3

Attribution Science

Insights into Climate Change and Its Consequences

*Carly A. Phillips, L. Delta Merner, and Friederike Otto**

3.1 INTRODUCTION

The consequences of climate change are growing increasingly severe, leading to significant damages and losses globally. As a physical process, the science is overwhelmingly clear – more than a century of burning fossil fuels and degrading ecosystems has led to an accumulation of greenhouse gases in the atmosphere, raising global temperatures, acidifying oceans, and amplifying extreme events.[1] Warming ocean waters and marine heatwaves have led to widespread coral bleaching and mortality. On land, extended droughts have increased tree mortality, while priming forests for severe wildfire.[2] Building on the introduction to climate science in the preceding chapter, this chapter provides an overview of the science establishing these causal links, attribution science, as presented in the Intergovernmental Panel on Climate Change (IPCC), and it further explores three types of attribution science – trend, source, and event – to understand the current state of the science and research findings globally.

The IPCC stands as an authority in the realm of climate attribution science. Through its rigorous evaluations and synthesis of scientific research, the IPCC has brought clarity and consensus to understanding how human actions are directly linked to climatic shifts and extreme weather events. Its comprehensive assessments have solidified and contextualised the role of attribution science as a fundamental aspect of our understanding of climate change. Climate attribution science, which

* Carly A. Phillips is a research scientist with the Science Hub for Climate Litigation at the Union of Concerned Scientists. L. Delta Merner is a lead scientist with the Science Hub for Climate Litigation at the Union of Concerned Scientists. Friederike Otto is a senior lecturer in climate science at the Grantham Institute for Climate Change and the Environment at Imperial College London.

[1] 'IPCC, 2023: Summary for Policymakers' in Hoesung Lee and others (eds), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2023).

[2] 'IPCC, 2022: Summary for Policymakers' in Priyadarshi Shukla and others (eds), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2022).

identifies and quantifies the contribution of human-induced climate change to global trends and extreme events, reveals critical insights about how human-caused climate change has and continues to impact communities worldwide.[3] Event attribution research has been around for about two decades, which makes it a comparatively new scientific endeavour. In that short time, however, the field has made impressive advances and is growing rapidly. By comparing models of Earth's climate with and without human influence as well as weather observations of past and present, studies in this field can now explain how climate change makes a heatwave hotter or a heavy rainfall event more intense.[4]

Source attribution science traces the origin of the pollutants that cause climate change and quantifies their role in driving climate impacts.[5] This research determines the relative contributions of different emission sources, including governments, oil and gas, agriculture, and other sectors, to the overall increase in concentrations of heat-trapping gas in the atmosphere and subsequent impacts like sea level rise and global temperature increase.[6] This research is particularly useful since significant portions of the emissions driving climate change can be traced to a relatively small number of actors.[7]

With this foundation, the chapter will delve into specific regional impacts, showcasing how attribution science has illuminated the ways in which different parts of the world – Africa, the Americas, Europe, the South Pacific, and Asia – are experiencing and responding to the unique challenges posed by a changing climate.

3.2 CLIMATE ATTRIBUTION SCIENCE

Climate attribution science is an umbrella term that encompasses distinct yet intertwined scientific research subfields. This section provides context on the integration of attribution science in the IPCC, establishing attribution as a robust scientific field. It further explores three types of attribution science: trend, source, and event. Each represents a critical aspect of our understanding of climate phenomena. Trend attribution systematically analyses long-term climatic shifts, discerning patterns amidst the global climate upheaval. Source attribution rigorously traces the

[3] 'IPCC, 2023: Section 2.1.2' in Hoesung Lee and others (eds), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2023).

[4] Sonia I. Seneviratne and others, 'Chapter 11: Weather and climate extreme events in a changing climate' in Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

[5] Brenda Ekwurzel and others, 'The rise in global atmospheric CO_2, surface temperature, and sea level from emissions traced to major carbon producers' (2017) 144 Climatic Change 579–590.

[6] ibid.

[7] Richard Heede, 'Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers 1854–2010' (2014) 122 Climatic Change 229–241.

genesis of these changes, pinpointing the human and natural factors contributing to our evolving climate. Event attribution, with its focus on acute phenomena, examines specific extreme weather occurrences, elucidating their links to broader climatic trends. By exploring the definitions, scope, methodologies, and examples of studies within each domain, this chapter provides insight into how these three facets of attribution science have evolved in parallel, offering distinct yet complementary perspectives for understanding climate change.

3.3 ATTRIBUTION SCIENCE IN THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The IPCC is an international body that provides the world with objective, scientific information about climate change. Established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has become the foremost authority on climate science, synthesising research from thousands of scientists across the globe. Its comprehensive assessment reports, released every few years, are critical in informing international policy and debate on climate change. By rigorously analysing and compiling the latest scientific findings, the IPCC plays a vital role in enhancing global awareness and guiding policy decisions aimed at mitigating and adapting to the effects of a warming world.

The IPCC operates through structured assessment cycles that culminate in comprehensive reports. Within each cycle, the IPCC organises its work into three Working Groups, each focusing on a distinct aspect of climate change. Working Group I (WG1) deals with the physical science basis of climate change, synthesising the latest scientific findings on climate processes, changes, and impacts. Working Group II (WG2) addresses climate change impacts, adaptation, and vulnerability, offering insights into how climate change affects natural and human systems and potential ways to adapt. Working Group III (WG3) tackles the mitigation of climate change, exploring strategies and policies for reducing greenhouse gas emissions and mitigating the effects of climate change. Together, these Working Groups produce detailed reports that provide a comprehensive, multidisciplinary understanding of climate change, its implications, and potential responses. The IPCC also produces a synthesis report, which synthesises all information contained in the three reports comprising the most recent IPCC assessment cycle.

According to the IPCC, 'Human-caused climate change is already affecting weather and climate extremes in every region. This has led to widespread adverse impacts and related losses and damages to nature and people (*high confidence*)'.[8]

[8] The statement summarises the findings generated by assessing the literature on extreme event and trend attribution in the WG1 Report, particularly Chapter 11, and impact attribution in WG2. In the WG2 Report, attribution literature is assessed in almost every chapter as one important line of

Quoted from the Summary for Policymakers (SPM) of the IPCC Sixth Assessment (AR6) Synthesis Report, this statement is the second key finding that the report highlights, preceded only by the fact that greenhouse gas emissions from burning fossil fuels have already warmed the climate by over 1°C.

Attribution, and particularly the rapid development of extreme event attribution since the previous IPCC assessment cycle (AR5), has been highlighted as a major new development. The third key finding of the SPM of WG1 in AR6 notes – 'Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heat waves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5' – is one example.[9] Particularly notable is that this is stated without any uncertainty and confidence language, which means it is a fact, carrying the same level of scientific confidence as the statement that human influence has warmed the climate.

In AR5, a chapter was dedicated to attribution in WG1[10] and WG2, respectively,[11] where the attribution of extreme events was introduced. With the science having now matured, attribution science is used as an important additional line of evidence to assess the impacts of human-induced climate change in all regions and for a range of different types of extreme weather events, as detailed in the following section.

Marking a significant milestone in the evolution of climate science, attribution science was highlighted in a 'cross working group box' reproduced in the first chapter of WG reports from AR6 for the first time in the history of the IPCC – underscoring the scientific consensus around its methods and findings. Attribution science was the one topic deemed relevant across all three working groups. Written by authors from different reports, the box provides a brief introduction to attribution science and an overview of the major publications. It also serves as a signpost to all of the chapters throughout the IPCC reports that assess attribution.

evidence and summarised in Chapter 16. See Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021) and Brian O'Neill and others, 'Chapter 16: Key risks across sectors and regions' in Hans O. Portner and others (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2022).

9 'IPCC, 2021: Summary for Policymakers' in Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021) (IPCC, 2021: Summary for Policymakers).

10 Nathaniel L. Bindoff and others, 'Detection and attribution of climate change: From global to regional' in Thomas F. Stocker and others (eds), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2013).

11 Wolfgang Cramer and others, 'Chapter 18: Detection and attribution of observed impacts' in Christopher B. Field and others (eds), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2014).

In summary, the IPCC uses attribution as a key line of evidence throughout all assessments dealing with the impacts of the burning of fossil fuels on the climate as well as human and natural systems. This not only provides much more detail on local and regional impacts and losses and damages but also corroborates earlier model projections that have now become reality. Attribution thus brings observations and model projections together in a comprehensive framework reducing uncertainty within climate science overall.

3.4 TREND ATTRIBUTION

3.4.1 *Definition and Scope of Trend Attribution*

Trend attribution science detects and quantifies the link between human-driven changes to the climate system and key global trends, with early studies focused on indicators like average surface temperature[12] and sea level.[13] Research in this area was the first to fingerprint human influence in the climate system,[14] and it provided the basis for a scientific understanding of climate change. While trend attribution began as a more narrow field, it has since expanded to cover a range of climate impacts including drought, ocean acidification, arctic sea ice loss, and increases in precipitation in mid-high latitudes.[15]

3.4.2 *Methodologies and Models Used in Trend Attribution*

Methodologies for trend attribution have evolved since the release of the IPCC's First Assessment report in 1990, leading to more complex global climate models, a more sophisticated representation of system dynamics, and an unequivocal understanding that human influence has warmed the planet and induced rapid, widespread changes across the world.[16] Similar to other types of attribution research, trend attribution studies often use observed historical data alongside the output of models with and without anthropogenic warming. These simulations (currently from the sixth iteration of the Coupled Model Intercomparison Project, i.e. CMIP6)

[12] Simon F. B. Tett and others, 'Causes of twentieth-century temperature change near the Earth's surface' (1999) 399 Nature 569–572.

[13] Veronika Eyring and others, 'Chapter 3: Human influence on the climate system' in Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

[14] Gabriele C. Hegerl and others, 'Climate change detection and attribution: Beyond mean temperature signals' (2006) 19 Journal of Climate 5058–5077.

[15] Eyring and others (n 13).

[16] Delian Chen and others, 'Chapter 1: Framing, context, and methods' in Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

provide counterfactual evidence of a climate without the interference of human-caused greenhouse gas emissions and associated impacts, which allows scientists to better tease out the impact of human-caused climate change.

3.4.3 *Trend Attribution Studies*

Trend attribution studies span a wide range of climate impacts and can form the basis for other types of attribution science. For example, human-caused climate change has increased global surface temperatures by 1.07°C (0.8°C–1.3°C) since the pre-industrial period and led to a 40 per cent reduction in September Arctic sea ice area since the 1980s.[17] In addition, human influence was the main driver of the rise of 0.2 m (0.15 to 0.25 m) of global mean sea level between 1901 and 2018.[18] On a regional scale, climate attribution of wildfires in forests of western North America found that human-caused climate change led to an additional 4.2 million acres burned between 1984 and 2015.[19]

Recent work has expanded the findings from trend attribution studies to explore how economic and health impacts can be linked to climate change. While still a relatively young field, this 'impact attribution' research can provide key insights into the toll that climate change exacts on society and ecosystems. For example, recent research on the economic impacts of Hurricane Sandy, which hit the East Coast of the United States in 2012, found that roughly $8 billion of the more than $60 billion in overall damages were attributable to 'climate-mediated anthropogenic sea-level rise'.[20] Similarly, a study of global heat exposure found that 37 per cent (20.5%–76.3%) of heat-related deaths during the warm season from 1991 to 2018 are attributable to anthropogenic climate change.[21]

3.5 SOURCE ATTRIBUTION

3.5.1 *Definition and Scope of Source Attribution*

Source attribution research, which quantifies how emissions from specific sources contribute to a given impact, highlights how industries, states, and ecosystem processes drive climate change and its consequences. These studies allow scientists to pinpoint, for example, how carbon dioxide from the fossil fuel industry, methane from the agricultural sector, or cumulative emissions from an individual country

[17] IPCC, 2021: Summary for Policymakers (n 9).
[18] ibid.
[19] John T. Abatzoglou and A. Park Williams, 'Impact of anthropogenic climate change on wildfire across western US forests' (2016) 113 PNAS 11770–11775.
[20] Benjamin H. Strauss and others, 'Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change' (2021) 12 Nature Communications 2720.
[21] Ana Maria Vicedo-Cabrera and others, 'The burden of heat-related mortality attributable to recent human-induced climate change' (2021) 11 Nature Climate Change 492–500.

like the United States contribute to increases in global temperature or ocean acidification. As a result, such studies provide important information for mitigation and adaptation to climate change.

3.5.2 *Methodologies and Models Used in Source Attribution*

Similar to other detection and attribution research, source attribution methodology uses models to simulate Earth's climate with and without emissions from specific sources. The case studies described later in this chapter use a global energy-balance carbon-cycle model to explore scenarios that include and exclude carbon dioxide and methane emissions traced to the eighty-eight largest 'carbon majors', institutions representing investor-owned, state-owned, and nation-state fossil fuel producers and cement manufacturers.[22] This model, derived from the impulse response function approach in the IPCC's Fifth Assessment report (AR5) and other studies,[23] incorporates AR5-consistent parameters for atmospheric residence times of CO_2 and methane. It extends the AR5 model to include a term scaling CO_2 time constants with global mean surface temperature (GMST) anomaly and cumulative carbon uptake[24] and includes contributions to the climate system from historical, natural, and anthropogenic sources. The contributions of these eighty-eight entities (previously ninety, now eighty-eight due to mergers and acquisitions) represent both Scope 1 and 3 emissions, that is direct emissions from an entity's activities as well as downstream emissions from the use and combustion of their products.[25] To date, the majority of source attribution studies have focused on emissions impacts from the fossil fuel industry because the combustion of fossil fuels is the primary driver of observed increases in Earth's surface temperature.[26]

3.5.3 *Source Attribution Studies*

In the past decade, source attribution research has grown rapidly, tracing emissions from eighty-eight 'carbon majors' to rapidly rising temperatures, sea levels, ocean acidification, and wildfires. Indeed, nearly two-thirds of global industrial carbon

[22] Heede (n 7).

[23] See Gunnar Myhre and others, 'Chapter 8: Anthropogenic and natural radiative forcing supplementary material' in Thomas F. Stocker and others (eds), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2013); Fortunat Joos and others, 'Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis' (2013) 13 Atmospheric Chemistry and Physics 2793–2825.

[24] Richard J. Millar and others, 'A modified impulse-response representation of the global response to carbon dioxide emissions' (2017) 17(1) Atmospheric Chemistry and Physics 1–20.

[25] Edgar Hertwich and Richard Wood, 'The growing importance of scope 3 greenhouse gas emissions from industry' (2018) 13 Environmental Research Letters 104013.

[26] See US Global Change Research Program, *Climate Science Special Report: A Sustained Assessment Activity of the US Global Change Research Program* (Donald Wuebbles and others (eds) 2017).

dioxide and methane emissions since 1751 can be traced to these eighty-eight entities.[27] Such a rapid increase in the concentration of atmospheric greenhouse gases (GHGs) has led to profound changes in Earth's climate, with more than 40 per cent of the GMST increase between 1880 and 2010 being traceable to the combustion of their products.[28] More than 35 per cent of this attributable temperature increase has occurred in the last fifty years,[29] and an even smaller subset of carbon producers have played an outsized role. Emissions traced to the top twenty investor and state-owned companies contributed to nearly 25 per cent of the increase in GMST between 1880 and 2010.[30] In addition to GHGs and temperature, emissions from eighty-eight 'carbon majors' contributed more than 55 per cent of the increase in ocean acidification[31] and 34 per cent of the increase in global sea level rise between 1880 and 2015.[32] When evaluating investor-owned enterprises alone, emissions traced to forty-eight 'carbon majors' contributed 15 per cent of the increase in both global average temperature and ocean acidification.[33]

In 2023, scientists published the first regional source attribution study, pinpointing the contribution of emissions traced to eighty-eight carbon majors to wildfire-prone conditions and burned area in forests of western North America. This research showed that more than a third of burned area between 1986 and 2021 and nearly half of the increase in wildfire-prone conditions since 1901 are attributable to emissions from these eighty-eight companies.[34] These case studies provide additional evidence to underscore the historical and on-going role of major carbon producers and the fossil fuel industry in driving climate change.

3.6 EVENT ATTRIBUTION

3.6.1 *Definition and Scope of Event Attribution*

Extreme event attribution relies on several different methods[35] to assess and quantify the relative contribution of multiple causal factors, such as anthropogenic

[27] Heede (n 7).
[28] Ekwurzel and others (n 5).
[29] Heede (n 7).
[30] Ekwurzel and others (n 5).
[31] Rachel Licker and others, 'Attributing ocean acidification to major carbon producers' (2019) 14 Environment Research Letters 2.
[32] Ekwurzel and others (n 5).
[33] Licker and others (n 31).
[34] Kristina A. Dahl and others, 'Quantifying the contribution of major carbon producers to increases in vapor pressure deficit and burned area in western US and southwestern Canadian Forests' (2023) 18(6) Environment Research Letters 1.
[35] See Myles Allan, 'Liability for climate change' (2003) 421 Nature 891–892; Sjoukje Philip and others, 'A protocol for probabilistic extreme event attribution analyses' (2020) 6 Advances in Statistical Climatology, Meteorology and Oceanography 177–203; Geert Jan van Oldenborgh and others, 'Pathways and pitfalls in extreme event attribution' (2021) 166 Climatic Change 13.

climate change, to an extreme weather event.[36] Over the past two decades, scientists have released more than 500 event attribution studies,[37] highlighting the strong influence of human-induced climate change across the world. This growing body of evidence is complementary to other analyses that document observed and modelled trends in extremes due to climate change and that project future risk. The evidence from attribution studies adds value by highlighting the role of human-induced climate change as a causal driver in experienced events, which in turn is useful for building future resilience.[38] It also enables the attribution of impacts, which is useful for cost–benefit analysis of mitigation and is a potential avenue for the exploration of drivers of loss and damage from climate-related extremes.[39] Despite the growing breadth of event attribution research, these studies address only a fraction of impactful extreme events occurring any year, and as a result, do not give a comprehensive overview of the attributable impacts of human-induced climate change.[40]

3.6.2 *Methodologies and Models Used in Event Attribution Studies*

Event attribution research involves the comparison of a world with and without anthropogenic climate change using both 'probabilistic' and 'storyline' approaches. These methods compare observed historical changes, simulated under observed forcings (i.e. with climate change), to a counterfactual climate simulated in the absence of all or some components of anthropogenic forcing (without climate change).[41] For 'probabilistic' event attribution, such comparisons are made in a quantitative, statistical way, allowing scientists to assess the overall likelihood of an event, as well as whether and to what extent the likelihood and intensity of an event has changed due to anthropogenic climate change.[42] In one study,[43] scientists found that the prolonged heat in Siberia in 2020 was made at least 600 times more likely by human-induced

[36] Friederike E. L. Otto, 'Attribution of extreme events to climate change' (2023) 48 Annual Review of Environment and Resources 813–828.

[37] 'Attributing extreme weather to climate change' (*Carbon Brief*, 4 August 2022) <www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/> accessed 18 April 2024.

[38] Emmanuel Raju and others, 'Stop blaming the climate for disasters' (2022) 3 Nature Communications Earth and Environment 1.

[39] Rachel A. James and others, 'Attribution: How is it relevant for loss and damage policy and practice?' in Reinhard Mechler and others (eds), *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* (Springer 2019).

[40] Friederike EL. Otto and Emmanuel Raju, 'Harbingers of decades of unnatural disasters' (2023) 4 Nature Communications Earth and Environment 280.

[41] Otto (n 36).

[42] Seneviratne and others (n 4).

[43] Andrew Ciavarella and others, 'Prolonged Siberian heat of 2020 almost impossible without human influence' (2021) 166 Climatic Change 1–18.

climate change and that an event of the same likelihood as the heat experienced in 2020 (estimated to be approximately a 1-/130-year event) would have been two degrees cooler in a world without climate change.[44] In contrast, 'storyline' attribution studies address the atmospheric dynamics that led to an event, specifically focusing on how an event would have developed with and without human-induced climate change, thereby creating a counterfactual storyline for a given event.[45] Research using a storyline approach might find, for example, that 50 per cent of the magnitude of a given event under the same dynamical conditions as observed can be explained by natural variability,[46] but it does not address the likelihood of an event.

Many studies incorporate elements of both methods,[47] for example, by defining atmospheric conditions that accompany an extreme event and then assessing how the relative frequency of such occurrences has changed. In the case of the Mediterranean storm Apollo of 2021, the frequency of similar situations leading to heavy storms increased significantly in September when the storm occurred.[48] In this way, the primary difference between these event attribution approaches lies in their fine-tuning rather than their underlying process, leading scientists and bodies like the IPCC to assess all attribution studies together[49] rather than separating by methodology.

It is important to note that not all hazards are equally understood or studied with current attribution methods. While there are attribution studies for an increasing number of different types of physical hazards, the main hazards studied to date are heat and cold waves, storms, heavy rainfall and associated flooding, droughts, and wildfires. The focus on these hazards in attribution science stems from their significant impacts, clear scientific links to climate change, data availability, and public and policy relevance. However, the absence of an attribution study does not imply that climate change did not intensify or increase the likelihood of a particular event. Rather, it reflects that the resources and human capacity to conduct these studies are finite, meaning an attribution study for every extreme event is not possible. Here we briefly summarise event attribution studies for key impacts that are strongly attributable to climate change, specifically heat, heavy rainfall, drought, and wildfire.[50]

44 Mathias Hauser and others, 'Methods and model dependency of extreme event attribution: the 2015 European drought' (2017) 5 Earth's Future 1034–1043.

45 Chen and others (n 16); Theodore G Shepherd and others, 'Storylines: an alternative approach to representing uncertainty in physical aspects of climate change' (2018) 151 Climatic Change 555–571.

46 Theodore G. Shepherd, 'A common framework for approaches to extreme event attribution' (2016) 2 Current Climate Change Reports 28–38.

47 Aglaé Jézéquel and others, 'Behind the veil of extreme event attribution' (2018) 149 Climatic Change 367–383.

48 Davide Faranda and others, 'A climate-change attribution retrospective of some impactful weather extremes of 2021' (2022) 3 Weather and Climate Dynamics 1311–1140.

49 Seneviratne and others (n 4).

50 Ben Clarke and others, 'Extreme weather impacts of climate change: an attribution perspective' (2022) 1 Environmental Research Climate 012001.

3.6.2.1 Heat

Heat and cold extremes represent the most dramatic changes in extreme weather induced by climate change. The likelihood, duration, and intensity of heat extremes, like heatwaves, are increasing while cold extremes are declining. The IPCC's WG1 2021 report, which represents the global scientific consensus, clearly states that increases in heat on every continent are the result of human-caused climate change:[51]

> A heatwave that would once have had a chance of 1 in 10 to occur in any given year in the pre-industrial climate will now occur 2.8 (1.8–3.2) times more frequently and be 1.2°C hotter. At 2°C of global warming, it will occur 5.6 (3.8–6.0) times more frequently and be 2.6°C hotter. A heatwave that would have had a 1 in 50 chance to occur in any given year in the pre-industrial climate will now occur 4.8 (2.3–6.4) times more frequently and be 1.2°C hotter. At 2°C of global warming, it will occur 13.9 (6.9–16.6) times more frequently and be 2.7°C hotter.[52]

By 2015, the likelihood of moderate heat extremes on land was roughly five times higher than in pre-industrial times and roughly 75 per cent of moderate heat extremes were attributable to human-induced climate change.[53] Globally, previously very rare heat is now just unusual,[54] while extreme heat events today reach temperatures that were formerly all but impossible.[55] Together, heat attribution studies and projections of future heat trends highlight the impacts wrought by each fraction of a degree of warming.

[51] Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

[52] Clarke and others (n 50).

[53] Erich Fischer and Reto Knutti, 'Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes' (2015) 5 Nature Climate Change 560–564.

[54] See Markus G. Donat and others, 'Temperature and precipitation extremes in century-long gridded observations, reanalyses, and atmospheric model simulations' (2016) Journal of Geophysics Research Atmospheres 11174; Andrew D. King, 'Attributing changing rates of temperature record breaking to anthropogenic influences' (2017) 5 Earth's Future 1156–1168; Robert Dunn and others, 'Development of an updated global land in situ-based data set of temperature and precipitation extremes: HadEX3' (2020) Journal of Geophysics Research Atmospheres; Min-Gyu Seong and others, 'Anthropogenic greenhouse gas and aerosol contributions to extreme temperature changes during 1951–2015' (2021) 34(3) Journal of Climate 857–870.

[55] See Stefan Rahmstorf and Dim Coumou, 'Increase of extreme events in a warming world' (2011) 108 PNAS 17905–17909; Yukiko Imada and others, 'The July 2018 high temperature event in Japan could not have happened without human-induced global warming' (2019) 15A SOLA 8–12; Sebastian Sippel and others, 'Climate change now detectable from any single day of weather at global scale' (2020) 10 Nature Climate Change 35–41; Alexander Robinson and others, 'Increasing heat and rainfall extremes now far outside the historical climate' (2021) 4 NPJ Climate and Atmospheric Science 45.

3.6.2.2 Heavy Rainfall and Associated Flooding

Since the 1950s, human-caused climate change has led to increases in the frequency and intensity of heavy rainfall across most parts of the world.[56] While the evidence and confidence in trends vary geographically, the likelihood of heavy precipitation has not strongly decreased anywhere.[57] Indeed, a previously one-in-ten year rainfall event currently occurs 1.3 (1.2–1.4) times every ten years and is 6.7 per cent wetter. At 2°C of global warming, such an event will occur 1.7 (1.6–2.0) times per ten years and be 14 per cent wetter.[58] Additionally, short-duration extreme rainfall events are intensifying,[59] while regional attribution studies show that downpours are increasing in frequency and intensity, particularly across North America, Asia, and Europe.[60] Data are more sparse in Africa and South America but recent studies do see a strong increase in some events attributable to human-induced climate change.[61]

3.6.2.3 Drought

Human-induced climate change is a key driver of increasing drought in several drought-prone regions of the world,[62] as well as globally.[63] While specific categories of drought (meteorological, agricultural, and hydrological) have different drivers

[56] See Fischer and Knutti (n 53); Erich Fischer and Reto Knutti, 'Observed heavy precipitation increase confirms theory and early models' (2016) Nature Climate Change 986–991; Seneviratne and others (n 4).

[57] Table 11.9, Seneviratne and others (n 4).

[58] Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

[59] Hayley J. Fowler and others, 'Anthropogenic intensification of short-duration rainfall extremes' (2021) 2 Nature Reviews Earth and Environment 107–122.

[60] See Huopo Chen and Jianqi Sun, 'Contribution of human influence to increased daily precipitation extremes over China' (2017) 44 Geophysical Research Letters 2436–2444; Huopo Chen and Jianqi Sun, 'Anthropogenic influence has increased climate extreme occurrence over China' (2021) 66 Science Bulletin (Beijing) 749–752; Seungmok Paik and others, 'Determining the anthropogenic greenhouse gas contribution to the observed intensification of extreme precipitation' (2020) 46 Geophysical Research Letters; Siyan Dong and others, 'Attribution of extreme precipitation with updated observations and CMIP6 simulations' (2021) 34 Journal of Climate 871–881; Qiaohong Sun and others, 'A global, continental, and regional analysis of changes in extreme precipitation' (2021) 34 Journal of Climate 243–258.

[61] See 'Climate change exacerbated heavy rainfall leading to large scale flooding in highly vulnerable communities in West Africa' *(World Weather Attribution)* <www.worldweatherattribution.org/climate-change-exacerbated-heavy-rainfall-leading-to-large-scale-flooding-in-highly-vulnerable-communities-in-west-africa/> accessed 18 April 2024; 'Climate change increased heavy rainfall, hitting vulnerable communities in Eastern Northeast Brazil' (*World Weather Attribution)* <www.worldweatherattribution.org/climate-change-increased-heavy-rainfall-hitting-vulnerable-communities-in-eastern-northeast-brazil/> accessed 18 April 2024.

[62] See Chen and Sun (n 60); Benjamin Cook and others, 'Climate change and drought: From past to future' (2018) 4 Current Climate Change Reports 164–179.

[63] Kate Marvel and others, 'Twentieth-century hydroclimate changes consistent with human influence' (2019) 569 Nature 59–65.

with implications for various parts of society, droughts across the world are complex, powerful events that impact billions of people. All types of drought are connected and broadly refer to a moisture deficit relative to a baseline in either precipitation, soil moisture, or groundwater reservoirs.[64] While drought in some regions, like the Mediterranean and Southern Africa, is due to decreases in precipitation, globally, drought is largely driven by higher temperatures which increase evaporation and decrease snowpack, reducing the contribution of meltwater to surface water flows.[65] In other regions like central Chile and southwest Australia climate change has dried out these ecosystems and communities, which are now more prone to drought.[66] In some regions suffering regularly from drought, such as East Africa, attribution studies have found that while changes in meteorological drought cannot be attributed to climate change, human-caused climate change has a strong impact on agricultural drought, turning periods of low rain that would have been unproblematic in a cooler climate into extreme droughts.[67]

3.6.2.4 Wildfire

Climate change has increased the risk of wildfire across the world, including the western US, Alaska, and Canada,[68] the Mediterranean,[69] Amazonia,[70] southeast Asia,[71] and Australia.[72] Dry and hot conditions prime forests for wildfire, and

64 Cook and others (n 62).

65 ibid.

66 Richard Seager and others, 'Climate variability and change of Mediterranean-type climates' (2019) 32 Journal of Climate 2887–2915.

67 Joyce Kimutai and others, 'Human-induced climate change increased drought severity in Horn of Africa' (2023) UNU-EHS Working Paper.

68 See Simon Allen and others, 'Summary for policymakers' in Christopher B. Fields and others (eds), *Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2012); Philip E. Dennison and others, 'Large wildfire trends in the western United States, 1984–2011' (2014) 41 Geophysical Research Letters 2928–2933; Jennifer K. Balch and others, 'Switching on the big burn of 2017' (2018) 1(1) Fire 17; Michael Goss and others, 'Climate change is increasing the likelihood of extreme autumn wildfire conditions across California' (2020) 15 Environmental Research Letters 094016.

69 See John T. Abatzoglou and others, 'Global emergence of anthropogenic climate change in fire weather indices' (2019) 46 Geophysical Research Letters 326–336; Renaud Barbero and others, 'Attributing increases in fire weather to anthropogenic climate change over France' (2020) 8 Frontiers in Earth Science; Danielle Touma and others, 'Human-driven greenhouse gas and aerosol emissions cause distinct regional impacts on extreme fire weather' (2021) 12 Nature Communications 212.

70 See Ane Alencar and others, 'Temporal variability of forest fires in eastern Amazonia' (2011) 21 Ecological Applications 2397–2412; Ane Alencar and others, 'Landscape fragmentation, severe drought, and the new Amazon forest fire regime' (2015) 25 Ecological Applications 1493–1505; Abatzoglou and others (n 69); Touma and others (n 69).

71 Touma and others (n 69).

72 See Andrew J. Dowdy, 'Climatological variability of fire weather in Australia' (2018) 57 Journal of Applied Meteorology and Climatology 221–234; Andrew J. Dowdy and Acacia Pepler, 'Pyroconvection

fire risk is particularly pronounced during periods of extreme fire weather, when conditions of low humidity, lack of rain, high temperature, and high windspeed co-occur with dried out vegetation, increasing the likelihood of fire growth and spread.[73] Major wildfire seasons in recent years have illustrated the consequences of this heightened risk. During British Columbia's record-breaking 2017 wildfire season, climate change increased the area burned by a factor of 7–11, and increased the likelihood of the extreme season by a factor of 2–4.[74] In addition, extreme fire risk events in western Canada were made 1.5 to 6 times more likely by climate change, including the 2016 Fort McMurray wildfire event in Alberta, Canada, which burned 600,000 ha and displaced 80,000 people.[75] Climate change also made extensive Swedish forest fires in 2018 10 per cent more likely,[76] the record-breaking Australian bushfire season of 2019 and 2020 at least 30 per cent more likely,[77] and the extreme wildfires in Southern China in 2019 at least seven times more likely.[78] Further, by increasing the drying power of the atmosphere, climate change more than doubled burned area in forests of western North America between 1984 and 2015.[79]

3.7 CASE STUDIES: ATTRIBUTION SCIENCE ACROSS CONTINENTS

Attribution studies have been conducted all around the globe. Here, we present studies that exemplify the diverse nature of climate-related impacts and the scientific inquiries being pursued across different regions, notably Africa, the Americas, Asia, Europe, and the South Pacific/Oceania. While not exhaustive, this compilation offers glimpses into the types of findings and conclusions being drawn in each region. It highlights how attribution science is being applied to understand and

risk in Australia: Climatological changes in atmospheric stability and surface fire weather conditions' (2018) 45 Geophysical Research Letters 2005–2013; Sarah Harris and Chris Lucas, 'Understanding the variability of Australian fire weather between 1973 and 2017' (2019) 14 PLOS One.

73 See Van Wagner, *Development and Structure of the Canadian Forest Fire Weather Index System* (Forestry Technical Report 35, Canadian Forestry Service 1987); Andrew J. Dowdy and others, *Australian Fire Weather as Represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index* (The Centre for Australian Weather and Climate Research 2009).

74 Megan Kirchmeier-Young and others, 'Attribution of the influence of human-induced climate change on an extreme fire season' (2019) 7 Earth's Future 2–10.

75 Megan Kirchmeier-Young and others, 'Attributing extreme fire risk in Western Canada to human emissions' (2017) 144 Climatic Change 365–379.

76 Folmer Krikken and others, 'Attribution of the role of climate change in the forest fires in Sweden 2018' (2021) 21(7) Natural Hazards and Earth Systems Sciences 2169.

77 Geert Jan van Oldenborgh and others, 'Attribution of the Australian bushfire risk to anthropogenic climate change' (2020) 21 Natural Hazards and Earth System Sciences 941–960.

78 Jizeng Du and others, 'Attribution of the extreme drought-related risk of wildfires in spring 2019 over Southwest China' (2021) 102 Bulletin of the American Meteorological Society S83–S90.

79 Abatzoglou and Williams (n 19).

address region-specific climate phenomena, and underscores the global reach and relevance of attribution science. As not all regions are equally represented in the attribution literature, the discussion of some regions will review case studies while others will point to trends.

3.7.1 *Africa*

Although understudied, attribution science in Africa offers valuable insights into the region's changing climate dynamics. These studies range from drought analysis in the Horn of Africa to the examination of tropical storms and their consequences. Each provides critical evidence of how human-induced climate change influences weather patterns and extreme events in Africa, underscoring the need for targeted adaptation and mitigation strategies. The following are some notable examples of attribution science at work in Africa, demonstrating the significant and varied impacts of climate change across the continent. One study focused on attributing the impacts of a prolonged drought in the Southern Horn of Africa, affecting parts of Ethiopia, Somalia, and Kenya, from 2020 to 2022, to human-induced climate change.[80] The study employed climate models and observational data to demonstrate that low rainfall events during the long rains have become twice as likely due to climate change. Additionally, the research highlighted the role of temperature in exacerbating drought severity, making events like the record-breaking drought in 2020–2022 about 100 times more likely. The study underscores the urgent need for adaptation strategies that address both wet and dry extremes, considering the substantial impacts on agriculture, pastoralism, and vulnerable communities in the region. Furthermore, the findings emphasise the importance of preparing for prolonged droughts in the face of state fragility, conflict, and potential challenges to existing drought management systems.

Another study focused on the impacts of tropical storms Ana and cyclone Batsirai, with flooding identified as the primary cause of damage.[81] Madagascar, Malawi, and Mozambique, already vulnerable due to prior flooding and underlying conditions like conflict and drought, faced compounded challenges. Despite well-forecasted events by meteorological centres, communication breakdowns and damaged infrastructure hindered effective warnings in some areas. Meteorologically, Ana was an extreme event with a one in fifty years return period, while storms like Batsirai occurred more frequently (one in two years over Madagascar). Sparse rainfall data

80 'Human-induced climate change increased drought severity in Horn of Africa' (*World Weather Attribution*) <www.worldweatherattribution.org/human-induced-climate-change-increased-drought-severity-in-southern-horn-of-africa/> accessed 18 April 2024.

81 'Climate change increased rainfall associated with tropical cyclones hitting highly vulnerable communities in Madagascar, Mozambique & Malawi' (*World Weather Attribution*) <www.worldweatherattribution.org/climate-change-increased-rainfall-associated-with-tropical-cyclones-hitting-highly-vulnerable-communities-in-madagascar-mozambique-malawi/> accessed 18 April 2024.

in the region complicates trend assessments, but qualitative analysis suggests an increase in heavy rainfall associated with tropical cyclones over time. The findings align with future projections, affirming that climate change contributed to the heightened likelihood and intensity of rainfall linked to Ana and Batsirai.

Yet another study focused on drought patterns in the Horn of Africa from 1979 to 2019, employing the Standardized Precipitation Evapotranspiration Index (SPEI).[82] Results indicate an increasing trend in the frequency, duration, and intensity of droughts in the region over the past decades. The most severe drought occurred in the 'short rains' of 2016 and 'long rains' of 2017, with a calculated return period of 250 years based on the SPEI index. While precipitation anomalies alone couldn't explain this extreme drought, statistical analysis revealed that abnormally high temperatures (1.02°C higher than normal) and exceptional evaporation (1-in-131 years event) played crucial roles. The study suggests that compound droughts, exacerbated by the simultaneous occurrence of low precipitation and high temperatures, may become more prevalent in the Horn of Africa due to continuous anthropogenic warming. This underscores the importance of considering combined impacts for accurate future drought predictions and effective adaptation measures in the region.

3.7.2 *The South Pacific/Oceania*

While few attribution studies focus on the South Pacific, global studies combined with region-specific research provide compelling evidence of how climate change has amplified extreme events and threatened communities, ecosystems, and livelihoods. For example, climate change has already increased sea levels in the South Pacific by 100 to 200 mm, an increase greater than many other regions globally.[83] As a result, damages from storms are higher than they would have been without human-induced climate change,[84] particularly when it comes to storm surge.[85] Indeed, during Typhoon Haiyan in 2013, storm surge height was made 20 per cent greater due to climate change,[86] a finding that is transferable to other similar events due to the role of sea level rise. Further, the observed poleward migration of tropical cyclones highlights the risks faced by communities in the South Pacific. While scientists have not investigated the role of climate change

[82] Xue Han and others, 'Attribution of the extreme drought in the Horn of Africa during short-rains of 2016 and long-rains of 2017' (2022) 14(3) Water 409.

[83] Hans O. Pörtner and others (eds), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (Cambridge University Press 2019).

[84] ibid.

[85] Kathleen L. McInnes and others, 'Quantifying storm tide risk in Fiji due to climate variability and change' (2014) 116 Global and Planetary Change 115–129.

[86] Izuru Takayabu and others, 'Climate change effects on the worst-case storm surge: A case study of Typhoon Haiyan' (2015) 10 Environmental Research Letters 1.

for individual storms, the overall increase in tropical cyclones is attributable to human-caused climate change.[87]

As with all regions in the world, every heatwave occurring today in the South Pacific has been made more likely to occur, and is hotter and longer due to the burning of fossil fuels.[88] Heatwaves are, in most parts of the world, the deadliest extreme weather events, costing thousands of people their lives every year, with even more deaths likely going uncounted in these totals.[89] Studies on heatwaves in the Global South, including the Pacific Islands, are sparse, but recent research shows that extreme temperatures have increased significantly across the South Pacific region, in line with global trends.[90] Further, extreme temperatures, like those experienced in Indonesia in 2015, are entirely attributable to human-induced climate change.[91] Together with the attribution assessments of extreme heat from the IPCC,[92] this research provides strong evidence of the impact of human-induced climate change on extreme heat in the South Pacific.

The impact of climate change on marine heatwaves is equally pronounced in the South Pacific. These periods of very warm ocean temperatures have devastating impacts on marine ecosystems and the societies depending on them. The increase in frequency and intensity of marine heatwaves has been assessed as a key impact of human-induced climate change by the most recent IPCC report.[93] Globally, including in the South Pacific, human-induced climate change has increased the most severe marine heatwaves by a factor of twenty,[94] while anthropogenic warming in combination with natural drivers of extreme heat in the South Pacific (like El Nino Southern Oscillation) led to the most severe marine heatwaves in the last decade.[95]

Overall, global evidence strongly links human-induced climate change to rising sea levels, intensified storms, and more severe heatwaves.

[87] Seneviratne and others (n 4).

[88] See Clarke and others (n 50); Ben Clarke and others, 'When don't we need a new extreme event attribution study?' (2023) 176 Climatic Change 60.

[89] Kristie L. Ebi and others, 'Using detection and attribution to quantify how climate change is affecting health' (2020) 39 Health Affairs 12.

[90] Simon McGree and others, 'Recent changes in mean and extreme temperature and precipitation in the Western Pacific Islands' (2019) 32 Journal of Climate 4919–4941.

[91] Andrew David King and others, 'Climate change and El Nino increase likelihood of Indonesian heat and drought' (2018) 97(12) Bulletin of the American Meteorological Society S113–S117.

[92] Seneviratne and others (n 4).

[93] Baylor Fox-Kemper and others, 'Chapter 9: Ocean, cryosphere and sea level change' in Valerie Masson-Delmotte and others (eds), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2021).

[94] Charlotte Laufkötter and others, 'High-impact marine heatwaves attributable to human-induced global warming' (2020) 369 Science 1621–1625.

[95] Neil J. Holbrook and others, 'A global assessment of marine heatwaves and their drivers' (2019) 10 Nature Communications 2624.

3.7.3 *The Americas*

Climate change has caused major disruptions to communities, infrastructure, and industry throughout the Americas. Attribution science in this region has primarily focused on understanding the impacts of precipitation, heat, and drought. Studies generally agree on an increase in both precipitation and extreme heat due to climate change, while the attribution of droughts presents a more complex picture.

The frequency and intensity of heavy precipitation and flooding, attributed to climate change, have been a significant focus in the Americas. Research has shown a substantial increase in the risk of extreme rainfall events, as seen in the Uruguay River Basin, leading to widespread flooding and notable social and economic impacts.[96] The exceptionally wet conditions in Peru in March 2017 were estimated to be at least 1.5 times more likely to occur, when compared to pre-industrial times.[97] These examples underline the challenges in managing water resources and protecting vulnerable populations from flood-related hazards.

The region has also witnessed an escalation in temperature extremes due to climate change. The increased risk of heatwave events, like the one Argentina experienced in December 2013, was quantified as being five times greater due to climate change.[98] A clear anthropogenic signal has been identified in temperature extremes across South America, though the specific impacts vary by region.[99] These temperature variations pose significant threats to public health, agriculture, and local ecosystems.

As mentioned previously, the first regional source attribution study was conducted in North America and found that 19.8 million acres burned – 37 per cent of the total area scorched by forest fires in the western United States and south-western Canada since 1986 – can be attributed to heat-trapping emissions traced to the world's eighty-eight largest fossil fuel producers and cement manufacturers.[100] Emissions from these companies also contributed to nearly half of the observed increase in drying conditions that raise the risk of large, severe forest fires across the region since 1901. The findings provide new data that can advance efforts to hold companies accountable for past, present, and future climate damages and risks.

In South America, particularly in the Andes, the hazard of glacial lake outbursts has emerged as a growing concern due to climate change. The risks these outbursts

[96] Rafael C. de Abreu and others, 'Attribution of detected temperature trends in Southeast Brazil' (2019) 46 Geophysical Research Letters 8407–8414.

[97] Nikolaos Christidis and others, 'The extremely wet March of 2017 in Peru' (2019) 100 Bulletin of the American Meteorological Society S31–S35.

[98] Alexis Hannart and others, 'Causal influence of anthropogenic forcings on the Argentinian heat wave of December 2013' (2015) 96 Bulletin of the American Meteorological Society S41–S45.

[99] Matilde Rusticucci and Natalia Zazulie, 'Attribution and projections of temperature extreme trends in South America based on CMIP5 models' (2021) 1504 Annals of the New York Academy of Sciences 154–166.

[100] Dahl and others (n 34).

pose, especially in regions like Peru, highlight the need for increased attention and research in these areas.[101] The case of Lake Palcacocha, which sits below the summits of Palcaraju and Pucaranra and above the city of Huaraz, exemplifies the increasing hazard from such events, driven by human-induced glacier retreat. An outburst flood in 1941 killed more than 1,800 people and destroyed one-third of the city of Huaraz. A study found that the retreat of Palcaraju glacier to its current state is not solely attributable to natural variability and that the glacier's retreat observed by 1941 likely represents an early consequence of anthropogenic greenhouse gas emissions.[102] This same research highlighted how anthropogenic climate change has continued to drive glacier retreat and glacial lake outburst flood hazard and how it presents a significant threat to the community of Huaraz.

Research on droughts in South America presents contrasting evidence. While a study on the prolonged Northeast Brazil hydrometeorological drought (2012–2016) suggested that climate change was not a significant factor,[103] other research points to the intensification of the dry season and reduced water availability in parts of South America and the northern Andes as consequences of human-induced climate change.[104] This divergence in findings illustrates the complexity in attributing droughts to climate change and highlights the necessity for region-specific investigations.

3.7.4 *Asia*

In Asia, a diverse range of attribution studies have focused on the impacts of climate change on extreme weather events, particularly emphasising the increased frequency and intensity of rainfall, flooding, and temperature extremes.

Several studies have concentrated on flooding and extreme rainfall. In the Lancang-Mekong River Basin, climate change has been linked to a 14 per cent increase in the magnitude and a 45 per cent increase in the frequency of floods compared to the baseline period of 1985–2007.[105] Similarly, research on the 2019 rainy season in Southern China and the record-breaking rainfall in Western Japan in July 2018 has shown a substantial increase in the severity and likelihood of such

[101] Caroline Taylor and others 'Glacial lake outburst floods threaten millions globally' (2023) 14 Nature Communications 487.

[102] Rupert Stuart-Smith and others, 'Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat' (2021) 14 Nature Geoscience 85–90.

[103] Eduardo Martins and others, 'A multimethod attribution analysis of the prolonged Northeast Brazil hydrometeorological drought (2012–16)' (2018) 99 Bulletin of the American Meteorological Society S65–S69.

[104] Ryan Padrón and others, 'Observed changes in dry-season water availability attributed to human-induced climate change' (2020) 13 Nature Geoscience 477–481.

[105] Xiaobo Yun and others, 'Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin' (2020) 590 Journal of Hydrology 125472.

events due to human-induced climate change. The certain extreme rainfall events in Western Japan, for instance, now has a return period of 20.7 years, significantly shorter than the 68.0 years under pre-human influence conditions.[106] In China, the detectable anthropogenic influence on summer precipitation has been linked to changes in heavy, moderate, and light precipitation, with future projections suggesting an increase in heavy precipitation.[107]

Contrary to the increased frequency of extreme rainfall events in some parts of Asia, a study in Southern China found that anthropogenic forcings have reduced the likelihood of heavy precipitation events like those experienced in March–July 2019 by about 60 per cent, highlighting regional variability in the impacts of climate change.[108]

The contribution of atmospheric circulation to extreme weather events has been a subject of interest, particularly regarding the record-breaking precipitation and heat events in the middle and lower reaches of the Yangtze River and South China during the Meiyu period in 2020. A study found that the risk of an event reaching or exceeding the 2020 Meiyu amount increased 5.1 times in the current climate, with 80 per cent of this increase attributable to climate change.[109]

In Bangladesh, studies have shown varying impacts of climate change on flooding and extreme pre-monsoon precipitation. While one study suggested a negligible role of climate change in exacerbating 2017's floods, future projections indicate an increased probability of such events. Another study found that climate change had doubled the likelihood of extreme pre-monsoon rainfall. These results do not indicate that the science is unsuitable, but rather that in certain seasons, like the pre-monsoon season in Bangladesh where rainfall is highly variable from year to year, attribution studies need to take future projections into account to complement shorter observed records.[110]

In the 2022 study by Li and Otto,[111] the catastrophic effects of Typhoon Hagibis, which struck the Tokyo metropole region in October 2019, were closely examined to understand the role of human-induced climate change in exacerbating its impacts.

[106] Yukiko Imada and others, 'Advanced risk-based event attribution for heavy regional rainfall events' (2020) 3 NPJ Climate and Atmospheric Science 37.

[107] Chunhui Lu and others, 'Detectable anthropogenic influence on changes in summer precipitation in China' (2020) 33(13) Journal of Climate 5357–5369.

[108] Rouke Li and others, 'Anthropogenic influences on heavy precipitation during the 2019 extremely wet rainy season in Southern China' (2020) Bulletin of the American Meteorological Society S103–S109.

[109] Yangbo Ye and Cheng Qian, 'Conditional attribution of climate change and atmospheric circulation contributing to the record-breaking precipitation and temperature event of summer 2020 in southern China' (2021) 16 Environmental Research Letters 044058.

[110] Ruksana H. Rimi and others, 'Risks of pre-monsoon extreme rainfall events of Bangladesh: Is anthropogenic climate change playing a role?' (2019) 100 Bulletin of the American Meteorological Society S61–S65.

[111] Sihan Li and Friederike EL. Otto, 'The role of human-induced climate change in heavy rainfall events such as the one associated with Typhoon Hagibis' (2022) 172 Climatic Change 7.

The typhoon led to substantial destruction, including significant loss of life and livelihoods, with economic damages surpassing $10 billion USD. The study's findings show an increase in the likelihood of such an extreme rainfall event, ranging from 15 per cent to 150 per cent, directly attributable to anthropogenic climate change. Additionally, the study quantified the fraction of attributable risk to understand impacts, and conservatively estimated that about $4 billion of the total damages could be attributed to the climate change-induced intensification of the rainfall. This research not only highlights the escalating economic toll of climate change but also stresses the urgency for effective adaptation strategies to mitigate the risks associated with such extreme weather events.

3.7.5 *Europe*

Heatwaves in Europe have been a significant focus of attribution studies, revealing a trend towards increased frequency and intensity of these extreme weather events. Anthropogenic forcings have markedly influenced European temperature extremes from 1961–2010, contributing to a more frequent occurrence of heatwaves,[112] and were a major contributor to the conditions leading to the 2015 central Europe heatwave.[113] Human-induced climate change significantly increased the likelihood of the unprecedented June–July 2019 Europe heat event, increasing its likelihood by up to twenty-three times since the 1980s.[114] A strong human influence was identified in the extremely warm May of 2020 in western Europe, estimating that such events are now forty times more likely due to human activities.[115] Research from the World Weather Attribution project further supports these findings, indicating clear trends towards more frequent heatwaves in Northern Europe, including Ireland, the Netherlands, and Denmark, with a twofold increase in the likelihood of heatwaves in Dublin, Ireland, and a fourfold increase in Denmark.[116] Climate change significantly amplified the intensity and frequency of the June 2017 heatwave in Portugal and other parts of Europe, making such extremes at least twice as likely in Belgium and up to ten times as likely in Portugal and Spain.[117] Additional research has quantified the proportion of heat-related mortality that can be attributed to climate

[112] Nikolaos Christidis and Peter A. Stott, 'Attribution analyses of temperature extremes using a set of 16 indices' (2016) 14 Weather and Climate Extremes 24–35.

[113] Buwen Dong and others, 'The 2015 European heat wave' (2016) 97 Bulletin of the American Meteorological Society S57–S62.

[114] Feng Ma and others, 'Unprecedented Europe heat in June–July 2019: Risk in the historical and future context' (2020) 47 Geophysical Research Letters.

[115] Stephanie Herring and others (eds), *Explaining Extreme Events of 2020 from a Climate Perspective* (2022) 103(3) Bulletin of the American Meteorological Society S1.

[116] 'Heatwave in northern Europe, summer 2018' (*World Weather Attribution*) <www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/> accessed 18 April 2024.

[117] 'Record June temperatures in western Europe' (*World Weather Attribution*) <www.worldweatherattribution.org/european-heat-june-2017/> accessed 18 April 2024.

change, finding that an average of 37 per cent of heat-related deaths between 1991 and 2018 are attributable, and that this trend in mortality is detectable on every continent.[118] These studies collectively underscore the growing impact of anthropogenic climate change on the frequency and severity of heatwaves across Europe.

Drought attribution studies in Europe have shed light on the increasing severity and likelihood of such events in the region. The record-breaking drought that affected western and central Europe from July 2016 to June 2017 serves as a prime example. This event, unusual in its spatial pattern affecting both northern and southern European regions, was identified as the most severe European drought at the continental scale since at least 1979.[119] It caused significant impacts on water supplies, agriculture, hydroelectric power production, and forest fires in Iberia. Additionally, a study on the record low rainfall in western Europe during December 2016 suggests that this extreme event may have been buoyed by an unprecedented reduction of Arctic sea ice, a condition likely driven by anthropogenic climate change.[120] These studies collectively point to a trend of more severe and frequent droughts in Europe, exacerbated by both dynamic atmospheric patterns and thermodynamic processes associated with climate change.

A handful of studies also look at flooding in the region. One study looked at flooding in the aftermath of storm Desmond in December 2015, yielding significant insights into the impact of climate change on such occurrences. The findings revealed that climate change had contributed to increasing the likelihood of similar, single-day precipitation events by approximately 40 per cent. A further, more detailed analysis using additional data and considering a broader event definition indicated an estimated 59 per cent increase in the frequency of such events, albeit with a wider confidence interval.[121] This study exemplifies the growing body of evidence suggesting an enhanced likelihood of severe precipitation and flooding events in Europe, influenced by the on-going shifts in climate patterns.

3.8 NAVIGATING ATTRIBUTION SCIENCE

The field of attribution science, while significantly robust, does have limitations and challenges, namely data inequities, misinterpretation of scientific uncertainty, and intrinsic event complexity. The disparity in access to high-quality climatic

[118] Ana Maria Vicedo-Cabrera and others, 'The burden of heat-related mortality attributable to recent human-induced climate change' (2021) 11 Nature Climate Change 492–500.

[119] Ricardo García-Herrera and others, 'The European 2016/17 drought' (2019) 32(11) Journal of Climate 3169–3187.

[120] Stephanie Herring and others (eds), Explaining extreme events in 2017 from a climate perspective (2019) 100(1) Bulletin of the American Meteorological Society S1–S117.

[121] Freiderike E. L. Otto and others, 'Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond – a real-time event attribution revisited' (2018) 13(2) Environmental Research Letters 024006.

data is profound, particularly in developing countries in the Global South. These countries, often most vulnerable to climate change, suffer from sparse observational networks, leading to significant data gaps. This scarcity hampers the precision of attribution studies and, by extension, the formulation of targeted adaptation strategies. Moreover, the established reliance on *global* climate models, while beneficial for broad-scale analysis, can fall short in capturing localised climatic variations, especially in data-poor regions. Enhancing local data collection capabilities and developing more nuanced, region-specific models are crucial steps towards addressing this inequity.

Attribution science, with its inherent complexities, faces the challenge of distinguishing human-induced changes from natural climatic variability, which – as in all scientific modelling – involves navigating uncertainties. However, the primary issue lies not in the presence of uncertainty, which is a fundamental aspect of scientific inquiry, but rather in effectively communicating these uncertainties within a legal context. In the scientific domain, uncertainty is a measure of our knowledge's depth and precision, a concept crucial to attribution science. It is methodically reported, often via confidence intervals, acknowledging the intrinsic limitations of models while underscoring their value in enhancing our understanding.

Finally, as mentioned earlier, the attribution of specific types of weather events to climate change varies considerably in ease and accuracy. Events such as heatwaves often present a more direct and easily discernible link to climate change, primarily due to their close association with rising global temperatures. Conversely, more complex phenomena like droughts or floods involve intricate interactions with various factors, including local geography, atmospheric conditions, and human activities, making their attribution to climate change more challenging. This complexity is compounded by varying temporal and spatial scales, as some events might exhibit clearer signals of climate change influence over larger areas or extended periods, while others are more perceptible at local scales or in shorter time frames.

Addressing these challenges is essential for the continuous improvement of the field and its application in informing climate litigation and adaptation measures. As research in this area progresses, attribution science is set to play an increasingly crucial role in enhancing our understanding of climate change impacts and guiding global responses.

3.9 THE PIVOTAL ROLE OF ATTRIBUTION SCIENCE IN CLIMATE RESPONSE

The emergence and rapid advancement of attribution science marks a transformative moment in our understanding of climate change, offering a powerful tool for quantifying the ties between human actions and shifting climate impacts. Attribution science is well established and accepted by the scientific community, as evidenced by its inclusion and prominence in the latest IPCC assessment.

With its three distinct strands – trend, source, and event – attribution science provides a comprehensive picture of how human activities influence climatic trends, the origin of emissions, and the frequency and intensity of extreme weather events. Each branch of this discipline adds a unique layer to our scientific understanding of the complexities of a rapidly evolving global climate system. These studies not only serve as a testament to the impact of anthropogenic factors on the climate, but also as a clarion call for immediate and decisive action.

As we stand at the crossroads of a climate crisis, the role of attribution science becomes increasingly pivotal. It bridges the gap between abstract climate models and the tangible reality of climate impacts, providing a foundation for informed policy decisions, effective adaptation strategies, and, crucially, climate litigation. The insights derived from attribution science are not just academic exercises; they are tools for accountability and change, guiding us towards a more resilient and sustainable future.

As attribution science continues to evolve, it is poised to play an ever-more critical role in our collective response to climate change. It empowers us with the knowledge to understand the past, address the present, and prepare for the future, forging a path towards a more informed and proactive global response to the climate crisis.