AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL064018

Key Points:
- Definition of flash drought
- Flash droughts are in decline
- Droughts occur less often and cover smaller areas

Supporting Information:
- Texts S1 and S2 and Figures S1–S3

Correspondence to:
K. C. Mo,
kingtse.mo@noaa.gov

Citation:
Mo, K. C., and D. P. Lettenmaier (2015), Heat wave flash droughts in decline, *Geophys. Res. Lett.*, *42*, 2823–2829, doi:10.1002/2015GL064018.

Received 30 MAR 2015
Accepted 30 MAR 2015
Accepted article online 3 APR 2015
Published online 24 APR 2015

Heat wave flash droughts in decline

Kingtse C. Mo[1] and Dennis P. Lettenmaier[2]

[1]Climate Prediction Center, NCEP/NWS/NOAA, College Park, Maryland, USA, [2]Department of Geography, University of California, Los Angeles, California, USA

Abstract Flash drought is a term that was popularized during rapidly evolving droughts in the Central U.S. in 2012 that were associated with heat waves. We posit that there are two kinds of flash droughts, and we will focus on heat wave flash droughts, of which the 2012 events were typical. We find, based on an analysis of temperature observations and model-reconstructed soil moisture (SM) and evapotranspiration from 1916 to 2013, that heat wave flash droughts in the conterminous U.S. (CONUS) are most likely to occur over the Midwest and the Pacific Northwest during the growing season. We also find that the number of such events across the CONUS has been decreasing over the last century but rebounded after 2011. The long-term downward trends appear to be associated with generally increasing trends in SM resulting from increasing trends in precipitation over the areas where heat wave flash droughts are most likely to occur.

1. Introduction

Flash drought is a term that was popularized during the rapid onset of the Central U.S. drought in May and early June 2012. Once established, the 2012 event continued in a manner similar to conventional more slowly evolving droughts through the end of summer. There is a general sense that some flash droughts follow the pattern of the 2012 event: decreases in soil moisture associated with anomalously high temperatures and increases in actual (as contrasted with potential) evapotranspiration (ET) [*Hunt et al.*, 2008].

We hypothesize that there are two kinds of flash droughts. In the first kind, which we term heat wave flash droughts, high temperatures cause ET to increase and lead to deceases of soil moisture (SM). Precipitation plays an important role, but P anomalies do not initiate this type of flash drought. In the second kind, which we term precipitation deficit flash drought, lack of P causes ET to decrease and temperature to increase. The two types of flash droughts are initiated and maintained by different physical mechanisms. In this paper, we focus on heat wave flash droughts.

The manifestations of heat wave flash droughts, which are most apparent in agricultural areas, include withering of crops that can accompany the rapid onset of these events. Economic losses to crops and livestock from these events have been reported in the billions of $US [*Wallander et al.*, 2012; U.S. Department of Agriculture Risk Management Agency (http://www.rma.usda.gov/data)]. Even though flash drought has been used to describe rapidly evolving short-term drought, there is no universally accepted definition. Because flash droughts evolve rapidly, there is often no early warning to the agricultural community and hence no opportunity to mitigate losses. For example, the U.S. Drought Monitor [*Svoboda et al.*, 2002] did not capture the 2012 event until late June. There is also interest in flash droughts from the perspective of climate change; while the 2012 drought appears to have resulted from natural variability, the probability of severe droughts in the Great Plains may be increasing [*Hoerling et al.*, 2014]. Remotely sensed thermal infrared imagery is able to detect sudden changes in ET [*Otkin et al.*, 2013, 2014] and has the potential to provide early warnings of flash droughts. Satellite imagery increases the awareness of flash droughts. There is a question though as to whether flash droughts have been occurring more often in the recent past. Here we offer a definition of heat wave flash drought and examine long-term trends in their occurrence.

There is a consensus from many studies that P has increased over most of the conterminous U.S. (CONUS) excepting the Southwest over the last century [*Lettenmaier et al.*, 1994; *Groisman et al.*, 2004]. However, while P is a key driver of meteorological drought, soil moisture (SM) is the proximate determinant of both agricultural and hydrological drought. Unfortunately, there are few long-term SM observations. It is possible, however, to reconstruct SM using land surface models (LSMs) driven by carefully quality controlled surface forcings [*Maurer et al*., 2002; *Wang et al*., 2009]. Here we used gridded P and T_{air} daily forcings derived from a set of 2400 index stations distributed across the CONUS with records that go back almost a century. We used the daily gridded forcings to drive four LSM-predicted SM and ET. The index stations were selected so as to avoid false trends due to changes in station coverage and record lengths to the extent possible consistent with forming a record of 98 years in length. *Andreadis and Lettenmaier* [2006] used an earlier version of the same gridded data to examine drought trends and found that reconstructed SM generally had overall upward trends over much of the CONUS over the period of 1915–2003. Here we examine trends in heat wave flash droughts and explore their causes.

2. Data Sets

We used archived output from the University of Washington Surface Water Monitor [*Wang et al*., 2009]. The gridded daily P and T_{air} derived from approximately 2400 index stations were used to drive the four LSMs, from which total column (depth varies but typically around 1 m) SM as well as ET were taken. All models computed ET using the Penman-Monteith formula but with different parameters. The four LSMs are VIC 4.0.6, Noah 2.8, Sacramento/Snow 17 (SAC), and Catchment. Model descriptions can be found in *Wang et al*. [2009]. The data sets cover the base period from 1916 to 2013. The horizontal resolution is 0.5°. We used pentads (5 day means) to capture the short duration of flash droughts. We computed pentad mean climatologies for the base period for each model and each variable. We defined anomalies as departures from the climatology during the base period.

3. Frequency of Occurrence of Heat Wave Flash Drought

Heat wave flash drought is agricultural drought in nature, so we use SM (expressed as a percentile relative to its long-term record, SM%) as an indicator instead of P. Soil moisture measurements over the Midwest suggest that heat wave flash droughts occur mostly in the growing season [*Hunt et al*., 2008], so we focused on pentads from April to September when vegetation coverage is dense, hence 36 pentads per year. Over our 98 year period of record, there were $N_{total} = 3528$ pentads. In the supporting information, we consider four different scenarios for heat wave flash droughts. The definition we adopted here is that (a) T_{air} anomaly is greater than 1 standard deviation (SD) computed from the base period for that pentad, (b) ET anomaly is >0, and (c) SM% < 40. Heat wave flash droughts are temperature driven, so we require the T_{air} anomaly to exceed 1 standard deviation. High temperature increases the total ET, so we require ET anomalies to be positive. It is agricultural drought, so we also require SM% < 40. Even though there is no explicit criterion for P, negative P anomalies before the onset are usually needed to bring down SM anomalies to satisfy the SM requirement.

For each pentad and each grid point, a flash drought event was identified when all above requirements were satisfied. The first pentad in which all conditions were met was defined as onset. For each grid point, we computed the total number of pentads N under heat wave flash drought over the entire record for each model. We defined the frequency of occurrence (FOC) as the percent of pentads under heat wave flash drought (N/N_{total}) for each grid cell. We then computed the ensemble mean FOC by averaging over the four models.

Figure 1a shows the ensemble mean FOC for heat wave flash droughts across the CONUS. Heat wave flash droughts do not occur often; the maximum FOC is on average only 4–5% of the total record. They are most likely to occur over the Midwest, with a smaller secondary maximum in the Pacific Northwest. The Midwest maximum is located along a band from Iowa to Indiana that more or less coincides with the Corn Belt where vegetation coverage is dense during the growing season. There are few events over the Southwest, the Southern Great Plains, and the western interior region where vegetation is sparse.

P is not one of requirements for heat wave flash drought because agricultural drought is defined based on SM deficits. Figure 1b shows the composite of P anomalies for pentads under heat wave flash drought averaged over four models. It shows that P anomalies are negative over the areas where heat wave flash droughts are most likely to occur. To satisfy SM% below 40, the P anomalies are almost always negative. Therefore, there is no need to specify P anomalies as a condition. If we change the criteria to $T_{air} > 1$ SD, ET anomaly > 0, and P anomaly < 0, then the pattern of the FOC does not change but the number of events

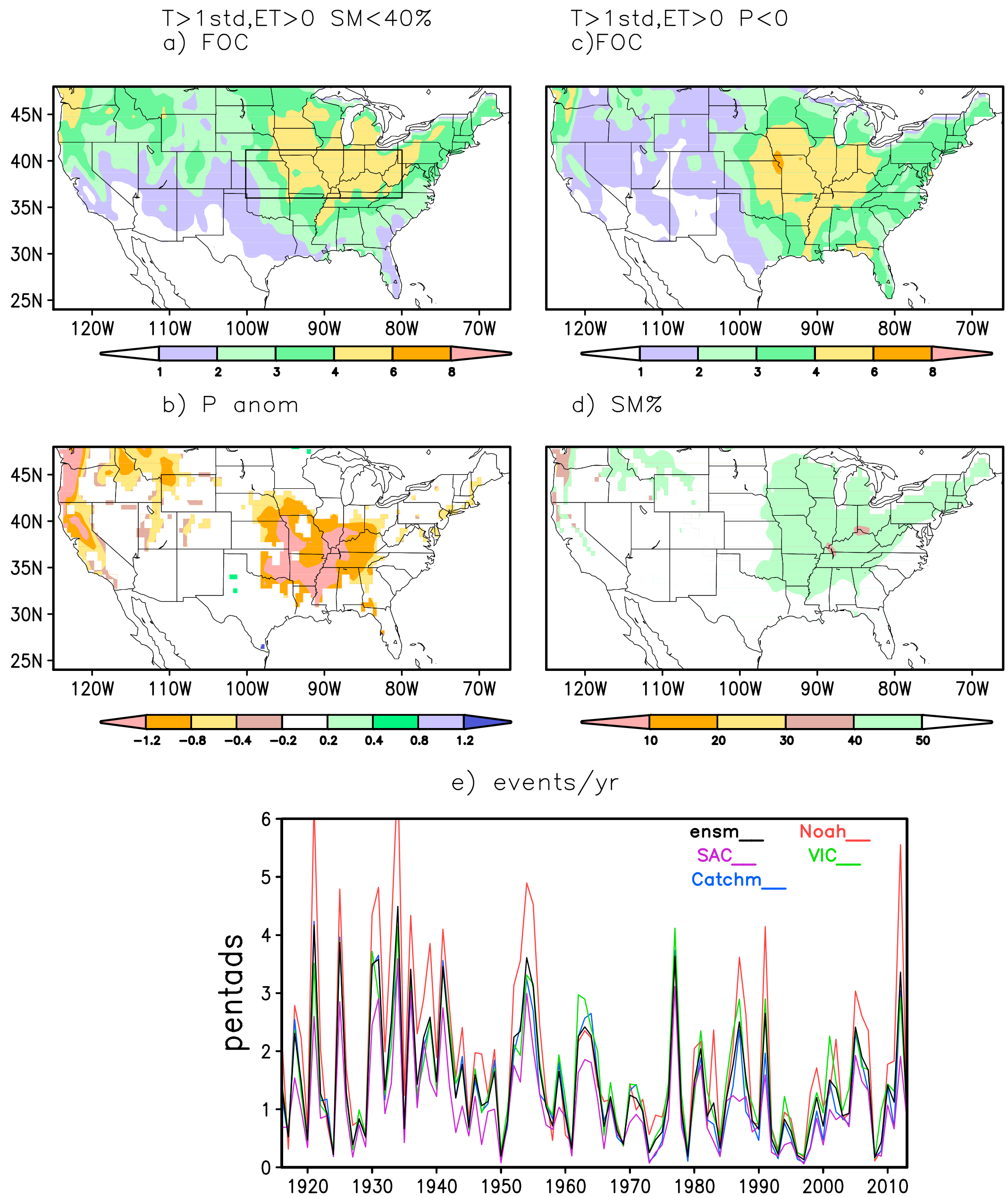

Figure 1. (a) Ensemble mean frequency of occurrence (FOC) of pentads under heat wave flash droughts. Heat wave flash drought is defined as $T_{air} > 1$ standard deviation (SD), ET anomaly > 0, and SM% < 40. Contours are given by the color bar. The unit is in percent. (b) Composite of P anomalies for pentads under heat wave flash drought defined in Figure 1a. Contours are given by the color bar. Unit is in mm d^{-1}. (c) Same as Figure 1a but heat wave flash drought is defined as $T_{air} > 1$ SD, ET anomaly > 0, and P anomaly < 0. (d) Composite of SM% for pentads under heat wave flash drought defined in Figure 1c. Unit is in percent. (e) Number of pentads under heat wave flash drought per year averaged over the box (36–42°N, 80–100°W) for ensemble mean and each model.

increases; in particular, the maxima increase to about 6–7% of the total pentads. The composite of SM% indicates that the SM% over the areas of frequent heat wave flash drought occurrence is greater than 40, which is too high to be classified as agricultural drought. If we increase P threshold to P anomaly < -1 SD, the FOC magnitude decreases to 5%, but SM% is still above 40. In the supporting information, we examine the sensitivity of FOC and composites of P and SM% to the definitions by changing the SM% criterion (Figure S1 in the supporting information). The pattern of the FOC is always the same because heat wave flash droughts are associated with vegetation coverage. The magnitudes of FOC differ. The *P* anomaly composites for all cases indicate deficits over the areas where heat wave flash droughts are likely to occur.

We require a heat wave flash drought event to meet all three conditions ($T_{air} > 1$ SD, ET anomaly > 0, and SM $\% < 40$). According to our definition, heat wave flash drought has a rapid onset because heat waves occur suddenly (supporting information). They also do not persist because T_{air} and ET anomalies do not persist even though SM anomalies tend to persist longer. Only 55–60% (30–35%) of heat wave flash droughts persist for one (two) pentad(s). However, once an event is established, SM percentiles can remain below 30–40% for 4–5 pentads after the T_{air} and ET requirements cease to be met (Figure S3 in the supporting information).

4. Trends in Heat Wave Flash Droughts

To give an example of interannual variability, we plotted in Figure 1e the number of pentads under heat wave flash drought averaged over the box (36–42°N, 80–100°W) per year averaged over the growing season (Figure 1a) for each model along with the ensemble mean. Modest changes in the location of the box do not change the conclusion. There are differences among models, but overall, they all show downward trends until 2011. Most noticeable is that there were many more events from 1920 to 1945 than later in our period of analysis. The number of events reached a minimum from 1965 to 1972. Then the number increased slightly in the 1980s, but it decreased again in the recent past (1990–2009).

To determine trends in the occurrence of heat wave flash droughts, we applied the Mann Kendall test [*Hirsch et al.*, 1982; *Hirsch and Slack*, 1984] to the time series of the total number of pentads under flash drought each year for grid cells for which the ensemble mean FOC is larger than 1% for each model. Figure 2a indicates areas where trends are statistically significant for all models. There are differences among the models (not shown), but they all indicate downward trends in the total number of pentads under heat wave flash drought per year; there were no statistically significant upward trends. Similar to trends in conventional drought over the CONUS domain [*Andreadis and Lettenmaier*, 2006], heat wave flash droughts generally occurred less often in recent decades. It should be noted that the relative large number of events early in our period of analysis (through the 1930s) contributed substantially to the trends.

5. Attribution of Trends

Are trends in the total number of heat wave flash drought occurrence related to trends in the forcings such as T_{air} and *P*? We performed the Mann Kendall test on T_{air} averaged from April to September during the base period (Figure 2c). The signature of upward trends over the West and downward trends in the Southeast is evident, and it is consistent with temperature trends from 1948 to 1988 [*Lettenmaier et al.*, 1994]. However, there are few statistically significant trends in T_{air} over the areas where flash drought events are most likely to occur. Kendall's tau between the total number of pentads under heat wave flash drought per year and T_{air} averaged from the growing season is not statistically significant (not shown). This suggests that the trends in heat wave flash drought occurrence are *not* associated with trends in T_{air}.

Next, we tested relationships between trends in *P* and SM and trends in heat wave flash drought occurrence. The Mann Kendall test for *P* averaged over the growing season (April–September) indicates that there are increasing trends in *P* in the places where heat wave flash drought is most likely to occur (Figure 2b), consistent with previous studies [*Lettenmaier et al.*, 1994; *Groisman et al.*, 2004]. The pathway for *P* to influence the occurrence of heat wave flash drought events is through SM because *P* is the major forcing driving SM. There are increasing trends in SM anomalies averaged from April to September for all models as indicated by Figure 2d. To evaluate the linkages between trends in the number of pentads under heat wave flash drought and SM averaged over the growing season, we computed Kendall's tau between them for each model. Figure 2e shows Kendall's tau averaged over the four models. Tau is negative over the regions where heat wave flash drought events are most likely to occur. Over the North Central region and the Ohio basin, tau is between -0.3 and -0.5. These negative correlations suggest that the decreasing trends in the occurrence of heat wave flash drought events are associated with wetter (upward) trends in SM.

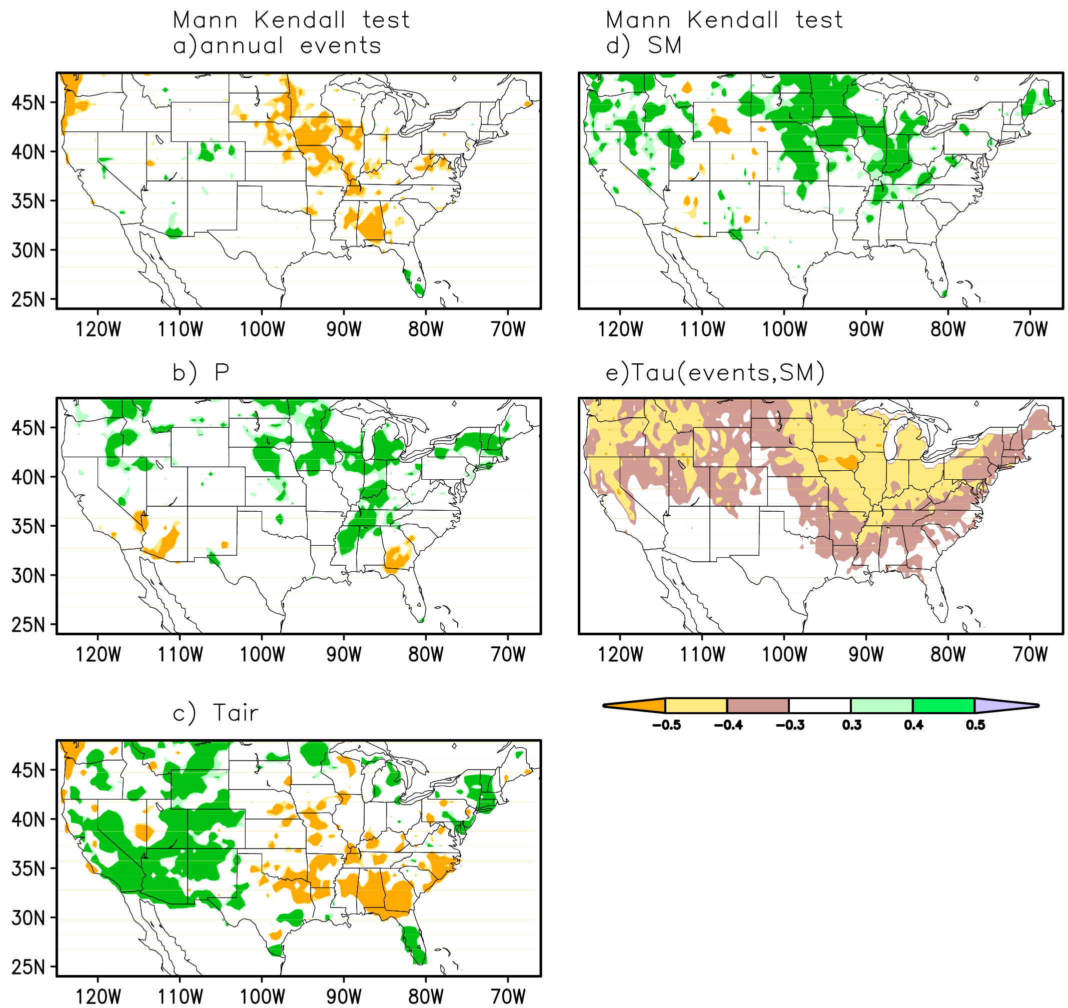

Figure 2. (a) Trends in the number of pentads per year under heat wave flash drought. Trends which are statistically significant at the 5% level determined by the Mann Kendall test for all four models (VIC, SAC, Noah, and Catchment) are colored. Orange indicates downward trends, and green indicates upward trends. Areas where trends are not statistically significant at the 5% level are white. (b) Same as Figure 2a but for trends in *P* mean from April to September. (c) Same as Figure 2b but for T_{air}. (d) Same as Figure 2a but for SM anomalies for all four models and (e) Kendall's tau between the total number of pentads under heat wave flash drought per year and SM mean anomalies over growing season averaged over four models. Magnitudes are indicated by color bar, which are statistically significant at the 5% level.

6. Physical Mechanisms for Trends in Heat Wave Flash Drought

Heat wave flash droughts are temperature driven, but trends in the number of heat wave flash drought events per year are linked to SM and *P* rather than T_{air} (Figure 2). What are the relationships between heat wave flash droughts and SM or *P*? Heat wave flash droughts are caused by high temperatures. High temperature causes ET to increase because of the response from vegetation. The increased ET results in increases in SM deficits. This mechanism can occur irrespective of the *P* forcing; high temperature can cause SM to drop. However, the decreases in SM anomalies are not large. Figure 3a shows that the composite of SM changes due to high-temperature events ($T_{air} > 1$ SD and ET anomaly > 0) between the onset pentad and one pentad before without the SM% requirement. It is compared to the composite of SM anomalies for the onset pentads under heat wave flash drought ($T_{air} > 1$ SD, ET anomaly > 0, and SM $\% < 40$). We computed composites for each model separately and averaged over all four models. Statistical significance was assessed based on the Student's *t* test; areas where anomalies are statistically significant at 5% level are shaded.

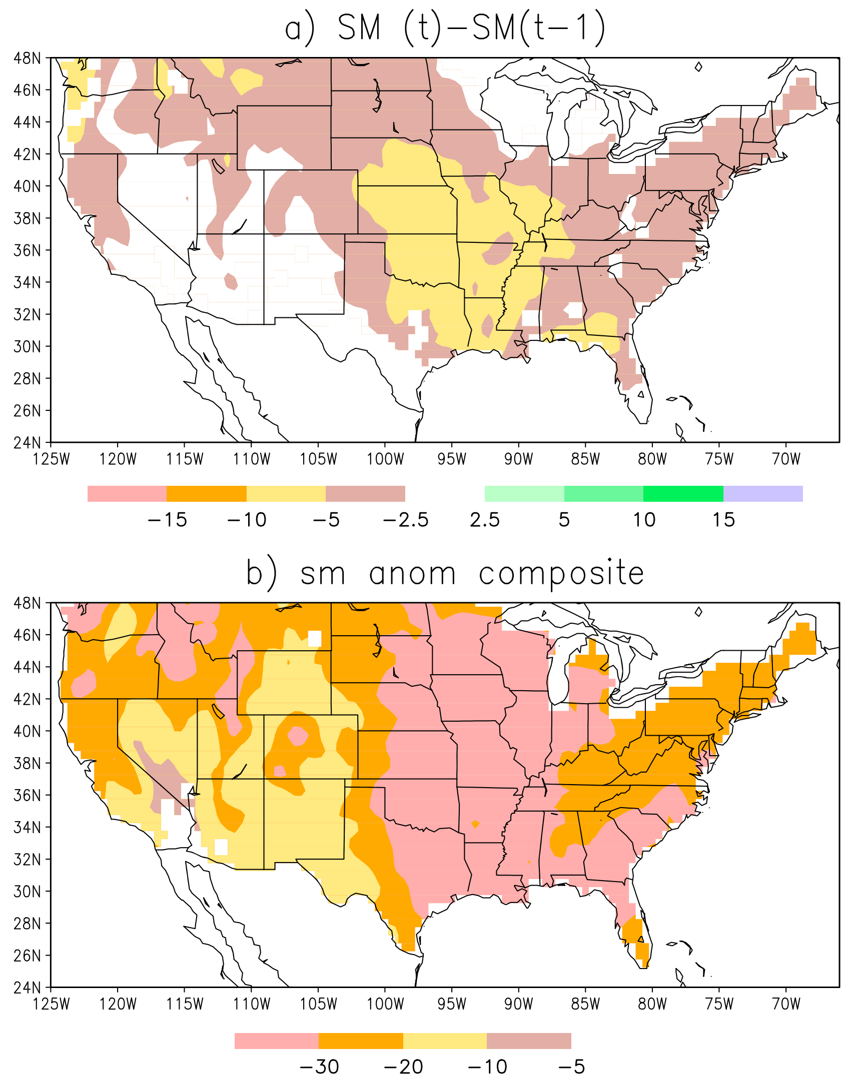

Figure 3. (a) Composite of SM change due to high-temperature events ($T_{air} > 1$ SD and ET anomaly > 0) between the onset pentad and one pentad before averaged over all events and averaged over four models, in millimeter. Contour intervals are given by color bar, which are statistically significant at 5% level. (b) Same as Figure 3a but SM anomalies under heat wave flash drought defined as $T_{air} > 1$ SD, ET anomaly > 0, and SM% < 40).

The composite SM anomaly for pentads under heat wave flash drought indicates that the SM deficits needed for these events to occur are on the order of 20–30 mm (Figure 3b). However, the decreases in SM due to heat waves ($T_{air} > 1$ SD and ET anomaly > 0) are only about 5–10 mm over the areas of flash drought occurrence (Figure 3a) which may not be large enough to push the total SM deficits below the 40% to be classified as drought. Therefore, SM deficits before the onset are needed for the occurrence of heat wave flash drought, in addition to the SM reduction associated with the high temperature that initiates the events. The lack of *P* before the onset of heat wave flash drought is needed to increase the SM deficits and makes the conditions more favorable for such events to occur. In this sense, *P* plays an important role in enhancing the possibility of heat wave flash drought occurrence. The implication is that to monitor flash drought, SM anomalies as well as changes in ET and *P* must be monitored.

7. Discussion and Conclusions

Heat wave flash droughts are characterized by high temperatures, rapidly decreasing SM due to increased ET at the onset of events when SM is already in deficit. They occur suddenly with little warning. Because these events are characterized by SM deficits, they fall within the category of agricultural drought and are most likely to occur over the Farm Belt in the Midwest in the growing season. High temperatures and SM depletion can cause severe damage to crops, with economic losses in the billions.

The 2012 flash drought and the advent of satellite observations brought greater awareness to flash droughts and perhaps an impression that they have been increasing. Our work shows, however, that heat wave flash droughts have been decreasing in frequency over the 20th and early 21st century. For instance, the frequency of occurrence of heat wave flash droughts was highest in the 1920s through 1940s and was lower in the periods 1960–1972 and 1991–2006, although they increased again after 2011. This decline is linked to increasing trends in P and generally increased growing season SM in the heat wave flash drought occurrence areas.

Acknowledgments
This project was supported by NOAA grant GC14-189A to the NOAA Climate Prediction Center and by grant NA14OAR4310293 to the University of California, Los Angeles. The data from the LSM used in this paper will be available by contacting Kingtse Mo (e-mail: kingtse.mo@noaa.gov).

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Andreadis, K. M., and D. P. Lettenmaier (2006), Trends in 20th century drought over the continental United States, *Geophys. Res. Lett.*, *13*, L10403, doi:10.1029/2006GL05721.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore (2004), Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations, *J. Hydrometeorol.*, *5*, 64–85.

Hirsch, R. M., and J. R. Slack (1984), A nonparametric trend test for seasonal data with series dependence, *Water Resour. Res.*, *20*, 727–732, doi:10.1029/WR020i006p00727.

Hirsch, R. M., J. R. Slack, and R. A. Smith (1982), Techniques of trend analysis for monthly water quality data, *Water Resour. Res.*, *18*, 107–121, doi:10.1029/WR018i001p00107.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager (2014), Causes and predictability of the 2012 Great Plains drought, *Bull. Am. Meteorol. Soc.*, *95*, 269–282.

Hunt, E. D., K. G. Hubbard, D. A. Wilhite, T. Arkebauer, and A. L. Dutcher (2008), The development and evaluation of a soil moisture index, *Int. J. Climatol.*, doi:10.1002/joc.1749.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis (1994), Hydro-climatological trends in the continental United States, 1948–1988, *J. Clim.*, *7*, 586–606.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long term hydrologically based dataset of land surface fluxes and states for the conterminous United States, *J. Clim.*, *15*, 3237–3251.

Otkin, J. A., M. C. Anderson, C. Hain, I. E. Mladenova, J. B. Basara, and M. Svoboda (2013), Examining rapid onset drought development using the thermal infrared based evaporative stress index, *J. Hydrometeorol.*, *14*, 1057–1074.

Otkin, J., M. C. Anderson, C. Hain, and M. Svoboda (2014), Examining the relationship between drought development and rapid changes in the evaporative stress index, *J. Hydrometeorol.*, *15*, 938–956.

Svoboda, M., et al. (2002), The drought monitor, *Bull. Am. Meteorol. Soc.*, *83*, 1181–1190.

Wallander, S., M. Aillery, D. Hellerstein, and M. Hand (2012), The role of conservation programs in drought risk adaptation, Economic Research Service. [Available at http://www.ers.usda.gov/publications/err-economic-researchreport/err148.aspx.]

Wang, A., T. J. Bohn, S. P. Mahanama, R. D. Koster, and D. P. Lettenmaier (2009), Multi model reconstruction of drought over the continental United States, *J. Clim.*, *22*, 2684–2712.