Critique of Chapter 6 "Extreme Weather" of the Department of Energy Report "A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate"

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Executive Summary

Chapter 6 of the draft DOE report examines whether global warming exacerbates extreme weather. It rightly notes that because events such as hurricanes are rare, detecting their response to climate change in short and imperfect historical records is extremely difficult—if not impossible. Yet the authors devote most of the remainder of the chapter to attempting just that. By omitting to frame such efforts in the context of theory and models, they commit three fundamental errors: 1) searching for trends where none were predicted, 2) neglecting important variables for which trends were predicted and 3) overlooking—or failing to acknowledge—that some predicted trends are of a magnitude that is not *a priori* detectable in existing noisy and short data sets. The draft report also overlooks recent literature on climate change effects on weather extremes, and quotes selectively and misleadingly from the most recent report of the Intergovernmental Panel on Climate Change (IPCC). For these reasons, I find much of Chapter 6 to be of questionable utility.

There are at least three climate change-induced trends in hurricane-related hazards that were predicted theoretically, simulated by models, and confirmed by observations:

1. Hurricanes are producing more rain, causing increased flooding. As water, not wind, is the source of most damage and mortality in hurricanes, this is the most consequential scientific finding.
2. The proportion of hurricanes that reach high intensity is increasing.
3. Hurricanes are intensifying more rapidly.

There is no robust scientific finding that hurricane frequency is increasing or expected to increase. Thus, much of Chapter 6 of the DOE report is devoted to refuting a hypothesis unsupported by scientific consensus.

The short section on tornadoes does not include other more destructive aspects of severe convective storms, such as hail and damaging straight-line winds, and as with the section on hurricanes, omits inferences from theory and models.

The following is a detailed critique of the portion of Chapter 6 that addresses hurricanes and severe thunderstorms, with references to recent and robust scientific findings.

1. Introduction

The purpose of the DOE report is stated clearly by Secretary of Energy Chris Wright in his foreword. He begins by noting that “we are told—relentlessly—that the very energy systems that enabled this progress now pose an existential threat. Hydrocarbon-based fuels, the argument goes, must be rapidly abandoned or else we risk planetary ruin.” To counter this narrative, he commissioned this report “to encourage a more thoughtful and science-based conversation about climate change and energy.” This objective aligns well with the stated purpose of the six full reports of the Intergovernmental Panel on Climate Change (IPCC), “to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options”. One may presume that Secretary Wright, who has reviewed IPCC reports, wanted to build a bridge between their highly detailed technical content and the overly simplified and sometimes exaggerated narratives issuing from news outlets. Indeed, this DOE report relies heavily, though not exclusively, on recent IPCC reports.

As a scientist who has devoted much of his career to understanding tropical cyclones (TCs, aka “hurricanes”), severe convective storms and their relationship to climate, I thought it important to review this new DOE report for scientific accuracy, focusing exclusively on the discussion of TCs and severe convective storms in Chapter 6, “Extreme Weather”. Herewith, my findings.

2. The Problem with Extreme Event Attribution

What constitutes an “extreme event”? One presumes it to mean an event that is damaging and rare. These two attributes go together: Society is well adapted to frequent events and most damage arises from unusual events like strong TCs. Empirically, we know that long-term damage from natural hazards is usually dominated by events that occur less frequently, on a regional scale, than about once in 50 years.

In a nutshell, the problem is that robust detection of even once-in-50-year events requires about 500 years of data, which we do not begin to have. The authors of the DOE report are well aware of this problem, stating on p. 46 that “Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own.” The authors also recognize that in a short record of extreme events, “If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed, attribution to human-caused warming does not necessarily follow.” In other words, extreme event attribution is difficult if not impossible based on historical records alone. But they should have added that the absence of evidence in short, noisy time series is not evidence of an absence of a trend.

What is odd about the rest of Chapter 6 is that it based mostly on attempts to detect trends in noisy and often suspect data, just what the authors said cannot be done. Once more, they are selective in presenting this evidence, ignoring locations and metrics that do show – and often were predicted to show – upward trends.

A good example is found on p. 50, where citing published research on continental U.S. landfalling hurricanes, they state that "While the largest numbers of landfalling hurricanes are from 2004, 2005 and 2020, there is no statistically significant trend since 1920". They are correct. But in stating this, they seem to overlook their earlier statements recognizing that no plausible trend is detectable in a record this short and noisy. Let's look at this more quantitatively. A *minimum* estimate of noise in this record is Poisson noise based on the observed long-term annual mean of U.S. landfalling hurricanes of about 2.2. (In reality, the "noise" includes natural variability as well as human climate influences other than greenhouse gas warming.) I created 10,000 times series spanning 1920-2024 consisting of an imposed linear trend of a 20% increase over the period and Poisson noise based on an average of 2.2 events per year. *Only about 12% of these series have positive slopes detectable at the conventional statistical significance level of 95%*. Stated another way, one has, a priori, only about a 12% chance of detecting the imposed upward trend at conventional levels of statistical significance. Even if one imposes an upward trend of 50%, there is still only a 40% probability of detecting the trend amidst the noise. When it comes to major hurricane landfalls, at only about one per year, the detection problem is even worse.

The DOE report should not have merely stated that "the relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability." It should have added that the observational data set cannot rule out even large underlying trends in U.S. landfalling hurricanes, and that there is no robust scientific consensus that the frequency of TCs – landfalling or not – should increase. These important omissions stem from the authors' decision not to discuss theoretical and model-based evidence for changing TC climatology.

3. The Importance of theory and models

Throughout the history of science, theory and models have played an important role not only in advancing understanding but in assessing risks. An example is global warming itself. Around the turn of the last century century, the Swedish chemist Svante Arrhenius predicted (Arrhenius 1896, 1906) that the accumulation of carbon dioxide in the atmosphere would lead to warming at a rate of about 4 K per doubling. Not long after accurate measurements of CO_2 commenced in 1958, the increase of it and other greenhouse gases was firmly established, and well before the end of the 20th century Arrhenius's prediction of greenhouse gas-induced warming was confirmed. In 1979, the National Academy of Sciences commissioned a report about climate change, authored by some of the leading atmospheric scientists and oceanographers of that period, led by Jule Charney (National Research Council 1979). The report estimated that the equilibrium response of global mean temperature to a doubling of CO_2 would be $3 \pm 1.5\,^{o}C$, based on physics, simple models, and the rather primitive general circulation models then available. Contemporary estimates of equilibrium climate sensitivity are similar, and there has been little or no reduction in the uncertainty of this prediction. It may well be several decades before observations pin down the true sensitivity of climate to changes in greenhouse gas concentrations.

A wonderful example of the interplay of theory and observations in science is gravitational radiation. Its existence was predicted by general relativity, but its detection presented formidable practical challenges, requiring the design and construction of large and expensive antennas. The project, called LIGO, involved roughly 1,000 scientists and many more amateur volunteers. It was the most expensive single project ever funded by the National Science Foundation and finally succeeded in detecting gravitational radiation in 2016.

There are two interesting differences between the climate and LIGO examples. First, it is unlikely that gravitational radiation would have been detected by now had there been no theoretical predictions of its existence, whereas global warming would have become obvious even without a prediction. Second, as far as we know, gravitational radiation has no effect on human welfare. For this reason, the LIGO scientists could and did demand an extraordinary level of statistical significance before they were ready to declare that a signal had been detected. In contrast, global warming may have serious implications for our wellbeing and thereby constitutes a risk. There is a world of difference between signal detection and risk assessment. In the case of extreme weather events, we can and indeed must assess risks largely in the absence of statistically significant signal detection. As Verner Suomi, then head of the Climate Research Board, stated in his foreword to the Charney report, "A wait-and-see policy may mean waiting until it is too late".

For this reason, the absence of a theoretical and modelling component to Chapter 6 of the DOE report represents a serious omission that calls into question the scholarly rigor of the report. The report dismisses the whole endeavor with two sentences on page 46: "Process-based understanding and simple thermodynamic arguments have been invoked to assert that warming is worsening extreme weather events. However, it is naïve to assume that any recent extreme event is caused by human influences on the climate." This is worse than simply dismissing theory and models as relevant to the problem: with their use of the word "however", the authors link process-based understanding and simple thermodynamic arguments to the fallacy that climate change can be inferred from single extreme events. This is just wrong. Theory and models can and have been used both to understand and predict global and regional changes in the statistics of extreme events, and to put particular extreme events in the context of expectations based on theory and models. Both of these are legitimate scientific endeavors.

Any legitimate effort to summarize the current scientific understanding of changes in extreme events would focus on theory and models, given that historical records are too short and flawed for purpose.

Here are three examples of predictions of extreme events based on theory and models that are supported by historical records.

The first is rainfall extremes associated with tropical cyclones (and many other meteorological phenomena). Air ascending in the cores of tropical cyclones is very nearly water saturated through the whole atmospheric column, and its water vapor content is governed by the Clausius-Clapyron equation, a bedrock principle of thermodynamics that shows that saturated water vapor content nearly doubles for each 10ºC of temperature increase. This strongly suggests that a given TC will produce more rain, an important consideration given that water kills far more people in TCs than wind. This could be compensated by weakening vertical motion in the core, but as discussed presently, we expect the opposite. And, yes, TCs could become less frequent. But to ignore this fundamental piece of physics is a serious omission.

Quite a few studies have set particular TC-related flooding events in the context of theoretical and modeling-based expectations of the effects of climate change. For example, three independent analyses of the flooding of Houston, TC by Hurricane Harvey of 2017 (van Oldenborgh et al. 2017; Risser and Wehner 2017; Emanuel 2017a) concluded that climate change had already palpably increased the probability of TC-related rain of the observed magnitude and a fourth study (Trenberth et al. 2018) directly attributed Harvey's extreme rainfall to the warmth of the Gulf of Mexico. Yes, this is a strictly local analysis, of necessity because rainfall in not reliably measured over oceans, but examining how climate change affects extreme weather in highly populated areas is nevertheless a valuable enterprise. The three research papers cited above, and other similar papers, were cited by AR6 but ignored in the DOE report. Examining tropical cyclone rainfall observations across the eastern U.S., Kunkel et al. (2010) concluded that "During 1994–2008, the number of TC-associated events was more than double the long-term average while the total annual national number of events was about 25% above the long-term (1895–2008) average", and that "While there has been a recent increase in the number of landfalling U.S. hurricanes, the increase in TC-associated heavy events is much higher than would be expected from the pre-1994 association between the two". These findings led the IPCC AR6 to conclude that "there is medium confidence that anthropogenic forcing has contributed to observed heavy rainfall events over the USA associated with TCs and other regions with sufficient data coverage". This was omitted from the DOE report.

Going back to research conducted in the early 1950s (Riehl 1950; Kleinschmidt 1951), we have come to understand that TC wind speeds are bounded by the thermodynamic state of the ocean and atmosphere. This upper limit, called potential intensity, can be calculated from standard climate data in analyses and models, and when the peak intensity of individual observed TCs is divided by the potential intensity at the time and location the peak occurred, the results fall into a universal probability distribution (Emanuel 2000). This implies that a change in potential intensity will be reflected in the actual peak intensities of TCs, but has no implication for overall TC frequency. An increase in potential intensity should increase the proportion of high intensity TCs relative to all TCs. It can also be shown the vertical motion in TC cores is proportional to their intensity.

Simple calculations with single-column and global models indicate that increasing greenhouse gases will increase potential intensity (Emanuel 1987). Such an increase is indeed evident in reanalysis data (Bhatia et al. 2022; Studholme et al. 2021). Moreover, an increase in the proportion of TC observations that are at major hurricane (categories 3-5) intensity has been detected in satellite-based estimates of TC intensity that account for changing radiometer technology (Kossin et al. 2020). This is an example of a theoretical prediction supported by careful observational analysis. Once again, this work was discussed in AR6 but not mentioned in the DOE report. Instead, the report presents a non-peer-reviewed graphic of global TC frequencies (Figure 6.2.2, p. 49). This shows no statistically significant trends in either hurricanes or major hurricanes, but there *is* a statistically significant trend in their ratio, which is not mentioned in the DOE report. The theoretical prediction pertained to this last quantity, not to the other two. Indeed, throughout the DOE report there is an implied prediction that TC frequencies should increase with warming, whereas there has never been a robust scientific consensus about how TC frequency responds to climate change. In that sense, the DOE report sets up a strawman (that TC frequency should increase with warming) and knocks it down, while avoiding observational tests of actual scientific predictions (e.g. that TC rainfall extremes and the proportion of very intense TCs will increase).

Another theoretical prediction is that the rate of intensification of tropical cyclones should increase with global warming, and do so at a normalized rate faster than that of intensity itself (Emanuel 2017b; Bhatia et al. 2018). Such a trend has been detected in North Atlantic tropical cyclone intensification rates (Bhatia et al. 2019). This is important, as rapid intensification just prior to landfall can catch forecasters off guard and reduce the time window in which residents can prepare and evacuate.

4. Selective Quotation of AR6

Three quotations of AR6 are presented at the beginning of section 6.2 of the DOE report, p. 48:

> *1. There is low confidence in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021 p. 1585)*
>
> *2. It is likely that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is low confidence in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2023 SPM p. 9)*

3. A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows no trend in the frequency of U.S. landfall events. (IPCC 2021 p. 1585)

All three quotations pertain to what can be inferred from the historical record alone. An important context, that there is no consensus on what might happen to TC frequency, is not mentioned.

But IPCC reports use all available scientific information to assess climate risk, not just historical records. This is particularly important in the case of weather extremes, for which the historical record is usually too short to detect plausible trends, as fully acknowledged early in the DOE report.

Here is what Working Group I of AR6 said about historical tropical cyclone trends in their summary for policy makers (p. 9):

It is likely that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades, and it is very likely that the latitude where tropical cyclones in the western North Pacific reach their peak intensity has shifted northward; these changes cannot be explained by internal variability alone (medium confidence). There is low confidence in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. Event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (high confidence), but data limitations inhibit clear detection of past trends on the global scale.

Note that the trend in the latitude at which TCs reach peak intensity is passed over in the DOE report, as is the statement that attribution studies and physical understanding indicate, with high confidence, that human-induced climate change should increase TC-related rainfall.

On page 1519, Working Group 1 further notes that

The global frequency of TC rapid intensification events has likely increased over the past four decades.

There is no mention of this in the DOE report.

With regard to the future, AR6 states (p. 16) that

The proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence). {8.2, 11.4, 11.7, 11.9, Cross-Chapter Box 11.1, Box TS.6, TS.4.3.1} (Figure SPM.5, Figure SPM.6)

and, on p. 71,

There is high confidence that average peak TC wind speeds and the proportion of Category 4–5 TCs will increase with warming and that peak winds of the most intense TCs will increase.

These statements about future projections of TC hazards are missing from the DOE report.

5. Other omissions

The DOE report attributes multi-decadal oscillations of North Atlantic TC metrics to a putative Atlantic Multidecadal Oscillation. However, since the AR6 was finalized, new evidence has emerged pointing to anthropogenic sulfate aerosols as the source of the North Atlantic hurricane drought of the 1970s and 80s (Murakami 2022; Rousseau-Rizzi and Emanuel 2022). This had been suggested in earlier work (Booth et al. 2012; Dunstone et al. 2013; Mann and Emanuel 2006), but the calculated radiative forcing by sulfate aerosols alone could only account for about half the cooling of tropical North Atlantic sea surface temperatures. Sulfate aerosols of European origin have been shown to have weakened the African summer monsoon, drying soils there and leading the documented increase in African mineral dust lofting during this period (Prospero 2015). The addition of African mineral dust accounts for the missing radiative forcing over the tropical Atlantic (Rousseau-Rizzi and Emanuel 2022). This makes a difference to future projections of North Atlantic TC activity, since it is unlikely that high concentrations of sulfate will return.

The DOE report devotes one half of page 66 to tornadoes, and none to straight-line winds or to hail, which causes roughly twice as much damage as tornadoes in the U.S. In Figure 6.5.1 on p. 67 they present a non-peer-reviewed analysis of trend in U.S. tornado statistics. The upward trend in weak tornadoes from 1950 to 1990 is, rightly, dismissed as a consequence of more reporting, the advent of hand-held video cameras, etc. But the downward trend in violent tornadoes is given credence despite the rapidly changing technology for estimating tornadic winds during this period, including the advent of ground transportable Doppler radar. This appears to be an amateurish effort by scientists with little or no familiarity with tornadoes to produce their own analysis, dismissing upward trends while holding downward trends to be credible.

AR6 makes it clear that the detection of trends in small-scale events like severe convective storms is, at present, nearly impossible:

> *In nearly all regions, there is low confidence in changes in hail, ice storms, severe storms, dust storms, heavy snowfall, and avalanches, although this does not indicate that these CIDs [Climate Impact Drivers] will not be affected by climate change. For such CIDs, observations are often short-term or lack homogeneity, and models often do not have sufficient resolution or accurate parametrizations to adequately simulate them over climate change time scales.*

Yet AR6 presents an extensive discussion of what theory and models do say about likely trends in severe convective events, devoting a whole subsection (11.7.3) to the subject. While we can, at present, neither reliably detect nor explicitly model trends in severe convective storms, we can use our extensive knowledge of the large-scale conditions that conduce to such events to make some inferences about likely changes. According to AR6,

> *Climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe thunderstorms that combine tornadoes, hail, and winds (high confidence), but there is low confidence in the details of the projected increase.*

As with TCs, the DOE report ignores inferences from theory and models.

6. Summary

Among the more serious potential consequences of climate change are changes in the incidence of severe convective storms and tropical cyclones. Almost by definition, damaging storms are rare and historical records are generally not long enough or of high enough quality to reliably detect trends. The DOE report clearly recognizes this shortcoming, yet relies almost entirely on analysis of historical trends in extreme events to reach conclusions that are only partially and selectively in agreement with those of the far more comprehensive IPCC AR6, ignoring important evidence from theory and models reported therein or in subsequent peer-reviewed literature. They stress the finding that there are no statistically significant trends in, e.g., U.S. landfalling hurricane frequency, while not informing the reader that a) there was never a consensus prediction of such a trend and b) that plausible trends cannot be detected given the random noise and natural variability in the series. At the same time, they ignore more recent peer-reviewed literature as well as non-peer-reviewed data they themselves present that show an upward trend in the proportion of tropical cyclone intensity estimates that are of major hurricane intensity, a trend that *was* predicted. They do not directly address the AR6 finding that tropical cyclone rainfall is likely to increase, based on simple physics, or that TC intensification rates are likely to rise. These are serious omissions, as flooding is the main source of mortality and damage in tropical cyclones, and increasing intensification rates will shorten the time window for preparations and evacuation.

The DOE report gives scant attention to the problem of severe convective storms, which do more damage than tropical cyclones, both in the U.S. and worldwide. The report presents time series of both weak and violent U.S. tornadoes, dismissing the upward trend of the former as unreliable yet giving credence to the downward trend in the latter, despite large changes in reporting and measurement technology over the period. They do not address the problem of hail, which is twice as damaging as tornadoes in the U.S. As with tropical cyclones, they ignore theory- and model-based evidence of climate change effects on severe convective storms.

Secretary Wright commissioned the DOE report to "to encourage a more thoughtful and science-based conversation about climate change and energy." One presumes that by "more thoughtful" he meant in relation to hyped media reports. What better way to foster thoughtful, science-based discussion than to hear from a broad array of scientists who devote their professional lives to understanding climate? That is just what the IPCC reports accomplish. By selectively quoting from the latest such report, by refusing to consider theory or models, and by relying on short and often error-prone historical time series that the authors themselves recognize as not fit for purpose, the DOE is presenting a distorted view of the science of climate effects on extreme weather that is bound to mislead the public.

7. References

Arrhenius, S., 1896: On the influence of carbonic acid in the air upon the temperature of the ground. *Phil. Mag.;*, **41**, 237-276.

Arrhenius, S., 1906: Die vermutliche Ursache der Klimaschwankungen. *Meddelanden från K. Vetenskapsakademiens Nobelinstitut*, **Band1**.

Bhatia, K., G. Vecchi, H. Murakami, S. Underwood, and J. Kossin, 2018: Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model. *Journal of Climate*, **31**, 8281–8303, https://doi.org/10.1175/jcli-d-17-0898.1.

——, and Coauthors, 2022: A potential explanation for the global increase in tropical cyclone rapid intensification. *Nature Communications*, **13**, 6626, https://doi.org/10.1038/s41467-022-34321-6.

Bhatia, K. T., G. A. Vecchi, T. R. Knutson, H. Murakami, J. Kossin, K. W. Dixon, and C. E. Whitlock, 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, **10**, 635, https://doi.org/10.1038/s41467-019-08471-z.

Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, **484**, 228-U110, https://doi.org/10.1038/nature10946.

Dunstone, N. J., D. M. Smith, B. B. B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic aerosol forcing of Atlantic tropical storms. *Nat Geosci*, **6**, 534–539, https://doi.org/10.1038/Ngeo1854.

Emanuel, K., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483-485.

Emanuel, K., 2017a: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences*, https://doi.org/10.1073/pnas.1716222114.

Emanuel, K., 2017b: Will global warming make hurricane forecasting more difficult? *Bull. Amer. Meteor. Soc.*, **98**, 495–501.

Emanuel, K. A., 2000: A statistical analysis of tropical cyclone intensity. *Mon. Wea. Rev.*, **128**, 1139–1152.

Kleinschmidt, E., Jr., 1951: Grundlagen einer Theorie der tropischen Zyklonen. *Archiv fur Meteorologie, Geophysik und Bioklimatologie, Serie A*, **4**, 53–72.

Kossin, J. P., K. R. Knapp, T. L. Olander, and C. S. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences*, **117**, 11975–11980, https://doi.org/10.1073/pnas.1920849117.

Kunkel, K. E., D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2010: Recent increases in U.S. heavy precipitation associated with tropical cyclones. *Geophysical Research Letters*, **37**, https://doi.org/10.1029/2010GL045164.

Mann, M. E., and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *EOS*, **87**, 233–244.

Murakami, H., 2022: Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years. *Science Advances*, **8**, eabn9493, https://doi.org/10.1126/sciadv.abn9493.

National Research Council, 1979: *Carbon dioxide and climate: a scientific assessment*. The National Academies Press, https://doi.org/10.17226/12181.

van Oldenborgh, G. J., and Coauthors, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environ Res Lett*, **12**, 124009.

Prospero, J. M., 2015: Characterizing the temporal and spatial variability of African dust over the Atlantic. *DUST*, **24**, 68.

Riehl, H., 1950: A model of hurricane formation. *J. Appl. Phys.*, **21**, 917–925.

Risser, M. D., and M. F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44**, 12,457-12,464, https://doi.org/10.1002/2017GL075888.

Rousseau-Rizzi, R., and K. Emanuel, 2022: Natural and anthropogenic contributions to the hurricane drought of the 1970s–1980s. *Nature Communications*, **13**, 5074, https://doi.org/10.1038/s41467-022-32779-y.

Studholme, J., A. V. Fedorov, S. K. Gulev, K. Emanuel, and K. Hodges, 2021: Poleward expansion of tropical cyclone latitudes in warming climates. *Nature Geoscience*, 1–15, https://doi.org/10.1038/s41561-021-00859-1.

Trenberth, K. E., L. Cheng, P. Jacobs, Y. Zhang, and J. Fasullo, 2018: Hurricane Harvey Links to Ocean Heat Content and Climate Change Adaptation. *Earth's Future*, **6**, 730–744, https://doi.org/10.1029/2018EF000825.