Characteristics of Some Days Involving Abrupt Increases in Fire Danger*

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(Manuscript received 2 March 2015, in final form 19 June 2015)

ABSTRACT

A class of fire-weather events has been identified recently in which the normal, often diurnal, rise and fall of fire danger is interrupted by abruptly worsening conditions, or ''spikes,'' for which fire managers may be unprepared. Frequent observations from a site in Tasmania, Australia, show that spike events are associated with the passage of negatively tilted upper-tropospheric troughs, leading to descent into the atmospheric boundary layer of dry, high-momentum air—a result that is supported by satellite water vapor imagery. Case studies from other major fire events, both in Australia and in the Northern Hemisphere, show similar characteristics. Statistically significant differences exist between the location and placement of trough and jet-streak features during spike events and normal fire-weather events, with differences in satellite water vapor imagery features also evident. The seasonality of spike events differs significantly from other fire-weather events, with their occurrence peaking from late spring to early summer in Tasmania, in contrast to broad summer primary and midspring secondary peaks for nonspike events.

1. Introduction

Fire weather is the occurrence of weather conditions conducive to the spread of dangerous wildfires. Fire-weather events are of concern to land managers and communities around the world. In most fire-weather events, a fire-danger index increases following the erosion of an overnight inversion and will frequently reach a peak during the middle of the day or the afternoon, varying around the peak until a diurnal easing in the evening occurs or a cool change moves through (Millán et al. 1998; Mills 2002). In some cases, however, occasionally even after what appears to be the peak of an event, a further, abrupt, increase in fire danger occurs, with conditions becoming substantially worse as a result of a rapid increase in wind, decrease in relative humidity, or both. It is notable that temperature does not necessarily change dramatically with humidity or wind [e.g., the cases in Mills (2008a) and Fox-Hughes (2012, hereinafter referred to as FH2012)]. In the latter case, temperature varied in a smooth, apparently diurnal, fashion as wind speed increased by 10 $\mathrm{m\,s^{-1}}$ and dewpoint temperature decreased by 5°C. Fire-weather events in which conditions have rapidly worsened have been documented in numerous locations around the globe (FH2012; Kaplan et al. 2008; Kondo and Kuwagata 1992; Mills 2008a,b; Sharples et al. 2010; Zimet et al. 2007), including southeastern Tasmania, Australia. Southeastern Tasmania is subject to outbreaks of dangerous fire weather and occasional devastating wildfires (Bond et al. 1967; Foley 1947), most recently on 4 January 2013 when over 200 structures were destroyed around the township of Dunalley (the fire weather on that day fits within the definition of abruptly increasing fire danger that is considered below but is outside the period examined).

FH2012 investigated two fire-weather events occurring in this region, identifying characteristics of one event, which resulted in a ''spike'' of fire danger during the early evening, that was absent in the other ''non-spike'' (but still very dangerous) event. In the spike event, a lobe of air with high potential vorticity (PV) extended from the tropopause to heights that were well below the top of the mixed surface layer of the atmosphere over southeastern Tasmania at the time, allowing

* Supplemental information related to this paper is available at the Journals Online website: http://dx.doi.org/10.1175/JAMC-D-15-0062.s1.

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DOI: 10.1175/JAMC-D-15-0062.1

the passage to the surface of high-momentum, low-relative-humidity air through thermal mixing and topographic forcing (Mills 2008b; FH2012). This mixing resulted in the rapid increase in fire danger. In the nonspike event, such a lobe of high-PV air also existed but was clearly cut off from the surface. A feature of many fire-weather events in which rapid increases in fire danger have occurred is the presence of an elongated dry band in satellite water vapor (WV) imagery (Mills 2008b). Such a dry band was evident during the spike event documented in FH2012. Midlatitude dry bands are often associated with stratospheric PV intrusions in the vicinity of jets and cold fronts (Santurette and Georgiev 2005). Such PV intrusions can, as noted above, descend to relatively low levels and transport high-momentum, dry air to the top of the boundary layer from where it may reach the surface via several mechanisms as noted above and discussed in, for example, Browning (1997) and Mills (2008b). Both events above occurred during the Tasmanian springtime, September–November. During this season, there has been a marked increase in dangerous fire weather in eastern and especially southeastern Tasmania over the last several decades (Fox-Hughes 2008).

This paper aims to investigate whether the characteristics of the spike and nonspike fire-weather events in FH2012 can be generalized by developing an objective means of identifying spike days, performing a composite analysis of spike and nonspike days, comparing satellite WV imagery for spike and nonspike events, and identifying whether spike events have contributed to the occurrence of dangerous springtime fire-weather events in southeast Tasmania. In section 2, details of the selection of spike and nonspike days are discussed, together with the generation of composite plots of atmospheric parameters. Results are presented and analyzed in section 3, and section 4 presents concluding remarks and suggests implications of some of the findings of this paper.

2. Data and methods

Half-hourly weather observations at Hobart International Airport, in southeastern Tasmania (Fig. 1), were used to derive values of the McArthur forest fire danger index (FFDI) (McArthur 1967; Noble et al. 1980) during the period of 3 October 1990–28 June 2010. More details on the derivation of the FFDI values used are contained in Fox-Hughes (2011). North-to-northwesterly airstreams are associated with the most significant fire-weather events in Tasmania, and the Hobart airport is well placed to experience a well-mixed boundary layer in these events. A combination of thermal mixing, due to the site's position on the warmer lee side of the Tasmanian landmass, and mechanical turbulence, due to the presence of substantial orography upwind of Hobart, ensures that the boundary layer extends to at least 2000 m on such days (FH2012 highlights the boundary layer depth in the two cases examined).

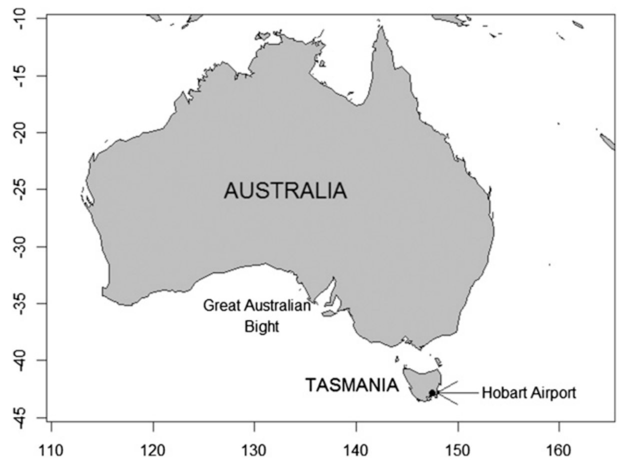

FIG. 1. Map showing location of Hobart International Airport, Tasmania.

Observations of FFDI exceeding 24 (''very high'' fire danger) were selected. These occurred on 230 days. Within each day, the daily mean and standard deviation (SD) of FFDI for the selected observations were calculated, and days for which the SD was null (only one very high FFDI observation occurred) or zero (a few identical very high FFDI observations) were rejected. The maximum daily FFDI was noted, and the number of SD of the maximum FFDI from the mean was calculated (again, each of these quantities was calculated separately for each day selected). These data are listed in Table S1 in the online supplemental material. Days on which the maximum FFDI was more than 2 SD from the mean were classed as spike fire-weather days. To summarize, the selection process was

1) select days with maximum FFDI > 24,
2) calculate mean and SD of FFDI for observations > 24,
3) reject days for which SD is undefined or zero, and
4) classify days for which (maximum FFDI − mean FFDI) > 2 SD as spikes.

This process was undertaken to identify days on which fire-weather conditions were already very dangerous (the FFDI was already very high) but then abruptly became substantially worse for a period. The threshold of 2 SD was chosen by experimentation to include sufficient cases to be representative while excluding those cases that did not exhibit a strong spike. Some 37 days were classed as spike days on this basis. The standard deviation was chosen as a simple tool to identify fire-danger observations that deviated from the mean of observations of dangerous conditions on any individual day. Days on which a fire-danger spike occurred tended to be those on which fire danger increased rapidly (and were therefore of concern for the safety of life and property) but also decreased rapidly following a generally short peak, thereby giving the event its spike quality and making it amenable to identification using the standard deviation. It does not matter whether the observations are normally distributed to employ the standard deviation in this way, because the SD is not being employed as a statistical tool. It is possible to construct series of data that fulfill the above criteria for inclusion as spikes, but such series are generally very different from those that might be expected from data from automatic weather stations. To ensure that the selected days did have the desired characteristic of a spike in fire danger, however, the time series of FFDI on each of the 37 days selected by the above process was plotted and then visually confirmed as a spike day.

To contrast spike days with days that lack this feature, events were selected, following the above procedure, for which the maximum FFDI exceeded the mean of very high observations by less than 1.5 SD. In this case, however, the maximum FFDI was required to be at least 38, the level of fire danger at which the Tasmania Fire Service generally considers the imposition of a total fire ban to prevent the ignition of fires in the open. This criterion ensured that the nonspike data subset included days of very significant fire danger but, by definition, lacked an additional abrupt increase in the fire danger experienced during the course of the event. Note that these days could be (and are, in some cases) among the most severe fire-weather events in the entire dataset—FFDI may have increased relatively steadily over a period to an extreme value so that they did not have a step increase in FFDI once the fire was ''Very High'' that would lead to selection into the spike set. The threshold of 1.5 SD was chosen so that there would be the same order-of-magnitude number of days in each set but the SD multiplier would not appear to be completely artificial (thus, e.g., 1.5 rather than 1.6759). There were 25 days that satisfied these criteria. The selection process in this case can be summarized as

1) select days for which the maximum FFDI $>=$ 38,
2) calculate mean and SD of FFDI for observations $>$ 24, and
3) classify days for which (maximum FFDI $-$ mean FFDI) $<$ 1.5 SD as nonspikes.

Composites of atmospheric parameters were plotted for each type of event from NCEP–NCAR reanalysis data (Kalnay et al. 1996), using the facilities of the Physical Sciences Division (PSD) of NOAA's Earth System Research Laboratory (ESRL). Composites were generated as the mean fields of each parameter considered for each day of the two types of event, after obtaining individual event data from PSD. In addition, 0000 UTC mean sea level pressure (MSLP) analyses prepared by the Australian Bureau of Meteorology National Meteorological and Oceanographic Centre (NMOC, now known as the Bureau National Operations Centre) that correspond to each type of fire-weather event were manually examined. The WV imagery for spike and nonspike events was examined for the presence of dark bands, indicative of very dry air in the mid- to upper troposphere (e.g., Mills 2008b), which has generally descended from higher in the atmosphere.

3. Results and discussion

a. Synoptic characteristics of events

MSLP charts at 0000 UTC (1100 local time during the months considered here) were examined first for days in both fire-weather sets. It has been well documented (Brotak 1980; Marsh 1987) that days of elevated fire danger in Tasmania, particularly in the southeast of the island, are generally associated with a frontal passage across the island. On each spike day (see Fig. S1 in the online supplemental material), a cold front was approaching Tasmania or had very recently crossed the state. In the latter cases, Tasmania (in particular, the observation site at the Hobart airport) was subject to a vigorous postfrontal airstream. Most days associated with nonspike events (see Fig. S2 in the online supplemental material) were equally also days of frontal or trough passages, however. In each of these cases, the fronts were embedded in a broader trough in the westerlies. In nonspike events, however, it was generally the case that fronts, and the broad troughs in which they were embedded, were located farther westward than was the case with spike events, and consequently Tasmania was subject to a more well-defined northwesterly flow in nonspike events.

Daily composite MSLP images of spike and nonspike events are presented in Figs. 2a and 2b, respectively. In both composites, troughs are located close to Tasmania, as indicated by dashed lines in each case, with low pressure centers well south of the island, consistent with the NMOC analyses. The troughs extend from south of Australia through to heat lows over the northwest of the continent. High pressure centers are located in the Tasman Sea and in the Indian Ocean to

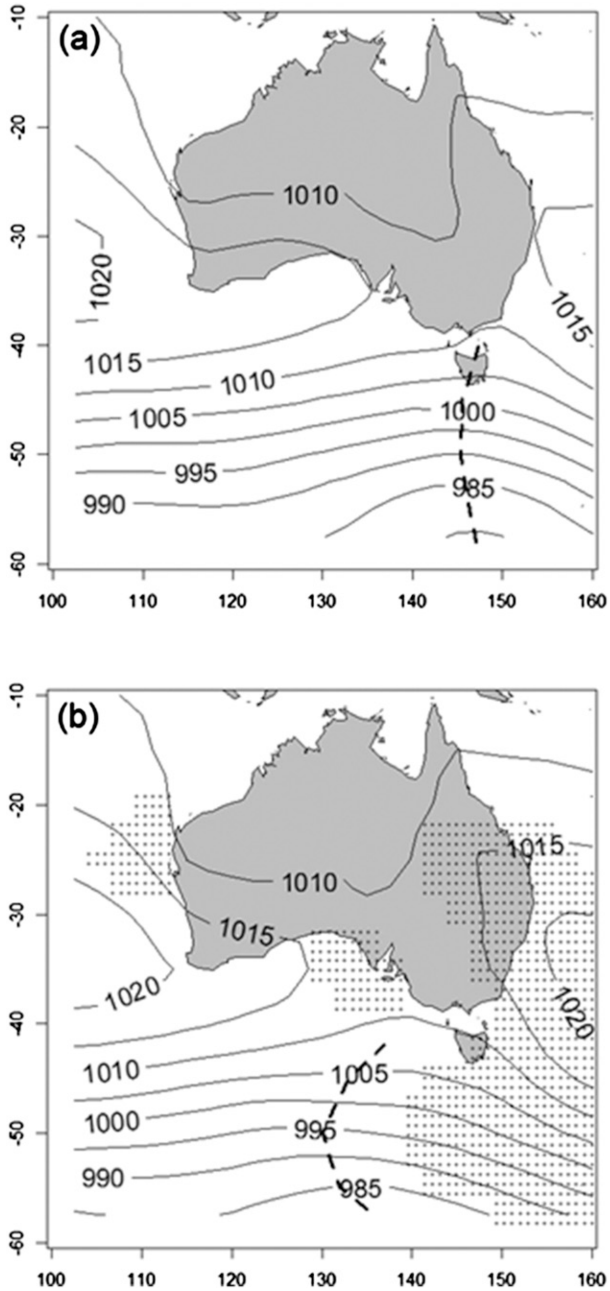

FIG. 2. Composite MSLP plots of (a) spike and (b) nonspike fire-weather events from daily NCEP–NCAR reanalyses. The stippled area in (b) indicates the region where the difference between spike and nonspike composites is significant at the 95% level.

the west of the Australian continent. Both plots correspond well to the observations noted above relating days of elevated fire danger to approaching frontal systems. The most pronounced difference between the two plots is that the trough axis is more advanced in the spike composite than in the nonspike case, with the eastern high center located correspondingly farther east. In Fig. 2b, stippled areas indicate where differences between the spike and nonspike MSLP patterns are significant at a 95% confidence level on a two-tailed *t* test. The differences noted above are included in the stippled area, which extends over the eastern seaboard of Australia, including eastern Tasmania, the Tasman Sea to 160°E and 60°S (the edge of the domain considered), and areas at the head of the Great Australian Bight and waters immediately off the Western Australian coast.

A similar, though more pronounced, difference in the position of the respective composite troughs is evident in a comparison of 250-hPa wind speed plots (Fig. 3). Troughs are evident to the south of the Australian continent in both composite plots, and a wind maximum lies on the eastern flank of the trough, to the south of Tasmania. The spike composite trough (Fig. 3a) is located at 140°E and 40°S, whereas the nonspike trough (Fig. 3b) is well west, between 125° and 130°E at the same latitude. Although the nonspike 250-hPa jet core is larger than that of the spike plot, with a greater area in excess of 45 m s^{-1}, the core axis lies near 50°S. The spike wind maximum is smaller, but its axis runs over the south coast of Tasmania. The maximum value of the wind speed is similar in both composites, however: 49 m s^{-1} in the nonspike composite jet as compared with 48 m s^{-1} in the spike case. Further, the composite jet at 250 hPa is cyclonically curved for the spike events but is weakly anticyclonically curved in the nonspike case. The entrance region of the cyclonically curved jet near Tasmania is a favorable location for convergence and hence descent (Moore and Vanknowe 1992) of dry, high-momentum and high-PV air. Vertical motion at 600 hPa for the composite spike case is superimposed on the wind speed field in Fig. 3a, with red tones indicating descent and blue indicating ascent, illustrating a close alignment with the results of Moore and Vanknowe (1992). The 600-hPa vertical motion field in Fig. 3b less closely approximates the anticyclonic curvature case of Moore and Vanknowe (1992), resembling more their straight-line-jet vertical motion field. Important, however, is that the maximum of upward vertical motion at that level lies over Tasmania, which is very different from the spike case. The ascent/descent circulation in the cyclonically curved (spike) case is, in addition, likely to be stronger (by up to a factor of 2.5) than that in the anticyclonically curved (nonspike) case (Moore and Van Knowe 1992). Stippled regions again represent areas where differences between the spike and nonspike 250-hPa wind fields are significant at the 95% confidence level on a two-tailed *t* test. The stippled area encompasses the regions surrounding the jet streaks, including Tasmania, but excludes a strip immediately south and

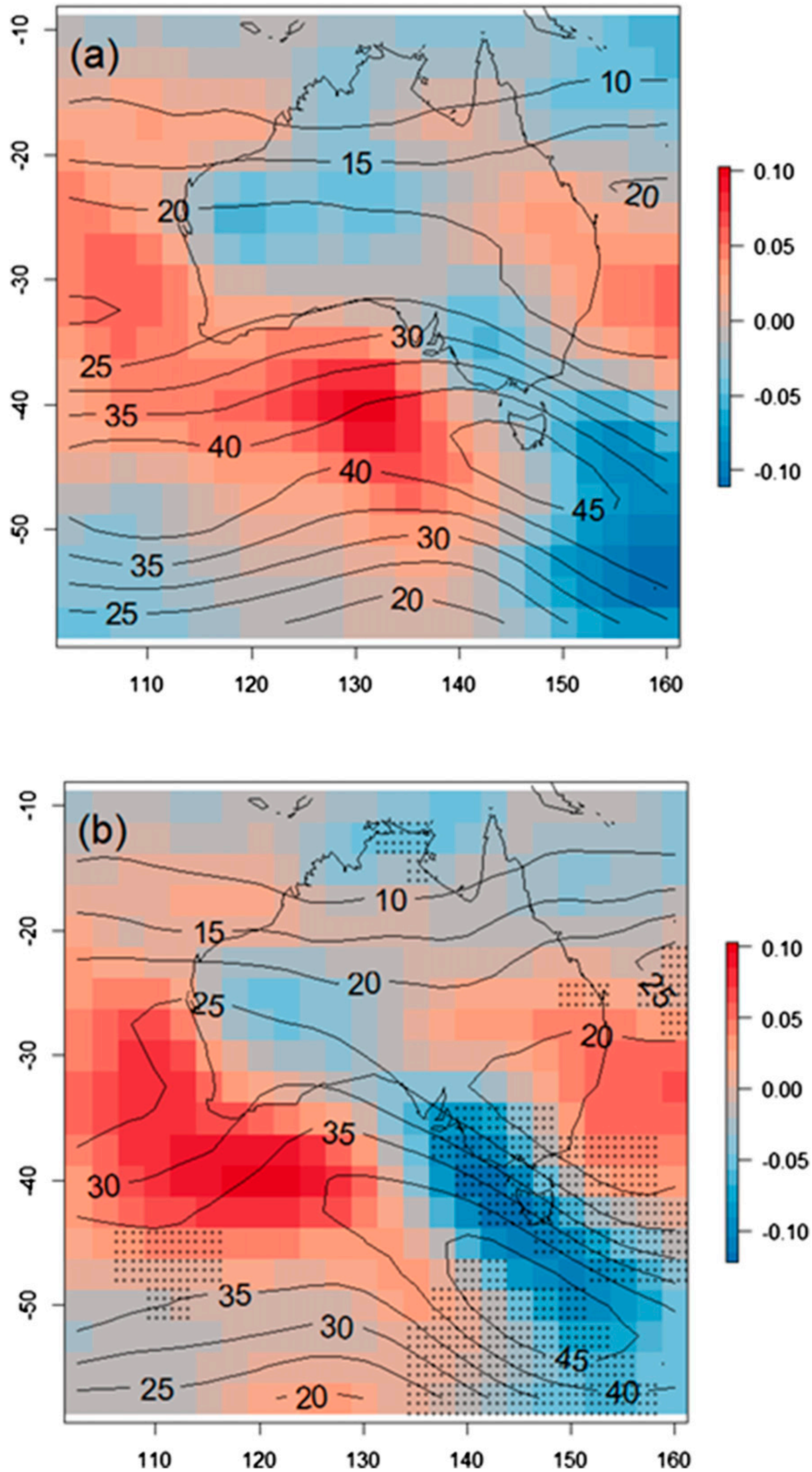

FIG. 3. Composite plots of 250-hPa wind isotachs for (a) spike and (b) nonspike fire-weather events from daily NCEP–NCAR reanalyses. Vertical motion at 600 hPa (hPa s^{-1}) is indicated in red (descent) and blue (ascent). The stippled area in (b) indicates the region where the difference between spike and nonspike composites is significant at the 95% level.

west of the island where the two composite jet streaks overlap.

It is worth investigating the evolution of the spike-event trough in a little more depth. A sequence of 6-h composite reanalysis plots at 1800, 0000, and 0600 UTC (corresponding to early morning, late morning, and mid- to late afternoon local time) on the days of spike events is displayed in Fig. 4. They show a progressive increase in asymmetry of the trough, particularly at higher latitudes, as it advances eastward toward Tasmania, to assume a ''negative'' tilt (i.e., increasing longitude of the trough axis with proximity to the equator), suggesting rapid system development and potential for severe weather due to increasing vertical circulation. Note that the increasing negative tilt of the trough near Tasmania increases the cyclonic curvature of the jet streak near the trough apex and hence the magnitude of the vertical circulations (Moore and Van Knowe 1992). Atallah et al. (2007) note a similar structure in the extratropical transition of tropical cyclones, and Speer and Leslie (2000) have documented a number of negatively tilted troughs associated with heavy-rainfall events. Macdonald (1976) and Glickman et al. (1977) describe such troughs in relation to the development of convective outbreaks. One such trough was observed, in particular, during the spike event that is documented in FH2012.

To further investigate the differences between the two types of event, composites of 0600 UTC vertical motion at 500, 700, and 850 hPa are presented in Fig. 5 for spike and nonspike events. Clear differences are apparent: at 500 hPa both composites have upward vertical motion over Tasmania, but it is weaker in the spike case and the region of descent to the west (associated with the trailing flank of the trough) is much closer to the island. In the spike composite, the area of descent slopes to the east with lower elevation so that descending air occurs over all of Tasmania at 850 hPa. The incursion of descending air in the nonspike case, if it exists at all, is much less clear, resulting in little or no descent over the state.

b. Satellite imagery

Water vapor satellite imagery was available over the region of interest from 1995 onward, with imagery available for 31 (of 37) spike events and 15 (of 25) nonspike events (see Figs. S3 and S4 in the online supplemental material). The imagery in the hours leading to peak fire danger on spike and nonspike days was examined for features that indicate dry conditions in the upper troposphere. Images were categorized as 1) having a dry band within 5° of Tasmania, 2) having an area of reduced WV within 5° of Tasmania, 3) having a dry band or area of reduced WV within 10° of Tasmania, or 4) having no evidence of reduced WV content within

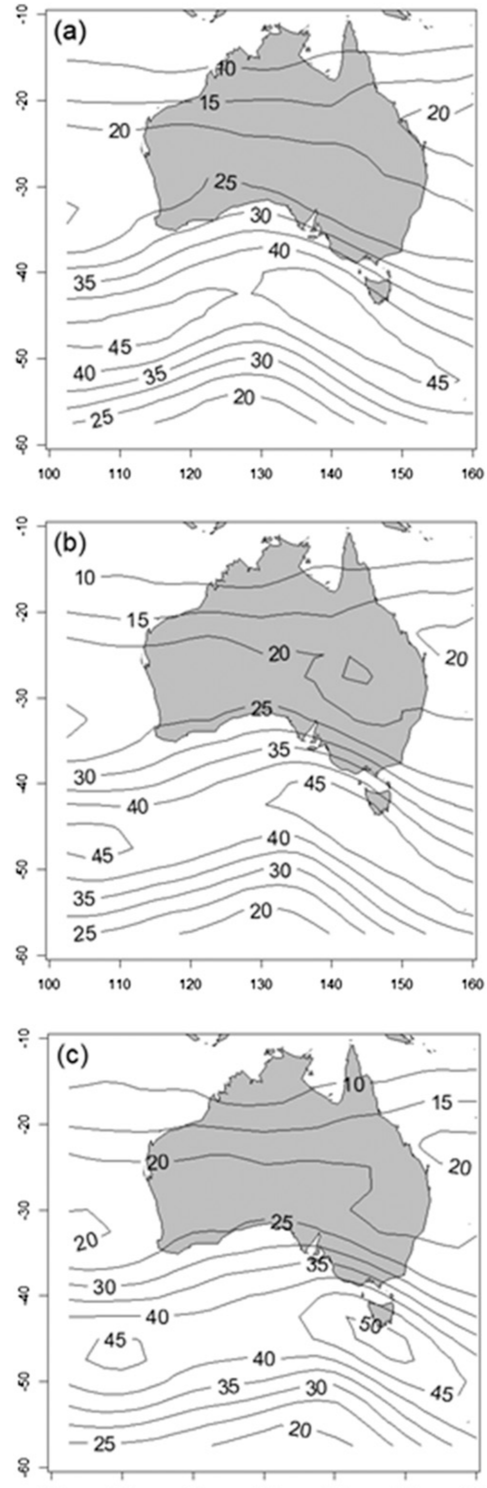

FIG. 4. Composite plots at successive 6-h intervals of NCEP–NCAR reanalysis 250-hPa wind speed at (a) 1800, (b) 0000, and (c) 0600 UTC.

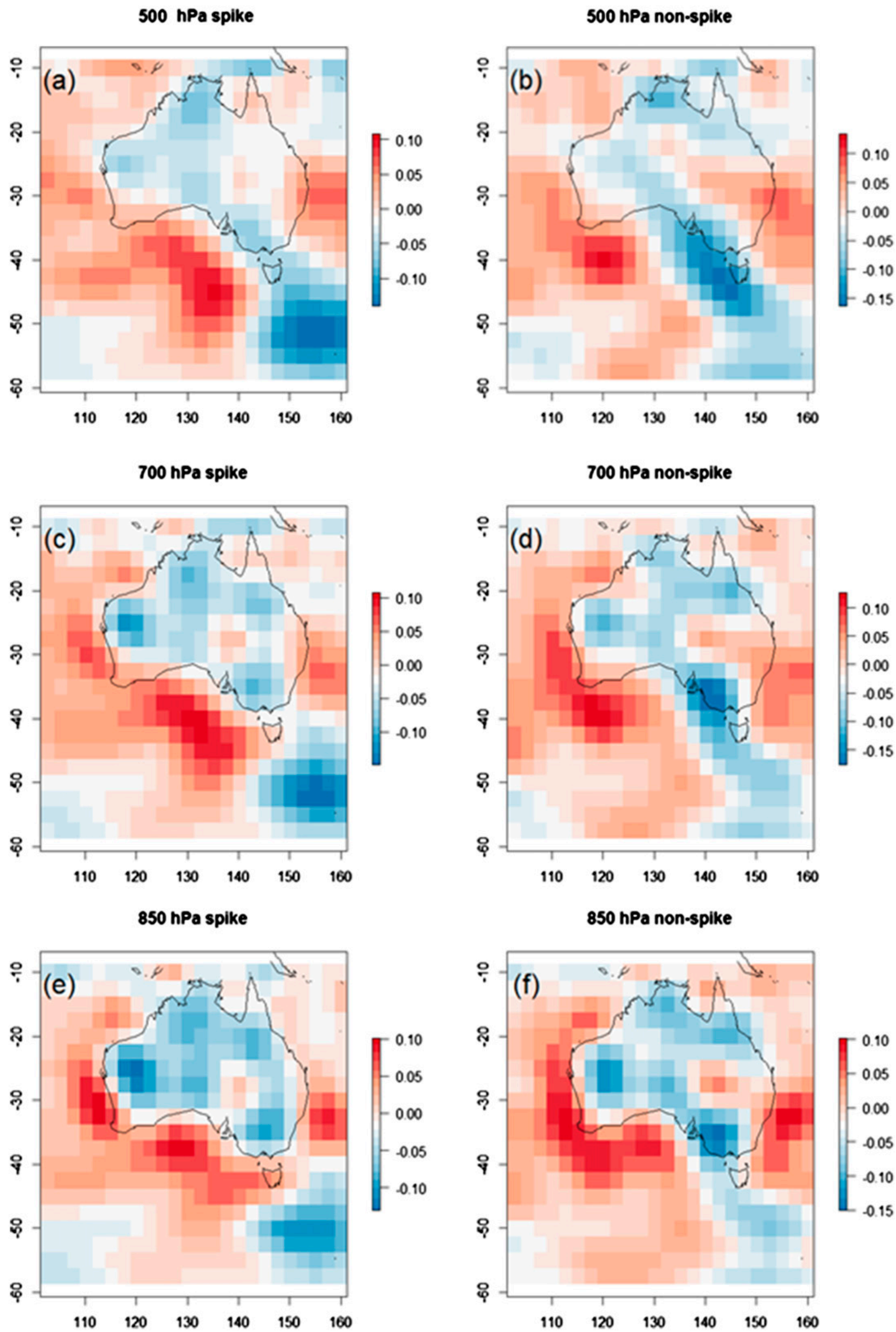

FIG. 5. Composite plots of 0600 UTC vertical motion (Pa s^{-1}) for (a),(b) 500, (c),(d) 700, and (e),(f) 850 hPa for (left) spike and (right) nonspike events. Red areas indicate descent, and blue areas indicate ascent.

TABLE 1. Satellite WV features associated with spike and nonspike events.

Nature of WV feature	No. of spike events	No. of nonspike events
Band within 5° of Tasmania	22	0
Area within 5° of Tasmania	3	8
Band/area within 10° of Tasmania	6	4
No feature within 10° of Tasmania	0	3

10° of Tasmania. Here, a "dry band" refers to a narrow, elongated region of reduced water vapor, such as is evident on 20 November 2009 to the southwest of Tasmania (Fig. S3), and an "area" is a broad region of low upper-tropospheric WV such as that visible over continental southeastern Australia and surrounding waters on 18 February 2004 (Fig. S3).

Table 1 displays the categorization: 22 spike events occurred with a dry band within 5° of Tasmania, while images corresponding to the remaining 13 events indicated an area of reduced WV within 5° of Tasmania or a dry band or area of reduced WV within 10° of Tasmania. No nonspike events had a dry band within 5° of Tasmania. There were 12 nonspike events for which WV imagery indicated an area of reduced WV within 5° of Tasmania or a dry band or area of reduced WV within 10° of Tasmania, and three events showed no evidence of reduced WV content within 10° of Tasmania.

From the above, there is little evidence to link nonspike events with dry areas in satellite water vapor imagery, especially dry bands. On the other hand, the results strongly suggest a connection between spike events and WV features indicative of dry upper-tropospheric conditions. In particular, most spike events (63%) were accompanied by a WV dry band within 5° of Tasmania, indicative of pronounced descent of high-PV upper-tropospheric or stratospheric air and supporting the evidence presented in section 3a that the structure of the composite trough and jet streak near Tasmania in the spike case was conducive to descent of upper-level air. Fire-weather events are characterized by a deep, well-mixed boundary layer, increasing the likelihood that the upper-level air evident in a dry band can reach the earth's surface and affect surface wind speed and moisture level, generating a spike in fire danger. Further, other mesoscale effects, including orographic forcing and frontal vertical circulations, can contribute to deliver air from the top of the boundary layer to the surface, as described in, for example, Mills (2008b) and FH2012.

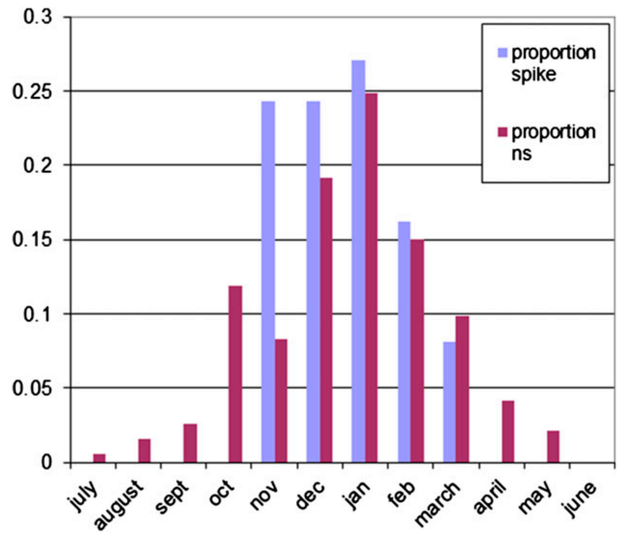

FIG. 6. Proportional annual distribution of spike events in comparison with nonspike events.

c. Seasonal distribution of spike and nonspike days

Figure 6 displays a bar plot of the proportional occurrence of spike and other fire-weather events over the period 1990–2009 of the dataset (where "other" events include all days of very high fire danger at Hobart International Airport that are not spike days, including nonspike days as defined above). Events that are not spikes are approximately normally distributed about January and occur during most months, with the exception of June. On the other hand, spike events are strongly clustered around late spring and early to midsummer. A Wilcoxon signed rank test was used to test the difference between the two distributions. The Wilcoxon signed rank test is a nonparametric test and does not assume that the two sets of observations are normally distributed. The result is significant at the $p = 0.005$ level, strongly suggesting that there is an underlying real difference between the distributions.

Spike events dominate the occurrence of dangerous fire-weather days at the observation site in late spring–early summer. A secondary springtime peak in the seasonal occurrence of fire danger has been observed in recent decades in eastern and southeastern Tasmania (Fox-Hughes 2008), and it is possible that spike events have contributed to this peak. Nine of the 37 spike events were recorded in November (the only Tasmanian springtime month that recorded spike events), and four of these events were the peak events for the corresponding fire season (7 November 2002 and 15 November 2003) or were secondary peaks for their season (13 November 1990 and 18 November 2004). Thus, spike events have contributed to the occurrence of springtime fire-danger peaks in Tasmania during the two-decade period for which data are available, but they have not been the sole mechanism involved.

One further observation relating to the seasonality of spike events is a tendency for them to cluster within a fire season. Thus, for example, during the 2003/04 fire season, some seven spike events but no nonspike events occurred (Fig. S1). On the other hand, during the 2006/07 season, five nonspike events but no spike events occurred. Other seasons, however, experience both (e.g., 2009/10), and so the tendency toward spike or nonspike events is not exclusive. It does seem that there may be a climatological influence operating, which is worthy of further investigation but is outside the scope of the current study.

d. Applicability of results to other locations

The presence of negatively tilting upper-tropospheric troughs on days already forecast to be dangerous fire-weather days may be a useful indicator of the potential for abrupt increases in fire danger. It is of interest to assess whether this approach is applicable in other geographic locations. It is beyond the scope of this paper to perform this assessment in a rigorous fashion, but a preliminary investigation of the upper-trough structure in previously documented events is worthwhile. Figure 7 presents 300-hPa geopotential height plots for the dates and areas of events mentioned earlier in this article. In each case, there is a clearly defined negatively tilting trough present. In Fig. 7a, a negatively tilting trough is evident south of the Australian continent on 18 January 2003, the date of the devastating Canberra (Australian Capital Territory) fires (McLeod 2003; Mills 2005). A similar, but more pronounced trough can be seen in Fig. 7b, corresponding to the Wangary, South Australia, fire (Mills 2008a). In the Northern Hemisphere, a negatively tilted trough extended from central northern Canada to the northeastern United States (Fig. 7c) on the date of the Double Trouble State Park fire in New Jersey (Charney and Keyser 2010; Kaplan et al. 2008), in which erratic fire behavior accompanied rapid surface drying and gusty winds. In this event, dry-air descent followed the frontal passage rather than being ahead of it. Similar events are described in Mills (2008a,b), Browning (1997), and Danielsen (1964). On the date of the Mack Lake fire in Michigan (Zimet et al. 2007), another such trough lay just off the Pacific coast of the United States (Fig. 7d), with a further developing negatively tilted trough extending from the Canadian Arctic over the Great Lakes region. The rapid growth of forest fires in northeastern Japan on 27 April 1983 (Kondo and Kuwagata 1992) was accompanied by a negatively tilted trough in the upper troposphere (Fig. 7e). These examples strongly suggest that the results discussed above could be considered at other locations.

4. Conclusions

On the basis of the above synoptic analysis, it is more likely in spike events than in nonspike events that air will be transported from the upper troposphere to the surface, via the ageostrophic circulations associated with jet-stream cores coupled with turbulent mixing in a deep convective boundary layer [as described in, e.g., Kaplan et al. (2008)]. Further, the negative tilt of the upper-level trough in spike events tends to more tightly focus vertical motions near to the trough (i.e., close to Tasmania) than is the case in positively or neutrally tilted troughs associated with nonspike events (Bluestein 1993), at a time of day (mid- to late afternoon) when the mixed layer is likely to be deepest and most able to couple to overlaying layers of the troposphere. Available WV imagery reinforces this conclusion, with a majority of spike events being associated with WV dry bands and reduced upper-tropospheric WV content close to Tasmania evident at the time of all other spike events. A much weaker association exists between WV-image features and nonspike events.

A marked difference in seasonality between spike and nonspike events is interesting and potentially useful for meteorologists and fire managers. The basis for the difference, however, is not currently clear. It may relate to the seasonality of negatively tilting troughs in the Australian region, but this hypothesis awaits further exploration.

The differences evident between the synoptic patterns associated with fire-weather events characterized by abrupt spikes in fire danger at Hobart International Airport and those events lacking such features can be used by meteorologists to assist in the forecasting of fire-danger spikes well in advance of the commencement of the events. A brief assessment of the nature of the upper trough associated with other documented cases of abrupt increase in fire danger is encouraging but does not constitute confirmation of the generality of the technique. It will be necessary to ensure that these results can be robustly generalized to other locations, of course. If that is possible, the technique is likely to be a useful tool to highlight situations conducive to the occurrence of a dangerous phenomenon. Thus, the method provides an immediate tool for Tasmanian fire-weather meteorologists, with the potential to extend its use to other parts of the globe.

Acknowledgments. Reanalysis plots and data were provided by the NOAA/ESRL/Physical Sciences Division (http://www.esrl.noaa.gov/psd/). Hobart International

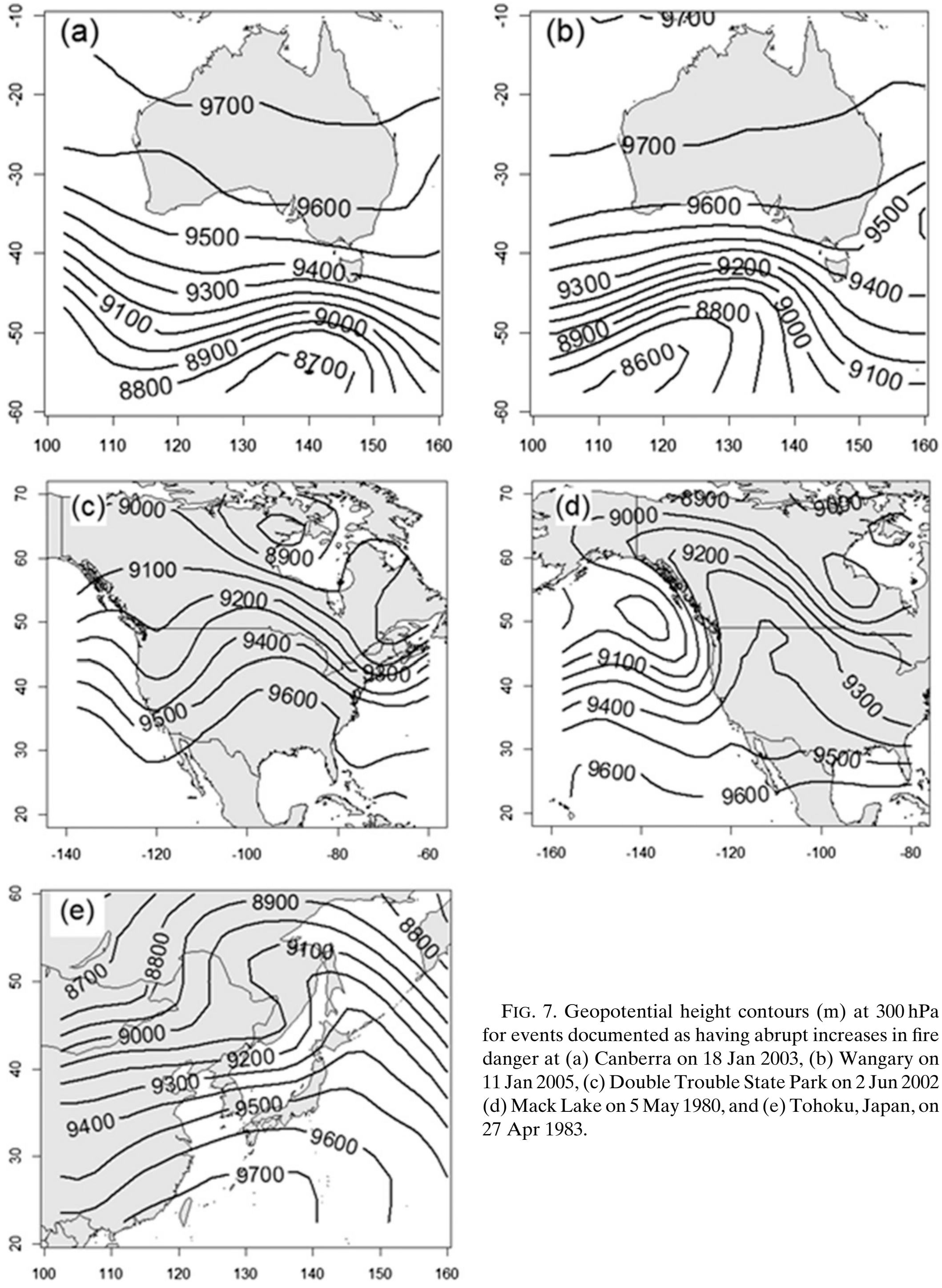

FIG. 7. Geopotential height contours (m) at 300 hPa for events documented as having abrupt increases in fire danger at (a) Canberra on 18 Jan 2003, (b) Wangary on 11 Jan 2005, (c) Double Trouble State Park on 2 Jun 2002 (d) Mack Lake on 5 May 1980, and (e) Tohoku, Japan, on 27 Apr 1983.

Airport observations were obtained from the Australian Bureau of Meteorology's ADAM (Australian Data Archive for Meteorology) database, and MSLP analyses were obtained from the Bureau of Meteorology National Operations Centre (formerly the National Meteorological and Oceanographic Centre). Helpful reviews and comments on the content of this paper were made by Graham Mills, Mike Pook, and Kevin Tory of the Centre for Australian Weather and Climate Research. The often detailed comments of the anonymous reviewers were very helpful in clarifying the arguments presented in the manuscript, and in flagging some errors.

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