Employing Numerical Weather Models to Enhance Fire Weather and Fire Behavior Predictions

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Abstract—This paper presents an assessment of fire weather and fire behavior predictions produced by a numerical weather prediction model similar to those used by operational weather forecasters when preparing their forecasts. The PSU/NCAR MM5 model is used to simulate the weather conditions associated with three fire episodes in June 2005. Extreme fire behavior was reported across the Southwest, Great Basin, and Southern California Incident Areas during this time period. By comparing the simulation results against reports of extreme fire behavior, the ability of the model to differentiate between the three episodes is assessed, and relationships between weather conditions and extreme fire behavior are suggested. The results of these comparisons reveal that the most extreme fire behavior occurred in locations where near-ground temperatures were the highest. While relative humidity did not vary substantially across the three episodes, variations in temperature led to a greater potential for evaporation and fuel drying, which could have been a factor in the observed extreme fire behavior. Additional analyses reveal that the diurnal variations in mixed layer processes also explain some of the variability in fire behavior in the episodes.

This paper represents a step towards realizing the full potential of atmospheric physics models for fire weather and fire behavior forecasting. As researchers and operational personnel come to understand the relationships between fire behavior and atmospheric processes that can be predicted by weather forecast models, these concepts can be tested in the broader context of day-to-day fire weather forecasting. Eventually, these techniques could provide additional information for the fire weather forecasters and fire managers, using tools that are already available and used routinely in weather forecast offices.

Introduction

The fire weather tools that are currently employed in National Weather Service (NWS) forecast offices are typically the product of empirical studies that were designed to establish statistical relationships between certain types of fire danger or fire behavior and observed weather conditions (see e.g. Fosberg 1978, Lavdas 1986, Haines 1988). As these indices were being developed by the fire weather community, the broader atmospheric science community was more focused on severe storms and hurricane research, and developed tools such as radar and high-resolution numerical weather prediction (NWP) models to aide in those research endeavors. As the research evolved, these tools became intrinsic to the operational weather forecasting process, and are now used every day throughout the world for forecasting extreme weather events.

Until very recently, these same tools were seldom if ever used as part of NWS fire weather forecasting, nor were they applied in research projects

trying to improve our understanding of fire-atmosphere interactions. While radar observations have limited application for fire weather forecasting, beyond determining when and where precipitation is and will soon occur, NWP models can provide temporally and spatially detailed information about numerous aspects of fire-weather that could directly or indirectly impact fire behavior. Researchers can employ these models to establish *physical* relationships between weather phenomena and observed fire behavior, rather than relying upon empirical and statistical relationships whose broad applicability is questionable (Potter 2002). These physical relationships lead to the development of new fire weather indices and diagnostic techniques (Charney and Keyser, 2003) that can, in turn, be passed on to operational fire weather forecasters for use in day-to-day fire weather forecasting. Fire weather forecasters can then implement these new tools to analyze output from existing NWP models, enabling them to provide guidance to fire managers making decisions that pertain to prescribed burn planning and ignition, as well as wildfire decision support that can help save lives and property.

This paper will examine the performance of an NWP model during three periods of June, 2005: June 17-18 (hereafter referred to as Episode 1), June 23-24 (Episode 2), and June 27-28 (Episode 3), during which very high to extreme fire indices were reported in Arizona, New Mexico, and Nevada. Despite the extreme fire indices, reports of extreme fire behavior varied considerably across the three episodes. We hypothesize that variations in weather conditions during these periods can help explain the variability in observed fire behavior. In section 2, we will detail the observed fire behavior reports. Section 3 will discuss the NWP model employed to study the weather conditions during the three periods identified above. Section 4 will present the fire-weather predictions from the NWP model, and discuss relationships between the simulated weather conditions and the observed fire behavior. Section 5 will include discussion and concluding statements.

Observed Fire Behavior

In May and June 2005, extreme fire indices were reported in the National Interagency Coordination Center (NICC) Incident Management Reports across the Southwest, Southern California, and Eastern Great Basin Incident Areas (see e.g. http://iys.cidi.org/wildfire/ for archived NICC Incident Management Reports). This extended period of extreme fire indices was associated with numerous fires during the period. For the purposes of this study, we choose to focus our attention on three periods in the last two weeks of June, during which particularly extreme fire behavior was reported, including rapid spread rates, crown fires, spotting and torching, and flame lengths of 50 to 80 feet.

Episode 1 occurred on June 17-18 (Fig. 1a). In the areas of interest, extreme fire indices were reported. Three large fires were reported in New Mexico and Arizona, two of which were designated as Wildland Fire Use (WFU) fires. The non-WFU fire in Arizona reported active but not extreme fire behavior.

Episode 2 occurred about a week later, on June 23-24 (Fig. 1b). During this time period, eight large fires were reported across central Arizona and more than twelve fires were active across southern California, southern Nevada, northwestern Arizona, and southwestern Utah. Extreme fire behavior was observed at all of these fires. The central Arizona fires were reported to
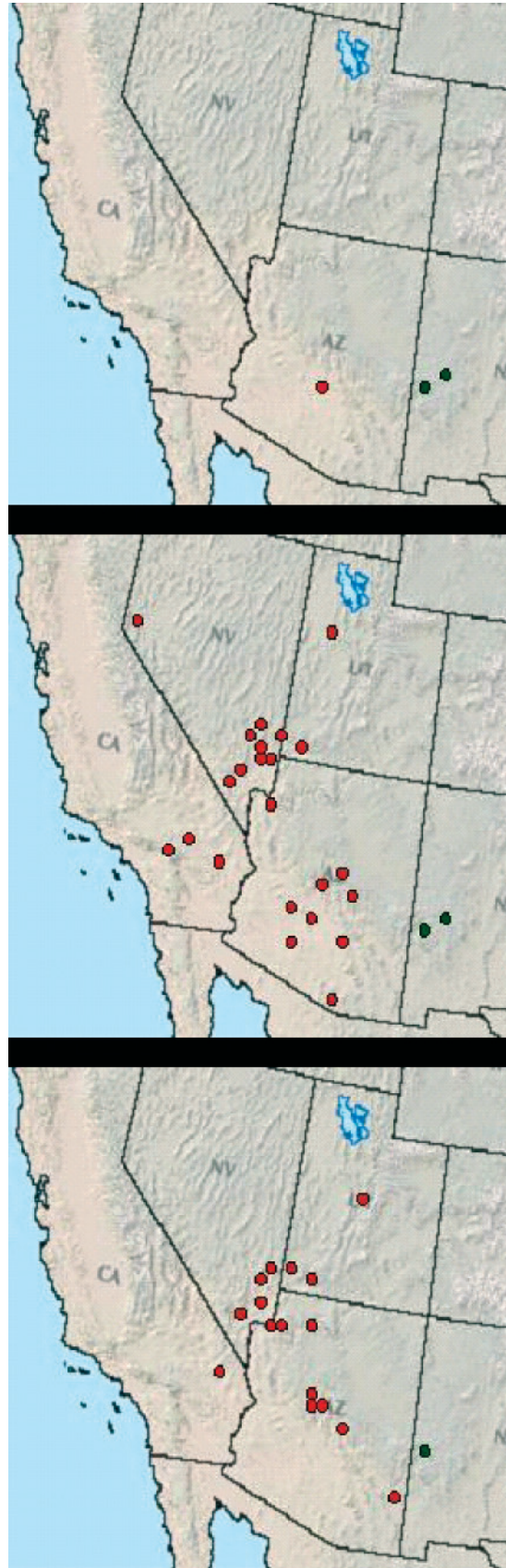
Figure 1—Locations of NICC Incident Management Reports of extreme fire behavior during large fire incidents on a) 17-18 June, 2005, b) 23-24 June, 2005, and c) 27-28 June, 2005. Red dots indicate wildfire incidents and green dots indicate large fires designated as Wildland Fire Use fires.

exhibit plume-dominated behavior, with active running and crowning, and rapid uphill rates of spread. Additionally, there was one report of thunderstorm activity in the vicinity of the fire generating downdrafts that impacted fire behavior. The fires in California, Nevada, and Utah exhibited extreme rates of spread and flame lengths. Gusty winds, flashing fuels, crowning, and dry thunderstorm outflow boundaries also inhibited firefighting activities in the area.

Episode 3 occurred three days later on June 27-28 (Fig. 1c). On these dates, the fires in central Arizona had slowed considerably, such that few reports of extreme fire behavior were submitted. Rapid spread rates, downdrafts from dry thunderstorms, and isolated torching were reported in California, Nevada, and Utah.

Overall, the reported fire behavior can be characterized as moderate to high in isolated areas during Episode 1, high to extreme across the region with very large flame lengths and running fires during Episode 2, and decreasing intensity with localized incidents of extreme fire behavior during Episode 3. It should be noted, however, that situation reports filed during and after large fire incidents do not accurately represent all of the variations in fire behavior across the region. It is quite probable that extreme fire behavior occurred on smaller fires that either went unobserved or unreported. The purpose of this study is to determine if the extreme fire behavior that *was* reported can be explained by changes in the weather conditions at those locations and across the region.

Numerical Weather Predictions

The variability in fire behavior reported during the three episodes could have been caused by a wide variety of mechanisms, including local terrain influences (e.g. north vs. south facing slopes), fuel moisture and fuel type, and varying weather conditions. Given that fire indices were reported as extreme throughout the period, and that fuel conditions are an important component of the fire indices, we assume for the purposes of this study that differences in fuel conditions were not the main reasons for the differences in observed fire behavior. Information is not readily available on all of these fires concerning the specifics of the local terrain. Thus, we propose to explore whether variations in weather conditions both at the ground and aloft can help explain the differences in observed fire behavior. We explore this question by using an NWP model. An NWP model is a physical atmospheric model that employs equations describing spatial and temporal variations in weather conditions at the ground and aloft to predict future weather conditions. An NWP model is initiated with observations that characterize the current state of the atmosphere, and then predicts the future weather from that observed state. NWP models allow weather forecasters to forecast the weather with some degree of accuracy multiple days in advance.

An NWP model can also be used to simulate the weather conditions of events in the past, using the observations from that time to initiate the model and then simulating the evolution of the weather conditions throughout the event. The main advantage of this technique is that the NWP models generate much more information about the weather conditions at the ground and aloft than can readily be observed. In the vicinity of a fire and across the region, this information can be analyzed to try to understand how the atmospheric conditions simulated by the NWP model might have impacted the fires.

The NWP model employed for this study is referred to as the Penn State University/National Center for Atmospheric Research Mesoscale Model version 5.3 (MM5) (Grell et al., 1995). This model has been developed over the last thirty years by the meteorological research community, and is one of the most widely used "mesoscale" models in the world. A mesoscale model is an NWP model that is designed to simulate the weather conditions across an area roughly 1/2-1/4 the size of the United States and resolve the detailed flows associated with thunderstorms, fronts, and other local weather phenomena. As indicated in the Introduction, these models are used routinely by NWS (and other) forecasters to produce forecasts of severe storms and precipitation systems.

We have employed the MM5 as a research tool to simulate the weather conditions associated with the three episodes defined in the previous section. Separate simulations were performed for the three episodes, such that hourly weather conditions at the ground and aloft were generated from 0000 UTC on the first day of each episode and continuing for 48 hours. Model output is generated in the form of a 3-dimensional cube of weather data (temperature, winds, humidity, clouds, rain, sunlight, etc) which can then be analyzed in detail. This output is then analyzed to produce horizontal maps and time series at specific locations.

Fire Weather Predictions

The model results for the three episodes indicate similarities that would be expected considering the season and the region, while also revealing some notable differences between the episodes. The surface weather conditions were very hot and dry throughout the three episodes, as one would expect climatologically. Figure 2 shows the surface relative humidity (RH) and wind speed and direction for episodes 1, 2, and 3. It is noteworthy that while there are variations in RH and wind speeds across the three episodes, the variations are not particularly noteworthy. The RH in central Arizona, southern California, and southern Nevada vary from between about 10-15%. While these are very low RH values, particularly for a model that is known to often overestimate RH, differences of this magnitude would not by themselves explain the observed differences in fire behavior. Similarly, the simulated wind speeds across the region were moderately high, with speeds of about 15 mph commonly occurring, but do not indicate pronounced variations among the episodes.

One of the huge advantages of working with NWP model output instead of observations is that the weather conditions aloft are as straightforward to generate as surface weather conditions. Thus, the model includes information about the diurnal evolution of the mixed layer for each of the episodes. This enables us to analyze the weather conditions in the layers of the atmosphere that are most likely to interact with a fire, rather than focusing almost exclusively on surface weather conditions. Figure 3 shows mixed-layer averaged temperatures for the three episodes. Clearly, the mixed-layer air in the areas where extreme fire behavior was reported was considerably warmer in Episode 2 than in Episode 1. However, this increase in temperature did not manifest as a pronounced change in RH. RH is often used by fire weather forecasters and fire managers to anticipate when the atmosphere will contribute to fuel drying and, by association, more extreme fire behavior. But RH is dependant upon temperature, such that a 20% RH at 30°C indicates a different impact
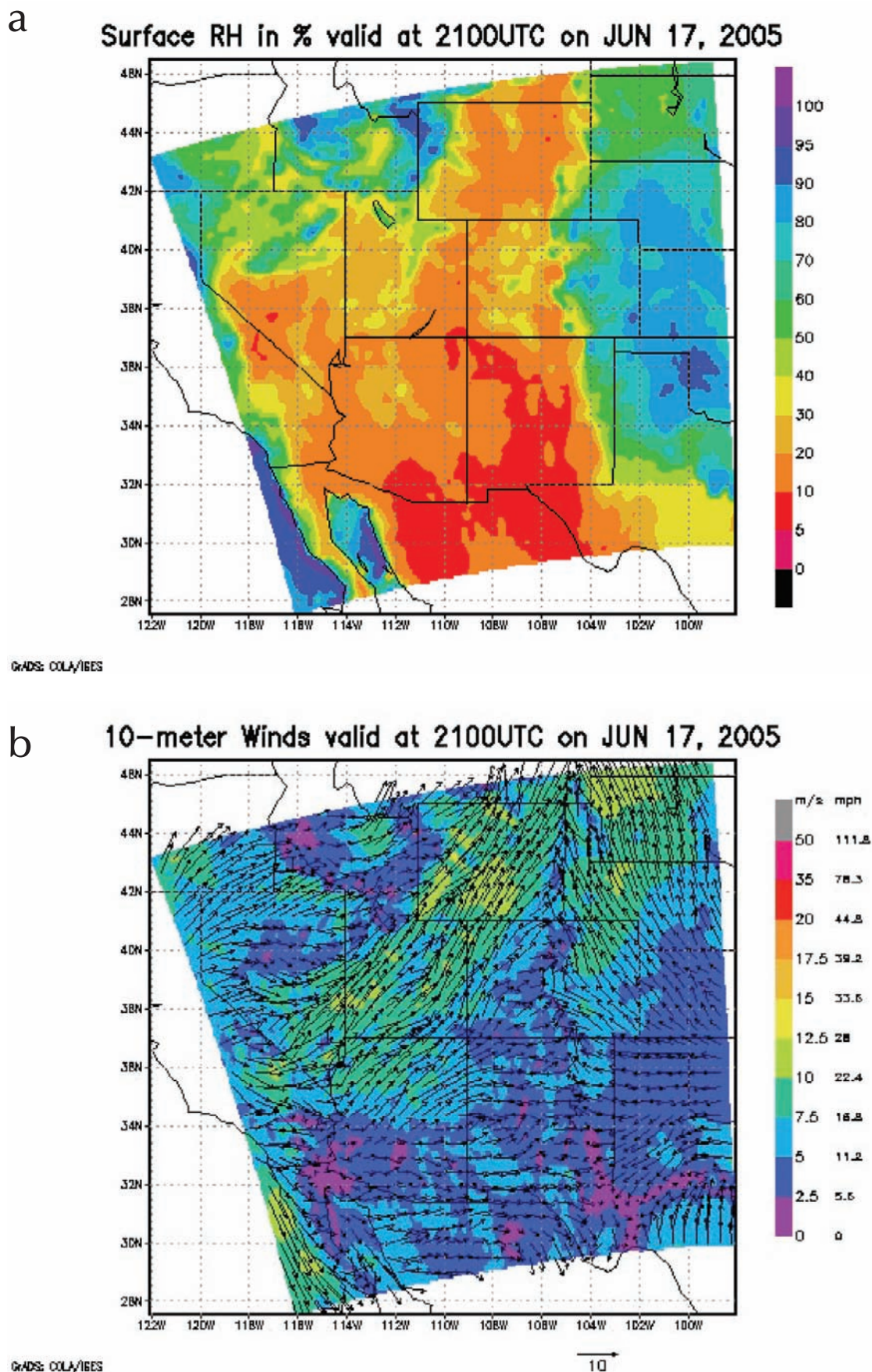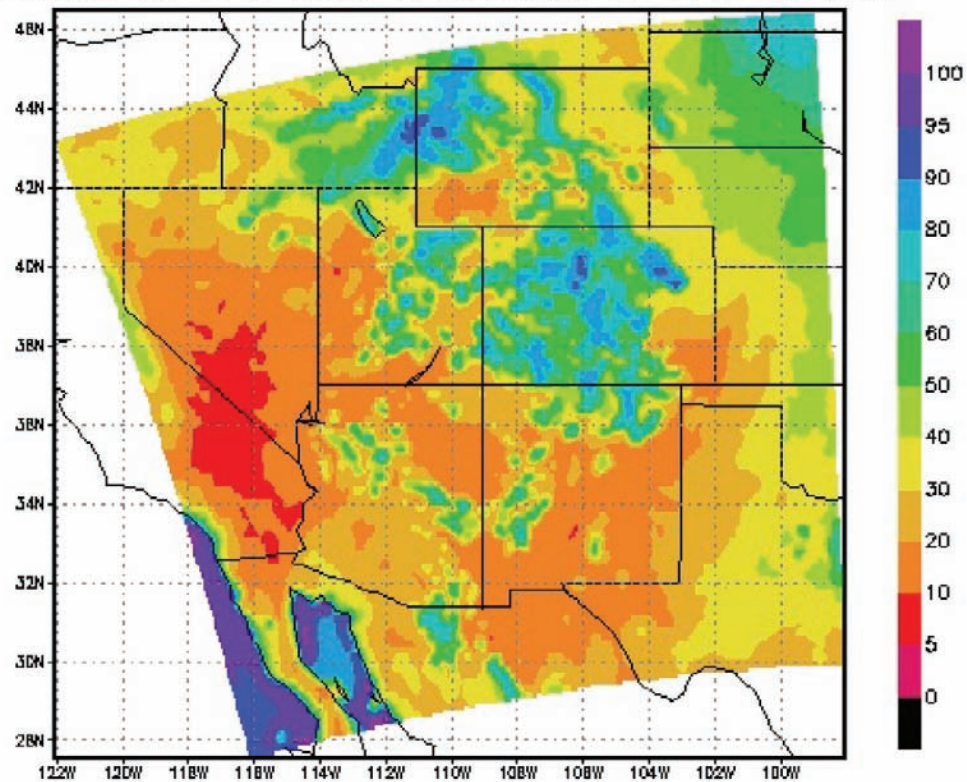
a

Surface RH in % valid at 2100UTC on JUN 17, 2005

b

10-meter Winds valid at 2100UTC on JUN 17, 2005

Figure 2—Simulated a) surface relative humidity and b) surface wind speed and direction for 2100 UTC 17 June, 2005. c) and d) are the same as a) and b) for 2100 UTC 23 June, 2005. e) and f) are the same as a) and b) for 2100 UTC 27 June, 2005.
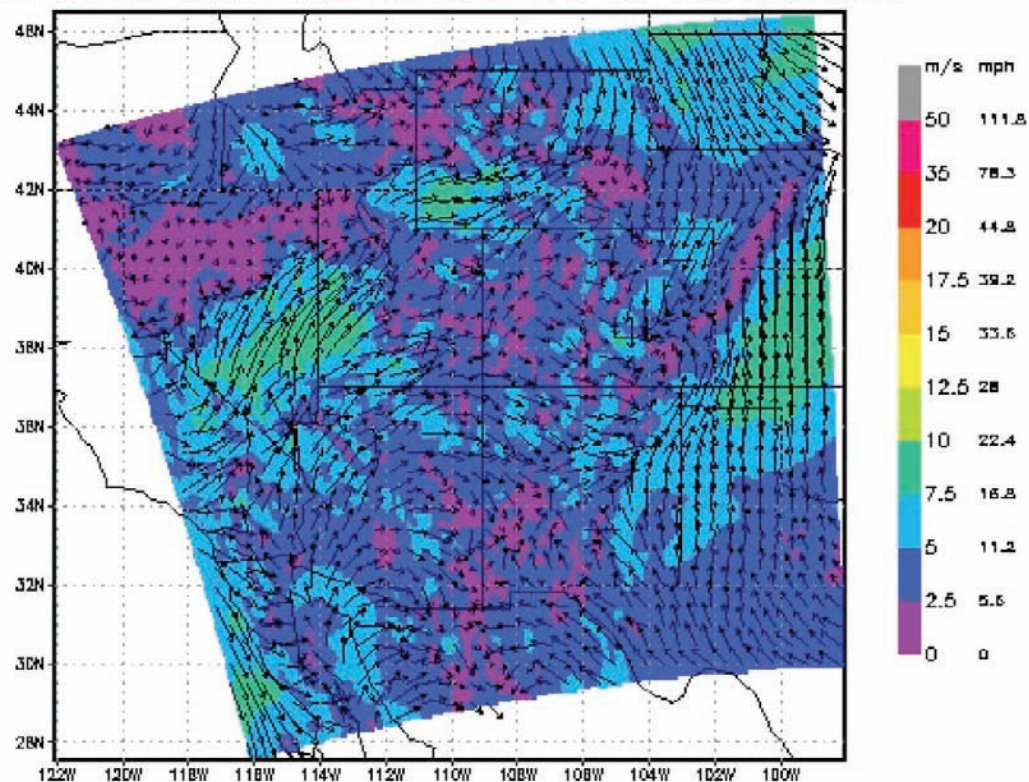
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Surface RH in % valid at 2100UTC on JUN 23, 2005

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d

10-meter Winds valid at 2100UTC on JUN 23, 2005

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e

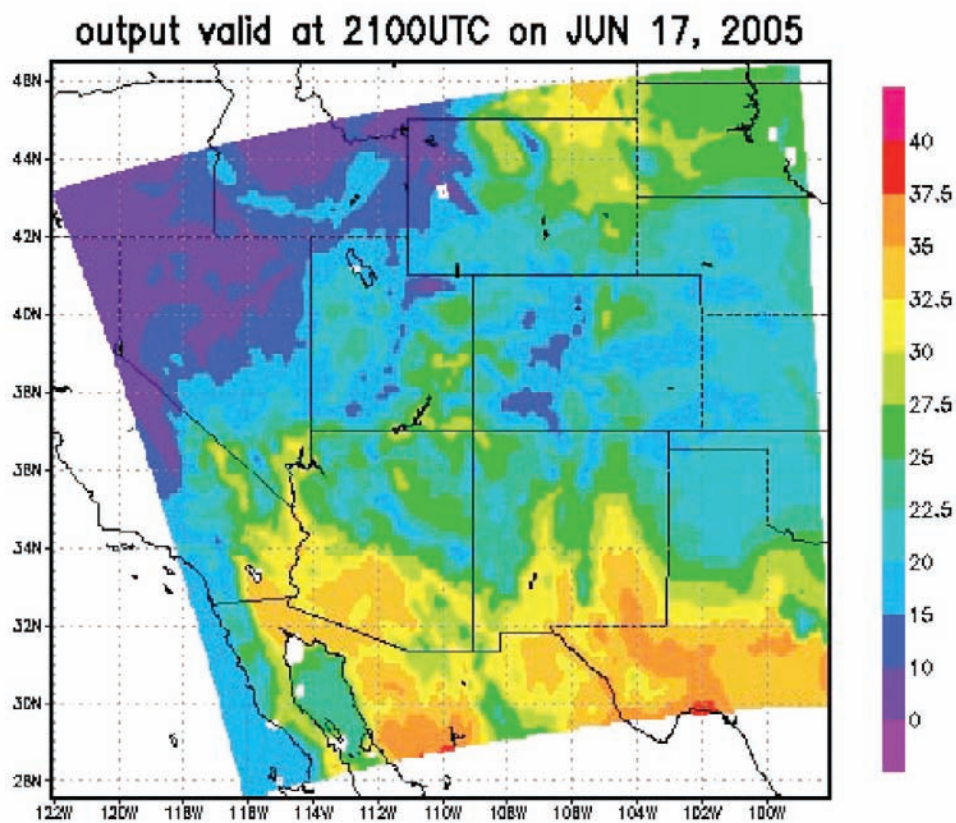## Surface RH in % valid at 2100UTC on JUN 27, 2005
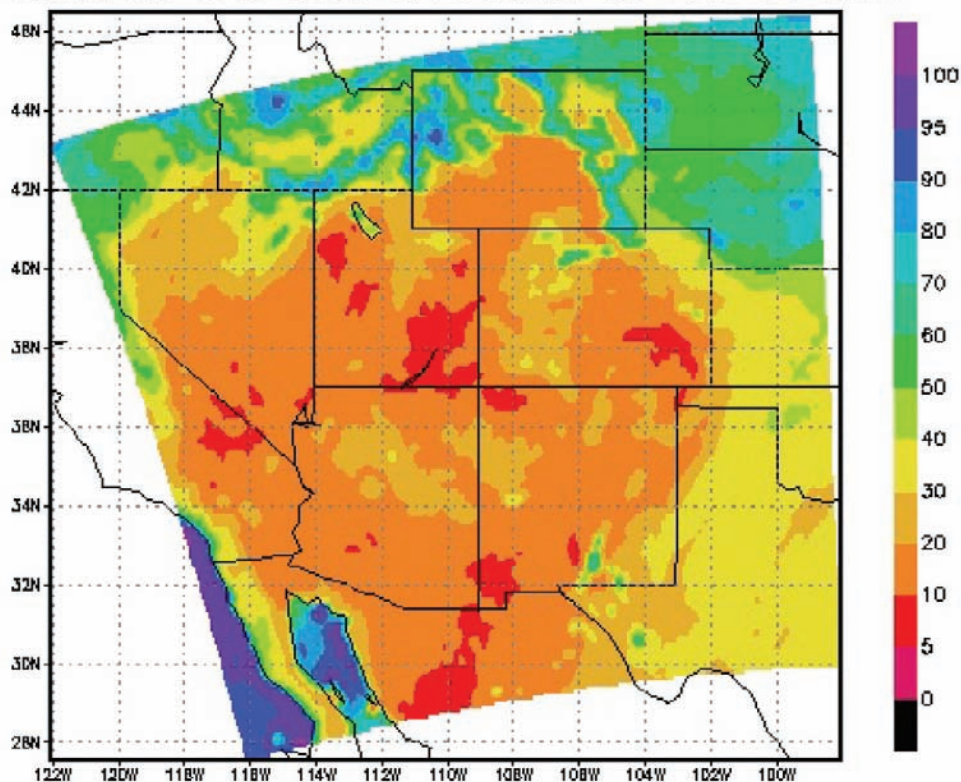
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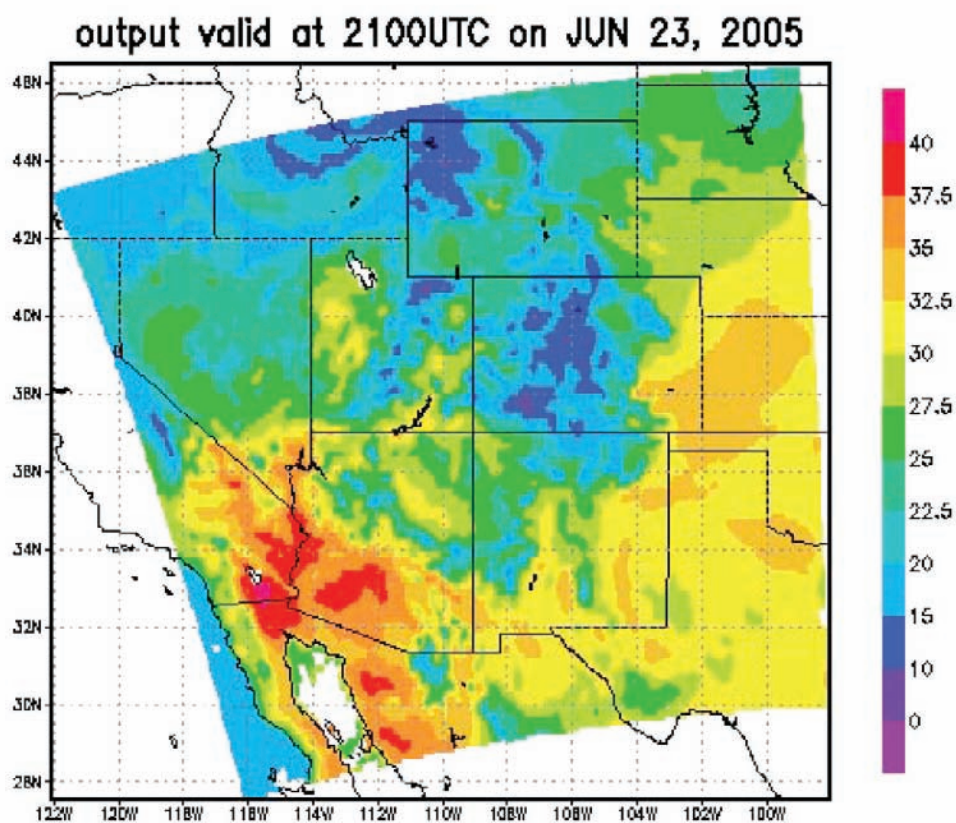## 10-meter Winds valid at 2100UTC on JUN 27, 2005
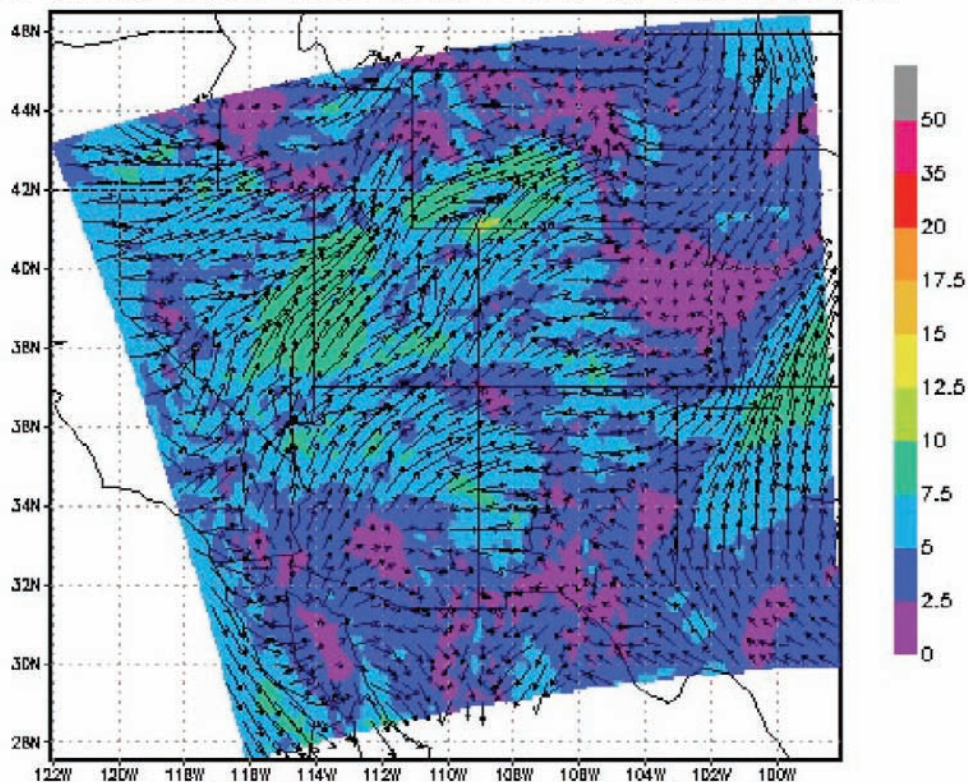
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a

output valid at 2100UTC on JUN 17, 2005

b

output valid at 2100UTC on JUN 23, 2005
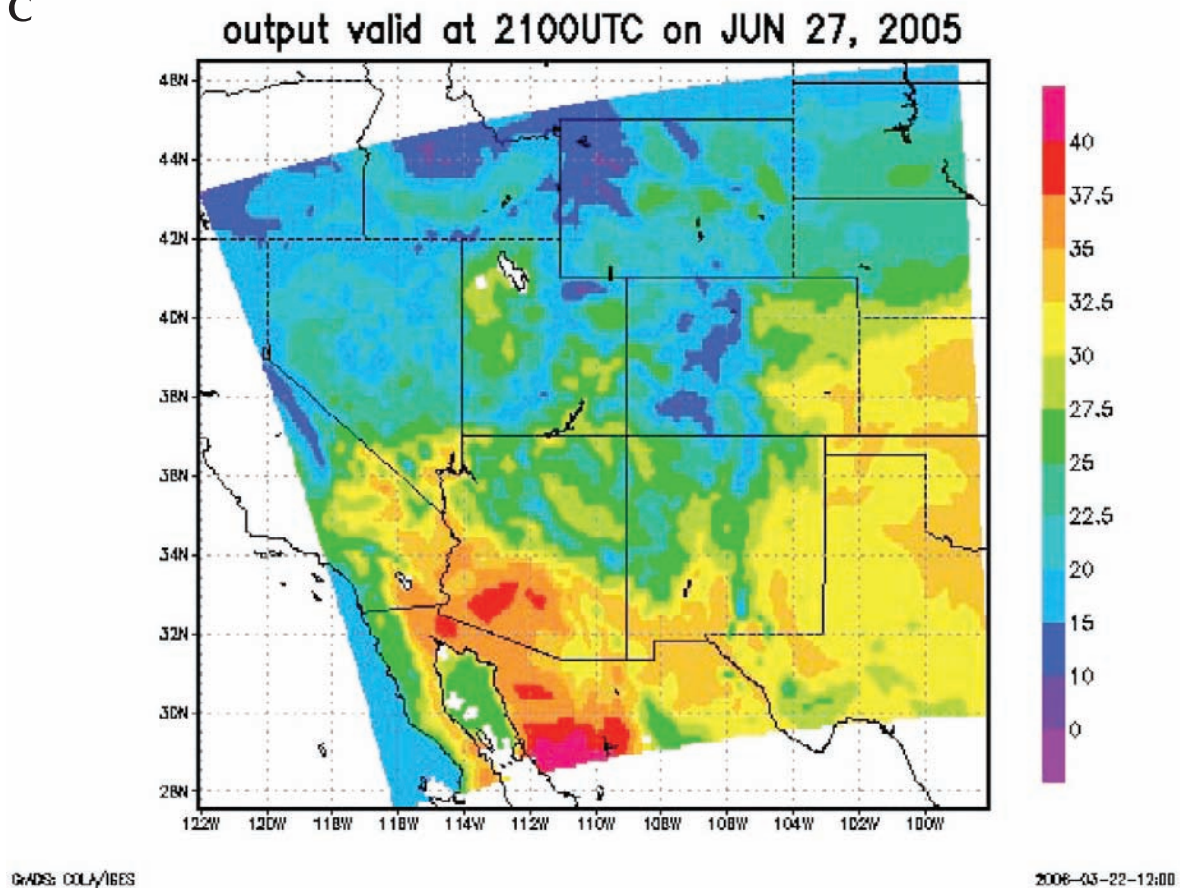
Figure 3—Simulated mixed-layer averaged temperature for: a) 2100 UTC 17 June, 2005, b) 2100 UTC 23 June, 2005, c) 2100 UTC 27 June, 2005.

C

output valid at 2100UTC on JUN 27, 2005

GRADS: COLA/IGES   2006-03-22-12:00

on fuels than a 20% RH at 40°C. A more definitive quantity for the potential impact of humidity on fuel drying is the vapor pressure deficit (VPD), which indicates how much water vapor can be evaporated into a volume of air regardless of the temperature. Figure 4 shows mixed-layer averaged VPD for the three episodes. The VPD varies from around 3500 Pa in Episode 1 to about 6000 Pa in Episode 2 along the Arizona/California/Nevada border, which corresponds to an increase of over 70%. This sort of difference would be expected to have a noticeable impact on fuel moistures during a fire.

An NWP model also enables the analysis of fire-weather conditions at an arbitrary location in a region. When using an NWP model, a fire weather forecaster or fire manager can obtain weather data that is locally valid even when a weather station is not nearby. By combining this aspect of NWP data with the availability of weather data aloft at every location within the model area, new insights can be obtained into the diurnal evolution of weather conditions throughout the day.

The traditional classification of fire as surface, ground, or crown relates the fire's characteristics to fuel. Just as fuel in these three layers has different characteristics that influence the fire's behavior, the atmosphere is not the same at all heights. As a fire grows, and its plume deepens, air from higher levels descends to interact with the fire and fuels (Fig. 5). If that air is drier, hotter, or windier than air at the ground, it may cause dangerous and unexpected changes in the fire's behavior such as torching, runs, or spotting. Looking at the air that is influencing fire behavior at a particular time, we
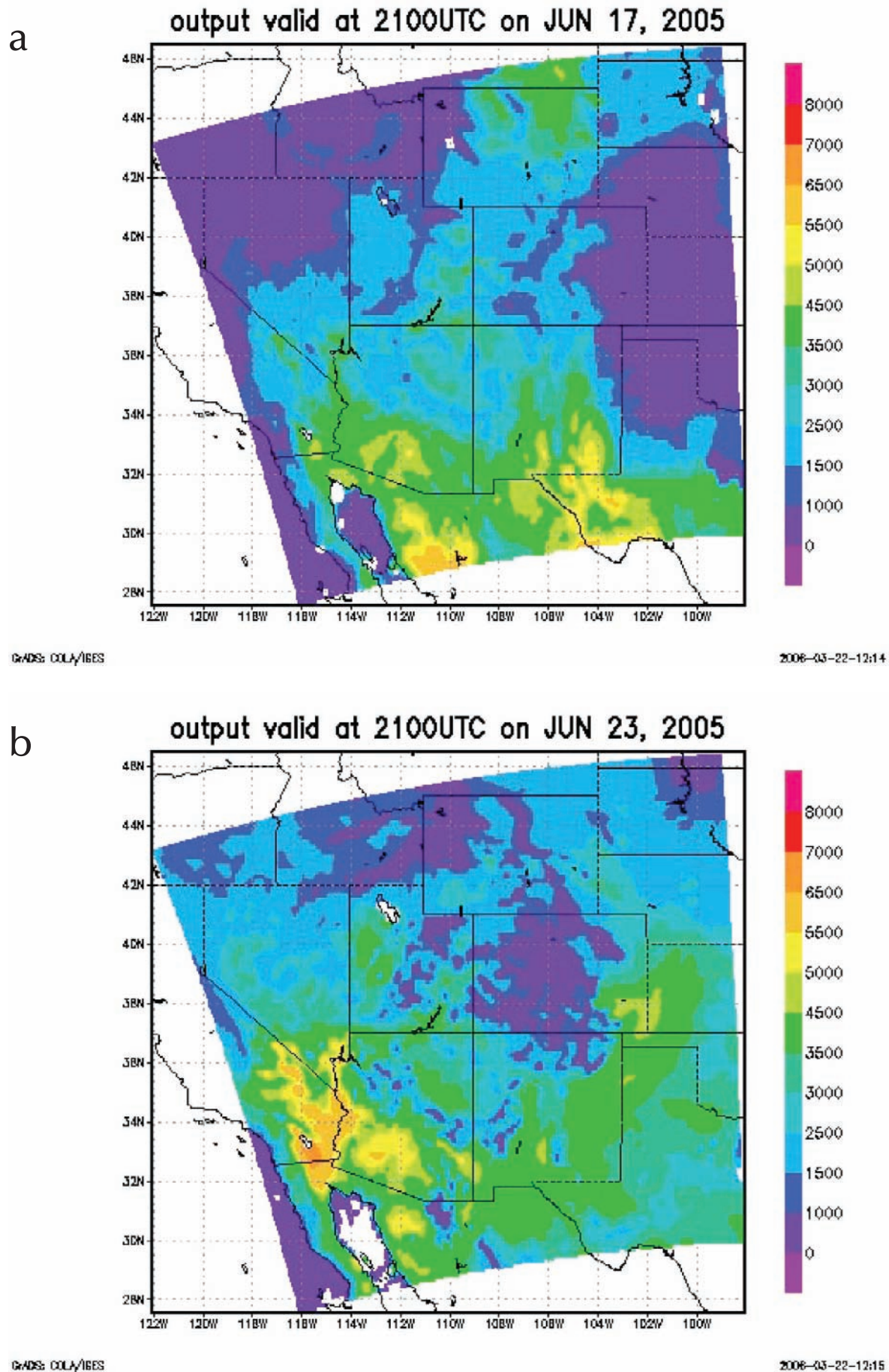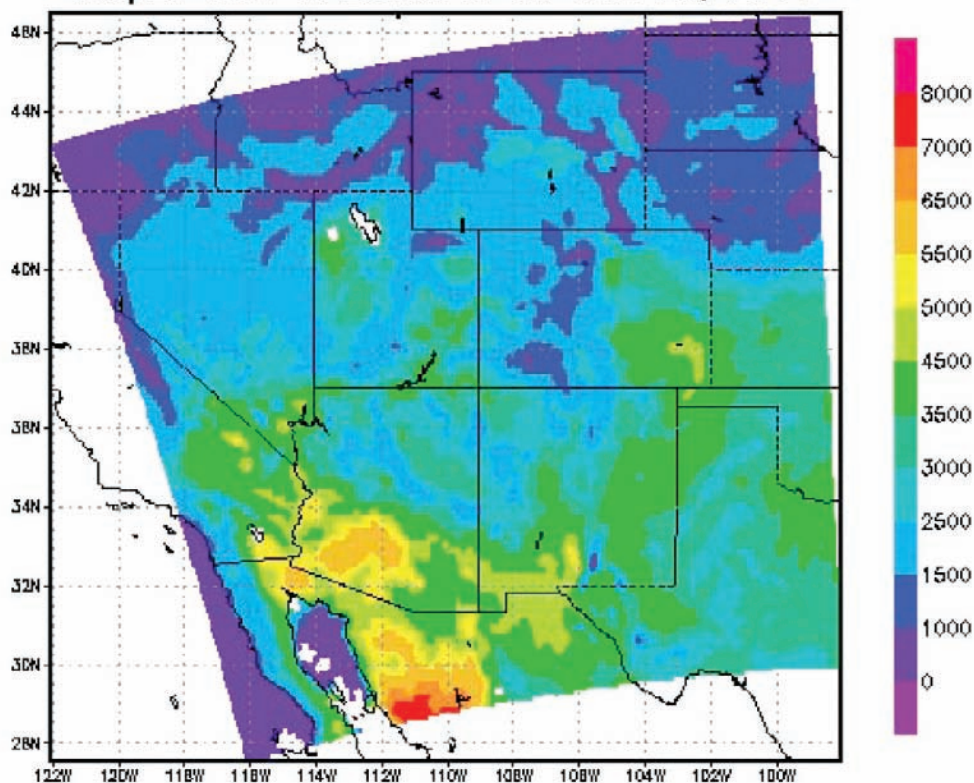
a

output valid at 2100UTC on JUN 17, 2005

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b

output valid at 2100UTC on JUN 23, 2005

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Figure 4—Simulated mixed-layer averaged vapor pressure deficit for: a) 2100 UTC 17 June, 2005, b) 2100 UTC 23 June, 2005, c) 2100 UTC 27 June, 2005.
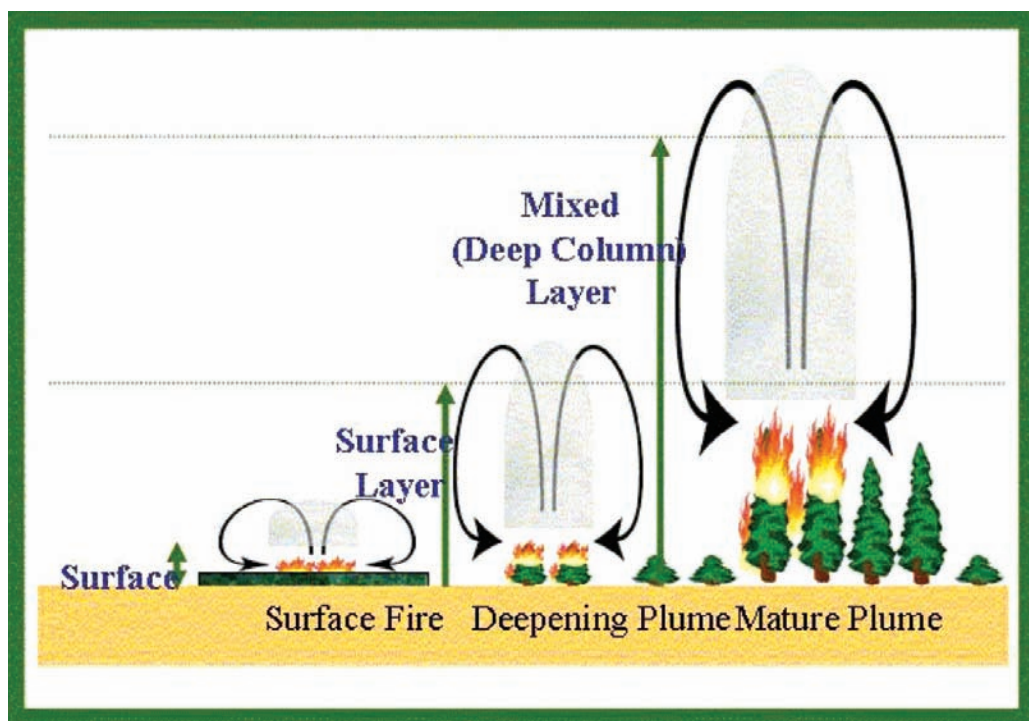
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Figure 5—Conceptual diagram of the 3-layer model showing potential interactions between a fire and layers of the atmosphere.

ask three questions: 1) what type of air influences a fire while it is forming a plume, 2) what type of air influences a fire right after it ignites, and 3) what type of air influences a fire that has established an identifiable plume? These questions lead to a conceptual model which we refer to as the three-layer model (Potter, 2002; Charney et al., 2005), in which we employ the NWP model to calculate weather variables at the ground, averaged throughout the mixed layer, and averaged from the ground to a point 500 m above the mixed layer. By looking at how these quantities vary at a point through the day, the impact of mixed-layer processes on surface conditions can be diagnosed and, in some cases, predicted hours or even days in advance.

Figure 6 shows time series of 3-layer model quantities for Episodes 2 and 3 for a point in extreme southern Nevada. It is noteworthy that when the mixed-layer starts to grow during the daytime, the wind speed at the ground in both episodes increases and the RH decreases dramatically. This progression indicates the importance of mixed-layer processes in the development of dry and windy conditions for both episodes. The time series for Episode 2 suggests that prior to sunrise on June 23rd, the surface air was drier and windier than the air 500m above the ground. As the mixed layer grew after sunrise, this signal was eliminated and the usual structure of drier and windier air aloft than at the ground transpired. However, the unusual vertical structure prior to sunrise on the 23rd preceded the fire reports of extremely high flame lengths (50-80 feet) on the 23rd. Without exploring the details of the atmospheric processes that led to the formation of the anomalous structure during the night, we cannot state whether the fire reports and this unusual mixed-layer structure is related. But the anomalous the mixed-layer structure and anomalous fire behavior suggest that a possible cause and effect relationship should be explored in future studies.

Figure 7 shows a time series of 3-layer model quantities for Episode 3 for a point in central Arizona. The development of the surface and mixed-layer averaged winds is notable in this case. At sunrise, the winds were quite light, with values on the order of 3 mph. As the mixed layer grew through the day, surface wind speeds increased rapidly to about 15 mph. The wind speeds just above the mixed layer, however, remained sharply higher than the mixed-layer wind speeds throughout the day. This is noteworthy in that a strong fire circulation in that environment could "tap into" air above the mixed layer and transport momentum from outside of the mixed layer to the ground, leading to anomalously strong surface winds, possibly with gusts that are even higher than indicated by the time series. Furthermore, note that the strong winds aloft remained in place even after the mixed layer collapsed (e.g. when the green line in the plot disappears) indicating that even at night, this fire might continue to experience stronger winds than expected.

Discussion And Conclusion

The NWP model results presented in the last section indicate that variations in weather conditions associated with three fire episodes in late June, 2005 can help explain some of the variations in observed fire behavior. The simulations demonstrate that substantial differences occurred in the fire-atmosphere interactions during the episodes. And while these interactions appear to rely upon the presence of dry air, the simulations reveal that RH is not the best quantity for assessing the impact of dry air on fuel conditions, and by association, fire behavior. Since the most pronounced difference
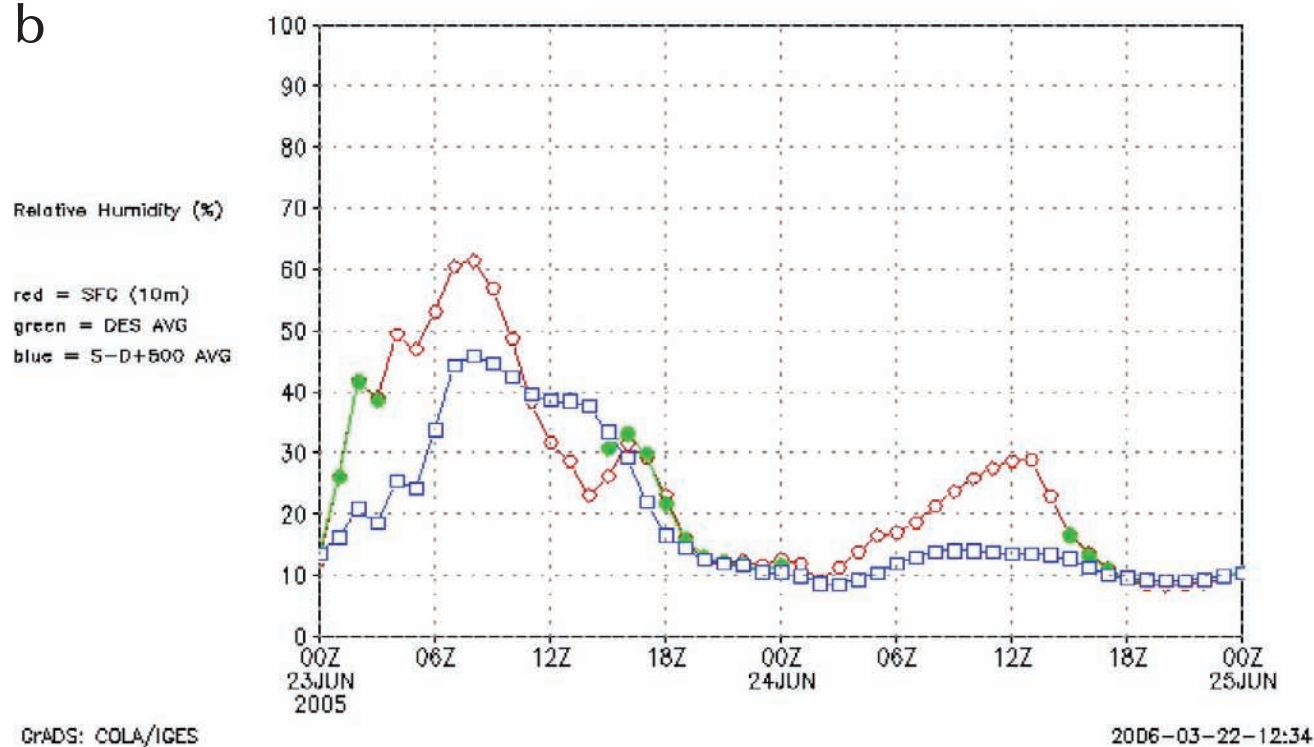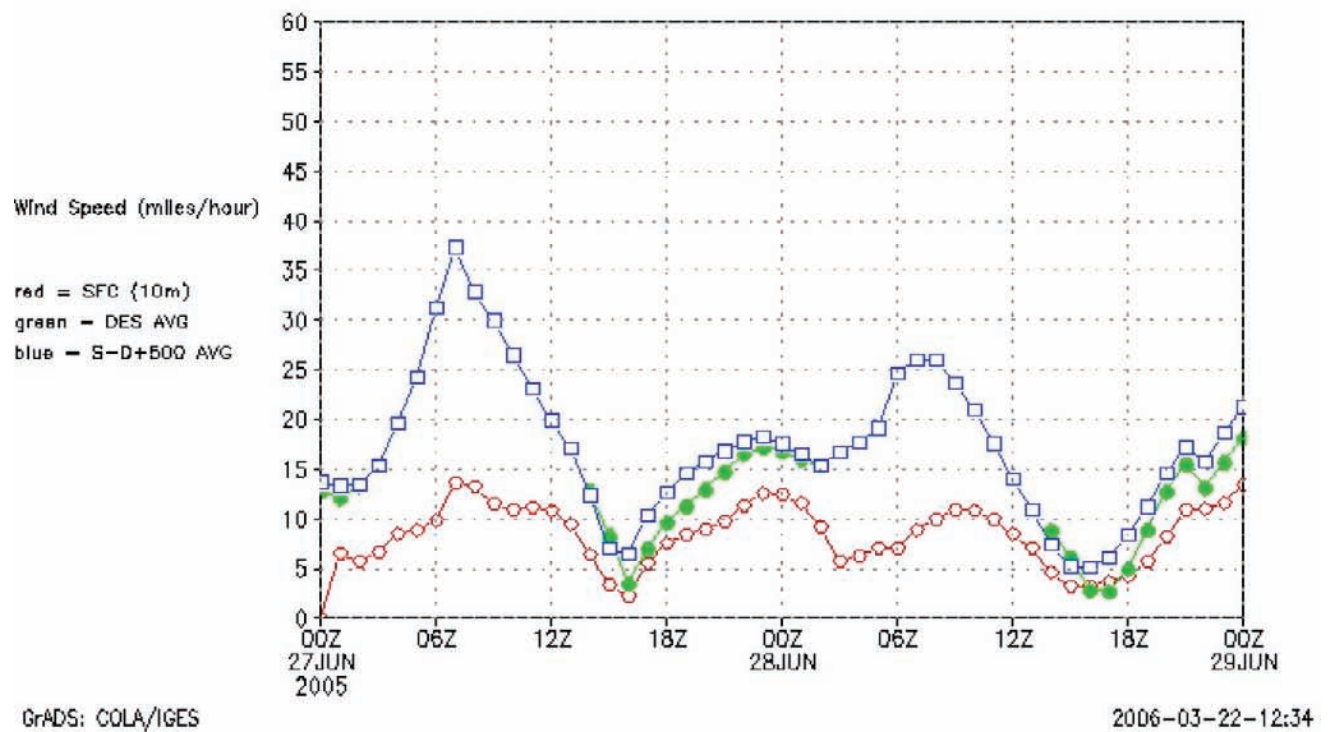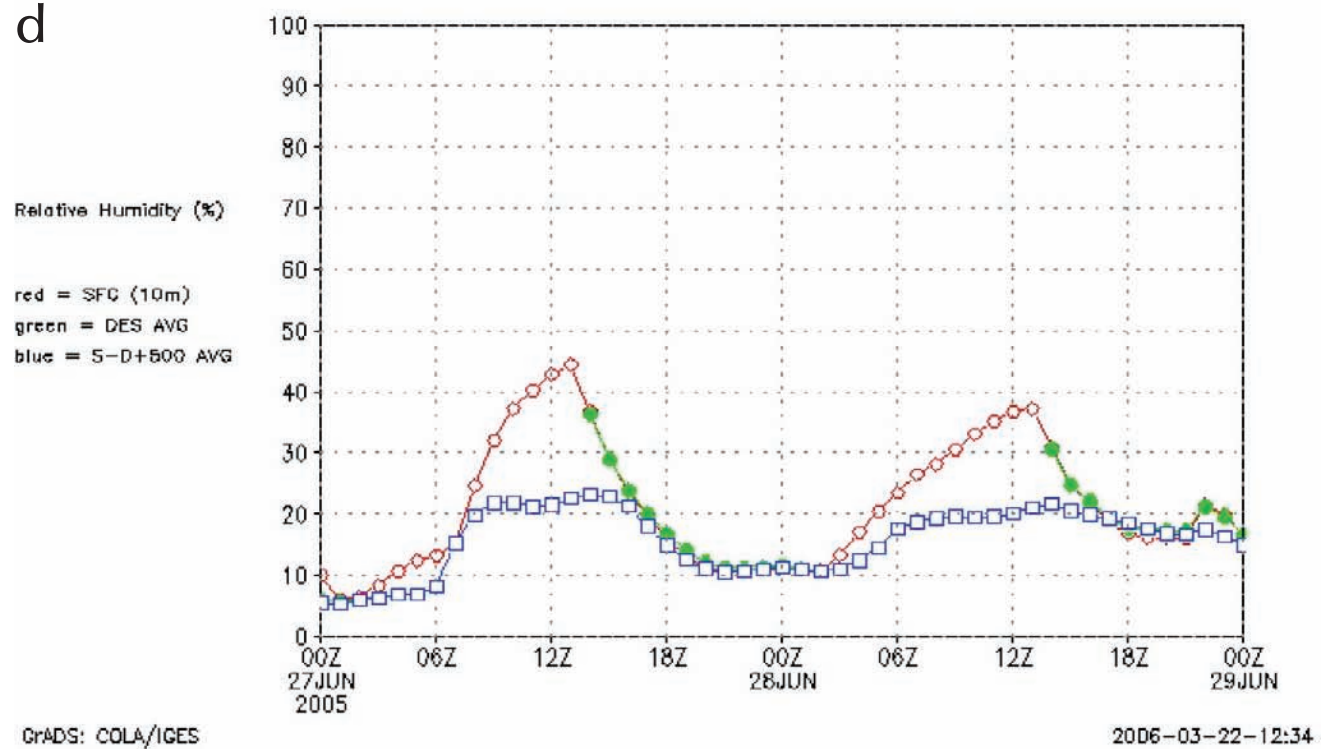
a

Southern Nevada
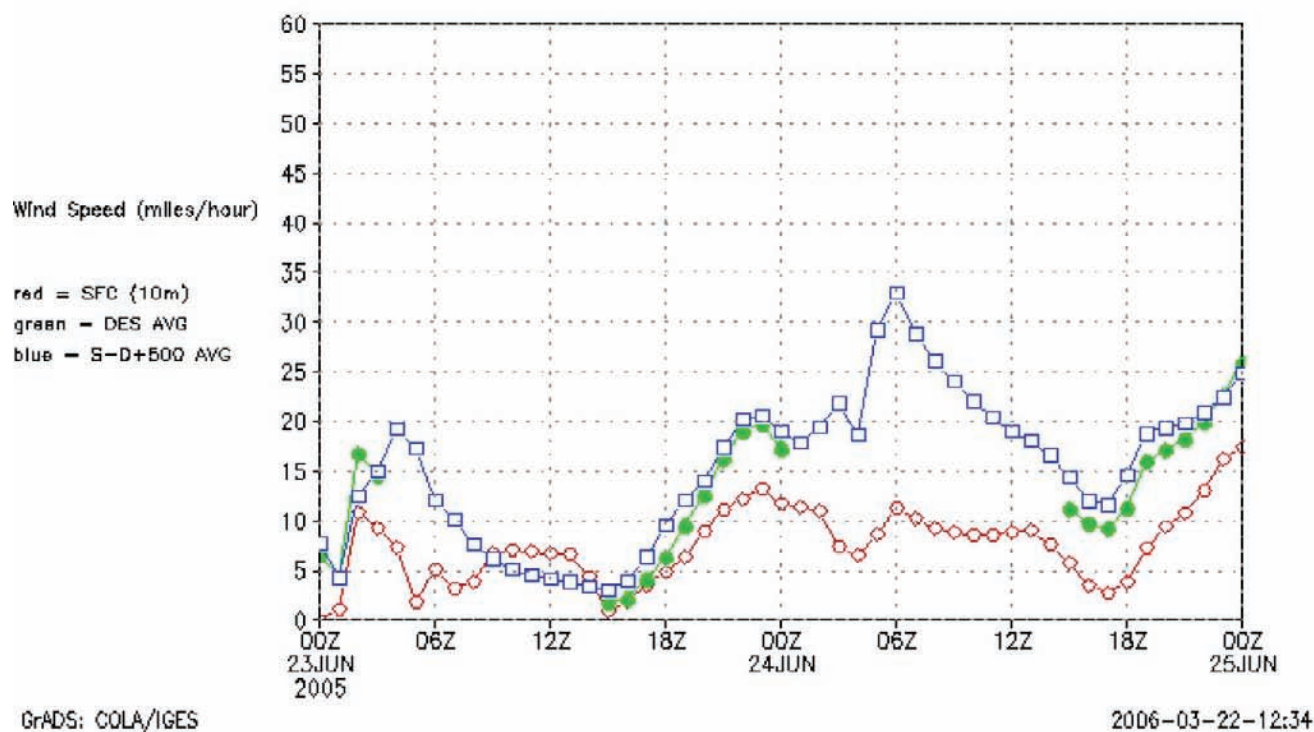
b

Figure 6—Time series in southern Nevada of a) surface wind speed, mixed-layer average wind speed, and mixed-layer + 500m average wind speed in mph and b) surface relative humidity, mixed-layer average relative humidity, and mixed-layer + 500 m average relative humidity from 0000 UTC 23 June through 0000 UTC 25 June 2005. c) same as a) from 0000 UTC 27 June through 0000 UTC 29 June 2005. d) same as b from 0000 UTC 27 June through 0000 UTC 29 June 2005.
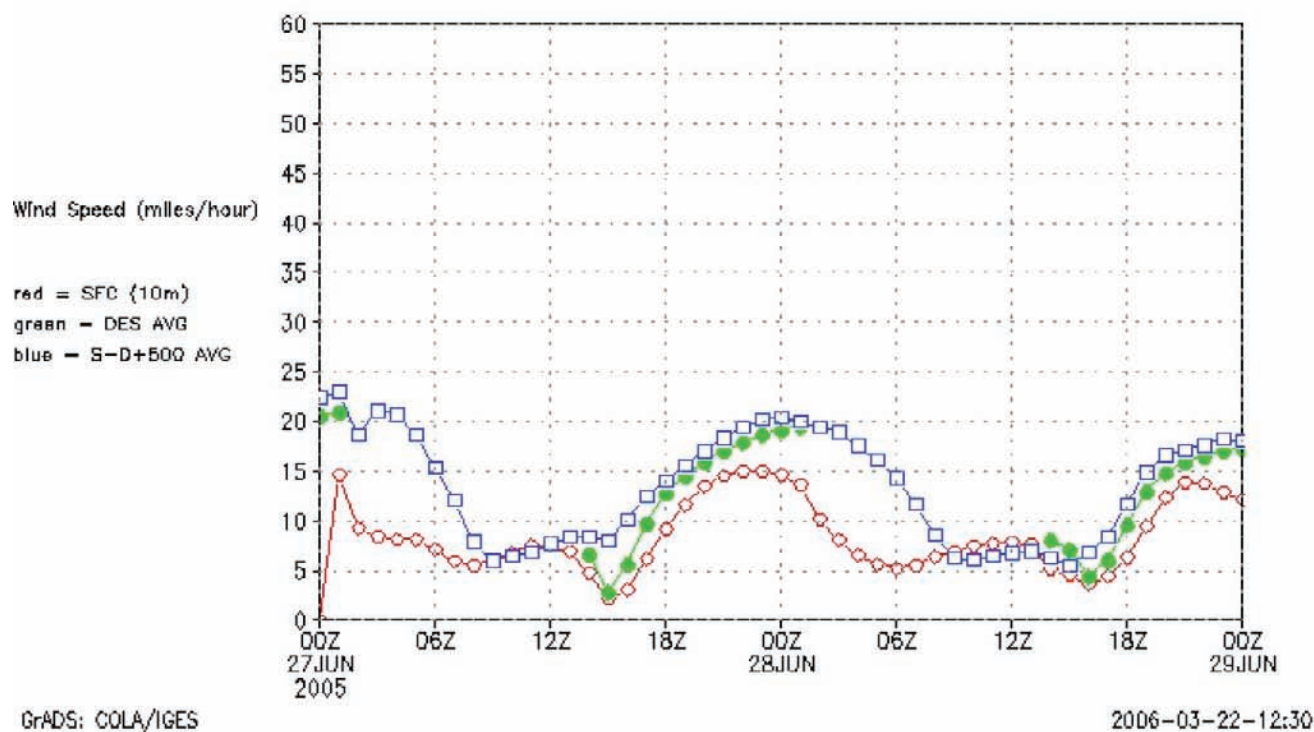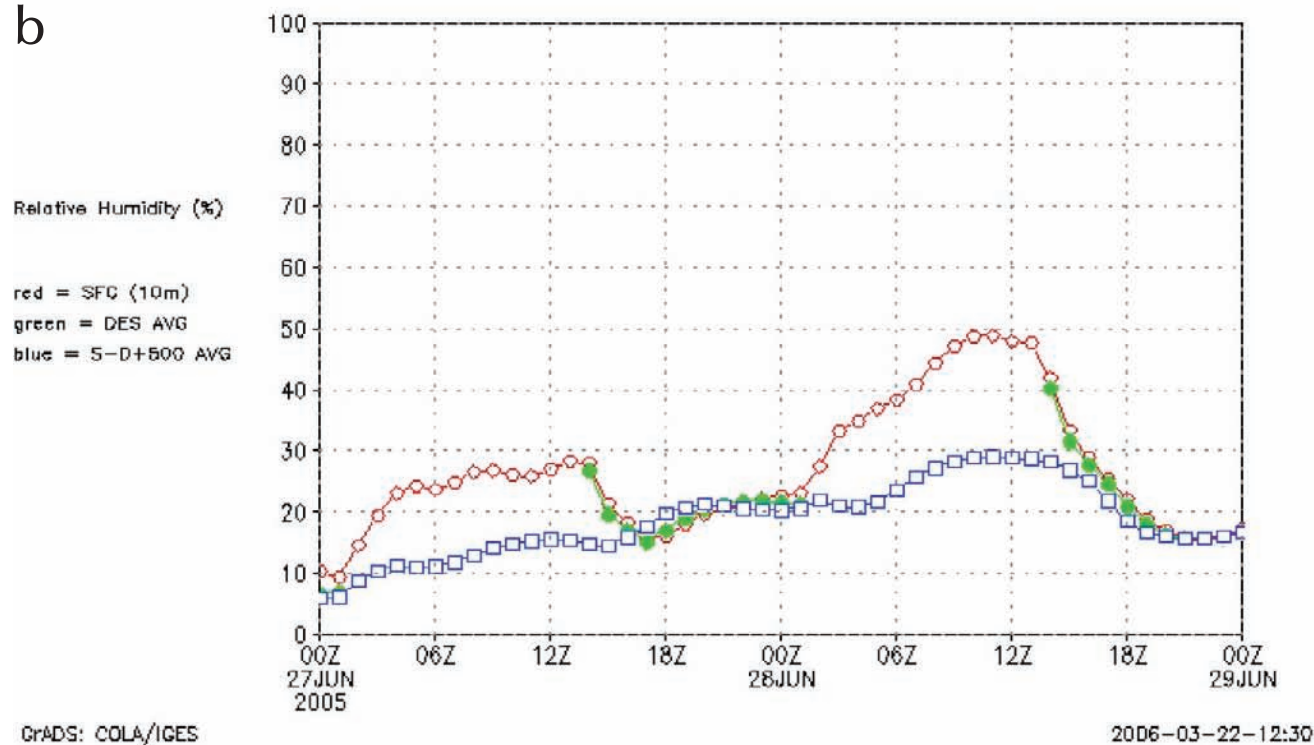
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Southern Nevada

d

a

b

Figure 7—Time series in central Arizona of a) surface wind speed, mixed-layer average wind speed, and mixed-layer + 500 m average wind speed in mph and b) surface relative humidity, mixed-layer average relative humidity, and mixed-layer + 500 m average relative humidity from 0000 UTC 27 June through 0000 UTC 29 June 2005.

between the episodes was found in near-ground temperatures, RH would be expected to be ambiguous. However, the vapor pressure deficit shows a more pronounced change in conditions between the episodes, and in these situations, represents a more precise means of diagnosing the potential fuel drying due to atmospheric processes.

The potential for local conditions at the ground and aloft to affect the fires was addressed using the so-called three-layer conceptual model, which employs NWP model output to calculate the surface, mixed-layer, and mixed-layer plus 500 m winds and humidities. These analyses highlighted highly anomalous mixed-layer structures coinciding with the most extreme fire behavior reported during the episodes. In other locations, the analyses indicate the potential for a fire to tap into fast-moving air just above the mixed layer; air that could be mixed down to the surface and produce unexpected and potentially hazardous changes in fire behavior. The preliminary analyses of these time series indicate that the three-layer model could be used to anticipate the potential for anomalous fire behavior associated with diurnal variations in atmospheric mixed layer processes. Additional work is necessary, however, before the ultimate usefulness of this diagnostic tool can be determined.

This paper represents a step towards realizing the full potential of atmospheric physics models for fire weather and fire behavior forecasting. As researchers and operational personnel come to understand the relationships between fire behavior and atmospheric processes that can be predicted by weather forecast models, these concepts can be tested in the broader context of day-to-day fire weather forecasting. Eventually, these techniques could provide additional information for fire weather forecasters and fire managers, producing new information from tools that are already available and used routinely in weather forecast offices.

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