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Changing Climate and Weather

Evidence from Attribution Science

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The levels of scientific evidence in terms of the chain of causality, from anthropogenic climate forcings to local effects on weather and hydrology, impacts affecting societies and loss and damage, are very different. For the first step, from emitters to emissions and concentration, our understanding is very good and we have an inventory of emissions (Chapter 2 in this volume). For the second step, from concentrations to long-term climate change, our understanding with respect to global mean temperature is also very good (Haustein et al. 2017); more patchy for rainfall (Chapter 2 in this volume); and for regional temperatures, the evidence is becoming increasingly strong. The third step in the chain of causality, that is, from global warming to individual weather and climate-related events, is now possible and has been the focus of event attribution studies, but only a handful of such studies currently exist for India. This scientific development now also makes the last step possible, namely, attributing damages and losses from extreme weather to

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climate change, but at this point in time, applications have been restricted to a couple of European cities (for example, Mitchell et al. 2016; Schaller et al. 2016).

Being able to more completely understand this causality chain from emissions to localized impacts is crucial and allows for a true assessment of changing risks on the spatial scales (cities and countries rather than continents) decisions are made. Recent publications (for example, Haustein et al. 2017) on the attribution of global mean temperature have analysed, very carefully, the uncertainty in our understanding of the attribution of global mean temperature stemming from a choice of models used and, in particular, from the fact that observations of temperatures at the end of the nineteenth and the beginning of the twentieth centuries are less accurate than today.

After taking all possible sources of uncertainty into account, the finding of this analysis and similar publications is that the observed warming is, with very high confidence, attributable to anthropogenic greenhouse gas (GHG) emissions and that this attributable warming is already at 1°C. This highlights the very high confidence we have in the causal relationship between emissions and global mean temperature, and that at the current rate, the political goal of 1.5 degrees global mean temperature increase is only a few years away.

Anthropogenic GHG emission is, however, not the only driver of climatological change, natural variability as well as other man-made drivers like aerosol pollution play a particularly large role on regional scales. At the same time, drivers outside the climate system, like river management, sewage water systems, and the sheer number of people in harm's way, determine to a large degree the impacts of changing weather and climate. If we, as a society, want to understand what climate change has meant for India so far and estimate how risks are changing, then it is important to disentangle these drivers in order to understand what the adaptation options are. In other words, we need to attribute observed changes to drivers of change and answer the question of whether and to what extent anthropogenic climate change alters the risk of extreme weather.

While the science of attributing extreme weather events is new, it is rapidly growing and over 170 studies have been published worldwide, most of which in the last two years (Schiermeier 2018). These studies are heavily biased towards regions in Europe and Australia and the types of events attributed are often heatwaves and extreme rainfall events, which are not necessarily the most damaging. However, increasingly, the large number of studies available allows for drawing some general conclusions. In particular for heatwaves, where more than 50 individual events have been analysed, we see very clearly that almost all cases show an increase in the severity and likelihood of the event because of climate change. In two-thirds of all studies, climate change has been found to play a significant role. While not representing every extreme event that has happened in the last years, these studies do not provide a full inventory of climate change impacts. However, it is within this context that the extreme events that have been analysed for India need to be understood. In India, at the moment, there are only three published attribution studies on particular extreme events: record-breaking heat in Rajasthan in 2016; a large-scale heatwave in Andhra Pradesh in 2015; and massive flooding in Chennai in 2015. These studies, while focusing on some of the most damaging events in the last few years, described in detail in this chapter, give a good overview of the methods used in this emerging science and highlight some challenges particular to the Indian context, they do not represent how climate change manifests in India.

Therefore, before introducing the emerging science of extreme event attribution, we will first review the detection and attribution of long-term climate change over India and identify hot spots of regional climate change. We close the chapter with a discussion on the implications of these new scientific developments on policy, politics, and disaster risk reduction, and provide an outlook on where the frontier of the science is likely to move in the coming years.

Long-Term Climate Change

When we think of climate change, we usually associate it with gradual changes in the mean state of the climate—typically over many decades. The global mean temperature, for example, is known to vary due to El Niño events and volcanic eruptions, but has nevertheless seen an increasing trend over the last few decades (Bindoff et al. 2013). On a regional or local level, variations in temperature and rainfall can be much larger in amplitude, caused by oscillations unique to that place (Chapter 2 in this volume). Any changes resulting from natural factors (such as volcanoes and solar output changes) and human-caused factors (such as GHGs, aerosols, and changes in land use and land cover) are on top of this. Therefore, separating what is natural from what is caused by human activity is hard. The purpose of detection and attribution studies is to be able to separate what is natural from what is human-induced.

The Intergovernmental Panel on Climate Change (IPCC) defines 'detection' as the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. 'Attribution' of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. Attribution studies typically rely on a 'fingerprint'—a typical pattern of change—that is unique to the different drivers of climate change. The fingerprint of, say, GHGs is very different from that resulting from aerosol emissions, which is in turn different from those resulting from volcanoes or solar output changes. These fingerprints are deduced from climate models and one statistically analyses the observations to find the strength of each of the patterns. Fundamental to this is the confidence that climate models represent the known science accurately so that the fingerprints may be physically realistic. This involves rigorous validation of models against observations to ensure that they represent the relevant processes and phenomena accurately.

On a global scale, changes in temperature, humidity, and ocean heat content—all indicators of fundamental changes in the earth's energy balance—have been attributed to anthropogenic causes (Barnett et al. 2005; Bindoff et al. 2013; Gleckler et al. 2012; Jones, Stott, and Christidis 2013; Santer et al. 2007). At regional scales, the human influence on surface temperature has been documented over China and New Zealand, and also in those areas of the Pacific and Atlantic Oceans where tropical cyclones form (Dean and Stott 2009; Gillett, Stott, and Santer 2008; Knutson, Zeng, and Wittenberg 2013; Santer et al. 2006; Xu et al. 2015)

There have been numerous studies that have documented changes in the climate over India, as seen in Chapter 2 in this volume. Very few of these have focused on attributing the causes of these changes. A recent work by Dileepkumar, AchutaRao, and Arulalan (2018) finds that annual mean temperatures over India can be attributed to anthropogenic causes. The GHGs contribute to a larger warming trend than observed, which is then tempered by the effect of other anthropogenic forcings that tend to exert a cooling effect (such as aerosols and land use–land cover changes). Among the homogeneous temperature zones (classified by Indian Institute of Tropical Meteorology [IITM], Pune, based on climatological features), Western Himalayas, west coast, and east coast regions reveal robust warming across seasons attributable to anthropogenic forcings. Sonali and Kumar (2016) have analysed changes in maximum and minimum temperatures (T_{max} and T_{min}) during the second half of the twentieth century and could detect a significant change in T_{min} but could not attribute it to any specific causative factor.

With increased temperatures, the water vapour holding capacity of the atmosphere increases at about 7 per cent/°C of warming (Allen and Ingram 2002). This results in larger rainfall totals—much of it coming down as heavy downpours. Mukherjee et al. (2018) have examined observed precipitation records over India and found that the annual maximum rainfall during the period 1979–2015 has increased over much of India, with increases more prominent in southern India than in the north, especially since 1982. Using multiple climate model simulations with and without anthropogenic forcing, they find a clear anthropogenic influence on the frequency of extreme precipitation events. A natural place to look for signals of increased rainfall is in the river basins, which act as integrators of the precipitation. The Mahanadi River basin has been an area of intense research to study the anthropogenic influence from a hydrological perspective. Mondal and Mujumdar (2012) attempted a formal detection and attribution analysis to study the changes in the observed monsoon precipitation and stream flow in the rain-fed Mahanadi River basin. They found that the decreases observed in stream flow and precipitation over the second-half of the twentieth century are consistent with those expected from anthropogenic emissions of GHGs. However, their results were sensitive to which climate model was used, leading to a less than robust conclusion on the anthropogenic influence.

Extreme Event Attribution

Extreme downpours, heatwaves, and droughts have happened and disrupted public life throughout India's history. Nowadays, with the rising awareness that increasing global mean temperatures will, on average, lead to an increase in the number of heatwaves and more heavy rainfall events, one of the first questions the media, decision makers, and knowledge brokers and politicians ask whenever an extreme weather event takes place is: what the role of climate change was in the particular event?

Two common assumptions have routinely been provided as answers: (i) we are living in a changing climate, so all weather is affected by climate change; and (ii) individual weather events cannot be attributed to anthropogenic climate change. While the former is trivially true and provides no information on whether and to what extent the risk of such an event occurring has changed, the latter is wrong. Scientists are now able to assess how and to what extent the frequency and magnitude of individual types of extreme weather and climate-related events is changing due to human-induced climate change. The method of how to do this is simple in its concept, but complex in its execution. As every extreme weather event is ultimately unique and always the result of a combination of external drivers (solar radiation, volcanoes, GHGs), natural and human-induced, as well as internal climate variability and noise (day-to-day weather conditions), to say with certainty that an event could not have occurred without anthropogenic influence is impossible. It is, however, possible to assess how a particular external driver, namely, GHGs in the atmosphere resulting from burning fossil fuels, alters the probability of an extreme event occurring. To answer the question whether climate change has altered the likelihood of an extreme event to occur, one needs to assess the likelihood of that event in a climate with today's GHG concentration (called the factual or actual climate) and the likelihood in a climate without man-made climate change (called the counterfactual climate). Comparing these two likelihoods gives the role of climate change.

Applying this approach is now possible for an increasing number of extreme weather events. The possible outcomes of an event attribution study are, thus, probabilistic assessments of changing hazards.

In principle, there are two ways in which climate change can affect weather. In a warming world with increasing average temperature, we also expect an increase in extreme temperatures, and thus more and hotter heatwaves and a decrease in cold waves. A warmer atmosphere can also hold more water vapour than a colder one, we therefore expect, on average, more extreme rainfall. However, climate change does not only have this so-called thermodynamic (that is, warming) effect on the climate, but a changing composition of the atmosphere also affects the atmospheric circulation (the so-called dynamics), including the monsoon circulation and where and when tropical cyclones develop. Both effects can work in the same direction and thus increase the change in likelihood of an event more than would be expected from one effect alone, or they can act in the opposite direction and cancel each other out, or one effect can be much stronger than the other. Therefore, every attribution study has a priori four possible outcomes: (i) the event could have been made more likely because of anthropogenic climate change; (ii) it could have been made less likely; (iii) there is no detectable change in the likelihood or magnitude of an event occurring from anthropogenic climate change; or (iv) with current understanding and available climate simulations, it is not possible to robustly assess the role of external drivers in the event.

The approach was introduced by Allen (2003), and subsequently applied to a few European events before 2012 (Stone and Allen 2005; Stott, Stone, and Allen 2004). From 2012 onwards, the science of extreme event attribution has emerged as a field of climate research in its own right (Herring et al. 2014, 2015, 2016, 2018; Peterson et al. 2013a and 2013b), with the first set of attribution studies on extreme weather events in India published in 2016, attributing the floods in Chennai in 2015 (van Oldenborgh et al. 2016) and the heatwave in Andhra Pradesh in the same year (Wehner et al. 2016). A third event attribution study focusing on an event in India has been published in 2018, assessing the role of climate change in the record-breaking extreme temperature in Phalodi in 2016 (van Oldenborgh et al. 2018). The role of climate change is different in these three events and hence, the results are different. The findings of the Andhra Pradesh heatwave study match what we expect on a global average in a warming climate (Chapter 2 in this volume), where a strong increase in the likelihood of the heatwave to occur is found. We, therefore, use this study to introduce the method of event attribution in more detail, followed by a discussion of the floods in Chennai and the heatwave in Phalodi.

Heatwave in Andhra Pradesh

The main concept behind the probabilistic approach is an assessment of possible weather events of the type of event of interest (for example, a heatwave in Andhra Pradesh, Telangana, and Odisha in the pre-monsoon season of 2015) under present-day climate conditions, and possible weather under counterfactual climate conditions as they would have been without human-induced climate change. Figure 3.1

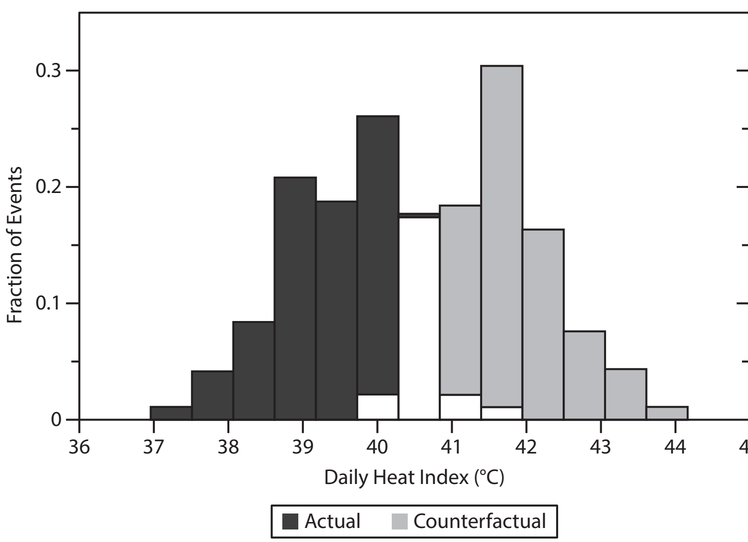

Figure 3.1 Histograms of Possible Daily Maximum Heat Index in Andhra Pradesh for Counterfactual (black) and Actual (light grey) Simulations of May 2015
Source: Adapted from Wehner et al. (2016).

shows an example of the heatwave in Hyderabad in 2015, where the light grey histogram represents possible heat in May in the present-day (actual) climate and the black histogram depicts the distribution of possible heat in May in the counterfactual world. In both worlds, the occurrence frequency of the extreme event can now be calculated and compared. For example, a heat index of 42 would be a relatively frequent event (expected to occur every other year) in the present-day climate, but rather rare (expected to occur once in 50 years) in the counterfactual world. Comparing these two likelihoods of 0.5 and 0.02 would mean that human-induced climate change has made the event 25 times more likely. Wehner et al. (2016) found that human-induced climate change increased the likelihood of a heatwave, like the one observed in Andhra Pradesh, occurring by more than 1,200 per cent, that is, the heatwave was made an order of magnitude (which is more than 10 times) more likely.

While the approach in principle is straightforward, there are different methodologies of estimating possible weather and the likelihood of occurrence of an extreme weather event. Due to the fact that we only have a very limited number of observations of weather events in the present day and no observations of the counterfactual world, event attribution always depends on climate and weather simulations; these can be based on observed or reanalysis data and statistical modelling (for example, van Oldenborgh 2007) or climate model simulations (for example, Lewis and Karoly 2013 and Pall et al. 2011). Each method has advantages and disadvantages, and both observations and climate models are imperfect. Therefore, the most robust estimates of the role of human-induced climate change can be obtained by combining different methodologies (National Academies of Sciences, Engineering, and Medicine 2016). While straightforward in principle—the need for the availability of high-quality data and large ensembles of high-resolution climate model simulation, as well as the fact that these simulations need to be thoroughly evaluated in each individual case—extreme event attribution studies in practice are quite elaborate. In the case of Andhra Pradesh, observations and models aligned and the attribution result is an increase in the risk of heat, and hence what one would expect a priori in a warming world. This is not the case for the Chennai flooding and the heat in Phalodi.

Flooding in Chennai

The first step of every event attribution study relating to a high-impact event is to identify what happened from a meteorological point of view. In the case of flooding, for example, it is often not a priori clear whether a localized, extreme one-day event caused the flood, or whether it was a comparably less extreme event but at the end of a very wet season, and whether the rainfall in the area of the floods was the main cause or whether precipitation further upstream needs to be taken into account as well. Having identified the heaviest one-day rainfall in the region in more than a century as the primary driver behind the flooding, extreme one-day precipitation in the area encompassing 10–15°N, 79.5–81°E was taken as the definition of the event. There will always be a trade-off between what climate models can reliably be expected to simulate and what caused the impact on the ground. Using this definition to assess possible extreme rainfall with and without climate change in statistical modelling and two different climate models, the study found no significant change in the likelihood of the event occurring. Figure 3.2 (between pages 326 and 327) shows the result from one of the climate models, depicted as return time of the event in three different climate model simulations: the year 2015 as observed (red); the year 2015 as it might have been without anthropogenic climate change (blue); and in the current climate in the years before 2015 (green). The overlapping error bars show that the change in likelihood is not significant.

This may seem a surprising result given what we expect in a warming world, but we might be seeing a case of dynamics and thermodynamics working in opposite directions, thus cancelling each other out overall. In other regions of the world, methods have been applied to disentangle these two effects (for example, Vautard et al. 2016). Alternatively, it could be that drivers other than GHGs, such as aerosols, play a role, or the fact that sea surface temperatures in the Bay of Bengal, which are known to influence rainfall, have not increased substantially with global warming. The result highlights that event attribution is clearly different from estimating trends and that the influence of climate change on weather can locally be very different. This fact is highlighted even more by the analysis of heat in Phalodi.

Extreme Heat in Phalodi, Rajasthan

In 2016 in Rajasthan, the city of Phalodi set a new maximum temperature record for India as it hit 51°C on 19 May 2016. In this case, the event definition was therefore taken as the hottest day of the year (TXx) at the point of Phalodi (grid point closest to the city in climate models). For the model evaluation, observed trends of maximum temperature over India were compared with the trends simulated by models, with the result that the state-of-the-art model simulations that provide the basis for the IPCC fifth assessment report (Coupled Model Intercomparison Project Phase 5 [CMIP5], Taylor, Stouffer, and Meehl 2012) simulate very different trends than the ones observed.

A regional climate model (HadRM3P, Massey et al. 2015) performed better and was included in the analysis. The attribution analysis was thus performed by simulating possible extreme heat in Phalodi, in factual and counterfactual climates, using statistical modelling and observations and the regional climate model. The authors found that the observation-based methodology did not show an increase in the likelihood of maximum temperature, whereas the purely model-based methodology showed a small increase that was, however, not statistically significant. This result is in contrast to the attribution study on the heatwave in Andhra Pradesh (Wehner et al. 2016) and in contrast to attribution of long-term temperature changes in India, discussed earlier. This makes it likely that the effect of anthropogenic climate change may be masked by other external drivers, like aerosols, or local effects, like an increased use of irrigation or other land-use changes. The event attribution study on the heatwave in Phalodi thus resulted in the fourth category of possible outcomes, as without further investigation it is not possible to give a robust result.

While this is not the result one hopes for in an event attribution study, an unclear result like this, however, does not mean that the study was not useful to understand the impact of anthropogenic climate change on heat extremes in India. First, the results show that, in particular locally, drivers other than GHGs have a strong impact on heat. Second, estimating the return time of the event in today's climate, which was more than 40 years in the case of Phalodi heat, is useful information in itself.

Event attribution is an emerging science and currently comprises a very small number of studies globally and over India, in particular. The studies that do exist, however, already show that the impacts of climate change are locally very different, and also differ from event to event. Not all extreme events are being made worse by climate change, while others become orders of magnitude more likely. Thus, the methodology of event attribution provides vital information for adaptation decisions as well as understanding present-day risks.

Discussion

We have discussed the enormous scientific progress that has been made in recent years in understanding not only how emissions affect global temperatures (Chapter 2 in this volume) but also how global temperatures affect regional climate and extreme weather events. The number of studies is still small, but the science has advanced within the last few years to now provide the tools that would allow the development of a more comprehensive overview of what the impacts of global anthropogenic emissions are across India. The last step in this chain of causality, from meteorology and hydrology to impacts on people and assets and loss and damage, has been explored in a handful of studies outside of India (Mitchell et al. 2016; Schaller et al. 2016), and while in these studies a significant increase in mortality and flooded properties, respectively, has been attributed to anthropogenic climate change, damages and losses of life crucially depend on the vulnerability and exposure. For example, in a city like Ahmedabad that has a heat action plan, excess mortality due to heat could be orders of magnitude lesser than in cities without an action plan (Knowlton et al. 2014).

The levels of scientific evidence for mitigation and adaptation are still different, but the gap has begun to close. These differing levels, however, have consequences on the basis of policy decisions on mitigation, adaptation, loss and damage, and disaster risk management. With respect to mitigation, while the exact carbon budget to limit global warming to 1.5°C or 2°C is uncertain, the fact that global emissions need to reach zero within this century is certain, and thus mitigation questions are more political, moral, and economic than scientific. In terms of adaptation, however, the scientific evidence is more uncertain for regional changes in temperature and precipitation—in particular for localized and extreme events. It is these scales of cities and municipalities where adaptation takes place. With the rapid development of the science of attributing extreme weather events to anthropogenic climate change in the last few years and the application of traditional detection and attribution methodologies on a regional scale, it is now increasingly possible to assess the role of anthropogenic climate change on scales relevant for risk management and adaptation planning.

As the examples across the world show (for example, Herring et al. 2016), attribution assessments are relatively straightforward for some kinds of events, while others represent the current boundary of the rapidly evolving field. What type of climate and weather events belong in which category depends not only on the event itself but also on data availability and understanding of local meteorology. In particular, in comparatively data-poor regions and for more complex events like droughts, uncertainties are still rather high.

At the same time, it is at these kinds of places and events where climate change and development challenges meet and are at risk to be played against each other. Recent extreme weather events have been associated with poor harvests, water shortages, and forced migration in communities struck by floods, droughts, and tropical cyclones. Stories, photographs, and videos of this destruction have frequently been used as evidence of the impacts of anthropogenic climate change; for example, by journalists, campaigners, and researchers in the climate adaptation and development/aid community (for example, blogs and newspapers[1]). Such coverage implies that global warming is making these extreme weather events more frequent and intense, and that for every damaging event climate change is to blame. Examples discussed here show that this is not always the case, and incorrect attribution stemming from misunderstanding or for political reasons will, in the long term, prohibit spending sparse resources on adapting to those kinds of impacts where climate change

[1] Some examples are Gsottbauer and Gampfer (2014), Goldenberg (2014), Saño (2013), and Wojewoda (2014).

is really a game changer. The findings from the very limited body of event attribution literature in India show that climate change is not a major player in two of the three events. This highlights the importance of taking other drivers of extreme weather into account in decision making.

However, at the same time, while long-term predictions cannot provide the only guide to adaptation planning, attribution results need to be understood across timescales. Even though today a heatwave in Phalodi has not been made more likely due to climate change, this will likely change in the future when the climate signal surpasses the masking drivers. Model simulations of the likelihood of the 2016 heatwave occurring in a world of 1.5°C and 2°C higher global mean temperatures indicate a doubling and fivefold increase, respectively (Otto et al. 2018).

In conclusion, to interpret these findings from the attribution literature in India, three things are important: first, the sample of India studies to date is small and has to be read with the broader global literature which finds that global warming plays a substantial role in the majority of extreme events worldwide. With a broader range of India studies, the overall picture might well look different. Second, whether and to what extent the overall risk of an extreme event is changing is only partly a question of what happens with the hazard. Vulnerability and the number of people and assets in harm's way determine, to a large degree, losses and damages of extreme events. Last, event attribution is very powerful because it applies on the scales decisions are made and where people feel the impacts of changing risks. Analysing events that have already happened is concrete and resonates much better with people than abstract future information. However, in order to make the right decisions for the future, attribution assessments and climate projections need to be combined. The scientific development of event attribution has made it possible but, for India, this now needs to be implemented.

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