Extreme Hail Storms and Climate Change: Foretelling the future in tiny, turbulent crystal balls?

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Problem Statement

In 2018, hailstorms accounted for three of the fourteen 2018 U.S. Billion Dollar Disasters: a June 6 2018 storm in Texas, and two Colorado hailstorms (June 18 – 19; August 6 – 7). What is the role of climate change in changing hail risk? Can current research methods address the space and time scales required to adequately assess hail risk? Can the available data distinguish between changes in storm frequency, changes in storm reporting practices, and changes in economic risk and our built environment? 2018's billion dollar hailstorms have highlighted the limited capabilities of the scientific community to predict how climate change will impact hail storm risks, while raising concern about the vulnerability of society to these storms. Like any weather disaster, 2018's hailstorms provide an opportunity to re-evaluate methods for anticipating similar future weather extremes.

Hailstorms: What we do(n't) know

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 and moister sub-cloud air accelerates the melting process. Anticipating the potential for hail on any given day – much less anticipating possible changes to the frequency and intensity of hail in the more distant future – thus requires understanding the inter-play between the environmental support for hail-generating convective storms, key microphysical and dynamical characteristics of the storm updraft region over which hail growth occurs, and the depth and temperature of the lower atmosphere where melting occurs. In short, this is a tall order!

Severe convective storms (SCSs) are the parent weather phenomenon responsible for producing most damaging hail. SCSs are relatively small and short-lived, and as a result, their impacts (e.g., strong winds, large hail, tornadoes) are very localized and not comprehensively captured by conventional meteorological observations. While research and available model data continue to actively expand in this area (e.g., see recent workshop summaries by Martius et al. 2017, NCAR 2018), these challenges of scale and limited observations render the consensus state of knowledge regarding future projected changes in hail largely unchanged from the IPCC Special Report on Extremes (Seneviratne et al., 2012): "confidence is still low for hail projections particularly due to a lack of hail-specific modelling studies, and a lack of agreement among the few available studies." Yet for stakeholders affected by potential changes in hail risk, what can be done given this apparent lack of actionable scientific guidance? Here we briefly examine the state of the science, areas of emergent scientific consensus, and how – even in the face of significant uncertainty – research can best serve end-user needs.

State of the research: How do we currently consider hail and climate change?

a. Historical hail trends and observing challenges

Vast data heterogeneities of observed hail means that detection of past hail trends is also exceedingly difficult. For example, observations of U.S. hail do indicate significant increases over the latter half of the 20th century, but these are widely understood to be artifacts of increased reporting frequency rather than actual meteorological trends (e.g., NAS2016; Allen and Tippett 2015; Fig. 1). Studies considering the effects of observed warming on hail have largely relied upon the linkage of proxy atmospheric indicators and (usually sparse) hail observations, and are thus fundamentally inhibited by a) the inadequate historical record of past hailstorms, b) the coarseness of the datasets employed (usually global data and climate model simulations), and c) the questionable connection between large-scale environmental parameters and small-scale weather extremes. Thus, despite a small sample of specific regions demonstrating robust observed changes [e.g., downward trends in both hail days and hailstorm frequency in China (e.g., Xie et al. 2010; Li et al. 2016) and increasing hail intensity (with decreasing hail frequency) in SW France (Dessens et al. 2015)], the conclusions that can be drawn from these types of studies are limited (e.g., Allen 2018).

b. Climate model projections: Assessing hailstorm ingredients

Global and regional climate models (GCMs and RCMS) are generally run at resolutions far too coarse to realistically simulate SCSs, much less SCS impacts. While climate model projections generally indicate increasing SCS likelihood as a result of increasing thermodynamic instability (e.g., Diffenbaugh et al. 2013; Hoogewind et al., 2017), details pertaining to changes in seasonality, regionality, and SCS impacts are less certain.

A common approach to understanding how SCSs may change in the future is to use GCM and RCM projections to evaluate how SCS-favorable environmental parameters change in future climate projections, thereby focusing on SCS "ingredients" as proxies for SCS impacts such as hail (e.g., Brooks et al. 2003; Trapp et al. 2007; Diffenbaugh et al. 2013; Allen 2018). As noted above, studies of this nature are also inherently inhibited by both the coarseness of the datasets employed, and the often tenuous connection between environmental proxies and weather impacts. These studies are also incapable of describing storm-scale criticalities including possible changes in convective mode (i.e., a shift away from severe-hail-generating rotating supercells), the relationship between in-cloud hail generation vs. surface-impacting hail, and the fundamental reality that specific SCS hazards (large hail, damaging winds, and tornadoes) do not favor the same environmental conditions (Brooks, 2013).

Some climate model signal consistency has emerged however, e.g., European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) models find an expected future increase in hail frequency for parts of Europe (e.g., Martius et al. 2017; Rädler et al. 2019). Similarly, Brimelow et al. (2017) used an off-line single-column hail growth model to ingest environmental profiles from 50-km RCM output, also finding fewer days with smaller hail over the some regions of the United States, with increases in spring and summer large hail over the northern plains. While using GCM/RCM output as proxies or as input into offline models reduces computational limitations, the general approach does not actually simulate storms; this, and other limitations of the environmental approach, have thus pushed the research community to seek additional approaches to refine and complement the guidance that can be gleaned from larger-scale data.

c. High-resolution, convection-permitting simulations

Leveraging computing power increases, high-resolution convection-permitting (CP) model simulations allow a more direct representation of SCSs likely to produce hail. Some CP simulations have adapted the pseudo–global warming approach, where present-day hail events are simulated in high-resolution in both current and future atmospheric environments (e.g., Mahoney et al. 2012). Such studies generally support the notion of increased likelihood of large hail and decreased likelihood of small hail, and at such high-resolution, also offer insight into physical process-based rationale to explain aggregate hail changes. Another recent CP modeling approach applied to hail specifically uses a "continual restart approach" to downscale GCM projections over the CONUS in 30-year historical and future time slices, and finds broad increases in the frequency of large hail during all four seasons and mixed signals in small – medium hail (Trapp et al. 2019). These results and others (e.g., NCAR 2018) – while computationally limited in the number of climate projections or events that can be evaluated – also share some consensus that the seasonality of hail risk is likely subject to change, with several studies indicating a lengthening at both the beginning and end of the convective season, and also possibly exhibiting more interannual variability in the future.

d. Near-term opportunities and challenges

Though high-resolution simulations offer increasing insight by explicitly simulating hail-producing storms in future climate states, it is important to underscore that even at these relatively high resolutions, these studies still only resolve the parent SCS and not the details of hail production nor hail size spectra. Additional caveats exist: for example, even very recent, state-of-the-art high-resolution CP studies such as Trapp et al. (2019) often rely on a hail diagnostic to connect model-produced hydrometeor concentration output with heuristically-generated hail diameter assignments. The enduring requirement for microphysical parameterization to approximate hail formation and maintenance processes further clouds the connection between model-approximated hail and surface damage potential. Furthermore, effects including the role of atmospheric aerosols, the storm-scale interplay between theoretically-increasing updraft strength and potentially-decreased buoyancy due to additional hydrometeor weight, and hydrologic sensitivities as previously-frozen precipitation instead melts and falls as rain, all point to a daunting chain of uncertain – yet critical – small-scale physical system dependencies and interactions.

It is impossible to choose a single "best" method given basic computational trade-offs in a) *many* coarse-scale GCM projections (which cannot simulate physically-realistic SCSs), and b) *singular*, or limited-member, high-resolution downscaled projections (which lack fundamental uncertainty and robustness indicators). But perhaps recognizing outright the impracticality of a perfect blend can ultimately yield greater insight into the future of hail via a holistic, thoughtful curation of complementary research approaches including observational, theoretical, and model-based study methods (e.g., Shepherd 2016).

Actionable attribution science

Despite the considerable uncertainties surrounding the future of hail risk, key industries and stakeholders must still act -- ideally on the best information that our collective weather and climate research communities can provide. Decision-making under the conditions of deep uncertainty ("DMDU"; e.g. Marchau et al. 2019) is a concept well-known in certain stakeholder communities (e.g., water supply planning), and accepts that traditional, deterministic science approaches are unlikely to provide usable stakeholder answers in isolation. ''Storytelling'' frameworks (e.g., Hazeleger et al. 2015; Shepherd 2016) in particular focus on "multiple futures" or "scenarios" (e.g., Star et al. 2016), and thus complement and add physical insight to traditional climate projections.

Considering approaches beyond those rooted purely in the physical sciences, Owen (2019) details the actuarial industry's extensive experience in managing uncertainty. Insured events are evaluated in risk models according to (i) the probability the event will occur, (ii) the timing of the event, and (iii) the distribution of the severity of the expense of the event. Of course, the addition of economic or other supporting data does not reduce the original uncertainties in the physical system; Owen (2019) further highlights the large cost sensitivity in these models: even "small deviations from estimations of future costs have considerable financial consequences."

Just as a priori economic valuation data may usefully bound potential economic losses from hail, it is key to recognize also that hail disaster planning also requires assessment of vulnerability (i.e., exposure). Figure 2 borrows an "expanding target" schematic from Ashley et al. (2014)'s study on tornado risk, illustrating the concept that as populations grow and spread, hazards to lives and property increase. Combining physical science methods with vulnerability and economic assessment may enable scientists and risk experts to provide a more informed menu of future hail risk scenarios.

Summary

Assessing potential changes in hail frequency, intensity, and hailstone size distribution in a warmer climate is complex. While research to-date provides some indication of more intense hailstorms in a warming climate alongside enhanced melting of small hailstones, considerable uncertainty and variability qualifies these findings. As computing power increases, attribution studies of SCSs may become increasingly feasible, but for hail itself, explicit simulation in global or regional model attribution studies is unlikely to be practicable in the near future. Integrated, curated, complementary research approaches suited to specific decision-making applications are likely required to optimally address this challenging question.

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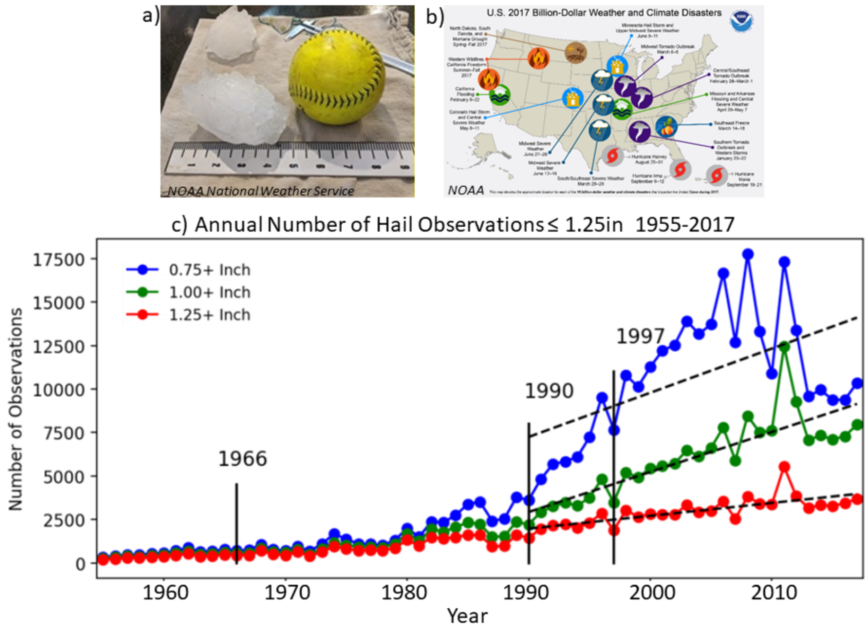

Figure 1. Despite a number of recent hail records and high-impact hail events (e.g., 2019 Colorado new record hailstone size and multiple high-impact 2018 and 2019 hail storms; panels a and b, respectively), detecting past hail trends is challenged by inconsistent observations. Panel c) shows the 1998 – 2017 time series of the fraction of hail reports ≥0.75 in (1.9 cm). Adapted from Allen and Tippett (2015), Figure 3a.

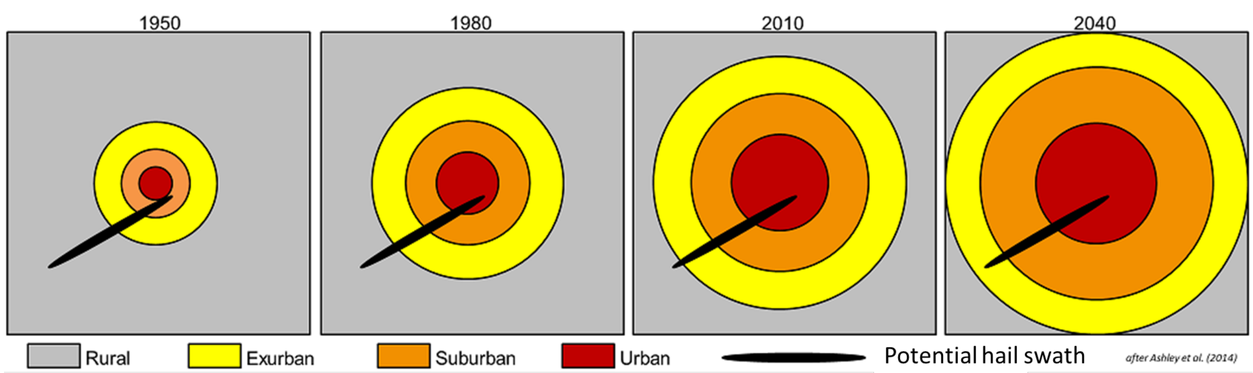

Figure 2. Adapted from Ashley et al. (2014), a conceptual model of the “expanding bull’s-eye effect” for a hypothetical metropolitan region characterized by increasing development spreading from an urban core over time. A sample hail swath is overlaid to show how expanding development creates larger areas of potential impacts from hazards.