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Trends in 20th century drought over the continental United States

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[1] We used a simulated data set of hydro-climatological variables to examine for 20th century trends in soil moisture, runoff, and drought characteristics over the conterminous United States (U.S.). An increasing trend is apparent in both model soil moisture and runoff over much of the U.S., with a few decreasing trends in parts of the Southwest. The trend patterns were qualitatively similar to those found in streamflow records observed at a station network minimally affected by anthropogenic activities. This wetting trend is consistent with the general increase in precipitation in the latter half of the 20th century. Droughts have, for the most part, become shorter, less frequent, and cover a smaller portion of the country over the last century. The main exception is the Southwest and parts of the interior of the West, where, notwithstanding increased precipitation (and in some cases increased soil moisture and runoff), increased temperature has led to trends in drought characteristics that are mostly opposite to those for the rest of the country especially in the case of drought duration and severity, which have increased. **Citation:** Andreadis, K. M., and D. P. Lettenmaier (2006), Trends in 20th century drought over the continental United States, *Geophys. Res. Lett.*, *33*, L10403, doi:10.1029/2006GL025711.

1. Introduction

[2] Droughts are one of the most costly natural disasters, with estimated annual U.S. losses between \$6–8B [*Federal Emergency Management Agency*, 1995]. According to NOAA's National Climate Data Center (NCDC), the recent western U.S. drought cost over \$10B for 2002 alone [*National Climate Data Center*, 2003]. Potential changes in the characteristics of drought would have adverse effects on water management and aquatic ecosystems. Changes in the severity of drought associated with mid-continental drying predicted by some climate models over the next century [*Wetherald and Manabe*, 1995] are therefore of great concern. Although droughts are generally associated with decreased precipitation (and on average, global precipitation is projected to increase in the future by most climate models); increased rainfall does not necessarily mean less intense droughts. For example, less frequent but heavier precipitation events could lead to longer dry periods, even though rainfall amounts might have increased.

[3] There is a general consensus that temperature and precipitation increased in the latter half of the 20th century over the continental U.S. [*Intergovernmental Panel on Climate Change*, 2001]. Nonetheless, the nature of evaporation changes is unclear (due largely to the paucity of records that measure actual, as opposed to potential, evaporation), and so the nature of changes in the characteristics of drought is not immediately apparent from the observed precipitation and temperature (or streamflow, for that matter) changes. Furthermore, long-term records of a key variable related to drought, soil moisture, are essentially nonexistent. For this reason, the need for an objective method for investigating changes in the frequency and severity of droughts becomes apparent [*Trenberth et al.*, 2004].

[4] We suggest an approach to the problem that is based on reconstructions, using a well-validated land surface hydrology model, of key hydro-climatic variables that have not been observed directly over the long term. *Andreadis et al.* [2005] successfully used a long- term simulated data set to reconstruct 20th century drought conditions over the continental U.S., and compared the extent, severity and durations of the largest events for that period. While that study did not evaluate changes in drought characteristics, the underlying methods nonetheless form the basis for the analyses we present here. The goal of this paper, therefore, is to determine whether changes in drought characteristics have occurred over the continental U.S. in the past 80 years, and if so, to explore the nature of the changes that have occurred.

2. Hydrologic Model and Data Sets

[5] We used the Variable Infiltration Capacity (VIC) model [*Liang et al.*, 1994] to simulate soil moisture and runoff over the continental U.S., at a spatial resolution of one-half degree and a daily timestep. VIC essentially solves an energy and water balance over each model grid cell, and accounts for the effects of sub-grid scale variability in soil, vegetation, precipitation, and topography by partitioning each grid cell into different tiles. The soil column is represented as three layers, while vegetation and topography data as well as calibration parameters were identical to those used in [*Maurer et al.*, 2002]. The forcing data, which include precipitation, air temperature, and wind speed, were obtained from the NCDC using the methods outlined in [*Maurer et al.*, 2002], and extended from 1915 to 2003 (also used as the simulation period). In addition, the data were corrected for temporal heterogeneities using the procedure described in [*Hamlet and Lettenmaier*, 2005] that essentially adjusts the decadal variability to match that of the high-quality Historical Climatology Network (HCN). In previous studies [e.g., *Maurer et al.*, 2002] the VIC model has been applied at higher resolutions (typically one-eighth degree), however droughts tend to be spatially persistent over large areas, and for this purpose the coarser one-half degree resolution is adequate.

[6] VIC has been successfully used to simulate streamflow over a number of large river basins in North America and elsewhere, and at continental to global scales as well

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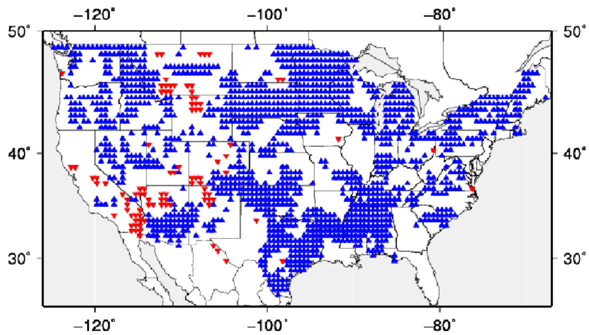

Figure 1. Annual trends in model soil moisture. Blue triangles show upward trends, while downward trends are shown as red inverted triangles.

[*Nijssen et al.*, 1997]. In previous applications to the continental U.S., *Maurer et al.* [2002] and others have demonstrated good agreement between simulated soil moisture and point measurements, between observed and simulated snow water equivalent, and between observed and simulated streamflow.

3. Drought Characteristics

[7] A generally accepted definition of drought is elusive, although many definitions appear in the literature. Here, we use the threshold approach described by *Dracup et al.* [1980], where a drought is said to have occurred when the variable of interest (e.g., streamflow) is below a predefined threshold. In general four different types of drought can be considered: meteorological, agricultural, hydrological, and socio-economic. In this study we examine agricultural and hydrological droughts, using model-derived soil moisture and runoff as drought indicators.

[8] Model soil moisture and runoff were aggregated to monthly values, with the first 10 years of simulated data truncated to minimize model initialization effects. Soil moisture and runoff values were expressed as percentiles relative to all simulated values for a given grid cell and month. This facilitates the identification of droughts across the domain, because anomalies in absolute terms reflect different severities in different parts of the domain due to climatic, vegetation, soils, and other differences. Furthermore, percentiles are convenient in that they provide an ordinal range from zero to one, over which the variables vary uniformly by construct, and seasonal variations are removed as well.

4. Trend Analysis

[9] One of the most widely used statistical tests for trend in hydro-climatic time series, is the Mann-Kendall (MK) test [*Mann*, 1945]. The test is non-parametric, so it does not make any assumptions about normality or linearity. *Hirsch et al.* [1982] proposed a modified version of the MK test more appropriate for seasonal data, termed the Seasonal MK test. An advantage of the seasonal MK test for hydrologic data is that trends in seasons with small values are not dominated by larger values in other seasons [*Lettenmaier et al.*, 1994]. The seasonal MK test also accounts for serial dependence, for example, correlation between seasons (months), by inflating the variance of the test statistic [*Hirsch and Slack*, 1984]. While the seasonal test does not account for serial correlation over years (e.g., correlation from one January to the next), this issue can be addressed using an effective independent sample size as proposed by *Hamed and Rao* [1998].

5. Results

5.1. Trends in Soil Moisture and Runoff

[10] We applied the seasonal MK test to the monthly simulated soil moisture and runoff data, and the standard MK test to the series of individual months. A value of 0.05 was chosen as the local significance level for a 2-sided test. The statistically significant trends for model soil moisture can be seen in Figure 1, which shows that 1450 cells (43.6% of the domain) exhibit an upward trend, while many fewer trended downward (95 cells, or 2.9%). Figure 1 shows that the wetting trends cover the majority of the country, with most of the drying trends being in the Southwest. Annual trends in runoff are very similar to those found for soil moisture. In particular, upward trends were found for 41.5% of the U.S. (1377 cells), while the number for downward trends was 2.3% (77 cells). These results agree with previous studies that have suggested a general increase in streamflow over the conterminous U.S. [*Lins and Slack*, 1999; *McCabe and Wolock*, 2002].

[11] In order to provide a rough assessment of the inferred trends, we tested stations in the Hydro-Climatic Data Network (HCDN) for trends. This data set contains streamflow daily data from a set of 256 stations that have minimal upstream regulation making them suitable for identifying long-term trends. The stations used here are a subset of the stations utilized by *Lettenmaier et al.* [1994] for which we were able to obtain data from 1925–2003 so as to be consistent with our model results. Results from the application of the seasonal MK test to the HCDN data set are qualitatively similar to the model results (Figure 2), with 72 stations (28.1%) having an upward trend and only 6 stations (2.3%) having downward trends. It is important to note that we would not expect an exact correspondence because, among other reasons, the HCDN stations observe streamflow, which is effectively an integrator of runoff over an area, whereas the model produces grid cell runoff. In

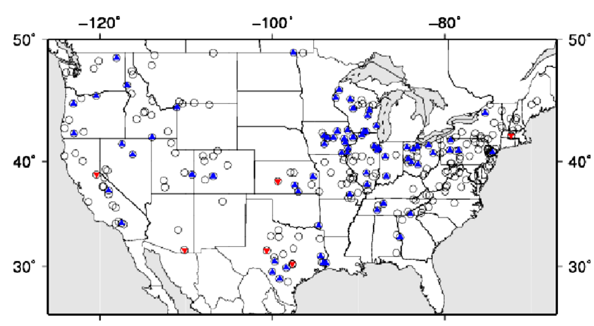

Figure 2. Annual trends in streamflow observed from the HCD Network. Upward (blue triangles) and downward (red inverted triangles) trends are shown in the larger map. Circles show the locations (spatial coverage) of the HCDN stations.

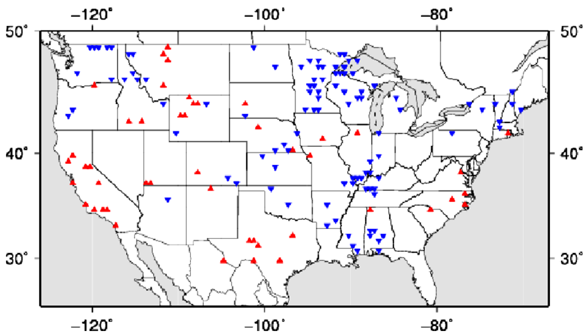

Figure 3. Trends in drought duration. Blue inverted triangles show downward trends, and red triangles show upward trends.

addition, spatial coverage of the HCDN stations that provided a long-term record is much smaller. Nonetheless, the general consistency in the number of trends is encouraging.

[12] When examining the spatial patterns of statistically significant trends for each month (not shown), a set of persistent clusters of wetting trends exist over the Great Lakes region, and over parts of the northeast U.S. which is most evident during the winter months. Another upward trend cluster appears in the Lower Mississippi and Gulf regions during October–December, however during the summer months there is a group of drying trends in the Southeast. In addition, a few drying trends occur over the Colorado River basin and California during the summer months.

[13] One of the features of the annual trends map is the spatial clustering of uptrends and downtrends. This is somewhat expected, because climatological data are highly correlated spatially. The question arises as to how this spatial correlation affects the results of the trend analysis. This issue was first addressed in the context of climatic trends by *Livezey and Chen* [1983] who proposed a construct for local (e.g., grid cell) and field (e.g., spatial domain) significances. They proposed to resolve the issue of spatial correlation via a Monte Carlo procedure that replicates the spatial structure of the input fields, and performs the statistical test on the generated fields (where the null hypothesis is true by construct). From the number of rejections of the null hypothesis one can build an empirical distribution and determine the threshold fraction for field significance. We applied this procedure and evaluated field significance by resampling the model-derived data by creating 500 permutations of the years of data and shuffling the order of the time series, thus retaining the spatial correlations. Using a level of 0.05 for field significance, the fraction thresholds were exceeded (20.4% for soil moisture, and 14.1% for runoff) indicating that the trends observed are unlikely to have occurred due to chance given the observed spatial correlation.

5.2. Trends in Drought Duration, Frequency, Severity, and Spatial Extent

[14] Time series of drought durations were constructed for each model grid cell by creating sequences of the number of consecutive months in which the soil moisture/runoff percentiles were below specified thresholds (from 10 to 50%). Figure 3 shows a map of the locations where significant (0.05 level) trends were found using the MK test for a drought threshold P = 20%. The number of significant trends is not large, 47 upward (increased duration) and 102 downward (decreased duration) for runoff, and 62 upward and 161 downward for soil moisture. There are clear spatial patterns, however. Figure 3 shows that the Great Lakes, Mississippi basin, and Pacific Northwest have decreasing drought durations, while parts of the west including California and the interior have increased drought durations. A noteworthy feature is that although the Pacific Northwest had a predominantly wetting trend, extreme droughts (P = 10%) have become longer.

[15] Drought severities were computed for each grid cell as the cumulative departure of runoff from the 20th percentile threshold, averaged sequentially for the duration of each event identified. Figure 4 shows the location of statistically significant trends in drought severity for model runoff. Decreasing trends (198 cells) are mostly found in the Northeast, Great Lakes, Lower Mississippi, and the Pacific Northwest. Upward trends are fewer (121 cells) and are located mostly in Texas, the Southwest and intermountain West. The results were similar for model soil moisture, with 73 grid cells having upward and 180 cells having downward trends. Field significance cannot be evaluated properly in the case of drought characteristics, since the time series do not have the same length for different model grid cells.

[16] The MK test was also applied to time series of drought frequency for different thresholds (not shown). There is a predominant reduction in drought frequency for the eastern U.S. and Midwest, with a few significant upward trends in parts of the Southwest. As the drought threshold was reduced so did the area covered by the downward trends. In contrast, the number of upward trends in the Southwest was almost invariant with respect to the drought threshold.

[17] Finally we examined trends in the spatial extent of drought, that is the percent area of the U.S. that was experiencing drought (using different thresholds) at each month. Soil moisture (and runoff) drought spatial extent showed a downward trend which however was insignificant for all thresholds (10–50%).

6. Discussion

[18] An obvious question arises as to the causes of the observed trends. Soil moisture results from a complicated balance of precipitation (the partitioning of which into

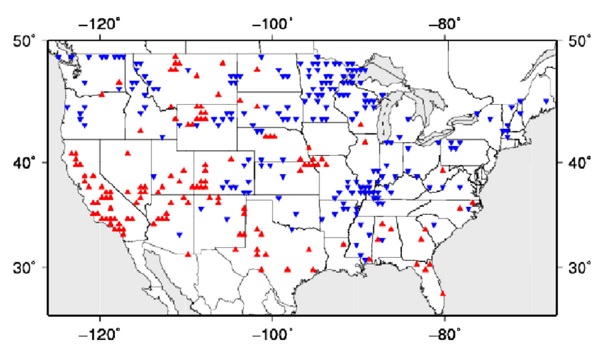

Figure 4. Trends in drought severity. Upward trends are shown as red triangles, while downward trend as blue inverted triangles.

infiltration and runoff is a nonlinear function of soil moisture), and evaporation, which depends on surface atmospheric conditions as well as soil moisture. Over much of the U.S., there has been a general upward trend in precipitation, but temperature has increased as well. Aside from the Southwest and parts of the interior west, model soil moisture has been increasing, as have most soil moisture-related drought indicators. While no long observation records of soil moisture exist, our results for runoff are similar to those for soil moisture, and our runoff trends are comparable to those in observed streamflow records (most trends are upward, aside from parts of the Southwest and West). The area covered by decreasing soil moisture and runoff (and increases in most drought indicators) is interesting, as precipitation has increased in this area as well. While a detailed analysis is beyond the scope of this paper, we can examine the spatial patterns of trends in precipitation and temperature and compare them qualitatively with the soil moisture and runoff trends. Over the period of our analysis, precipitation has either increased or remained (statistically) unchanged at the vast majority of locations (499 uptrends and only 19 downward trends). In addition, the spatial patterns of the precipitation trends (not shown) agree fairly well with those for runoff. On the other hand, the effects of temperature trends on the spatial patterns of soil moisture/runoff are not so clear. Over the period of analysis, temperature increased for most of the western U.S. and the Northeast (750 cells), while there were significant decreases for the Gulf region and part of the Southeast (345 cells). It appears that in those locations of the Southwest and West where downward trends in soil moisture were observed, the effect of increased evaporative demand associated with the higher temperatures more than cancelled the effects of increased precipitation [*Walter et al.*, 2004].

7. Conclusions

[19] We used a constructed time series of soil moisture and runoff over the continental U.S. to examine trends in soil moisture and runoff, and drought characteristics related to these variables for the period 1925–2003. Over much of the country, there has been a wetting trend, reflected in a predominance of upward trends in both model-derived soil moisture and runoff. These trends are generally consistent with increases in precipitation during the latter half of the 20th century observed over most of the U.S. [*Groisman et al.*, 2004], and are in general agreement with results from other studies [*Dai et al.*, 2004; *Milly et al.*, 2005]. Furthermore, trends in the simulated runoff are similar to those in observed records of streamflow at a set of index stations that have been minimally affected by anthropogenic activities. Trends in most drought characteristics are similar to those in soil moisture and runoff, that is, droughts have, for the most part, become shorter, less frequent, less severe, and cover a smaller portion of the country over the last century. The main exception is the Southwest and parts of the interior of the West, where, notwithstanding increased precipitation (and in some cases increased soil moisture and runoff), increased temperature has led to trends in drought characteristics that are mostly opposite to those for the rest of the country especially in the case of drought duration, severity and frequency, which have increased.

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