5.3 APPLICATION OF NARR-BASED NLDAS ENSEMBLE SIMULATIONS TO CONTINENTAL-SCALE DROUGHT MONITORING

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1. INTRODUCTION

Government estimates indicate that droughts cause billions of dollars of damage to agricultural interests each year. More effective identification of droughts would directly benefit decision makers, and would allow for the more efficient allocation of resources that might mitigate the event. Land data assimilation systems (LDAS), with their high quality representations of soil moisture, present an ideal platform for drought monitoring, and offer many advantages over traditional modeling systems (Mitchell et al., 2004). The recently released North American Regional Reanalysis (NARR, Mesinger et al., 2006) covers the North American LDAS (NLDAS) domain and provides all fields necessary to force the NLDAS for 28 years. This presents an ideal opportunity to combine NARR and NLDAS resources into an effective real-time drought monitor. Toward this end, our project seeks to validate and explore the NARR's suitability as a base for drought monitoring applications—both in terms of data set length and accuracy.

Along the same lines, the project will examine the impact of the use of different (longer) LDAS model climatologies on drought monitoring, and will explore the advantages of ensemble simulations versus single model simulations in drought monitoring activities. We have produced a NARR- and observation-based high quality 28 year, 1/8th degree, hourly, land surface and meteorological forcing data sets. An investigation of the best way to force an LDAS-type system will also be made, with several forcing options explored.

This AMS paper will focus on an overview of the drought monitoring project, and will include a summary of recent progress.

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2. PROJECT OVERVIEW

The NASA GSFC drought research project is proceeding as part of the ongoing collaborative NLDAS research project which includes partners from NASA GSFC, NOAA NCEP, NOAA CPC, NOAA OHD, Princeton University, Rutgers University, the University of Washington, and the University of Maryland. Research will proceed in three main stages as depicted in Figure 1.

- Construction and validation of 1/8th degree, hourly forcing
- Execution and validation of ensemble 1/8th degree LSM simulations
- Construction, execution and analysis of drought monitor processing system

2.1 *Forcing Data*

The first stage of the project is complete, with forcing data now available for the 1979-2007 time period, and with an automated extension in place for real-time daily forcing production. As with the original NLDAS forcing data set (Cosgrove et al., 2003), the new NARR- and observation-based forcing data set includes the standard surface, 2-meter, and 10-meter meteorological fields needed to force a land surface model in a set of "A" files (Table 1). However, the 2-meter and 10-meter NWP model-based fields included in this and other forcing data sets are often extrapolations from the model's lowest prognostic layer, located well above a 2-

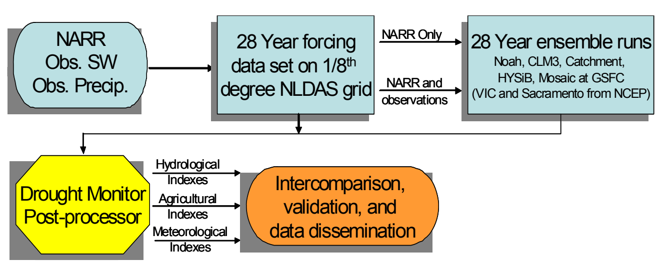

Figure 1. Overview flowchart of forcing production and drought analysis system.

Forcing Field	Units	Height	Data Source	File
U Wind Component	m/s	10m	NARR	A
V Wind Component	m/s	10m	NARR	A
Air Temperature	K	2m	NARR	A
Specific Humidity	kg/kg	2m	NARR	A
Pressure	Pa	Surface	NARR	A
Downward Longwave Radiation	W/m2	Surface	NARR	A
Downward Shortwave Radiation	W/m2	Surface	Bias-corrected NARR	A
Total Precipitation	mm	Surface	Multiple Observations	A
Convective Fraction of Precipitation	-	Surface	NARR	A
CAPE	J/kg	Surface	NARR	A
Potential Evaporation	mm	Surface	NARR	A
Height "H" of Lowest NARR Prognostic Layer	m	-	NARR	B
U Wind Component	m/s	H	NARR	B
V Wind Component	m/s	H	NARR	B
Air Temperature	K	H	NARR	B
Specific Humidity	kg/kg	H	NARR	B
Pressure	Pa	H	NARR	B
Downward Shortwave Radiation	W/m2	Surface	NARR	B
Total Precipitation	mm	Surface	NARR	B
Convective Precipitation	mm	Surface	NARR	B
Categorical Precipitation Type	-	Surface	NARR	B
NARR Surface Exchange Coefficient	kg/m2s	Surface	NARR	B

Table 1. Contents of new NLDAS "A" and "B" forcing files.

meter height. This extrapolation depends greatly on the model's particular method of modeling the aerodynamic conductance of the "surface" or "constant flux" layer. In order to allow LSMs to calculate their aerodynamic conductance from surface fields that are mostly independent from the aerodynamic conductance approach used by the NARR, an additional set of meteorological fields is being supplied in a secondary "B" file (Table 1).

Backwards compatible with earlier NLDAS forcing data sets, the new forcing data uses 32km, 3-hourly NARR meteorological fields as a data backbone. These fields are temporally interpolated to an hourly resolution, and spatially interpolated to a 1/8th degree resolution. As NLDAS 1/8th degree topography differs significantly from the topography of the 32 km NARR output grid, the next processing step involves adjusting the surface pressure, incident longwave radiation, 2 m temperature and 2 m humidity NARR-based fields to account for such differences following the lapse rate-based adjustments detailed in Cosgrove et al. (2003).

The total precipitation field contained in File A is derived from CPC daily CONUS gauge data (with the PRISM topographical adjustment (Daly et al., 1994), CPC daily North American gauge data, hourly Stage II and HPD precipitation data (Higgins et al., 2000), half-hourly CMORPH data (Joyce et al., 2004), and 3-hourly NARR precipitation data. Reflecting the strengths of each data set, NLDAS precipitation is derived by using the hourly Doppler radar and half-hourly CMORPH products to temporally disaggregate the daily gauge products. This process, described in detail below, capitalizes on the accuracy of the daily gauge product, and on the temporal and spatial resolutions of the Doppler radar and CMORPH products.

CPC PRISM-adjusted daily gauge analyses serve as the backbone of the NLDAS hourly precipitation forcing. Outside of the CONUS, where this dataset is unavailable, CPC's 1 degree (0.25 degree after 2001) North American daily gauge product is used instead. In NLDAS, these gauge-only daily precipitation analyses are first processed to fill in any missing values, and then are temporally disaggregated into hourly fields. This is accomplished by deriving hourly disaggregation weights from NWS real-time, 4 km Stage II and 8km CMORPH hourly precipitation analyses. Stage II data is available from 1996 to the present, while CMORPH data is available from 2002 to the present. The Stage II product consists of WSR-88D Doppler radar-based precipitation estimates that have been bias corrected using hourly multi-agency gauge data (Fulton et al., 1998), and mosaicked into a national product over the Continental United States (CONUS) by NCEP/EMC (Baldwin and Mitchell, 1997). This CONUS mosaic of the Stage II product is interpolated to 1/8th degree and any gaps in radar coverage (which total on average 13% of the area of the CONUS and are due to lack of radar coverage or equipment maintenance) are filled in with nearest neighbor Stage II data from within the local region. If no Stage II data are available, then CMORPH data are used instead, and if no CMORPH data is available, then HPD precipitation data is used. CMORPH data is also used over the Mexican portion of the NLDAS domain which is outside of the Stage II's region of coverage. When CMORPH data is unavailable, NARR data is used instead.

The patched, hourly Stage II and CMORPH fields are then divided by fields of patched Stage II and CMORPH daily precipitation totals to create hourly temporal disaggregation weights representing the proportion of the 24 hour total precipitation which fell in each hour. If the daily Stage II or CMORPH total is zero in an area of non-zero CPC precipitation, hourly weights are set to 1/24 to spread the precipitation evenly over the entire day. These hourly weights are then multiplied by the daily gauge-only CPC precipitation analysis to arrive at temporally disaggregated, hourly NLDAS fields. Since the Stage II and CMORPH data is only used to derive the hourly disaggregation weights, a daily summation of these NLDAS precipitation fields will exactly reproduce the original CPC daily precipitation analysis. Since daily gauge and hourly precipitation data is sparse over Canada, NARR precipitation is used over all Canadian regions within the NLDAS domain. Rather than have an abrupt cutoff at the United States border, a one degree wide blending area is used. In this region, precipitation forcing consists of a weighted combination of the precipitation datasets discussed above.

Observations are also used in the production of the downward shortwave radiation field contained in the A-files. In particular, the NARR downward shortwave radiation field in the NLDAS forcing files (A-files) is bias corrected using the University of Maryland Surface Radiation Budget (SRB) data set produced under the GEWEX Continental Scale International Project (GCIP) and GEWEX Americas Prediction Project (GAPP) (Pinker et al. 2003). Data from the GOES-8 satellite was processed using an inference model to produce hourly estimates of downward shortwave radiation fluxes. This dataset was produced on the native $1/8^{th}$ degree NLDAS grid and no further interpolation was necessary. A ratio-based (Berg et al., 2003) bias correction was applied to the NARR downward shortwave radiation field as follows:

1) Monthly mean diurnal cycles of downward shortwave radiation were derived from both the UMD SRB data and the NARR data (interpolated to $1/8^{th}$ degree NLDAS grid). In order to ensure consistency both mean data sets include only the years common to both datasets, 1996-2000.
2) A ratio-based correction was applied to NARR data:

   (1) $S \downarrow NLDAS_i = \dfrac{S \downarrow (GOES)}{S \downarrow (NARR)} \times S \downarrow NARR_i$

   Where $S \downarrow (GOES)$ and $S \downarrow (NARR)$ are monthly mean downward shortwave radiation values (W/m^2) from the UMD SRB and NARR data sets at hour i, $S \downarrow NARR_i$ is the instantaneous NARR downward shortwave radiation value (W/m^2) at hour i, and $S \downarrow NLDAS_i$ is the resulting bias corrected field contained in the NLDAS "A" forcing files.
3) Quality control procedures were applied to the bias corrected data to ensure the new values at each gridpoint fell below the maximum value possible (value < $\cos(zenth\angle) \times S_{\max}$, where $S_{\max}$ = 1367 W m^{-2}). If the bias corrected data exceeded the threshold at a given NLDAS grid point, the value was set to the maximum value possible ($\cos(zenth\angle) \times S_{\max}$) at that grid point.

2.2 *Ensemble LSM Simulations*

Land surface output from an ensemble of LSMs will form the basis of the drought monitor, and will aid in ongoing LSM improvement activities as the current NLDAS research effort has done. Noah, CLM3, HySSiB, Catchment, Mosaic, Sacramento, and VIC LSMs will each be executed on the common 1/8th NLDAS grid from 1979-Present, and will produce 3-hourly output. A runoff routing scheme (Lohmann, 2004) will be applied to each LSM's output to calculate stream flow, and an extensive intercomparison and validation effort will be conducted making use of SCAN and Oklahoma Mesonet in-situ observation networks as well as CPC's 50-year Noah LSM simulation.

2.3 *Drought Monitor Processing System*

The drought monitoring processing system will make use of the new NLDAS forcing data, output from the ensemble NLDAS LSM simulations, and NARR land surface states to depict the extent and severity of agricultural, hydrological, and meteorological drought over the continental United States. As outlined in Table 2, a range of standard and new NLDAS-based drought indices will computed in a retrospective and real-time fashion. Of particular note is the CLM3 vegetation health index (VHI) which will harness CLM3's ability to produce LAI and NDVI fields to depict the overall condition of vegetation in a fashion that can be validated against remotely sensed observations of similar fields.

Analysis of output from the drought monitor processing system will address several key questions including:

1) How does the depiction of drought vary by LSM?
2) What impact does the use of ensemble mean versus single model output have on drought detection?
3) How do ensemble NLDAS simulations, NARR simulations, and the US Drought Monitor differ in their characterization and detection of drought?
4) How does climatology length affect drought characterization?

2.4. *Real-time Web-based Drought Monitor*

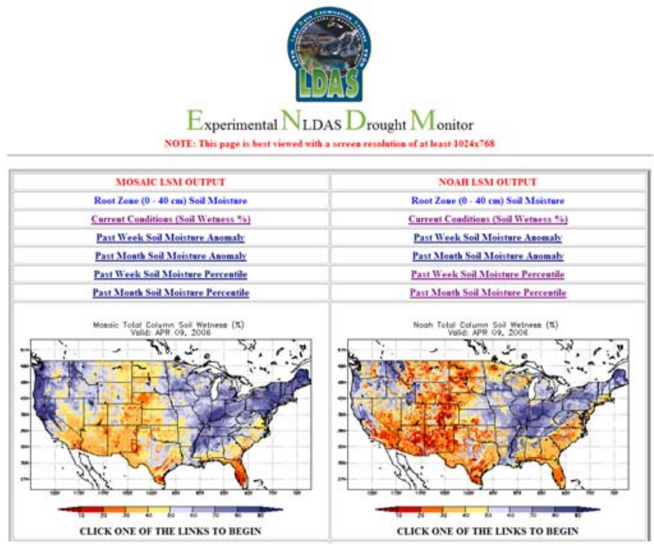

Figure 2. Snapshot of experimental real-time NLDAS drought monitor (http://ldas.gsfc.nasa.gov/monitor/).

Serving as a web-based means of distributing the drought indices produced from the forcing data above, a prototype real time drought monitor has been constructed and is located at http://ldas.gsfc.nasa.gov/monitor/ (Figure 2). This page follows in the footsteps of several established drought monitoring sites including those at the University of Washington, Princeton University, and NOAA CPC. Featuring absolute, percentile, and anomaly depictions of soil moisture from the Mosaic and Noah LSMs, this drought monitor page is updated each day through a series of automated model scripts and data transfers. Currently only in the testing stages, the drought monitor page will soon be updated with additional drought indices, LSMs, and interactive capabilities.

	Drought Index	Drought Type	Required NARR/NLDAS Monitor Data	Comparison Data
Standard Indices	Wtd/UnWtd PDSI	Meteorological	Forcing	NCDC PDSI
	SPI	Meteorological	Forcing	U. Nebraska SPI
	PHDI	Hydrological	Forcing	NCDC PHDI
	TWD	Hydrological	Streamflow Output	USGS Streamflow
	Palmer Z	Agricultural	Forcing	NCDC Palmer Z
	LSM Percentile	Agricultural	LSM Soil Moisture Output	U. Washington
	Self Calibrating (duration and climate characteristic parameters)			
Experimental LDAS Indices	LDAS PDSI	Meteorological	LSM Output and Forcing	NCDC PDSI
	LDAS PHDI	Hydrological	LSM Output and Forcing	NCDC PHDI
	LDAS Palmer Z	Agricultural	LSM Output and Forcing	NCDC Palmer Z
	CLM3 VHI	Agricultural	CLM3 LAI/NDVI Output	NOAA VHI

Table 2. Overview of drought indices that will be computed in the proposed drought monitor.

3. INITIAL RESULTS

Initial simulations have been completed using the Mosaic and Noah LSMs and a test version of the new NLDAS forcing data set. Analysis of these runs has focused on the impact of climatology length, meteorological forcing data, and model selection on drought characterization.

3.1 *Climatology Length*

Accurate drought detection depends on ability of the analysis system to place the current soil moisture or stream flow levels into proper historical context. Droughts are relative in nature, that is, they consist of a negative departure from normal moisture levels. As such, drought detection systems can be greatly impacted by the length of the climatology upon which they are based.

In order to determine whether the land surface conditions in question constitute a drought, the climatology must contain a representative number of wet and dry events. To examine the impact of climatology length on this analysis problem, two Noah LSM soil moisture climatologies were generated; the first drew on output from the full 28 Year 1979-2007 study period, while the second was derived from a 10 year subset of the same data set from 1997-2007. As Figure 3 shows, differences in the climatologies lead to large differences in the characterization of drought severity and extent. This is especially evident over the Midwest, where use of the 10 year climatology leads to the characterization of total column soil moisture conditions as drought level 4 (D4), the most severe level of drought, while only D2 in the analysis based on the 28-year climatology. Additional studies with other LSMs will further examine this issue.

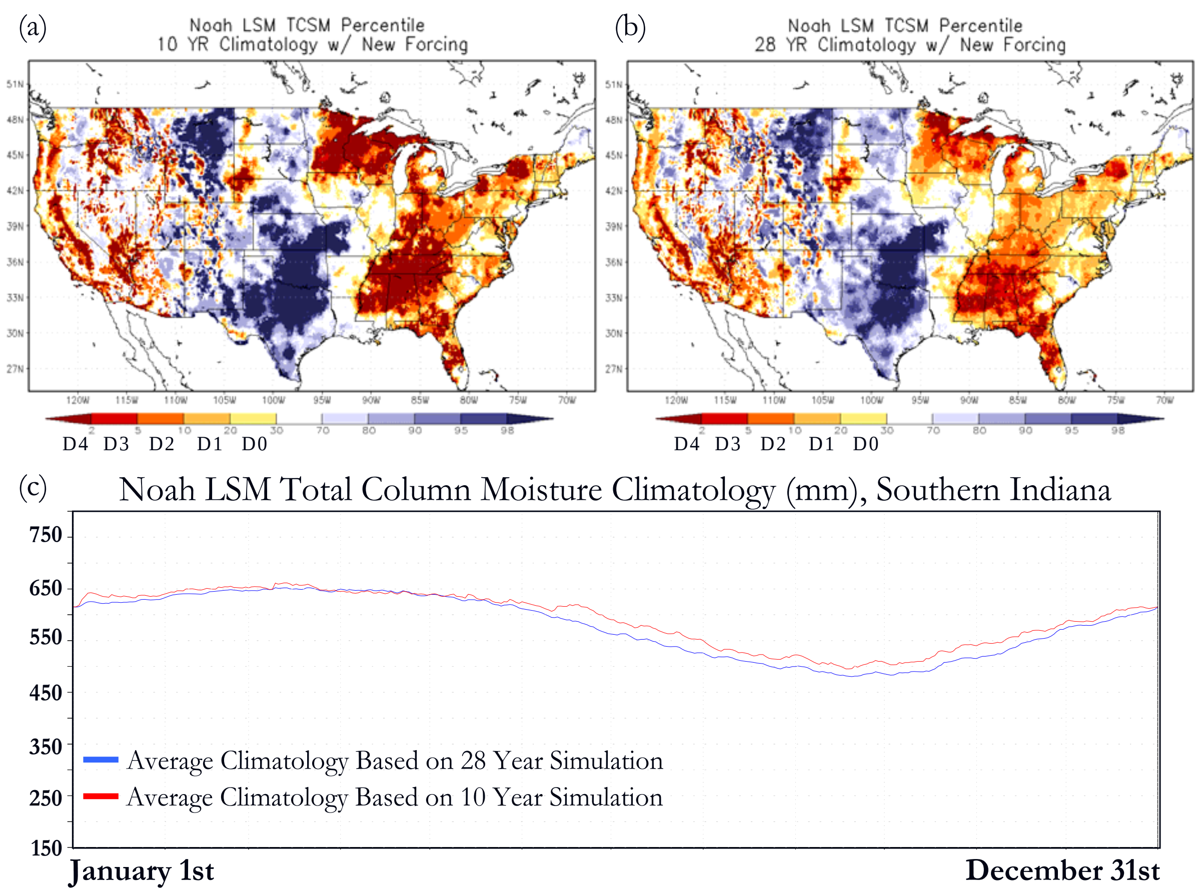

Figure 3. Figures illustrate impact of climatology length on average annual cycle of total column soil moisture (c), and on resulting drought depictions using a soil moisture percentile index (a) and (b). Contour intervals and colors correspond to those used by the U.S. Drought Monitor.

3.2 *Meteorological Forcing Data*

The drought monitor outlined in this paper is highly dependent upon accurate land surface model simulations, which, in turn, are highly dependent upon accurate forcing data. To determine how sensitive LSM-based drought characterization is to the forcing data used to drive each model, two sets of Noah LSM simulations were conducted over the 1997-2007 time period. The first simulation used a 10 year subset of the new NLDAS forcing data set, while the second simulation used a 10 year subset of the original NLDAS forcing data set (Cosgrove et. al, 2003).

Although similar in concept—each data set features a model-based backbone of data overlaid with observation-based precipitation and SW radiation—the specifics of each data set differ. The new data set uses a NARR data backbone, precipitation based on PRISM, Stage II, HPD, and CMORPH data sets, and GOES-based bias-corrected NARR SW fields. By contrast, the original data set uses EDAS fields, precipitation based on CPC and Stage II data sets, and GOES SW fields. These differences lead to significant differences in the simulations of total column soil moisture, which then manifest themselves as differences in drought placement and severity. Figure 4 shows that drought severity increases in some areas, decreases in other areas, and even changes sign (from drought to overly wet conditions) over the upper West. Validation of the new NLDAS forcing data set has not yet be completed. Once completed, it will be possible to determine whether increases in forcing accuracy lead to increases in the accuracy of drought detection. It might be expected that this would be the case, but given the non-linear processes and parameterizations present in

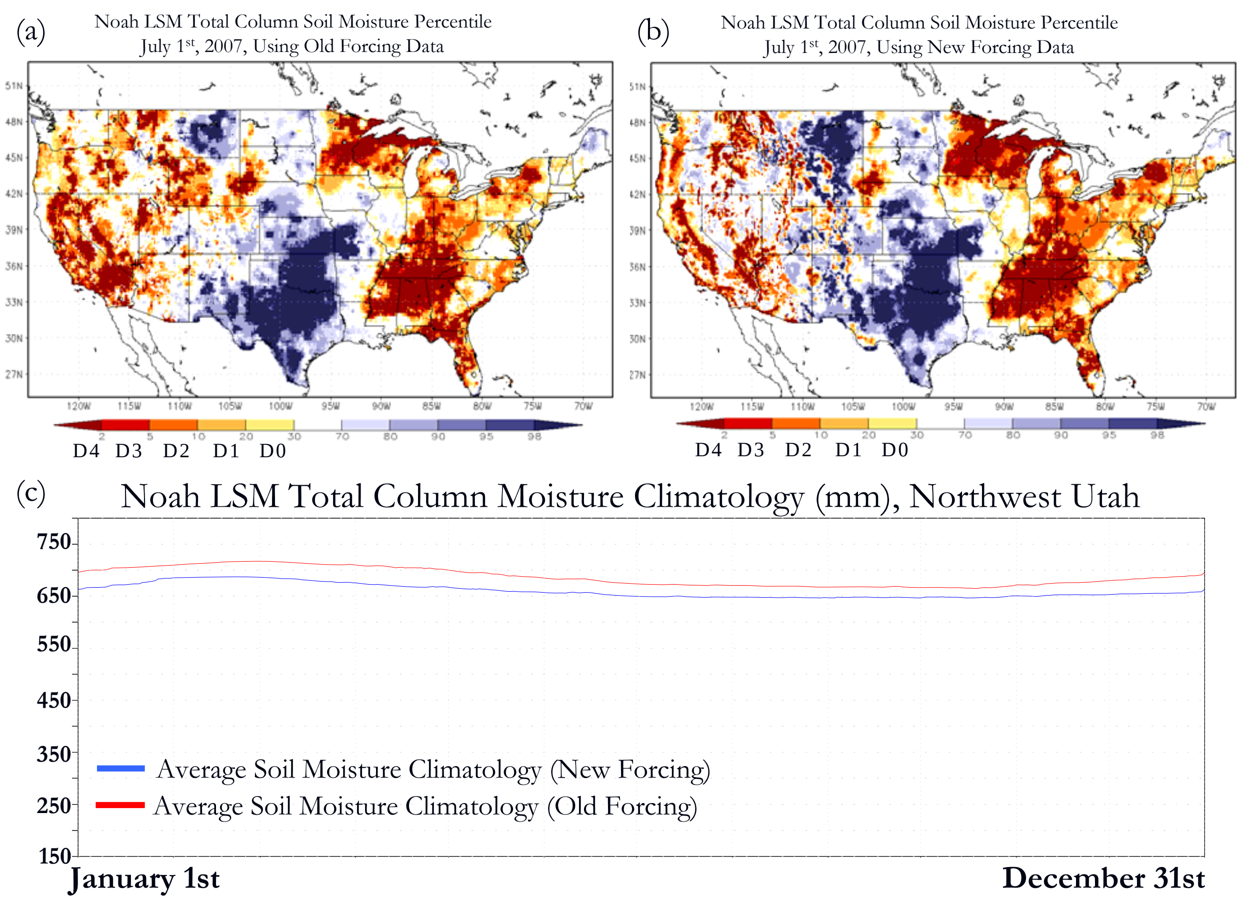

Figure 4. Figures illustrate impact of forcing data on average annual cycle of total column soil moisture (c), and on resulting drought depictions using a soil moisture percentile index (a) and (b). Contour intervals and colors correspond to those used by the U.S. Drought Monitor.

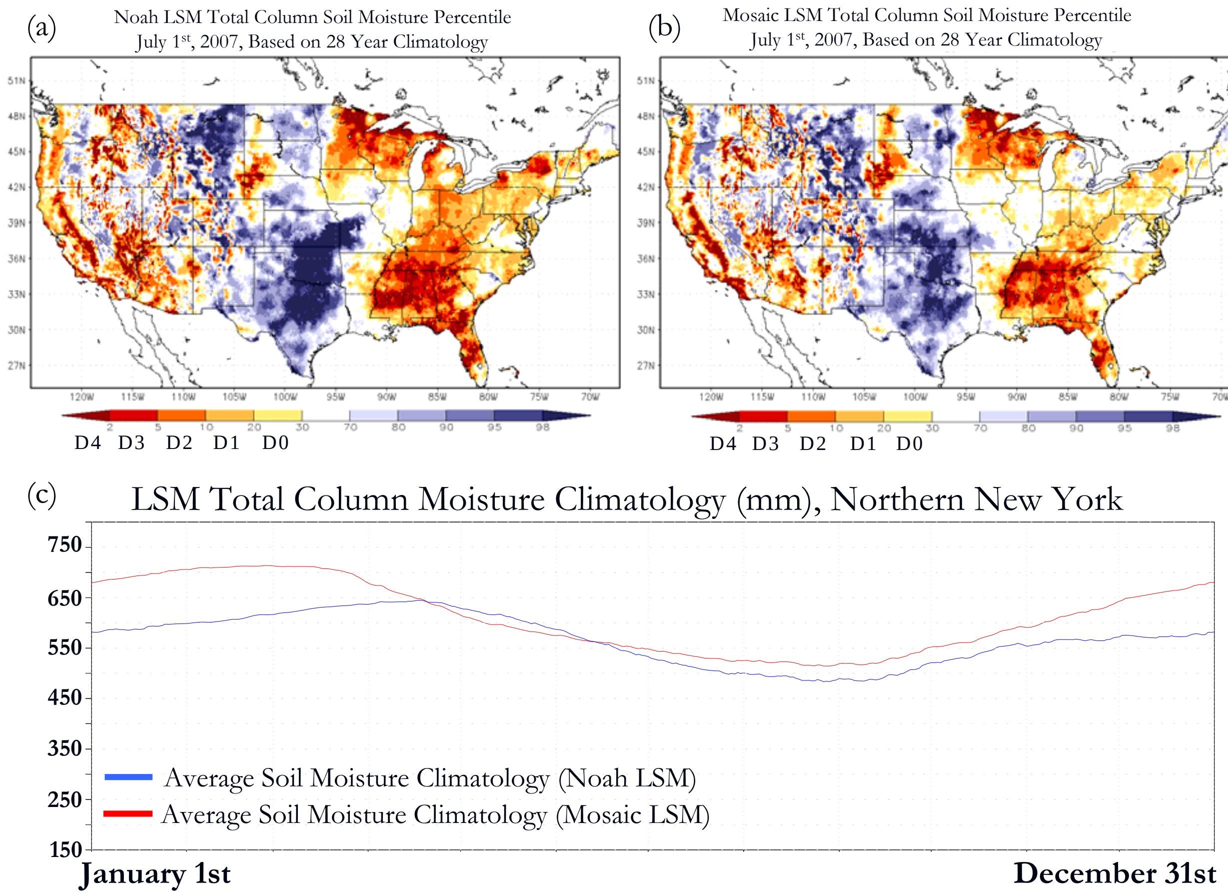

Figure 5. Figures illustrate impact of land surface model selection on average annual cycle of total column soil moisture (c), and on resulting drought depictions using a soil moisture percentile index (a) and (b). Contour intervals and colors correspond to those used by the U.S. Drought Monitor.

LSMs, it may be true only in certain cases.

3.3 *Land Surface Model Selection*

Just as climatology length and forcing data impact the characterization of droughts, so too does the choice of LSM used to produce the land surface conditions needed to drive the drought analysis system. Each LSM has a unique formulation and thus a unique set of land surface states. This is evident in Figure 5, which depicts the average annual total column soil moisture climatology from the Mosaic and Noah LSMs over a point in northern New York State. Each simulation was conducted using the new 28-year NLDAS forcing data set, and using the same vegetation and soil type maps. The differences which appear in the time series trace give rise to the CONUS wide differences in drought characterization. Over the Northeast United States for example, the Noah characterizes conditions as mostly drought category D1 to D2, while Mosaic places a D0 to D1 drought over the same region. That difference, although seemingly minor, can have broad implications in terms of the drought relief measures that are put into action. Studies using the proposed ensemble of seven LSMs will further examine this issue.

4. SUMMARY AND CONCLUSIONS

The ongoing NASA GSFC NLDAS drought research project seeks to use NARR- and observation-based forcing data and a seven member ensemble of LSMs to create an accurate, real-time drought monitor that is able to depict drought conditions in ways that emphasize the strengths of land surface models (i.e., Figure 6). Forcing production has been completed, and initial test runs have highlighted the substantial impact of climatology length, forcing data, and land surface model selection on drought characterization. Initial

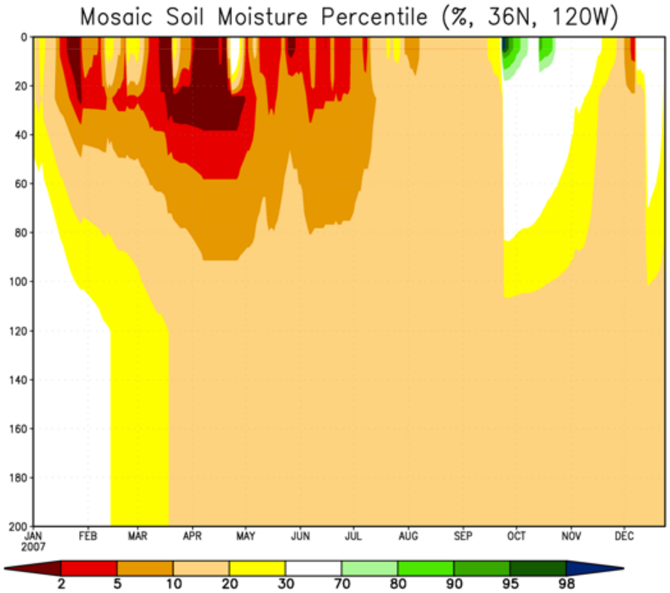

Figure 6. Time and depth cross section of Mosaic LSM soil moisture percentile (%) for a region in south-central California. Soil depth increases from 0cm at the top to 200cm at the bottom, and time flows from left to right in this figure.

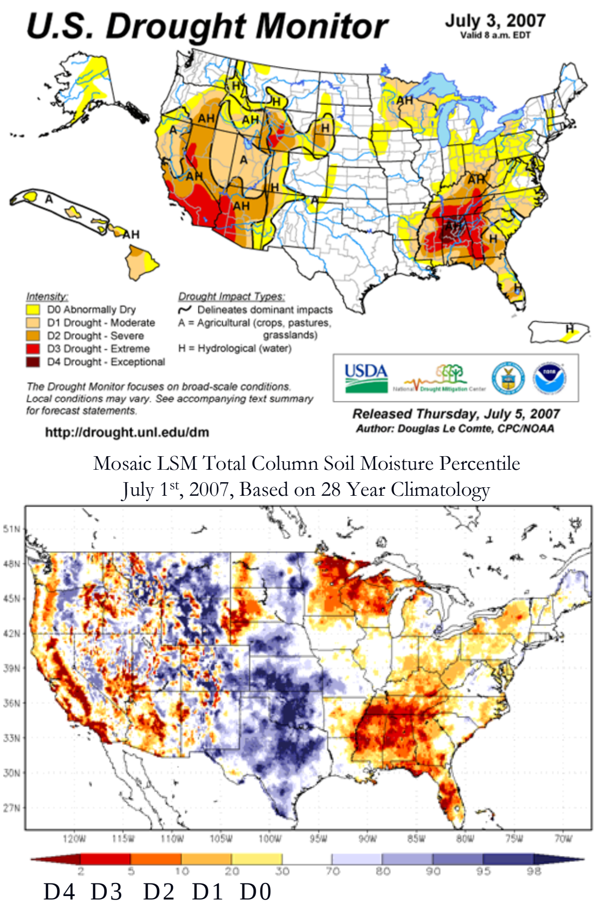

Figure 7. U.S. Drought Monitor (top) and NLDAS-Mosaic drought monitor feature similar depictions of drought in this early July 2007 snapshot.

output compares well with established drought monitors such as the U.S. Drought Monitor (Figure 7), and future work will leverage a seven-member ensemble of LSMs, as well as a broad range of drought indices to improve drought detection and characterization.

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