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# Objective Blends of Multiple Ensemble-Mean NLDAS Drought Indices

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## 1. Introduction

The multi-institution North American Land Data Assimilation project (NLDAS) has experienced four stages since it was initiated in 2000 (Mitchell *et al.* 2004). The first stage established infrastructure including selection of land surface models, generation of surface forcing data, and collection of soil and vegetation datasets, and in-situ and satellite-retrieved observations. Four model groups ran their models separately for a 3-year period (from 1 October 1997 to 30 September 1999). NCEP Environmental Modeling Center's land-hydrology group ran the community Noah model, Princeton University's land group ran the VIC model, NASA Goddard Space Flight Center's hydrology group ran the Mosaic model, and National Weather Service's Office of Hydrologic Development ran the SAC hydrological model. The model outputs were evaluated and compared with in-situ observations and satellite-retrieved products. Overall results showed that all four models are able to capture broad features for these validated variables such as energy fluxes (*e.g.*, net radiation, sensible heat, latent heat, and ground heat), water fluxes (*i.e.*, evapotranspiration, total runoff) and state variables (*i.e.*, soil temperature, soil moisture, land surface temperature, snow cover fraction, snow water equivalent). The validation tools and overall results are detailed in Mitchell *et al.* (2004).

The second stage focused on improving model physics, tuning model parameters and improving surface forcing data quality and reliability based on the findings from the first stage, and further expanding the short-term (*i.e.*, 3 years) model products to long-term (> 30 years) model products. The NCEP NLDAS team improved Noah simulation in cold season (Livneh et al. 2010) and warm season (Wei *et al.* 2012) through collaboration with University of Washington. The Princeton Land group improved the VIC simulation by calibrating model parameters (Troy *et al.* 2008), and the NCEP NLDAS team also improved SAC simulation by using climatologically averaged observed potential evaporation (Xia *et al*. 2012a), while Mosaic was improved little. For surface forcing data, the CPC gauge precipitation has been bias-corrected by PRISM (Parameter-elevation Regressions on Independent Slopes Model, Daly *et al.* 1994) precipitation to reduce the impact of topography on gauge precipitation. Four models were retrospectively run from 1 January 1979 to 31 December 2008. After then, they are run in a near-realtime mode (with a 3 and half day lag).

The third stage moved toward evaluating and validating the quality and reliability of long-term NLDAS products using as many as available in-situ observations and satellite-retrieved products (short-term *vs.* long-term, different time scales from hourly to annual, different spatial scales from site and basin to continental United States). These observations include energy fluxes (*e.g.*, downward shortwave and longwave radiation, upward shortwave and longwave radiation, net radiation, sensible heat flux, latent heat flux, ground heat flux, *etc.*), water fluxes (*e.g.*, evapotranspiration, streamflow), and state variables (*e.g.*, soil moisture, soil temperature, land surface/skin temperature, snow water equivalent, snow cover fraction). Evaluation/validation works have made significant progress during the recent two years. An overall evaluation and comparison was detailed in Xia *et al.* (2012a, 2012b). Overall results show that the NLDAS products generated from the stage 2 have better quality when compared to those generated from stage 1, due

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to both model and surface forcing data improvement. The simulated total runoff was evaluated against the observed streamflow at 986 small-medium size basins and 8 large size basins which were measured by the U.S. Geological Survey (USGS). In west coast and eastern U.S., all four models are able to capture the broad features of observed streamflow. Four- model ensemble mean outperforms any individual model in term of errors. The similar conclusion can be found for the validation of simulated evapotranspiration. The simulated soil moisture was evaluated using three observational datasets (Xia *et al.* 2012c): 20-year (1985-2004) monthly mean soil moisture from Illinois (17 sites), 6-year (1997-2003) daily mean soil moisture from Oklahoma Mesonet (72 sites), and 8-year (2002-2009) daily soil moisture from Soil Climate Analysis Network (SCAN, 121 sites) over the continental United States. The results show that simulation skills of all four models are quite good in term of anomaly correlation for both daily and monthly time scales although simulated soil moisture magnitude shows large errors, where some models may overestimate and other models may underestimate observed soil moisture. Like streamflow and evapotranspiration evaluations, the four-model ensemble mean shows the most robust simulation skills over continental United States when compared to any individual model.

The focus of fourth stage is to apply long-term NLDAS products to support the National Integrated Drought information System (NIDIS, drought.gov) and U.S. operational drought monitoring and prediction. One key application of the near real-time NLDAS is its drought monitoring over continental United States, shown at the “NLDAS Monitor” tab of the NLDAS website (Sheffield *et al.* 2012; NCEP/EMC NLDAS website: http://www.emc.ncep.noaa.gov/mmb/nldas/; NASA NLDAS website: http://ldas.gsfc.nasa.gov/nldas/NLDASnews.php). At the same time, the NLDAS team also uses a cron job to routinely provide four-model ensemble mean daily, weekly, and monthly percentiles of top 1m soil moisture, total column soil moisture, total runoff and evapotranspiration to the U.S. drought monitor author group to directly support the USDM. This team also provides NLDAS drought indices to support CPC monthly drought briefing and seasonal drought outlook. However, these NLDAS drought indices are not comprehensively assessed as there are few reference drought datasets. The USDM (http://droughtmonitor.unl.edu/), an operational product (Svoboda *et al.* 2002), has generated many statistics (*i.e.*, drought area percentages for the forty-eight states). How to use these statistics to improve U.S. operational drought monitoring is still a challenging issue. This study will develop an objectively blended approach by establishing the linkage between NLDAS products and USDM statistics. The approach will use an optimization method to search for optimally blended weights and equations by minimizing the root mean square error (RMSE) between drought area percentage derived from an NLDAS and from USDM. In turn, the USDM drought area percentage will be used to evaluate simulation skills of optimally blended NLDAS drought index.

## 2. Methodology

Weekly drought area percentages were downloaded from the USDM archives website (http://droughtmonitor.unl.edu/dmtabs_archive.htm) for five categories and 48 states. This dataset covers a 12-year period from 2000 to 2011. Five drought categories are from abnormally dry to exceptional (D0-D4), moderate drought to exceptional (D1-D4), severe drought to exceptional (D2-D4), extreme drought to exceptional (D3-D4), and exceptional (D4-D4). Monthly mean drought percentages were calculated using the number of days as weights to average weekly values. For NLDAS, percentiles of monthly mean top 1m soil moisture (SM1), total column soil moisture (SMT), evapotranspiration (ET), and total runoff (Q) derived from four-model ensemble were used as four NLDAS drought indices. A linear combination of the four indices was used as the blend in this study. We calculated monthly drought area percentage from the blend for forty-eight states using land mask, state mask, and the USDM drought categories. 10-year monthly drought area percentages were used to construct our error function (the last 2 years were used for validation as the USDM authors have referenced NLDAS products since 1 January 2010). The root mean square error E can be defined as:

$$E = \frac{1}{MT}\sum_{t=1}^{MT}\sqrt{\frac{1}{C}\sum_{c=1}^{C}(A_{t,c} - O_{t,c})^2} \qquad (1)$$

where MT is total number of months (120 in this study), C is the number of drought categories (5 in this study), $A_{t,c}$ and $O_{t,c}$ are the drought percentage area from the blended NLDAS drought index and the USDM, respectively. The ranges of all four weights are selected to be from 0 to 1. By an optimization process, Very Fast Simulated Annealing (VFSA, Xia 2007) automatically searches for optimal weights to minimize the error function E. The optimization process was performed for each state separately (Xia *et al.* 2013, "Application of USDM Statistics in NLDAS-2: Objective Optimal Blended NLDAS drought Index over the Continental United States", in preparation for Journal of Geophysical Research).

The basic evaluation method for this study includes bias, root mean square error (RMSE), correlation coefficients, and Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970). The Nash-Sutcliffe efficiency is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^{MT} (A_t - O_t)^2}{\sum_{t=1}^{MT} (O_t - \bar{O})^2} \tag{2}$$

In equation (2) $A_t$ and $O_t$ are, respectively, drought area percentage derived from NLDAS and USDM, and $\bar{A}$ and $\bar{O}$ are their mean values for any given time period. The NSE is a measure of the drought area percentage simulation skill of the method as compared to the mean USDM drought area percentage, and ranges in value from minus infinity (poor model skill) to one (perfect model skill). An efficiency of 0 ($NSE = 0$) indicates that the model simulations are as accurate as the mean of the USDM data, whereas an efficiency less than zero ($NSE < 0$) occurs when the USDM mean is a better predictor than the model.

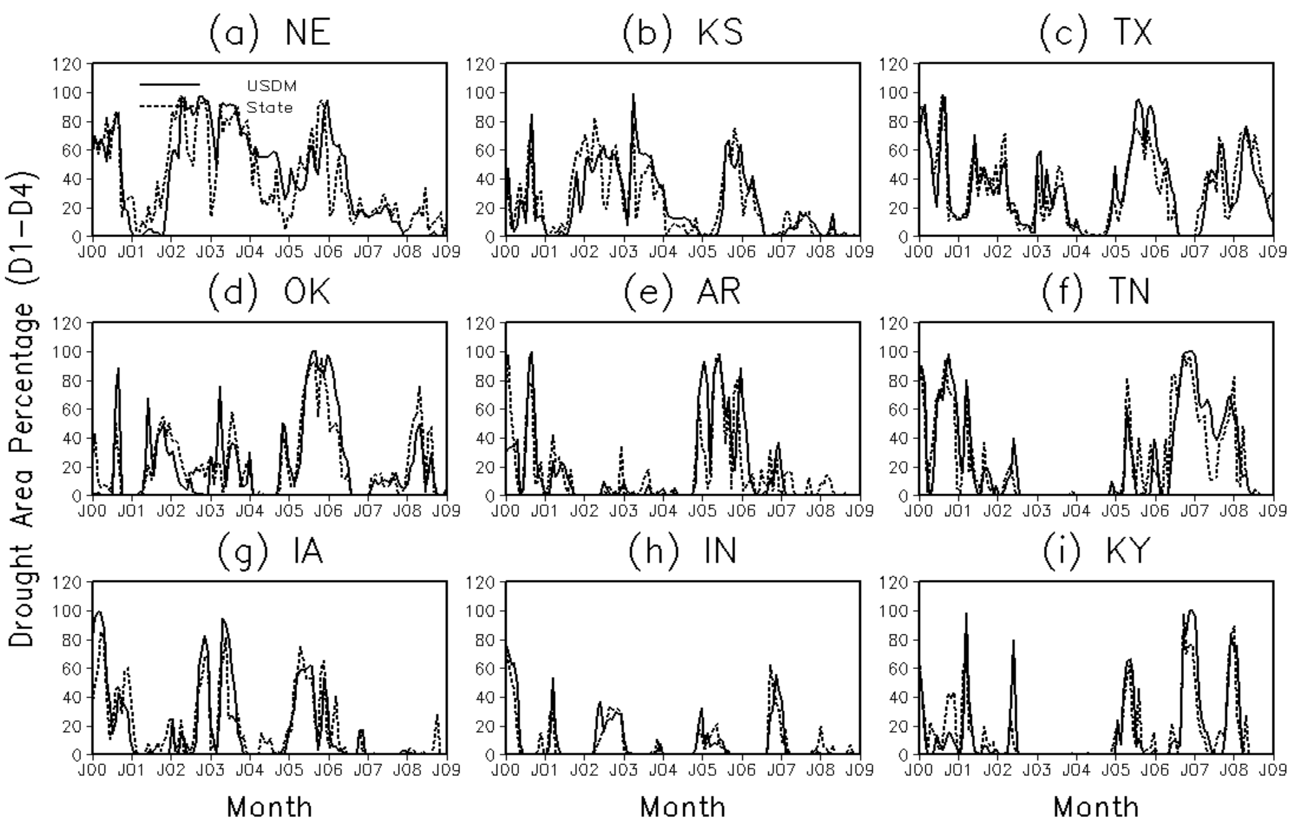


**Fig 1** Comparison of drought area percentage for D1-D4 derived from USDM and objective NLDAS blend (represented State in Fig.1) in (a) Nebraska (NE), (b) Kansas (KS), (c) Texas (TX), (d) Oklahoma (OK), (e) Arkansas (AR), (f) Tennessee (TN), (g) Iowa (IA), (h) Indiana (IN), and (i) Kentucky (KY) for January 2000 to December 2009.

## 3. Results

Figure 1 and Figure 2 show the comparison between USDM and NLDAS drought area percentage (D1-D4) for nine states and different periods: the training period (2000-2009) and the validation period (2010-2011), respectively. These states have the highest correlation for both training and validation period. The

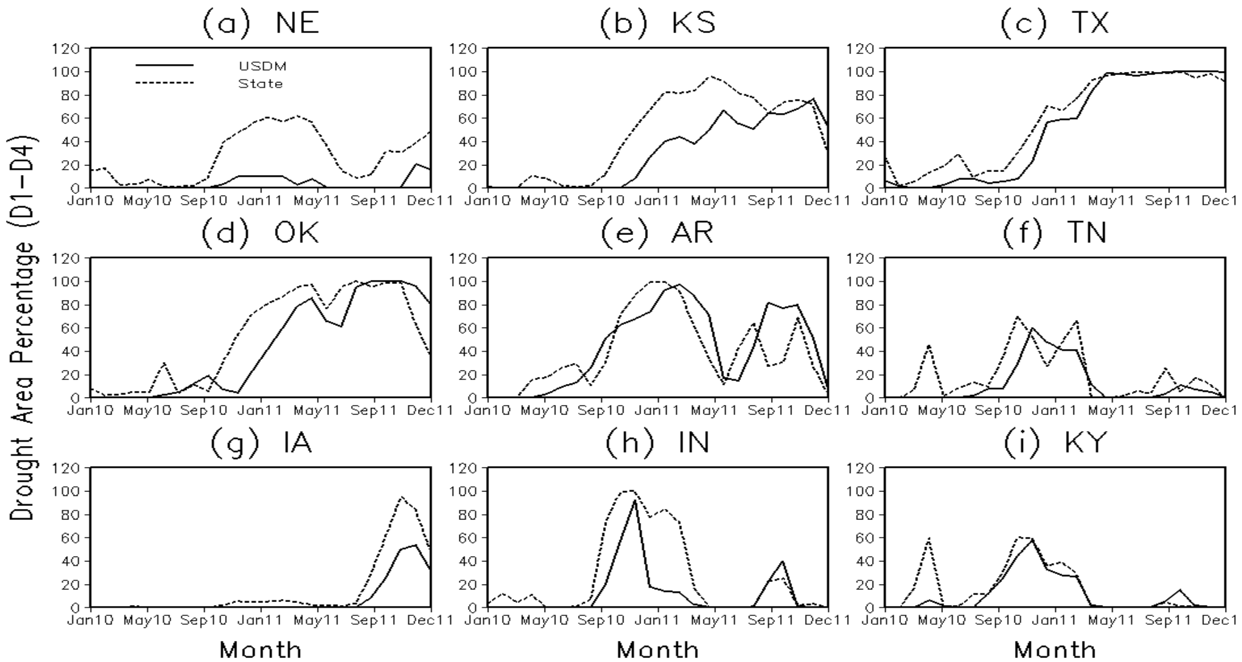


**Fig. 2** The same as Figure 1 except for the validation period from January 2010 to December 2011.

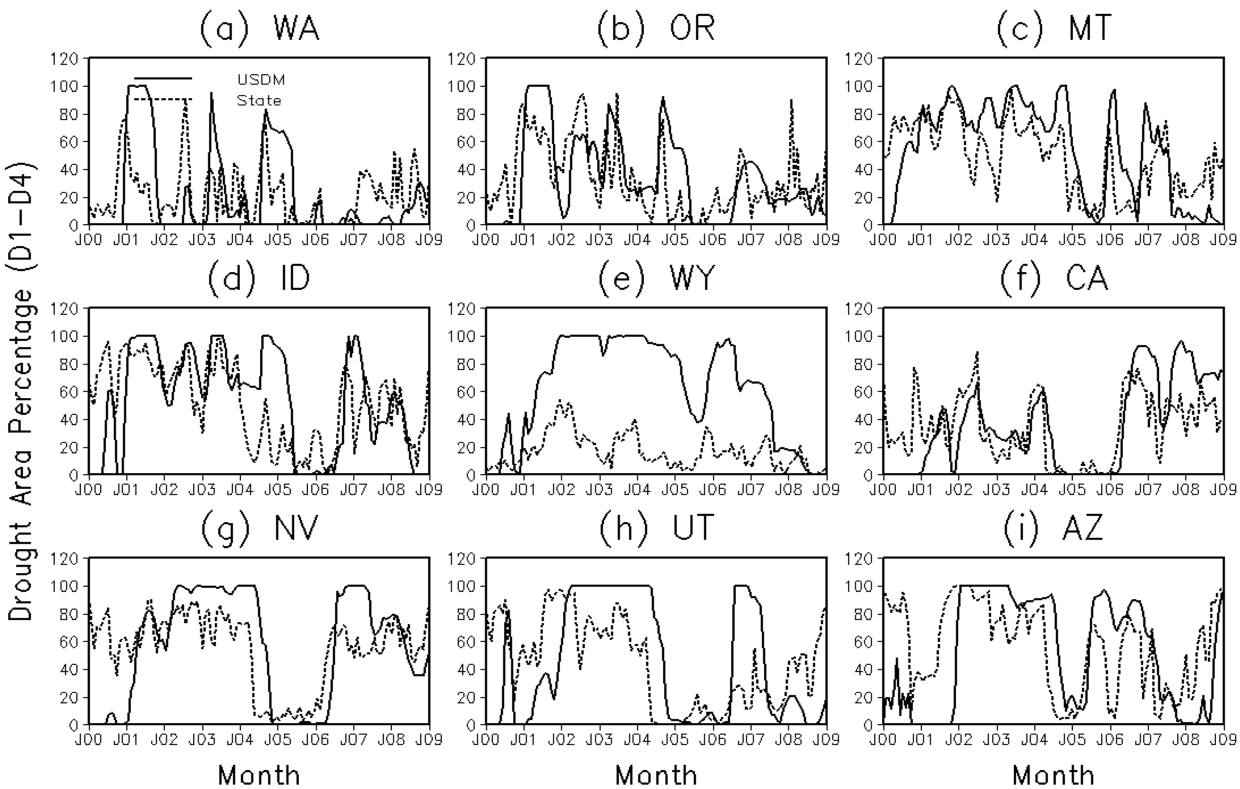


**Fig. 3** The same as Figure 1 except for (a) Washington (WA), (b) Oregon (OR), (c) Montana (MT), (d) Idaho (ID), (e) Wyoming (WY), (f) California, (g) Nevada (NV), (h) Utah (UT), and (i) Arizona (AZ).

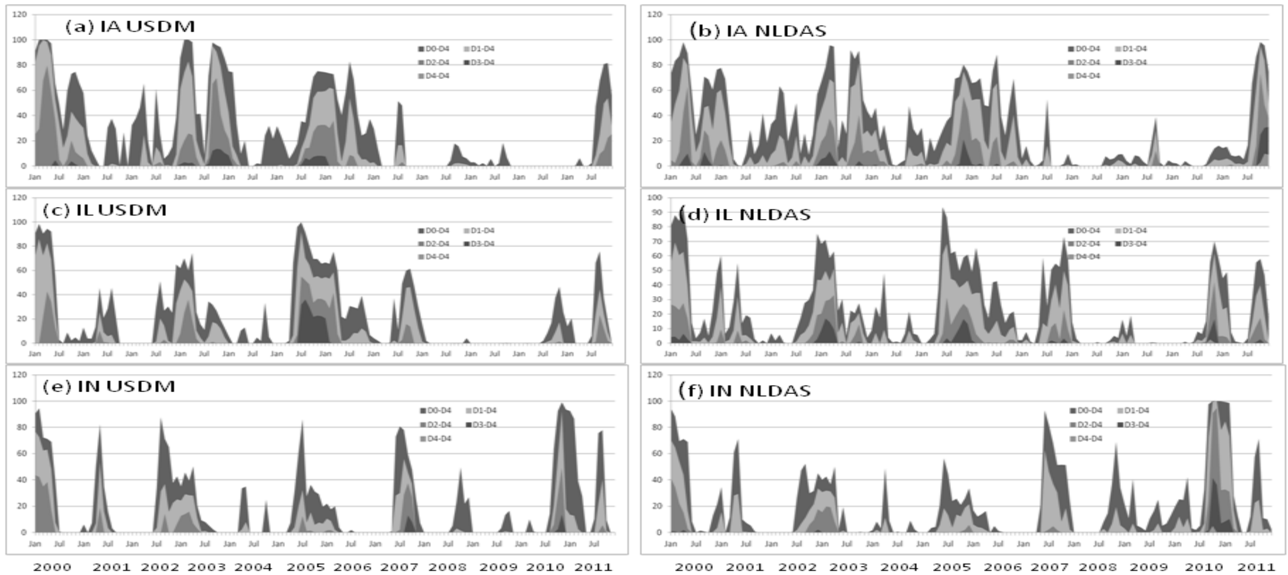


**Fig. 4** Comparison of drought area percentages for five drought categories (D0-D4, D1-D4, D2-D4, D3-D4, D4-D4) derived from USDM (left panel) and objective NLDAS blend (right panel). The data covers the period from January 2000 to December 2011. From top panel to bottom panel represent Iowa (IA), Illinois (IL), and Indiana (IN).

results show that the objective NLDAS blend can capture variability and magnitude of monthly drought events very well for both the training period and validation period although the blend overestimates USDM drought area percentage for almost all nine states during the validation period. The performance of the objective blend varies from state to state. Basically, most states in Southern and Southeastern U.S. have quite good performance, and the states in Northeastern, Midwestern, and Western U.S. have low simulation skills. An example for nine states over western U.S. is shown in Figure 3. The objective NLDAS blend shows quite low simulation skill over western U.S. regions for both monthly magnitude and variability, in particular for Washington and Wyoming. The possible reason may be (1) inaccurate precipitation data and (2) low simulation skills for soil moisture, ET and Q (Xia *et al.* 2012a, 2012b). As indicated by Mo *et al.* (2012), the number of precipitation gauges has significantly decreased since 2002. Therefore, precipitation estimates may be not representative for that region. Moreover, because of complex topography, snow processes, and frozen soil processes, combined with inaccurate precipitation over the western mountainous region, further results in poor simulation of soil moisture, ET and Q in that region. Figure 4 shows monthly variation of drought area percentage for 5 drought categories in three states derived from USDM (left panel) and objective NLDAS blend (right panel). The results show that the NLDAS blend quite well captures the monthly magnitude and variability of the USDM drought area percentage for these three states, in particular for the first two drought categories. The inability of the objective NLDAS blend to capture USDM drought area percentages for severe drought or above categories is due to their small sample sizes. Therefore, a long-term USDM product (*i.e.*, 30 years) can be expected to improve severe drought simulation. The spatial distribution of Nash-Sutcliffe efficiency for three drought categories (*i.e.*, D0-D4, D1-D4, and D2-D4) was shown in Fig. 5 for the training period (left panel) and the validation period (right panel). The results show that objective NLDAS blend has quite good simulation skills in southern and southeastern states, and poor simulation skills in western, mid-northern, and northeastern states, in particular for the validation period and the severe drought case. The simulation skills of objective NLDAS blends are reduced from the training period to the validation period for most states. The reduction of the simulation skills also occurs when drought categories vary from D0-D4 to D3-D4. The reason for both reductions may be due to the short record-length of USDM data.

## 4. Summary and future direction

Currently NLDAS is a quasi-operational system to support U.S. operational drought monitoring and seasonal hydraulic prediction, in particular for the National Integrated Information System including U.S.

Drought Monitor (USDM) and Monthly Drought Briefing. Detailed information about NLDAS can be found at NOAA (http://www.emc.ncep.noaa.gov/mmb/nldas) and NASA (http://ldas.gsfc.nasa.gov/nldas/) websites. The system consists of a retrospective 29-year (1979-2008) historical execution and a near real-time daily update execution using four land surface models (NCEP/Noah, NASA/Mosaic, NWS/OHD/SAC, and VIC developed by Princeton University and University of Washington) on a common 1/8th degree grid using common hourly land surface forcing. The non-precipitation surface forcing is derived from the NCEP retrospective North American Regional Reanalysis (NARR), and now realtime NCEP operational Regional Climate Data Assimilation System (RCDAS). The precipitation forcing is anchored to daily gauge-only precipitation over Continental United Sates (CONUS) that applies Parameter-elevation Regressions on Independent Slopes Model (PRISM) corrections. This daily precipitation analysis is then temporally disaggregated to hourly precipitation amounts using radar products. The NARR-based surface downward solar radiation is bias-corrected using seven years (1997-2004) of satellite-derived solar radiation retrievals.

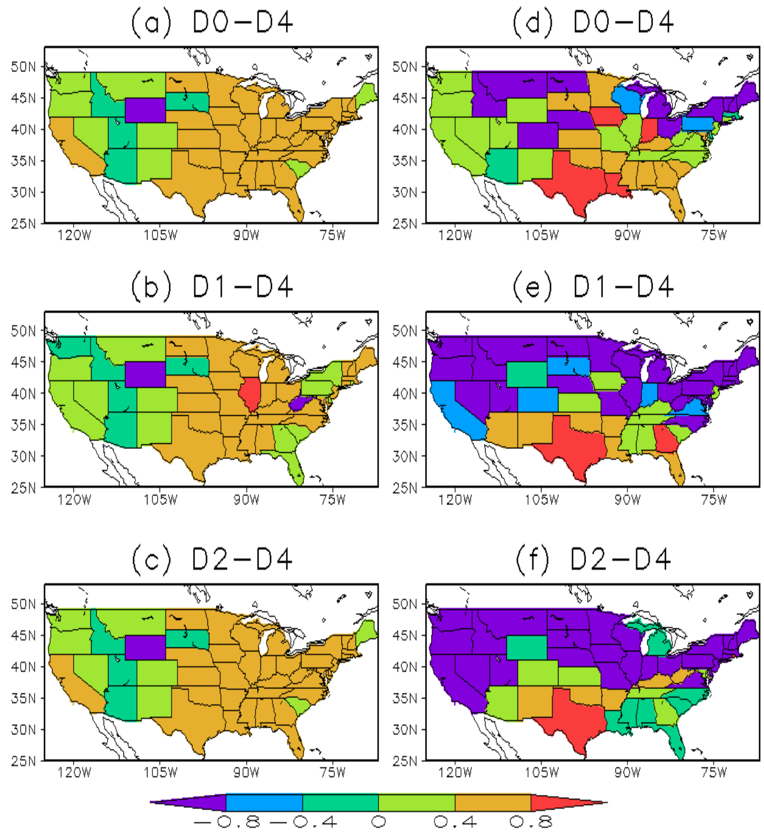


**Fig. 5** Spatial distribution of Nash-Sutcliffe efficiency (NSE) for three drought categories (*i.e.*, D0-D4, D1-D4, and D2-D4) and different periods: the training period (left panel) and the validation period (right panel). Negative NSE indicates poor simulation for USDM drought area percentages.

The 29-year NLDAS retrospective run is used to derive the climatology of each of the four land models. Then current near real-time (past week, past month) land states (*e.g.* soil moisture, snowpack), and water fluxes (*e.g.* evaporation, total runoff, streamflow) of each of the four models from daily executions are depicted as anomalies and percentiles with respect to their own model climatology. The simulated streamflow, soil moisture, snowpack, and evapotranspiration from the four models are well evaluated and validated using in-situ observations from the U.S. Geological Survey, Illinois, Oklahoma, and CONUS soil moisture, and evapotranspiration from U.S. surface flux measurement sites. This evaluation provides a basis to apply NLDAS products. One key application of the near real-time updates is drought monitoring over CONUS, shown at the "NLDAS Drought" tab of the NLDAS website. NLDAS ensemble mean drought indices are directly provided to the U.S. Drought Monitor author group through a daily cron job.

NLDAS has become mature enough and will be implemented in NCEP operations in the near future. At the same time, we recognize that the current NLDAS is not an "actual" land data assimilation system because remotely-sensed estimates of land-surface states such as soil moisture and snowpack, and in-situ observations such as streamflow and soil moisture, are not yet assimilated into current version of NLDAS. The NCEP/EMC NLDAS team is collaborating with the NASA Goddard Hydrological Sciences Laboratory to add their Land Information System (LIS; Kumar *et al.* 2006) to the current NLDAS system which would allow assimilation of remotely-sensed data and in-situ observations, *e.g.* via an ensemble Kalman filter approach.

The comparison analysis of drought area percentages shows that the objective NLDAS blend is able to capture broad features of drought area percentage such as magnitude and monthly variability for the first two categories in many states which are mainly located in the South, Southeast, High Plains and Midwest regions. However, there is still significant room for improvement for enhancing simulation skills, in particular for most states of the Western and Northeast regions, and for the strongest drought events (D3-D4, D4-D4). Impact of accurate gauge precipitation on simulation skills in the Western region will need to be addressed in the future work by rerunning the four NLDAS models using a retrospective gauge precipitation dataset. In addition, after more independent inputs such as observed streamflow (*e.g.*, percentile) from USGS, remote sensing drought indices (*e.g.*, Evaporative Stress Index, Ground Water Storage), and Climate Prediction Center (CPC) operational drought indices (*e.g.*, standard precipitation index, Palmer Drought Index, Palmer Hydrological Drought Index, Objectively Blended Drought Indicators) will be used to blend with the four NLDAS drought indices used in this study, further improvement can be expected. It should be noted that the objective NLDAS blend is easily reproducible, which is quite different from the USDM, which is based on a combination of objective and subjective analysis, making it not easily reproducible. Therefore, this approach can be used to reconstruct long-term drought area percentages and drought indices.

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