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The role of global reanalyses in climate services for health: Insights from the *Lancet* Countdown

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Abstract

As the linkages between extreme weather events, changes in climatic conditions and health impacts in exposed populations become clearer, so does the need for climate-smart decisions aimed at making the public health sector more responsive and resilient. By integrating climate and health information, climate services for health provide robust decision-support tools. The *Lancet* Countdown monitoring system uses global climate reanalyses products to track annual changes in a set of health-related outcomes. In the monitoring system, multiple variables from reanalysis datasets such as ERA5 and ERA5-Land are retrieved and processed to capture heatwaves, precipitation extremes, wildfires, droughts, warming and ecosystem changes across the globe and over multiple decades. This reanalysis-derived information is then input into a hazard–exposure–vulnerability framework that delivers, as outcomes, indicators tracking the year-by-year impacts of climate-related hazards on human mortality, labour capacity, physical activity, sentiment, infectious disease transmission, and food security and undernutrition. Building on the reanalysis gridded format, the indicators create worldwide 'maps without gaps' of climate–health linkages. Our experience shows that reanalysis datasets allow standardization across the climate information used in the framework, making the system potentially adaptable to multiple geographical scales. An ongoing challenge is to quantify how the inherent bias of global reanalyses influences indicator outcomes. We foresee the health sector as a key user of reanalysis products. Therefore, public health professionals and health impact modellers should be involved in the co-development of future iterations of reanalysis datasets, to reach finer spatial resolutions and provide a wider set of health-relevant climate variables.

KEYWORDS

climate services, health, impact modelling, indicators, preparedness, reanalyses

1 | INTRODUCTION

There is growing and incontrovertible evidence that climate change is affecting human health (Cissé et al., 2022). Extreme weather events (EWEs) can affect physical and mental well-being as well as access to healthcare, food, clean water, sanitation and physical safety, potentially leading to illness, injury or death (Ebi et al., 2021). Gradual changes in weather and climatic conditions can result in increases in exposure to warming, disease transmission and poor water quality (Cissé, 2019; Oppermann et al., 2021; Rocklöv & Dubrow, 2020; Vezzulli et al., 2016).

To reduce the adverse impacts of climate change on health, the health sector would benefit from improved understanding and quantification of the risks of climate change on health in terms of disease burden and opportunities and effectiveness in the public health response (Ghebreyesus et al., 2009). For this to happen, information from the health sector alone is insufficient and knowledge of the past, present and future state of the Earth's climate needs to be considered. Climate services for health stem from the integration of health and climate information. Climate services for health are defined as 'the entire iterative process of joint collaboration between relevant multidisciplinary partners to identify, generate and build capacity to access, develop, deliver, and use relevant and reliable climate knowledge to enhance health decisions' (WHO/WMO, 2019).

To date, climate services for health have been successfully implemented in a variety of initiatives across the globe and make use of climate data from in situ observations, satellite-based remote sensing and climate reanalysis datasets (Del Corral et al., 2012; Ford et al., 2016; Tewary et al., 2021; Thomson et al., 2019; WHO/WMO, 2019). The use of climate reanalysis datasets in climate services for health offers multiple advantages. By combining observations with numerical weather prediction model outputs through data assimilation, reanalyses provide climate information as spatially contiguous (gridded) data across multiple spatial and temporal scales. From these data, historical trends, climatological baselines and EWEs can be defined in any location within the reanalyses' spatial domain, including those regions in the world where the lack, poor quality or poor coverage of monitoring systems (e.g., meteorological stations) can prevent high-quality long-term observations of the climate. Interestingly, those regions are often the ones where climate change is expected to have the most profound impact on human health (Carleton et al., 2022; Chambers, 2020; Dinku et al., 2014; Islam & Winkel, 2017; Stewart-Ibarra et al., 2019). Further, climate reanalyses contain estimates of multiple atmospheric, land-surface and sea-state parameters, thus offering a comprehensive description of the Earth's climate as it has evolved during recent decades. As the human population interacts with multiple ecosystems (e.g., terrestrial, marine, atmospheric and urban), climate reanalyses can be used to understand, in an integrated way, how climate change has been affecting such ecosystems and, through these, human health.

One initiative that uses climate reanalyses as the main source of climate information is the '*Lancet* Countdown: Tracking Progress on Health and Climate Change'. The *Lancet* Countdown follows on from the work of the 2015 *Lancet* Commission on Health and Climate Change, which recognized anthropogenic climate change as a threat to the past 50 years of gains in public health and identified a comprehensive response to climate change as 'the greatest global health opportunity of the 21st century' (Watts et al., 2015). The *Lancet* Countdown aims to provide a global monitoring system for this paradigm shift. The system comprises five interrelated domains: (i) health hazards, exposures and impacts; (ii) adaptation planning and resilience for health; (iii) mitigation actions and health co-benefits; (iv) economics and finance and (v) public and political engagement (Watts et al., 2017). For each domain, the system tracks the extent to which any progress (or lack of) towards a public health system that is more responsive and resilient to climate change is occurring over time. It does so via a set of indicators that are documented by annual reports (Romanello et al., 2022a; Romanello, Mcgushin, Drummond, et al., 2021; Watts et al., 2019, 2021; Watts, Amann, Arnell, et al., 2018; Watts, Amann, Ayeb-Karlsson, et al., 2018). In the 'health hazards, exposures, and impacts' domain, indicators track the health impacts related to anthropogenic climate change and their trends to date. Using data from global climate reanalyses among other sources, indicators identify EWEs and gradual changes in weather and climatic conditions across several decades and integrate this information with health data to derive the spatiotemporal dimension of climate-related risks to human health (Di Napoli et al., 2022).

It has been reported that 'the climate services community often does not fully appreciate all public health concerns and needs, and the role climate services can play to support public health' (GFCS, 2014). Further, a thorough documentation on how climate information is integrated into the health sector and informs health decision-making is currently missing (Soares et al., 2018). In response to these shortcomings, we provide evidence showing how climate reanalyses can serve and advance climate services for health based on our experience from the *Lancet* Countdown. We first illustrate why and which climate reanalysis data are used to construct *Lancet* Countdown indicators, with a focus on those in the 'health hazards, exposures and impacts' domain. We then describe the methodologies underlying the integration of reanalyses with health information in the indicators that constitute the monitoring system documented in the 2022 annual report. We then share lessons learned and current limitations in our approach. Finally, we discuss future directions.

2 | GLOBAL CLIMATE REANALYSIS IN THE *LANCET* COUNTDOWN

In the *Lancet* Countdown monitoring system, the indicators in the 'health hazards, exposures and impacts' domain (or *Lancet* Countdown indicators in brief) are summary measures tracing the linkages between climate change and health. The indicators are based on a hazard–exposure–vulnerability framework where each component represents a dimension of the coupled human–climate system (Di Napoli et al., 2022). The framework makes use of geospatial data to capture spatial and temporal variability in the climate–health linkages. For the hazard component of the framework, the geospatial data are represented by climate reanalysis data. In this section, we describe the characteristics that make climate reanalysis information suitable for the monitoring system's purposes, the methodologies adopted to integrate such information with health information in the *Lancet* Countdown indicators and the corresponding outcomes.

2.1 | Characteristics

Reanalyses represent a suitable source of climate information for the *Lancet* Countdown monitoring system for two reasons.

First, the *Lancet* Countdown monitoring system aims to provide a worldwide perspective on the impacts of climate change on human health. Climate reanalyses can have global coverage, thus enabling global indicators to be defined and calculated. As climate-sensitive health risks cross borders (Brimicombe et al., 2021; Ghebreyesus et al., 2009), the use of global indicators supplies an understanding of the overall magnitude of climate-change-related impacts and informs the development of international processes for climate-informed health decision-making. Further, climate reanalyses extend back several decades. This enables the *Lancet* Countdown monitoring system to track climate change impacts over a long time period and show their year-by-year variability, potentially revealing those areas in the world where such impacts occur more frequently and should be prioritized in the international agenda.

Second, *Lancet* Countdown indicators must satisfy five quality criteria—representativeness, relevance, robustness, reproducibility and timeliness—to be relevant and useful to the scientific and policy-making health communities (Di Napoli et al., 2022). The robustness and the reproducibility criteria demand indicators to be built based on open-access and quality-controlled data from publicly available databases, and those developed by international organizations, governmental bodies or academic institutions, are preferred. Most climate reanalyses satisfy both the robustness and reproducibility criteria. The timeliness criterion is also fulfilled, that is, climate reanalyses are usually updated regularly, with a short lag between the period when the latest data are available and the present time. This allows *Lancet* Countdown indicators to be computed in near real time, and thus to be documented in the annual report with minimal lag (the monitoring system tracks progress on health and climate up to the year before the report's release).

One climate reanalysis dataset that fulfils the needs of the *Lancet* Countdown monitoring system is ERA5. ERA5 is the fifth generation ECMWF (European Centre for Medium Range Weather Forecasts) reanalysis of the global climate and is produced by the Copernicus Climate Change Service (C3S) at ECMWF (Hersbach et al., 2020). ERA5 spans the globe and is available from the 1950s to near present time at $0.25^\circ \times 0.25^\circ$ (ca. 31×31 km) spatial resolution; it is publicly available from the Copernicus Climate Data Store (CDS, Raoult et al. (2017)); it is released as a consolidated dataset (i.e., quality-checked) with a 2–3-month lag. Moreover, ERA5 data are provided at multiple time resolutions, from hourly to monthly. These characteristics allow both EWEs and gradual changes in climatic conditions to be defined from the same reanalysis, thus guaranteeing consistency across indicators. ERA5 has been used in several climate and health studies. Topics include the exposure of human populations to heatwaves and droughts (Chambers, 2020; Zhang et al., 2021), heat-related mortality (de Schrijver et al., 2021; Royé et al., 2020; Urban et al., 2021), heat-related labour loss and productivity (Dasgupta et al., 2021; Kong & Huber, 2022; Parsons et al., 2021), mental health (Florido Ngu et al., 2021) and food insecurity in terrestrial and marine systems (Dasgupta & Robinson, 2022; Laudien et al., 2022; McGlue et al., 2020; Post et al., 2021; Shettigar et al., 2020; Verschuur et al., 2021; Zhou et al., 2021). These ERA5-based research topics align with those addressed and tracked by *Lancet* Countdown indicators. The above-listed characteristics make ERA5 a suitable provider of climate information for most of the *Lancet* Countdown indicators. Another reanalysis from which indicators source climate information is ERA5-Land. ERA5-Land is produced by rerunning the land component of the ECMWF ERA5 climate reanalysis (Muñoz-Sabater et al., 2021) and provides a publicly available estimate of land variables from 1950 to near present time at $0.1^\circ \times 0.1^\circ$ (ca. 9×9 km) spatial resolution.

2.2 | Integration

In the 2022 annual report, 10 *Lancet* Countdown indicators are defined and implemented in the 'health hazards, exposures and impacts' domain across four thematic clusters: heat; weather and climate extremes; infectious diseases; and food security and undernutrition (Romanello et al., 2022a). These reflect the main linkages between climate change and human health (Rocque et al., 2021). As climate–health linkages are multiple with synergies and feedback loops, the choice to use more than one indicator in the *Lancet* Countdown monitoring system enables human health to be tracked and thus protected in an integral way (Linares et al., 2020).

Figure 1 shows how *Lancet* Countdown indicators are constructed via a hazard–exposure–vulnerability framework. Climate reanalyses represent the data source from which the hazard component is defined. Estimates of climate variables—air temperature, relative humidity (usually calculated from dew point temperature), radiation, precipitation, wind speed and sea surface temperature—are retrieved from climate reanalysis and used to define EWEs such as heatwaves and precipitation extremes as well as gradual changes in weather and climatic conditions (e.g., warming) leading to heat stress, drought or ecosystem changes. As the *Lancet* Countdown focuses on human health, the exposure component contains information on human populations, specifically population density. The vulnerability component incorporates the spatiotemporal dimension of any economic, demographic, social, physical or geographic factor that can reduce the ability of exposed populations to prepare for and cope with the impacts of climate-change-related hazards. *Lancet* Countdown indicators consider vulnerabilities linked to age, urban areas, altitude and income.

The gridded nature of climate reanalyses allows the hazard component to depict EWEs and gradual climatic changes grid cell by grid cell. Hazards can thus be defined anywhere in the world, even in locations where observations are not comprehensive (a comprehensive map of currently active surface-based observing stations and platforms is available from the OSCAR/Surface repository, WMO (2023)). This is relevant for *Lancet* Countdown indicators, which must be valuable to policy and decision-makers at multiple spatial scales, from global to local (relevance criterion, Di Napoli et al. (2022)). For this to happen, exposure and vulnerability components also need to be in a gridded format so that the three components can be combined coherently, and

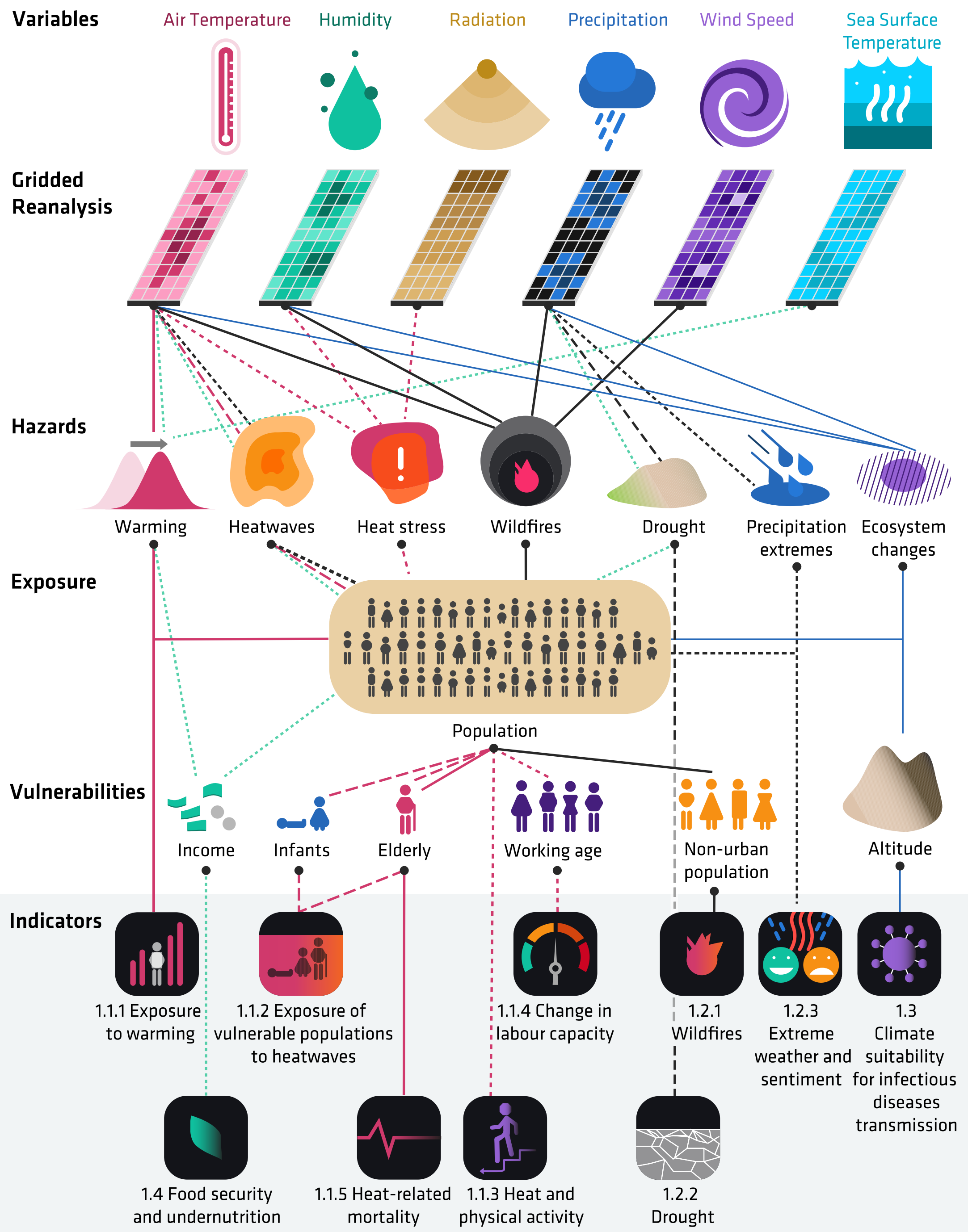

FIGURE 1 Flow chart describing how *Lancet* Countdown indicators are calculated from reanalysis data in the 2022 report. Red lines refer to indicators of the heat cluster; black lines refer to indicators of the weather and climate extremes cluster; blue lines refer to indicators of the infectious diseases cluster; and green lines refer to indicators of the food security cluster.

health outcomes estimated at each grid cell. The exposure component is sourced from the gridded NASA Socioeconomic Data and Applications Center (SEDAC) Gridded Population of the World (GPWv4) dataset, and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Histsoc dataset (ISIMIP, 2021; NASA, 2021). The first provides population data from 2000 to present at 0.25° × 0.25° spatial resolution, the same as ECMWF ERA5; the latter provides population data from 1980 to 2000 at 0.5° × 0.5° spatial resolution. We apply post-processing steps to resample the datasets to a common spatiotemporal resolution and extent (Chambers, 2022). As for the vulnerability component, data are in various formats. Altitude data are sourced at 0.25° × 0.25° spatial resolution from the University of Washington Joint Institute for the Study of the Atmosphere and Ocean (JISAO, 2014).

Urban areas are defined from the GPWv4 and Histsoc datasets as those grid cells with a population density higher than 400 persons/km^2. Age and income data are provided at a country level (Cafiero et al., 2018; UN, 2022) and converted to grids via post-processing.

After hazard, exposure, and vulnerability data are retrieved and standardized in format, they are inputted to the framework, which facilitates the calculation of *Lancet* Countdown indicators via two methods. The first method consists of spatially overlaying the reanalysis-derived hazard data with exposure and/or vulnerability information. In the heat cluster, for instance, the exposure to warming indicator (1.1.1) overlays population data on the reanalysis-derived hazard component to monitor the year-by-year temperature increase in inhabited land areas. The exposure of vulnerable populations to heatwaves indicator (1.1.2) adds a vulnerability layer on top of that, represented by the distribution of the population above the age of 65 (the elderly) and between 0 and 1 years old (infants) that are known to be more susceptible to illness from heat extremes (Mayrhuber et al., 2018). Similarly, the wildfire indicator (1.2.1) tracks the danger of wildfires by overlaying the hazard component with an exposure component that accounts exclusively for human populations outside densely populated areas (direct exposure to fires from forests, grasslands, or prairies does not occur in cities). This is complemented with the population exposure to fire smoke, which can be transported from remote fires (Kollanus et al., 2017). The second method integrates reanalysis-derived hazard data with exposure and vulnerability information via health impact models. These include: exposure–response functions for the heat-related mortality indicator (1.1.5) and change in labour capacity indicator (1.1.4); models of heat stress risk in the heat and physical activity indicator (1.1.3) or risk of an outbreak in arboviral diseases in the climate suitability for infectious diseases transmission (1.3); and econometrics models in the food security indicator (1.4).

2.3 | Outcomes

Once the hazard–exposure–vulnerability framework is applied, *Lancet* Countdown indicators are calculated to deliver an outcome. As the initiative aims to track progress on health and climate change, indicator outcomes consist of trends. These include trends of climate variables, human population exposure and health impacts associated with EWEs or gradual climatic changes. Trends are expressed in absolute terms or relative to a baseline.

Thanks to the nature of the framework's input data, trends are defined at each grid cell. Trends are grouped in three different ways to reflect the *Lancet* Countdown's goal of ensuring that health is at the centre of how governments understand and respond to climate change at multiple levels. One way to group trends consists of averaging trends of grid cells within a country's borders as defined by United Nations agencies. Comparison among country-specific trends helps the monitoring system reveal which countries have been most affected by climate change in a given year as well as those countries in which climate-related threats to health are emerging the fastest. Country-specific trends are also used by the *Lancet* Countdown in policy briefs to provide evidence and recommendations tailored to single countries (Lancet Countdown, 2022b). The policy briefs can support national governments that have a responsibility, under the United Nation Framework Convention on Climate Change (1992), to carry out formal assessments of the risk posed by global climate change to their population's health. A second way to group trends considers averaging across the six regions defined by the World Health Organisation (WHO, 2022), whereas a third way consists of averaging trends based on levels of the human development index (HDI). Defined by the United Nations Development Programme, the HDI is a summary measure of the life expectancy, education and income of a country's population (UNDP, 2022). HDI grouping was first introduced and applied in the 2021 annual report (Romanello, Mcgushin, Di Napoli, et al., 2021).

Indicator trends constitute the *Lancet* Countdown monitoring system. The system can be consulted and used and shared publicly via a dedicated online platform (Lancet Countdown, 2022a). In the platform, country-averaged trends are provided as worldwide maps, which can be navigated across the years and by country via an interactive, user-friendly interface. This representation aligns with the current evidence on maps as effective tools in climate information for health: indicator trends help visualize and communicate climate–health information as well as support health decision-making based on it (WHO/WMO, 2019). The platform also includes trends grouped by WHO region or HDI level and visualized as time series. For each indicator, maps and trends are accompanied by a description of the methods and data sources used, climate reanalysis included.

3 | DISCUSSION

3.1 | Lessons learnt

Based on our multiyear experience from the *Lancet* Countdown, we here report the four main lessons learnt from using global reanalysis information in a climate-information-for-health context.

1. *Standardization*: One climate reanalysis dataset enables the definition and calculation of multiple indicators by providing a diverse set of terrestrial, marine and atmospheric variables. In the 2022 annual report, we use ERA5 to define the hazard component in 8 out of 10 *Lancet* Countdown indicators (Romanello et al., 2022a). This allows us to guarantee standardization across the climate data input into the hazard–exposure–vulnerability framework. The standardization involves indicators tracking the impacts of different hazards as well as indicators focused on a single hazard. The extreme weather and sentiment indicator (1.2.3), for instance, tracks how human sentiment changes in days affected by EWEs compared with days when EWEs did not occur between 2015 and 2021. The indicator identifies EWEs as precipitation extremes and heatwaves, with the latter defined using the criteria described by the exposure of vulnerable populations to heatwaves indicator (1.1.2).
2. *Multi-purpose*: The characteristics of reanalyses as gridded and long-running datasets enable us to create indicator-based 'maps without gaps' of climate–health linkages spanning multiple decades. To the best of our knowledge, the *Lancet* Countdown monitoring system is the only worldwide system that uses reanalysis data for such a purpose. We further leverage on the spatiotemporal characteristics of reanalysis information to adapt the system to local and continental scales (European Climate and Health Observatory, 2022; Robinson et al., 2020). Four *Lancet* Countdown indicators, for instance, have been included in the European Climate and Health Observatory, where they can be accessed as maps covering the 38 European Environment Agency member and cooperating countries.
3. *Co-production*: The 'health hazards, exposures, and impacts' domain is developed with the contribution of a group of experts across a broad range of relevant disciplines, including climate, geography, epidemiology, economics, computational social science, ecology and occupational health. As *Lancet* Countdown indicators must be updated annually to provide the most recent picture of climate change's impacts on human health (Di Napoli et al., 2022), we found an interdisciplinary approach useful for choosing which climate reanalysis best fits the aim of each indicator based on spatial resolution, data availability and uncertainty. The approach also helps integrate the reanalysis-derived indicators into other *Lancet* Countdown domains (*nesting*) so that the global monitoring system can be holistic, robust and actionable. In the 2022 annual report, the change in labour capacity (1.1.4) and the heat-related mortality (1.1.5) indicators were integrated into two indicators of the 'economics and finance' domain to spatiotemporally track the monetized loss caused by heat-related mortality and labour capacity reduction due to extreme heat, respectively (Romanello et al., 2022a).
4. *Emerging hazards*: We found that climate reanalyses provide relevant information on the climate–health relationships even when these are not yet described by impact models. This is the case for the marine component of the food security and undernutrition indicator (1.4). Marine food security results from multiple, often compounded, effects that can be socio-economic (shift to farm-based fish products of lower nutritional quality) or environmental (ocean acidification, reduced oxygenation and increase in sea surface temperature) (Barange et al., 2018). The indicator currently tracks the yearly changes in monthly sea surface temperatures, as provided by ERA5, in the coastal waters of 142 countries across the world. This can be used as the hazard component in future models aimed at spatiotemporally quantifying marine food security.

3.2 | Current limitations

Although we find the use of global reanalysis datasets meaningful to the purposes of the *Lancet* Countdown monitoring system, limitations exist, warranting further discussion.

1. *Bias*: It is well known that the relatively coarse horizontal resolution of global reanalyses and the paucity of observations in certain regions can make it difficult to resolve atmospheric processes, introducing systematic deviances from the observed climate as a consequence (Haiden et al., 2021; Parker, 2016). In the hazard–exposure–vulnerability framework of *Lancet* Countdown indicators, this deviance translates to biases in the hazard component, which are then reflected in the outcomes of the health impact model used and their trends. For instance, ERA5 is found to underestimate hourly and monthly maximum air temperatures by 1–4°C, especially in coastal regions (Romanello, Mcgushin, Di Napoli, et al., 2021; Sheridan et al., 2020). Combined with high population concentrations near the coast, the work hours lost (WHL) results of the change in labour capacity indicator (1.1.4) appear conservative. As a comparison, the calculation of the indicator from climate data sourced from weather stations shows that the ERA5-based calculation underestimates WHL by 40% (Romanello et al., 2022b).
2. *Resolution*: Health and epidemiological data are often aggregated to administrative units (i.e., district and

province levels). They are thus at much finer scales than global climate reanalysis data, challenging the ability of the latter to resolve the urban or neighbourhood scales at which microclimates can cause large disparities in the ambient environment (Fletcher et al., 2021; Krüger & Di Napoli, 2022). In indicator 1.3, the climate suitability for the transmission of four infectious diseases (dengue, chikungunya, zika and malaria) is calculated from ERA5-Land variables (Romanello et al., 2022b). ERA5-Land was preferred to ERA5 as its enhanced spatial resolution (9 km) enables to detect finer scale differences in the suitability, also between administrative units. It is also possible to combine climate data from ERA5-Land with land surface information. For example, the computation of the number of months suitable for malaria transmission uses land classes at a 100-m resolution from the Copernicus Global Land Monitoring Service to include areas suitable for the survival and breeding of *Anopheles* mosquitoes (Romanello et al., 2022b). In addition, as described in Section 2.2, we had to consider adjustments to a common (or closer) spatial unit between the reanalysis-based hazard component and the vulnerability component (e.g., age and income data).

3. *Missing variables*: Although global climate reanalyses provide estimates for an extensive number of variables, some are yet to be included. In indicator 1.3, the percentage of global coastal waters suitable for the transmission of *Vibrio cholerae*, a pathogen whose spread is driven by inadequate sanitation as well as climate conditions, is calculated by forcing sea surface temperature and chlorophyll-*a* data into an ecological niche model. To date, no global reanalysis dataset provides chlorophyll-*a* data. For the indicator, these are currently sourced from satellite data, namely the observations of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor in the Aqua satellite (Castaneda-Guzman et al., 2021; Romanello et al., 2022b). Recently there have been attempts to model chlorophyll-*a* biomass using ERA5 variables as predictors (Stefanidis et al., 2021), but global-extent, fine-resolution, multidecadal data are not available to date. In addition, such models would be too laborious to allow for yearly updates within the timelines of the *Lancet* Countdown yearly reporting cycle. For composite variables, we therefore make use of datasets that provide ready-to-go data that are however not derived from ERA5. This is the case for the drought indicator (1.2.2), which tracks the global land area affected by extreme drought using the Standard Precipitation Evapotranspiration Index (SPEI). The indicator is based on SPEI data from the Global SPEI Database, which enables a quick computation of yearly estimates without a pre-computation of SPEI values (Beguería et al., 2010; Romanello et al., 2022b).

3.3 | Future perspectives

Future applications of global reanalysis data for the health sector are identified and described below across four themes. The themes are conceptualized within the context of the *Lancet* Countdown initiative but are equally important to other global reanalysis data in health-related research and applications.

1. *Tracking climate–health hotspots*: Health professionals are increasingly concerned about how climate change can influence global health priorities and affect their ability to protect the health of their communities (WHO/WMO, 2019). An EWE that happens simultaneously to or after another EWE, which overlaps with other health emergencies (including those related to more gradual changes in weather and climatic conditions) can, when combined with inherent vulnerabilities (e.g., the lack of adequate health infrastructure), expose affected populations to multiple adverse health impacts. These can happen at once or across a short time period, putting the response of local health authorities to test. Identifying locations where climate change affects people negatively through multiple concurrent or cascading pathways can help limit those impacts by setting priorities in the health decision-making agenda (Di Napoli et al., 2022). Thanks to their gridded format (inherited from the global reanalysis data used in input) and the standardization across the climate information input into the hazard–exposure–vulnerability framework, *Lancet* Countdown indicators are suitable for such a task, with climate–health hotspots identified and tracked by overlapping multiple *Lancet* Countdown indicators across the globe.
2. *Quantification of uncertainties*: By definition, indicators are tools aimed at assessing and communicating climate-induced impacts on population health and supporting the successful development and implementation of interventions intended to minimize adverse health outcomes (Di Napoli et al., 2022). As shown in the previous section, biases in global reanalysis datasets can affect the outcome of Lancet Countdown indicators and, in turn, influence any policy-making based on the monitoring system. The impact of bias in reanalysis data will be evaluated by means of validation, for example, by calculating an indicator using weather station or satellite data as input and then comparing it with the reanalysis-derived one.

Quantifying reanalyses uncertainties will then enable the evaluation of indicators' uncertainties associated with climate information. It could also provide information to downscale indicators at higher spatial resolutions, thus allowing health outcomes to account for regional climatic influences, such as local topography (Cooney, 2012). Future efforts should seek to characterize and address additional sources of bias relevant for computing human health impacts, including systematic bias arising from the difference between location-specific reanalysis records of outdoor conditions and in situ population exposures to proximal ambient environmental conditions.

3. *Climate projections*: The use of global reanalysis data enables *Lancet* Countdown indicators to track the health impacts of climate change in recent years and contextualize them with respect to previous decades. The monitoring system, therefore, suggests how those impacts will likely evolve in the future without efforts to mitigate or adapt to climate change. There has recently been an increase in studies that extract future health impacts from global climate models (GCMs) with the aim to provide evidence that can be used to advocate both mitigation and adaptation programming (Ebi, 2022; Nissan & Conway, 2018). Furthermore, climate change projections are the climate information most frequently used by health stakeholders in Europe (Soares et al., 2018). Current indicators can provide the base against which a *Lancet* Countdown monitoring system based on future GCMs can be compared.
4. *Next generation of reanalyses*: In past decades, reanalyses providers have delivered more and more sophisticated datasets by integrating more complete data, improved quality controls, and state-of-the-art assimilating model and analysis systems (Dee et al., 2016). As a result, current reanalyses have a higher spatial and temporal resolution, provide an enhanced number of single and composite output parameters (e.g., thermal comfort indices), and enable a much-refined view of weather systems than previous reanalyses (Di Napoli et al., 2021; Hersbach et al., 2020). The improvements achieved in the next generation of reanalyses will benefit the development of climate-related health information even further. For instance, a reduced grid cell size will allow health impact models to input climate data with a spatial resolution closer to that of health and epidemiological data. Correspondingly, health can be a driver for the development of reanalysis products that can support and facilitate health-relevant climate information. For instance, future reanalyses could include ready-to-use composite products or products derived from their variables, such as heatwaves data. This would save time from the hazard computation and facilitate impact modelling. We are open to partnering and collaborating with reanalysis providers so that climate data are selected and used in health impact models in a way that makes climate information sustainable and meaningful for health decision-makers (*co-delivery*).

4 | CONCLUSIONS

Global reanalyses are the core source of climate data for *Lancet* Countdown indicators, which use them to document and understand the impacts of climate change on human health via a hazard–exposure–vulnerability framework.

In the framework, each component represents a dimension of the coupled human–climate system. The hazard component is derived from global reanalyses such as ERA5 and ERA5-Land, which provide multiple climate variables at worldwide spatial coverage, decade-long time series and near real-time availability. This enables the indicators to track hazards (EWEs, gradual changes in weather and climatic conditions) and their corresponding effects on exposed populations, particularly the most vulnerable. The result is a global monitoring system that can describe, grid cell by grid cell, current climate-related hazards and impacts in their historical context. The impacts, conveniently grouped (by country, WHO region, HDI level), are documented in an annual report and disseminated via a data platform. These provide health decision-makers with evidence and tools they can use to harness climate knowledge (and its linkages with climate-sensitive health risks) for action.

An ongoing challenge is to quantify how the inherent bias of global reanalyses influences the indicator outcomes. Further, the lack of variables in global reanalyses (e.g., marine variables) prevents a complete standardization of climate data across the indicators. Addressing these shortcomings will enable reanalyses (and derived indicators) to represent the foundations on which the health impacts associated with future climate scenarios can be determined in a more robust and holistic way.

AUTHOR CONTRIBUTIONS

Claudia Di Napoli: Conceptualization (equal); investigation (equal); methodology (equal); project administration (equal); resources (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Marina Romanello:** Methodology (equal); project administration (equal); writing – review and editing (equal). **Kelton Minor:** Methodology (equal); visualization (equal); writing – review and editing (equal).

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