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Review article

Impact of climate change on human infectious diseases: Empirical evidence and human adaptation

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ABSTRACT

Climate change refers to long-term shifts in weather conditions and patterns of extreme weather events. It may lead to changes in health threat to human beings, multiplying existing health problems. This review examines the scientific evidences on the impact of climate change on human infectious diseases. It identifies research progress and gaps on how human society may respond to, adapt to, and prepare for the related changes. Based on a survey of related publications between 1990 and 2015, the terms used for literature selection reflect three aspects — the components of infectious diseases, climate variables, and selected infectious diseases. Humans' vulnerability to the potential health impacts by climate change is evident in literature. As an active agent, human beings may control the related health effects that may be effectively controlled through adopting proactive measures, including better understanding of the climate change patterns and of the compound disease-specific health effects, and effective allocation of technologies and resources to promote healthy lifestyles and public awareness. The following adaptation measures are recommended: 1) to go beyond empirical observations of the association between climate change and infectious diseases and develop more scientific explanations, 2) to improve the prediction of spatial–temporal process of climate change and the associated shifts in infectious diseases at various spatial and temporal scales, and 3) to establish locally effective early warning systems for the health effects of predicated climate change.

Contents

1. Introduction

Climate change refers to long-term statistical shifts of the weather, including changes in the average weather condition or in the distribution of weather conditions around the average (i.e. extreme weather events). Despite many discussions on the causes for climate change, there is a general recognition of an on-going global climate

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change and the non-minor role of human activities during this process (IPCC, 2007). According to the European Environment Agency (EEA, 2008), the global average surface temperature has increased by 0.74 °C in the 20th century, the global sea level has been rising 1.8 mm per year since 1961, and the Arctic sea ice has been shrinking by 2.7% per decade. Moreover, mountain glaciers are contracting, ocean water becomes more acidic, and extreme weather events occur more often. The Intergovernmental Panel on Climate Change (IPCC) predicted an average temperature rise of 1.5–5.8 °C across the globe during the 21st century, accompanied by increased extreme and anomalous weather events including heat-waves, floods and droughts (IPCC, 2001). Responding to global changes by pursuing a sustainable development is a major challenge to human society (Weng et al., 2013; Yang et al., 2013). Climate change can affect human health (Costello et al., 2009; Epstein, 1999; Kovats et al., 2000; Willox et al., 2015), especially when infectious diseases are concerned (Altizer et al., 2013; Bouzid et al., 2014; Epstein, 2001a). Three components are essential for most infectious diseases: an agent (or pathogen), a host (or vector) and transmission environment (Epstein, 2001a). Some pathogens are carried by vectors or require intermediate hosts to complete their lifecycle. Appropriate climate and weather conditions are necessary for the survival, reproduction, distribution and transmission of disease pathogens, vectors, and hosts. Therefore, changes in climate or weather conditions may impact infectious diseases through affecting the pathogens, vectors, hosts and their living environment (Epstein, 2001a; Wu et al., 2014). Studies have found that long-term climate warming tends to favor the geographic expansion of several infectious diseases (Epstein et al., 1998; Ostfeld and Brunner, 2015; Rodó et al., 2013), and that extreme weather events may help create the opportunities for more clustered disease outbreaks or outbreaks at non-traditional places and time (Epstein, 2000). Overall, climate conditions constrain the geographic and seasonal distributions of infectious diseases, and weather affects the timing and intensity of disease outbreaks (Kuhn et al., 2005; Wu et al., 2014).

A warming and unstable climate is playing an ever-increasing role in driving the global emergence, resurgence and redistribution of infectious diseases (McMichael et al., 1996). Many of the most common infectious diseases, and particularly those transmitted by insects, are highly sensitive to climate variation (Kuhn et al., 2005; Tian et al., 2015a). New and resurgent vector-borne communicable diseases, including dengue, malaria, hantavirus and cholera, are evident widely (Tian et al., 2015b; Watson et al., 1997; Yu et al., 2015). Other infectious diseases, such as salmonellosis (Chretien et al., 2014), cholera and giardiasis, may show increased outbreaks due to elevated temperature and flooding. Accordingly, long-term collaborations are called upon to develop Early Warning Systems (EWS) for infectious diseases by considering climate change (e.g. Watson et al., 1997). The successful prediction of a rising malaria risk in Botswana, which initiated timely anticipatory mitigations, was a successful effort of such (Thomson et al., 2006).

This research presents a systematic literature review on the scientific evidences for the impact of climate change on human infectious diseases. The study examines the observed and predicted impacts of changes in major climate variables and extreme weather events on the pathogen, host, and transmission of human infectious diseases. Through discussing the research progress and gaps on the possible strategies for human society to respond to, adapt to, and prepare for the impact of climate change, the research sheds light for future studies. The rest of this article is organized into five sections. Section 2 introduces the research framework that guides the literature selection and review. Section 3 focuses on the scientific evidences on the impacts of climate variable changes on human infectious diseases. Section 4 reviews the literature on extreme weather events' impacts on human infectious diseases, pointing to the needs for better understanding of the changes in climate variables and the combined weather effects during an extreme weather event. Section 5 discusses the social and institutional factors that may interfere or mediate the impacts of climate change on human infectious diseases. The last section summarizes the current status of the related studies and discusses their limitations as well as future directions on reducing vulnerability through adaptation and preparation.

2. Methods

As previously mentioned, the impact of global climate change on human infectious diseases can be examined through its impacts on the three disease components: pathogen, host, and transmission environment. Humans are an important and active factor during this process; they may mitigate the impact of climate change through adaptation practices such as those recommended by Kovats et al. (2000). Fig. 1 illustrates the relationships between climate change, human infectious diseases, and human society, forming the framework that guided the literature search for this review.

Three sets of terms were used to define the searching keywords for the literature survey of this study; the returned records must include at least one entry from each of the three sets. The first set describes the components of diseases: pathogen, host or vector, and disease transmission. The second set describes the climate and weather, including climate variables (such as temperature, precipitation, and humidity), or large-scale extreme weather events (such as El Nino), or meteorological hazards (such as drought, flood, and heatwaves). The third set describes the selected infectious diseases, including vector-borne diseases (e.g. malaria), water-borne diseases (e.g. cholera), air-borne diseases (e.g. influenza), or food-borne diseases (e.g. Campylobacter). Inputs from subject experts were further obtained to revise the search strategy and to locate additional citations.

A comprehensive literature search was conducted using Web of Science/Knowledge, Google Scholar (http://scholar.google.com), Elsevier ScienceDirect (http://www.sciencedirect.com/), Springer Online Journals (http://link.springer.com/) and CNKI (http://www.cnki.net/). The focus was on the peer-reviewed articles and government reports between 1990 and 2015. In addition, a few earlier milestone seminal articles before 1990 were included. Other major and closely relevant synthesis reports were also reviewed, including those by the IPCC, World Organization for Animal Health (OIE), World Health Organization (WHO), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), Pan American Health Organization (PAHO) and Interagency Working Group on Climate Change and Health (IWGCCH).

Initially, a total of around 400 publications were identified. A further review of the abstracts, titles, and keywords led to an elimination of about 270 citations due to their lack of direct relevance. Finally, a set of 131 articles and reports were included for this review research. These publications share a focus on the impact of climate change on pathogen, host and transmission of human infectious diseases, and the related human behavior as a mediator.

3. Climate change and human infectious diseases

Climate changes include alternations in one or more climate variables including temperature, precipitation, wind, and sunshine. These changes may impact the survival, reproduction, or distribution of disease pathogens and hosts, as well as the availability and means of their transmission environment. The health effects of such impacts tend to reveal as shifts in the geographic and seasonal patterns of human infectious diseases, and as changes in their outbreak frequency and severity.

Abundant literature addresses the factorial and potential impacts of climate change on many types of infectious diseases, including vector-borne, water-borne, air-borne, and food-borne diseases. This section of the paper provides a systematic literature survey on the influences of changes in climate variables on the three aspects of disease — pathogen, host, and transmission.

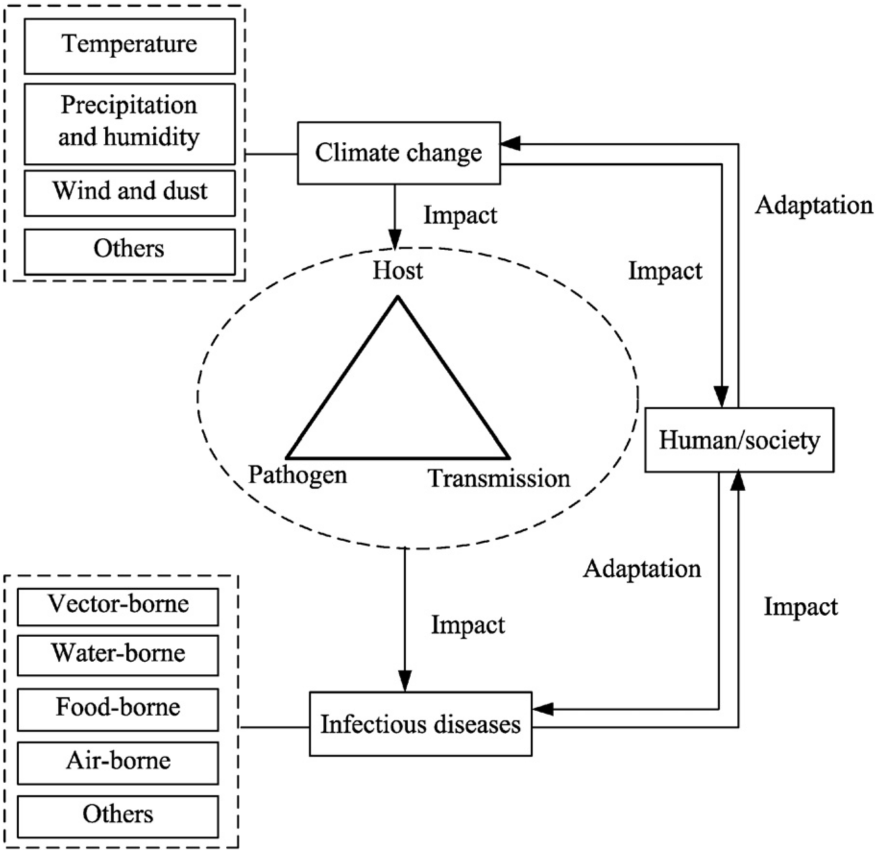

Fig. 1. Climate change, human infectious diseases, and human society.

3.1. Climate change and pathogens

Pathogen refers to a wide range of disease agents, including virus, bacterium, parasite germ, and fungi. The impact of climate change on pathogens can be direct, through influencing the survival, reproduction, and life cycle of pathogens, or indirect, through influencing the habitat, environment, or competitors of pathogens. As a result, not only the quantity but also the geographic and seasonal distributions of pathogens may change.

Temperature may affect disease through impacting the life cycle of pathogens. First, a pathogen needs a certain temperature range to survive and develop. For example, the two thresholds, maximum temperature of 22–23 °C for mosquito development and minimum temperature of 25–26 °C for Japanese Encephalitis Virus (JEV) transmission, play key roles in the ecology of JEV (Mellor and Leake, 2000; Tian et al., 2015a). Excessive heat can increase the mortality rates for some pathogens (Gerba, 1999; Kuhn et al., 2005). The development of malaria parasite (*Plasmodium falciparum* and *Plasmodium vivax*) ceases when temperature exceeds 33°–39 °C (Patz et al., 1996). Second, rising temperature can influence the reproduction and extrinsic incubation period (EIP) of pathogens (Harvell et al., 2002). For example, the EIP for *P. falciparum* reduces from 26 days at 20 °C to 13 days at 25 °C (Bunyavanich et al., 2003). On the contrary, lower ambient temperature is likely to lengthen EIP, which may in turn decrease the transmission of diseases such as dengue because fewer mosquitoes can live long enough. Third, extended periods of hot weather can raise the average temperature of water bodies and food environment, which may provide an agreeable environment for microorganism reproduction cycles and algal blooms. For example, *Vibrio* spp. bacteria, native to the Baltic and the North Sea, showed an increased growth rate during the hot summers in 2006 (Frank et al., 2006). Salmonellas is a food-borne disease; the reproduction of the bacteria increases as temperature rises in that range between 7 °C and 37 °C (IWGCCH, 2010). Lastly, rising temperature may limit the proliferation of a pathogen through favoring its competitors. For example, *Campylobacter* spp., the bacteria of food-borne disease *Campylobacter*, was found to be more concentrated in surface water at low temperature and during winter (Jones, 2001); it is believed that warmer temperature supports other bacteria to out-compete *Campylobacter* spp. and that ultraviolet light prohibits the survival of *Campylobacter* (Obiri-Danso et al., 2001).

Climate change may cause shifts in precipitation, which affects the dissemination of water-borne pathogens. Rainfall plays an important role in the development of water-borne disease pathogens. Rainy season is related to the increase of fecal pathogens as heavy rain may stir up sediments in water, leading to the accumulation of fecal microorganisms (Jofre et al., 2010). However, unusual precipitation after a long drought can result in an increase of pathogens, causing a disease outbreak (Wilby et al., 2005). Droughts/low rainfall lead to low river flows, causing the concentration of effluent water-borne pathogens (Hofstra, 2011; Semenza and Menne, 2009).

Humidity change also impacts the pathogens of infectious diseases. The pathogens of air-borne infectious disease such as influenza tend to be responsive to humidity condition. For example, absolute humidity and temperature were found to affect influenza virus transmission and survival (Shaman and Kohn, 2009; Xu et al., 2014). Lowen et al. (2007) proposed that cold temperature and low relative humidity are favorable to the spread of influenza virus. Humidity change also affects the viruses of water-borne diseases. For example, the survival of water-borne viruses near water surface is limited due to the drying effect of surface water (Gerba, 1999). Lastly, virus of vector-borne diseases may be impacted by humidity change. Humidity was found to affect malarial parasite development in Anopheline mosquito (Patz et al., 2003). Thu. et al. (1998) found that the temperature and humidity during rainy season in Yangon and Singapore favor dengue virus propagation in mosquitos, contributing to the outbreaks of dengue hemorrhagic fever in these regions.

Sunshine is one more important climate variable that may affect the pathogens of infectious diseases. For example, sunshine hours and temperature act synergistically during cholera periods to create a favorable condition for the multiplication of *Vibrio cholerae* in aquatic environments (Islam et al., 2009).

Wind is a key factor affecting the pathogens of air-borne diseases. Literature suggested a positive correlation between dust particle association/attachment and virus survival/transporting (Chen et al., 2010; Chung and Sobsey, 1993). It has been reported that the presence of desert dust in the atmosphere during Asian dust storms (ADSs) is associated with increased concentration of cultivable bacteria, cultivable fungi, and fungal spores (Griffin, 2007; Schlesinger et al., 2006). Chen et al. (2010) found that the concentration of influenza A virus was significantly higher during the ADS days than normal days. Studies further suggested that the viruses of infectious diseases be transported across ocean by dust particles (Chung and Sobsey, 1993; Cox, 1995; Griffin, 2007), which may facilitate the transmission of viruses between distant hosts.

3.2. Climate change and vectors/hosts

Hosts refer to living animals or plants on or in which disease pathogens reside. Vectors are intermediate hosts and they carry and transmit pathogen to living organisms which become hosts. This review focuses on animal hosts, especially insects. The geographical locations and population changes of insect vectors are closely associated with the patterns and changes of climate. Thus, climate change may cause changes in range, period, and intensity of infectious diseases through its impacts on disease vectors.

Temperature affects the spatial–temporal distribution of disease vectors. As temperature continues to rise, the insects in low-latitude regions may find new habitats in mid- or high-latitude regions and in areas of high altitude, leading to geographical expansion or shift of diseases. Recent studies have found that some vector-borne human infectious diseases, including malaria, African trypanosomiasis, Lyme disease, tick-borne encephalitis, yellow fever, plague, and dengue have distributed to a wider range (e.g. Harvell et al., 2002). Most of these diseases have extended into areas of higher latitude, following the habitat expansion of mosquitoes, ticks, and midge vectors. In China, as the winter temperature continues to rise, *Oncomelania hupensis*, the intermediate host of *Schistosoma japonicum*, extended its geographic distribution into new areas including northern China (Zhou et al., 2010).

However, temperature change may as well restrict the distribution of disease vectors. For example, *Aedes aegypti* is the mosquito host for yellow fever and dengue fever viruses (Epstein, 2001a). Laboratory experiments found that *A. aegypti* larvae perish when the water temperature surpasses 34 °C; the adults start to die when the air temperature is above 40 °C (Christophers, 1960). As global warming continues, the disease hosts such as *A. aegypti* may disappear from some regions where temperature rises beyond their thresholds. Similarly, since the *Anopheles*-borne *falciparum* malaria mostly exists when temperature is above 16 °C (Beck-Johnson et al., 2013; Martens et al., 1997), a temperature dropping to below this threshold will benefit malaria control.

Disease vectors/hosts may survive climate change by taking shield in small-scaled environment where ambient temperature change does not prevail. For example, *A. aegypti* mosquito was found to hide from the high summer temperature of 40 °C in Jalore Town of Rajasthan, India by using household pitchers or cement water tanks underground (Tyagi and Hiriyan, 2004). Similarly, field observations have recorded viable *A. aegypti* larvae in ice-encrusted water (Christophers, 1960). Historical record reported the presence of *A. aegypti* in Memphis, USA where the winter temperature normally falls below 0 °C (Reiter, 2001).

Changes in precipitation may impact disease vectors/hosts as well. Many vector-borne infectious diseases are found to be positively associated with rainfall. Larval development of some mosquito vectors accelerates with increased rain and rising temperature (Hoshen and Morse, 2004). Adult Anopheline, vector of malaria, reproduce in small natural ponds of clean water; droughts may limit the quantity and quality of breeding sites for these mosquitoes, resulting in reduction in vector population and disease transmission (Gage et al., 2008). The cocoliztli outbreaks in Mexico proved that rainfall can affect the outbreaks of rodent-borne diseases through its impact on rodent population (Zell, 2004).

However, rainfall is not always agreeable for vectors. Excessive precipitation may have catastrophic impacts on mosquito population because strong rain may sweep away their breeding sites (Kuhn et al., 2005). On the contrary, drought in wet regions may decrease flow velocity in brooks and provide mosquitoes with more pools of stagnant water as breeding places (Kovats et al., 2003). The primary carrier of West Nile virus is a type of mosquito named *Culex*, which usually breeds underground in the nasty water pools in city drains and catch basins. Drought allows for rotten organic materials to accumulate in those pools, forming favorite condition for *Culex*; heavy precipitation would wash the drains and water down the pools (Epstein, 2001b), limiting the spread of West Nile virus.

Many disease hosts tend to respond strongly to humidity change. Relative humidity affects malaria transmission through impacting the activity and survival of mosquitoes. If the mean monthly relative humidity is under 60%, the lifespan of malaria vector mosquito becomes too short to incur malaria transmission (Pampana, 1969). When wet and warm weather is intersected by dry-spells, the mosquito vectors carrying West Nile virus and Lyme disease may move into non-traditional areas such as Canada and Scandinavia (Senior, 2008). Low humidity can negatively affect the adult survival of *A. aegypti*, therefore reduce dengue disease transmission (Christophers, 1960). Generally speaking, low humidity, especially when coupled with high temperature, forms unfavorable condition for ticks and fleas (e.g. grasslands or forestlands), limiting the spread of the related infectious diseases (Gage and Kosoy, 2005).

Wind has dual effects on disease vectors/hosts. Wind may affect the malaria cycle both negatively and positively. Strong wind can reduce the biting opportunities for mosquitoes, but can extend their flight distance. During a monsoon season, wind is able to change the spatial distribution of mosquitoes (Reid, 2000).

Sunshine can affect a disease host through the synergistic function. A time series analysis of cholera cases in Matlab, Bangladesh suggested that increased temperature and prolonged sunshine are positively related to the monthly cholera occurrences (Islam et al., 2009). Specifically, high temperature and medium sunshine hours together form the most agreeable condition for cholera outbreak. Relatively low temperature may still support cholera vector if long-hour sunshine is available.

3.3. Climate change and disease transmission

Depending on the transmission route, disease transmission can be direct or indirect. Direct transmission refers to the transmission of a disease from one person to another through droplet contact, direct physical contact, indirect physical contact, air-borne transmission, or fecal–oral transmission. Indirect transmission refers to the transmission of a disease to humans via another organism, a vector, or an intermediate host.

Many studies have proved that climate variables and weather conditions may affect disease transmission, despite some uncertainty about the specific mechanisms. Rather than focusing on the disease transmission mechanisms, this section discusses the impacts that climate change may impose on the spreading of human infectious diseases. This impact can be direct as changes in climate condition may alter disease transmission by directly influencing the viability of pathogens. It can be indirect if a change in the transmission routes resulted from the responding behaviors of humans and vectors/hosts to climate change.

Temperature change alone, or together with other variable changes such as rainfall, may alter the transmission of diseases. Studies have reported an association between interannual variability in temperature and malaria transmission in the African highlands (Bouma, 2003). In the highlands of Kenya, hospital admissions for malaria have been associated with rainfall and high maximum temperature during the preceding 3–4 months (Githeko and Ndegwa, 2001). Hemorrhagic Fever with Renal Syndrome incidence closely correlates with meteorological factors that include temperature, rainfall, and humidity (Xiao et al., 2014).

Wind and dust storms affect the transmission of infectious diseases. Wind can act as a transportation means for pathogen and virus of airborne diseases. Pathogens can spread from endemic regions to other regions through interregional dust storms. Human influenza virus could be transported from Asia to the Americas in winter months by prevailing wind over the Pacific (Hamnett et al., 1999). Chen et al. (2010) found that avian influenza outbreaks tend to occur in downwind regions of ADS (e.g. Japan and South Korean) during the dust storm season.

Climate change can affect the transmission of infectious diseases through altering the contact patterns of human–pathogen, human–vector, or human–host. An analysis of the de-trended time-series malaria data in Madagascar found that the cross-year variation in malaria prevalence can mostly be explained by the minimum temperature at the start of the transmission season, corresponding to the months when the human–vector contact is the greatest (Bouma, 2003). Evidences showed that diseases transmitted by rodents sometimes increase during heavy rainfall and flooding events because of altered patterns of human–pathogen–rodent contact. For example, during hazard periods deer mice may enter human dwellings searching for food and thereby transmit *hantavirus* to humans, leading to hantavirus pulmonary syndrome (HPS) cases (Engelthaler et al., 1999). There have been reports on flood-associated outbreaks of leptospirosis (Weil's diseases) in Central and South America and South Asia (Ahern et al., 2005; Confalonieri, 2003; Ko et al., 1999). The risk factors for leptospirosis for peri-urban population in low-income countries include flooding of open sewers and streets (Sarkar et al., 2002).

Climate variation plays an important role in shaping the patterns of human and other host activities and behaviors, such as seasonal occupation, migration, winter–summer lifestyles, and physical exercises (Viboud et al., 2004); these in turn can significantly influence the patterns of disease transmission (Kuhn et al., 2005). The seasonal prevalence patterns of influenza infection in Europe are believed to be related to people spending longer hours indoor during winter (Halstead, 1996; Lofgren et al., 2007). It was shown that within each wild fowl migratory flyway, the timing of H5N1 outbreaks and viral migrations is closely associated (Tian et al., 2015c). Live poultry markets particularly in the holiday season serve as sources of human infected avian influenza and interacting with migratory birds may also contribute to the transmission of the virus (Zhang et al., 2014; Wang et al., 2014). The elevated morbidity of gastroenteritis in temperate developed countries during summer months could be related to increased picnics and other outside-cooked meals (Altekruse et al., 1998). The re-emergence of kala-azar (visceral leishmaniasis) in the cities of the semi-arid northeastern region in Brazil in the early 1980s and 1990s was caused by the rural–urban migration of the subsistence farmers (Kuhn et al., 2005). A global cross-sectional study of diarrhea incidences in children under 5 found a negative association between rainfall and diarrhea rates, pointing to increased using of unprotected water sources and reduced hygiene practices when water is scarce (Lloyd et al., 2007). With global warming, water scarcity will become a broader and more severe issue, which may lead to more diarrhea cases worldwide (Lloyd et al., 2007).

Climate change can harm human immunity and susceptibility to disease, thereby affecting disease transmission. It may lead to ecosystem degradation, which will possibly bring pressure on agricultural productivity, causing issues such as crop failure, malnutrition, starvation, increased population displacement, and resource conflict. These pressures can contribute to increased human susceptibility to infectious diseases. The early malaria-predicting models in the 1920s found that when food was short, the rising wheat price coupled with crop failure and malnutritioncauses harm to human immunity (Hay et al., 2002). Water-borne diseases may become prevalent in some regions if climate change continues to cause shortage of clean surface water (CDC, 2010). The territorial expansion of the risk for malaria and other tropical diseases has a great potential to reach southern Europe (Semenza and Menne, 2009).

4. Extreme weather events and infectious diseases

Extreme weather events refer to a value of a weather or climate variable going beyond a threshold near the upper (or lower) end of the range of observed values (IPCC, 2012). They include global scale extreme events (e.g. El Nino, La Nina, and Quasi-Biennial Oscillation (QBO)) and regional or local scale meteorological hazards (e.g., drought, heatwaves, flood). Although these events are rare and occur less than 5% of the time (Zhu and Toth, 2001), their frequency and intensity have been on the rise, representing an important aspect of global climate change (IPCC, 2012; Lubchenco and Karl, 2012). They are commonly accompanied by dramatic changes in one or more climate variables, and can potentially change the dynamics of human infectious diseases by impacting pathogens, vectors/hosts, or transmission routes.

Much literature examined the impact of extreme weather events and meteorological hazards on human infectious diseases, as summarized in Table 1. However, most of them are empirical studies, lacking a comprehensive understanding of the mechanism — how weather conditions change and how they affect disease patterns. This could be an important reason for the findings on the relationship between extreme weather events and diseases to be contradictory at some times or very local or regional specific at other times. For example, the outbreaks of malaria in Ecuador, Peru, and Bolivia were found to be related to heavy rains that were accompanied by an El Nino event in 1983 (Nicholls, 1993). During both the 1988 El Nino winter and 1999 La Nina winter, risk for diarrhea symptom disease increased by an average of about 10% for each 2.5 h of weekly water exposure (Dwight et al., 2004). However, other studies (Hay et al., 2002; Shanks et al., 2002) analyzed the climate time-series data and hospital admission data of the highlands in East Africa and found that malaria epidemics have nothing to do with El Nino/La Nina or other extreme weather events in those areas. Moreover, Lindsay et al. (2000) found that malaria strikingly decreased during and after the 1997/98 El Nino event in highlands of Usambara Mountains, Tanzania.

There is a need to fully understand the changing patterns and magnitude of climate variables and the combined weather effects during an extreme weather event. Knowledge in this regard builds the foundation for predicting the health effects of these weather events on human infectious diseases. Similar extreme weather events may lead to different health effects due to variation in magnitude. For example, Chen (1999) found that the outbreaks of Hemorrhagic Fever with Renal Syndrome (HFRS) obviously increased during the 1954, 1975 and 1991 floods, indicating that flood has a positive impact on the HFRS outbreaks. However, the HFRS cases decreased during the 1998 flood, showing that flood has a negative impact on the HFRS cases. Further analysis found that outbreaks of the HFRS mainly depend on an increasing number of rodents, and rodent population decreased significantly in flooded areas during the 1998 flood. Similarly, Pan et al. (2003) believed that the HFRS outbreak following a flood is closely related to the change in water level in a particular geographic area of the flooded region. Furthermore, the combined effects of extreme weather events must be understood when health effects are concerned. The worst epidemic of cocoliztli during 1545–1548 was believed to be associated with prolonged drought periods intermingled with short wet periods (Acuna-Soto et al., 2002).

As pointed out by Lubchenco and Karl (2012), we need to know how much and how frequent any changes in climate variable(s) should be expected with an extreme weather event in order to predict its impacts

Table 1
Key studies that assess the relationship between extreme weather events and infectious diseases.[a]

Extreme weather events	Disease type	Authors, year	Main findings
El Nino	Vector-borne disease	Epstein (1999)	Increasing outbreaks of emerging diseases were linked to El Nino event.
		Haines and Patz (2004)	Outbreaks and epidemic of malaria were positively connected with El Nino events in many regions.
		Lindsay et al. (2000)	Strikingly less malaria were found in the El Nino year than in the preceding year in the Usambara Mountains, Tanzania.
		Hjelle and Glass (2000)	Record of hantavirus cardiopulmonary syndrome has been found to be related to El Nino events in the Colorado Plateau.
	Water-borne disease	Dwight et al. (2004)	The risk of symptoms associated with diarrhea is twice the previous when exposed to southern California coastal waters during an El Nino winter.
La Nina	Vector-borne disease	Chretien et al. (2007)	Chikungunya fever epidemic was connected with the drought incurred by La Nina.
		Nicholls (1993)	La Nina year produced an epidemic of West Nile fever and Japanese encephalitis.
	Water-borne disease	Bunyavanich et al. (2003)	Risk increased across diarrhea symptom during a La Nina winter.
Quasi-Biennial Oscillation (QBO)	Vector-borne disease	Dwight et al. (2004)	QBO has been found to be linked to the incidence of Ross River virus in south-eastern Queensland.
Heatwaves	Vector-borne disease	Paz (2006)	Heatwave was associated with outbreak of West Nile fever in Israel in 2000.
	Air-borne disease	Kan (2011)	Heatwave contributes to the increased morbidity and mortality from infectious respiratory diseases.
Drought	Water-borne disease	Epstein (2001a)	Diarrheal diseases are frequent during drought especially in refugee camps.
	Vector-borne disease	Khasnis and Nettleman (2005)	Drought has been found to be associated with hantavirus pulmonary syndrome (HPS).
		Wang et al. (2010)	Increased West Nile virus risks follow the drought.
		Shaman et al. (2002)	The risk for transmission of St. Louis Encephalitis virus would increase, during the droughts.
		Chretien et al. (2007)	The Chikungunya fever epidemic may be associated with droughts.
Flood	Water-borne disease	MacKenzie et al. (1994)	Flood favors water-borne disease transmission such as *Cryptosporidium* infection.
		Reacher et al. (2004)	A significant increase in risk of gastroenteritis was associated with depth of flooding in the town of Lewes in Southern England.
	Vector-borne disease	Epstein (1999)	Floods in Mozambique led to spread of malaria, typhoid and cholera
		Mackenzie et al. (2000)	Strong rain or flood can lead to outbreak of Ross River fever
		Ahern et al. (2005)	After a flood, such diarrheal disease cases as cholera may grow
		Woodruff et al. (1990)	Increases in diarrhea and malaria incidences were observed after floods in 1988 in Khartoum, Sudan.
		Nielsen et al. (2002)	There have been reported increases in lymphatic filariasis in different areas.
		Cordova et al. (2000)	There have also been reported increases in arbovirus disease after flood
		Chen (1999)	Hemorrhagic Fever with Renal Syndrome diseases may increase during flooding
		CDC (2000)	HPS diseases may also increase during flooding
		Leal-Castellanos et al. (2003)	Leptospirosis diseases may also increase during flooding in different areas.
Hurricane	Vector-borne disease	Epstein (2000)	Following the hurricane, malaria and dengue fever occurred in Honduras and in Venezuela.
Cyclone	Vector-borne disease	Sanders et al. (1999)	A cyclone tends to increase the incidence of leptospirosis.
	Water/food-borne disease	Shultz et al. (2005)	A cyclone tends to increase the incidence of cholera.

[a] The table includes empirical findings published after the 1990s.

and to make sound decisions. However, human beings' knowledge varies greatly across different types of extreme weather events. When coupled with the uncertainty in predicting the spatial and (sometimes) temporal scopes of the impact of an extreme weather event, our ability to predict the health impacts of infectious diseases is actually limited.

5. Societal response and human factor

It is essential to recognize that social and economic factors play a significant role in predicting the changing risk for infectious diseases caused by climate change (Semenza and Menne, 2009; Wu et al., 2014; Xu et al., 2014). Some population and regions are more vulnerable to the elevated risks due to their lack of the ability to effectively respond to the stresses and challenges imposed by climate change (Li et al., 2014; Wang et al., 2013; Wei et al., 2012). Levels of vulnerability are partly a function of the programs and measures that are in place to reduce burdens of climate-sensitive health determinants and outcomes, and partly a result of the success of traditional public-health practices, including access to safe water and improved sanitation, and biosecurity and surveillance programs to identify and respond to infectious diseases outbreaks (Bai et al., 2014; Confalonieri et al., 2007; Jiang et al., 2014; Li et al., 2014). In India, unplanned urbanization has contributed to the spread of *P. vivax* malaria (Akhtar et al., 2002) and dengue (Shah et al., 2004). Since diarrhea morbidity increases as water becomes scarce, the segments of population who are projected to have restricted water access may be more vulnerable to diarrhea (Lloyd et al., 2007). Exceptions to this impact are those societies that can gather advanced technologies and abundant financial resources to eliminate or alleviate water shortage situation.

A society's vulnerability to climate change induced health risk of infectious diseases is related to its social development. Many infectious diseases often break out in developing countries after tropical cyclones, but they are rare in developed nations (Guill and Shandera, 2001). Examples include the outbreak of Balantidias on the Pacific Island of Turkey and typhoid fever in Mauritius (Toole, 1997), acute respiratory infection and leptospirosis in Puerto Rico (Sanders et al., 1999), acute respiratory infection and self-limiting gastrointestinal disease in Dominican Republic (CDC, 1999), cholera in Guatemala, Nicaragua, and Belize, leptospirosis in Nicaragua, and gastrointestinal disease in Honduras (PAHO, 1998). However, a surveillance report of the post-hurricane infectious diseases in developed nations found no increase (Toole, 1997). The inadequate financial and medical resources coupled with the less-effective communication and public health education in developing countries limit these societies' ability to prepare for and respond to climate change induced health issues.

A society's vulnerability to climate change induced health risk of infectious diseases is further related to its existing public health system and infrastructure. Developing countries tend to be more sensitive to an elevated health risk caused by climate change due to the lack of resources and capabilities for their public health system to effectively respond to the various challenges. The interference to public health service and anti-malaria spraying by Hurricane Flora of 1963 may have led to more than 75,000 cases of *P. falciparum* malaria in Haiti (Bissell, 1983). After Hurricane Mitch of 1998, morbidity of dengue fever amplified in Guatemala and Honduras; so did malaria morbidity in Guatemala and Nicaragua

(PAHO, 1998). The much poorer public health service (e.g. poor sanitary) caused by the earthquake and furthermore by a hurricane led to the rapid spread of imported *Vibrio* cholera (Kouadio et al., 2012). These outbreaks resulted from inadequacy of preventive measures to respond to changes in mosquito breeding sites and increased environmental exposure among survivors (CDC, 2005). There was a deferred increase in infectious diseases (including typhoid and paratyphoid fever, infectious hepatitis, gastroenteritis, and measles) five months after Hurricanes David and Fredrick in the Dominican Republic in 1979. The delay was believed to be partially due to the prolonged stay of the hurricane-impacted populations in crowded dwellings, where sanitary facilities were insufficient, food and water supplies were disrupted and contaminated, and immunization rates were low (Ebi et al., 2001). Abdelwhab et al. (2010) argued that the outbreaks of H5N1 in Egypt resulted from the Egyptian government's failure to control and prevent the epidemic following the failure of commercially available H5 poultry vaccines.

Vulnerability to the changing risks for infectious diseases may be reduced with proper adaptation measures. Adaptation can be effective in addressing climate change induced challenges. For example, better drainage, building sea walls, reforestation, and desalinization are among the recommended measures to help Africans minimize the impacts of climate change (UNEP, 2013). As a response to epidemic malaria, various public health programs are in place in most of Africa to reduce the morbidity and mortality. It is predicted that climate change may facilitate the spread of malaria further up some highland areas. As an adaptation practice, the related public health programs for malaria control should be implemented in these highland areas, and this process must follow a timetable that is carefully designed based on an evaluation of the spatiotemporal habitat expansion of the vector (Confalonieri et al., 2007). It is important to point out that the success of a proactive adaptation as such depends largely on correctly predicting the changing landscape of the health risk for infectious diseases.

Adaptation measures can be informed by improved weather forecast, including the forecast of extreme weather events and meteorological hazards. By developing an early warning system that is based on accurate weather forecast, a society can better prepare for climate change related health risks. For example, when a strong El Nino was developing in 1997/1998, the Pacific ENSO Application Center (PEAC) alerted governments that severe droughts could occur, and that some islands were at unusually high risk of tropical cyclones. The intervention practices launched following the warning, including public education and awareness campaigns, were effective in reducing the risk of diarrheal and vector-borne diseases (Hamnett et al., 1999). As a result, fewer children than normal were admitted to hospitals with severe diarrheal disease. Another example is the mitigation of an increased malaria risk in Botswana based on a successful forecast system that linked global coupled ocean–atmosphere climate models to health risks (Thomson et al., 2006). However, an early warning system is not always practical considering our limited knowledge to some aspects of climate change, especially some extreme weather events and meteorological hazards (Lubchenco and Karl, 2012).

6. Conclusions and discussion

Climate change results in variations in weather conditions and patterns of extreme weather events. The health effects of climate change (including changes in climate variables and extreme weather events) on human infectious diseases are imposed through impacts on pathogens, hosts/vectors, and disease transmission. First, a series of infectious diseases is spatially and temporally restricted by climatic variables. Changes of climate variables in spatial and/or temporal scales will affect the development, survival, reproduction, and livability of disease pathogens, hosts, and their interaction with human beings. Second, sudden and dramatic changes in weather conditions due to extreme weather events and meteorological hazards have profound effects on many infectious diseases. Due to our incomplete knowledge to some of these extreme weather events, being able to accurately predict their patterns and their health impacts remains challenging. Last, extreme weather, including large-scale extreme weather events and meteorological hazards, often involves combined shifts of several climate variables, making it more complicated to predict the implications for disease pathogens, hosts, and transmission.

Humans are more than passive recipients of climate change induced health effects. We can play a significant and active role by adopting proactive adaptation measures in order to control and alleviate the negative health impacts of climate change. First, the magnitude of changes in climate variables varies across the globe, posing more challenges and stresses for some societies than others. Regional specific projection of climate change induced health implications on infectious diseases is necessary. Second, given the same magnitude of climate change, some population groups and areas are more vulnerable to the elevated risks due to their lack of the ability and resources to effectively respond to the stresses and challenges. Recognizing that infectious diseases do not confine themselves within a vulnerable population group, developed countries and capable societies should work together with developing countries and less capable societies to reduce their vulnerability to climate change induced health risks. Third, human vulnerability to the changing risks for infectious diseases may be altered through proper adaptation measures. One example of such is to continuously improve public health programs and to timely (re-)allocate financial and health care resources following scientific projection of spatial–temporal changes in health risk for human infectious diseases. Early warning systems based on such projections have been proven effective in helping societies take proactive measures to prevent or alleviate the possible health impacts.

Through conducting this literature survey, it is clear to us that there are two groups of scientific investigations on the issues related to the health impacts of climate change on human infectious diseases. One group examines the problem through the lens of climate change, trying to predict what climate variables will change that may cause elevated health risks. The other group focuses on identifying the range of climate variables or weather conditions favorable to or suitable for certain disease pathogens, hosts/vectors, or transmission to be active. There tends to be a lack of collaboration/communication between these two groups, leaving a gap between understanding the climate change patterns and forecasting the changing landscape of health risks for infectious diseases. Meanwhile, as discussed previously in this article and pointed out by Confalonieri et al. (2007) and Hamnett et al. (1999), there are both needs and past successful examples of directly connecting an accurate prediction of spatial–temporal shifts and magnitude of changing climate variables with the knowledge of how these changes may impact the risks for infectious diseases; a marriage of these two can nurture effective proactive adaption measures for preventing and minimizing the negative health effects of climate change. We hope this review can serve as a call for more cross-disciplinary collaborations leading to mapping out both timetable and magnitude of climate variable changes and the change induced health risk shifts.

Another observation from the literature survey is the empirical nature of most studies that explore the relationship between climate change and health risk impact. Abundant studies revealed empirical association between the occurrence of certain weather condition and the observed morbidity or mortality change in a certain infectious disease. But many of these studies shun establishing a causal relationship and therefore failed to contribute to building a definite connection between shifts in climate variables and changes in health risks. A direct result of this practice is that literature do not always agrees with each other on the health effects of changes in climate variables. It is not unusual for different studies to associate similar weather condition changes with different health risks. One possible reason for this may be the scientific uncertainty or knowledge limitation regarding the net-outcome of the climate change induced health effects when the three aspects of infectious diseases (i.e. pathogen, host, and transmission) may be influenced in different ways. For example, three mechanisms could potentially explain the observed effects of relative humidity on air-borne disease transmission (Lowen et al., 2007).The first one acts on the host by claiming that low relative humidity makes the host more susceptible to respiratory virus infections — breathing dry air could cause desiccation of the nasal mucosa, leading to epithelial damage, and reducing mucociliary clearance. The second one acts at the virus particle level and suggests that high relative humidity would break the stability of the virus, which is a key determinant of virus transmission. The third one acts on the means for transmission, the respiratory droplet. Droplet nuclei that are less than 5 μm in diameter increase in quantity with high humidity, and therefore can remain airborne for an extended period of time, thereby increasing the opportunity for transmission of pathogens (Bridges et al., 2003). Climate change may have contrasting effects on pathogen, vector, thus disease outcomes at different spatial and temporal scales. The outcomes are disease, climatic factor, density, spatial scale, and temporal scale dependent. It demonstrated that how both short and long-term climate variations impact upon the form and outcome of species interactions through different influences on density-dependent and density-independent processes (Stenseth et al., 2015). A second reason for our insufficient knowledge of the overall health impacts of climate change may be the complexity when multiple changes work together, affecting any of the three aspects of human infectious diseases. For example, studies examining the association between malaria outbreak and 1997/98 El Nino winter led to sharply different conclusions (Dwight et al., 2004; Hay et al., 2002; Lindsay et al., 2000; Shanks et al., 2002).

Climate change will continue to affect the health risk for human infectious diseases, limiting some disease transmission but creating opportunities for others. Reducing vulnerability through adopting adaptation measures is among the most effective approaches for human society. The identification of most effective adaptation measure calls for scientific and social advances in several aspects. First, scientific advances are needed to go beyond empirical observations of the association between climate change and shifts in infectious diseases and to more explanatory conclusions. This advancement to explanatory approach depends on our knowledge about the net-outcome of health implications on all three aspects of infectious diseases; it also depends on our understanding of the net-health effects induced by changes in multiple climate variables. Second, there is a need for better understanding and modeling of the spatial–temporal process of climate change (including extreme weather events and meteorological hazards). Being able to map out this changing process through time and across space is the foundation for health impacts prediction and adoption of proper adaption measures. Put another way, we need a comprehensive global map (yet to local details) of changes in climate variables — not changes in sporadic and individual climate variables but the magnitude and sequence of all variable changes and the combined results. Last, on a practical level, effective early warning systems for health effects of climate change should be established broadly. Related to such early warning systems, protocols are needed for information sharing, public health awareness campaign, and resources sharing and relocation.

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