ANALYSIS OF SPACE/TIME CHARACTERISTICS OF ERRORS IN AN INTEGRATED WEATHER/FIRE SPREAD SIMULATION

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1. INTRODUCTION

Fire spread modeling systems such as FARSITE (Finney 1998) require significantly higher spatial and temporal resolution of weather data than fire danger rating systems. The weather modeling centers established to management--FCAMMS support fire (Fire Consortia for Advanced Modeling of Meteorology and Smoke)-offer the means and opportunity to fulfill this data requirement. A common goal of the FCAMMS centers is to provide gridded fire weather predictions at a grid spacing of 4 km. With co-registered geodata that include high resolution fuels and topography, all of the essential inputs will be available to generate fire spread predictions from given ignition scenarios.

In fact, fuels and terrain data populate much denser grids; grid spacings of 30 m are typical. The resolution and quality of data are among many factors that determine the accuracy of the As these modeling systems simulations. develop, users must be wary of the quality of their predictions. An understanding of the space/time characteristics of fire spread modeling errors will provide perspective for determining risks in using model predictions, and possibly provide statistical corrections for model biases. This paper addresses the evaluation of errors in integrated weather/fire spread simulations, from data obtained in June 2002 for the Troy Fire in San Diego County, California. The next section describes the weather modeling aspects of the study, followed by details of the fire simulations. Currently, the study is still in progress, but we present the results obtained to date, and a description of the work remaining.

2. WEATHER MODELING WITH MM5

The PSU/NCAR Mesoscale Model 5 (MM5, version 3) is used for real-time forecasts at the



Figure 1. Nested domains of the MM5 model. Horizontal grid spacings are 36, 12, 4 and 1.3 km, respectively.

University of California Santa Barbara (UCSB)¹. The project is a collaboration between UCSB and the Forest Fire Laboratory in Riverside, California (USDA-FS), to develop fire weather applications for California (e.g., high resolution fire danger forecasts). In this study, the MM5 model is used to simulate the atmospheric conditions during a wildfire that occurred on 19 June 2002 in San Diego County, California.

The MM5 model is a non-hydrostatic mesoscale model in sigma vertical coordinates (Grell et al. 1994). The UCSB operational forecast version has 37 sigma levels, each with three nested horizontal grids of 36 km, 12 km and 4 km spacings, respectively (Fig. 1). The numerical model solves the fully compressible non-hydrostatic equations allowing the three grids to interact among themselves (two-way The current real-time model nestina). configuration uses the Schultz (1995) cloud microphysics scheme, which accounts for ice and graupel/hail processes. Additionally, Kain-Fritsch cumulus parameterization in the outermost two grids (36 km and 12 km) is employed. We assume the grid spacing of the innermost domain (4 km) is sufficient to resolve

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¹ www.icess.ucsb.edu/asr

cumulus convection explicitly, so no cumulus parameterization is used there.

A combined cloud-radiation shortwave and longwave numerical scheme is used to calculate atmospheric radiative transfer considering the effects of clouds. This scheme is based on the Rapid Radiative Transfer Model (RRTM) described by Mlawer et al. (1997). Planetary boundary layer processes are represented with a numerical scheme that uses counter-gradient terms and K profiles in a well mixed boundary layer as implemented in the Medium Range Forecast (MRF) global model from NCEP (Hong and Pan 1996).



Figure 2. MM5 domains 3 (4 km) and 4 (1.3 km). Domain 3 terrain contours appear at 250 m intervals (zero contour omitted). Dots indicate locations of weather stations considered for model comparisons. Small red box shows the Troy.Fire subgrid used by FARSITE.

The NOAH land-surface model² we used predicts soil moisture with MM5 and temperature in four layers (10, 30, 60 and 100 cm thick), as well as canopy moisture and water-equivalent snow depth. It also outputs surface and underground run-off accumulations. The model makes use of vegetation and soil type in handling evapotranspiration, and has effects such conductivity as soil and gravitational flux of moisture. This scheme uses a diagnostic equation to obtain a skin temperature, and the exchange coefficients have to allow for this by use of a suitable molecular diffusivity layer to act as a resistance to heat transfer (Chen and Dudhia 2001).

For the Troy Fire simulations, we nested an additional grid of 1.3 km horizontal spacing inside the 4 km domain over southern California (Fig. 1). The model was initialized on 19 June 2002 00Z, from initial and boundary conditions of the NCEP Early Eta Analysis Model. Output variables for the two innermost grids (4 km, 1.3 km) were saved every hour.for 48 hours of the simulation.

We performed preliminary evaluations of the accuracy of the MM5 forecasts by comparing them with surface hourly observations from nearby weather stations. Figure 2 shows domains 3 (4 km) and 4 (1.3 km), as well as the locations of 135 weather stations operated by various organizations. We only used stations that reported more than 6 observations of surface wind speeds, temperature and relative humidity in the simulation period. The red box in Figure 2 marks the area of the Troy Fire. MM5 hourly forecasts within that box drove the FARSITE fire spread simulations.

3. FIRE SPREAD MODELING WITH FARSITE

We used the FARSITE fire modeling system (Finney 1998) to simulate the Troy Fire. The FARSITE simulations cover a much smaller area than the MM5 simulations described in the previous section. But the FARSITE grid interval is a mere 30 m, compared to the 1.3 km interval of the highest resolution MM5 grid.

Apart from the resolution of the input data, FARSITE has three parameters which control the spatial and temporal resolution of the simulation at runtime: timestep, perimeter, and distance resolution. The timestep parameter determines the duration of the simulation at each iteration. The perimeter resolution sets the maximum distance allowed between vertices of the fire perimeter. Each vertex is essentially an ignition point from which an ellipse propagates the fire locally in response to the fire environment variables at the vertex. Finally, the distance resolution is the maximum distance the simulation will advance the fire in the direction normal to the perimeter segment. When this distance is reached within an iteration, FARSITE determines the fire environment variables at that point.

FARSITE defaults the timestep to 30 min, perimeter resolution to 60 m, and distance resolution to 30 m. Larger values of timestep, perimeter and distance resolutions decrease the computing time, so we tested the sensitivity of the simulation results to a doubling of each of the parameters in turn, which yielded eight different simulations (2x2x2=8). The fuels,

² See the readme file describing the NOAH LSM at ftp://ftp.ncep.noaa.gov/pub/gcp/ldas/noahlsm/ver_2.2.



Figure 3. MM5 forecasts on 19 June 2002 12:00PM PDT (4 km domain). Large yellow box indicates the domain 4 (1.3 km) and small box inside is the location of Troy.

weather and topography were the same across simulations. In each case, the simulated start time was 1200 PDT, and the ending time was 1700 PDT.

4. PRELIMINARY RESULTS

4.1 MM5 simulations for 19 June 2002

Surface Winds (10m) 12:00 PDT 6/ 19/ 2002



Surface Winds (10m) and Air. Temp. (2 m) 12:00 PDT 6/ 19/ 2002





Figure 4. MM5 forecasts on 19 June 2002 12:00PM PDT (1.3 km domain). FARSITE fire spread simulations were performed over the Troy domain indicated by thin yellow lines.

To briefly summarize the main mesoscale circulation features on the day of the fire, Figure 3 shows the MM5 forecast from the 4 km domain at 1200 PDT. In general, surface winds were predominantly from the west/northwest over the Troy Fire location and wind speeds ranged from 2-4 m/s (5-10 mph). Temperature values were typically in the range of 30-35°C (86–95°F), whereas relative humidity was quite low: 10–20%. Figure 4 shows the more detailed view of the local circulations simulated on the 1.3 km domain.



Figure 5. Comparison between MM5 forecast (solid lines) and observation (stars).

Figure 5 illustrates a comparison between MM5 forecasts and observations for a location close to the Troy Fire. Somewhat good agreement was observed for the forecasts of temperature and relative humidity. By contrast, higher differences were found for the forecasts of wind speed. A qualitative comparison over other locations indicates that the MM5 forecasts tended to overpredict the magnitude of the wind speed on the lee side of the Troy Fire area, especially during the night.

4.2 FARSITE Sensitivity Tests

The results in Table 1 show that substantial differences can arise from different parameter settings. Comparing the second and third simulations, we see that doubling the perimeter resolution and halving the distance resolution had the effect of producing a fire half as large.

Table 1. Results of sensitivity test of the effect of timestep, perimeter and distance resolution settings on simulated area burned and maximum spread distance.

Time step (min)	Perim res (m)	Dist res (m)	Area burned (ha)	Max dist (m)
30	60	30	947	4251
30	60	60	1028	4412
30	120	30	507	2565
30	120	60	892	4495
60	60	30	963	4211
60	60	60	1017	4218
60	120	30	494	2354
60	120	60	875	4319





Figure 6. FARSITE simulations with resolution settings of 60 m perimeter and 60 m distance (top), compared to 120 m perimeter and 30 m distance (bottom). The timestep was 30 min in both cases.

Figure 6 shows the terminal frames of the sensitivity simulations summarized in rows 2 and 3 of Table 1. The perimeters in each frame show the hourly progression of the fire, beginning at 1200 PDT. Apparently, the higher perimeter resolution of the simulation at the bottom of the figure produced somewhat smoother perimeter segments, particularly at the head of the fire. The top simulation burned a larger area apparently upon reaching a different fuel type, which accelerated the spread rate. The slope of the terrain also changed at that point, but with the effect of turning a fire burning upslope to one burning downslope. The vectors show the MM5 simulated wind field at 1700 PDT. The simulated fire at this time was burning in the direction of the wind.

5. WORK IN PROGRESS

This study capitalizes on the opportunity to evaluate fire spread simulations with high quality high resolution fire spread data from an

airborne infrared imaging system. During the course of the Troy Fire, overflights captured its progress at 10 minute intervals in the space of an hour. This frequency of sampling allows a novel investigation of the space/time characteristics of the fire spread simulation errors. A description of the error analysis methodology follows.



Figure 7. Thermal image of the Troy Fire on 19 June 2002, 1556 PDT. The colors indicate temperatures calibrated from the radiant energy measured by the imaging system at selected infrared wavelengths. Image provided by Dr. Phil Riggan, USDA Forest Service, Riverside, California.

5.1 Fire Spread Error Analysis

Fujioka (2002) described a method to evaluate fire spread simulations, which addressed spatial variability of fire spread modeling errors. Let { $R(\theta_j, t)$ } denote the perimeter points simulated by FARSITE at time *t*, where θ is the azimuth angle in polar coordinates from the ignition point to the perimeter point, and *R* is the distance between the two points. Denote the corresponding point on the *observed* perimeter at time *t* by $r(\theta_{j},t)$. Fujioka (2002) defined the ratio error measure:

$$G(\theta_j, t) = r(\theta_j, t) / R(\theta_j, t), \ R(\theta_j, t) > 0$$
(1)

G is a valid error measure when there is a one-to-one correspondence of *r* and *R* for every θ . This condition was somewhat problematic in the data obtained for the 1996 Bee Fire in southern California (Fujioka 2002). Fujioka (2001) suggested the use of an orthogonal coordinate system tailored to the

geometry of the fire, which would in principle avoid the lack of one-to-one correspondence in the function describing the fire perimeter.

FARSITE simulations produce numerous perimeter points, particularly in the latter stages, when the perimeter encompasses a large area. As Figure 6 shows, the perimeter details for the Troy Fire simulation were exceptionally fine, more so when the perimeter resolution parameter was smaller. The actual fire perimeter in the infrared image of the Troy Fire appears smoother by comparison (Figure 7). At the scale of the image, the fine perimeter detail is probably extraneous, therefore we will smooth out some of the details by using an average ratio error.

5.2 Area-averaged Ratio Error

In addition to smoothing the high frequency spatial variations of the error defined in Equation 1, the process of averaging finds a locally representative error within each sector. If computing the average is problematic, for example if difficulties arise in finding r and R for each θ , an alternative averaging method calculates the ratio of the sector areas bounded by the actual and simulated perimeters within each sector. The Generalized Theorem of the Mean (Protter and Morrey 1964) establishes a relationship between the sector area ratio and the "mean" path length ratio of the type given by G:

$$\frac{f(b) - f(a)}{F(b) - F(a)} = \frac{f'(\xi)}{F'(\xi)}$$
(2)

On the left side of Equation 2, let the numerator represent the integral function that gives the area burned by the observed fire in the sector interval (a,b), and the denominator similarly the integral function that evaluates to the sector area in (a,b) covered by the FARSITE simulation. Then the right side of the equation is the ratio of the respective integrand functions at some point ξ within the interval (a,b); for example,

$$\left. f'(\xi) = \frac{d}{dx} f(x) \right|_{x=\xi} \quad a < \xi < b \tag{3}$$

Geometrically, $f'(\xi)$ represents the length of the burn path taken by the actual fire at the point ξ in segment (*a*,*b*) of the starting perimeter. Exactly where in the interval ξ falls is unspecified. In summary, we interpret the Generalized Theorem of the Mean to say that the ratio of the areas covered by the actual and simulated fires, respectively, is equivalent to the ratio of the burn path lengths traveled by each, at some point in the sector interval. This ratio is a mean in the sense of the Mean Value Theorem. We will investigate its usefulness for fire spread modeling error analysis.

6. SUMMARY

This study combines the elements of high resolution weather modeling and fire spread modeling with high resolution fire spread monitoring. These emerging technologies will soon find their way into fire operations. The production requirements of the weather modeling component are daunting, but the FCAMMS centers will fulfill the purpose for fire management applications. The FARSITE fire simulation system has had even greater exposure among fire specialists than high resolution weather models. The integration of weather and fire behavior models will provide fire managers with unprecedented capability to predict fire growth.

Although the weather and fire behavior models are the results of decades of scientific research, much work remains to establish their usefulness in fire management. The user needs information about the characteristics of model errors. This in turn requires high quality fire growth data, such as the fire imaging system in this paper provides. Research funded by the National Fire Plan and the Joint Fire Science Program is making headway in these areas.

REFERENCES

- Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569-585.
- Finney, M.A., 1996: FARSITE: Fire Area Simulator—Model Development and Evaluation. USDA Forest Service Research Paper RMRS-RP-4, Ogden, UT, 47 p.
- Fujioka, F.M., 2001: Characterization and analysis of fire spread modeling errors in an integrated weather/wildland fire model. Ph.D. dissertation, University of Calfornia, Riverside.
- Fujioka, F.M., 2002: A new method for the analysis of fire spread modeling errors. *Intl. J. Wildland Fire*, **11**, 193-203.

- Grell, G., A., J. Dudhia, D. R. Stauffer: 1994, A description of the fifth generation Pennsylvania State Unversity/NCAR mesoscale model. NCAR/TN-398+IA, National Center for Atmospheric Research, Boulder, Co, 116pp.
- Hong, S.-Y., and H. L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322-2339.
- Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J.
 Iacono and S.A. Clough (1997): Radiative
 Transfer for inhomogeneous atmospheres:
 RRTM, a Validated correlated-k model for
 the longwave. *J. Geophys. Res.*, **102**,
 16,663-16,682.
- Protter, M.H., and C.B. Morrey, Jr., 1964: *Modern Mathematical Analysis*, Addison-Wesley Publishing Co., 66-67.
- Schultz, P., 1995: An explicit cloud physics parameterization for operational numerical weather prediction. *Mon. Wea. Rev.*, **123**, 3331-3343.