EXPLAINING EXTREME EVENTS OF 2018

From a Climate Perspective

Special Supplement to the
Bulletin of the American Meteorological Society
Vol. 101, No. 1, January 2020

EXPLAINING EXTREME EVENTS OF 2018 FROM A CLIMATE PERSPECTIVE

Editors

Stephanie C. Herring, Nikolaos Christidis, Andrew Hoell,
Martin P. Hoerling, and Peter A. Stott

BAMS Special Editors for Climate

Andrew King, Thomas Knutson,
John Nielsen-Gammon, and Friederike Otto

Special Supplement to the

Bulletin of the American Meteorological Society

Vol. 101, No. 1, January 2020

AMERICAN METEOROLOGICAL SOCIETY

CORRESPONDING EDITOR:

Stephanie C. Herring, PhD
NOAA National Centers for Environmental Information
325 Broadway, E/CC23, Rm 1B-131
Boulder, CO, 80305-3328
E-mail: stephanie.herring@noaa.gov

COVER CREDIT: iStock.com/Alena Kravchenko—River Thames receded during a heatwave in summer 2018 in London, United Kingdom.

HOW TO CITE THIS DOCUMENT

Citing the complete report:

Herring, S. C., N. Christidis, A. Hoell, M. P. Hoerling, and P. A. Stott, Eds., 2020: Explaining Extreme Events of 2018 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, **101** (1), S1–S128, doi:10.1175/BAMS-ExplainingExtremeEvents2018.1.

Citing a section (example):

Mahoney, K., 2020: Extreme Hail Storms and Climate Change: Foretelling the Future in Tiny, Turbulent Crystal Balls? [in “Explaining Extremes of 2018 from a Climate Perspective”]. *Bull. Amer. Meteor. Soc.*, **101** (1), S17–S22, doi:10.1175/BAMS-D-19-0233.1.

TABLE OF CONTENTS

1. The Extreme 2018 Northern California Fire Season	1
2. Anthropogenic Impacts on the Exceptional Precipitation of 2018 in the Mid-Atlantic United States	5
3. Quantifying Human-Induced Temperature Impacts on the 2018 United States Four Corners Hydrologic and Agro-Pastoral Drought	11
4. Extreme Hail Storms and Climate Change: Foretelling the Future in Tiny, Turbulent Crystal Balls?	17
5. The Extremely Cold Start of the Spring of 2018 in the United Kingdom	23
6. The Exceptional Iberian Heatwave of Summer 2018	29
7. Analyses of the Northern European Summer Heatwave of 2018	35
8. Anthropogenic Influence on the 2018 Summer Warm Spell in Europe: The Impact of Different Spatio-Temporal Scales	41
9. On High Precipitation in Mozambique, Zimbabwe and Zambia in February 2018	47
10. The Record Low Bering Sea Ice Extent in 2018: Context, Impacts, and an Assessment of the Role of Anthropogenic Climate Change	53
11. The Late Spring Drought of 2018 in South China	59
12. Anthropogenic Influence on 2018 Summer Persistent Heavy Rainfall in Central Western China	65
13. Conditional Attribution of the 2018 Summer Extreme Heat over Northeast China: Roles of Urbanization, Global Warming, and Warming-Induced Circulation Changes	71
14. Effects of Anthropogenic Forcing and Natural Variability on the 2018 Heatwave in Northeast Asia	77
15. Anthropogenic Influences on the Persistent Night-Time Heat Wave in Summer 2018 over Northeast China	83
16. Anthropogenic Contributions to the 2018 Extreme Flooding over the Upper Yellow River Basin in China	89
17. Attribution of the Record-Breaking Consecutive Dry Days in Winter 2017/18 in Beijing	95
18. Quantifying Human Impact on the 2018 Summer Longest Heat Wave in South Korea	103
19. The Heavy Rain Event of July 2018 in Japan Enhanced by Historical Warming	109
20. Deconstructing Factors Contributing to the 2018 Fire Weather in Queensland, Australia	115
21. A 1-Day Extreme Rainfall Event in Tasmania: Process Evaluation and Long Tail Attribution	123

EXTREME HAIL STORMS AND CLIMATE CHANGE: FORETELLING THE FUTURE IN TINY, TURBULENT CRYSTAL BALLS?

KELLY MAHONEY

In 2018, hailstorms accounted for three of the fourteen 2018 U.S. billion dollar disasters: a 6 June 2018 storm in Texas, and two Colorado hailstorms (18–19 June and 6–7 August). 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? The billion dollar hailstorms of 2018 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 interplay between the environmental support for hail-generating convective storms, key microphysical and dynamical charac-

teristics 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. (2018) and 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” (p. 148). 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.

AFFILIATIONS: MAHONEY—National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Physical Sciences Division, Boulder, Colorado.

CORRESPONDING AUTHOR: Kelly Mahoney,
kelly.mahoney@noaa.gov

DOI:10.1175/BAMS-D-19-0233.1

For information regarding reuse of this content and general copyright information, consult the [AMS Copyright Policy](#).

STATE OF THE RESEARCH: HOW DO WE CURRENTLY CONSIDER HAIL AND CLIMATE CHANGE?

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 twentieth century, but these are widely understood to be artifacts of increased reporting frequency rather than actual meteorological trends (e.g., National Academies of Sciences, Engineering, and Medicine 2016; 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 1) the inadequate historical record of past hailstorms, 2) the coarseness of the datasets employed (usually global data and climate model simulations), and 3) 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. 2008; 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).

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; Tippett et al. 2015; 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 versus 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: for example, 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. 2018; Rädler et al. 2019). Similarly, Brimelow et al. (2017) used an offline 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.

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 a 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 continental United States (CONUS) in 30-yr 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.

FIG. 1. Despite a number of recent hail records and high-impact hail events, such as (a) 2019 Colorado new record hailstone size and (b) multiple high-impact 2018 and 2019 hail storms, detecting past hail trends is challenged by inconsistent observations. (c) The 1998–2017 time series of the fraction of hail reports ≥ 0.75 in (1.9 cm). Adapted from Allen and Tippett (2015, their Fig. 3a).

Near-term opportunities and challenges. Although 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 or hail size spectra. Additional caveats exist: for example, even very recent, state-of-the-art high-resolution CP studies such as that of 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 the basic computational trade-offs in 1) *many* coarse-scale GCM projections (which cannot simulate physically realistic SCSs) and 2) *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 1) the probability the event will occur, 2) the timing of the event, and 3) 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” (p. S6).

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.’s (2014) study on tornado risk, illustrating the concept that as populations grow and spread, hazards to lives and property increase.

FIG. 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.

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.

REFERENCES

- Allen, J. T., 2018: Climate change and severe thunderstorms. Oxford Research Encyclopedias: Climate Science, <https://doi.org/10.1093/acrefore/9780190228620.013.62>.
- , and M. K. Tippett, 2015: Characteristics of the United States Hail Observations Dataset 1955–2014. *Electron. J. Severe Storms Meteor.*, **10**, 1–31, .
- Ashley, W. S., S. Strader, T. Rosencrants, and A. J. Krmenec, 2014: Spatiotemporal changes in tornado hazard exposure: The case of the expanding bull's eye effect in Chicago, IL. *Wea. Climate Soc.*, **6**, 175–193, <https://doi.org/10.1175/WCAS-D-13-00047.1>.
- Brimelow, J. C., W. R. Burrows, and J. M. Hanesiak, 2017: The changing hail threat over North America in response to anthropogenic climate change. *Nat. Climate Change*, **7**, 516–522, <https://doi.org/10.1038/nclimate3321>.
- Brooks, H. E., 2013: Severe thunderstorms and climate change. *Atmos. Res.*, **123**, 129–138, <https://doi.org/10.1016/j.atmosres.2012.04.002>.
- , J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, [https://doi.org/10.1016/s0169-8095\(03\)00045-0](https://doi.org/10.1016/s0169-8095(03)00045-0).
- Dessens, J., C. Berthet, and J. L. Sanchez, 2015: Change in hailstone size distributions with an increase in the melting level height. *Atmos. Res.*, **158–159**, 245–253, <https://doi.org/10.1016/j.atmosres.2014.07.004>.
- Diffenbaugh, N. S., M. Scherer, and R. J. Trapp, 2013: Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proc. Natl. Acad. Sci. USA*, **110**, 16 361–16 366, <https://doi.org/10.1073/pnas.1307758110>.
- Hazeleger, W., B. J. J. M. van den Hurk, E. Min, G. J. van Oldenborgh, A. C. Petersen, D. A. Stainforth, E. Vasileiadou, and L. A. Smith, 2015: Tales of future weather. *Nat. Climate Change*, **5**, 107–113, <https://doi.org/10.1038/nclimate2450>.
- Hoogewind, K. A., M. E. Baldwin, and R. J. Trapp, 2017: The impact of climate change on hazardous convective weather in the United States: Insight from high-resolution dynamical downscaling. *J. Climate*, **30**, 102081–102100, <https://doi.org/10.1175/JCLI-D-16-0885.1>.
- Li, M., Q. Zhang, and F. Zhang, 2016: Hail day frequency trends and associated atmospheric circulation patterns over China during 1960–2012. *J. Climate*, **29**, 7027–7044, <https://doi.org/10.1175/JCLI-D-15-0500.1>.
- Mahoney, K., M. A. Alexander, G. Thompson, J. J. Barsugli, and J. D. Scott, 2012: Changes in hail and flood risk in high-resolution simulations over Colorado's mountains. *Nat. Climate Change*, **2**, 125–131, <https://doi.org/10.1038/nclimate1344>.
- Marchau, V. A. W. J., W. E. Walker, P. J. T. M. Bloemen, and S. W. Popper, Eds., 2019: *Decision Making under Deep Uncertainty: From Theory to Practice*. Springer, 405 pp., <https://doi.org/10.1007/978-3-030-05252-2>.
- Martius, O., A. Hering, M. Kunz, A. Manzato, S. Mohr, L. D. Nisi, and S. E. Trefalt, 2018: Challenges and recent advances in hail research. *Bull. Amer. Meteor. Soc.*, **99**, ES51–ES54, <https://doi.org/10.1175/BAMS-D-17-0207.1>.
- National Academies of Sciences, Engineering, and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The National Academies Press, 186 pp., <https://doi.org/10.17226/21852>.
- NCAR, 2018: *Proc. 2018 North American Workshop on Hail & Hailstorms*. Boulder, CO, NCAR, <https://www.mmm.ucar.edu/north-american-hail-workshop>.
- Owen, R., 2019: Actuaries are paying attention to climate data [in “Explaining Extremes of 2017 from a Climate Perspective”]. *Bull. Amer. Meteor. Soc.*, **100** (1), S5–S8, <https://doi.org/10.1175/BAMS-D-18-0293.1>.
- Rädler, A. T., P. H. Groenemeijer, E. Faust, E., R. Sausen, and T. Púčik, 2019: Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. *npj Climate Atmos. Sci.*, **2**, 30, <https://doi.org/10.1038/s41612-019-0083-7>.
- Seneviratne, S. I., and Coauthors, 2012: Changes in climate extremes and their impacts on the natural physical environment. *Managing the Risks of Extreme*

- Events and Disasters to Advance Climate Change Adaptation*, C. B. Field et al., Eds., Cambridge University Press, 109–230.
- Shepherd, T. G., 2016: A common framework for approaches to extreme event attribution. *Curr. Climate Change Rep.*, **2**, 28–38, <https://doi.org/10.1007/s40641-016-0033-y>.
- Star, J., and Coauthors, 2016: Supporting adaptation decisions through scenario planning: enabling the effective use of multiple methods. *Climate Risk Manage.*, **13**, 88–94, <https://doi.org/10.1016/j.crm.2016.08.001>.
- Tippett, M. K., J. T. Allen, V. A. Gensini, and H. E. Brooks, 2015: Climate and hazardous convective weather. *Curr. Climate Change Rep.*, **1**, 60–73, <https://doi.org/10.1007/s40641-015-0006-6>.
- Trapp, R. J., N. S. Diffenbaugh, H. E. Brooks, M. E., Baldwin, E. D., Robinson, and J. S. Pal, 2007: Changes in severe thunderstorm frequency during the 21st century due to anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA*, **104**, 19 719–19 723, <https://doi.org/10.1073/pnas.0705494104>.
- , K. A. Hoogewind, and S. Lasher-Trapp, 2019: Future changes in hail occurrence in the United States determined through convection-permitting dynamical downscaling. *J. Climate*, **32**, 5493–5509, <https://doi.org/10.1175/JCLI-D-18-0740.1>.
- Xie, B., Q. Zhang, and Y. Wang, 2008: Trends in hail in China during 1960–2005. *Geophys. Res. Lett.*, **35**, L13801, <https://doi.org/10.1029/2008GL034067>.