Objective Drought Classification Using Multiple Land Surface Models

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ABSTRACT

The current generation of drought monitors uses physically based indices, such as the standardized precipitation index (SPI), total soil moisture (SM) percentiles, and the standardized runoff index (SRI) to monitor precipitation, soil moisture, and runoff deficits, respectively. Because long-term observations of soil moisture and, to a lesser extent, spatially distributed runoff are not generally available, SRI and SMP are more commonly derived from land surface model–derived variables, where the models are forced with observed quantities such as precipitation, surface air temperature, and winds. One example of such a system is the North American Land Data Assimilation System (NLDAS). While monitoring systems based on sources like NLDAS are able to detect droughts, they are challenged by classification of drought into, for instance, the D0–D4 categories used by the U.S. Drought Monitor (USDM), in part because of uncertainties among multiple drought indicators, models, and assimilation systems. An objective scheme for drawing boundaries between the D0–D4 classes used by the USDM is explored here. The approach is based on multiple SPI, SM, and SRI indices, from which an ensemble mean index is formed. The mean index is then remapped to a uniform distribution by using the climatology of the ensemble (percentile) averages. To assess uncertainties in the classification, a concurrence measure is used to show the extent to which the different indices agree. An approach to drought classification that uses both the mean of the ensembles and its concurrence measure is described. The classification scheme gives an idea of drought severity, as well as the representativeness of the ensemble mean index.

1. Introduction

Drought is one of the costliest natural disasters in the United States, with average losses exceeding $10 billion per event (NCDC 2011). Better real-time monitoring has the potential to assist local and federal governments in the allocation of resources to mitigate drought impacts (Hayes et al. 2004). Drought indices are often used for drought monitoring (e.g., Mo 2008; Shukla et al. 2011). Because there are many aspects of drought, no single index is appropriate for monitoring all aspects of drought (Keyantash and Dracup 2002). Among the various objective measures that have been used to assess drought are standardized precipitation indices (SPIs) at different time scales (accumulation intervals), which are measures of meteorological drought (McKee et al. 1993, 1995); soil moisture (SM) percentiles (SMPs), which measure agricultural drought; and standardized runoff indices (SRIs) on different time scales (Mo 2008; Shukla and Wood 2008), which are measures of hydrological drought.

As a result of the sparseness of observations of SM and the complexities of the relationships between (spatially distributed) runoff and observed streamflow, the use of model-derived SM and runoff from efforts like the North American Land Data Assimilation System (NLDAS) (Mitchell et al. 2004; Xia et al. 2012) and extensions thereof by Maurer et al. (2002) and Livneh et al. (2013) have become popular. The Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) and the University of Washington (UW) both routinely produce hydroclimate fields, including soil moisture and runoff, from NLDAS-derivative systems in near–real time with 1–3 days latency that support the U.S. Drought Monitor (USDM; Svoboda et al. 2002).
Current drought monitoring systems (e.g., the UW and NCEP systems) are able to detect droughts but are challenged by the classification of drought into, for instance, the D0–D4 categories used by the USDM, in part because of variations among multiple drought indicators, different land surface models, and forcings. Mo et al. (2012) compared the NCEP and UW products, which use different land surface models and forcing data. They found that the SM and runoff differences between systems are larger over the western than the eastern United States, and in general, the differences were too large to support drought classification. The differences between the two sets of products were mostly attributable to differences in the precipitation datasets that force the models to produce the drought indicators. Errors in other model forcings had a much more modest effect.

While all drought indices are able to detect drought at the peak of a drought event, agricultural drought (defined by the depletion of SM) can lag meteorological drought by a few months (Mo 2011). The interval between the onset and demise of meteorological and agricultural droughts depends on the season and location. It also depends on the SM accumulation, evapotranspiration, and surface conditions. This implies that the inferred onset of drought may also depend on the index used to classify drought. Hao and AghaKouchak (2014) have recently introduced a multivariate multi-index drought monitoring approach. They derived a drought index based on the joint distribution of the SPI and SMP to avoid the index dependency of drought detection. They argue that the new index has a higher drought detection rate than any individual index.

We propose here to use a concurrence measure in combination with the adjusted mean of multiple drought indices to address the uncertainties in multimodel and multi-index drought classification. In so doing, we evaluate 18 indices from the two NLDAS systems noted above. As in past studies (e.g., Shukla et al. 2011; Wang et al. 2009), we represent all indices as percentiles. Following Milly et al. (2005), we define a concurrence measure as the fraction of indices that agrees with the grand mean index. The grand mean index condenses information from the various component indices and the concurrence among which is dependent on geographic differences in the climate forcings, indicates the robustness of the grand mean index. The drought concurrence should always be used together with the grand mean for drought classification. To monitor hydrologic or agricultural drought, we can apply the same procedures to form the mean 3-month SRI (SRI3) or SMP index and the corresponding concurrence measure. In addition to giving users a basis for assessing the representativeness of the mean index, it also provides risk managers with best and worst scenarios (based on the range of drought severity classes associated with the individual model and index classifications) and a basis for estimating the probability of occurrence of each scenario.

Shukla et al. (2011) evaluated a drought monitoring system for Washington based on indices from the UW NLDAS. They found that the reconstructed drought index–based system was able to detect drought a few months before state declarations of drought emergency. We evaluate here whether the grand mean index with the concurrence measure can also provide early warning of drought, specifically using as examples the 2007–08 drought over the Southeast, the 1988–89 drought over the eastern United States and the North Central region, and the 2000–05 multiple drought episodes over the western United States.

We briefly describe data used and procedures in section 2. The hydroclimate of the United States has a strong east–west contrast. The western United States, aside from the coastal regions, is arid to semiarid and has a large water-holding capacity (Wang et al. 2009), and for this reason, droughts in this region are more likely to persist than in the east. Past studies (e.g., Wang et al. 2009; Mo et al. 2012) have shown less concurrence among models in this region than in the wetter eastern United States. Another key difference between the eastern and western parts of the continental United States (CONUS) domain is that precipitation in the east has a weaker seasonal cycle, so drought in one season is more likely to be relieved by rain in another season. In section 3, we evaluate our proposed drought classification scheme by using the three examples noted above. Conclusions and discussion are given in section 4.

2. Data and procedures

a. Data

Retrospective simulations from the NCEP and UW NLDAS systems for the period from January 1979 to November 2012 are the basis for our study.

1) THE UW SYSTEM

Precipitation (P) and temperature forcings for the UW system were derived from a set of index stations
(Wood and Lettenmaier 2006; Mo et al. 2012). The index stations, totaling about 2400 over the CONUS, were selected based on data quality and stability of the stations. These stations are a subset of the National Climatic Data Center’s (NCDC) Cooperative Observer stations (Andreadis et al. 2005). The station reports include all precipitation that gets into the gauge. The other model forcing variables were derived from the daily temperature and temperature range. Downward solar and longwave radiation and humidity were estimated using the mountain microclimate simulator (MTCLIM) approach of Hungerford et al. (1989; see also Bohn et al. 2013). Surface wind was taken from the NCEP–NCAR reanalysis (Kalnay et al. 1996).

We included the same four land surface models (LSMs) in the UW multimodel system used by Wang et al. (2009): Variable Infiltration Capacity (VIC) 4.0.6 (Liang et al. 1994), Noah 2.8 (Koren et al. 1999; Ek et al. 2003), Sacramento/SNOW-17 (SAC) (Burnash et al. 1973; Anderson 1973), and the Community Land Model 3.5 (CLM3.5; Oleson et al. 2007). Model descriptions and properties can be found in Wang et al. (2009).

2) THE NCEP SYSTEM

Precipitation forcing for the NCEP system was derived from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) unified precipitation analysis (Xie et al. 2010). The P input for the NCEP system was taken from the CPC/Office of Hydrologic Development 0.125° daily precipitation gauge dataset. The other variables were taken from the North American Regional Reanalysis (NARR; Mesinger et al. 2006). For surface variables, 2-m temperature and specific humidity and 10-m winds were used. The data were adjusted to the surface for terrain height (Cosgrove et al. 2003), and biases in the NARR downward solar radiation climatology were corrected using satellite observations from Pinker et al. (2003).

The NCEP system also has four land surface models: VIC, Noah, SAC, and Mosaic. Detailed descriptions and configurations of the NCEP system are given by Xia et al. (2012). (Updates to the NCEP system are documented at http://ldas.gsfc.nasa.gov/ndl/md/NLDAS2forcing.php.)

b. Grand mean index

Our study domain was the CONUS, which all models represented at a horizontal resolution of 0.5°. We used a common period of the NLDAS systems from January 1979 to November 2012. From monthly mean P datasets from the UW and the NCEP systems, we computed the corresponding 6-month Standardized Precipitation Index (SPI6) by using the procedures developed by McKee et al. (1993, 1995) and converted to percentiles. For each LSM, we computed drought indices from the time series for runoff and total soil moisture as percentiles: SMP from the soil moisture data and 3-month SRI (SRI3) from the runoff data as outlined in Shukla and Wood (2008).

Our analysis was based on a total of 18 monthly mean time series: two for precipitation (SPI6 previous 6-month accumulation), eight for SM (one for each LSM), and eight for runoff (also one for each model, accumulated over the previous 3 months). These variables were selected in part because they are roughly on the same time scales. There are systematic differences between the UW and the NCEP systems (Mo et al. 2012), so we selected the same number of indices (nine) from each system. To account for the different characteristics of indices, we also selected the same number (eight members) of SRI3 and SMP. In addition, we wanted to represent the effects of uncertainties in precipitation, one of the key drivers of droughts, so we used precipitation from the UW and the NCEP systems.

The grand mean is the equally weighted ensemble mean of all 18 indices. We then remapped the grand mean index to a uniform distribution using the empirical cumulative distribution function of the percentile average. The grand mean index therefore has a uniform distribution ranging from 0 to 1, as do each of the individual indices. The same procedure can be applied to the SRI3 ensemble mean [SRI3(en)] with eight members, the SMP ensemble mean [SMP(en)] with eight members, and the SPI6 ensemble mean [SPI6(en)] with two members. All indices were converted to percentiles.

We classified the grand mean index at each grid cell and at each time step into six categories: above 30% (no drought), 20%–30% (abnormally dry, D0), 10%–20% (moderate drought, D1), 5%–10% (severe drought, D2), 2%–5% (extreme drought, D3), and less than 2% (exceptional drought, D4). These categories are the same as those used by the USDM (Svoboda et al. 2002). Similarly, we classified the SPI6(en), SMP(en), SRI3(en), and 18 indices into the same six drought categories.

c. Concurrence measure

There is no metric on which to base an evaluation of the best index for monitoring. We propose here to use a drought concurrence measure to assess the uncertainties of the grand mean index. To provide some spatial coherence, we used 18 × 9 index values from a total of nine cells, including the target cell and its eight closest neighbors at each time step. We counted the number of indices (Ni) in the Di category (i = 0, 1, 2, 3, 4). The concurrence measure is defined as the fraction of indices in the Di category:

\[
C(D_i) = \frac{N_{i}}{N} \times 100 \%
\]  

(1)
where $N$ is the number of indices. In this case, $N = 18 \times 9 = 162$ for grid cells in the interior of the CONUS domain. We used the same procedure to compute the concurrence measure for SMP(en) and SRI3(en).

d. Percentage of area over the United States under drought

Drought impact is usually related to the spatial extent, duration, and severity of a drought (Andreadis et al. 2005). One variable of interest is the percentage of area over the CONUS covered by drought. The approach is outlined below.

We determined the base area, which is the maximum area coverage of a given drought event over its entire course (hence, the base area is expected to be somewhat larger than the area covered by drought at any specific time). First, we located drought centers. These are local minima from the time series of the grand mean index maps over the duration of the event. For each drought center, we shaded areas near the center where the index was below 20% and repeated the practice through the duration of the event. The base area consists of grid cells in the shading areas on at least one of the maps. For each index, the area coverage at each time step is defined as the number of grid cells ($N_c$) in the base area where the grand mean index is below 20% (e.g., D1 category or higher). We then computed the percentage of area over the CONUS covered by drought as the ratio of $N_c$ to the total number of grid cells (3400) in the CONUS domain.

3. Drought cases

In this section, we consider three examples of our proposed drought classification scheme, including the grand mean index and its concurrence measure. We use drought cases that span the CONUS from east to west to highlight differences in concurrence among indices.

a. The 2007–08 Southeast drought

The Southeast is, in general, a wet region. The 2007–08 drought, which started in the spring of 2007, covered less than 20% of the CONUS land area at its maximum. However, for Georgia, North Carolina, and Alabama, the drought destroyed billions of dollars of crops, drained municipal reservoirs, and sparked legal wars among states. Following its initiation in the spring of 2007, the drought intensified quickly (Fig. 1). By May, Georgia and Alabama were in the D3–D4 category (Fig. 2q). The concurrence maps indicate that 90% of indices were in D2 (Fig. 2g) or higher, and 70% of indices were in the D3 and D4 categories at the center of drought. In summer, the lack of rainfall from tropical storms intensified the drought, which expanded northward to the Ohio Valley and northeastward to the Carolinas. The drought lowered rivers in Alabama, Georgia, and North Carolina to the point where there was insufficient streamflow to meet demands for water supply and power plants. Georgia and Alabama asked people in the metropolitan areas to take drastic actions to conserve water supplies. In July 2007, the state of Alabama was declared a drought disaster by the U.S. Department of Agriculture. On 20 October 2007, the governor of Georgia requested a presidential drought disaster declaration because of prolonged exceptional drought conditions.

At the peak of drought in June, the concurrence maps show that 90% of indices were in the D2 category or higher. In July and August, 70%–80% of indices were in the D2 or higher category at the center of drought. Overall, there is good consistency among the indices, so the concurrences are high. In October, D2 drought reached North Carolina and the Tennessee Valley. North Carolina declared a drought emergency. The drought continued through winter and ended in spring 2008. Because of the impact of this event, the governor of North Carolina signed a Drought Management Act into law in July 2008 to improve drought preparedness and response. For this drought event, Fig. 1 indicates that the grand mean index would have detected the onset and development of drought conditions up to 3 months before the state’s drought declaration.

Figure 3a shows the area under drought indicated by each index and the grand mean. The base area covered 20% of the CONUS (inset map in Fig. 3a). At its peak in June 2007, the daily drought coverage was about 14%–15% of the CONUS at its maximum. Therefore, this was a local drought. The drought lasted from January 2007 to April 2008. The differences in area coverage among the indices are not large.

The degree of agreement among mean indices SPI6(en), SRI1(en), and SMP(en) with the grand mean index is shown by a scatter diagram (Fig. 3b). We selected an area (30°–37°N, 80°–90°W) at the center of the drought and formed a subset by selecting every fourth grid cell in the area. We plotted the mean index against the grand mean index for this subset of grid cells for January 2007 to December 2007, when the grand mean index was below 20%. A dot along the thick red line indicates that the mean index corresponds well with the grand mean index. Dots above (below) the thick line indicate that the mean indices represented by dots are weaker (stronger) than the grand mean indices. The scatter diagram (Fig. 3b) shows high concurrence among indices. The SPI6(en) (red dots) shows more scatter than SRI3(en) and SMP(en), but there was no index that was consistently stronger or weaker than others for 2007.
Fig. 2. Concurrency map for the grand mean in the D3 and D4 categories for (a) March 2007, (b) May 2007, (c) June 2007, (d) July 2007, and (e) August 2007. Contours are given by the color bar. Areas not under drought are shaded gray. (f)–(j) As in (a)–(e), but for the D2–D4 categories. (k)–(o) As in (a)–(e), but for the D1–D4 categories. (p)–(t) As in Figs. 1b–f.
b. The 1988–89 drought

The 1988–89 drought was widespread, intense, and accompanied by record heat waves. Damages from the drought have been estimated to range from $80$ billion to almost $120$ billion in 2008 dollars (Live Science 2004).

Figure 4 shows the grand mean index for selected months. In the beginning of 1988, drought started to form north of 45°N from the Pacific Northwest (PNW) to Minnesota (Fig. 4b). Meanwhile, drought also appeared from the Gulf Coast to the Ohio Valley. In spring, drought intensified at both centers (Fig. 4d). In June, drought intensified quickly and reached the D3 and D4 categories over the North Central area (40°–48°N, 90°–100°W) and the Ohio Valley. In July, D3 and
D4 drought covered most of the area east of 100°W. Over the upper Missouri basin, the drought was in the D1–D2 category. Iowa and Pennsylvania declared drought emergencies in July 1988 and Illinois followed in August 1988. Over the eastern United States, drought was also accompanied by intense heat waves. In December 1988, the drought over the Southeast and the southern states started to dissipate. By the late summer of 1989, recovery from the drought was mostly complete.

In June, the concurrence maps (Fig. 5) show that 80% of indices were in the D2 category or higher and 50%–70% of indices were in the D3 and D4 categories from the northern Great Plains to the Ohio Valley. The fraction of indices in the D3 and D4 categories increased as the drought intensified from June to July. The drought in the upper Missouri basin was less intense; the concurrence maps (Fig. 5) do not show indices in the D3 or D4 category, but rather more commonly in the D1 category. In general,
the concurrence maps are able to indicate areas where severe drought in the high categories is unlikely, information that should be useful to water resources managers.

The fraction of indices in the D2 category increased from June to August as the drought’s intensity increased (Figs. 5f,g,q,r). In the recovery phase, the concurrence maps show the fraction of indices in the D2 or higher categories decreased in October 1988, when drought was mostly in the D1 or D2 category. Overall, there is a good correspondence between the drought concurrence measure and the grand mean classification, but the concurrences are not as high as the Southeast case. The fraction of indices in the D3 and D4 categories was only 50%–70% at the peak of drought over the North Central region (Fig. 5b), when the grand mean indices were in the D3 or D4 categories. This means that there were still about 30%–50% of indices in the lower categories. For users, we believe that the concurrence provides important information about uncertainties in the grand mean index. In general, by the time that state drought declarations began to be issued, the grand mean indices would already have detected D2

Fig. 5. Concurrence map for the grand mean in the D3 and D4 categories for (a) June 1988, (b) July 1988, (c) August 1988, (d) October 1988, and (e) February 1989. Contours are given by the color bar. Areas not under drought are shaded gray. (f)–(j) As in (a)–(e), but for the D2–D4 categories. (k)–(o) As in (a)–(e), but for the D1–D4 categories. (p)–(r) As in Figs. 4e–g, (s) as in Fig. 4i, and (t) as in Fig. 4k.
or higher drought with concurrences of 80% a few months earlier.

Figure 6a shows the area under drought indicated by each index and the grand mean. The base area covered 63% of the CONUS (inset in Fig. 6a). The daily drought coverage at the peak of drought in July 1988 was about 50%. The differences among the indices are not large. There was no index which had consistently more or less area coverage than others for the duration of the drought from April 1987 to June 1989.

A scatter diagram (Fig. 6b) was plotted for the region (35°–42°N, 80°–90°W) for indices from January 1988 to December 1988. As compared with Fig. 3b, the differences among indices are larger than the Southeast case. Overall, the SMP(en) (blue dots) and SRI3 (green dots) correspond relatively well with the grand mean index. We notice that the SPI6(en) index (red dots) is stronger than the grand mean index when the grand mean index is in the 10%–20% range (D1 category).

c. The 2000–05 multiple drought episodes over the western United States

The 2000–05 case is a contrast to the 1988–89 case. The uncertainties among the UW and NCEP systems...
and the diversity among indices are much larger and the concurrences are lower than the previous two cases. Figure 7 shows the evolution of the drought based on the grand mean index with the concurrence measures given in Fig. 8 for selected months.

The drought started in 2000 over the Southwest. In 2001, it expanded northward to the PNW. In January 2001, the drought reached D2–D3 intensity along the coastal PNW. Farther inland, the drought was weaker and was in the D1 category, except in northwestern Montana. In March 2001, the governor of the state of Washington declared a drought emergency. At that time, the grand mean index had already indicated D2–D3 drought for 2 months. The concurrence maps (Fig. 8) show at least D2 severity in March 2001 with 50%–60% of indices in the D3 or D4 category along the coast of the PNW (Figs. 8a, f, k, p). For the interior of the region, no index was in the D3 or even D2 category, and there were only 40%–60% of indices in the D1 category. The drought inland was weaker and at most in the D1 category.

Meanwhile, drought was reestablished in the Southwest in the winter of 2002. In the summer of 2002, D2 and D3 drought centered in the Four Corners area expanded northeastward to Arkansas and the North Central region. In April 2002, the governor of Kansas signed a drought emergency. Colorado followed in June 2002, and Arizona declared a drought emergency in August 2002. The concurrence maps indicate the intensification of drought over the Four Corners area from April to July 2002. At the core of the drought over Four Corners, the drought severity was at least in the D2 category, with 40%–50% of indices in the D3 and D4 categories (Figs. 8b–d). The concurrences at the peak of this drought were lower than the previous two cases.

Drought improved in the winter of 2003 but returned briefly in the fall of 2003. The drought in 2003 was only in the D1 category, except over Colorado, where it was mostly in the D2 category. There were no indices in the D3 or higher categories, as indicated by the concurrence maps (Fig. 8), but 30%–40% of indices indicated drought in the D2 category over Colorado. The center of the drought migrated over its course, which eventually ended in 2005. This migration allows us to divide it into three separate but related episodes: the 2001 drought over the Pacific Northwest, the 2002 drought over the Southwest, and the 2003 return of drought over much of the western United States.

The base area for the 2000–05 droughts covered 59% of the United States, but on a daily basis the average fraction of the CONUS covered was less than 35% (Fig. 9a). That is because the drought shifted substantially over time, as indicated above. There were substantial differences among the indices, even at the peaks of the drought. The SPI6 indices show more area coverage and the SRI3 indices (green) show less area coverage. The duration was from June 1999 to January 2005. From Fig. 9a, the 2002 drought over the Southwest had the highest drought area coverage.

An example of the diversity of indices is given by the scatter diagram for the region (36°–43°N, 103°–113°W) for the 2002 drought over the Southwest from January 2002 to January 2004 (Fig. 9b). There are systematic differences between the grand mean index and the mean indices. The SMP(en) (blue dots) corresponds well with the grand mean index. However, the SPI6(en) was considerably stronger than the grand mean and all other indices. The SRI3(en), on the other hand, was weaker than the grand mean index.

We plotted SPI6(en), SMP(en), and SRI3(en) for selected months in Fig. 10, which can be compared with the grand mean index (Fig. 7) to indicate the diversity. For March 2001, all indices indicated more intense drought along the coastal PNW than the upper Missouri basin in winter 2001. However, the intensity differs from one index to another. Along the coast, both SPI6(en) and SRI3(en) classified drought in the D3 or D4 category. The SMP(en) classified drought in the D2 category for most of the state of Washington. For the inland areas, the SRI3(en) index was slightly weaker than the other two indices.

For the 2002 drought over the Southwest, all indices showed intensification of drought from spring to summer, with an increase of the area covered. They all show that the drought reached a peak in July 2002. However, there are large differences in magnitudes. The SPI6(en) index showed D3–D4 drought in the summer of 2002. Both the grand mean index and the SMP(en) classified drought in the D3 category with isolated regions in the D4 category. The SRI3(en) index classified drought in the D2–D3 category. For October 2003, all indices show the weakening of drought.

Overall, the grand mean index and SMP(en) gave similar classification. The SRI3(en) shows a weaker drought and the SPI6(en) index consistently shows more intense drought over the western region. It could be that snow plays an important role in the water cycle over the drought region, and the grand mean index is therefore more representative than SPI6(en), which includes the precipitation that gets into the gauge.

We now consider the ability of the concurrence maps for SMP(en) to represent uncertainties in classifications of agricultural drought (Fig. 11). For the 2001 PNW drought, the intensity of drought over the coastal PNW was weaker than the grand mean and the concurrence map shows only 40%–50% of indices in the D3–D4
Fig. 8. Concurrence map for the grand mean in the D3 and D4 categories for (a) March 2001, (b) April 2002, (c) June 2002, (d) July 2002, and (e) October 2003. Contours are given by the color bar. Areas not under drought are shaded gray. (f)–(j) As in (a)–(e), but for the D2–D4 categories. (k)–(o) As in (a)–(e), but for the D1–D4 categories. (p) As in Fig. 7e, (q) as in Fig. 7h, (r) as in Fig. 7i, (s) as in Fig. 7j, and (p) as in Fig. 7n.
categories. Farther inland, the concurrence maps indicate that the drought was most likely to have been D1. For the Southwest case, droughts depicted by the SMP(en) and the grand mean are similar. The concurrence maps show that 70%–80% of indices were in D2 or above.

4. Conclusions and discussion

The current generation of drought monitors uses physically based indices, such as the standardized precipitation index (SPI), total soil moisture percentiles (SMPs), and the standardized runoff index (SRI) to monitor precipitation, soil moisture, and runoff deficits, respectively. Because long-term observations of soil moisture and spatially distributed runoff are not readily available, SRI and SMP are more commonly taken from model-derived variables from sources such as NLDAS. While monitoring systems based on NLDAS are able to detect droughts, they are challenged by classification of drought into, for instance, the D1–D4 categories used by the USDM, in part because of uncertainties among multiple drought indicators, models, and assimilation systems. Another motivation is that users desire to have
FIG. 10. SPI6(en) for (a) March 2001, (b) April 2002, (c) June 2002, (d) July 2002, and (e) October 2003. Contours are given by the color bar. (f)–(j) As in (a)–(e), but for SRI3(en); (k)–(o) as in (a)–(e), but for SMP(en). All indices are in percentiles. Areas not under drought are shaded gray.
Fig. 11. As in Fig. 8, but for the concurrence maps for SMP(en) mean index.
one index to represent overall drought conditions instead of using three different measures for monitoring.

We have demonstrated the utility of a simple scheme for drought classification that uses a grand mean index together with a concurrence measure. Our approach is based on multiple SPI, SM, and SRI indices, from which we form an equally weighted ensemble mean index, which we then remap to a uniform distribution by using the climatology of the ensemble (percentile) averages. Drought classification is based on this grand mean index, and the uncertainties of drought classification are determined by the concurrence measure, which is the percentage of indices in each drought category. It measures the fraction of indices that agree with the grand mean index.

Through application of this method to three drought cases discussed above, we found the following conclusions.

- In the 2007–08 Southeast regional drought, the uncertainties among the NLDAS indices were small, and the concurrences among indices were high. We attribute this in part to the fact that the Southeast is a semihumid region with a weak seasonal cycle of precipitation.
- In contrast, the 1988–89 drought was widespread, intense, and covered over half of the CONUS at one time or another through its duration. The concurrences for this event were still high, but slightly lower than for the 2007–08 drought over the Southeast.
- The 2000–05 western U.S. droughts had three separate but related episodes over the Pacific Northwest and the Southwest. The drought shifted substantially over much of the western half of CONUS through its duration, and in some cases, drought was reestablished. Concurrence measures for this drought were much lower than in the other two cases, likely in part because the region is mostly dry and soil moisture tends to persist, leading to greater inconsistencies between the grand mean index and other drought indices. The uncertainties in the NLDAS also contribute to the low concurrence.
- For all three droughts, the grand mean index was able to detect the onset of drought up as much as 3 months before the drought declarations by the affected states. In most cases, drought had reached the D2–D3 categories before state declarations and high concurrences among the metrics would have aided in early detection of drought.

One question is, how independent are the indices? Clearly, it makes no sense to include indices that are highly correlated, as this implies that the information provided is redundant. If the indices are highly correlated, then the spread will be very low. To examine the diversity of drought indices, we computed the RMS difference between all pairs of indices when one index indicated drought (below 20%). We then took the average of the total of 153 pairs of indices and plotted in Fig. 12a. The mean RMS difference indicates that the differences are above 25% over the western region, except for coastal areas, and slightly less (15%–25%) over the eastern United States. When the area is under drought, indices are able to provide meaningful measures of spread for drought classification purposes. Our results are consistent with other studies (Wang et al. 2009) to the extent that our case studies indicate that drought concurrence measures (albeit structured somewhat differently than the ones we use here) tend to be higher over the eastern United States than the western interior region.

For the 2002 Southwest drought, the scatter diagram (Fig. 9b) shows that the SPI(en) was stronger than the grand mean index, but the SRI3(en) was slightly weaker than the grand mean from January 2002 to January 2004. To find whether these differences are systematic, we computed the difference between the grand mean index and the SPI6(en) [or SRI3(en)] averaged over months where the grand mean index was below 20%. The mean differences between the SRI3(en) and the grand mean are small (Fig. 12c). However, the SPI6(en) is consistently stronger than the grand mean index over the western region, except the PNW (Fig. 12b). The difference is about 5%–10%, which is large enough to put drought in different categories. Therefore, SPI6 may not be a good index to monitor drought over the western interior region.

We emphasize that the purpose of this paper is not to develop drought prediction methods; our results are for nowcasts with no forecast element. However, we did evaluate the likelihood that droughts, identified based on the grand mean index, will persist—in particular, for 3–4 months from the onset of drought as determined by the nowcasts. The onset is defined as the first time that the grand mean index is below 20%. We then took the average of the total of 153 pairs of indices and plotted in Fig. 12a. The mean RMS difference indicates that the differences are above 25% over the western region, except for coastal areas, and slightly less (15%–25%) over the eastern United States. When the area is under drought, indices are able to provide meaningful measures of spread for drought classification purposes. Our results are consistent with other studies (Wang et al. 2009) to the extent that our case studies indicate that drought concurrence measures (albeit structured somewhat differently than the ones we use here) tend to be higher over the eastern United States than the western interior region.

We started by examining the robustness of decisions made on the basis of the drought classes. For each grid cell, we calculated the fraction of times that the drought persists more than 3 or 4 months after the onset when the grand mean index is below 20% and in the Di category (i = 1–4) (Fig. 13). Figure 13 indicates that the persistence of a drought event depends on its severity. If the drought is in the D3 and D4 categories, in 70–80%
(60%-70%) of the cases, the drought will persist at least 3 (4) months, except for coastal areas and the path from Mississippi to Indiana, where droughts tend to have less persistence. If the drought is in the D1 category at the onset, the probability for the drought reduces significantly. The probability for drought to persist for 3 (4) months drops to 40%-50% (30%-40%) for areas west of 90°W and less than 40% (30%) for areas east of 90°W. If the drought is in the D2 category, the probability that the drought will persist for 3...
months is about 60%–70% overall. In general, the probability that a drought will persist is greater over the areas west of 95°W than for areas to the east.

We also investigated whether persistence in the grand mean index is related to concurrence among the component indices. We calculated the fraction of times that the drought persists more than 3 or 4 months after the onset time when the grand mean index is below 20% and the concurrence measure is above 70%, 50%–70%, and 30%–50%. The concurrence measure indicates the robustness of the grand mean index. Figure 14 shows that when the grand mean indicates drought with a high concurrence measure, the drought is more likely to persist than for lower concurrence measures (and the same value of the grand mean index). Similar to Fig. 13, drought persistence is generally higher in the west than in the east.

Overall, the persistence of drought depends on its severity and the concurrence measure. When the drought is in the D3 or D4 category with the concurrence measure above 70%, then the drought is very likely to persist for 3 months or longer. When the
drought is in D1 category with concurrence measure below 50%, then the drought is likely to dissipate quickly.

The method we have proposed is simple and flexible and is well adapted to inclusion in, for instance, the U.S. Drought Monitor and similar drought classifications elsewhere. It is easy to add more indices if and as they are available. The concurrence measures provide useful information about uncertainty in the drought classifications. It is important to recognize that the degree of concurrence varies climatically.

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FIG. 14. Fraction of times that the grand mean remains below 20% for at least 3 months from onset when the concurrence measure is above (a) 70%, (b) between 50% and 70%, and (c) between 30% and 50% at the onset. (e)–(g) As in (a)–(c), but for the grand mean remaining below 20% for at least 4 months.


