Earth and Space Science

Supporting Information for

Developing a Multivariate Agro-Meteorological Index to Improve Capturing Onset and Persistence of Droughts Utilizing Vapor Pressure Deficit (VPD) and Soil Moisture

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Text S1.

1. Data

RH is the ratio of the vapor pressure (e) to saturation vapor pressure (e_s), or it can be expressed as the ratio of mass mixing ratio (ratio of the mass of water vapor (m_v) to the mass of air (m_d)) of actual water vapor (w) to mass mixing ratio of saturated water vapor (w_s). Specific humidity is the mass of water vapor (m_v) in mass of dry air plus water vapor (Wallace and Hobbs 2006):

$$q = \frac{m_v}{m_v + m_d} = \frac{w}{1+w} \qquad (1)$$

Since the value of w is only a few percent, it can be said that the numerical values of q and w are nearly equal (q ≈ w) (Wallace and Hobbs 2006).

The saturation mixing ratio (w_s) is the ratio of the mass of water vapor (m_{vs}) in a specific volume of air which is saturated to the mass of the dry air (m_d) and since water vapor and dry air both obey the ideal gas equation we have (Wallace and Hobbs 2006):

$$w_s = \frac{m_{vs}}{m_d} = \left(\frac{e_s}{R_v T}\right) \Big/ \left(\frac{P - e_s}{R_d T}\right) \qquad (2)$$

Where e_s is saturation vapor pressure, p is the total pressure, T is temperature, R_v is the gas constant for 1 kg of water vapor, and R_d is the gas constant for 1 kg dry air. Since $\frac{R_d}{R_v} = 0.622$, therefore w_s can be simplified to the following equation:

$$w_s = 0.622 \frac{e_s}{p - e_s} \qquad (3)$$

At the range of temperatures observed in the earth's surface, p>>e_s; w_s can be estimated as:

$$w_s \approx 0.622 \frac{e_s}{p} \qquad (4)$$

Saturation vapor pressure e_s can be calculated by Clausius-Clapeyron relation (Wallace and Hobbs 2006) as below:

$$e_s(T) = e_s(T_0) \times \exp\left(\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \qquad (5)$$

Where $e_s(T)$ is the saturation vapor pressure at temperature T, $e_s(T_0)$ is the saturation vapor pressure at temperature T_0 (reference temperature), R_v is the gas constant for 1 kg of water vapor, L is the latent heat of evaporation for water, T is temperature, and T_0 is 273.15 k and $e_s(T_0)$ is 6.11 mb. Finally, RH can be calculated by following equation:

$$RH = \frac{w}{w_s} \times 100 \approx \frac{q}{\frac{0.622 e_s}{p}} = 26.3pq\left[\exp\left(\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right)\right]^{-1} \qquad (6)$$

Where p is monthly surface pressure (Pa), q is monthly specific humidity (dimensionless), and T is monthly air temperature (k). These variables (p, q, and T) are obtained from MERRA2 data. L is the latent heat of evaporation for water and varies between L=2.501×10^6 Jkg^{-1} at T=273.15 k and L=2.257×10^6 Jkg^{-1} at T=373.15 k, R_v is 461.50 $Jkg^{-1}k^{-1}$, and T_0 is 273.15 k.

After obtaining RH values, for calculating vapor pressure deficit, we first calculated dew point temperature by using monthly surface air temperature (T°C) and monthly surface relative humidity (RH %) evaluated from (eq. 6) as below:

$$T_d = \frac{B_1\left[\ln\left(\frac{RH}{100}\right) + \frac{A_1 T}{B_1 + T}\right]}{A_1 - \ln\left(\frac{RH}{100}\right) - \frac{A_1 T}{B_1 + T}} \qquad (7)$$

Here, A_1 and B_1 are coefficient. Alduchov and Eskridge (1996) recommended the following values for the coefficients: A_1=17.625, B_1=243.04°C. (Lawrence 2005)

After calculating T_d, vapor pressure deficit (VPD), which is difference between saturation (e_s) and actual (e) vapor pressure was calculated using monthly air temperature (T°C) and monthly dew point temperature (T_d°C) (Weiss et al. 2012) using the following formula:

$$VPD = a \times \exp\left(\frac{b \times T}{T + c}\right) - a \times \exp\left(\frac{b \times T_d}{T_d + c}\right) \qquad (8)$$

Where a=0.611 kPa, b=17.502, c=240.97°C and VPD is monthly mean vapor pressure deficit (kPa).

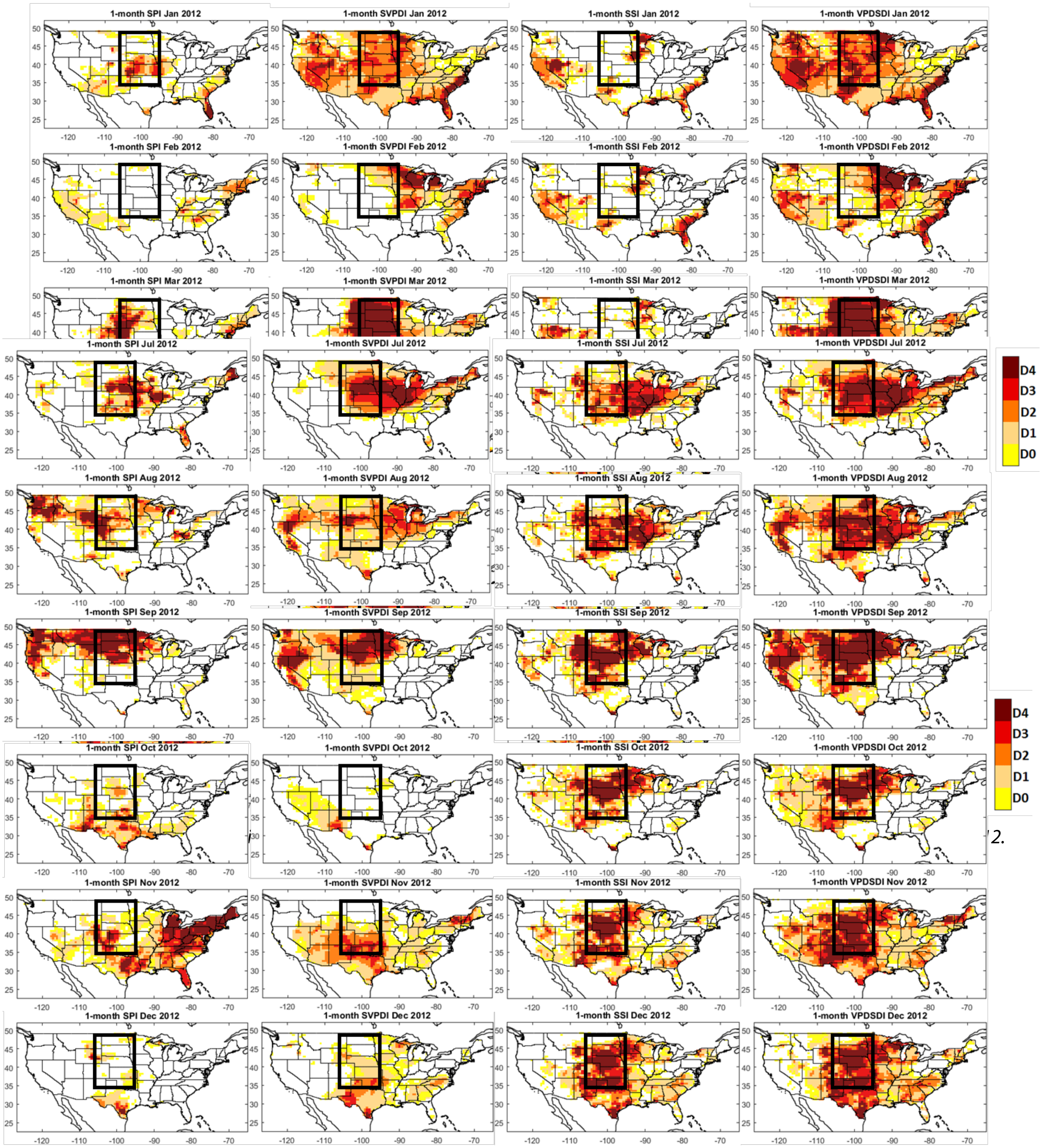

Figure S1 (b). *(left to right) MERRA2–based 1-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) July-December 2012.*

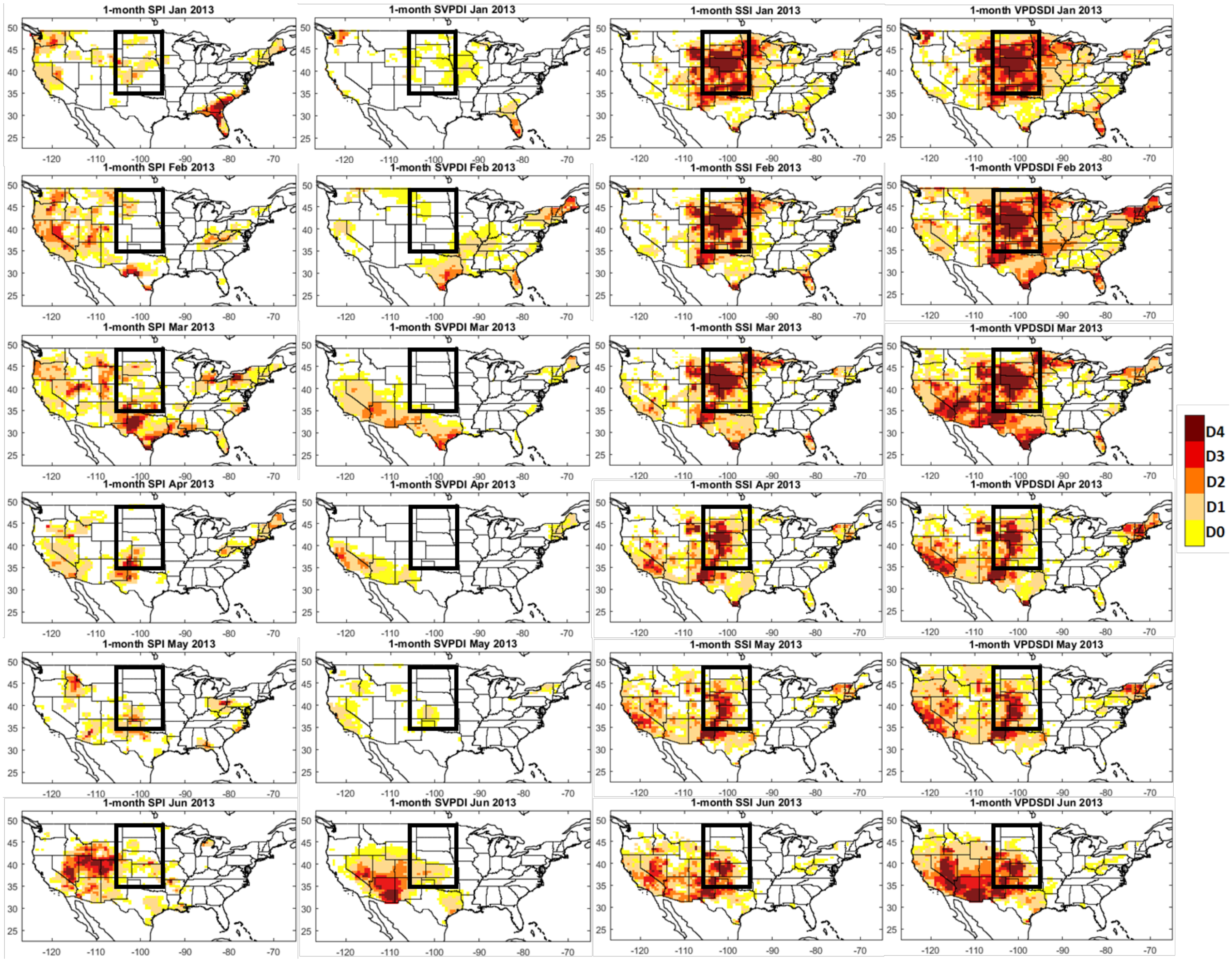

Figure S1 (c). *(left to right) MERRA2–based 1-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) January-June 2013.*

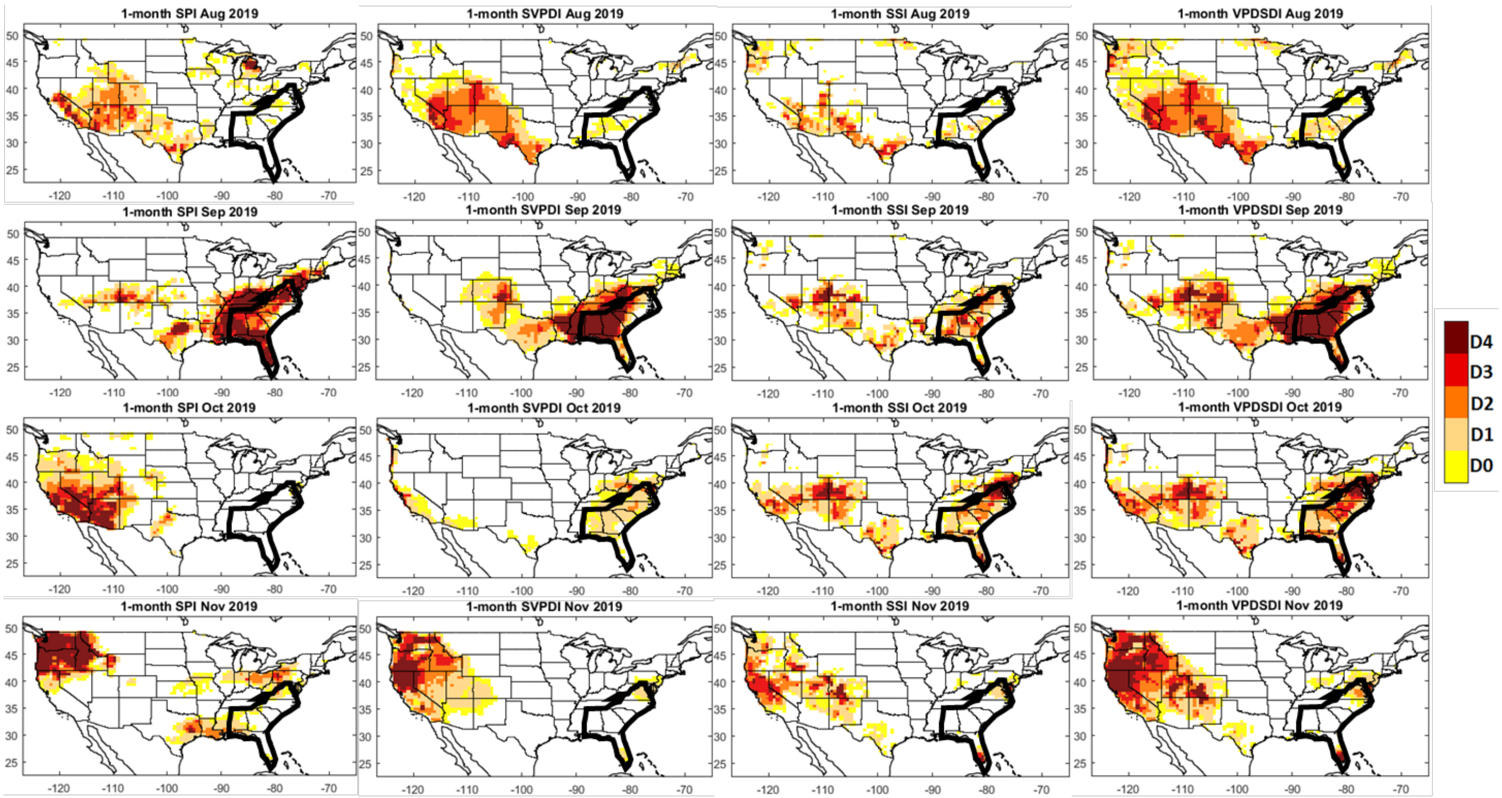

Figure S2. *(left to right) MERRA2–based 1-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) August-November 2019.*

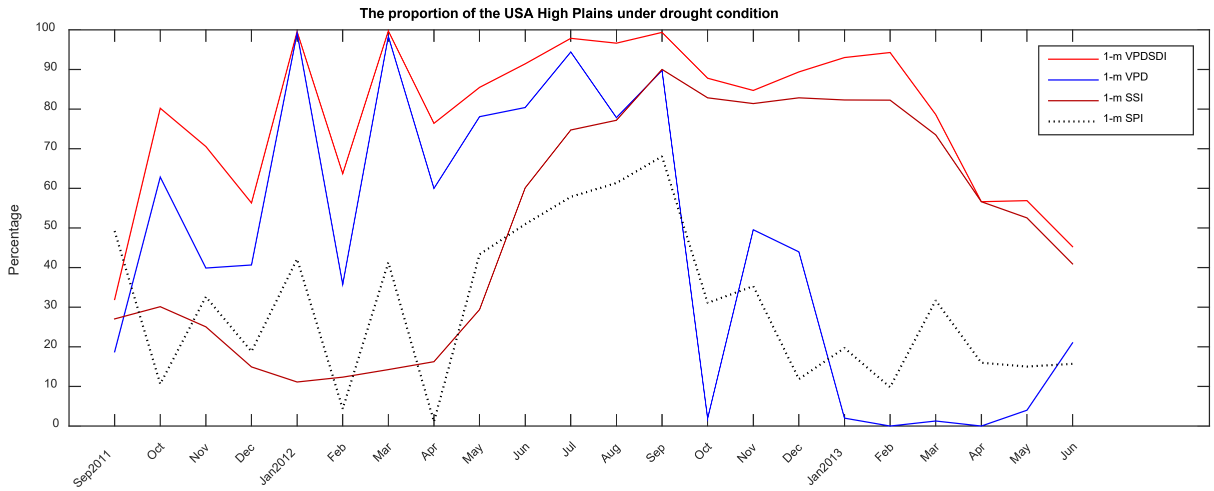

Figure S3. *Proportion of the High Plains that showed drought between September 2011 and June 2013*

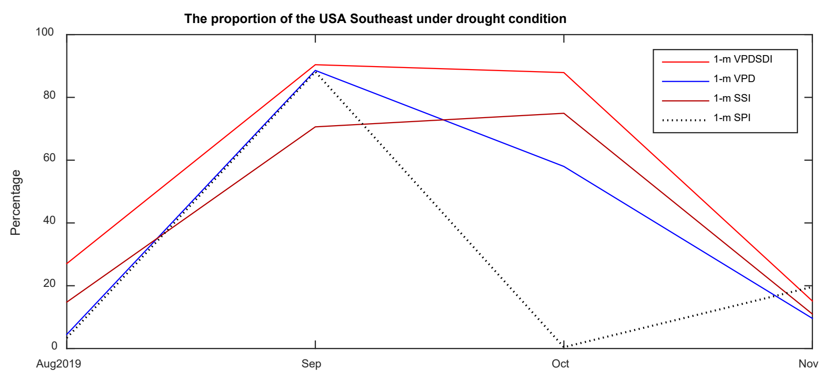

Figure S4. *Proportion of the Southeast that showed drought between August and November 2019*

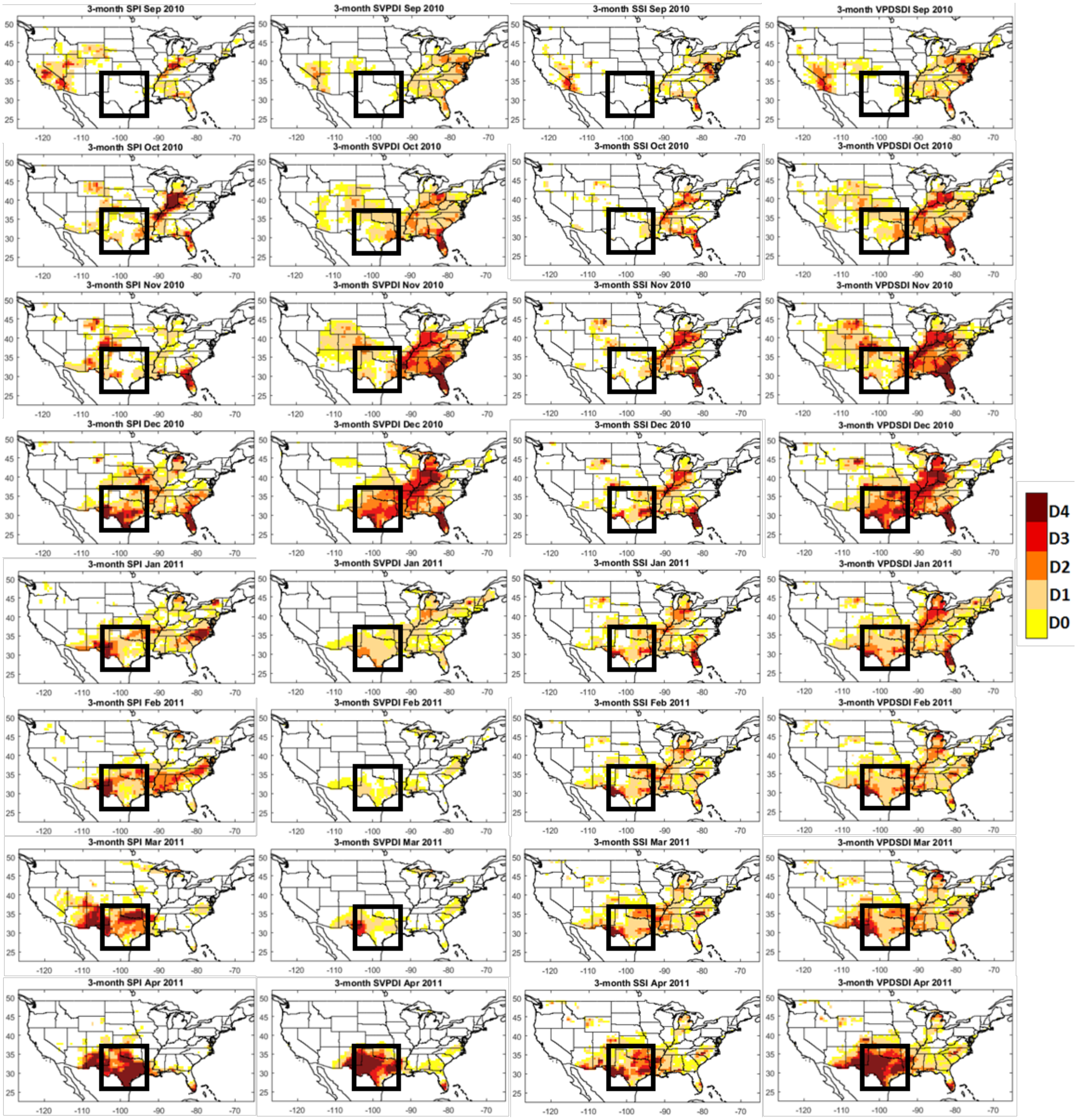

Figure S5 (a). *(left to right) MERRA2–based 3-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) September 2010-April 2011.*

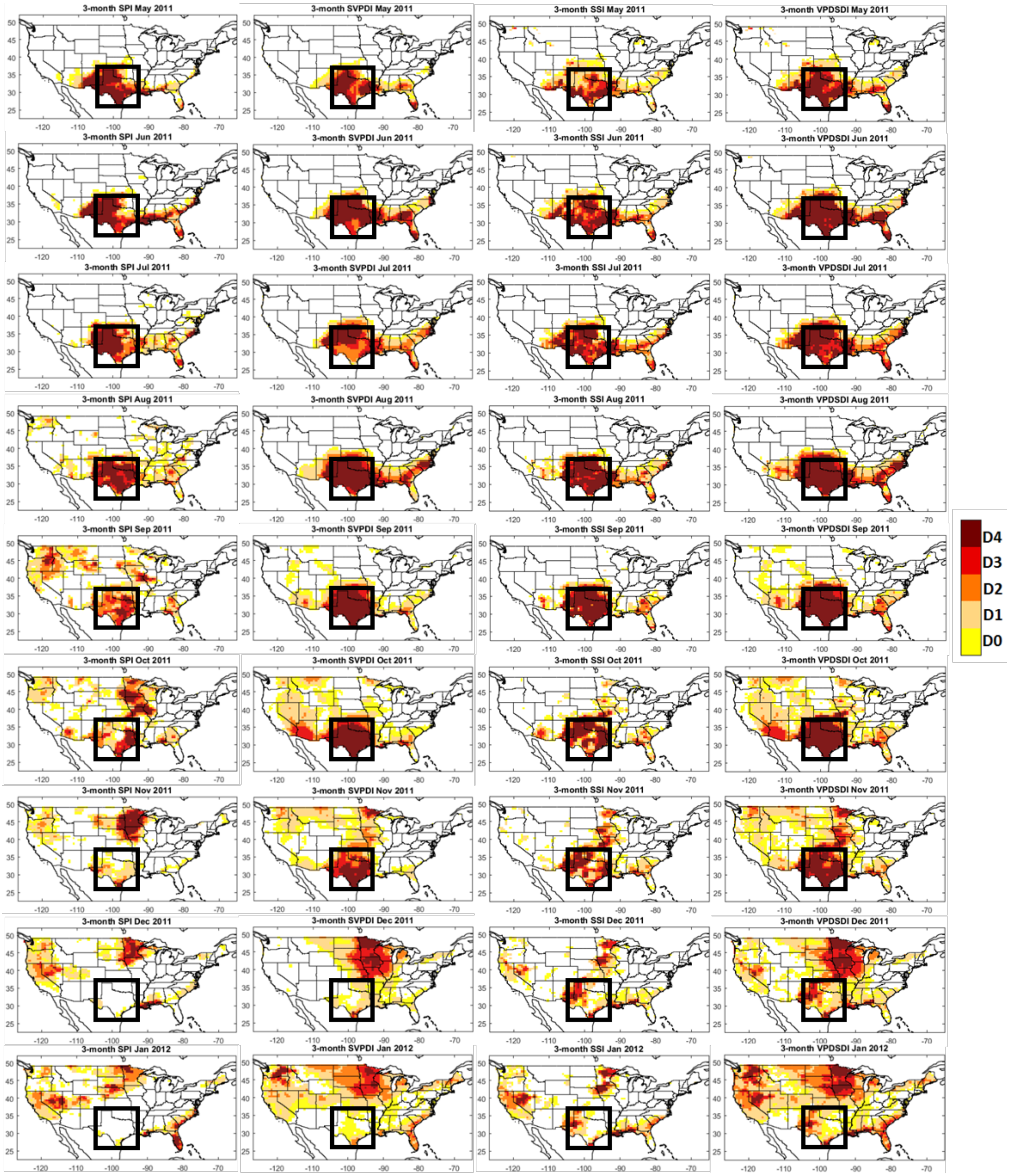

Figure S5 (b). *(left to right) MERRA2–based 3-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) May 2011-January 2012.*

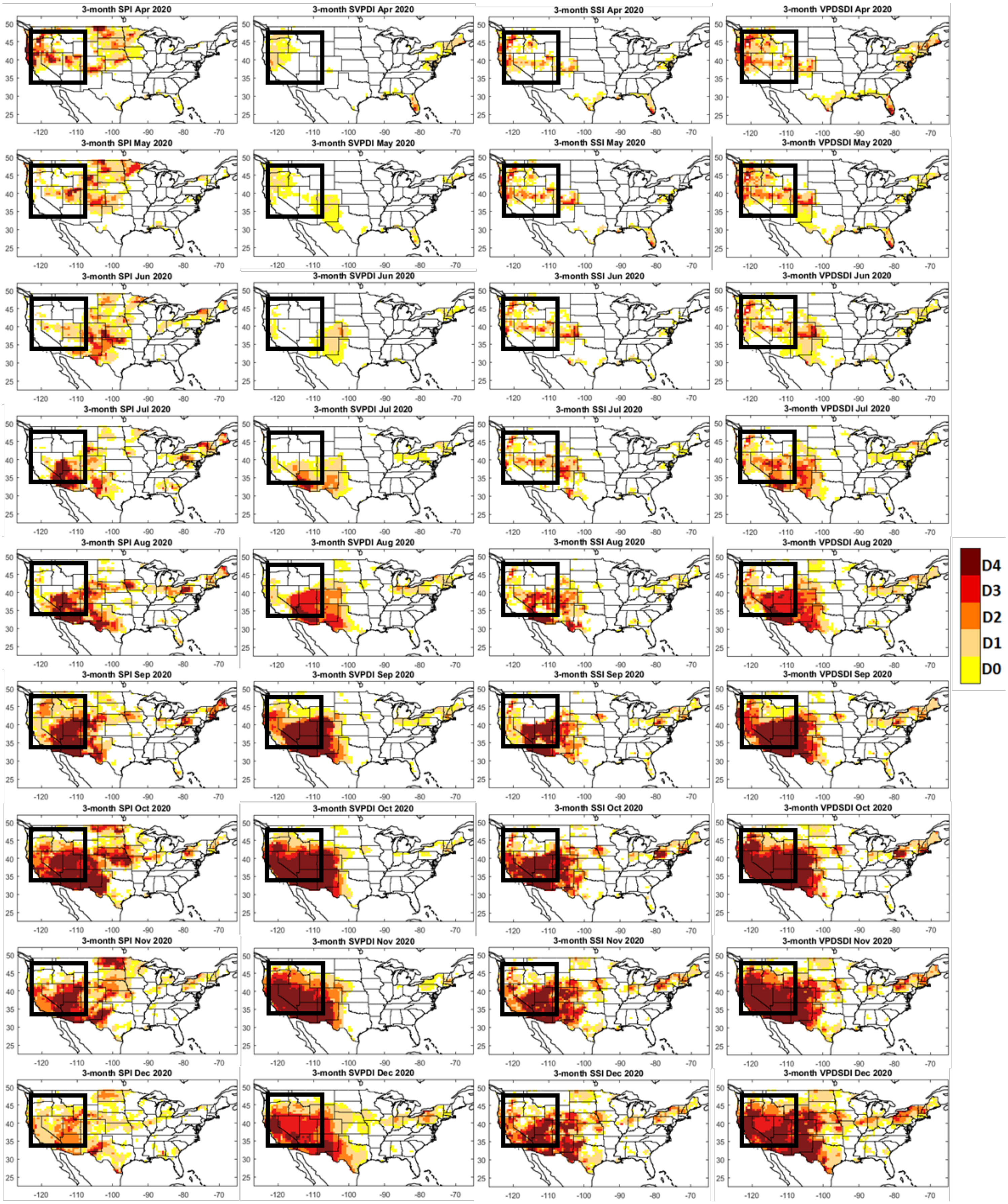

Figure S6 (a). *(left to right) MERRA2–based 3-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) April-December 2020.*

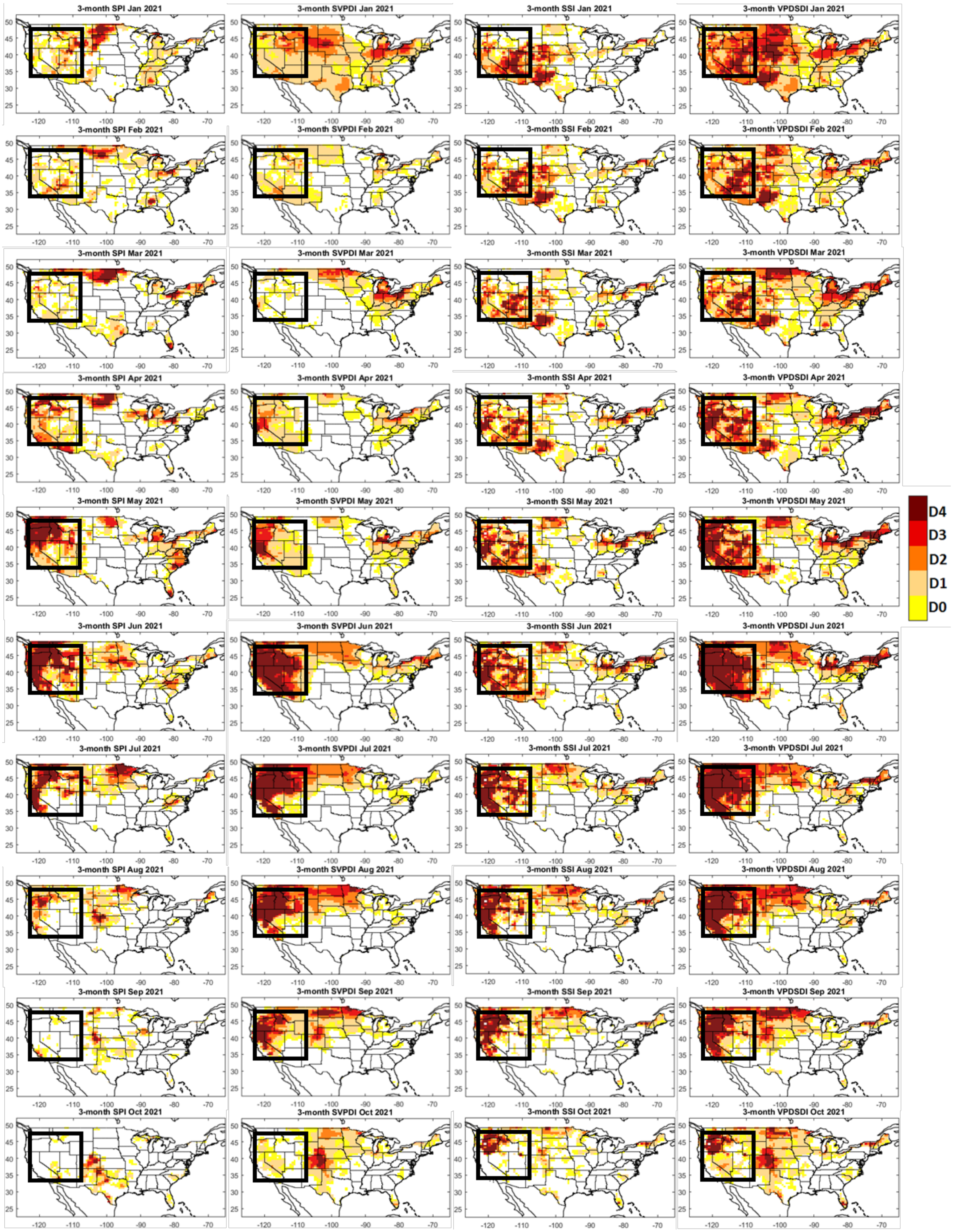

Figure S6 (b). *(left to right) MERRA2–based 3-month: SPI, SVPDI, SSI, and VPDSDI. (top to bottom) January-October 2021.*

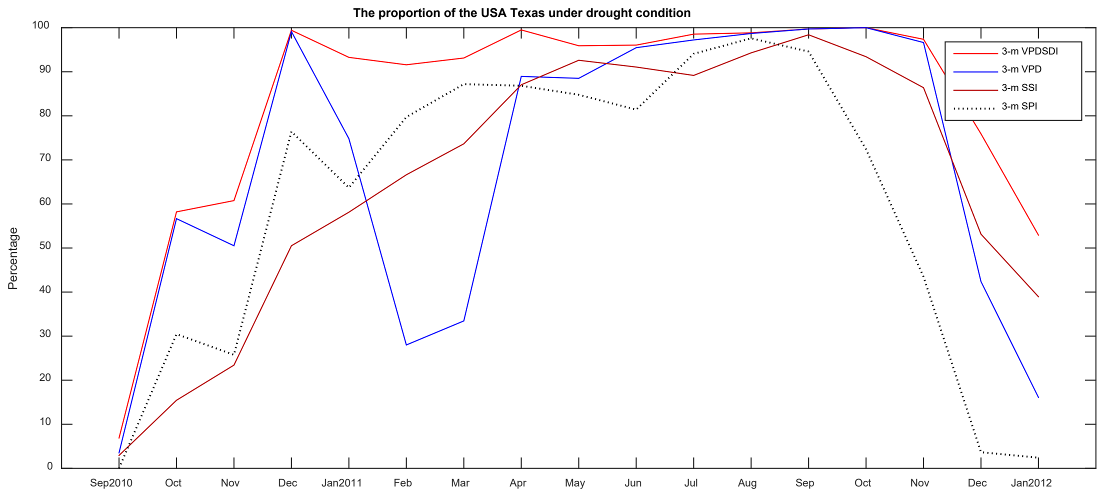

Figure S7. *Proportion of Texas that showed drought between September 2010 and January 2012*

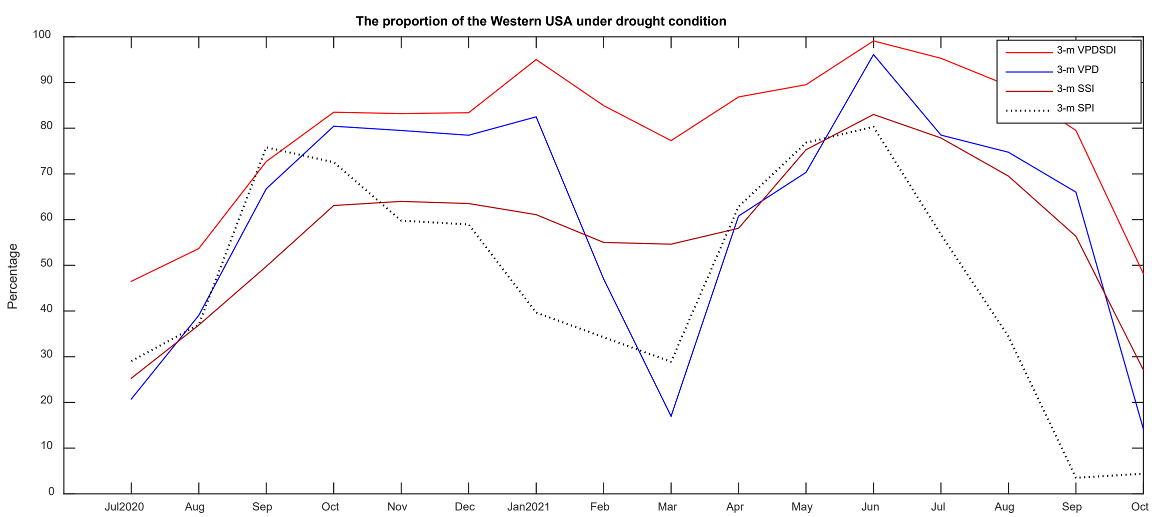

Figure S8. *Proportion of the Western USA that showed drought between July 2020 and October 2021*