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Diagnosing conditional anthropogenic contributions to heavy Colorado rainfall in September 2013

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ABSTRACT

The Colorado floods of September 2013 caused severe damage and fatalities, and resulted from prolonged heavy rainfall unusual for that time of year – both in its record-breaking amounts and associated weather systems. We investigate the possible role of anthropogenic climate change in this extreme event. The unusual hydrometeorology of the event, however, challenges standard frameworks for attributing extreme events to anthropogenic climate change, because they typically struggle to simulate and connect the large-scale meteorology associated with local weather processes. Therefore we instead employ a part dynamical modelling- part observational- based event attribution approach, which simulates regional Colorado rainfall conditional on boundary conditions prescribed from the observed synoptic-scale meteorology in September 2013 – and assumes these conditions would have been similar in the absence of anthropogenic forcing. Using this 'conditional event attribution' approach we find that our regional climate model simulations indicate that anthropogenic drivers increased the magnitude of heavy northeast Colorado rainfall for the wet week in September 2013 by 30%, with the occurrence probability of a week at least that wet increasing by at least a factor of 1.3. By comparing the convective and large-scale components of rainfall, we find that this increase resulted in part from the additional moisture-carrying capacity of a warmer atmosphere – allowing more intense local convective rainfall that induced a dynamical positive feedback in the existing larger scale moisture flow – and also in part from additional moisture transport associated with larger scale circulation change. Our approach precludes assessment of changes in the frequency of the observed synoptic meteorological conditions themselves, and thus does not assess the effect of anthropogenic climate drivers on the statistics of heavy Colorado rainfall events. However, tailoring analysis tools to diagnose particular aspects of localized extreme weather events, conditional on the observed large-scale meteorology, can prove useful for diagnosing the physical effects of anthropogenic climate change on severe weather events – especially given large uncertainties in assessments of anthropogenic driven changes in atmospheric circulation.

1. Introduction

The Colorado Front Range experienced severe floods following days of heavy rainfall during the second week (9th–15th) of September 2013 – resulting in over $2 billion of damages and nine fatalities (Gochis et al., 2015; Hamill, 2014). Only once before, in September 1938, were similar multi-day rainfall totals recorded, although more localized and shorter duration flash flooding has also occurred in the region. The 2013 event reflected the unusual occurrence, in September, of a weather pattern more akin to the summer North American Monsoon (Mahoney et al., 2015). It was dominated by strong low-pressure over the western US and relatively weaker lower-level high-pressure over the Southern Plains that together drove a deep plume of moisture into the Midwest from the tropical eastern Pacific and Gulf of Mexico, resulting in an unusual mixture of continental convective and then tropical-like rainfall over Colorado (Gochis et al., 2015).

A recent climate model-based study (Hoerling et al., 2014) suggests the probability of an extreme five-day rainfall event over northeast Colorado, with rainfall totals like those observed in early September 2013, likely decreased due to anthropogenic climate change. However, that model concurrently simulates an increase in precipitable water over the region and is unable to reproduce the observed precipitation or

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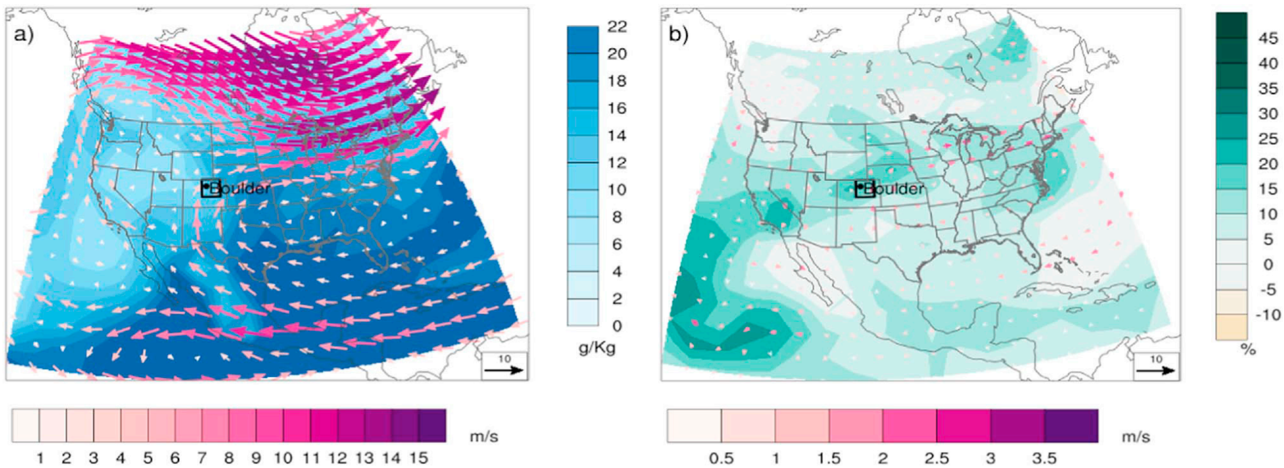

Fig. 1. Modelled synoptic situation and change for the rainy week of September 2013. (a) Total 7-day (00Z 9 September – 00Z 16 September 2013) precipitable water (g/Kg), and average 7-day 700 hPa winds (m/s) over the WRF model domain. Values are ensemble-averages over an ensemble of 101 WRF model simulations under anthropogenic conditions. (b) Corresponding change (%) relative to the ensemble-average of 101 WRF model simulations under non-anthropogenic conditions. Black box demarcates the northeast Colorado target area, including Boulder.

large-scale precipitable water anomalies for early September 2013 – despite realistically characterizing the region's historical extreme rainfall statistics, and large-scale precipitable water climatology. This contrary behavior is posited to be due primarily to changes in features of atmospheric dynamics requiring further investigation, and perhaps to the model lacking requisite spatial resolution for capturing the dynamics of what was an extremely rare event (Trenberth et al., 2015).

Given this complexity, we instead use a part observational- part model-based event attribution framework to investigate how the influence of anthropogenic climate drivers on the observed large-scale meteorological conditions might have changed modelled heavy northeast Colorado rainfall in the second week of September 2013. In this way we partly follow standard probabilistic event attribution frameworks for climate model-based attribution of flood events to anthropogenic climate drivers (e.g. Pall et al., 2011; Wolski et al., 2014; Schaller et al., 2016), but also allow for a more mechanistic event attribution framework seeking to elucidate changes in the event's physical components. This latter event attribution framework was first applied to extreme-temperature related events (Dole et al., 2012, 2014; Otto et al., 2012; Hoerling et al., 2013), and has increasingly been applied to hydrometeorological events (Takayabu et al., 2015; Lackmann, 2015; Meredith et al., 2015; Shepherd, 2016).

Standard probabilistic event attribution frameworks typically involve the use of atmospheric climate models to simulate the weather during a 'time-slice' covering the event of interest, under two driving scenarios: firstly, an 'anthropogenic' scenario representing conditions (greenhouse gas concentrations, sulphate aerosols, sea surface temperatures, sea ice concentrations, etc.) actually present during the event; secondly, a 'non-anthropogenic' scenario representing hypothetical conditions that might have arisen during the time of the event in the absence of the anthropogenic climate drivers. Ensembles of multiple weather simulations – each typically differing by small perturbations to account for uncertainty in the exact weather state at some time in the past when the scenarios were equivalent – are generated under each scenario, thus building up samples of possible weather sequences constituting the climate pertaining to that scenario. The samples are then used to estimate change in occurrence probability of an extreme event between climates.

However, given how unusual the September 2013 Colorado rainfall event was (Hamill, 2014), it is unlikely that the correct large-scale meteorological patterns necessary to reproduce the observed high rainfall amounts will occur in any practical-sized ensemble of climate model simulations that are not in some way initialized with realistic conditions specific to that time (Trenberth et al., 2015; Shepherd, 2016). Indeed, this may be why the observed amounts were not realized in the simulations of (Hoerling et al., 2014).

Hence in this study, we alter the design of the modelling experiment from a standard climate simulation- to a conditional weather hindcast-experiment: by prescribing regional WRF (Weather Research and Forecasting) model simulations with realistic observational-based NCEP (National Centers for Environmental Prediction) large-scale atmospheric and surface anthropogenic initial conditions (ICs) just prior to the event, and subsequently forcing the simulations with observational-based lateral boundary conditions (LBCs). Those anthropogenic ICs and LBCs are then adjusted to hypothetical non-anthropogenic conditions and the simulations are repeated (see Methods).

Our alteration to the standard probabilistic event attribution framework to a more conditional event attribution approach has consequences for the interpretation of simulated results (Shepherd, 2016) – particularly the anthropogenic change (if any) in probability of exceeding a particular extreme event threshold. In event attribution studies using full atmosphere-ocean coupled climate models, uninitialized by observations, this result is usually conditional on the statistical model used to extrapolate large-scale climate to events (e.g. Stott et al., 2004). In studies using atmospheric models with prescribed ocean surface conditions (e.g. Pall et al., 2011), the result is further conditional on the ocean state, which may be in a particular phase of climate mode (e.g. El Niño). In this study, using a regional model, the prescribed ICs and LBCs impose another condition: the observational-based large-scale meteorological pattern. For early September 2013, this pattern was a complex blocking pattern (Fig. 1(a); see also ref. Hoerling, 2014 figure 5.1(b)), which changes little when adjusted (Fig. 1(b); see Section 2) to non-anthropogenic conditions. Indeed, assessing changes in probability of blocking events due to anthropogenic climate change can be difficult, as climate models tend to underestimate blocking frequency (Scaife et al., 2010), and there is generally less confidence in observed and projected changes in atmospheric circulation (Shepherd, 2014; Hoskins and Woollings, 2015).

2. Methods and data

2.1. Modelling approach

Our experiment design is based fundamentally on a standard regional-model ensemble weather-hindcasting approach. We generate hindcasts using a part observational- part model-based setup, whereby a representation of the large-scale weather state derived from the National