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Changes in hail and flood risk in high-resolution simulations over Colorado's mountains

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The effect of a warming climate on hailstorm frequency and intensity is largely unknown. Global climate models have too coarse resolution to simulate hailstorms explicitly; thus it is unclear if a warmer climate will change hailstorm frequency and intensity, and if so, whether such events will become more likely through intensified thunderstorms or less likely owing to overall warmer conditions. Here we investigate hail generation and maintenance for warm-season extreme precipitation events in Colorado, USA, for both present-day and projected future climates using high-resolution model simulations capable of resolving hailstorms. Most simulations indicate a near-elimination of hail at the surface in future simulations for this region, despite more intense future storms and significantly larger amounts of hail generated in-cloud. An increase in the height of the environmental melting level due to climate warming is found to be the primary reason for the disappearance of surface hail, as the warmer atmosphere increases the melting of frozen precipitation. A decrease in future surface hail at high-elevation locations may imply potential changes in both hail damage and flood risk.

Understanding the impact of global climate change on local weather extremes is a persistent challenge for research, decision-making, and stakeholder communities. Hailstorms are a weather extreme of particular concern owing mainly to the significant damage to property and agriculture that they inflict each year across the United States. Within the United States, the lee side of the Rocky Mountains (especially eastern Colorado) experiences the greatest hail frequency, the greatest hail intensity, the largest average hailstone size, the highest average number of hailstones, and the longest hailstorm durations[1–3]. Portions of this geographic region are also extremely prone to flood because of the steep, complex terrain and the potential for heavy rainfall when moist air impinges on the mountains. Although the societal implications of hailstorms are usually considered solely within the context of hailstone-induced property damage, precipitation that arrives at the surface as hail, as opposed to heavy rain, may actually help prevent or delay flash flooding. A 'rule-of-thumb' in Colorado is that most extreme warm-season precipitation above 7,500–8,000 ft elevation falls predominantly as hail, delaying and decreasing precipitation runoff as the hailstones melt over a long enough period of time to reduce the threat of flooding[4,5]. This perception of decreased flood risk, also supported by palaeoflood evidence[6–10], has ramifications in the water resources engineering community. It is sometimes argued that because of a lessened flood potential above 7,500 ft in the Colorado region, dams and other water control structures above this elevation threshold need not be held to maximum flood safety standards[10,11].

One of the challenges inherent to understanding hail changes in the context of global climate change is the stark mismatch of scale. Climate models simulate large-scale patterns of change owing to both natural and anthropogenic effects representing spatial and temporal scales on the order of 100 km and decades to centuries, respectively. Weather models (and more specifically, convective-scale weather models) are used for predicting and diagnosing small-scale weather phenomena such as hail and extreme rainfall. Owing to the fine scales required, computational limitations commonly restrict spatial and temporal coverage to 1–10 km grid spacing and hours to days, respectively. Therefore, understanding the potential effects of global-scale changes on local-scale weather requires novel research approaches to connect the questions and processes across both weather and climate scales.

This study represents one such integrated approach by investigating possible changes in hail formation and maintenance in future climates using a dynamical downscaling framework that sequentially interfaces climate- and weather-scale data. Global simulations are first downscaled to a medium/regional-scale resolution; the resulting simulations are then further downscaled using a high-resolution weather model. The high-resolution model is able to explicitly simulate intense thunderstorms at the cloud-scale, resolve the small-scale physical processes that generate hail and determine how much hail arrives at the earth's surface. The weather-scale simulations conducted for past and future climate projections are used to investigate how hail may change over Colorado in the future. This methodology thus encompasses a large spatial spectrum of atmospheric processes, from very large climate-scale signals to very small hail-formation physics. The specific questions to be addressed are: (1) will changes in large-scale thermodynamics and kinematics due to climate change affect the generation and/or surface existence of hail and (2) do potential changes in future hailstorms indicate shifts in public risk/flood potential for certain geographic regions?

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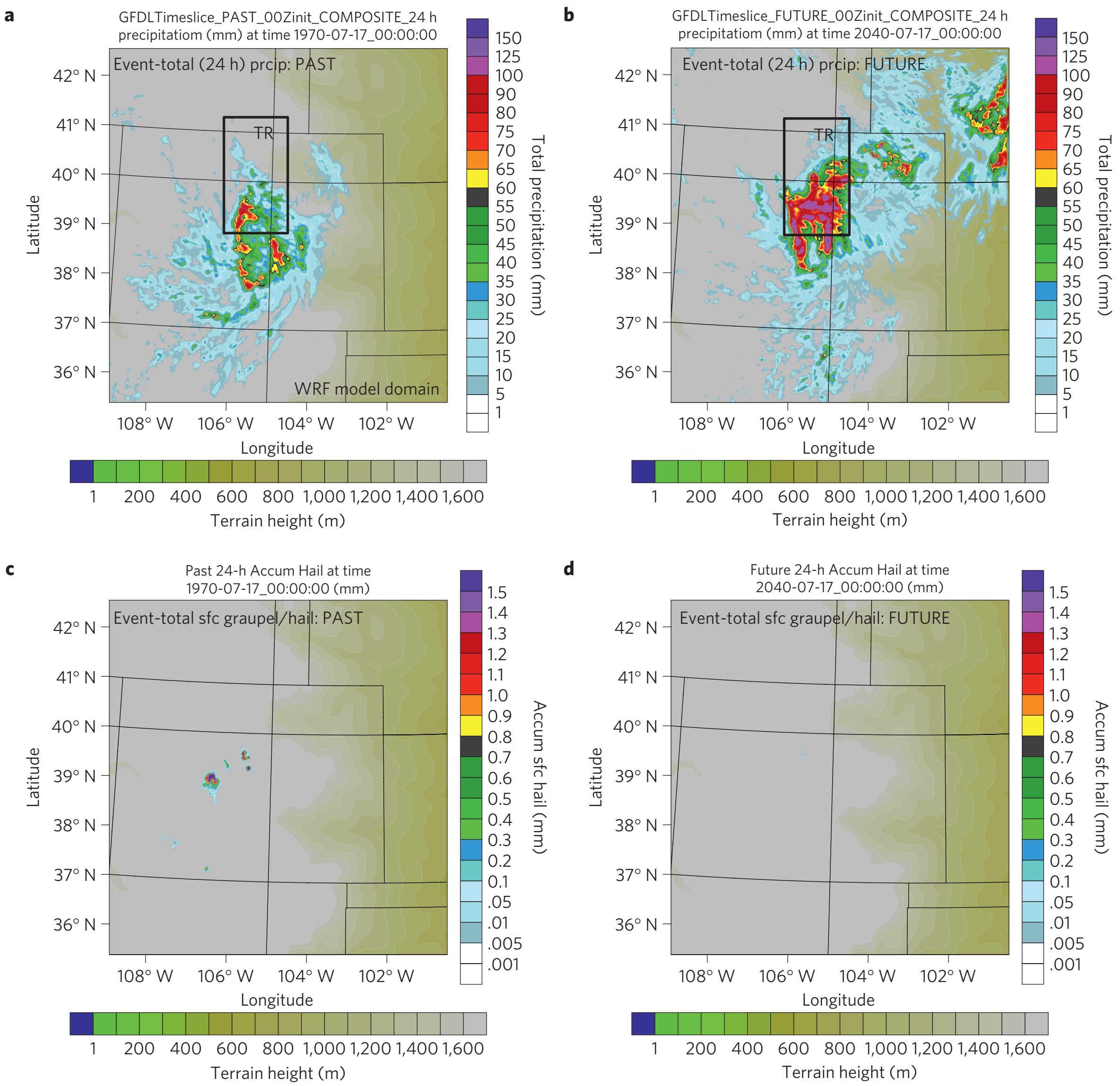

Figure 1 | A comparison of precipitation and hail/graupel accumulation for PAST and FUT simulations. a,**b**, Event-total (24-h) accumulated precipitation (mm, shaded as in the colour bar at the right) for PAST (**a**) and FUT (**b**). **c**,**d**, Event-total (24-h) accumulated surface graupel/hail (mm, shaded as in the colour bar at the right) for PAST (**c**) and FUT (**d**). Terrain height (m) is shaded as in the bottom colour bar. The target region (TR) is indicated by the box in **a**; the model domain for WRF simulations is the entire area plotted in the panels.

Hail challenges at the weather-climate model interface

Intense warm-season rainfall in the high plains of the United States, and specifically in Colorado, is frequently mixed with hail and/or graupel (a hydrometeor similar to hail but formed in non-convective clouds through the accretion of supercooled water on a snowflake). The large amount of ice observed at the ground in this region is primarily due to intense thunderstorms occurring in elevated terrain and low relative humidity in the sub-cloud layer. Elevated terrain reduces the likelihood of hail melting by decreasing cloud-to-ground distance, and dry air provides cooling from precipitation evaporation, which increases downdrafts and the likelihood that hail will survive to the ground[1,12,13].

Hail forms in thunderstorms when strong vertical air motions allow frozen particles to grow by the accretion of supercooled liquid water. When hailstones grow large enough such that they are no longer supported by surrounding rising air motions, they begin to fall. Smaller ice particles melt more quickly and at levels nearer to the melting level than larger ones; warmer sub-cloud air accelerates the melting process[14,15]. With these processes in mind, two opposing (yet not mutually exclusive) hypotheses emerge in terms of the potential impact of a warming climate on hailstorms: (1) a warmer and moister climate will produce stronger thunderstorms with stronger updrafts, increase hail production and increase the amount of hail at the surface, and/or (2) a warmer climate will increase the height of the melting level, increase the melting of hailstones and reduce the amount of hail at the surface.

Representing hail in models is a challenge, as the relevant processes span from very small scales (for example, melting and sublimation on the surface of a hailstone) to large scales (for example, synoptic-scale forcing for thunderstorm genesis). Nearly all climate models are run at resolutions that prohibit the representation of hail at all, and most weather models must still employ some type of microphysical parameterization to represent hail formation and maintenance processes. The treatment of ice microphysics has a large impact on both weather and climate model simulations, and considerable research effort is devoted to optimizing microphysical parameterization to balance computing capability with resolution needs. Furthermore, many of

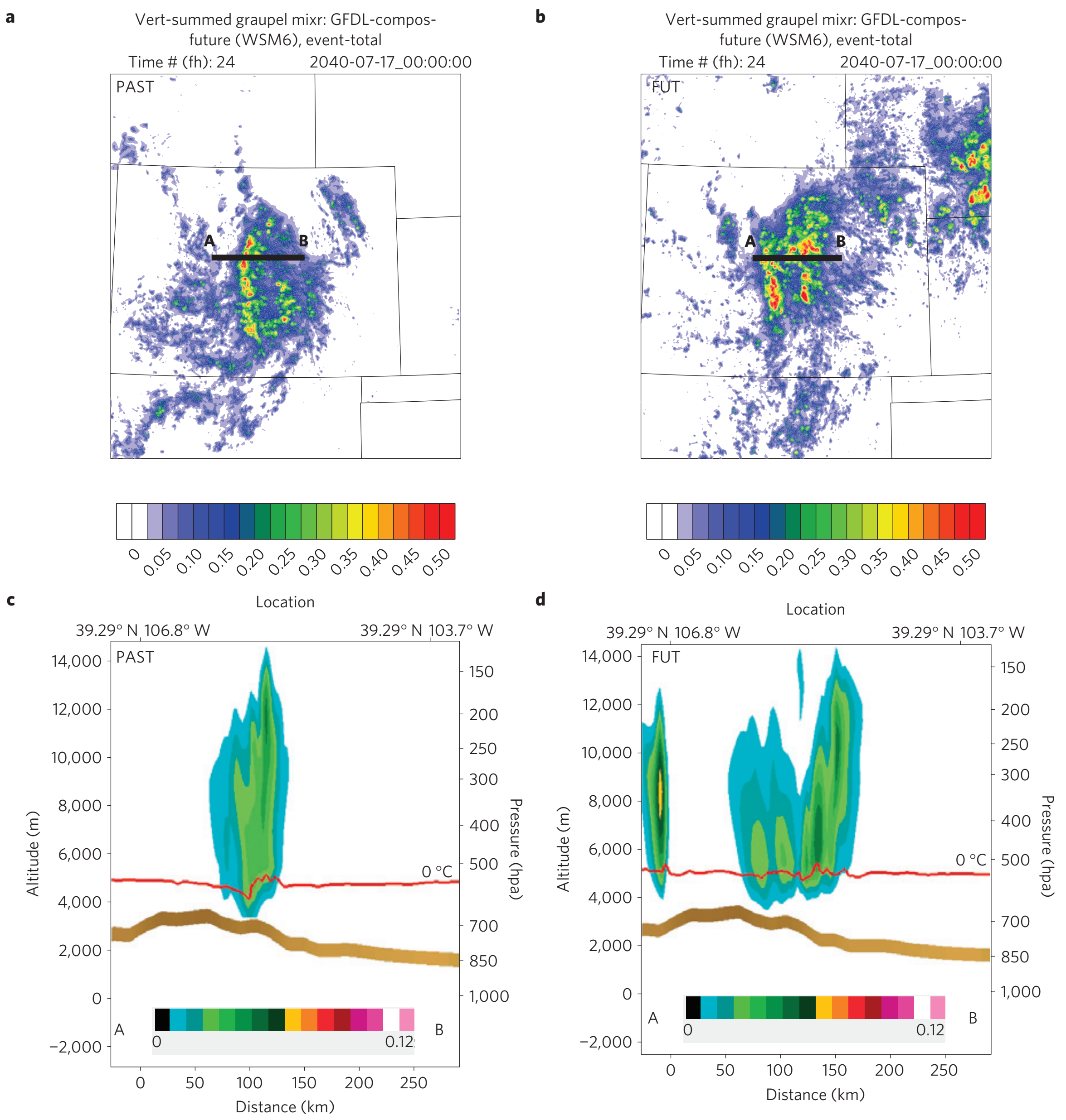

Figure 2 | A comparison of hail throughout the full atmospheric column. a,**b**, Vertically-summed event-total (24-h) graupel/hail mixing ratio (kg kg^{-1}, shaded) for PAST (**a**) and FUT (**b**). Black lines 'AB' indicate the cross-sections taken in lower panels. **c**,**d**, Instantaneous vertical cross-section of graupel/hail (kg kg^{-1}, shaded as in colour bar at the bottom) at hour three of the simulation, 0 °C-isotherm (red contour) and terrain height (thick brown contour) for the section 'AB', PAST (**c**) and FUT (**d**).

the microphysics schemes accounting for ice processes available in current operational weather forecast models group hail and graupel into the same hydrometeor category, and there is considerable sensitivity to the details of these model settings[16–18].

Previous studies considering the effects of climate change on hail have largely relied on the linkage of proxy atmospheric indicators and (usually sparse) hail observations. Niall and Walsh[19] used convective forecast indices such as convective available potential energy (CAPE) from reanalysis data to determine the influence of climate change on hail events in Australia; still earlier studies have linked parameters such as minimum temperature increases to various percentage increases in hail damage[20–22]. Xie *et al.*[23] found a decrease in observed hail over China from 1960 to 2005 that corresponds to observed increases in melting level height. However, given only surface observations of hail, one cannot evaluate whether hail generation itself decreases (as suggested by Xie *et al.*[23]), or whether only the hail realized at the surface decreases. As Niall and Walsh[19] further note, all past studies of this nature are inhibited by (1) the inadequate historical record of past hail storms, (2) the coarseness of the datasets employed (usually global data and climate model simulations) and (3) the often tenuous connection between large-scale environmental parameters and small-scale weather extremes. Thus, the conclusions that can be drawn from these types of studies are limited. In this study, we use large-scale climate data as input to a high-resolution weather model; in so doing, hail generation can be examined directly, instead of inferring hail likelihood from large-scale fields.

A high-resolution modelling approach

High-resolution (1.3-km grid spacing) model simulations are produced for warm-season extreme precipitation events over Colorado. In this three-tiered downscaling approach, global

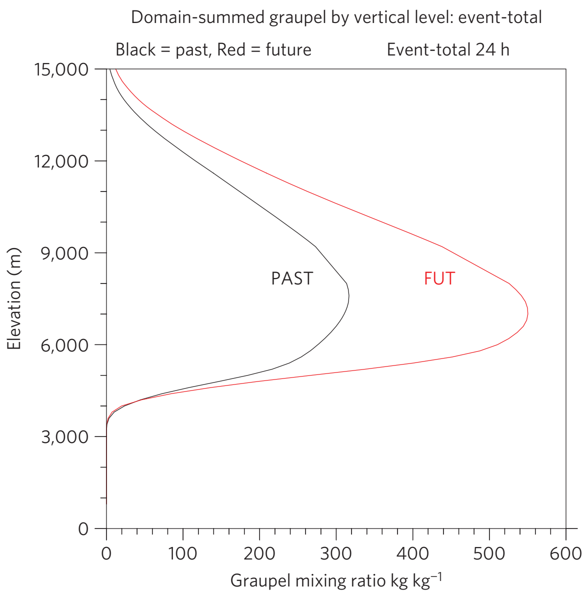

Figure 3 | A comparison of graupel/hail amount by vertical level in PAST and FUT simulations. Vertically-summed event-total (24-h) graupel/hail mixing ratio (kg kg^{-1}) across the entire domain for PAST (black) and FUT (red).

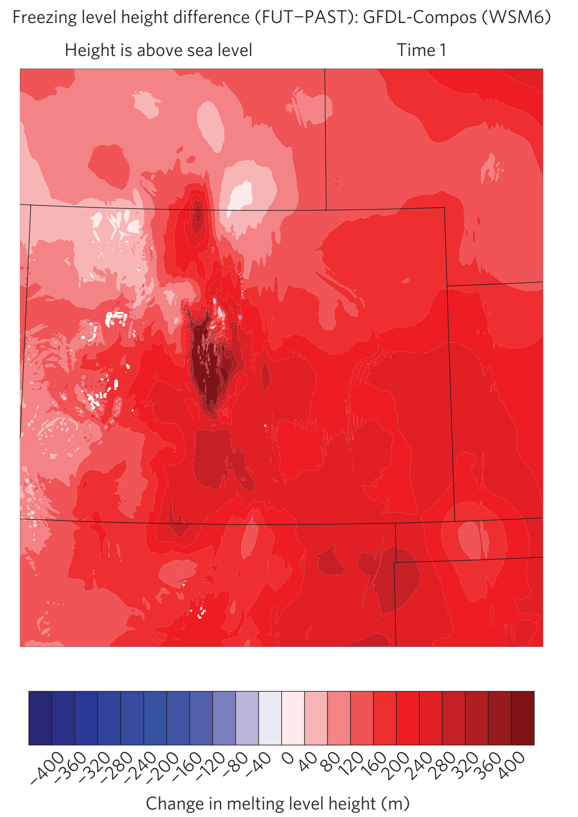

Figure 4 | Change in melting level height (height of 0 °C isotherm) at initial time from PAST to FUT simulations (m, shaded).

climate model simulations are first downscaled to 50-km grid spacing as part of the North American Regional Climate Change Assessment Program (NARCCAP; ref. 24). NARCCAP regional climate models (RCMs) are driven by a set of atmosphere–ocean general circulation models (GCMs) according to a business-as-usual emissions scenario (SRES A2). The NARCCAP RCM simulations span 30 years in the past (1971–2000) and 30 years in the future (2041–2070), and extreme precipitation events that occur in NARCCAP are further downscaled using a high-resolution model (1.3-km grid spacing) capable of explicitly simulating the intense thunderstorm events.

This work focuses on warm-season extreme events, and examines only the largest precipitation events found from June to August for the two respective 30-year periods. The ten largest 24-h precipitation totals from unique events for 1971 to 2000 and 2041 to 2070 are selected using a target region centred over the Front Range of the Colorado Rocky Mountains (Fig. 1). Past and future high-resolution simulations were thus completed as 24-hour-long, individual extreme events. A further set of high-resolution simulations were initialized using composite past and future environments. The Weather Research and Forecasting (WRF) model[25] is used to produce all of the high-resolution simulations; for details regarding its configuration and the generation of the initial conditions, see Methods. The WRF model domain is shown in Fig. 1; noteworthy aspects of the configuration employed here are the high resolution (1.3-km grid spacing) domain and the explicit representation of convection. The explicit (that is, non-parameterized) representation of convection allowed by the high-resolution simulations is important, as the coarse grid spacing and approximations necessitated by cumulus parameterization schemes are two of the main challenges in accurately representing and predicting extreme precipitation processes and events in climate-scale models[26–28].

Although multiple experiments were performed using two different RCM projections as initial conditions to the WRF model, the particular NARCCAP RCM experiment to be discussed herein is the 'Timeslice' experiment from the Geophysical Fluid Dynamics Laboratory (GFDL) model (http://www.narccap.ucar.edu/about/timeslices.html). To streamline the display of results here, we focus on the composite-based past and composite-based future simulations (PAST and FUT, hereafter). The near-elimination of hail found for the two composite-based simulations are also found across the larger collection of individual event simulations (see Supplementary Information for more detail).

Simulation results reveal a marked increase in event-total (24-h) precipitation from PAST to FUT (Fig. 1a,b). In response to increases in both ambient temperature and moisture from the past to future environments (not shown), the 24-h total precipitation local maxima increase by 50–70% in both the target region and across the entire domain (approximately 100 mm in PAST versus 165 mm in FUT) and the domain-averaged 24-h precipitation increases by more than 100% in FUT. Although events were chosen based on the target region described above, the model domain is far larger, and thus significant rainfall also occurs outside of the case-selection target region; however, changes in rainfall amount and intensity are the focus of a separate manuscript. This investigation focuses on the occurrence of surface hail: the PAST simulation produces surface hail over central portions of higher elevations of the Colorado Rocky Mountains (Fig. 1c), with several local maxima in excess of 1 mm (surface hail units are a water equivalent of hail/graupel assuming a particle density of 500 kg m^{-3}). Remarkably, despite more intense rainfall, almost no hail is found at the surface in FUT (Fig. 1d).

The near-total elimination of surface hail persists across the other individual event simulations and also across simulations initialized by two independent climate projections (see Supplementary Information). That the decrease in surface hail remains consistent across simulations driven by two different WRF model methodologies (individual event and composite-based) and two different initial datasets (see Supplementary Information) suggests a robustness in the results. Using a Monte Carlo method

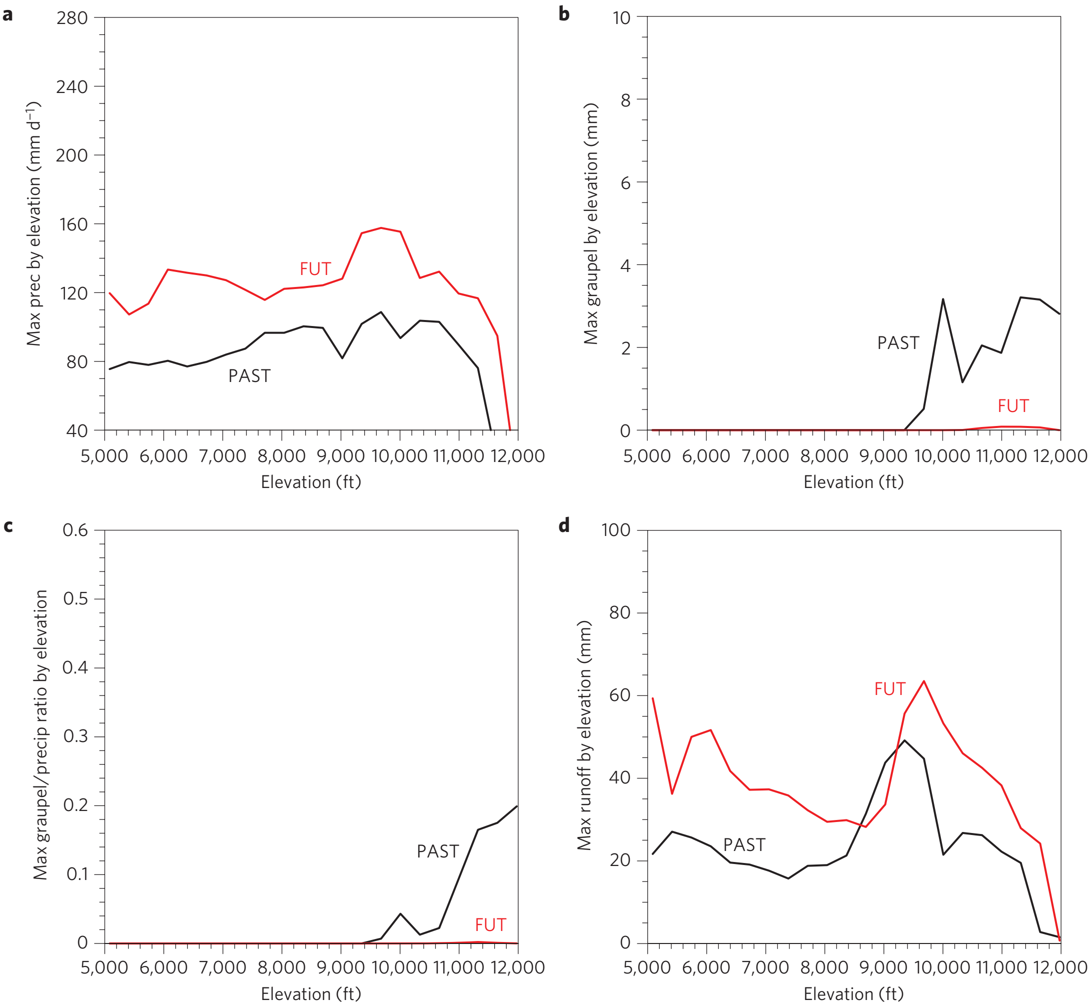

Figure 5 | A comparison of precipitation, hail/graupel and surface runoff relative to elevation. a, Maximum grid point event-total precipitation (mm d^{-1}) versus elevation. **b**, Maximum liquid-equivalent accumulated surface hail/graupel (mm) versus elevation. **c**, Maximum ratio of graupel/total precipitation versus elevation. **d**, Maximum surface runoff (mm) versus elevation. For all plots PAST is shown in black and FUT in red.

re-sampling procedure, the change in surface hail across these simulations is found to be statistically significant at the 99% level for hail averaged over the model domain, and at the 98% level for hail averaged over the Colorado Front Range target region.

Why does hail decrease when storms become stronger?

To understand the dramatic decrease in hail at the surface in the future simulations, we first assess whether (1) hail formation itself decreases, and/or (2) hail melting above the surface increases. As suggested by the increase in event-total precipitation, the FUT storm is significantly stronger, and therefore, high mixing ratios of in-cloud hail/graupel are still generated (Figs 2 and 3). Despite large amounts of hail found in vertical cross-sections from both the PAST and FUT simulations (for example, Fig. 2c,d), less hail in the FUT simulation reaches the surface. Integrating the hail/graupel mixing ratio fields at all vertical levels above the surface shows that hail formation indeed increases across much of the domain from PAST to FUT, as evidenced by larger total hail amount and greater spatial coverage in FUT (Figs 2 and 3). Therefore, melting or sublimation (the phase transition of ice to vapour) must explain how greater amounts of in-cloud hail in the future are eliminated before reaching the surface.

The initial melting level (that is, the 0 °C-isotherm) in PAST is approximately 5,000 m (above sea level), but in a warmer climate, the initial height of the 0 °C-isotherm in the FUT simulation increases to an average height of approximately 5,500 m. The greatest increases in melting level height from PAST to FUT are concentrated over central Colorado (Fig. 4; model validation of melting level height is discussed in the Supplementary Information). The additional 300–500 m of above-freezing atmosphere through which the hail passes thus seems to be sufficient to melt all hailstones in FUT before they would reach the surface. Analysis of the heating tendency field from the model microphysics scheme supports this finding, showing an increase in parameterized cooling (implying enhanced melting, as melting is a cooling process) at and below the melting level (not shown). Further experiments in which hail melting is disabled in the microphysical parameterization scheme also confirm that large amounts of hail accumulate at the surface in the absence of melting. These findings are corroborated by those of Xie *et al.*[23,29], in which more modest increases (roughly 200 m) in melting-level height over China are linked with a decrease in observed hail frequency and modified regional hail size distributions.

A significant qualification of the preceding analysis is that the melting of hail is dependent on model microphysics parameterizations. Relevant microphysics scheme details include the classification of hail/graupel itself and the size distribution of hail; the representation of hail size is of particular importance, as small hail will be considerably more affected by changes in melting level height than large hail[29]; indeed, it is important to emphasize that large hailstones (those that tend to be responsible for the most hail damage in severe storms) may be minimally impacted by the process illustrated here. It is beyond the scope of this study to determine the 'best' specific parameterization settings, and although hail representation does demonstrate sensitivity to model microphysics, agreement is found across other schemes tested with respect to a decrease in the ratio of surface hail to total precipitation (see Supplementary Information).

Implications

The results of this study reveal future changes in warm-season convective storm intensity and characteristics for the Colorado Front Range and Rocky Mountain regions, particularly in the realization of surface hail. The changes detailed herein suggest stronger future storms that produce more in-cloud hail but also possess a higher melting level; the latter effect outweighs the former and results in a decreased proportion of precipitation reaching the surface as hail versus rain (owing to hail melting over a deeper vertical layer of above-freezing temperatures). Although a decrease in future surface hail may imply less damage potential from hail itself, the implications for increased flood risk may pose new storm-related hazards.

Although the Front Range of Colorado is a flood-prone region[4,30], some previous studies and operational practices suggest that the dominance of hail over rain in high-elevation extreme precipitation events negates, or at least mitigates, flood risk above 7,500 ft (ref. 5). Thus, the combined effect of decreased hail and increased rainfall may be especially significant in Colorado's complex terrain, especially in mountainous regions with relatively impervious surfaces. Specifically, if high-elevation regions that currently experience hail as opposed to rain instead experience all-liquid precipitation in the future, flash flooding may become more likely. An analysis of maximum precipitation totals as a function of terrain elevation shows that future simulations produce larger total maximum precipitation across most elevations in this region (Fig. 5a), while simultaneously producing less (almost no) hail at the surface (Fig. 5b,c). An increasing future trend is also seen in surface runoff, with future increases evident at most middle-to-high elevation locations (Fig. 5d). Furthermore, as the model currently does not account for the slow melting of hail versus the instantaneous conversion of rainfall to runoff, it is likely that the potential for increased flood risk in these locations is still underestimated.

Potential sensitivity to model microphysical parameterization awaits further investigation. The need for further research bridging climate and weather scales may challenge the climate research community to reconsider the relevant scales of model physics in dictating 'weather-relevant' results, and also prompt the mesoscale meteorology and numerical weather prediction communities to continue developing such schemes as they become used for realms beyond near-term weather forecasting. In particular, sensitivity to hail size and storm type (for example, large, supercell thunderstorms versus smaller, less organized thunderstorms) should be further examined, especially as they may relate to changes in hail damage potential. Finally, in any model-based study, the possibility of model bias and inherent model uncertainty (at the global, regional and local scale) cannot be ignored. Although the GFDL-'Timeslice' RCM experiment used to initialize these high-resolution simulations compares reasonably well with reanalysis data and observations, the possibility that a warm model bias (or other model-based uncertainty) could significantly affect melting level height and perhaps in turn alter the degree of surface hail response should not be overlooked.

Changes in hailstorm frequency and intensity may impose significant consequences from both a public risk/property loss perspective, but may also alter flash flood risk for a given region. For stakeholders and decision-makers trying to plan and prepare for potential changes, these results represent a step towards an improved understanding of the potential for climate change effects on extreme weather events. To optimize the utility of these findings, further research is underway to address a larger spectrum of future climate change scenarios and the sensitivity to model microphysics, and also to evaluate how findings in the Colorado Rocky Mountains compare to other geographic regions.

Methods

Initial and boundary conditions for the high-resolution WRF simulations are RCM data from the NARCCAP project[24,31]. NARCCAP provides a set of RCMs driven by a set of atmosphere–ocean general circulation models (GCMs) over a domain covering the conterminous United States and most of Canada. Each GCM–RCM combination simulates a past (1971–2000) and future (2041–2070) period, and all downscaling is performed to 50-km grid spacing. The GCMs have been forced with the SRES A2 emissions scenario for the twenty-first century. The NARCCAP RCM experiment discussed in this manuscript was the 'Timeslice' experiment from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model[32]. This dataset was produced by downscaling the fully-coupled ocean–atmosphere GFDL CM2.1 global model simulation to 50-km grid spacing using the GFDL-AM2.1 model; this method derives the surface boundary conditions from the fully-coupled global model. Further details pertaining to the RCM dataset are given in Mearns *et al.*[24] and references therein (see also http://narccap.ucar.edu).

The largest precipitation events across the past and future periods from June to August are examined using a case-selection target region centred over the Front Range of the Colorado Rocky Mountains (Fig. 1). All RCM grid points in the target region were identified and, for each of these points, daily precipitation totals from June, July and August were evaluated. The ten largest 24-h precipitation values from unique events for 1971 to 2000 and 2041 to 2070 defined the ten largest cases for the past and future simulations, respectively. These collections of extreme events were compared to observations and reanalysis data to ensure that precipitation totals and synoptic-scale forcing in the RCM data were reasonably represented; indeed, precipitation maxima and environmental conditions for individual RCM extreme events closely match those found in reanalysis data (not shown). Each 'top 10' event was then simulated in high resolution individually, as well as used to construct a composite (average) environment to be used by further simulations (details below). Individual event simulations were performed for both the past and future sets of 'top 10' events using both the GFDL-Timeslice experiment and the WRF-CCSM experiment from the NARCCAP project. Although the latter is not discussed here (and for clarity, is distinct from the WRF simulations otherwise discussed here), the qualitative results regarding near-elimination of future hail were consistent with those shown here.

For the composite-environment-based simulations, extreme event composites were constructed by averaging together all available fields (temperature, moisture and winds at all vertical levels) from each of the ten heavy precipitation events in the past and future periods, respectively. The resulting composite datasets were then used as initial and boundary conditions for high-resolution simulations using identical model domains, simulation durations and physical parameterization selections as for the individual event simulations (see Supplementary Information). For clarity and conciseness (that is, comparing two simulations as opposed to twenty at a time), these composite-environment-initialized simulations are the focus of this manuscript.

The Weather Research and Forecasting (WRF) model version 3.1.1 was used for all of the high-resolution simulations in this study. WRF is a fully compressible, non-hydrostatic model and uses a terrain-following hydrostatic pressure vertical coordinate. Model configuration details are provided in Supplementary Table S1 (see Supplementary Information) and the model domain is shown in Fig. 1. Each WRF simulation was initialized approximately 6 h before the largest 3 h precipitation total as generated by the RCM simulation of the event, and each WRF simulation lasts 24 h in duration. Model output is produced hourly, and the internal model timestep is 8 s.

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32. http://www.narccap.ucar.edu/about/timeslices.html.

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Author contributions

K.M. carried out the model simulations and led the writing of the paper. M.A.A. provided project planning and leadership, as well as climate modelling expertise. G.T. contributed updated model microphysics code and provided microphysics parameterization counsel. J.J.B. provided project planning and counsel, and J.D.S. provided model initial condition files to be used for the high-resolution simulations, as well as reanalysis-based analyses, model validation, and graphics support. All contributed to editing the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.M.