | 150 | 100 |
| 24-Feb-03 | 15:00 | *1400* | 1050 | 650 | **1350** | **1300** |
| 10-Mar-03 | 10:00 | *700* | 450 | 300 | **750** | 450 |
| 10-Mar-03 | 15:00 | *1900* | 1350 | 1350 | **1550** | **1700** |
| 11-Mar-03 | 14:20 | *1400* | 1850 | **1650** | 1750 | **1650** |
| 04-Apr-03 | 10:15 | *1100* | 500 | 450 | **1050** | **950** |
| 04-Apr-03 | 15:00 | *1400* | 1700 | **1600** | 2150 | 1850 |
| 19-Aug-03 | 13:25 | *1100* | 1700 | 1900 | **1150** | × |
| 11-Feb-04 | 10:40 | *600* | **550** | 400 | × | **500** |
| 11-Feb-04 | 15:25 | *900* | 550 | 300 | × | 450 |
| 19-Feb-04 | 10:20 | *350* | 100 | 200 | 250 | 200 |
| 19-Feb-04 | 15:40 | *1200* | 600 | 550 | 950 | 900 |
| 20-Feb-04 | 09:54 | *500* | 150 | 100 | **450** | 150 |
| 20-Feb-04 | 15:15 | *1900* | 750 | 750 | 1500 | 1200 |
| 23-Feb-04 | 10:05 | *450* | 150 | 200 | 350 | 550 |
| 23-Feb-04 | 14:58 | *1250* | 200 | **1050** | 350 | **1500** |
| 01-Mar-04 | 14:05 | *2350* | 1850 | 1650 | **2150** | × |
| 02-Mar-04 | 10:13 | *700* | 500 | **600** | **600** | **800** |
| 02-Mar-04 | 15:00 | *2000* | **1900** | **1900** | **2300** | **2300** |
| 03-Mar-04 | 10:20 | *450* | 350 | 350 | 1200 | 850 |
| 03-Mar-04 | 15:02 | *1900* | **1650** | **1700** | **2050** | **2150** |
| 04-Mar-04 | 09:58 | *350* | **300** | **300** | 450 | 450 |
| 04-Mar-04 | 14:23 | *2200* | 900 | 350 | 1600 | 1200 |
| 05-May-04 | 09:06 | *450* | 200 | 200 | 650 | **450** |
| 06-Jun-04 | 09:10 | *600* | **600** | **550** | **500** | 900 |
| 18-Jun-04 | 14:02 | *1500* | **1750** | **1700** | 1000 | 150 |
| 04-Mar-05 | 12:50 | *2000* | 1100 | 650 | × | × |
| 09-Mar-05 | 13:48 | *1200* | **1250** | **1300** | × | × |
| 10-Mar-05 | 13:25 | *1800* | 1400 | 1300 | × | × |
| 22-Mar-05 | 13:01 | *1200* | 450 | 450 | × | × |
| 24-Mar-05 | 13:15 | *1200* | **1000** | **1050** | × | × |
| 25-Mar-05 | 12:45 | *1800* | 150 | 100 | × | × |
| 30-Mar-05 | 13:55 | *1300* | **1150** | **1050** | × | × |
| 31-Mar-05 | 11:05 | *350* | **350** | 200 | × | × |
| 05-Apr-05 | 10:50 | *2200* | 600 | 450 | × | × |
| 29-Apr-05 | 11:24 | *1050* | 550 | 600 | × | × |
| 14-Feb-06 | 13:45 | *1100* | 650 | 500 | 850 | **900** |
| 15-Feb-06 | 13:10 | *2000* | 550 | 350 | 1050 | 1150 |
| 08-Mar-06 | 12:17 | *1300* | 950 | 450 | **1200** | **1200** |
| 16-Apr-07 | 13:00 | *1650* | **1600** | **1750** | **1800** | **1900** |
| 17-Apr-07 | 13:00 | *1350* | **1100** | 1000 | **1100** | 1050 |
| 18-Apr-07 | 13:00 | *1300* | 2100 | 2050 | 2100 | 1950 |
| 19-Apr-07 | 13:00 | *2700* | 1500 | 2000 | **2250** | **2200** |
| 20-Apr-07 | 13:00 | *1650* | **1500** | **1700** | **1450** | **1700** |

*Table 2: Comparison of Observed and Simulated Mixing Heights*

It is particularly difficult to estimate mixing depth during the earlier times (i.e. ~10 EST). This period of day represents a transition period when the atmospheric boundary layer is growing (Stull, 1988). Error in the time at which this growth occurs leads to errors in the mixing depth estimate. Overall model agreement with observations of mixing depth is improved somewhat if the earlier times (i.e. before 13 LST) are not considered.

## 4. DISCUSSION/CONCLUSIONS

On a monthly basis, seasonal trends are as expected with the highest mixing depth predictions occurring during the summer months, although lower maximum summer values are predicted to occur in the earliest year (2003) of this study. The variation in average mixing depth during the summer months agrees with annual variability in local observations (i.e. average temperature, precipitation, and heat stress).

Comparison of the RAMS simulations with measured mixing depth using balloon soundings at SRS reveals relatively good agreement for many of the simulations. The newer RAMS model (R43) tends to generate more accurate estimates of mixing depth. The vast majority of the soundings were collected during the late winter to early-spring time frame. It would be of interest to gather more data relative to the summer period.

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