Priority climate and health modelling needs

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Climate and health modelling is necessary for improving understanding of the current and future distribution and timing of climate-related health risks. However, underinvestment in this area has limited the understanding required to inform policies that enable multisectoral interventions to safeguard health. We synthesised insights from a survey of 65 global climate and health modelling experts and 36 participants in a hybrid meeting to identify priority strategies for enhancing the validity, utility, and policy relevance of climate and health models. Foundational investments to support modelling included strengthening research capacity, establishing a network of multinational centres of excellence for transdisciplinary research and capacity building, improving data collection and sharing infrastructure, investing in scenario development and quantitative elaboration, assessing adaptation effectiveness, and committing to intermodel comparisons and interdisciplinary modelling activities. Specific recommendations included updating the 2014 WHO Quantitative Risk Assessment to cover a wider range of causal pathways and health endpoints, using interdisciplinary methods that facilitate model intercomparisons. Additional recommendations included supporting modelling of a broader set of climate–health outcomes, developing models to support early warning systems and investments in their implementation, evaluation, and maintenance, and improving health system capacity for modelling in low-resource settings.

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Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change,[1,2] the 2023 report of the *Lancet* Countdown on health and climate change,[3] and several national assessments[4,5] concluded that there is growing evidence of morbidity and mortality associated with climate variability and change. These reports warn that risks will continue to increase for nearly all climate-sensitive health outcomes as climate change progresses, while health systems remain highly vulnerable. In this context, modelling can make substantial contributions to the broader scientific efforts required to address the health challenges posed by climate change. Mathematical and statistical models are valuable tools for understanding the extent to which weather, climate variability, and climate change affect and alter future health burdens, given the complex linkages between climate processes and health outcomes.[6]

However, conservative investment in climate change and health research over the past three decades has left substantial gaps, including a paucity of modelling approaches to inform effective policy and practical interventions both within and beyond the health sector. Most modelling efforts to date have focused on the most tractable causal pathways, emphasising on direct linkages between changing weather patterns and health outcomes, particularly heat-related mortality and geographical shifts in vector-borne diseases such as malaria and dengue to non-endemic areas driven by the spread of mosquito vectors and pathogens (eg, *Anopheles* spp and *Aedes* spp).[2,7] In contrast, modelling of climate-sensitive health outcomes with more complex pathways (eg, undernutrition and mental health) and secondary outcomes (eg, migration) remains insufficient. Important knowledge gaps persist in four key areas: data, modelling approaches and methods, decision support for health-relevant sectors, and human capital.[2,8,9]

Using multiple modelling approaches to explore a particular causal pathway helps to compare results, identify areas of agreement, and reveal sources and range of uncertainties that should be acknowledged in decision making.[10] In other sectors, such as agriculture, it is standard practice to conduct intercomparisons of multiple models of climate impacts using similar inputs to increase the robustness of assessment conclusions.[1] With adequate human and financial resources, applying this practice could strengthen climate and health modelling and generate key insights for decision making.

The underinvestment in climate and health modelling within the health sector has also slowed progress in related fields, such as sociology, demography, climatology, and economics. Incorporating health-related impacts and wellbeing into the modelling efforts of these disciplines would improve the robustness of risk estimates and help to quantify the health benefits of mitigation policies and technologies. Integrated assessment modellers are increasingly interested in projecting risks across a range of climate and development scenarios to estimate the costs and benefits of mitigation and adaptation.[11,12] These assessments are more effective when multidisciplinary teams incorporate population health expertise to capture essential processes.[13] In contrast, relying on simplistic health impact and damage functions while keeping non-climate drivers (such as demographic change) constant can lead to misleading projections of the scale and burden of future health risks.[14,15]

To improve understanding of priority modelling needs, better quantify the health risks of climate change, and inform policy and decision making at national to

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international levels, the University of Washington and Wellcome conducted a survey among experts in climate, health, and related disciplines. A subset of these experts was subsequently convened to identify key priorities for advancing policy-relevant climate and health modelling.

We did not undertake a formal prioritisation of climate-sensitive health outcomes, as this would depend on factors such as the geographical area of focus, the current burden of disease, and a priori estimation of the extent to which there could be change over the coming decades (eg, whether the health burden is likely to remain similar, increase, or decrease). Priorities would also vary according to national or regional health concerns, the availability of data at the required temporal and spatial scales, and other factors. Such prioritisation has been undertaken through national and international assessments, including the Intergovernmental Panel on Climate Change and the UK Climate Change Risks Assessment 2022,[5] as well as by health organisations and institutions.

Methods

In preparation for a 3-day workshop held May 15–17, 2023, in London, UK, Wellcome and the University of Washington developed an online survey to identify priority opportunities for improving the understanding of how climate change could further alter the magnitude and patterns of the burden of climate-sensitive health outcomes and for enhancing the policy relevance of model outputs, including through collaborations with climate, ecosystem, and integrated assessment modellers (appendix pp 3–11). A snowball sampling approach was used to identify modellers of the current impacts and future health risks of climate change and of the upstream drivers of climate-sensitive health outcomes. Potential survey respondents included the following groups of individuals: experienced health modellers, identified from highly referenced publications and international processes and collaborations, including the Intergovernmental Panel on Climate Change; interdisciplinary modelling groups with expressed interest in including health into their models, such as the Integrated Assessment Modeling Consortium, PBL Netherlands Environmental Assessment Agency, International Institute for Applied Systems Analysis, Potsdam Institute for Climate Impact Research, and Asia-Pacific Integrated Model; and researchers recommended by those from the groups previously listed and from Wellcome. Details about the respondents are provided in the appendix (pp 3–11).

The survey was administered through SurveyMonkey, and the responses were anonymous. Simple descriptive statistics were used to analyse the survey responses (eg, percentage of respondents who selected a particular response; appendix pp 12–17).

Potential attendees for the subsequent workshop were selected to ensure representation across communities, regions, and practice areas and to ensure gender balance. In total, 36 scientists participated, including both in-person and online attendees, with numbers varying over the course of the workshop. Among them were four modellers conducting research in low-income or middle-income countries (LMICs) and ten modellers with extensive, long-term collaborations with researchers from LMICs.

The workshop featured plenary presentations that provided an overview of the current state of modelling in environmental health, integrated assessment, and ecological systems, along with a summary of the survey results. The remainder of the workshop consisted of breakout groups or plenary discussions. Participants volunteered to join two of the four breakout groups: priority modelling opportunities, approaches to integrate health into other models and modelling efforts, strategies to increase the policy impact of modelling, and funding and infrastructure needs. Each group selected a chair and a rapporteur, who then presented the key discussion points to the plenaries for wider debate. The workshop concluded with a final group discussion to finalise the priority recommendations.

Notes from the breakout groups and subsequent reports to the full workshop were synthesised by KLE and JJH into priority recommendations with accompanying text. This draft text was shared with all authors for their feedback. The text underwent two rounds of revision to ensure that all comments were addressed.

Results

Survey results

The survey was distributed to 65 scientists and modellers worldwide, of whom 40 responded. The results of the survey are presented in the appendix (pp 12–17); no responses were excluded. These results were shared with workshop participants to support their discussions. Although the results were not explicitly used in developing the priority modelling needs, they indirectly informed the recommendations.

The survey captured diverse perspectives, with broad consensus on several priorities, including the need for standardised counterfactual baseline mortality and socioeconomic development models; prioritising a subset of shared socioeconomic pathway (SSP)–representative concentration pathway scenarios for climate and health modelling; extending the SSP narratives and quantifications to meet the specific needs of health modellers; and the need for multimodel intercomparisons and models estimating the total impact of climate on health at regional and global scales. Respondents emphasised that principles such as equity, justice, inclusion, and diversity should be central to all modelling efforts and investment strategies.[16,17] There was also strong agreement on the importance of investments to quantify damage functions, including informing international negotiations on climate change-related loss and damage.

Workshop outcomes

Workshop discussions were summarised into a set of recommended investments. A common recommendation from participants was to start the modelling efforts with a co-production process involving decision makers and implementation stakeholders for greater impact. This approach would ensure that research questions and modelling methods directly address priority knowledge gaps. While discovery research remains important for numerous climate-sensitive health outcomes with few quantified exposure–response functions, such studies should be co-designed to ensure that the findings can be rapidly translated into policy planning to safeguard and promote population health, even as the climate continues to change.

The recommended investments were categorised by theme, without prioritisation, into the following: cross-cutting themes, particularly training, capacity building, and expanding research and modelling in LMICs; quantifying exposure–response relationships for under-researched health issues at geographical and temporal scales relevant for decision making; developing models with sufficient skill and applications for use in early warning and response systems; projecting health risks across a range of scenarios of climate and development pathways; facilitating collaborations with other sectors and exploring alternative modelling approaches; enhancing data collection and infrastructure for climate-related exposures and outcomes; and strengthening workforce capacity and computational support through establishing regional training centres.

Underlying these investment opportunities is the need to improve data in multiple domains by developing better data collection, sharing, and archival infrastructure and the need to increase modelling capacity, particularly in LMICs. These investments would support a shift from discovery modelling (eg, quantifying associations between weather and climate patterns and climate-sensitive health outcomes) toward assessing how locally relevant and culturally appropriate metrics influence health risks at scales of relevance for decision making. For example, projections of heat-related morbidity and mortality over this century should account, at minimum, for demographic change, adaptation, and urbanisation in LMICs. This approach facilitates a clearer understanding of priority intervention opportunities and the extent to which projected risks can be reduced.

Discussion and recommendations

Cross-cutting themes

An overarching issue highlighted across all recommendations was the need to build climate and health modelling capacity in the regions and communities most affected by climate change. At present, most research is conducted in high-income and upper-middle-income countries. Research in lower-middle and low-income countries is often insufficient and lacks in-country partnerships. Ensuring input from these regions will better reflect the challenges and perspectives of the populations most directly affected by climate change. Inequities also exist within countries, where the most vulnerable communities are often underserved by data and models, leaving their risks obscured within national trends.

Underlying all recommendations is the need to train and support the next generation of researchers. Ensuring the active participation of early and middle career researchers and students, especially those from LMICs, will be essential. These investments should be made in parallel with investments in data collection and data infrastructure to support co-production more broadly.

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See **Online** for appendix

For more on the **SurveyMonkey**, see https://www.surveymonkey.com/

Quantify exposure–response relationships for high-priority under-researched health issues

There are hundreds of under-researched climate-sensitive health outcomes, as highlighted in the appendix (pp 12–17). Even for well-studied outcomes, such as heat-related health outcomes and diseases carried by *Aedes* spp mosquitoes, substantial knowledge gaps remain (eg, how the timing of heat exposure affects adverse pregnancy outcomes, and how demographic change and adaptation could alter projected health risks). In addition, exposure–response relationships that focus on particularly vulnerable sub-populations, such as individuals with diabetes or kidney disease, are also needed to inform modelling and guide interventions that enhance preparedness for a changing climate.

Prioritising climate-sensitive health outcomes over the short-term is essential, including mental health; vector-borne diseases other than malaria, particularly those transmitted by *Aedes* spp mosquitoes; diarrheal diseases; nutritional security; occupational injuries and illnesses; and worker productivity. Participants also emphasised the importance of understanding the complex interactions between environmental change and migration, and in improving detection and attribution of impacts of climate change, including the collection and incorporation of data on relevant variables and effect modifiers. The complete list of under-researched climate-sensitive health outcomes identified through the survey is included in the appendix (pp 18–22). Although not comprehensive, this list highlights the top research needs across scales—some are relevant at all geographical levels, whereas others pertain primarily to local or subnational scales.

Develop models with sufficient skill and applications for use in early warning and response systems

A key application of modelling to facilitate adaptation is to inform national and subnational early warning and response systems. Recent advancements in the skill of seasonal to subseasonal forecasts provide opportunities for these systems to prevent morbidity and mortality across a wide range of climate-sensitive health outcomes. These include heat-related outcomes (eg, emergency department visits and ambulance callouts, adverse pregnancy outcomes, work-related injuries and illnesses, as well as reduced outdoor worker productivity and mortality); vector-borne diseases such as dengue fever, Zika fever, chikungunya, malaria, and Lyme disease; and other infectious diseases including diarrheal diseases.

Effective early warning systems protect the health and wellbeing of vulnerable individuals and groups while avoiding the creation of systems that primarily serve the privileged and overlook those at greater risk. However, most health models developed to support early warning systems have not been implemented, partly because quantification of associations between climate and disease risk is often conducted without collaboration with operational agencies or clear pathways and funding support for operationalisation, evaluation, and maintenance. In addition, models are rarely validated or have their skill quantified, and communication barriers persist between model developers and public health professionals expected to act on forecasts.

Project health risks under various climate and development scenarios

Understanding the current and possible future magnitude and distribution of climate-sensitive health outcomes can inform ministries of health and national adaptation and development plans as well as public education efforts. Projections of future risks should incorporate a range of climate and development scenarios, including how potential confounding factors might shift and how risks could compound and cascade across and within regions, with indirect or secondary health effects. Projecting risks involves exploring a range of possible interactions among diseases and the social, environmental, and economic factors that influence them (eg, syndemics)[18] while acknowledging the uncertainties in future health conditions and demographics, particularly later in the century.

Effectively planning for a changing climate requires incorporating the upstream drivers of climate-sensitive health outcomes into policies and plans, ensuring stronger coordination and collaboration across ministries and sectors. For example, modelling efforts should include assessing how adaptation could prevent climate-sensitive diseases and how population ageing increases the risk of climate-sensitive morbidity and mortality later in this century.

A staged approach to investing in projections was suggested, beginning with health-specific extensions of the SSP narratives and quantifications to enable more robust predictions of climate-related health risks. Apriority is updating the global estimate of the overall health burden of climate change under different climate and development scenarios, for a broader range of health outcomes—the previous global assessment was updated in 2014.[19]

Develop extensions of the SSP narratives and quantifications for health

The limited uptake of SSPs in health modelling often means that projections do not incorporate key non-climate drivers, such as demographic change and urbanisation. Health extensions should, therefore, build on the updated demographic projections, with 2020 as the baseline and incorporate education-specific fertility levels, country-specific and region-specific education differentials in mortality rates, and education-specific migration rates.[20] Projections of the extent of urbanisation over coming decades are being updated. Extending SSP narratives for health also should incorporate quantification and narrative elements for other important non-climate drivers of health, particularly equity and access to health care.[21]

Ideally, a process should be established for extending a minimum set of SSPs for use in health modelling, specifying geographical and temporal scales, estimating resource needs for the extensions, and a data platform to make projections available for use by modellers within and outside the health sector. Explicitly linking this process with ongoing efforts to further extend the SSPs—for example, through integrated assessment projects funded by the EU —would be a cost-effective approach. It would also be prudent to align with the Intergovernmental Panel on Climate Change recommendations on SSP extensions in preparation for the Seventh Assessment Report.[22]

Develop health adaptation pathways

Building on relevant publications,[23–25,] it was recommended to organise a workshop to agree on a set of adaptation pathways for use in projections. At present, only broad qualitative statements can be made about health adaptation under the SSPs.[24] For example, in a world pursuing sustainable development, health system adaptation would likely face fewer constraints and be more effective than under other SSPs. However, few health projections have incorporated estimates of adaptation effectiveness, with limited consistency across studies.[19,26] Thus, the processes underlying health adaptation remain largely uncharacterised and unquantified.

The role of adaptation pathways could be similar to that of mitigation pathways, describing how adaptation might evolve under different assumptions about challenges and opportunities. These pathways could lead to alternative futures, some characterised by increased resilience and reduced inequities, others by declining resilience and widening inequities. The initial set of adaptation pathways is envisioned at the global scale, with narratives and quantifications structured to facilitate downscaling to regional contexts. These pathways could be used in projections of health risks to quantify the extent to which adaptation could reduce the projected burden of disease. Compared with recent projections, those using adaptation pathways would offer deeper insight by accounting for the central role of adaptation in preparing for and managing climate change-related health. These projections could inform decisions on the scale and direction of investment.

Ideally, there should be opportunities for two-way interactions between global and regional modelling efforts, as there will be instances when specific variables in regional pathways do not sum to the values in global pathways. Such discrepancies provide opportunities to advance understanding and refine scenarios. Regional pathways developed through other processes can be categorised into solution space segments to facilitate national and international assessments.

Agreeing on a set of adaptation pathways would require the involvement not only of health researchers but also of demographers, international development experts, and others to frame narratives and quantifications of adaptation relevant for the burden of climate-sensitive health outcomes on individuals, health systems, health organisations, non-governmental organisations, and businesses. Participants in these discussions should include strong representation from LMICs.

Update the WHO Quantitative Risk Assessment[19]

In addition to extending the SSPs for health and developing adaptation pathways, updating the WHO Quantitative Risk Assessment[19] published in 2014 should also be prioritised. Although this modelling effort was state-of-the-art a decade ago, its estimates are now outdated due to advances in scientific understanding of and modelling approaches to climate-sensitive health outcomes. This assessment was the only global effort across multiple climate-sensitive health outcomes in which common approaches and assumptions facilitated comparison of diarrheal diseases, malaria, childhood undernutrition, and heat-related mortality in older adults. Although the projections are widely acknowledged to underestimate the actual numbers of deaths, they continue to be cited, including in the health chapter of the Intergovernmental Panel on Climate Change Sixth Assessment Report.[2] There are multiple opportunities to add, for example, morbidity and mortality from a wider range of climate-sensitive health outcomes for infectious and chronic diseases and work-related injuries and illnesses. Updating these estimates is an opportunity to show the utility of leveraging multiple modelling methods and conducting model intercomparisons to identify common strengths and potential biases and weaknesses of specific approaches.

The next assessment is recommended to be undertaken as a collaborative effort to develop standard inputs (eg, climate models, demographics, urbanisation, and changes in mortality under different SSPs) and baselines. Ideally, this quantitative modelling would be conducted at global and regional scales.

Other considerations when projecting health risks

Assessing the extent to which local and global scales meet when projecting health risks is essential. Research is needed to understand the conditions under which downscaled projections (eg, demographic and socioeconomic change or specific health risks) approximate local projections. A clearer understanding of when these approaches yield similar or divergent results is important for improving model robustness. Moreover, understanding the underlying processes can enhance the accuracy of projections for adaptation.

Explicitly considering synergies and trade-offs among adaptation, mitigation, and development policies is important, similar to the tables from the Intergovernmental Panel on Climate Change Working Group III that map synergies and trade-offs between mitigation options and the Sustainable Development Goals.[27] For example, this consideration involves moving beyond estimating the health benefits of mitigation policies to also consider the trade-offs between meeting the Paris Agreement and ensuring nutritional security, because low greenhouse gas emission pathways might reduce the land available for food, potentially increasing food prices. Such analyses should also incorporate the indirect benefits of mitigation policies for health through multiple pathways.[28,29]

Facilitate collaborations with other sectors and modelling initiatives

Because many drivers of climate-sensitive health outcomes occur upstream of the health sector, modelling efforts should include broader collaborations, particularly with integrated assessment and ecosystem modelling efforts. A more systematic incorporation of health into ecosystem models provides an opportunity to better understand, for example, the potential health consequences of biodiversity loss, land-use change, and other global environmental changes. Adopting a One Health approach recognises that the health of humans, domestic and wild animals, plants, and broader ecosystems is interdependent and that policies should aim to sustainably balance and optimise these interconnected systems.[30]

Quantifying damage functions that link hazard intensity to health-related impacts, enabling their incorporation into integrated assessment models, should also be prioritised. This approach would enhance projections of metrics such as the social cost of carbon, which estimates the economic damage associated with emitting an additional tonne of carbon dioxide. The social cost of carbon reflects the present value of avoiding projected damages. The social cost of carbon has high policy relevance but rarely includes health risks beyond heat-related impacts on mortality and outdoor worker productivity. Incorporating a broader range of health risks into the social cost of carbon would increase the present value of mitigating greenhouse gas emissions. Furthermore, once greenhouse gas emissions peak and begin to decline, damage functions could help to model health risks based on cumulative emissions.

Both opportunities highlight the value of broadening modelling teams to include those with social science and other expertise, as well as other knowledge systems, to facilitate systems-based approaches for understanding the magnitude and pattern of climate change-related health risks.

Data, infrastructure, and capacity-building needs

The previous recommendations rely on improving access to robust health-related data in under-resourced countries and regions, including for marginalised and remote populations in high-income countries. Digitising current data, exploiting digital technologies to improve data collection, and investing in long-term data collection can be effective approaches to improving data availability and quality. For example, several low-income countries collect health-related data on a monthly basis, limiting the ability to detect infectious disease outbreaks or to robustly quantify exposure–response relationships. Access to meteorological data is also restricted in many low-income countries, necessitating the use of remotely sensed data or alternative data sources. Another promising step is the digitisation of health records from selected surveillance health facilities in low-income countries, which could provide crucial health outcome data for modelling.

A key recommendation is to develop data hubs and data repositories of common inputs that can be used to develop models of exposure–response relationships and projections of health risk, including extensions of the SSP narratives to include elements informative for health projections and quantifications of, for example, equity and adaptive capacity under the SSPs. Numerous datasets are already available to health modellers, including the International Institute for Applied Systems Analysis SSP database that covers quantifications of demographic and economic change, urbanisation, and others;[31] the Inter-Sectoral Impact Model Intercomparison Project database of climate-impact simulations; and socioeconomic data from the Center for International Earth Science Information Network. Participants generally agreed that capacity building is needed to enable the accurate and effective use of these datasets, particularly among modellers new to climate change and health.

For more on the **Inter-Sectoral Impact Model Intercomparison Project**, see https://www.isimip.org/

For more on the **Center for International Earth Science Information Network**, see https://www.ciesin.columbia.edu/

Incorporating weather and climate data into health data repositories will require clear protocols to ensure timely updates as new data become available. However, some questions remain, including who will establish the criteria for selecting climate projections (eg, specific SSP–representative concentration pathway combinations and climate model runs).

Another important priority is to update and expand inventories of modelling approaches to document the range of health models, including their strengths and challenges. Ideally, these inventories would also include models used in other impact sectors, such as ecosystems, water, and infrastructure, providing valuable insights for increasing the robustness of health models. Such an inventory would benefit the many researchers interested in climate change and health and could be developed by a central group with a transparent process for modelling groups to verify entries.

Integrated assessment approaches should be enhanced to better capture human responses to climate change (ie, adaptation) and to reflect the complex linkages among climate change, health, and ecosystems within the context of the Sustainable Development Goals.

Establishing a network of regional multinational centres of excellence would further strengthen coordination and collaboration across modelling groups, including those in health and other sectors, and facilitate capacity building. Although some successes exist,[32] partnerships between health and meteorological scientists remain uncommon, partly due to the high cost of acquiring meteorological data in some countries, resulting in less robust data analyses. Multidisciplinary centres of excellence could address this gap by fostering long-term collaborations that advance understanding and uptake of appropriate metrics and statistical approaches, leveraging the strengths of diverse scientific disciplines. The absence of data and data infrastructure in some regions should not be a barrier to modelling estimated health impacts; local expertise can often provide valuable insights. The urgent nature of this research indicates that qualitative estimates can play a crucial role while a more robust infrastructure is being built.

Funding for centres of excellence should require collaboration with other relevant initiatives to avoid siloed efforts—for example, facilitating interactions with centres focused on pandemic preparedness, planetary health, or One Health approaches to enrich data collection useful for modelling.

Strong engagement with decision makers at local, national, and global scales should be integral to these centres to define priority modelling questions and to increase the likelihood that the results are suitable for guiding existing and new policies and programmes. This approach would also foster greater trust in models among policy makers and the public.

Guidelines for projecting health risks should be developed at various scales, drawing on the expertise and recommendations of organisations such as the International Institute for Applied Systems Analysis, Potsdam Institute for Climate Impact Research, PBL Netherlands Environmental Assessment Agency, and Asia-Pacific Integrated Model, all of which contributed to the development of the SSPs and representative concentration pathways. Cross-sectoral collaboration with domains such as ecosystems and water further facilitates projections of upstream drivers of health over the coming decades. These guidelines should be broadly reviewed to ensure accuracy, relevance, and usability and should be disseminated in multiple formats—including peer-reviewed papers, videos, and workshops—to reach diverse audiences.

Capacity should be strengthened for modelling the health impacts and risks of climate variability and change, including effects on health systems. There is unmet demand for training in climate change and health from ministries of health, universities and colleges, non-governmental organisations, and international organisations. A training of trainers approach is an effective and sustainable way to build capacity. Training materials could take various forms, including didactic modules, web-based programmes, and videos. Knowledge transfer and exchange should also extend to non-specialist health and policy professionals.

Creating an inventory of existing training materials to identify resources on which new materials could be drafted is recommended. Given the wide scope and depth of topics to cover, prioritising key areas would help to focus the training efforts on urgent needs. A consortium approach to developing training materials, with each member contributing from their specific area of expertise, can be effective and build on ongoing initiatives.

SSP extensions and adaptation pathways should be integrated with capacity building initiatives to ensure that emerging results can be effectively used. This approach could include developing guidance documents and training resources to support new projections for future health risks. There are many opportunities to leverage existing efforts for this capacity building, such as training workshops offered by the University of Cape Town Climate System Analysis Group and the Independent University of Bangladesh International Centre for Climate Change and Development.

Incorporating mentorship and student engagement into training programmes is desirable, particularly during in-person workshops, providing opportunities for student engagement at more in-depth contexts and facilitating student involvement, such as note-taking and listening sessions.

Conclusions

The survey and workshop identified priority global modelling needs to improve the understanding and quantification of climate change-related health risks and to inform policy and decision making at national and international levels. Ultimately, modelling priorities should also be established at national and local levels,[33] incorporating the perspectives of indigenous people and marginalised communities, and directed towards strengthening resilience and sustainability by reducing vulnerabilities and inequities. Strong commitments from the ministries of health to support such research would further enhance the integration of results into national and local control strategies.

However, this study also has some limitations. The survey had a 67% response rate, and space restrictions limited the number of workshop participants. The recommendations could have differed with additional participants, particularly by including more experts in ecosystem modelling and integrated assessment modelling. Over time, the recommendations are expected to evolve as future investments address research gaps and growing knowledge identifies new areas for exploration.

A priority investment area is updating the WHO Quantitative Risk Assessment. This will require extending SSP narratives and quantification for health, including key elements of health adaptation pathways, to inform the scenarios selected. Risk assessments should also account for the indirect effects on health arising from the impact of climate change on other sectors, such as the mental health consequences of climate change impacts on ecosystems. Using common inputs, projected climate-related health risks could be aggregated at global and regional levels to generate updated damage functions and estimates of the social cost of carbon. These scenarios could then be adopted by other modelling groups to project changing health risks under climate change.

Advancements in climate and health modelling would support the integration of climate change considerations into health investments, ensuring that policy choices support climate resilience and environmental sustainability and reduce inequities. We recommend investing across research domains. For example, for understudied health outcomes, targeted investments in data collection and infrastructure are essential for robust quantification of exposure–response relationships and for projecting how risks could evolve with further climate change. When relevant and feasible, developing effective early warning and response systems could help to reduce morbidity and mortality while enhancing preparedness for a warmer future. Collaborations and capacity building with other modelling disciplines and sectors—such as integrated assessment modelling and ecosystem modelling—could introduce novel approaches, broadening the range of methods and tools available for health researchers to better understand indirect impacts. Fulfilling these research opportunities will require substantial investments, ideally from a mix of national and international funders. Coordination across funders could facilitate filling important knowledge gaps with high policy impact, such as strengthening research capacity, establishing a network of multinational centres of excellence for transdisciplinary research and capacity building, improving data collection and sharing infrastructure, investing in scenario development and quantitative elaboration, assessing adaptation effectiveness, and committing to intermodel comparisons and interdisciplinary modelling activities.

For more on the **Climate System Analysis Group**, see https://acdi.uct.ac.za/climate-system-analysis-group-csag

For more on the **International Centre for Climate Change and Development**, see https://icccad.net/

Contributors

KLE, JJH, and FCG conceptualised the workshop. KLE and JJH led the workshop. All authors contributed to the discussions that informed the manuscript, contributed to the writing of the original and revised manuscript, and approved the final version.

Declaration of interests

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