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Key Points:
- The contribution of major greenhouse gas emitters to future temperature extremes is calculated
- Projected future extremes depend on current and near-future CO_2 emissions trajectories of the major emitters
- Major emitters' calculated contributions to future temperature extremes is reduced through emissions mitigation

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Assessing Contributions of Major Emitters' Paris-Era Decisions to Future Temperature Extremes

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Abstract The likelihood and severity of high-impact future temperature extremes can be reduced through climate change mitigation efforts. However, meeting the Paris Agreement warming limits requires notably stronger greenhouse gas emissions reduction efforts by major emitters than existing pledges. We examine the impact of Paris-era decision-making by the world's three largest greenhouse gas emitters (EU, USA, and China) on projected future extreme temperature events. Country-level contributions to the occurrence of future temperature extremes are calculated based on current emissions policies and sequential mitigation efforts, using a new metric called the Contribution to Excess Risk Ratio. We demonstrate the Contribution concept by applying it to extreme monthly temperature projections. In many regions, future extremes depend on the current and future carbon dioxide emissions reductions adopted by major emitters. By implementing stronger Paris-era climate pledges, major emitters can reduce the frequency of future extremes and their own calculated contributions to these temperature extremes.

Plain English Summary Temperature extremes can damage aspects of human society, infrastructure, and our ecosystems. The frequency, severity, and duration of high temperatures are increasing in some regions and are projected to continue increasing with further global temperature increases as greenhouse gas emissions rise. While the international Paris Agreement aims to limit warming through emissions reduction pledges, none of the major emitters has made commitments that are aligned with limiting warming to 2 °C. In this analysis, we examine the impact of the world's three largest greenhouse gas emitters' (EU, USA, and China) current and future decisions about carbon dioxide emissions on the occurrence of future extreme temperatures. We show that future extremes depend on the emissions decisions made by the major emitters. By implementing stronger climate pledges, major emitters can reduce the frequency of future extremes and their own calculated contributions to these temperature extremes.

1. Introduction

Increasing temperature extremes pose significant risks to human society, infrastructure, and ecosystems. The likelihood and severity of regional temperature extremes (Ciavarella et al., 2017) can be reduced through climate change mitigation efforts. The 2015 Paris Agreement on Climate Change (hereafter the ‘Paris Agreement’) commits to “Holding the increase in the global average temperature to less than 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to only 1.5°C above pre-industrial levels” (UNFCCC, 2016). Limiting warming to 1.5 °C, rather than 2 °C, is of substantial benefit for reducing the frequency of regional extreme temperatures in the future (e.g., Intergovernmental Panel on Climate Change [IPCC], 2018; King et al., 2017; Perkins-Kirkpatrick & Gibson, 2017).

While this effect on extreme weather and climate events is demonstrated in the scientific literature, the consequences of current decision-making on anthropogenic greenhouse gas (GHG) emissions on the severity of future climate change is not reflected in national climate mitigation commitments. Global carbon dioxide (CO_2) emissions grew in 2017 and 2018 and are projected to rise in 2019 (Jackson et al., 2018; Le Quéré et al., 2018). Existing climate pledges are estimated to result in a median global warming range of 2.6–3.1 °C above pre-industrial levels (Rogelj et al., 2016). Indeed, no “major emitter can at present claim

Table 1
Greenhouse Gas Emission Storylines for G3 for Future Warming (Johnston, 2016)

Storyline	EU	USA	China
1.5	62% below 1990 levels by 2030	60% below 2005 levels by 2030	Peak by 2025, then reduce at 5% per year
2	47% below 1990 levels by 2030	45% below 2005 levels by 2030	Peak by 2025, then reduce at 2% per year
3 (NDCs[a])	40% below 1990 levels by 2030	26% below 2005 levels by 2030	Peak emissions at 2030, lower the carbon intensity of GDP by 60–65% below 2005 levels by 2030
End-of-century (EP2)	Breaching NDC	Breaching NDC	Breaching NDC

[a] Current NDC commitments (outlined above) are projected to result in a mean global warming of 2.6–3.1 °C above pre-industrial levels (Rogelj et al., 2016).

to show the necessary leadership in the concerted effort of avoiding warming of 2°C" (Meinshausen et al., 2015). Meeting the Paris warming limits requires notably stronger CO_2 emissions reduction efforts.

The effect of current CO_2 emissions decision-making on future extreme events is calculable. Here, for the first time, we quantify emitter-level contributions to the frequency of future extremes based on *current* emissions reduction policies. We assess the impact of current and near-future ("Paris-era") decisions by emitters on future temperature extremes using the concept of Storylines. To do this, we

1. Define a set of idealized Storylines (summarized in Table 1) that outline emitters' current Nationally Determined Contributions (NDCs; nonbinding pledges) and the required emissions reduction targets for major emitters that are necessary to limit global mean warming to Paris Agreement thresholds (Figure 1)
2. Calculate changes in risk of excess extreme monthly temperature events in various worlds defined by increments of mean warming (e.g., 2 or 3 °C above pre-industrial and end-of-century warming) compared to 1.5 °C world.
3. Quantify country-level contributions to the changing risk of excess future extreme temperatures based on Storylines.

The usefulness of these calculated emitter-level contributions to future climate extremes is manifold, providing knowledge for discussions on collective action under the global stocktake and to impel

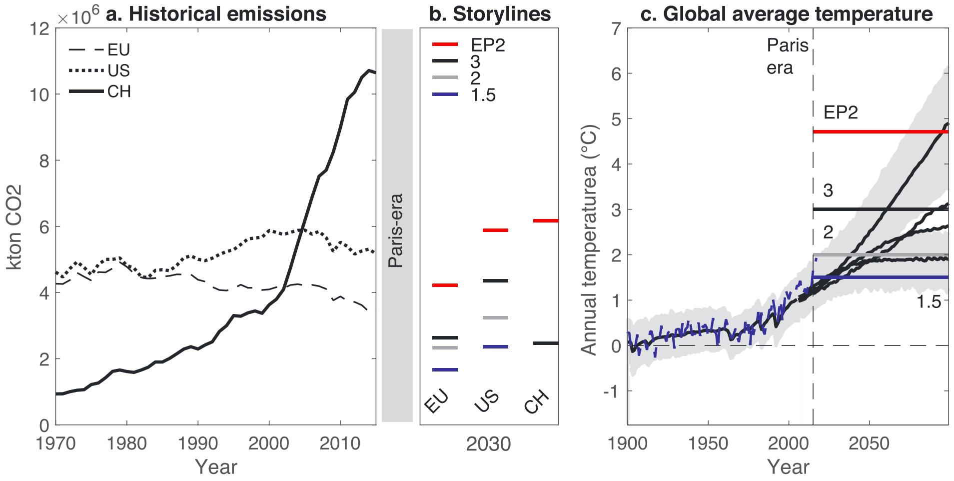

Figure 1. Summary of CO_2 emissions, emissions Storylines, and observed and projected 21st century global mean warming. (a) Historical emissions of CO_2 from 1970 to 2015 for the EU28, USA, and China (totals of fossil fuel use and industrial processes from Emissions Database for Global Atmospheric Research (EDGAR, 2017). (b) Indications of 2030 emissions required for the G3 for Storylines of various levels of global mean warming. Emissions reductions relative to the historical that are less significant than the red horizontal EP2 bar are likely to result in RCP8.5 end of century warming. Indications of 2030 emissions for China for Storylines 2 and 3 are not shown as these are transient pledges (see Table 1). (c) Global annual average temperatures from observations (blue dashed line) and multimodel mean values from historical and RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Solid black lines show ensemble mean values for each experiment, and gray envelopes show the 5th to 95th percentile model range for the historical and RCP2.6 and RCP8.5 scenarios. Horizontal lines show key warming thresholds above pre-industrial.

governments to strengthen pledges. We also speculate that such quantifications may usefully inform climate mitigation efforts by providing knowledge about the culpability of different governments in causing future extremes.

2. Establishing Climate Leadership Through Paris Pledges

The concept of leadership is central to international climate policy. The Paris Agreement stipulates that developed country Parties “shall continue taking the lead by undertaking economy wide absolute emission reduction targets … with the view to achieving the purpose of [the] Agreement” (UNFCCC, 2016). At the subsequent Katowice Conference of Parties (CoP) in 2018, China's role as a major emitter and leader, despite its developing status, was emphasized. Climate mitigation action taken by a smaller group of benchmark nations, including China, motivates other nations to follow (Schwerhoff, 2016). Conversely, minimal, delayed or obstructive action by a major emitting country may prompt a free-rider effect in which other countries reduce their efforts. Therefore, ambitious action from the largest emitters is necessary for the overall success of the Paris Agreement.

Post-2020 Paris Agreement pledges are voluntary, self-determined, and nonbinding. Parties are legally required to submit a new pledge every 5 years that constitute “a progression over time.” The agreement is vulnerable to political volatility, which can weaken or negate, rather than strengthen, prior pledges, as evident in the announced withdrawal of the United States from the agreement in 2017 (Kemp, 2017a, 2017ab). We quantify the contributions of “benchmark countries” (G3: China [CH], the United States [US], and the EU28 [EU]; Meinshausen et al., 2015) to future extremes. We focus on just these major emitters as they have the greatest capability to lead on limiting global mean warming (Meinshausen et al., 2015) and, hence, the severity of projected future extreme temperatures, although we note that this a simplified application of the leadership concept. We also focus on CO_2 rather than the full suite of GHG emissions. This focal point of our analysis on the major emitters does not, however, negate the importance of emissions made by other countries.

3. Calculating Changing Excess Future Extreme Temperatures

Future extremes are investigated using observations and climate models (see supporting information section S1). Observations of current temperature records are derived from CRUTEM4 (Jones et al., 2012). Future extremes are explored in Coupled Model Intercomparison Phase 5 models (Taylor et al., 2012) using Representative Concentration Pathway (RCP) experiments RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (tas variable; see supporting information Table S1). Baseline extreme temperatures are first calculated for each analyzed land-based IPCC regions (IPCC, 2012). Values are calculated for 17 land-based IPCC regions with sufficient observational coverage, and a sufficient number of the Coupled Model Intercomparison Phase 5 models accurately capture the observed variability (supporting information Tables S2 and S3). Calculated temperatures are the multimodel mean T_{95} (95th percentile values of monthly mean temperatures) values under 1.5 °C of global mean warming. This is a comparatively moderate definition of extremes (Barriopedro et al., 2011; Fischer et al., 2009), rather than using rarer, high-impact extremes. This moderate definition allows the robust diagnosis of changes in the frequency and intensity of events that are potentially detrimental to environmental and human systems.

Next, we determine simulated *excess* future extremes, which are extremes associated with mean warming above the baseline 1.5 °C global warming (see supporting information Figure S1). For example, 2 °C excess events are calculated as T_{95} under 2 °C of global mean warming (decadal-average temperatures 2 ± 0.2 °C warmer than the equivalent model realizations pre-industrial climatology). Heat events are calculated for various levels of the 21st century global mean warming, relative to the same pre-industrial climatology:

1. T_{95}_15: Baseline warming events calculated as multimodel mean T_{95} under 1.5 °C of global mean warming
2. T_{95}_2: 2 °C events calculated as multimodel mean T_{95} under 2 °C of global mean warming
3. T_{95}_3: 3 °C events calculated as multimodel mean T_{95} under 3 °C of global mean warming
4. T_{95}_EP2: Endpoint (end-of-century) warming events calculated as multimodel mean T_{95} in RCP8.5 experiment for years 2090–2100

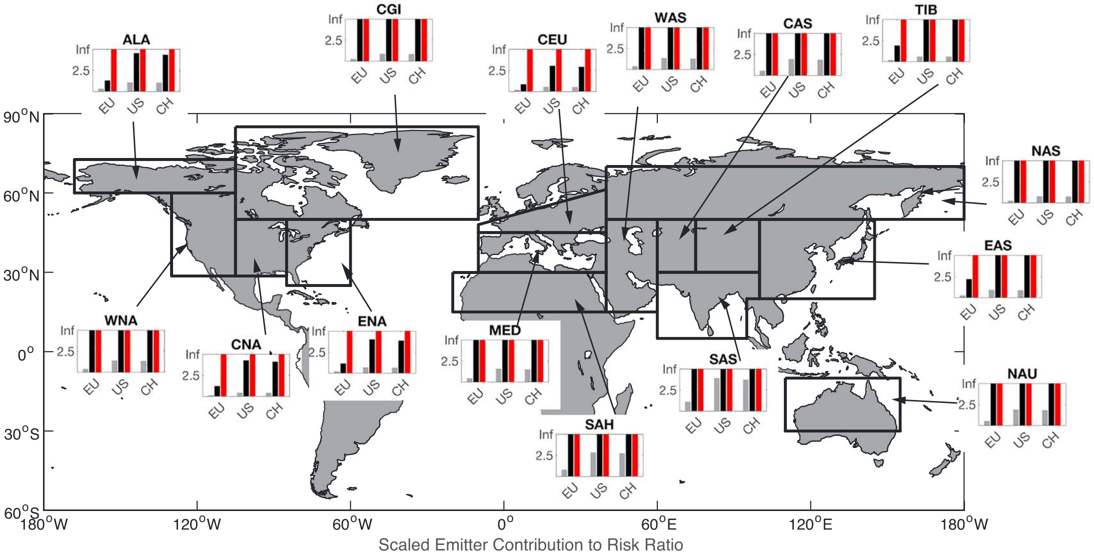

Figure 2. Range of Contribution Excess Risk Ratio values for future extremes for G3 emitters, where a per capita emissions scaling factor is applied. For each emitter (EU, USA, and China), the Contribution is shown for each analyzed AR5 region for exceeding T_{95} values under 2 (gray bars) and 3 °C (black bars) of global mean warming and EP2 end-of-century warming (red bars). Where the Excess Risk Ratio value is infinite, Contributions are indicated as such. ALA = Alaska/N.W. Canada; CGI = Canada/Greenland/Iceland; WAS = West Asia; CAS = Central Asia; CEU = Central Europe.

Global mean warming worlds of 1.5, 2, and 3 °C are defined following King et al. (2017) as decades when decadal-average temperatures are within ±0.2 °C of these thresholds warmer than the equivalent model realizations pre-industrial climatology. Extreme temperatures are described as "excess," relative to baseline 1.5 °C warming above pre-industrial (T_{95}_15). Excess events are calculated as the frequency of events above the multimodel mean T_{95} under 2 °C of global mean warming minus the frequency of such events at 1.5 °C of warming. We also determined the standard deviations of the simulated T_{95} values.

Second, changes in the risk of these excess future extremes occurring are calculated using Risk Ratios. The widely used Risk Ratio (or related Fraction of Attributable Risk [FAR]) method (Herring et al., 2018) is a quantification of the change in the probability of an extreme that can be attributed to a particular cause (i.e., anthropogenic GHG forcings). For the first time, we extend this probabilistic approach to quantify the occurrence of *excess* extreme events above specific global mean warming levels, demonstrating, for example, the changing probability of temperature extremes in the 2 °C, compared to the 1.5 °C worlds. This is the *Excess* Risk Ratio, calculated as follows:

$$\text{Excess RR}_2 = \frac{P_2}{P_{1.5}} \tag{1}$$

where $P_{1.5}$ denotes the probability of a T_{95}_2 event occurring under baseline 1.5 °C of global mean warming and P_2 occurring under 2 °C of global mean warming. Equivalent RR values are calculated for 3 °C worlds and the end of the 21st century (EP2) warming as assessments of changes in the risk of regional temperature extremes with increasing levels of global mean warming (supporting information Table S4).

As sequentially warmer global thresholds are breached, significantly higher T_{95} values are simulated, with the largest temperature anomalies occurring in the high northern latitude regions (Figure 2). Furthermore, Excess RR values increase with mean warming levels (from 0 to infinite or FAR values of 1), indicating the far greater likelihood of excess heat events occurring in warmer worlds. In a 3 °C world, Risk Ratio values are predominantly infinite, meaning that T_{95} values of this magnitude are not simulated if aggressive GHG reductions are implemented, showing the clear value of current and future mitigation efforts to reduce the frequency of future extreme temperatures.

4. Quantifying Emitter-Level Contributions to Future Extremes

Previous studies allocate historical responsibility for or assess observed climate change based on identifying national cumulative historical contributions to global warming (Otto et al., 2017; Raupach et al., 2014).

Although cumulative historical emissions are important for driving climatic change and should not be entirely overlooked, for several key reasons, we focus here on current emissions and the importance of current decision-making. First, while historic emissions are highly inequitable, climate change is not a purely historic issue and the seriousness of current emissions inequities must also be considered. Second, while prior to 1990's first IPCC assessment, GHG emissions were made in scientific and political naivety of future impacts (Page, 2008), Paris-era pledges are informed by a wealth of evidence and are made cognisant of both the foreseeable consequences of enhanced warming and the actions of others. Finally, while GHGs have varying residence times and enduring impacts on the climate system, peak warming occurs about a decade after carbon dioxide emission (Ricke & Caldeira, 2014), and hence current and near future emissions are important for future extremes. For these key reasons, we focus on the climate outcomes of emitters' current decisions about near-term emissions, using the Storyline approach connecting CO_2 emissions pledges with warming levels, while also noting that cumulative historical emissions are an important consideration for temperature changes. Because we focus on current and near-term emissions targets, we also calculate changes in *excess* temperatures above baseline warming under 1.5 °C of global mean warming.

To assess contributions to these extreme events, we calculate a scaling factor that is applied to each emitter's recent CO_2 emissions proportion (see supporting information section S4). The G3 are accountable for the change in risk of future extreme climate events based solely on their *own* decision-making around Storyline, regardless of the actions of the other countries. Our simplified approach is grounded in the combined concepts of both leadership and sovereign responsibility, whereby leading emitters have the responsibility for climate mitigation action, in order to reduce global emissions and to motivate other nations to follow. The occurrence of specific climate events may, however, depends on combinations of emitters' adopted Storylines, and a more complex approach of leadership and assessment of contributions would incorporate multilateral assessments of contributions to events. We also note that calculating a scaling factor based on an emitter's share of cumulative, rather than current, emissions would give differing Contribution values. Our calculation of proportion also does not consider transient emissions trajectories, although likely provides low-range estimates of contributions given reported recent emissions increases for USA and China (Jackson et al.,2018

The population-adjusted emissions scaling factor is determined to measure the level of emissions inequality —emitters that have higher current per capita emissions compared to the global average citizen are penalized accordingly (see supporting information for description). Next, the Contribution to Excess Risk Ratio value (or simply Contribution) is calculated. This value integrates an estimate of the Excess RRs for future heat events, leadership behavior based on Storylines, and the scaled proportion of recent global emissions (EDGAR, 2017) and population (The World Bank, 2015). A per capita emissions scaling factor is first determined as a quantification of the level of inequality emissions, whereby countries that have higher per capita emissions compared to the global average citizen are penalized. This scaling factor is calculated as follows:

$$\text{Per capita Emissions Scaling Factor} =$$

$$\frac{\text{Country}'\text{s Emissions}\%\text{of Global Total}}{\text{Country}'\text{s Population}\%\text{of Global Total}}/\text{Global Average Emissions per Person} \tag{2}$$

Countries (or emitters) with higher per capita emissions (e.g., the USA) than the global average are penalized relative to countries (or emitters) with low per capita emissions (see supporting information Table S5). This per capita perspective to assessing contribution is based on each emitter's current share of the total population and their recent emissions proportion.

Furthermore, while we argue that per capita-based assessments of emissions are most useful for evaluating contributions to extremes (see also Davis & Caldeira, 2010), we also apply an absolute (nonpopulation-weighted) approach as a comparison to the per capita perspective (supporting information Figure S2), where the emitter Contribution value depends only on the emitter's absolute emissions percentage (supporting information Figure S3). Differing values are determined when applying a methodology scaled only by emissions proportions and not adjusted by population, including a greater Contribution to Excess Risk Ratios value for China.

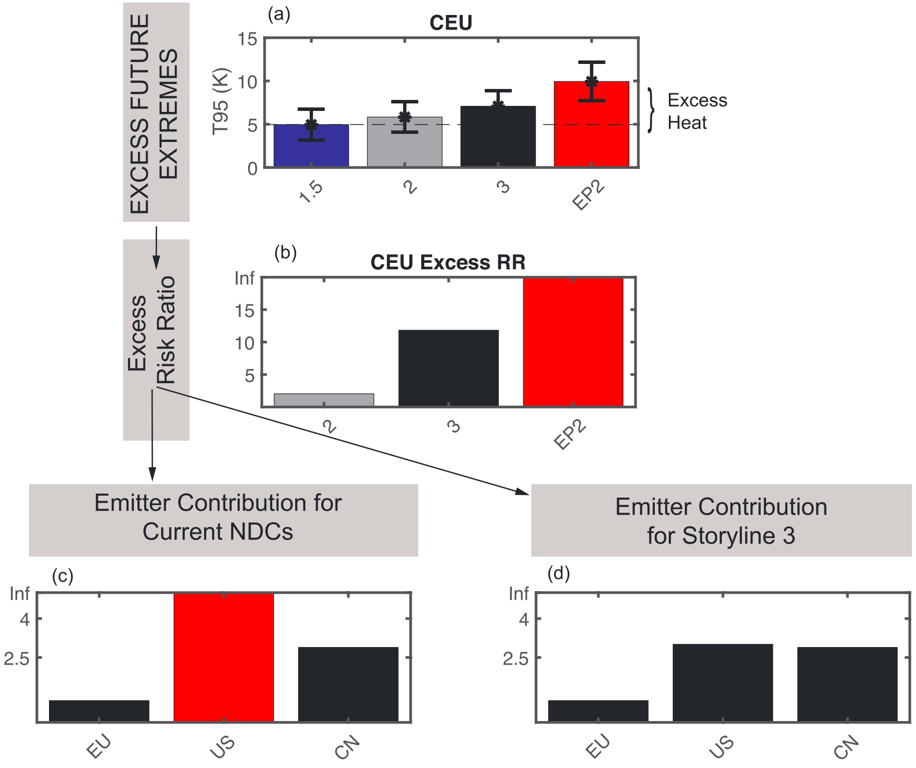

Figure 3. Application of Contribution to Excess Risk Ratio (RR) concept to the Central Europe (CEU) case study. (a) Excess Future Extreme values are calculated for various levels of global mean warming for Central Europe. (b) Excess Risk Ratio values are calculated as the change in probability of an event occurring in a world with global mean warming thresholds (2 or 3 °C of global mean warming have been breached or EP2 values), compared to 1.5 °C. (c) Contributions to Excess Risk Ratio values are calculated for each emitter (EU, USA, and China) based on current Nationally Determined Contributions (NDCs; nonbinding pledges), noting that the US is unlikely to meet this pledge (Kemp, 2017a, 2017ab). Emissions are scaled using a per capita factor that quantifies the level of inequality in emissions, relative to global average citizen (see supporting information). Bars are color-coded based on Storylines associated with emitters' current NDCs, as indicated in panel (b) (black for 3 °C of global mean warming and red for EP2). (d) Contribution values calculated for each emitter (EU, USA, and China) based on Storyline 3.

The Contribution approach is demonstrated by applying this concept to a case study for Central Europe (CEU; Figure 3), where a hypothetical future extreme occurs that exceeds T_{95}_3. Contribution values are presented for Storylines based on the G3's current NDCs or breaching these for the US (Kemp, 2017a, 2017ab). We calculate a Contribution value to this future extreme heat in Central Europe for EU28 as a one time attributable increase in event risk and China as 2.9 times attributable increase in event risk. As the US is unlikely to meet its NDC, the Excess Risk Ratio associated with this Storyline is infinite. The interpretation of such an RR is clearly more difficult than for a finite value and particularly in terms of assessing a fractional contribution to such an increase in risk. Hence, we describe this as a virtually certain contribution of the US to an increased probability of such extremes occurring. The emitter Contribution values can be reduced for each major emitter if a lower emissions Storyline is adopted compared to their current pledges. If Storyline 3 is adopted, the Central Europe Contribution value, the US is a three times attributable increase in risk (Figure 3).

Similar results are determined for other midlatitude and high-latitude regions (see supporting information Figures S3 and S4 for East North America region). Conversely, in several tropical and subtropical regions, such as South Asia and the Sahara, the assessed contribution to future extremes does not depend on current pledges and decision-making. These regions demonstrate rapid regional warming relative to variability with increasing background temperatures. Hence, the Excess Risk Ratio and Contribution values calculated for each emitter are largely consistent across Storylines.

5. Implications of Contributions for Climate Leadership and Equity

The Contribution to Excess Risk Ratio provides an assessment of individual emitter-level contributions to the frequency of future extremes based on current emissions policies and emissions contributions. This approach demonstrates that current actions can have a calculable effect on future climate events. While we limit our Contribution analysis to the G3, it could feasibly and fairly be extended to the other 44 developed country parties impelled to lead on climate action, in addition to analyzing high emitting developing countries. Contributions to future extremes could be calculated, for example, for Australia, which is not on track to meet its Paris pledges (Climate Action Tracker, 2019). In addition, broader application of this approach could consider greater complexity around the location in which emissions occurs, such as emissions from China based on the production of consumer goods for export elsewhere. Further analysis of Contributions to future extremes could be calculated by using more elaborate Storylines based on time-evolving emissions trajectories for each emitter. This more sophisticated approach would allow each emitter's attributable contributions to be isolated and an independent FAR or RR value determined.

This contribution-based quantification approach could also be applied to a broader suite of extremes, such as hydrological extremes. The impacts of future extreme weather and climate events such as those rivaling the 2017 Hurricanes Irma or Maria, or the severe 2015 heatwave in southern India (Ratnam et al., 2016), could be disaggregated into contributions by major emitters based on their current climate policies using the Contribution to Excess Risk Ratio approach. These event types may provide cases where the highest emitting countries provide compensation for climate change impacts through existing mechanisms for loss and damage (Verchick, 2018).

However, we highlight that application of this approach to other extremes requires rigorous model evaluation in the first instance. We also note that the Contribution values presented here demonstrate a concept for the first time: they are based on specific, hypothetical future events calculated in a suite of climate models, with one conceptualization of climate leadership. The precise values of Contributions would change if different emissions and populations data sets were used, different extreme event definitions were applied, or different conceptualizations of leadership and contributions were implemented, including analysis of cumulative emissions. Hence, these specific values should not be applied directly to observed extremes as absolute determinations of emitter contributions without expanded analyses.

Our simplified quantification demonstrates that the contributions of the highest emitters to future extremes in many regions increase in proportion to their adopted pledges and hence also demonstrates the multiple benefits in implementing ambitious reductions. For these major greenhouse emitters, benefits include demonstrating leadership (a key climate policy concept) and reducing their own contributions to future extreme climate events that may also limit liability to domestic litigation. Arguably, greater benefits emerge for low emitting countries: climate leadership by emitters most significantly benefits countries that are least responsible for, and most vulnerable to, climate change (Althor et al., 2016). By committing to lower warming Storylines, major emitters can reduce the likelihood of future extremes in less developed and lower emitting nations.

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