Northeast Colorado Extreme Rains Interpreted in a Climate Change Context

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Summary: *The probability for an extreme five-day September rainfall event over northeast Colorado, as was observed in early September 2013, has likely decreased due to climate change.*

1. Introduction

Welcome rains over northeast Colorado starting on 9 September 2013 turned into a deluge during 11 September and continued through 15 September. Boulder, an epicenter of this regional event (http://www.crh.noaa.gov/bou/?n=stormtotals_092013), almost doubled its daily rainfall record (from 12.2 cm in July 1919 to 23.1 cm on 12 September 2013), with 43.6 cm for the week. Widespread flooding took 10 lives and caused at least $2 billion in property damage, second only to the June 1965 floods of eastern Colorado (http://www.reuters.com/article/2013/09/19/us-usa-colorado-flooding-idUSBRE98H1BA20130919).

Events of similar magnitude are not unprecedented during summer in the Colorado Front Range (Hansen et al. 1978; McKee et al. 1997). Some reach that size in a few hours and are more localized (e.g., Big Thompson in late July 1976), while others take longer and have larger footprints as in June 1965 and September 1938. Interestingly, attributes of the 2013 event including its late-summer occurrence, regional scale, long duration, and slowly changing atmospheric circulation (see Gochis et al. 2014) that transported extreme moisture into the Front Range also characterized the 1938 event.

Does the recent occurrence of this extreme event indicate that its likelihood has increased due to global warming? Globally, the atmosphere has become warmer and moister, with the observed rate of increase since the 1970s broadly consistent with that expected from the Clausius–Clapeyron relation (~7% per °C; Hartmann et al. 2013).

Heavy precipitation events have increased over much of the United States since 1901, however, with no significant long-term trends over the northern Great Plains or Southwest (Kunkel et al. 2013). Further, the relationship between heavy precipitation and atmospheric water vapor varies seasonally, with moisture availability rather than moisture-holding capacity being a more dominant factor in summer than winter (Berg et al. 2009). Thus, the answer to our question cannot be readily gleaned from globally and annually averaged statistics but requires careful consideration of place and time.

2. Datasets and methods

The Global Daily Climatology Data (GDCN; Klein Tank et al. 2002) of station observations is used to create a gridded daily analysis at 1° resolution for 1901–2013. Daily column precipitable water (PW) is based on the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis product for 1948–2013 (Kalnay et al. 1996).

Climate simulations using NASA's Goddard Earth Observing System (GEOS-5) atmosphere model are diagnosed to determine the effect of time varying forcing on the region's five-day averaged precipitation and PW. The GEOS-5 model (Rienecker et al. 2008, Molod et al. 2012) employs finite-volume dynamics and moist physics as described in Bacmeister et al. (2006). The simulations consist of 12 ensemble members, forced with observed monthly SST, sea ice, and time-varying greenhouse gases for the period 1871–2013 (Schubert et al. 2014). The model was run at 1° horizontal resolution with 72 hybrid-sigma vertical levels.

The 1° gridded daily observational and model data are spatially averaged over the northeast Colorado study region (Fig. 1, box), and they are used to calculate running five-day precipitation and PW for September. A region larger than the scale of the event was selected in part to accommodate model capabilities but also to avoid selection bias. Nonetheless, the 2013 heavy rainfall event was large in spatial scale. Weather predictability of the event per se is not addressed herein (see Hamill 2014), but rather how climate change may have affected the relative likelihood of heavy precipitation in this large region. For this purpose, the modeled statistics of heavy five-day rainfall of the recent 30-year period (1983–2012) are compared to that of the last 30 years of the 19th century.

3. Results

a. Model suitability

The footprint of 2013 rains (Fig. 1a) was partly organized by the Continental Divide and the elevation gain from the Great Plains—topographic features pronounced enough to be captured at 1° resolution in GEOS-5, even though smaller scale aspects of the Front Range terrain are not resolved. The rains were also linked to an abundance of atmospheric water vapor in early September 2013 (Fig. 1b, blue shading) that was transported principally from source regions over the southern Great Plains and Gulf Coast as implied by the anomalous 700-hPa winds superposed on climatological PW (Fig. 1b). Such large-scale PW sources are also realistically simulated in GEOS-5, whose climatology includes a strong gradient separating dry west-central Colorado air from moist air over the Great Plains and Gulf of California (c.f., Fig. 1b,d). Most importantly, GEOS-5 generates realistic statistics of five-day September rainfall over the case study region. First, the frequency distribution describing the observed statistics (Fig. 1c, red curve) lies within the spread of curves summarizing the five-day rainfall statistics for the 12 model simulations. Second, the statistics of tail events, estimated from 100-year block maxima for any consecutive five-day rainfall total averaged over our northeast Colorado study region, indicate that the model's tail behavior is quite realistic (Fig. 1c, inset). The 2013 event is a rare occurrence relative to both model and observed tail behavior, though the model does generate a few stronger cases in its historical simulation.

b. Simulated long-term change

The ensemble averaged GEOS-5 simulations for September 2013 do not reproduce the observed conditions for either the regional precipitation or PW anomalies (c.f., Fig. 1b,d). The results can be interpreted to indicate that the specific SST/sea ice boundary forcing and greenhouse gas forcings were not the primary drivers, implying a substantial random component of the event itself. Perhaps model biases were related to its failure to simulate the 2013 event such as an inability to depict the particular pattern of atmospheric circulation and its interaction with complex topography. Yet, this must be weighed against the realistic characterization of the statistics of extreme rainfall events over northeast Colorado (Fig. 1c). Ultimately, further analysis using other climate models will be required to clarify these issues.

Nonetheless, the absence of such events in the 12-member September 2013 simulations neither affirms nor refutes a possible effect of long-term change on event likelihood or intensity. To address this issue, we compare five-day rainfall statistics over northeast Colorado between two 30-year periods: one for 1983–2012 that is representative of current climate and the other for 1871–1900 that is representative of preindustrial climate. The model produces realistic global changes between these periods that compare well with observations—global land surface temperature rises 0.9°C (Fig. 2a) and global PW rises 5.7% (Fig. 2b).

Despite a warmer and moister climate, the frequency of September heavy five-day rain events does not increase in the simulations but substantially declines in northeast Colorado (Fig. 2c). Using the model's 95th percentile of five-day rainfall totals, we find a 12% decline in occurrence during recent decades compared to the late 19th century. Using the model's 99th percentile, we find a 44% decline in frequency. The simulated magnitude of September heavy five-day rainfall over northeast Colorado also declines. For the 99th percentile, the threshold value falls from 49 mm in the late 19th century to 45 mm in the recent period.

c. Conditioning of heavy five-day rain events

To understand the above results we examine the relationship between the probability of heavy five-day rainfall and atmospheric water vapor. Statistics of five-day rainfall are examined for the lower and upper decile of five-day PW (Fig. 2e). For dry atmospheric conditions (red curve), very few rainfall occurrences exceed 35 mm (95th percentile) and none exceed 50 mm (99th percentile). For wet atmospheric conditions (black curve), the full range of five-day rainfall amounts is possible. Thus, though a necessary condition for extreme rainfall, high atmospheric water vapor is not sufficient.

Even though the simulated long-term increase in PW over northeast Colorado is small in magnitude (~6%), high five-day PW events increase in frequency (Fig. 2d). One would thus expect to also witness an increase rather than a decrease in heavy rain event probabilities over the region in GEOS-5. The contrary behavior suggests changes in other climate features (e.g., atmospheric circulation and vertical stability) act to counter the increase in water vapor over the region in the model.

4. Conclusion

Our analysis of the GEOS-5 simulations leads to a diagnosis that the occurrence of extreme five-day rainfall over northeast Colorado during September 2013 was not made more likely, or more intense, by the effects of climate change. From an observational perspective, analogous events have occurred before in the Front Range, perhaps most strikingly similar in September 1938, long before appreciable climate change.

Although our model results suggest that the occurrence of this recent extreme has become less probable over northeast Colorado due to climate change, model projections do show an increase in the intensity of maximum five-day precipitation over the globe and for annual averages as a whole by the end of the 21st century (Sillman et al. 2013). Yet, a slight decline in intensity of the maximum five-day precipitation over the central Great Plains during summer is also projected (Sillman et al. 2013), emphasizing that global and annual perspectives of climate change may not always pertain to events at a specific place and time.

A strength of our study is the availability of an ensemble of long-term climate simulations spanning 1871–2013, conducted at 1° spatial resolution, that permits an analysis of statistical properties of the change in extreme events. For the purpose of studying regional five-day rainfall events over northeast Colorado, the GEOS-5 model has the attribute of realistically characterizing the tails of the distribution. A weakness of our study is that results are based on a single model and thus require confirmation using additional models. Also, the physical reasons for the decline in simulated frequency of extreme five-day rainfall over northeast Colorado during September are not addressed. Better understanding of the delivery mechanisms for atmospheric moisture that produce heavy rain events and how those mechanisms respond to global warming will be critical.

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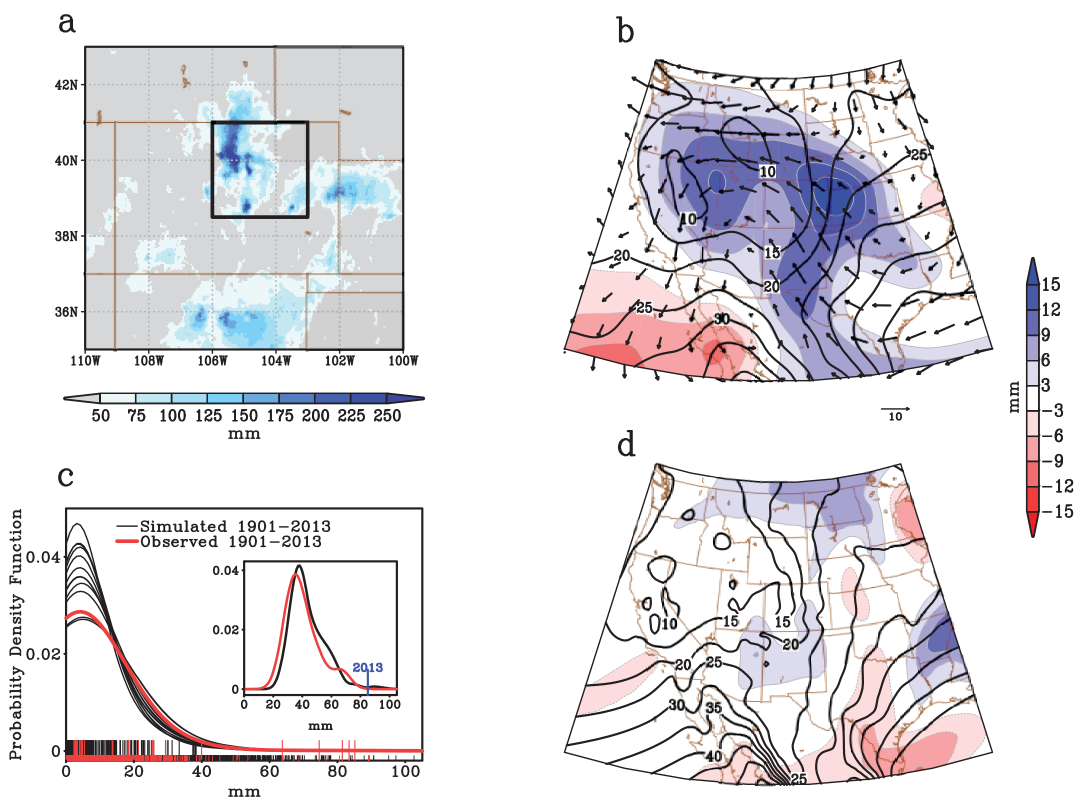
Figure Captions

Figure 1. a) Observed five-day cumulative precipitation totals during September 10-14, 2013, for Colorado and neighboring states at the peak of the extreme event. The box outline denotes the northeast Colorado domain of most extreme precipitation with estimated 84mm five-day precipitation. b) Observed five-day average column precipitable water (PW) for the period September 10-14, 2013. Shaded values are departures from a 1948-2013 reference period; the overlain contours indicate the reference period climatology for that 5-day period, overlain arrows are 700 hPa wind anomalies. (Data source: NCEP/NCAR Reanalysis) c) Frequency distributions (PDFs) of five-day cumulative precipitation during September averaged over the study area shown in Fig 1a for observation (red curve, 3390 values) and for individual ensemble members of climate model simulations (black curves, 3390 values per simulation, 51480 total) for the period 1901-2013. Individual 5-day running totals are shown with tick marks, and the September 2013 values are indicated with taller tick marks. The PDFs are non-parametric curves utilizing kernel density estimation and a Gaussian smoother. Inset shows the frequency distribution of 100-year block maximum values of the wettest 5-day rainfall for all consecutive five-day periods in September based on observations (red; 30 samples), and the ensemble of GEOS-5 simulations (black; 360 samples) for the 100-year period 1913-2012. Observed 5-day peak value in September 2013 shown by blue tick mark. d) As in Figure 1b but for the GEOS5 climate simulations. The simulated departures (shades) are based on the 12-member ensemble mean, and are computed relative to the model climatology (contours).

Figure 2. a) Simulated long-term change in September monthly averaged surface temperature displayed as the difference between 1984-2013 and 1871-1900. b) As in Fig 2a but for the simulated change in September monthly averaged PW expressed as % change of the 1871-1900 reference. c) Climate model simulated frequency distributions of five-day September precipitation totals (mm) over the study area for 1871-1900 (black curve) and the 1984-2013 (red curve) period utilizing twelve GEOS5 model simulations (10800 values). Tick marks indicate individual samples. d) As in Fig. 2c but for five-day September PW for 1871-1900 (black) and 1984-2013 (red) 2e. Simulated PDFs of September five-day precipitation totals conditioned by the lowest 10% of PW (red curve, n=5139) and the highest 10% PW (black, n=5195) values.



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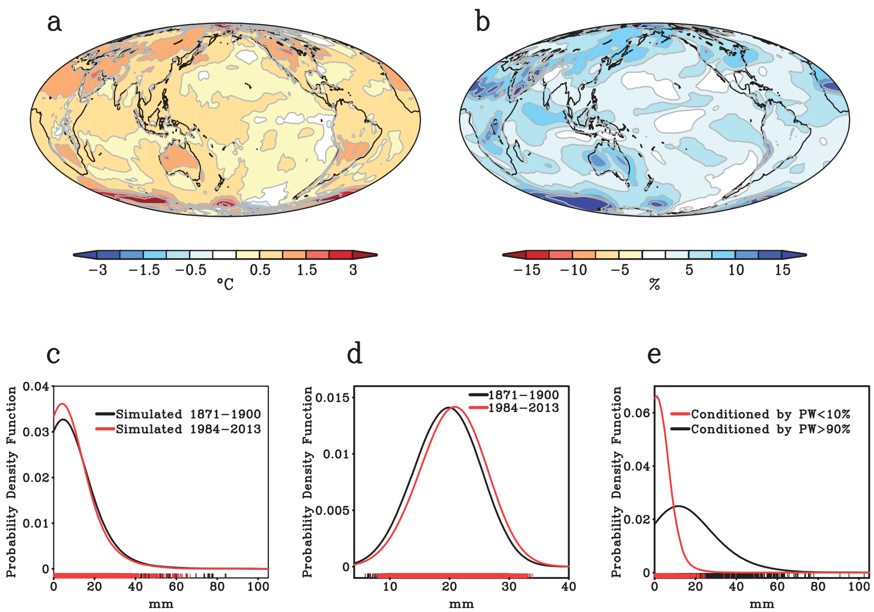

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