Drought onset and recovery over the United States

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Received 27 April 2011; revised 28 July 2011; accepted 28 July 2011; published 19 October 2011.

[1] This study employs precipitation (*P*) and ensemble soil moisture data sets from 1916 to 2007 to study the drought onset and demise over the United States. Both meteorological drought, classified using the standardized precipitation indices (SPIs), and agricultural drought, classified using the soil moisture percentiles, are studied. Drought onset is more predictable than drought demise. It takes 5–8 months for a region to accumulate enough *P* deficits to begin a drought, whereas a drought demise can come within one month to one season. A few strong rainfall episodes can end drought. The preferred season for the meteorological drought onset is at the beginning of the rainy season. Even though drought has a preferred season to begin, the ratio between the onset occurring in that season and the total drought events is less than 45%. For agricultural drought, the ratio is 60% or higher for the northwestern interior states and the Southwest. Over the Southern Plains, a cold El Niño–Southern Oscillation (ENSO) event occurs one season before the onset of drought. No drought events occur during the warm ENSO years. Therefore, the occurrence of a cold ENSO event can serve as an early warning for drought. For other areas influenced by ENSO, such as the lower Mississippi basin, the Ohio Valley, the Pacific Northwest, the upper Missouri basin, and the Southeast, most drought events occur during ENSO. The one-to-one correspondence between ENSO and drought is not good. For these areas, ENSO can only serve as a signal for intensive drought watch.

Citation: Mo, K. C. (2011), Drought onset and recovery over the United States, *J. Geophys. Res.*, *116*, D20106, doi:10.1029/2011JD016168.

1. Introduction

[2] Drought is a process that starts slowly and becomes noticeable only when its effects start to ravage a region [*Wilhite*, 2006]. Because drought starts slowly, a better understanding of conditions associated with the drought onset can improve the drought early warning system. If the precursors of drought can be identified, then forecasters can use the information to improve their drought outlook. The demise of drought is more difficult to predict because drought can end abruptly after a few heavy rain events. *Karl et al.* [1987] studied the climatological probability to end or ameliorate drought over the United States based on the Palmer Drought Severity Index (PDSI) and the Palmer Hydrological Drought Index (PHDI). They found that the seasonal cycle plays an important role. For a given region under drought, the demise depends on the probability for the region to receive large precipitation anomalies needed to end drought [*Karl et al.*, 1986]. There are many studies on the maintenance of drought, but the onset and demise of drought are not fully understood.

[3] Because drought means persistent dryness, it is often associated with persistent sea surface temperature (SST) anomalies (SSTAs). Over the United States, the El Niño–Southern Oscillation (ENSO) has a strong impact on drought. Both observational studies [*Ropelewski and Halpert*, 1986, 1989] and model experiments [*Schubert et al.*, 2009] indicate that drought is more likely to occur over the Southwest, the Great Plains, and the Southeast during cold ENSO events. The North Pacific SSTAs also have an impact on drought over the western region. For example, rainfall over the Pacific Northwest and the Southwest is modulated by ENSO conditions and the Pacific Decadal Oscillation [*Goodrich*, 2007]. The direct impact of the Atlantic SSTAs is small, but they can modulate the impact of ENSO on rainfall [*Mo et al.*, 2009; *Schubert et al.*, 2009]. While the influence of SSTAs on maintaining drought is well studied, it is unclear whether SSTAs can trigger the onset or demise of drought.

[4] In this paper, the focus is on the drought onset and demise over the United States. The standardized precipitation index (SPI) derived from observations and the soil moisture (SM) anomaly percentiles from the North American Land Data Assimilation System (NLDAS) are used to identify meteorological and agricultural droughts respectively. The objectives of this paper are (1) to determine whether droughts over the United States have a preferred month or season to begin or recover, and (2) to determine the precursors of drought onset or demise. Data and procedures to compute drought indices are given in section 2. The definition of the drought onset or demise is given in section 3. The preferred season for drought to begin or end

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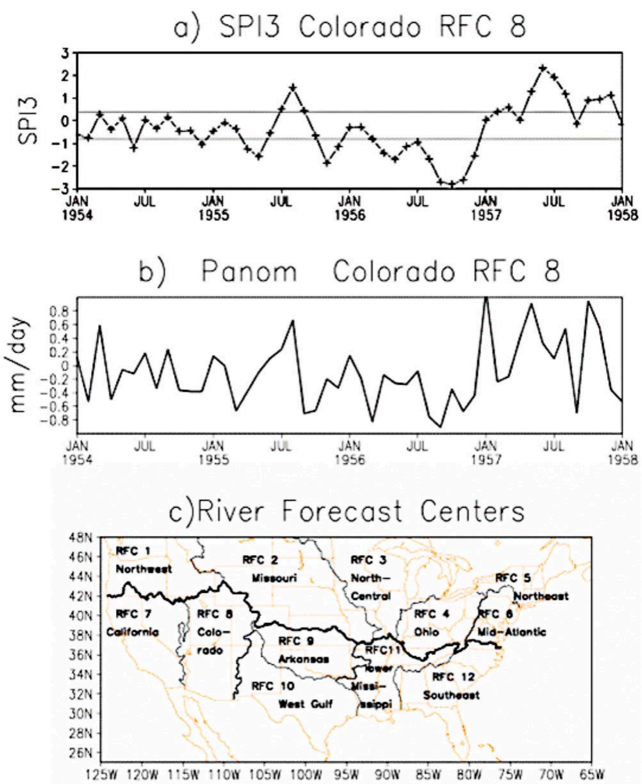


Figure 1. (a) Three-month SPI (SPI3), (b) P anomaly for the Colorado RFC from January 1954 to January 1958, and (c) the locations of 12 River Forecast Centers.

is examined in section 4. The influence of SSTAs on drought onset or demise is examined in section 5. Conclusions are given in section 6.

2. Data and Procedures

[5] The precipitation (P) data set used in this study is the monthly mean P data set obtained from the University of Washington (UW). P was derived from selected index stations [*Wood and Lettenmaier*, 2006]. The horizontal resolution is 0.5°. The data set covers the study period from 1916 to 2007.

[6] A meteorological drought results from P deficits. The SPI is often used to measure a P shortage. To compute the 3-month SPI (SPI3), a 3-month P mean (P_3) time series is obtained. P_3 at time t is the mean of P from $t - 2$ to t. P_3 obeys a probability distribution function similar to a gamma distribution [*Wilks and Eggleston*, 1992; *Ropelewski et al.*, 1985]. The P_3 time series is transferred from the gamma distribution to a Gaussian distribution [*McKee et al.*, 1993, 1995]. SPI3 is determined according to the transferred data set. The 6-month SPI (SPI6) can be obtained the same way.

[7] Agricultural drought is measured by the SM deficit [*Keyantash and Dracup*, 2002]. Because there is no long-term SM observational data set available, SM data are taken from the UW NLDAS. The NLDAS uses a suite of land surface models (LSMs). The LSMs are derived by forcing terms, which consist of P, maximum and minimum surface temperatures and surface winds to produce SM, and other surface variables. There are three LSMs in the UW system. They are variable infiltration capacity model (VIC) [*Liang et al.*, 1994, 1996], Noah [*Koren et al.*, 1999; *Ek et al.*, 2003], and Sacramento (SAC) [*Burnash et al.*, 1973]. Model descriptions and properties can be found in the work by *Wang et al.* [2009]. All models are driven by the same forcing.

[8] *Robock et al.* [2003] compared four LSMs from an early version of the National Centers for Environmental Prediction (NCEP) NLDAS. They found that although the differences in SM climatology are large among models, anomalies defined as the departures from the model's monthly mean climatology are much closer to each other. For each model, the monthly mean SM anomalies are obtained by taking out the model's monthly mean climatology. Because the SM anomalies obey a normal distribution function, the SM anomaly percentiles are calculated from the standardized SM anomalies [*Mo*, 2008]. *Dirmeyer et al.* [2006] analyzed model outputs from the Global Soil Wetness Project (GSWP) and found that the ensemble mean SM anomalies are more representative than SM anomalies from individual models. Therefore, the ensemble mean SM percentiles are calculated by taking an equally weighted average of the SM anomaly percentiles from three models.

[9] In this paper, the SPI and SM anomaly percentiles are used to classify drought events. A drought episode is identified when the SPI index is less than −0.8 or the SM percentile is below 25% for one season or longer [*Svoboda et al.*, 2002]. Therefore, both short- and long-term droughts are included in this study. To study the influence of SST on drought, the monthly reconstructed SST data set from *Smith et al.* [1996], updated to 2007, is used. Climatological monthly means are calculated for the base period 1916–2007. Monthly mean SSTAs are defined as the departures from the monthly mean climatology for that month.

[10] The selection of ENSO events is based on the Nino34 index defined as the SSTAs averaged over the tropical Pacific (5°S–5°N, 170°E–240°E). A warm (cold) event is selected when the Nino34 index is greater (less) than 0.5 (−0.5) standard deviations for 3 months or longer. ENSO events from 1950 to the present are listed on the Climated Prediction Center web site (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/).

[11] The impact of ENSO on P over the United States is influenced by the Atlantic Multidecadal Oscillation (AMO). Based on studies by *McCabe et al.* [2004] and *Enfield et al.* [2001], the warm phase of the AMO was present during the periods 1930–1959 and 1995–2006 and the cold phase of the AMO was present during the periods 1915–1925 and 1965–1990 for the study period. The influence is large when the SSTAs in the tropical Pacific and the Atlantic are opposite in phase. The positive (negative) phase of the AMO will enhance the impact of a cold (warm) ENSO on drought (wet spells) over the Great Plains, the Southwest, and the Southeast. The ENSO influence on drought is weak when the SSTAs in the tropical Pacific and the Atlantic are in phase [*Mo et al.*, 2009]. The influence of the North Pacific SSTAs is concentrated over the Pacific Northwest and the Southwest [*Gershunov and Barnett*, 1998].

[12] The United States is divided into 12 regions using the National Weather Service River Forecast Center (RFC) deli-

neations. These regions are appropriate for studying features with large-scale influence as SSTAs because each RFC has a similar hydroclimate. The locations of the 12 RFCs are given in Figure 1c. The monthly mean SPIs or SM percentiles are calculated from P or SM anomalies averaged over each RFC region.

3. Drought Onset and Demise

[13] For a given area, the drought event is selected when the SPI or SM index is below a certain threshold for the duration τ. τ is defined as a time period longer than 3 months. The onset month T_o is the first time that the index falls below the threshold. The demise month T_d is the first time that the index rises above the threshold once the area has been classified as under drought. The threshold for onset is −0.8 for SPI index and 25% for SM. To make sure that the area fully recovers from drought, the threshold for demise is defined as −0.2 for SPI and 35% for SM percentiles. The demise comes quickly; conclusions are not sensitive to slight variations in the threshold.

[14] An example for defining drought onset and demise is given in Figure 1. Figures 1a and 1b show the SPI3 and P anomaly averaged over the Colorado RFC (RFC8) from January 1954 to January 1958, respectively. SPI3 fluctuated between −0.8 and 0.2 from January 1954 to February 1955. The index dropped below −0.8 in April 1955 and stayed below −0.8 for a total of 2 months. The event did not last long enough to be classified as a drought event. In March 1956, the index went below −0.8 and stayed below −0.8 for 10 months. It went positive in January 1957. By May 1957, the index was above 0.8 and the area entered a wet period. For this drought event, the onset month T_o was March 1956, the duration τ was 10 months, and the demise month T_d was January 1957. Before March 1956, there were many months that P anomalies were negative (Figure 1b). The number of months that P is negative before the area is declared under drought can be considered as the transition period leading to the drought onset. The transition period varies from one drought event to another. If the mean transition period leading to drought is long, then the water resource managers can use that information to mitigate the impact of drought during the transition period.

[15] Because monthly mean P anomalies are very noisy, it can be difficult to define the transition period. The transition period leading to the drought onset N_o is determined by counting the number of months that P anomalies are negative from one year before the drought onset to the onset month T_o (T_o − 12 to T_o). One year is chosen as the time interval based on the characteristic time for SPIs. The characteristic time is a measure of persistence [*Trenberth*, 1984; *Mo and Schemm*, 2008a]. For the United States, the characteristic times for SPI3 and SPI6 on average is about 6–12 months. The P anomaly averaged over these months is the mean P anomaly needed for an area to enter drought. For the RFC 8 case in 1956, the transition period N_o was 6 months.

[16] The mean drought duration is on average about 6–7 months. The transition period leading to the drought demise N_d is determined by counting the months that P anomalies are positive from 6 months before the demise to the demise month T_d (T_d − 6 to T_d). The transition period for demise is much shorter than onset. For the 1956 event, the demise of drought came suddenly in January 1957. The transition period leading to the drought demise N_d was only 1month.

[17] The transition periods leading to drought onset (demise) are computed based on SPI3 and SPI6, respectively. The differences in transition periods based on SPI3 and SPI6 are small (Figure 2). In most cases, it takes more than 5 months to accumulate enough P deficit for an area to enter drought, but drought ends quickly within 2–3 months. If the same threshold is used for demise as is used for onset (−0.8 for SPI or 25% for SM), then N_d is only 1 to 2 months (not shown).

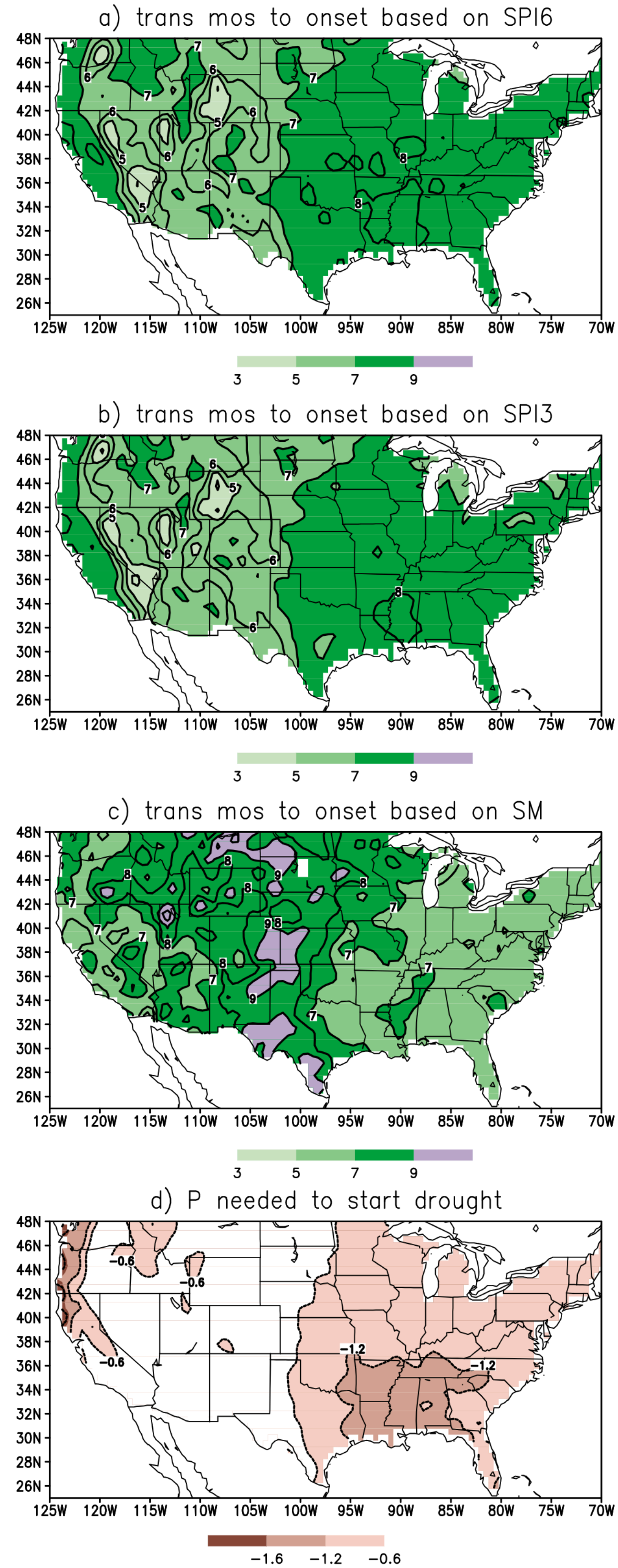
[18] The transition period N_o is about 7–8 months for the wet regions over the eastern United States and the West Coast. The transition period for the western interior states is about 5–6 months. The western interior region is the dry area where drought is more likely to occur and persist [*Mo and Schemm*, 2008a], but the transition period is only slightly shorter than the period for wet areas. If the SM index is used to classify drought, N_o is 7–8 months over the western interior states and is about 6–7 months over the eastern region. The transition period N_d is still about 2–3 months. The longest period N_o is about 10 months over the central United States. These results confirm the common knowledge that drought starts slowly, but can end rather quickly.

[19] The mean P anomaly needed for an area to enter drought averaged over all drought events (Figure 2d) is larger over the West Coast north of 36°N and the Gulf states than the western interior dry region. This pattern is similar to the annual mean P climatology (not shown). The mean P anomaly needed to end drought has a similar pattern, but the values are higher (Figure 2h).

4. Preferred Season for Drought Onset and Demise

[20] Does drought have a preferred season in which to occur or recover? At each grid point, drought events are selected according to SPI6 and SPI3 from 1916 to 2007. This makes it possible to count the number of drought events that started or ended in each season. The ratio of the drought events that start or terminate in each season to the total number of drought events based on SPI6 is given in Figure 3. Results obtained using SPI3 as the indicator are similar. If drought onsets or demises are equally distributed through the year, then the ratio values for a given season should be 0.25. The ratios are statistically significant even though they are small (Figure 3). The maximum value is about 0.4–0.45 for drought onset. This means that 55%–60% of drought events can start in other seasons. The ratios are smaller for demise.

[21] The ratio values given in Figure 3 vary greatly by the region. This is because the P seasonal cycle, which also varies by region, plays a role in determining the preferred season for onset or demise. Drought is more likely to start or end at the beginning of the rainy season. Over the Northern Plains, including eastern Montana, eastern Wyoming, and the Dakotas, droughts are more likely to start or end in



a) trans mos to onset based on SPI6
e) trans mos to demise based on SPI6
b) trans mos to onset based on SPI3
f)trans mos to demise based on spi3
c) trans mos to onset based on SM
g) trans mos to demise based on sm
d) P needed to start drought
h) P needed to end drought

Figure 2

April–June (April, May, June; AMJ) (Figures 3b and 3f). For that region, the P maximum occurs in May and June and winter is their dry season (Figure 4a). The spring season (AMJ) is the transition season from the dry to the wet season.

[22] The Southwest has two rainy peaks, but the summer monsoon rainfall gives the larger contribution to the annual mean (Figure 4e).The monsoon season lasts from July to September, which corresponds to the preferred season for drought onset or demise. To determine whether drought is more likely to occur in the beginning or at the end of the monsoon season, the ratio of drought events that start or terminate in each month from June to October to the total number of drought events based on SPI3 is determined. July is the preferred month for the onset and demise of drought (not shown). That is consistent with findings by *Gutzler* [2004] that an early (late) start to the monsoon season often signals a strong (weak) monsoon.

[23] Over the West Coast, rainfall starts for the Pacific Northwest in October and November and spreads to California in December (Figures 4b and 4d). The P maximum occurs in winter. Drought is more likely to start or end in the transition season, October–December (October, November, December; OND).

[24] For agricultural drought, drought onset (demise) is determined based on the SM percentiles. The ratio of the number of drought events that start or terminate in each season to the total number of drought events is given in Figure 5. The ratio values are higher than these for meteorological drought. For the Southwest and California, the preferred season for drought to start or end is similar to those for meteorological drought. The values are 0.6 or higher for onset. For demise, the values are slightly lower. For the northwestern interior region (42°N–48°N, 100°W–120°W), the sources of SM include both rainfall and spring snowmelt. Both reach a maximum in April–June (Figure 4f), which is the preferred season for drought to occur. For the Northern Plains, the preferred season for drought to occur is July–September even though the maximum rainfall occurs in May and June (Figure 4a). Figure 2 indicates that the transition period leading to the drought onset for the central United States is longer than other regions. The strong land-atmosphere interaction may play a role for the delay.

[25] The SPI is the indicator for meteorological drought, and the SM anomaly percentile index is the indicator for agricultural drought [*Keyantash and Dracup*, 2002]. The question is whether the two indices are able to capture the same drought events. The simultaneous correlation between SPI6 and SM percentiles for the period 1916–2007 is over 0.7 for most regions except areas over the interior mountains and the Pacific Northwest (Figure 6a). The simultaneous correlations are higher than the correlations, with SM lagging by 1 month (Figure 6b). This suggests that the two indices are on the same time scales. The ratio of the number of months that both SPI6 and SM percentiles indicate drought to the number of months that either index indicates drought is roughly 60%–70% (not shown). Most strong meteorological drought events are also classified as agricultural drought events.

[26] A high correlation does not imply that meteorological and agricultural droughts will start at the same time. For the same drought event, the onset of meteorological drought occurs a few months earlier than agricultural drought. The interval between two drought events is difficult to predict statistically. It depends on the season and location. It also depends on the SM deficit just before the onset of meteorological drought. The onset dates for meteorological and agricultural drought events are determined. Figure 6c shows the ratio of the number of cases that the onset of agriculture drought events lags behind the onset of meteorological drought events by 0–6 months to the total number of meteorological events. Over the eastern United States, the ratio varies from 20% to 40%. Over the western region, the ratio is only 10%. There are less than 10% cases in which the onset of agriculture drought occurs before meteorological drought (Figure 6d).

5. Influence of the SSTA Forcing

[27] Both observations and model experiments indicate that drought over the United States is modulated by ENSO. The question is whether ENSO will trigger or end drought. The atmospheric responses to ENSO are often large scale in nature. Therefore, the impact of SSTAs on drought will be examined for droughts in the RFC areas.

[28] For each RFC, P is averaged over the RFC domain (Figure 1c) and the SPI indices are computed. When the SPI6 index drops below −0.8 for longer than 3 months, the area is identified as being under drought. The onset and demise months are then identified for each drought event. The monthly mean SSTAs are averaged over the duration of each drought event. If the composite shows negative (positive) SSTAs of less than −0.5°C (greater than 0.5°C) in the tropical Pacific, the drought event is considered to be influenced by cold (warm) ENSO. Additional SSTA composites are prepared using only ENSO-influenced drought events from $T_o - 2$ to T_o, where T_o is the onset month. For drought demise, a second set of composites is made for these ENSO-influenced events from T_d to $T_d + 2$, where T_d is the demise month.

Figure 2. (a) Number of months that P anomaly is negative from one year before the drought onset to the drought onset. Drought events are selected based on SPI6. The contour interval is one month. (b) Same as Figure 2a but for drought events selected based on SPI3. (c) Same as Figure 2a but for drought events selected based on SM percentiles. (d) P anomalies needed to start drought averaged over all drought events. Drought is selected based on SPI3. The contour interval is 0.6 mm day^{-1}. (e) Same as Figure 2a but for the number of months that the P anomaly is positive from 6 months before the drought demise month to the drought demise. Events are selected based on SPI6. (f) Same as Figure 2e but for drought events selected based on SPI3. (g) Same as Figure 2e but for drought events selected by the SM percentiles. (h) Same as Figure 2d but for P anomalies needed to end drought defined by SPI3 averaged over all drought events.

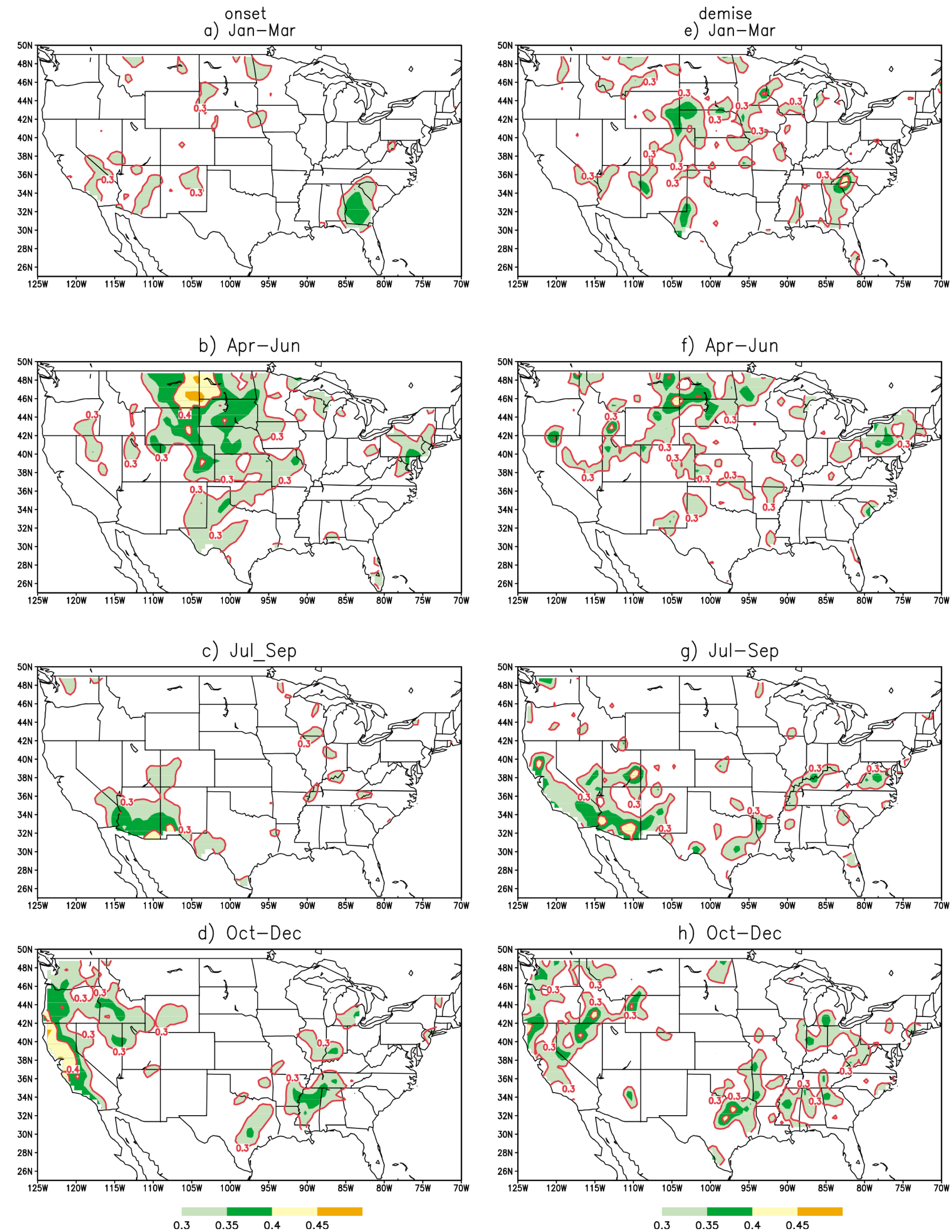


Figure 3. Ratio of the number of drought onsets occurring in (a) January–March (JFM), (b) April–June (AMJ), (c) July– September (JAS), and (d) October–December (OND) to the total number of drought events. The contour interval is given by the color bar. Values less than 0.3 are omitted. (e–h) Same as Figures 3a–3d but for drought demise. Droughts are classified according to SPI6.

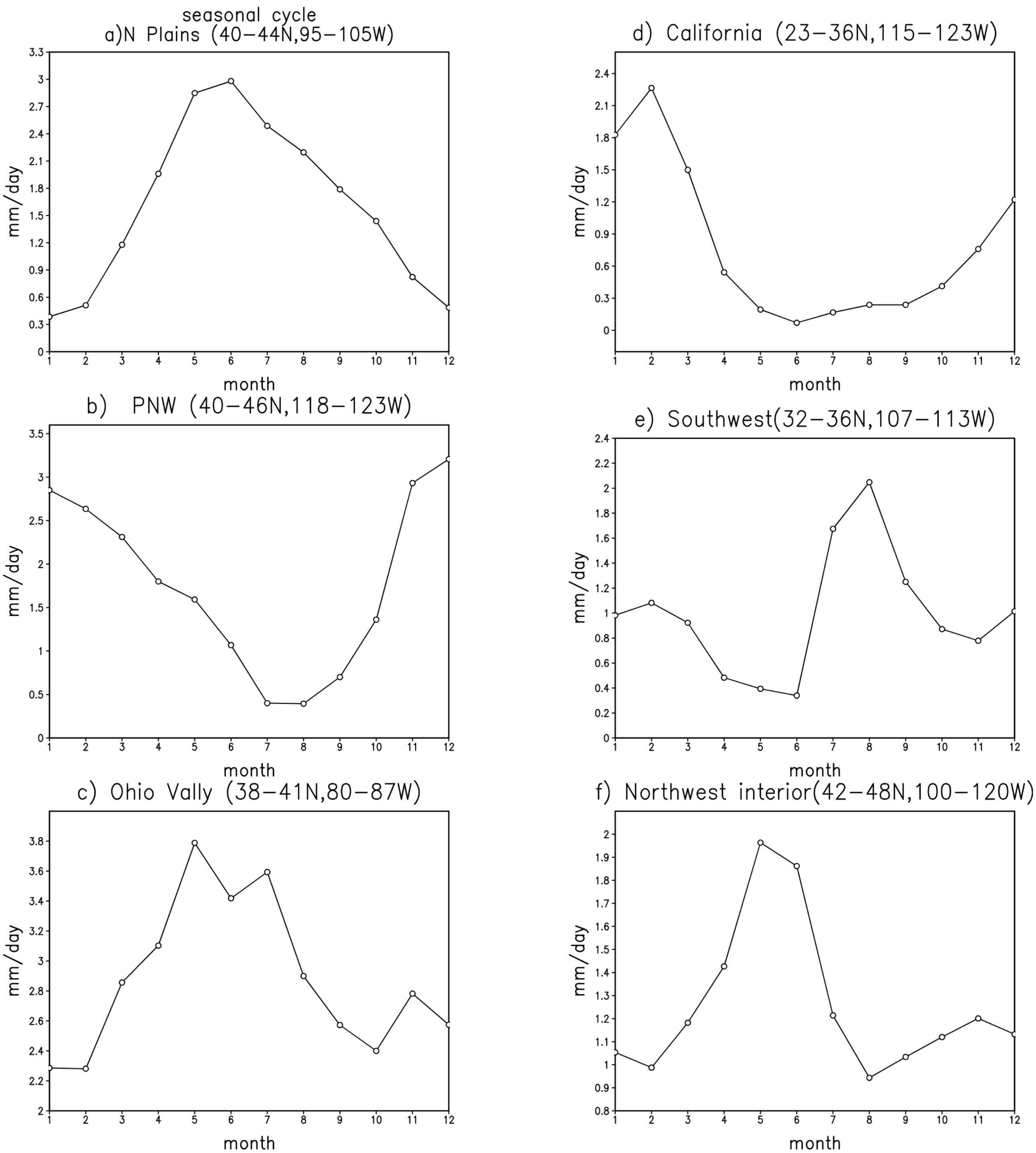


Figure 4. Seasonal cycle of precipitation monthly mean climatology averaged over (a) the Northern Plains (40°N–44°N, 95°W–105°W), (b) the Pacific Northwest (40°N–46°N, 118°W–123°W), (c) the Ohio Valley (38°N–41°N, 80°W–87°W), (d) California (23°N–36°N, 115°W–123°W), (e) Southwest (32°N–36°N, 107°W–113°W), and (f) the Northwest interior region (42°N–48°N, 100°W–120°W).

[29] In addition to ENSO, the North Pacific and the decadal AMO can modulate the impact of ENSO on drought, but their direct impact on drought is more regional [*Schubert et al.*, 2009; *Mo et al.*, 2009; *Gershunov and Barnett*, 1998]. The influence of the North Pacific SSTAs is to modulate the impact of ENSO on *P* over the Pacific Northwest (RFC1) and the Southwest (RFC8). The influence of the AMO is to modulate the impact of ENSO on *P* over the Great Plains (RFC9 and RFC10), the Southwest (RFC8), and the Southeast (RFC10). The influence of both the AMO and the North Pacific SSTAs on drought will be discussed together with the impact of ENSO.

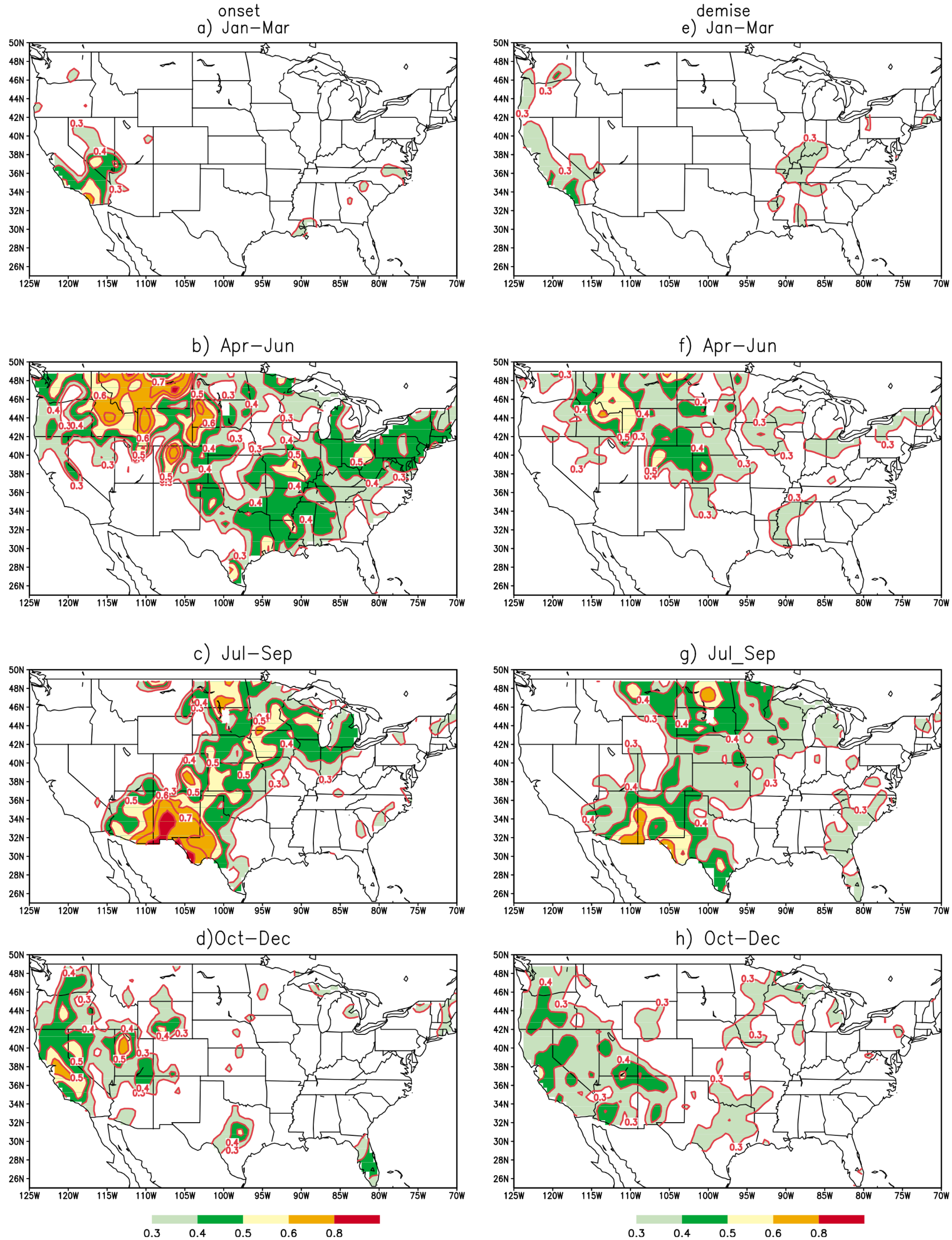


Figure 5. Same as Figure 3 but droughts are classified based on SM percentiles.

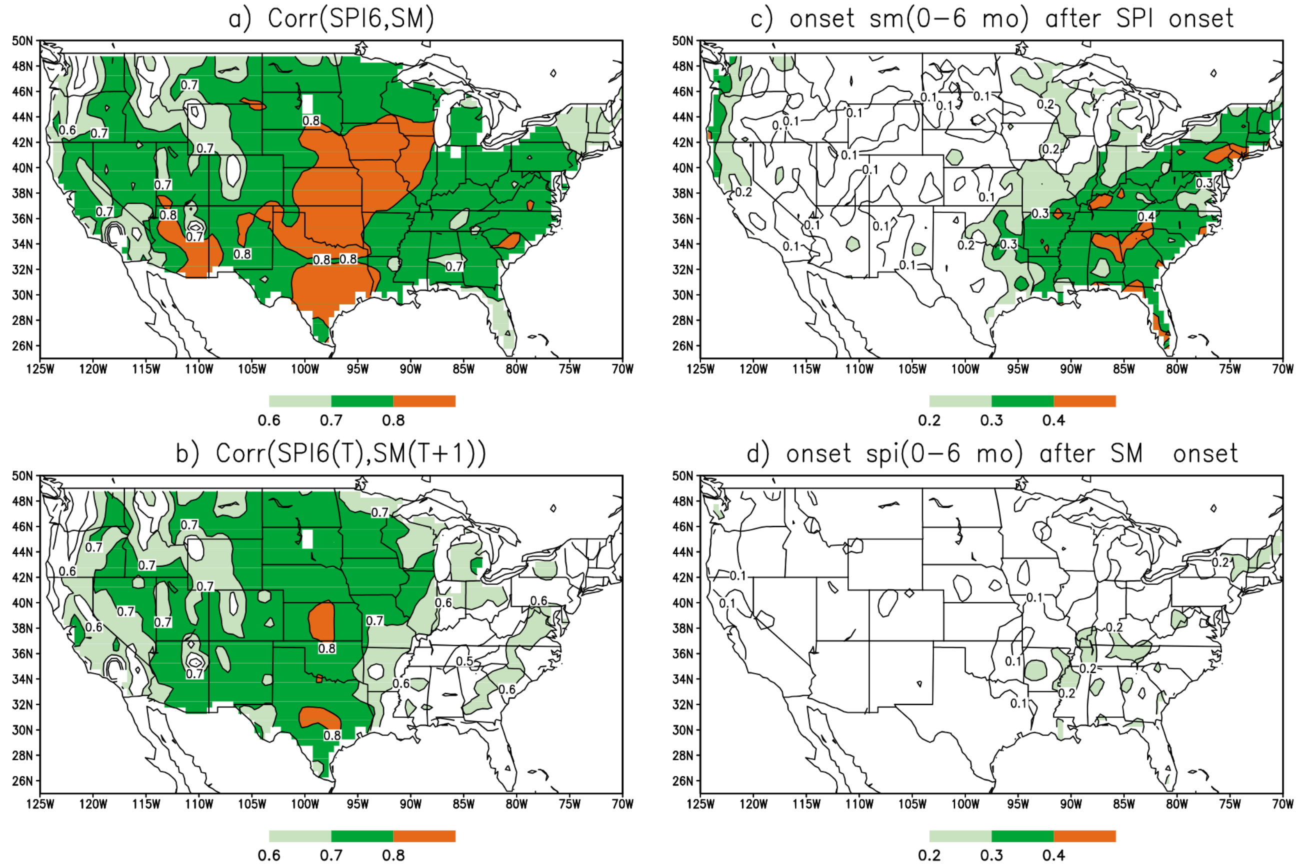


Figure 6. (a) Correlation between SPI6 and SM percentiles. The contour interval is 0.1. (b) Same as Figure 6a but with SM lagging behind a month. (c) The ratio of the number of agricultural drought events occurring 0–6 months after the meteorological drought events to the total number of the meteorological drought events. The meteorological drought events are selected based on SPI6. The contour interval is given by the color bar. (d) Same as Figure 6c but for the ratio of the number of agricultural drought events occurring 0–6 months before the meteorological drought events to the total number of the meteorological drought events.

[30] For each RFC, the number of drought events, the mean duration, and the number of drought events under the influence of cold and warm ENSO events are given in Table 1.

[31] On average, there are about 23 drought events per RFC for the study period, and the mean duration is 7.12 months. To see whether drought events occur at regular intervals, the recurrent time, defined as the period between the demise of drought to the onset of the next drought event, is computed for each RFC. For each RFC, the mean recurrent time for drought is given in Table 1. Droughts do not occur at regular intervals. Overall, the mean recurrent time is 47.6 months.

5.1. ENSO as an Early Warning for Drought

[32] For the Southern Plains (Arkansas RFC9 and West Gulf RFC10), more than 85% of drought events occur during cold ENSO episodes. No drought events occur during warm ENSO episodes. For the Arkansas RFC, 17 of the 20 drought events occur during a cold ENSO event. Four of these 17 events occur during the cold phase of the AMO. Eleven events occur during the warm phase of the AMO. For the West Gulf RFC, 17 of the 21 drought events occur during a cold ENSO event. Thirteen events occur during the warm AMO phase and four events occur in the cold AMO phase. The AMO does not influence the onset or demise of drought, but it increases the probability for drought to occur when the AMO is in the warm phase, consistent with the

Table 1. Number of Drought Events, Mean Duration, and Number of Events in Warm and Cold ENSO Years

RFC	Number of Drought Events	Duration (month)	Recurrent Time (month)	Number of Events in Warm ENSO	Number of Events in Cold ENSO
1. Northwest	23	6.8	38.7	14	6
2. Missouri	21	7.2	45.5	5	13
3. North-central	22	6.7	42.3	6	10
4. Ohio	22	6.6	42	12	5
5. Northeast	21	5.2	53.2	5	5
6. Mid-Atlantic	25	7.2	48.8	5	8
7. California	27	6.8	48	5	8
8. Colorado	21	7	56.2	5	10
9. Arkansas	20	7.8	56.7	0	17
10. West Gulf	21	8.8	47.4	0	17
11. Mississippi	22	8.5	53.1	5	15
12. Southeast	26	6.9	40.2	5	17

findingd of *Mo et al.* [2009]. Does drought always occur during cold ENSO years? For RFC10, drought occurred in every cold ENSO event except the 1988–1989 case for the study period. For RFC9, drought occurred in every cold ENSO event before 1979. After that, drought occurred in two of four cold ENSO events.

[33] Figures 7a and 7b show the SSTA composites for the ENSO-influenced events before onset for RFC9 and RFC10, respectively. Both show that the negative SSTAs are already established before the onset of drought for these two RFCs. Therefore, it seems that during a cold event, conditions are favorable for *P* deficit to occur over the Southern Plains. After a few months of negative *P* anomalies, drought starts. For these RFCs, the establishment of a cold ENSO event can serve as an early warning signal for drought. The SSTA composites for the ENSO-influenced events during demise show no significant SSTAs in the tropical Pacific (Figures 7e and 7f). When there is no ENSO forcing in the tropical Pacific, drought recovers.

5.2. ENSO as a Signal for Drought Watch

[34] For the Mississippi basin (RFC11) and the Missouri RFC (RFC2), drought is likely to occur during cold ENSO events. For the Southeast (RFC12), drought is more likely to occur during cold ENSO events in winter. For the Pacific Northwest (RFC1) and the Ohio Valley (RFC4), drought is likely to occur during warm ENSO events. Unlike the Southern Plains, there are drought events during the opposite phase of ENSO and there are many ENSO years with no drought occurrence. Therefore, for these five RFCs, ENSO can serve as a signal only for the need of intensive drought watch. Forecasters need to pay attention to the *P* and SM deficits and *P* forecasts for the coming months before issuing a drought warning.

[35] For the lower Mississippi basin (RFC11), there is a total of 22 drought events, with 15 events occurring during a cold ENSO. There are 5 drought events that occur during warm ENSO years. The SSTA composite for these 15 events influenced by cold ENSO events (Figure 7c) indicates that the cold SSTAs are established before drought onset. The composite of SSTAs at the drought demise indicates that drought diminishes when the cold ENSO event has weakened considerably and conditions become ENSO neutral (Figure 7g). When these drought events are examined individually, 9 of the 15 drought events show a weakening of SSTAs in the central Pacific before the drought demise. For the other 6 events, negative SSTAs are still located in the central Pacific.

[36] For the Missouri RFC (RFC2), there are 21 drought events; 13 events occur during cold ENSO events and 5 events occur during warm ENSO events. The composite of the 13 events influenced by the cold ENSO episodes shows that most drought events start after the establishment of the cold ENSO (Figure 7d). It also shows negative SSTAs along the West Coast and positive SSTAs in the North Pacific. The composite of SSTAs for the 13 events influenced by ENSO during the demise phase of drought shows that the cold ENSO weakens, but negative SSTAs are still located in the tropical Pacific.

[37] The next two RFCs are influenced by warm ENSO events. The Pacific Northwest RFC (RFC1) has 23 drought events. Fourteen events occur during warm ENSO episodes. Six drought events occur during cold ENSO events. For RFC1, drought is modulated not only by ENSO but also by the SSTAs in the North Pacific or the Pacific Decadal Oscillation [*Gershunov and Barnett*, 1998]. The composite for 14 events influenced by warm ENSO (Figure 8a) indicates that warm SSTAs are located in the central Pacific before the onset of drought. It also shows negative SSTAs in the North Pacific and warm SSTAs along the West Coast. The composite of SSTAs near the drought demise indicates that SSTAs are weaker, but positive SSTAs are still located over the central Pacific (Figure 8c).

[38] For the Ohio RFC (RFC4), there are 22 drought events, and 12 of them occur during warm ENSO years. The composite of these 12 events indicates that warm SSTAs are located in the tropical Pacific before the onset of drought. During the drought demise, the warm SSTAs move to the central Pacific.

[39] For the Southeast (RFC12), the relationship between ENSO and drought is seasonally dependent. Drought is more likely to occur during a cold ENSO event in winter. For summer season, a cold ENSO event favors an active tropical storm season that will bring rainfall to the region [*Mo and Schemm*, 2008b]. There is a total of 26 drought events, and 17 events start in the extended winter (October–March). The composite of these 17 events shows cold SSTAs in the tropical Pacific before the drought onset. Figure 9a also shows warm SSTAs in the Atlantic consistent with the influence of the AMO. The composite of SSTAs during the demise phase of drought shows neutral ENSO conditions in the Pacific. There are also nine drought events that occur during summer. Five of them occur during a warm ENSO event in summer. However, the composite of SSTAs of these five events does not pass the field statistically significant test (Figure 9c).

[40] For the Colorado Basin RFC (RFC8), statistics do not indicate a strong influence of ENSO on drought (Table 1) because drought events are selected according to the SPI6 calculated from the mean rainfall over the entire basin. For the upper Colorado Basin (north of 36°N), rainfall is suppressed during a cold ENSO event in the warm phase of the AMO [*Mo et al.*, 2009]. Rainfall over the lower Colorado Basin in Arizona is dominated by the summer monsoon. Monsoon rainfall is influenced by both ENSO and the SSTAs in the North Pacific [*Castro et al.*, 2001; *Higgins and Shi*, 2000].

[41] For the other RFCs, the impact of ENSO on drought is either not strong or is not systematic. Therefore, ENSO cannot be used as an indicator for drought.

6. Conclusions

[42] This paper employs the time series of precipitation analysis and ensemble mean SM data sets from the NLDAS obtained from the University of Washington to study drought onset and demise over the United States. Meteorological drought classified using the SPI indices and agricultural drought classified using SM percentiles are studied.

[43] Drought onset is more predictable than drought demise because it takes longer to occur. It takes 5–6 months to accumulate enough of *P* deficit for the western interior region to enter drought. Over the eastern region and the West Coast, the transition period to onset is about 7–8 months.

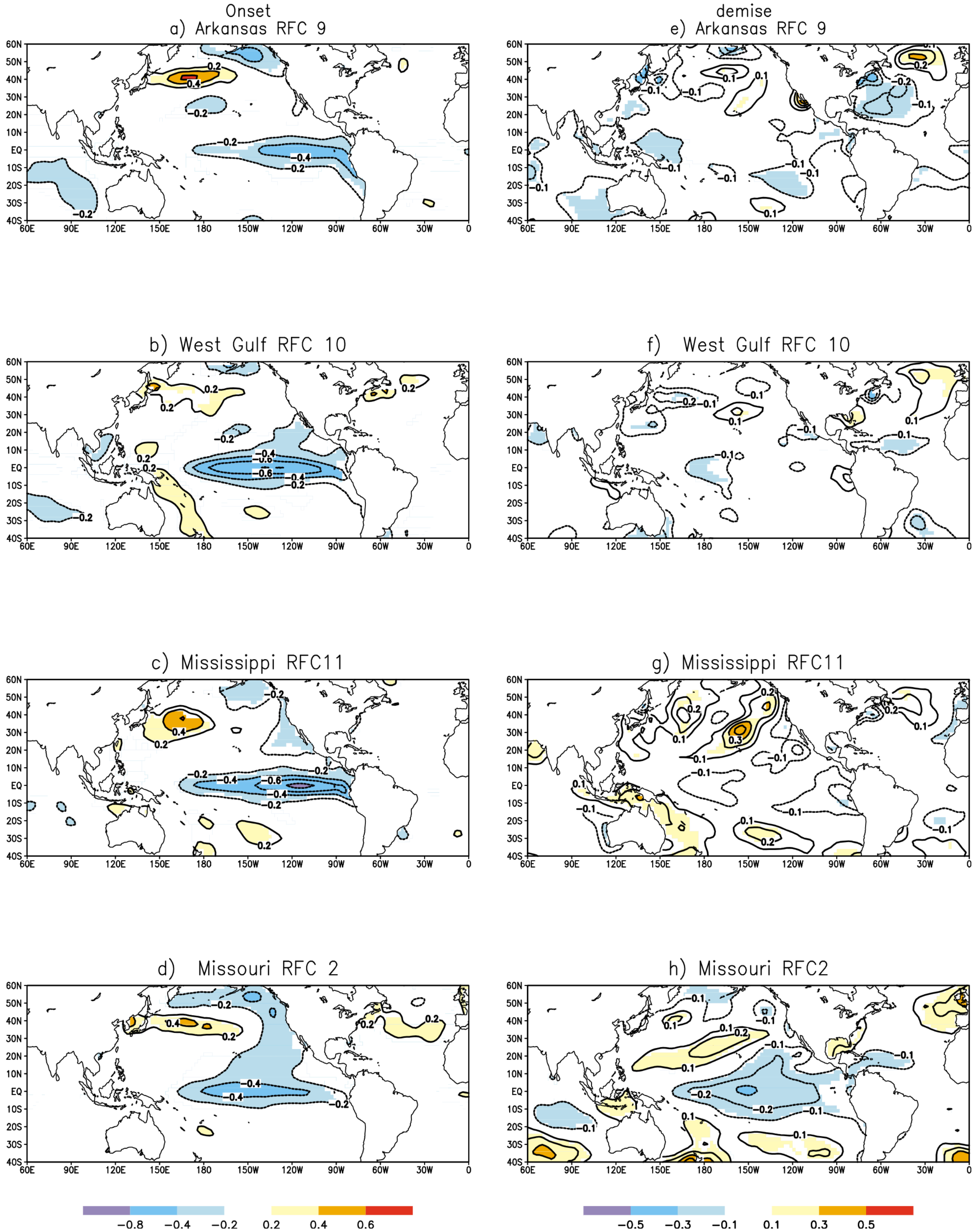


Figure 7. Composite of SSTAs over the period from 2 months before the onset to the onset for the drought events influenced by the cold ENSO events for (a) the Arkansas RFC9, (b) the West Gulf RFC10, (c) the Mississippi RFC11, and (d) the Missouri RFC2. The contour interval is 0.2°C. Areas where values are statistically significant at the 5% level determined by the student *t* test by assuming that each event is one degree of freedom are shaded. (e–h) Same as Figures 7a–7d but for the composites of SSTAs from the demise to 2 months after the demise month. The contour interval is 0.1°C.

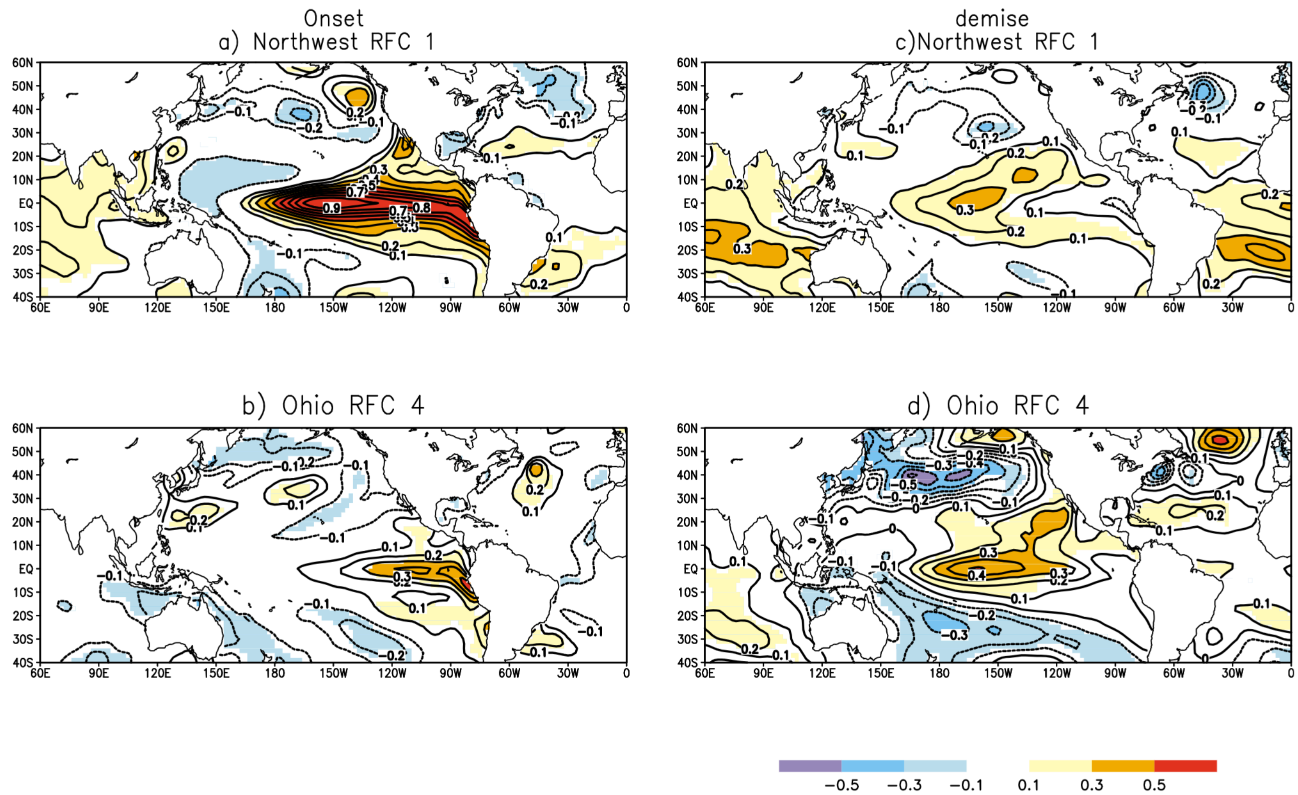


Figure 8. (a) Same as Figure 7a but for drought influenced by the warm ENSO for the Northwest RFC1. (b) Same as Figure 8a but for the Ohio RFC4. (c–d) Same as Figures 8a and 8b but for the composites of SSTAs from the demise to 2 months after the demise. The contour interval is 0.1°C.

However, drought demise comes within 2 to 3 months. A few strong raining episodes can end drought, which makes the demise of drought difficult to predict.

[44] Meteorological drought over the United States prefers to start at the beginning of the rainy season. However, although drought has a preferred season to begin, it does not mean that is the only season in which drought will occur. The ratio between the onsets occurring in that season and the total drought events is less than 45%. This means that 55% of drought events can start in other seasons. The ratio values for drought demise are less. For agricultural drought, the ratio values are larger than 60% for the northwestern interior states, including the Dakotas, eastern Wyoming, eastern Montana, and the Southwest. For the northwestern interior states, the preferred season for drought to start or end is spring. For the Southwest, the preferred season for drought onset and demise is in July at the beginning of the monsoon season. For the Northern Plains, the preferred season is July–September. Agricultural drought often occurs a few months after meteorological drought. The interval between them is difficult to predict. It depends on the location and the timing of drought. It also depends on the historical record of SM before the onset of meteorological drought.

[45] Drought over the United States is modulated by ENSO. However, ENSO development can be used as an early warning signal for drought for two RFCs over the Southern Plains. For these RFCs, a cold ENSO event is established at least one season before the onset of drought and no drought occurs during warm ENSO. When the ENSO weakens, drought improves. The AMO does not influence the onset and demise of drought, but it increases the chance for drought to occur over the Southern Plains when the AMO is in the warm phase during cold ENSO events.

[46] Over the Missouri and the Mississippi RFCs, drought is more likely to occur during cold ENSO episodes while the majority of drought events occur during warm ENSO episodes for the Ohio Valley and the Pacific Northwest RFCs. For the Southeast, the relationship between ENSO and drought holds during winter. Drought is more likely to occur during a cold ENSO episode in winter. For these five regions, ENSO occurs at least one season prior to the onset of drought. However, drought can also occur in the opposite phase of ENSO. Therefore, ENSO can be viewed as only one factor that triggers drought. Other information is needed in collaboration in order to issue a warning for drought. For example, if *P* deficit increases during a cold ENSO year for the Mississippi RFC, then that may be a precursor for drought onset. One reason that the correspondence between ENSO and drought is not as good as the RFCs over the Southern Plains is that drought over these five regions is also influenced by the North Pacific SSTAs and the AMO.

[47] The relationship between ENSO and the drought demise is not clear for these five RFCs. There are cases in which drought diminishes when ENSO weakens; however, there are also cases in which drought ends during an ENSO event. Demise of drought can occur quickly after a few rainfall events and it is more difficult to forecast.

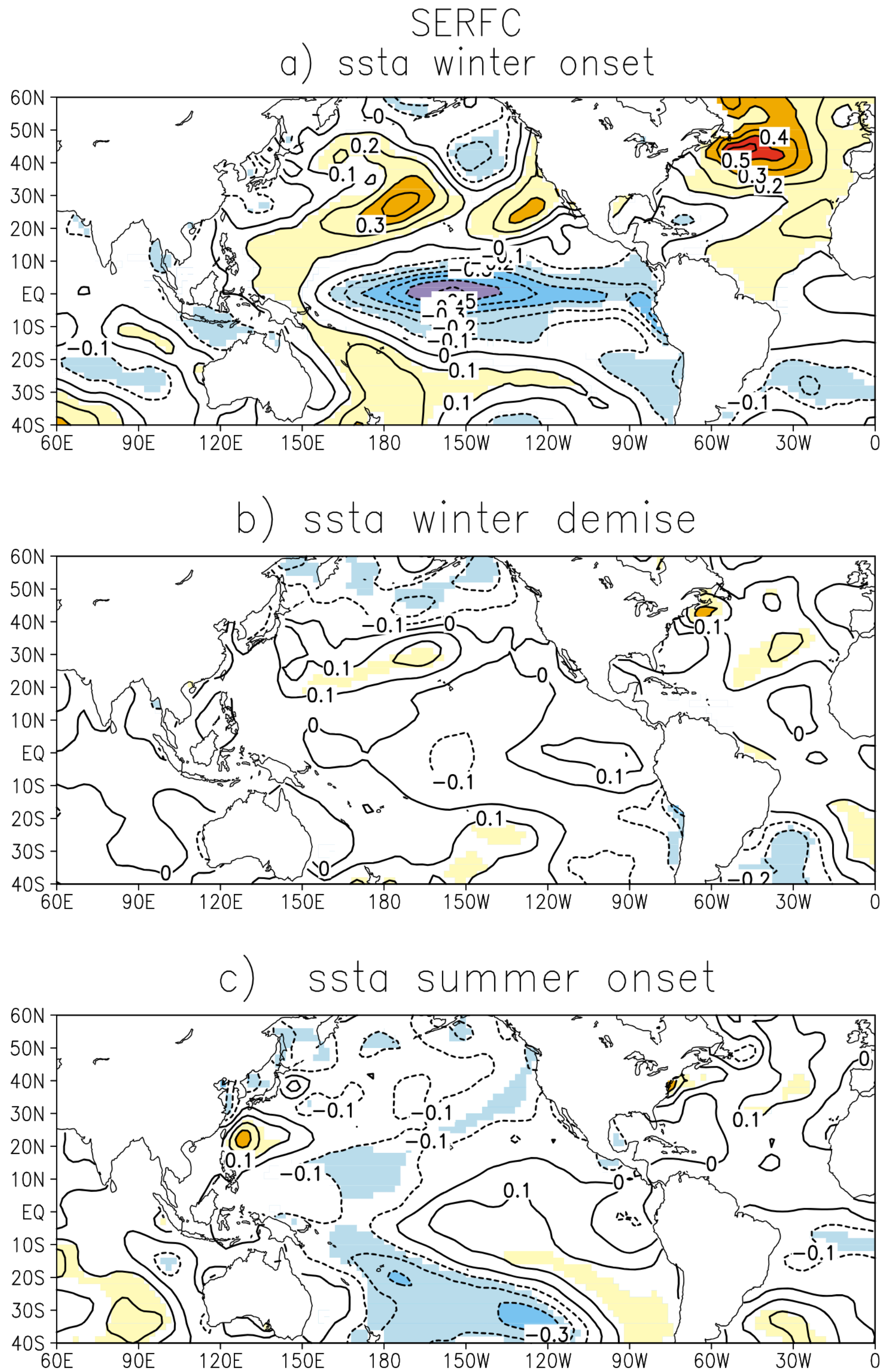


Figure 9. (a) Same as Figure 7a but for winter drought events influenced by the cold ENSO events for the Southeast RFC12. (b) Same as Figure 9a but for the composite of SSTAs from the demise of the winter drought events to 2 months after the demise. (c) Same as Figure 9a but for summer drought events. The contour interval is 0.1°C.

[48] **Acknowledgments.** I wish to thank Lindsey Long for carefully reading the manuscript. The NLDAS data were obtained from the University of Washington. This project is supported by the NOAA (CPPA) grant NA09OAR4310189.

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