Precipitation Deficit Flash Droughts over the United States

Kingtse C. Mo

Climate Prediction Center

NCEP/NWS/NOAA

and

Dennis P Lettenmaier

Department of Geography

University of California, Los Angeles

Corresponding author: Kingtse Mo, Climate Prediction Center, NCEP/NWS/NOAA,

5830 University Research Ct, College Park, MD 20740,

Email: Kingtse.mo@noaa.gov

Abstract

Flash drought refers to relatively short periods of warm surface temperature and anomalously low and rapid decreasing soil moisture (SM). Based on the physical mechanisms associated with flash droughts, we classify these events into two categories: heat wave and precipitation (P) deficit flash droughts. In previous work, we have defined heat wave flash droughts as resulting from the confluence of severe warm air temperature, which increases evapotranspiration (ET), and anomalously low and decreasing soil moisture (SM). We explore here a second type of flash droughts caused by precipitation deficits. We term these events P deficit flash droughts, which we associate with lack of P, which causes ET to decrease and temperature to increase. P deficit flash droughts are more common than heat wave flash droughts. We analyze P deficit flash droughts based on observations of P and SM and ET reconstructed using land surface models for the period 1916 to 2013. We find that P deficit flash droughts are about twice as likely to occur as heat wave flash droughts averaged over the conterminous U.S. (CONUS). They are most prevalent over the southern United States with maxima over the Southern Great Plains and the Southwest, in contrast to heat wave flash droughts which are mostly likely to occur over the Midwest and the Pacific Northwest where the vegetation cover is denser.

1. **Introduction**

During spring 2012, high temperature and severe depletion of soil moisture (SM) occurred suddenly over the agricultural heartland of the U.S. Midwest, and withered recently planned crops in a matter of days. The relatively short period of intense warm air temperature (T_{air}) and anomalously low and declining soil moisture (SM) was termed flash drought following Senay et al. (2008) and Hunt et al. (2008); a term that had not previously been widely used, and for which there was no accepted definition. This event was also detected by remote sensing (using the evaporative stress index; ESI); (Otkins et al. 2013, 2014, Anderson et al. 2011, and Anderson et al. 2013). The 2012 spring event was evidenced by rapid increases in evapotranspiration (ET). The early detection and severity of the 2012 event lead to an increasing awareness of flash drought.

In previous work (Mo and Lettenmaier, 2015), we labelled flash droughts with characteristics similar to the 2012 event as heat wave flash droughts because such events are initialized by heat waves, which in turn lead to increased ET and reduced SM. Accordingly, we suggested a definition for heat wave flash droughts which includes anomalously high temperatures (T_{air}> 1 standard deviation (SD)), increases of ET (ET anomaly>0) and soil moisture deficits (SM % < 40%). We also hypothesized (but did not explore) another kind of flash drought which is initialed by the lack of Precipitation (P).

Yang (2013), in a study of the 2011 Texas drought, referred to the sudden occurrence of heat waves and rapid reduction in SM in June 2011 as a flash drought. We argue that the 2011 Texas drought had characteristics that are fundamentally different from what we refer to as heat wave flash drought. Myoung and Nielsen-Gammon (2010a, 2010b) investigated the physical mechanisms responsible for the 2011 Texas drought. They found that the P deficits existed prior to the onset of the drought. We refer to this type of drought as P deficit flash drought because the lack of SM was caused primarily by P deficits which were responsible for (rather than caused by) the onset of heat waves. There are other cases of P deficit flash droughts. For example, Lyon and Dole (1995) studied the 1980 and 1988 heat waves over the central United States. They described these events as drought induced. Atmospheric circulation anomalies initialized the establishment of heat waves, but the lack of P and SM prolonged the events.

Both heat wave and P deficit flash droughts are characterized by high temperatures and SM deficits. However, they are caused and maintained by different physical mechanisms and have different characteristics. Most previous studies of heat waves and droughts have been regional in nature (Chang and Wallace 1987), and therefore are difficult to generalize. We attempt here to give a general definition and to examine characterization that should improve our ability to monitor and provide early warning of intense flash drought conditions, and potentially to mitigate them. We first revisit the definition of heat wave flash drought and suggest a definition for P deficit flash drought. We then examine the characteristics of the two types of flash droughts and their evolution by using reconstructed meteorological and soil moisture records over the conterminous United States (CONUS) for the period 1916 to 2013 using the model reconstruction approach described by Wood and Lettenmaier (2006).

2. **Data sets and procedures**

a) Data sets

We used gridded daily gridded P and T_{air} data from a set of approximately 2400 index stations over the conterminous U.S. (CONUS) selected based on data quality and stability of the stations (Wood and Lettenmaier 2006). This is the same data set used by Mo and Lettenmaier (2015) to study heat wave flash droughts. We then derived daily forcings for four land surface models (LSMs) from daily P, maximum and minimum temperatures (T_{max} and T_{min}) and surface wind speed. Surface wind speed was taken from the lowest level of the NCEP-NCAR atmospheric reanalysis (Kalnay et al. 1996) as in Livneh et al. (2013) and Maurer et al. (2002).

Prior to 1950, the surface wind speed was represented by the mean seasonal cycle. Livneh et al. (2013) have shown that this assumption has only a modest effect on the LSM output. The daily forcings drove the same four land surface models (LSMs) as in Mo and Lettenmaier (2015) which produced SM and ET. The models used were VIC 4.0.6 (Liang et al. 1994), Catchment (Koster et al. 2000. Ducharne et al. 2000) , Noah 2.8 (Koren et al. 1999, Ek et al. 2003) and Sacramento/Snow 17 (SAC, Barnash et al. 1973, Anderson 1973) . The data sets used here also form the foundation for the UCLA/University of Washington Surface Water Monitor http://www.hydro.washington.edu/forecast/monitor/).

To study the circulation anomalies associated with flash droughts, we used the daily 500 hPa heights from the Twentieth Century reanalysis V_2 (Compo et al. 2006, 2011). The horizontal resolution is 2 degrees and the reanalysis data cover the period from 1871 to 2012. We used the 500 hPa heights for the Northern Hemisphere from 1916-2012.

Because flash drought events typically last only a few days, we used pentad data. As in Mo and Lettenmaier (2015), we constructed the pentad data from the daily gridded data (in the case of leap years, the 12^{th} pentad has 6 days). The pentad mean climatologies were computed for the base period for each model and each variable. Anomalies are the departures from the climatology. The base period is 1916-2013 for the land surface variables and 1916-2012 for the Twentieth Century reanalysis.

b) Procedures

Variations in evaporative demand are largest in the growing season, hence we focused on pentads from April through September (36 per year). There are a total of 98 years in our record, and the record length N_{total} therefore is 3528 pentads. To determine the preferred regions for flash drought occurrence, we computed the frequency of occurrence (FOC) by using a threshold method. We processed each model separately. For a given pentad T and grid point x , we identified a flash drought event when a given definition of flash drought was met. That pentad was defined as the onset. There was no persistence requirement so an event can be as short as one pentad. For each grid point, we computed the total number of pentads N under flash drought of either type for the entire record for a given model. We define the FOC as the percentage of pentads under heat wave or P deficit flash droughts.

$$\text{FOC (model)} = \frac{N}{N_{total}} X100\% \qquad \text{Eq.(1)}$$

We computed the FOC for each model separately and then took the ensemble mean of the FOC values over four models. To study the evolution of flash droughts, we made composites of P, T_{air} , ET and SM anomalies from 4 pentads before to 4 pentads after the onset of both types of flash drought events. We assessed statistical significance using the student's t test. Areas where values are statistically significant at the 5% level are shaded.

3. P deficit flash drought

a) Example

The 1980 summer drought over the Central United States is a good example of a P deficit flash drought event. The time-longitude plots of pentad mean T_{air}, ET, P and SM anomalies averaged over the center of the heat waves from (34-40 ^{o}N) illustrate the life cycle of the event

(Fig. 1). Fig. 2 shows the corresponding 15-day mean 500 hPa height anomalies for June and July 1980. The SM and ET anomalies are ensemble means of four models.

Figs. 1 and 2 show that P deficits (negative P anomalies) occurred in spring and early summer more than one month before the establishment of heat waves in July. SM anomalies were already negative at the beginning of 1980 but recovered somewhat in early spring. In May, SM anomalies responded to the lack of P and decreased again. In June, an anticyclone moved into the Central U.S. and intensified (Fig. 2). P deficits continued and reached a minimum in the early July when the positive height anomalies reached a maximum (Fig. 2c). SM deficits (negative anomalies) increased as responses to the lack of P and persisted through the end of summer (Fig. 1d). The interesting point is that although SM and P deficits occurred in May and early June, ET did not respond to the depleted SM until early July (Fig. 1b) when SM anomalies were less than -40 mm (about one standard deviation SD). T_{air} anomalies were already warm in June. Heat waves occurred only after ET started to decrease around 1 July. T_{air} anomalies were above 5^{o}C in mid–July when ET anomalies reached a minimum. The anticyclone moved out of the region after 16 July and temperatures declined.

The evolution of the 1980 event was very different from a heat wave flash drought even though both show rapid increases of temperature and decreases of SM. For heat wave flash droughts, high temperature is the major driver. ET anomalies are *positive* as they respond to high temperature (Mo and Lettenmaier 2015). In the 1980 case, P was a major driver. ET anomalies decreased in response to the decreases of SM caused by P deficits. The Bowen ratio increased and temperature increased as a response to (rather than cause of) the decreases in ET.

b) Definition and frequency of occurrence

During the dry season over the Southwest, there is little rain but temperature can increase above 1 SD. Because this is a recurring climatological condition, it cannot be considered as flash drought. To distinguish P deficit flash droughts, we only consider areas where the pentad P climatology is greater than 0.2 mmday^{-1}. Over the CONUS, this has the effect of screening out portions of southern California in spring and the dessert over the Southwest in spring and early summer. We impose as our requirement for P deficiency that the P anomaly be <40%., i.e., less than the 40th percentile for that pentad. Percentiles are determined from data in the base period. In addition to the requirement of P anomalies, we require that the ET anomaly be negative in order to distinguish from heat wave flash droughts. The temperature anomalies are required to be above 1 SD to assure that temperature is high. We test four different scenarios for the possible definition of P deficit flash droughts:

Case 1 : ET anom<0, P anom<40%;

Case 2: ET anom<0, P anom<40% and T_{air}> 1 SD;

Case 3: ET anom<0, SM anom <40% and T_{air}>1 SD;

Case 4: ET anom<0. Panom<20% and T_{air}>1 SD

We computed both pentad SD and percentiles for the base period from 1916-2013. For each case and each model, we selected pentads that met the criteria listed above and computed FOC. We then composited standardized T_{air} , P anomalies and SM percentiles for all pentads under drought (Fig.3). Modest changes in the criteria change the number of events, but not the general space-time patterns.

The case 1 scenario tests whether the lack of P and negative ET anomalies alone are sufficient to increase T_{air} above 1 SD so these events can be qualified as P deficit flash droughts. Case 2 is a subset of events in case 1 for which T_{air} anomalies are specified to be above 1 SD.

The requirements for case 3 are similar to the definition of heat wave flash droughts except ET anomalies are negative. Comparison of case 2 and case 4 tests the sensitivity of P anomaly requirements.

The case 1 composites indicate that on average, the lack of P and negative ET anomalies alone usually decrease SM to below 40% (Fig. 3d). However, The SM deficits are not strong enough to increase T_{air} above 1 SD (Fig. 3b). Therefore, P deficits and negative ET anomalies are necessary but not sufficient conditions for P deficit flash droughts.

Case 2 is a subset of case 1. The composite shows that T_{air} is above 1.4 SD. There is no explicit requirement of SM %, but SM % is below 30% except the western dry region where SM is below 40%. The SM minimum is located in the Great Plains. Because of the SM connection, flash droughts as defined by the case 2 criteria are agricultural droughts.

Case 3 is similar to the definition of heat wave flash droughts except ET anomalies are negative. The FOC pattern similar to case 2 but there are more events over the Great Plains and southern states. The composites of P, T_{air} and SM anomalies are also similar to case2, but magnitudes are weaker. There is no requirement for P, but the composite indicates that P is below normal and slightly weaker than case 2. When P deficits cause SM% to drop below 40%, case 3 events will occur even if P deficits are greater than 40%. Case 3 has more relaxed requirements than case 2. Because these are P deficit droughts, we decided to use the P anomaly as an indicator, and in particular, we adopted case 2 as our definition of P deficit flash drought. Case 4 tests the sensitivity of the FOC to P deficits. When the P percentile requirements are below 20%, the FOC pattern is similar to case 2 but values are lower. The maximum of the FOC is still located over Texas, but the magnitudes are 1% less (Fig. 4c).

We replotted the FOC for P deficit flash drought in Fig. 4a and reproduced the FOC for heat wave flash drought in Fig. 4b from Mo and Lettenmaier (2015) for comparison. It is apparent that there are more P deficit flash drought events than heat wave flash drought events. Furthermore, P deficit flash drought events can occur everywhere but are more likely to occur over the South with maxima extending from the Southern Great Plains to the Southwest where heat wave droughts are infrequent. There are fewer events over the North Central region and the Ohio Valley where heat wave flash droughts are most likely to occur. This contrasts with a maximum in the FOC of heat wave flash droughts in the North Central region of the U.S., with a secondary maximum in the Pacific Northwest. However, both types of flash droughts can occur at a given location; they are not mutually exclusive. For instance, there are both types of flash droughts in the North Central/ Ohio Basin region.

One feature that distinguishes flash droughts from longer meteorological and agricultural droughts is that flash droughts generally do not persist because T_{air} anomalies tend not to be persistent. For heat wave flash droughts, most events only last for one to two pentads (Mo and Lettenmaier 2015). We evaluated persistence for P deficit flash drought as the number of events that persisted for one pentad to three or more pentads after the onset. We did so for each event and for each LSM separately. Then we averaged over all events and averaged over all four models (Fig. 5). Most P deficit flash drought events over the CONUS only persist for one pentad. Events over Texas tend to be more persistent. 20-30% of events over Texas persist for three pentads or longer.

4. Physical mechanisms for flash droughts

Heat wave flash droughts are temperature driven. Figure 6c shows the vegetation coverage averaged from April to September. From the FOC (Fig. 4b), it is evident that heat wave flash droughts tend to be located over areas where vegetation coverage is dense. Over the interior of the West where vegetation cover is sparse, there are few events. As the term implies, high temperatures cause ET to increase and SM to decrease due to vegetation moisture extraction (Mo and Lettenmaier 2015).

In contrast, P deficit flash droughts are P driven. From the 1980 case, we noticed that T_{air} was already warm at the onset of the events but had not reached one SD before the event's onset. From this example, we posit that for a P deficit flash drought to occur, (i) the sequence is that the lack of P drives down SM and negative SM anomalies cause T_{air} to increase and (ii) T_{air} anomalies are positive by the onset of the event.

a) SM and T_{air} relationship

One measure of the relationship between T_{air} and SM anomalies is the correlation between pentad SM and T_{air} anomalies over the growing season from April to September. We computed correlations for each LSM separately. The ensemble mean over the four LSMs is given in Fig. 6a. Assuming the degrees of freedom to be the years of record minus 2, correlations needed to be greater than 0.148 (or less than -0.148) in order to be statistically significant at the 5% level. Fig. 6a suggests that (positive) negative SM anomalies are related to cool (warm) T_{air} over the Great Plains and the southern U.S. with a minimum over the Southern Great Plains. Koster et al. (2009) indicated that these are areas where temperature is sensitive to wetness and meteorological drought can lead to warmer T_{air} . The processes go through ET because in these regions, ET responds to SM almost linearly (Koster el al 2009). Fig. 6b shows the correlation between pentad ET and SM anomalies for April to September from 1916-2013.

They are positively correlated over the areas where P deficit flash droughts are most likely to occur (Fig. 4a). Hence ET decreases in responses to declining SM, and the reduced ET results in warming T_{air}. P deficit flash droughts occur less often over the North Central region and the West. The North Central region has relatively dense vegetation coverage (Fig. 6c), hence ET tends to respond positively to high temperatures. Therefore, conditions in these regions are more favorable to heat wave flash droughts. The West, in general, is a dry region. Accordingly, Koster et al. (2009) argued that SM variability there is too weak to cause strong ET responses.

b) T_{air} before onset

In the 1980 case, T_{air} was already warm before the onset of the flash drought. In this section, we explore why this is a necessary condition for P deficit flash droughts to occur. We have shown that P deficits will lead to increases of T_{air}. The question is whether the increases are large enough to push T_{air} above one SD which is one of our requirements for occurrence of P deficit flash droughts. The composite of T_{air} anomalies when P percentiles are less than 40% and ET is negative (case 1) averaged over four models indicates that the changes of T_{air} anomalies are less than 1 SD (Fig. 3b). These increments are not large enough to be qualified as P deficit flash droughts unless T_{air} anomalies are already positive before the onset of the events. This is consistent with the 1980 case. This is also similar to the heat wave drought case. High temperatures will cause SM to decrease, but increments are not large enough to be qualified as heat wave flash drought unless SM is already negative at the onset.

5. **Trends in the occurrence of P deficit flash droughts**

Figures 7e and 7f show the number of pentads under P deficit flash drought per year (April-September) averaged over a box over the Southern Great Plains (28-36 ^{o}N, 95-105^{o}W) and a box over the Southwest (32-36^{o} N, 110-116^{o} W) for each LSM along with the ensemble mean respectively. Modest changes in the location of the boxes do not change the conclusions. Unlike the heat wave flash drought, there are only modest differences among LSMs because the forcing terms P and T_{air} are the same for all; only ET is different from model to model. There are no statistically significant trends in the occurrence of P deficit flash drought events in the Southern Great Plains. The 2011 event, however, was exceptionally strong (Fig. 7e). Over the Southwest, there were slight upward trends in the number of P deficit events from 1920-1960. However, after 1990, the occurrence of the flash drought events increased dramatically. The trends correspond roughly to increasing trends in T_{air} anomalies averaged over the Southwest (Fig. 7g); T_{air} warming accelerated after 1990. The P trends (Fig. 7h) are also mostly decreasing from 1920-1960 in this region, but there is no dramatic increase post-1990.

To determine trends in the occurrence of flash droughts, we applied the Mann Kendall test to the time series of the total number of pentads under drought each year on a grid cell by grid cell basis. The test was performed for each model separately. Only trends that were present in all four models were plotted. We reproduce the Mann Kendall test for heat wave flash drought events in Fig. 7d from Mo and Lettenmaier (2015) for comparison. Figure 7a which passes the field significant test of Livezey and Chen (1983) indicates that there were upward trends over the Southwest and Four Corners regions while heat wave flash droughts had downward trends over the North Central region (Fig. 7d). For meteorological drought, there were downward trends in the occurrence due to the upward trends in P and SM (Andreadis and Lettenmaier 2006; Andreadis et al. 2005).

For P, there were upward trends in the North Central region where heat wave flash droughts had downward trends. But P deficit flash droughts are relatively infrequent in that region, so the influence of P trends is in the larger context. Overall, trends in the number of P deficit flash droughts tend to be associated mostly with trends in T_{air}. The lack of P will increase T_{air}, but the increments as indicated by Fig. 3b are not large. If a particular decade is anomalously warm and T_{air} is already positive before the onset of P deficit flash drought events, then they are more likely to occur. P deficit flash drought is P driven but the trends in occurrence are associated with trends in T_{air} , while heat wave flash drought is temperature driven, but trends in occurrence are associated with trends in P.

6. Evolution of flash droughts

We explore the evolution of both types of flash droughts through examination of P, SM, ET and T_{air} anomalies from four pentads before to four pentads after the onset. To show the atmospheric circulation anomalies associated with P deficit flash drought, we formed composites of the 500 hPa height pentad anomalies from the Twentieth Century Reanalysis V_2 (Compo et al. 2006, 2010) using an index method. The index we used in Mo and Lettenmaier (2015) for heat wave flash droughts was based on the average number of events in the rectangle (38-45 ^{o}N, 90-95^{o}W). For P deficit flash drought, we took the box as (28-36^{o}N ,95-105^{o}W). The selection of the boxes in both cases was intended to locate them over the area of the maximum FOCs (Fig. 4). We processed each LSM separately. For each pentad, we calculated the number of flash drought events averaged over the rectangle. We then averaged over the four LSMs. We computed the composite of 500 hPa height anomalies for pentads for which the index was greater than 0.5.

a) Heat wave flash droughts

The life cycle of heat wave droughts is given by composites in Fig. 8. Heat wave flash drought is temperature driven, but P deficits are needed to set up desirable conditions for flash drought to occur. P deficits start to appear over the North Central region two pentads before the onset and that cause SM to decrease to below 40% one pentad before onset (Fig. 8l).

Temperature anomalies are about 1-2 ^{o}C one pentad before onset. Temperature increases rapidly over the Midwest and the North Central during onset. When T_{air} anomalies are above 3 ^{o}C, ET starts to increase. That drives SM below 30%. SM anomalies persist more than 2 pentads after onset. The interesting point is that P deficits only appear before onset. As indicated by Mo and Lettenmaier (2015) the important role of P is to set up favorable conditions for heat wave flash drought to occur. It does not play an active role in raising temperature or increasing ET. Heat waves in general are not very persistent. At one pentad after onset, temperature already starts to cool down on average. Heat wave flash drought has atmospheric circulation support. The composite of 500 hPa heights based on the number of heat wave flash drought events in the box (38-45^{o}N ,90-95^{o}W) indicates that there are anticyclones located in the North Central near the maxima of the FOC of heat wave flash droughts (Fig. 9a).

b) P deficit flash droughts

The evolution of P deficit flash drought is given in Fig. 10. P deficits start to appear about four pentads before onset and gaining strength toward onset. At pentad -2, there are already -2 mmday^{-1} negative P anomalies over the Great Plains which is about half a standard deviation. P deficits cause SM to decrease. ET starts to respond to the SM deficits. T_{air} anomalies are already above 1-2 ^{o}C before onset. During onset, the composite of 500 hPa height anomalies shows an anti-cyclone strengthening over the Southern Great Plains and both P and SM anomalies reach a minimum (Fig. 9b). SM anomalies persist through +2 pentads and beyond. T_{air} anomalies reach 2-3 ^{o}C during the event onset which is over one SD of T_{air}. There is a strong correspondence between SM and ET and also good correspondence between the decreases of ET and the increases of T_{air}.

5 . Discussion and Conclusions

We define flash droughts as short periods of warm temperature and anomalously low and rapidly declining SM. Based on physical mechanisms associated with flash droughts, we have classified them into two types: heat wave flash droughts and P deficit flash droughts, the characteristics of which are compared in Table 1. We have shown that following our definitions, P deficit flash droughts are more common than heat wave flash droughts. They can occur in most areas of the U.S., but they are most prevalent in the southern U.S while heat wave flash droughts are most likely to occur in the North Central and the Pacific Northwest regions. The P deficit flash droughts are precipitation driven events. The lack of rain prior to the onset of an event reduces SM and decreases ET, which in turn leads to high temperatures. It is very different from heat wave flash droughts which are temperature driven and tend to occur in more densely vegetated areas.

Flash droughts have a large impact on crops and early warming may help to mitigate associated agricultural damages. P deficit flash droughts occur during meteorological drought so conventional drought indices such as the standardized precipitation index and runoff and SM percentiles have some ability to detect them (Svoboda et al. 2002). Heat wave flash droughts occur when SM is already in deficit. Given the short duration of flash droughts relative to conventional droughts, shorter time steps (e.g., pentad or weekly vs monthly) need to be used to monitor them. More importantly, the shorter time scales relative to conventional drought (which are close to weather forecast time scales) offer some hope of forecasting both the onset and termination of these events.

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Table 1 Comparison between heat wave and P deficit flash droughts

Features	Heat wave flash drought	P deficit flash droughts
Temperature	above 1 SD	above 1 SD
Soil moisture	below 40% over high FOC areas	below 40% over high FOC areas
Precipitation	Below normal before onset	Below normal before onset and reaches a minimum during onset
ET anomaly	Positive	Negative
FOCs		
locations	Midwest and the Pacific Northwest	Southern United States
Maximum frequency	~4%	8-9%
Persistence	mostly one pentad	mostly one pentad
mechanisms	temperature driven	precipitation driven
trends	decreasing trends North Central region	increasing trends over the Southwest
Trend related forcing	increasing precipitation trends	increasing temperature trends

References

Anderson , E.A. ,1973: National Weather Service River Forecast System: Snow Accumulation and ablation model. NOAA Tech Meno. NWS Hydro-17, NWS., Silver Springs. MD.

Anderson, M.C., C. Hain, B. Wardlow, A. Prinstein, J.R. Mecikalski and W.P. Kustas, 2011: Evaluation of drought indices based on thermal remote sensing and Evapotranspiration over the continental United States. *J. Climate* 24, 2025-2044.

Anderson. M.C., C. Hain, J. Otkin, X. Zhan, K.C. Mo, M. Svoboda, B. Waedlow and A. Pimstein, 2013: Intercomparison of drought indicators based on thermal remote sensing and NLDAS-2 simulations with U.S. Drought Monitor classifications. J. *Hydromet. 14*, 1035-1056.

Andreadis, K.M. , E. A. Clark, A. W. Wood, A. Hamlet and D. P. Lettenmaier ,2005: Twentieth Century drought in the Conterminous United States. J. Hydromet 6, 985-1001

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

Barnash, R.J.C., R.L. Ferral and R.A. McGuire, 1973: A generalized streamflow simulation system: Conceptual models for digital computers, tech report. Joint Fed-State River Forecast Center U. S. Natl. Weather Serv and California Dept. of Water resources. Sacramento, CA.

Chang, F.C., and J.M. Wallace 1987: Meteorological conditions during heat waves and droughts in the United States Great Plains. *Mon. Wea. Rev*., 115, 1253-1269.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brennimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. *Quarterly J. Roy. Meteorol. Soc*., 137, 1-28. doi: 10.1002/qj.776.

Compo, G.P., J.S. Whitaker, and P.D. Sardeshmukh ,2006: Feasibility of a 100 year reanalysis using only surface pressure data. *Bull. Amer. Met. Soc*., 87, 175-190.

Ducharne, A., R.D. Koster, M.J. Suarez, M. Stieglitz, and P. Kumar, 2000: A catchment-based approach to modeling land surface processes in a general circulation model. *J. Geophys. Res*., 105, 24 823–24 838.

Ek, M.B., K.E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J.D. Tarpley, 2003: Implementation of Noah land surface model advances in the NCEP operational mesoscale Eta model. *J. Geophy. Res.* 108, doi:10.1029/2002JD003296.

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.

Kalnay E., and co-authors, 1996: The NMC/NCAR Reanalysis Project. *Bull. Amer. Meteor .Soc.* **77**, 437-471.

Koren, V., J. Schaake, K. Mitchell, Q. Duan, F. Chen and J. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models. *J. Geophy. Res.*, 104, 19569-19585.

Koster, R.D., S.D. Schubert and M.J. Suarez, 2009: Analyzing the concurrence of meterological droughts and warm periods, with implications for the determination of evaporative regime. *J. Climate*, 22, 3331-3341.

Koster, R.D., M.J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar, 2000: A catchment-based approach to modeling land surface processes in a general circulation model 1. Model structure. *J. Geophys. Res*., 105, 24 809–24 822

Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges , 1994: A simple hydrologically based model of land surface water and energy fluxes for General Circulation Models. *J. Geophy. Res.*, 99, 14415-14428.

Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. Andreadis, E.P. Maurer, and D.P. Lettenmaier, 2013: A long-term hydrologically based data set of land surface fluxes and states for the conterminous United States: Updates and extensions. *Journal of Climate*, 12 doi:10.1175/JCLI-D-12-00508.1.

Livezey, R. E., and W. Y. Chen ,1983: Statistical field significant test and its determination by Monte Carlo techniques. *Mon. Wea. Rev.*,111,46-59.

Lyon, B., and R.M. Dole ,1995: A diagnostic comparison of the 1980 and 1988 U. S. summer heat wave-drought. *J. Climate*, 8, 1658-1675.

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. Climate*, **15**, 3237-3251.

Mo, K.C. and D.P. Lettenmaier, 2015: Heat wave flash droughts in decline. *Geophy. Res Let.* 42, doi: 10.1002/2015GL06418.

Myoung, B. and J. W. Nielsen-Gammon, 2010 a: The convective instability pathway to warm season drought in Texas. Part I: The role of convective inhibition and its modulation by soil moisture. *J. Climate*, 23**,**4461-4470.

Myoung, B. and J.W. Nielsen-Gammon, 2010b: The convective instability pathway to warm season drought in Texas. Part II: Free tropospheric modulation of convvctive inhibition, *J. Climate*, 23,4474--4488.

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. Hydromet.* 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. Hydromet.*, 15**,** 938-956.

Senay, G.B., M.B. Budde, T.F. Brown and J.P, Verdin, 2008: Mapping drought in the Southern Great Plains. 22nd conferences of hydrology, American Meteorological Society, New Orleans. LA

Svoboda, M., and co-authers, 2002: The drought monitor. *Bull. Amer. Meteor. Soc*., 83, 1181-1190.

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. Climate* 22, 2684-2712.

Wood, A.W., and D.P. Lettenmaier, 2006: A test bed for new seasonal hydrologic forecasting approaches in the western United States. *Bull. Amer. Meteor. Soc.* 87, 1699-1712.

Yang, Z., 2013: Developing a flash drought indicator for the U.S. Great Plains. MS Thesis, University of Texas at Austin.

Figure Captions

Fig.1: Time-longitude diagram for (a) T_{air} anomalies averaged from 34-40^{o}N from January to December 1980. Contours are given by the color bar; units ^{o}C; (b) same as (a), but for ET anomalies averaged over four models; units mmday^{-1} ; (c) same as (a) but for P anomalies; units mmday^{-1} , and (d) same as (b) but for SM anomalies; units mm.

Fig. 2: 500 hPa height anomalies for (a) 1-15June , (b) 15-30June, (c) 1-15July and (d) 16-30 July, 1980. Contours are given by the color bar; units m.

Fig. 3 (a) The FOC for scenario case 1 (P anomaly< 40%, ET<0), (b) the composite of standardized T_{air} anomalies for pentads under flash drought for case 1. Values are given by the color bar; units ^{o}C ,(c) same as (b), but for P anomalies; units 1mmday^{-1} and (d) same as (b), but for SM percentiles; units percentile, (e)-(h) same as (a)-(d), but for case 2 (Panomaly<40%, ET<0 and Tair>1SD), and (i)-(l) same as (a)-(d), but for case 3(SM percentile<40%, ET<0 and Tair>1SD).

Fig. 4: Ensemble mean frequency of occurrence (FOC) of pentads under (a) P deficit flash drought and (b) heat wave flash drought and (c) P deficit flash drought for scenario case 4 (Panomaly<20%, ET<0 and Tair>1SD). Contours are given by the color bar.

Fig. 5: Percentages of P deficit flash droughts that persist for (a) one pentad, (b) two pentads and (c) three pentads after onset. Contours are given by the color bar.

Fig. 6: (a) Correlation between pentad T_{air} and SM anomalies for pentads from April to September from 1916 to 2013 averaged over four models. Contours are given by the color bar; (b) same as (a), but for correlation between ET and SM pentad anomalies; and (c) vegetation cover averaged from April-September. Units are percentile.

Fig.7: (a) Trends in the number of pentads per year under P deficit flash drought. Trends which are statistically significant at the 5% significance level as determined by the Mann Kandall test for all four models (VIC, SAC, Noah and Catchment) are shaded. Green shading indicates upward trends and red shading indicates downward trends, (b) same as (a) but for mean T_{air} anomalies averaged from April to September and (c) same as (a), but for P anomalies and (d) same as (a) but for heat wave flash drought events, (e) number of pentads under P deficit flash drought per year averaged over a rectangle in the Southern Plains (28-36^{o}N, 95-105^{o}W) for four models and the ensemble mean, (f) same as (e), but for a rectangle over the Southwest (32-36^{o}N, 105-116^{o}W) and (g) same as (f) but for T_{air} anomalies averaged from April to September and (h) same as (g) but for P anomalies.

Fig. 8 Composite of T_{air} anomalies for heat wave flash droughts for (a) two pentads before onset, (b) one pentads before onset, (c) onset, (d) one pentads after onset and (e) two pentads after onset. Contours are given by the color bar; units ^{o}C, , (f)-(j) same as (a)-(e) but for ET anomalies averaged over four models; units mm day^{-1} ;(k)-(0) same as (f)-(j), but SM percentiles ; units percentiles and (p)-(t) same as (a)-(e) but for P anomaly ; units mm day^{-1}.

Fig. 9: (a) Composite of 500 hPa height anomalies based on the number of heat wave flash drought events in rectangle (38-45 ^{o}N, 90-95^{o}W) and (b) same as (a) but for P deficit flash drought events in rectangle (28-36^{o}N ,95-105^{o}W) during onset Contours are given by the color bar; units m.

Fig. 10 Composite of P anomalies for P deficit flash droughts for (a) two pentads before onset, (b) one pentads before onset, (c) onset, (d) one pentads after onset and (e) two pentads after onset. Contours are given by the color bar; units mm day^{-1} , (f)-(j) same as (a)-(e) but for SM percentiles, and (k)-(o) same as (a)- (e), but for ET anomalies averaged over four models; units mm day^{-1} and (p)-(t) same as (a)-(e) but for T_{air} anomaly ; units ^{o}C.

Figure 1

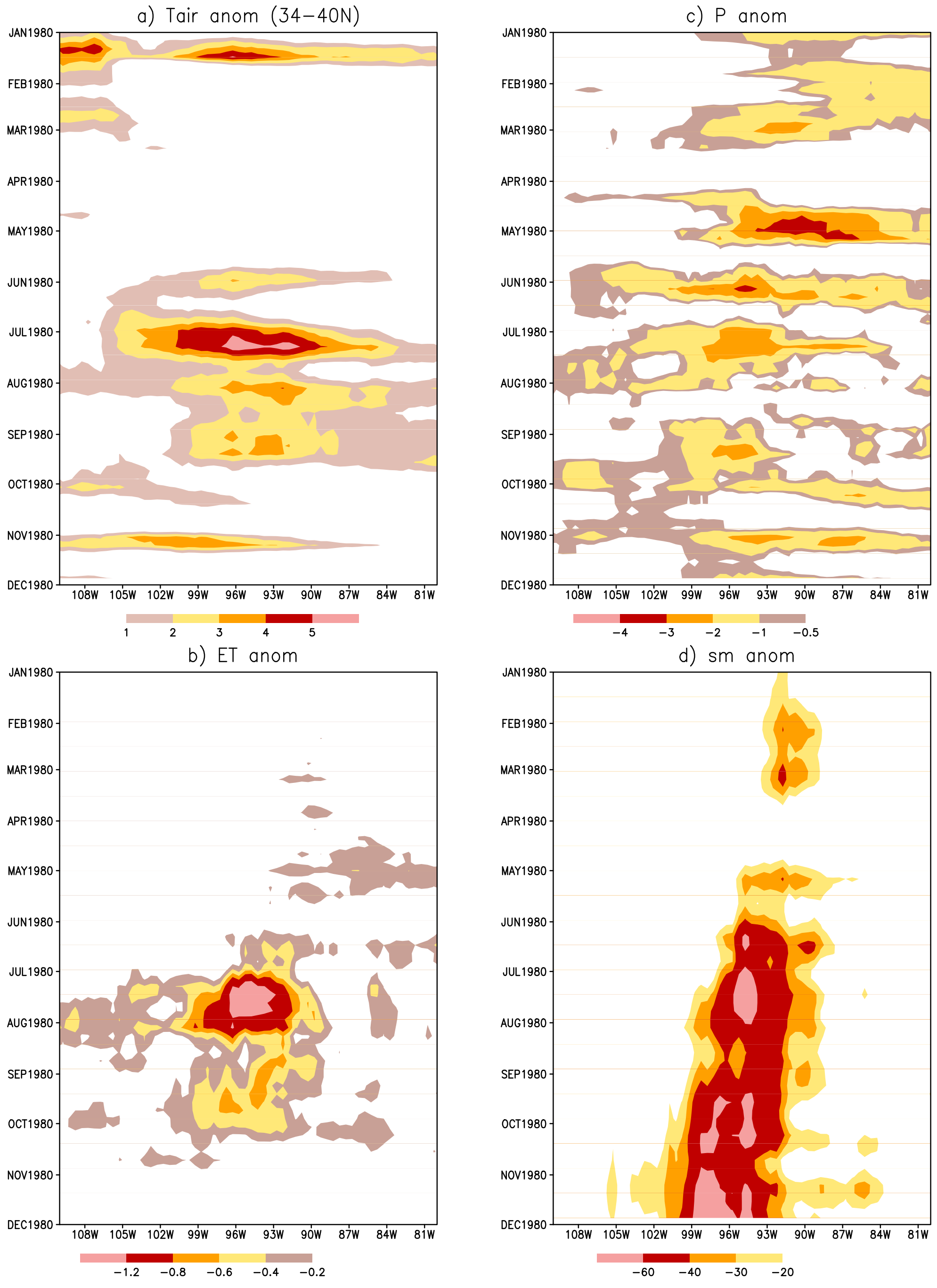

Fig.1: Time-longitude diagram for (a) T_{air} anomalies averaged from 34-40°N from January to December 1980. Contours are given by the color bar; units °C; (b) same as (a), but for ET anomalies averaged over four LSMs; units mmday^{-1} ; (c) same as (a) but for P anomalies; units mmday^{-1} , and (d) same as (b) but for SM anomalies; units mm.

Figure 2

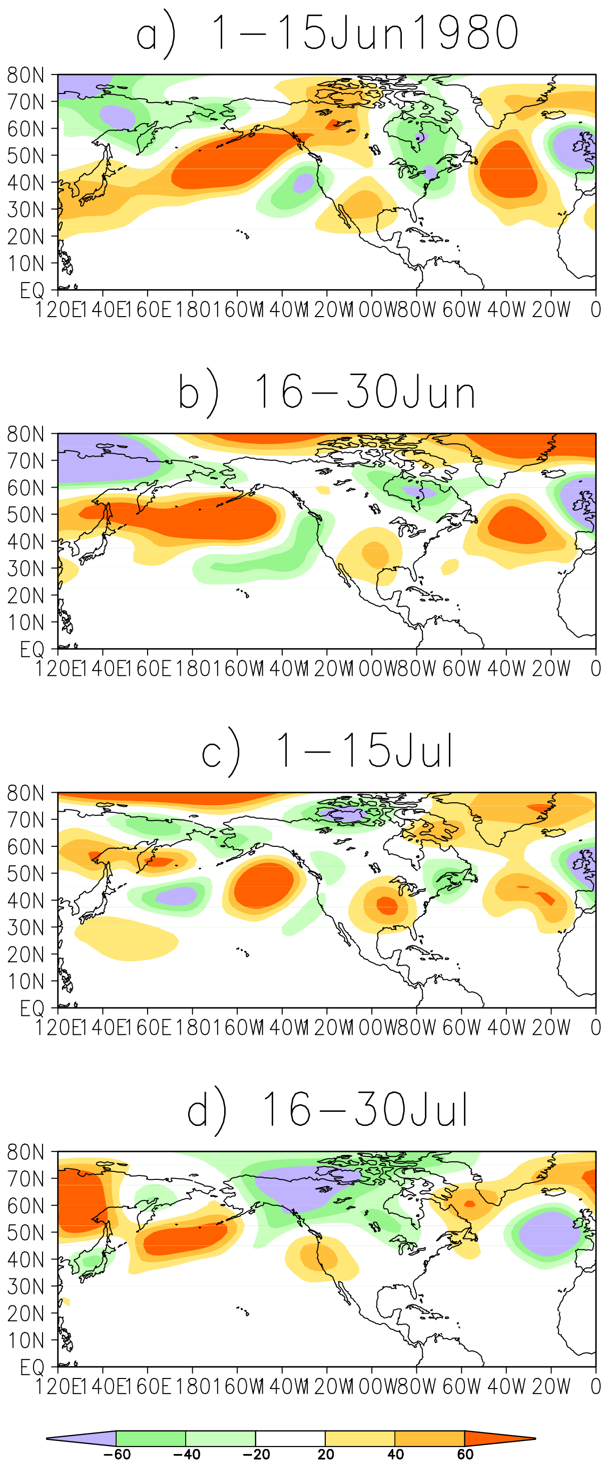

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Figure 3

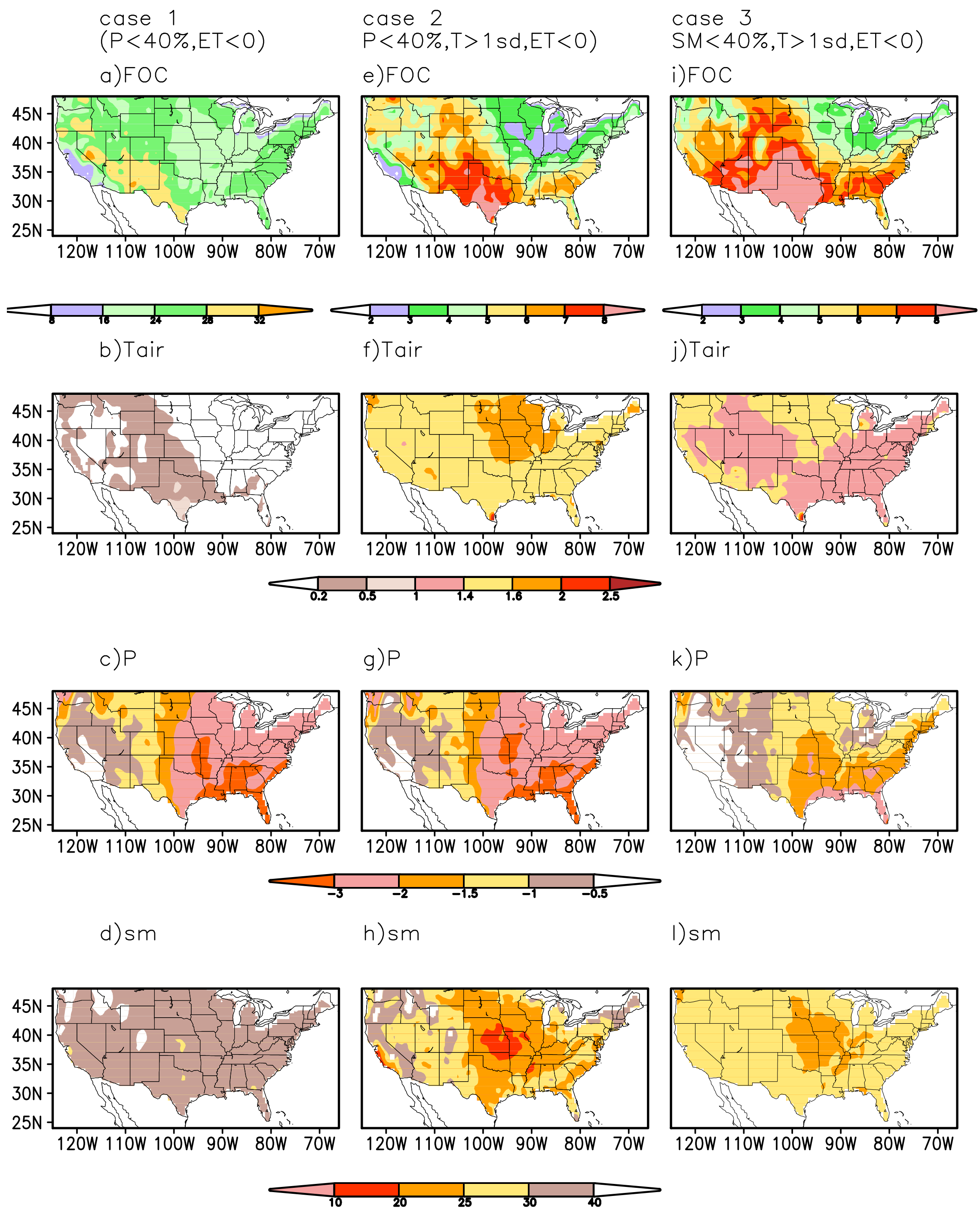

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Figure 4

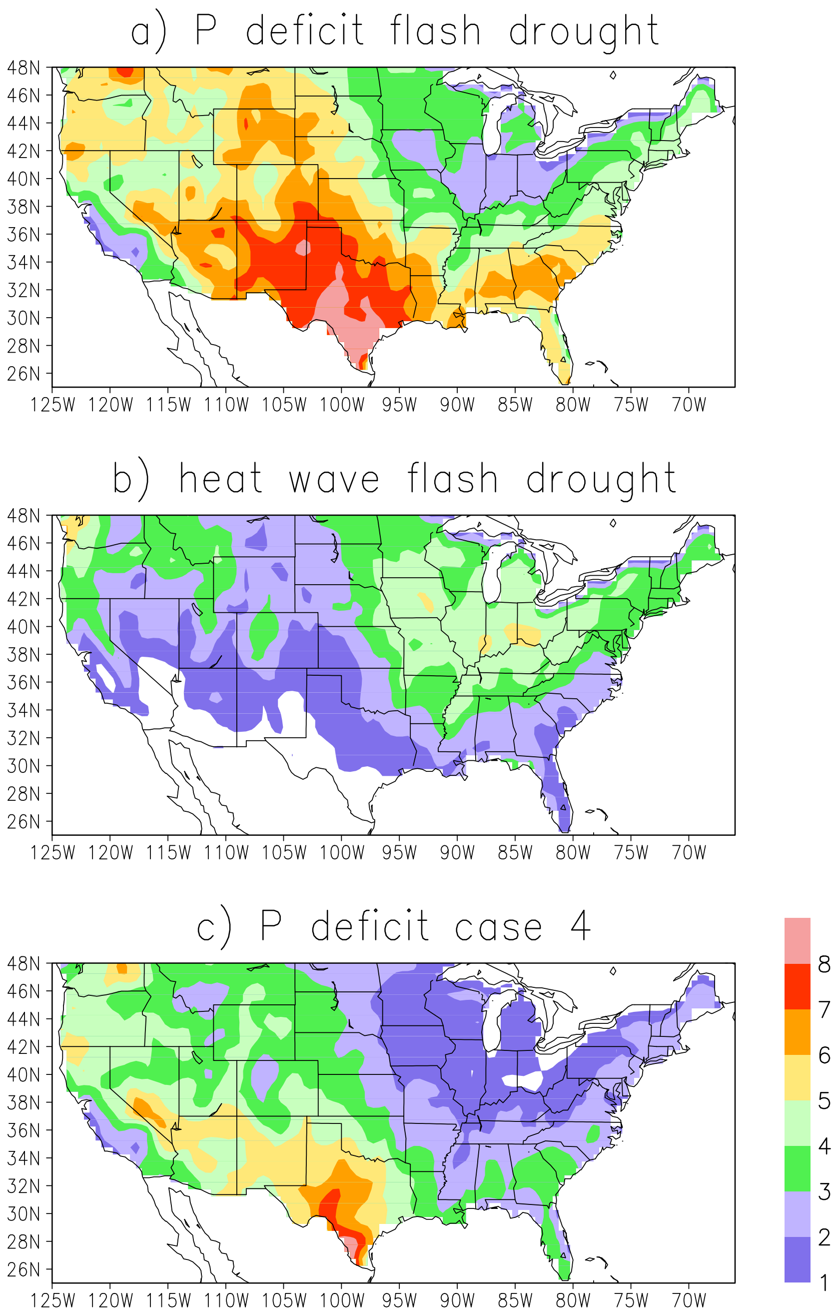

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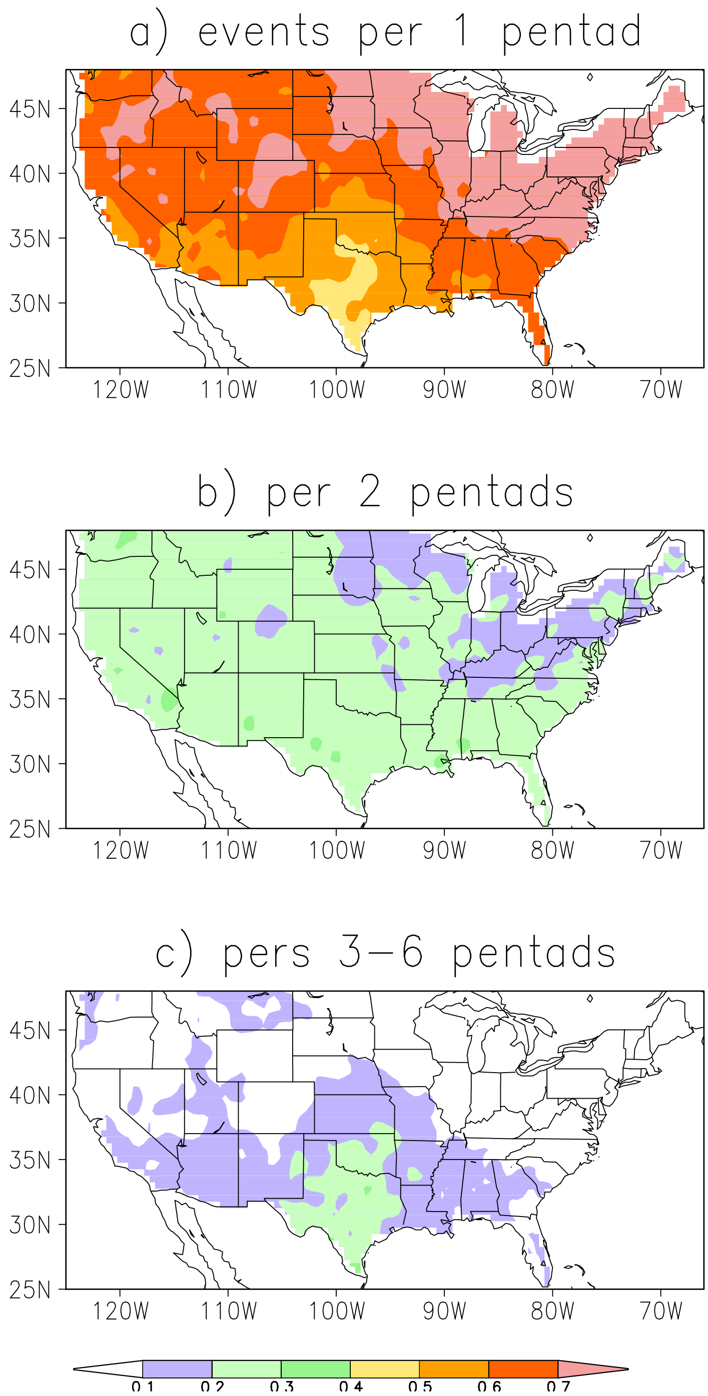
Figure 5



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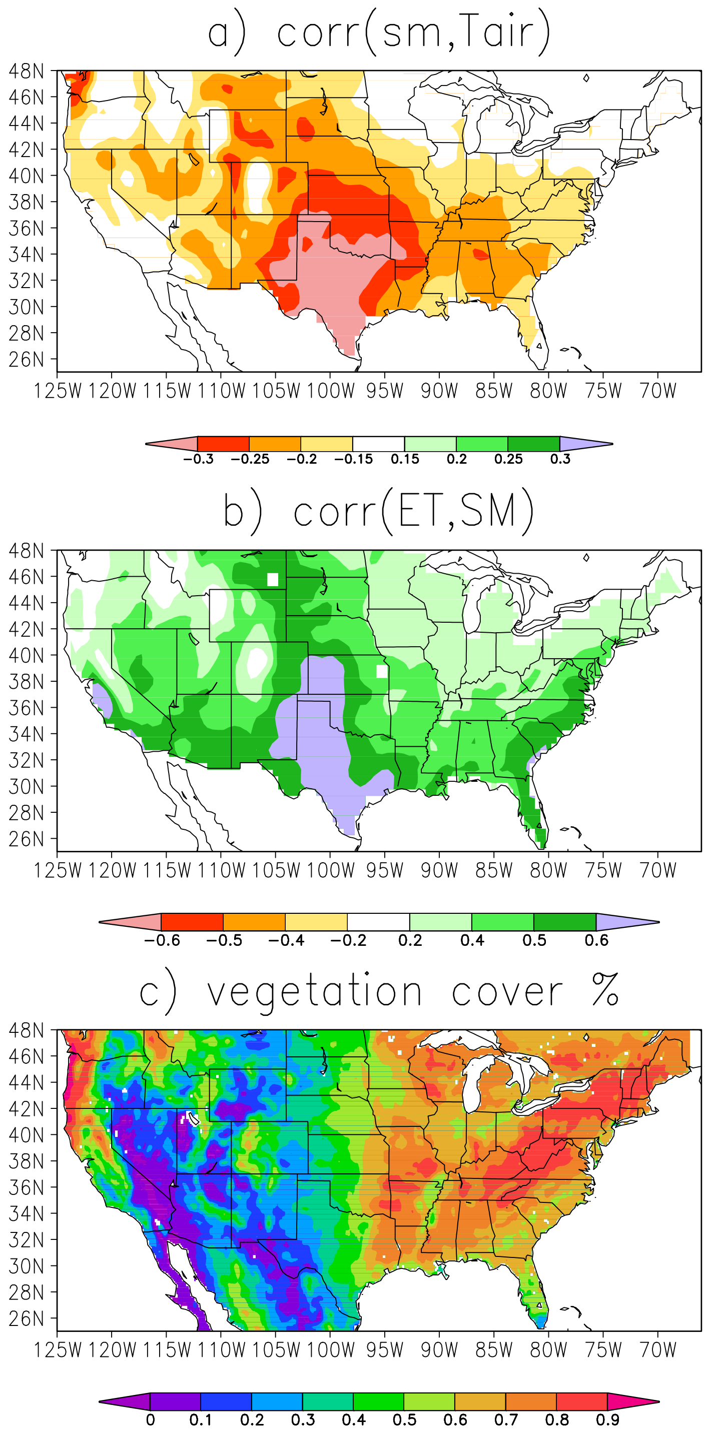

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Figure 7

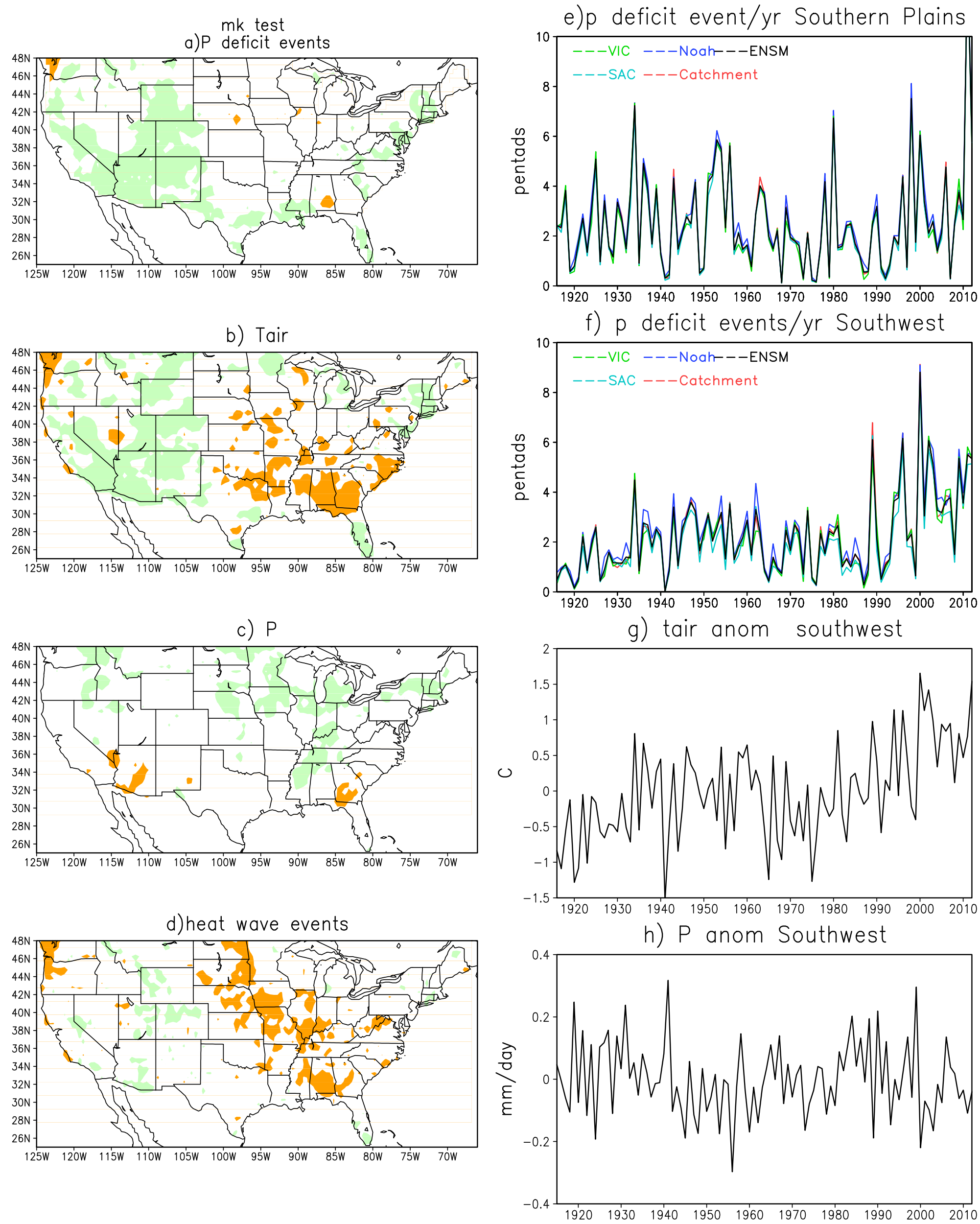

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Figure 8

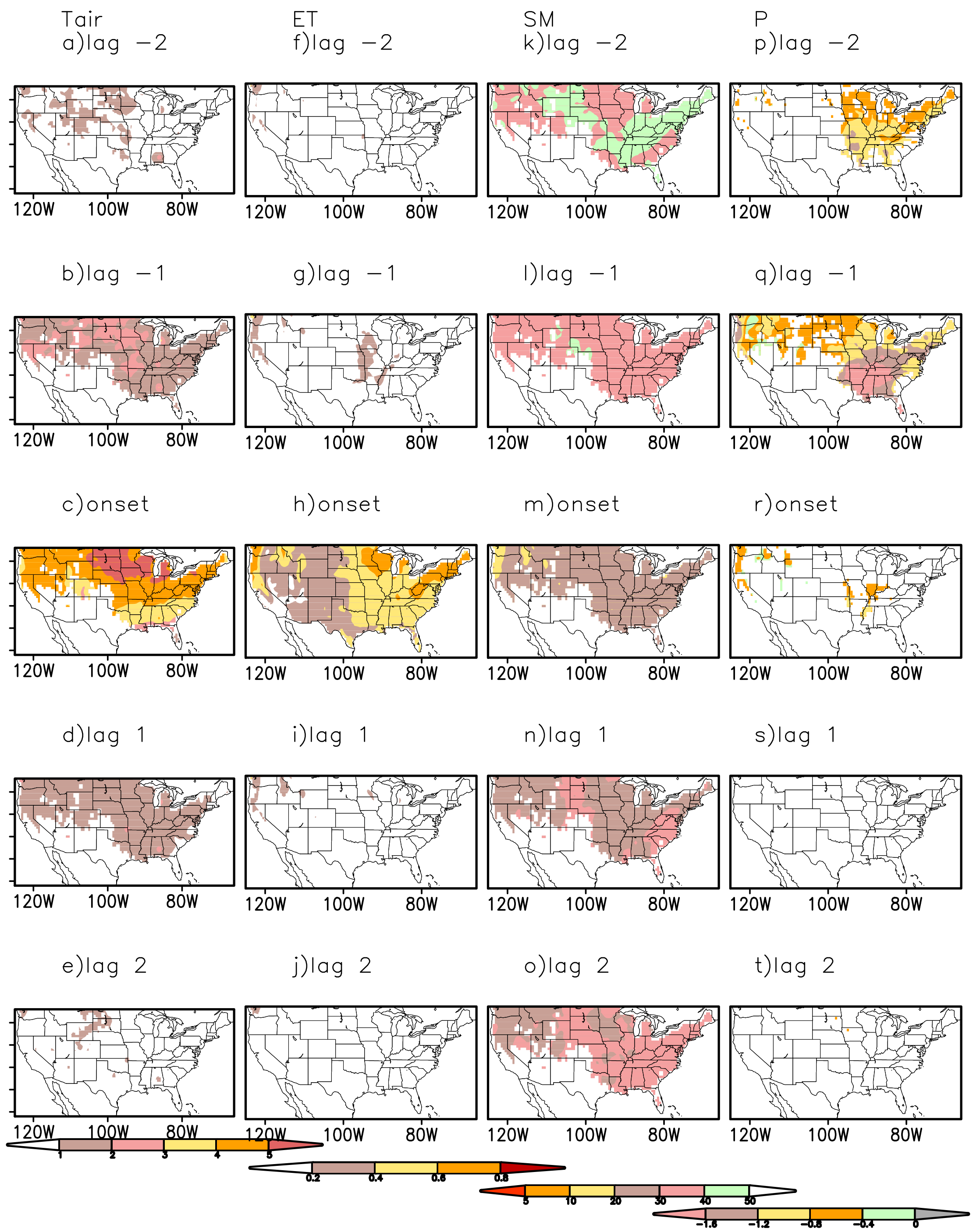

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Figure 9

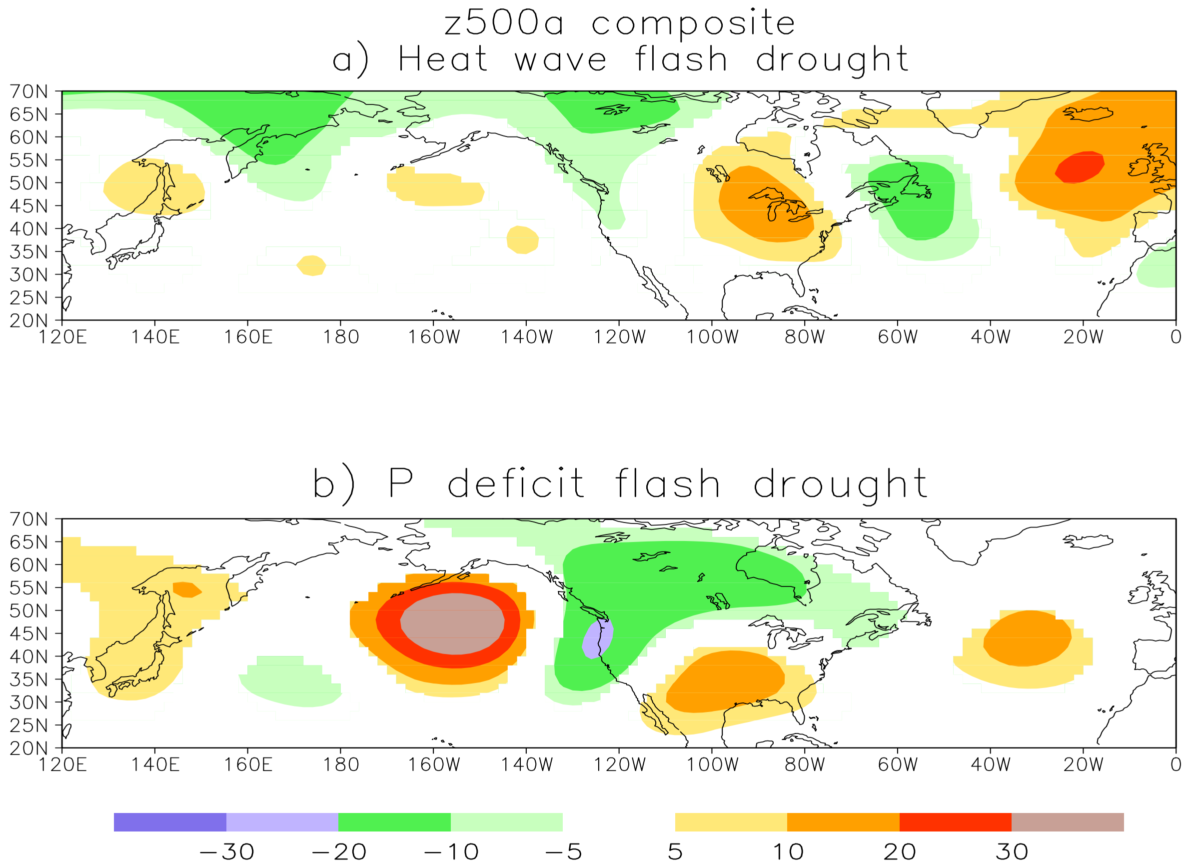

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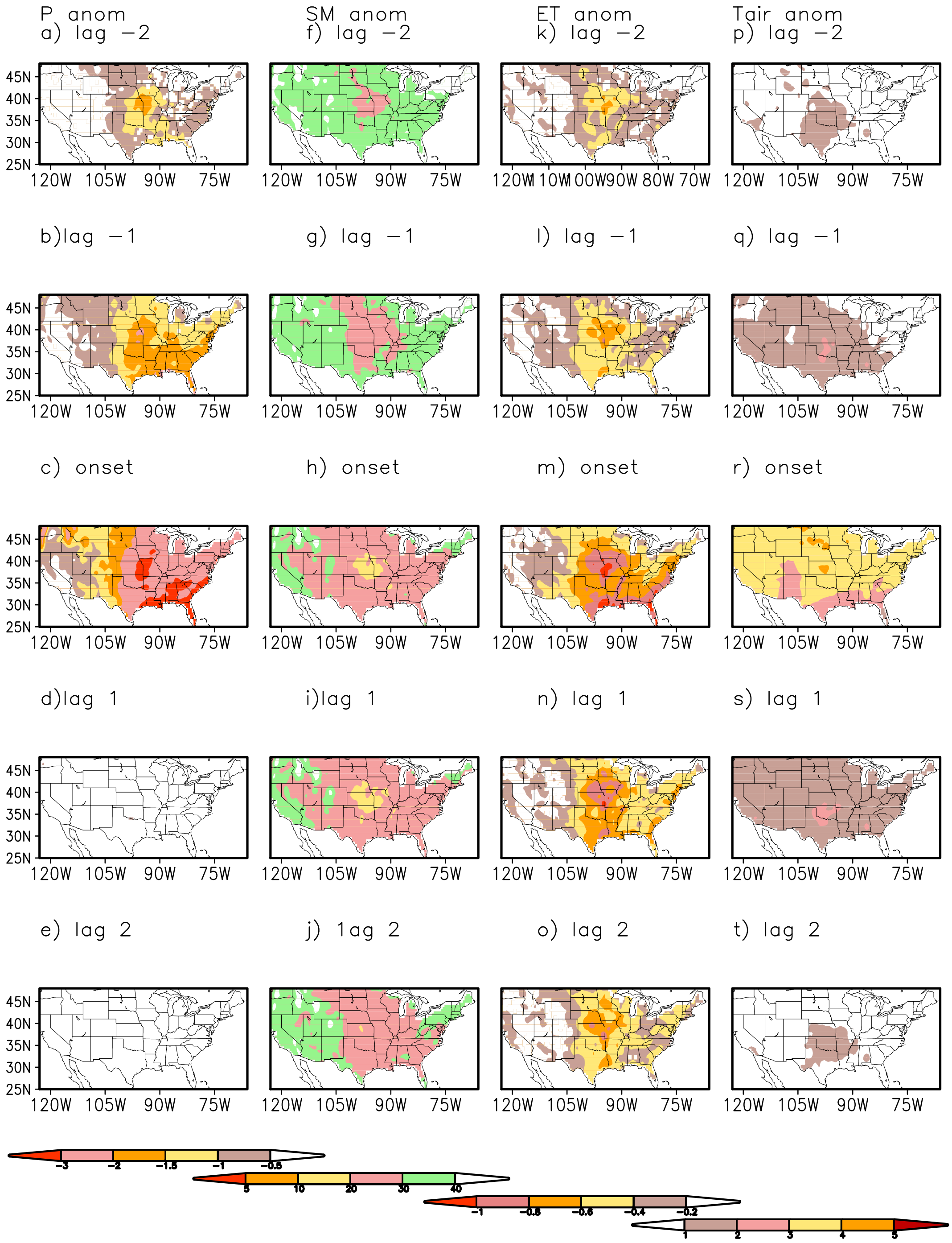
Figure 10



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