Taking globally consistent health impact projections to the next level

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Despite intensive research activity within the area of climate change, substantial knowledge gaps still remain regarding the potential future impacts of climate change on human health. A key shortcoming in the scientific understanding of these impacts is the lack of studies that are conducted in a coordinated and consistent fashion, producing directly comparable outputs. This Viewpoint discusses and exemplifies a bottom-up initiative generating new research evidence in a more coordinated and consistent way compared with previous efforts. It describes one of the largest model comparisons of projected health impacts due to climate change, so far. Yet, the included studies constitute only a selection of health impacts in a variety of geographical locations, and are therefore not a comprehensive assessment of all possible impact pathways and potential consequences. The new findings of these studies shed light on the complex and multidirectional impacts of climate change on health, where impacts can be both adverse or beneficial. However, the adverse impacts dominate overall, especially in the scenarios with more greenhouse gas forcing. Overall, the future population at risk of disease and incidence rates are predicted to increase substantially, but in a highly location-specific and disease-specific fashion. Greenhouse gas emission mitigation can substantially reduce risk and resultant morbidity and mortality. The potential positive impact of adaptation has not been included in the models applied, and thus remains a major source of uncertainty. This bottom-up initiative lays out a research strategy that brings more meaningful research outputs and calls for greater coordination of research initiatives across the health community.

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Background

Climate change is increasingly recognised as a potent risk to health across the globe and its associated changes in hazards, exposure, and risks to populations can, to some extent, already be observed today.[1,2] Climate is intrinsically related to health in many ways, from direct health stress from heat exposure to more indirect and complex pathways through ecological systems of vector-borne and water-borne diseases, to food production and nutrition, and extreme climatic events.

Currently, health impacts are rarely systematically investigated, and the health community does not exhibit the strong coordination mechanisms shown by the other climate impact communities (eg, agriculture, water). The reason for this is likely that the health impacts from climate change are many and that the research community is scattered across a variety of different medical and health disciplines, with the common denominator restricted to specific disease types or exposures—ie, nutrition epidemiology, infectious epidemiology, and occupational and environmental epidemiology. These groups generally assemble at different meetings, and there is rarely cross-talk among these various health issues. This has made coordinated initiatives across the area of public health impacts from climate change rare. To generate richer insights across the field of public health overall, there exists an important need to break out of climate change health impact researchers' silos and promote studies that are coordinated and directly comparable across many different health impacts.

Multi-model impact studies

The overall lack of continuous systematic and coordinated assessment within the climate change and health research domain is in stark contrast to climate sciences, where there is a long-standing tradition to assess such influences and uncertainties, most prominently in the Coupled Model Intercomparison Project (CMIP).[3] This initiative engages a large community of climate researchers and contributes in an independent but synchronised manner to generate comparable model outputs. Beyond climate science, research communities in the non-health impact sectors are also advanced in joining efforts to reveal the additional benefits that model intercomparisons have to offer.[4,5] The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) is the largest of these projects aiming to conduct climate impact research across sectors.[6–8] ISIMIP strives to develop innovative approaches for generating estimates that are synchronised and comparable by harmonising the input data (climatic and non-climatic) and defining common simulation protocols. One important benefit of following this approach is that the impact estimates become comparable across and within sectoral impact models. Currently, ISIMIP brings together researchers working on climate impacts in 12 different sectors, encompassing water, agriculture, marine ecosystems, biomes, forests, lakes, and energy. The project hosts a data repository which makes both the climate and socioeconomic input data, as well as the results achieved, available to the entire community of climate impact researchers and other interested entities.

The health sector has been represented in ISIMIP since its foundation, but initially only focused on vector-borne diseases.[9] The process-based models used in this area of health impact research more closely resemble the dynamic modelling approaches used in other impact

	Health risk indicators	Time periods	Scenarios	Hotspot criteria and key figures
Martinez-Solanas et al, 2021[10]	Excess mortality attributable to heat, cold, and non-optimal temperatures; European scale	Mid-century (2035–64) End-century (2070–99) *vs* present-day (1976–2005)	RCP2.6, RCP6.0, RCP8.5; no SSP narratives	Anomaly in heat attributable mortality fraction >2% by mid-century and >4% by end-century for RCP8.5; figures 3, 4 Europe only
Chua et al, 2021[11]	Temperature-attributable mortality due to enteric infections, considering ten different aetiologies	Reporting period: 2080–95 Temperature baseline: 1976–2005	RCP2.6 and SSP1 RCP4.5 and SSP2 RCP6.0 and SSP3 combined with study-specific scenarios on other health indicators	Annual mean number of attributable deaths combining all aetiologies >0 by 0·5° × 0·5° grid cell for 2080–95 RCP6.0 and SSP3 (with low health investment); figure 3
Colón-González et al, 2021[12]	Spatiotemporal suitability for malaria or dengue exposure	2006–99 *vs* 1951–2005 baseline	RCP2.6 and SSP1 &2 RCP4.5 and SSP2 RCP6.0 and SSP2 RCP8.5 and SSP2&5	1 to ≥3 month increases in length of transmission season for both pathogens under RCP 8.5 scenario; figure 2
Trinanes and Martinez-Urtaza, 2021[13]	*Vibrio* suitability (sea surface temperature >18°C and salinity <28 psu) and population at risk	2015–2100 *vs* 1850–2014 baseline	SSP245 SSP585 (CMIP6)	1 month increase every 30 years in temporal suitability for *Vibrio* under SSP245; figure 4
Dasgupta et al, 2021[14]	Labour supply, productivity, and combined (effective labour)	GCM and warming level-specific 20 year periods *vs* baseline (1986–2005)	1·5°C, 2°C, and 3°C global warming above pre-industrial SSP2 population data	>20% reduction in effective labour in outdoor work under a 3°C scenario; figure 4
Zhao et al, 2021[15]	Percentage of excess deaths attributable to heat, cold, and non-optimal temperatures	2000–19	Retrospective study	This study was not included in the hotspot map because it did not include future projections

RCP=Representative Concentration Pathway. SSP=Shared Socioeconomic Pathway. CMIP=Coupled Model Intercomparison Project. GCM=General Circulation Model.

***Table*: Overview of studies and criteria for defining hotspot locations**

sectors and were therefore good first candidates for inclusion into the model intercomparison framework. More recently, the ISIMIP health sector has expanded to other climate-sensitive health outcomes, including empirical modelling approaches commonly used in epidemiology. One of the major benefits of ISIMIP—besides the comparability of output data generated—has been that it makes the data and knowledge required for undertaking health impact projections based on global climate model input more accessible to epidemiologists with little or no training in the climate sciences.

This special issue of *The Lancet Planetary Health*, includes six Articles[10–15] that are the result of bottom-up activity, kicked off at a workshop in Barcelona in 2018 that brought together health impact modellers from various disciplines. Most of the studies adhere to the guidelines and framework developed in the second round of ISIMIP, with a focus on future projections (ISIMIP2b). Bias-corrected climate input data derived from CMIP5 were based on up to four different climate models, up to four different emission concentration pathways (Representative Concentration Pathways: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, where the numbers refer to the actual radiative forcing of the anthroponegic concentration of greenhouse gases in the atmosphere, ie, 2·6, 4·5, 6·0, and 8·5 W/m^2), and combined with one or several socioeconomic scenarios (Shared Socioeconomic Pathways, SSPs; table). With the exception of one paper, which focuses on Europe,[10] the health impact assessments united in this issue are all global in scale. In addition, although Zhao and colleagues[15] do not present future projections, they do present a new approach to estimate temperature-attributable mortality on a global grid, forming a perfect starting point to produce more reliable projections of the impact of climate change at the global scale.

Previous coordinated assessments of climate-health risks

Only a few previous large assessment initiatives have focused on health impacts of climate change to date. The largest and the most frequent being the *Lancet* Countdown on health and climate change, which monitors the development of key health risk indicators and how their trends have developed over the past decades up to current time, but it does not attempt to assess future impacts.[1]

Before the first *Lancet* Countdown indicator report, in 2014, WHO published its last coordinated climate change impact assessment—a comparable risk assessment.[16] The assessment included studies on major climate sensitive diseases covering diarrhoeal disease, heat-related mortality, malaria, dengue, and undernutrition. All the impact topics were assessed likewise using the same climate and SSP input data. However, they did not use multiple climate models within each scenario, or so-called model ensembles, to investigate climate model uncertainties. The health impact models were also different from many of the current health impact models. The statistical models were less advanced in terms of non-linearity, lags, spatial covariance, and the process-based impact models neither captured the details of the dynamics of disease processes and disease ecology, nor allowed for complex dynamic interplay between aetiological agents and hosts.

Need for health impact model intercomparisons

Studies including and contrasting outputs from several impact models that are independently developed within

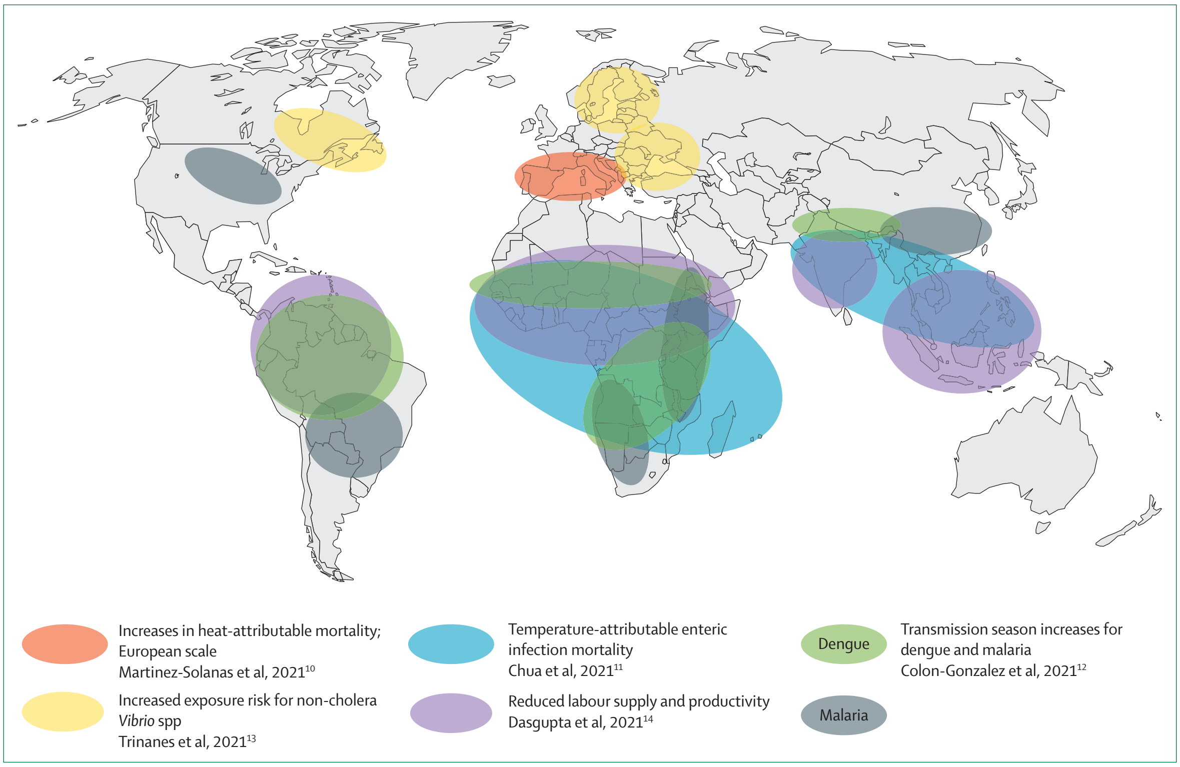

***Figure:* Hotspots of climate-health risks**
Coloured shapes indicate geographical areas identified as especially vulnerable in the studies of this special issue.[10–14] Some studies considered relative impacts (eg, percentage changes against present-day) and others absolute impacts (eg, number of people at risk or affected). Details on hotspot criteria are shown in the table. Note that Martinez-Solanas et al[10] only considered the European scale.

the same research effort can reveal new insights in model structural uncertainty. However, research encompassing structural uncertainty across health impact models has been hitherto rare. In the studies presented here, uncertainty has primarily been assessed by considering different climate and socioeconomic scenarios (ie, differing RCP and SSP scenarios) and by incorporating data from a range of global climate models. Colon-Gonzalez et al[12] is the only study in this special issue that compared structurally different health impact models, encompassing both statistical and dynamic models for malaria and dengue transmission. An earlier study[9] on the risk of malaria under climate change, which took a similar approach, found that the uncertainty from the health impact models was larger than the uncertainty from the climate models and RCPs. Thus, for more comprehensive assessments of the uncertainties in projections, future research should strive for more impact model intercomparisons beyond the area of vector-borne diseases. The models should also strive to be standardised, for example, in terms of prediction validity to comprehensive health datasets.

Summary and synthesis of papers

In the following paragraphs, we briefly highlight the value of a multi-model approach by summarising the five papers in this special issue that have used a variety of RCP and SSP scenarios to generate future projections of the climate-associated health burdens. We condense the findings to generate a map of disease hotspots projected by the studies (figure; table).

Non-optimal temperature-related mortality rates impose a high mortality burden worldwide.[17] Martínez-Solanas and colleagues analysed the impact of non-optimal temperatures on mortality rates from 1998 to 2012 in 147 contiguous regions from 16 European countries covering a population of 420 million people.[10] An estimated 7·2% of all-cause deaths registered in Europe were attributable to temperature, of which the majority were due to cold (6·5%). They then projected the fraction of deaths attributable to temperature by the end of the century under differing RCP scenarios, to represent different greenhouse gas concentration trajectories, as compared with the baseline reference period trend. Cold-related mortality is predicted to decrease less quickly than the current trend under RCPs 2.6 and 6.0 (low and medium high greenhouse gas concentration scenarios, respectively), whereas heat-related mortality is expected to increase far faster than the current increasing trend, but only under RCP8.5 (high greenhouse gas scenario). By the end of the century, total mortality attributable to non-optimal temperatures is projected to exceed current levels under the RCP6.0 scenario, whereas this excess would occur far earlier under the RCP8.5 scenario. In particular, within Europe, the Mediterranean region is predicted to be most affected under all three scenarios (figure). Combined RCP and SSP analyses would be useful to shed light on how socioeconomic development could exacerbate or alleviate the findings of this study and hence what adaptation strategies might be most appropriate and where.

Enteric bacterial and viral water-borne infections encompass a large suite of aetiological agents that collectively impose a significant public health burden, especially in low-income and middle-income countries (LMICs). Global warming is anticipated to lead to an increase in mortality associated with such infections both directly through temperature-dependent growth rates and indirectly through water quality.[18] However, viral and bacterial infections have different temperature sensitivities and in this study Chua and colleagues[11] address how climate change will differentially impact ten key enteric pathogens. Focussing on SSP1 (sustainability or "taking the green road"), SSP2 (middle of the road), and SSP3 (regional rivalry or "a rocky road"), they first analysed the projected mortality rate ignoring warming. Then temperature-attributable mortalities per aetiological agent were estimated incorporating projected temperature anomalies and aetiology-specific temperature sensitivities using RCPs 2·6, 4·5, and 6·0. Without consideration of warming trends, global mortality rates from all-cause (ten) enteric infections are projected to significantly decrease across all SSP scenarios. However, temperature-attributable deaths due to enteric infections might worsen under RCP6.0. This worsening projection is mainly attributable to bacterial infections shigellosis, cryptosporidiosis, and typhoid, particularly in sub-Saharan Africa and South Asia (figure), which already bear the brunt of mortality associated with such infections. On a positive note, key viral infections associated with mortality, notably rotaviruses, are projected to decrease in importance. This study underlines the importance of considering aetiological agents independently for projections of future outcomes.

For the **ECDC Vibrio Map Viewer** see https://geoportal.ecdc.europa.eu/vibriomapviewer/

Mosquito-borne pathogens, notably malaria parasites and the arboviruses (dengue, Zika, chikungunya) impose a huge burden of disease on the world's population, especially in the tropics and subtropics, and are anticipated to extend their current geographical ranges.[19,20] Climate has a potentially large impact on the incidence of mosquito-borne diseases, through the effect of temperature and rainfall on mosquito abundance and vectorial capacity.[21] Models have previously shown that climate change will exacerbate the burden and distribution of these diseases, but under a relatively restricted set of RCPs and SSPs.[9] In this issue, Colon-Gonzalez and colleagues implemented an ensemble modelling approach incorporating three different models for both dengue and malaria, four RCP scenarios, and three SSP narratives.[12] The authors combine WHO regions into six regions: Africa, eastern Mediterranean, the Americas, Europe, southeast Asia, and western Pacific. Using the ensemble mean predictions, the authors find that by the end of the century, the transmission season extends to a small degree for malaria in the Africa, southeast Asia, and western Pacific regions, but increases more significantly with altitude. Under the RCP8.5 scenario, the transmission season extends more in Europe and the Americas at low and intermediate altitudes. The transmission season extension is greater for dengue in all regions, but only under the RCP8.5 scenario in Europe, southeast Asia, and the western Pacific. Stratifying by urban or rural areas and population density, stark geographical heterogeneities are revealed. Using the ensemble means across all scenarios, in the Americas, the transmission season for malaria is found to decrease in rural areas but increase in urban areas (see appendix of Colón-González et al[12]). Significant increases in Europe are only found in rural areas. For dengue, there are notable very large increases in the transmission season (>1 month) in urban high density areas in all four regions, especially Africa.

The incidence of vibriosis has been rising over the past decades and spreading into areas where environmental conditions had been considered adverse for pathogenic *Vibrio* spp. Rising sea water temperature and decreasing salinity as a result of climate change have been identified as being among the major drivers of disease emergence.[22] Currently, a web-based tool (the ECDC Vibrio Map Viewer) has been developed to monitor environmentally suitable marine areas for *Vibrio* growth in quasi-real time but lacks any consideration of SSPs. Trinanes and Martinez-Urtaza[13] have applied a subset of the last generation of CMIP data (CMIP6) with SSP–RCP combinations to develop a new generation of *Vibrio* risk models to provide more realistic estimates of future changes in *Vibrio* suitability and population at risk. Projections under both SSP–RCP scenarios reveal a clear pattern of expansion for *Vibrio* suitability at rates of 183–449 km of coast per year on a global scale. 15 555–38 165 km of new coastal regions will become favourable for *Vibrio* by 2100 under the SSP2–4.5 (a combination of SSP2, the middle of the road path, and RCP4.5) and SSP5–8.5 (a combination SSP5, the high dependence on fossil fuel and high development path, and RCP8.5) scenarios. Particular hotspots are projected to occur in the Baltic and Black Sea regions, as well as North America (figure). Populations living in coastal cities and thus potentially exposed to *Vibrio* are estimated to grow from 610 million in 1980 to almost double that by 2050 under the SSP2–4.5 scenario. Incidence rates from such an increase in exposure are projected to reach nearly half a million cases globally taking into account the high rates of under-reporting.

A further effect of temperature is heat-related morbidity that can cause occupational health risks, reduced work capacity, and hence negative impacts on labour productivity. Dasgupta and colleagues[14] extend previous approaches by generating a new metric, effective labour impacts, which combines the effect of temperature on both labour supply and productivity. Within the context of an SSP2 (medium challenge to mitigation and adaptation) narrative, the authors estimated projected impacts of an increase in global mean temperatures of 1·5, 2, and 3°C above pre-industrial levels. Following the approach of ISIMIP, the authors conduct a multi-model comparison based on five different exposure response functions, which they then combine to generate an augmented mean response function. The five functions used were: psychological performance, individual capacity to safely perform heavy labour under heat stress, reduction of hourly work capacity for heavy work, work output per hour of rice farmers for India, and time efficiency measures in China. They found that, under all three warming scenarios, labour metrics are estimated to decrease in the low exposure sector and significantly more so for outdoor labour activities. The largest impact is estimated to occur in the tropics, with greater impacts on LMICs (figure), thereby exacerbating the already existing socioeconomic disparities. However, the models do suggest a potential benefit of warming on labour productivity in northern latitudes. The authors call for a case by case approach to mitigating against the impact of global warming on the labour market, separately developing adaptation strategies in rural versus urban and tropical versus temperate regions of the world.

Finally, Zhao and colleagues present the most comprehensive study to date on the impact of heat and cold on mortality, using time-series data amounting to 130 million deaths from 750 locations in 43 countries spread across all six inhabited continents.[15] Overall, they find that mortality due to non-optimal temperatures accounts for 9·4% of all excess deaths, of which cold-related deaths contribute the majority (8·5%). They find stark geographical disparities, with the Asian continent, particularly south and east Asia, which represent a combined 45% and 39% of the total global excess deaths due to cold and heat-related exposures, respectively. Sub-Saharan Africa accounts for 23% of the total global excess deaths due to cold exposure and Europe for 37% due to heat exposure. Although this might seem counter-intuitive, optimal temperatures are place-specific and are defined as the temperature associated with minimum temperature-related mortality. Thus, optimal temperatures will be lower in Europe than in Africa and hence non-optimal temperatures are also different. Although this study did not perform any future predictions under RCP or SSP scenarios, they demonstrate a trend over the period 2000–19 for a decrease in the cold-related contribution to excess mortality and an increase in the heat-related contribution. In light of the high quality data on climate projections now available, future projection models would be an invaluable next step to anticipate geographical hotspots for non-optimal temperature-related mortality.

Taking globally consistent health impact projections to the next level

Besides the disease-specific insights that each study discussed here provides, the ensemble of consistent projections across climate-sensitive health outcomes forms the basis for a much needed comprehensive global assessment of the health risks of climate change. First, comparable future estimates can be incorporated into economic studies of the costs of climate change, underpinning the urgent renewal of health-related damage functions.[23] Second, following the approach also adopted by Dasgupta,[14] the scenario-based results can be easily translated into impacts at different levels of global warming (1·5°C, 2°C, and 3°C rise in global mean temperatures above pre-industrial levels). This would then allow for the evaluation of the policy goals of the Paris Agreement against business-as-usual pathways in terms of avoided health impacts at the global scale. Such an analysis would also form a reliable input into overarching assessments of climate change impacts aimed at policy makers and the broader public, such as the “reasons for concern” used in the reports of the Intergovernmental Panel on Climate Change (IPCC).[24] Third, combining the studies can allow for global mapping of the health risks of climate change. The idea would be to identify regional hotspots that are particularly vulnerable with respect to one or several climate-sensitive diseases. The figure provides an illustration of this idea, based on the qualitative results assembled in this issue. A more thorough quantitative assessment of climate-health risk hotspots rests on the generation of a more comprehensive inclusion of health issues studied. With time, this then can lay the ground for more rigorous hotspot studies based on the ample data available. Such hotspot maps could then guide public health agencies, including WHO, as well as international multilateral climate finance mechanisms (eg, Green Climate Fund) in prioritising funds for adaptation.

Priority areas for strengthening the evidence base

This collection of studies identifies four priority areas for consideration to advance methods for predicting future climate-associated health burdens, with implications for designing adaptation responses.

The first area is the generation of a cross-health impact database that allows policy and public health decision makers to prioritise health adaptation efforts from a more comprehensive evidence base using a systems approach. This would be done within a context of prioritising how to spend efforts and budget according to where the largest impact hotspots and adaptation opportunities are identified. For this, one needs to have multi-model health impacts from as many health impact pathways as possible to compare and make decisions from.

The second area for consideration is the importance of understanding context and scale, both when designing and interpreting research and when designing policy and practice responses. This should include capturing differences in vulnerability in relation to social and economic vulnerability. For example, clear geographical differences exist in terms of excess deaths due to cold and heat-related exposures, with south and east Asia together accounting for 45% and 39% of the total global excess deaths due to cold and heat-related exposures respectively.[15] In relation to types of settings and health impacts, urban areas appear to be particularly at risk, with the example of increased exposure to dengue highlighting this differentiation.[12]

The third issue is also one of scale, specifically timescale. The impact models presented in this special issue typically project conditions far out into the future (eg, 2050, 2080). Given the immediacy of the health impacts we are already witnessing, it is important for the health community to consider adapting these timescales so as to connect us more closely with the health impacts that are currently being realised. In terms of policy making processes, this shorter-term horizon also has a much more feasible and relevant point of reference that has the potential to substantially aid evidence-based policy making. Future research should further consider which timescales are of greatest relevance for specific policy making, which can involve studying impacts in relation to decadal, seasonal, or short-term climate forecasts.

The fourth area for consideration is that these multi-model comparison research activities are an important piece of the puzzle, but cannot be taken as a perfect solution. They must be balanced with other types of evidence and knowledge. This is particularly relevant when working towards policy impact arising from this research. A co-design approach, where researchers, policy makers and practitioners collaborate and agree on priorities for investigation, is a key mechanism to support a balanced approach. Co-design approaches allow for the setting of research and policy priorities amid national and subnational specific challenges.

Immediate benefits of stronger health systems

All of the health impacts investigated in this special issue focus on prolonged and persistent challenges that have plagued global health for decades: access to clean and safe drinking water and sanitation facilities, protection from vector-borne diseases, adequate housing, and safe employment. These basic health fundamentals require urgent and substantial efforts in health system strengthening, with collaborations needed across health-determining sectors. The difference now is that we must plan appropriately for our health systems in the decades to come with the knowledge of climate projections, and the related implications for the health system. It is within this context that robust model predictions and associated geographical hotspot maps (eg, figure) can inform health system development.

These health impact models would be well suited to being incorporated within the building of climate resilient health systems via the WHO's operational framework.[25] This framework adopts the building blocks of health systems to focus on climate and health policy and programmatic responses. Countries are being encouraged by WHO to adopt this framework in their climate change and human health planning. However, there are limitations in terms of its current use, particularly around the development of indicators to measure progress.

Nevertheless, guidance at a local scale by forecast models can and should enable improved focus on projected local health system needs and their development within the WHO framework. Reducing uncertainty in model forecasts will be crucial for stakeholder buy-in and thus considerably more effort needs to be made in the health modelling community to generate objective predictions. In the current day context of increasing availability of large amounts of climate data and sociodemographic projections, more impact model inter-comparisons across the myriad of climate-related health issues are needed. Insofar as public health governance will operate at country and within-country levels, projected disease burden trajectories will need to be made at the pertinent scale. In addition, and one notable lacuna generally across most of the research domain is the need to make explicit the potential adaptation strategies that could be considered on a case by case basis.

The health sector, although currently perceived as such, is not isolated from the many other sectors potentially impacted by climate change. In this respect, multisectoral considerations need to be borne in mind and discussions on adaptation strategies held accordingly. While this will be no mean feat, local stakeholders will be faced with important and difficult operational decisions. This is at the heart of the ISIMIP project, and improved coherence in the comparability of forecast modelling outputs in the health sector is a first necessary step for the health sector to catch up with other sectors and start on the long and winding road to health preparedness. Whilst a daunting task, as Hegel once aptly summed, "The valor that struggles is better than the weakness that endures."

Conclusion

Health systems already undertake a multitude of activities to respond to health outcomes that are climate-sensitive; the issue here is to ensure that these systems can respond to the pressures that climate change will bring. Evidence-based robust ensemble projections to inform local stakeholders on what health burdens are and where they will be are sorely needed. Multiple modelling techniques that can generate ensemble projections can decrease bias and quantify uncertainty in forecasts and reassure stakeholders of the robustness of the projections. The inclusion of adaptation strategies remains an important field for development, within the health sector and in the context of other sectors working to tackle and cope with climate change.

Contributors

JR, VH, KB, and RP together conceived the idea of the manuscript, and all authors helped throughout the process of drafting and refining the manuscript and analyses.

Declaration of interests

We declare no competing interests.

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