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Hazard Hexagons: The influence of anthropogenic climate change on extremes in regions globally

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Abstract

The sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) presented regional summaries of the scientific knowledge of changing weather extremes and the human influence upon this. The hexagon figures, found in the Summary for Policymakers (SPM), were a key part of this presentation. They provided clear visual overviews of this understanding on three hazard types (hot extremes, heavy precipitation and agricultural and ecological drought) for policymakers, scientists and communicators alike. We have shown that since 2021, when AR6 was published, there has been a rapid advancement in knowledge of changing extremes on the timescale of individual years, with a greater than doubling in the number of extreme event and trend attribution studies coupled with advances in methodologies, rising levels of anthropogenic forcing, and a growing sample of manifested extreme events. The coming seventh assessment report (AR7) is an opportunity to update and iterate these figures, expand to other hazard types and, we argue, to facilitate more regular updates in line with this rapidly advancing field of knowledge. To this end, we have updated the AR6 hexagons in several ways: we have added evidence levels to the figures to provide additional information without sacrificing visual clarity; we have built on the AR6 regional synthesis process with a step-by-step procedure and accompanying expert guidance and discussion; we have applied this to six illustrative regional case studies for heavy precipitation; we have updated the evidence tables and figures directly for hot extremes and heavy precipitation.

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1. Introduction

Every fraction of a degree of warming affects the likelihood and intensity of extreme weather hazards around the world [1–4]. Changes in dangerous extremes are of crucial societal relevance, as they can result in severe impacts on people, economies and ecosystems [5–9]. However, the specific changes in hazards vary across both different types of extreme weather and different regions, as does the degree of scientific understanding of these changes [5,10,11]. To both motivate mitigation of large-scale climate change and to adapt to changes in extremes to reduce the risk of severe impacts, policymakers require timely and up to date information on observed and projected changes across hazards and regions [12,13].

In 2021, the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) synthesized the evidence on changing likelihood and intensity of extremes and the confidence with which the observed changes can be attributed to climate change. In particular, this evidence was collated for three different hazards: hot extremes, heavy precipitation and drought (agricultural and ecological), and for all 45 AR6 WG1 regions. The primary evidence base is found in the ‘Large tables’ in Chapter 11 of working group 1 and summarised in figure 3 in the summary for policymakers - the ‘hexagons’ figure [11]. This is also a key figure in the AR6 synthesis report, which synthesises the assessments from all three working groups on the physical science base, adaptation and vulnerability, and mitigation [14], highlighting its significance beyond physical science. These figures represent the IPCC regions using equally sized hexagons to provide an overview of the observed and attributed changes in each region, assessed from all available literature. Crucially, this provides a compelling and easily interpretable overview that is not visually distorted by geography and projections. These figures do, however, remain critically dependent on the availability of literature in each region.

There are clear differences in the findings across both hazards and regions. For hot extremes, the evidence is conclusive in almost all regions that there has been an increase, that this is due to anthropogenic climate change, and in more than half of regions that this can be stated with high confidence (Table 1). For rainfall, the picture is less clear due mostly to a limited evidence base, which comes from a lack of available studies, limited high quality observational and climate model data, high natural variability and/or lack of a clear signal, or a combination of all of these. In particular, around 40% of regions show increasing trends, but in all but two of those there is low confidence in the attribution of these changes to human influence, and another 40% of regions show no trend due to limited evidence (shown by the grey hexagons). Finally, for drought, the picture is very mixed with no trend due to limited agreement in the available evidence in around 60% of regions (shown by the crossed hexagons).

Extreme type	Number of IPCC AR6 regions				
	Observed change, confidence in attribution to human influence			No observed change	
	High	Medium	Low	Limited agreement	Limited evidence
Hot extremes	23	16	2	2	2
Heavy Precipitation	1	1	17	8	18
Drought (Agricultural and Ecological)	0	2	11*	28	4

Table 1: Summary of levels of evidence of changing extremes for each hazard in each region presented in the sixth assessment report of the IPCC. *a single region (NAU – Northern Australia) has the opposite direction of change to all others with a reduction in drought. As there is only a single departure across all three maps, the changes are not broken down by the sign of change.

These figures represent our knowledge of changing extremes and the human influence upon this at a fixed point in time. At the literature cut-off for AR6, in late 2020, there were around 400 published attribution analyses (generally counting each event definition separately, so a single article may feature multiple ‘analyses’, though any objective count is challenging due to methodological variation across studies). This is for extreme events mostly occurring after the year 2000 (Fig. 1; [15]). This makes up a significant component of the evidence base for the review alongside large-scale analyses of trends in extremes indices, such as the ETCCDI indices of temperature and precipitation (e.g. [16,17]). However, each year, the climate continues to warm due to increases in atmospheric greenhouse gases, and more extremes occur within this constantly changing baseline. Commensurate with this, more attribution studies are produced every year by an ever-growing list of international, regional and nationally focused groups (Fig. 1), in addition to other complementary literature on regional and grid-scale trends in extremes (e.g. [18]).

Here, we use the CarbonBrief database to study recent developments in the attribution literature. Between the cut-off for AR6 and the end of 2025, more than 550 additional attribution analyses were published, either as rapid studies with peer-reviewed methods or as peer-reviewed analyses, suggesting much more than a doubling in the available literature (Fig. 1; [15]). Considering that many of the newer studies are also based on events occurring at higher warming levels, applying a more mature suite of methods and expert judgment, and based on newer observation-based and

model datasets, such studies likely elucidate the role of human influence more clearly than previous work. The period of only 5 years since AR6 therefore represents a new phase in the scientific understanding of the human influence on extremes and suggests a step change in knowledge on the timescale of individual years. This in turn suggests that there is a need to update summaries of changing extremes, such as the hexagon figures, ahead of the next IPCC assessment. Further, it also suggests that the requirement for timely information on extremes has not been well met by the most recent IPCC cycle and likely will not be met by relying solely on this process going forwards, as argued for other key global indicators [13].

On top of this, we have found that attribution studies have mostly been conducted for events occurring in global north countries (and mostly by scientists from global north countries), leading to a global-scale heterogeneity of evidence on changing risks. Figure 1 (lower panel) highlights this geographical discrepancy, using a very simple broad categorisation method based on the associated regional tags in the CarbonBrief database: ‘Global North’ is considered as all of Europe, North America and Australasia as well as any studies tagged as covering the Northern Hemisphere as a whole (which inevitably also includes some Global South regions); ‘Global South’ is then counted from all events in Asia, Africa, South and Central America and Oceania (which inevitably also includes some Global North regions). It is challenging to clearly divide all nations into a Global North-South binary, as any such classification for a given nation depends on several interlinked political and economic factors, including income, cumulative and present emissions, vulnerability, and research capacity, among others. However, this broad region-based approximation is likely to provide a conservative estimate of the studies in Global North regions while being sufficiently spatially aggregated to account for extreme events crossing borders, which is an inherent challenge for tallying events by nation. We further caution that the simple system we apply here is intended only as a basis for this particular discussion. More detailed analysis of study counts could directly separate nations by income or other specific indicators, or display study counts by IPCC region as is shown for heavy rainfall in section 4.

Using this system, we find that up to the AR6 call for evidence, approximately twice as many studies were conducted for events in Global North regions than in Global South regions. The balance of new studies is reversed in the period from 2021-2025, with approximately 40% of new studies in the Global North and 50% in the Global South regions (and the remainder as Arctic, Antarctic or fully Global studies; Fig. 1). This recent period therefore represents a huge increase in knowledge of changing extremes for the majority of the population of the world.

However, regional inequities in knowledge remain. Over all time more than 50% of attribution studies remain concentrated in the Global North regions. It should also be noted that nearly half of the ‘Global South’ studies from 2021-2025 are for China exclusively, after a remarkable rise in attribution assessments in the region in recent years thanks to very high national research capacity. This case in particular highlights the challenge of separating nations into a binary Global North and South division. Furthermore, when considering the ratio of attribution analyses between these two broad Global regions as a proportion of exposed population or land area, both

of which are vastly larger in this simplified classification of the Global South than North, the discrepancy remains incredibly stark. This persists for a variety of reasons including data availability and research capacity [19–21]. Coupled to the disparity in the recording of impacts [5,19,22], this presents a major challenge to understanding changing risks in some of the world’s most exposed and vulnerable regions. As more work is conducted in the Global South it is therefore essential that it is integrated into these regional summaries on a timescale shorter than IPCC cycles to highlight both the latest knowledge on changing extremes and ongoing disparities in evidence. The next assessment report provides an ideal opportunity, amid this explosion of attribution evidence, to prepare for more regular updates.

The regional summaries presented in AR6 provide an effective platform for communicating observed changes in extremes and the human influence on these changes. However, these summaries were published based on a combination of expert judgment and a fixed snapshot of published evidence. Given that the upcoming AR7 will almost inevitably involve updating these summaries with the latest evidence, it presents an opportunity to also review and formalise them for future, regular, updates. This is particularly crucial for hazards and regions with a more limited evidence base (Fig. 1).

To this end, we set out several objectives in this article. First, we discuss the purpose and interpretation of the regional summaries as a form of guidance for both different producers of evidence for, and users of, these summaries. Within this, we also review the information shown in the AR6 figures and assess ways in which additional knowledge may be included without sacrificing the effective visual overview provided. Second, we propose a framework through which evidence on changing extremes can be kept up to date between IPCC cycles using a simple structured set of questions with accompanying guidance to aid expert judgment.

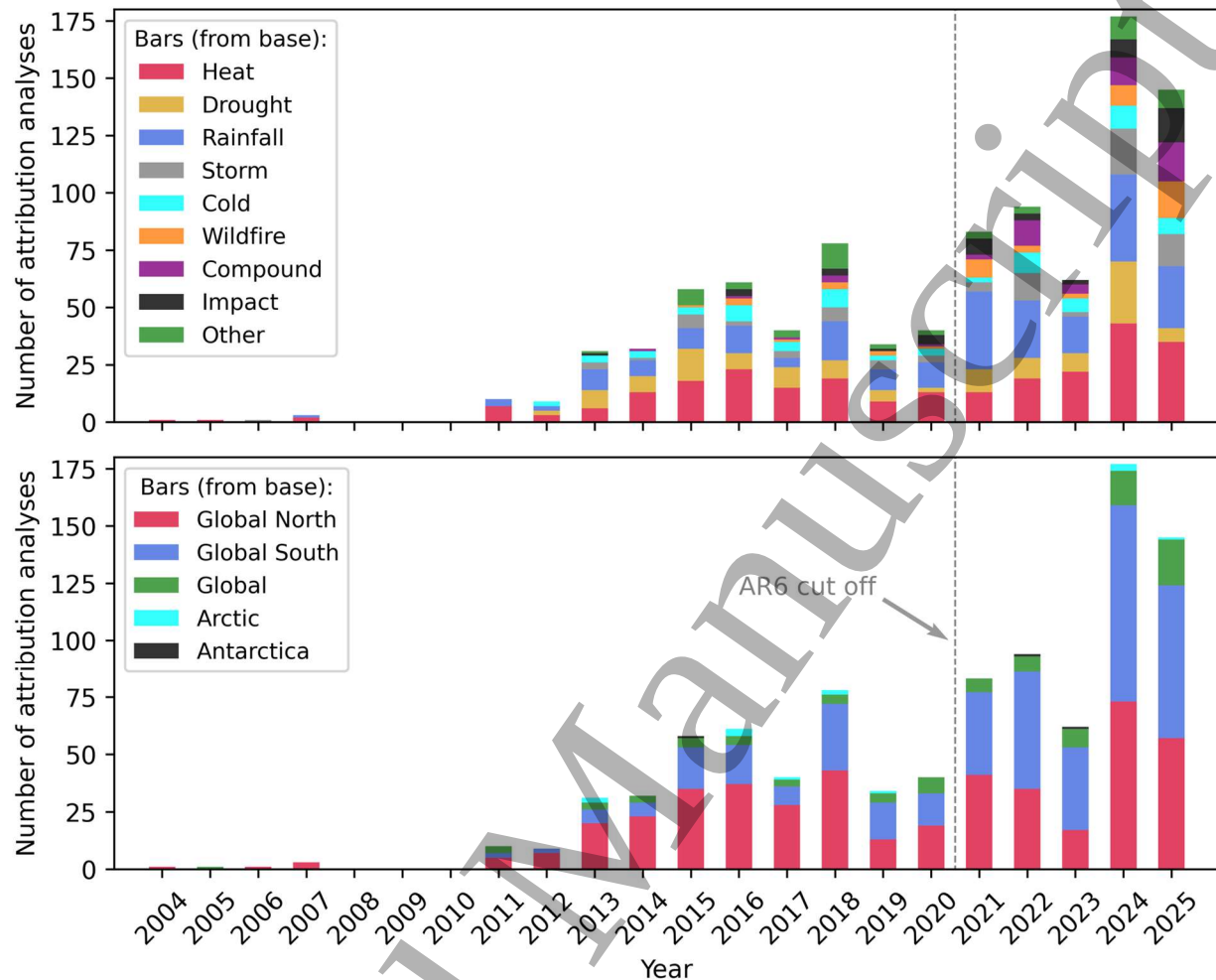


Figure 1: Number of attribution studies published per year since 2004. Upper panel: shown by hazard types including heat, drought, rainfall, storm, cold, wildfire, as well as compound events, impact studies and 'other', including studies on oceans, river levels and sunshine durations. Lower panel: shown by the region of the world in which the event occurred, with simple continent-based definitions for Global North (Europe, North America and Australasia as well as any covering the Northern Hemisphere), Global South (Asia, Africa, South and Central America, Oceania), as well as the Arctic, Antarctica, and studies on Global phenomena. In both cases, the approximate cut-off for evidence used in AR6 (the end of 2020) is shown by the grey dashed line.

Here we use the example of heavy precipitation to illustrate this process across several case studies. This is because the evidence available for heavy precipitation at the time of AR6 contained both the most hexagons with either no trend due to a lack of evidence or low confidence in attribution due to limited evidence, primarily (but not always) due to a paucity of attribution studies for the region (Table 1). There has also been significant growth in the number of attribution studies on rainfall and storms since 2021 (Fig. 1). This hazard therefore provides the most potential case studies of regions in which knowledge has advanced between IPCC

cycles. Finally, we apply the guidance developed here to update the regional summaries of both heavy precipitation and heat extremes with the latest literature and discuss next steps, including other cases for which similar regional summaries may be informative.

2. Reviewing the Hexagon figures

In this section, we review the Hexagon figures in AR6. In particular, we set out the intended purpose of these figures and how they can and should be interpreted by their intended audience(s). We then discuss their limitations and how they can be updated to present additional information without sacrificing visual clarity. This section therefore forms a foundation for formalising and iterating the figures in subsequent sections.

2.1 Motivation and interpretation

The IPCC was created to “to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.”[23] As part of the working group 1 summary for policymakers, the hexagon figure was therefore principally created to provide a broad summary of observed changes in extremes in each region and the scientific knowledge on the link between this trend and anthropogenic influences on the climate for the purposes of policymakers. Specifically, this forms part of the foundation for adaptation and mitigation efforts, including justifying further investigation into changing hazards at local scales.

Such summaries may also provide value to other users. First, in the wake of impactful extreme events, climate journalists and communicators seek to provide an immediate answer on the role of climate change in the event. Even in the absence of tailored attribution studies, these regional summaries provide a basis for informing the public how similar extremes are affected (or not) by anthropogenic forcings in their region, with an accompanying confidence level. Second, for the scientific community, these summaries and the accompanying evidence tables provide a relatively complete database and synthesis of literature on changes in extremes for each region. This highlights points in the region-hazard matrix where evidence is still lacking, helping to prioritise efforts in understudied regions, encourages methodological diversity, and allows contextualisation of new results.

All of these use cases require careful interpretation and should include appropriate guidance. Specifically, it should be made clear that these figures show summaries of evidence over large regions, typically overlapping the borders of several nations. Therefore, within any given IPCC region, some subregions or locations may show different changes in extremes or in the human influences upon the observed changes. This can be due to a range of factors including spatial variation in hazard types and climatology, orographic effects, aerosols, land use, and myriad other factors. In addition, changes in extremes and the human influence on this in a region may

also vary by season. For instance, in Northern Europe in AR6, heavy precipitation was found to be increasing due to human influence with high confidence in winter but not in summer. Furthermore, due to variations in the evidence base in different regions, this granular breakdown by season, hazard type, and other factors may or may not be clear.

To address the myriad dimensions reduced by regional summaries, the range of factors affecting the conclusion about the existence of an overall trend (or not) in the region, and the human influence on this, is generally built into the accompanying confidence level (see section 3). For instance, a region in which one major subregion shows consistent intensification of extremes due to human influence and no change elsewhere (or with no evidence elsewhere) might be concluded to show a change, but with low or medium confidence due to limited agreement (or limited evidence). However, in some cases this ‘smoothing’ could hide important changes in particular subregions, seasons or variables. Then, given an understanding of context, the challenge of capturing different signals can also be addressed through prioritising policy- and impact-relevant extremes and by providing an appropriate caveat, as in Northern Europe described above. To give two general examples: changes in short-duration extreme precipitation in the wet season are generally much more intense and therefore impactful than in the dry season, when what is considered extreme may be moderate at most on the annual scale; similarly, anomalous heat events can have widespread and devastating impacts on health in warmer seasons that would not be nearly as impactful in a cool season.

In general, these regional summaries focus on observed and attributable changes to potentially impact- and policy-relevant extremes, using confidence levels to capture the applicability of the result to extremes around the region. More specific caveats are also included where necessary in the accompanying evidence tables. Nonetheless, these summaries should always be considered in the light of the broad spatial and seasonal pooling required to create them, as well as variations in the underlying evidence base between regions and subregions, and ultimately as a foundation for further investigation of specific risks.

2.2 Figure format

To further aid usage and interpretation, we also review the format of the figures themselves, with a focus on how the results are categorised and thus communicated. The possible categories of result given for the AR6 hexagons can be summarised as follows: no observed change (due to either limited evidence or limited agreement), observed change with low confidence in attribution to human influence (also due to either limited evidence or limited agreement), or observed change with medium or high confidence in the attribution. We propose 4 opportunities for providing additional information and clarity by slightly expanding this system without compromising the visual effectiveness of the figure, and one additional clarification for the figure caption.

First, the system in AR6 does not distinguish between regions in which there is attribution evidence that constitutes low confidence (either due to limited agreement or evidence), and regions in which there is an observed change but no attribution of this is possible. Instead, any case in which a change is observed is assumed to also have low confidence in attribution even in the absence of any attribution evidence. For instance, in West Central Asia (WCA), there were multiple analyses showing increases in heavy precipitation, but no attribution analyses (or at least none available in English). In spite of this, the region is classified as increasing with low confidence in attributing this increase to human influence. To address this, we propose adding an additional category: ‘observed change, no attribution’, which can be further broken down into limited evidence or limited agreement. This would encompass large parts of Asia like WCA in which there is evidence of trends but little or no evidence of human influence, as opposed to regions in which attribution studies already exist, thereby highlighting an important research gap (Fig. 2).

Second, while the ‘observed change, low confidence in attribution’ tier (and now also the ‘observed change, no attribution’ tier) distinguishes the primary reason for its classification, i.e. either limited agreement or evidence, the same information is not provided by the medium confidence tier. It would be simple to add an additional piece of information, using the same system as for no attribution and low confidence, to distinguish why a given tier of confidence is not ranked as the tier above.

Third, the hexagons in which there is no trend have both a colour (white or grey) and a dot, which both distinguish between limited evidence and limited agreement. This is largely redundant information and may be confusing given that dots (both hollow and black) are associated with attribution evidence in the AR6 figure. To address this, we propose two changes. First, only black dots are used to denote the tier of attribution evidence; 1, 2 or 3 for low, medium and high. Second, removing the grey hexagons and using a system of hollow dots, shaded white or grey, to distinguish all cases (in all evidence tiers) in which the evidence is classified as a given tier “due to limited agreement or evidence”, respectively. This system is also in line with the previous two suggestions, enabling the information on constraint due to limited evidence or limited agreement to be clarified throughout. Finally, we propose that the figure caption should be further clarified to reflect the figure interpretation described above (e.g. Figs. 2, 6 and S1 captions).

Fourth, one ‘blind spot’ remains regarding regions in which a change is observed but that is confidently not attributable to human influence on the climate. While such cases are likely rare due to the preeminence of human forcings at the regional scale and above, it remains possible. In such a case, it is important to avoid conflating this knowledge of a lack of a signal with other classifications such as ‘no attribution, limited evidence’, which arises due to a lack of knowledge about a signal. We therefore propose adding an additional ‘x’ marker, to be applied in the same way as the black dots, to denote confidence in the finding of no attribution.

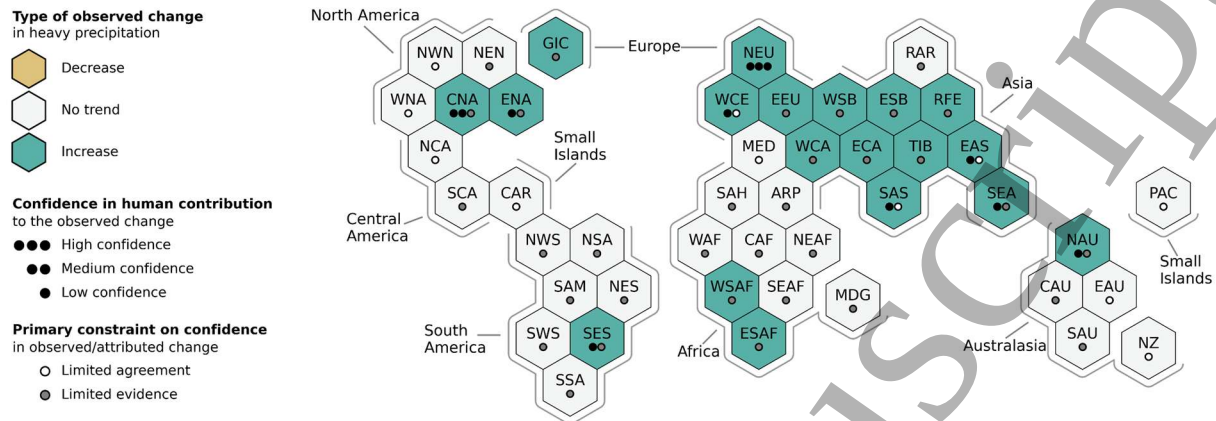


Figure 2: Figure SPM.3b recreated using the proposed system developed here. The colour of the hexagon denotes the presence and direction of an observed trend, with teal for an increasing trend and white for no trend. Black dots show the confidence with which this observed trend is attributable to human influence, with 0, 1, 2 and 3 black dots representing no attribution and low, medium and high confidence in the attribution, respectively. The hollow white and grey dots show what factor primarily restricts the summary from reaching the subsequent tier of confidence, whether it is due to limited agreement or limited evidence, respectively. The data in this figure should be interpreted as broad regional summaries and as a foundation for further investigation of hazards and risks. While important subregional or seasonal changes in extremes are highlighted where possible, they may in some cases be too complex to display on this scale. Note that important region-specific caveats are also included in the accompanying evidence tables.

Figure 2 shows the hexagons for heavy precipitation from AR6 levels of evidence, reproduced using the changes proposed above. The accompanying evidence tables, modified from the ‘Large tables’ (Tables 11.4-11.21) in WG1 Chapter 11 of AR6 are shown in the Supplementary material. The visual overview provided by the figure remains clear but provides additional information on each tier. For instance, in South Asia and Southeast Asia the increasing trends in heavy precipitation are attributed with low confidence to human influence, but in the case of South Asia this low confidence is primarily due to limited agreement from the available evidence (white hollow dot), while in Southeast Asia it is primarily due to limited evidence (grey hollow dot). Similarly, there is no observed change in the Mediterranean due to limited agreement in the available evidence, while in the Sahara there is a dearth of evidence altogether.

3. Regional synthesis through expert judgment

Expert judgment is necessary in combining evidence from different studies across many different spatial scales, regions and hazard types (even within a given extreme, such as heavy precipitation), using different datasets, methods, lines of evidence and levels of confidence. For AR6, the process for gathering, evaluating and synthesising evidence as used in the hexagon figures is described as part of the approach towards ‘constructing regional climate change information’, which is broadly documented across several chapters.

Cross Chapter Box 10.3 sets out the ‘Assessment of Climate Change Information at the Regional Scale’ using three stages: 1) Collection and assessment of the fitness-for-purpose of available information, which requires assessment of evidence robustness including observational data quality and model fidelity; 2) Assessment of confidence of the multiple lines of evidence, which involves expert judgment on a range of factors for each line of evidence, such as consistency between datasets, before considering overall coherency across all lines of evidence; 3) Distillation of regional information and synthesis of the independent assessments, which includes documentation of evidence sources across the report and synthesising the evidence [11]. This synthesis process is not set out explicitly but is explored through two case studies with different levels of complexity and agreement. A further example of this synthesis, or ‘distillation’, process is also shown for the explanation of the Interactive Atlas, in the Technical Summary (Box TS.12; [11]). Nonetheless, the key steps and considerations within this process are not explicitly set out.

Several other chapter subsections are also relevant to the regional synthesis. Box 1.1 in Chapter 1 describes the confidence and uncertainty language for the report, describing key types of evidence (observations, experiments, theory, statistics and models), considerations in evaluating this evidence (type, quality, quantity and consistency), and the evaluation of confidence (from very low to very high) based on a matrix of agreement and evidence. For instance, high agreement across limited evidence (or vice versa, or medium in both) gives medium confidence overall, while high confidence in both dimensions results in at least high overall confidence. Section 11.9 explicitly details how this calibrated language is applied to regional information on extremes, with additional considerations for each type of extreme assessed. Finally, Tables 11.4-11.21 in Chapter 11 clearly display the evidence base applied for each region, providing a transparent foundation for the subsequent synthesis.

We suggest that, to facilitate updating these hazard summaries on a regular basis and the expert judgment involved, it is essential to build a more explicit synthesis process. This should include a clear framework with accompanying guidance for key considerations, and additional case studies to illustrate this process. This clarity is primarily for the purpose of traceability across regions and for justifying choices that have been made by any given expert(s).

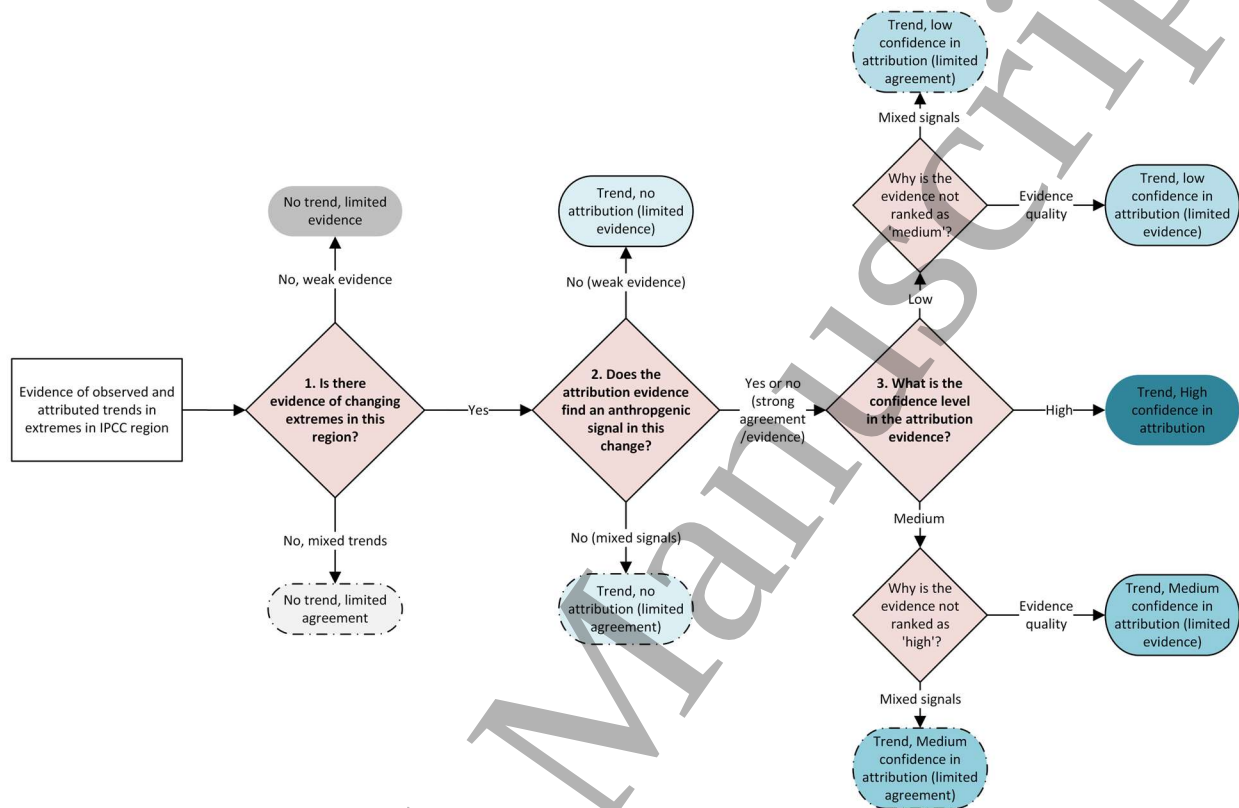


Figure 3: Flowchart for key steps in summarising regional evidence on observed changes in an extreme and attribution of this change to human influence. Red diamonds show the set of decision points needed when combining the body of available evidence, which each have accompanying guidance in section 3.1, while the white, grey and blue ovals show the 9 possible results from this process. The steps are further illustrated in ‘child’ flowcharts (Figs. 4&5).

3.1 Guidance

Figure 3 shows a framework for determining the overall summary given the relevant body of evidence for a region. With respect to the process described in Box 10.3 from AR6, this constitutes an expansion to steps 2 and 3b, specifically exploring considerations around the synthesis and confidence assessment. The process of gathering relevant lines of evidence is detailed in Cross-Chapter Box 10.3 in step 1 but remains largely informal: “Once the indices of change are properly defined, the relevant climate information is collated from the available sources.” For the purpose of regularly updating these summaries, it would be valuable to build a more systematic approach to both gathering and assessing evidence that considers the relevance

of the included studies. This could be based on factors such as the quality of data and methods used, which will become increasingly relevant as the field ages and both techniques and the global warming level advance. Further, it could employ tools such as an operational integration from key recognised operational groups, and a standardised and formal submission template for new evidence. While establishing such a system is beyond the scope of this initial work, which focuses on the synthesis process, it would be a valuable discussion in AR7 and beyond.

For each step below, the aim is to determine whether the available evidence meets a given threshold to proceed (as described within the guidance), and, if it does not, to identify why this is the case (be it limited evidence or limited agreement).

3.1.1 Step 1) Is there an observed change in extremes in the region?

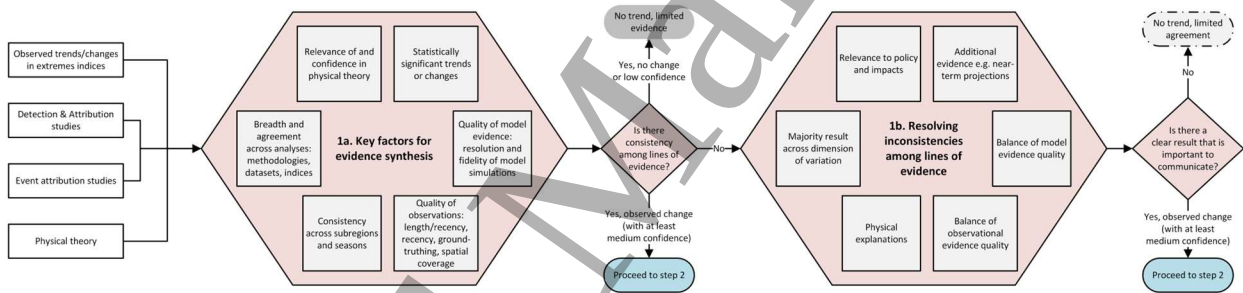


Figure 4: Flowchart detailing the process in summarising regional evidence on observed changes in an extreme (step 1 in Fig. 3). Red diamonds and hexagons show the key set of factors and decision points needed when combining the body of available evidence, with accompanying guidance in section 3.1. The grey and blue ovals show the possible results from this process.

The first step requires summarising evidence from all sources pertaining to changes in the extreme of interest. This includes (but is not limited to): trends in relevant extreme indices at the grid or station scale or changes in these indices between a historical and present period (e.g. [17,24,25]); trends or changes in indices averaged over regional scales (e.g. [16,18,26]); event attribution studies using observation-based data and climate models to assess changes (and the role of forcings) in a class of extreme events, ranging from a minimally conditioned spatiotemporal index of some extreme variable (e.g. [27,28]) to a highly conditioned circulation pattern or specific weather system (e.g. [29–31]). Evidence from attribution studies are included in this step because many such studies feature an analysis of observed changes in extremes as a component of the analysis.

Additional evidence from robust physical theory is also integrated here. For instance, the direct thermodynamic influence of a warmer atmosphere on heat events and rainfall extremes are clear and well understood, through the direct influence of hotter near-surface air temperatures (particularly over land regions) and the Clausius-Clapeyron relationship, respectively, which describes the increased moisture holding capacity of a warming atmosphere at a rate of $\sim 7\% / K$ (as well as the robust intensification of shorter-term intense rainfall exceeding this rate globally; [32]). For more complex hazards, such as droughts, wildfires and tropical cyclone winds (see section 4 for a discussion of other potential hazard hexagon maps), the net influences of background warming are less clear. Nonetheless, even such complex hazards can be understood as a series of interacting drivers within which physical reasoning often still applies to certain elements with higher confidence (as illustrated by causal matrices in [33]). For instance, the net water balance may be reduced through additional heat-driven evaporation even when rainfall patterns are unchanging or uncertain, thus amplifying drought conditions [34–36]. Similarly, hotter sea surface temperatures may directly lead to more favourable environmental conditions for landfalling cyclone intensity in some basins [37,38]. The physical theory line of evidence therefore often provides an a-priori expectation that, while not superseding more specific analysis that can account for more complex and higher order effects such as dynamical shifts, can nonetheless be used as an anchor for comparison and understanding of results and to enhance robustness.

In combining this varied evidence to determine the existence and direction of a change in the extreme across a large region, a range of factors are crucial to consider. First, the range of analyses, including different methodologies, datasets and indices, and the agreement among those analyses. Second, consistency of changes across the region of interest and across different seasons. Third, the relevance of and confidence in physical theory on the hazard of interest. Fourth, the presence of statistically significant trends or changes, which is a relevant factor rather than a necessary condition. Finally, the quality of evidence, which relates to the historical length of observation-based data and how up to date it is to account for recent warming, the existence of weather station data for ground-truthing, contribution of local expertise, the resolution and fidelity of model simulations, and the spatial coverage of such data within the region. These criteria can be thought of as a range of spectra contributing to the overall confidence level, with greater confidence indicated by: a larger range of analysis methods, spatiotemporal scales and seasons with agreement; robust relevant physical theory; statistical significance; higher quality of evidence.

There are several possible conclusions for this question based on various combinations of evidence. In the case of consistency among the available lines of evidence, the result may be either ‘yes’ (that a change is found), or ‘no trend, limited evidence’ (a change is consistently not found). Without needing to reconcile different results, there is only one further condition required for advancement, as indicated by the IPCC AR6. That is, the hexagon figures show evidence of

an observed change where there is at least ‘medium confidence’ in this evidence. Following the AR6 guidance on confidence, this requires either high agreement and limited evidence, medium agreement and medium evidence, or low agreement but robust evidence (Box 1.1; [11]). This suggests that multiple analyses displaying a high level of agreement, or more limited or single analyses backed up by robust physical theory, significant results, and/or high quality datasets are sufficient to meet this level. If this threshold is not met, the result ‘no trend, limited evidence’ is appropriate.

Often, regions will display changes in an extreme that varies across one or more of several dimensions: subregions, relevant indices, seasons, datasets and data availability, analysis methods, and others. In such cases, expert judgment of the relative balance of evidence to draw a conclusion about the overall change to communicate is essential. This depends both on an assessment of the criteria set out above to determine the evidence for a detected change, as well as a further consideration of the most pertinent information for users. While there is no way of setting objective evidence thresholds, an additional range of factors should be considered in determining the regional summary. These include:

- Majority result - in the case of subregional variation, the direction of trends over the majority of the regional domain may be most pertinent.
- Potential relevance to policy and impacts - for instance, in the case of varied seasonal changes in heavy rainfall, changes in wet season heavy rainfall are likely the most pertinent. Similarly, a single subregion displaying strong increases in extreme rainfall while there is little change observed elsewhere may reasonably be considered worthy of reporting as a trend across the region, when the alternative is smoothing out this important changing hazard.
- Evidence quality - different analyses provide a different weight of evidence based on simple indicators. For instance, higher quality evidence is typically provided by longer term observations, high resolution and ground-truthed datasets, locally built and tailored models rather than coarse global models, use of more event indices and climate models to explore sensitivity.
- Physical explanations - in some cases in which trends vary over time, this may be due to known phenomena such as changes in concentrations of atmospheric aerosols, which can be accounted for.
- Additional evidence - in some cases, relatively near-term (such as to 1.5 or 2 degrees of global warming) can be used to infer additional information about the role of anthropogenic warming in the presence of highly variable signals at present levels.

In some cases, even following these considerations, no clear change over the region may be seen, in which case we would assign ‘no trend (limited agreement)’. This may arise due to weak and spatially variable trends, or equal but opposing trends across a complex region. However, if expert judgment based on these factors suggests that it is pertinent to communicate a change in the extremes of interest despite limited agreement, then we can assign an answer of ‘yes’ but caveated by this factor. This is most likely to be due to the factors discussed within the ‘potential relevance to policy and impacts’ point above. For instance, in AR6 in Eastern North America there was a ‘Significant intensification of heavy precipitation but lack of a trend over Canada’. While such a caveat should be a last resort, as it will not be immediately apparent upon reading from the figure, it is preferable to inadvertently smoothing out highly relevant and confident subregional trends. This caveat may then also play a role in the remainder of the assessment, including in the assessment of confidence in human influence on this change.

3.1.2. Step 2) Does the available attribution evidence show an anthropogenic signal in this change?

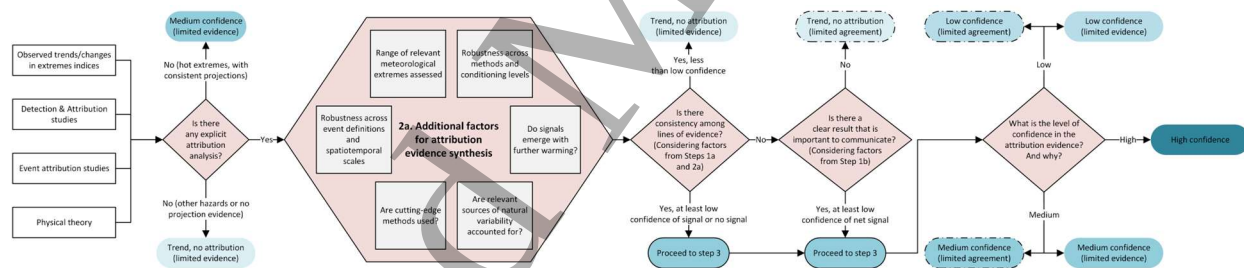


Figure 5: Flowchart detailing the process in summarising regional evidence on observed changes in an extreme (steps 2 & 3 in Fig. 3). Red diamonds and hexagons show the key set of factors and decision points needed when combining the body of available evidence, with accompanying guidance in section 3.1. The grey and blue ovals show the possible results from this process.

Once it has been concluded that there is a change in the extreme of interest at the regional scale, the aim of the next step is to determine whether there is sufficient evidence (at least low confidence) on attribution of this change to human influence. This relies upon only the attribution elements of the evidence base used in step 1 and any additional caveats from the conclusion of that section, and involves assessing the range of results and reconciling apparent differences.

In the case of consistency among analyses of changes, as above the answer to this question may be either ‘yes’ (that an attributable signal is found), or ‘trend, no attribution (limited evidence)’ (an attributable signal is consistently not found). Three special cases exist. The first is where there are no attribution studies. In general, this results in ‘trend, no attribution (limited evidence)’. However, in the case of heat extremes, the direct physical influence is unequivocal and the evidence is clear globally that any observed change is also related at least in part to human influence on the climate. This aligns with the treatment of temperature extremes in AR6, laid out in section 11.9, in which “medium confidence of a human contribution is assessed: when there is strong evidence of changes from observations that are in the direction of model-projected changes for the future; when the magnitude of projected changes increases with global warming; and where there is no other evidence to the contrary. This assessment is further supported by an understanding of how temperature extremes change with the mean temperature and overwhelming evidence of a human contribution to the observed larger-scale changes in the mean temperature and temperature extremes.” We can therefore move to the following part and assign a result of ‘attribution with medium confidence (limited evidence)’ even without an explicit study, when projections also indicate increasing trends.

The second case is when the analyses consistently and robustly find that there is no attributable signal for a given observed trend, as set out in section 2.2. In this case, the framework still applies in the same way as if an attributable signal was found, with the proceeding steps remaining appropriate to assign a degree of confidence in this finding. Step 2 in Fig.3, with further detail in Fig. 5, shows how this emerges from ‘no (strong agreement/evidence) and can be treated similarly to a ‘yes’.

The third case is when the analyses are consistent but may be too specific to apply to the broader region. For instance, this may be the case with only a single study on a local scale, while two studies at different spatiotemporal scales in agreement on human influence constitute enough evidence for at least a low confidence assessment. Assessment of whether this is the case requires considering the range of factors as described below to determine if the analysis is regionally generalisable, or of sufficient importance to be communicated even if not generalisable to the whole region.

If the array of analyses find apparently inconsistent results, this requires an assessment of the relative strength of evidence similar to that required in part 1 and considerations around the generalisability of a given result, including: the range of analyses (including different attribution methods with varying levels of conditioning), the consistency in the signal across the region and different seasons, physical understanding, significance of results, and the quality of evidence across observations and models. Additionally, for attribution evidence, we can specifically consider the diversity of event definitions considered (varying spatially, temporally and seasonally) and the different types of hazards assessed.

Only ‘low confidence’ in the attribution evidence is required to move forwards, as confidence levels are disaggregated in question 3. According to the guidance on confidence from AR6, a statement of low confidence arises from a combination of low and medium evidence and agreement, in either combination. Therefore, in this case of mixed signals in a given region, the more substantial the disagreement among studies is, the stronger the evidence for a particular outcome must be to indicate a response of ‘yes’ to this question. The most common form of disagreement is that some analyses, subregions or seasons show no signal while others do (as opposed to directly opposing signals). This may constitute (up to) medium agreement, suggesting that only low confidence in the attribution evidence across the other criteria described above is required in such a case to proceed. This is especially the case when a ‘lack of signal’ from some analysis is judged entirely by statistical significance, but the results themselves are qualitatively similar and are backed up by robust physical theory, for instance. Lower agreement arises when analyses, subregions or seasons show qualitatively opposing signals. In such a case, at least medium confidence in the evidence is required to proceed, which requires a ranking of at least medium across a majority of the various contributing criteria, according to expert judgement.

Finally, if the evidence for one outcome is not sufficiently strong relative to another, the result of ‘trend, no attribution (limited agreement)’ is assigned. If a conclusion can be drawn, ‘yes’ is appropriate and the next question can be addressed but with the caveat of low agreement brought forwards.

3.1.3. Step 3) What is the confidence level in the attribution evidence?

The final part of the assessment requires the same evidence base as part 2 and is based on many of the same considerations as both previous sections. The outcome is a specific assessment of the confidence level along with a justification in the event of a low or medium confidence assignment as to why the confidence was not higher (i.e. due to limited agreement or evidence). The expert judgement of the confidence level should consider the following factors, described in previous sections and illustrated in Fig.5, but also summarised below:

- How many independent analyses are there and what is the agreement across these?
- Is there well-understood robust physical theory for part or all of the causal chain?
- Are the results statistically significant, where this is appropriate? And at what level?
- Are there variations in the results across subregions or seasons?
- What is the quality of evidence within the analyses? Considering the following: What level of anthropogenic forcing is assessed? Are there both observation-based and model-based datasets? For observations, how many datasets are used and of what type(s)? Are the records long, quality-controlled and homogenised? For climate models, how many are

used? Are they able to reproduce the extremes of interest at an appropriate resolution and accounting for local and/or regional effects?

- What is the diversity of event definitions used, across spatial and temporal scales?
- What is the diversity of relevant hazard types covered by the analyses?
- What is the diversity of methods and conditioning level(s) used across the analyses? Are cutting-edge methods employed?

In any given case, the evidence can be weighed against each of these criteria and assigned a partial confidence level based on each one. By combining these confidence levels, a conclusion may be drawn from the average or majority result. We do not suggest such an explicit approach as considering each criterion individually, as there is ultimately no objective way to assess and weigh the evidence in each case and to do so would be intensely time consuming for little benefit. Instead, this should be understood as the underlying logic of this process and could be applied in exceptional cases. Meanwhile, in practice, each of these factors should be broadly considered in each case and an overall judgment be drawn from this. This entire process (steps 1-3) is demonstrated through six case studies below, which were selected to cover each continent as well as a range of evidence tiers both at AR6 and by 2025.

3.2 Case studies

The following case studies and all updated hexagon tables shown in this study are based on attribution studies included in the CarbonBrief database (XXX), as well as studies found through Google Scholar by combining the following basic search terms: hazard type, such as “rainfall extremes” or “heavy precipitation”, or “hot extremes” or “heatwaves”; nation or region, such as “Western Canada”, “Western United States” or “Western North America”; a finally an indication of analysis of changes, such as “trend” or “climate change”. Regional, continental and global studies of changes in extremes indices were also searched for in a similar way. No fully systematic approach was taken due to differences in the naming of hazards and extremes indices across the literature, and heterogeneity in the scale of both IPCC regions and nations.

3.2.1 Eastern North America (ENA)

For Eastern North America (ENA), AR6 reported evidence of a significant intensification in heavy precipitation though with a lack of a significant trend over Canada, which makes up a small part of the northern edge of the domain (Table 2). This is based on several studies combining both event attribution from an event occurring within the region (e.g. [39]) and one that later passed into the region, as analyses of Hurricane Harvey were included in the AR6

assessment (e.g. [28,40–43]), as well as trend analyses (e.g. [16,17,44]), and detection and attribution analysis (e.g. [45]).

For the evidence up to AR6, considering the first step in the flowchart (Figs. 3 & 4), we take into account several factors. Across the abundance of studies, while there is subregional variation in both evidence availability and findings, the increasing trends dominate the region geographically and in the strength of change. The increases are in line with expectations of increasing precipitation due to the thermodynamic response of increased water vapour availability in a warmer atmosphere, known as the Clausius-Clapeyron (CC) relationship, as well as additional physical factors. For instance, 'dynamical amplification', in which increased latent heat due to CC-related results in further vertical ascent, thus resulting in further precipitation, is also known to result in super-CC scaling for temporally shorter events [46], along with other local factors [32]. Furthermore, this region has excellent observational data coverage and many of the trends are found to be statistically significant. Drawing these lines of evidence together, an increasing trend was reported for the region.

Considering step 2, we isolate the body of attribution studies, which are consistent in finding evidence of a human influence on such extremes. Step 3 then requires an assessment of the confidence in this attribution, which is based on a range of factors. First, we recall that there is a subregional variation in the evidence of trends, which poses an important caveat to any regional-scale finding. Second, we consider an additional array of factors beyond those for step 1. Only one event attribution study was quoted for a single type of hazard, and which is based on only one climate model (Teufel et al., 2019). Additional attribution evidence arises from regional-scale changes in extreme indices, which provides a complementary line of evidence. Overall, it was concluded that while there was evidence of a human contribution to some events, this could not be generalised across the region due primarily to a lack of sufficient evidence, and was therefore ranked as low confidence.

Incorporating evidence up to the end of 2025, as well as studies that were not explicitly included in the AR6 assessment, adds substantially to this picture. First, a study using updated observational and reanalysis data found that wet day precipitation is increasing across most of eastern Canada [47], while a separate study assessing changes in the wettest day in each season found increases in all seasons (and statistical significance in 3/4) when averaged across ENA [18]. This reduces subregional variation in evidence availability and qualitative signal and therefore reinforces that there are increasing extremes in the region. For question 2, all additional attribution evidence is consistent with a human influence. Finally, for question 3, this body of studies now encompasses studies for multiple different hazards in multiple subregions, employs multiple attribution methods and datasets, assesses events and trends over different spatiotemporal scales and in different seasons [48–55], thus constituting high confidence across most dimensions of potential variation. There is therefore high confidence in attribution of the observed increase in heavy precipitation extremes to human influences.

ENA	Evidence (Observational and attribution literature)	Synthesis steps	Summary
Up to AR6	Significant intensification of heavy precipitation (Wu, 2015; Easterling et al., 2017; Emanuel, 2017; Risser and Wehner, 2017; van Oldenborgh et al., 2017; Trenberth et al., 2018; S.-Y.S.Wang et al., 2018; Dunn et al., 2020; Sun et al., 2021), but a lack of a significant trend over Canada (Shephard et al., 2014; Mekis et al., 2015; Vincent et al., 2018) Evidence of a human contribution for some events (Easterling et al., 2017; Teufel et al., 2019; Kirchmeier-Young and Zhang, 2020), but cannot be generalized	1. Yes - Increasing trends consistent across studies but not in southeastern Canada 2. Yes - Consistent attributable signals 3. Low - Studies include regional average / gridded trends, one event attribution from far northern edge of domain using single model	Low confidence (limited evidence)
Up to 2025	Significant intensification of heavy precipitation (Dai et al., 2025, Barnes et al., 2025) Evidence of a human contribution to observed intensification of extreme precipitation (van der Wiel et al., 2016; S.-Y.S.Wang et al., 2016; Hoerling et al., 2021, Huang et al., 2021, Reed et al., 2020, Kirchmeier-Young et al., 2021, Clarke et al., (2024)*, Clarke et al., 2025*).	1. Yes - Increasing trends consistent across studies, formerly not seen in southeastern Canada, several studies now provide evidence for this 2. Yes - Consistent attributable signals 3. High - Studies on events from across spatial scales and subregions, range of observations and models, different event types, different methods	High confidence

Table 2: Summary of regional evidence and synthesis process for the Eastern North America region using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

3.2.2 New Zealand (NZ)

For New Zealand, AR6 reported there was a lack of agreement on the evidence of trends [17,56,57] and limited evidence of a human contribution to observed intensification of extreme precipitation [58].

Since the publication of AR6, numerous attribution studies focused on the New Zealand region have been published, strengthening confidence in our understanding of the anthropogenic intensification of extreme precipitation in the region. Frame et al. (2020)[59] presented a sequence of probabilistic attribution analyses for multiple heavy rainfall events between 2007 and 2017, all relying on a large initial-condition ensemble of simulations from a single regional climate model. Most events showed a small but nevertheless non-zero attributable increase in the likelihood of witnessing the heavy rainfall event in question. Stone et al. (2022)[60] sought to examine an array of different methods and modelling tools commonly used in attribution studies, using a sequence of case study events through which to explore any differences in the subsequent attribution analyses. While specific differences emerged for selected combinations of models and modelling frameworks, there was broad consistency in the attributable increase in both the frequency and intensity of rainfall events around the country, focusing on four heavy rainfall events in April 2017 (entire North Island), July 2017 (Otago), May 2021 (Canterbury) and July 2021 (Westport).

Alongside probabilistic attribution studies, several forecast attribution studies have also been published from the region [61]. This includes a 2024 paper by Stone and colleagues which systematically demonstrates the total amount of rainfall associated with Cyclone Gabrielle (February 2023) was 10% more intense than if an identical weather system occurred in a pre-industrial world, while the most impactful (and intense) individual hours of the storm recorded attributable intensification rates nearer 20% [31].

Since AR6, there have also been an array of new studies improving our understanding of future projected changes in extreme rainfall over New Zealand which are relevant to inform our process-based understanding of attributable rainfall changes under current levels of global warming. This includes demonstrating the importance of higher-resolution models to capture the processes responsible for producing heavy rainfall over New Zealand, particularly to resolve orographic processes [31,60] but also the broader dynamical controls on the occurrence and severity of both atmospheric river [62] and tropical cyclone events [63].

The intensity of the wettest days of the year is projected to increase with additional global warming across all of New Zealand [31,60,62,64–67]. The frequency of extreme rainfall events

is also projected to increase with future warming, though very high interannual variability in the occurrence of heavy rainfall events reduces confidence in projected changes in the frequency of extreme rainfall events for any individual region [67,68].

NZ	Evidence (Observational and attribution literature)	Synthesis steps	Summary
Up to AR6	Lack of agreement on the evidence of trends (Donat et al., 2016a; Dunn et al., 2020; MfE and Stats NZ, 2020) Limited evidence (Rosier et al., 2015)	1. No - mixed trends across region 2. N/A 3. N/A	No trend (limited agreement)
Up to 2025	Intensification of heavy precipitation in parts of the region (Rosier et al., 2025), mixed elsewhere. Evidence of a human contribution to the observed intensification of heavy precipitation (Tradowsky et al., 2023, Stone et al., 2022, Harrington et al., (2023)*, Stone et al., 2024, Frame et al., 2020)	1. Yes - NZ-specific studies showing increases at locations across the country, albeit at variable rates, some locations showing opposite trends. 2. Yes - One event study found no clear signal due to known modelling challenges, but strong observed increases. Other studies for the same event and others all found increases. 3. Medium (limited agreement) - Broadly consistent increases, several events across subregions and spatial scales, similar temporal scales, multiple methods, multiple hazard types. Some events show unclear signals and/or caution over-interpretation. Mixed trends weaken evidence.	Medium confidence (limited agreement)

Table 3: Summary of regional evidence and synthesis process for New Zealand using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

3.2.3 Eastern Southern Africa (ESAF)

For Eastern Southern Africa (ESAF) AR6 reported an increase in heavy precipitation with medium confidence based on two global studies. Donat et al. 2013 [69] analysed several indices based on the HadEX observations and found rather mixed trends for heavy precipitation in the region, depending on the season, but a relatively strong increase in RX5day. Sun et al., 2021 [16], corroborated this finding an increase in heavy precipitation in the IPCC ESAF region for RX1day and RX5days. As the region was not covered in any attribution study at the time of AR6 there is no attribution statement made due to limited evidence.

Since the publication of AR6, four attribution studies covering parts of the region have been published [70–73], as well as one additional trend analysis [74]. This brings the number of studies that can answer the first question up to seven. All of these report an increase in heavy rainfall, despite examining different rainfall metrics and focusing on different parts of the region, which strengthens confidence in the overall signal. While subregional or seasonal variations are often an important caveat in precipitation analyses, they are less relevant here because the reported changes all occur within the clearly defined rainy season, indicating that the signal is coherent within the dominant rainfall period. The intensification of rainfall is broadly consistent with expectations from thermodynamic reasoning related to atmospheric moisture increases, and is based on a range of estimates from both gridded observational and reanalysis datasets and rain gauge measurements that concur with [74]. However, subregional variations in the observed and attributable trends make it difficult to quantify the magnitude of the change. As a result, it is currently not possible to determine whether the increase follows Clausius–Clapeyron scaling or represents a stronger response, such as the very large (~60%) increase in rainfall intensity reported by Clarke et al. (2025)[71] and Engelbrecht et al., (2025)[70] (~40%) suggests. Nevertheless, despite uncertainty in magnitude, the available evidence consistently supports an increase in rainfall intensity.

The available attribution studies indicate that anthropogenic climate change has contributed to the observed increase in rainfall intensity. Pinto et al. (2022)[73] find that climate change has approximately doubled the likelihood of rainfall events such as those analysed in Kwa-Zulu Natal. Otto et al. (2022)[72], focusing specifically on rainfall associated with tropical cyclones, conclude that greenhouse gas and aerosol emissions have played a role in the observed increases, although they do not quantify the magnitude of the attributable signal. A similar conclusion is reached by Clarke et al. (2025)[71], who also find evidence of a contribution from anthropogenic forcing but refrain from providing a quantitative estimate. Taken together, these studies provide consistent evidence that part of the observed trend can be attributed to climate change. While uncertainties remain substantial, particularly regarding the exact magnitude of the anthropogenic contribution, the overall body of attribution literature supports the conclusion that human influence has increased the likelihood or intensity of these rainfall events. A fourth study,

employing a storyline approach (Engelbrecht et al., 2025) found a 40% increase in intensity attributable to human-induced climate change.

Confidence in the attribution of this increase to anthropogenic climate change is somewhat lower than confidence in the observed trend itself. In particular, because climate models tend to perform poorly in representing rainfall extremes in this region, adding further uncertainty to attribution estimates. There is, however, still the physical reasoning that rainfall extremes intensify at least in line with Clausius–Clapeyron relationship. Furthermore, the existing studies are broadly consistent in identifying a human influence, despite differences in how events are defined across subregions and seasons. Finally, the available studies apply a range of independent methodological approaches. For example, Engelbrecht et al. (2025) use a highly conditional storyline approach, while the other three studies employ probabilistic attribution frameworks. Considering the agreement across these independent studies, as well as the diversity in regional focus and methodological approaches, there is medium confidence that anthropogenic climate change has contributed to the observed increase, despite the comparatively poor data quality and no study explicitly looking exactly at the IPCC defined region.

ESAF	Evidence (Observational and attribution literature)	Synthesis steps	Summary
Up to AR6	Intensification of heavy precipitation (Donat et al., 2013b; Sun et al., 2021) Limited evidence	1. Yes - consistent increases 2. No - no studies 3. N/A	Trend, no attribution (limited evidence)
Up to 2025	Intensification of heavy precipitation (Grab & Nash, 2023). Evidence of a human contribution to observed intensification of extreme precipitation (Pinto et al., 2022* , Otto et al., 2022* , Clarke et al., 2025* , Engelbrecht et al., 2025)	1. Yes - consistent increases 2. Yes - consistent increases 3. Medium (limited evidence) - broadly consistent results, across subregions and different seasons, multiple hazard types, multiple approaches using multiple models, model quality generally poor	Medium confidence (limited evidence)

Table 4: Summary of regional evidence and synthesis process for the Eastern Southern Africa region using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

3.2.4 South American Monsoon (SAM)

For the South American Monsoon region, AR6 reported that there was no observed trend due to limited evidence. This was from a combination of insufficient data coverage across the region and insignificant trends where data was available (Table 5), and emerges from analyses of changes in extreme indices based on weather station data [16,17,75], and gridded reanalysis and climate model datasets [76,77]. Considering the first question in the flowchart, there is a clear lack of evidence across the region due to sparse in-situ observations. This is further compounded by variation in trends across both datasets and extremes indices in reanalyses and models.

The evidence base has increased since AR6. Specifically, analysis of HadEX3 finds a significant intensification of Rx1day across all seasons [18]. While this remains caveated by the comparatively limited data coverage in this region (and much of the Southern hemisphere), this is also in agreement with model-based analysis [77], though CMIP6 models perform poorly at reproducing this trend. Considering question 1, while there is still mixed agreement in the region across different datasets and spatial coverage is relatively low, the evidence for the observed changes is strong and significant, suggesting medium confidence of an increasing trend.

For the second question, two studies assess the anthropogenic influence on rainfall extremes in the region, one on changes in grid- and regional-scale extremes at benchmark return periods using a large ensemble of atmosphere-only climate models [77] and an event attribution study on 4-month (December-March) precipitation over the Juruá River Basin using the HadGEM3-A climate model [78]. Both studies find attributable increases in such extremes due to present warming.

Moving to the third question, we assess our confidence in this finding. The two attribution studies cover a range of temporal scales, lending robustness to the finding. However, several limitations remain. First, these studies are based only on climate models (albeit with some validation using observations) and employ similar probabilistic methods. Second, grid-scale analyses suggest subregional variations in the attributable changes, with disagreements across models on the spatial structure of this. Finally, confidence is hampered by the lack of evidence on observed trends over parts of the region and the poor performance of CMIP6 models at reproducing observed trends. As a result, confidence remains low, primarily due to limited evidence.

SAM	Evidence (Observational and attribution literature)	Synthesis steps	Summary
Up to AR6	Insufficient data coverage and trends in available data are generally not significant (Avila-Diaz et al., 2020; Dereczynski et al., 2020; Dunn et al., 2020; Sun et al., 2021) Evidence of a human contribution for some events (S. Li et al., 2020), but cannot be generalized	1. No (limited evidence) - poor data coverage, non-significant 2. N/A 3. N/A	No trend (limited evidence)
Up to 2025	Intensification of heavy precipitation (Dai et al., 2025) Evidence of a human contribution to the observed intensification of heavy precipitation (Quevedo et al., 2025)	1. Yes - increases across all seasons, all significant 2. Yes 3. Low (limited evidence) - additional study on 4-month precip, single model	Low confidence (limited evidence)

Table 5: Summary of regional evidence and synthesis process for the South American Monsoon region using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

3.2.5 Mediterranean (MED)

At the time of AR6 there was a substantial evidence base on trends in heavy precipitation, with 12 studies cited covering most of the region (Table 6). Many of these studies are based on analysis of some or all of the standard set of indices produced by the Expert Team on Climate Change Detection and Indices (ETCCDI; e.g. [17]), including both near-term projections (e.g. [79]) and historical trends (e.g. [80,81]). Despite the abundance of evidence, the AR6 concluded that there was a “lack of agreement on the evidence of trends”, suggesting a result of ‘No, due to limited agreement’ within question 1 of the framework developed here.

In general, studies display agreement for specific subregions. For instance, Ribes et al., (2018) [80] and Jacob et al., (2018)[79] find increases in the wettest day (Rx1day) and wettest consecutive 5-day period (Rx5day) in southern France, respectively. Dunn et al., 2020 [17] find

comparable results for Rx1day, albeit with minor subregional variation. However, there are two primary sources of disagreement or inconsistency. One arises when considering different indices. For instance, contrary to the findings above, in southern France [Dunn et al., 2020](#) also find decreasing (or no) trends in the number of days with precipitation exceeding 10 mm. This is a minor disagreement that can be reconciled as a likely change in the character of precipitation, with a decrease in moderate rainy days but an intensification of extremes. However, the larger source of disagreement arises due to subregional heterogeneity. For instance, in the western Mediterranean, the increases in indices such as Rx1day (or Rx5day) in southern France and the western Iberian peninsula contrast with decreases (or no change) in the southern central and eastern Iberian peninsula ([Jacob et al., \(2018\); Dunn et al., 2020](#)), as well as strong seasonal variation in Croatia [82]. Similarly, in the eastern Mediterranean, the region including Greece and Turkey shows significant increases in Rx5day while the subregion further south, covering parts of Syria, Lebanon and Israel shows decreasing trends [81]. This also contrasts with Rx1day, with most locations across Turkey also showing significant decreases [81].

Compared to many other IPCC regions, the Mediterranean is both large and climatologically diverse, encompassing temperate, continental and semi-arid areas from the Iberian Peninsula to parts of central Europe and west Asia around Greece and Turkey, as well as temperate, semi-arid and arid regions of both west Asia and North Africa. This lack of agreement can therefore be attributed to strong variation in trends at a subregional scale, illustrating the challenge of synthesising evidence across different climate zones.

When considering the evidence up to 2025, a comprehensive review on studies of daily extreme rainfall trends in the Mediterranean provides a clear message: “The evidence does not support a basin-wide intensification of extreme precipitation, and observed trends appear more strongly influenced by local geographic and synoptic factors, or linked to specific analysis time windows, than by a coherent signal of global climate forcing.” [83]. Since AR6, several event attribution studies have been conducted for events around the region. Some studies find an influence of anthropogenic climate change for events in the region, with increasing extreme rainfall around the Black sea [84,85], Portugal [86], and associated with Storm Alex in southern France and northern Italy [87]. However, one did not find a signal for extreme rainfall in Emilia-Romagna [88], and more broadly these studies do not contradict the findings of the review above. We therefore conclude that there is still no evidence of trends due to limited agreement, which can be primarily attributed to strong subregional variation in the direction of trends.

MED	Evidence	Synthesis steps	Summary
	(Observational and attribution literature)		

Up to AR6	Lack of agreement on the evidence of trends (Casanueva et al., 2014; Donat et al., 2014a; de Lima et al., 2015; GajićČapka et al., 2015; Rajczak and Schär, 2017; Jacob et al., 2018; Mathbout et al., 2018b; Ribes et al., 2019; Dunn et al., 2020; Peña-Angulo et al., 2020a; Coppola et al., 2021a; Sun et al., 2021) Limited evidence (Añel et al., 2014)	1. No (limited agreement) - strong subregional variation 2. N/A 3. N/A	No trend (limited agreement)
Up to 2025	Lack of agreement on evidence of trends (Gonzalez-Hidalgo & Begueria, 2025) Evidence of a human contribution for some events (Zachariah et al., (2023)* , Pons et al., 2025 , Terray & Bador, 2025 , Zachariah et al., 2024*), but not others (Barnes et al., (2023)*). Cannot be generalized.	1. No (limited agreement) - strong subregional variation 2. N/A 3. N/A	No trend (limited agreement)

Table 6: Summary of regional evidence and synthesis process for the Mediterranean region using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

3.2.6 South Asia (SAS)

At the time of the AR6, there was high confidence in an observed increase in heavy precipitation, supported by numerous observational studies [17,89–95]. However, confidence in attributing these changes to anthropogenic climate change was low. This was largely because only a small number of attribution studies were available [96–98], focussing on very localised events and reporting contrasting results. These inconsistencies were thought to arise in part from the complex influence of anthropogenic aerosols, which can modulate regional precipitation responses and obscure the underlying greenhouse-gas-driven signal as has also been observed in a more detailed assessment of the South Asian monsoon in chapter 8 of the AR6 [11].

The strong evidence for an observed increase in heavy rainfall has been further strengthened since AR6. An additional global analysis by Dai et al. (2025) [18] identifies a detectable increasing trend in the region. In parallel, a growing number of attribution studies focusing on

individual extreme rainfall events in the region [26,29,99–103] have also documented consistent increases in heavy rainfall. Taken together, this expanded body of literature reinforces the observational evidence and strengthens the overall assessment. As a result, the answer to the first question remains a yes with high confidence.

All available studies, including the global analysis by Dai et al., (2025) identify an attributable increase in heavy rainfall in the region during the monsoon season, where most of the heavy rainfall occurs. The magnitude of the attributable signal varies across studies but is broadly consistent with expectations based on the Clausius–Clapeyron relationship. Importantly, the studies show a high degree of agreement despite employing very different methodological approaches and datasets.

Only one study ([Dhasmana et al., 2023](#))[104], which examined a specific extreme event in Kerala, reported an attributable decrease in likelihood or intensity. However, another study analysed the same event using a similar methodological framework but with a larger set of climate models and instead found an attributable increase. This suggests that the divergent result is likely related to differences in model sampling rather than a fundamentally inconsistent signal. Considering the relative strength and quality of the available evidence, the overall literature consistently supports the presence of an attributable anthropogenic signal in the observed increase in heavy rainfall.

With regard to confidence in the attribution, we assess high confidence that anthropogenic climate change has contributed to the observed increase in heavy rainfall. The available studies consistently identify a positive attributable signal, with results that are broadly consistent with expectations based on the Clausius–Clapeyron relationship. Importantly, this conclusion is supported by multiple independent lines of evidence as the studies employ a range of methodological approaches, including different probabilistic attribution frameworks and storyline approaches, yet arrive at similar conclusions. In addition, the evidence spans multiple hazard types (e.g., seasonal precipitation and rainfall associated with specific events) and covers several subregions within the broader IPCC SAS region. Finally, it is in agreement with findings about strong wettening monsoon rains with further warming [105]. The consistency of results across these diverse methods, event definitions, and geographical contexts provides a robust basis for assessing high confidence in the attribution of increasing heavy rainfall to human influence for the heaviest rain in the year.

SAS	Evidence (Observational and attribution literature)	Synthesis steps	Summary
Up to AR6	Significant intensification of heavy precipitation (Hussain and Lee, 2013; Singh et al., 2014a; Pai et al., 2015;	1. Yes - consistent trends	Trend, no attribution

	Sheikh et al., 2015; Malik et al., 2016; Roxy et al., 2017; Kim et al., 2019; Dunn et al., 2020) Disagreement among studies (Singh et al., 2014b; van Oldenborgh et al., 2016; Mukherjee et al., 2018b)	2. No - disagreement among studies, influence of aerosols 3. N/A	(lack of agreement)
Up to 2025	Significant intensification of heavy precipitation (Dai et al., 2025) Evidence of a human contribution to observed intensification of extreme precipitation during summer monsoon season (Dong et al., 2022 , Otto et al., 2023 , You et al., 2024 , Zachariah et al., 2024* , Weisheimer et al., 2025 , Zachariah et al., 2025* , Kew et al., 2025* , Dai et al., 2025), but not for some events (Dhasmana et al., 2023), and not in winter (Dai et al., 2025).	1. Yes - consistent trends 2. Yes - consistent attributable signals 3. High - consistent signals, multiple methods, multiple hazard types, multiple subregions and spatiotemporal scales	High confidence

Table 7: Summary of regional evidence and synthesis process for the South Asia region using the evidence available at the time of AR6 (top row) and until the end of 2025 (bottom row).

4. Hexagons for AR7 and beyond

In this final section we apply the new format of the figure and the steps for collating evidence to integrate the evidence that has emerged since AR6. We highlight how the understanding of extremes and the anthropogenic influence upon them has evolved, and where the evidence base is still limited. In doing so we highlight the value for more regular updates by the community. Finally, we set out the key takeaways and discuss potential next steps for these regional summaries.

4.1 Updated hexagons

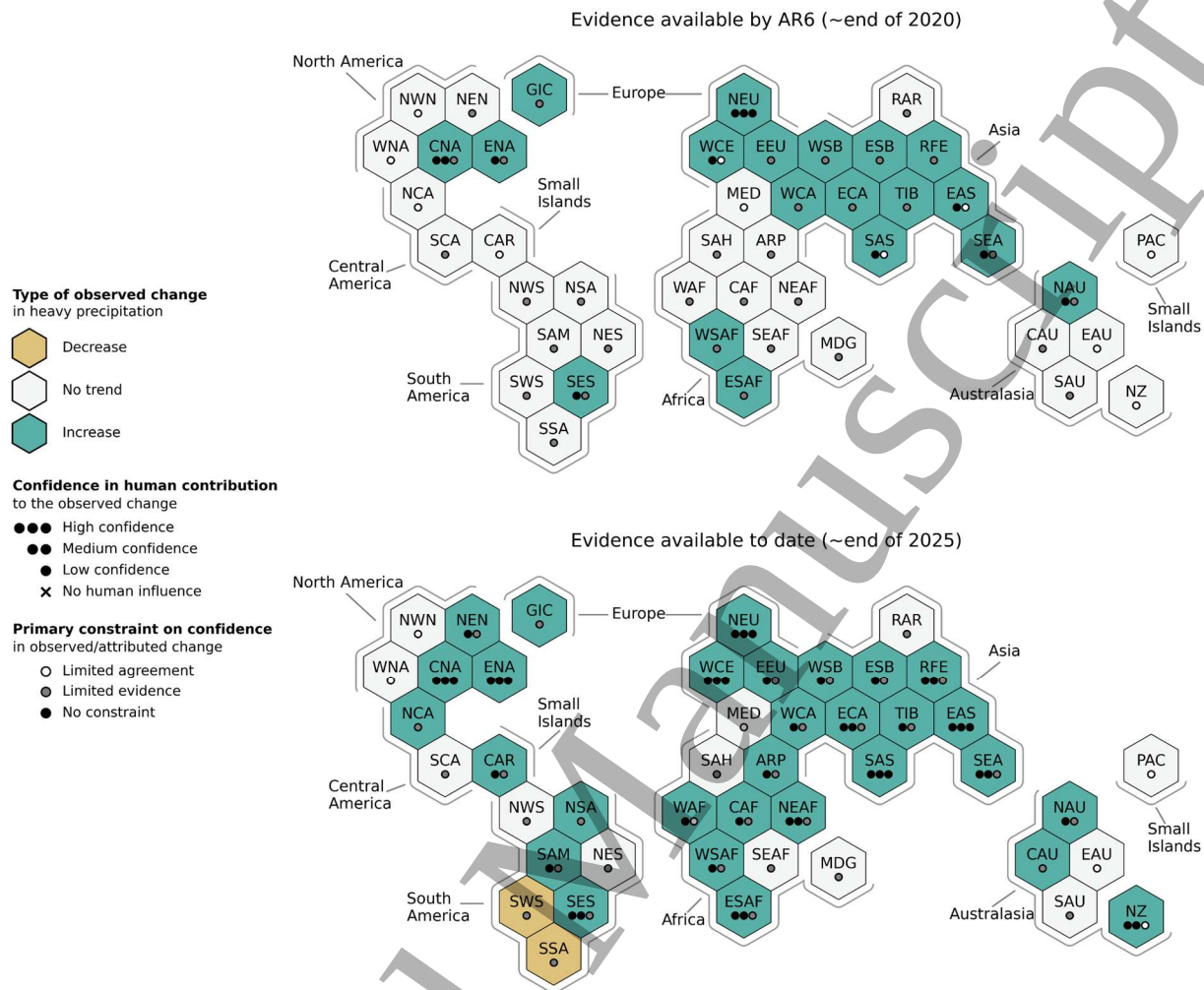


Figure 6: Figure SPM.3b recreated using the proposed system developed here for evidence available to AR6 (top panel) and up to the end of 2025 (bottom panel). The colour of the hexagon denotes the presence and direction of an observed trend, with teal for an increasing trend, light brown for a decreasing trend, and white for no trend. Black dots (x's) show the confidence with which this observed trend is (not) attributable to human influence, with 0,1,2 and 3 black dots representing no attribution and low, medium and high confidence in the attribution, respectively. The hollow white and grey dots show what factor primarily restricts the summary from reaching the subsequent tier of confidence, whether it is due to limited agreement or limited evidence, respectively. The data in this figure should be interpreted as broad regional summaries and as a foundation for further investigation of hazards and risks. While important subregional or seasonal changes in extremes are highlighted where possible, they may in some cases be too complex to display on this scale. Note that important region-specific caveats are also included in the accompanying evidence tables.

4.1.1 Heavy precipitation

Figure 6 shows the hexagon figure for heavy precipitation using the system developed in this paper for evidence available as of AR6 and as of the end of 2025. Clearly, there has been a substantial increase in regions in which a change in this hazard is observed, from roughly 42% to around 71% by 2025 (Table 8), with the most widespread changes across Africa and the Americas. Similarly, the number of regions with attributable evidence has risen substantially, with a notable increase across large parts of Asia. Interestingly, the overall number of regions in which there is an observed change but low (or no) confidence in attribution of this change to human influence has remained similar. This is because of a huge rise in the number of regions of medium or high confidence in attribution, from 2 to 13 regions (1 to 7 and 1 to 6, respectively), coupled to a similarly large decrease in regions with no detectable trend (26 to 13; Table 8), suggesting a rise across much of the world. It is also noteworthy that two regions (SWS and SSA) now show robust decreases in heavy rainfall. While this is not well represented in climate models and attribution evidence is limited, this change is hypothesized to be due to reductions in westerly flow associated with warming, which in turn has reduced orographic rainfall over the Andes [18,106].

Figure 7 shows the total number of studies feeding into this evidence base for each region at AR6 and by 2025. First, there are clear hotspots in the geographical distribution of research in both phases, in particular East Asia (EAS), Eastern North America (ENA), Western Central Europe (WCE), South Asia (SAS), and the Mediterranean (MED). These regions reflect both high densities of researchers but also high concentrations of both impactful extremes and overall populations. These regions have also all seen a rise to high confidence except for MED, in which observed changes remain too diverse to summarise meaningfully. Second, while there have been new studies conducted in most regions of the world, there remains a clear geographical heterogeneity, with few studies across much of Africa and none in Pacific Island nations, the Sahara, or Russian Arctic.

Evidence period	Trend, confidence in attribution to human influence			No trend	
	High	Medium	Low (or no)	Limited agreement	Limited evidence
AR6	1	1	17	8	18
Up to 2025	6	7	19	5	8
Change	+5	+6	+2	-3	-10

Table 8: Summary of levels of evidence of changing heavy precipitation extremes in each region presented in the sixth assessment report of the IPCC and updated to include evidence available by the end of 2025.

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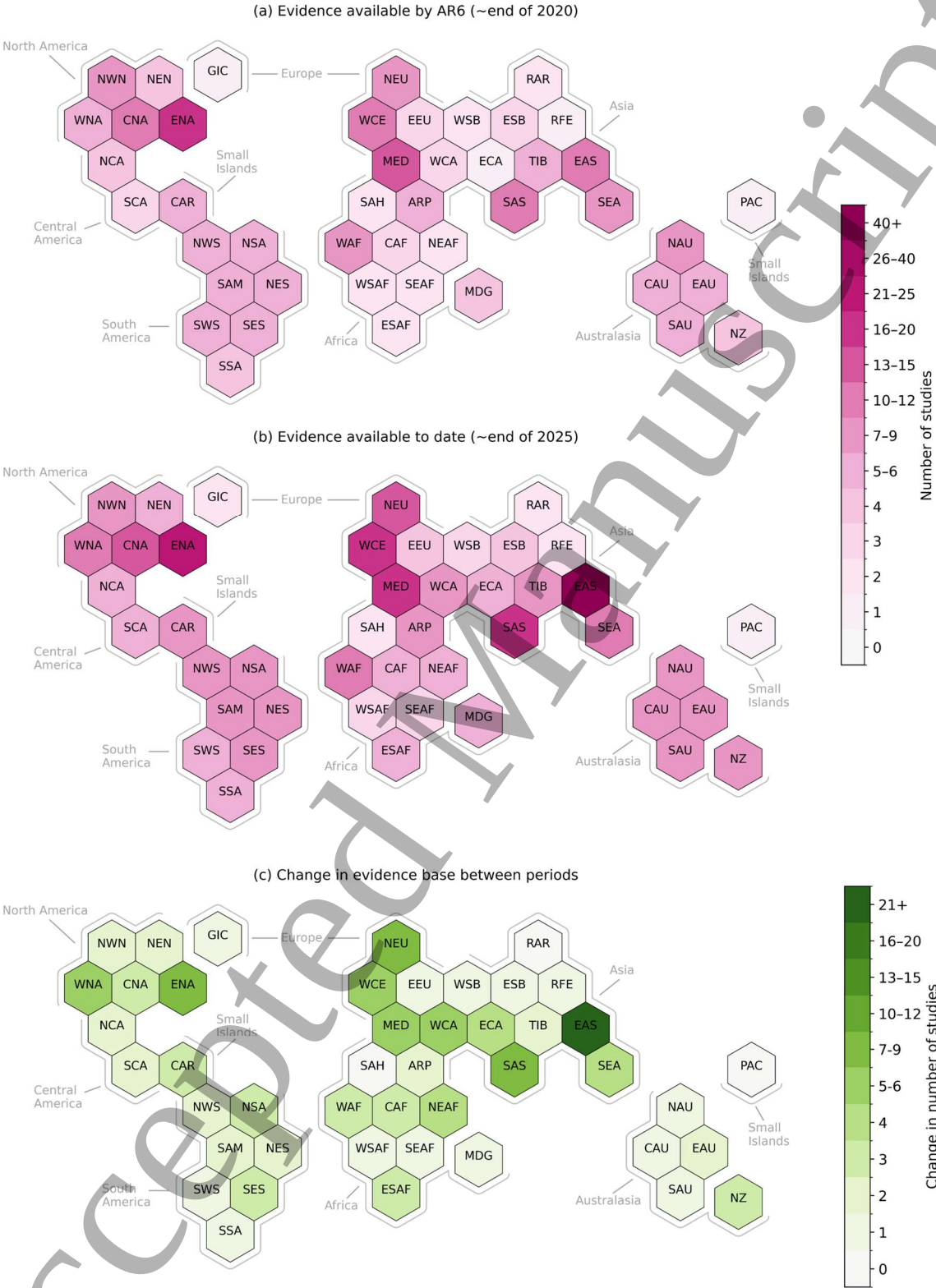


Figure 7: Total number of studies contributing to evidence base for each period (panels a and b) and the change between them (panel c) for each region, corresponding to the new evidence available from 2021-2025.

4.1.2 Other extremes

For hot extremes, the updated evidence tables, hexagon maps and statistics of evidence tiers are shown in the Supplementary material (Tables S7-S12, Fig. S1; Table S13). Almost all regions are now in the high confidence tier due to an array of new studies, with 38/45 regions at high confidence, 6/45 at medium, and the remaining region (SSA) at ‘no trend’ due to limited evidence with no dedicated studies for the region. There are similar research hotspots to those for heavy precipitation, with a host of new studies in Europe and EAS in particular. Medium confidence is found in 6 regions, with two distinct categories. Low agreement is found in two regions of North America (CNA and ENA), which have mixed warming signals both across subregions and heat indices. Meanwhile, medium confidence due to limited evidence is found across the small island regions (CAR and PAC), and parts of Latin America (NSA, which includes most of the Amazon basin, and SWS, which includes most of Chile). To enable further comparison of the system proposed here with that employed in AR6, we have also recreated the final panel of Figure SPM.3 on agricultural and ecological drought (Fig. S2).

4.2 Next steps

The rapid rise in event and trend attribution studies, as well as the ongoing rapid heating of the atmosphere and oceans leading to changing extremes, necessitates regular updates of the scientific understanding of these changes. While AR6 of the IPCC provided a visually clear and compelling way to summarise and present this information with the ‘Hexagon’ figures, these changes are now occurring more rapidly than can be met by IPCC cycles alone. AR7 should therefore present new and updated versions of these figures and facilitate more regular updates. Given the rate of production of attribution studies, we suggest annual updates are appropriate, commensurate with other key climate indicators [13]. In this article, we have provided a platform for the updates in AR7 and beyond by: refining the format of the figures to provide more information; building on the AR6 regional synthesis process with a step-by-step procedure; applying this to six illustrative regional case studies; updating the evidence tables and figures directly for hot extremes and heavy precipitation.

Beyond the hazards presented here, the massive expansion in the attribution literature also means that many other hazard types would now benefit from this format. For instance, changes in fire weather indices are now increasingly observed and attributed for different regions around the world, with both major individual events and active seasons studied in recent years [107,108].

The use of higher resolution modelling frameworks and synthetic storm models has also enabled

the study of human influences on extreme wind speeds from different types of events. The development of coastal and ocean hexagons could enable inclusion of impactful marine heatwaves, which are known to be robustly warming due to human influence. Finally, compound events as an entire meta-category of hazards are increasingly studied, with almost all attribution studies conducted since 2021; regional summaries of these studies would highlight the emerging literature, and could be disaggregated by specific compound event type as the evidence base grows.

As attribution is increasingly operationalised with regular updates and recognised service providers, it may be possible to integrate this synthesis as part of a wider effort to assess and iterate the state of knowledge. Key considerations in such a system include how to ensure the inclusion of non-english language evidence, which methodologies and groups/centres would qualify for automatic inclusion, a standardised format for submitting other evidence, and a version control system to ensure consistency over time. The latter, for instance, could be maintained through a database using standard elicitation templates for the various studies and expert judgments, as is shown as a template in table S14 and an example region in S15.

To conclude, AR7 will soon provide a major update to our collective knowledge and awareness of changing extremes and the human influence upon them; we should not and do not need to wait until AR8 to do so again.

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