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The Fire Weather Accuracy and Lightning Ignition Probability System

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Project Website: http://fireweather.sonomatechdata.com/

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Abstract

Weather forecasts can help identify environmental conditions conducive to prescribed burning or to increased fire danger. These conditions are important components of fire management tools such as fire ignition potential maps, fire danger rating systems, fire behavior predictions, and smoke dispersion modeling. Fire managers use these tools to make decisions on when to conduct prescribed burns, how to manage wildfires, and how to pre-position fire suppression forces. Forecast weather conditions provide variables such as temperature, relative humidity, solar radiation, precipitation (or lack thereof), and wind—these are used in models to predict outbreaks of dry thunderstorms, the moisture content of fuels, and fire behavior. Forecast accuracy varies by model and by location; therefore, improved forecast accuracy, data accessibility, and tools to aid decision makers were identified as important gaps to be filled.

In this project, we created a website and underlying system that combines meteorological observations and four weather forecasting systems with two fire danger rating systems to produce spatial forecasts of lightning probability, dry lightning probability, and fuel ignition potential over three- to seven-day forecast time periods. The system identifies potential forecast bias in the spatial domain of each of the meteorological forecast systems to aid in selecting the best fire weather forecast for the location of interest. Maps of fuel moisture, fire danger rating indices, and other parameters aid in assessing flammability status across the landscape. The results will aid decision makers in positioning resources, making "go/no go" decisions on prescribed burns, determining when fire might be used to meet resource management needs, and determining the local certainty of fire weather forecasts (**Figure 1**).

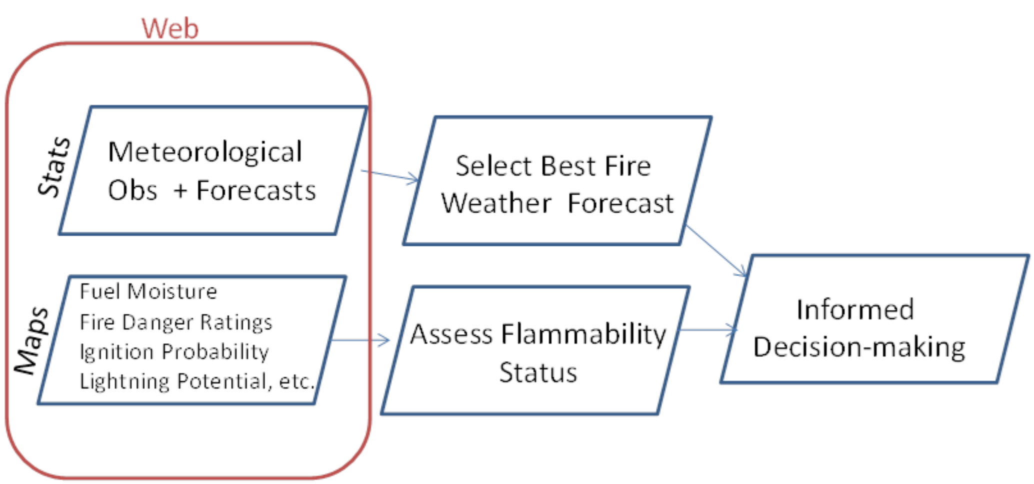

Figure 1. Fire weather forecast accuracy and lightning ignition probability system overview.

Our system provides an easily accessible set of web-based products that include (1) color contour displays of sustained ignition probability at 2.5-km resolution for the western United States; (2) color contour displays of key meteorological parameter forecasts (at resolutions based on the model selected); and (3) meteorological model performance assessments of model bias, model reliability, and overall performance of predictions of fire weather variables used in predictions of ignition risk potential. By integrating fire weather forecasts, forecasted fire danger rating, lightning occurrence probabilities, rainfall predictions, and gridded fuels information. The system provides levels of confidence for fire weather forecasts, forecasts dry lightning probability, and forecasts fuel moisture conditions.

Key Findings

- ***Access to data in a meaningful, accessible, easily interpretable manner can aid land management decisions*.** Fire managers have many options for obtaining data, but they are often overwhelmed by the quantity of data available, the difficulty involved with obtaining the data, the technical skill needed to manage the data, and the time required for data interpretation. Compiling and displaying multiple data sets in an online format in a simple, straightforward way provides more opportunity for fire managers to use the data when making management decisions. Ultimately, having real-time access to the data and the forecast products should lead to more informed management decisions.
- ***Access to model forecasts from multiple sources is vital because of the lack of consistent patterns or bias shown when comparing forecasts to observations.*** We conducted preliminary studies on meteorological forecast model performance and found that none of the models showed a consistent pattern or bias. For example, a specific model could provide high estimates (high bias) for one period of time and low estimates for another period of time (low bias). These preliminary studies indicated that weather persistence over a period of the last seven days provided the most consistent assessment of the current values and of how the models should be corrected for bias. A site's proximity to large water bodies (such as the ocean) or elevation is a key indicator of potential disagreement with a model.
- ***Combining forecasted lightning occurrence potentials with forecasted weather and fuel moisture estimates improves fire potential information.*** Land managers often do not have time to look at all the variables that go into producing fire occurrence potential predictions so they can make informed decisions on where naturally caused fires are most likely. Preliminary evaluations and discussions with fire managers indicate that identifying where lightning-caused fires are most likely to occur will quickly and easily improve their ability to make fire suppression decisions. Fire managers have indicated they often have to make these decisions in minutes; the fire weather system automatically provides ignition probability maps that can be rapidly evaluated to determine the likelihood of lightning-caused fires across multiple scales. This capability should support rapid management decision-making.

Background and Purpose

Fire weather forecasts can identify environmental conditions that give rise to high fire danger, but these forecasts are not always accessible—in terms of availability, clarity, and reliability—to those on the ground who need them. The interagency Joint Action Group (JAG) conducted a national wildland fire weather needs assessment, which recognized the need for improvements in the accessibility and reliability of fire weather forecasts and products (Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2007). JAG members identified several fire weather forecast areas requiring urgent attention, including more statistical information on current accuracy and verification for fire weather forecasts, additional information regarding upper-level atmospheric parameters and stability conditions, improved spatial and temporal reliability of fuel moisture predictions, and standard representations of fuels information that is integrated with meteorological conditions and fire weather threats (Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2007). This project aimed to improve fire weather forecast accuracy which in turn can improve the accuracy of fire ignition potentials, fire danger rating systems, fire behavior predictions, and smoke dispersion modeling.

In this project, we produced a set of meteorological model performance assessments to provide end-users with near real-time information about meteorological model bias, model reliability, and overall performance of predictions of fire weather variables used, in turn, to predict ignition risk potential across approximately 2,200 Remote Automatic Weather Stations (RAWS) and Automated Surface Observing Systems (ASOS) in the western United States. Our system integrates fire weather forecasts, the Bothwell lightning prediction model (Bothwell, 2008), forecast precipitation amounts from the National Digital Forecast Database (NDFD), and gridded fuels information, to provide end-users spatially explicit digital maps of fire weather forecasts out three to seven days, forecasted lightning probabilities, forecasted dry lightning probabilities, and forecasted fuels ignition potentials.

The fire weather system provides an easily accessible set of web-based products that include (1) color contour displays of lightning occurrence probability, dry lightning occurrence probability, and sustained ignition probability at 2.5-km resolution for the western United States; (2) color contour displays of key meteorological parameter forecasts at a range of resolutions based on the model selected; and (3) information about confidence in the meteorological forecasts including time-series plots and statistics that provide model-to-model and model-to-observation comparisons. The results can aid decision makers in positioning resources, making “go/no go” decisions on prescribed burns, determining when fire might be used to meet resource management needs, and determining the local certainty of fire weather forecasts.

Our objectives included:

1. Incorporate fuels information into our predictions of dry lightning outbreaks (developed under JFSP projects 01-61-6-08 and 07-2-1-42) to produce new forecast products that predict the risk of sustained fire ignitions from dry thunderstorm outbreaks.
2. Create a web-based information display system that provides real-time evaluation/verification and estimates of uncertainty of model-predicted fire weather variables that will be used in the fire ignition risk predictions.

Predicting the probability of sustained fire ignitions is a complicated exercise because many conditions must exist at the same time. Both current and future weather conditions are important, as well as fuel type, fuel loadings, and fuel moisture. Whether an ignition continues to grow and spread into the surrounding landscape depends on the location of the ignition, the resources available to extinguish the ignition in a timely manner, and whether wetting rains occur after ignition. While we cannot incorporate estimates of resource availability, we were able to produce lightning probability potentials and ignitions probability potentials by incorporating forecasted weather and fuel conditions information.

In summary, forecasted weather conditions provide variables such as temperature, relative humidity, solar radiation, precipitation (or lack thereof), and wind variables that are used in models to predict where outbreaks of dry thunderstorms are likely to occur, the moisture content of fuels, and fire behavior. Ultimately, improved understanding of the forecast accuracy in a location of interest, improved spatial understanding of flammability, and up-to-date information that is readily accessible, will lead to improved decision-making.

Study Description and Location

This study focused on the western United States because of the large RAWS and ASOS system, the large percentage of lightning-started wildfire in the West, and prior research indicating that lightning-started fires in the West are predominately dry lightning fires (Rorig and Ferguson, 1999). In this project, we created a website and a two-part underlying system:

1. The ***forecast performance system*** compares meteorological observations and the outputs of four forecasting systems to produce statistical-based measures of forecast accuracy and forecast correction factors.

2. The forecasted weather parameters are incorporated to produce ***fire danger indices*** from two fire danger rating systems and ***spatial forecasts*** of lightning probability, dry lightning probability, and fuel ignition potential over three- to seven-day forecast periods.

The system identifies potential forecast bias in the spatial domain of each of the meteorological forecast systems to aid in selecting the best fire weather forecast for the location. Maps of fuel moisture, fire danger rating indices, and other parameters aid in assessing flammability status across the landscape. Maps of lightning occurrence potentials and fuel ignition probability provide insight into potential ignition sources and the ignition status of the fuels across the landscape. The following sections discuss the data acquisition and forecast evaluation system components and methods; fuel layers and fuel moisture estimation methodologies; lightning and ignition probabilities; and the website.

Data Acquisition and Forecast Evaluation System

System Overview

The forecast performance evaluation system provides information on weather predictions and forecast accuracy uncertainty. The system routinely acquires observed and forecast meteorological data, and provides real-time evaluation/verification and uncertainty estimates of the model-predicted surface fire weather variables that are used in the fire ignition probability predictions. The web-based system, displays results as time-series and spatial plots that are continually updated as new observations and forecasts become available. Spatially and temporally integrated results of the real-time comparison of predicted and observed fire weather parameters are used as an indicator of model performance for the given model. The observed data and meteorological models accessed in this system are listed in **Table 1**.

Table 1. Sources of observed and forecast meteorological parameters used in the fire weather forecast performance evaluation system.

Data Sources	T_{sfc}	RH_{sfc}	E	Precip.	u_{sfc}	T_{aloft}	$T_{dp, aloft}$
Observed							
ASOS	✓	✓		✓	✓		
RAWS	✓	✓	✓	✓	✓		
RAOB						✓	✓
Forecast							
UW WRF	✓	✓	✓	✓	✓	✓	✓
NDFD	✓	✓		✓	✓		
NAM	✓	✓	✓	✓	✓	✓	✓
GFS	✓	✓	✓	✓	✓	✓	✓

Parameters: T_{sfc} = surface air temperature; RH_{sfc} = surface relative humidity; E = solar radiation; Precip. = precipitation; u_{sfc} = surface wind velocity; T_{aloft} = aloft temperature; $T_{dp,aloft}$ = aloft dew point temperature
Observations: ASOS = National Weather Service (NWS) Automated Surface Observing Systems; RAWS = Remote Automatic Weather Stations; RAOB = NWS radiosonde observation
Models: UW WRF = University of Washington's Pacific NW Weather Research and Forecasting model; NDFD = National Digital Forecast Database; NAM = North American Model; GFS = Global Forecast System

Real-time model verification in the forecast performance evaluation system is a data-intensive process that requires a robust system for acquiring, processing, storing, and retrieving observed and modeled meteorological data. Our system consists of (1) a data acquisition system to manage and coordinate real-time data transfers and downloads; (2) extraction software to retrieve site-specific model data values and prepare data for database import; and (3) a database to facilitate storage and retrieval of observed and modeled meteorological data sets. Our database currently stores and manages over 2.6 billion weather observations, model forecasts, and forecast-derived fuel moisture products. Each component of this system, along with the data sources used, is represented in Figure 2 and described in the following paragraphs.

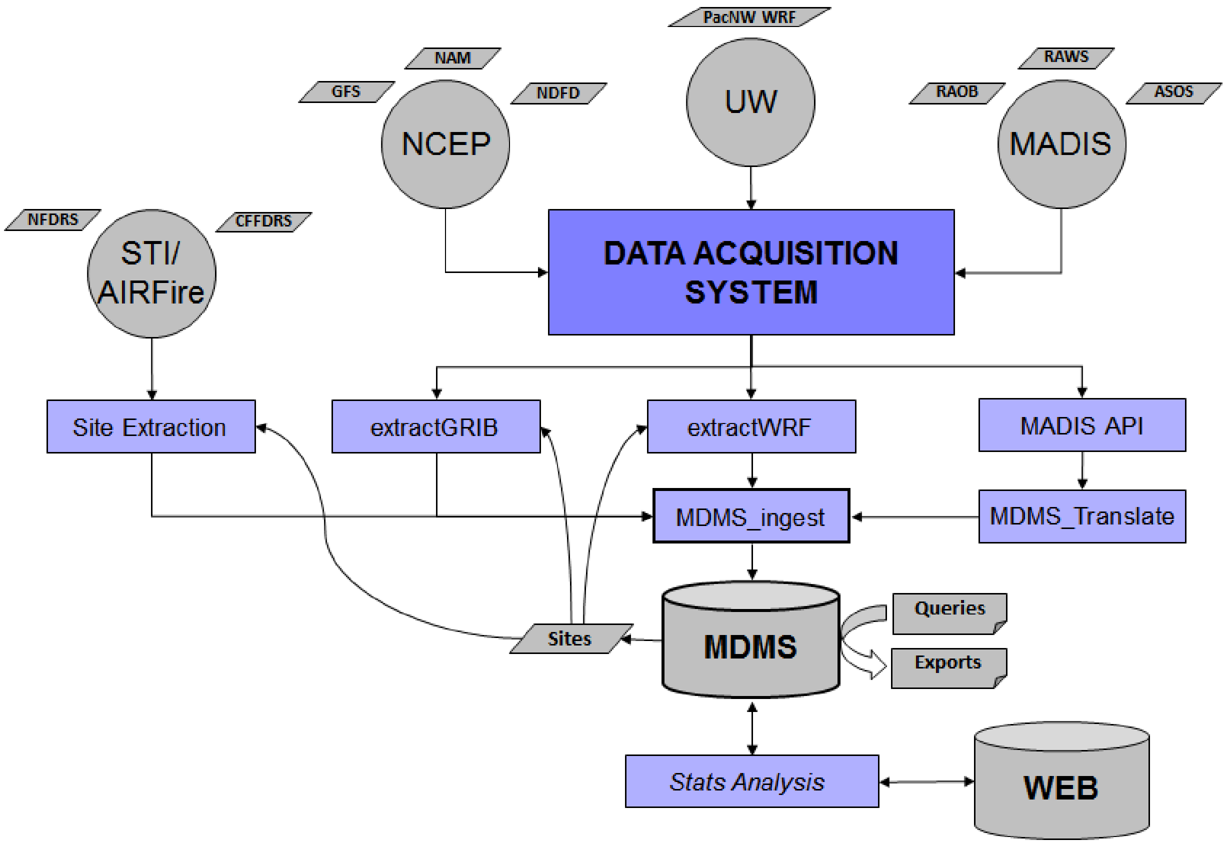

Figure 2. Flow diagram of the real-time fire weather data acquisition and forecast evaluation system and its relation to the overall sustained ignition potential forecasting.

Data Acquisition System

A data acquisition system (DAS) was developed to provide a single program for managing and coordinating continuous remote file transfer protocol (FTP) and customizable local data transfers from multiple sources. The DAS features a logging capability for tracking system failures, and command-line options for manually spawning one-time transfers. The DAS is written in Python (version 2.6) and leverages the queue and threading modules from the Python standard library. Every minute, the main program scans the transfer times for all transfer jobs and places any scheduled jobs into a transfer queue. An asynchronous runner thread performs file transfers as the jobs arrive in the transfer queue. The algorithm is illustrated by the flowchart in Figure 3.

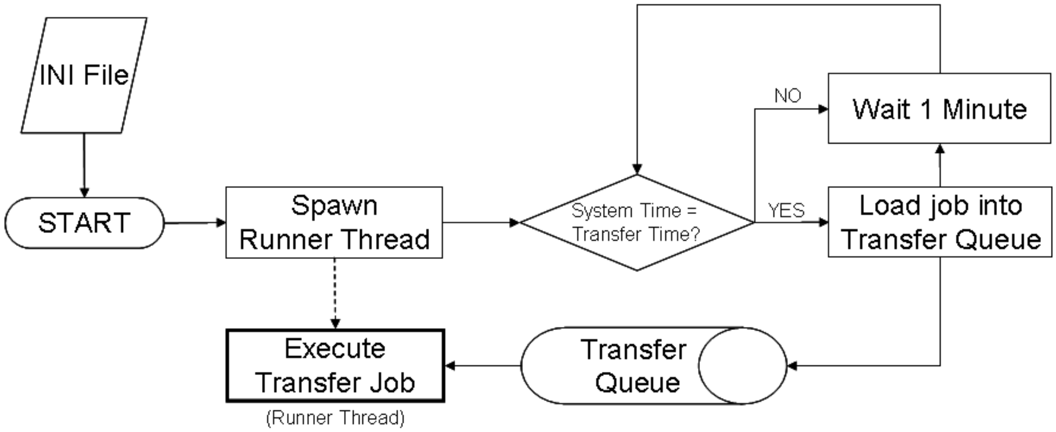

Figure 3. Flow diagram of the data acquisition algorithm.

Data Extraction and Processing

The fire weather system is currently extracting hourly surface weather data observations from 2,200 weather stations in the Interagency Remote Automatic Weather Stations (RAWS; http://raws.fam.nwcg.gov/) network and the National Weather Service's Automated Surface Observing Systems (ASOS; http://www.nws.noaa.gov/asos/) network. The system collects upper air weather data from the Universal Rawinsonde observation program (RAOB; http://www.raob.com/). RAWS is a network of federal, state, and locally managed weather stations that provide data to support fire and land management decisions. RAWS stations also provide solar radiation data, which are important for evaluating modeled solar radiation predictions used to drive fuel moisture models. The ASOS network is used to complement the RAWS network by providing observations from airports across the country. The RAOB network provides twice-daily upper-air pressure, temperature, and moisture data from 20 sites in the western United States.

Several different operational meteorological models are considered in the forecast performance evaluation system (also shown in Table 1). These include the University of Washington (UW) regional Weather and Research Forecast (WRF) model at 4-km resolution for the Pacific Northwest, the National Centers for Environmental Prediction (NCEP) North American Model (NAM) at 12-km resolution, the NDFD at 2.5-km resolution, and the NCEP global forecast system (GFS) model. The NAM, based on the WRF model, provides 84-hr forecasts over the continental United States. The GFS model, a global model, provides medium- and long-range forecasts out to 384 hours at 0.5-degree (~55 km) resolution. The NDFD provides a seamless mosaic of digital forecasts from NWS field offices working in collaboration with NCEP (Glahn and Ruth, 2003).

The DAS is currently configured to acquire the observed and modeled meteorological data sets from three sources: (1) the National Oceanic and Atmospheric Administration's (NOAA) Earth Systems Research Laboratory (ESRL) Global Systems Division (GSD) Meteorological Assimilation Data Ingest System (MADIS) (http://madis.noaa.gov); (2) NCEP; and (3) the UW Department of

Atmospheric Sciences. Surface and upper-air observations are acquired from the MADIS platform. MADIS provides a single point of access to quality-controlled meteorological observations from hundreds of networks and agencies around the world. MADIS data are extracted from their raw netCDF format with data dump utilities from the MADIS Applications Programming Interface (API), and prepared for database import by the *MDMS_Translate* program (Figure 2).

Model forecast data are acquired from NCEP in GRIB2 format. The DAS currently acquires forecast data from the NAM and GFS. We acquire the NAM 84-hr forecasts for the continental United States (CONUS) at 12-km resolution and the global GFS seven-day forecasts at 1.0-degree (~110 km) resolution. The NDFD is a hybrid human-model forecast product, and it is available at 2.5-km resolution for the CONUS. The DAS acquires 3-hourly forecast data at the 0000 UTC model initializations. Data are extracted from GRIB2 data at the observation sites and prepared for database import by the *extractGRIB* program, which uses the wgrib2 GRIB2 decoder.

The UW WRF system produces 72-hr forecasts initialized at 0000 UTC with 4-km resolution. Because the hourly forecast data sets are large, a USFS computer hosted at UW runs a pre-processing script to "thin" the forecast data by selecting only certain variables before transfer. The thinned forecast data are acquired in the native WRF output format by the DAS and extracted at the observation sites and prepared for database import by the *extractWRF* program.

STI/AirFire Fire Danger Indices and Fuel Moisture Estimations

Fire danger indices and fuel moisture estimates are produced by STI and the AirFire team. We produce daily, spatially resolved, forecasted National Fire Danger Rating System (NFDRS) and Canadian Forest Fire Danger Rating System (CFFDRS) fire danger and fuel moisture products using inputs from the GFS, NAM, and WRF model forecasts. The resulting fire danger indices and fuel moisture estimates are output as netCDF files for viewing on the website and ingesting into the database.

Database Platform

A PostgresSQL database platform called the Model Data Management System (MDMS) was developed to facilitate efficient storage and retrieval of modeled and observed meteorological data. The MDMS stores site-specific data using a minimized data table for optimal storage and retrieval, and accommodates the unique challenges posed by model data sets with multiple daily cycles. A Java-based automated ingest system is also built into the MDMS to import modeled and observed data in real time as they are acquired and processed. Although the MDMS was developed for the fire weather forecast performance evaluation system, its design is quite generic and flexible.

Data are obtained from MDMS by building queries and stored procedures (which codify a pre-defined set of queries). Interactive tools, such as *pgAdmin*, can be used to explore the database and query MDMS data interactively. Database connections can also be established through programming languages such as R or Python to perform automated queries and robust statistical analyses.

Forecast Analysis and Evaluation

To create our real-time analysis system, we compared historic observational data with coupled model forecast data to look for trends in model accuracy. We looked at a number of statistical analyses commonly used for evaluating paired model outputs and physical observations including linear regressions, skill scores, time-series trends, and difference measures. Since our goal was to evaluate model accuracy, and to provide a methodology to improve model accuracy and user confidence in modeled forecasts, we determined that difference measures including model error bias provided the best correction factors. For all records at 1300 LT, we used the open source R statistical package to calculate the magnitude and direction of the error using absolute and percent differences. The observed differences were summarized and used to create bias correction factors over annual, monthly, past-30-day, and past-7-day periods.

Through a series of comparisons using model bias calculated (1) annually for all stations, (2) monthly for all stations, (3) using the prior 7 days for all stations, (4) using the past 30 days for individual sites, and (5) using the past seven days for individual sites, we determined that model bias calculated independently for each site over the past-7-day period provided the greatest improvement in forecast accuracy (**Figure 4**). This is basically an example of persistence, i.e., the best indicator of tomorrow's temperature is found by looking at the previous days' temperatures. The models track the trends well (Figure 4) but they can be calibrated to the local area by looking at the historic model variability or bias. The seven-day period selected for calculating our model bias correction factor proved to be the most useful when trying to improve the accuracy of the short three- to seven-day forecasts in our system. Using longer historic time periods such as months or years can be useful, but we found that the magnitude and direction of model bias not only varied spatially from site to site but also temporally within a site.

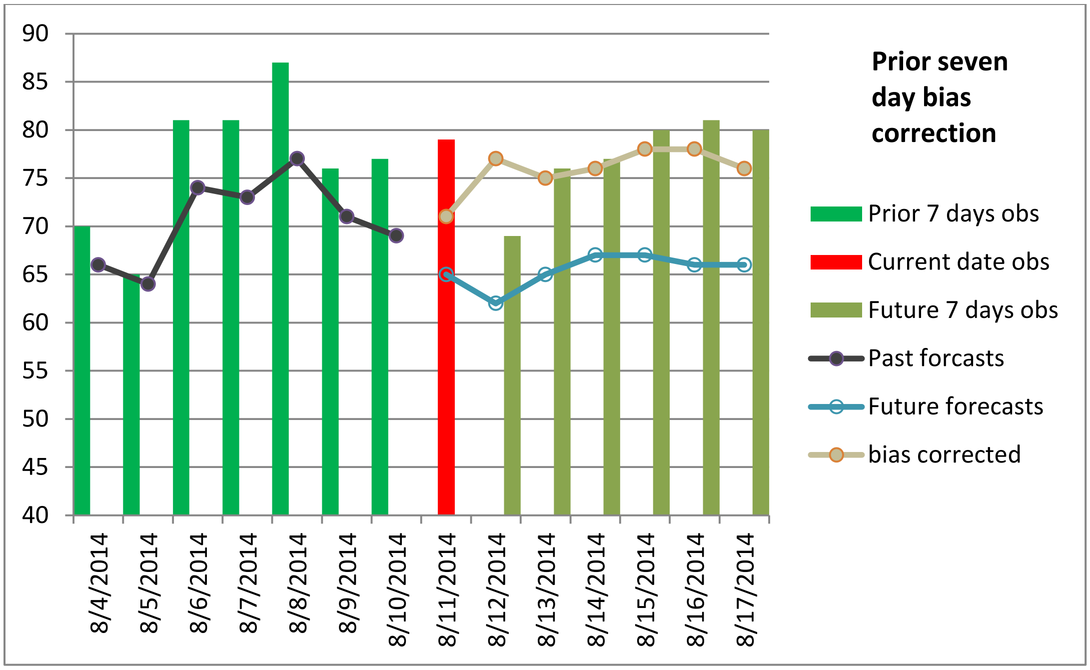

Figure 4. Example of bias correction for a RAWS weather station in Santa Rosa, California (RSAC1). Data are from a 15-day window. The past seven days prior to the current date of August 18, 2014, were used to determine how the model was performing and calculate a bias correction. A bias correction of approximately -10 was then applied to provide a corrected model forecast.

Assess Fuels Layers

We investigated a number of fuel loading maps and fuel moisture estimation methodologies for use in the fire weather system. Fuel loading maps provide estimates of the biomass (fuels) available to burn across landscapes (see **Appendix**). Three sets of mapped fuel loading models were selected for inclusion in the fire weather data and model integration system. The NFDRS (Burgan et al., 1997; 1998) fuel models were included to provide NFDRS users a fuels data set from which to estimate ignition potentials. The NFDRS fuels layer is used, in combination with NFDRS fuel moisture (1-hr fuels) and fire danger indices (Energy Release Component [ERC]), to produce ignition probability maps. The Fuels Characteristics Classification System (FCCS) fuelbed map layer (McKenzie et al., 2007) was included to provide users with fuel models to estimate the amount of biomass on site. These fuel models serve as inputs for fire effects models to estimate fuel consumption and smoke production. Future versions of the fire weather assessment system will provide users with mapped fuel consumption and smoke emission maps to provide insights on smoke production potentials given current and forecasted weather parameters. The Standard 40 fire behavior fuel models (Scott and Burgan, 2005) were included to provide information for fire weather assessment users to rapidly assess fire behavior (such as flame length and rate of spread). In the future, the fire weather system could include pre-run estimates of fire behavior potentials using the forecasted fire weather variables. The system is set up to facilitate adding additional mapped data sets when needed. Each fuel model set is described in more detail in the Appendix.

Lightning and Ignition Probabilities

The lightning occurrence and ignition probability system uses NOAA's lightning probability prediction system (Bothwell, 2008) to produce digital maps of the likelihood that a lightning strike will occur, the likelihood that lightning will be dry lightning, and the likelihood that the ignition source will encounter ignitable fuels. For determined lightning and dry lightning probabilities, we had originally intended to use the same methodology for computing lightning probably as was used previously for the Pacific Northwest region (Rorig et al., 2007). Preliminary investigations revealed that the statistical methods used in the earlier dry lightning predictions were not suitable for the current study because of the larger meteorological model domains and different model resolutions that were used. Additionally, it was more computationally efficient and physically consistent to use lightning probabilities generated directly from the model variables (Bothwell, 2008), rather than interpolating statistics generated from observational data. The Bothwell method uses modeled data and a perfect prognosis technique to compute the probability of cloud-to-ground lightning strikes. Dry lightning probabilities are calculated by coupling the Bothwell probability of lightning equation with NDFD precipitation forecasts. A lightning strike is determined to be dry if it occurs with less than 0.1 inch of rainfall (Rorig et al., 2007). The lightning and dry lightning equations are produced daily and digitally mapped for display on the fire weather website.

Three digital ignition probability maps are produced daily by the lightning occurrence and ignition probability system. First, an ignition probability map is produced by combining 1-hr fuel moisture values and the ERC index from the NFDRS forecasts with the NFDRS fuels layer. The NFDRS fuels layer provides information on the quantity and type of fuels present within each map pixel. The 1-hr fuel moisture is used to estimate the ignition status of the fine fuels, which determine whether the ignition source will initially ignite the fuels. Moisture of extinction values (MOE) taken from Cohen and Deeming (1985) set the "burn/no burn" threshold values for 1-hr fuels. Ignition probabilities are set to zero if the 1-hr fuel moisture is estimated to be above the MOE. The ERC index provides information about the burnability of the entire fuel complex; within our system, ERC is used to help determine whether the fuels will spread from the initial ignition into the surrounding fuels. The ignition probability maps are agnostic of ignition source. The lightning and dry lightning ignition probability maps combine the ignition probability map with the lightning and dry lightning occurrence probability maps. The lightning and dry lightning ignition potential maps provide users with fire occurrence potential maps that tie together the potential fuels on the ground, the potential that an ignition source will encounter the fuels, and the estimated flammability status of the fuels.

Website Description

The fire weather system website (fireweather.sonomatechdata.com) is divided into two functions: (1) a fire weather accuracy assessment in which weather parameter forecasts—

including temperature, relative humidity, wind speed, and wind direction—can be compared with direct meteorological measurements, and (2) a set of ignition probabilities in which the likelihood of lightning that can ignite fuels will occur and the likelihood that lightning will encounter receptive fuels are forecast. The system covers the western half of the contiguous United States. The website is organized around three pages: **Site Info, Time Series Graph**, and **Data Map**. Information provided in each page is listed in **Table 2**.

On the **Site Info** page, users are able to view observational data for 2,200 weather stations, including both RAWS and ASOS stations. Users can locate weather stations in their area using a mapping system that includes topographic maps, street maps, and satellite imagery. Once users have identified the weather station they want to investigate, the website zooms to the site location showing an aerial view with site information (site code, latitude, longitude, and elevation) and the most recent hour's weather information. Users can compare the observations for temperature, relative humidity, wind speed, and wind direction with the forecasts from the NDFD, NAM, GFS, and WRF models. The fire weather system produces graphs of temperature, relative humidity, wind speed, and wind direction observations collected at 1300 local time (LT) on a daily basis. The 1300 LT observations are compared with the nearest forecast from each of the four forecasted systems. The fire weather assessment forecast adjustment, based on model bias over the past seven days, is shown as well.

On the **Time Series Graph** page, users can assess forecast observations diurnally over the past seven days. Users can compare forecasts for each of the four forecasting systems (NDFD, NAM, GFS, WRF), either separately or together. The system displays all weather station observations available in the system for a 15-day window (seven days prior to current date, current date, and seven days after current date).

The **Data Map** display page provides digital maps for the forecasting systems, the calculated NFDRS and CFFDRS, the three fuel loading maps, and the forecasted lightning probability maps. The forecasted weather parameters are displayed at increasingly finer spatial resolution. Map resolutions are as follows: GFS is displayed at roughly 55 km, NAM is shown at 12 km, WRF is at 4 km, and NDFD is at 2.5 km resolution for dates since August 19, 2014 (or at 5 km for dates on or before August 19, 2014).The forecasted fire danger rating indices are displayed at the resolution of the meteorological models used to calculate the indices (GFS, NAM, WRF). Each fuel loading map (NFDRS, FCCS, FB40[1]) is shown at 1 km resolution, with the lightning and ignition probability maps displayed at 2.5 km resolution.

[1] Standard 40 fire behavior fuel models

Table 2. Fire weather system contents.

Data Type/Source	Parameters
Data Map Page	
Base Layers	World street map, imagery map, topo map
NDFD	WS, WD, T, RH, Rainfall
GFS	WS, WD, T, RH, P
NAM	WS, WD, T, RH, P
WRF	WS, WD, T, P, Short-wave radiative flux
NFDRS (using GFS, NAM, or WRF)	Burning index; ERC; 1-hr, 10-hr, 100-hr, 1000-hr, 10,000-hr fuel moisture; ignition component; Keech-Byram drought index; spread component
CFFDR (using GFS, NAM, or WRF)	Duff moisture code, drought code, initial spread index, build up index, weather index, severity rating
Fuel loading	FCCS, NFDRS, FB40
Lightning probability	NDFD lightning 24-hr, 48-hr, 72-hr; Dry lightning 24-hr, 48-hr, 72-hr
Site Info Page	
Observations and forecasts	WS, WD, T, RH
Models	GFS, NAM, WRF, NDFD
Time Series Graph Page	
Observations and forecasts	WS, WD, T, RH

Models: NDFD = National Digital Forecast Database; GFS = Global Forecast System; NAM = North American Model; UW WRF = University of Washington's Pacific NW Weather Research and Forecasting model
Parameters: WS = wind speed; WD = wind direction; T = air temperature; RH = relative humidity; P= barometric pressure; ERC = energy release component
Fuel Models: FCCS = Fuel Characteristic Classification System; NFDRS = National Fire Danger Rating System; FB40 = standard 40 fire behavior fuel models

Management Implications

The fire weather system provides improved confidence when using weather forecasts for making fire management decisions. In addition, the fire weather system provides forecasted lightning occurrence and ignition potential information in an easily accessible, readily available, online format.

Fire weather system users can identify which forecasts provide the most reliable and accurate information for their local area. By comparing weather station observations with modeled forecasts, fire managers can track model performance and identify which forecasting system provides the most reliable information for their area, identify where on the landscape one forecast may be more accurate than the others, or how to use the models concurrently. For example, land managers tasked with managing fire in a highly variable landscape may find that across an elevation gradient each modeling system may represent specific elevation zones better than the others; the GFS may be better at high elevations but do a poor job at lower elevations within the same landscape, while the NAM forecasts may more accurately represent those lower elevations. The different model forecasts and associated fuel moisture forecasts could then be used to evaluate fire behavior potentials along the elevation gradient.

Fire weather forecasts are often used to decide whether conditions are appropriate for igniting prescribed fires. Land managers have narrow windows of opportunity for conducting prescribed burn operations. Providing more confidence in forecasts for an area, and making those forecasts more accessible, allows fire managers to plan dates over the next three to seven days when the conditions should be appropriate for meeting their burn objectives.

Fire weather forecasts serve as inputs into systems that evaluate wildfire potentials such as fire danger rating systems and ignition potential maps. Improving fire weather inputs allows for improved fire danger assessments and provides more confidence to fire managers when using wildfire potential maps for assessing fire risk maps for fire suppression strategies. This information can help fire managers decide (1) where to position resources, (2) when to use unplanned ignitions, (3) when to use direct attack strategies, or (4) when to use other fire suppression tactics.

The fire weather system also provides fire weather and fuel moisture data estimates in a readily accessible, easy-to-use format for input into fire behavior and fire effects models, including smoke production models. Improved fire weather forecast accuracy will provide more confidence when using the forecasts to estimate fire behavior potentials, including rate of spread and flame length. Improved fire effects estimates, such as estimated future fuel consumption, will provide better estimates of smoke production for making smoke management plans or informing the public when harmful levels of smoke are likely to be produced.

The fire weather system also addresses a data management issue by overcoming some major data compatibility issues. The system obtains data from multiple sources, with widely different data formats and time frames, and synthesizes the data to provide forecasts for different time frames.

Relationship to Other Recent Findings and Ongoing Work

The fire weather system complements other online systems, including the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE; http://firesmoke.ca/smartfire/), the Interagency Fuels Treatment Decision Support System (IFTDSS; http://iftdss.sonomatech.com/), the Smoke Emissions Modeling Intercomparison Project (SEMIP; http://www.airfire.org/projects/semip/), and the BlueSky Framework (http://www.airfire.org/bluesky/). The fire weather data and related products housed within the system can serve as inputs to each of these models and enhance the efficacy of each of these modeling systems. As discussed in the following section, future work should include adding direct links to each of these tools from the fire weather system; incorporating the functionality developed in the fire weather system into an online modeling framework such as IFTDSS; or incorporating many of the useful fire detection, fire behavior modeling, fire effects modeling, and smoke production tools found within these systems into the fire weather system.

Future Work Needed

The fire weather system platform is set up to accommodate a much wider range of modeled and measured parameters than are currently being supported. Future versions could incorporate all the parameters and provide a basis for additional comparative research and bias prediction. Examples of future work are as follows:

***Update NFDRS fuel models*.** The fire weather system could be greatly enhanced by research to update the NFDRS fuel model maps. The original NFDRS map provides general, widespread vegetation maps which have proved very useful. However, these maps were produced in 1998 and have not been upgraded since. Undoubtedly, the vegetation has changed due to anthropogenic and natural disturbances such as wildfire; using modern techniques to remap the NFDRS fuel models and capture these changes would provide improved fuel loading data for estimating ignition potential.

***Link FCCS and standard fire behavior fuel models to predict sustained ignition potential*.** New research on how to use existing fire effects and fire behavior fuel models has the potential to improve sustained ignition estimations. The fire weather system is a good start towards integrating fire occurrence and fire danger in an online format, but new basic and applied research that links fire occurrence potentials, fire behavior potentials, fire effects, smoke emissions, and smoke dispersion in a seamless, transparent way would greatly improve the system. Research that directly focuses on using the existing, and more frequently updated, FCCS and/or Standard 40 fuel model sets to estimate fire occurrence potentials would be a good first step towards producing an inclusive cradle-to-grave modeling system.

Improve dead fuel moisture estimates. The fire weather system would be greatly improved by new research into modeling dead fuel moisture and/or incorporating the Nelson fuel moisture model into the system. There has been a noticeable lack of research into estimating dead fuel moisture since the 1980s. Moisture content is one of the biggest determinants of fuel ignition; therefore, improving the way fuel moisture is estimated across landscapes could potentially improve our estimates of when fuels will ignite, when fire will spread from an initial ignition, and when those ignitions are likely to grow into larger fires. A short-term improvement to dead fuel moisture estimation within the current fire weather system could be to add the Nelson fuel moisture model. Adding the Nelson model would allow the system to forecast fuel moisture diurnally every three hours over a 24-hour period. Understanding diurnal patterns in fuel moisture would greatly improve our fire ignition probability maps. We originally planned to incorporate the Nelson fuel moisture model in this project but could not do so because of the intense computational nature of the Nelson fuel moisture model. The computational issues with the Nelson fuel moisture model could be overcome with additional time and funding.

Test the implementation of NFDRS and CFFDRS fire danger indices and fuel moisture estimates. NFDRS and CFFDRS fire danger indices and fuel moisture forecasts play important roles in the fire weather system. We were able to periodically evaluate the fire danger and fuel moisture trends visually over time, and our forecasts were in line with the concurrent weather patterns. However, it was beyond the scope of the current project to evaluate how well the dead fuel moisture estimates were tracking actual fuel moistures in the landscape. Measuring in-the-field fuel moisture contents to compare with the forecasted fuel moistures would greatly improve the efficacy of the fire weather system.

Add live fuel moisture estimates to the fire weather system. Live fuel moisture content is an important determinant of the potential for fuels to ignite and burn. Incorporating live fuel moisture into the fire weather system would likely improve our ignition potential probability mapping. Although research on how to accurately measure live fuel moisture is needed, there are several ways of providing live fuel moisture estimates, including the use of satellite imagery such as the Normalized Difference Vegetation Index (NDVI, an index of plant "greenness" or photosynthetic activity) product.

Investigate the efficacy of the Richardson Perfect Prog Approach to forecasting dry thunderstorms for inclusion in the fire weather system. Lindsey Richardson, working with Phillip Bothwell on this project, produced a master's thesis where she looked at forecasting dry lightning probability using historical data and principal components analysis to create dry lightning prediction algorithms. It was beyond the scope of the current project to add this analysis into the lightning probability system. Having an alternative way of forecasting dry lightning probability would provide confidence in the ability of the system to forecast dry lightning.

Forecast fire behavior potentials. The fire weather system is able to incorporate the production and display of spatially explicit, forecasted fire behavior potentials. Tools and algorithms have been produced for IFTDSS that, if incorporated into the fire weather system, would produce spatial forecasts of fire behavior potential. Understanding potential fire behavior across the landscape in near-real time would be very useful to fire managers when making decisions on when to use fire for land management or how aggressively to suppress the fire.

Forecast fire effects including tree mortality, fuel consumption, and smoke emissions. Including spatially explicit fire effects forecasts would greatly enhance the fire weather system. Understanding the potential adverse effects of fire on natural resources such as timber would provide fire managers with more information on whether to ignite a prescribed burn or which type of suppression strategy to use on unplanned ignitions. Landscape-scale fuel consumption and smoke emissions forecast maps could be paired with wind speed and wind direction forecasts to produce more effective smoke management plans or inform the public when hazardous smoke conditions may occur.

New research or verification research for using Moisture of Extinction. Moisture of extinction values are integral parts of the fire weather system. We conducted an intensive literature search looking for potential uses of MOE when estimating ignition probability, but could find little new research since the work of Rothermel (1972) and Cohen and Deeming (1985). New research to evaluate the use of MOE when estimating ignition potentials, particularly when estimating non-ignitable conditions, will greatly improve user confidence when using fire weather ignition probabilities for making management decisions.

Deliverables

The deliverables specified in our proposal are shown in **Table 3**. We have developed additional deliverables in the course of this project, primarily additional presentations, as outlined in **Table 4**.

Table 3. Original list of deliverables provided in our proposal.

Deliverable Type	Description	Delivery Dates
Website	Preliminary sustained lightning ignition probability maps and verification plots	Summer 2011
Non-refereed publication	Sustained lightning ignition probability map user guide	Summer 2011
Presentation	Forest and Fire Meteorology Conference	Fall 2011
Presentation	Northwest Fire Weather Meteorologist Meeting	Fall 2011
Refereed publication	Description of sustained lightning ignition probability algorithm	Spring 2012
Refereed publication	First results and verification of sustained lightning ignition probability algorithm	Fall 2012
Webinars	Webinar series targeting land management community on prediction verification and ignition probability tools	Fall 2012
Two presentation	Conferences to be determined	2012

Table 4. Deliverables provided. Items in *italics* are additional deliverables.

Deliverable Type	Description	Citation
Website	Fire Weather Accuracy and Lightning Ignitions Probability Website	http://fireweather.sonomatechdata.com/
Non-refereed publication	Fire Weather Accuracy and Lightning Ignitions Probability Website User's Guide	Uploaded to JFSP
Presentation	Ninth Fire and Forest Meteorological Conference, Palm Springs	Drury et al., 2011
Presentation	Northwest Fire Weather Meteorologist Meeting	This Meeting was not attended. Substituted presentations are listed below in *italics*.
Refereed publication	The Fire Weather Assessment System – Comparing Model Performance with Direct Observations	Paper forthcoming, abstract provided
Refereed publication	Evaluating the Fire Weather Accuracy Assessment System Ignition Probability Maps	Paper forthcoming, abstract provided
Webinars	Provided webinar to Heath Hockenberry and Robyn Heffernan at Boise Predictive Services	Informational and feedback gathering webinar presented on 10/22/2014
Additional presentations	*1. Community Modeling and Analysis (CMAS) Conference* *2. American Association of Geographers, Annual Meeting* *3. Southwest Regional Meeting of the American Association of Fire Ecologists* *4. Northern California Prescribed Fire Council Bi-Annual Meeting* *5. Fifth Annual Meeting of the Association for Fire Ecology* *6. Tenth Annual Symposium on Fire and Forest Meteorology*	*1. Wheeler et al., 2011* *2. Drury et al., 2012a* *3. Drury et al., 2012b* *4. Drury et al., 2012c* *5. Drury et al., 2012d* *6. Drury et al., 2013*
Master's thesis	A Perfect Prog Approach to Forecasting Dry Thunderstorms over the CONUS and Alaska	Richardson, 2013

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Appendix

Fuel Loading Maps: Description

This Appendix describes the fuel loading maps used within the fire weather system to provide estimates of the biomass (fuels) available to burn across landscapes.

National Fire Danger Rating System (NFDRS) Fire Danger Fuel Model Map. The NFDRS fuel model map provides a spatially consistent map of fuel loadings at a 1-km resolution for the continental United States (Figure A-1). The NFDRS fuel model map was created by Robert Burgan, Colin Hardy, and others in the mid-1990s as a tool to aid in fire danger rating (Burgan et al. 1997; 1998). The mapped NFDRS fuel models include fuel quantity information for live woody fuels (shrubs), herbaceous fuels, and downed and dead woody fuels. Woody fuels are further classified into moisture classes by diameter: 1-hr woody fuels are 0-0.635 cm in diameter, 10-hr fuels are 0.635–2.54 cm in diameter, 100-hr fuels are 2.54–7.62 cm, and 1,000-hr fuels are >7.62 cm in diameter (Anderson, 1982). NFDRS maps do not include information on larger woody fuels, decomposed (rotten) woody fuels, canopy fuels, litter, or duff.

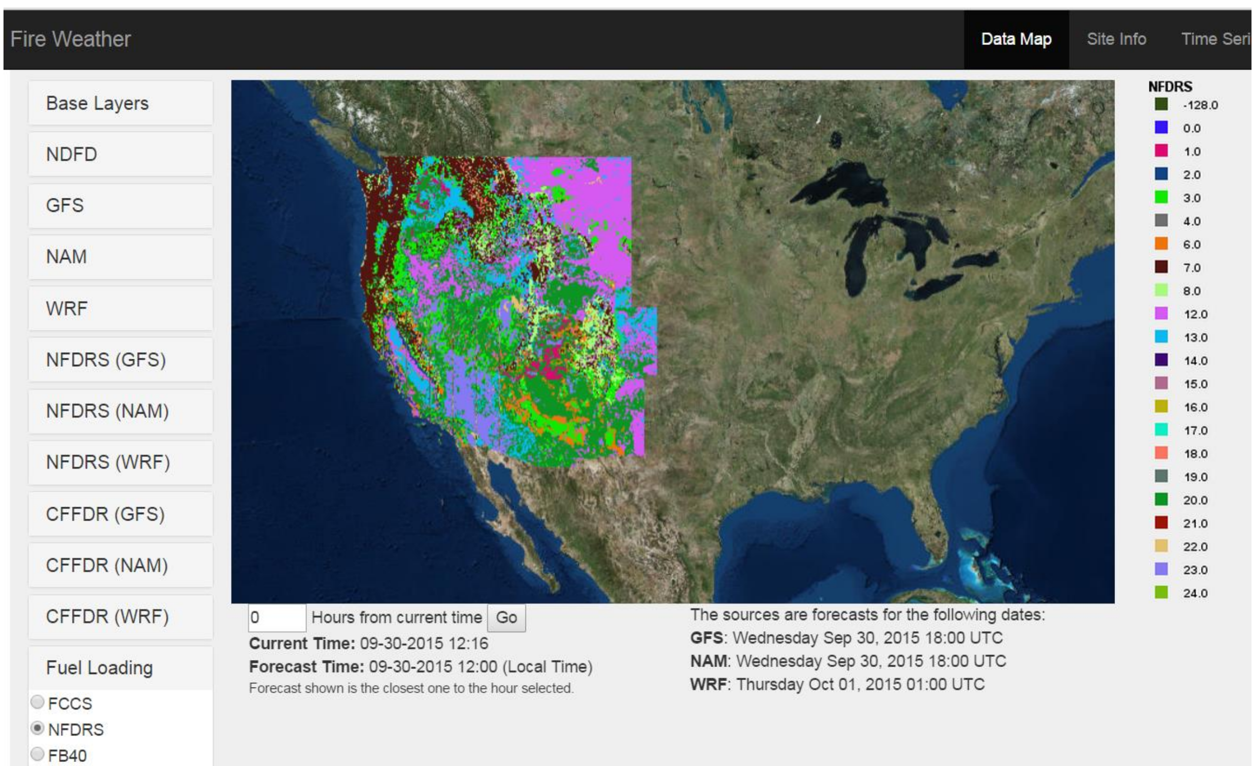

Figure A-1. National Fire Danger Rating System (NFDRS) fuel loading map.

Fuel Characteristic Classification System (FCCS). The FCCS fuel loading map (Figure A-2) provides fuel loading information at a 1-km scale for the continental United States. FCCS maps were created by the Fire and Environmental Research Applications (FERA) team working out of the Pacific Northwest Research Station's Seattle lab (McKenzie et al., 2007). The FCCS fuel loading map currently used in the fire weather assessment system contains 111 Western fuel beds. Assigned to pixels using LANDFIRE Existing Vegetation Type (EVT) vegetation map, FCCS fuel beds provide detailed information for the fuels stratum—canopy, shrubs, nonwoody, woody, litter-lichen-moss, and duff. Each stratum contains fuel loading information in tons/acre for use in modeling fuel consumption and smoke emissions (Ottmar et al., 2007). The FCCS fuelbed concept is the most comprehensive of the fuel maps and includes downed woody fuels (1-, 10-, 100-, 1000-, >10000-hour), shrubs, herbs, grasses, canopy fuels, dead standing trees (snags), stumps, litter, moss, lichens, and duff.

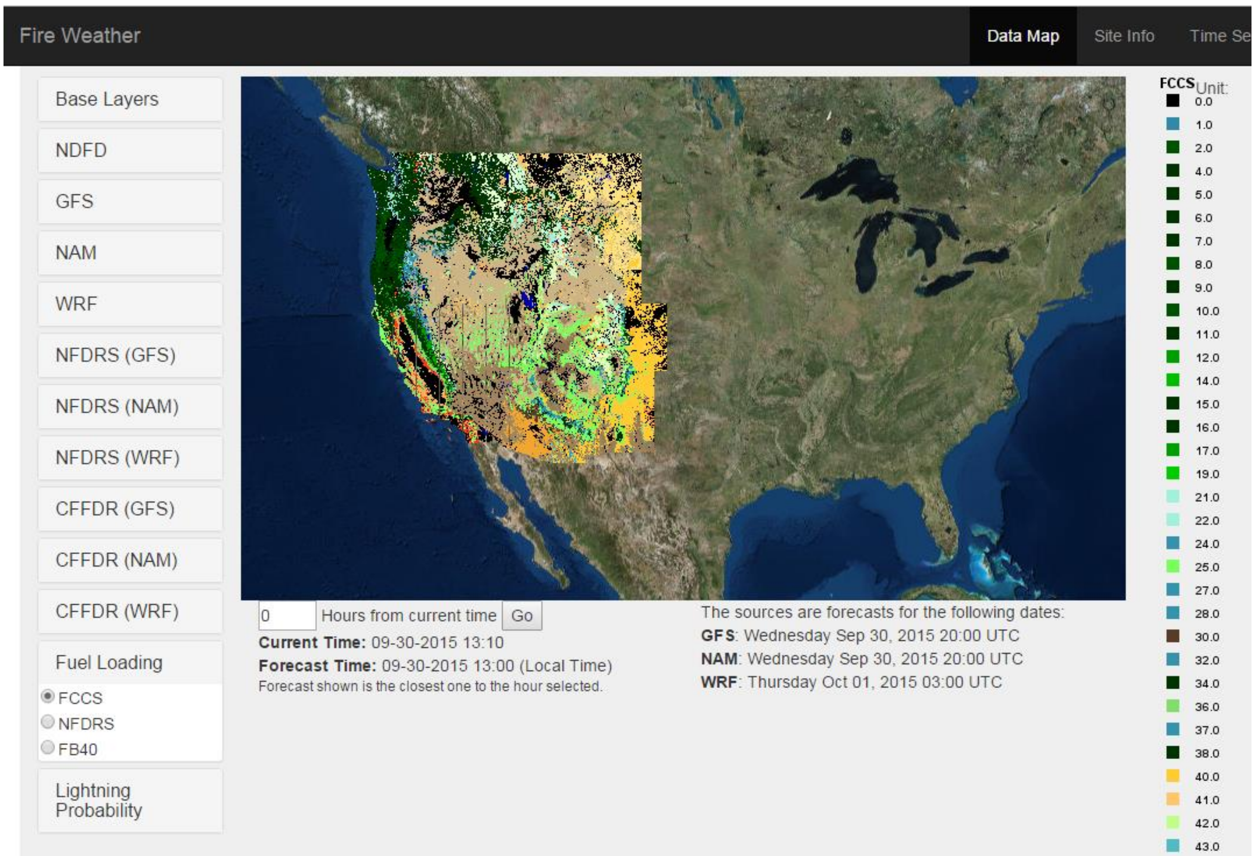

Figure A-2. Fuels Characteristics Classification System (FCCS) fuel bed map.

Standard 40 Fire Behavior Fuel Models (FB40). Commonly referred to as the Scott and Burgan 40, the FB40 fire behavior fuel map (Figure A-3) was produced and is currently maintained by the LANDFIRE project (Rollins, 2009). Primarily used as input to the Rothermel fire spread model (1972), which drives the Farsite and FlamMap family (Finney et al., 2006) of spatial fire behavior modeling tools, the FB40 fuel model maps contain fuels information for fine live and dead fuels (Scott and Burgan, 2005). The Standard 40 fire behavior fuel models should be used exclusively for modeling fire behavior.

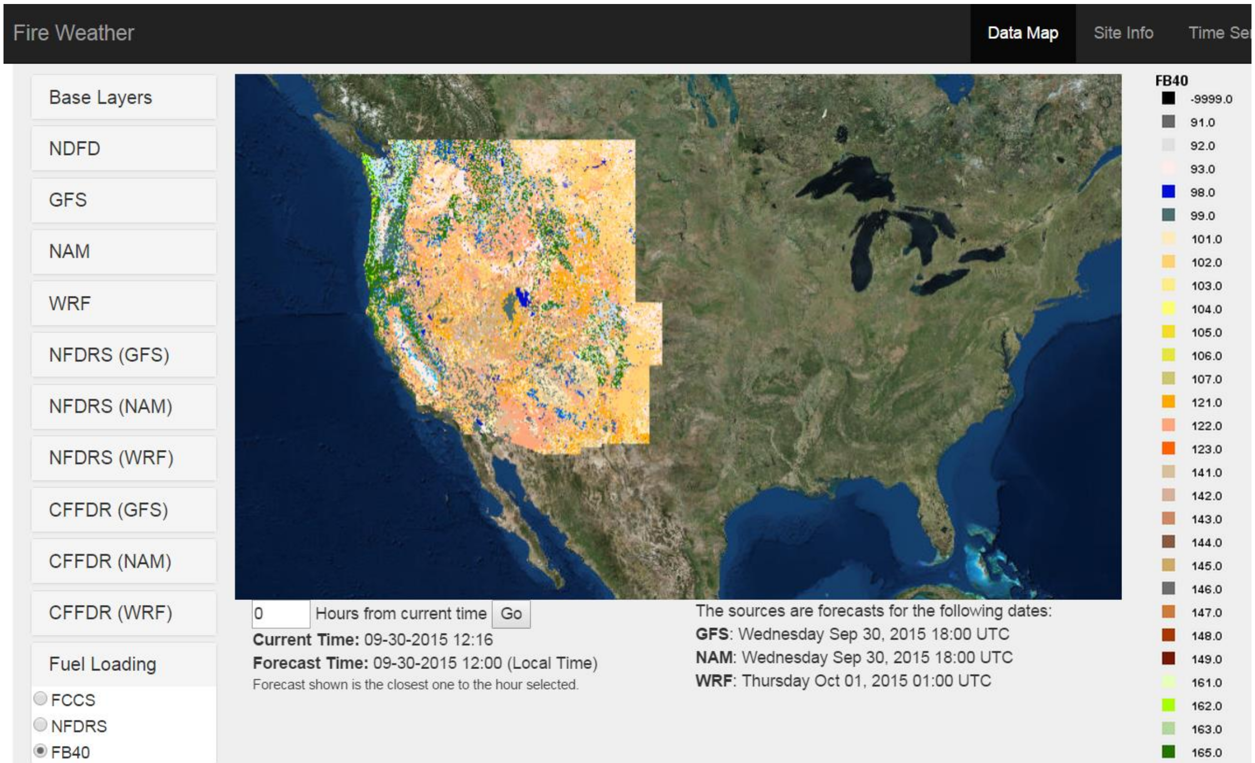

Figure A-3. Standard 40 fire behavior fuel model maps.

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