Potential impacts of climate change on the ecology of dengue and its mosquito vector the Asian tiger mosquito (Aedes albopictus)

R A Erickson1,2, K Hayhoe3, S M Presley1,2, L J S Allen2,4, K R Long4 and S B Cox1,2,5

1 Department of Environmental Toxicology, Texas Tech University, Lubbock, TX 79409, USA
2 Institute of Environmental and Human Health, Texas Tech University, Lubbock, TX 79409, USA
3 Department of Political Science, Texas Tech University, Lubbock, TX 79409, USA
4 Department of Mathematics and Statistics, Texas Tech University, Lubbock, TX 79409, USA
5 Research and Testing Laboratory, LLC, Lubbock, TX 79416, USA

E-mail: richard.erickson@ttu.edu, raerickson@gmail.com and stephen.cox@ttu.edu

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Abstract
Shifts in temperature and precipitation patterns caused by global climate change may have profound impacts on the ecology of certain infectious diseases. We examine the potential impacts of climate change on the transmission and maintenance dynamics of dengue, a resurging mosquito-vectored infectious disease. In particular, we project changes in dengue season length for three cities: Atlanta, GA; Chicago, IL and Lubbock, TX. These cities are located on the edges of the range of the Asian tiger mosquito within the United States of America and were chosen as test cases. We use a disease model that explicitly incorporates mosquito population dynamics and high-resolution climate projections. Based on projected changes under the Special Report on Emissions Scenarios (SRES) A1fi (higher) and B1 (lower) emission scenarios as simulated by four global climate models, we found that the projected warming shortened mosquito lifespan, which in turn decreased the potential dengue season. These results illustrate the difficulty in predicting how climate change may alter complex systems.

Keywords: climate change, vector-borne diseases, vector ecology

1. Introduction

Environmental changes threaten ecosystems, communities and households on both global and local scales (Adger et al 2009). These changes can be complex and difficult to understand. A growing source of environmental and ecological change is global climate change (Walther et al 2002). While much emphasis has been placed on the melting of ice caps and projected increases in sea level, increasing temperatures and shifting precipitation patterns may have profound impacts on environmental and human health (Patz et al 2005) due to alterations of system characteristics at levels ranging from the physiology of the individual to entire ecosystems. Ecological changes already associated with climate change include shifts in plant communities, changes to marine fisheries production and altered avian migration timing (Walther et al 2002). Another impact of climate change has been the expansion of the tropical belt by 2.0°–4.8° latitude between 1979 and 2005, a change that had not previously been predicted to occur until the end of the twenty-first century (Seidel et al 2008).
The widening of the tropical belt has many implications for ecological systems, including the potential expansion of tropical and sub-tropical diseases, their infectious agents, and vectors that are affected by climatic conditions (McMichael et al 2006). One such vector-borne disease is dengue, which is resurging to become ‘the most important vector-borne virus’ (Campbell-Lendrum and Corvalán 2007). Previous studies have examined the potential impacts of climate change on dengue at a global scale (e.g., Jetten and Focks 1997, Patz et al 1998, Hales et al 2002). However, the purpose of this study was to investigate the dynamics of a dengue outbreak at a local scale and to determine how climate change may potentially alter these dynamics.

As a test case, we examined the risk of potential dengue outbreaks for Atlanta, GA, Chicago, IL and Lubbock, TX. We chose these cities because all near the edge of the current range of Aedes albopictus. Additionally, Atlanta and Lubbock are near regions that currently have endemic dengue, and are therefore at risk as dengue’s range expands (Jetten and Focks 1997). We first used a population model (described previously in Erickson et al 2010a) to examine the potential response of population dynamics of the Asian tiger mosquito (Aedes albopictus) to climate change. The Asian tiger mosquito is an important dengue vector that often outcompetes dengue’s other primary vector, the Yellow fever mosquito (Aedes aegypti; Gratz 2004).

Specifically, we examined three hypotheses. First, we predicted that projected temperature changes would increase the season length for Asian tiger mosquitoes. Second, we expected larger mosquito population sizes under predicted conditions compared to model outputs for present conditions due to more favorable climatic conditions. Third, we hypothesized that the potential dengue season (which depends on a variety of factors in addition to the availability of vectors) under projected conditions would be longer than the potential season (assuming dengue introduction) under current conditions. To test this final hypothesis, we used a previously described dengue model (Erickson et al 2010b).

2. Methods

To examine potential changes in the population dynamics of the Asian tiger mosquito caused by projected climate change, we used an existing stage-structured population model. This model used ordinary differential equations to describe the life stages of the Asian tiger mosquito (Erickson et al 2010a; figure 1(a)). Six life stages were modeled, including egg, larvae, pupae, immature adults, gestating adults and reproducing adults. The three adult stages were included because new adults are not able to feed until a day after emerging. In addition, the gestating period varies based upon temperature. The model contains parameters that are forced by temperature, using climate projections to assess potential changes in future population dynamics. The relationships between parameters and temperature were based on current literature and have been described previously (Erickson et al 2010a). Furthermore, model stability, behavior and parameter sensitivity also have been examined (Erickson et al 2010a).

The potential change in dengue disease dynamics was examined using an existing dengue model (Erickson et al 2010b; figure 1(b)). This model incorporated the previously described population model into a disease model containing Susceptible, Exposed, Infectious, Recovered (SEIR) human disease (dengue disease) model with a stage-structured vector (Ae. albopictus) model. Observed temperature data for current years (1980–2010) came from the Hartsfield Atlanta International Airport, Atlanta, GA, the O’Hare International Airport, Chicago, IL and US Department of Agriculture’s (USDA) Wind Erosion and Water Conservation Unit in Lubbock, TX. These cities were chosen as test cases because they are on the edge of the Asian tiger mosquitoes range within North America. A seven-day moving mean of the average daily temperature was used to increase numerical stability of the simulation. Our analysis of future conditions is based on simulations from four atmosphere–ocean general circulation, or climate, models: NCAR/CCSM3, a mid-range sensitivity model (Collins et al 2005); UKMO/HadCM3, a mid-high sensitivity model (Collins et al 2001); NOAA/GFDL CM2.1, a mid-high sensitivity model (Delworth et al 2005); and DOE/NCAR PCM, a low sensitivity model (Washington et al 2000). Future simulations are forced by the IPCC Special Report on Emission Scenarios (SRES, Nakićenović et al 2000) higher (A1fi) and lower (B1) emissions scenarios. Together, these scenarios bracket the range of IPCC non-intervention emissions futures with atmospheric CO₂ concentrations.
reaching approximately double and triple pre-industrial levels, at 550 ppm (B1) and 970 ppm (A1fi), by 2100.

We used downscaled model outputs for weather stations at the Hartsfield Atlanta International Airport, Atlanta, GA (ATL), the O’Hare International Airport, Chicago, IL (ORD) and the Preston Smith International Airport, Lubbock, TX (LBB). The methods used to downscale these data were similar to methods previously described (Hayhoe et al. 2004), and we used a seven-day moving mean of the average daily temperature for both mid-century projections (2035–65) and end of century projections (2069–99). Temperature projections for both mid-century and end of century projections had greater means, and standard deviations, than the observed seven-day mean values from 1980 to 2010 (table 1). Thus, the projected temperatures are not only warmer, but also more variable than current conditions.

We ran the population model using current temperatures, mid-century, and end of century projections for all three cities with projections from all four models and with both climate change scenarios. Thus, nine simulations were run for each test case city. Results based upon the mid-century and end of century simulations were summarized for each climate scenario using a mean and 95% confidence interval to examine the potential impact of climate change on the disease dynamics of dengue, we ran the disease model using parameters described previously in Erickson et al. (2010a) with mosquito dynamics being forced by the previously described temperature projections. For these simulations, the population model was run for the year preceding the arrival of 10,000 infectious vectors to allow the vector population to reach its deterministic trajectory. We used 19 different arrival dates, beginning with day 62 (3 or 4 March) and increasing by 14 days until day 314 (10 or 11 November). We also ran the simulation partway into the year after the arrival to examine if the dengue outbreak could overwinter. Thus, each disease simulation was run for 1000 days. We recorded the outbreak size as the number of recovered humans, and we calculated the mean and 95% confidence interval for each outbreak date. Results were summarized similar to the population model outputs.

3. Results

3.1. Population model outputs

Our initial hypotheses about how climate would alter the population dynamics of the Asian tiger mosquito were partially supported by model results (figure 2). Atlanta and Lubbock both saw the mosquito season increase in length for both mid and end of century simulations. However, mid-summer temperatures became too warm for *Ae. albopictus* in the end of century projections, and this resulted in a bimodal abundance distribution. Moreover, by the end of the next century, the mosquito population had decreased in both Lubbock and Atlanta, primarily due to an increase in mosquito mortality rates caused by increased temperatures. Alternatively, in Chicago, the dynamics were similar to what we had hypothesized: season length and population size increased.

3.2. Disease model outputs

For both emission scenarios (figure 3), the arrival date of infected Asian tiger mosquitoes was an important factor in determining outbreak size. For example, a bimodal distribution of the total number of recovered humans existed as the arrival day changed. In general, if the infected mosquitoes arrived as the susceptible mosquito population was increasing, then the epidemic would be larger than if the mosquito population was decreasing. Also, epidemic outbreaks were larger when the mosquito population was larger and stable. Compared to the disease model with present temperatures, the season lengths when dengue outbreaks could occur were greater. However, the outbreaks that occurred under projected conditions infected a smaller portion of the human population than outbreaks under current temperatures. Higher mid-summer temperatures increase Asian tiger mosquito mortality, which in turn decreases the vector lifespan and limits the extrinsic incubation of dengue.

4. Discussion

The Asian tiger mosquito is an important mosquito species of both epidemiological and ecological importance. Low winter temperatures currently limit the range of this species within North America (Swanson et al. 2000, Roiz et al. 2011), and cold winters currently prevent the establishment of the Asian tiger mosquito in locations such as the Northeastern USA (Andreadis 2009). Therefore, projected climate change will likely change the distribution and abundance of this species through time and space. Additionally, understanding how climate change alters the ecology of this species is

| City | Atlanta, GA | Chicago, IL | Lubbock, TX |
|------|-------------|-------------|-------------|
| Emission scenario | Present | A1fi | Mid | End | Present | A1fi | Mid | End | Present | A1fi | Mid | End |
| Time period | | | | | | | | | | | | |
| Mean (°C) | 17.0 | 18.6 | 20.2 | 18.2 | 19.3 | 9.8 | 13.1 | 15.2 | 12.8 | 13.7 | 16.0 | 18.4 | 20.5 | 17.9 | 18.9 |
| SD (°C) | 7.7 | 8.2 | 8.2 | 8.1 | 8.2 | 10.5 | 10.8 | 10.7 | 10.7 | 10.6 | 8.6 | 9.3 | 9.2 | 8.8 | 8.9 |
| Min (°C) | −6.4 | −4.7 | −5.5 | −4.5 | −2.8 | −21.1 | −17.0 | −5.5 | −18.0 | −2.6 | −11.1 | −6.8 | −6.7 | −8.7 | −6.2 |
| Max (°C) | 32.4 | 31.5 | 32.8 | 31.8 | 34.2 | 29.7 | 31.8 | 33.0 | 31.8 | 31.9 | 32.3 | 34.0 | 35.2 | 34.0 | 34.3 |
Critical to understanding how vector-borne infectious diseases such as dengue will shift with changing climates (Randolph 2009). However, the relationships between climate change and ecological systems are often complex, and such complex interactions often are nonlinear and difficult to predict prior to the change (Adger et al. 2009).

Our initial hypotheses about expanding temporal seasons and population sizes demonstrate the difficulty of predicting the future. While our predictions were correct for Chicago, IL, an unexpected shift occurred in Atlanta, GA and Lubbock, TX where the dengue seasons increased in length, but peak population sizes decreased and peak numbers shifted to a spring and fall peak rather than a summer peak. The impactions of climate change on the Asian tiger mosquito also impacted the dynamics of dengue in an unpredicted, but similar fashion. This finding supports the general hypothesis that climate change will shift, rather than expand the spatial range of some diseases (Lafferty 2009a). This hypothesis is not without controversy, but it demonstrates the profoundly different results that can occur by studying different spatial scales (e.g., global compared to local models; Lafferty 2009b). The simulations for Chicago show how the potential...
for dengue increases at higher latitudes, which is in agreement with previous studies that only directly examined dengue, without explicitly considering its vector (Jetten and Focks 1997, Patz et al 1998, Hales et al 2002).

Our initial assessment about the potential impact of climate change on dengue and its vector, the Asian tiger mosquito, raises several additional questions for future research. First, will the patterns observed in the three test case cities hold on a broader geographic scale? Second, will the Asian tiger mosquito adapt to hotter summer peak temperatures? If so, how will this impact the potential for dengue outbreaks? Even if the Asian tiger mosquito adapts to live through hotter summer, the risk for dengue may not increase because the individual’s lifespan may still be shorter than the virus’s extrinsic incubation period within the mosquitoes. Ecological change can result in rapid evolutionary change, although the exact rate of this change is unknown and varies among species (Pelletier et al 2009). Furthermore, the Asian tiger mosquito subspecies that currently lives within North America does not appear to be adapting to different temperatures across its range, despite being present since the 1980s (Leinsnham et al 2008). The third question that deserves attention is, how might climate change alter competition with other Aedes spp.? Currently, the Asian tiger mosquito outcompetes the yellow fever mosquito (Aedes aegypti), but will this still occur in future climate situations? Additionally, what if another mosquito Aedes spp. arrives?

The other major component of climate change that will directly impact mosquito population dynamics is precipitation. Although water (e.g., humidity, rainfall, evaporation) plays an important role in mosquito life history, modeling the impacts of water is much more complex than modeling the impacts of temperature. For example, the Asian tiger mosquito breeds in trees and containers, and this habitat size (an important component of the carrying capacity for mosquito species) depends upon not only precipitation, but also evaporation. To complicate matters further, the way in which changes in precipitation as a consequence of climate change will translate into changes in mosquito habitat are unclear. Not only will the amount of precipitation likely change, but the frequencies and patterns of precipitation will likely change as well. These changes will interact with changes in temperature to impact both evaporation and relative humidity. However, studies directly assessing the impacts of these aspects of moisture availability on various mosquito life history characteristics are lacking. Although accounting for these factors will greatly increase the complexity of future modeling efforts (e.g., see Focks et al...
1993 for a yellow fever mosquito (Aedes aegypti) population model that considers these factors, model development must focus on incorporating water related conditions (e.g., precipitation, humidity, evaporation).

5. Conclusion

The impact of climate change on dengue will likely change the distribution and seasons of this disease. Our test case results demonstrate some possible outcomes of how climate change can alter disease dynamics. These findings may be useful in assessing how climate change will impact human populations as dengue’s range spreads north across the United States of America.

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