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ORIGINAL ARTICLE

Impact of climate change on human zoonoses, with an emphasis on COVID-19

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Over the last few decades, the world has experienced several pandemic outbreaks of various pathogens and the frequency of the emergence of novel strains of infectious organisms has increased in recent decades. Many studies have found associations between climatic conditions and zoonoses transmission. However, there is debate about the future impacts of climate change on zoonoses transmission, especially with the rise of SARS-CoV-2 (COVID-19).

Keywords: Lyme, Malaria, West nile, Dengue, COVID-19, Climate change, Zoonoses, Temperature, Precipitation, Humidity, Wind.

Introduction

In the context of the current COVID-19 pandemic, this study investigated the major causative climatic factors that influence the repeated emergence of pandemics, by examining the current impact of climate change on viral (e.g., West Nile and Dengue) and non-viral (e.g., Lyme and Malaria) zoonoses transmission. A literature search was conducted, using the electronic databases: PubMed, Scopus, ScienceDirect, Web of Science, GEOBASE and CINAHL. The search focused on peer-reviewed primary research articles published in English from 2004 through 2020. 52 studies met the inclusion criteria and the majority of the studies showed that the transmission of pathogens is highly sensitive to climatic conditions, especially temperature, rainfall, relative humidity and wind. This study suggests that temperature is the most significant climatic variable affecting zoonotic pathogen incidence, compared to wind, relative humidity and precipitation. Higher relative temperatures tend to decrease pathogen incidence for COVID-19, but the opposite relationship is evident for West Nile, Lyme, Dengue and Malaria. Extrapolating this towards the epidemiology of COVID-19 proposes a modest reduction in COVID-19 transmission during the summer. This information can be utilized for future research related to COVID-19 transmission and alleviation. Future research should also focus on improved pathogen surveillance and a better understanding of bioclimatic relationships from interdisciplinary perspectives.

Impact of climate change on human zoonoses, with an emphasis on COVID-19

Approximately 60% of emerging human pathogens are zoonoses. A zoonosis is any disease or infection, microbial or viral, that is naturally transmissible from animals to humans (Allen, T., et al., 2017 ; Bartlow, A.W., et al., 2019). Zoonotic pathogens in comparison with non-zoonotic were found to be twice as likely to emerge, especially viruses (Mills, J.N., et al., 2010). Of the reported zoonoses in humans, 44% were caused by viruses (Ogden, N.H., et al., 2016). The increasing imbalance created in the human-animal interfaces increases the potential risks of zoonoses. Wild-life hunting and trading, interactions between wild and domestic animals, migration of infected wild birds, transportation of infected domestic animals, and loss of biodiversity, have contributed to the spread of zoonotic diseases and persistence of respective pathogens (Bartlow, A.W., et al., 2019 ; Ogden, N.H., et al., 2016 ; Waits, A., et al., 2018). Pathogens have evolved from closely related species, for example, in the case of HIV (Chimpanzees to Humans) or by species that are distant from humans in genetic homology (Ogden, N., 2006).

The current COVID-19 pandemic is supposed to have been transmitted to humans from animals of the Wuhan fish market. The genome analysis shows that SARS-CoV-2 is 96% identical to a bat coronavirus, but the exact source has not been confirmed yet (Chan, K.H., et al., 2011 ; Menebo, M.M., 2020). When viruses spread via multiple hosts, the chances of viral mutations are high and the resulting evolution of novel strains of pathogens with pandemic potential are higher (Mills, J.N., et al., 2010). Recent developments in the field have led to a renewed interest in climatic factors like temperature, relative humidity, wind and rainfall which can contribute to zoonotic pathogen evolution. This review aims to evaluate the impact of major climatic factors which were found to be influential in the repeated emergence of pandemics in the context of viral and non-viral zoonotic pathogens, with an emphasis on COVID-19 to indicate future opportunities and research directions. Since viral and non-viral zoonoses possess differences in terms of epidemiology, they will play a role in strengthening the study as they can be investigated further in correspondence to climatic variables.

Non-viral

Lyme and climate change

Tick-borne diseases, such as Lyme disease, are some of the most researched infectious diseases associated with climate change. Temperature and precipitation significantly influence the life cycle and distribution of ticks and consequently affect the spread of Lyme disease. Warmer temperature, for example, can accelerate the ticks' development and reproduction, permit range expansion, and expand woodlands and vegetation, resulting in improved habitat conditions. Increased precipitation (severe flooding) however, can negatively affect the tick population and range (Ogden, N., 2006).

Studies found that the combination of high temperature and lower humidity was lethal to ticks. At high humidity, about four-fifths of the ticks were able to survive temperatures in the 90s for four days or more. But at the mid-range humidities, less than a third of the ticks survived the high temperatures for that long (Ogden, N., 2006). Another commonly observed behaviour is that ticks will quest at a lower height when temperatures are high and relative humidity is low, probably because of the need to descend to moist microhabitats for rehydration. This lower questing height reduces the probability that ticks will come into contact with large vertebrate hosts, including humans (Burtis, J.C., et al., 2016, Ogden, N., 2006). Additionally, strong winds reduce mosquito density and make it difficult to find a host. However, wind also helps to extend the mosquito range (Ogden, N., 2006).

Malaria and climate change

The distribution of Malaria is governed by abiotic factors such as temperature, rainfall, humidity and wind. The number of blood meals a mosquito takes from humans depends mainly on the rapidity with which a blood meal is digested, which increases as temperature rises. Between certain limits, the longevity of a mosquito decreases with rising temperature and increases with increasing relative humidity. Mosquitoes prefer humidities above 60%, and the optimum temperature for mosquito survival is in the range of 20-25°C. Excessive temperatures will increase mortality, and there is a threshold temperature above which death ensues (Lieshout, M.V., 2004).

Rainfall plays a crucial role in Malaria epidemiology because it provides the medium for the aquatic stages of the mosquito life cycle. Rain may prove beneficial to mosquito breeding if moderate, but if excessive it may flush out the mosquito larvae. Rainfall may also increase the relative humidity and hence the longevity of the adult mosquito (Apply, A., 2020; Onyango, E.A., et al., 2016).

Wind conditions, as well as other environmental conditions, are likely to influence Malaria transmission through the behaviours of *Anopheles* mosquitoes, especially around water reservoirs. Wind-induced waves in a reservoir impose mortality on aquatic-stage mosquitoes. Mosquitoes' host-seeking activity is also influenced by wind through the dispersion of CO_2 (Apply, A., 2020 ; Lieshout, M.V., et al., 2004).

Viral

West Nile and climate change

West Nile is a zoonotic pathogen transmitted by the stick of *Culex* mosquito vectors (Giordano, B.V., 2017). Increased temperature permits overwintering of species and can expand the range of the disease-causing vectors. In a Canadian study investigating the relationship between *Culex* mosquito populations, climate data, and the prevalence of West Nile virus, a strong correlation was identified between the abundance of mosquitos and human cases, and between temperature and infected mosquito pools. In this study, there was not a strong correlation between average precipitation, humidity or rainfall and amount of human cases (Harrigan, R. J., et al., 2014).

High levels of precipitation correlate with reduced transmission potential due to the flushing of drainage channels with larvae. Lower levels of precipitation correlate with increased transmission due to standing water which attracts several species of birds and mosquitoes; this increases the interaction between mosquitoes and birds resulting in an amplification of the virus. Relative humidity positively correlates with the vector population dynamics and morbidity in humans. Finally, wind contributes to the spread of the virus by having an impact on wind-blown organisms and on arboviruses they transmit (Paz, S., 2015).

Dengue and climate change

Dengue, transmitted by *Aedes* species, is sensitive to change in climatic factors, especially temperature. Temperature may affect mosquitoes from multiple aspects. First, temperature can affect different stages of a mosquito's life cycle. A study showed that during the mosquito development period, the duration and survival rate are different under different temperatures; in a cold environment, the incubation period is longer (Tuladhar, R., et al., 2019). Second, mosquito density is related to temperature. According to a study in Fuzhou city, mosquito density increases as temperatures become high, but when temperature is above 32°C, mosquito density decreases significantly (Yuan, H., et al., 2020). Third, female mosquitoes require a blood meal for ovarian development, and their biting behaviour is influenced by temperature. A study in Yunnan Province found that biting activities of mosquitoes are limited to temperatures between 15°C and 35°C, and the optimal temperature range is 25°C-30°C (Butterworth, M.K., et al., 2017). Fourth, temperature change may bring changes in the spatiotemporal range of mosquito distribution (Li, C., et al., 2018).

Rainfall has been generally thought to be a positive predictor of Dengue vector abundance as it provides essential mosquito habitats. Recent studies, however, have demonstrated that excess rain may also flush away eggs, larvae or pupae of mosquitoes and remove mosquito breeding sites, hence negatively affecting Dengue incidence (Tuladhar, R., et al., 2019). Another study has found that dry seasons followed by a period of excess rainfall can lead to a high risk of Dengue outbreaks, indicating that either positive or negative effects can occur, however, with different time lags (Yuan, H., et al., 2020). Additionally, humidity affects flight, host-seeking behaviour, the lifespan of vectors and vector reproduction. Humidity and wind directly affect the evaporation rates of vector breeding sites. Strong winds reduce mosquito density and make it difficult to find a host. However, wind also helps to extend the mosquito range (Butterworth, M.K., et al., 2017).

COVID-19 and climate change

COVID-19 (SARS-CoV-2) is a novel coronavirus that is currently being passionately researched due to its recent severity and therefore, research is still unclear. However, numerous studies suggest a negative correlation between temperature and COVID-19 incidence. A negative correlation was also found between COVID-19 transmission and humidity (Chan, K.H., et al., 2011; Menebo, M.M., 2020; Rendana, M., 2020; Zhan, J., et al., 2020). Other climatic variables, such as wind and precipitation have been hardly analyzed resulting in unreliable outcomes as the COVID-19 pandemic is a recent occurrence. However, temperature does seem to be the most significant climatic variable as COVID-19 has a lower survival rate at higher temperatures (Chan, K.H., et al., 2011).

The stability of the virus at different temperatures and relative humidity on smooth surfaces were studied. The dried virus on smooth surfaces retained its viability for over 5 days at temperatures of 22-25°C and relative humidity of 40–50%, that is, typical air-conditioned environments. However, virus viability was rapidly lost at higher temperatures and higher relative humidity. The better stability of SARS coronavirus at low temperature and low humidity environment may facilitate its transmission in subtropical areas during the spring and in air-conditioned environments. It may also explain why some Asian countries in tropical areas with high temperature and high relative humidity environments did not have major outbreaks of SARS (Menebo, M.M., 2020).

Many studies have revealed that COVID-19 is transmitted person-to-person through direct contact and respiratory droplets. Since the virus can remain viable in the air for multiple hours, climatic variables are reliable indicators in terms of the viability, transmission and range of the virus. One of the climatic factors which affect the spread of pollutants in the air is wind speed and direction. Therefore, wind plays an important role in the measurement of air pollutants such as biological contaminants including bacteria and viruses. Based on this reason, studies suggest that a low wind speed can lead to an increase in the number of COVID-19 cases, because the virus may stay viable in the air for a couple of hours (Rendana, M., 2020).

The current study aims to further refine and deepen understandings regarding the impact of climatic variables on zoonoses, with an emphasis on COVID-19, as this is a current pandemic that immediately requires further investigation. The studies mentioned above analyze geographical areas where climatic variables coexist, which prevents the proper characterization in terms of individual climatic variables. This study will examine and integrate up-to-date research and determine the climatic variable that has the strongest association with zoonotic pathogen incidence. This information will suggest a new insight into the direction of COVID-19 research.

Materials and Methods

Search strategy

Using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines, a literature search was conducted using the electronic databases: PubMed (n=13), ScienceDirect (n=11), BIOSIS (via Web of Science) (n=14), GEOBASE (n=8), Scopus (n=3) and CINAHL (n=3) to obtain information on the impact of climatic variables on viral and non-viral zoonotic pathogen transmission, specifically West Nile, Lyme, Dengue, Malaria and COVID-19. The search string used was "(climate OR climate change OR climatic variables OR global warming OR greenhouse effect OR temperature OR precipitation OR humidity OR wind) AND (zoonotic disease OR zoonoses OR West Nile OR Lyme OR Dengue OR Malaria OR COVID-19) AND (infectivity OR transmi* OR spread)." References and citations of the articles identified were logged into Zotero and checked to ensure that all relevant articles were included. An excel document was created to catalogue and synthesize all 52 articles. This document organized the studies based on viral or non-viral zoonotic pathogen, author, date, organism, spatial resolution, population, research type, methodology, key findings and conclusion. Using this document, a comprehensive literature review on well-known viral and non-viral zoonotic pathogens was conducted.

Selection criteria

Two selection criteria were used to select articles from the search results for detailed consideration. First, in order to obtain authoritative information, this review included only peer-reviewed primary research articles. Second, articles had to include larger geographical areas and at least one climate-based projection of future zoonosis transmission. The search terms used for each search were recorded as well as the number of results retrieved for each search. Article titles and abstracts were evaluated for their relevance to the inclusion criteria. All articles that appeared to meet the criteria were selected for a full-text review. The articles that met the inclusion criteria after the full-text review were included in this review. If an article was found in more than one database, it was only counted for the first database it was found in, eliminating duplicates from the selection process. Fig. 1 includes the selection process and the number of articles selected at each phase from the databases.

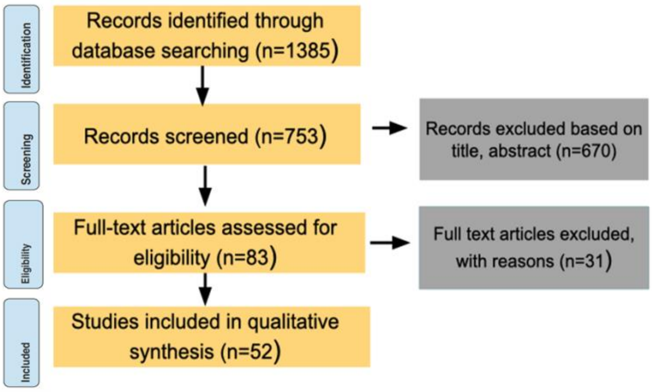

Fig. 1. Search strategy employed based on PRISMA guidelines. Records were obtained from PubMed (n=13), ScienceDirect (n=11), Web of Science (n=14), GEOBASE (n=8), Scopus (n=3), and CINAHL (n=3).

Results

The initial search yielded 753 studies of which 83 were deemed to be potentially relevant and were subjected to further perusal. This led to 52 studies which met the inclusion criteria and were considered in detail: West Nile (n=12), Dengue (n=10), Lyme (n=10), COVID-19 (n=10) and Malaria (n=10).

The following major climatic variables have been considered in the studies: temperature, precipitation, relative humidity and wind. It is important to consider which climatic variables are the best predictors of viral and non-viral zoonoses transmission and the research reported here indicates that temperature has the strongest association to zoonoses transmission, but that precipitation, wind and relative humidity are also significant contributors. It is apparent from Fig. 2 that 29 out of the 52 (56%) studies assessed deem temperature as the most significant contributor to zoonotic pathogen incidence.

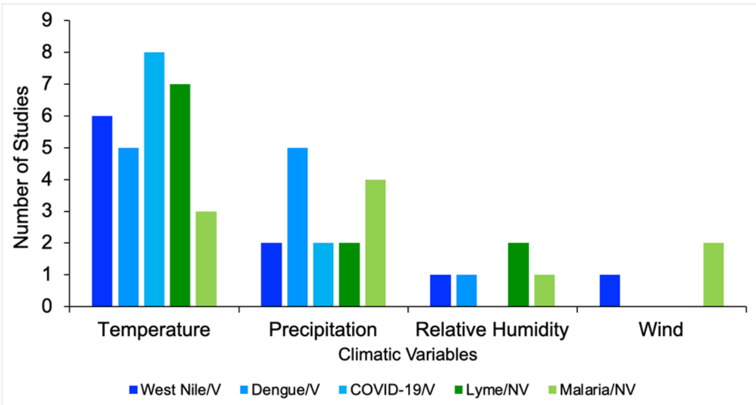

Fig. 2. The results of the literature review (n=52) categorized across climatic variables: Temperature (n=29), Precipitation (n=15), Relative Humidity (n=5) and Wind (n=3). Viral zoonoses (West Nile, Dengue and COVID-19) are represented with shades of blue, non-viral zoonoses (Lyme and Malaria) are represented with shades of green.

The majority of the research to date has considered a negative correlation between temperature and COVID-19 incidence. In contrast, studies have determined a positive correlation between temperature and West Nile, Dengue, Lyme and Malaria incidence.

Discussion

Climatic factors play a significant role in mosquito and tick biology, the viruses they transmit, and the transmission cycles for West Nile, Lyme, Dengue and Malaria. Higher temperatures increase the rate of larval development and shorten the emergence of adult mosquitoes, increase the biting rate of mosquitoes and reduce the time required for virus replication within the mosquito (Mills, J.N., et al., 2010).

Relative humidity and rainfall are other key factors that influence mosquitoes' and tick's life cycle at different stages. The combined effect of temperature, humidity and rainfall significantly influences the number of blood meals and can also affect the survival rate of the vector, and the probability that it will become infected and able to transmit disease. In contrast, wind did not appear to play a significant role because many breeding sites of mosquitoes and ticks were more dependent on human behaviour than on wind for their development and survival (Allen, T., et al., 2017; Bartlow, A.W., et al., 2019; Ogden, N.H., et al., 2016). This might partly explain the lower impact of wind compared to other climatic variables on disease incidence. These associations are further explained in Fig. 3.

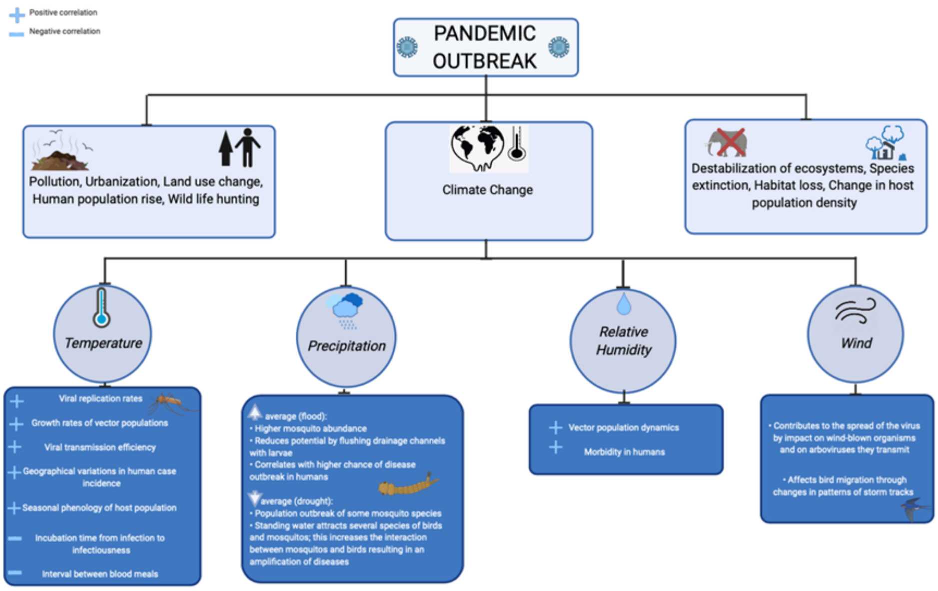

Fig. 3. In addition to host variation, climatic variables which can trigger changes that contribute to pathogen evolution and the emergence of pandemics are indicated. Factors that positively and negatively correlate with the four main climatic variables (temperature, precipitation, relative humidity and wind) are also specified.

Necessary actions should be taken to conduct required research on COVID-19 with a focus on temperature, as this climatic variable has the strongest association to zoonoses transmission. Contrary to expectations, majority of the research to date has considered a negative correlation between temperature and COVID-19 incidence (Chan, K.H., et al., 2011; Menebo, M.M., 2020; Rendana, M., 2020; Zhan, J., et al., 2020). This finding was unexpected as studies have determined a positive correlation between temperature and West Nile, Dengue, Lyme and Malaria incidence (Apply, A., 2020; Burtis, J.C., et al., 2016; Butterworth, M.K., et al., 2017; Harrigan, R.J., et al., 2014). This inconsistency may be due to a lack of research on COVID-19 due to its recent occurrence. These findings, while preliminary, suggest that further research is required on COVID-19.

Strengths and limitations

The strengths of this review include using a systematic approach and multiple databases. The limitations of this review include the language restriction, the rigidity of the inclusion criteria, and the search terms selected. Studies published in a language other than English were also excluded from this review. Several articles met one out of the two inclusion criteria (i.e., incorporated a large geographical area, but no climate-based projection of future zoonotic disease transmission). The search terms used may have also limited the articles found for the review. Future reviews could use different keywords to formulate a more effective search string.

Several methodological issues emerged when I conducted this literature review on climate change and zoonoses transmission. These issues include data availability, human behaviour, funding, time period, scale of analysis and other factors associated with zoonoses transmission. In terms of data availability, there is a lack of real-time data to inform disease forecasting models. Specifically, real-time data on mosquito prevalence and diversity at various spatial resolutions is limited and often non-existent (Bartlow, A.W., et al., 2019). The second major challenge to accurately forecasting zoonoses is human behaviour. Unlike climate, humans can be unpredictable and, as a host, they play a key role in the spread of zoonotic diseases. Human behaviour, such as vaccination, can reduce or increase the probability of infection (Allen, T., et al., 2017; Waits, A., et al., 2018). Thus, understanding what people do during a pandemic is crucial for modelling disease dynamics. However, no databases are monitoring human behaviour and although Internet data streams, such as social media, have been used to capture population sentiment, there are biases and uncertainty in using this information (Bartlow, A.W., et al., 2019; Waits, A., et al., 2018). Additionally, zoonotic disease forecasting needs significant investment in building the infrastructure necessary to collect data about the environment, the vectors, and the hosts at all spatial and temporal resolutions (Allen, T., et al., 2017; Mills, J.N., et al., 2010; Waits, A., et al., 2018). Choosing a baseline time period for climate data is also important. Climate and pathogen relationships in the same area can be very different between the 1900s and the 2000s. Differences could be due to socioeconomic changes and urbanization. Another issue to be considered when modelling is the spatial-temporal scale of analysis. This is because spatial and temporal characteristics may provide useful information on risk assessments to be used by pathogen prevention and control programs to prepare for and respond to pandemics (Lieshout, M.V., et al., 2004; Ogden, N., 2006).

Recommendations for future research

I recommend the following five directions for future research: 1) Disease surveillance needs to be improved for effective disease prevention. 2) Better understanding of the ecology is required to predict the bioclimatic relationships on disease transmission. 3) Application of advanced spatial-temporal modelling approaches in disease/virus research is required to more fully understand the complex relationship between climate and zoonotic pathogen transmission. 4) Uncertainties due to confounding effects of urbanization, population growth and tourism development are required to develop scenarios based on future projections of population growth and socio-economic development, including human behaviour. 5) There is a clear need for inter-disciplinary collaborations with ecologists, sociologists, micro-biologists, biostatisticians and epidemiologists. Two areas need special attention: one is in the area of climate modelling to address issues of analytical methods, and the other relates to disease incidence data quality control with the reporting agencies (e.g., laboratories, hospitals, health centers) addressing issues such as underreporting and misdiagnosis. In addition, more emphasis should be given to data quality and the use of information for decision-making (Bartlow, A. W., et al., 2019; Butterworth, M.K., et al., 2017; Paz, S., 2015).

Conclusion

The novel SARS-CoV-2 has caused the global outbreak of COVID-19, and human society has suffered greatly from this pandemic. Researchers have called for attention to the climatic factors affecting the transmission of COVID-19. Roles of major climatic factors like temperature, humidity, rainfall and wind have been elucidated in the transmission of viral and non-viral zoonoses through this review, but new knowledge and insights on COVID-19 should also be updated constantly. The current review emphasizes the strong negative correlation between temperature and COVID-19 transmission, suggesting that the summer may offer a modest reduction in COVID-19 incidence, but this will not be large enough to control the pandemic.

People are striving for the elimination of this public health crisis, yet there is a long way to go, and more knowledge of the virus's survival, evolution, and transmission in the environment are urgently needed. Although numerous research findings have been obtained, strong evidence and conclusive results remain to be achieved. In this regard, we highlight the importance of being aware of the limitations of the different approaches, and the need to analyze transmission data with great caution. This review indicates that governments should remain vigilant and maintain the restrictions in force against the pandemic. This paper is concluded by recommending: promoting more advanced research on the relationship between climatic variables and zoonoses transmission, developing regional-specific models for the high-risk regions, encouraging interdisciplinary collaboration between climate studies and health services, and enhancing public health education and management.

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