CLIMATE CHANGE

What precipitation is extreme?

How extreme precipitation is defined affects the conclusions drawn about the way it changes with warming

By **Angeline G. Pendergrass**

A warmer atmosphere has more water vapor. Scientists have been trying to predict what this means for precipitation, but this is more complex and harder to model than temperature. One explanation has been that the intensity of extreme precipitation events will increase at a rate proportional to the increase in atmospheric moisture. But recent findings show that this explanation is too simplistic. There are many ways to define extreme precipitation, and the choice of definition affects how it responds to warming. Researchers must choose their definition of extreme precipitation with care and articulate it clearly, and users should consider how extreme precipitation is defined when interpreting analyses of its change with warming.

One way to quantify extreme precipitation change is to determine how much more intense an event becomes in a warmer climate. The conventional wisdom (*1*, *2*) is that the intensity of the most extreme events rises by 6 to 7% per degree of warming, which is also the rate of moisture increase (*3*). That is, moving toward progressively more extreme precipitation events, the rate of increase of individual events in response to warming approaches the rate of moisture increase. If the change of extreme precipitation intensity did indeed converge to the rate of moisture increase, then the magnitude of the change in extreme precipitation intensity would be independent of how extreme precipitation is defined.

But there are indications that extreme precipitation does not always change at the rate of moisture increase. Take, for example, the record-breaking rainfall associated with Hurricane Harvey, which led to devastating flooding in Houston, Texas, last year. Three groups have published attribution studies of Hurricane Harvey (*4*–*6*) and compared their results against the increase in moisture (*7*). All three studies found that climate change increased the intensity of the precipitation during this very extreme event by more than the increase in moisture. Studies of large-scale changes in precipitation also suggest that not all extreme precipitation events intensify at the rate of moisture increase (*8*–*11*).

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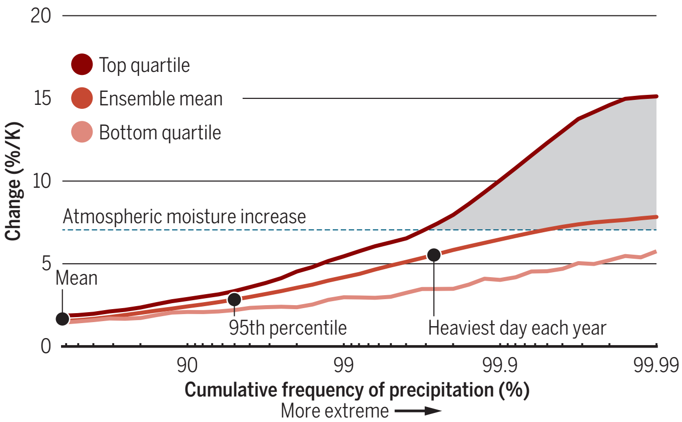
Extreme precipitation response to warming

The intensity of more extreme events (which are more intense and less frequent) increases more than the intensity of less extreme events in response to warming. The change in precipitation beyond levels of the cumulative frequency distribution of daily precipitation in the global mean in an ensemble of climate model simulations (*11*) is shown.



Definitions of extreme precipitation

The percentage of total precipitation classified as extreme depends strongly on the definition of extreme precipitation, as shown by this comparison of different definitions for two observing stations between 1978 and 2017. Also shown is the frequency beyond which 50% of precipitation falls. Data are from (*14*).

DEFINITION	SAN DIEGO, CA, US	TROMSØ, NORWAY
1 day	16%	3.0%
99th percentile	42%	9.5%
98.6 percentile	50%	
95th percentile	89%	32%
90.5 percentile		50%
90th percentile	99%	52%
Wet day 95th (≥1 mm/d)	23%	17%

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At least three mechanisms influence the change in precipitation intensity with warming. First, increasing moisture drives increases in the intensity of all precipitation events, if atmospheric circulation does not change. However, atmospheric circulation affects, and is in turn affected by, precipitation. This leads to two other mechanisms: Atmospheric stability increases with warming, weakening circulation and reducing the intensity of precipitation events. Also, latent heat release strengthens the storms that drive precipitation events in proportion to their intensity, amplifying the most extreme events by the largest amount.

Overall, changes in atmospheric circulation drive larger increases in more extreme precipitation events compared with less extreme ones. The most extreme events could increase at or above the rate of moisture increase. In climate model simulations, these tendencies are seen both in the tropics (*8*) and in mid-latitudes (*12*). The result is that not all extreme events change in the same way: There is no convergence to the rate of atmospheric moistening.

The variation in the magnitude of extreme precipitation change can be illustrated by examining the response of extreme precipitation to warming in climate model simulations (see the figure). We begin with the most extreme precipitation events (see the figure, right) and then expand the definition of "extreme" to include ever more moderate events, until all precipitation events are included. Eventually, the no-longer extreme precipitation will increase at the same rate as total precipitation. But, total precipitation changes more slowly than moisture because of the role of precipitation in the planetary energy budget (*2*). In order to maintain energy balance in the atmosphere, precipitation can increase only as much as radiative and sensible heat exchange with the surface. We should thus expect that for some sufficiently moderate definition of "extreme," extreme precipitation will increase at a rate below that of atmospheric moisture.

More precipitation falls in events that can be considered extreme than is often appreciated. The table lists the fraction of total precipitation falling in events considered extreme by various metrics at two observing stations: San Diego, California, where most precipitation falls in a small number of events, and Tromsø, Norway, where it rains very frequently, and precipitation is thus spread over many events.

One common definition of extreme precipitation is the 95th percentile of the cumulative frequency distribution of daily precipitation (including days with no precipitation)—that is, the top 5% of days in terms of their accumulated precipitation. In San Diego, almost 90% of precipitation falls above the 95th percentile. Even in Tromsø, more than half of precipitation falls in events above the all-day 90th percentile, which is sometimes used as a metric for extreme precipitation. But in San Diego, the degree of extreme beyond which half of all precipitation falls is striking: the 98.6th percentile, equivalent to the top 5.1 days each year. In both locations, the day with the most precipitation each year makes up a much smaller fraction of total precipitation. We might thus expect this measure to change with warming at a higher rate than total precipitation. For extreme precipitation to evade energetic requirements and increase faster than total precipitation, it can only constitute a small fraction of total precipitation.

"...how we define extreme precipitation affects the conclusions we draw about the way it changes."

The point at which precipitation events considered extreme by some definitions increase at a rate close to the total precipitation arrives sooner than might be expected. Moderate events increase more slowly than the rate of moistening, whereas the most extreme events increase as much or possibly faster. Uncertainty about changes in extreme precipitation is largest for the most extreme events (see the figure), particularly in the tropics. Meanwhile, there is often some definition for which extreme precipitation does change at the same rate as atmospheric moisture. Some studies explicitly address how the definition of extreme precipitation affects its rate of change with atmospheric warming (*9*), but many do not. Scaling changes of extreme precipitation to the rate of atmospheric moisture increase remains the default null hypothesis, regardless of how extreme precipitation is defined.

There are caveats. The magnitude of extreme precipitation change will vary with location and season (*10*). It will also vary with the time scale considered, the mechanisms driving the event, and other factors. In some places, no definition of extreme precipitation will follow the rate of moisture increase; this is, for example, the case in places affected by systematic shifts in the location of precipitating systems (such as those that find themselves in the newly expanded subtropical dry zones). There are also yet more ways to define extreme precipitation—for example, the increase in frequency of events above a certain threshold, or with only wet days (or wet hours) rather than all days (or all hours) (*13*). These definitions will be affected differently by changes in moisture and circulation.

The key implication is that how we define extreme precipitation affects the conclusions we draw about the way it changes. We should expect moderate precipitation events to change more slowly than the rate of moisture increase in the atmosphere. On the other hand, the most extreme events might increase at or above the rate of atmospheric moisture increase, as studies have indicated in the case of Hurricane Harvey. The decision of what definition of extreme precipitation to use is important when climate change information is carried into other areas, such as engineering, socioeconomic impacts, adaptation, and policy. The rate of moisture increase provides a starting point for understanding extreme precipitation change, but the whole story is more nuanced because of the complex relationship among precipitation extremes, atmospheric circulation, moisture, and warming. ■

REFERENCES AND NOTES

1. K. E. Trenberth, *Clim. Change* **42**, 327 (1999).
2. M. R. Allen, W. J. Ingram, *Nature* **419**, 224 (2002).
3. P. Pall, M. R. Allen, D. A. Stone, *Clim. Dyn.* **28**, 351 (2007).
4. M. D. Risser, M. F. Wehner, *Geophys. Res. Lett.* 10.1002/2017GL075888 (2017).
5. G. J. van Oldenborgh *et al.*, *Environ. Res. Lett.* **12**, 124009 (2017).
6. S.-Y. S. Wang, L. Zhao, J.-H. Yoon, P. Klotzbach, R. Gillies, *Environ. Res. Lett.* 10.1088/1748-9326/aabb85 (2018).
7. K. E. Trenberth *et al.*, *Nat. Clim. Change* **5**, 725 (2015).
8. A. G. Pendergrass, E. P. Gerber, *J. Clim.* **29** 10.1175/JCLI-D-16-0097.1 (2016).
9. A. F. Prein *et al.*, *Nat. Clim. Change* **7**, 48 (2017).
10. S. Pfahl *et al.*, *Nat. Clim. Change* **7**, 423 (2017).
11. A. G. Pendergrass, D. L. Hartmann, *J. Clim.* **27**, 8372 (2014).
12. P. A. O'Gorman, T. M. Merlis, M. S. Singh, *Q. J. R. Meteorol. Soc.* 10.1002/qj.3195 (2017).
13. C. Schär *et al.*, *Clim. Change* **137**, 201 (2016).
14. M. J. Menne *et al.*, *NOAA Natl. Clim. Data Center* 10.7289/V5D21VHZ (2012).

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QUANTUM MATERIALS

The expanding materials multiverse

Heat capacity and Raman experiments point to fractionalized excitations in a dipole liquid

By **Ben J. Powell**

High-energy physicists are limited to studying a single vacuum and its excitations, the particles of the standard model. For condensed-matter physicists, every new phase of matter brings a new "vacuum." Remarkably, the low-energy excitations of these new vacua can be very different from the individual electrons, protons, and neutrons that constitute the material. The materials multiverse contains universes where the particle-like excitations carry only a fraction of the elementary electronic charge (*1*), are magnetic monopoles (*2*), or are their own antiparticles (*3*). None of these properties have ever been observed in the particles found in free space. Often, emergent gauge fields accompany these "fractionalized" particles (*2*, *4*, *5*), just as electromagnetic gauge fields accompany charged particles. On page 1101 of this issue, Hassan *et al.* (*6*) provide a glimpse of the emergent behaviors of a putative new phase of matter, the dipole liquid. What particles live in this universe, and what new physics is found in this and neighboring parts of the multiverse?

Liquids and gases look the same everywhere, but the periodic arrays of atoms in crystals break translational and rotational symmetries. This broken symmetry leads directly to the important differences between a crystal and a fluid—for example, the crystal's rigidity (*7*). The differences between gases and liquids are more subtle. Particles move freely in a gas, like cars on the open road. In a liquid, the motion of particles is correlated—i.e., it depends on what other particles are doing, like city driving (see the figure). Continuing this analogy, a glass is like a traffic jam, and a crystal resembles a parking lot with every particle neatly in place.

Some phases of matter are easier to detect than others. In ferromagnets, the spins

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