analyse a 16- instead of 4-dimensional version of DICE-2007. This study separates the coefficient of relative risk aversion from the coefficient of relative intergenerational inequality aversion (that is, 3.07 and 0.67, whereas the values for DICE-2007 are both 1.45), and uses experts to calibrate the likelihood of each of five tipping points (reorganization of the Atlantic conveyor belt, disintegration of the Greenland Ice Sheet, collapse of the West Antarctic Ice Sheet, dieback of the Amazon rainforest and a more persistent El Niño regime) and how it depends on the state of the others[7]. It adds realism by allowing for slow and differential impacts of each catastrophe. Nevertheless, much bigger effects of tipping points are found: the optimal carbon price increases from US$15 to $116 per tCO_2. It is optimal to shut down carbon emissions by mid-century and cap temperature rise at 1.4 °C instead of 3 °C by 2100 in the baseline. In that case, there is only an 11% chance of crossing one or more tipping points by 2100 compared with a 46% chance in the baseline. A big part of the reason for the eightfold — rather than double — increase of the carbon price is due to using high relative risk aversion and low intergenerational inequality aversion coefficients. There are both positive and negative effects on the risk of crossing other tipping points after a tip, which is why the net effect is a modest increase in the expected optimal price of carbon from US$109 to $116 per tCO_2. However, some interactions in specific sample paths can have big effects on the expected price. The collapse of ice sheets might have already been crossed, increasing the risk of reorganization of the Atlantic conveyor belts, but this should nevertheless lead to intensified efforts to curb carbon emissions to cut the risk of other tipping points.

The more imminent risk of catastrophes at higher temperatures offers a better narrative than the usual approach that only considers costs at moderate degrees of temperature rise. It might encourage policymakers to finally take significant action to curb global warming. Such a change of discourse should also stimulate institutional investors to decarbonize their portfolios and avoid tail risks of climate catastrophes. Hedging strategies generate low-carbon portfolios that achieve the same return as the benchmark if there is no stepping up of climate policy but outperform the benchmark as soon as CO_2 is properly priced[8].

Future research is important. First, we need to know what can and should be done in terms of adaptation to prepare for potential calamities. This will probably involve precautionary saving, but also large-scale investment in water defences and other projects that weaken the impact of catastrophes. Second, research is needed to estimate the insurance society is willing to pay to limit the impact of catastrophes. One study finds that society is willing to pay a permanent tax of 7% if revenues are used to limit catastrophic losses to less than 15%[9]. Third, one needs to allow for substitution between renewable energy and fossil fuel and for green technical progress on optimal climate policy. Fourth, one must allow for anticipation effects resulting from future scarcity of fossil fuel on climate policy. Delayed policies lead to faster extraction of oil and gas before it becomes more expensive, thus increasing global warming and the risk of tipping (the so-called green paradox). Finally, climate catastrophes interact with non-climate catastrophes such as mega-virus pandemics, nuclear terrorists, bioterrorists, earthquakes or an asteroid hitting Earth. Cost–benefit analysis yields strange results as it is no longer necessarily optimal to prioritize averting the catastrophe with the largest benefit-cost ratio[10]. Policies associated with different catastrophes are therefore inextricably intertwined. ❐

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EXTREME PRECIPITATION

Increases all round

Globally, extreme rainfall is expected to increase with warming, but regional changes over land have been less certain. Now research shows that this intense precipitation has increased across both the wetter and the drier parts of the continents, and will continue to do so as global warming continues.

William Ingram

People, crops and cities cannot survive long without fresh water, which almost entirely originates from rain. But one can have too much of a good thing — our habit of living by sources of fresh water may be convenient, but it also increases the risk of flooding. Global average precipitation is expected to increase moderately with global warming[1,2], but nobody lives in the global average. It is extreme rain in a particular catchment that can have devastating consequences, so changes on smaller space- and timescales are important for planning and adaptation. Over the ocean, we expect the overall geographical pattern to follow a ‘wet gets wetter, dry gets dryer’ trend[2]. This means that net evaporation will increase where it already exceeds precipitation, whereas net precipitation will increase where it dominates at present. But over the continents, where most of the world’s population lives, it has been less clear to what extent this trend applies[2]. Writing in *Nature Climate Change*, Markus Donat and colleagues[3] show that observations and models agree in showing that extreme rain increases when averaged over either the drier or the wetter parts of the continents.

We confidently expect that the concentrations of atmospheric water vapour (which supplies the water for precipitation) will increase in rough proportion to the saturation concentrations at the Clausius–Clapeyron rate[1,2], that is, 6–7% per °C of warming. But we expect global average precipitation to increase at only about 2–3% per °C (ref. 1). This means that the atmospheric part of the hydrological cycle must slow with global warming: in some way the atmosphere must become less prone to rain. One way that this could happen is if rain increases at the Clausius–Clapeyron rate when it does fall, but falls less often, making precipitation events more extreme. This is what we typically see in GCMs (general circulation models), our most detailed and physically based models of the climate system[2]. However, the distribution of precipitation, particularly in the tropics and on smaller scales in space and time, is one of their weaker points[4]. Another point is that the heat released by the condensation of water itself tends to pull more moisture into a precipitating system. This suggests that intense rain might instead increase with warming at even higher rates than the Clausius–Clapeyron — perhaps twice as fast, as some observations for short timescales (minutes to hours) seem to show[5]. On the other hand, as the atmosphere's capacity to evaporate moisture from arid regions and to transport it away will increase at the Clausius–Clapeyron rate, arid regions are expected to become drier still, and it seemed plausible that this would reduce all precipitation (from light to heavy) in these regions[2].

Donat and colleagues[3] analyse the changes in observations of annual total and extreme (the most to fall on any single day in the year) precipitation over land for 1951–2010. To maximize the visibility of the climate change signal against the random weather noise, they average separately over the drier and the wetter parts of the continents. They find that the fraction of the year's rain that falls on the wettest day increases consistently with the Clausius–Clapeyron rate across both these regions. GCM simulations of the same period are consistent with these observations, and ones of the late twenty-first century (where the greater global warming signal again helps them distinguish it from noise) show that the trend continues. Therefore we can have some confidence that extreme precipitation risk will increase not only in wet regions but also in dry ones (which may be unprepared for such events).

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By deriving a robust and socially relevant result from a recently expanded observational dataset[6], this study reminds us how vital it is to continue making, sharing and recovering actual measurements of climate-monitoring quality, especially where they are currently sparse and where long series of data already exist. Although remote sensing (for example, satellite measurements and radar) provides far higher data volumes, and in GCMs researchers can quantify everything and carry out actual experiments, nothing can replace measuring the real world *in situ*. Although the volume of the dataset used here has greatly increased recently[6], its coverage remains poor in the tropics. Thus the conclusions of Donat *et al.* may not be valid in the tropics, precisely where the changes are likely to be greatest, where complex physical interactions make prediction hardest, and where the ecosystems and societies might be most sensitive to these changes. Also, with extreme rainfall data widely available only for the daily timescale, we cannot know how it will change on shorter and longer timescales, which each dominate flood risk in different places[7]. Given the intrinsic rarity of extreme events, these results do not tell us what will actually happen in any particular location, but rather how risks will change — which is precisely the information needed by emergency planners. Donat *et al.* show that although we can expect dry regions to get generally drier with global warming, we can still expect extreme rain to increase in these areas. ❐

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