



Ambient Temperature and Major Infectious Diseases in China

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Abstract

Infectious diseases are a group of diseases which have complex transmission ways and various influencing factors. Clarifying the correlation between ambient temperature and major infectious diseases in China is a crucial step toward the successful control of infectious diseases including vector-borne diseases, water-borne diseases, food-borne diseases, respiratory infectious diseases, etc. and the

implementations of climate change adaption strategy and measures in China. However, no study has systematically reviewed the available evidences on the impact of ambient temperature on the incidence of major infectious diseases, and such information is essential for policymakers and stakeholders to take specific actions to control infectious diseases and protect the vulnerable population in the future. In order to fill this gap, we systematically review

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the current evidence for the effect of ambient temperature on major infectious diseases in China. The findings could provide explicit information for the scientific prevention and control of infectious diseases in China.

Keywords

Ambient temperature · Climate change · Infectious diseases · China

5.1 Introduction

Infectious diseases continue to be the major health threats in most regions globally. As one type of important infectious diseases, vector-borne diseases (VBDs) are expected to affect about 80% of the world's population. According to WHO's report, 17% of the global burden of communicable diseases was due to vector-borne diseases.

In China, 10 of the 39 notifiable infectious diseases are vector-borne diseases. Great achievements have been made in the control of infectious diseases in the past decades, and five notifiable infectious diseases were eradicated or nearly eradicated at present, including polio, filariasis, severe acute respiratory syndrome (SARS), plague, and diphtheria [1]. The incidences of some notifiable infectious diseases were reduced, including cholera, hepatitis A, bacterial dysentery, amoebic dysentery, typhoid, paratyphoid, gonorrhea, pertussis, epidemic cerebrospinal meningitis, epidemic hemorrhagic fever, rabies, leptospirosis, anthrax, typhus, encephalitis, malaria, tuberculosis, and tetanus. By contrast, an increasing trend was observed for 11 notifiable infectious diseases, including human immunodeficiency virus (HIV), brucellosis, hepatitis C, hepatitis E, syphilis, scarlet fever, dengue, influenza, infectious diarrhea, hydatid disease, leishmaniasis, and schistosomiasis.

Among these diseases, dengue fever (DF), malaria, hemorrhagic fever with renal syndrome (HFRS), plague, and severe fever with thrombocytopenia syndrome (SFTS) were the most prevalent vector-borne diseases in China.

According to literature review, these diseases mentioned above are all sensitive to the variations of meteorological factors, especially for ambient temperature [2, 3]. Water-borne diseases are conditions caused by pathogenic microorganisms that are transmitted in water. The infection would occur when people ingested contaminated water or contacted with infected water containing various forms of intestinal pathogens during bathing or swimming. As a type of old diseases, the occurrence of schistosomiasis and its vector could also be impacted by ambient temperature [4]. At present, the epidemic of hand-foot-mouth disease (HFMD) is very serious in China, and it is believed that heat could facilitate the spread of HFMD [5]. Regarding respiratory infectious diseases, influenza is surely a representative infectious diseases sensitive to ambient temperature in China [6]. Therefore, to better understand the relationship between meteorological factors and infectious diseases in China, it is essential to carry out prediction and projection of important infectious diseases under the context of climate change which will be of great significance to the prevention and control of infectious diseases in future.

However, little information was available regarding the effect of ambient temperature on infectious diseases in China. In this chapter, we extensively reviewed the available evidence on the effect of ambient temperature on major infectious diseases in China, in order to make up this gap, and provide scientific guidance for policy-makers to implement corresponding actions to reduce the incidence of major infectious diseases.

5.2 Ambient Temperature and Vector-Borne Diseases

5.2.1 Ambient Temperature and Mosquito-Borne Diseases

In this chapter, some representative mosquito-borne diseases with the biggest diseases burden or public health significance were selected.

Literatures concerning these themes are reviewed to clarify the relationship between ambient temperature and mosquito-borne diseases.

5.2.1.1 Dengue

DF is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years. Three quarters of the population exposed to dengue are in the Asia-Pacific region. Since the first recorded outbreak of dengue in Foshan, Guangdong, in 1978, DF occurs frequently in southern China and becomes a major public health threat in China [7]. In 2017, 5893 DF cases occurred in China with two of these dead. In recent years, indigenous cases of DF occurred in Yunnan, Guangxi, Guangdong, Hainan, Fujian, Zhejiang, Anhui, Shanghai, Henan, and Shandong, while imported cases happened in all provinces except for Tianjin and Tibet in 2017. In China, the principal vectors for DF, including *Aedes aegypti* and *Ae. albopictus*, are all sensitive to climate. *Ae. albopictus* is the most important mosquito in DF transmission in Guangdong and Zhejiang, while *Ae. aegypti* is the major DF vector in Yunnan.

The means by which ambient temperature affects DF are via the following bioecological aspects: dengue virus, *Aedes* mosquitoes, human population, and its transmission environment [2]. The ambient temperature could not only impact the reproductive of dengue virus in *Aedes* mosquitoes but also the distribution of *Aedes* mosquitoes. In China, regarding the impact of ambient temperature on dengue vector distribution, Wu et al. found that *Ae. albopictus* have expanded their geographic range to areas with an annual mean temperature below 11 °C and a January mean temperature below -5 °C using CLIMEX model [8]. Temperature plays an important role in vector competence. Liu et al. found that temperature increase enhances the competence of *Ae. albopictus* to transmit dengue virus [9]. Most studies in China believed that temperature can drive dengue transmission [10, 11], showing a nonlinear effect [11, 12]. Among those studies, different models are employed such as generalized additive model (GAM), autoregressive integrated moving average (ARIMAX) model,

ecologically based model, etc. In recent years, most studies were carried out in Guangdong and Yunnan provinces considering the higher frequency of DF outbreak. Local DF cases were positively associated with temperature with different time lags in Guangzhou [13]. The minimum temperature at a lag of 1 month was positively associated with dengue incidence in Guangzhou [14]. The mean and minimum temperatures were positively associated with increased DF risk, while the maximum temperature was negatively associated with DF transmission [15]. Xiang et al. demonstrated that a reversed U-shaped nonlinear association was found between ambient temperature and DF in Guangzhou. The optimal maximum temperature (T_{max}) range for dengue transmission was 21.6–32.9 °C and 11.2–23.7 °C for minimum temperature (T_{min}) [16].

In Guangzhou, a negative binomial regression model was adopted, and the results showed that average temperature (T_{ave}) and previous month's minimum temperature (T_{min}) were positively associated with DF incidence. A threshold of 18.25 °C was found in the relationship between the current month's T_{min} and DF incidence [17].

Regarding the comparative studies of the influence of ambient temperature on DF in the domestic and abroad, the current studies in China mainly focus on the influence of ambient temperature on the distribution and spread of DF and its vectors via the application of different models. And this is consistent with the international researches. However, at present, very little information is available regarding the impact mechanism of the ambient temperature on dengue virus, vectors, and ultimately dengue transmission mechanism, and limited literatures could be found regarding the impact of social and economic factors on DF, and these field should be the focus in future study.

5.2.1.2 Malaria

As a representative vector-borne disease, malaria is due to parasites of the genus *Plasmodium* and transmitted by four species of female *Anopheles* mosquitoes in China, including *An. sinensis*, *An. lesteri*, *An. minimus*, and *An. dirus*, respectively.

Despite dramatical reductions in the incidence of malaria observed at present, imported cases still constitute a threat to the malaria elimination commitment of the Chinese government to WHO.

Most studies found that temperature was a fundamental meteorological factor related to malaria incidence in China [18]. Extreme high temperature restricts the development of mosquitoes and reduces the transmission of malaria since higher temperature increases mosquito growth, virus replication, and biting frequency of vectors. Generally speaking, temperatures lower than 16 °C or higher than 30 °C are not conducive to mosquitoes development [19]. Daily variations on temperature could impact necessary mosquito and parasite characteristics that help to malaria transmission intensity [20]. In Jinan, maximum temperature with a 1 °C rise may be relevant to a 7.7–12.7% increase in malaria cases, while minimum temperature with a 1 °C rise might lead to about 11.8–12.7% increase in malaria cases [21]. Li et al. reported that each 1 °C rise in temperature amounts to an increase of 0.90% in the monthly malaria cases in Guangzhou [3]. However, the correlation between temperature indexes and incidence of malaria may not be throughout the year. Tian et al. found an increased risk of transmission due to a high temperature in warmer winters [22]. The effect of ambient temperature concerning malaria frequently leads to a lag-time effect because of the life cycle of *Anopheles* and the parasite [23]. Zhou et al. revealed that a 75.3% variation on monthly malaria incidence was related to the average temperature in last 2 months in central China [18]. In four counties of Yunnan, an increasing temperature resulted in increased malaria risk the varied lag periods for these associations [24].

Almost all studies mentioned above identified an association between ambient temperature indicators and transmission of malaria in different sites and periods lag in China. This is coherent to the similar studies abroad. However, very few studies focus on the impact mechanism of the ambient temperature on malaria parasites, vectors, and its transmission.

5.2.2 Rodent-Borne Diseases

5.2.2.1 Ambient Temperature and Plague

Plague, caused by *Yersinia pestis*, is one of the most devastating infectious diseases in human history. The three plague pandemics have caused numerous deaths worldwide and changed human civilization [25, 26]. In China, plague is belonging to category A of 39 notifiable infectious diseases and once constituted a great burden during the initial stage of new China. At present, the disease was well controlled, and the incidence of plague keeps very low level.

Climate affects the plague intensity through its effect on maintenance and replication of the pathogen, host, and vector populations by affecting temperature and precipitation in some studies [27–29]. Suitable climate could increase the reproductive rate of pathogenic microbes [30] and contribute to form stable plague foci [31]. Rodent populations and flea survival respond rapidly to climate variations [30]. Epizootics are likely to occur when rodent and flea number exceed a certain threshold [32–34]. The high abundance of rodents and fleas would also increase the human plague risk [35]. Temperature seems to determine the distribution of *Yersinia pestis*. Nearly 95% of human plague occur in regions with an average annual temperature greater than 13 °C, and most large plague outbreaks occur within areas with an annual temperature of 24–27 °C [36]. Additionally, outbreaks of historical plague pandemics also seemed to be driven by climate change. The introduction of the Black Death is associated with climate fluctuations in Central Asia, with an approximate delay of 15 years [37]. The above-normal warmer and wetter climate during 1855 and 1870 may be responsible for extensive plague outbreaks in China during the Third Pandemic [36]. The associations between climate and plague can vary by regions [38, 39].

Regarding the comparative studies, most studies have focused on the individual effect of precipitation or temperature, or the mixed effect of two climate variables. As for the high tem-

perature, plague would increase under this condition in western United States [38, 40]. In Arizona and New Mexico, plague would increase if the number of days above a certain temperature threshold increased, with 80 °F for New Mexico and 85 °F for Arizona, respectively [38]. However, the transmission between fleas and mammalian hosts was significantly reduced when temperature excess 27.5 °C [41]. The mixed effect of precipitation and temperature also revealed a regional difference. *Yersinia pestis* prevalence was shown to increase with warmer springs and wetter summers in gerbils in Kazakhstan [42]. Similarly, the rodent and flea densities, as well as the presence of plague in Mongolian gerbils, are positively correlated with the precipitation and temperature in China [43]. High risk of human plague tends to follow the plague outbreaks in hosts [33]. However, an increased plague incidence can be expected in Vietnam during the hot, dry seasons [41]. Besides, plague outbreaks in preindustrial period were more frequent in cold and arid climate in Europe [44]. Plague is also associated with large-scale weather events [28]. El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are related to precipitation and temperature which could in turn affect plague dynamics [45, 46]. The increasing rate of human plague was closely associated with Southern Oscillation Index (SOI) and Sea Surface Temperature of east Pacific equator (SST) in China. Ari et al. found PDO explained much of the human plague variation in western United States. However, as the association between large-scale climate and plague was non-stationary and nonlinear in Madagascar and Europe [45, 47], we should pay more attention to the scale of the climate and the complexity of the interaction in the ecosystem when analyzing large-scale climate and plague systems.

5.2.2.2 Ambient Temperature and HFRS

HFRS caused by the Hanta virus and results in about 200,000 hospitalized cases yearly. It is generally thought that ambient temperature is

one of the most key meteorological factors exerting the impact of endemic intensity of HFRS [48], because warm temperature is in ideal condition for the growth of crops and increase of rodent. Furthermore, it is probably that surface air temperature can increase more obviously in winter and spring than in other seasons, particularly in the northern China [49]. As the temperature increases, areas with relatively lower temperature could become beneficial to rodent breeding then extend the breeding seasons, which have a potential impact on the number, scale, and emergence of new natural foci of HFRS. In China, most studies showed that HFRS is sensitive to ambient temperature. Temperatures from 10 to 25 °C are most beneficial to rodent growth, and breeding rates for both *A. agrarius* and *R. norvegicus* would decrease when temperatures were out of this range [48]. Temperature of 17 °C as a threshold was identified in a study, below which there was a positive association, while above the threshold there was an inverse association [50]. Likewise, it is reported that the highest incidence of HFRS is with temperatures about 17.5 °C [51]. Temperature above 23.7 °C and below 6 °C revealed positive effects on the HFRS incidence of 3 months later; in contrast, temperature between 6.0 °C to 23.7 °C was negative with the incidence of HFRS [52].

However, it is difficult to compare findings across different studies given the range of metrics and methodologies used. A recent comprehensive review suggested that many studies that quantified HFRS-ambient temperature associations have drawn different conclusions (either positive [53–59] or negative [49, 60, 61]), possibly because of the use of different statistical methods and climate characteristics of the study regions. Variables from different studies included mean, minimum, maximum ambient temperature and land surface temperature. Land surface temperature mainly impacts the distribution and abundance of populations of *A. agrarius* [62], while ambient temperature mainly affects the behavior of rodent and human.

5.2.3 Tick-Borne Diseases

SFTS is an emerging infectious disease which was firstly identified in 2009. Although SFTS is considered to be transmitted by air or direct contact with secretion or blood of SFTS patients, the current evidences reveal that the majority of SFTS cases were infected via tick bites. The majority of cases were happened from April to October. Meteorological factors may exert some impact on ecology of SFTSV directly or indirectly by affecting tick in itself, tick-human interactions, and virus replication.

Table 5.1 listed the related studies of climatic factors and SFTS in China. Sun et al. conducted an analysis concerning ambient temperature and SFTS in 21 counties in Henan and Hubei via distributed lag nonlinear models (DLNMs). They reported that the effects of temperature on incidence of SFTS were nonlinear, with larger relative risk (RR) at the higher temperature on lag 0. The high temperatures had acute and short-term effects, while the effects in low-temperature ranges were persistent over longer lag periods. Higher temperatures such as 23.97 °C and 29.30 °C had the maximum RR for SFTS cases on the current week, which decreased quickly in the next weeks. Low temperatures including 1.62 °C and 6.97 °C had the minimum RR on the current week and had the maximum RR at lag 13 weeks, which decreased slowly in the next

weeks. The effects of lower temperatures could last 24 weeks, but the effect of 29.30 °C was not significant at lag 8 weeks [63].

A negative binomial regression model (NBM) established by Sun et al. revealed that the occurrence of SFTS would increase by 25.68% and 10.31%, respectively, if monthly maximum temperature and mean relative humidity increase one unit [64]. Du et al. studied geographic distribution and related factors of SFTS and found that temperature is one of the key environmental factors affecting the occurrence of SFTS [65]. Similarity, cattle density, rain-fed cropland, built-up land, temperature, and relative humidity were independent risk factors for the distribution of SFTS [66]. The risk of SFTS increased when reached a threshold with monthly average temperature higher than 19.65 °C, or monthly average relative humidity higher than 74.5%, or (95% CI) were 12.889 (2.307, 72.016) and 13.417 (3.042, 59.171), respectively [67].

5.3 Ambient Temperature and Water-Borne Diseases

Schistosomiasis, caused by a trematode worms belonging to the genus *Schistosoma* [68], is a kind of water-borne diseases, bringing a heavy burden on the residents of the endemic areas [69]. The parasite species which can infect human

Table 5.1 Summary of included studies on ambient temperature and SFTS in China

Source	Location	Time period	Key findings
Sun et al. [64]	Henan, Hubei	2011–2015	A nonlinear effect existed between weekly temperature and SFTS. The exposure-response curve was a reversed U-shape
Sun et al. [64]	Henan, Hubei	2011–2015	Temperature and relative humidity were significantly correlate to the occurrence of SFTS
Du et al. [65]	Shandong	2010–2013	Temperature, precipitation, land cover, normalized difference vegetation index (NDVI), and duration of sunshine were the key environmental factors affecting SFTS occurrence
Wang et al. [66]	Hubei	2011–2016	Temperature, relative humidity, cattle density, rain-fed cropland, and built-up land were independent risk factors for the distribution of SFTS
Zhai et al. [67]	Zhejiang	2011–2014	Monthly average temperature, atmospheric pressure, and relative humidity were associated with incidence of SFTS

include *Schistosomiasis haematobium*, *Schistosomiasis japonicum*, *Schistosomiasis mansoni*, *Schistosomiasis intercalatum*, *Schistosomiasis mekongi*, and *Schistosomiasis malayensis* [70]. *Schistosomiasis japonica* that caused by *S. japonicum* is widely spread in China since 2000, particularly in areas along the Yangtze River and further south [71]. *Oncomelania hupensis*, the sole intermediate host of *S. japonicum*, plays an important role in the transmission of *S. japonicum* in China and correlates closely with the distribution of this disease [72, 73]. *S. japonicum* completes its life cycle through a sexual generation in the vascular system of the definitive host (i.e., mammals) and an asexual generation in *O. hupensis*.

Ambient temperature is an important ecological factor for growth and development of *S. japonicum* and the presence of *O. hupensis*, which can influence the prevalence and distribution of schistosomiasis in China [74–79]. In the process of transmission of schistosomiasis, ambient temperature plays a vital role in the biological activity of *O. hupensis* and the development of *S. japonicum* within the intermediate host. The optimal temperature range for miracidia infecting *O. hupensis* is between 10 °C and 20 °C. There is no significance in infection rates when temperature ranges between 21 °C and 31 °C and low infection rates under 10 °C. However, miracidia can never infect *O. hupensis* when temperature drops to 3.2 °C [4, 80]. After the invasion, *S. japonicum* arrested their development in snails when temperature was kept at about 15.3 °C or above 37 °C, while the optimum development occurred at 25 °C–30 °C, which means within a temperature range of 15.3 °C–30 °C, the higher the temperature is, the shorter the pre-patent period of *S. japonicum* within *O. hupensis* will be [79, 81]. Temperature could also influence the cercaria effusion, where 25 °C–30 °C were the optimal range [82]. The optimal temperature for *O. hupensis* ranges between 20 °C and 25 °C, which means any temperature out of this range would result in delayed or arrested development and reproduction of *O. hupensis* [74, 83, 84]. Physiological functions of *O. hupensis* declines as environmental temperature drops [74]. When

the temperature drops to 5.8 °C–6.4 °C, half of the snails were in hibernation (ET_{50}) [79, 81]. In Yunnan, it is concluded that the optimal LST for *O. hupensis* was ≥ 22.7 °C after considering land surface temperature (LST) as the most suitable environmental factor for snail habitat prediction [85]. In Dongting Lake Region, the mean snail density increased gradually when the temperature was between 24.30 and 25.70 °C, while mean snail density decreased gradually when the temperature was from 24.15 to 22.40 °C in the GWR (Geographically Weighted Regression) model. A possible suitable range of temperature was from 22.73 to 24.23 °C estimated by interquartile range in high-high clustered areas. [86]. The accumulated degree-days (ADD) are considered to be similar to growing degree-days (GDD), which both reflects the heat accumulation during the development of the organism. It was estimated that the mean ADD for the development of *S. japonicum* in its intermediate host snail was 842.9–852.6 degree-days, and the same index for the development of a generation of *O. hupensis* was 3846.3 degree-days [79, 87]. Several studies conducted in Yunnan, Jiangxi, Anhui, and Hunan have drawn the similar conclusion that the mean LST, the median night-time LST, the maximum LST at daytime, the maximum and minimum LST at night, and average temperature in June were positively associated with the prevalence of *S. japonicum*, which showed the importance of LST [5, 88–93]. From another perspective, a spatio-temporal kriging model suggested seasonal variation of LST at daytime were negatively associated with the risk of schistosomiasis [94], for the possible reason that large seasonal temperature differences would impede the development of *S. japonicum* [79]. The January temperature is a significant determinant to the distribution of schistosomiasis. When the January mean minimum temperature is below -4 °C or the annual extreme low temperature drops under -7.6 °C, it is not suitable for *O. hupensis* to survive, which is the main reason that restricts transmission of *S. japonicum* shifting toward to north [79, 95]. However, the northern limit of the schistosome-endemic zone has shifted due to climate change. Yang et al. [96] found that the distribu-

tion limits of *O. hupensis* have shifted from 33°15'N to 33°41'N due to an increase of 0.96 °C of January temperature in the past 30 years. In other words, the potential transmission area have expanded by more than 40,000 km², which resulted in an additional 20.7 million people at risk of schistosomiasis [90]. The average minimum temperature in January and in winter had predominant influence on *Oncomelania* density and frame occurrence rate of living *Oncomelania*, respectively. The variation of average minimum temperature in January by 1 °C would lead to the change of *Oncomelania* density by 5.08–6.71%. The variation of average minimum temperature in winter by 1 °C would lead to the change of frame occurrence rate by 15.521–15.928% [97]. What's more, *O. hupensis* can only exist in areas with an annual mean temperature of 16–20 °C [98]. Yang et al. found that the lowest air temperature in a year was one of the factors that significantly affect the occurrence of snails in Hunan, China. When the lowest air temperature in a year ranges from –2.88 to –2.10 °C, the snails could exist, while no snail can survive when the range was between –2.88 and –2.34 °C [99]. A predictive model based on distribution of schistosomiasis in eastern China has been constructed to estimate the probability that schistosomiasis occurs in a target area, which showed a mean temperature of coldest quarter was of significance in model [100]. However, air temperature is less suitable for predicting snail density compared to soil temperature [101].

Having realized the ambient temperature is one of the most principal elements affecting distribution and transmission of schistosomiasis, researchers in China focused on related studies from different perspectives. Generally, the conclusions that we had drawn are in line with those of other countries, while the subtle difference is probably due to geographic variation of the temperature. Though large number of studies that involving different temperature-related variables have been conducted, the question that which one is the most closely related to the schistosomiasis is still unknown. In addition, widespread use of GIS/RS promotes the multi-scale studies in China, but there is not many

studies carried out on national level yet where the trend of temperature variation is more stable. That's the direction we should focus on in future.

5.4 Ambient Temperature and Intestinal Infectious Diseases

Hand-foot-mouth disease (HFMD) is an infectious disease of infants and children [102] caused by viruses from the group called enteroviruses. According to WHO's report, outbreaks of HFMD occur every few years in different parts of the world, but in recent years these have occurred more in Asia. Countries with recent large increases in the number of reported HFMD cases in Asia include China, Japan, Hong Kong (China), Republic of Korea, Malaysia, Singapore, Thailand, and Vietnam. In China, HFMD is one of the most common infectious diseases [103]. It tends to occur in outbreaks during spring, summer, and autumn seasons. There has been a substantial increase of HFMD in many parts of the country in recent years [104].

Most of literatures reported that HFMD is a climate-sensitive disease, and it positively correlates with temperature with some days lag. A study in Beijing revealed that mean temperature was positively associated with HFMD [102]. In Jiangsu, average temperature was positively correlated to HFMD incidence, while low temperature or high temperature was negatively related [105]. In Zhengzhou, average atmospheric temperature with 2 or 3 weeks lagged were identified as significant predictors for the number of HFMD and the pathogens [106]. Using meta-analysis, Cheng et al. analyzed the relationship between ambient temperature and HFMD in East and Southeast Asia and found that ambient temperature could increase the incidence of HFMD in Asia-Pacific regions. It was revealed that 1 °C increase in the temperature was significantly correlated to the increasing of the incidence of HFMD [107]. As to the specific threshold, when the temperature was above 24.85 °C and the relative humidity was between 80.59 and 82.55%,

the RR of HFMD was 3.49 relative to monthly average incidence [108].

Regarding the relationship between HFMD and ambient temperature, most studies in other countries focus on the temperature threshold for the risk of HFMD and the quantitative relationship between temperature increase and HFMD. And this is consistent to China's study. In Japan, Sumi A revealed that the average temperature data indicated a lower threshold at 12 °C and a higher threshold at 30 °C for risk of HFMD infection. Maximum and minimum temperature data indicated a lower threshold at 6 °C and a higher threshold at 35 °C [109], and the threshold is higher than that in Du et al.'s study in China in 2016. In South Korea, at an average temperature below 18 °C, the HFMD rate increased by 10.3% for every 1 °C rise in average temperature (95% confidence interval (CI), 8.4, 12.3%) [110]. In Vietnam, a 1 °C increase in average temperature was associated with 5.6% increase in HFMD rate at lag 5 days (95% CI 0.3–10.9) [111]. However, very little information is available regarding the relationship between HFMD and socioeconomic factors and demographic features. Therefore, more studies are needed to clarify the relationship between ambient temperature and incidence of HFMD in various settings with distinct climate, socioeconomic, and demographic features.

5.5 Ambient Temperature and Respiratory Infectious Diseases

Respiratory infectious diseases are a group of commonly and frequently occurring diseases, the lesion mainly in the trachea, bronchus, lungs, and thoracic cavity. Climatic conditions may have affected the incidence of respiratory infectious diseases. Influenza, commonly known as “the flu,” is a representative respiratory infectious disease caused by some influenza virus. Regarding the virus classification, influenza viruses belong to RNA viruses that include three of the five genera of the family *Orthomyxoviridae*, that is, influenza A virus, influenza B virus, and influenza C virus. A fourth family of influenza viruses has

been proposed – influenza D. The type species for this family is bovine influenza D virus which was first isolated in 2012. The influenza A virus can be subdivided into some serotypes on the basis of the antibody response to these viruses. The serotypes confirmed in humans and ordered by the number of known human pandemic deaths include H1N1, H2N2, H3N2, H5N1, H7N7, H1N2, H9N2, H7N2, H7N3, H10N7, H7N9, and H6N1, respectively.

Climate change may alter the incidence and severity of respiratory infections by affecting vectors and host immune responses [112]. Most literatures revealed that influenza is a climate-sensitive disease [113]. Climate change may affect the distribution and migration of the host of influenza virus and will eventually affect the transmission cycle, prevalence, and intensity of influenza. Most of studies revealed that ambient temperature was correlated to influenza risks with possible nonlinear, interactive, and lagged effects [114]. In China, the majority of studies focus on the influenza A virus, and studying the relationship between ambient temperature and H1N1, H7N9, few studies focus on avian influenza virus (AIV) and influenza B virus. Lower temperature was the climatic factor facilitating local transmission of 2009 pandemic influenza A (H1N1) in mainland China after correction for the effects of school summer vacation and public holidays, as well as population density and the density of medical facilities [115]. In Changsha, the sensitive climatic factors did have a “driving effect” on the incidence of influenza A (H1N1). In the initial stage of the disease, a 6-day lag was found between the incidence and the daily minimum temperature. In the peak period of the disease, the daily minimum temperature was negatively relevant to the incidence [116].

The outbreak of human infections with an emerging avian influenza A (H7N9) virus occurred in China in early 2013. A boosted regression tree (BRT) models revealed that temperature significantly contributed to the occurrence of human infection with H7N9 virus [117, 118]. In Shanghai, H7N9 incidence rate was significantly associated with fortnightly mean temperature (relative risk (RR), 1.54; 95% cred-

ible interval (CI), 1.22–1.94) [119]. Mean monthly temperature was significantly associated with the occurrence of human H7N9 infection [120]. Zhang et al. found that both daily minimum and daily maximum temperature contributed significantly to human infection with the influenza A H7N9 virus [121]. Models incorporating the nonlinear effect of minimum or maximum temperature on day 13 prior to disease onset were considered to have the best predictive effect. Liu et al. investigate the independent and interactive effects of ambient temperature (TM) and absolute humidity (AH) on H7N9 risks in China. Significantly nonlinear negative associations of TM and VP with H7N9 risks were observed in all cases, and in cases from northern and southern regions. Different risky windows of H7N9 infection exist in the northern (TM, 0–18 °C; VP, 313 mb) and southern areas (TM, 7–21 °C; VP, 3–17 mb) [122]. Temperature was correlated to the avian influenza virus (AIV) invasion in the destination to some degree [123]. Since the end of 2003, highly pathogenic avian influenza viruses (HPAI) H5N1 have caused lots of outbreaks in poultries and wild birds from East Asia and have spread to at least 48 countries. Liu et al. developed a new climatic approach for early predicting future HPAI outbreaks and preventing pandemic disasters. The results demonstrate a temperature drop shortly before these outbreaks in birds in each of the Eurasian regions stricken in 2005 and 2006. Dust storms, like those that struck near China's Lake Qinghai around May 4, 2005, exacerbated the spread of HPAI H5N1 virus, causing the deaths of a record number of wild birds and triggering the subsequent spread of H5N1 [124]. Climate factors were the strongest predictors of influenza B seasonality, including minimum temperature [125]. In comparison with the incidence of influenza to climatic factors during 2000–2007 in five countries, Tang et al. found that the mean temperature was the key climate variable associated with the incidence of influenza B in Hong Kong, Brisbane, Melbourne, and Vancouver [126]. Furthermore, Internet search metrics in conjunction with temperature [127] could be adopted to predict influenza outbreaks, which

can be regarded as a prerequisite for establishing early-warning systems using search and temperature data.

Currently, most studies focus on influenza A virus, and very few studies are available regarding the correlation between ambient temperature and influenza B, C, and D virus. There is still lack of enough evidences concerning the independent and interactive effects of ambient temperature and other complicated climatic factors on the risk of influenza in China and comparative studies in different countries [128]. In addition, most studies in China consider the effect of specific temperature on influenza rather than a decrease of temperature; this is also important. Jaakkola K et al. found that a decrease rather than low temperature increases the risk of influenza epidemic in a cold climate [129].

5.6 Ambient Temperature and Other Infectious Diseases

In China, there are 39 notifiable infectious diseases including 2 from category A, 26 from category B, and 11 from category C. Besides the major infectious diseases mentioned above, there are still some other infectious diseases that correlate to ambient temperature such as Japanese encephalitis (JE) and Chikungunya.

5.6.1 JE

JE is an important mosquito-borne disease and is commonly transmitted via the bite of *Culex tritaeniorhynchus* with pig as a reservoir host and source of infection. At present, the morbidity and mortality of JE has declined gradually year by year. However, JE is still one of the threats to the public, and it has recently spread to new territories.

In China, some studies revealed the positive relationships between ambient temperature and JE when controlling for non-climatic factors. Using ARIMA models, monthly average temperature was positively associated with incidence of JE in Linyi, Shandong after adjusting for mass vaccination in this area [130]. Correlation analy-

sis and back propagation artificial neural work were applied; the annual JE incidence was considered to be positively correlated with maximum temperature and extreme maximum temperature [131]. In areas close to the three gorges dam, a significant positive association between temperature with a lag of 1 and 3 months and JE incidence was found [132]. Few studies believed that temperature has a threshold effect on JE cases. In 2007, Bi et al. have clarified positive relationships between monthly maximum temperature, minimum temperature, and JE transmission in a rural region of Anhui and a metropolitan area of Shandong with no rice plating and the uncertain role of pigs in JE transmission [133]. In Jinan, an obvious increase in JE cases occurred when the monthly mean maximum temperature was higher than 25.2 °C or the minimum temperature was over 21.0 °C [133]. These findings mentioned above are consistent with the threshold temperature detection in Linyi [130].

5.6.2 Chikungunya Fever

Chikungunya fever is an emerging infection of Chikungunya virus (CHIKV), constituting a serious public health problem. It is transmitted mainly by mosquitoes of the genus *Aedes* although other ways of transmission by blood transfusions and vertical transmission have also been reported [134]. It is a climate-sensitive mosquito-transmitted viral disease which was first identified in Africa; now its distribution spread to Asia. In China, the first outbreak of Chikungunya happened in Dongguan, Guangdong, 2010. After that, the outbreak happened in Zhejiang in 2016. However, few studies are available at present concerning the correlation between ambient temperature and Chikungunya fever in China.

5.7 Projection of Important Infectious Diseases Under Different Climate Scenarios

Projection of important infectious diseases under the context of climate change is beneficial to the prevention and control of infectious disease in

the future. In this section, we summarized the projection of representative vector-borne diseases including rodent-borne diseases, water-borne diseases, intestinal infectious diseases, and respiratory infectious diseases.

5.7.1 Mosquito-Borne Diseases

5.7.1.1 DF

Ambient temperature could impact the distribution of dengue vectors in China in the future. Fan et al. adopted CLIMEX model to project the changes of suitable habitat range of *Ae. albopictus* in the current climatic situation and under different climatic scenarios (RCP 2.6, RCP4.5, RCP6.0, and RCP8.5) under different times (2020s, 2030s, 2050s, and 2100s). It is revealed that future climate change will lead to the distribution of *A. albopictus* suitable area expanding to high latitude. Compared with dengue distribution of the current climatic situation (1981–2010), ambient temperature could also impact dengue transmission under RCP 2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios under 2020s, 2030s, 2050s, and 2100s, respectively. Based on the findings from Fan et al., 168 million people of 142 counties (districts) in China are in the high-risk area of DF at present. Under RCP8.5 scenario, the high-risk area of DF will further expand, and it will increase to 456 counties (districts) (490 million population) in 2100.

5.7.1.2 Malaria

In China, very little literatures are available regarding the distribution of malaria in the future. Using Maxent species distribution model, the environmentally suitable area (ESA) of *A. dirus* and *A. minimus* will increase by 49 and 16% in the context of three climatic scenarios (RCP2.6, RCP4.5, and RCP8.5) in the 2030s. In the 2050s, the ESA of *A. lesteri* and *A. sinensis* under two scenarios (RCP4.5 and PCP8.5) will increase 36% and 11%, respectively. Meanwhile, considering the level of land use and urbanization, the population of exposed to four *Anopheles* mosquitoes in the 2030s and the 2050s showed a significant net increase [135].

Regarding the trend of malaria incidence in different scenarios in the future, it will show the

similar trend with *Anopheles* mosquitoes [136]. In 205 counties in Henan and Anhui from 2004 to 2010, B₁ low emission scenario, A₁B intermediate scenario, and A₂ high emission scenario, that are nearly consistent to the scenarios RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively, were used, and GP-based model was adopted to describe the nonlinear relationship among incidence, temperature, and humidity and then project the change of incidence under different years. It is demonstrated that malaria incidence will increase markedly, and the distribution area of malaria will expand markedly in the future under the scenario of no malaria control. Specifically, the malaria incidence in North China will increase 19–29% in 2020s.

5.7.2 Rodent-Borne Diseases

Based on literature review, at present, no information is available regarding the projection of rodent-borne diseases such as HFRS, plague under different climatic scenarios. In future, the research in this field should be strengthened.

5.7.3 Schistosomiasis

With the development of new technologies and methods, accurate and stable prediction of ambient temperature-based schistosomiasis transmission becomes possible. Based on the historical data, some researchers applied the future temperature data into the transmission model for schistosomiasis projection [137].

According to historical data of temperature from 1960 to 2000 in China, a prediction that the mean January temperature will increase by 0.9 °C in 2030 and by 1.6 °C in 2050. Based on biologic model, for these temperature increases, potential risk areas for schistosomiasis transmission will increase an additional 662,373 km² and 783,883 km² by 2030 and 2050, respectively. Disease transmission is thus likely to occur in previously non-endemic areas, such as the southern parts of Shandong and Henan. Under the cir-

cumstances, the transmission intensity is possible to increase in areas already endemic for schistosomiasis [79]. To some extents, the predictions might explain the recent observations of reemergence of this disease in areas where up to the criteria for transmission control, or even interruption [71, 138, 139].

Based on the data of mean temperature and monthly minimum temperature in January in China, the impact of warming climate in winter to the scale of schistosomiasis spreading was assessed using the indexes of 0 °C mean temperature and −4 °C monthly minimum temperature in January. Results showed the possibility that *O. hupensis* moves northward [140]. Through comparison in January average temperature 0 °C, January average minimum temperature −4 °C, and January average temperature 0.9 °C, Peng et al. found the last one fitted the schistosomiasis endemic areas best. By this standard, the potential epidemic areas moved toward north, and endemic areas would significantly increase in 2100 compared to that in 2050 [141].

Zhu et al. utilized fine-tuned Maxent (fMaxent) and ensemble models to anticipate potential distributions of *O. hupensis* under future climate change scenarios on the background of SNWDP in China. Results indicated increased suitability and range expansion in *O. hupensis* in the future. The southern Central Route of SNWDP will coincide with suitable areas for *O. hupensis* in 2050–2060. Its suitable areas will also expand northward along the southern Eastern Route in 2080–2090 [142]. Modeling with application of GIS and RS that integrated ambient temperature (i.e., LST) resulted in a good predictive accuracy for the presence of *O. hupensis* in recent years [143]. Zhou et al. applied the mean monthly temperature and other environment variables in GIS model to predict the transmission of schistosomiasis in the southern part of China. *S. japonicum*-endemic areas were restricted to settings with a transmission risk index exceeding 900, which is mostly consistent with the −4 °C average minimum temperature isotherm in China, while an improved model conducted by Zhao et al. supposed isotherm was at −2 °C [144–146].

After that, an improved GIS forecast model combined with mean minimum temperature in January revealed hotspots of high transmission intensities in Jiangsu and adjacent areas in different transmission seasons, which showed a high sensitivity of 88.9% [146].

By using the results from PRECIS on reference years (1991–2005), more than 20 meteorological indexes including the highest and lowest temperature of the day in 2050s (2046–2050) and 2070s (2066–2070) were estimated under A_2 and B_2 scenario, which were developed in the IPCC (Intergovernmental Panel on Climate Change) Special Report on Emissions Scenarios (SRES) to reflect the extent of climate change. The biology-based model is used to calculate the corresponding risk areas and potential transmission index in China in response to different climate scenarios. The transmission areas of schistosomiasis are supposed to extend to north both in 2050s and 2070s under A_2 and B_2 scenario, especially in Jiangsu and Anhui, and the extended areas in 2070s are larger than that in 2050s. North boundary of the transmission areas will extend further north under A_2 than that under B_2 in 2070s, which has reached Shandong. Compared with the year of 2005, the high-risk areas with potential transmission index >1500 increased by 89.6% and 81.3% under A_2 and B_2 in 2050s, respectively, which further increased in the 2070s [147].

5.7.4 HFMD

Based on literature review, the association between temperature and HFMD varies across China and that the future impact of climate change on HFMD incidence will vary as well. Zhao et al. projected the change in HFMD cases due to projected temperature change by the 2090s [148]. They found that the projected incidence of HFMD increased by 3.2% and 5.3% by the 2090s under the RCP 4.5 and 8.5 scenarios, respectively. However, regional projections suggest that HFMD may decrease with climate change in temperate areas of central and eastern China.

Wang et al. adopted the spatial regression model to project the incidence of HFMD according to projected climatic factors and population under different emission scenarios. There was not significant variation of the average incidence of HFMD from 2030s to 2080s under RCP 2.6 scenario. The incidence of the disease was also increased under RCP 4.5 and RCP 6.0 scenarios. However, the average incidence of HFMD would increase linearly under RCP 8.5 scenario with the fastest growth rate (unpublished). Regarding the trend of HFMD in various major administrative regions under different climate scenarios, the incidence of HFMD in the northeast and northwest regions declined continuously in the future, while the increase of the incidence of the southwest region was under RCP 2.6 scenario. Under the scenario of RCP4.5, the incidence of HFMD in North China, East China, Central China, southern China, and southwest increased continuously. In the context of RCP6.0, the incidence of the disease in north China, East China, Central China, and southern China increased continuously. And in the context of RCP 8.5, the incidence of the disease in other regions, except in the northeast, increased. According to the trend of HFMD in various climate zone under different climate scenarios, the trend of the incidence of HFMD is increased in the Qinghai Tibet plateau and the middle subtropical region while that decreased in the middle temperate zone under the scenario of RCP 2.6. Under the RCP 4.5 scenario, the incidence of HFMD in the warm temperate zone, the northern subtropical zone, the middle subtropical, and the south subtropical regions is increased continuously while that decreased in the moderate temperate zone and the cold temperate zone; and the incidence of HFMD in warm temperate, northern subtropical, south subtropical, and marginal tropics is increased continuously while that decreased in middle temperate zone and cold temperate zone under RCP 6.0 scenario; and the incidence of HFMD in other regions increased except that in the middle temperate zone and cold temperate zone under RCP 8.5 scenario.

5.7.5 Respiratory Infectious Diseases

Regarding the projection of influenza in China, at present, very little information is available. Take H5N1 avian influenza for example, based on 20 global climate projection models under the future scenarios, Chen et al. obtained seasonal distribution of migratory birds in the context of different climate models and the seasonal distribution of H5N1 avian influenza in migratory birds. The results show that Japan and southern China will become high-risk areas of H5N1 highly pathogenic avian influenza in January and February. Northern Africa, Western Asia, and Central Asia entered a high-risk period from April to June. The west coast of Africa, West Asia, India, and southern China become areas high risk of outbreak after October. Compared with the current situation in high-risk areas, high-risk areas in Africa will move northward from the central part of the continent. In addition, the high-risk area of H5N1 avian influenza in winter in future will spread from low latitudes to high latitudes.

5.8 Summary

In this chapter, the relationship between ambient temperature and infectious diseases were systematically summarized in China. We focused on not only the impact of temperature on the current situation of infectious diseases including vector-borne diseases, rodent-borne diseases, water-borne diseases, HFMD, and respiratory diseases but also future trend of these diseases mentioned above. The findings may provide scientific evidence for the prevention and control of infectious diseases in China. The summary information of infectious diseases due to ambient temperature may provide a valuable knowledge for the policymaker to develop the climate-based intervention strategies and adapted measures to protect public health from ambient temperature.

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