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A seasonal-scale climatological analysis correlating spring tornadic activity with antecedent fall–winter drought in the southeastern United States

Marshall Shepherd[1], **Dev Niyogi**[2] **and Thomas L Mote**[1]

[1] Climate Research Laboratory, Department of Geography, University of Georgia, Athens, GA 30602, USA

[2] Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA

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Abstract

Using rain gauge and satellite-based rainfall climatologies and the NOAA Storm Prediction Center tornado database (1952–2007), this study found a statistically significant *tendency for fall–winter drought conditions to be correlated with below-normal tornado days the following spring* in north Georgia (i.e. 93% of the years) and other regions of the Southeast. Non-drought years had nearly twice as many tornado days in the study area as drought years and were also five to six times more likely to have multiple tornado days. Individual tornadic events are largely a function of the convective-mesoscale thermodynamic and dynamic environments, thus the study does not attempt to overstate predictability. Yet, the results may provide seasonal guidance in an analogous manner to the well known Sahelian rainfall and Cape Verde hurricane activity relationships.

Keywords: drought, tornadic activity, seasonal prediction, water cycle, extreme events, natural hazards

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC 2007) recently projected that frequency and severity of droughts may increase over time. Very little is known about how drought conditions affect the frequency or intensity of severe weather hazards like tornadoes. Because of the lack of studies on drought–severe-weather interactions, there is a need to provide observational and modelling analyses relating the frequency and intensity of meteorological hazards to extreme hydroclimate anomalies like drought.

1.1. Motivation

Satellite-derived rainfall anomalies (figure 1) illustrate that cumulative rainfall was 20–60% below normal from Feb 2006 to Feb 2008 for a significant portion of the southeast United States (study area 2), including north Georgia (study area 1). During the 2006–2008 drought, several deadly tornado outbreaks struck north Georgia, including the central business district of Atlanta on 14 Mar 2008. This outbreak motivated a research question concerning the relation between drought conditions and tornadic activity. There is a paucity of literature documenting how drought conditions feedback to the frequency or intensity of tornadic activity. There are several reasons for the lack of study on regional tornado-activity–drought relationships. The evidence for changes in the number or intensity of tornadoes relies on local reports and may have discontinuities and gaps related to mode of reporting, population density or assessment, and technological advancements (IPCC 2007, Ashley 2007, Verbout *et al* 2006, Brooks and Doswell 2001).

Galway (1979) noted a weak relationship between both annual and seasonal precipitation totals and tornado activity

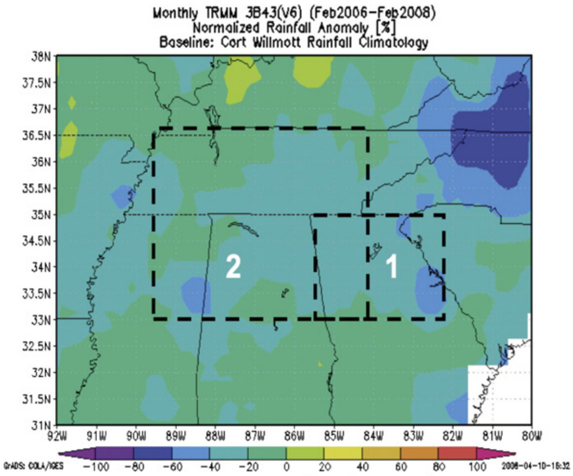

Figure 1. Normalized rainfall anomalies from Feb 2006 to Feb 2008 over north Georgia (study area 1, excluding South Carolina coverage) and a larger region of the southeast (study area 2). The TRMM-based monthly rainfall anomalies use the Willmott–Matsuura rainfall climatology as the baseline.

(1953–1976) for three regions: the Southeast (Georgia–Alabama), the Great Plains (Kansas–Oklahoma), and the Great Lakes (Illinois and Indiana). He found a slight trend for wet years to have more tornadoes than dry ones. Galway identified five independent years as under 'drought' conditions in his sample. Galway found no evidence that tornado activity was at a minimum under drought conditions. Galway (1979) spans a period in which tornado counts were likely underestimated due to lack of extensive Doppler radar networks and relatively modest populations. Further, that study was only concerned with simultaneous rainfall and tornado activity over a relatively short period of time (i.e. 1953–1976). Galway (1979) also acknowledged that a limitation of their study was the use of point-source rain gauge data to represent average seasonal rainfall over two-state regions.

It is well known that soil-moisture–convective feedbacks exist (Teuling *et al* 2005, Findell and Eltahir 2003, Koster *et al* 2004). Numerical and field studies have confirmed that soil moisture can influence surface fluxes, convergence and boundary layer processes that lead to convection (McCumber and Pielke 1981, Lanicci *et al* 1987, Pielke 2001, Berbery *et al* 2003, Findell and Eltahir 2003, Trier *et al* 2004, Holt *et al* 2006). Raddatz and Cummine (2003) found that moisture fluxes from the Prairie agro-ecosystem were linked with the seasonal pattern of tornado days. More, recently, Hanesiak *et al* (2009) found that soil moisture in the Canadian prairie might be a good predictor of severe summer convective weather (i.e. hail, tornadoes, heavy rains, or strong winds).

These studies noted soil moisture and soil moisture boundaries were critical for the evolving atmospheric structure, mesoscale circulations and convective triggers. On the other hand, Taylor and Ellis (2006) investigated soil moisture impacts on convection and found a negative feedback (i.e., convective initiation over dry soils). Ek and Holtslag (2004) noted the complexity of precipitation and suggested that soil moisture effects were not necessarily positive. Salvucci (2001) found no causal relationship between soil moisture and subsequent precipitation in observations. Pal and Eltahir (2003) suggested a possible feedback mechanism between soil moisture distribution and storm tracks. It is clear that a lack of consensus exists concerning the role of surface moisture anomalies and convection.

It is entirely possible that suppressed tornado activity during drought is a manifestation of teleconnections associated with El Nino, La Nina, or other periodic large scale forcing. The literature provides clear evidence that mean jet stream position varies as a function of ENSO phase (Cook and Schaffer 2008). However, there is no consensus on how such jet stream variability affects tornadic activity. For example, Hagemeyer (1998) noted increased tornado activity in Florida during the El Nino phase, while Bove (1998) found that tornadic activity was reduced during El Nino and La Nina. Rhome *et al* (2000) found no direct evidence of a link between tornado frequency and ENSO classes. Marzban and Schaefer (2001) only found a very weak but significant correlation between Pacific sea surface temperatures and tornado counts in a limited subset of geographic areas in the United States. Etkin *et al* (2001) argued that the La Nina phase might suppress tornadic activity in Canada. More recently, Cook and Schaffer (2008) highlighted the continued uncertainty in whether seasonal and monthly variations in tornadic activity are linked with ENSO phase. To remove the uncertainty associated with the ENSO debate, we consider a new approach by focusing on antecedent drought conditions for a region.

1.2. Research objective

The objective of this study was to provide a *seasonal-scale*, climatological analysis correlating spring tornadic activity with antecedent fall–winter drought in the southeastern United States, particularly Georgia. Because individual tornadic storms are dependent upon convective-mesoscale thermodynamic and shear environments, we do not suggest that soil moisture or antecedent precipitation is a direct control on what individual storms will spawn tornadoes. Further, we do not seek to conduct an in-depth analysis of physical mechanisms herein. Instead, we seek to examine longer term seasonal relationships (e.g., Rhome *et al* 2000).

Gray (1990) established that variability in intense Atlantic basin hurricanes was linked with seasonal and multidecadal variability in western Sahelian rainfall and offered some guidance on seasonal predictability. Similarly, we hypothesize that tornado activity during spring 'tornado season' (i.e., defined herein as Mar–Jun) is correlated with antecedent precipitation in the previous six months. More specifically, we seek to test the research hypothesis that fall–winter drought is a strong indicator of reduced tornadic activity in the spring.

Section 2 will describe the multiple data sets and methodologies that were applied to this problem. Section 3 presents the results of the analysis. Section 4 provides concluding remarks. The concluding section also identifies key deficiencies of the analysis and possible considerations for future studies on the topic.

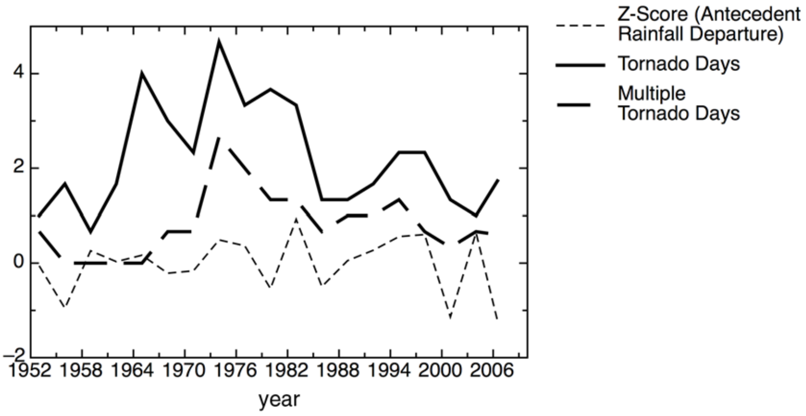

Figure 2. Time series (3-year running mean) of tornado and multiple tornado days 1952–2007 in north Georgia. The z-score for rainfall departure is also plotted.

2. Data and methodology

We acquired the NOAA Storm Prediction Center's (SPC) historical database of severe thunderstorm and tornado occurrences from 1951 to 2006 and compiled tornado days for the study areas using the SVRPLOT interface (Hart 1993). Additionally, we analysed storm data reports from the National Climatic Data Center to extend the SPC database to 2007. The tornado day metric has proven to be more reliable than tornado counts for climatological studies (Raddatz and Cummine 2003) due to aforementioned issues with reporting.

From the NASA Goddard Distributed Active Archive Center, we acquired the global, 0.5° rainfall database. The dataset is composed of Global Historical Climatological Network (GHCN) and Legates and Willmott (1990a, 1990b) gauge precipitation measurements interpolated to a regular space grid following methods described in Willmott *et al* (1985) and Shepard (1968). This dataset provided monthly precipitation estimates for the period 1951–1999. For the period 2000–2007, we used a 0.25° product based on the multi-satellite precipitation analysis (TMPA) described by Huffman *et al* (2007). The daily product is composed of available microwave (i.e., TRMM microwave imager, special sensor microwave imager (SSM/I), advanced microwave scanning radiometer (AMSR) and advanced microwave sounding unit (AMSU)) and calibrated infrared (IR) estimates. We employed the monthly accumulation version of the TMPA. For the period Jan 1998–Dec 1999, TMPA and Willmott–Matsuura data overlapped and the correlation was very high ($R = 0.97$). This finding provides confidence in our methodology of extending the gauge-based record to 2007 with satellite data.

North American Regional Reanalysis (NARR) data archived at the NOAA Earth System Research Laboratory (ESRL) were used to generate composites of convective available potential energy (CAPE) for the state of Georgia. CAPE values were composited using the online ESRL compositing tool that enables daily, monthly, and seasonal composites (http://www.cdc.noaa.gov/cgi-bin/data/narr/plotmonth.pl).

Mean area-averaged values were computed for antecedent (i.e. Sep–Feb) cumulative rainfall, tornado days (Mar–Jun), and multiple (>1) tornado days (Mar–Jun) in the study areas (1952–2007). We primarily focused on tornado activity in the Mar–Jun time frame because it is the most active period for tornadoes in north Georgia, and it minimizes likely influences from tropical cyclone-spawned tornadoes (Verbout *et al* 2007). From normal values, per cent of normal antecedent rainfall, tornado days, and multiple tornado days were computed. Time series and regression analyses were conducted for antecedent rainfall departure and tornado activity (tornado days and multiple tornado days). Statistical testing was also applied to evaluate significance of correlations.

To specifically focus on drought–tornado activity relationships, we conducted a rank analysis to sort the dataset by antecedent rainfall departure. The palmer drought severity index is popular in hydroclimate studies (e.g., Palmer 1965, Doublin and Grundstein 2008) and includes soil moisture. We assumed the 'meteorological drought' definition of Hoyt (1936). Historical drought indices such as Hoyt (1936) and Thornthwaite (1963) used various categorizations of precipitation to define drought. A 'drought' period was defined as a period in which annual precipitation occurs at less than 85% of normal. Our modification simply applies the 85% threshold condition to antecedent (fall–winter) season rainfall and it correlated well to the drought depiction in the US Drought Monitor maps (Svoboda *et al* 2002). Hereafter, the term antecedent drought will refer to the seasonal drought of the preceding fall and winter.

3. Results

We examined the three-year running means of tornado days, multiple tornado days, and z-score for antecedent precipitation departure (figure 2) in the north Georgia study area. Qualitatively, there is no apparent correlation between dry periods and tornado days. It is interesting to note the period from the late 1950s to early 1980s where tornado days were consistently higher. This may reflect the National Weather Service implementation of a tornado watch and warning programme in the mid-1950s (Galway 1979) or it may reflect observational or reporting uncertainty. A correlation analysis (figure 3) was conducted to further examine tornado–antecedent-rainfall relationships. For the period 1952 to 2007,

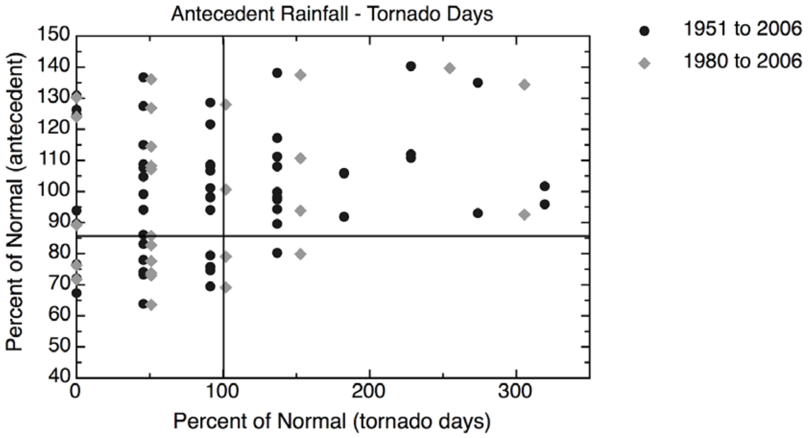

Figure 3. Relationship between per cent of normal tornado days and 6-month antecedent rainfall for the pre-modern (1952–2007, black dot) and post-modern (1980–2007, grey diamond) eras. The horizontal drought threshold line represents rainfall that is below 85% of normal rainfall; the vertical line represents normal tornado days.

linear regression analyses revealed a weak positive correlation ($R = 0.22$), significant at approximately the 95% confidence level ($p = 0.055$). In the modern radar era (defined here as after 1980 although WSR-88D radar deployment occurred in the 1990s), we assume some degree of stability in reporting, which may be reflected by the reduction in mean tornado days after 1982 in figure 2. Similar statistical analysis in the modern radar era also verified a weak positive correlation ($R = 0.23$) but because of a reduction in the number of degrees of freedom, it was only significant at roughly the 88% confidence level ($p = 0.12$). Our results suggest a weak correlation between antecedent seasonal precipitation and the following spring season tornadic activity; however, the results were dominated by large scatter associated with above-normal days.

For years in which antecedent season drought were identified, a stronger signal emerged. There was an apparent lack of years with above-normal tornado days in spring. Conversely, most years with above-normal tornado days were associated with above-normal antecedent rainfall. In fact, the top 35th-percentile of tornado day occurrences is exclusively associated with non-drought conditions. It is clear that antecedent seasonal drought scenarios in north Georgia were *almost never* associated with above-normal tornadic activity during the following spring season over the 50-year period. We further quantified this resulting using a chi-square test for independence. The expected value for tornado days for antecedent drought years (non-drought years) was 50% of normal (150%). We found low p-values for both cases indicating that there is a significant relationship between antecedent drought conditions and spring tornado activity. Our results *do not* suggest that antecedent drought years were not associated with any tornado days, however, they tend to be below normal (i.e. $< \sim 2$ days) in the spring. The results were quite similar when we examined the number of days with multiple tornadoes over the study period.

Generally, antecedent drought years were most likely to be associated with below-normal tornado days (93% of the years) and were only associated with above-normal tornado days 7% of the years (table 1). For the single antecedent drought year with above-normal tornado days, the departure from normal was less than 50%. Table 1 lists other key descriptive statistics for the composite antecedent and non-antecedent drought years. On average, antecedent non-drought years had nearly twice as many tornado days in the study area as antecedent drought years. Antecedent non-drought years were also five to six times more likely to have multiple tornado days than in antecedent drought years. An analysis of variance (ANOVA) test was performed to determine if per cent normal antecedent rainfall and tornado day differences were significant at the 95% confidence level. We conducted the single factor ANOVA for two different sets, (antecedent drought, antecedent non-drought, modern era) and (antecedent drought, antecedent non-drought, all years). Based on both outcomes (F-value $\gg$ F-critical), we could conclude that the differences were not caused by random chance. Our results suggest that there is a statistically significant reduction in tornado activity during the tornado season following meteorological drought in the preceding fall and winter.

To test the robustness of the result, we examined per cent of normal relationships for a larger area of the southeast United States (figure 1, study area two) for the total period (1952–2006) and modern era (1980–2006). The results for north Georgia were essentially replicated for the larger region encompassing Tennessee, Georgia, Alabama, and Mississippi. For the total period, the results indicated that 75% of years characterized by antecedent drought conditions had below-normal tornado occurrence. Approximately 92% of antecedent drought years produced either below-normal tornado days or no greater than 25% above-normal tornado days. The majority of above-normal tornado days and activity was associated with above-normal antecedent rainfall. When the data were stratified after 1980, the findings are not as robust but still indicate that 'drought' years rarely produce tornado days greater than 25% above normal.

Recently Frye and Mote (2009) found that soil moisture variability might be related to convective parameters like CAPE. In generally, high CAPE environments are more

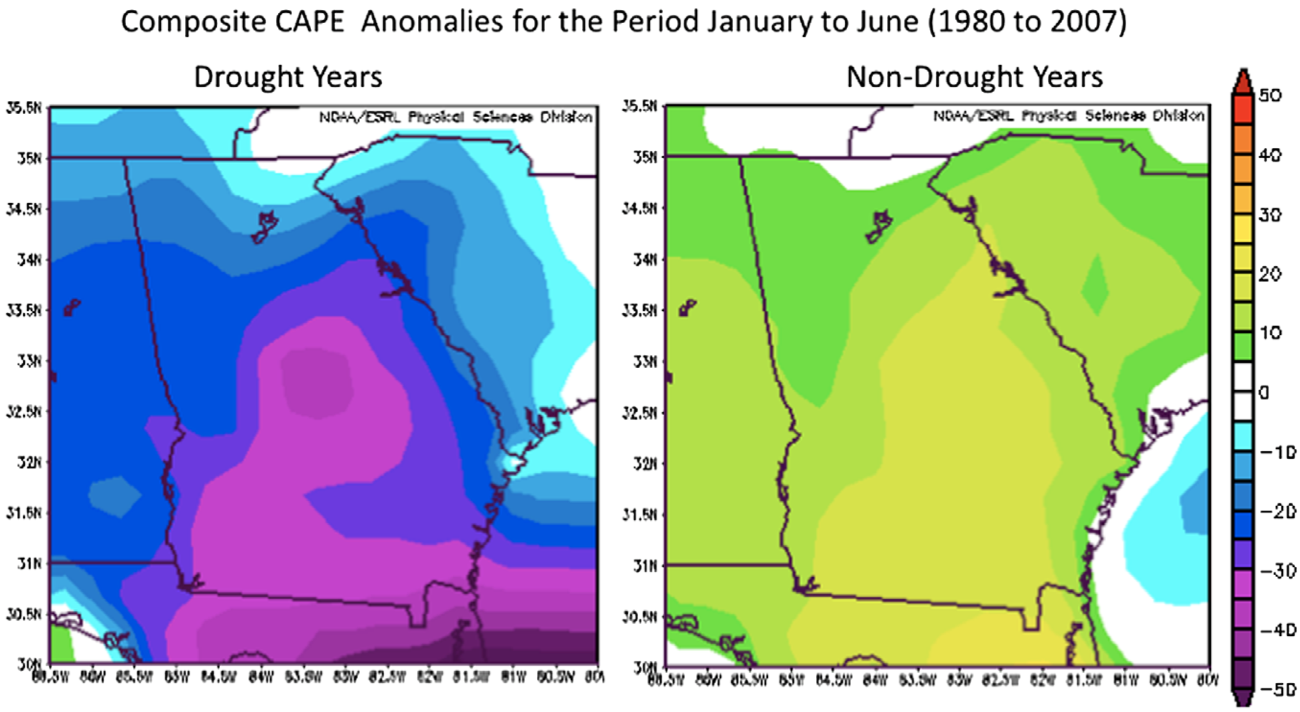

Figure 4. Composite convective available potential energy (CAPE in J kg^{-1}) over the months Jan–Jun (1980–2007). The left panel represents drought years (11), and the right panel represents non-drought years (17). Source: http://www.cdc.noaa.gov.

Table 1. Attributes of drought, non-drought, and Doppler era years.

	Drought years only	Non-drought years only	1980–2007 (modern era)	1952–2007 (all years)
Number of years	14	42	28	56
Antecedent rainfall (% of normal)	74.6	108.5	100.0	100.0
Tornado days (% of normal)	57.7	114.2	100.0	100.0
Mean number of tornado days (Mar–Jun)	1.28	2.54	1.96	2.23
Mean number of multiple tornado days (Mar–Jun)	0.35	1.96	0.89	0.82
Years with above-normal tornado days (%)	7.2	45.3	42.9	35.7
Years with below-normal tornado days (%)	92.8	54.7	57.1	64.3

conducive to convective activity. A composite analysis of CAPE values over Georgia during antecedent drought and non-drought years spanning the post-1980 period yields some compelling results. Figure 4 clearly indicates that during the antecedent drought (non-drought) year composite CAPE anomalies in northern Georgia are negative (positive) during the Jan–Jun period (i.e., the period leading into and inclusive of the spring tornado season). We emphasize that the CAPE analysis is not central to our findings and CAPE can vary significantly, spatially and temporally. However, this preliminary analysis suggests that soil moisture 'memory' from the preceding seasonal drought may be apparent in the thermodynamic structure of the atmosphere leading into the spring tornado season. The intent of this manuscript was not to investigate physical mechanisms related to the findings, but the composite analysis suggests potential mechanisms to extend our results and direction for future research.

4. Conclusions

In this analysis, we employed historical rain gauge and satellite data to quantify area-averaged rainfall departures in north Georgia. The departures were used to define antecedent drought and non-drought years for analysing the tornado day statistic in the following spring season. An array of statistical tests (i.e. rank, correlation, ANOVA, chi-square) were also implemented in the analysis. Our results are interesting but should be interpreted very cautiously until the analysis is repeated for other locations. The study region was a geographic region that experiences, climatologically, fewer tornado days than more active tornado regions. It would be interesting to replicate this study for very active tornado regions to ensure that results presented herein are not skewed or biased. Even with its limitations, the study does provide a contemporary analysis of antecedent precipitation and tornado relationships not shown in previous literature. It also provides statistical evidence that, on seasonal scale, antecedent fall–winter drought is correlated with a reduction in tornado days the following spring. The results further suggest that meteorological drought and by inference, soil moisture displays a ‘memory’ effect that translates to the subsequent tornado season. Future analysis might explicitly examine new satellite and *in situ* soil moisture data now becoming available (Entin *et al* 2000) for climate studies. It would be instructive to verify whether the same relationships hold throughout the year as well as during the peak spring season. Ongoing studies in the Midwestern United States (Jeff Trapp, 2009, personal communication) are consistent with our findings.

Our ongoing studies employ emerging reanalysis and satellite datasets like the North American Regional Reanalysis (NARR, http://www.emc.ncep.noaa.gov/mmb/rreanl/) and NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA, http://gmao.gsfc.nasa.gov/research/merra/pubs/) to composite ‘drought’ and ‘non-drought’ years as a function of soil moisture. Future analysis will also consider different antecedent periods (e.g. 6-month, 2-month, and 1-month) and consideration of larger scale influences like ENSO phase, convective environment, and shear profiles.

Another hypothesis that we are simultaneously evaluating is whether ‘pockets’ of antecedent soil moisture under drought conditions may be related to tornado activity. Periodic rain events may moisten soil and lead to important land–atmosphere interactions related to moisture and energy that could initiate or enhance convection (Niyogi *et al* 2008). We are currently using coupled atmosphere–land models with remotely-sensed soil moisture forcing to investigate this hypothesis.

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