Chapter 17

Synthesizing impacts of extreme weather events across systems

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Abstract

This chapter discusses synthesis assessments of the impacts of extreme weather across multiple types of impacts. It includes discussion of the motivation for such assessments, challenges in performing syntheses related to extremes, and possible methods for assembling a synthesis. The focus is on the detection and attribution of impacts during the past half-century, but implications for predictions of future changes in risk are also discussed. The only synthesis assessment of past impacts related to extreme weather is reviewed, noting

that its shortcomings can only be overcome through further developments in a number of areas including monitoring and process understanding.

17.1. A reason for concern

In 1992, the nations of Earth agreed to limit "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" according to the prescriptions of the United Nations Framework Convention on Climate Change (UNFCCC) [United Nations, 1992]. The meaning of "dangerous" was not specifically defined, but it was made clear that action should be taken so as "to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". More recently, countries participating in the UNFCCC process noted "the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events..." [United Nations, 2015]. In doing so, the countries recognised that "adverse effects of climate change" will impose "loss and damage", but remained silent on whether such loss and damage might be "dangerous". To highlight the distinction, consider the hypothetical situation in which anthropogenic climate change inflicts damage to the property of one person on the planet. That damage may not be considered dangerous to society (although of course it might to the individual concerned!). If damage is inflicted on the property of a sizeable fraction of the world's property owners, on the other hand, that may result in a dangerous situation for the world's insurance industry, economic stability, food security, or political stability. Hence, whatever might ultimately be designated as “dangerous”, it will need to be informed by global monitoring that synthesizes across regions and across natural, managed, and human systems.

This chapter is concerned with possibilities and challenges of syntheses that might inform the UNFCCC process (and hopefully other national and international activities) with specific respect to adverse effects inflicted by extreme weather events. Why the focus on extreme weather? Does it matter whether impacts result as a consequence of extreme weather rather than of other manifestations of anthropogenic climate change? If that is your paradigm for judging dangerousness, then yes.

In 2001, the Intergovernmental Panel on Climate Change (IPCC), tasked with assessing current understanding of anthropogenic climate change in order to inform the UNFCCC process, identified five “reasons for concern” (RFCs) each “consistent with a paradigm that can be used... to help determine what level of climate change is dangerous” [Smith et al., 2001]. These reasons for concern have continued to provide synthesizing structure more recently [Smith et al., 2009, Oppenheimer et al., 2014, Cramer et al., 2014]. One of these reasons for concern is the relationship between anthropogenic climate change and risks associated with extreme weather events. The rationale for its consideration is that much contemporary risk management focuses on reducing exposure and vulnerabilty to, and increasing resilience against, natural disasters. Infrastructure is designed to withstand certain thresholds of extreme weather, and insurance is purchased as a hedge against damage from uncertain but plausible extreme weather. Thus one possible lens for defining “dangerous” is through the definition implicit in current design specifications and in what is considered affordable levels of insurance: in other words, through risks associated with extreme weather.

This chapter will focus on the detection and attribution of recent impacts, that is evaluating the combined evidence from monitoring and system understanding, including their comparison, in order to document how anthropogenic emissions have already affected various aspects of human, managed, and natural systems around the world via extreme weather. A benefit of the focus on detection and attribution is that it highlights the role of monitoring. Implications for predicting future changes in risk will be discussed at the end. The chapter consists of three further sections. The next section will examine various steps involved in generating a synthesis assessment, particularly focusing on challenges. The third section with then review the single existing synthesis assessment of past changes in risk associated with extreme weather, with the final section describing implications for predicting future extreme-weather-related risk.

17.2. Of truths and trivialities

17.2.1. Philosophy versus practice

Niels Bohr used to say that it was the task of science to reduce deep truths to trivialities [Pais, 1991]. When it comes to informing climate policy, however, the opposite might be more a more useful dictum. A substantial component of current disagreement over the impacts associated with extreme weather events comes from a lack of clarity over what is meant by impacts of extreme weather events. This means that trivialities about natural hazards are often taken as truths about impacts of climate change. But the truth is a much more complicated amalgam of weather hazard, policy, economics, community organisation, and just plain luck. Understanding this truth will be easier if we clarify how trivialities might be informative.

17.2.2. Weather extremes or impact extremes?

We will start first with the distinction between weather and impacts (of weather). While the distinction is generally commonly understood for long-term impacts of long-term climate changes, this is not the case with extremes. Extreme weather is often confused with natural hazards. For instance, in its review titled "Attribution of extreme weather events in the context of climate change", the U.S. National Academy of Sciences in fact considered non-geological natural hazards including floods and wildfires [National Academies of Sciences, Engineering, and Medicine, 2016]. However in the most recent IPCC Assessment Report, floods and wildfires are considered to occur outside of the climate system, in the hydrological and ecological systems respectively [Settele et al., 2014, Cramer et al., 2014].

In this chapter we will distinguish between "extreme weather events" and, for lack of a better term [Cramer et al., 2014], "extreme impact events". We will consider an "extreme weather event" to be any event in the climate system that is episodic in nature and is far from average in some standard climatological measure. "Far from average" is ill-defined, but we may consider fairly mundane mid-latitude storms even if they are not all that rare. An "impact event" is something like a flood (hydrological event), wildfire (ecological event), pest outbreak (agricultural event), or stockmarket crash (economic event), also being episodic and far from average, but occurring outside of the climate system.

Why care about this syntax. Just as an extreme weather event need not necessarily result in an extreme impact event, an extreme impact event may happen regardless of what the weather is doing. Note also that an extreme weather event (or series thereof) may have long-term consequences beyond an immediate impact due to destruction of infrastructure. Is it more appropriate then to focus on weather events or impact events? It depends on the purpose. For instance, while Cramer et al. [2014] generally considered their remit to focus on impact events, the assessment with regards to the extremes RFC was explicitly focused on weather events. This chapter is motivated by the extremes RFC, so we will focus on extreme weather.

17.2.3. Detection and attribution

This chapter uses detection and attribution as a framing, and so we should clarify a few points about it before continuing further, even if they have little to do with extremes or synthesizing per se. Detection and attribution is a term used to describe the process of comparing predictions of what should have happened in the past and observations of what has actually happened, in order to develop a comprehensive documentation of cause and effect [Hegerl et al., 2010, Stone et al., 2013]. The predictions should be made based on some understanding of how the relevant systems operate, perhaps based on explicit numerical modelling of the component processes or through extrapolation of empirical relationships. Importantly, the demand on monitoring and modelling is high, such that conclusions are supported by a full wealth of information. However, the flip side is that confident conclusions are not always possible for any of a variety of reasons, including that a specific impact may not have been monitored. Hence, while “very high confidence of a major role of climate change” should be considered a definitive statement on what has happened and why, “very low confidence” does not necessarily mean the inverse [Hansen and Cramer, 2015].

17.2.4. Building an evidence base

The first step in any synthesis is to have data and conclusions to synthesize. In the context of detection and attribution, we are particularly keen for observations of recent impacts. However, comprehensive monitoring of climate change impacts is still mostly an aspiration. Some particular types of “impact events” may have reasonable long-term monitoring, but the explicit documentation of the link to extreme weather events is rare. For instance, wildfires have been well documented for decades in many countries, but the connection between those fires and extreme weather has not been well documented. A notable exception is bleaching and mortality of warm water corals [Cramer et al., 2014].

In some subsequent analyses in this chapter we will use the Storm Events Database, Version 3.0 (https://www.ncdc.noaa.gov/stormevents/, downloaded 24 May 2018), to our knowledge a unique documentation of extreme weather and its impacts. This database is produced by the U.S. National Oceanic and Atmospheric Administration to document the occurrence of extreme weather events and their effects over the United States of America. Coverage depends on the type of weather event, with the tornado record starting earliest in January 1950. Data include the type of weather event, the county in which it occurred, the intensity of the event, and quantified impacts. We exclude Alaska and U.S. dependendent territories (e.g. Guam, Puerto Rico, and the U.S. Virgin Islands) from analyses here because of incomplete records or complications from changes in county/burrough boundaries. It is important to note that this product is not advertised as being a reliable documentation of trends in extreme weather and their impacts over the past 68 years. We will consider possible issues relating to that later in this section. Nevertheless, the product's focus on extreme weather events, and its documentation of the weather type, location, and impacts, makes it ideal for the demonstrative analyses to be conducted in this chapter.

We will also make use, indirectly, of a second resource, that being published literature that was assessed as part of the chapter on "Detection and Attribution of Observed Impacts" in the IPCC Fifth Assessment Report [Cramer et al., 2014]. This will be used as part of an examination of how that chapter performed an assessment concerning the "Risks associated with extreme weather events" RFC (their section 18.6.4) and how that assessment was synthesized across systems in Oppenheimer et al. [2014], including how they managed to surmount or circumvent challenges, and how their approach has limitations. Other synthesis approaches will also be mentioned, but as yet they have not been applied to the specific topic of the impacts of extreme weather.

17.2.5. Cause and effect

Understanding cause and effect is the specific goal of detection and attribution, but some understanding is also needed for meaningful prediction of future changes in risk. It also has specific importance when interpreting an IPCC RFC: we are interested in the effect of human interference with the climate system, not on whether risks will grow simply in line with population or some other contributing factor. We examine this point here because, ultimately, we are considering synthesis across these sorts of studies.

Figure 17.1 shows a simple way of diagnosing the contributors to the year-to-year variability and long-term trends of two impacts of tornadoes over the United States of America. The black lines indicate direct injuries to humans and direct human deaths attributed to tornadoes over the 1950-2017 period according to the NOAA database. Also show are other coloured lines (other than red) that indicate variations in various factors that may contribute to these variations and trends, all adjusted to the same scale as the historical impact data: the tornado frequency (count of segments, which counts twice if an individual tornado crosses a county boundary or touches down twice); the tornado intensity (approximated by the ratio of the counts of “F4” over “F1” intensity tornadoes); the national human population (for the states included in the analysis); and the projection of the spatial pattern of tornado incidence onto human population (labeled “population migration” in the figure label, but also affected by shifts in tornado location). A multiple linear regression of observed impacts onto these four driving factors is shown in red.

The regression is dominated by the tornado intensity index for both impacts. Visually, the intensity peaks in 1953, 1965, and 1974 closely match the injury and death peaks in those years. However, the decline in injuries since 1980, and the lack of a long-term trend in deaths, is not matched by the large(r) decline in intensity, which is mainly compensated for by the long-term trends in event frequency and (in a nonsensical negative sense) by population. Note though that the long-term behaviour of the impacts and hazard data should be treated with caution, because of long-term changes in reporting practice and technology [Gall et al., 2009]. For example, the widespread deployment of weather radar in the early 1990s corresponds to an increase in event counts; if radar increased the detection rate of weaker tornadoes, that would also have induced a downward shift in our intensity measure.

There are, however, some broad conclusions we can still take from this analysis. First, tornado intensity is the dominant factor influencing year-to-year variations in injuries and fatality risk. Second, year-to-year causal relationships may not be the major determinant of long-term trends in risk: at the very least, population has little short-term variability but could have doubled the impacts over this period. Finally, the missing driving factor in these plots, namely vulnerability, has likely decreased substantially over this period: given that suspected biases in the underlying data might have induced a bias toward increasing trends, that population has approximately doubled, and that there is no upward trend in either impact, it stands to reason that a decrease in vulnerability has also played a role.

17.2.6. Finding a common currency

The two tornado impact analyses above are quite restricted in the type of impact, with a very specific metric. Under the ethical and judicial standards of the United States, all deaths are equivalent, making it a natural metric. Counts of injuries is a less clear-cut metric, however, because some injuries (a cut, say) may not be considered as serious as others (amputation, perhaps). So alternative injury measures could be plausible. In effect, we have already started a limited synthesis in that analysis. But if we want to synthesize across multiple types of impacts, then the requirement for a common metric becomes a bigger challenge. A starting point might be money, considering that so much of our lives is spent using it as a universal currency. But can we put a monetary value on a species going extinct though? Or on various aspects of livelihoods and culture?

A partial way around this challenge is to use a qualitative measure of relative change instead of a quantitative metric [Smith et al., 2001, 2009, Oppenheimer et al., 2014, Cramer et al., 2014]. For instance, in their synthesis assessment of the detection and attribution of changes in risk associated with extreme weather, Cramer et al. [2014] only synthesized across like systems (e.g. bleaching/stress/-mortality of warm water corals) when assigning a level of confidence to the evaluation of whether observed climate trends had played a major or minor role in an observed change. Hence, their summary statement highlighted "*High-temperature spells have impacted one system with high confidence (coral reefs), indicating Risks Associated with Extreme Weather Events. Elsewhere, extreme events have caused increasing impacts and economic losses, but there is only low confidence in attribution to climate change for these.*" but included no cross-system synthesis. However, these system-specific conclusions were then aggregated into a past-through-to-future assessment of the qualitative change in risk by Oppenheimer et al. [2014]. The main advantage of qualitative measures of relative change for synthesizing across systems is that they can be performed in a way that might be more robust to modification of the weightings across systems, especially if accompanied by some overall assessment of confidence. However, the trade-off is a lack of transparency over technical details that may be important.

An alternative approach is to convert results of individual studies into a binary metric, such as "predictions consistent with observations" versus "predictions inconsistent with observations" [Rosenzweig et al., 2007, 2008, Savo et al., 2016]. For predictions of future impacts, a possible binary metric would be "damaging" versus "not damaging". With some loss of information

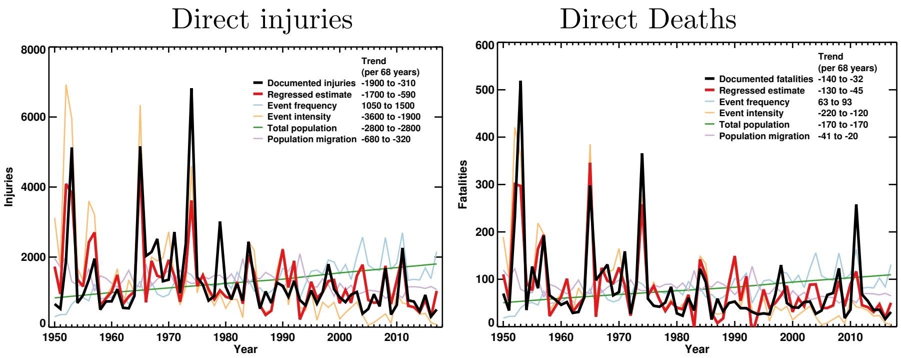

Figure 17.1: **Annual variations in impacts from tornadoes over the United States of America during 1950-2017.**

Documented impacts are shown in black. Tornado frequency and a measure of average tornado intensity (the ratio of the frequencies of F-scale 4 to F-scale 1 tornadoes) are also plotted as measures of the climate hazard, while the total U.S. population and the spatial projection of tornado frequency onto population (at the county scale) are plotted as measures of exposure [Manson et al., 2017]. A regression of the documented impacts against the measures of hazard and exposure is plotted in red. The uncertainty ranges of the contributed trends from the various regressed measures of hazard and exposure are estimated by removing the linear least-squares trends from all regressed time series, resampling the residuals using 1000 bootstrap samples, adding the linear trends back to these samples, calculating their linear trends, and then taking the 5-95th percentile range of the trends. All time series are scaled to the same units as the documented impact data. Tornado data are from the NOAA Storm Events Database (https://www.ncdc.noaa.gov/stormevents/).

about severity, this approach can in practice produce a single synthesis measure. However, it has several important assumptions [Stone et al., 2013]. Most importantly, by assuming that each unit of study (for which a binary result is assigned) is equivalently important, it is still assigning value. Such an approach has yet to be applied specifically to impacts related to extreme weather.

17.2.7. The arithmetic of synthesis

There are two possible dimensions in which one can conduct a synthesis analysis: horizontally, across like systems; or vertically, along the causitive chain. Figure 17.2 shows a simple example from Cramer et al. [2014] in which both dimensions were explicitly invoked in developing a synthesis conclusion of the detection and attribution of "increased erosion of Arctic coasts". Vertically, synthesis assessments of individual steps in the causal chain, from "decreasing Arctic sea ice cover in summer" through "lack of sea ice protection from wind storms" were used to build the final assessment.

Alternatively, the final assessment can be seen as the horizontal synthesis across multiple like systems, in this case across the Arctic regions of Asia, Alaska, and Canada. While the various causitive steps of the regional assessments were not listed in the published report, they were necessarily implicit in the development of the regional assessments; similarly the various Arctic-wide assessments were developed from regional information. Thus in fact this figure should appear more as a grid, but for which only certain cells have published assessments.

The nature of synthesis across the two dimensions differs. Sensibly, confidence along the vertical causal chain, in the existence of a trend in the first step

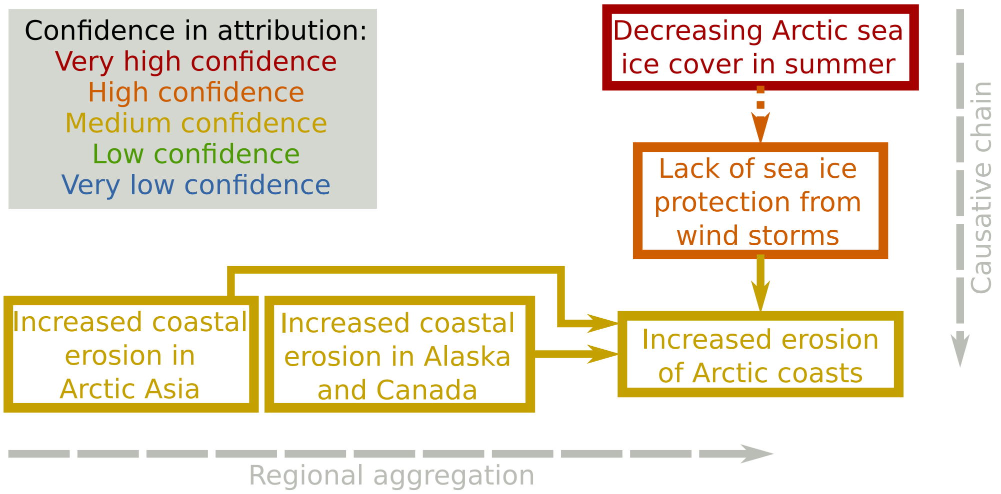

Figure 17.2: **Synthesis assessments from the IPCC AR5 concerning the attribution of increased erosion of Arctic coasts.**

In Cramer et al. [2014] synthesis assessments were made for various aspects of the information feeding the overall assessment. The overall assessment can be viewed as being developed through a causative chain, or as aggregation across regional assessments. Confidence is for the existence of a trend for “decreasing sea ice cover in summer” and for a “major role” in causing trends along the arrows from one box to another.

and of causation in the last two steps, decreases as the assessment proceeds through the impact chain. Along the horizontal regional dimension, though, confidence in the Arctic-wide assessment is the same as for the regional assessments. This is sensible enough, but what if the assessment for Asia had been for "very low confidence"? Basing the Arctic-wide assessment on the more or less confident result would mean that the existing synthesis assessment would not be representative of the entire Arctic [Stone et al., 2013]. On the other hand, taking some qualitative average (i.e. "low confidence") would hide the existence of "medium confidence" in at least some impacts. Cramer et al. [2014] attempted to deal with this issue by adopting the practice of assigning confidence to carefully worded synthesis statements, with the explanation that "*the confidence statements refer to a globally balanced assessment*". So for instance, the assessment of "changes in flood frequency and magnitude in non-snowmelt-fed rivers" referred to changes of any nature, not applicable to all non-snowmelt-fed rivers around the planet but rather to the existence of such changes in at least a major river in most continents.

This issue of "horizontal arithmetic" does not only apply to the confidence measure used by Cramer et al. [2014]. For the binary synthesis approach described above, Rosenzweig et al. [2007] consider if one assessment concluded no impact, or an impact in the opposite sense of another region (e.g. decreased erosion for the example above). A high "no impact" count implies a lesser overall combined impact, even though this is by no means necessarily the case. On the other hand, given uncertainty in the assessments, picking the most extreme case would be biased, as it would produce a large combined impact estimate even in the absence of climate change. At the other extreme, the fact that one particular system is not being impacted may have little overall relevance, and so should not be selected as representative [Stone et al., 2013].

17.2.8. Is there power in numbers?

A final concern is in understanding the uncertainty in any final synthesis measure. This depends not only on factors listed above, but also on interdependence of the individual studies contributing to the synthesis [Cramer et al., 2014]. For example, in synthesis studies of shifts in the geographic ranges of multiple species it is assumed that each species shifts its range independently of others [e.g. Hockey et al., 2011, Parmesan et al., 2011, Rosenzweig and Neofotis, 2003]. In that case the addition of observations of the range shift of an additional species adds substantial new information to the synthesis. However, the independence is hard to confirm when species are shifting their ranges as part of a general relocation of an entire ecosystem: observations for a species that is simply following its food (with the observations of that species already included) will lend confidence to the observations of its food, but will not truly add a new item within the synthesis.

17.3. Synthesizing across everything

In the previous section we listed some of the challenges involved in developing a cross-system synthesis assessment of the impacts of climate change mediated through extreme weather. While some qualitative extreme-specific syntheses have been developed for predictions of the coming century [Smith et al., 2001, 2009, Oppenheimer et al., 2014], only one such exercise has been attempted for the historical period. It comprised two main steps: a number of synthesis

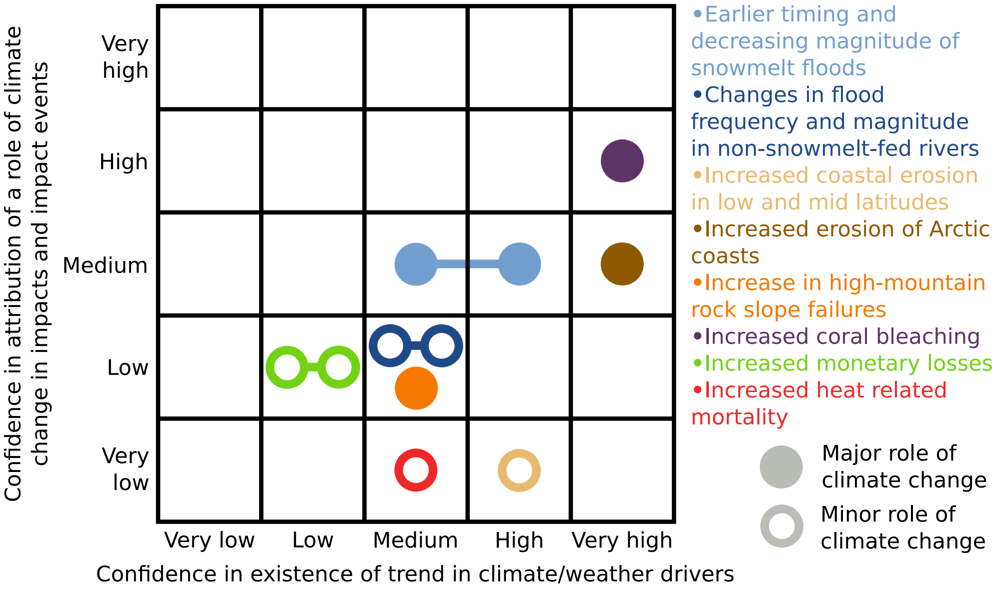

Figure 17.3: **Confidence in attribution of observed trends in impacts related to extreme weather**

Graphical interpretation of the table in Cramer et al. [2014] documenting the synthesis of evidence of an effect of historical trends in extreme weather on various natural, managed, and human systems.

assessments, each across similar impacts [Cramer et al., 2014], and a collective synthesis across all impacts [Oppenheimer et al., 2014].

The first step is illustrated in Figure 17.3 in a graphical representation. The position on the vertical axis indicates the degree of confidence [Mastrandrea et al., 2010] in the attribution of a role of observed climate change in an observed impact. The position on the horizontal axis indicates the confidence of a long-term trend in the relevant climate drivers. Some impacts have multiple climate drivers, being represented by multiple symbols connected by a line. The different types of impacts are denoted by different colours, with identification of a major role (it is a dominant factor) or a minor role (it may be involved but is not dominant) of observed climate change.

In the figure, confidence in the impact is necessarily no higher than confidence in the relevant climate driver, since the latter is a component of the former. Note that no assessment was made over whether the climate trends were driven by human activities or represent some natural fluctuation. Hansen and Stone [2016] did examine the role of humans in trends in climate averages that they considered relevant for the extreme weather, and thus provided some indication of the robustness of some assessments to the inclusion of attribution to human activities. In general, the snowmelt flood and coral bleaching assessments ought to be unaffected, while the effect on the Arctic coastal erosion assessment depends on the balance between the importance of thermofrost degradation (unaffected) versus regional sea ice retreat (strongly affected); effects on the other assessments in this figure were not conducted.

There are three main observations one may make from this illustration. The most obvious is that not that many impacts were covered, and many included were limited to very specific statements (for instance, the distinction between erosion of Arctic versus non-Arctic coasts). The synthesis was conducted for two types of impacts: broad synthesis statements of general interest (e.g. monetary losses), or assessments of a more narrow set of impacts selected on the basis of whether strong evidence existed one way or the other (e.g. Arctic coastal erosion). In this sense, the assessment fell short of a full global synthesis across all systems, at least in part because it was conducted under the framework of detection and attribution.

The second observation is that the figure is an amalgam of trends in impacts related to extreme weather, but not necessarily trends in impacts of trends in extreme weather. For instance, the evidence of increased erosion of Arctic coasts is based on understanding that storms can now erode the coast more easily because the summer permafrost has disappeared and is no longer providing structural strength, and because there is a much longer distance for waves to grow in the space vacated from retreating sea ice. In other words, the erosion occurs during the storms, but the storms themselves are not changing, only the way they interact with the coast is because of more gradual changes.

The third, more arguable, observation is that there are two types of conclusions present. The assessments for coral bleaching, snowmelt floods, and Arctic coastal erosion are all of at least medium confidence of a major role of climate change (which is mostly unaffected when extended to a major role of anthropogenic climate change). The other assessments are of lower confidence and only apply to the existence of a role of climate change. The former group arise because large-scale warming is a simple direct driver, warming is the most visible manifestation of recent climate change, the warming and impacts have been fairly well monitored, and the systems are relatively sensitive to temperature (e.g. the snow-line on mountains, or the sea ice edge). One or more of these factors is lacking in the second group.

17.4. Implications for the future

This chapter has mainly focused on the past, and specifically about detection and attribution of changes. This places heavy burdens on the evidence base that has the advantage of producing coherent, strongly supported conclusions, but also has the disadvantage of being unable to provide information on some types of impacts. Does this matter when predicting future impacts? After all, predictions concerning risks related to the extremes RFC were made many years before the first evaluation of changes in past risks.

There are three possible reasons for detection and attribution analysis to provide inconclusive results: poor monitoring, poor understanding of how the system operates, or bad luck (the observations and understanding do not match because of a statistical fluke). Poor understanding will be just as relevant for errors in predicting the future as they are for the past, in fact perhaps more so because of thresholds in some systems that may soon be passed. Statistical flukes occur because the analysis is inherently probabilistic in nature, but ought to happen rarely. It does remind us that specific aspects of the predicted future may not materialise because the climate and various impact systems are inherently chaotic. Poor monitoring is also relevant though, because if we do not have a reliably observed baseline and if we do not obtain reliable observations of future states, then we will lack an important input in the process of refining later predictions.

The focus on extremes is partly artificial. But the reason for the extremes RFC is that it fits into current decision-making systems that are based on natural disasters, including those resulting from weather. Development of more comprehensive synthesis assessments focusing impacts related to extreme weather, for both the historical period and the future, will require improved comprehensiveness and consistency in monitoring of extreme weather, improved documentation of its impacts, and further development of methods for synthesizing across disparate types of impacts.

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