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Climate and infectious disease in the southwestern United States

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Abstract: As in many parts of the world, climate variability has a strong impact on infectious diseases within the southwestern USA. Moisture and temperature conditions can either indirectly impact disease by providing an environment conducive to the growth of an animal host or reservoir, or directly through the survival and dispersal of an infectious agent. It is also expected that climate change will affect the number of cases and/or the spatial distribution of infectious diseases. Before the effects of climate change on diseases can be determined, an understanding of the basic relationship between incidence and climate variability should be established. A review of climate impacts on four infectious diseases (hantavirus, plague, dengue and coccidioidomycosis) currently found in southwestern USA (or potentially found in the southwest in the case of dengue) is followed by suggested future research to further understand the relationship between climate variability/change and disease.

Key words: climate and health, coccidioidomycosis, dengue, hantavirus, infectious disease, landscape epidemiology, plague, Southwest USA.

I Introduction

The southwestern United States of America, similar to other regions, experiences disease outbreaks that are partially related to climate conditions. Particular combinations of moisture and temperature levels can be conductive to the growth of an animal host or reservoir, or the survival of an infectious agent. This paper examines several infectious diseases of the Southwest, and reports climate links and potential future research. Research needs for understanding the effects of climate change on incidence of the selected diseases are also taken into account.

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Interest in the field of climate and health is growing, and the importance of examining the influence of climate and environmental conditions on disease occurrence has been recognized. The chapter on human health in the third report of the Intergovernmental Panel on Climate Change is much expanded on the chapter from the second report (McMichael and Githeko, 2001), and much work has been done in recent years on applying the latest remote sensing and geographic information systems technology to the field (Crombie *et al.*, 1999; Rogers *et al.*, 2002).

Hantavirus, plague, dengue and valley fever are important diseases in the Southwest (or potentially so in the case of dengue) and have not been reviewed before in one paper. Given the relatively clear climate signal in the incidence of each, they are outlined here. Other infectious diseases present in the Southwest, including influenza, are somewhat influenced by environmental conditions, however the relationship is much less clear than that of the selected diseases and other factors such as human behaviour are much more important in their spread. The West Nile virus was recently found in the Southwest and represents another important infectious disease in the region that is in part mediated by environmental conditions.

The southwestern USA was selected as the study site for this research for several reasons. The Southwest is influenced by both mid-latitude and subtropical circulations and, when combined with the varied topography of the region, is consequently highly variable and complex climatically, which is reflected in the range of environmentally mediated infectious diseases found there. The region is also experiencing rapid population growth, particularly among groups that are more susceptible to severe forms of some diseases such as the elderly and the immunocompromised.

It is important to consider the potential implications of climate change on disease. Several models predict slightly increased precipitation in the Southwest under future climate scenarios (Southwest Regional Assessment Group, 2000). The seasonal timing of increased precipitation is vital when examining potential disease behaviour. Changing summer precipitation patterns will affect some diseases, while different winter patterns will affect others. Before tackling the task of exploring the impact of climate change on disease, basic relationships between climate and incidence must be understood. There is much uncertainty in future climate predictions (although models are continually improved); therefore a better understanding of how climate variability affects a certain disease will improve disease–climate change predictions. It is also important to note that climate represents only one variable in the complex system of infectious diseases, and other factors including human behaviour and adaptation also play important roles in disease occurrence.

This paper presents a review of four infectious diseases found in the southwestern USA that are impacted by climate conditions. Hantavirus and plague are spread by rodents, dengue is transmitted through the bite of the *Aedes* mosquito and coccidioidomycosis is caused by a soil-dwelling fungus. While not an exhaustive list, the diseases reviewed here are important ones in which climate plays a significant role in the variability of incidence. For each disease, an introductory section briefly outlines the importance of the illness within the Southwest, and a review of climate impacts on the disease follows. Finally, future research needs, to more clearly understand the relationship between climate and incidence, are described.

II Hantavirus pulmonary syndrome

Since May 1993 (when case count began), 283 cases of hantavirus pulmonary syndrome (HPS), transmitted to humans by rodents, have been identified in the USA. The recognition of the disease was prompted by an outbreak of HPS that occurred in June and July 1993 in the Four Corners region of Arizona, New Mexico, Colorado and Utah. Cases have also been reported across much of the western USA, in some eastern states and in parts of Central and South America. As shown in Figure 1, hantavirus is mainly present in higher elevation locations, and is rarely found in the low desert region. Several different hantaviruses are responsible for the disease but, in the Southwest, cases of HPS have been linked to Sin Nombre virus (Centers for Disease Control and Prevention, 2000). Infections occur when the virus, which is shed in the urine and faeces of rodents, becomes airborne and is inhaled (Centers for Disease Control and Prevention, 2000). Infections may also occur if an infected rodent bites a person, but this situation is rare. The virus is not spread from person-to-person.

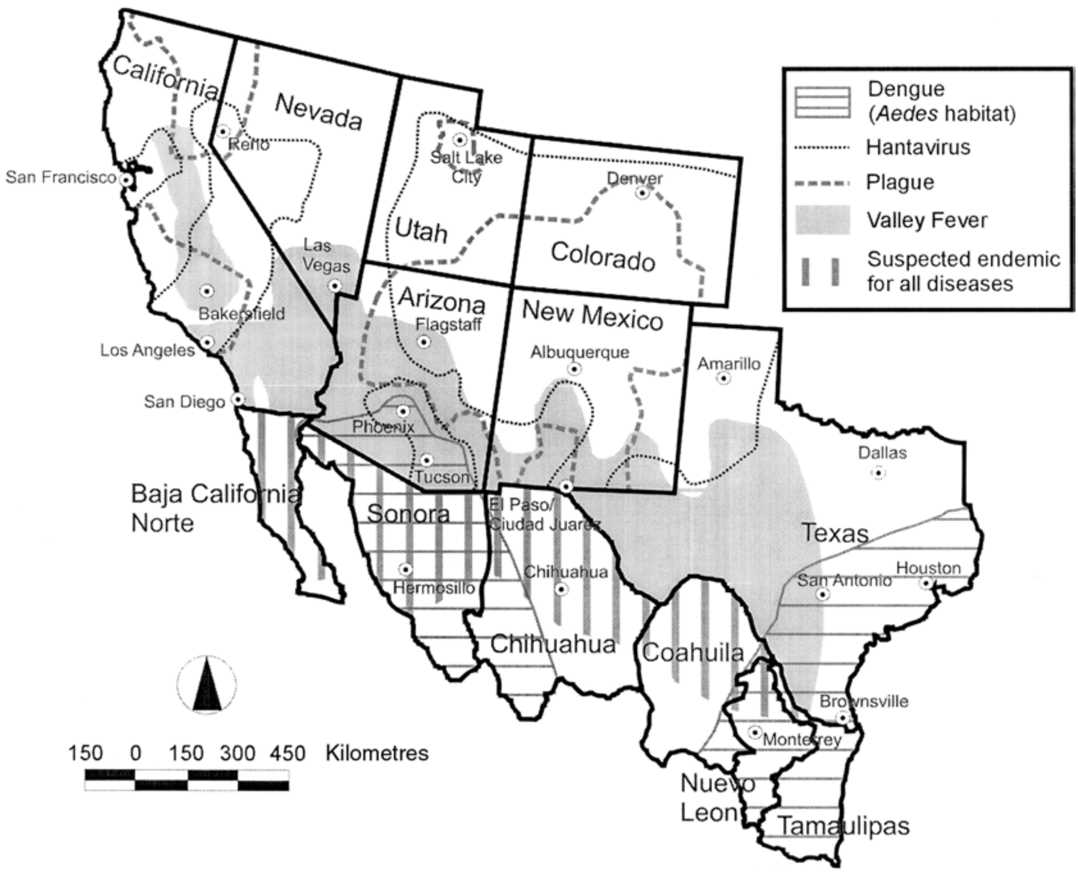

Figure 1 Generalized potential endemicity map of the Southwest for hantavirus, plague, dengue and valley fever, based on past case locations and/or animal reservoir locations

Early symptoms include fatigue, muscle aches, fever and dizziness, and may progress to coughing and shortness of breath.

1 Climate relationships

The 1993 Four Corners HPS outbreak has been linked to climate conditions. The outbreak occurred during the summer following a winter with above average precipitation associated with an El Niño event. Increased precipitation likely resulted in an abundance of food for rodents, which then led to an increase in rodent populations and raised the likelihood of viral transmission (Engelthaler *et al.*, 1999). For example, Chapman and Khabbaz (1994) report that piñon nuts were harvested all year long in 1993, whereas normally they are only available during a few months of the year. It is estimated that the deer mouse population grew ten-fold from May 1992 to May 1993 (Chapman and Khabbaz, 1994), increasing the likelihood of humans interacting with virus-carrying rodents. Given this background, Engelthaler *et al.* (1999) found that the impact of the 1992–93 El Niño was correlated with an increased number of HPS cases for up to two years following the above average precipitation received during the winter of 1992–93.

Satellite imagery was used by Glass *et al.* (2000) to describe the local environmental setting. Topographic variables, including slope, elevation and aspect, were imported into a geographic information system (GIS), along with Landsat Thematic Mapper images, to identify areas at risk for a high number of HPS cases. Boone *et al.* (2000) used a similar technique to examine whether or not deer mouse populations were infected with Sin Nombre virus in Nevada and California, and the vegetation type that these mice inhabited. It was found that GIS and remote sensing can be used to aid in the determination of the infection status of deer mice (Boone *et al.*, 2000). Similar remote sensing techniques could provide advance warning of an HPS outbreak if comparable environmental conditions are found in the future.

2 Future research needs

Previous research recognized the link between increased precipitation during the 1992–93 El Niño and an outbreak of HPS in the Southwest. In order to better understand the outbreak and prepare for future epidemics, the mechanisms and processes between the precipitation and the outbreak should be analysed. A multiyear study has been initiated to monitor the seasonal changes in rodent populations and identify environmental factors in rodent population growth and virus transmission, and will add greatly to the current state of knowledge regarding hantavirus in the Southwest (Mills *et al.*, 1999a,b). The impact of climate conditions on local vegetation growth, and the subsequent influence of specific vegetation types as a food source for growing rodent populations are important keys to the 1993 outbreak. Also, the behaviour patterns that led to contact between infected rodents and humans should be examined. How did climate conditions, ecological factors, rodent behaviour and human behaviour interact in 1993 to produce the outbreak?

Increased winter precipitation in the Southwest resulting from El Niño events or other climate phenomena has occurred in the past, as well as after the outbreak during the winter of 1997–98 when an increased number of HPS cases was not apparent, although some cases have been identified. Other winters with above average precipitation should be examined in an attempt to understand why outbreaks were not experienced during those times. Perhaps the right mix of climate, ecological and behavioural factors came together in 1992–93 to produce the outbreak, and have not been repeated. However, if those conditions recur, will there be another outbreak? What was different about the winter of 1992–93 that produced unique conditions conducive to an outbreak of HPS?

After establishing an improved understanding of HPS and climate, the potential incidence under future climate conditions should be addressed. From research during the 1993 outbreak, it appears that above average winter precipitation may contribute to an increased likelihood of experiencing an outbreak of HPS, and if climate models indicate increased future winter precipitation, outbreaks of HPS may become more common.

III Plague

Plague, caused by the bacterium *Yersinia pestis*, is contracted from a bite by an infected flea usually carried on a rodent or possibly through face-to-face contact with an infected person (Centers for Disease Control and Prevention, 2001a). In the past, outbreaks of plague were found in urban areas, but today cases in the USA are more often found in rural regions. Symptoms include fever, fatigue and cough and, if caught early, antibiotics are an effective treatment when administered promptly (Centers for Disease Control and Prevention, 2001a). The Centers for Disease Control and Prevention (CDC) reports that within the Southwest, outbreaks of plague have occurred in recent years in northern New Mexico, northern Arizona and southern Colorado (Centers for Disease Control and Prevention, 2001a). As indicated in Figure 1, plague, which is more likely to be found in higher than lower elevation regions, has a similar distribution to hantavirus, given that both are related to rodent populations.

1 Climate relationships

Similar to hantavirus, outbreaks of plague have been linked to periods of increased rainfall. Increased food availability can support a greater number of rodents and, as rodent populations grow, contact between rodents and humans may be more likely, increasing the potential for infection with *Yersinia pestis*. It has been hypothesized that above average rainfall during winter and spring increases food resources for rodents, and may also improve flea survival (Parmenter *et al.*, 1999). Research conducted on historical plague outbreaks that occurred in Scotland in the 1300s and 1400s show a link between climate conditions and incidence (Duncan, 1992). Although other factors such as trade and migration played a role in disease epidemics during this time (and continue to do so), cool temperatures in northern Scotland appear to have limited the spread of the plague to this region, while warmer temperatures and increased moisture conditions in other parts of the country were conducive to plague outbreaks.

An analysis of plague incidence since 1948 in New Mexico found similar results to the historical study. Parmenter *et al.* (1999) conducted a correlation analysis between plague incidence and precipitation and the Southern Oscillation Index (SOI). A significant positive relationship was found between incidence and local precipitation; 60% more plague cases were found following winters with above average precipitation (Parmenter *et al.*, 1999).

2 Future research needs

As with hantavirus, the various dynamics between precipitation, vegetation patterns, rodent and flea lifecycles, and human behaviour need to be explored. The impact of specific temperature and moisture conditions on rodent food resources and the lifecycles of fleas and rodents are important keys to understanding how climate indirectly affects plague incidence. How does climate variability affect each of these factors, and how do the factors interact to result in increased plague incidence?

Parmenter *et al.* (1999) recognize the usefulness of their results for predicting increased plague potential, but a plague predictive model has not been developed, and the usefulness of such a model has not been analysed. Following a winter with above average precipitation, public health officials and healthcare providers should be warned that the potential for a plague outbreak exists. Therefore, what climate, vegetation, and human variables would constitute a plague model? How would the model be implemented, and who would find it most useful?

Finally, the impact of climate change on plague incidence should be considered. The relationship between increased winter precipitation and plague outbreaks has been recognized, but the application of these results to future climate scenarios has not been conducted. How will warmer temperatures and changing precipitation patterns affect the growth of vegetation that serves as rodents' food resources? Will the timing of precipitation change, such that food is not available for rodents during crucial times in their lifecycle? Similarly, how will temperature and precipitation changes affect the lifecycle of the flea? Finally, will future climates be more or less conducive to the survival of *Yersinia pestis* in the Southwest?

IV Dengue

Dengue is not considered to be endemic in the southwestern USA, but several cases have been acquired near Brownsville, Texas near the US–Mexico border (Rawlings *et al.* 1996). More frequently, travellers import cases into the USA after visiting endemic countries. However, the mosquito vectors that can carry and spread dengue have been found in southern Arizona (*Aedes aegypti*) and are endemic to the southern USA (*Aedes albopictus*) (Engelthaler *et al.*, 1997). As illustrated in Figure 1, the *Aedes* mosquito is present in southern Arizona and eastern Texas, as well as in regions of Mexico. If a person infected with the dengue virus, whether an infection acquired within the USA or outside of the country, is bitten by an *Aedes* mosquito in the USA, an outbreak could occur when that mosquito then bites a susceptible person. The CDC (2001b) reports that '[t]here is a small, but significant, risk for dengue outbreaks in the continental United States'. Therefore, although the likelihood is low, the potential exists for an outbreak within the USA, and the role that climate conditions play in the lifecycle and activity level of the vectors should be examined in order to prepare for such an event.

Although dengue was first recognized in the late 1700s as a tropical disease, a pandemic began in the late 1940s and, following a failed Pan American Health Organization (PAHO) eradication programme in the 1960s and 1970s, has since strengthened in intensity and scope (Gubler, 1989). Since the end of the eradication programme, *Aedes aegypti* has spread from South America and the Caribbean and is currently prevalent in northern Mexico. Therefore, the potential exists for endemic transmission of dengue within the USA, including the Southwest, if the dengue virus is introduced to the mosquito population. Owing to the potential dengue risk that exists in the Southwest, the climate links with dengue outbreaks will be explored in this paper.

1 Climate relationships

As with other mosquito species, *Ae. aegypti* and *Ae. albopictus* require water to carry out some portion of their lifecycle. The *Aedes* mosquitoes are considered to be 'urban' mosquitoes since they have adapted to living among humans and frequently lay their eggs in standing water around homes (Gubler and Meltzer, 1999). Therefore, during times of high precipitation, containers outside homes or low-lying areas may collect water that can serve as breeding grounds for mosquitoes. On the other hand, the storage of collected water may increase if a region is experiencing drought, and in that way outside containers could also serve for mosquito breeding, even if little precipitation is received. A link between temperature and dengue has also been recognized; warm temperatures shorten the mosquito's lifecycle and increase biting activity (Patz *et al.*, 1996).

Many studies examining climate–dengue relationships have focused on the role of climate variability associated with the El Niño–Southern Oscillation (ENSO) and incidence. Since the southwestern USA is often impacted by ENSO, mosquito populations may also be impacted. A study conducted in the South Pacific found a positive correlation between the number of dengue epidemics in the region and the Southern Oscillation Index (SOI) (Hales *et al.*, 1996). In this region, a positive SOI (La Niña) is often associated with above average rainfall, which may provide a larger breeding area for mosquitoes. A more in-depth study conducted in the same region found a positive correlation between the SOI and the specific number of dengue cases in several countries in the southern Pacific Ocean (Hales *et al.*, 1999). Above average dengue incidence was experienced in Asia in 1998, believed to be associated with the El Niño event of 1997–98 (Kovats, 2000). It has been established that Indonesia appears to experience higher than normal dengue incidence during the year following an El Niño (Kovats, 2000). Gagnon *et al.* (2001) conducted a correlation analysis between temperature and precipitation data and dengue incidence in northern South America and Indonesia. In South America, it was found that dengue epidemics are associated with above average temperatures and drier moisture conditions; in Indonesia, this relationship was apparent as well, but the epidemic occurred following the El Niño-related drought (Gagnon *et al.*, 2001). There appears to be a contradiction in the results, as studies have found both a positive and a negative correlation between incidence and precipitation, and future research should address this inconsistency.

Within the Southwest, specifically the city of Tucson, surveillance of the *Aedes aegypti* populations established throughout the city has recognized some patterns related to climate conditions. It appears that the number of mosquitoes in the city increases following rainfall (Fink *et al.*, 1998). There may also be a link between the use of evaporative coolers and the presence of *Aedes aegypti*; the humidity released by the coolers may be important for the survival of the mosquitoes (Fink *et al.*, 1998).

2 Future research needs

Overall, more research should be conducted on how *Aedes aegypti* and *Aedes albopictus* respond to changes in climate conditions. Research conducted in South America and the Pacific islands found somewhat conflicting results; in some cases, dengue incidence was high following above average rainfall, but in other cases incidence was high following drought. How do periods of high rainfall and periods of drought affect the lifecycle and survival of the mosquito? It has been recognized that human behaviour plays a role in the mosquito's breeding through their use of outdoor containers that may store water. How does the practice of collecting and storing water change with varying moisture conditions in different parts of the world? More specifically for the southwestern USA, how do irrigation practices change with moisture conditions, and how does irrigation affect mosquito populations?

Even though dengue is currently not endemic in the southwestern USA, the potential for endemic transmission exists since the mosquitoes responsible for its spread are present. Continued surveillance of mosquito populations will determine if fluctuations related to climate conditions occur in a regular pattern. What conditions (human behaviour and mosquito habitat) are necessary for endemic transmission of dengue in the Southwest, and how will various mechanisms interact to result in an outbreak?

With climate change, some scientists think that the range of mosquito-borne diseases may expand and/or shift (Epstein, 1998; McMichael and Githeko, 2001). Therefore, the current distribution of the *Aedes* mosquitoes may change, thereby changing the spatial pattern of dengue. Others feel that human behaviour is much more important in determining the range of mosquitoes, and climate change will have little effect on their spatial distribution (Reiter, 2000). More research is needed to understand the mechanisms, including climate, that play a role in establishing mosquito habitat. With climate change, how will the distribution of the *Aedes* mosquito change, if at all?

V Coccidioidomycosis

Coccidioidomycosis (valley fever), caused by the soil-dwelling fungus *Coccidioides immitis* (*C. immitis*), is endemic in the Southwest as well as in the San Joaquin Valley of California and parts of Central and South America. It has recently been recognized that a new *Coccidioides* species is responsible for spreading valley fever outside of the San Joaquin Valley, referred to as *Coccidioides posadasii* (Fisher *et al.*, 2002). Since all past studies refer to *C. immitis* in spreading valley fever, we will not specify between the two species in this paper for the sake of clarity. Within the USA, southern Arizona and the southern San Joaquin Valley are the most highly endemic regions (Figure 1). It is estimated that there are approximately 100 000 new infections of valley fever each year within the southwestern USA (Valley Fever Center for Excellence, 1999). The majority of those infected through the inhalation of the fungus are asymptomatic or experience only mild symptoms, while others may experience 'flu-like conditions, and may or may not seek medical treatment (Smith *et al.*, 1946). About 1% of those infected experience serious, potentially life-threatening conditions such as meningitis and organ and joint damage when the fungus disseminates beyond the lungs (Einstein and Johnson, 1992). Given that part of the fungus' lifecycle is carried out within the soil, *C. immitis* is sensitive to changes in moisture and temperature (Kolivras *et al.*, 2001).

1 Climate relationships

Both the amount and timing of precipitation play a role in the growth and/or dispersal of the fungus. Moisture is required for the fungus to complete its lifecycle, while a lack of moisture within the soil allows the fungus to become airborne (Pappagianis, 1980). Previous studies have shown that *C. immitis* is more likely to be found in the soil following wet periods than following dry periods (Egeberg and Ely, 1956; Elconin *et al.*, 1957). When examining incidence, past research shows that the highest number of cases are often found during the dry period following the rainy season (Hugenholtz, 1957; Maddy, 1965; Jinadu, 1995; Stevens, 1995). The climate of the endemic regions in southern Arizona and California are therefore conducive to the growth and dispersal of *C. immitis* given the alternating wet–dry periods experienced in both locations.

Temperature also plays a role in *C. immitis'* lifecycle, although the relationship is less clear than that of precipitation. It is thought that during very hot, dry periods, the surface soil is sterilized of microorganisms, but *C. immitis* remains viable beneath the surface (Maddy, 1965; Reed, 1960). When rain falls, the fungus is able to grow in the surface soil relatively free of competing organisms (Maddy, 1957).

The occurrence of dust storms, relatively frequent in the Southwest, has also been linked to increased valley fever incidence. A strong storm that moved through the San Joaquin Valley of California in December 1977 carried dust as well as *C. immitis* spores far outside of the traditional endemic region and led to an unexpected high number of cases (Pappagianis and Einstein, 1978). Dust clouds from landslides generated by the Northridge earthquake were implicated in an outbreak of the disease in 1994 (Schneider *et al.*, 1997).

While basic climate relationships are generally understood, much of the research examining climate and valley fever was conducted in the 1950s and 1960s; very few studies have quantitatively evaluated the disease and climate conditions until recently. Kolivras and Comrie (2003) analysed incidence and climate data for Pima County, Arizona, and developed an experimental valley fever predictive model. However, much research remains to be done to separate the various environmental factors that lead to increased incidence.

2 Future research

The use of incidence data for analyses adds many uncertainties. Over time, reporting and diagnosis methods have changed, leading to variability in the data that may or may not be true. Also, incidence is several steps removed from the impact of climate conditions on the growth of the fungus in the soil. Therefore, future research should include a seasonal analysis of fungal counts, when such data are available, rather than examining the variability of the incidence record following specific climate conditions. How does the amount and spatial distribution of fungal spores change with varying climate conditions? What are the precise climate mechanisms that result in the dispersal of the fungus and an outbreak of valley fever?

The potential impact of climate change on valley fever should be examined with an improved understanding of the effect of climate variability. How will the number of cases, as well as the endemic region, change or shift with climate change? Will soil conditions change so that the current endemic region is no longer viable for the fungus, but other possibly more heavily populated areas may become suitable for the growth of the fungus? Climate change may have a more direct impact on valley fever incidence than on the other diseases reviewed in this paper given the absence of an animal reservoir and the lack of human adaptation potential.

VI Conclusion

Climate variability and change can affect disease incidence through the lifecycle and survival of an infectious agent and/or of an animal reservoir. An understanding of how climate conditions affect disease can help the healthcare community prepare for a potential outbreak by mobilizing resources such as disease specialists and treatment medication. In the case of each disease outlined in this paper, the spatial and temporal quality of the incidence data will determine if relationships between environmental conditions and disease outbreaks can be ascertained. Given quality disease data, further research can lead to the development of a predictive model that can provide early warning of an outbreak. Knowledge of the impacts of climate variability on disease can provide a framework for understanding how incidence may be affected by climate change.

In the Southwest, several diseases are in some way impacted by climate, and four were outlined in this paper. This review included the main infectious diseases affected by climate in the region, and included an in-depth look at climate relationships with an analysis of future research needs. The overlapping generalized endemic zones on Figure 1 reveal the complexities of climate–disease relationship in the Southwest. Hantavirus and the plague are present at higher elevations, while the valley fever endemic area and the dengue potential zone are both at lower elevations. Many questions remain to be answered, and future work will provide important knowledge for healthcare providers and public health officials on potential outbreaks that may occur given certain climate conditions.

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