Climate Models Go Viral: Simulating Climate and Environmentally Driven Infectious Diseases

Cory Morin
NASA Postdoctoral Program Fellow
cory.morin@nasa.gov
Climate Variability and Change

- Shift in mean and variance
- Increase in frequency of extreme conditions

IPCC 2013
Outline of Presentation

• Background on climate and health
  • Climate change and vulnerability
  • Health effects and disease ecology

• Systems modeling

• Steps in climate and health research
  • Simulation of disease incidence (San Juan, PR)
  • Investigation of outbreaks (Hermosillo, MX)
  • Disease forecasting (San Juan, PR)
  • Projected risk under future climate (Southern US)

• Conclusions and Future work
Climate Change Deaths

- 150,000 lives annually over last 30 years (WHO)
- Who & where? How & why?

WHO estimated mortality attributable to climate change by the year 2000
Climate Effects on Human Health

Pathogens
- Vector-borne
- Water-borne
- Air-borne

Extreme Temperatures

Extreme Weather
- Flooding
- Hurricanes
- Tornadoes

Air Quality
- Pollen
- Ozone
- Particulate Matter
Interdisciplinary Research

Risk
- Vulnerability
  \[ V = f(E, S, A) \]
- Exposure
- Sensitivity
- Adaptive Capacity

Environmental Stimulus

Social Resilience

Human Systems

Disease

Natural Systems

Interdisciplinary Research
- Social Science
- Epidemiology
- Geography
- Disease Ecology
- Climate Science
Challenges in Climate and Health Research

- Reporting problems
  - Misdiagnosis
  - Subclinical cases
  - Reporting errors/bias
  - Availability of data

- Knowledge gaps
  - Incubation periods
  - Transmission probabilities
  - Evolution and adaptation of virus and human immunity

- Human vs. climate influences
  - Socioeconomic status
  - Microclimatic influences
  - Human adaptations to climate
Infectious Disease Transmission Cycles

Anthroponoses

TB, measles

Human Diseases

Direct transmission

HUMANS ➔ HUMANS

malaria, dengue

Indirect transmission

HUMANS ➔ VECTOR/VEHICLE ➔ HUMANS

Zoonoses

Animal Diseases

rabies

ANIMALS ➔ ANIMALS ➔ HUMANS

West Nile virus, Lyme

ANIMALS ➔ VECTOR/VEHICLE ➔ ANIMALS ➔ VECTOR/VEHICLE ➔ HUMANS

National Research Council, 2001
## Vector-borne Diseases in the US

### Dengue Viruses
- Annually ~ 96 million cases of symptomatic disease (WHO)
- Endogenous transmission in Texas and Florida
- Symptoms: muscle and bone ache, fever, and hemorrhagic manifestations in rare cases

### West Nile Virus
- In the US: 39,557 cases of disease and 1,668 deaths (CDC, 1999-2013)
- Disease ranges from mild fever to encephalitis and meningitis
- Now endemic in most of the United States

### Lyme Disease
- Transmitted by the tick *Ixodes scapularis* (*Ixodes pacificus*)
- Symptoms: rash, joint pain, headaches, arthritis
- 11-30,000 cases per year in US

### Chikungunya Virus
- In 2013 first locally acquired cases reported in the Americas
- Symptoms include fever, joint pain, headaches, and rash
How does weather/climate affect mosquito-borne disease risk and can it be predicted?

- Increases in the range of diseases
- Increases in the seasonality of diseases
Epidemiologic Triangle of Disease (Vector-borne Diseases)

- A *multi-factorial* relationship between hosts, agents, vectors and environment
“A system is an interconnected set of elements that is coherently organized in a way that achieves something.”

- Donella H. Meadows

• Why this method?

• Allows us to consider multiple elements of disease ecology and nonlinear relationships
Modeling Aedes aegypti and Dengue Virus Ecology
Simulating Dengue Fever in San Juan, PR

- Vector population are not always reliable measures of transmission risk
  - Added pathogen and human transmission component to the model

- *Aedes aegypti* mosquitoes
  - Urban, container breeding
  - Live in tropical habitats
  - Anthropophilic

- San Juan, PR
  - Tropical climate
  - Seasonal precipitation
  - Endemic dengue
  - Seasonal cycles of transmission
Data and Methods

• Study Area
  • San Juan Municipality, Puerto Rico

• Meteorological and Health Data
  • Daily maximum and minimum temperatures and total precipitation for San Juan, PR
  • Weekly clinically diagnosed dengue case counts for 2010-2013 from CDC for San Juan Municipality, PR

• Model
  • Parameterized for *Aedes aegypti* mosquitoes
  • Daily time step
  • Run over time period 2009-2013 under varying parameters
    • 9600 runs
  • Chose best 1% of runs by comparing output to CDC reported data
Simulation Results (By Year)

A
2010
$R^2 = 0.90$

B
2011
$R^2 = 0.83$

C
2012
$R^2 = 0.94$

D
2013
$R^2 = 0.25$
### Parameter Statistics

- **Open containers vs. water storage**
  - Climate dependence
  - Socioeconomic dependence

#### Proportion Uncovered Container

<table>
<thead>
<tr>
<th>Proportion Uncovered Container</th>
<th>All</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0</td>
<td>44</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
<td>32</td>
<td>37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>4</td>
<td>18</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
<td>8</td>
<td>14</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>96</td>
<td>8</td>
<td>5</td>
<td>76</td>
<td>96</td>
</tr>
</tbody>
</table>

#### Annual Precipitation

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Precip</td>
<td>227.51</td>
<td>223.99</td>
<td>140.30</td>
<td>216.33</td>
</tr>
</tbody>
</table>
Conclusions: Modeling Dengue Fever in San Juan, PR

• Climate is a key regulator of dengue transmission in San Juan County, PR
  • Temperature limits viral replication during winter
  • Precipitation limits mosquito populations during spring

• Human response to weather and climate is important
  • Permanent water sources during dry years

• Non-climatic factors are important
  • Immunity, virus genetics, public health response
Investigating Dengue Transmission in Sonora Mexico

• Why is there little/no dengue transmission in nearby Nogales?
• Hypothesis: Climate conditions are cooler
  • Suppression of mosquito population
  • Extension of extrinsic incubation period (EIP)
• Experiments:
  • 1: Perform simulations for Hermosillo and evaluate with reported case data
  • 2: Rerun Hermosillo simulations with Nogales meteorological data
  • 3: Rerun experiment 2 with 1°C warming
Modeling Dengue Fever in Hermosillo, MX

- **Study area**
  - Hermosillo, Mexico
  - Arid climate, summer monsoon

- **Meteorological/Dengue case data**
  - Daily maximum and minimum temperatures (NLDAS)
  - Daily precipitation (TRMM, NLDAS)
  - Weekly suspected dengue cases for Hermosillo, MX 2006-2011

- **Model**
  - Parameterized for *Aedes aegypti*
  - Run from 2005-2011 (500 simulations)
  - Best 3% of runs chosen by comparison with suspected case data ($r^2$)
Model Parameter Estimation

• Containers
  • Based on household surveys (Hermosillo)
  • Human managed and open containers
  • Used mean values and +/- 25% and 50%

• Minimum infectious rate
  • Minimum amount of infectious humans
  • Maintains virus within the population
  • Based on case data and previous study in San Juan, PR

• Maximum larval density
  • Used to calculate density-dependent mortality
  • Based on observations, literature, and previous study in San Juan, PR
• 2008 and 2010 are largest dengue years

• Generally epidemics follow monsoon rains

• Precipitation magnitude has little influence on dengue magnitude

• Introduction from nearby areas is likely important
Hermosillo/Nogales Comparison: Mosquitoes

- Little/no dengue is simulated under Nogales meteorological conditions
- With warming, there is a modest mosquito population increase in 2008
  - No dengue
- Warming increases the mosquito considerably population in 2010
  - Results in increased virus transmission
Hermosillo/Nogales Comparison: EIP

- EIP is considerably longer under Nogales conditions
- Under Nogales conditions, the EIP is longer during the transmission season in 2008
  - Prevents completion of EIP during mosquito lifetime
- EIP shortened under 1°C warming conditions
  - Especially during transmission season
Conclusions

• Dengue epidemics follows monsoon rains
  • Timing is consistent, however, the magnitude is not well correlated

• Climate is an important regulator of dengue transmission in Nogales
  • Affects mosquito population dynamics and the virus incubation period
  • Year to year variability is important

• Dengue transmission dynamics in northern Mexico may affect dengue risk in the United States
  • Travel, climate change
  • Recent dengue epidemic in Nogales
Forecasting Dengue in San Juan, PR

- Produce weekly forecasts of dengue incidence using weather forecasts
  - Allow public health workers to allocate appropriate resources for disease treatment and prevention

- Meteorological data
  - Real-time numerical weather prediction (NWP) model forecasts
  - Daily min + max temp, total precipitation

- Dengue case data
  - Puerto Rico Department of Health
  - Updated weekly
Creating and Operational Model

- Iterative weekly process: using weather forecast (SPoRT) and weekly reported dengue data

  - Run multiple simulations of model using weather data
  - Evaluate model with dengue data
  - Choose best fit simulations
  - Drive model with weather forecast data
  - Make predictions based on model results
  - Small increase in dengue incidence
• Results are difficult to evaluate because of anomalously low dengue transmission due to El Nino caused drought

• Most spikes in cases are predicted

• However, not all of them
  • Algorithm has difficulty recovering from zero
Climate Change and Expanding Dengue Risk

- Dengue outbreaks in the US were common in 19th and early 20th century
  - Mostly around port cities
  - Improved public health measures largely eradicated the disease
- Recent transmission in the US
  - Along the Texas-Mexico boarder
  - Southern Florida (2009 – Pres)

Modified from Brady et al. 2010 in PLoS NTD
Modeling Dengue Risk under Projected Climate Conditions in the US

• Simulate *Aedes aegypti* populations and dengue transmission in 32 locations in the southern US
  • Use parameter values from San Juan, PR
  • Drive model with current and projected future meteorological data
    • Meteorological data produced using a weather generator trained with data from the National Climatic Data Center
    • Projected change in temperature and precipitation from the 15 global climate models run using the SRA1B scenario from IPCC AR4 report

• Simulated mosquito populations and cases are compared to San Juan, PR
  • Dengue is endemic in San Juan
  • Could not parameterize the model for US locations
  • Isolate the effects of climate / climate change
Change in Aedes aegypti Population Dynamics

• *Ae. aegypti* populations increase under projected climate conditions

• Populations near San Juan levels during summer

• Winter populations low excepts in summer Florida
Change in Dengue Transmission Dynamics

• Dengue range is more limited than that of *Ae. aegypti*

• Future summer and fall case magnitudes match those of San Juan

• Winter transmission is almost non-existent
Conclusions

• The future risk of dengue transmission is not synonymous with that of *Ae. aegypti*

• Most locations in the southern US can support dengue transmission but only for a short period during the year
  • Creates risk of small, local outbreaks

• Winter temperatures are likely a major barrier for sustained dengue transmission in the continental US
Overall Conclusions and Future Work

- Understanding climate and environmental effects on infectious disease ecology provides opportunities to simulate, investigate, and predict transmission dynamics.
- However, natural and human systems are complex and coupled, requiring interdisciplinary efforts to truly understand.
- Future research must identify methods to transition research to better public health practice.
  - Incorporate socio-economic and demographic variables into models.
  - Creation of seasonal forecasts to help preparedness.
Thank You for Your Attention!

“Pull out, Betty! Pull out! ... You’ve hit an artery!”