Forecasting of Fire Weather and Smoke Using Vegetation-Atmosphere Interactions

Final Report to the Joint Fire Science Program 2003-1
Tasks 1 and 3

Project Number: 03-1-3-02

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September 2006

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Executive Summary

Forecasting of Fire Weather and Smoke Using Vegetation-Atmosphere Interactions

Overview

Accurate forecasting of regional weather is an important aspect of modern fire and smoke management. Fire weather impacts prescribed burn decisions, allocation of firefighting resources, and fire-fighters safety. Regional weather forecasts are currently produced by 3-D numerical models of atmospheric circulation (e.g. MM5). Due to high non-linearity of atmospheric processes, weather models are rather sensitive to boundary conditions defined as the fluxes of mass and energy at the borders of the spatial domain of the model. High model sensitivity means that small changes in boundary conditions may lead to large shifts in the predicted weather pattern over a short period of time.

Research over the past 10 years has demonstrated the critical importance of terrestrial ecosystems as lower boundary conditions in atmospheric models for predicting meso-scale weather. Lower boundary controls the partitioning of incoming solar energy into sensible and latent heat flux at the Earth surface. Sensible heat warms / cools the air, while latent heat evaporates water. This surface partitioning of total energy is a key factor governing the development of planetary boundary layer and atmospheric circulation at the meso-scale level. Current atmospheric models do not describe well biophysical processes of land-surface energy exchange. For example, these models oftentimes utilize simple semi-empirical relationships to predict canopy transpiration and soil evaporation and do not use leaf area index (LAI, a measure of vegetation density) as an independent data layer to scale energy fluxes from leaf to canopy level. As a result, atmospheric models often fail to simulate realistic lower boundary conditions, which negatively impacts regional weather predictions.

The goal of this project was to test the hypothesis that a physically robust simulation of lower boundary conditions (i.e. fluxes of sensible and latent heat from vegetation) in an atmospheric model will improve the accuracy of fire-weather forecasts at a continental scale. The project had three main objectives: (1) Couple the MM5 Community atmospheric model with FORFLUX, a state-of-the-art land-surface biophysical model of soil-vegetation-atmosphere interactions (Zeller & Nikolov 2000; Nikolov & Zeller 2003), and evaluate performance of the new MM5-FORFLUX model; (2) Provide real-time operational weather forecasts for the Western USA using MM5-FORFLUX; (3) Deliver forecast products generated by MM5-FORFLUX to fire management officers and federal land managers using a user-friendly Web interface.

The process of coupling FORFLUX with MM5 passed through five stages: 1) Writing code to interface the input and output routines of FORFLUX to make the model spatially explicit and capable of running on a 2D grid required by MM5. FORFLUX was originally designed to run at a point through time; 2) Writing a Fortran code to interface the FORFLUX subroutine with the MM5 planetary boundary layer module (called MRF). This step also included a lengthy process of debugging the new model code; 3) Estimation of FORFLUX input eco-physiological parameters for 27 vegetation (land-cover) types found in MM5; 4) Estimation of FORFLUX input parameters for 19 soil types used in MM5; 5) Ingestion of a satellite-derived LAI dataset (Nikolov & Zeller 2006) into the MM5-FORFLUX execution environment to allow correct scaling of energy fluxes by the FORFLUX module. Such a data layer does not exist in the standard MM5 environment.

Results

Coupling of MM5 with FORFLUX resulted in a new atmospheric model called MFF (i.e. MM5-FORFLUX). The model was set up at the USFS Rocky Mountain Center (RMC) to run in real time over the entire West at two horizontal resolutions - 12 km and 8 km. A comprehensive verification system was developed to evaluate MFF predictions against ground observations and standard MM5 forecasts at over 500 locations across the Western US. Results from the MFF runs and model verifications are available in real time 24/7 at http://fireweather.sc.egov.usda.gov/mm5_forflux.htm .

FORFLUX predicted markedly different partitioning of the incoming energy at the land surface compared to the standard MM5 NOAH scheme. Differences are significant both spatially and temporally. Analysis of the modeled surface energy exchange led to the following conclusions:

- The standard MM5 NOAH scheme tends to significantly overestimate daytime latent heat fluxes (i.e. evapo-transpiration) over vegetated areas (i.e. LAI > 0.5 m^2 m^{-2}).
- FORFLUX produces considerably smaller daytime latent heat fluxes than NOAH that are consistent with observations over both vegetated and arid areas.
- Compared to the NOAH scheme, FORFLUX predicts a much more realistic (i.e. smaller) gradients of latent heat flux between arid and vegetated areas.
- Nighttime fluxes of latent heat are similar between the two models with the NOAH scheme showing a greater tendency towards more negative fluxes in some coastal and mountainous areas.
- Disparities in estimated latent heat flux cause large differences in predicted sensible heat flux between the two models. Thus, during daytime, FORFLUX produces a significantly higher sensible heat flux than NOAH while, at night, it predicts a smaller (more negative) sensible heat flux. This creates a greater daytime heating of the lower atmosphere in MFF compared to MM5 and a stronger cooling at night.

Differences in predicted sensible heat flux between FORFLUX and the NOAH scheme produced noticeable improvements in the weather forecast fields of MFF compared to MM5. Specifically:

- MFF delivers a markedly improved forecast of surface air temperature, which completely removes a decade-old systematic bias in the diurnal temperature amplitude of MM5. The MM5 bias consists of predicting lower than observed maximum daily temperature and higher than observed minimum nighttime temperature;
- MFF predicts significantly more accurate fields of relative humidity than MM5. The improvement of humidity forecast is mainly due to better temperature predictions by MFF and to a lesser extent to better dew point calculations (MFF produces only a small improvement in dew-point estimates over MM5);
- MFF improves slightly wind forecasts. On average, MFF predictions of wind speed show larger diurnal amplitude compared to MM5, which agrees better with observations. Also, wind directions generated by MFF tend to have a smaller mean bias than MM5 predictions;
- MFF manifests greater physical robustness than MM5. Comparison of verification results between model runs using different spatial resolutions (i.e. 12 km vs. 8 km) showed that mean bias and absolute error of MFF forecasts are not affected by changes in horizontal grid spacing. This is not true for MM5, where increasing model resolution from 12 km to 8 km noticeably improves the forecast accuracy of that model. This implies that, unlike MM5,

MFF can be run at coarser resolution without sacrificing forecast quality, thus saving time and computational resources.

In conclusion, results from this project have proven the hypothesis that a more accurate simulation of the energy partitioning at the lower boundary of an atmospheric model will improve meso-scale weather forecasts. The improvement is most significant to predictions of air temperature and relative humidity, which are key variables in fire meteorology and fire-danger assessment. In addition, the improved simulation of surface heat exchange has increased the physical robustness of the new atmospheric model with respect to spatial resolution. The combined MM5-FORFLUX model opens new possibilities to develop novel NFDRS indices and improve existing ones using more accurate estimates of moisture content in live and dead vegetation based on FORFLUX energy-balance calculations.

Crosswalk Between Proposed and Delivered Activities

Proposed	Delivered	Status
New atmospheric meso-scale model producing improved fire-weather forecasts using an advanced land-surface module.	MFF – a new atmospheric model was created by coupling the MM5 meso-scale weather model with the FORFLUX ecosystem biophysical model.	Done
Real-time fire-weather forecasts over the Western USA using the improved atmospheric model.	MFF is currently running operationally twice per day for the Western USA in two spatial resolutions (12 km and 8 km) at the USFS Rocky Mountain Center in Colorado.	Done
Interactive user-friendly Website delivering improved fire-weather forecast products to FMOs, GACC meteorologists, and land managers.	MFF forecast products (including maps and point forecasts) are available online 24/7 at: http://fireweather.sc.egov.usda.gov/mm5_forflux.htm	Done
Verification of the new fire-weather forecast model	A comprehensive real-time verification system was developed for the MFF model using weather observations from over 500 automated Stations in the Western US. Results are available on line 24/7 at: http://fireweather.sc.egov.usda.gov/mm5_forflux.htm	Done

INTRODUCTION

Forecasting of the regional weather is an important aspect of today's fire and smoke management process. Accurate prediction of meteorological conditions over the next 72 hours is critical when fighting wildland fires, and making go/no-go decisions about prescribed burns. Knowing with a high degree of certainty how future wind fields and atmospheric stability might change over a region is also indispensable for evaluation of smoke dispersion due to prescribed burns. The latter is essential for air quality management and mitigation of the smoke impact on public health. The safety of fire fighters is another vital management issue, which calls for reliable and accurate local weather forecast. Incident meteorologists (IMETS) are required to use information about future weather conditions when designing safety measures during fire fighting.

Regional weather forecasts are currently produced by 3D numerical models of meso-scale atmospheric circulation. These models (e.g. MM5) describe atmospheric physics in great details. Due to a high non-linearity of atmospheric processes, weather models are quite sensitive to initial and boundary conditions. Initial conditions are the fields of temperature, humidity, winds etc. provided as input at the beginning of each simulation. Boundary conditions are the fluxes of mass and energy at the borders of the spatial domain of the model. High model sensitivity means that small changes in boundary conditions may lead to large shifts in the predicted weather pattern over a short period of time.

Research conducted over the past 10 years has demonstrated the importance of lower boundary conditions (i.e. terrestrial vegetation) in predicting mesoscale atmospheric circulation (e.g. Chase et al. 1996; Fennessy & Xue 1997; Pielke *et al*. 1997, 1998; Pielke 2001). Lower boundary is defined in meso-scale models by the fluxes of sensible and latent heat emitted from vegetation and soils. Short-wave and thermal radiation received from the Sun and the upper atmosphere is partitioned at the land surface into energy that evaporates water (latent heat flux) and heat that warms the air (sensible heat flux). This energy partitioning is a key factor controlling the development of the planetary boundary layer (PBL), which governs meso-scale weather phenomena (including near-surface temperature, humidity fields, and winds). The amount of latent heat flux (also known as evapo-transpiration) emitted from the land surface depends on the type of vegetation present, its canopy density (defined as leaf area index, LAI), soil texture, soil moisture, and current meteorological conditions. Vegetation exercises a major control over the latent heat flux (hence, the energy partitioning) through its physiology (e.g. leaf stomatal conductance), spatial coverage, and foliage density. Thus, vegetation plays an important role in atmospheric dynamics and weather formation at the meso-scale level (Pielke *et al*. 1997, 1998; Lynn et al. 2001).

Current atmospheric models do not describe well biophysical processes of land-surface energy exchange. These models often utilize surface schemes that only provide a crude simulation of the complex vegetation-atmosphere interactions. For instance, current atmospheric models do not use leaf area index (a measure of vegetation density) as an independent data layer to scale energy fluxes from leaf to canopy level. LAI is a critical structural parameter of vegetation controlling the latent heat flux and, hence, surface energy partitioning. In addition, these models utilize simple semi-empirical relationships to predict canopy transpiration and soil evaporation. As a result, current weather models oftentimes fail to simulate realistic lower boundary conditions, which adversely impacts regional weather predictions. This is particularly true for the mountainous terrain of the Western U.S., where vegetation patchiness creates a surface energy exchange pattern, which strongly influences regional airflow (Pielke 2001). Therefore, improving the surface scheme of meso-scale weather models is a viable approach towards a better forecast of regional fire weather.

The goal of this project was to test the hypothesis that a physically robust simulation of lower boundary conditions (i.e. fluxes of sensible and latent heat from vegetation) in an atmospheric model will improve the accuracy of fire-weather forecasts at a continental scale. The project had 3 main objectives: (1) Couple the MM5 Community atmospheric model developed jointly by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) (http://www.mmm.ucar.edu/mm5/mm5-home.html) with FORFLUX, a state-of-the-art land-surface biophysical model of soil-vegetation-atmosphere interactions (Zeller & Nikolov 2000; Nikolov & Zeller 2003), and evaluate the MM5-FORFLUX performance; (2) Provide real-time operational weather forecast for the Western US using the new MM5-FORFLUX model; (3) Deliver forecast products generated by MM5-FORFLUX to fire management officers and federal land managers online using a user-friendly Web interface.

METHODS

1. Linking FORFLUX terrestrial model with the MM5 atmospheric model.

FORFLUX is a multi-layered biophysical process model that simulates instantaneous exchange of water vapor, sensible heat, carbon dioxide, and ozone between terrestrial ecosystems and the atmosphere (Zeller & Nikolov 2000; Nikolov & Zeller 2003). The model mechanistically couples all major processes controlling ecosystem flows of water, carbon, and ozone by implementing state-of-the-art concepts of plant eco-physiology, micrometeorology, and soil physics. FORFLUX consists of four interconnected modules - a leaf photosynthesis model (LEAFC3, Nikolov et al. 1995), a canopy flux model, a soil heat-, water- and CO_2- transport model, and a snow pack model. FORFLUX predicts latent heat fluxes from all surfaces of the ecosystem (i.e. canopy, soil/litter, and snow pack) using explicit solution of the energy balance equation. The model provides detailed description of the biophysical processes governing plant stomatal conductance, which is critical for predicting transpiration from vegetation. Unlike other land-surface schemes, FORFLUX mechanistically couples evapo-transpiration with CO_2 uptake (i.e. photosynthesis) on a leaf level, and uses vegetation LAI to scale mass and energy fluxes from a leaf to canopy level. It also uses principles of the diffusion theory to provide robust simulation of the heat and water transfer in soils. FORFLUX requires input data on ambient temperature, relative humidity, incident short-wave radiation, precipitation, above-canopy wind speed, and (optional) ambient ozone concentration. Weather input can be provided by actual observations or model simulations. An ecosystem is defined in FORFLUX by latitude, longitude, elevation, slope and aspect, vegetation type (i.e. dominant plant species), leaf area index, and soil characteristics (such as texture, depth, and bulk density). Vegetation eco-physiology is characterized by 21 parameters. FORFLUX has been verified against tower flux measurements over several different ecosystems (Nikolov 1997; Zeller & Nikolov 2000; Amthor et al. 2001). Despite its comprehensive approach towards simulation of the ecosystems-atmosphere exchange processes, FORFLUX is computationally very efficient yielding itself ideal for use as a land-surface module in MM5.

MM5 currently provides four options of Land Surface Modules (LSM) to simulate lower boundary conditions (i.e. surface energy partitioning). Two LSMs contain no vegetation layer assuming that land surface is bare ground. The other two LSMs developed by the Oregon State University (OSU) and Xiu & Pleim (2000), respectively, consider a simple vegetation layer, but do not use canopy LAI as data layer independent of land cover to scale energy fluxes. Also, these LSMs utilize simplified semi-empirical relationships to predict latent heat flux. Currently, the most widely used LSM with MM5 is the NOAH scheme based on the OSU LSM. In this project, we replaced the NOAH LSM in MM5 with the FORFLUX biophysical model to produce a new weather forecast model called MFF (MM5-FORFLUX). We then compared fire-weather forecasts produced by MM5 and MFF to assess the impact of the new surface scheme.

The process of coupling FORFLUX with MM5 passed through five stages: (1) Writing code to interface the input and output routines of FORFLUX to make the model spatially explicit and capable of running on a 2-D grid required by MM5. FORFLUX was originally designed to run at a point through time; (2) Writing a Fortran code to interface the FORFLUX subroutine with the MM5 planetary boundary layer module (called MRF). This step also included a lengthy process of debugging the new model code; (3) Estimation of FORFLUX input eco-physiological parameters for the vegetation (land-cover) types found in MM5; (4) Estimation of FORFLUX input parameters for the soil types used in MM5; (5) Ingestion of a satellite-derived LAI dataset into the MFF execution environment. Such a data layer does not exist in the standard MM5.

2. Parameterization of the FORFLUX model within MM5.

MM5 uses a USGS land-cover dataset containing 27 vegetation types. FORFLUX defines a vegetation type through 21 functional parameters. These parameters differ greatly in kind and number from the parameters used by the original NOAH surface scheme employed with MM5. Values of the vegetation parameters required by FORFLUX were derived from literature (e.g. Wullschleger 1993) and expert estimates. Table 1 lists eleven of the most important FORFLUX vegetation parameters estimated for the 27 land-cover types of MM5. Table 2 explains these parameters and their units.

Table 1. Main input vegetation parameters required by FORFLUX for the 27 land-cover types used in MM5.

Land Cover Type	Vm25	Jm25	Ej	theta	Kc25	Ko25	f	m	Bs	Dleaf	Dshoot
Urban and Built-Up Land	60	113	40000	0.7	0.00027	0.41	0.48	9.75	0.0075	0.02	0.075
Dry Land Cropland and Pasture	72	136	40000	0.7	0.00027	0.41	0.49	10.5	0.0075	0.025	0.09
Irrigated Cropland and Pasture	100	189	43000	0.8	0.00028	0.43	0.6	12	0.02	0.04	0.7
Mixed Dry Land / Irrigated Cropland and Pasture	85	160	43000	0.8	0.00028	0.43	0.61	10.85	0.012	0.05	0.7
Cropland/Grassland Mosaic	88	166	45000	0.9	0.00028	0.43	0.61	9.95	0.007	0.06	0.7
Cropland/Woodland Mosaic	75	142	40000	0.7	0.00027	0.41	0.49	10.5	0.006	0.0065	0.06
Grassland	79	149	43000	0.8	0.00027	0.41	0.8	7.8	0.003	0.006	0.6
Shrub Land	43	81	41000	0.7	0.00027	0.41	0.48	9.75	0.001	0.003	0.075
Mixed Shrub Land / Grassland	59	111	43000	0.7	0.00027	0.41	0.48	8.6	0.006	0.009	0.085
Savanna	73	138	42000	0.8	0.00027	0.41	0.8	8.2	0.006	0.02	0.6
Deciduous Broadleaf Forest	65	123	44000	0.7	0.00027	0.41	0.5	10.4	0.003	0.06	0.2
Deciduous Needle-leaf Forest	62	119	40000	0.7	0.00025	0.41	0.49	9.9	0.0115	0.0011	0.065
Evergreen Broad-leaf Forest	65	123	40000	0.7	0.00027	0.41	0.5	10	0.008	0.09	0.2
Evergreen Needle-leaf Forest	59	110	39000	0.7	0.00022	0.41	0.5	9.9	0.009	0.0011	0.065
Mixed Forest	64	121	39000	0.7	0.00022	0.41	0.5	10	0.0085	0.02	0.065
Water Bodies	62	118	40000	0.7	0.00028	0.41	0.48	10	0.01	0.003	0.06
Herbaceous Wetland	70	132	40000	0.8	0.00028	0.43	0.61	12	0.023	0.04	0.2
Wooded Wetland	64	121	40000	0.7	0.00028	0.41	0.5	11.5	0.015	0.04	0.2
Barren or Sparsely Vegetated	41	78	40000	0.7	0.00028	0.41	0.5	7.8	0.001	0.04	0.2
Herbaceous Tundra	50	95	41000	0.7	0.00028	0.41	0.5	8.5	0.008	0.006	0.1
Wooded Tundra	56	107	40000	0.7	0.00028	0.41	0.48	8.8	0.005	0.002	0.06
Mixed Tundra	54	102	40000	0.7	0.00028	0.41	0.48	8.9	0.007	0.003	0.06
Bare Ground Tundra	43	81	40000	0.7	0.00028	0.41	0.48	7.5	0.001	0.003	0.06
Snow or Ice	40	75	40000	0.7	0.00028	0.41	0.48	8	0.01	0.003	0.06
Playa	49	91	40000	0.8	0.00028	0.41	0.08	7.1	0.007	0.003	0.05
Lava	49	91	40000	0.7	0.00028	0.41	0.48	7	0.003	0.003	0.06
White Sand	41	77	40000	0.7	0.00028	0.41	0.48	7	0.0008	0.002	0.06

Table 2. Key FORFLUX Vegetation Parameters and Their Units.

Parameter ID	Description	Units
Vm25	Maximum Carboxylation Velocity at 25 °C	μmol m^{-2} s^{-1}
Jm25	Light-saturated potential rate of electron transport at 25 °C.	μmol m^{-2} s^{-1}
Ej	Activation energy for electron transport.	J mol^{-1}
theta	Coefficient controlling the smoothness of transition between light and temperature limitations on the potential rate of electron transport.	non-dimensional
Kc25	Kinetic parameter for CO_2 at 25 °C	mol/mol
Ko25	Kinetic parameter for O_2 at 25 °C	mol/mol
f	Photosynthetic light loss factor	-
m	Composite stomatal sensitivity	-
Bs	Residual stomatal conductance	mol m^{-2} s^{-1}
Dleaf	Average leaf/needle width	m
Dshoot	Average shoot diameter	m

MM5 uses a geo-referenced soil dataset consisting of 19 soil types. FORFLUX defines soils via 5 parameters - percent of clay, sand, and organic carbon; bulk density (g cm^{-3}); and volumetric fraction of rocks. FORFLUX uses these parameters to compute internally soil hydraulic properties such as soil retention curves, soil field capacity, and residual water content. Using the USDA soil texture triangle and other soil data sources, we estimated values of these parameters for the 19 soil types found in MM5. Table 3 lists the soil parameters employed by the new MFF model.

Unlike previous LSMs, FORFLUX uses a spatial data layer of canopy LAI that is independent of vegetation types to predict fluxes of sensible and latent heat at the land surface. Other LSMs (including the MM5 NOAH scheme) assume a fixed correlation between peak-seasonal LAI and a vegetation type while no such relationship exists in reality. As a result, the NOAH scheme predicts incorrect energy partitioning at the land surface (see discussion below). Nikolov & Zeller (2006) derived a geo-referenced LAI data set for the conterminous US from 1-km resolution multi-spectral AVHRR satellite images from 1995 using inversion of an analytical canopy radiative transfer model. The dataset consists of 12 digital maps, one for each month of year 1995. A monthly LAI map refers to the 15th day of the month. Satellite-derived LAI values were validated against ground LAI measurements from a variety of ecosystems in the continental USA (Nikolov & Zeller 2006). Figure 1 depicts the summer-maximum LAI over Western USA as retrieved from satellite images. The original LAI dataset was in Goodies projection and had to be re-projected to Lambert Conformal projection to match existing data layers of land cover and soils in MM5. New arrays were defined and code was written to allow ingestion of the LAI data fields into MFF. The new MFF model computes LAI fields for individual days of the year from the monthly LAI dataset via linear interpolation of pixel values between adjacent months.

Table 3. FORFLUX parameter values estimated for 19 soil types used in MM5.

Soil Type	Clay (% mass)	Sand (% mass)	Bulk Density (g cm^{-3})	Carbon (% mass)	Rocks (% Volume)
Sand	3	92	1.30	0.100	0.25
Loamy Sand	6	82	1.22	0.500	0.25
Sandy Loam	10	63	1.20	0.900	0.20
Silty Loam	13	22	1.13	0.800	0.20
Silt	6	7	1.06	0.800	0.15
Loam	17	43	1.15	0.800	0.10
Sandy Clay Loam	26	61	1.15	0.500	0.20
Silty Clay Loam	33	11	1.10	0.700	0.15
Clay Loam	34	32	1.10	0.500	0.10
Sandy Clay	42	52	1.13	0.700	0.17
Silty Clay	46	6	1.05	0.700	0.09
Clay	48	26	1.08	1.000	0.08
Organic Material	1	3	0.95	20.000	0.05
Water	0	0	1.00	0.010	0.00
Bedrock	3	92	2.40	0.001	1.00
Land Ice	0	0	0.92	0.001	0.05
Playa	58	22	1.20	0.100	0.01
Lava	1	95	1.95	0.050	1.00
White Sand	2	95	1.32	0.050	0.10

RESULTS

The new MFF model (combining MM5 and FORFLUX) was set up at the USFS Rocky Mountain Center (RMC) to run in real time over the entire West at two horizontal resolutions- 12 km and 8 km. The model currently produces two 72-hour forecasts per day in each spatial resolution. Forecast initialization times are 11:00 MST and 23:00 MST. A comprehensive verification system was deployed to evaluate MFF predictions against ground observations and standard MM5 forecasts at over 500 locations across the Western US. Results from the MFF runs and model verifications are available 24/7 at http://fireweather.sc.egov.usda.gov/mm5_forflux.htm .

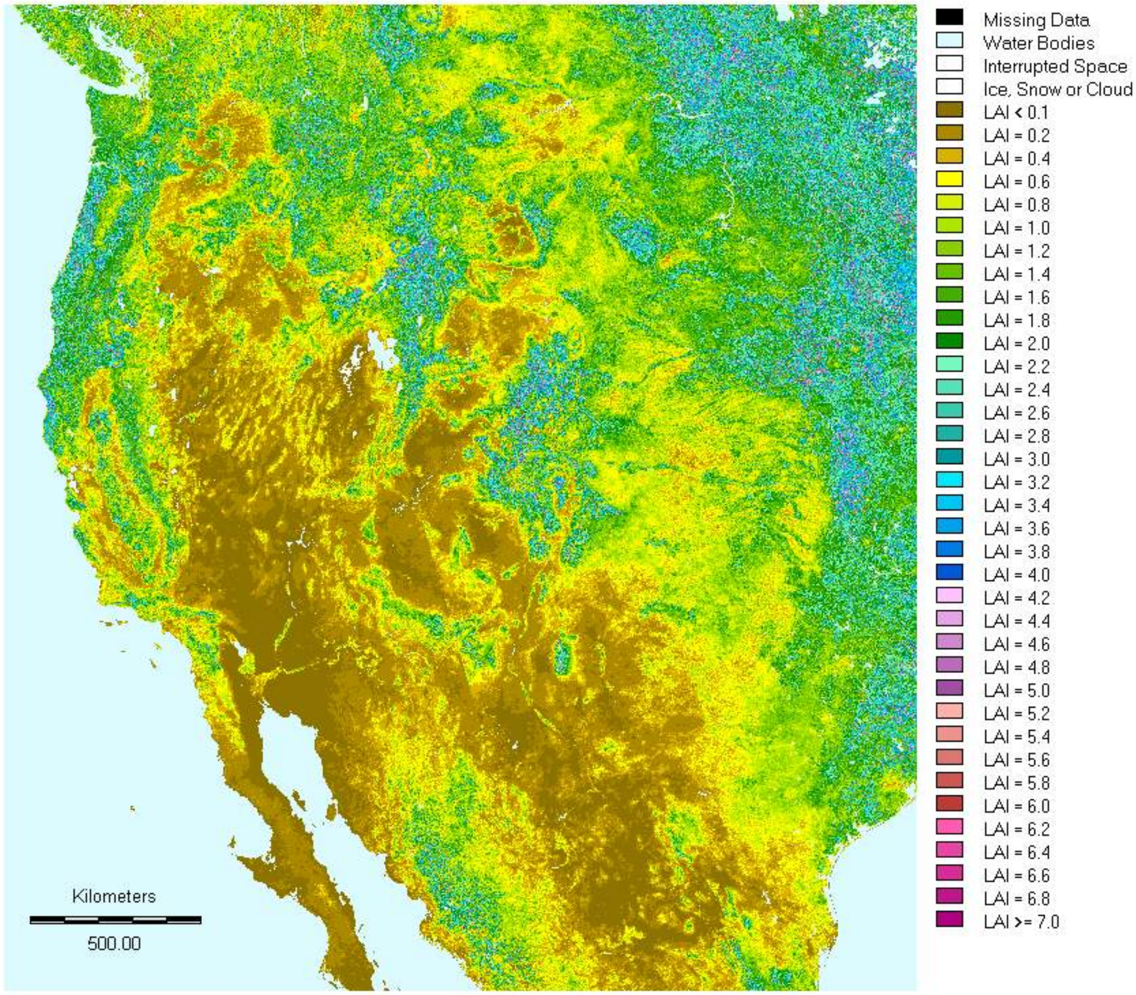


Figure 1. Summer-maximum canopy leaf area index (LAI) derived from 1-km resolution AVHRR multi-spectral satellite images (Nikolov & Zeller 2006) and used by the new MFF weather forecast model.

1. Effect of FORFLUX model on MM5 surface energy partitioning.

FORFLUX predicts markedly different partitioning of the incoming energy at the land surface compared to the NOAH scheme. Differences are significant both spatially and temporally. For example, Figures 2 and 3 illustrate the spatial differences in calculated daytime fields of latent and sensible heat fluxes predicted by MFF and MM5 for August 9 (i.e. 38 hours into the forecast) using the same initial and boundary conditions. Figures 4 and 5 compare corresponding spatial differences in nighttime fluxes between the two models for August 10 (i.e. 52 hours into the forecast).

Analysis of the modeled surface energy exchange led to the following conclusions. The standard MM5 NOAH scheme tends to significantly overestimate daytime latent heat flux (LH) (i.e. evapo-transpiration) over vegetated areas (i.e. where LAI > 0.5 m^2 m^{-2}).

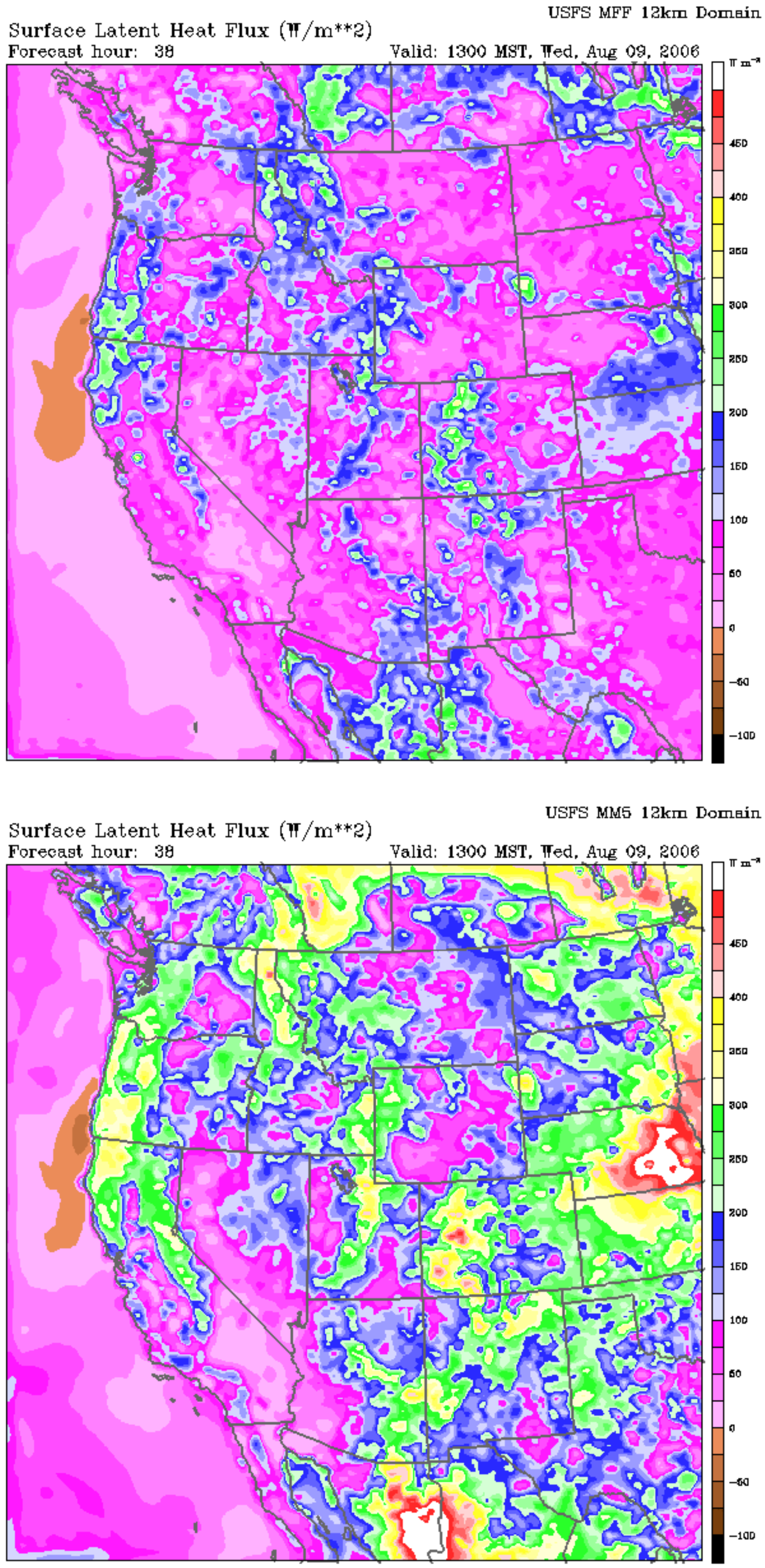


Figure 2. Daytime fields of *latent* heat flux predicted by MFF (upper plot) and MM5 (lower plot) at 13:00 MST on August 09, 2006 (38 hours into the forecast).

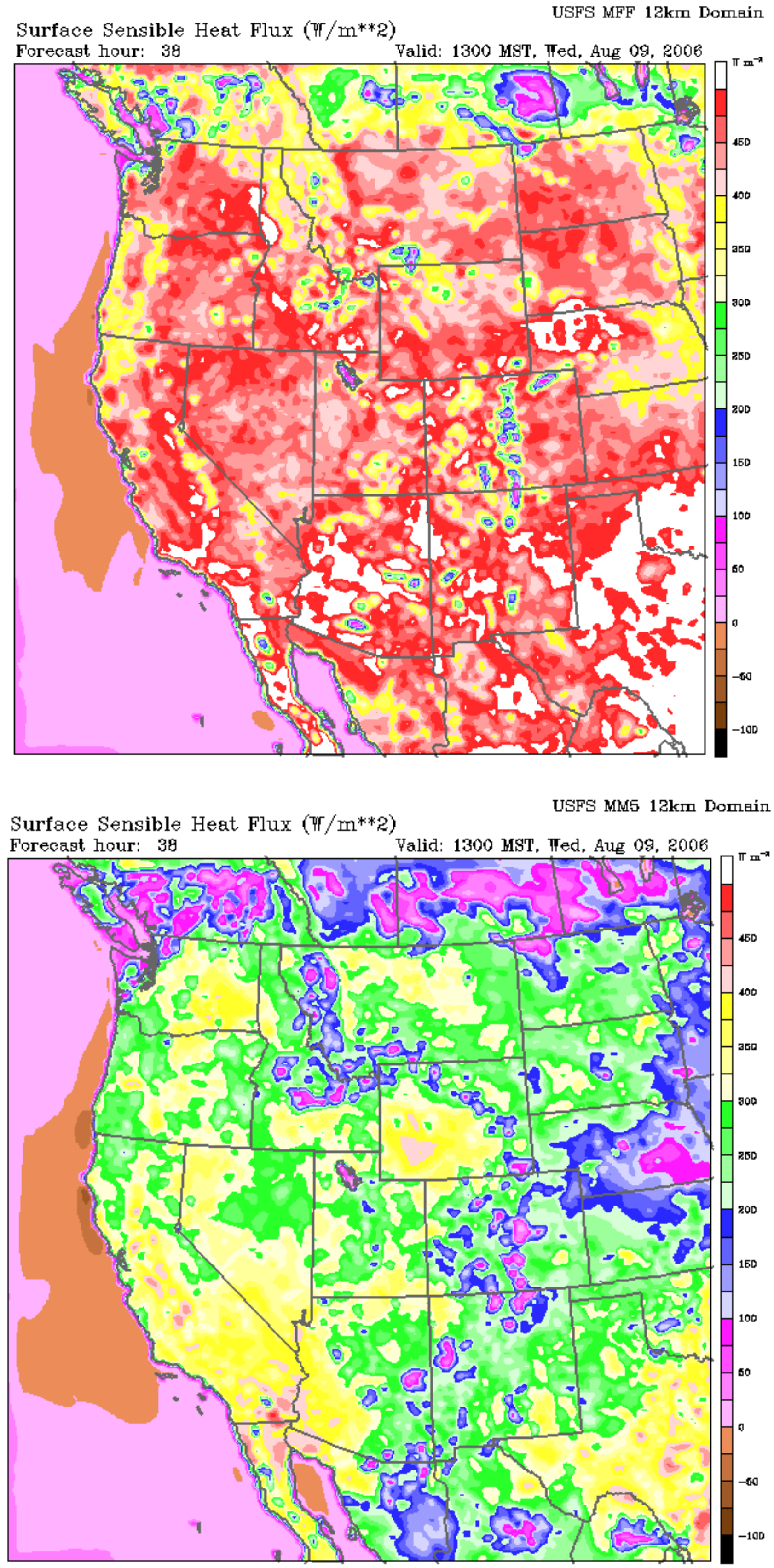


Figure 3. Daytime fields of *sensible* heat flux predicted by MFF (upper plot) and MM5 (lower plot) at 13:00 MST on August 09, 2006 (38 hours into the forecast).

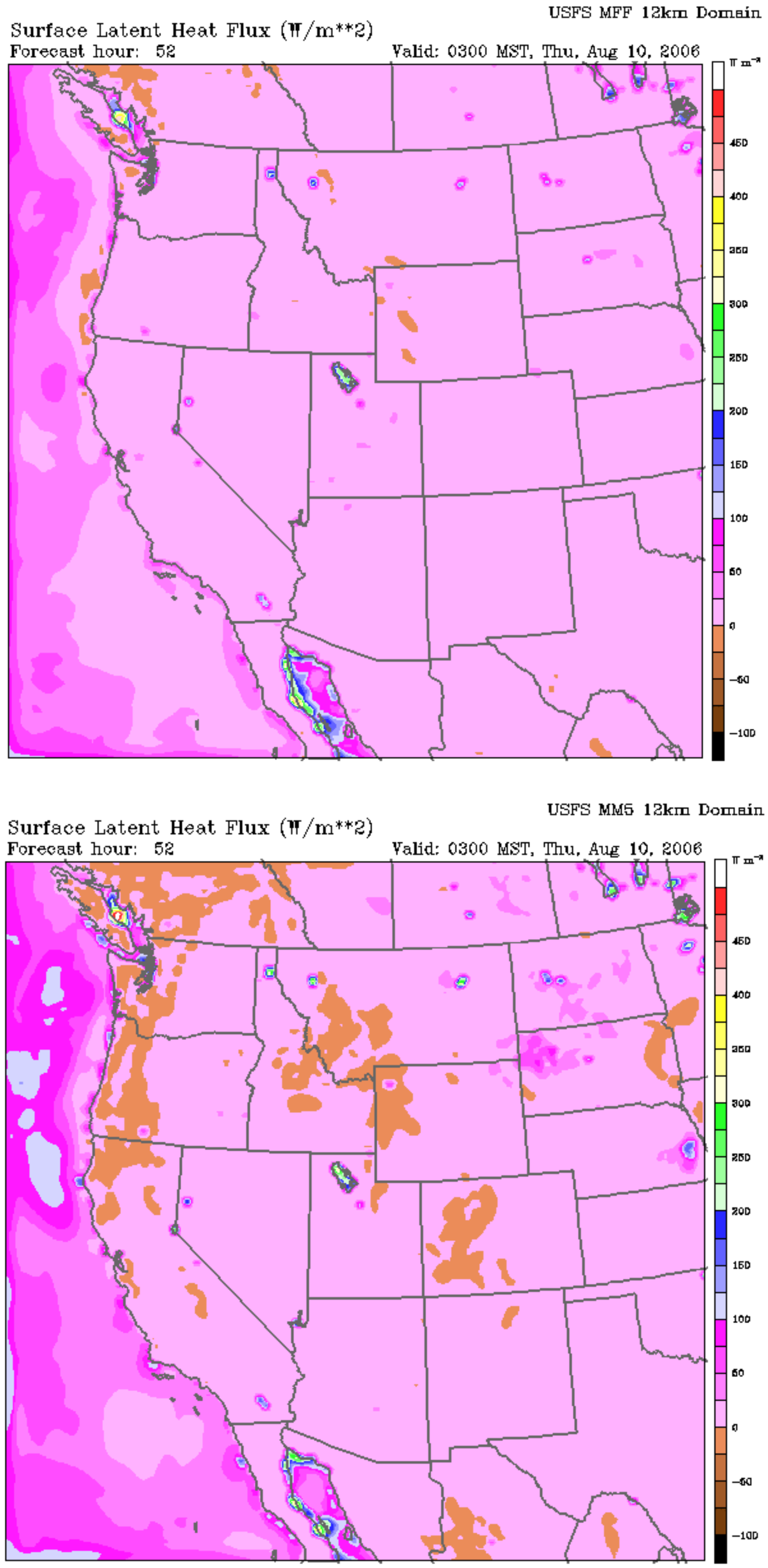


Figure 4. Nighttime fields of *latent* heat flux predicted by MFF (upper plot) and MM5 (lower plot) at 03:00 MST on August 10, 2006 (52 hours into the forecast).

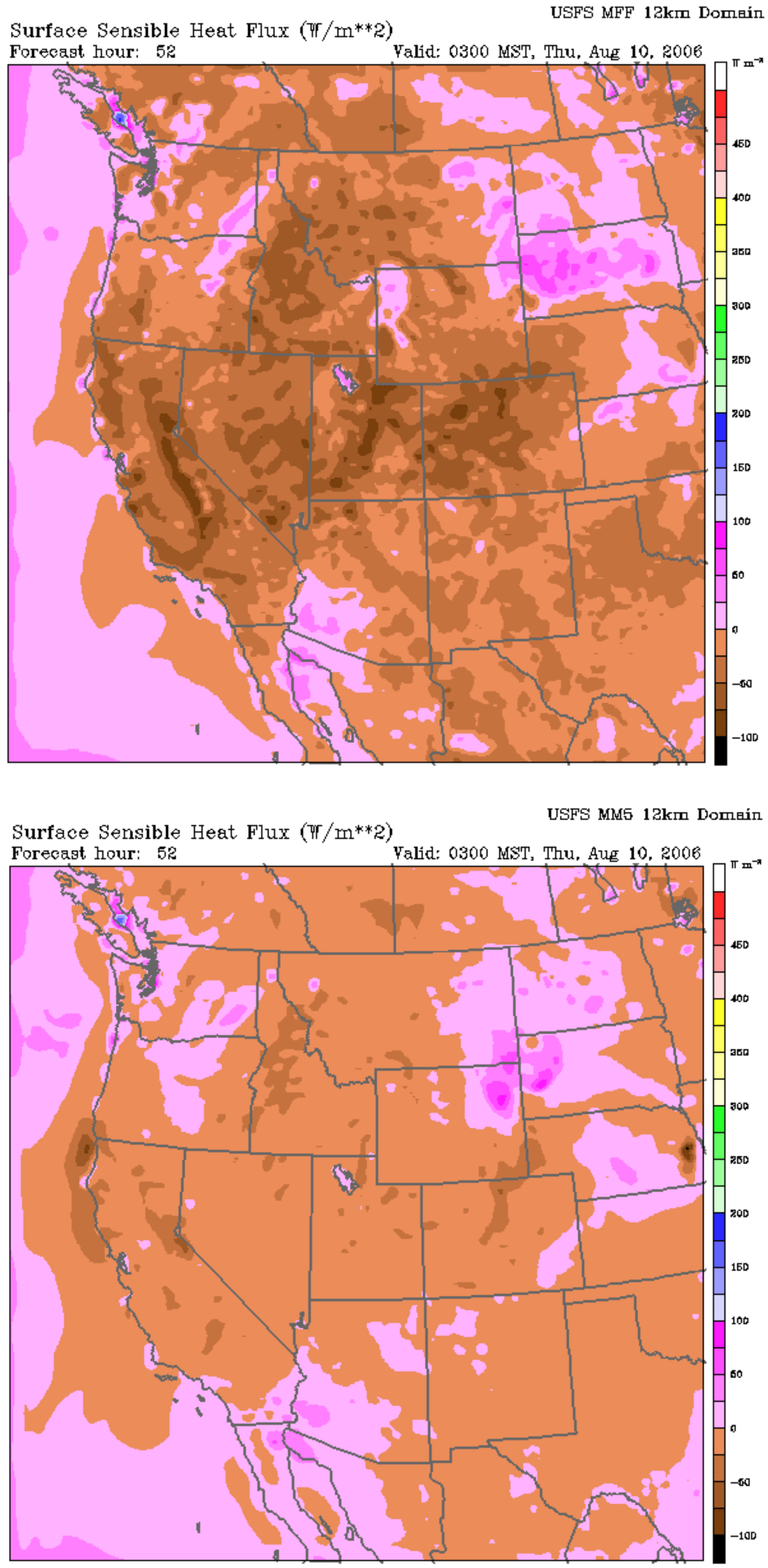


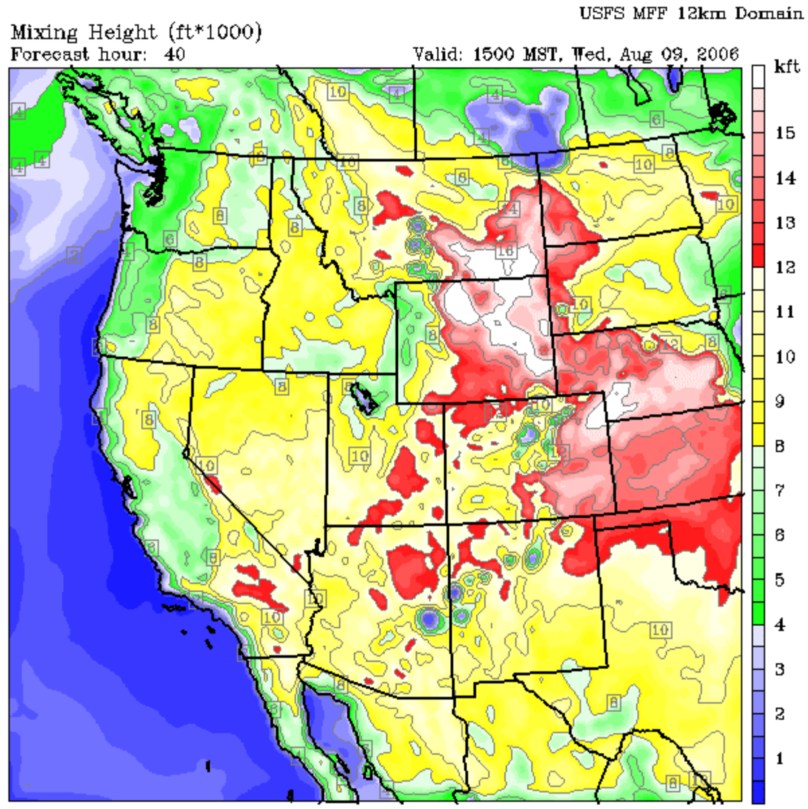
Figure 5. Nighttime fields of *sensible* heat flux predicted by MFF (upper plot) and MM5 (lower plot) at 03:00 MST on August 10, 2006 (52 hours into the forecast).

NOAH routinely produced latent heat values in excess of 350 W m^{-2} over forested and agricultural areas in early afternoon hours during the summer. Measurements using the eddy-covariance technique suggest that such high vapor fluxes are not feasible from dry canopies over large areas. The NOAH latent heat flux, which sometimes exceeded 450 W m^{-2} on a sunny day, is more typical for wet canopies of high LAI than the sparse dry canopies of the American West. FORFLUX, on the other hand, produced considerably smaller daytime latent heat fluxes (i.e. typically less than 250 W m^{-2}) that are consistent with observations over both vegetated and semi-desert areas. Compared to the NOAH scheme, FORFLUX predicted a much more realistic (i.e. smaller) gradients of latent heat flux between arid and vegetated areas. Nighttime fluxes of latent heat were similar between the two models with the NOAH scheme showing a greater tendency than FORFLUX towards more negative fluxes (i.e. higher vapor condensation on surfaces) in some coastal and mountainous areas.

Due to disparate evapo-transpiration rates predicted by MM5 and MFF, fluxes of sensible heat also differed considerably between the two models (Figures 3 and 5). Since sensible heat is the energy controlling the rate of vertical atmospheric mixing and the growth of planetary boundary layer (PBL) through warming and cooling of the air adjacent to the Earth surface, MM5 is much more sensitive to this flux than it is to latent heat. A large sensible heat flux can produce higher ambient temperatures during the day while a negative sensible heat flux can result in cooler air temperatures at night. During daytime, FORFLUX produces a significantly higher sensible heat flux than the NOAH scheme (Fig. 3) while, at night, it predicts a smaller (more negative) sensible heat flux (Fig. 5). This causes a greater daytime heating of the lower atmosphere in MFF compared to MM5 and a stronger cooling at night. The effect of higher surface heating by FORFLUX can also be seen in Fig. 6, which compares daytime fields of mixing height (i.e. PBL depth) produced by MFF and MM5. Mixing height in MFF is generally greater than that estimated by MM5 due to increased rate of vertical motion. Differences in predicted sensible heat flux between FORFLUX and the NOAH scheme produced marked improvements in the forecast fields of surface temperature and relative humidity by MFF compared to MM5.

2. Effect of FORFLUX model on MM5 fire-weather forecasts.

To evaluate the performance of the new MFF model and compare it to MM5, we have developed a real-time Web-based verification system, which utilizes hourly observations from 511 automated meteorological Stations across the Western US. Figure 7 displays a map highlighting the location of each Station. Weather observations from these stations are obtained through a NOAA Port, and then stored locally in a MySQL database at RMC. Point weather forecasts produced by MFF and MM5 for the exact locations of the met. Stations are generated after each model run and also saved in the MySQL database. A Pearl script runs every evening querying the database to create tables for each verification point that match model predictions with hourly observations of air temperature, dew point, relative humidity, wind speed, and wind direction. The script also generates 'Average Tables' containing hourly means of observed and modeled data that are representative of all 511 locations. These Average Tables were used to evaluate the accuracy of individual forecasts produced by MFF and MM5, and assess the overall impact of the FORFLUX model on fire-weather predictions.



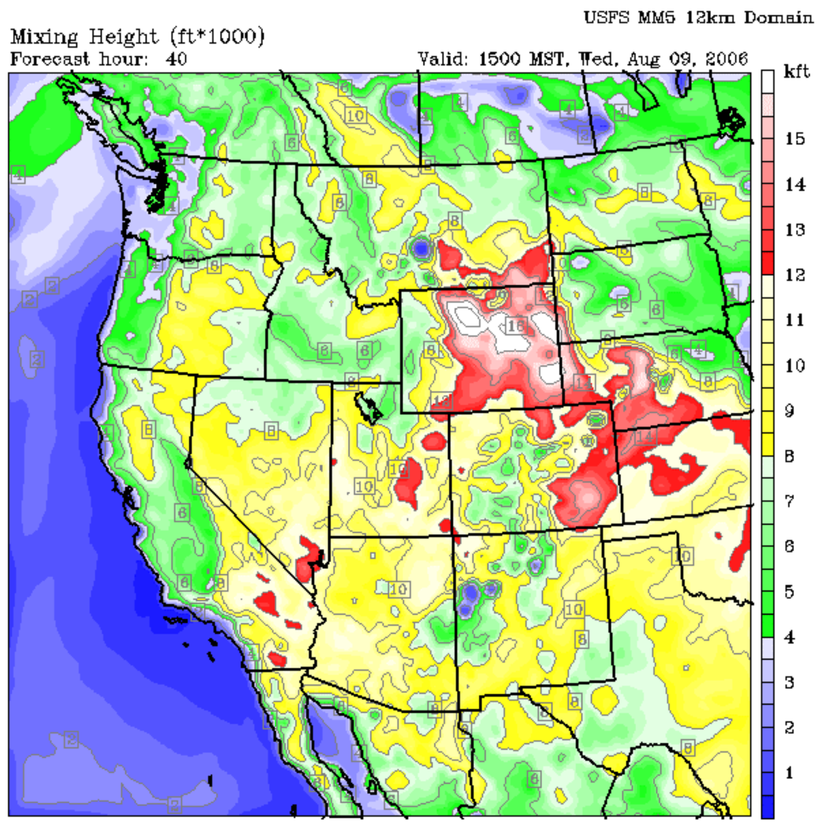


Figure 6. Daytime fields of *mixing height* predicted by MFF (upper plot) and MM5 (lower plot) at 15:00 MST on August 9, 2006 (40 hours into the forecast).

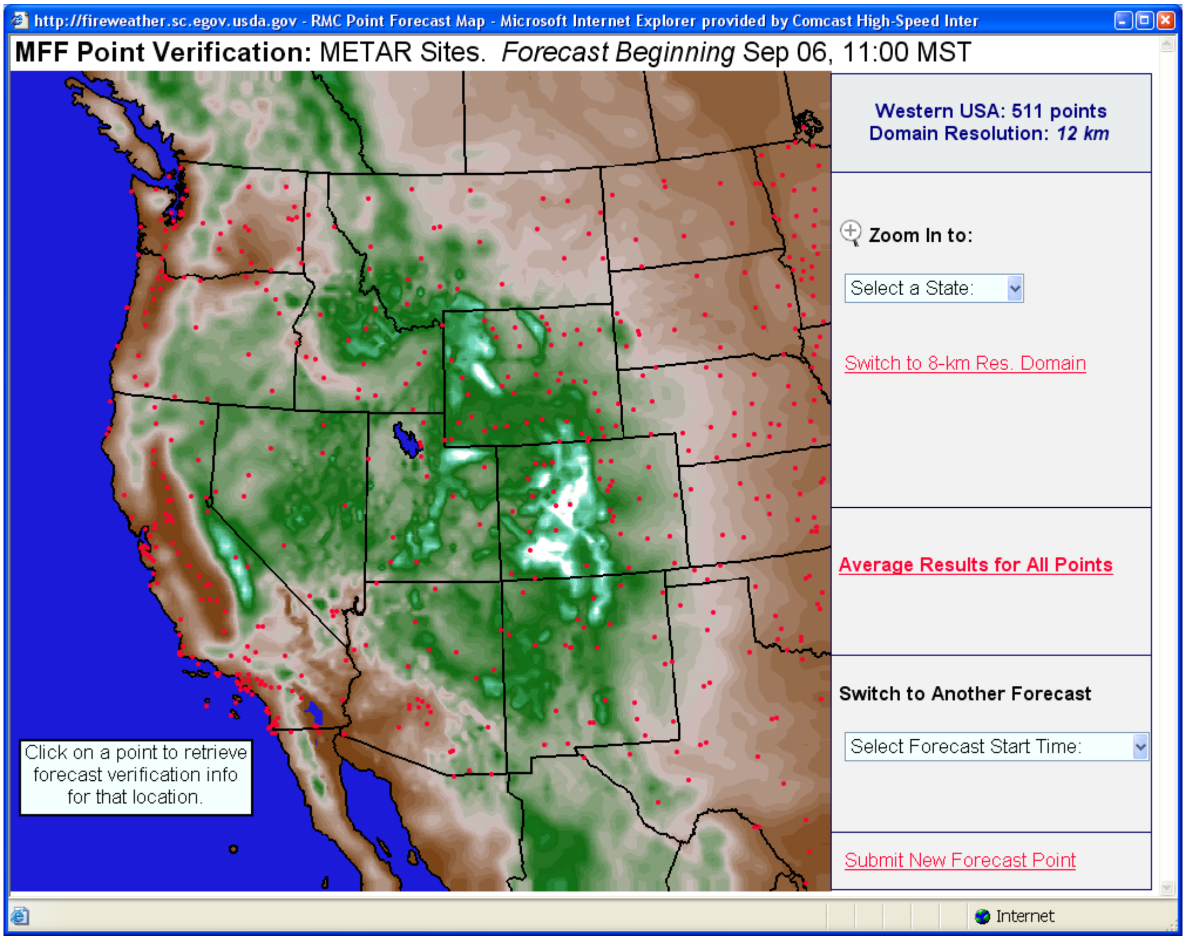


Figure 7. Screenshot of the MFF verification Web page displaying locations of all meteorological stations providing automated hourly observations.

On the MFF verification Web page, model forecasts are compared to observations using hourly time series of Mean Bias (MB) and Mean Absolute Error (MAE). MB and MAE are computed for every hour (h) using the formulas:

$$MB_h = (\Sigma\, m_i - \Sigma\, o_i) / N$$

$$MAE_h = [\Sigma\, |m_i - o_i|] / N$$

where m_i is the model prediction of a weather element at location i, while o_i is the observed value of that element at the same location, and N is the number of locations (met. Stations) participating in the comparison. Analysis of Average Verification Tables over a period of two months revealed the following pattern.

A. *FORFLUX markedly improves air temperature forecast*

For over a decade now, MM5 has been known for the presence of a systematic bias in forecasted surface air temperature. The bias consists of predicting lower than observed maximum daily temperature and higher than observed minimum nighttime temperature. As a result, MM5 tends to underestimate diurnal temperature amplitude by about $7^oF – 11^oF$. This error translates into a bias of predicted relative humidity (as discussed below). Due to improved simulation of the surface heat exchange by FORFLUX (section 1 above), MFF predicts larger temperature amplitude than MM5, thus, forecasting almost perfectly (on average) the observed minimum and maximum daily temperatures. Figure 8 illustrates this with verifications results for a weather forecast initiated at 06:00 GMT on August 19, 2006. While the mean bias of MM5-forecasted temperature fluctuates widely from $–3^oF$ in mid-afternoon to about $+7^oF$ in early morning, MFF only shows a small deviation of $\pm 1^oF$ from observations. The mean absolute error of MFF is also noticeably smaller compared to MM5. The simultaneous reduction of mean bias and absolute error is a certain sign of an improved temperature forecast by MFF. Hence, through a robust and more accurate simulation of the surface energy partitioning, FORFLUX was able to correct the decade-old temperature bias of MM5.

B. *FORFLUX significantly improves relative humidity forecast*

Our analysis showed that MFF typically predicts dew point temperature with a spatially averaged accuracy of $\pm 2.5^oF$. While this is better than MM5 (graph not shown), it is fair to say that the two models demonstrate similar skills in forecasting dew point. However, since MFF does a significantly better job of predicting air temperature, it also forecasts much more accurately relative humidity (RH) than MM5 throughout the day. Figure 9 illustrates this using the same forecast from August 2006 shown in Fig. 8. Note that both MM5 and MFF predict RH values close to observations in early afternoon hours, but the MM5 mean bias increases rapidly in the evening and early morning hours approaching 10%-12% at 06:00 MST. The MFF bias, on the other hand, does not exceed 2.5% throughout the entire period. Thus, MFF improved RH forecast most noticeably during nighttime.

C. *FORFLUX slightly improves wind forecast*

Forecasts of wind speed and wind direction by MFF were only marginally better than those produced by MM5. As demonstrated in Figure 10, wind speeds predicted by MFF match observations more accurately in terms of having larger diurnal amplitude and a bit smaller MB and MAE than MM5. Both MFF and MM5 appear to forecast wind speeds that are somewhat shifted in phase compared to observations. This pattern is only visible in the average results representing all verification points, and cannot be discerned at individual locations. We are currently looking into this phenomenon trying to explain it. With respect to wind direction, MFF tends to produce a slightly smaller bias than MM5 while mean absolute errors are virtually identical between the two models (Fig. 11).

It is important to point out that, of all fields, surface winds are perhaps the most difficult to forecast due to the influence of factors such as small-scale topography, discrepancy between model and measurement height, and local atmospheric stability profiles. Since models run at a horizontal step of 12 km, they cannot capture effects of micro topography on airflow that might impact local measurements. Winds are predicted at about 20 m height above ground while most measurements are made at 10 m. Wind forecasts could be improved by increasing spatial resolution of the models but this inevitably brings higher computational costs.

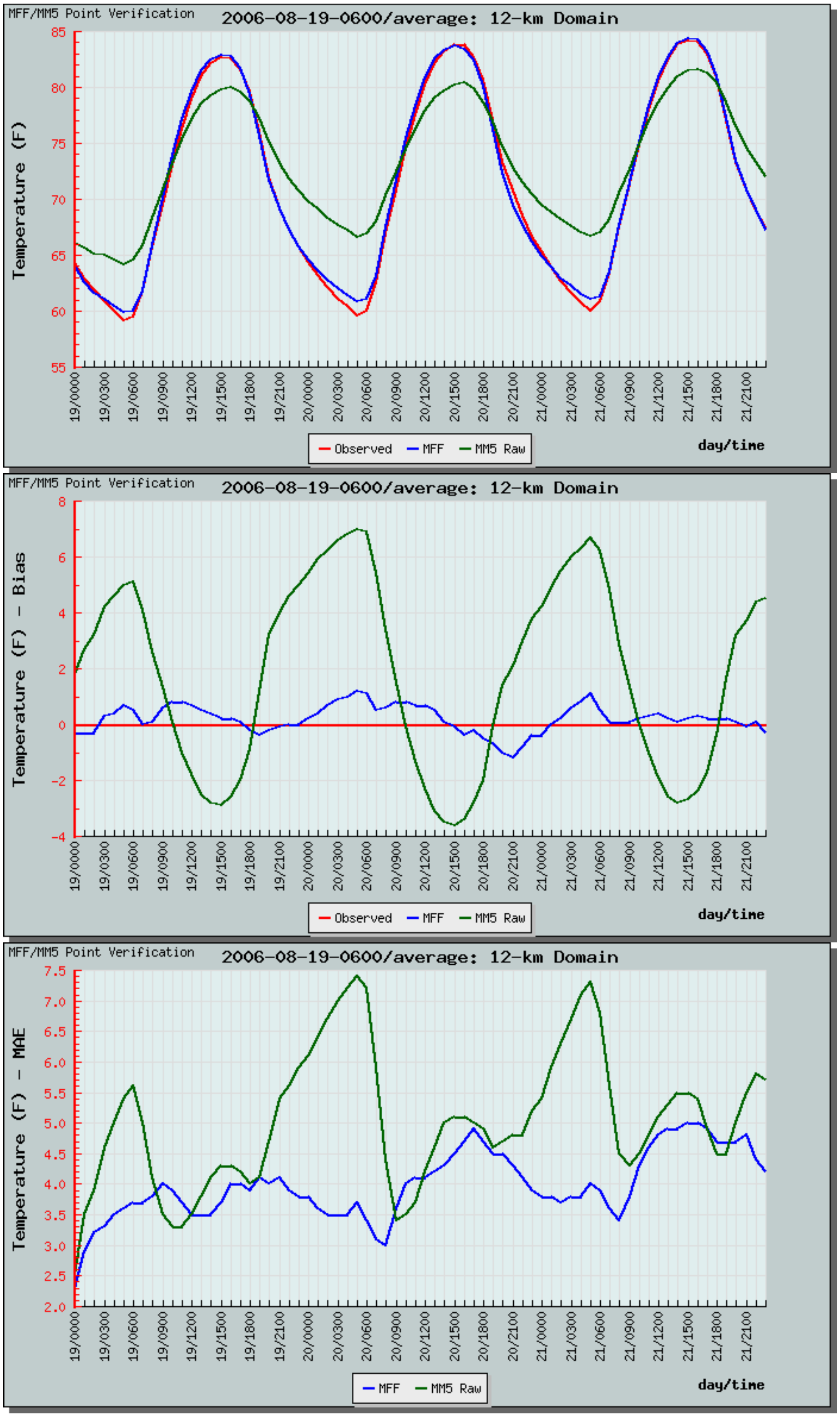


Figure 8. Forecast verification of surface air temperature produced by MFF and MM5 in August 2006. Each line represents an average of some 500 points in the Western US where modeled and observed data were simultaneously available.

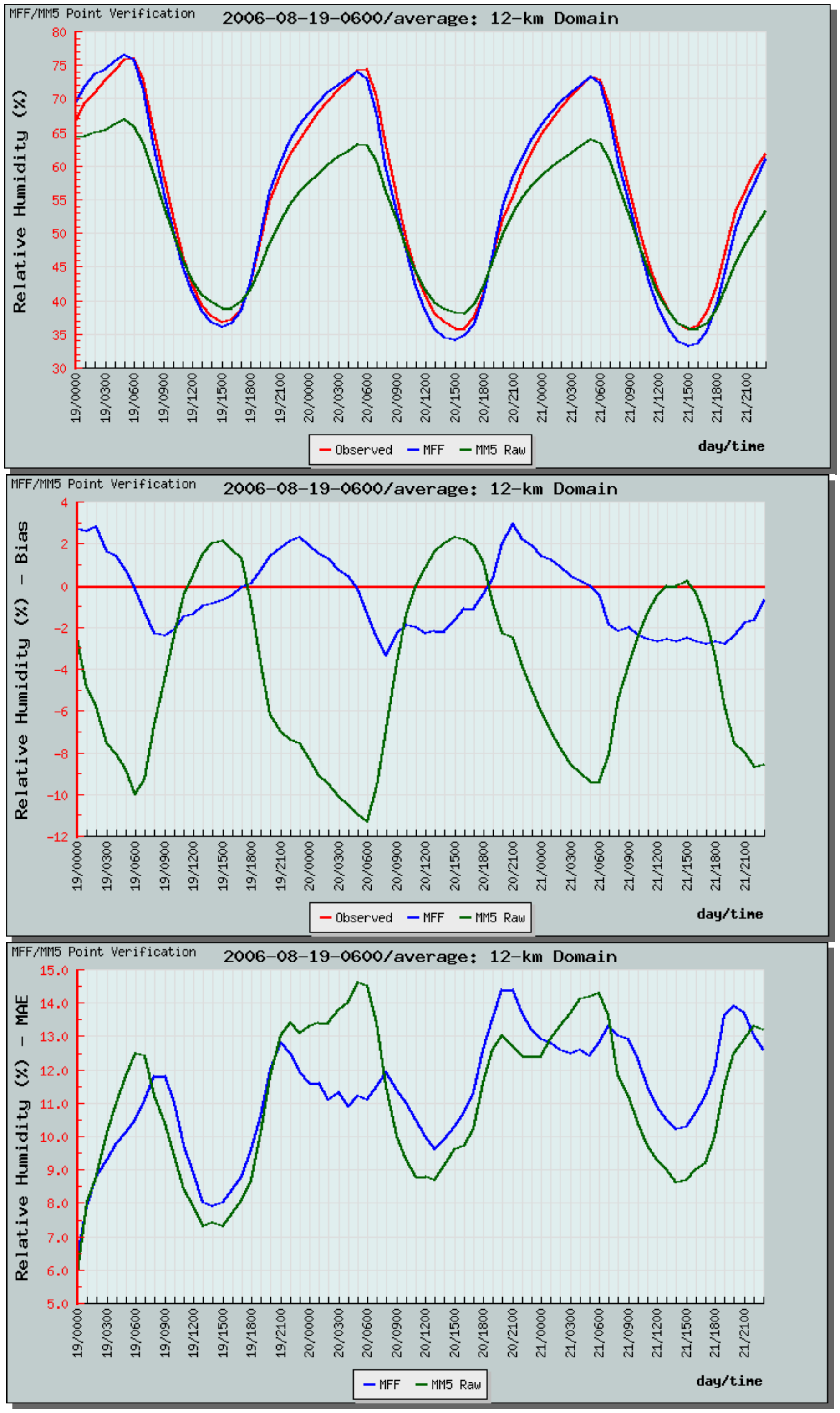


Figure 9. Forecast verification of surface relative humidity produced by MFF and MM5 in August 2006. Each line represents an average of some 500 points in the Western US where modeled and observed data were simultaneously available.

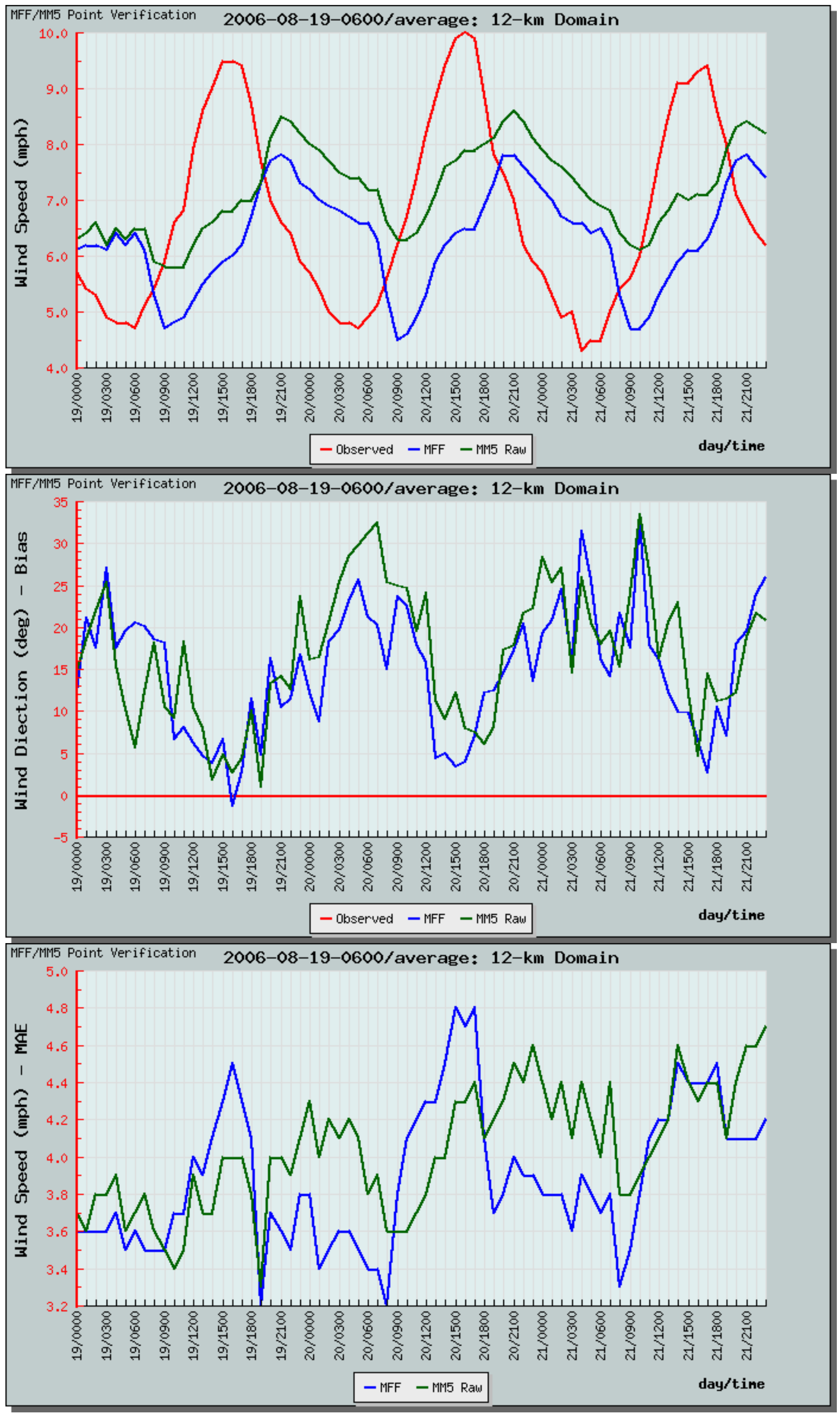


Figure 10. Forecast verification of 20-m wind speed produced by MFF and MM5 in August 2006. Each line represents an average of some 500 points in the Western US where modeled and observed data were simultaneously available.

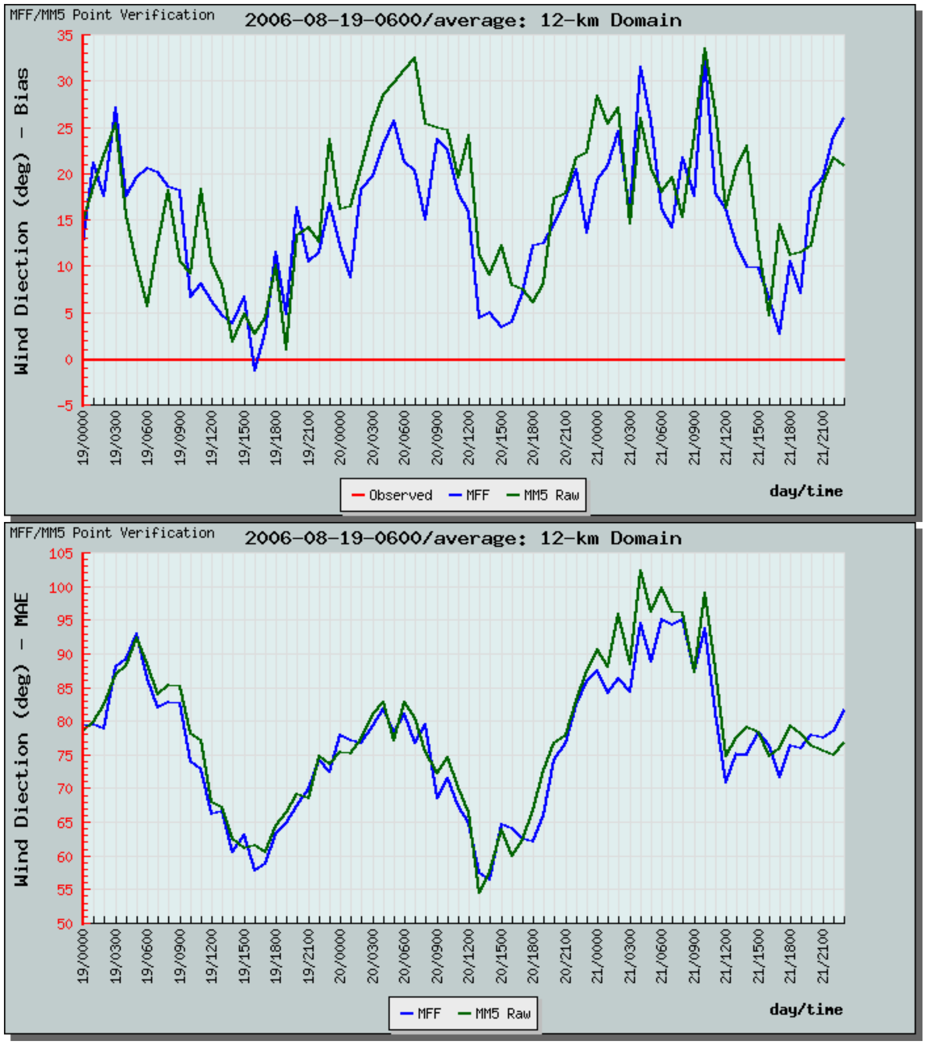


Figure 11. Forecast verification of 20-m wind direction produced by MFF and MM5 in August 2006. Each line represents an average of some 500 points in the Western US where modeled and observed data were simultaneously available.

D. *FORFLUX impacts predictions of precipitation and fire indices*

Comparison of forecasted fields of precipitation and weather-based fire indices produced by MFF and MM5 reveals differences that are attributable to the new FORFLUX surface scheme. For example, patterns of 72-h precipitation accumulation, while being grossly similar across the Western US, show noticeable differences at the regional level. Figure 12 illustrates this with precipitation maps for the Southwest generated by MFF and MM5 using identical initial and boundary conditions. The effect of FORFLUX on summertime precipitation can be explained by greater heating of the surface air and its subsequent impact on convective storms. Figure 13 shows a similar type of difference in forecasted upper-level Haines Index, which depends on vertical temperature profiles of the atmosphere. By the time of writing this report, we did not have access to a full set of necessary observational data to unequivocally conclude which model provides better forecast for these fields. Our indirect and ad-hoc observations, however, tend to indicate that MFF predictions were more accurate.

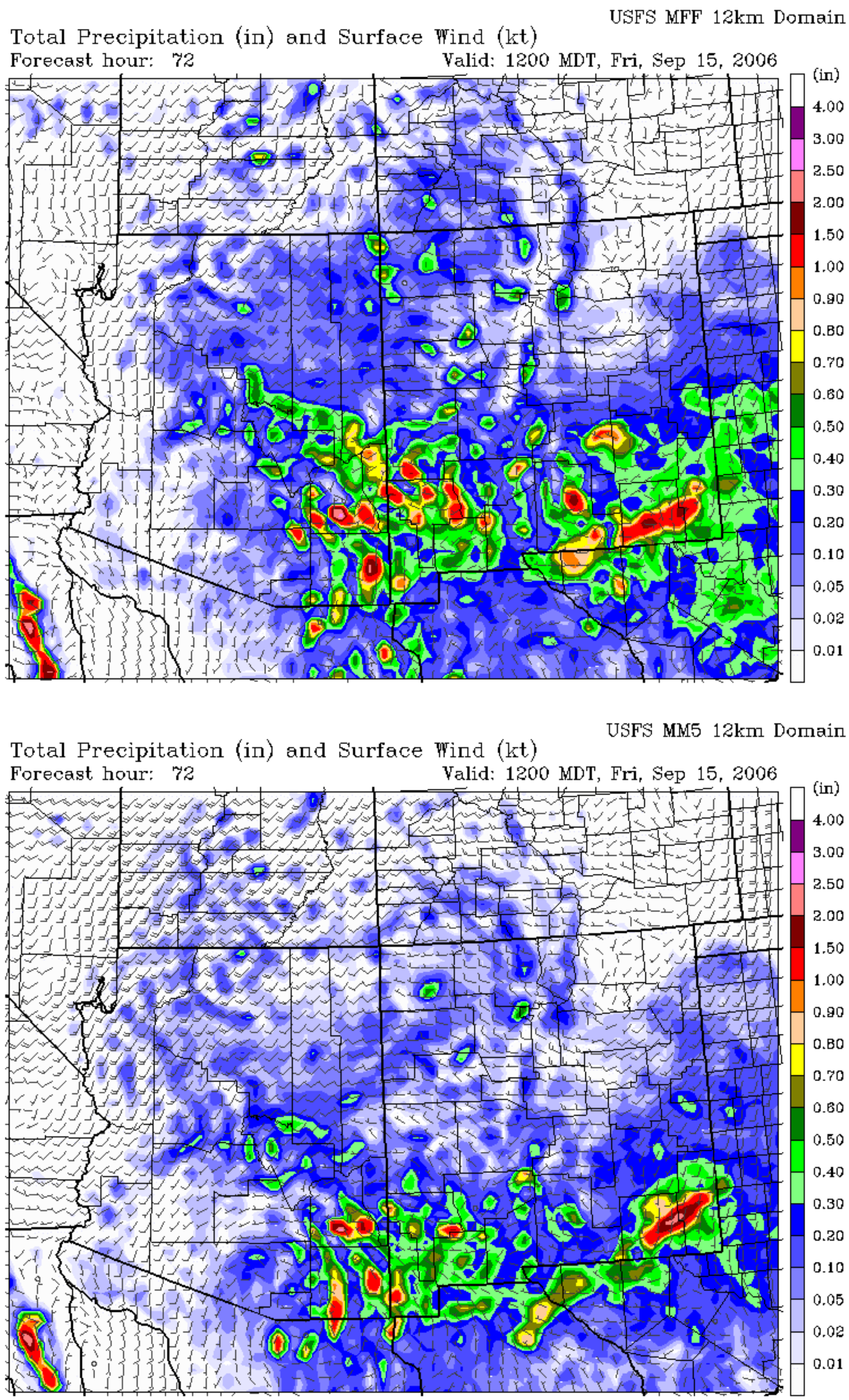


Figure 12. Fields of 72-h precipitation accumulation predicted by MFF (upper plot) and MM5 (lower plot) for the Southwest for a forecast period ending on Sep. 15, 2006.

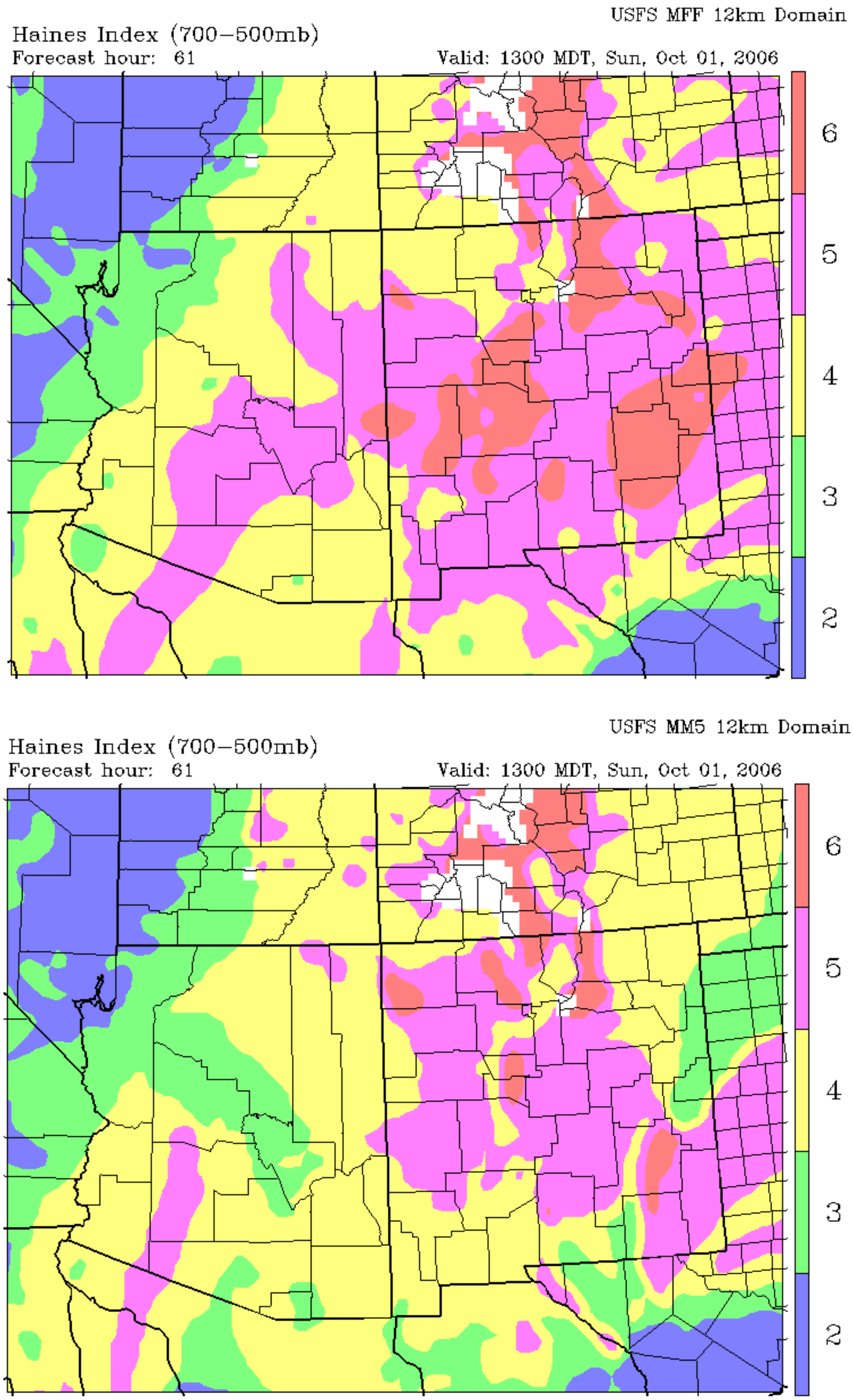


Figure 13. Fields of upper-level Haines Index predicted by MFF (upper plot) and MM5 (lower plot) for the Southwest using identical initial and boundary conditions.

F. *FORFLUX boosts meso-scale model robustness*

Comparison of verification results between model runs using different spatial resolutions (i.e. 12 km vs. 8 km) showed that mean bias and absolute error of MFF forecasts are not affected by changes in horizontal grid spacing as are MB and MAE for MM5. Figures 14 through 17 exemplify this with MB and MAE plots of forecasted temperature and relative humidity. Increasing model resolution from 12 km to 8 km improved noticeably the accuracy of MM5 forecasts as evident from the reduction of MB and MAE values. The fact that MFF performance is not affected by changing spatial resolution suggests a greater physical robustness of the new model. This implies that MFF can be run more efficiently using coarser resolution without sacrificing forecast quality. Such a conclusion, however, may not fully apply to wind forecasting.

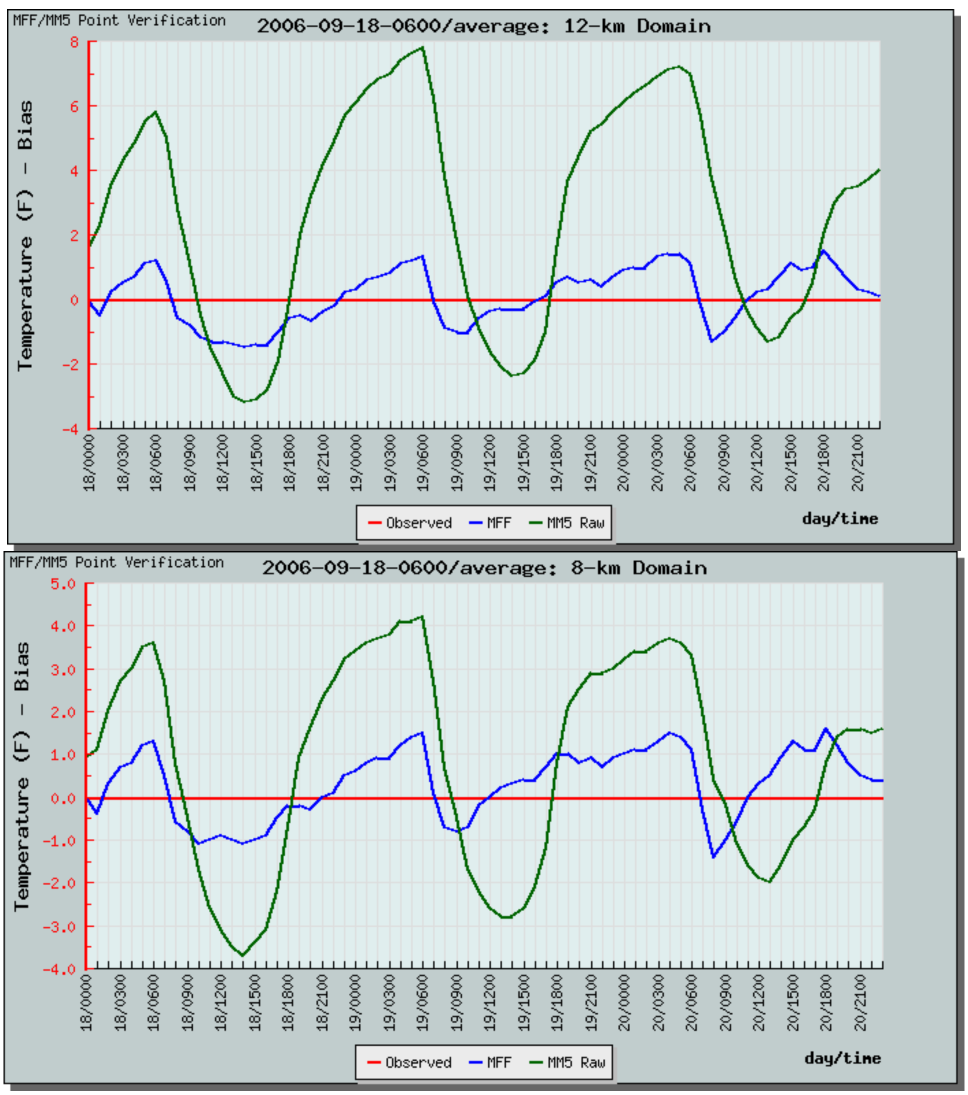


Figure 14. Model-specific variations in mean bias of predicted surface air temperature for runs utilizing horizontal grid spacing of 12 km (upper plot) and 8 km (lower plot). Each line represents an average of some 500 points in the Western US. *Note* the difference in scale of vertical axes between upper and lower plot.

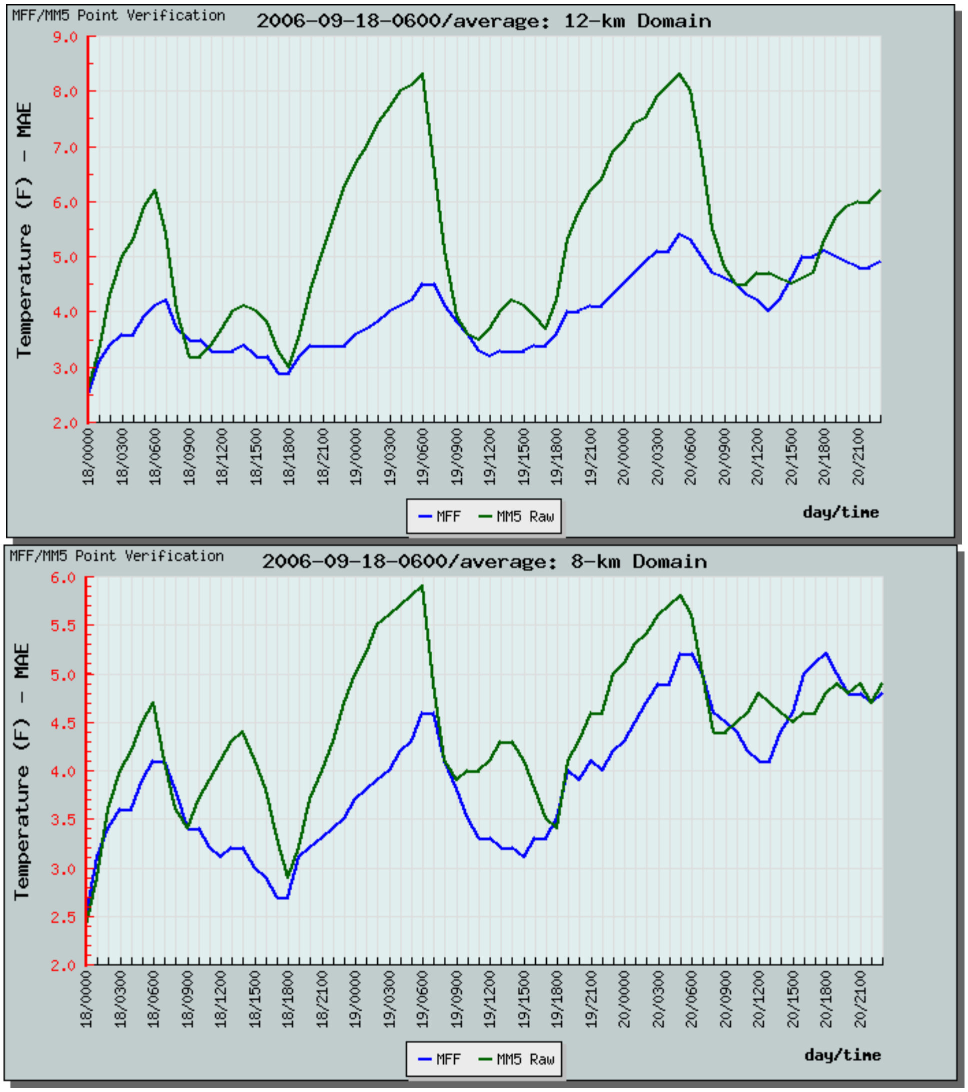


Figure 15. Model-specific variations in mean absolute error of predicted surface air temperature for runs utilizing horizontal grid spacing of 12 km (upper plot) and 8 km (lower plot). Each line represents an average of some 500 points in the Western US. *Note* the difference in scale of vertical axes between upper and lower plot.

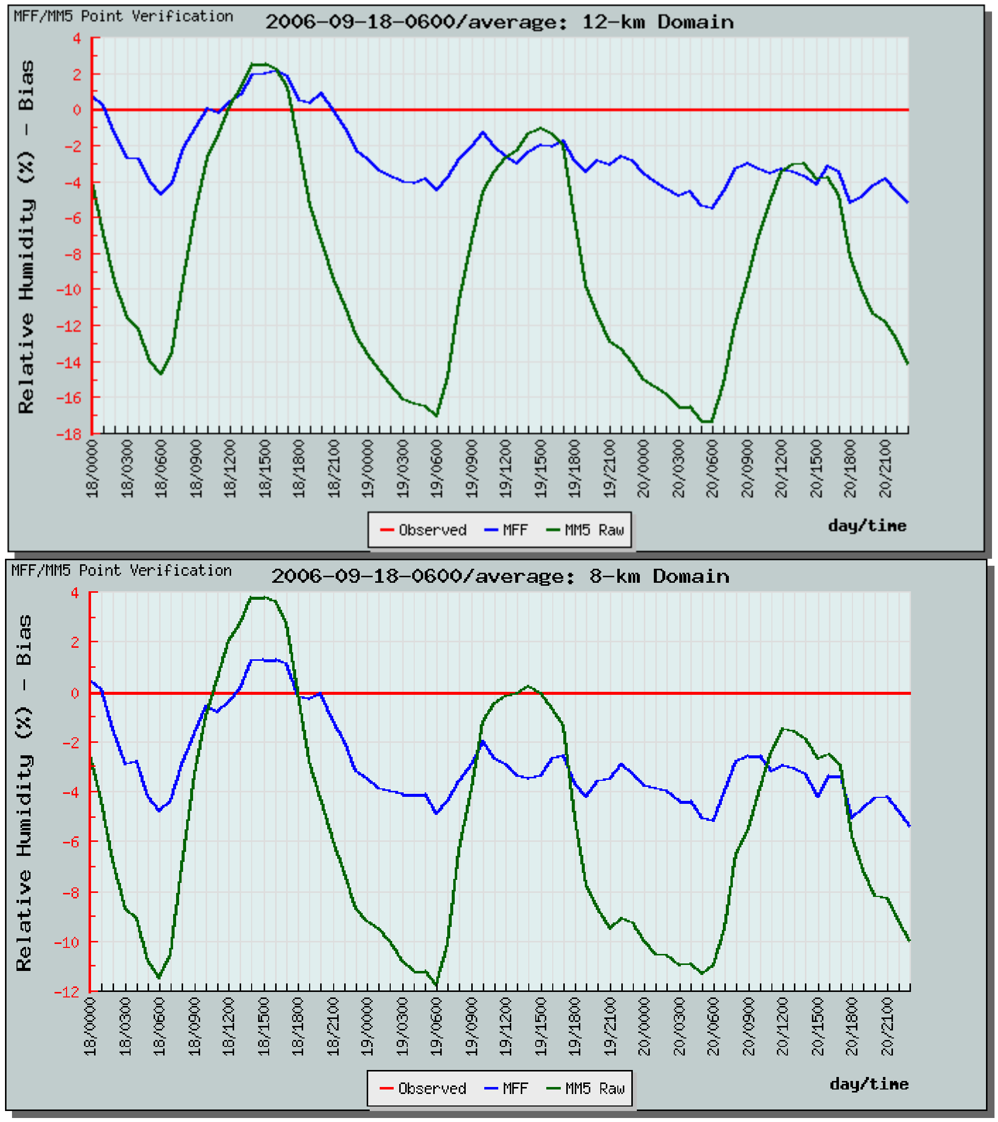


Figure 16. Model-specific variations in mean bias of predicted surface relative humidity for runs utilizing horizontal grid spacing of 12 km (upper plot) and 8 km (lower plot). Each line represents an average of some 500 points in the Western US. *Note* the difference in scale of vertical axes between upper and lower plot.

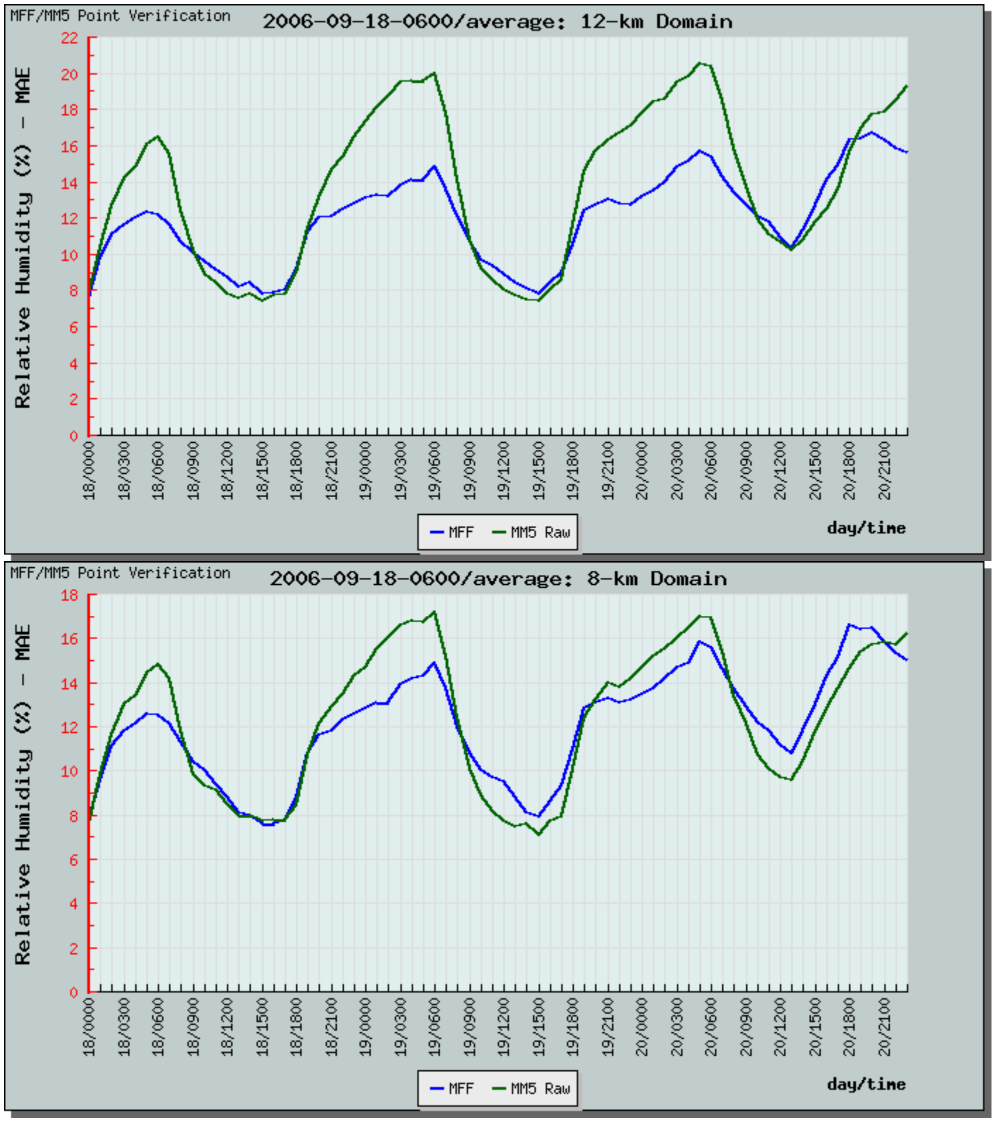


Figure 17. Model-specific variations in mean absolute error of predicted surface relative humidity for runs utilizing horizontal grid spacing of 12 km (upper plot) and 8 km (lower plot). Each line represents an average of some 500 points in the Western US. *Note* the difference in scale of vertical axes between upper and lower plot.

CONCLUSIONS

Results from this project have proven the hypothesis that a more accurate simulation of energy partitioning at the lower boundary of an atmospheric model will improve meso-scale weather forecasts. The improvement is most significant to predictions of air temperature and relative humidity, which are key variables in fire meteorology and fire-danger assessment. In addition, the improved simulation of surface heat exchange has increased the physical robustness of the atmospheric model with respect to spatial resolution.

ENVISIONED FUTURE WORK

The linking of MM5 with a comprehensive terrestrial biophysical model opened the possibility for further improvements of fire-weather perfections through:

- Simulation of sub-grid variability in energy partitioning using FORFLUX and the available high-resolution datasets of canopy LAI, land cover, and soil properties.
- Use of current LAI data derived from recent satellite images of MODIS or other sensors;
- Refinement of the FORFLUX input parameters for key vegetation types;
- Adding a 'duff' layer to the FORFLUX model to improve predictions of soil evaporation.

The new MFF model (incorporating FORFLUX) offers currently the possibility to:

- Predict more accurately NFDRS indices using MFF forecast information;
- Improve *BlueSky* predictions of smoke dispersion using MFF output;
- Develop new NFDRS indices or improve existing ones using more accurate estimates of moisture content in live and dead vegetation based on FORFLUX energy-balance calculations.

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