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Spatial variation in extreme winds predicts large wildfire locations in chaparral ecosystems

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[1] Fire plays a crucial role in many ecosystems, and a better understanding of different controls on fire activity is needed. Here we analyze spatial variation in fire danger during episodic wind events in coastal southern California, a densely populated Mediterranean-climate region. By reconstructing almost a decade of fire weather patterns through detailed simulations of Santa Ana winds, we produced the first high-resolution map of where these hot, dry winds are consistently most severe and which areas are relatively sheltered. We also analyzed over half a century of mapped fire history in chaparral ecosystems of the region, finding that our models successfully predict where the largest wildfires are most likely to occur. There is a surprising lack of information about extreme wind patterns worldwide, and more quantitative analyses of their spatial variation will be important for effective fire management and sustainable long-term urban development on fire-prone landscapes. **Citation:** Moritz, M. A., T. J. Moody, M. A. Krawchuk, M. Hughes, and A. Hall (2010), Spatial variation in extreme winds predicts large wildfire locations in chaparral ecosystems, *Geophys. Res. Lett.*, *37*, L04801, doi:10.1029/2009GL041735.

1. Introduction

[2] Large and severe wildfires in some regions of the world have been linked to climatic variability [*Swetnam and Betancourt*, 1990; *Carcaillet and Richard*, 2000; *Kershaw et al.*, 2002; *Field et al.*, 2009], while in others they are attributed to recent decades of fire suppression and fuel accumulation [*Parsons and Debenedetti*, 1979; *Agee*, 1993; *Covington*, 2000]. Across Mediterranean-climate ecosystems - those highly fire-prone regions experiencing cool, wet winters and warm, dry summers - devastating fires are often associated with short episodes of severe fire weather generated by hot and dry winds. Although such periods of extreme winds have received relatively little scientific study in relation to historical fire patterns, they are routinely reported in the popular press as the cause of unstoppable wildfires (Text S1 of the auxiliary material).[4] Many extreme fire weather conditions have been identified and named, such as the "sirocco" in the Mediterranean Basin, the "bergwind" of South Africa, and the "Santa Ana" of southern California [*Fendell and Wolff*, 2001].

[3] Given the widespread importance of fire weather episodes, there is relatively little quantitative information about where fire danger is likely to be most severe during extreme wind events. The Santa Ana winds of Mediterranean-climate southern California are a prime example of this knowledge gap, although they have long been linked to large wildfire occurrence [*Schroeder et al.*, 1964; *Countryman*, 1974; *Minnich*, 1983; *Moritz*, 1997; *Keeley et al.*, 1999; *Westerling et al.*, 2004]. Spatial variation in Santa Ana winds appears to affect the age of vegetation burned on different landscapes [*Moritz*, 2003] and even spatial patterns in offshore coastal upwelling patterns [*Hu and Liu*, 2003]. Consistent channeling of winds has also been noted in key mountain passes (Figure 1) during Santa Ana conditions [*Fosberg et al.*, 1966]. Despite the distinctive wind speed and direction, temperature, and humidity observed during Santa Ana events, there are no detailed maps of meteorological fields associated with them. If they were available, high-resolution fire weather climatologies could guide planning for fire-resistant development, enhance understanding of fire regimes at the landscape scale, and help quantify the relative importance of extreme wind patterns in driving fire activity. Here we report on the first detailed analysis of fire weather severity patterns during Santa Ana wind events and how they relate to past fire activity, particularly large fire events, in the chaparral ecosystems of Mediterranean-climate southern California.

2. Methods

[4] To create a relatively high-resolution map of fire danger patterns during extreme wind events, we used several years of reconstructed weather for the study area (Text S1). Weather data were provided by a high-resolution regional atmospheric simulation using the Penn State/National Center for Atmospheric Research (NCAR) mesoscale model version 5 (MM5), release 3.6.0 [*Grell et al.*, 1994]. The simulation model was designed to reconstruct weather across southern California, and its innermost 6 km resolution domain covers the entire region (Figure 1). The simulation in the 6 km nest thus acts as a reconstruction of local atmospheric conditions, based on known large-scale atmospheric conditions. We provide additional details of the physics parameterizations (e.g., boundary layer scheme, convection, ice microphysics, and cloud interactions) in the auxiliary material. Through comparison with point measurements, we have previously shown that the simulation reproduces local circulation statistics with a high degree of fidelity [*Conil and Hall*,

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[4] Auxiliary materials are available in the HTML. doi:10.1029/2009GL041735.

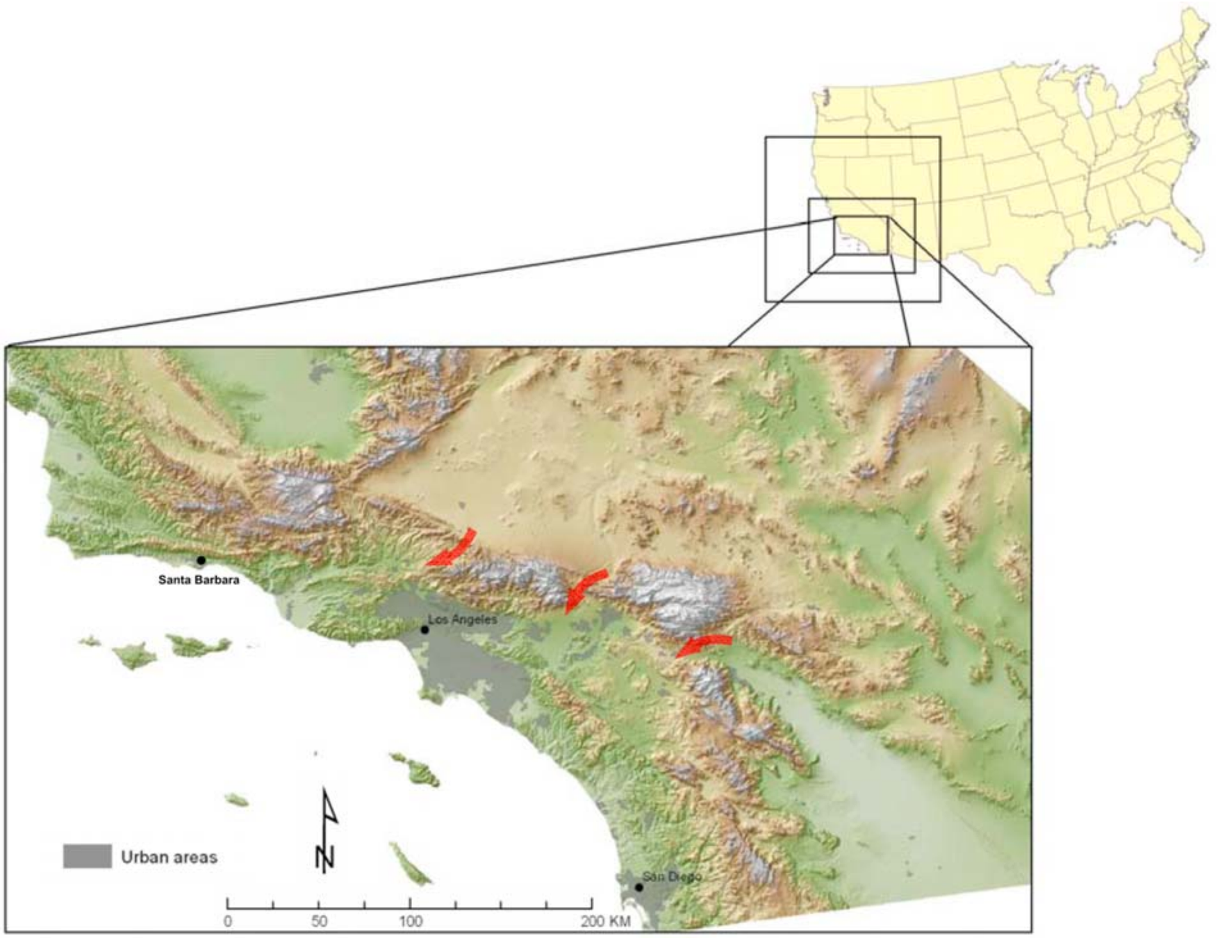

Figure 1. Nested modeling domains of the MM5 simulation. The study area, corresponding to the innermost model domain, is shown with topography shaded according to elevation. Well-known cities in the region are identified, and recognized passes that funnel offshore Santa Ana winds are shown by red arrows (west-to-east: Soledad Pass, Cajon Pass, and San Gorgonio Pass).

2006], including a specific validation of Santa Ana events [*Hughes and Hall*, 2010]. All major mountain complexes are represented in the weather simulation model (Figure 1), which is crucial for capturing wind corridors and meteorological patterns downwind of topography.

[5] As a subset of all possible Santa Ana wind events for analysis, we isolated those occurring in October for 1995–2003 based on wind speed and direction [*Hughes and Hall*, 2010]. We focused on October because it is late in the fire season and has been associated with some of the most devastating wildfires in the region, including major firestorms in both 2003 and 2007. Meteorological parameters for these October Santa Ana days (n = 18) were extracted from the MM5 time series at 2 PM local time, a standard for government agency assessments of fire danger. For each weather observation, we estimated fire weather severity by calculating the Fosberg Fire Weather Index (FFWI), based only on current temperature, humidity, and wind speed [*Fosberg*, 1978]. At each of ~3400 points in the 6 km domain, FFWI values were averaged over the 18 Santa Ana days to obtain a composite measure and then spatially interpolated using inverse distance weighting to create a continuous surface of mean FFWI (Figure 2).

[6] We used the official mapped fire history from 1950–2007 to test how well our models of long-term fire weather severity patterns predict large fire probabilities in the Mediterranean-type shrublands characteristic of the study area. To examine possible sensitivities to event size, different criteria were used to define "large" fires (i.e., > 500 ha, > 1000 ha, and > 5000 ha). Despite limited area burning each year outside shrublands, we excluded urban lands, deserts, and non-shrubland plant communities, to restrict analyses to landscapes dominated by chaparral vegetation. The resulting dataset contains over 1200 fires, representing over half a century of wildfire activity (Figure 3). Due to the importance of recent conflagrations in October and the fact that our fire weather indices were calculated from October wind events, we restricted statistical tests to fires occurring in this month (Text S1 of the auxiliary material). Although shrubland fires can certainly occur in almost any month in southern California, October alone accounts for roughly 25% of the total area burned. A disproportionate number of the biggest shrubland fires over the period of record have also been in October. Of the largest 30 events observed since 1950 (top ~2%), 40% occurred in this month. This highlights the importance of large Santa Ana-driven fires occurring in

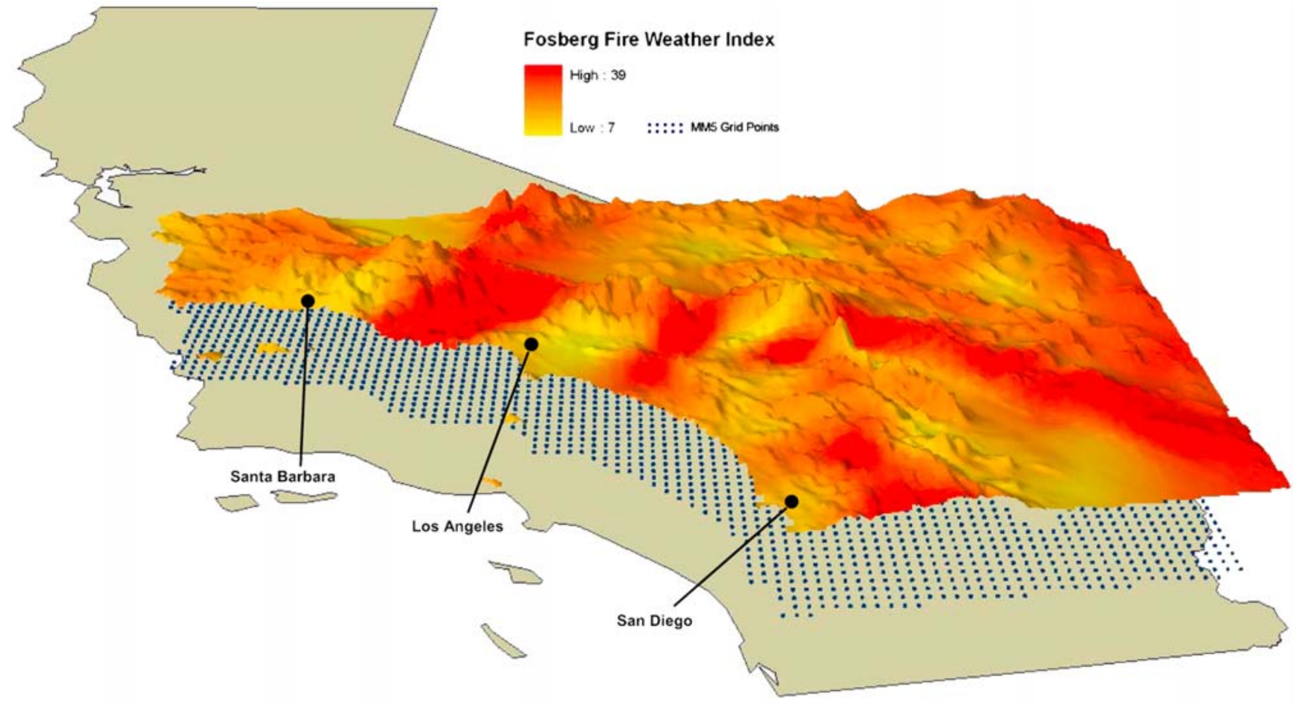

Figure 2. Mean Fosberg Fire Weather Index (FFWI) intensity (color) draped over elevation for all vegetation types across southern California. Mean FFWI calculated from 18 October Santa Ana wind events from 1995–2003, underlain by weather modeling grid points.

October, which are also common in both September and November; however, additional work is needed to quantify how representative October events are.

[7] Fire observations consisted of mapped events (centroid locations) in October meeting different fire size criteria; statistical tests considered whether large fires (Figure 3) occur more often in areas exposed to higher fire weather severities, compared to the available region-wide distribution (Figure 2) after being restricted to shrubland landscapes. We used a Kolmogorov-Smirnov two-sample test to assess differences between the two distributions, adjusted for spatial autocorrelation (Text S1 of the auxiliary material).

3. Results and Discussion

[8] The interpolated FFWI surface (Figure 2) represents our best estimate of mean fire weather conditions over nearly a decade of reconstructed Santa Ana wind events, and it is the first fire weather severity map available at this scale of analysis. There are clear spatial relationships between high fire danger (Figure 2) and key mountain passes (Figure 1),

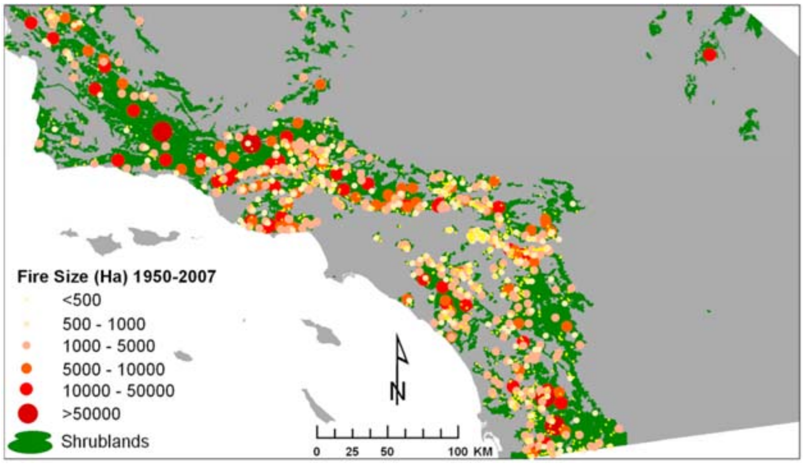

Figure 3. Fire data and shrubland distribution. Centroids of fires are shown scaled and colored by size, with shrubland landscapes in green as background. Non-shrubland areas within ~100 km of the coast tend to be highly urbanized, and those to the east are largely desert.

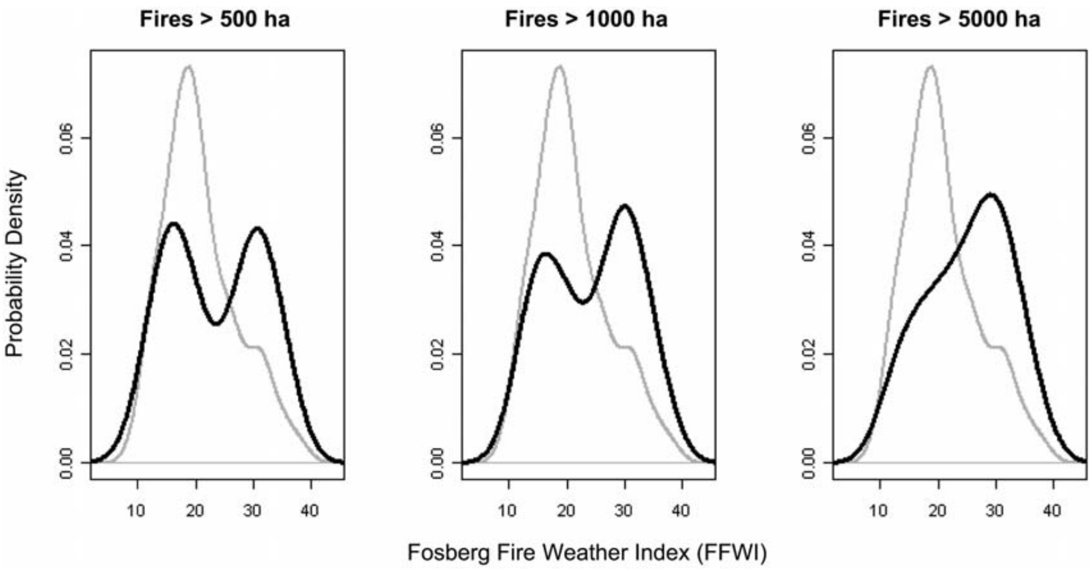

Figure 4. Density estimates of FFWI distributions, using different fire size cut-offs. The distribution of fire weather severity for large shrubland fires in October (dark line) was contrasted against values observed across shrublands of the entire study region (grey line).

but there are also broad regions of high severity conditions in the southwestern end of the study area that have not historically been associated with mountain passes; however, these high severity zones are the result of high wind speeds due to wind channeling around a lesser mountain range in the region (i.e., Laguna Mountains). Relatively sheltered regions, such as those covering much of coastal urbanized Los Angeles, are also evident. As some researchers have hypothesized, the northwestern portion of the study area near Santa Barbara are indeed shielded from the Santa Ana winds that impact southern California in general, despite having their own localized form of extreme fire weather [*Ryan*, 1991; *Moritz*, 2003].

[9] Based on modeled fire weather patterns, we found that large October wildfires consistently occur in locations experiencing higher fire weather severities, compared to distributions from all shrublands available to burn during Santa Ana events (i.e., distributions shifted rightward in Figure 4). Across the chaparral-dominated ecosystems of the region, only about one quarter (~24%) of the area experiences very high fire weather severities (e.g., index > 25) during the wind episodes we examined. Nonetheless, almost half (45%) of the large fires > 500 ha occurred in these regions prone to the highest fire weather severities, and the relationship is stronger in terms of area burned (65%). Because smaller fires can occur anywhere on the landscape, excluding them (i.e., higher fire size cutoffs) results in FFWI distributions for large fires that are more unimodal and more strongly associated with regions of the highest fire danger during Santa Ana conditions. (Figure 4 and Text S1 of the auxiliary material). These results are notable when one considers that wildfires tend to spread fastest where winds are strongest, but then may proceed to burn outside these corridors as normal winds return (i.e., expanding the fire's eventual perimeter away from higher fire weather severity regions).

[10] Recent analysis has shown that there are different types of Santa Ana wind events [*Hughes and Hall*, 2010], indicating that further study of fire weather patterns is needed for a deeper understanding of their spatial and temporal properties. Even so, our findings demonstrate that a relatively small number of extreme fire weather episodes allow prediction of where the largest wildfires are likely to occur in chaparral-dominated ecosystems of southern California. In a similar comparison of fire occurrence data (i.e., mapped number of times burned), we did not find a strong relationship with severe fire weather patterns (Text S1 of the auxiliary material). This indicates that fire frequency and ignition probabilities are controlled by other factors in the study area, such as human population and road densities [*Syphard et al.*, 2007], while the process of fire growth tends to be weather-driven. More generally, our findings show that any fire-prone region is likely to see wildfires become large and unstoppable, if ignitions occur where wind conditions tend to be most severe. Conversely, vegetation characteristics and fire suppression efforts should be more important to fire spread in regions sheltered from extreme fire weather. Although fuel modifications will be less effective in regions of high fire weather severity during episodic wind events, they may still be useful in strategic locations along the wildland-urban interface or under more moderate weather conditions. It is therefore important that the goals and performance expectations of fuel treatments be evaluated with respect to gradients in fire weather severity, the vast majority of which have yet to be mapped.

[11] By developing relatively high-resolution models of extreme wind patterns, we were able to quantify substantial spatial variation in the key driver of some of the most costly wildfires in the world. Reducing future ignition sources and urban development in the most exposed regions could reduce the probability of large fire occurrence, which has recently led to repeated short-interval fires and losses of native shrubland species [*Keeley et al.*, 1999; *Moritz*, 2003; *Syphard et al.*, 2007]. Little is known about how climate change will affect fire weather episodes, however, especially more localized wind patterns that are not simulated well in

general circulation models. Whether in the context of biogeochemical cycling [*Bowman et al.*, 2009] or the protection of lives and property in fire-prone Mediterranean-climate regions, spatial models of fire weather patterns should be developed for areas where large and wind-driven wildfires are recurring events.

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