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Comment

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The triple integration of data, users and policies required for successful climate health solutions

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The development of digital tools for climate health is considered an emerging field of action and an economic opportunity. Analysing international best practices, we propose a typology of these technologies and their functions. Climate health technologies share common challenges regarding data integration, the integration of users and policy alignment. Their effectiveness in enhancing public health depends on addressing these challenges through robust data integration, active user engagement, and policy coherence.

Functions and technologies in digital climate health solutions

Digital solutions offer new potentials for responding to the health challenges of climate change. Platforms, apps, and telemedicine may support public health programs, optimize epidemiological surveillance, and enable more efficient case identification and proactive public health interventions[1]. In addition, mobile applications, dashboards, and interactive platforms may facilitate effective communication, education, involvement in health management, real-time information exchange, and participatory health initiatives[2].

To understand the interplay between digital technologies and their functions, we have mapped the technological functions and the specific technologies employed in 90 best practice cases for digital climate health solutions in North America, Europe, Australia, and New Zealand. For this purpose, we have searched project databases of the World Health Organization, the European Environmental Agency, and the European Commission. Based on available documents, an inductive coding of projects was undertaken, and validated against interdisciplinary research literature on digital climate health solutions. The sampling was based on the following criteria: relevance to climate health, user engagement, interdisciplinary knowledge, evidence of impact, and complexity of technology.

Drawing from our sample of best practice projects, we have identified four major domains of digital climate health and resilience applications:

Heat warning systems (HWS): Heat warning systems rely on accurate meteorological forecasts, and reliable health impact assessments for disseminating risk information and early warnings to medical providers, emergency response teams, and patient groups[3]. Evaluating the health impacts of extreme heat events, HWS rely on climate models, health statistics, and given information on vulnerable populations. These systems are considered most effective when tailored to the geographical and demographic contexts they serve, offering localized alerts to at-risk populations[4]. However, timely dissemination of risk information and the effective reach-out to vulnerable groups remains a challenge for these systems due to technological barriers, a lack of social trust, and resource limitations[5].

Air pollution monitoring: monitoring air quality is mainly accomplished through a combination of stationary sensors, mobile applications, and online platforms[6]. Personalized approaches for vulnerable patients utilize smartphone GPS to generate individual time-activity patterns, linking data on concentrated air pollution to personal exposure[7]. This approach is widely used to provide real-time warnings, particularly for respiratory and cardiovascular patients[6]. The field of air quality also features citizen science tools enhancing public awareness and engagement on air quality issues, while providing spatially distributed real-time data[6].

Remote patient monitoring (RPM): RPM enables care providers to monitor and deliver care to patients regardless of their geographical distance[8,9]. Wearable sensor technologies are introduced as a promising way to measure personal risks and exposure continuously: indoors, outdoors, and even on the move[10]. Combining data from wearables with patient-reported outcomes can improve symptom monitoring, provide context to sensor outputs, support clinical decision-making, and empower patients' independence, especially during periods of unfavorable climate conditions[11].

Monitoring the distribution of vectors: efforts for monitoring the distribution of vectors, for instance ticks or tropical mosquitoes, combine technologies at different scales. Remote sensing and GIS facilitate the monitoring of weather and environmental factors producing risk maps and early warning systems[12]. Meanwhile, citizens are involved in gathering evidence on the encounters with vectors such as tropical mosquitos[13]. However, studies suggest that there are challenges in translating findings into actionable policies and effective adaptation strategies, often due to limited resources[14].

Tools in these domains provide information and opportunities for communication to address climate hazards, relying on a broad range of specific technologies. We have developed a typology of different digital health technologies and their respective functions. Technological functions refer to different scales, ranging from entire countries or populations to the level of single patients and vulnerable individuals. Figure 1 demonstrates the relationship between different technologies and technological functions, indicating the main links derived from our project database.

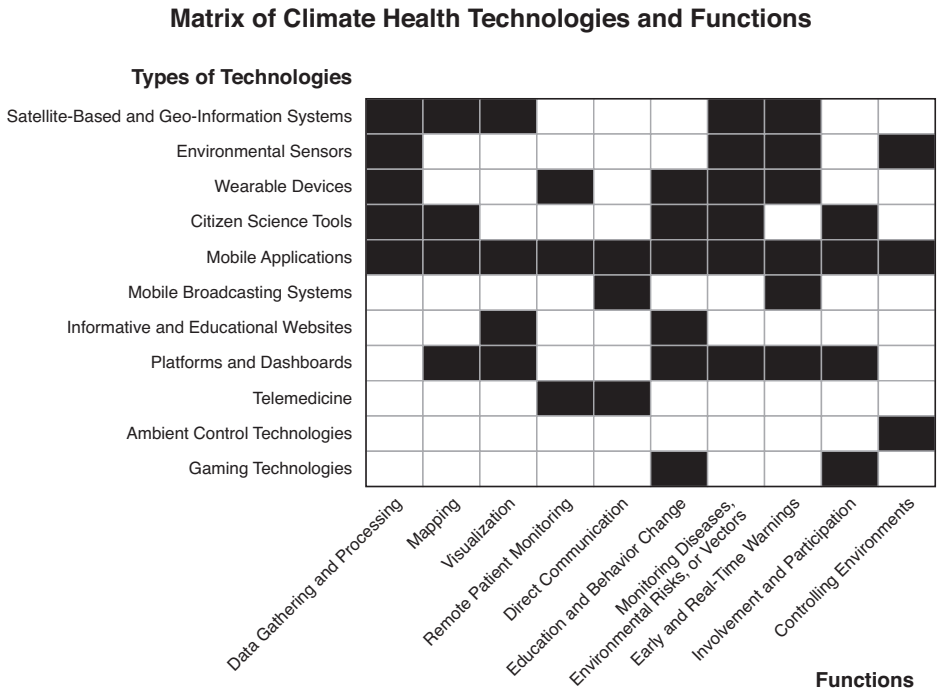

Fig. 1 | Typology of included best practice climate health technologies and their functions (created by authors). Figure 1 presents a typology outlining technological components frequently used and their main functions in digital climate health technologies. As depicted in the matrix, technologies such as satellite-based geo-information systems, environmental sensors, and citizen science tools encompass multiple functions including data gathering, processing, and mapping, which are crucial for decision-making, risk assessment, warning, and individual adaptation. These technologies integrate significant functions of monitoring diseases, environmental risks, or vectors by gathering high-resolution data on public health and environmental conditions. Geospatial data are visualized to create maps and diagrams for display in informative and educational websites, platforms, and dashboards, as well as mobile applications. Mobile applications are polyvalent and serve as a key to coordinating with other technological options. Wearable devices and telemedicine tools promote personal healthcare functions and the continuous tracking of patients' health metrics. Telemedicine tools are often connected with mobile applications and broadcasting systems, enabling both real-time and asynchronous communication between patients and healthcare professionals. Digital platforms potentially enable the involvement and participation to engage patients and the public in shaping climate health policies, fostering participatory approaches in healthcare. Correspondingly, digital gaming technologies enable users to generate avatars and engage with others, offering real-time communication features for distributing instructional resources, or creating virtual training settings for healthcare professionals.

Three requirements for successful digital climate health solutions

Successful digital health projects encompass diverse functions, combining one or even several technological elements. Across the digital climate health solutions analyzed, we find shared challenges regarding the integration of different data stocks, the integration of users in development of the process and efficient links with adherent policies.

Requirement 1: Integrating data stocks. Effective climate health tools rely on the integration of diverse types of data, including climate and weather data, clinical health data, and user-generated data. The required integration often faces challenges due to incomplete, fragmented or unharmonized data-sets, conflicting spatial and temproal scales, and at times also the quality of data gathered from different devices as well as by different disciplines and stakeholders. Different expert positions and, potentially even lay knowledge, have to be made commensurable in terms of compatibility and scale. In case of conflict, this may result in issues regarding the prioritization and validation of data and information[12]. Concrete challenges include the integration of climate and weather data of different spatial and temporal resolution, medical taxonomies, the evaluation of physicians, and potentially subjective patient data input. Responsibility for the integration of these knowledge stocks often lays within the technical operationalisation of different features, with a tendency of obscuring the underlying decision-making process[15]. However, decisions made in this regard are crucial for the design and functionality of tools and applications.

Transdisciplinary approaches are key enablers for data integration, as these emphasize collaboration across disciplines as well as the inclusion and empowerment of non-academic stakeholders, especially patients, in the research and development process[16]. Transdisciplinary collaboration and patient-centered approaches are particularly relevant in the context of climate health, as the fruitful intersection of environmental science, public health, and social sciences is critical. An example of successful data integration is the development of the Climate Data Library by the International Research Institute for Climate and Society at Columbia University (NY), which was designed as an integrated data platform in order to support the use of climate and environmental information by global public health professionals and decision-makers[17]. Climate scientists initiated the database to support exploratory data analysis, and it now serves as a platform for transdisciplinary researchers focusing on topics related to climate impacts on society[12,17].

Developers of climate health tools should actively seek to integrate diverse stocks of information and data from the outset of the development process. Transdisciplinary approaches include engaging local communities,

public health experts, and environmental scientists to ensure that tools are both scientifically robust and contextually relevant.

Requirement 2: Integrating users in the development process. The adoption and effectiveness of digital health tools depend on their usability and the extent to which they meet users' needs[18]. In most countries, the healthcare delivery model is multi-layered, with doctors and nurses as primary providers. Often built from a providers' perspective, many digital tools fail to gain traction due to a lack of user engagement in their development[19]. Accordingly, user-centered design (UCD) is a critical approach in this context, emphasizing the importance of involving users including patients, healthcare providers, or public health officials, during the development process[20]. UCD plays a key role in achieving user engagement in the implementation phase, thus improving the likelihood of the intervention's effectiveness, leading to higher adoption rates and better health outcomes[2,21].

Successful examples of user-centered design include mobile applications developed for people in unhealthy conditions like smoking, obesity, diabetes, and other chronic conditions that require behavioral changes for treatment[3]. These apps enable patients to track their condition and communicate with healthcare providers, as a means to motivate and track behavioral change[20]. The European Union-funded "PulsAir" mobile application and data ecosystem, for instance, serves both for collecting data from users to assess the individual risk of patients with asthma and type 2 diabetes and involves gaming elements such as avatars, points, and rewards motivating citizens to take action towards healthier behaviors[22,23]. User feedback on mock-up versions was integrated even before building the first prototype[22]. Once established, continued user feedback was shown to support strong links and active engagement with the application.

To enhance the adoption of climate health tools, developers should engage end-users in the first stages of the development process. This involves conducting user research, gathering feedback through iterative testing, and ensuring that the final product demonstrates high usability and effectively addresses the specific needs of its target users. Building a community of users who actively contribute to and benefit from the tool can then ensure its long-term user support.

Requirement 3: Integrating digital tools into public health policies. While the first two requirements target the development and use of applications, the third relates to their effective links to climate adapatation policies and public health strategies. Research has discovered multiple co-benefits between climate adaptation, mitigation and public health[24]. However, political responsibilities in these fields are commonly fragmented and policy priorities misaligned. Providing warnings, information on risk areas or toolkits for climate health adaptation, digital climate health platforms may serve as a vehicle for better integration. The concept of policy coherence is relevant here, emphasizing the need for alignment between digital health initiatives and existing public health frameworks[13]. Policy coherence ensures that digital tools are not only technically effective, but also supported by the necessary institutional and policy environments[14].

The development of the "AirRater app" in Australia is a successful practice in this field, as it managed to integrate air quality monitoring tools with public health policies[2]. AirRater offers individual-level and location-specific data and assists public health responses to environmental hazards by providing timely, accessible, and understandable environmental information[4,25]. It helps health departments communicate important information to populations, gather population-level health data during hazard events like smog or bushfires, and directly support individuals with personalized environmental information, thereby promoting improved health outcomes[6].

Developers should closely collaborate with policymakers to align digital health tools with public health priorities. This requires an understanding of the policy landscape, identifying opportunities for integration, and advocating for the inclusion of digital tools in public health strategies. Ensuring that tools are adaptable to changing policy environments is critical for their long-term success.

Context matters

This commentary has charted the field of digital climate health applications, set at the intersection of climate adaptation and the promotion of health and well-being. We have identified tools in four different domains: heat warning systems, air pollution monitoring, remote patient monoring and monitoring vectors. These tools provide an information basis for patients, vulnerable social groups as well as health providers and decision-makers, and offer a potential for individual monitoring, support, and empowerment. Linking insights from climate science, medicine and public health, digital climate health solutions may become an instrument for knowledge transfer and policy integration. The successful development and roll-out of climate health tools, we have argued, requires a triple integration of data, users, and policies. First, diverse data stocks should be integrated to ensure that these tools are scientifically robust and contextually relevant. Second, users should be engaged in the development process to ensure that the final tools are user-friendly and widely adopted. Third, aligning digital health tools with public health and climate adaptation policies is necessary to increase their impact and ensure their sustainability.

This commentary focuses on the discussion of different domains, technical features, and requirements for successful development processes in the field of climate health. While we have provided three requirements for improving the usability and effectiveness of these tools, we acknowledge potential shortcomings of digital health technologies, especially in terms of outreach to most vulnerable population groups, including homeless people, informalized migrants, and members of remote and indigenous communities[5,15]. While the applications in question can distribute information, the effectiveness of digital tools eventually relies on individual parameters, importantly including users' ability to act on the information provided. Contextual factors such as geographic isolation, socio-economic and language barriers, or low access to digital infrastructure affect the usage of these technologies by individuals and even may increase public health inequity. As Lokmic-Tomkins et al.[4] emphasize, despite the ever-increasing digital transformation of healthcare, health disparities are likely to persist when equitable access to digital health is not attained.

Further research is needed in several key areas of digital project development and use. One important avenue is the exploration of best practices for transdisciplinary collaboration for an efficient development process for climate health tools. Another is the systematization of specific target groups for effective methods for user-centered design methods to enhance the usability and adoption of these tools. This, importantly, requires an in-depth understanding of barriers for uptake and usability, especially with remote, marginalized, and vulnerable population. Finally, we need to conduct research on the effective integration of digital health tools into public health policies, especially in environments that are socially diverse and feature rapidly changing environmental conditions.

Data availability

The data underlying this Comment, especially the compiled list of best practice cases (=the minimum dataset), will be made available upon request.

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Author contributions

S.B. and R.R. have jointly worked in the conception and writing of this comment. The underlying empirical research was jointly conducted supervised by S.B. and R.R. S.B. was responsible for the final editing of the draft; R.R. in the final selection of references. S.B. and R.R. have read and approved the original and the revised manuscript.

Competing interests

The authors declare no competing interests.

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