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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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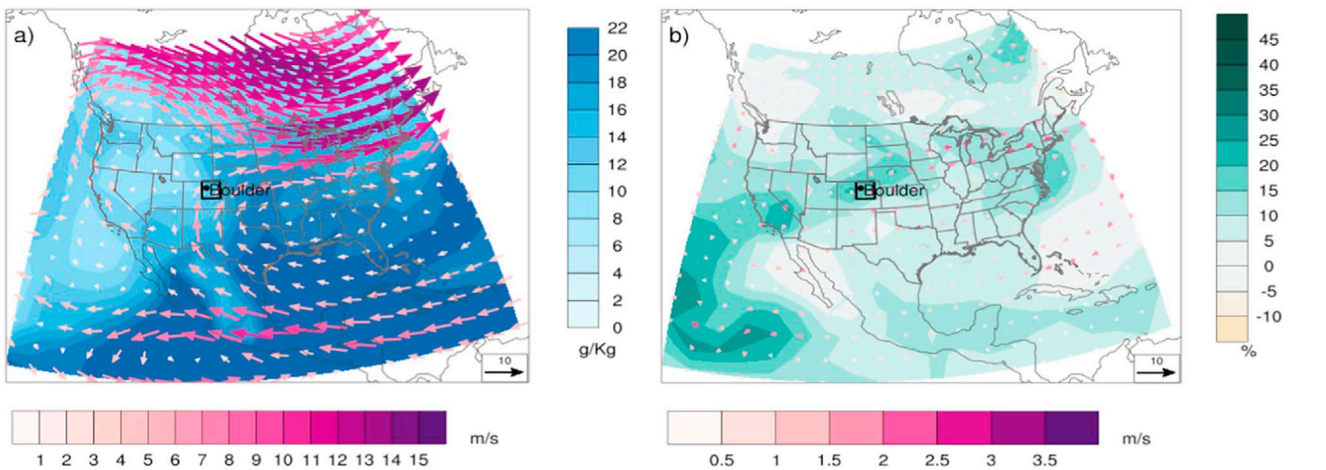

Fig. 1. Modelled synoptic situation and change for the rainy week of September 2013. (a) Total 7-day (00Z 9 September – 00Z 16 September 2013) precipitable water (g/Kg), and average 7-day 700 hPa winds (m/s) over the WRF model domain. Values are ensemble-averages over an ensemble of 101 WRF model simulations 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

Centers for Environmental Prediction/Department of Energy Atmospheric Model Intercomparison Project II (NCEP/DOE AMIP-II (NCEP2) (Kanamitsu et al., 2002)) observational-based Reanalysis, is prescribed as ICs and 6-hourly LBCs to the regional Weather Research and Forecasting (WRF, version 3.4.1 (Skamarock et al., 2008); see Supplementary information (a)) numerical model. The NCEP2 reanalysis has global coverage at 6-hourly frequency, with atmospheric data on a 2.5° horizontal resolution grid and 17 pressure levels, and surface data and sea surface temperatures (SSTs) on an approximately 1.9° horizontal resolution grid.

We generate two ensembles of hindcasts under anthropogenic and non-anthropogenic September 2013 driving scenarios constructed using the NCEP2 reanalysis as described below. Each ensemble consists of 101 WRF model simulations, with each simulation having identical ICs and LBCs but unique temporally and spatially correlated perturbations (see Supplementary information (a)) to account for uncertainty in the exact state of the weather. In this way we generate anthropogenic and non-anthropogenic September 2013 hindcast climates, from which the respective probabilities of exceeding some metric constituting flood-inducing rainfall occurrence (in this study based on the observed high precipitation) is computed, and thus change in probability (Allen, 2003; Stone and Allen, 2005) of flood occurrence – conditional on the observationally-derived large-scale circulation pattern – is estimated.

2.2. Constructing the anthropogenic driving scenario

The anthropogenic driving scenario represents realistic conditions during the rainy week period. It is constructed by prescribing large-scale NCEP2 reanalysis fields (three-dimensional zonal and meridional wind, temperature, specific humidity, and geopotential height; surface temperature, sea-level pressure, land-surface pressure, soil moisture and temperature, SSTs, sea-ice, and water-equivalent snow depth) at 00Z 7 September 2013, as proxy observed ICs and LBCs to the regional WRF model. These are typically prognostic fields used to derive the more detailed state of the weather in a reanalysis, and we adopt them here to instead derive the more detailed state of the weather in our WRF model domain. Furthermore, the LBCs and SSTs are updated every 6 h from the reanalysis, and all simulations run until 00Z 23 September 2013. Thus the WRF model is initialized just before the rainy week to allow its base state to adjust to the prescribed large-scale conditions but not drift too far from them before the week begins. Hence this anthropogenic scenario produces a hindcast ensemble of simulated contiguous U.S. rainfall (Supplementary figure 1(a,b)) given the large-scale meteorological conditions in September 2013.

2.3. Constructing the non-anthropogenic driving scenario

The non-anthropogenic driving scenario represents hypothetical conditions that might have been present during the rainy week period, in the absence of anthropogenic climate drivers. We construct it by simultaneously adjusting all the aforementioned anthropogenic NCEP2 reanalysis fields (listed in Section 2.2) that are prescribed as ICs and LBCs to the WRF model in the anthropogenic scenario. These adjustments remove an estimate of observed anthropogenic climate change, and are spatio-temporally coherent (obtained from a single set of off-line climate model simulations), described as follows.

The adjustments are obtained from simulations of the Community Atmospheric Model version 5.1 (Neale et al., 2010), run in the standard released configuration at approximately 1° horizontal resolution (CAM5.1-1degree) submitted to the Climate of the 20th Century Plus Detection and Attribution (C20C+ D&A) Project (Folland, 2010). The experimental design of the C20C+ D&A Project adopts the conventional atmospheric modelling framework for event attribution described above, following ref. Pall et al. (2011). The factual observed world is simulated with a 50-member perturbed-initial-condition ensemble of CAM5.1-1degree simulations, started over a decade before 2013, and driven with observed historical changes in radiative, land-surface, and ocean-surface boundary conditions. The counterfactual case of a world in which anthropogenic emissions never occurred is estimated with another similarly driven 50 simulations, except that radiative conditions are now set to year 1855 values, and SSTs and sea ice concentrations are modified by the benchmark 'Nat-Hist/CMIP5-est1′ estimate of the effect of anthropogenic emissions as estimated from fully coupled atmosphere-ocean climate models (Stone and Pall, unpublished results). Thus, the difference between the atmospheric variables output for September 2013 from these factual and counterfactual ensembles of CAM5.1-1degree simulations was subtracted from the aforementioned anthropogenic September 2013 NCEP2 reanalysis fields to provide adjusted non-anthropogenic ICs and LBCs for the WRF model; the counterfactual SSTs used for the CAM5.1-1degree simulations were also used for the WRF model. Greenhouse gas (GHG) concentrations in the WRF model were also reduced to preindustrial levels. Unlike in the counterfactual CAM5.1-1degree simulations, in the non-anthropogenic simulations the aerosol burdens and ozone concentrations were not altered. However, stratospheric ozone would not be expected to influence this mid-latitude region in late summer, while the effects of aerosols are weakest in cases of abundant atmospheric moisture, as was the case here. No other adjustments (e.g. land-surface properties) are made. We find that the main characteristics of the large-scale meteorological conditions are largely unaffected by all these alterations (Fig. 1(b)). Hence this non-anthropogenic scenario produces a plausible hypothetical hindcast ensemble of simulated contiguous U.S. rainfall (Supplementary figure 1(c,d)) in September 2013 had anthropogenic activities not altered the composition of the atmosphere, and not altered the large-scale meteorological conditions very much from those that actually occurred.

3. Results

Within the regional model, we target an analysis area over northeast Colorado (Fig. 1, black box) matching that of ref. Hoerling et al. (2014) when mitigating spatial selection bias, and analyze 7-day total rainfall for 00Z 9 September – 00Z 16 September 2013, covering the observed rainy week. Fig. 2 shows histograms of rainfall totals for anthropogenic and non-anthropogenic climates. Rainfall generally shifts towards higher totals in the anthropogenic climate, with a 30% increase (±9% standard-error-on-mean-based 95% confidence interval) in mean.

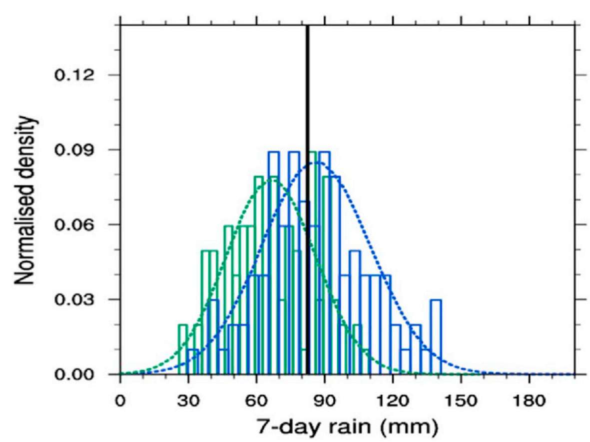

Fig. 2. Histograms of simulated northeast Colorado 7-day (00Z 9 September – 00Z 16 September 2013) rainfall. Blue (green) histogram is from an ensemble of 101 WRF model simulations under anthropogenic (non-anthropogenic) conditions; associated curve shows fitted normal distribution. Black vertical line marks corresponding observed 7-day rainfall from CPC data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

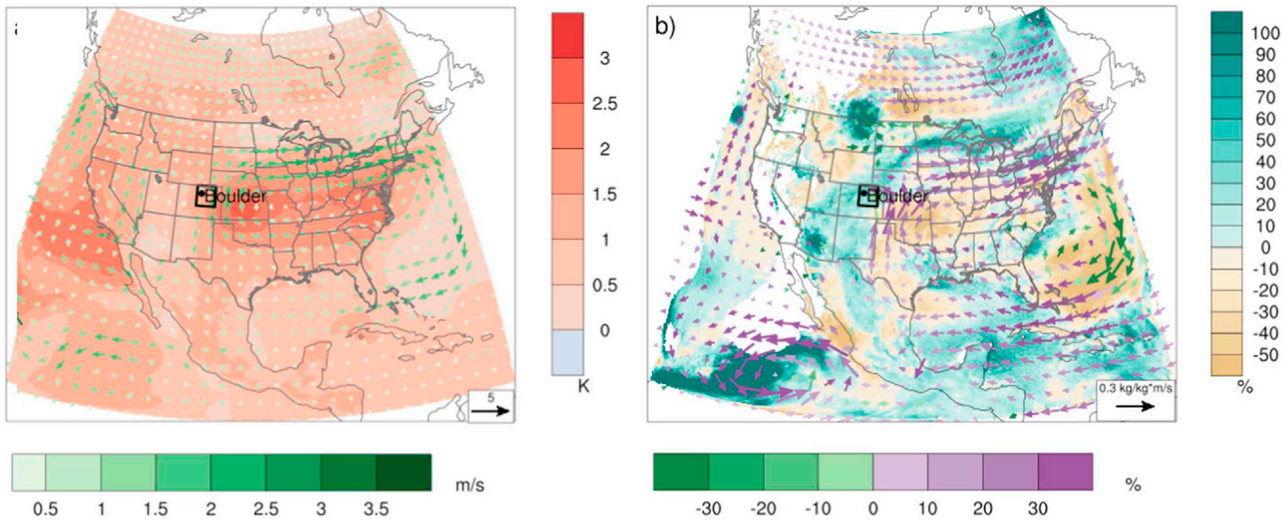

Fig. 3. Modelled change in synoptic situation for the rainy week of September 2013. (a) As Fig. 1(b), but now for change (K) in surface temperature (note also that 700 hPa winds arrows now shown on a different scale). (b) Corresponding change (%, vertical bar) in total rainfall and 850 hPa moisture flux (%, horizontal bar; absolute change indicated by arrow length). Areas of with an average daily rainfall of 0.25 mm or less were masked prior to the change computation.

3.1. Mechanistic analysis

Following a mechanistic event attribution framework, we seek to decompose this 30% increase into its physically-based components, by examining contributions from atmospheric thermodynamics and dynamics. We begin by considering the Clausius-Clapeyron relation, which governs the thermodynamic increase in saturation water vapour pressure corresponding to an atmospheric temperature increase; noting that although changes in actual atmospheric water vapour are approximately governed by Clausius-Clapeyron for a global climatological average given constant relative humidity, atmospheric water vapour changes are not expected to be governed by Clausius-Clapeyron for a regional synoptic event characterized by an unsaturated atmosphere. Fig. 3(a) shows that the temperature increase in the target area (the black box) is 1.3 K, and corresponding low-level relative humidity changes only 2.5% (Supplementary figure 1). This allows a 1.3 K $\times\sim$7%/K $\approx$9% thermodynamic increase in the capacity of the atmosphere to hold atmospheric water vapour there, as governed by the Clausius-Clapeyron relation at these latitudes (Trenberth et al., 2003). However, the actual increase in precipitable water in the target area is 15% (Fig. 1(b)), with a larger scale change in spatial structure over much of the WRF domain similar to that observed (Ref. Hoerling et al., 2014), figure 5.1(b)) – indicating that changes in dynamics are also important in contributing to the simulated changes in atmospheric water vapour. This is reinforced by an increase in mid-to-low atmospheric airflow into the target region, suggesting that moisture is additionally transported into the region (Fig. 3a).

In fact, the increase in rainfall in the target area is 30% (Fig. 3(b)), which is well beyond the above thermodynamically allowable increase there, indicating that dynamical factors play a major role in transporting moisture to the region. The large-scale pattern of change in low-level moisture flux (Fig. 3(b) arrows) shows that the increased moisture transport into the target region is dominated largely by an increase in anti-cyclonic circulation, extending from Colorado to the Atlantic Ocean – so as to increase southerly moisture flow primarily from the Gulf of Mexico and Eastern Tropical Pacific. This anticyclonic circulation response over the eastern U.S. is similar to the intensification and westward extension of the North Atlantic subtropical high that is projected in future warming scenarios by several coupled global climate models (Cook, 2008) and is associated with a strengthening of moisture transport from the Gulf of Mexico into the Central U.S. by the Great Plains low-level jet (Patricola and Cook, 2013).

To better understand the role of thermodynamics and dynamics we split the total rainfall into large-scale and convective components, and compute the change between climates (Supplementary figure 2). The large-scale rainfall in the target area exhibits mixed decreases and increases, with an overall 17% increase (Supplementary figure 2(e)). In contrast, convective rainfall increases almost everywhere in the target area, with an overall 45% increase (Supplementary figure 2(f)), and the increased ratio of convective to large-scale rainfall also manifests in our simulations over a broad range of northeast Colorado 7-day rainfall totals (Supplementary figure 3) – indicating a dominating role of increased convective processes here.

Thus we postulate that the southerly flow of moisture into the target area in the anthropogenic climate (Fig. 1(a)) has been enhanced, relative to the non-anthropogenic climate, in association with large-scale changes in the North Atlantic subtropical high and enhanced moisture transport by a strengthened Great Plains low-level jet. This moisture is convected and rained out, providing additional latent heat release and driving stronger local convection greater than that expected from Clausius-Clapeyron alone (Berg et al., 2013; Westra et al., 2014) that outweighs any general increase in tropospheric vertical stability arising from global warming. Furthermore the situation may establish a positive local feedback in which increased convective activity further enhances the flow of moisture into the heavy rainfall region from further afield. Concurrently, drawn-in moisture that encounters the Front Range in Colorado is orographically lifted and rains out, with the associated latent heat release reinforcing local convective activity that is in excess of that explained by Clausius-Clapeyron. This results in total rainfall increases of ~30% – much greater than the ~9% allowable by basic thermodynamic considerations alone in the target area (the increase in temperatures of about 1 K over the probable moisture source areas of the Gulf of Mexico and Eastern Tropical Pacific (Fig. 3(a)) also implies a thermodynamic increase in moisture available for transport there, but again this would be relatively small, about 7%).

3.2. Probabilistic analysis

Following a probabilistic event attribution framework, we assess the extent to which the 30% increase in rainfall affected the occurrence probability of flood-inducing totals. A flood-inducing total is considered as occurring in an individual WRF model simulation if that total meets or exceeds the corresponding observed 7-day total for the analysis area determined from NOAA Climate Prediction Center (CPC) observations (Chen et al., 2008). This observational-based threshold lies near the mode of the anthropogenic rainfall histogram (Fig. 2, black vertical line) – which is unsurprising given that the experiment design conditions anthropogenic rainfall to inhabit this extreme regime. In this sense, one can compute a conditional probability, *CP*, of flood-inducing rainfall occurrence – where the prefix '*C*' modifies conventional probabilistic event attribution nomenclature (Allen, 2003; Stone and Allen, 2005) to emphasize the strong conditionality of our results – as the number of simulations meeting or exceeding the threshold as a fraction of the total number of simulations in the ensemble. This returns $CPA=0.54$ and $CPN=0.27$ in the anthropogenic and non-anthropogenic ensembles respectively. Then defining the conditional probability ratio, $CPR=CPA/CPN$, as a measure of change analogous to the conventional probability (or risk) ratio (Allen, 2003; Stone and Allen, 2005), yields $CPR=2.0$ – suggesting a point estimate that anthropogenic climate drivers approximately doubled the probability of flood-inducing rainfall occurring, within the remit of our experiment design.

However this *CPR* estimate may be sensitive to the precise value of observational-based threshold used, which could depend on factors including the event's spatio-temporal definition and observational product. We examine this sensitivity by repeating the above computation for a range of thresholds (Fig. 4), while also estimating associated sampling uncertainty (see Supplementary information (b)). While *CPR* is clearly greater than unity over the range considered, its point estimates are sensitive to threshold. However, the lower bound of the associated uncertainty is relatively insensitive, remaining above 1.3 in the vicinity (65–100 mm; approximately±20%) of the CPC threshold (82 mm), suggesting this is a robust feature of our *CPR* (and may be a feature of probability ratio estimates generally (Jeon et al., 2016)).

4. Conclusions and discussion

We conclude from our mechanistic and probabilistic assessments that – conditional on the occurrence of the large-scale meteorological pattern that drove the September 2013 heavy rainfall event, and small prescribed changes therein, as well as the specified changes in GHG concentrations and sea surface temperatures – our simulations indicate anthropogenic emissions increased the magnitude of heavy northeast Colorado rainfall for the wet week of 9th–15th September 2013 by 30%, and the probability of a week at least that wet occurring at that time increased by at least a factor of 1.3.

We emphasize that the conditionality is crucial in interpreting these findings, as it necessarily precludes broader assessment of any anthropogenic change resulting from a range of other possible large-scale meteorological patterns that could produce heavy northeast Colorado rainfall, in September or otherwise; or the change in probability of such patterns occurring in the first place. This is a general limitation of conditional attribution approaches, and the net effect of anthropogenic climate drivers on heavy Colorado rainfall in September 2013 can be more fully assessed using conventional event attribution approaches that account for other possible meteorological patterns and anthropogenic changes in their occurrence probability, along with changes in the occurrence probability of the observed September 2013 pattern itself (Stott et al., 2016). We would welcome further such assessments, and comparisons with conditional approaches, by the event attribution community – for example as facilitated by the multi-model simulations available through the C20C+ D&A project (Folland et al., 2010).

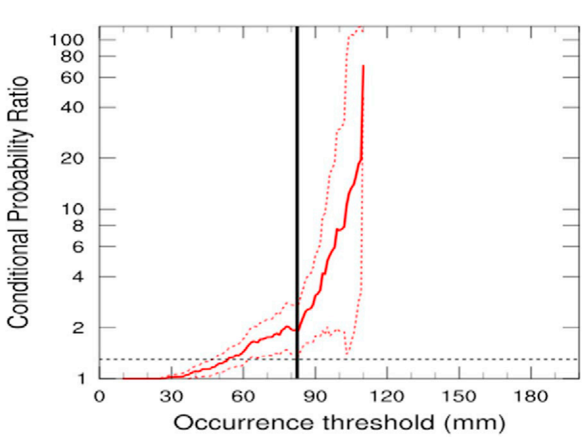

Fig. 4. Point estimates (solid line) of the conditional probability ratio (*CPR*) of simulated northeast Colorado 7-day (00Z 9 September – 00Z 16 September 2013) rainfall occurrence, as a function of occurrence threshold. Sampling uncertainty estimated using standard-error-based 95% confidence interval (dotted lines) on bootstrapped resamples of simulations (see Supplementary information (b)). Vertical solid line marks observational-based threshold from CPC data. Horizontal dotted line delineates a factor 1.3 increase in *CPR*.

Nonetheless, it has been argued that given deep uncertainty in anthropogenic changes in occurrence probability of meteorological patterns (e.g. due to low signal-to-noise, non-robust changes across models, and lack of process understanding), that our narrower conditional assessment is perhaps the most societally relevant (Trenberth et al., 2015; Shepherd, 2016; Hazeleger et al., 2015) – albeit we must guard against over-conditioning the experiment such that event conditions are so specific for the anthropogenic scenario that any adjustment to a non-anthropogenic scenario is bound to result in a change of event magnitude or occurrence frequency, and hence the possibility of misattribution (Allen, 2011). We can at least qualitatively address part of this latter concern by recalling that the large-scale meteorological pattern changes little when adjusted to remove an anthropogenic signal. So any change in northeast Colorado rainfall is due predominantly to physically well-understood anthropogenic warming plus subsequent local convective feedbacks to that thermodynamic response.

Because extreme weather events are rare and often dynamically complex, they present challenges to standard event attribution frameworks for understanding anthropogenic effects on climate. Yet many substantial impacts of climate change, anthropogenic or otherwise, arise from such events. The September 2013 Colorado floods are emblematic of this, with an intense instance of an unusual weather pattern shunting moisture into a region of extreme topographical variation – resulting in fatal floods plus severe damages. We have sought to understand the effect of anthropogenic emissions on this event through an approach to event attribution that foregoes some aspects of a broader, perhaps more uncertain, conventional assessment of the net effects of anthropogenic emissions on occurrence of a range of potential large-scale meteorological patterns and associated local Colorado rainfall events in September 2013 (Hoerling et al., 2013), in order to instead more forensically consider the role of physical processes particular to generating the September 2013 event by conditioning on the observed large-scale meteorology at the time. Such tailored approaches (see also Takayabu et al., 2015; Lackmann, 2015; Meredith et al., 2015; Shepherd, 2016) are proving useful additional tools for enabling diagnosis of the physical effects of anthropogenic climate change on severe weather events.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.wace.2017.03.004.

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