Part I:

Foundational basis for climate responsibility and liability: Attribution science, economics and philosophical perspectives

Climate change, its impacts, and attribution of causes: Current status and challenges

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Abstract

Current climate change progresses rapidly. The Earth has warmed globally by more than one degree Celsius since pre-industrial times. All components of the climate system are affected – oceans, ice, atmosphere, land, and biosphere. Changes are detectable in a wide range of climate indicators and the evidence is clear from observations. Moreover, extreme weather events are becoming more frequent and intense, with increasing risks and damaging impacts on the environment and society.

Attribution science identifies the drivers of climate change by separating natural causes from human-induced causes based on characteristic signatures, so-called fingerprints. Global warming can be clearly attributed to increasing concentrations of greenhouse gases in the atmosphere, mainly due to the burning of fossil fuels. It is unequivocal that human activities are the major cause.

Extreme event attribution provides information on the influence of human-induced climate change on extreme weather events in terms of probability, severity, and impact risks. It has revealed that many of the recent extremes would have been nearly impossible without human-induced climate change.

Here, we briefly review the current state of knowledge on climate change, its impacts and the attribution of causes. We discuss the challenges and limitations in attribution as well as recent progress toward operational attribution. Attribution studies are found essential for understanding human impacts of climate change. They provide vital information for adaptation and mitigation to climate change, for climate risk assessment and for climate litigation.

1 Introduction to climate change

> It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-induced climate change is already affecting many weather and climate extremes in every region across the globe.[1]

1 Intergovernmental Panel on Climate Change (IPCC), *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).

These are key statements of the Intergovernmental Panel on Climate Change (IPCC) on the current state of the Earth's climate and the urgency of action. In 2021, Working Group I (WGI) of the IPCC published the first part of its sixth Assessment Report (AR6) on the physical state of the climate.[2] Main findings are condensed in the summary for policymakers.[3]

Long-term climate observations show that global warming has reached 1.1°C in 2021 relative to the pre-industrial 1850-1900 average.[4] Beyond warming, changes are consistently measured in a range of climate indicators as all domains of the climate system – land, ocean, cryosphere, atmosphere, biosphere – are affected by global change. These indicators include the composition of the atmosphere, temperature and energy changes that arise from the accumulation of greenhouse gases and other factors, as well as the responses of land, oceans and ice. The scale and pace of recent changes across the climate system are unprecedented over many centuries to many thousand years shown in Fig. 1.[5] In 2021, the world remains on course to exceed the agreed temperature thresholds of either 1.5°C or 2°C above pre-industrial levels. Unless deep reductions in greenhouse gas emissions occur in this decade, the risk of harmful effects of climate change will increase beyond what we already experience.[6]

2 IPCC, 2021 (n 1).

3 IPCC, *Summary for policymakers. Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC 2021 SPM) (Cambridge University Press 2021).

4 World Meteorological Organization (WMO), 'United in Science 2021 – a multi-organization high-level compilation of the latest climate science information' <https://public.wmo.int/en/resources/united_in_science> last accessed 5 January 2022.

5 IPCC, 2021 SPM (n 3).

6 WMO, United in Science (n 4).

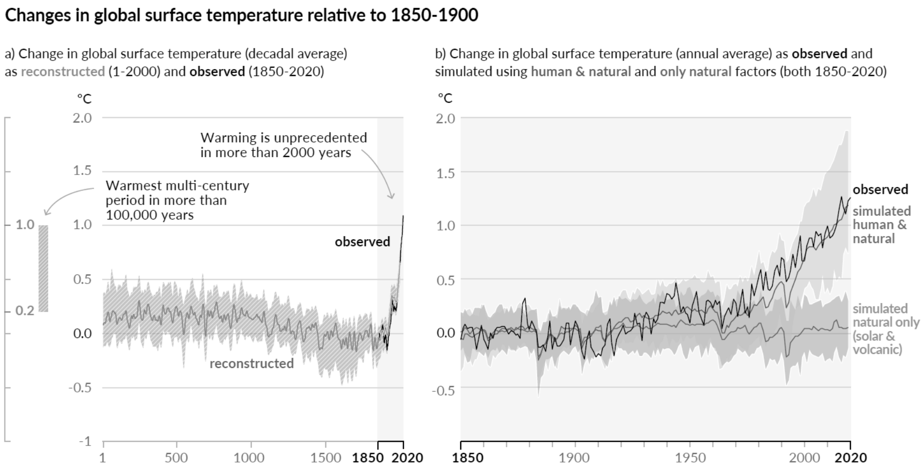

Figure 1. (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, 1-2000) and from direct observations (solid black line, 1850-2020), both relative to 1850-1900. **(b)** Changes in global surface temperature as observed (black line) relative to 1850-1900, simulated from climate models using both human and natural drivers (dark grey) and only natural factors (light grey). Natural only factors cannot explain current climate change.[7]

In a stable climate, the amount of incoming energy from the sun is in balance with the amount lost to space in the form of reflected sunlight and outgoing thermal radiation from the Earth. Naturally, greenhouse gases trap heat in the atmosphere and make our Earth a habitable planet. But fast increasing concentrations of atmospheric greenhouse gases (Fig. 1) from emissions due to human activities are causing a net energy increase in the climate system, which heats up the Earth's atmosphere, land, and oceans.[8]

About 90% of the accumulated heat in the Earth system is stored in the ocean. Sea surface temperatures are increasing with recent record warming observed in the upper oceans. Global warming has triggered the melting of the world's large ice sheets and glaciers at an increasing pace over the recent decades. Arctic sea ice is shrinking rapidly. Global average sea level has risen by about 20 cm since 1900 via thermal expansion of seawater due to ocean warming and due to ice melt. The rate of sea level rise has further accelerated since the beginning of this century, and some of the observed changes might be irreversible.[9] Moreover, increased uptake of carbon diox-

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7 IPCC, 2021 SPM (n 3) Figure SPM.1.

8 E.g., Karina von Schuckmann et al., 'Heat stored in the Earth system: Where does the energy go?' (2020) 12 Earth Syst. Sci. Data 2013-2041, <doi:10.5194/essd-12-2013-2020> accessed 15 March 20022; Andrea K Steiner et al., 'Observed temperature changes in the troposphere and stratosphere from 1979 to 2018' (2020) 33 Journal of Climate 8165-8194, doi:10.1175/JCLI-D-19-0998.1.

9 WMO, United in Science (n 4).

ide by the oceans has led to acidification that endangers marine species and ecosystem services.[10]

Climate change is also a growing global threat to biodiversity, ecosystems, and human well-being. Widespread impacts in many aspects of biodiversity comprise species extinction, distribution and range shifts, phenology, productivity and ecosystem function.[11] Observations show that the effects are accelerating in marine, terrestrial and freshwater ecosystems and are already impacting agriculture, aquaculture, and fisheries.[12]

Human health and mortality are affected by, e.g., water-borne and vector-borne diseases, and food insecurity through increasing temperatures, changing precipitation patterns, and more frequent and intense extreme weather events that bring about droughts, fires, and floods.[13]

Evidence for human-induced climate change is provided, first, by long-term observations of climate variables that are critical for monitoring climate. Second, detection studies demonstrate whether statistically significant long-term trends are detectable in observed changes, different from natural climate variability. Finally, attribution studies are essential to assess the drivers of climate change and determine whether change is due to natural or human-induced causes. Advances in attribution science have made it possible to attribute the drivers of climate change and the changing risks of extreme weather events, triggered by a growing interest in integrating attribution outcomes for effective climate change adaptation and mitigation.

We give a brief overview of the status of attribution science in Section 2, including attribution of long-term climate trends and of extreme weather events. We dis-

10 Jelle Bijma et al., 'Climate change and the oceans – what does the future hold?' (2013) 74 Marine Pollution Bulletin 495-505, https://doi.org/10.1016/j.marpolbul.2013.07.022.

11 Gian-Reto Walther et al., 'Community and ecosystem responses to recent climate change' (2010) 365 Philosophical Transactions of the Royal Society B: Biological Sciences 2019-2024, https://doi.org/10.1098/rstb.2010.0021; Céline Bellard et al., 'Impacts of climate change on the future of biodiversity' (2012) 15 Ecology Letters 365-377, <https://doi.org/10.1111/j.1461-0248.2011.01736.x> accessed 22 March 2022; Akira S Mori et al., 'Biodiversity-productivity relationships are key to nature-based climate solutions' (2021) 11 Nature Climate Change 543-550, https://doi.org/10.1038/s41558-021-01062-1.

12 Intergovernmental Science-Policy Platform on Biodiversity (IPBES), 'Global assessment report on biodiversity and ecosystem services' (IPBES 2019) <https://ipbes.net/global-assessment> last accessed 5 January 2022.

13 IPCC, *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (Cambridge University Press 2019); Nick Watts et al., 'The 2020 report of The Lancet countdown on health and climate change: Responding to converging crises' (2021) 397 The Lancet 129-170, <https://doi.org/10.1016/S0140-6736(20)32290-X> accessed 15 March 2022; Ana Maria Vicedo-Cabrera et al., 'The burden of heat-related mortality attributable to recent human-induced climate change' (2021) 11 Nature Climate Change 492-500, <https://doi.org/10.1038/s41558-021-01058-x> accessed 28 March 2022.

cuss the challenges in attribution science in Section 3 and provide a short summary and conclusions in Section 4.

2 Status of attribution science

2.1 Attribution of the causes of climate change

Attribution is the process of identifying the drivers of the observed change in climate variables or in extreme weather events. The observed climate change is separated into components that can be explained by natural variability (including internal variability generated within the climate system) and components that result from changes external to the climate system.[14] Natural variability comprises internal variability like temperature oscillations and external drivers like solar and volcanic influences. Factors due to human activities include increases in greenhouse gas concentration and aerosols, and land-use change.

The different climate drivers cause characteristic climate change signatures, so-called fingerprints. For the attribution of long-term changes, usually, observations and model simulations are used, the latter driven by different forcings. Fingerprint studies evaluate the spatial, temporal, or space-time patterns of response (fingerprints) to external forcings from climate model simulations, whether these fingerprints agree in the observations and whether they are stronger than natural variability. This enables to determine the causal factors of climate change and the uncertainty in the magnitude of this fingerprint in observations.[15] Klaus Hasselmann first developed these basic attribution methods, and already 50 years ago, Syukuro Manabe predicted

14 E.g., Gabriele C Hegerl and Francis W Zwiers, 'Understanding and attributing climate change', in IPCC, *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2007); Gabriele C Hegerl and Francis W Zwiers, 'Use of models in detection and attribution of climate change' (2011) 2 WIREs Climate Change 570-591, https://doi.org/10.1002/wcc.121; Bruce Hewitson et al., *2014: Regional Context, In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press 2014).

15 Klaus Hasselmann, 'Optimal fingerprints for the detection of time-dependent climate change' (1993) 6 Journal of Climate 1957-1971 <https://doi.org/10.1175/1520-0442(1993)006<1957:OFFTDO>2.0.CO;2> accessed 11 March 2022; Klaus Hasselmann, 'Multi-pattern fingerprint method for detection and attribution of climate change' (1997) 13 Climate Dynamics 601-611 <https://doi.org/10.1007/s003820050185> accessed 11 March 2022; Gabriele C Hegerl et al., 'Multi-fingerprint detection and attribution analysis of greenhouse gas, greenhouse gas-plus-aerosol and solar forced climate change' (1997) 13 Climate Dynamics 613-634 at <https://doi.org/10.1007/s003820050186> accessed 11 March 2022.

the human-caused fingerprint on atmospheric temperature change[16]; both are Nobel Laureates of 2021.

Over the past decades, unequivocal changes have been detected in the climate system, and attribution studies have shown that natural factors alone cannot explain the changes observed since the pre-industrial period. Human activities have been clearly identified as the main responsible factors for the observed climate change. Figure 1b clearly shows that the observed change in global average surface temperature can only be explained by human-induced and natural factors together.[17] Human fingerprints on climate are ubiquitous and have been identified in a range of climate variables beyond temperature.[18]

Moreover, investigating the relative contributions of different human-induced forcings, i.e., carbon dioxide, other greenhouse gases, and anthropogenic aerosols, shows that greenhouse gas warming is even partly masked by cooling due to aerosol emissions (Fig. 2). According to the IPCC (2021), the global surface temperature rise of 1.1°C since 1850-1900 (Fig. 2a) is mainly driven by well-mixed greenhouse gases, which contribute to a warming of 1.0°C to 2.0°C, while other human drivers (mainly aerosols) contribute a cooling of 0.0°C to 0.8°C (Fig. 2b-c). Natural drivers and internal variability only had a minor effect on the global surface temperature within –0.2°C to 0.2°C.[19]

16 Syukuro Manabe and Richard T Wetherald, ‘Thermal equilibrium of the atmosphere with a given distribution of relative humidity’ (1967) 24 Journal of the Atmospheric Sciences 241-259 <https://doi.org/10.1175/1520-0469(1967)024<0241:TEOTAW>2.0.CO;2> accessed 11 March 2022.

17 IPCC 2021 SPM (n 3).

18 E.g., Benjamin D Santer et al., ‘Identification of human-induced changes in atmospheric moisture content’ (2007) 104 Proceedings of the National Academy of Sciences 15248-15253 <https://doi.org/10.1073/pnas.0702872104> accessed 11 March 2022; Benjamin D Santer et al., ‘Human influence on the seasonal cycle of tropospheric temperature’ (2018) 361 Science 227 <https://doi.org/10.1126/science.aas8806> accessed 11 March 2022; Peter A Stott et al., ‘Detection and attribution of climate change: a regional perspective’ (2010) 1 WIREs Climate Change 192-211 <https://doi.org/10.1002/wcc.34> accessed 11 March 2022; Jianping Duan et al., ‘Detection of human influences on temperature seasonality from the nineteenth century’ (2019) 2 Nature Sustainability 484-490 <https://doi.org/10.1038/s41893-019-0276-4> accessed 11 March 2022; Gabriele C Hegerl et al., ‘Causes of climate change over the historical record’ (2019) 14 Environmental Research Letters 123006 <https://doi.org/10.1088/1748-9326/ab4557> accessed 11 March 2022; Céline JW Bonfils et al., ‘Human influence on joint changes in temperature, rainfall and continental aridity’ (2020) 10 Nature Climate Change 726-731 <https://doi.org/10.1038/s41558-020-0821-1> accessed 11 March 2022.

19 Nathan P Gillett et al., ‘Constraining human contributions to observed warming since the pre-industrial period’ (2021) 11 Nature Climate Change 207-212 <https://doi.org/10.1038/s41558-020-00965-9> accessed 11 March 2022; IPCC, 2021 SPM (n 3).

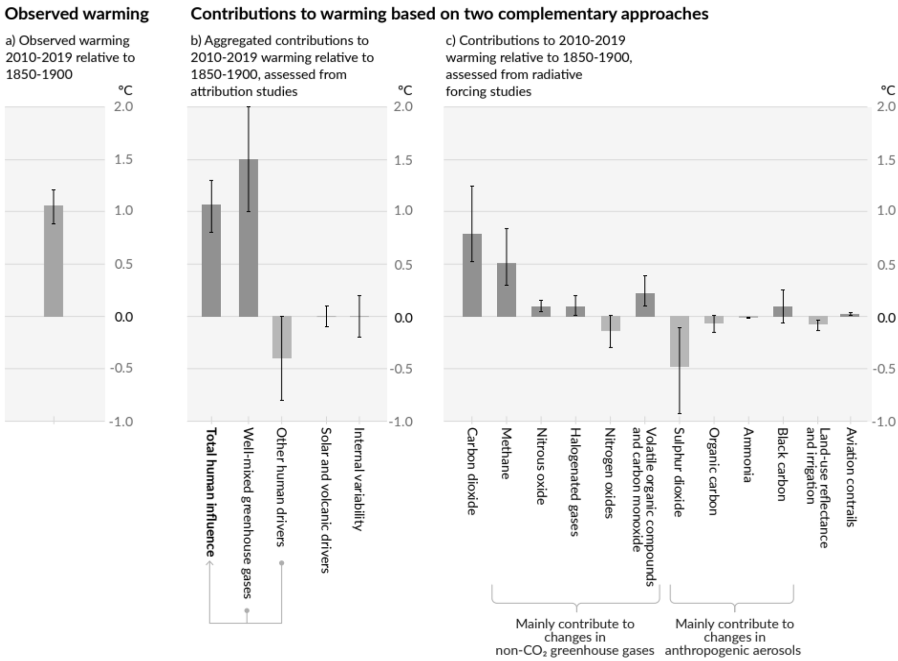

Figure 2. (a) Observed warming in the climate system, **(b)** total human-induced warming due to aggregated contributions of well-mixed greenhouse gases and other human drivers (mainly aerosols), natural drivers, and internal forcing, **(c)** individual contributions of different anthropogenic forcings.[20]

2.2 Attribution of extreme weather and climate events

Extreme events are rare by definition, and the extent to which climate change influences an individual weather or climate event is more difficult to determine. The challenge is to estimate how much human-induced climate change has affected the magnitude of a particular event or the probability of its occurrence. Event attribution uses mainly two approaches for estimating changes in probability and magnitude of extreme events, on the one hand analysing long-term observational records, on the other hand utilising model simulations for a world with human-caused climate change to a counterfactual world without human-caused climate change.[21]

20 IPCC, 2021 SPM (n 3) Figure SPM.2.
21 Peter Stott et al., 'Attribution of extreme weather and climate-related events' (2016) 7 WIREs Climate Change 23-41 <https://doi.org/10.1002/wcc.380> accessed 11 March 2022; National Academies of Sciences, Engineering and Medicine (NAS), 'Attribution of extreme weather

Confidence for attribution findings is greatest for those extremes that are related to temperature, such as the observed long-term warming, where human-caused changes are clear.[22] Changes in temperature extremes thus have a more robust basis, and also atmospheric moisture as the water-holding capacity of a warmer atmosphere increases at a rate of 7% per degree Celsius.

A range of attribution studies has provided quantitative estimates of anthropogenic contributions to changes in temperature extremes[23] and precipitation extremes[24] globally for different regions. Changes in extremes are already affecting most regions across the globe. Human influence contributes to the observed increase in hot extremes and heavy precipitation (Fig. 3) though for the latter, attribution is more difficult due to the lack of reliable climate data and limited local research capacities, particularly in the global south.[25]

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events in the context of climate change' (NAS 2016) <https://bit.ly/3Dkt7WV> accessed 28 March 2022.

22 NAS 2016 (n 21).

23 E.g., Siyan Dong et al., 'Observed changes in temperature extremes over Asia and their attribution' (2018) 51 Climate Dynamics 339-353 <https://doi.org/10.1007/s00382-017-3927-z> accessed 11 March 2022; Yukiko Imada et al., 'Climate change increased the likelihood of the 2016 heat extremes in Asia' (2018) 99 Bulletin of the American Meteorological Society 97-101 <https://doi.org/10.1175/BAMS-D-17-0109.1> accessed 11 March 2022; Chao Li et al., 'Widespread persistent changes to temperature extremes occurred earlier than predicted' (2018) 8 Scientific Reports 1007 <https://doi.org/10.1038/s41598-018-19288-z> accessed 11 March 2022; Hong Yin, 'Changes in temperature extremes on the Tibetan Plateau and their attribution' (2019) 14 Environmental Research Letters 124015 <https://doi.org/10.1088/1748-9326/ab503c> accessed 11 March 2022; Nikolaos Christidis et al., 'The increasing likelihood of temperatures above 30 to 40°C in the United Kingdom' (2020) 11 Nature Communications 3093 <https://doi.org/10.1038/s41467-020-16834-0> accessed 11 March 2022.

24 E.g., Seung-Ki Min et al., 'Human contribution to more-intense precipitation extremes' (2011) 470 Nature 378-381 <https://doi.org/10.1038/nature09763> accessed 11 March 2022; Erich M Fischer and Reto Knutti, 'Anthropogenic contribution to global occurrence of heavy precipitation and high-temperature extremes' (2015) 5 Nature Climate Change 560-564 <https://doi.org/10.1038/nclimate2617> accessed 11 March 2022; Andrea J Dittus et al., 'A multiregion model evaluation and attribution study of historical changes in the area affected by temperature and precipitation extremes' (2016) 29 Journal of Climate 8285-8299 <https://doi.org/10.1175/JCLI-D-16-0164.1> accessed 11 March 2022; Megan C Kirchmeier-Young and Xuebin Zhang, 'Human influence has intensified extreme precipitation in North America' (2020) 117 Proceedings of the National Academy of Sciences <https://doi.org/10.1073/pnas.1921628117> accessed 11 March 2022; Seungmok Paik et al., 'Determining the anthropogenic greenhouse gas contribution to the observed intensification of extreme precipitation' (2020) 47 Geophysical Research Letters e2019GL086875 <https://doi.org/10.1029/2019GL086875> accessed 11 March 2022; Siyan Dong et al., 'Attribution of extreme precipitation with updated observations and CMIP6 simulations' (2021) 34 Journal of Climate 871-881 <https://doi.org/10.1175/JCLI-D-19-1017.1> accessed 11 March 2022.

25 Friederike E L Otto et al., 'Challenges to understanding extreme weather changes in lower income countries' (2020) 101 Bulletin of the American Meteorological Society E1851- E1860 <https://doi.org/10.1175/BAMS-D-19-0317.1> accessed 11 March 2022; IPCC 2021 SPM (n 3).

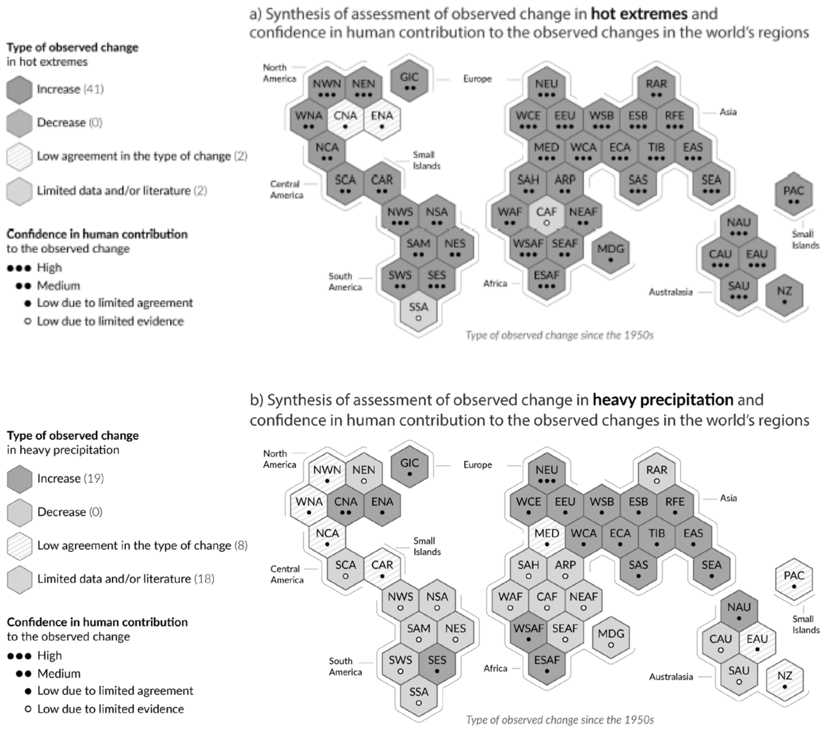

Figure 3. (a) Observed increase in hot extremes and **(b)** heavy precipitation, with confidence in human contribution indicated (dots). Each hexagon corresponds to one of the IPCC AR6 WGI reference regions.[26]

In the case of dynamically driven extremes that are modulated by atmospheric circulation and feedbacks, alternative approaches are made. Conditional attribution regards the circulation regime as being largely unaffected by climate change (given condition) and asks the question whether known changes in the thermodynamic state affected the impact of the particular event.[27] The confidence in attribution analyses of specific extreme events (Fig. 4) is highest for extreme heat and cold events, followed by drought and heavy precipitation, while confidence is low in the attribution of cyclones and tropical storms.[28]

26 IPCC 2021 SPM (n 3) Figure SPM.3a.
27 Kevin E Trenberth, John D Fasullo and Theodore G Shepherd, 'Attribution of climate extreme events' (2015) 5 Nature Climate Change 725-730; NAS 2016 (n 21).
28 NAS 2016 (n 21).

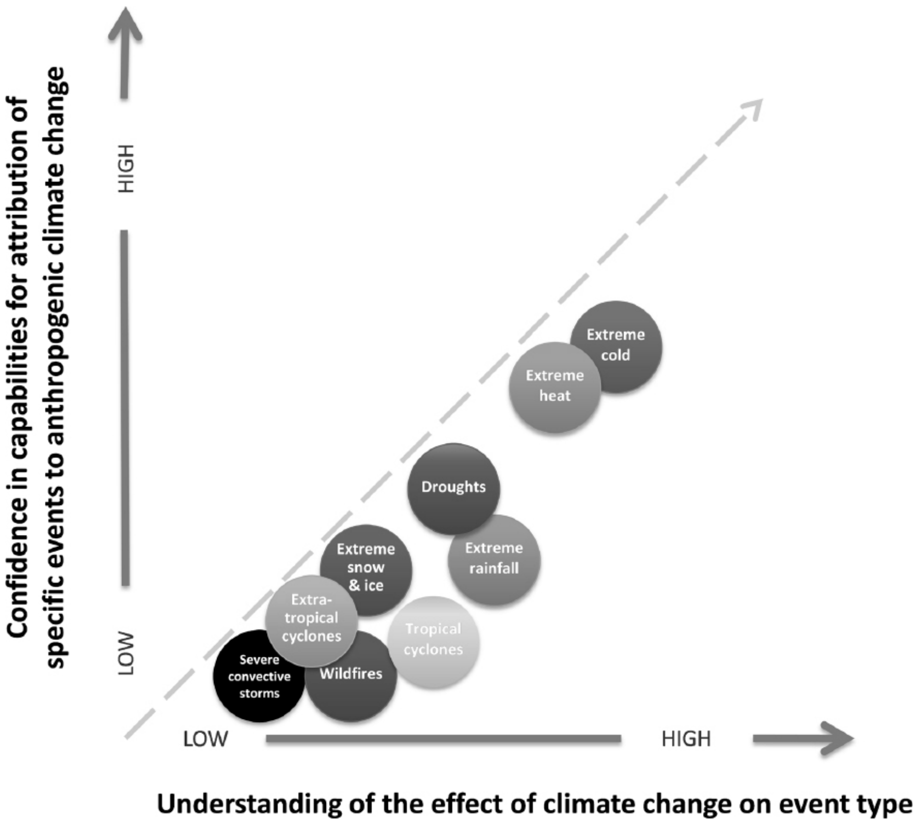

Figure 4. The state of attribution science for different extreme event types. In the horizontal, the level of understanding of the effect of climate change on the event type is reflected. In the vertical, the scientific confidence is reflected for attribution of specific events to anthropogenic climate change for that event type.[29]

Providing rapid information on extreme events with large impacts around the world is the aim of the World Weather Attribution (WWA), an international collaboration of climate scientists since 2015.[30] Attribution studies of recent major extreme events in 2021 showed that the heatwave in the Pacific Northwest of America in June and July 2021 is very rare in today's climate but would have been virtually impossible

29 NAS 2016 (n 21) Figure S.4.
30 Geert J van Oldenborgh et al., 'Pathways and pitfalls in extreme event attribution' (2021) 166 Climatic Change 13 <https://doi.org/10.1007/s10584-021-03071-7> accessed 11 March 2022.

without climate change. For the western Europe flood event, the heavy rainfall was found more likely due to climate change.[31]

From 1970 to 2019, over 22,326 disasters worldwide were recorded by the World Meteorological Organization (WMO), 11000 of which were attributed to weather, climate and water-related hazards. Most disaster-related human losses were caused by tropical cyclones (38%) and droughts (34%), while most economic losses were associated mainly with different types of floods (62%) and tropical cyclones (38%).[32] These impact numbers show that systematic attribution of losses to the underlying hazard and information on risks is crucial for society.

3 Challenges in attribution studies

Challenges in attribution science arise from the use of observational data and climate model simulations, both of which are subject to uncertainty, and from methodological approaches and limitations for different types of climate variables and events.

3.1 Climate change indicators and climate variables

Climate variables that are mainly driven by thermodynamics are robust indicators for the detection and attribution of human-induced climate change, such as temperature, sea level, large-scale precipitation patterns, arctic sea-ice extent, glacier extent, or upper-ocean heat content (Fig. 5 a-b). The changes are consistently found in observations, theory and climate model simulations.[33] Both our understanding and confidence on attribution findings for extreme events resulting from those variables are high (Fig. 4), although detectability and robustness decrease at regional scales.

Changes in dynamically driven climate variables (such as storm tracks, jet streams, or monsoons) are not detectable yet and/or less robust across observations, theory, and models, especially at regional scales where dynamics takes control.[34] Circulation-driven climate variables have larger variability (Fig. 5 c-d), resulting in a

31 World Meteorological Organization (WMO), ‘State of the global climate 2021: WMO provisional report (WMO 2021) <https://library.wmo.int/index.php?lvl=notice_display&id=21982> accessed 5 January 2022.

32 World Meteorological Organization (WMO), ‘WMO atlas of mortality and economic losses from weather, climate and weather extremes (1970-2029)’ (WMO 2020) <https://library.wmo.int/index.php?lvl=notice_display&id=21930#.YdW0g2jMI2w> accessed 5 January 2022.

33 Theodore G Shepherd, ‘Atmospheric circulation as a source of uncertainty in climate change projections’ (2014) 7 Nature Geoscience 703-708 <https://doi.org/10.1038/ngeo2253> accessed 11 March 2022.

34 Shepherd (n 33).

low signal-to-noise ratio and hindering trend detection.[35] Thus, confidence is lower in atmospheric circulation aspects of climate change.

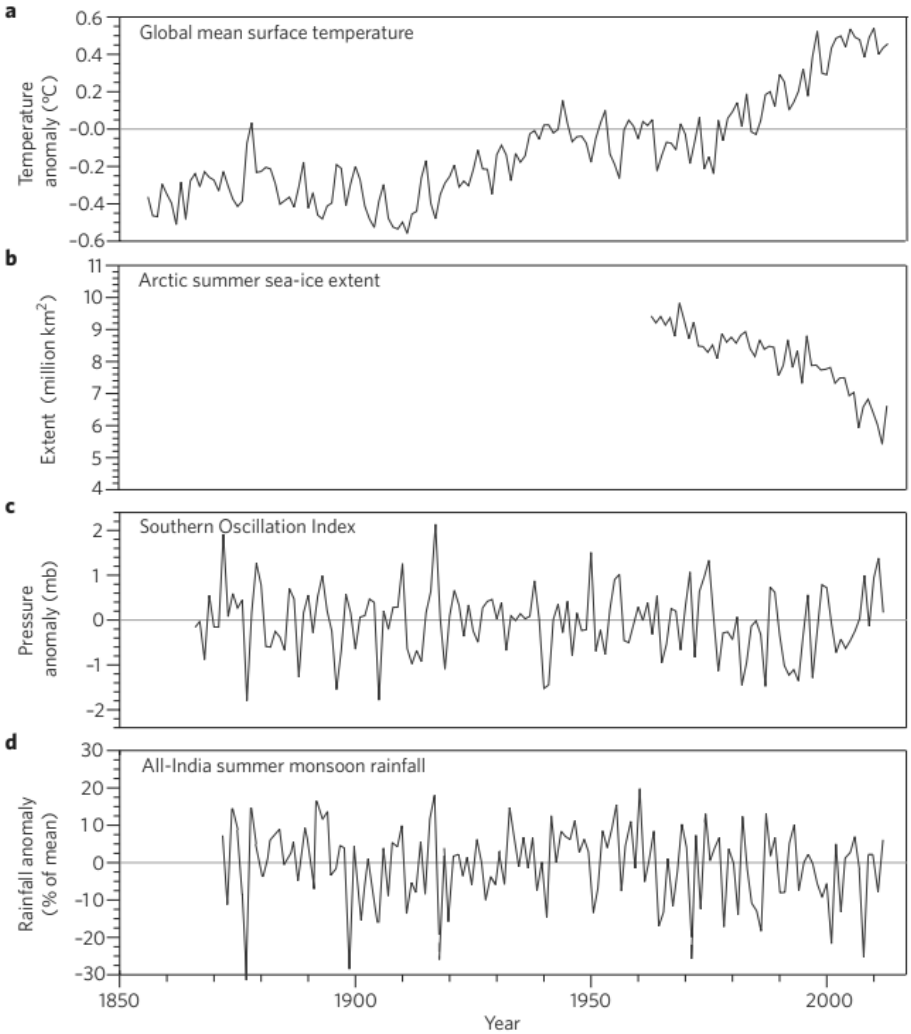

Figure 5. Observed changes in thermodynamic-driven climate indicators: **(a)** global annual mean surface temperature anomaly, **(b)** Arctic summer sea-ice extent, and in dynamically-driven indicators: **(c)** Southern Oscillation Index, **(d)** Indian summer monsoon rainfall.[36]

35 Shepherd (n 33); Trenberth et al. (n 27).
36 Shepherd (n 33) Figure 1.

3.2 Observational records

Consistent long-term observations with appropriate spatial coverage and adequate temporal resolution are an important prerequisite for detection and attribution studies. However, this is still challenging for certain indicators and regions. Observations can be sparse in space, for example in the oceans, over remote land regions, or in continental regions of the global south. Observations can be short in time or may not have the required temporal resolution. Observational records are affected by measurement errors, sampling and representation uncertainties, and inhomogeneities, e.g., due to changes in observing location or instrument types.

A range of statistical techniques and homogenisation methods is applied for establishing homogeneous observational time series with spatio-temporal gridding. However, different algorithms for the construction of time series and gridded data sets may lead to differences in detected changes and attribution results. Besides improving methods and continuous quality control, providing information on metadata and uncertainties is crucial. Improving spatial coverage, temporal resolution and overall data quality would be beneficial to attribution science. Increasing the number of observations and establishing infrastructures in data sparse regions, such as the global south, are extremely important as these regions are also particularly vulnerable to climate impacts.

3.3 Climate model simulations

Climate model simulations are an indispensable tool in almost all attribution studies. Since models are only a limited representation of the real world, it is critical to evaluate if they fit the respective purpose. Important aspects are that the underlying physics and meteorology are reasonably represented in the model, and that major global and local forcings are accounted for to yield realistic trends. Because many attribution methods rely on estimating event probabilities or distributions of events, models should have the skill to represent the extremes of interests and/or the climatology of an event class.[37] The statistics of modelled extreme events should match statistics of observed extremes.[38]

Most studies use atmosphere-only or coupled global climate models, regional climate models, or models constructed to represent a specific phenomenon.[39] Large ensembles or long experiments of multiple climate models are needed. Considering model uncertainties, properly accounting and correcting for model errors in simulat-

37 E.g., NAS 2016 (n 21).
38 Van Oldenborgh et al. (n 30).
39 NAS 2016 (n 21).

ing the probabilities of extreme event occurrences enables more reliable attribution of extreme weather and climate events.[40] Performance-based model selection might also aid attribution science.[41]

Attribution results can be sensitive to framing of the study, the choice of observations, the type of climate models, the number of ensemble members, and methodological choices. Hauser et al.[42] demonstrated this for the case of the 2015 European summer drought deriving contradicting conclusions on the relevance of human influence depending on the chosen data source and event attribution methodology. Appropriate framing and conditioning of the attribution question is thus crucial.[43]

Main pitfalls and challenges to overcome in extreme event attribution include the selection and definition of the event, analysis of observed probability and trends, climate model evaluation and analysis of modelled hazard trends, synthesis of the attribution of the hazard, analysis of trends in vulnerability and exposure, and communication.[44] A multi-model and multi-method framework in event attribution research is therefore crucial, especially for events with a low signal-to-noise ratio and high model dependency.[45]

Figure 6 illustrates synthesis plots for interpreting attribution results as an example. For the case of extreme precipitation in Fig. 6a, all model results agree well with each other and with observations, and the weighted mean is used as the attribution result. In the second case (Fig. 6b), there are discrepancies among models and a larger model spread, which must be reflected in the uncertainty statement of the attribution result. No attribution can be made for the storm case (Fig. 6c) because the modelled trend is clearly inconsistent with the observed trend.

Overall, in many cases, a consistent message and solid scientific results are found from the attribution study. In many cases, however, the quality of the available observations or models is not good enough to make a statement about the influence of climate change on the event in question.[46]

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40 Omar Bellprat et al., ‘Towards reliable extreme weather and climate event attribution’ (2019) 10 Nature Communications 1732 <https://doi.org/10.1038/s41467-019-09729-2> accessed 11 March 2022.

41 Veronika Eyring et al., ‘Towards improved and more routine Earth system model evaluation in CMIP’ (2016) 7 Earth System Dynamics 813-830 <https://doi.org/10.5194/esd-7-813-2016> accessed 11 March 2022.

42 Mathias Hauser et al., ‘Methods and model dependency of extreme event attribution: The 2015 European drought’ (2017) 5 Earth’s Future 1034-1043 <https://doi.org/10.1002/2017EF000612> accessed 11 March 2022

43 E.g., Daithi Stone, Suzanne M Rosier and David J Frame, ‘The question of life, the universe and event attribution’ (2021) 11 Nature Climate Change 276-278 <https://doi.org/10.1038/s41558-021-01012-x> accessed 11 March 2022.

44 Otto et al. (n 25); Van Oldenborgh et al. (n 30).

45 Hauser et al. (n 42).

46 Van Oldenborgh et al. (n 30).

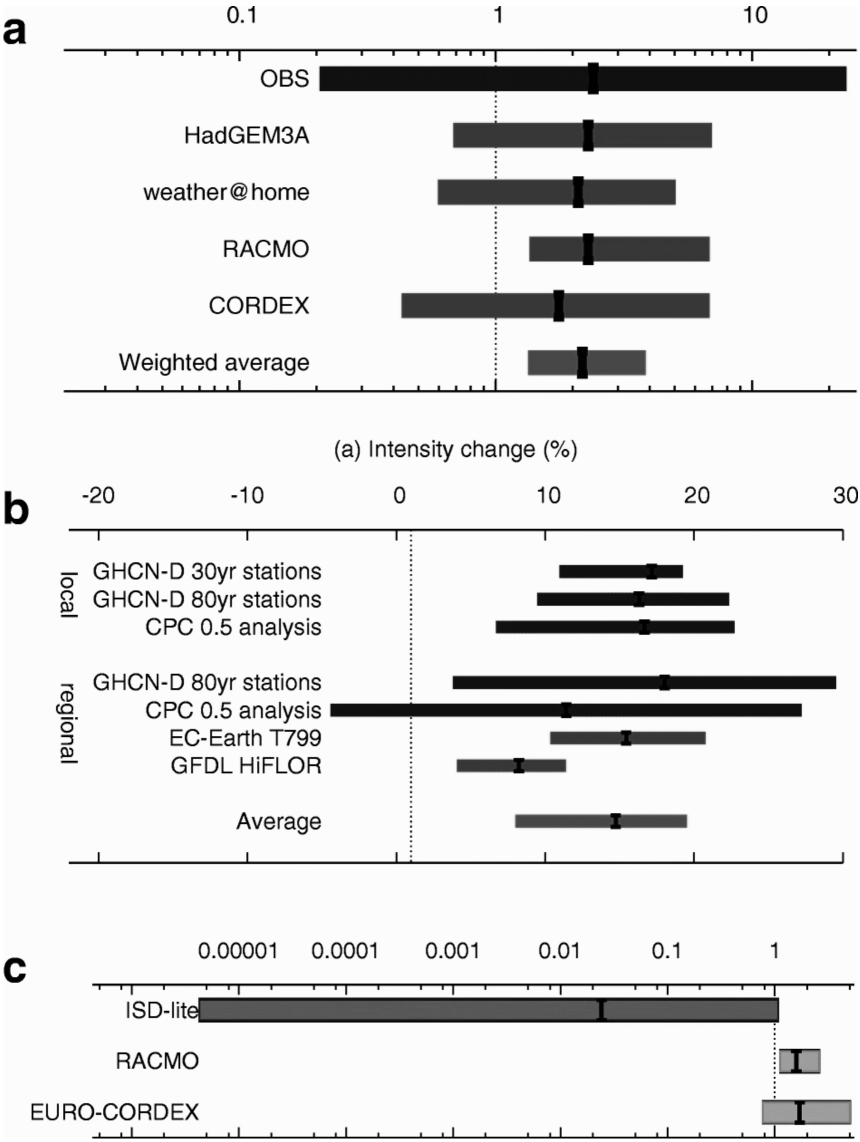

Figure 6. Synthesis of attribution results from observations, models, and the average for three studies **(a)** probability ratio of extreme precipitation in April-June over the Seine basin, **(b)** intensity of extreme precipitation on the Gulf coast, **(c)** probability ratio for changes in wind intensity over the region of storm Friederike on 18 January 2018.[47]

47 Ibid Figure 5.

4 Summary and conclusions

Climate change is progressing rapidly in all components of the climate system. The evidence is clear from observations. Significant trends and changes have been detected, warming of the land, oceans, and atmosphere to rising sea levels and melting ice. Extreme weather and climate events are becoming more frequent and intense in a warmer climate. Changes in extremes are already affecting most regions around the globe.

Identifying the drivers of the observed change, attribution studies have shown that natural factors alone cannot explain the rapid changes observed in the climate system. Human activities have been clearly identified as the main responsible factors for the observed climate change due to increasing greenhouse gas emissions from the burning of fossil fuels and other activities. Human fingerprints are ubiquitous and have been identified in a range of climate variables beyond temperature.

Confidence in attribution results is greatest for those changes and extremes that are related to temperature, such as observed long-term warming or the increase in hot extremes, where the evidence is clear on human-caused changes. Attribution for circulation-driven changes and extremes is more challenging, and new methods and approaches have been developed.

Extreme event attribution estimates the influence of human-induced climate change on the probability and/or severity of an observed extreme weather or climate event and the associated risk. While confidence in attribution of specific extreme events is highest for extreme heat and cold events, followed by drought and heavy precipitation, it is lower for cyclones and storms. Event attribution revealed that many recent events would have been less severe, less likely, or virtually impossible without human-induced climate change.

Challenges in attribution arise from the sensitivity of results to the framing of the study, the choice of observations, the type of climate models, and methodological choices, and simply from limitations and uncertainties of observations and climate models. A key aspect is appropriately framing the attribution question in a multi-model and multi-method framework.

Recent developments concern the clear definition of extreme events, not only in terms of physical indicators but also in terms of criteria related to the impact of the events. A series of thresholds are used, which combine meteorological extremes with extreme loss of life or extreme economic losses. Although assessing the exposure and vulnerability of systems is complex, there is a clear need to consider vulnerabilities and impacts of extremes in event attribution. Driven by the public interest in rapid information, efforts are underway to establish operational-scale attribution and to further improve short-term climate predictions.

Climate and attribution science provide key information for a better understanding of climate change, changing extremes, causes, and impact risks. Findings benefit society by providing a better understanding of extremes, information for decision-making, and improving early warnings. Moreover, attribution science provides vital information for mitigation and adaptation to climate change, for climate litigation and climate action, and for raising awareness of current and future climate change impacts.

Acknowledgements

This work was funded by the Austrian Science Fund (FWF) under research grant W1256 (Doctoral Programme Climate Change – Uncertainties, Thresholds and Coping Strategies).

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