

Model-Generated Predictions of Dry Thunderstorm Potential

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ABSTRACT

Dry thunderstorms (those that occur without significant rainfall at the ground) are common in the interior western United States. Moisture drawn into the area from the Gulfs of Mexico and California is sufficient to form high-based thunderstorms. Rain often evaporates before reaching the ground, and cloud-to-ground lightning generated by these storms strikes dry fuels. Fire weather forecasters at the National Weather Service and the National Interagency Coordination Center try to anticipate days with widespread dry thunderstorms because they result in multiple fire ignitions, often in remote areas. The probability of the occurrence of dry thunderstorms that produce fire-igniting lightning strikes was found to be greater on days with high instability and a deficit of moisture at low levels of the atmosphere. Based on these upper-air variables, an algorithm was developed to estimate the potential of dry lightning (lightning that strikes the ground with little or no rainfall at the surface) when convective storms are expected. In the current study, this algorithm has been applied throughout the western United States, with modeled meteorological variables rather than the observed soundings that have previously been used, to develop a predictive scheme for estimating the risk of dry thunderstorms. Predictions of the risk of dry thunderstorms were generated from real-time forecasts using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) for the summers of 2004 and 2005. During that period, 240 large lightning-caused fires were ignited in the model domain. Of those fires, 40% occurred where the probability of dry lightning was predicted to be equal to or greater than 90% and 58% occurred where the probability was 75% or greater.

1. Introduction

Wildfires have long been a land management issue in the western United States. Because people are increasingly building new houses and inhabiting the “wildland–urban interface” (WUI), the general public has also been increasingly impacted by the effects of wildfires. In addition to the danger of structure fires, the impacts from smoke on communities can be real and prolonged, especially when large fire complexes burn for weeks at a time. Lightning strikes start the majority

of wildfires in the western United States. Of particular concern are days with high-based thunderstorms that generate numerous lightning strikes but little or no rainfall at the surface (Colson 1960; Hall 2005). Fuquay (1962) determined that the average summer thunderstorm in the northern Rocky Mountains has a cloud base near 3650 m MSL and generates rainfall amounts of less than 1.3 mm. In the current study, dry thunderstorms are defined as those with cloud-to-ground lightning strikes that occur with less than 2.5 mm of rainfall at the surface.

Lightning-ignited fires present serious problems in the ever-expanding WUI, but lightning in the western United States also strikes in remote, inaccessible areas. Land managers therefore need long-range planning tools to anticipate the severity of wildfire seasons and to allocate resources for firefighting purposes. These include the seasonal, monthly, and weekly fire potential outlooks of the National Interagency Coordination

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Center Predictive Services section. In the short term, they use daily weather forecasts and other diagnostic planning tools, such as the National Fire Danger Rating System (NFDRS) indices (Deeming et al. 1977) and the lower-atmosphere stability index (Haines 1988), to assess the effects of weather and fuel conditions on fire starts and fire potential. New tools for fire weather forecasting continue to be developed. The National Weather Service Storm Prediction Center prepares fire weather outlooks for the current and next day that highlight areas of expected dry thunderstorms (Taylor et al. 2003). Hall (2005), using gridded rainfall data, recently determined that lightning-caused wildfires occurred more often with daily precipitation amounts of less than 2 mm. These results may facilitate the use of gridded model rainfall output in fire risk predictions. With the continued increase in computing power and decrease in computing costs, many regional modeling centers are now generating real-time mesoscale weather predictions (Mass et al. 2003). Because most fire weather forecasting tools use variables that are output by the mesoscale models, many value-added products are being generated in support of the fire community. For example, gridded next-day predictions of NFDRS indices are currently available for the continental United States (<http://www.fs.fed.us/land/wfas/wfas26.html>) and for the Pacific Northwest (<http://www.fs.fed.us/pnw/airfire/sf>) (Hoadley et al. 2006).

The current study uses numerical forecasts from the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) run operationally by the Northwest Regional Modeling Consortium (http://www.atmos.washington.edu/pnw_enviro) to develop predictions of the risk of dry lightning (the MM5 is a limited-area, three-dimensional meteorological model designed to simulate regional atmospheric circulations). Dry thunderstorms (also called dry lightning) are defined here as those with cloud-to-ground discharges that occur without significant rainfall (<2.5 mm) at the surface. This term is not without some controversy in the fire weather community, because it tends to overemphasize the importance of dry lightning in estimations of fire potential. Fire weather forecasters may issue “red flag warnings” if widespread, high-based thunderstorms are expected to generate significant lightning with low rainfall accumulations, but there are other considerations as well. Days with high winds and low relative humidity are of concern (conditions associated with dry cold fronts). The moisture content of the fuels is also very important, and this factor depends to a large extent on antecedent weather. If there has been a prolonged drought, conditions are ripe for large fire outbreaks. If,

on the other hand, recent rainfall has allowed the fuel moistures to increase significantly, then there may be little danger of large fire outbreaks despite widespread lightning with little or no rainfall. Furthermore, the effectiveness of suppression actions can determine whether an incipient fire is extinguished or is able to grow. It is therefore very difficult to estimate the risk of occurrence of large fires.

Our previous studies focused efforts on the atmospheric component of this problem. We developed an index to estimate the risk of dry thunderstorms based on the moisture content of the lower atmosphere as measured by the observed 850-hPa dewpoint depression and by a stability indicator, measured by the temperature difference between 850 and 500 hPa at Spokane, Washington (Rorig and Ferguson 1999, hereinafter RF1999). The utility of this index in identifying days when lightning-caused fires were ignited in the Pacific Northwest was then demonstrated for the 2000 fire season (Rorig and Ferguson 2002). In this study, it is demonstrated that this index of lower-atmospheric moisture content and stability can be used elsewhere in the western United States. A method was then developed for using MM5 output to generate predictions of the potential for dry thunderstorms. The predicted risk was compared with large fire starts in the northwestern United States in the summers of 2004 and 2005.

2. Methods

A discriminant algorithm (Mardia et al. 1979) using the dewpoint depression at 850 hPa and the temperature difference between 850 and 500 hPa was previously developed to discriminate between dry and wet convective days at Spokane (RF1999). This algorithm is applied here in a prognostic mode by using predicted upper-air variables from the MM5. The algorithm was modified to use the model’s vertical sigma levels rather than constant-pressure surfaces so as to accommodate the widely varying terrain in the model domain (Fig. 1). A complete set of the statistics for both dry and wet convective days (as defined below) used in the discriminant algorithm is computed for each grid cell in the model domain, and the predicted upper-air variables every day are used to estimate the probability of a thunderstorm being dry (should one occur).

a. Data

Because the probability of a convective day belonging to the wet or dry category is a function of the means and variances of the discriminating variables, a database of upper-air variables for convective days was



FIG. 1. Northwest Environmental Prediction System MM5 12-km model domain (depicted by the black box) and locations of stations used in the study.

compiled for most radiosonde stations in the western United States (Fig. 1). Some stations were omitted because exactly collocated surface and upper-air data were not available. The 12-yr period from 1990 through 2001 was used in the analysis because that is the period for which we had the most complete lightning-strike database (the most recent data when this study began were available through 2001). Upper-air data and surface data were obtained on CD-ROM from the National Climatic Data Center (NCDC 1993, 1997, 1999; Lott et al. 2001). The latest upper-air data not available on CD-ROM were downloaded directly from the Radiosonde Database Access Web site (<http://raob.fsl.noaa.gov>). Lightning-strike data from the National Lightning Detection Network (Cummins et al. 1998) were obtained from Vaisala (www.vaisala.com). At least one lightning strike within 10 km of the upper-air station classified a day as convective, and, using the surface observations, a precipitation cutoff at the station of 2.54 mm further categorized a convective day as wet or dry. This method could potentially result in some days being misclassified. For example, if there was significant rainfall close to, but not at, the upper-air observation station, then that day would be incorrectly classified as dry. Because there was a clear distinction between the mean values of the upper-air variables on dry and wet days (the means were significantly different

at a confidence level greater than 0.95), it was assumed this type of misclassification was rare and did not significantly affect the results. Note also that although upper-air data were available for the Canadian portion of the domain there was not a sufficiently long period of lightning-strike data. Without the lightning-strike locations it was not possible to identify convective days at the upper-air stations in Canada and compute the statistics necessary for the discriminant algorithm. Future improvements in the algorithm will include data for the Canadian portion of the domain.

b. Vertical interpolation

Although the discriminant equations used here were the same as those in the previous study, using variables from the 850-hPa level was inappropriate because of the mountainous terrain in much of the western United States. The dewpoint and temperature at the 700-hPa level are useful discriminators over regions of higher terrain; however, they are not useful for the lower-elevation locations (Table 1). For example, there is essentially no difference in the mean 700-hPa dewpoint depression between dry and wet convective days at Spokane (6.2° vs 4.9°C); whereas the difference in mean dewpoint depression is much more pronounced at the 850-hPa level (11.5° vs 6.6°C ; RF1999). For this reason, moisture and temperature variables from the

TABLE 1. Mean values of 700-hPa dewpoint depression (DD70) and temperature difference between 700 and 500 hPa (T70 – T50) for all convective days in the 12-yr study period at upper-air stations in the western United States.

Location	Mean DD70 (°C)	Mean T70 – T50 (°C)	Sample size	Station elev (m)
Albuquerque, NM (ABQ)	Dry: 11.6 Wet: 7.6	20.2 18.3	327 161	1619
Bismarck, ND (BIS)	Dry: 8.6 Wet: 7.8	17.9 17.6	118 178	503
Boise, ID (BOI)	Dry: 11.0 Wet: 5.0	20.4 8.0	68 36	871
Denver, CO (DEN)	Dry: 10.5 Wet: 6.6	20.7 18.6	305 167	1611
El Paso, TX (ELP)	Dry: 9.1 Wet: 7.2	19.5 18.4	249 135	1199
Glasgow, MT (GGW)	Dry: 8.6 Wet: 8.5	18.8 18.3	112 90	696
Grand Junction, CO (GJT)	Dry: 12.5 Wet: 6.8	21.2 18.6	277 105	1472
Great Falls, MT (GTF)	Dry: 9.2 Wet: 5.6	19.9 17.8	110 88	1118
Lander, WY (LND)	Dry: 12.0 Wet: 6.0	21.5 18.0	171 75	1695
Medford, OR (MFR)	Dry: 6.2 Wet: 4.0	18.6 17.6	42 33	397
Quillayute, WA (UIL)	Dry: 5.0 Wet: 4.0	15.6 16.5	5 30	56
Rapid City, SD (RAP)	Dry: 9.0 Wet: 6.8	19.6 18.3	194 163	966
Salem, OR (SLE)	Dry: 8.3 Wet: 5.8	18.7 17.3	12 14	61
Salt Lake City, UT (SLC)	Dry: 10.8 Wet: 5.2	20.5 18.3	216 113	1288
Spokane, WA (GEG)	Dry: 6.2 Wet: 4.9	17.4 17.3	60 51	720
Tucson, AZ (TUS)	Dry: 7.4 Wet: 5.5	18.6 17.4	285 160	788

vertical coordinate system of the MM5, or sigma levels, were used rather than constant-pressure levels. The sigma-coordinate system is quasi terrain following, in that the sigma levels follow the terrain closely near the ground and gradually relax to horizontal at the top of the model domain (which is 100 hPa in this case). By definition, the lowest sigma level is equal to 1.0 and the sigma level at the top of the domain is equal to 0.0. The dewpoint depression at the 0.90 sigma level and the temperature difference between the 0.90 and 0.48 sigma levels were chosen because these are very close to the 850- and 500-hPa levels at Spokane, where the discriminant algorithm was developed. By comparison, at a high-elevation location like Albuquerque, New Mexico (about 1600 m), these sigma levels correspond approximately to the 775- and 465-hPa levels, respectively. The use of only two mandatory vertical levels to represent

the moisture and stability of the atmosphere is certainly a simplification and does not characterize the entire subcloud layer; however, we determined in our earlier study (RF1999) that adding variables from additional vertical levels did not significantly increase the ability to distinguish between wet and dry convective days. In addition, the goal of the current study was to adapt the existing algorithm for use with model output in a prognostic mode, not to modify substantially the algorithm itself. In the future we will use additional variables to characterize the ambient vertical temperature and moisture profiles more realistically.

The temperatures and dewpoints were linearly interpolated vertically from the adjacent constant pressure levels to the 0.90 and 0.48 sigma levels for all of the upper-air soundings. Mean dewpoint depressions and vertical temperature differences were computed on these sigma levels for dry and wet convective days at each upper-air station (Table 2). Three upper-air stations (San Diego, California; Winnemucca, Nevada; and Amarillo, Texas) were added at this phase of the analysis to fill in gaps outside the model domain and to provide a smoother interpolation. Two of the stations (Winnemucca and San Diego) had incomplete periods of record; however, the quality of the results was improved by using some data rather than none. The third station (Amarillo) was located well outside the model domain but was included in the interpolation to minimize edge effects caused by lack of data outside the domain. The differences between the means of the variables on dry and wet days were significant (at the 95% level or higher) at most of the upper-air stations, regardless of elevation. The only real exceptions were at locations where dry thunderstorms are not a major factor, such as Quillayute, Washington, and Salem, Oregon.

c. Horizontal interpolation

The probability of any given day belonging to the dry or wet category depends on the values of the discriminating variables for that day (Mardia et al. 1979)—namely, dewpoint depression at the 0.90 sigma level and the temperature differences between the 0.90 and 0.48 sigma levels. The probability is also a function of several statistics derived from the historical record—mean values for each variable, and the variance–covariance matrices of those variables. There is one complete set of these statistics for dry convective days and a second set for wet convective days, and both sets are incorporated simultaneously in the calculation of the probabilities.

As a consequence, each of these statistics was estimated for the separate radiosonde stations and then

TABLE 2. Mean values of dewpoint depression at $\sigma = 0.90$ (DD90) and temperature difference between $\sigma = 0.90$ and $\sigma = 0.48$ ($T_{90} - T_{48}$) for all convective days in the 12-yr study period at upper-air stations in the western United States.

Location	Mean DD90 (°C)	Mean $T_{90} - T_{48}$ (°C)	Sample size	Station elev (m)
Albuquerque, NM (ABQ)	Dry: 20.3 Wet: 6.0	34.6 27.3	327 161	1619
Amarillo, TX (AMA)	Dry: 11.6 Wet: 7.4	30.8 28.0	202 248	1095
Bismarck, ND (BIS)	Dry: 9.1 Wet: 5.9	28.7 26.9	118 178	503
Boise, ID (BOI)	Dry: 16.4 Wet: 8.2	34.8 31.3	68 36	871
Denver, CO (DEN)	Dry: 13.4 Wet: 8.7	31.9 30.3	305 167	1611
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Grand Junction, CO (GJT)	Dry: 16.8 Wet: 9.5	32.7 28.8	277 105	1472
Great Falls, MT (GTF)	Dry: 13.4 Wet: 8.4	33.1 31.0	110 88	1118
Lander, WY (LND)	Dry: 15.0 Wet: 7.6	33.3 29.4	171 75	1695
Medford, OR (MFR)	Dry: 13.3 Wet: 9.6	34.2 32.5	42 33	397
Quillayute, WA (UIL)	Dry: 2.9 Wet: 1.4	26.0 29.7	5 30	56
Rapid City, SD (RAP)	Dry: 12.1 Wet: 7.1	32.1 29.8	194 163	966
Salem, OR (SLE)	Dry: 6.3 Wet: 3.5	29.3 29.2	12 14	61
Salt Lake City, UT (SLC)	Dry: 15.0 Wet: 8.6	33.8 30.9	216 113	1288
San Diego, CA (SAN)	Dry: 15.0 Wet: 4.8	31.6 28.5	21 20	134
Spokane, WA (GEG)	Dry: 11.2 Wet: 6.3	30.4 28.8	60 51	720
Tucson, AZ (TUS)	Dry: 15.2 Wet: 11.8	33.8 31.8	285 160	788
Winnemucca, NV (WMC)	Dry: 20.3 Wet: 6.0	34.6 27.3	46 14	1312

interpolated across the landscape independently. Because of the quadratic nature of the variance terms relative to the original data, standard deviations were interpolated and the resulting values were then squared, rather than the variance terms being directly interpolated. Within the region circumscribed by the radiosonde stations, the differences were negligible, but beyond this region, technically the region of extrapolation (which is omitted in the final product) rather than interpolation, the squared standard deviations yielded smoother surfaces along the edges of the MM5 domain.

Interpolation of daily values of DD90 and $T_{90} - T_{48}$

(defined in Table 2) for dry days and wet days prior to the calculation of these statistics was considered but was rejected as unfeasible and inappropriate for two reasons. First, days that are categorized in this study as dry and wet are not contemporaneous across the entire western United States, and so the interpolation of a single day's values of dewpoint depression, for example, would require either the combination of days categorized as both dry and wet or the removal of data points so as to consider only one of the categories at a time. Second, over the 12-yr period of record, there are numerous gaps in the data, resulting in a reduction in the already small number of upper-air observation locations for any given date. Rather than ignoring the variable numbers of dry and wet lightning days at the various sites, we incorporated these inherent differences in the construction of the variance-covariance matrices, and this variability is therefore a central component of the discriminant function.

Because of the relatively small number of radiosonde stations with complete data within the model domain (10 within the MM5 domain and 8 beyond the MM5 boundaries), a simple default interpolation method was applied by using the S-PLUS 6.0 (Insightful Corp. 2001) proprietary statistical software, which uses a bivariate interpolation method appropriate for irregularly distributed data (Akima 1978). More sophisticated methods were considered but were ultimately rejected for a lack of justification. Furthermore, the use of the sigma levels effectively minimizes, to some degree, the adverse effects of the variable nature of the topography, at least with respect to the prediction process.

This process yields a complete set of statistics for each grid cell in the model domain upon which calculations can be performed, resulting in the inverses and determinants of the variance-covariance matrices for each grid cell, which are the last required components for the discriminant algorithm. The predicted values of DD90 and $T_{90} - T_{48}$ are obtained from each day's model run initialized at 0000 UTC, and the probability of dry thunderstorms is computed from the difference between the predicted and mean values of DD90 and $T_{90} - T_{48}$ for each grid cell.

3. Results and discussion

The MM5 output from the 0000 UTC (1600 Pacific standard time) model initialization is used to compute 24-h predictions of the risk of dry thunderstorms. At the time of writing, these predictions were available daily online (<http://www.fs.fed.us/pnw/airfire/sf>, under "Lightning Probability Maps"). Note that these forecasts are only as good as the predicted variables gen-

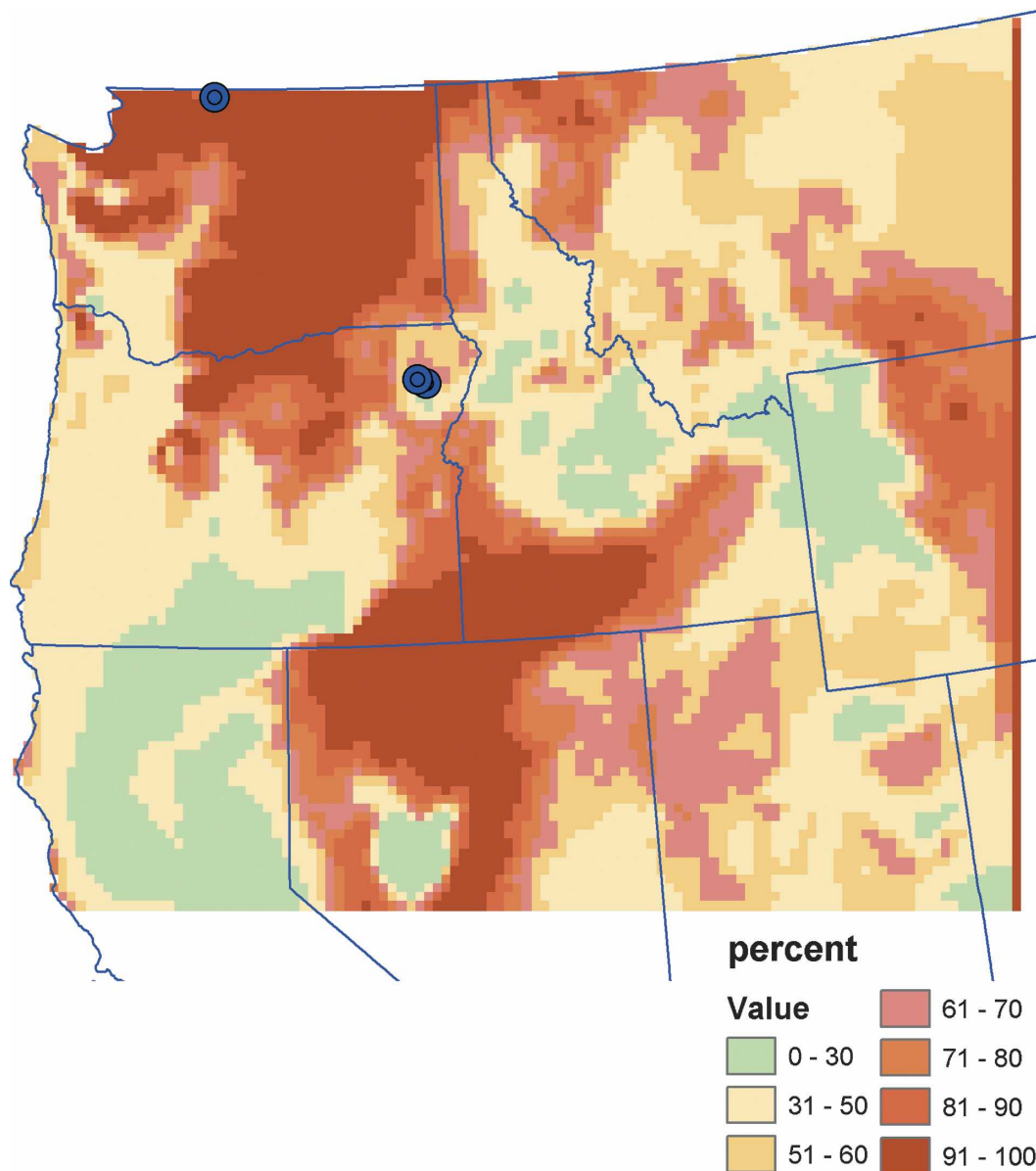


FIG. 2. A 24-h prediction of dry thunderstorm risk, valid at 0000 UTC 3 Aug 2004, and locations of lightning-caused fires (blue dots) on 2 Aug 2004.

erated by the MM5. In a comparison of several meso-scale models, Cox et al. (1998) found that the MM5 displays a negative bias for upper-air and surface dewpoint depression, with no significant bias for the other upper-air parameters. The negative bias in dewpoint depression would have the effect of underestimating the threat of dry thunderstorms.

Figure 2 shows an example of the predicted probability of dry thunderstorms valid at 0000 UTC 3 August 2004 (late afternoon on 2 August, local time), and lightning-caused fire ignitions on 2 August 2004. The probability grid has been clipped at the boundary of the

continental United States because the results are not meaningful outside the United States where there were no upper-air data (over the ocean) or long-term lightning-strike data (over Canada) available to develop the model. On this day, there was a high probability for dry thunderstorms over the central, northwest, and east-central portions of the modeling domain, including most of northern and eastern Washington; north-central Oregon; and most of northern Nevada, southeast Oregon, and southwest Idaho. One fire ignited in north-central Washington where the probability of dry thunderstorms was over 90%. Three fires (only two are

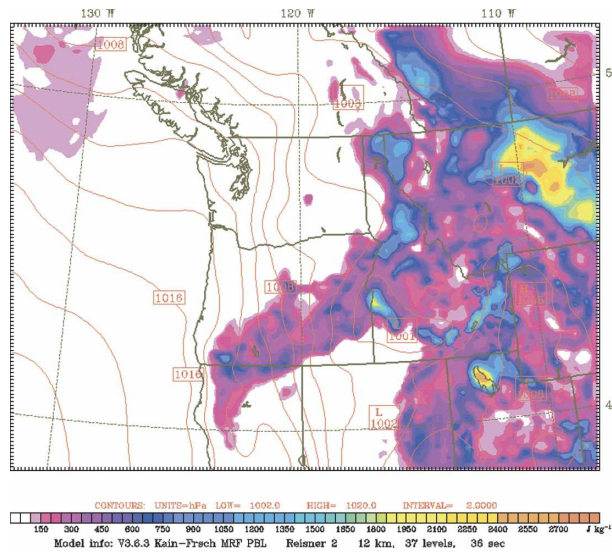


FIG. 3. A 24-h prediction of CAPE, valid at 0000 UTC 3 Aug 2004.

distinguishable at this map scale because two of the fires were very close to each other) ignited in northeastern Oregon, where the probability was in the 60%–70% range.

Because this discriminant algorithm was developed from a database of upper-air variables on convective days, the output depicts the probability of dry lightning only when convection is expected. The algorithm uses

common upper-air variables that are predicted every day; therefore, a dry thunderstorm risk prediction will be generated every day, whether or not convection is expected. The probability map can be compared with other convective indexes [e.g., convective available potential energy (CAPE), Fig. 3] to determine where convective activity is predicted to occur in the model domain. It can be seen by comparison with Fig. 2 that the three fires in northeastern Oregon started where instability was predicted to be high (although the probability of dry thunderstorms was moderate), whereas CAPE was predicted to be less than 100 J kg^{-1} where the single fire in Washington ignited. This may have been a particularly poor CAPE forecast, or perhaps it suggests that CAPE may not be the most appropriate index to use. Nevertheless, this algorithm needs to be modified to include a convective index so that a single risk map can be generated that depicts where the risk of dry thunderstorms is high only in areas where convection is predicted (more work is needed to determine the best convective index to use for this application).

In addition to the dry-lightning risk maps, maps of predicted DD90 and T90 – T48 were also generated (Fig. 4). In this example, the greatest vertical temperature difference is located in the central and northern regions of the domain, whereas the dewpoint depression is greatest in eastern Washington and in the south-central part of the domain. The risk of dry thunder-

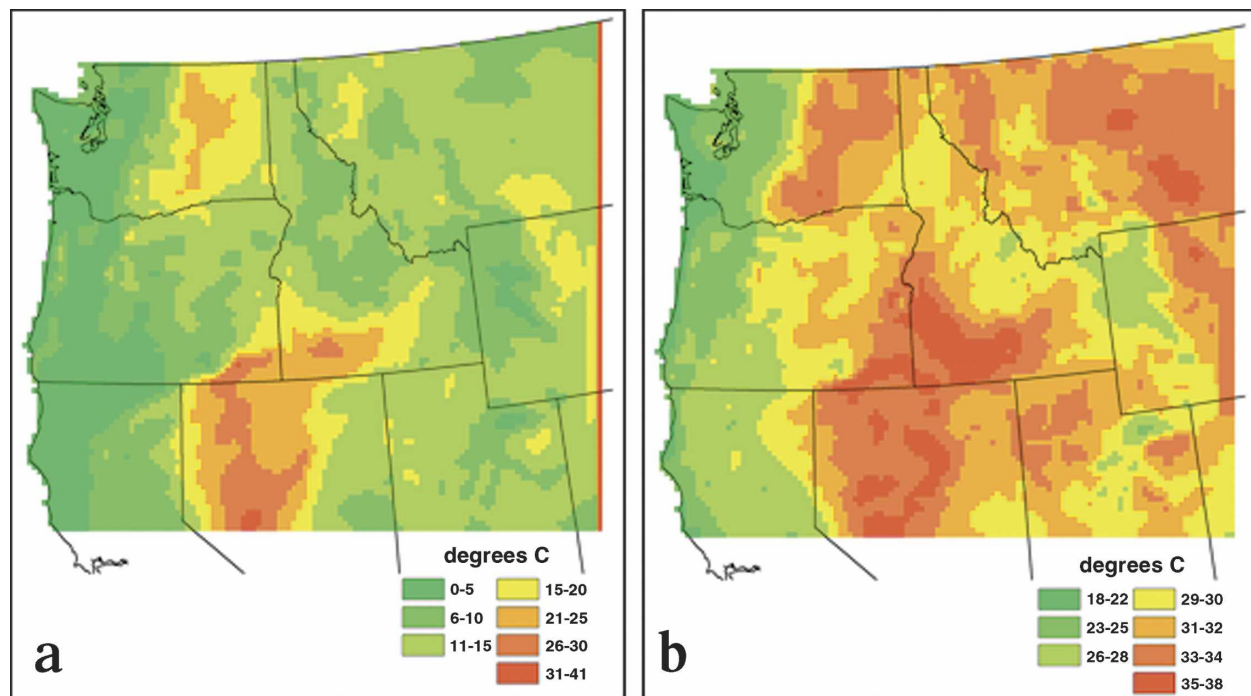


FIG. 4. (a) A 24-h prediction of dewpoint depression ($^{\circ}\text{C}$) at the sigma = 0.90 level, and (b) a 24-h prediction of temperature difference ($^{\circ}\text{C}$) between the sigma = 0.90 and sigma = 0.48 levels, valid at 0000 UTC 3 Aug 2004.

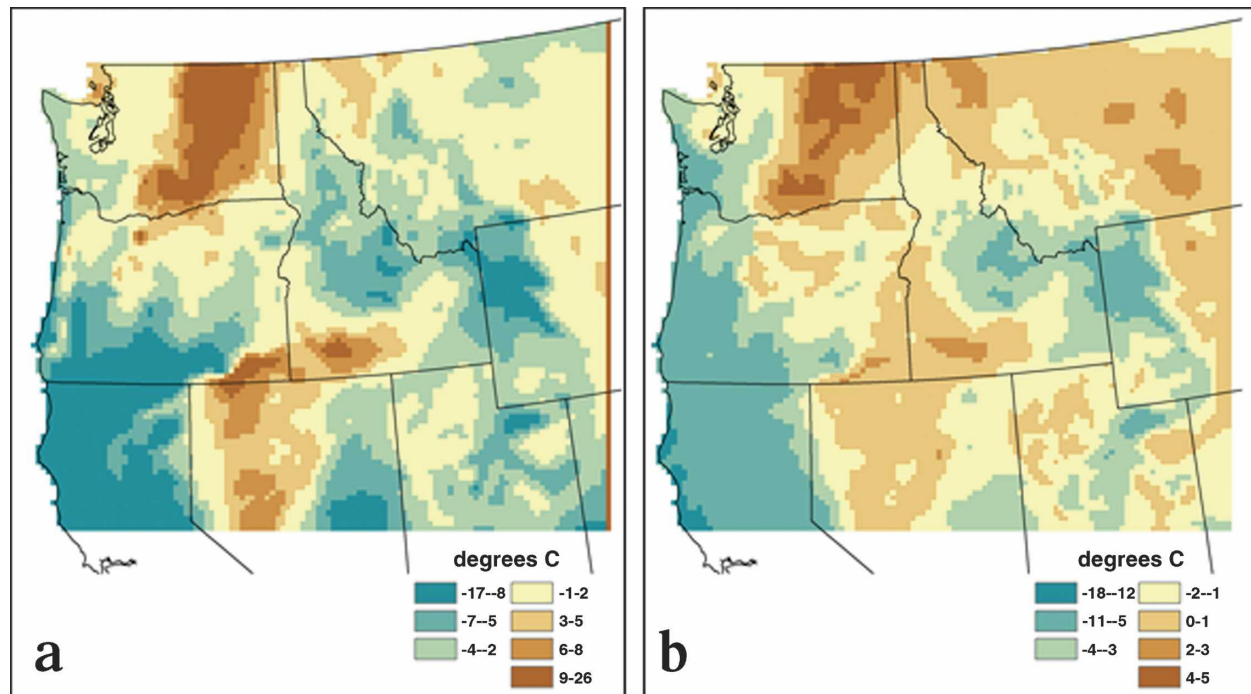


FIG. 5. (a) A 24-h prediction of dewpoint depression anomaly ($^{\circ}\text{C}$) at the sigma = 0.90 level, and (b) a 24-h prediction of temperature difference anomaly ($^{\circ}\text{C}$) between the sigma = 0.90 and sigma = 0.48 levels, valid at 0000 UTC 3 Aug 2004.

storms depends on the difference of the discriminating variables from the mean values of those variables on dry days. Therefore, when determining if a high risk of dry thunderstorms is driven more by a moisture deficit or by instability (or both), it is instructive to look at anomaly maps that depict the difference between the predicted daily value of the variables and the mean. This is important because the mean values of the discriminating variables vary widely over the model domain (Table 2). For example, a dewpoint depression of 10°C would be very dry relative to normal at Salem (where the mean for dry days is 6.3°C) but would be wetter than normal at Spokane, with a mean of 11.2°C on dry days. Figure 5 shows the DD90 and $T90 - T48$ anomaly maps, valid at 0000 UTC 3 August 2004. In this example it is evident that the high probabilities in eastern Washington and in the south-central part of the domain are the result of both high dewpoint depression and high instability, whereas the high probabilities in the east-central portions are due primarily to high instability.

To assess the utility of this predictive discriminant algorithm, the locations and dates of large fire starts for the summers of 2004 and 2005 were compared with the predicted risk of dry lightning. Large fires are defined as 40 ha or larger and are routinely recorded by the federal and state land management agencies (and

therefore are readily available for this study). The locations of all of the large lightning-caused fires that occurred from mid-May through early September in 2004 and 2005 are shown in Fig. 6. For each fire in the MM5 domain, the probability of dry lightning was determined for the pixel in which the fire was located on the date the fire ignition was reported. These results are shown in Fig. 7. There were 240 large lightning-caused fires in the model domain during the 2004 and 2005 fire seasons. Of those, 97 fires (40% of the total) ignited in locations where the probability of dry lightning was predicted to be 90% or greater and 140 fires (58%) occurred with a predicted probability of 75% or greater.

These preliminary results are encouraging; however, much work still needs to be done before this can be used as a reliable predictive tool. At the very least, because the algorithm generates a probability of dry thunderstorms whether or not convection is expected, overprediction is a problem. Because so many pixels in the domain have values greater than 70%–80% (e.g., see Fig. 2), it is not surprising that the majority of fire starts occurred in pixels with a high probability of dry thunderstorms. Because overprediction is occurring, it follows that the false-alarm rate is also high.

The large lightning-caused fires from two fire seasons constitute a small sample. The sample size is further

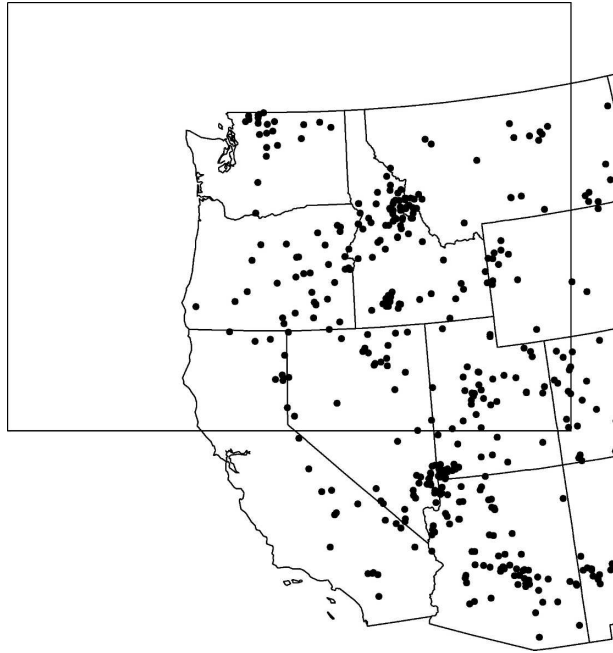


FIG. 6. Large (>40 ha) lightning-caused fires, for the summers of 2004 and 2005. The inner black square represents the model domain boundary.

limited by the use of “large” (greater than 40 ha) fires, because there may have been numerous ignitions either that were suppressed or for which the fuels were too wet to enable the fire to grow. The addition of smaller fires likely would not significantly change the results because of the overprediction issue discussed above. Nevertheless, because the majority of fires occurred where the predicted risk of dry thunderstorms was greater than 75%, these results indicate that this may be a useful tool in identifying days on which atmospheric conditions are ripe for wildfire outbreak. As we continue to improve this algorithm by adding a convective index, and as we continue to generate predictions from real-time MM5 output, more data will be available for verification (including small fire ignitions). This should result in less overprediction and therefore better assessment of the utility of this tool.

Comparing individual lightning-strike locations with fire ignitions is not practical for further verification purposes because of the temporal resolution of the fire-start data. Only the year, month, and day are reported for fire ignitions; the timestamp on lightning strikes includes the hour, minute, and second. Comparisons are also difficult because of inaccuracies in the recorded locations in both the lightning-strike and fire occurrence databases. In addition, the issue of “holdover” fires makes it difficult to compare lightning strikes with fire locations. In some cases, a lightning strike ignites

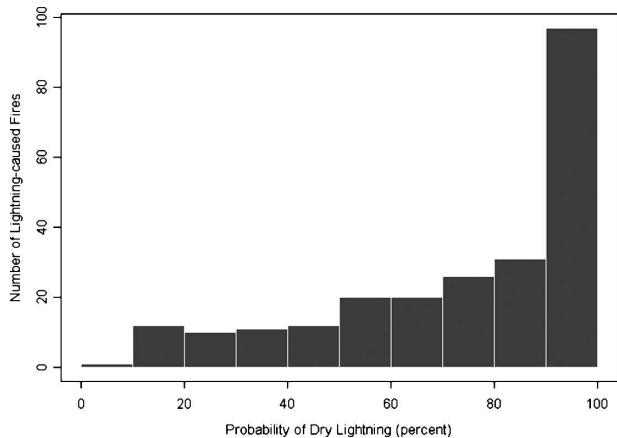


FIG. 7. The number of large lightning-caused fires vs the predicted probability of dry thunderstorms for the summers of 2004 and 2005.

dry fuel, which then smolders for days until the winds increase and relative humidity falls sufficiently for the fire to grow. The ultimate purpose of this study is to identify days and areas for which the atmospheric conditions are conducive to lightning-caused fires. For this reason comparing lightning-caused fire starts with the predicted risk of the ignition source provides the best verification.

4. Summary

An algorithm has been developed that uses MM5 output to predict the risk that thunderstorms will be dry (generate cloud-to-ground lightning with little or no rainfall at the surface) in the northwestern United States on days when convective storms are expected. Upper-level values of temperature and dewpoint from the MM5 terrain-following vertical sigma levels were found to be useful as discriminating variables across the western United States. Because moisture and stability variables are used separately in the prediction, if there is a high potential for dry thunderstorms, it can be determined whether this is because of extremely high instability, exceptionally dry conditions, or both. Daily predictions of the probability of dry thunderstorms are available online (at <http://www.fs.fed.us/pnw/airfire/sf>). An analysis of large lightning-caused fires in the model domain during the fire seasons of 2004 and 2005 showed that 97 of a total of 240 fires started where the probability of dry lightning was predicted to be 90% or greater and 140 of the fires ignited where the probability was predicted to be 75% or greater.

Much work is still needed to improve the utility of this algorithm. We will incorporate an index of convec-

tion that is appropriate for the high-based thunderstorms that are typically responsible for wildfire outbreaks in the western United States. We will also incorporate more recent lightning-strike data from Canada to produce predictions north of the United States–Canada border. With an improved algorithm and additional years of verification data, we will be able to assess more thoroughly the predictive skill, including parameters such as false-alarm rate, failure-to-warn rate, and other skill scores. This risk algorithm can be exported to other model domains by interpolating the means and variances of the discriminating variables from the upper-air stations to the new model grid and applying the algorithm. In the future it should be possible to integrate the predicted risk of dry thunderstorms with prognostic models of fuel condition and fire danger indices to provide land managers with more comprehensive tools to assess the risk of wildfire on public and private lands.

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