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Title: VALIDATION OF COUPLED ATMOSPHERE - FIRE BEHAVIOR MODELS

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VALIDATION OF COUPLED ATMOSPHERE-FIRE BEHAVIOR MODELS

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1) Introduction

Recent advances in numerical modeling and computer power have made it feasible to simulate the dynamical interaction and feedback between the heat and turbulence induced by wildfires and the local atmospheric wind and temperature fields. At Los Alamos National Laboratory, we have developed a modeling system that includes this interaction by coupling a high resolution atmospheric dynamics model, HIGRAD (Reisner et al. 1998), with a fire behavior model, BEHAVE (Andrews 1986), to predict the spread of wildfires. The HIGRAD/BEHAVE model is run at very high resolution (~10 meter grid cells) to properly resolve the fire/atmosphere interaction. At present, these coupled wildfire model simulations are computationally intensive. We believe, however, that coupled modeling represents the future of wildfire behavior prediction, because the fundamental physics contained in the model equations can capture the processes controlling fire spread. The additional complexity of these models require sophisticated methods for assuring their reliability in real world applications. With this in mind, a substantial part of our research effort is directed at model validation.

One of the many challenges encountered in coupled weather/wildfire model simulations has been locating data sources with sufficient resolution to adequately describe the state of the atmosphere, fuel, and fire throughout the history of an event. The necessity of building comprehensive data sets for model testing has led to collaborative research efforts to collect this data from controlled fires. To this end, several instrumented prescribed fires have been conducted with multi-agency support and participation from chaparral, marsh, and scrub environments in coastal areas of Florida and inland California. In this paper, we first describe the data required to initialize the components of the wildfire modeling system. Then we present results from one of the Florida fires, and discuss a strategy for further testing and improvement of coupled weather/wildfire models.

2) The Modeling System

The development of the Los Alamos wildfire modeling system has occurred over the past three years and is still in a rapidly evolving state. A diagram of the wildfire modeling system is shown in Fig. 1. In its present configuration, four models are being used. The three primary components include the Regional Atmospheric Modeling System (RAMS), the model for HIgh resolution and strong GRADient applications (HIGRAD), and FIRETEC, a physics-based fire behavior model. The three primary model components are enveloped by a dashed-line indicating that they are presently targeted at high performance computing (HPC) architectures. Also included in the model flow is the US Forest Service's BEHAVE model, from which several fire behavior subroutines have been extracted and coupled to HIGRAD. The BEHAVE model lies outside the HPC environment due to its low computational demands.

3) Model Initialization Data

Each of the modeling components has specific data input requirements. RAMS is a widely-used, comprehensive atmospheric modeling system based upon fundamental conservation relationships for heat, mass, and momentum transport. A general description of the model can be found in Pielke et al. (1992) and many other publications. Initial data for a RAMS weather forecast is generally obtained from gridded weather data analyses, such as those available from the USA's National Environmental Prediction Center (NCEP) or the European Center for Medium-Range Weather Forecasting (ECMWF). The RAMS model is initialized from these data and used to forecast weather variables, such as wind, temperature, pressure, humidity, and precipitation. The model's nested grids allow these forecasts to cover scales from 1000 km down to local scales in the vicinity of a fire (~1-2 km). This technique is useful for forecasting weather in highly complex terrain where many wildfires occur (Bossert et al., 1998). In the Florida case shown in this paper (section 4), however, such an effort was deemed unnecessary, due to the relative wealth of meteorological observations taken and the flat Florida terrain.

The HIGRAD model is initialized and nudged at the domain boundaries with successive RAMS forecast fields every 10-20 minutes. The model determine the local weather in the vicinity of the fire line. This prediction is strongly influenced by the complex dynamics occurring within the fire as it moves over variable fuel types and complex terrain. In addition to RAMS output, local weather data and fire perimeter data can also be incorporated. These data are useful for initializing HIGRAD or for reinitializing a HIGRAD/BEHAVE simulation that is not generating the observed fire behavior. An example of a useful data source is airborne infrared imagery, which can provide high resolution fire perimeter data for model initialization and also provide ongoing information on fire spread rate, heat intensity, and perimeter for model validation. To provide this data, the Airborne Infrared Disaster Assessment System (AIRDAS) four-channel infrared scanner was flown on a NASA-Ames Lear jet for the prescribed burn case discussed in section 4 to get relevant fire parameters for model testing.

The FIRETEC code is a recent Los Alamos development that describes the combustion process through a fuel canopy with physical equations. As such, the model can make use of very detailed remotely sensed data and ground measurements of fuel type, spatial distribution, and load as a function of height. One source for this data is radiance information from NASA's Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS). This instrument is being used to develop new data sets of vegetation type, canopy water content, and other relevant parameters at 20 meter resolution in California (Roberts et al. 1997). We are presently collaborating to use this information to improve the spatially-explicit representation of fuel for fire modeling. Adding other data layers to this spatial fuels data for total available fuel biomass, live/dead fuel moisture ratios, and vertical structure of the fuel canopy should greatly improve the accuracy of fire spread predictions.

The BEHAVE model is a point-based fire behavior model that we have extended to two-dimensions with a fire-front interface tracking method (see Reisner et al. 1998). The spread rate, heat amount, and flame length are predicted from Rothermel's (1972) equations. The model requires wind speed and direction, terrain slope amount, fuel type and fuel moisture as input. The winds and slope parameters are provided by HIGRAD, while the fuels information can come from a number of sources including that derived from satellite and ground sampling for the National Fire Danger Rating Systems fuel models (Burgan et al. 1998). This 1-km database covers the coterminous United States. For the high resolution coupled model validation purposes discussed in section 4, however, we require specialized data sets of fuels and fuel moisture for the specific prescribed burn area. As mentioned above, these can be obtained by high resolution airborne remote sensing instrumentation to get fuel type, combined with ground fuel sampling just before the burn to get fuel moisture. These observations require a substantial, highly coordinated effort. In the next section, we describe results from such an effort.

4) Model Validation

In this section, we describe a prescribed burn experiment for model validation where observations to adequately describe fire behavior were taken. In combination, these observations can provide a reasonably complete picture of the fire behavior. These data were used both to initialize HIGRAD/BEHAVE and to compare simulated results with the actual fire. The simulated fire behavior is compared with the observed data in terms of propagation rate and total burn area. These comparisons help us to examine the strengths and weaknesses of our modeling system and to develop more accurate representations of the critical physical processes controlling fire behavior.

The analysis here uses data from a prescribed burn conducted on April 11, 1997 at the Merritt Island National Wildlife Refuge, which is also on the site of the Kennedy Space Center in Florida, USA. The site was essentially flat, encompassing ~240 hectares of Florida scrub, intermixed with marsh areas and small forest stands. The burn plot is shown in Fig. 2 with some of the corresponding fuel types. A detailed fuel map including both type and height was produced by a combination of airborne imagery and ground sampling (not shown). Both live and dead fuel samples were collected just before the fire. These were processed in a drying chamber to arrive at fuel moisture ratios for the dominant species in the burn area. The fuel moisture values, discussed below, were relatively high for good fire behavior, and this had a strong impact on the vigor of the HIGRAD/BEHAVE simulated fire. The actual fire was ignited by terra-torch along a line cut through the scrub. It took approximately 15 minutes to completely ignite the 0.5 km initial fireline. The ignition process commenced at 1240 LST, ended at 1254 LST, and the fire burned for approximately 35 minutes. A second fireline was lit 0.25 km southeast of the first approximately 30 minutes after the first burn died out. This second fire burned up to the original fireline with vigorous fire behavior, despite the deteriorating weather conditions.

Unfortunately, fuels data and fire progression and intensity were not available for this second fire.

A 150 m tower with 7 levels of meteorological data was located 0.5 km to the south of the initial fireline (see Fig. 2). Tower data, shown in Fig. 3, reveal that wind direction was very steady from the southeast over the 150 m depth of the measurements, throughout the burn period. The wind speed varied between 3 to 5 m/s near the surface and was ~5 m/s at the start of the burn (1240 LST). Wind speeds increased to nearly 10 m/s at the 150 m level. The temperature and relative humidity profiles (Fig. 3b) show that at the start of the burn, and through the first 20-minutes after ignition, the temperature hovered near 23 deg. C near the surface. After this time the temperature decreased, falling to 20 deg. C by the end of the burn. The humidity profiles give some indication as to why the temperature decreased at midday. At the start of the burn humidity levels were near 75%, generally considered too high for strong fire behavior.
Moisture advection and an increase in cloudiness occurred during the burn period. This is shown by the increase in humidity values toward 90% by the end of the burn. Light rain showers occurred toward the end of the second burn around 1415 LST.

Overflights with the AIRDAS four-channel scanning infrared sensor aboard a NASA-Ames Lear jet provided information on fire spread rate and intensity during the burn. The four spectral bands of the sensor are specifically designed to look at very hot fire fronts as well as soil heating behind the fire front and thermal and vegetative characteristics of the surface. The resolution of the scans was approximately 5 m at the ground with a scanning width of 720 pixels. The time history of fire progression, based upon the sensor imagery is show in Fig. 4. The figure shows the uneven ignition with the northernmost (right side of Fig. 4) part of the fireline spreading rapidly into the fuel carried by the southeasterly winds. The fire progression rate was variable, but generally in the range of 0.15-0.25 m/s. The fire intensity derived from the sensor (not shown) reveals that the fire burned vigorously after ignition (flame lengths were estimated at 10-15 m), but died out rapidly after 1315 LST when the main fire front entered into a forested area with much higher live fuel moisture. The combination of wetter fuel type and deteriorating weather conditions acted in concert to curb the intensity of the fire, although the rapidity with which the fire died out is still somewhat mystifying.

The HIGRAD/BEHAVE model was used to simulate this particular prescribed burn. The model was initialized over a rectangular grid with 128 grid elements in the along fire and cross fire directions and with 101 grid cells in the vertical dimension. The grid spacing was 10 m in both the horizontal and vertical, with the top of the grid domain at 1000 m above ground level. The fuels data for the model were based upon the standard 13 BEHAVE fuel categories. The four classes used in the simulation were fuel model (3) - tall grass - to represent the marsh fuels, model (5) - 2 ft brush - to represent the short scrub oak, model (4) - chaparral - to represent the tall scrub, and model (9) - hardwood litter - to represent the forested areas. These fuel classes were mapped to the actual fuels which were digitized using a geographical information system (ArcView). The digitized data was sampled every 10 meters to correspond exactly to the HIGRAD grid mesh. The input fuel moisture data was taken as an average from multiple fuel samples of each dominant vegetation type.
Thus, fuel model (3) for marsh was input with 12% 1-hr dead fuel moisture and 105% 1-hr live fuel moisture. Similarly, fuel models (4) and (5) used 17% dead fuel moisture and 130% live, while fuel model (9) was 28% dead fuel and 150% live fuel moisture.

The HIGRAD code was initialized with meteorological data from the nearby tower mentioned above through the first 150 m of the grid mesh, and with estimates from nearby wind profilers above that level. The simulated fire was ignited in a time dependent sense, just as the actual fire was, along the southern boundary of the grid domain. The coupled model was integrated for a total of 30 minutes, which took several days of real time on a Sun Ultra 200 MHz workstation. The results after 22 minutes are shown in Fig. 5. The simulated fire burned primarily within the marsh and scrub fuel types and was stopped by the wetter hardwood forest, similar to the real fire. The structure of the simulated fire also shows three lobes that burned more readily as in the actual fire, but the dominant (middle) lobe was not well simulated. The rate of fireline advancement was similar overall to the real burn, but tended to be slower in the center lobe. One of the most significant results from the simulated fire was that it was "cool" and never generated much intensity in the BEHAVE code, contrary to the infrared observations of the real burn. This is due to the high dead and live fuel moistures that were observed and used as input to the BEHAVE model. BEHAVE's fire spread calculations are based upon empirical functions that greatly reduce the fire intensity and spread rate for high (> 10%) dead fuel moisture and prevent any fire with dead fuel moistures over 30%. While this may be reasonable in many situations and fuel types, humid Florida conditions combined with relatively volatile fuels seem to allow more intense fires, and these conditions are not presently incorporated in any fuel models.

5) Discussion

The previous sections have shown that intensive experimental efforts can produce data sets for fire behavior model initialization and validation. It seems obvious that more of this type of effort is needed to promote increased understanding of fire behavior and to use this knowledge to improve fire behavior models in real world conditions. To this end, we have collected data on an additional two fires that we hope to present, along with modeling results, at the conference.

The limited success of our HIGRAD/BEHAVE coupled model for simulated the Florida fire in variable fuels points to the need for much more testing and development of fire behavior models in a wide variety of potential burn conditions. One possible way to better calibrate the fuel models in BEHAVE, that determine fire behavior for a range of actual wind and fuel moisture conditions, is with a full-physics fire behavior model. The Los Alamos FIRETEC model (Linn and Harlow 1998), just now being coupled to the HIGRAD atmospheric dynamics code and undergoing testing and validation with prescribed burn data sets. The FIRETEC code provides a way to test, in a relative sense, the impact of fuel load, fuel moisture, slope, and winds on fire behavior in a self-determining way, based upon the physics of combustion. This model could provide the realism needed to build better empirical models of fire behavior. Some initial testing of this concept is presented in Reisner et al (1998). Ultimately, the coupling of HIGRAD to FIRETEC in three-dimensions using RAMS weather predictions for boundary conditions holds the promise of making actual wildfire progression predictions, given an adequate description of the fuels and wind, since this modeling system captures the essential driving physics of weather and fire behavior.

Acknowledgements

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County of Los Angeles Fire Department,
and the Sandia National Laboratory.
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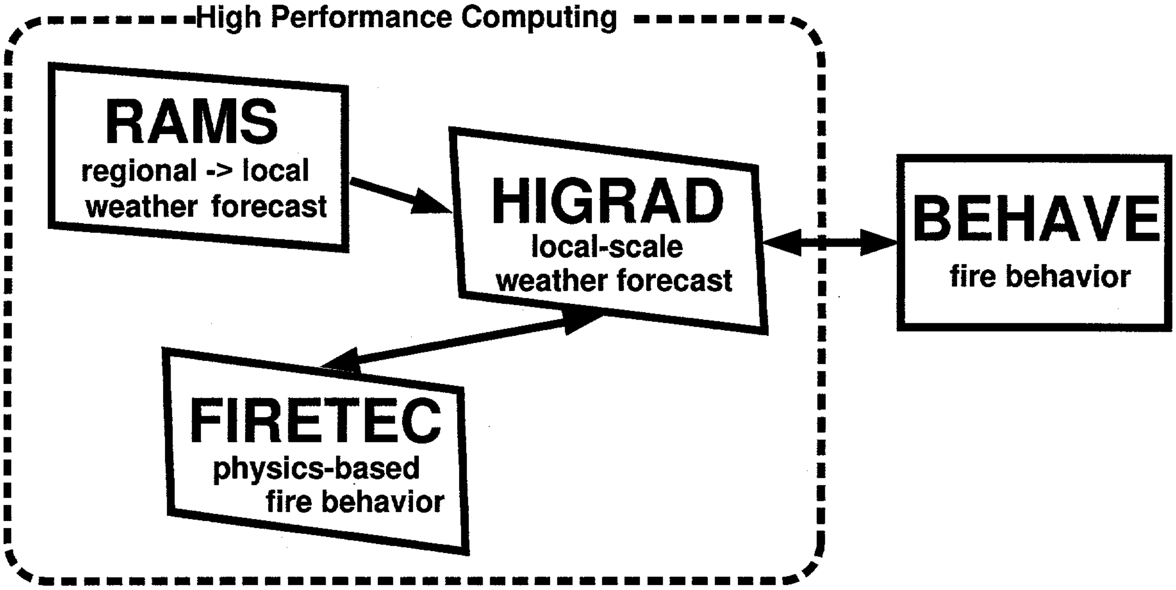

High Performance Computing
RAMS
regional -> local
weather forecast
HIGRAD
local-scale
weather forecast
FIRETEC
physics-based
fire behavior
BEHAVE
fire behavior

Figure 1

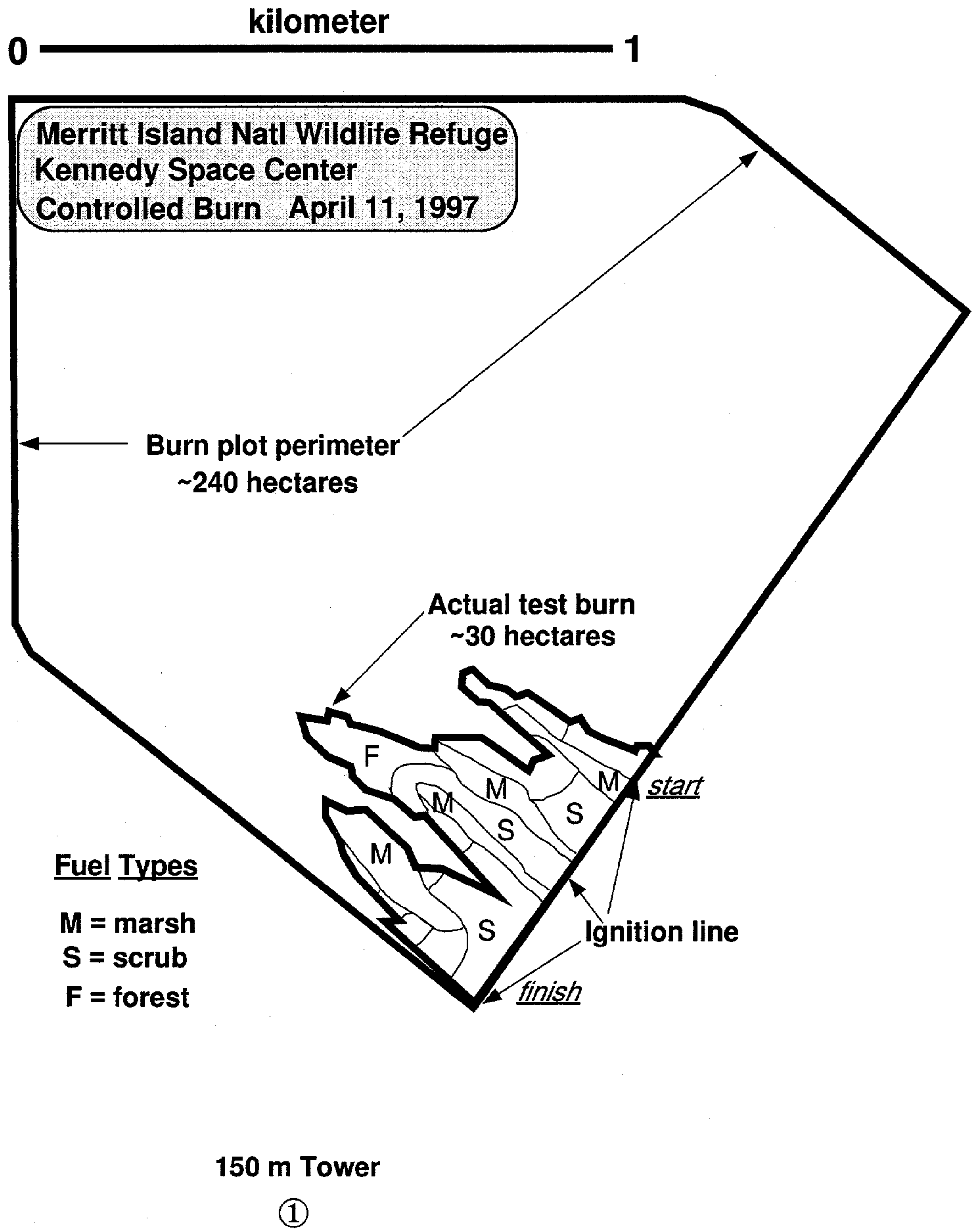
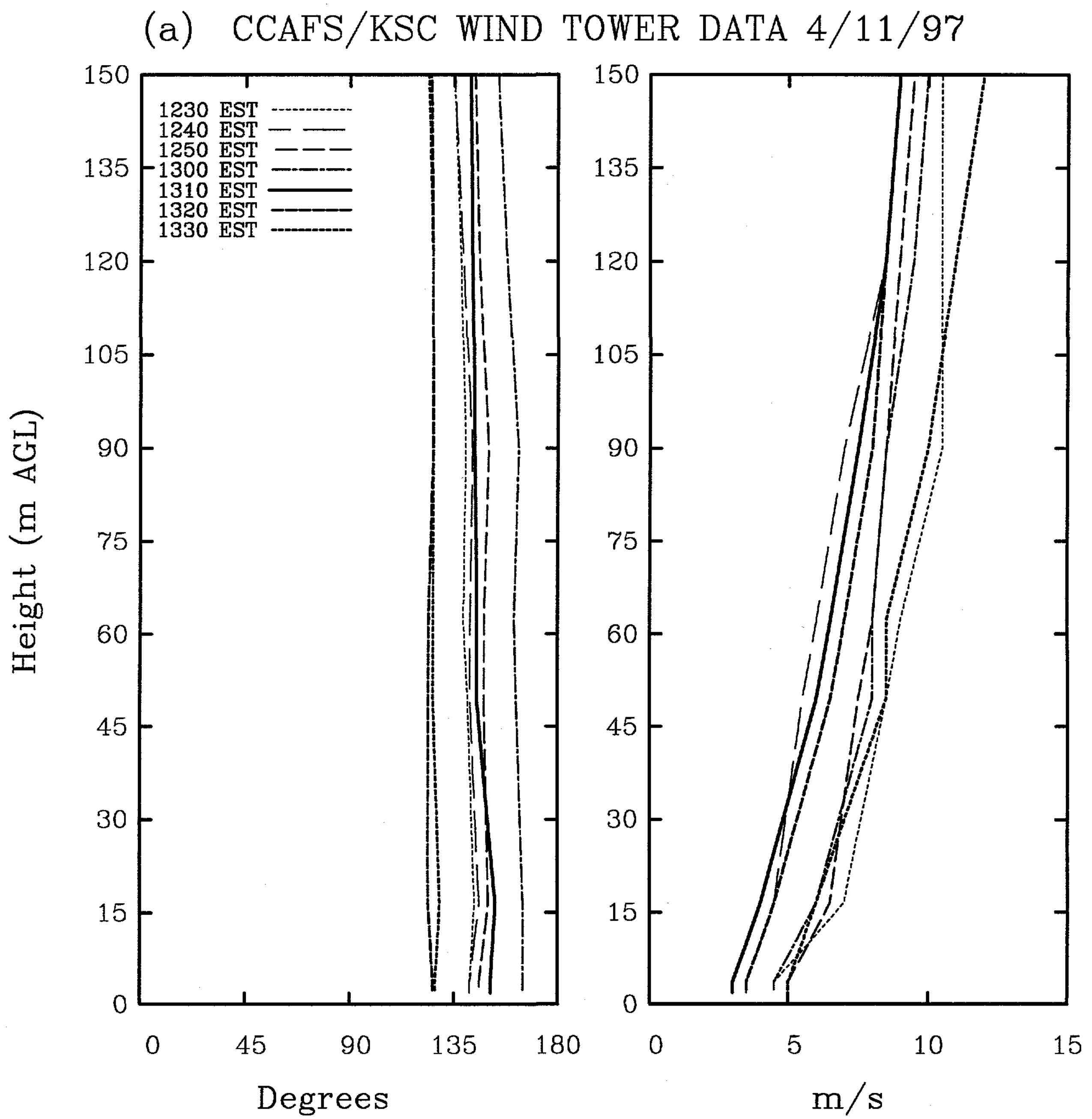
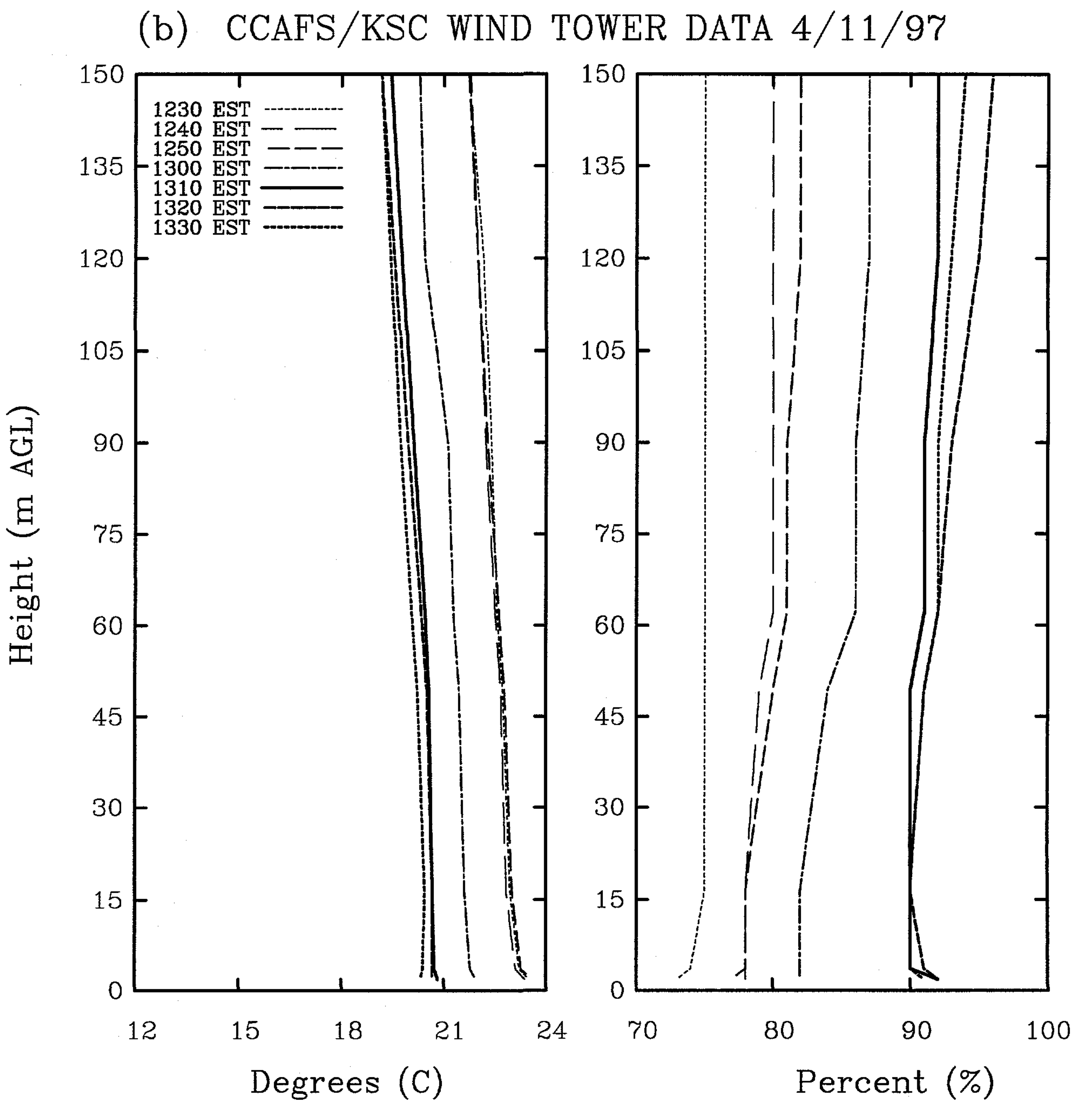

kilometer
0
1
Merritt Island Natl Wildlife Refuge
Kennedy Space Center
Controlled Burn April 11, 1997
Burn plot perimeter
~240 hectares
Actual test burn
~30 hectares
F
M
M
S
M
S
M
S
start
Ignition line
finish
Fuel Types
M = marsh
S = scrub
F = forest
150 m Tower
①

Figure 2



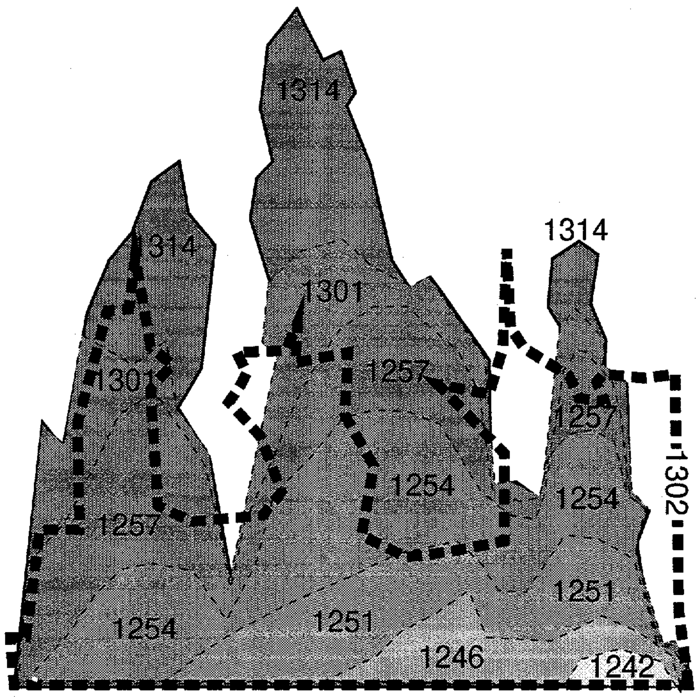
(a) CCAFS/KSC WIND TOWER DATA 4/11/97
1230 EST
1240 EST
1250 EST
1300 EST
1310 EST
1320 EST
1330 EST
Height (m AGL)
150
135
120
105
90
75
60
45
30
15
0
0
45
90
135
180
Degrees
0
5
10
15
m/s

Figure 3a



(b) CCAFS/KSC WIND TOWER DATA 4/11/97
1230 EST
1240 EST
1250 EST
1300 EST
1310 EST
1320 EST
1330 EST
Height (m AGL)
150
135
120
105
90
75
60
45
30
15
0
12
15
18
21
24
Degrees (C)
70
80
90
100
Percent (%)

Figure 3b



Time history of Actual burn (LST) and Simulated burn at 1302 LST

Figure 4