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Impact of climate change on health: what is required of climate modellers?

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Summary The potential impacts of climate change on human health are significant, ranging from direct effects such as heat stress and flooding, to indirect influences including changes in disease transmission and malnutrition in response to increased competition for crop and water resources. Development agencies and policy makers tasked with implementing adaptive strategies recognize the need to plan for these impacts. However at present there is little guidance on how to prioritize their funding to best improve the resilience of vulnerable communities. Here we address this issue by arguing that closer collaboration between the climate modelling and health communities is required to provide the focused information necessary to best inform policy makers. The immediate requirement is to create multidisciplinary research teams bringing together skills in both climate and health modelling. This will enable considerable information exchange, and closer collaboration will highlight current uncertainties and hopefully routes to their reduction. We recognize that climate is only one aspect influencing the highly complex behaviour of health and disease issues. However we are optimistic that climate—health model simulations, including uncertainty bounds, will provide much needed estimates of the likely impacts of climate change on human health.

1. Introduction

WHO estimates that in recent years around 150 000 lives per year have been lost as a result of temperature and rainfall changes brought about by humankind's alteration of climate through burning fossil fuels (Campbell-Lendrum et al., 2003). WHO expects the excess risk from climate change to more than double by 2030 (WHO, 2002). Although these estimates are highly uncertain, they make the point that the potential impacts of future climate change on human health are likely to be considerable. Malaria is a climate-sensitive disease currently resulting in an estimated 1 to 2 million

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deaths a year. Only a small change in the prevalence of malaria would therefore produce a large change in mortality. Any significant increase in mortality is most likely to occur in developing countries, which lack the resources to respond. Other impacts may be the result of direct climate—health relationships, such as heat stress, or may occur indirectly, as in the case of malnutrition due to famine caused by crop failure, and water-borne diseases caused by reduced water quality.

Development agencies recognize the potential impact of climate change on health and the need to incorporate this into planning for the future (for example, see the Department for International Development's keysheet at http://www.dfid.gov.uk/pubs/files/climatechange/4health.pdf). Such agencies need to allocate funds to increase the capacity of communities to adapt to climate change. However, although both the general sensitivity of the prevalence of disease to climate change, and estimates of the amount of climate change for a range of greenhouse gas emission scenarios can be estimated, at present research is providing little guidance on how to prioritize spending. There is thus an urgent need to provide a more scientific basis for these decisions. We argue that this can be achieved by closer collaboration between the climate and health modelling communities.

2. Climate change and climate modelling

The potential for fossil fuel burning to produce major changes in climate is creating an unprecedented level of public concern. It is now widely accepted that there has already been a warming of approximately 0.6 °C during the last century: a result derived from the statistical analysis of existing climate measurements. Large-scale computer models of the climate system (usually referred to as global climate models, or GCMs) allow different components of climate change to be analysed in isolation. Such 'attribution' studies (e.g. Stott et al., 2000) have led to the conclusion that this observed warming could not have occurred naturally, with the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report stating that ''...most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations'' (IPCC, 2001a). Summarizing the results of a range of different GCMs and a broad set of 'plausible' emissions scenarios (ranging from rapid advances in 'green technology' through to unmitigated burning of fossil fuels), the IPCC concluded that the global average temperature will increase between 1.4 and 5.8 °C for the period 1990 to 2100 (IPCC, 2001a). Even the lower value of this range will cause significant change to the Earth system.

Climate change will not result in a uniform warming over the globe. Oceanic and atmospheric circulations will alter, creating different large-scale climate patterns, which in turn will adjust smaller scale 'weather' features. The latter includes the frequency of extreme events, such as storms and floods, and heatwaves and droughts: the type of weather events to which human health is especially vulnerable. As the power of computers is increasing, the spatial scale of the information they create is becoming smaller, and with regional climate models (RCMs) 'nested' within GCMs, realistic predictions of future weather statistics at a horizontal scale of 10 km are now feasible. These can be used to investigate the likely future return periods of local extreme events such as floods and the diseases they bring. Some systematic biases in model predictions that exist at present can be removed by investigating the change in return period rather than its absolute value. This can then be added to the current observed return period, thus estimating future extreme behaviour of 'weather'. The RCM model scale is also now fine enough to resolve the climate of individual cities. The lack of vegetation in some cities creates the urban heat island effect, with higher temperatures being observed than in rural areas. For example, Maitelli and Wright (1996) observed that in the dry season the average maximum temperature difference between the city of Manaus (in Amazonia) and the surrounding forest was 3.5 °C. In some major cities, temperatures of up to 11 °C higher than surrounding rural areas have been recorded (Aniello et al., 1995). Future projections are that the urban heat island effect will amplify a general temperature increase (Martin Best, personal communication).

Despite extensive testing of GCM predictive ability against historical climate measurements, climate change predictions are still uncertain. This is reflected in the range of climate predictions that can be produced from even a single GCM as a result of uncertainty in the parameterization of processes. To quantify this, multiple 'perturbed parameter' GCM simulations are now undertaken (Murphy et al., 2004; Stainforth et al., 2005) that allow projections of future change to be made with uncertainty bounds. Society can then be alerted to potential unwanted impacts with estimates of confidence bounds on their occurrence. Nevertheless, inter-GCM differences in prediction of rainfall changes remain large, sometimes even with some models showing increases, others decreases for certain regions (see Figure 23 of Albritton et al., 2001). This is a particular problem, as rainfall variation is a key determinant in human vulnerability. For example, Huntingford et al. (2005) show in detail such lack of GCM consistency for the Soudan and Sahel regions, where livelihoods are particularly sensitive to climate. Such regions have smaller observational networks, allowing less model verification against present climatological conditions.

3. Potential future health issues

Many studies have translated GCM output into local impacts, but to date these have largely been concerned with predicting direct physical processes such as glacier retreat, changes in biodiversity (e.g. alterations in migration of mammal populations), agronomic concerns such as crop viability, or major structural engineering needed to cope with sea level rise and increased flood risk. A summary of impact studies by the IPCC (2001b) gives a few examples of investigations designed to predict the impacts of climate change on human health. More recent research extends these; Stott et al. (2004) have shown how the European heat wave of 2003 (which caused significant deaths, particularly in Paris) can be statistically linked to human-induced climate change. van Lieshout et al. (2004) have predicted changes in the timing and distribution of diseases. Others (Parry et al., 2004;

Wheeler et al., 2005) discuss how crop growth and yield may change (a balance between raised atmospheric CO_2 concentration aiding plant fertilization and climate change that may be detrimental to crop development; see, for instance, Challinor et al., 2005, in which this is discussed for tropical regions) and the implied changes in the number of people at risk of food shortages.

Research into the impacts of climate on the prevalence of diseases includes work on malaria (Hay et al., 2002) and host—parasite and disease—vector relationships (Dobson and Carper, 1992). Generally, temperature, rainfall and humidity are used to predict malaria distribution (e.g. Martens et al., 1999), with a reproduction rate partially dependent on temperature and humidity. These three variables are readily available from a GCM. Gedney and Cox (2000) suggest that the prediction of wetland area extent from GCMs (e.g. Gedney and Cox, 2003) is also an important, recently available model diagnostic that would aid in the assessment of the future spread of malaria. Rogers et al. (2002) showed the potential for using satellite-derived fields of temperature and moisture conditions to predict risk of malaria. Tanser et al. (2003) used data from the Mapping Malaria Risk in Africa (MARA) project combined with global climate change predictions to examine how the potential malaria risk might change over regions of Africa. Their results suggest a 16—28% increase in 'person-month' exposure to malaria risk by 2100 (excluding population change). Combining these approaches with socio-economic models would give tailored GCM/health 'sub-modules', allowing direct climate model projections of future areas at risk.

To our knowledge there have been as yet few attempts to couple climate model output with models of the incidence of other diseases, although the implications of climate change on the occurrence of epidemics could be far-reaching. However, the work of Hales et al. (2002) provides an example of what can be done: they developed a statistical model of future global distribution of dengue fever, driven by annual average vapour pressure, coupled with both expected population change and climate change. An extensive summary of climate—health issues is given in the book edited by Martens and McMichael (2002), including the spread of tick-borne diseases, water- and food-borne diseases, and other infectious diseases, and the complex social effects arising from climatic impacts. However, most of the contributions to Martens and McMichael (2002) are qualitative and heavily dependent on socio-economic assumptions; critically they lack formal equations depicting alterations in disease that are needed for coupling to GCM output. By contrast, Rogers and Randolph (2006) propose the basic reproductive number (R_o) as a quantitative tool to predict whether changes in climate will translate into changes in the occurrence of vector-borne diseases. For the incidence of disease to increase, R_o must cross a critical threshold. Whether or not this occurs will depend on the balance of such variables as the ratio of vector numbers to host numbers, against the mortality rate of the vectors. These variables are likely to be functions of climate and may therefore change in the future; hence vector-borne diseases should be amenable to modelling in terms of climate variables. Because of the uncertainties in biological models, and because epidemiological behaviours are highly dependent on local landscape characteristics and socio-economic environments, Rogers and Randolph (2006) conclude that 'attributing' changes to climate change will be difficult. However, we believe that it is possible, and we recognize as they do that there are similarities with the original climate change challenge (now broadly resolved) of differentiating between natural variability and emerging signals of change triggered by human activity.

Changes in atmospheric pollutant levels may also affect human health (WHO, 2003). Many of these chemical species are modelled in some GCMs (Collins et al., 2002). Using one such model, near ground level ozone concentrations, for example, have been shown to vary significantly in some locations under future climate change scenarios (Stevenson et al., 2006). Using earlier GCM projections, Knowlton et al. (2004) suggest that ozone-related deaths may increase by $\sim$4.5% by 2050 under a medium—high future emissions scenario. Research is required to understand how these predictions translate to damage to health through respiratory effects. Long et al. (2005) discuss the effects of ozone on future crop production: trials have shown that the yields of major crops decrease when exposed to raised levels of ozone. However, Long et al. (2005) point out that there is a paucity of experimental data from the tropics; this is needed to underpin the models of food security, which may have overestimated future yields, underestimating the resultant impact on malnutrition. The complexity of organic chemistry involved in predicting future 'summer-smogs', is likely to require RCM simulations with detailed chemistry modules 'nested' in broader-scale GCMs.

Research into the current vulnerability of population health to higher temperatures suggests not only that climate variability and extremes are important per se, but also adaptation (acclimatization) capacity (e.g. Donaldson et al., 2003; Honda et al., 1998). Should what is currently regarded as extreme temperatures become the norm, with appropriate planning then health impacts will be less than presently expected. To aid such planning, GCMs must accurately predict the statistical likelihood of temperature extremes over a range of different timescales (days to months). Adaptation could proceed not only through early warning systems of heatwaves (such as the systems now in place in France following the 2003 heatwave), but also by using novel building designs and urban planning (Koppe et al., 2004).

Combined climate—health simulations also have an important role at the seasonal forecasting timescale. Current fluctuations in significant seasonal rainfall patterns, such as the Indian monsoon or the El Niño Southern Oscillation alter inter-annual flood and drought risk and can also have major impacts on both regional food production and potential disease transmission through outbreaks of water-borne diarrhoeal diseases (Checkley et al., 2000; Hamnett et al., 1999). High rainfall may also increase the populations of vectors. For example, Linthicum et al. (1999) demonstrated a correlation between sea surface temperature anomalies in the Pacific and Indian Oceans with Rift Valley fever in East Africa. Higher rainfall during these events creates more mosquito breeding habitats. Verification and then enhancement of GCM capability includes assessing the ability of the GCM to predict the statistical nature of seasonal variation on the inter-annual timescale and for current climate. This includes yearly variability in sea surface temperatures and related impact of subsequent rainfall over land that is of importance to the health issues above. By taking the extra step of connecting existing health models with climate models, understood linkages between components of the Earth system (e.g. ocean—land couplings) means that observed emerging patterns in sea surface temperatures can allow assessment of imminent likelihood of raised levels of disease. Using an ensemble of different models would allow the uncertainty of projections to be quantified. Analysis of predictions against recorded health statistics at the inter-annual timescale would demonstrate deficiencies in combined climate—health modelling systems. Subsequent improvements would help to build a credible modelling structure to generate more robust future predictions.

4. Vulnerability and adaptive capacity

It could be argued that better information on the impacts of climate change on health will make little practical difference to operational disease prevention and control. The high uncertainty and long timescales of the predictions, other changes operating in parallel, and lack of resources to translate predictions of impacts into practical interventions can appear as overwhelming constraints. In addition, the inadequately coupled models and lack of data make the research inherently difficult and risky. We do not accept these arguments, basing our optimism on our experience of the progress that has been made in linking climate modelling with other disciplines, particularly in relation to water. Although linking climate and hydrological models is inherently simpler than linking climate and health models, in practice nearly all the above constraints apply. One example that attempts to address these constraints is provided in the work of Sullivan (2002) and Sullivan et al. (2003). In this work, an indicator-based approach has been developed to capture the links between water and poverty, and much interest in this has been generated (see Ashraf, 2002; Peet, 2003; World Water Assessment Programme, 2003). Taking this work further to take account of climate variability and change, a Climate Vulnerability Index (CVI) has been developed (Sullivan and Meigh, 2005). This considers the highly context-specific variations that societies must address, including climate hazards as well as all the social, economic and political drivers of change. This bottom-up approach links community-level statistics with the outputs of climate models, allowing maps of climate-related water vulnerability to be generated. Climate—health impacts could easily be incorporated into such an index, providing a useful tool for risk prioritisation and the development of adaptive capacity. This type of approach demonstrates how value can be added to climate model outputs by combination with other types of information.

5. Next steps and summary

Watson (2002) summarizes arguments for a massive extension of research in the climate—health field. Here, we suggest that the main challenge is to create multidisciplinary research teams that bring together skills to isolate (future) climate signals from the other continuously changing non-climatological factors (e.g. resistance to drugs and increased urban poverty), which influence the levels and extent of disease. Currently we see a gulf between the climate modelling research community, which provides predictions of future 'weather' such as temperature, humidity and rainfall, and those in the medical research community, which studies epidemics and the incidence of disease. Yet there is a crucial need to warn the policy- and decision-makers faced with the need to implement adaptive strategies of the future human health impacts of 'global warming'. To fulfil this need, climate and medical scientists must work together. Figure 1 depicts the required cross-disciplinary understanding in a schematic form.

Huntingford and Gash (2005) have argued for centres of excellence in climate science to be created in developing countries. The objective is to build both the technical and human capacity to predict the impacts of climate change, thereby empowering these countries to become more engaged in the international negotiations on managing global climate change. Extending the argument, we believe that building scientific capacity in climate—health science should not be limited to the developed world; building institutional capacity in the developing world must be a priority.

The Earth System Science Partnership (ESSP) of global research programmes is planning a new international initiative: 'Global Environmental Change and Human Health'. The objective is to create a new impetus for integrated, multidisciplinary research, which will bring the climate and medical research communities together, working to a common agenda. A crucial issue is how to connect the GCM output to models that can predict the incidence of disease from climate data. Both the scale and content of the GCM output that is required must be considered open to change if the end results are to be relevant to local health issues.

Previous experience of creating such cross-cutting initiatives has shown that successful outcomes only result if there is close collaboration from the start. The first task is for climate modelling and human health communities to exchange knowledge in their respective fields. This includes understanding of uncertainties that result from the current imperfections in both climate and health modelling. All participants must then be involved in drawing up the research questions. The process is time-consuming and requires an open-mindedness and willingness to compromise, but it is urgent and necessary if we are to make progress in creating new knowledge to warn of the future changes in the occurrence of disease and threats to human health that may be triggered by 'global warming'.

We acknowledge that given the complexity of health and disease issues, of which the influence of 'weather' is only one aspect, combined with remaining uncertainty in GCM projections (particularly of rainfall), then it would be naïve to think the solution to future climate—health projections is simply to 'bolt together' a single GCM with any available health models. However, with research initiatives as outlined above, we are optimistic that combined climate—health model simulations, including uncertainty bounds, could become routine (there are analogies here to the first attempts 10 years ago to describe climate—ecosystem interactions; now GCMs regularly estimate large-scale biome variation for increased atmospheric greenhouse gases). Climate—health GCM simulations will provide much-needed estimates of climate change effects on human health, and their relative importance

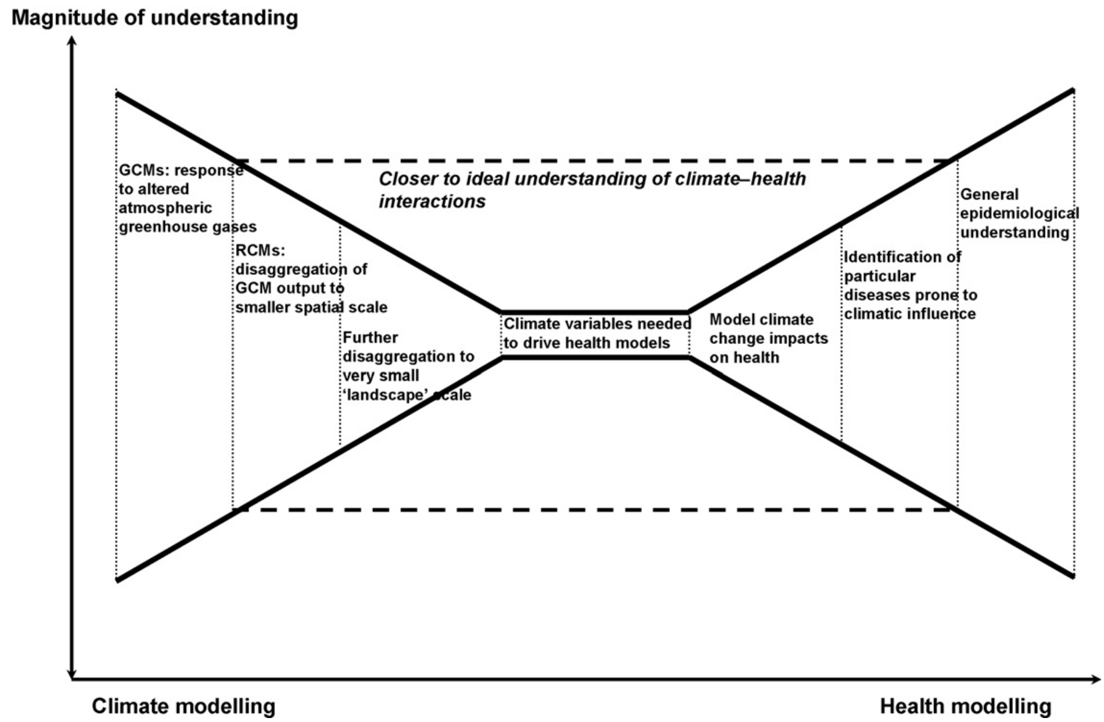

Figure 1 A simple 'cartoon' of level of understanding, depicted by distance between the upper and lower thick continuous black lines. Once global climate model (GCM) output has been disaggregated right down to landscape scale, as required for understanding specific climate change impacts on health, the distance between the lines is small. We argue that focused research initiatives will enable these lines to be opened out more towards the dashed lines. RCM: regional climate model.

compared to other local landscape and socio-economic influences.

Conflicts of interest statement
The authors have no conflicts of interest concerning the work reported in this paper.

Authors' contributions

CH and NG provided the climatological overview; DH and PAN provided the literature overview of the current state of understanding of 'weather' forcings on health; JHCG provided the international/development perspective. CH drafted the manuscript and acts as guarantor of the paper. All authors read and approved the final manuscript.

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