Localness in climate change

Article

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Prediction and Uncertainty

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Abstract

Climate change is a global problem, yet is experienced at the local scale, in ways that are both place-specific and specific to the accidents of weather history. This article takes the dichotomy between the global and the local as a starting point to develop a critique of the normative approach within climate science, which is global in various ways and thereby fails to bring meaning to the local. The article discusses the ethical choices implicit in the current paradigm of climate prediction, how irreducible uncertainty at the local scale can be managed by suitable reframing of the scientific questions, and some particular epistemic considerations that apply to climate change in the global south. The article argues for an elevation of the narrative, and for a demotion of the probabilistic from its place of privilege in the construction and communication of our understanding of global warming and its local consequences.

Keywords: climate change; climate ethics; uncertainty; narrative

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Introduction

In *The Great Derangement*, the novelist and anthropologist Amitav Ghosh asks why we find it so difficult to think about climate change. The question starts with literature but then extends to history and politics. His answer is that in all three arenas, the modern mindset has promoted the primacy of human, indeed individual, agency. In this mindset, there is no place for the uncanny – and climate change, especially at the local scale, is nothing if not uncanny. Not only does climate change require a rather different conception of agency, it also asks us to consider the geography of climate change as both uneven and unequal. For instance, the cities established through colonialism have been largely sited on coasts, in defiance of threats from tropical cyclones and coastal flooding, indeed often on landfill. The localization of climate change is perhaps most salient in these vulnerable and exposed places. Yet climate science takes the scale of the global as normative and the local as accidental. It thereby ‘detaches knowledge from meaning’[1], and enacts forms of what the philosopher Miranda Fricker has called ‘hermeneutic injustice.’[2] We describe here some ideas emerging from within climate science, informed by other disciplines, which express this critique and aim to address it.

1. The Scale of the Global

Global warming is, as the phrase says, global. Though the rate of human-induced temperature increase is not uniform in magnitude – most dramatically, the Arctic is warming faster than elsewhere – nearly everywhere on earth is warming. And the responsible increases in greenhouse gas concentrations, even more so than temperature, are truly global. Carbon dioxide is long-lived and well-mixed in the atmosphere, with a nearly uniform concentration, so a ton of CO_2 emitted anywhere is the same as a ton emitted anywhere else. Its global scale is one of the aspects that makes climate change such a daunting challenge for the human species.

Our confidence in the basic fact of a substantial human influence on climate rests in large part on our solid understanding of the greenhouse effect and its thermodynamic consequences – that is, it directly increases temperature, and almost as directly increases atmospheric moisture and raises sea level – which act, fundamentally, at the global scale. Yet the impacts of the warming will be felt at the local scale, and will differ according to all the particularities of place, both physical and human: geographic, social, political, economic, and cultural. The models used to make climate predictions have spatial resolutions on the order of 100 km. Resolution in these models is analogous to the resolution, or pixel size, in a digital camera image; nothing of this size or smaller can be represented. Yet a typical city, for example, is much smaller than this. Methods have been developed to 'downscale' climate predictions, but these tend to magnify uncertainties, which were already substantial at larger scales.[3] Thus the need to understand global warming's impacts on human society, and to adapt in order to reduce the harm it does, puts pressure on climate science to produce predictions at spatial scales much smaller than those at which it has historically been able to do so with any confidence.

In addition to being global in physical space, the dominant mode of doing and communicating climate science is also global in another, more conceptual sense: namely, it is global in the space of possible trajectories, or histories, of the climate system.

Chaos theory teaches us that immeasurably tiny, unknowable differences in the present state of the weather rapidly become large differences in the future state. This is the reason that useful forecasts of the daily weather more than a couple of weeks in advance are not possible, and that while the atmosphere in principle obeys deterministic laws, in practice its behavior has a component that is indistinguishable from that of a stochastic, or random system. It also means that the actual weather state, and in fact the entire temporal sequence of weather, in a sense is – within bounds set by larger physical constraints on the climate – an accident, just one possible history among many equally possible ones. When talking about cause and effect on long time scales, it makes sense to focus on averages (or other statistics) over all the equally likely weather states, to the extent that we can determine what these are.

Yet if the earth's climate history is just one of many equally possible histories, it is a deeply privileged one, scientifically and otherwise, in that it really did occur. No future climate trajectory is similarly privileged. Thus there is a fundamental disconnect in time between our knowledge of the climate's history, with all its specificity, richness of detail, and undeniable reality, and of its future, about which even a perfect prediction can only be probabilistic even in principle. In some respects, this disconnect mirrors that between the global scale – at which we truly understand the human influence on climate – and the local scale, at which its impacts are felt.

Other uncertainties in climate prediction are often treated similarly to the aleatoric one associated with chaos and the unpredictability of weather. Most important is the epistemic uncertainty that results from differences in climate model constructions. All models are designed to obey the laws of physics, but unavoidable imperfections associated with expressing those laws on computers lead to compromises that are made differently by different groups of model-building scientists. Not knowing which of the resulting models is the best, we generally consider them all to be equally likely and consider averages, or the whole distribution of different model results, in order to make predictions of the future. This is yet another sense in which climate science takes a global view. Among other outcomes, it leads us to regard agreement between different models as a measure of confidence, or 'robustness.'[4]

Rather than taking the scale of the global – in all three senses described above – as normative, we discuss below how this global approach leads to conservatism in the attribution of specific weather and climate phenomena to human influence, and how an approach that is local in one or more senses can change this. By considering specific individual past, present or future histories, rather than all of them together, we can at the same time provide more specificity and richness at the local scale in space.

This discussion has much in common with earlier thinking in other fields where one considers the tension between individual case studies and statistical analyses that pool all data, such as in the study of organizational behavior,[5] safety in health care,[6] and public health.[7] The study of specific, local narratives – though generally of only the past, not the future – is also fundamental to humanist scholarly fields, including history and anthropology. And to the extent that consideration of the most dire possible futures (among other specific ones) is used to advocate for mitigation, this view is not new even to the climate policy debate, but is familiar as the 'precautionary principle'. Any novelty here comes, perhaps, only from situating it in the context of the specific ways that climate science articulates the causal links between human greenhouse gas emissions and their effects. With physics as its disciplinary model, climate science tends to seek the most general explanations[8]. Given the constraints of chaos theory and model uncertainty, this leads to the global, statistical approach as normative. The limitations of that approach may be particularly difficult for many climate scientists to see due to their training, which is strongly influenced by physics, if not explicitly in that discipline (as is true of us, the authors).

In all of this our interest is in introducing better ways for climate science to address questions of moral responsibility. Arbitrary historical choices made by scientists, inherent to the very practice of science,[9] encode specific human values. This is as true in climate science as any other.[10] The specific choices made by climate scientists have consequences for the perception of the overall message outside the climate science community, and for the resulting use of that message in political contexts. We have come to view some of those choices as misleading and ethically questionable. We present here some newer methodologies that we argue are equally scientifically defensible to the traditional ones but designed, consciously, to incorporate local information and concerns.

2. Prediction

Scientific statements about climate change are normally expressed in the form "climate change is responsible for this", or "climate change will lead to that". Such statements can be regarded as scientific hypotheses that are either accepted or rejected by testing against the evidence available at the time. In hypothesis testing, there are two kinds of errors that can be made. 'Type 1' errors are false positives, or false alarms: a hypothesis is accepted that later turns out to be false. 'Type 2' errors are false negatives, or missed warnings: a hypothesis is rejected that later turns out to be true. (The other possibilities are true positives, and true negatives.)

In climate science, the tradition has been to guard against Type 1 errors[11]. This is exemplified by the detection-attribution framework[12] that forms the centerpiece of the assessments provided by Working Group I – the one focused most exclusively on physical science – of the Intergovernmental Panel on Climate Change (IPCC), and is illustrated by Figure 1a for globally-averaged surface temperature. First the observed changes (black line) are detected, meaning that the likelihood of them arising by chance is excluded. Then the changes are attributed to anthropogenic climate change, meaning that they can only be explained by including greenhouse gases and other anthropogenic 'forcing' in the simulations (shading). Whilst this framework is appropriate for making unequivocal statements about anthropogenic climate change, at the regional scale it generally leads to a paralysis, because the uncertainties are quite large at that scale. This is especially the case for precipitation, as is illustrated by Figure 1b, which shows model-predicted changes in precipitation over the 21st century under a high-end climate change scenario. In many regions the models do not provide a consistent prediction, with some suggesting an increase and some a decrease in precipitation. This lack of model agreement precludes the attribution of observed changes to climate change in these regions, where most people live.

When considering local manifestations of climate change, a focus on avoiding Type 1 errors can thus lead to the rejection of climate-change hypotheses. This raises the prospect of committing Type 2 errors.[13] Guarding against Type 2 errors has been controversial within climate science, perhaps because it can be construed as 'alarmism.'[14] Yet it is quite accepted in other fields of applied science. For example, with extreme weather warnings a balance is struck, and generally the public is more tolerant of Type 1 errors than of Type 2 errors. In drug testing, tests concerning the efficacy of the drug guard against Type 1 errors, whilst tests concerning the possibility of adverse side effects guard against Type 2 errors. Thus, the balance of concern between avoiding Type 1 and Type 2 errors depends very much on the context; there is no purely scientific basis for choosing one over the other.[15]

It follows that the decision on how to frame climate information, and the balance between guarding against Type 1 and Type 2 errors, has ethical implications. There is no such thing as value-free climate science[16]. In the IPCC detection-attribution framework, it is stated that data for scientific analysis should not be preselected based on observed effects, in order to avoid selection bias.[17] This implies that the questions about climate change must be driven by the scientists, rather than by those affected by climate change. It thereby represents a form of what the philosopher Miranda Fricker has called 'hermeneutic injustice.'[18] Similarly, the stated need to remove the influence of non-climatic factors — referred to by statisticians as 'confounding factors' — in order to isolate the pure climate signal[19] makes it extremely difficult to detect and attribute climate-change impacts involving non-climatic human factors that increase the vulnerability, e.g. in urban flooding or the urban heat-island effect. Yet these tend to represent the most dangerous climate-change impacts on humanity.

In order to address risk and thereby guard against Type 2 errors, Working Group II of the IPCC, which deals with impacts and adaptation, defines climate change as *any* observed change, not necessarily one attributed to anthropogenic causes.[20] This approach introduces a knowledge gap between Working Groups I and II, but is the only way to avoid the paralysis that would otherwise result for WGII[21].

Climate change at the local scale has the challenge that the evidence base is often legitimately contestable. Observational records are limited, and in any case do not always relate directly to anthropogenic climate change because of many confounding factors. The usual experimental test in science, using a controlled intervention, is not possible (as it is not, in general, in any of the earth sciences). Climate models, based on the governing physical equations, can be used for this purpose (as in Figure 1a), but they are not the real system, and can be wrong, particularly at local scales. Together this means that the likelihood of high-impact climate outcomes cannot be reliably quantified in a probabilistic manner, though this by no means implies that such outcomes are impossible or even improbable. Alternative ways need to be found to respond to local concerns and recognize anthropogenic climate change at the local scale without compromising scientific rigor.

3. Uncertainty

The limitations of scientific information are usually expressed in terms of uncertainties. There are three generic sources of uncertainty in how climate will change:[22] the future evolution of climate forcing (both natural and anthropogenic, the latter being dominated by increases in greenhouse gases), the response of the climate system to that forcing, and internal variability. The uncertainty in anthropogenic climate forcing is mainly social, political and economic. Response uncertainty is epistemic and is sometimes called 'model uncertainty'. Internal variability – that is, natural fluctuations in climate that would occur in the absence of human influence, and still do in its presence – reflects the chaotic nature of the climate system, and is mainly aleatoric rather than epistemic (although the statistics of extreme behavior may be quite uncertain, and internal variability can itself change with climate change). The relative importance of these three sources of uncertainty varies with spatial and temporal scale, and with climate variable.[23] Consideration of the human impacts of climate change adds yet another layer of uncertainty, moreover one associated with different forms of knowledge, because vulnerability and exposure depend on social and political factors.

It is instructive to consider the chain of causal factors leading to a particular climate risk, such as health impacts from heat waves (Figure 2). The traditional, 'scenario-driven' approach, as exemplified in Figure 1, is to start from the climate forcing scenario and predict the consequences, considering all possibilities. But this ignores the different kinds of uncertainty involved, and thereby leads to a blurred picture[24]. There are alternative approaches, which involve what statisticians call 'conditioning' on the different causal elements depicted in Figure 2, and thereby amount to a degree of localization within the space of possibilities. For example, it is recognized that future exposure and vulnerability – that is, what human assets will exist and how badly they might be damaged by a given level of natural disaster – are related to the same socio-economic factors that will determine future climate forcing (e.g. a society built on sustainability can be expected to be less vulnerable than one characterized by regional rivalries and competition for resources), and this relationship can be built into climate impact studies.[25]

Conditioning can also be applied within the physical climate system. If one wishes to know the consequences of a given magnitude of global warming, which is the sort of question envisaged by the Paris Agreement, then the longstanding epistemic uncertainty in climate sensitivity – i.e. how much the climate system warms for a given increase in CO_2 – is irrelevant. (Instead it affects the carbon budget that will result in that global warming magnitude.) If one further wishes to know the increase in severity of a historical heat wave in a warmer world, one may condition on the occurrence of the specific atmospheric circulation pattern leading to the heat wave, which – at the cost that one can no longer assign a probability to the event's occurrence – removes the major epistemic uncertainty associated with changes in extreme weather events.[26] Finally, from the IPCC WGII perspective, one can condition on the heat wave itself and assess the impacts of different adaptation options affecting exposure and vulnerability at the local scale, e.g. greening of an urban landscape, siting of senior-citizens homes, or changes in building codes.

The causal network depicted in Figure 2 thus provides a conceptual framework for finessing the uncertainty challenge: each of the conditionings represents a plausible storyline of climate change[27]. In analogy to the stress tests used in finance, the question is changed from "What will happen?" to "If X happens, what will be the consequences?". Appropriately chosen numerical models can be used to perform credible counter-factual 'what if' or intervention experiments, after such conditioning, allowing hard numbers to be placed on the results. In this way, information that is local – about a specific place, or a historical event, or a particularly worrisome model prediction – can be given meaning[28]. This avoids the blurring, and loss of information, that is inevitable when inhomogeneous data are pooled[29]. Local knowledge from historical events can also be meaningfully interpreted within such a framework, which helps address hermeneutic injustice by empowering citizen science[30] and making climate change 'visible.'[31]

It is possible to learn about future climate risk from a handful of events, or even from single events[32], though from a statistical perspective such a statement seems non-sensical. This is illustrated by Figure 3, which shows the heat island effect in southern Holland based on three nights of data. In order to discuss climate effects in this event, there is not only the issue of downscaling from the typical climate scale, but also the influence of the urban environment itself, through this heat island effect. From a climate science perspective, the latter is a confounding factor; but from an impacts perspective, it is the heart of the issue. Figure 3 shows how the urban environment increases nighttime temperatures. It is currently not possible to predict with any reliability the future likelihood of heat waves at such a local scale in an unconditional manner. However there is clearly information contained in Figure 3, most notably the fact that certain neighborhoods, which are often the poorest neighbourhoods, experience the highest temperatures. The reasons for this are generally very clear, e.g. less green space, denser construction, and more dark surfaces[33]. From this conditional perspective, one may infer that those neighborhoods are most at risk from the increasing heat waves expected from climate change. This is robust, actionable information.

4. The global south

As we consider the local vs. the global and at the same time the intersection of climate science with ethical and political questions, it behooves us to consider one major divide that is present in both the climate itself and our global human society, namely that between global south and north – or from a climate science point of view, between tropics and extratropics. The most glaring fact of global ethics when we consider climate change is that most of the emissions have come from the rich, developed, extratropical countries, whilst the most severe impacts will be felt in poor tropical countries. This is true but already widely understood. We focus here on issues that may be less so. In particular, the tropics is where the normative approach to climate prediction and uncertainty is most clearly found to be wanting. This adds a layer of hermeneutic injustice to the ethical divide between global south and north.

The greater risk in the tropics is, in part, simply a consequence of the sign of the temperature change. As the planet gets warmer, the regions that are already the warmest are those where the climate will first reach a regime not historically seen anywhere on the planet.

Another difference results from the different nature of climate variability in the tropics vs. extratropics. In climate predictions, the 'time of emergence' is loosely defined as the time at which the long-term anthropogenic change will be sufficiently large as to put some aspect of the climate state definitively outside its historical range, where that range is assumed to be determined by internal variability. Figure 4 shows that, for temperature, this will occur soonest in the tropics. Whilst the magnitude of the change is largest at high latitudes, the variability – both the seasonal cycle and year-to-year fluctuations – are as well, and to an even greater extent, such that it is in the tropics that temperature will first regularly exceed its historical range.

On the other hand, precipitation is also a crucial aspect of climate. Here the difference between tropics and extratropics lies in the poorer understanding of the expected precipitation changes – at least over land, which is where people live – in the tropics. Figure 1b illustrates this; over land the stippling, indicating agreement between models (a proxy, though an imperfect one, for our degree of understanding or confidence, since a greater degree of model agreement suggests a smaller epistemic uncertainty), is for the most part confined to the higher latitudes. Thus whilst we know that precipitation-related risks are greatest in the tropics, the potential for paralysis due to uncertainty – if one insists on preferentially guarding against Type 1 errors, as described above – is more pronounced in the tropics.

There are scientific factors that make tropical precipitation inherently challenging to predict. The tropical atmosphere is warmer and moister, and deep convection – cloud systems that produce heavy rain – is a more important factor than in the extratropics. The essential physical processes of deep convection act on relatively small space and time scales, and thus must be 'parameterized' in weather and climate models, meaning represented in ways that are partly empirical and not as tightly connected to the underlying laws of physics as the larger-scale processes are. Although there have been gradual advances over time on the convective parameterization problem, it remains a major weakness in current models.

Short-term climate variations represent an exception to this situation; here the understanding and predictive capacity is greater in the tropics. This is mainly because of the highly predictable El Niño–Southern Oscillation (ENSO) phenomenon, which occurs in the ocean and atmosphere of the equatorial Pacific, but strongly influences weather throughout the tropics and provides predictability on the time scale of months. At present, in fact, whilst weather forecast models predict precipitation more accurately at higher latitudes than in the tropics for the first few days, tropical predictions actually become more accurate at longer lead and averaging times – where 'longer' is as short as a week – and this appears to be at least in part because the ENSO signal begins to emerge that soon.[34]

Unfortunately this advantage does not translate to anthropogenic climate change. Most models predict that the average climate of the tropical Pacific will shift with warming to a state similar to an ENSO warm event. Whether this prediction is correct remains contentious, however. Analysis of the model physics on its own suggests the possibility that the model prediction could be wrong;[35] moreover the trend in observations in recent decades is in the opposite direction, towards a cold ENSO-like state.

The tropics is also the region most susceptible to tropical cyclones (also known as hurricanes, typhoons, and by other names). Tropical cyclones can cause enormous damage, with substantial long-term detrimental effects on economic growth in countries where they are endemic.[36] Global warming increases the risks from tropical cyclones in several ways: by increasing the precipitation they produce; by making their winds stronger, so that the future will likely see storms more powerful than any in the past; and by raising sea level, thus exacerbating coastal flooding from storm surge. How climate change will affect the number of storms, however, remains uncertain; we do not know whether storm frequency will increase or decrease, due to a lack of agreement between models and, even more importantly, a lack of physical understanding.[37] The frequency of the most severe events – think of Typhoon Haiyan (2013) in the Philippines, or Hurricane Maria (2017) in Puerto Rico – is likely to increase regardless, as overall increases in storm intensities make intense storms relatively more common compared to weak ones, but that prediction is not certain, particularly in any specific region. Regions of storm formation and intensification are likely to undergo some changes, increasing hazard dramatically in some regions while reducing it in others.

Some of these changes in tropical cyclone activity may already be evident; for example, an increase in tropical cyclone activity in the Arabian Sea – where cyclones are historically quite rare – is robustly predicted by climate models, and is arguably already being observed,[38] increasing hazard in the Middle Eastern, East African and South Asian nations around it. And beyond climate change – and perhaps even more important – continued urbanization increases the population at risk in many of the coastal cities most exposed to tropical cyclones. When all these factors are considered, the risks of tropical cyclone impacts are almost certainly increasing. Yet the specifics are quite uncertain – especially due to the uncertainty around storm frequency – and even that uncertainty is difficult to quantify, since most of it is epistemic in origin. This is precisely the sort of situation in which storyline approaches are needed. Ghosh imagines the nightmarish possibility of a major cyclone landfall in Mumbai, India, a city that appears unprepared for it, and exceedingly vulnerable. A subsequent scientific research study shows this specific storyline to be plausible, even though it is without precedent in the city's modern history[39].

5. Epilogue

Although the driving force of climate change is global, climate change is being and will be experienced at the local scale and in extreme events, in ways that are both specific to the nature of those places and the accident of the weather history particular to that place and period. In other words, climate change is experienced, and will be experienced, through storylines rather than through the global (and mostly unrealized) probabilities that are normative in climate science. An overreliance on probabilities dulls the edges, removes the human context, and inhibits us from facing the full reality of our climate future. We argue here for a more local perspective (in multiple senses); for an elevation of the narrative; and for a demotion of the probabilistic from its place of privilege in the construction and communication of our understanding of global warming and its local consequences.

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[1] Jasanoff, "A new climate for society."

[2] Fricker, *Epistemic Injustice*

[3] Wilby and Dessai, "Robust adaptation to climate change"

[4] Lloyd, "Model robustness as a confirmatory virtue"

[5] March et al., "Learning from samples of one or fewer."

[6] Wears, "Still learning how to learn"

[7] Rutter et al., "The need for a complex systems model of evidence for public health."

[8] Jasanoff, "A new climate for society."

[9] Kuhn, *The Structure of Scientific Revolutions*

[10] Winsberg, "Models of climate: values and uncertainties;" Lloyd and Oreskes, "Climate change attribution"

[11] Shepherd, "Storyline approach to the construction of regional climate change information"

[12] Hegerl et al., "Good practice guidance paper"

[13] Trenberth, Fasullo and Shepherd, "Attribution of climate extreme events"

[14] Lloyd and Oreskes, "Climate change attribution"

[15] Lloyd and Oreskes, "Climate change attribution"

[16] Shepherd, "Storyline approach to the construction of regional climate change information"

[17] Hegerl et al., "Good practice guidance paper"

[18] Fricker, *Epistemic Injustice;* Ottinger, "Making sense of citizen science"

[19] Hegerl et al., "Good practice guidance paper"

[20] Field, *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*

[21] Shepherd, "Storyline approach to the construction of regional climate change information"

[22] Hawkins and Sutton, "The potential to narrow uncertainty in projections of regional precipitation change"

[23] Hawkins and Sutton, "The potential to narrow uncertainty in projections of regional precipitation change"

[24] Wilby and Dessai, "Robust adaptation to climate change"

[25] O'Neill et al., "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6"

[26] Shepherd, "A common framework for approaches to extreme event attribution"

[27] Shepherd, "Storyline approach to the construction of regional climate change information"

[28] Cartwright, "Single case causes: What is evidence and why."

[29] Cartwright, "How to learn about causes in the single case."

[30] Ottinger, "Making sense of citizen science"

[31] Rudiak-Gould, "We have seen it with our own eyes;" Jasanoff, "A new climate for society."

[32] March et al., "Learning from samples of one or fewer"

[33] van der Hoeven and Wandl, *Haagse Hitte*

[34] Zhu et al.,"Seamless precipitation prediction skill in the tropics and extratropics from a global model;" Wheeler et al., "Seamless precipitation prediction skill comparison between two global models"

[35] DiNezio et al., "Response of the equatorial Pacific to global warming;" Sohn et al., "The role of the dry static stability for the recent change in the Pacific Walker Circulation"

[36] Hsiang and Narita, "Adaptation to cyclone risk: Evidence from the global cross-section"

[37] Walsh et al., "Tropical cyclones and climate change"

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[38] Murakami, Vecchi and Underwood, “Increasing frequency of extremely severe cyclonic storms over the Arabian Sea”

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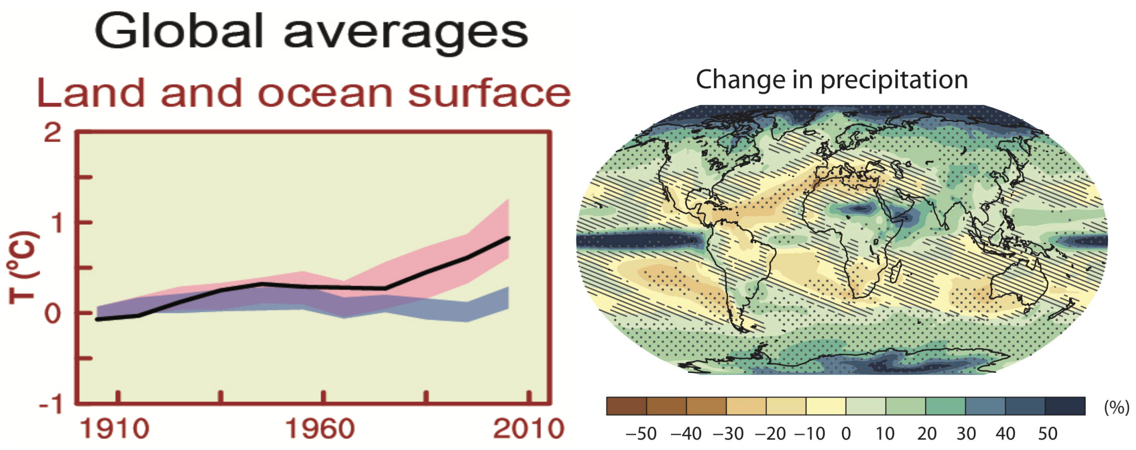

Figure 1. (a) Change in globally averaged surface temperature over the 20th century. Observations are shown with the black line, and the range of climate model simulations with and without anthropogenic climate change with the pink and purple shading, respectively. (b) Predicted changes in precipitation (in %) over the 21st century under a high climate forcing scenario (RCP8.5). Stippling indicates where the model predictions are robust, in the sense of agreeing on the sign of the change; otherwise the models do not agree. Hatching indicates where the average model changes are small compared with internal variability, but this does not mean that individual model changes are small. Both figures are from Stocker et al. (2014).

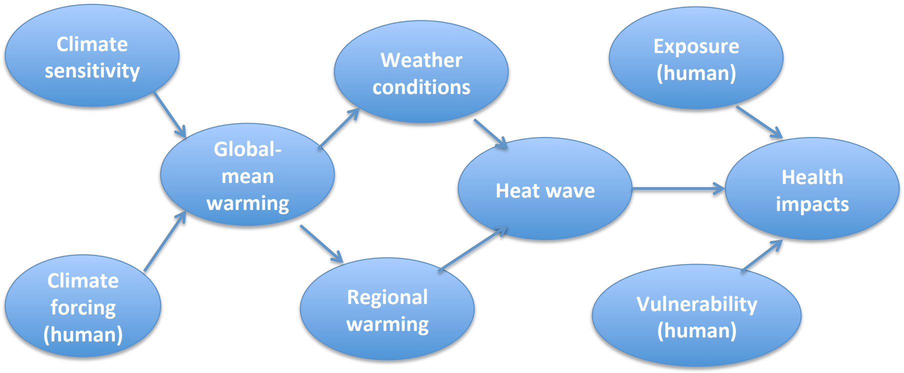

Figure 2. Schematic of a causal network depicting climate-related health impacts from a heat wave in a particular city. This factorizes the uncertainty. See text for details. Adapted from Shepherd (2019).

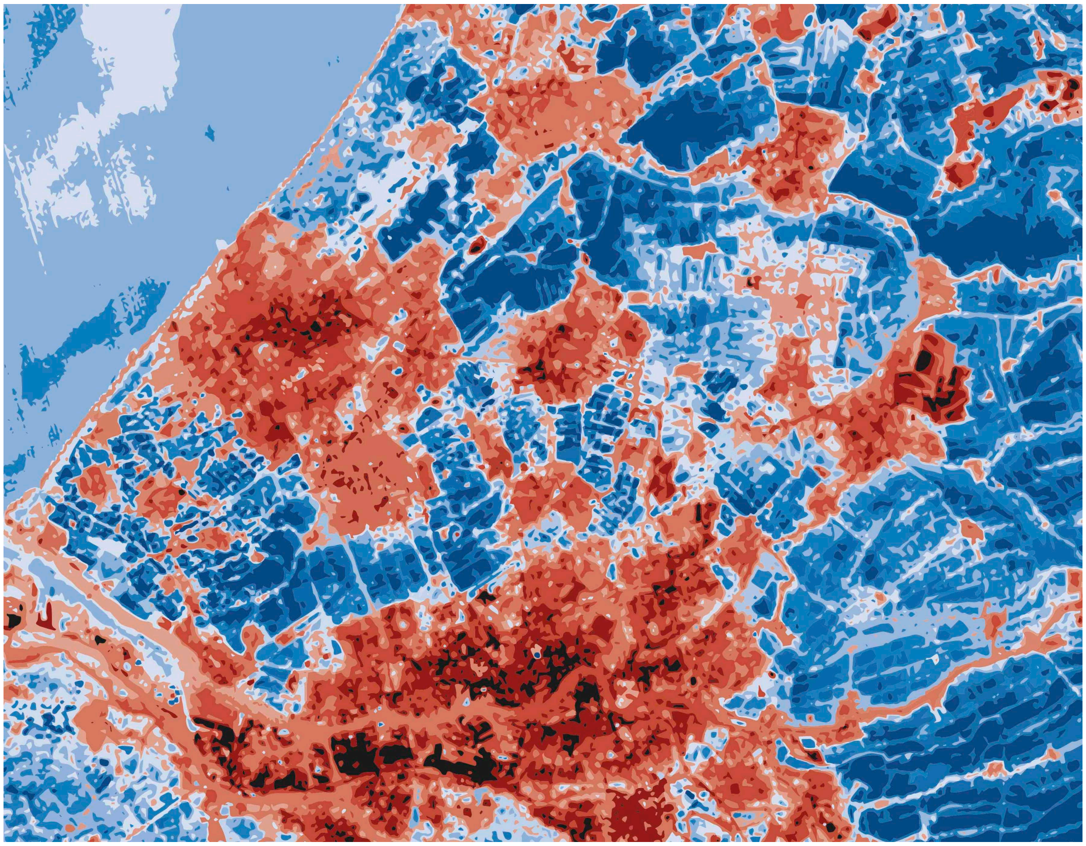

Figure 3. Surface temperature differences in the province of South Holland, using Landsat 8 images, averaged over the nights of 12/13 September 2016, 26/27 May 2017 and 18/19 June 2017. Each colour step represents an increment of 1°C, with red colours indicating higher temperatures. The nocturnal temperatures are a good indicator of the heat island effect, which is very evident in the cities: Rotterdam is at the bottom of the image, and The Hague to the upper left. From van der Hoeven and Wandl (2017).

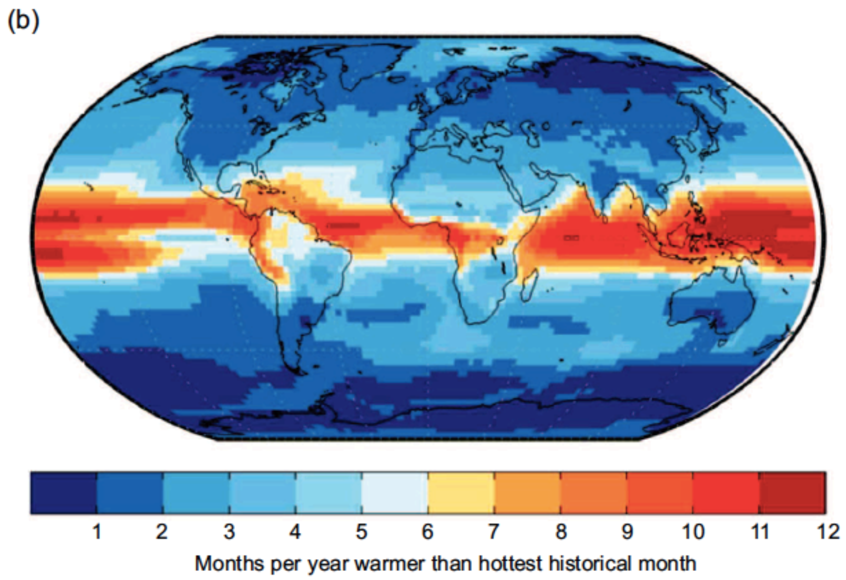

Figure 4. Predicted number of months per year in 2051–2100 that will exceed the maximum absolute temperature found across all months from 1951–2000, under a high climate forcing scenario (RCP8.5). From Harrington et al. (2017).