Cholera dynamics, multiple transmission pathways, and disease spread in Haiti

Marisa Eisenberg
University of Michigan

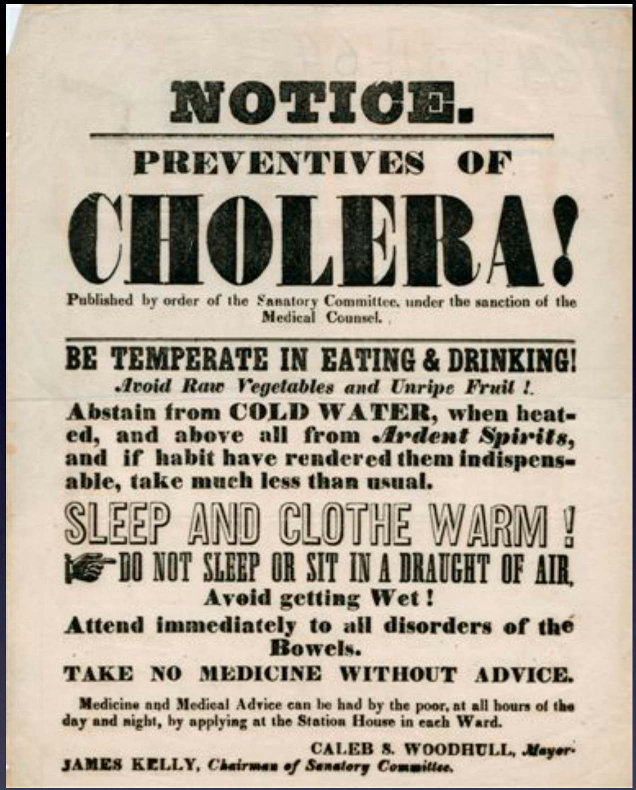
Everything Disperses to Miami
12/14/12

Outline

- Introduction to cholera
- SIWR model
- Haiti epidemic - initial outbreak - gravity model
- Spatial spread, new data - case data, human movement data, displaced person camps
- Incorporating rainfall & environmental factors
- Ongoing & future work

Introduction

- Cholera: 3-5 million cases/year and over 100,000 deaths/year
- Several pandemics during 1800's
- Recent outbreaks include Angola, Zimbabwe, Haiti (>597,000 cases, >7555 deaths)
- Endemic in many regions of India, Bangladesh, Africa, Peru


NOTICE.

PREVENTIVES OF

CHOLERA!

Published by order of the Sanatory Committee, under the sanction of the Medical Counsel.

BE TEMPERATE IN EATING & DRINKING!

Avoid Raw Vegetables and Unripe Fruit!

Abstain from COLD WATER, when heated, and above all from *Ardent Spirits*, and if habit have rendered them indispensable, take much less than usual.

SLEEP AND CLOTHE WARM!

DO NOT SLEEP OR SIT IN A DRAUGHT OF AIR.

Avoid getting Wet!

Attend immediately to all disorders of the Bowels.

TAKE NO MEDICINE WITHOUT ADVICE.

Medicine and Medical Advice can be had by the poor, at all hours of the day and night, by applying at the Station House in each Ward.

CALEB S. WOODHULL, *Mayor.*

JAMES KELLY, *Chairman of Sanatory Committee.*

Cholera

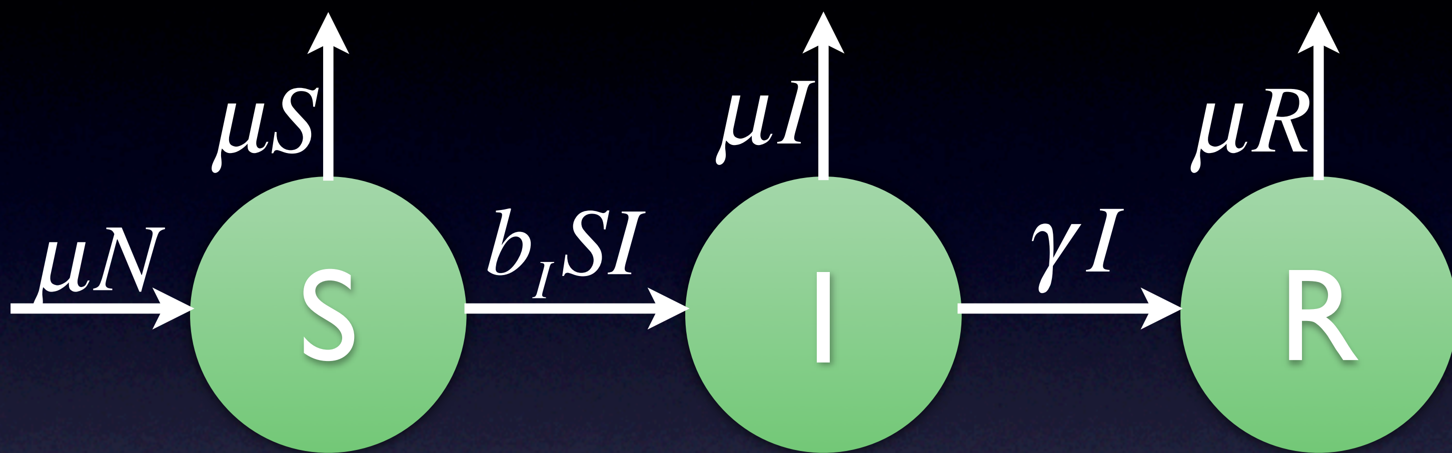
- Waterborne disease caused by bacterium *V. cholerae*
- Profuse, watery diarrhea, vomiting, dehydration
- Up to 50% fatal if untreated
- Infection-derived immunity
- Treatment: oral or IV rehydration
- Direct & environmental transmission

What are the implications of the different transmission pathways?

"In epidemic situations, a fundamental question regarding the epidemiology of cholera is: what is the relative importance of human-to-human (i.e. fecal-oral) versus environment-to-human transmission (i.e. exposure to the environmental reservoir of *Vibrio cholerae*)?"

– Hartley et al, PLoS Medicine 2006

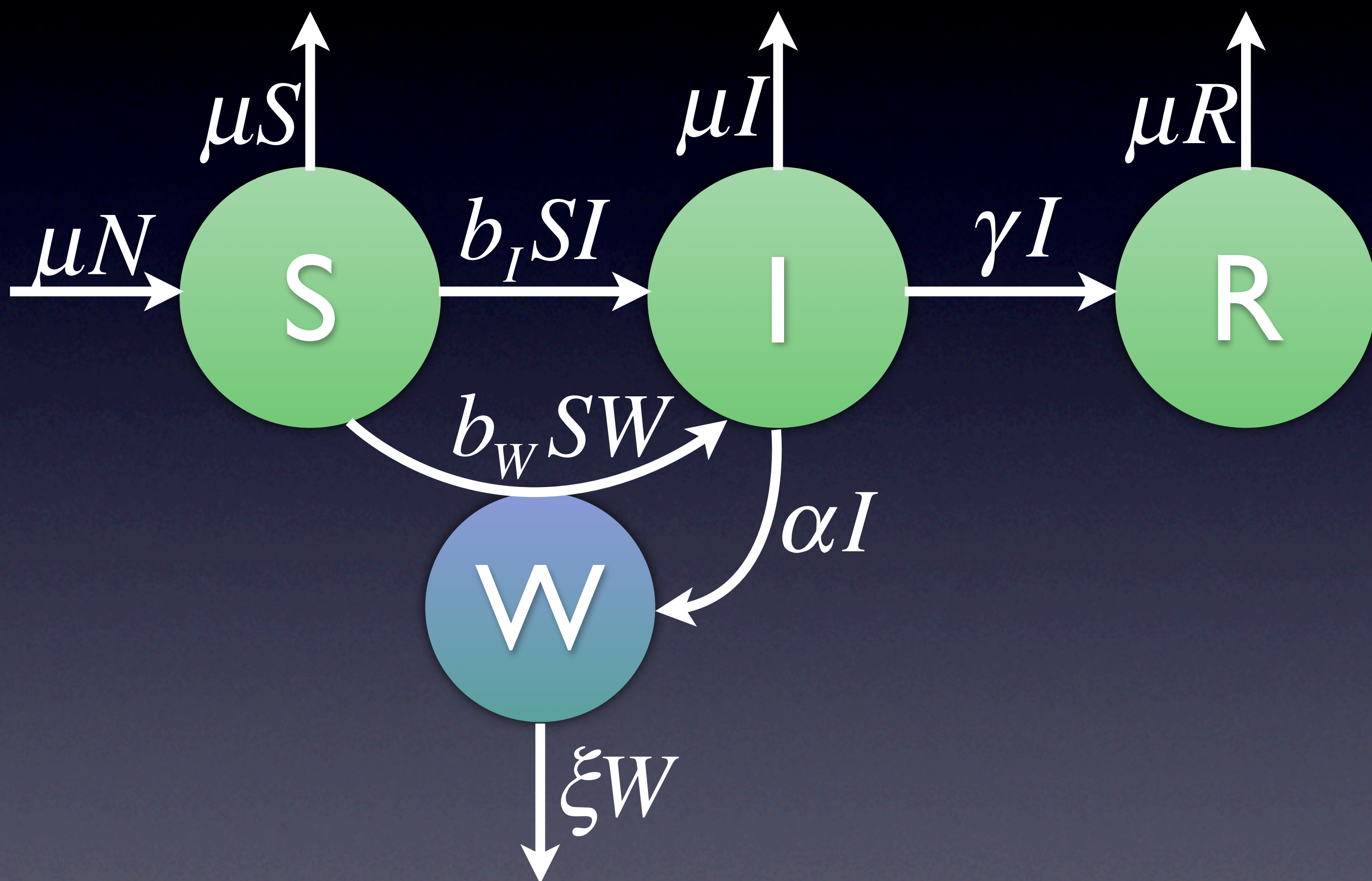
Cholera: SIWR Model



W = pathogen concentration in water reservoir

Tien & Earn, *Bull. Math. Biol.* 2010

Cholera: SIWR Model



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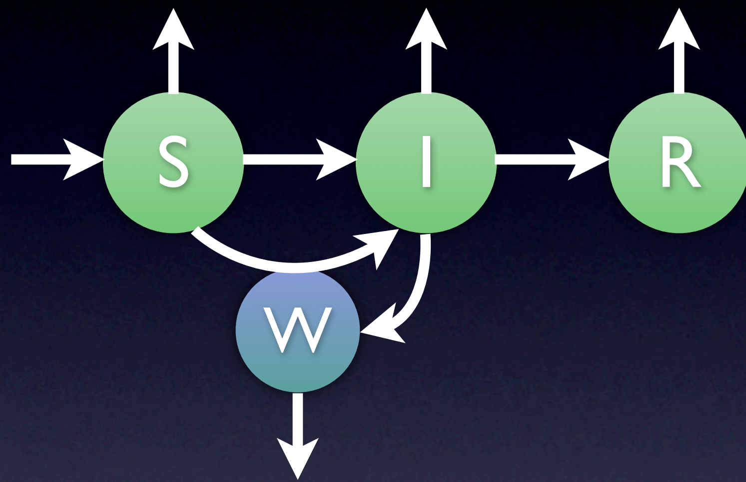
SIWR Model

$$\frac{dS}{dt} = \mu N - b_W SW - b_I IS - \mu S$$

$$\frac{dI}{dt} = b_W SW + b_I SI - \gamma I - \mu I$$

$$\frac{dW}{dt} = \alpha I - \xi W$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



$$R_0 = \frac{b_I N + b_W N \frac{\alpha}{\xi}}{\mu + \gamma}$$

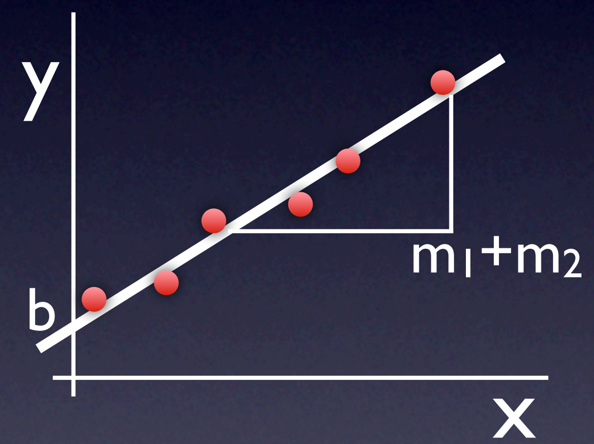
Tien & Earn, *Bull. Math. Biol.* 2010

Cholera: SIWR Model

- Can we estimate R_0? Can we predict total cases? Epidemic time course? Seasonality?
- What is the relative importance of water vs person-to-person transmission? How is cholera spreading? Water vs human movement?
- Environment (rainfall, temp, etc) effects on cholera transmission?
- Parameter estimation and identifiability for the SIWR model

Identifiability & Parameter Estimation

- Can we estimate the model parameters from the data?
  - Transmission parameters?
  - R_0?
- Identifiability - structural vs practical
  - Differential algebra approach



$$y = (m_1 + m_2)x + b$$

Eisenberg, Robertson, Tien 2012 (*Submitted*)

SIWR Identifiability

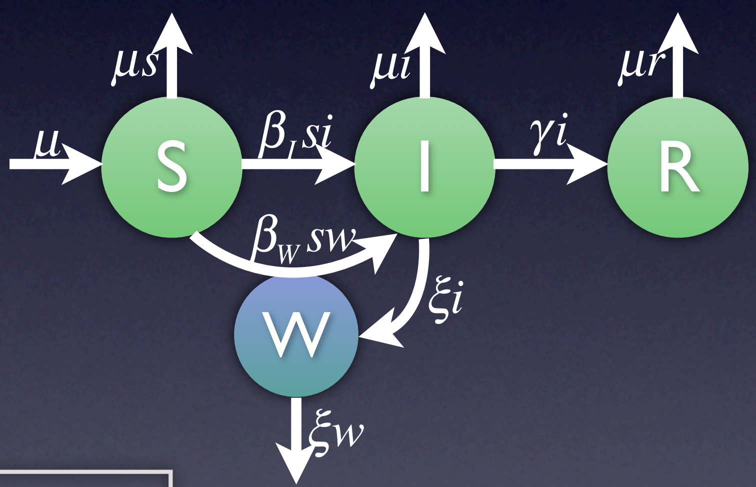
- SIWR model structurally unidentifiable
- Rescale to make globally identifiable (mostly)

$$\frac{ds}{dt} = \mu - \beta_W ws - \beta_I si - \mu s$$

$$\frac{di}{dt} = \beta_W ws + \beta_I si - \gamma i - \mu i$$

$$\frac{dw}{dt} = \xi(i - w)$$

$$\frac{dr}{dt} = \gamma i - \mu r$$



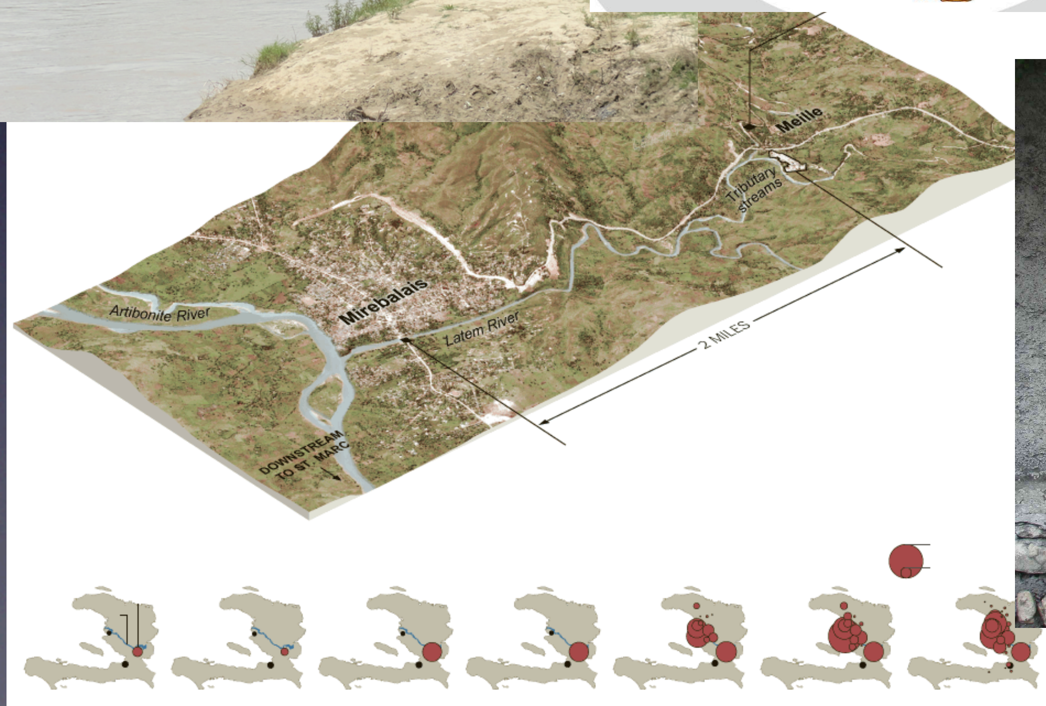
$$R_0 = \frac{\beta_I + \beta_W}{\mu + \gamma}$$

SIWR Identifiability

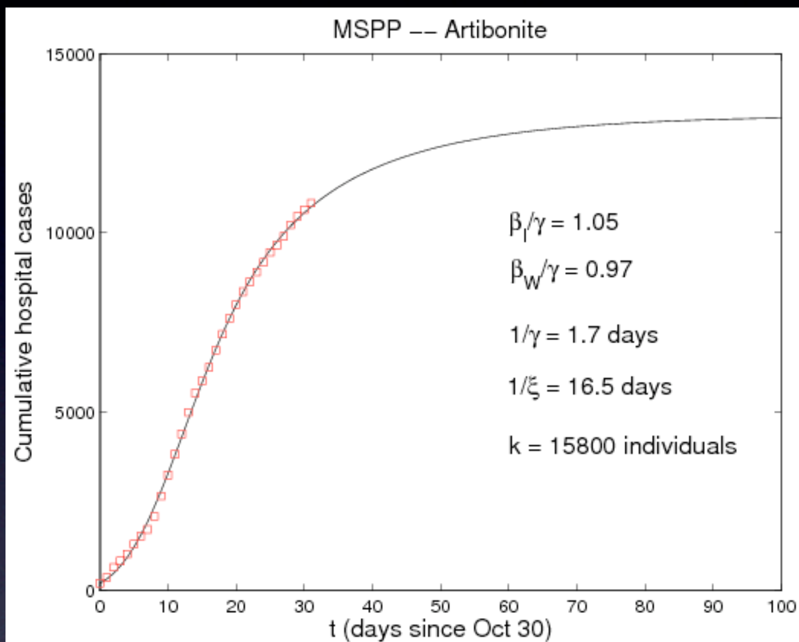
- SIWR model structurally unidentifiable
- Rescale to make globally identifiable (mostly)
  - Lose information about shedding rate α
- Identifiability can be lost if $\xi \to \infty$, yielding combination $\beta_W + \beta_I$
- Practical identifiability - dependence between β_W and $\xi \Rightarrow R_0$ unidentifiable
- Water measurements improve practical & structural identifiability

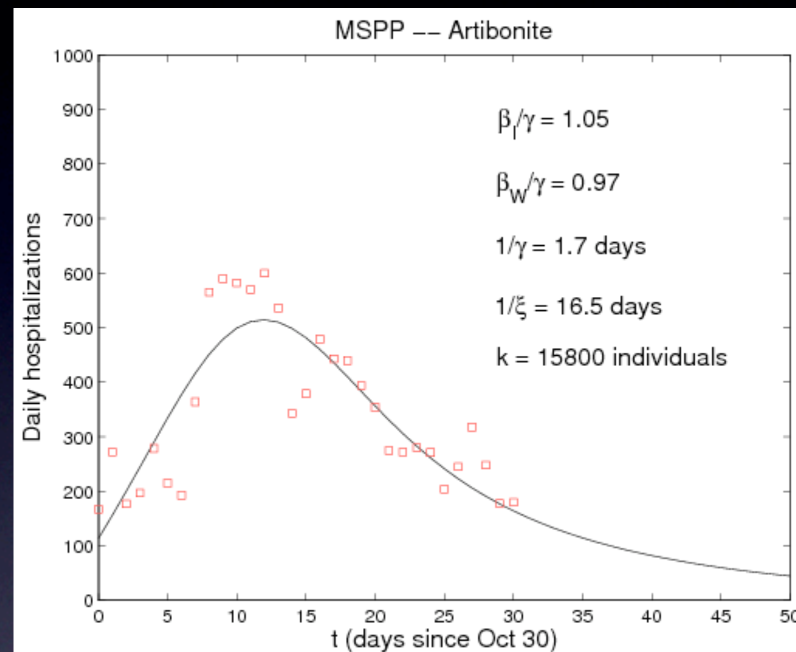
Eisenberg, Robertson, Tien 2012 (*Submitted*)

Haiti Cholera Outbreak



Artibonite Department

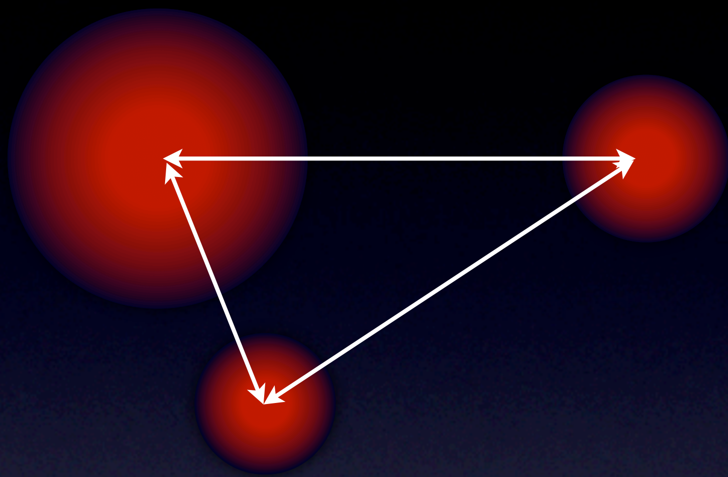




$\mathcal{R}_0 \approx 2$ $\qquad$ $1/\xi \approx 16.5$ days

- Outbreak began in St. Marc region of Artibonite Department
- Long tail in daily hospitalizations, due to persistence of V. cholerae in water

Modeling Spatial Spread in Haiti



- Multi-patch SIWR model with coupling via "gravity"
- Fit to hospitalization data from MSPP

$$\dot{s}_j = -\beta_W w_j s_j - \lambda_j s_j$$

$$\lambda_j = \sum_{j,k} \theta_{jk} i_k$$

$$\theta_{jk} = \begin{cases} \beta_j, & j = k \\ \dfrac{\kappa N_j N_k}{d_{jk}^2}, & j \neq k \end{cases}$$

Tuite, Tien, Eisenberg, et al. 2011 (*Annals of Int Med*)


Nord-Ouest
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Nord-Est
Artibonite
Centre
Ouest
Ouest
Grand-Anse
Nippes
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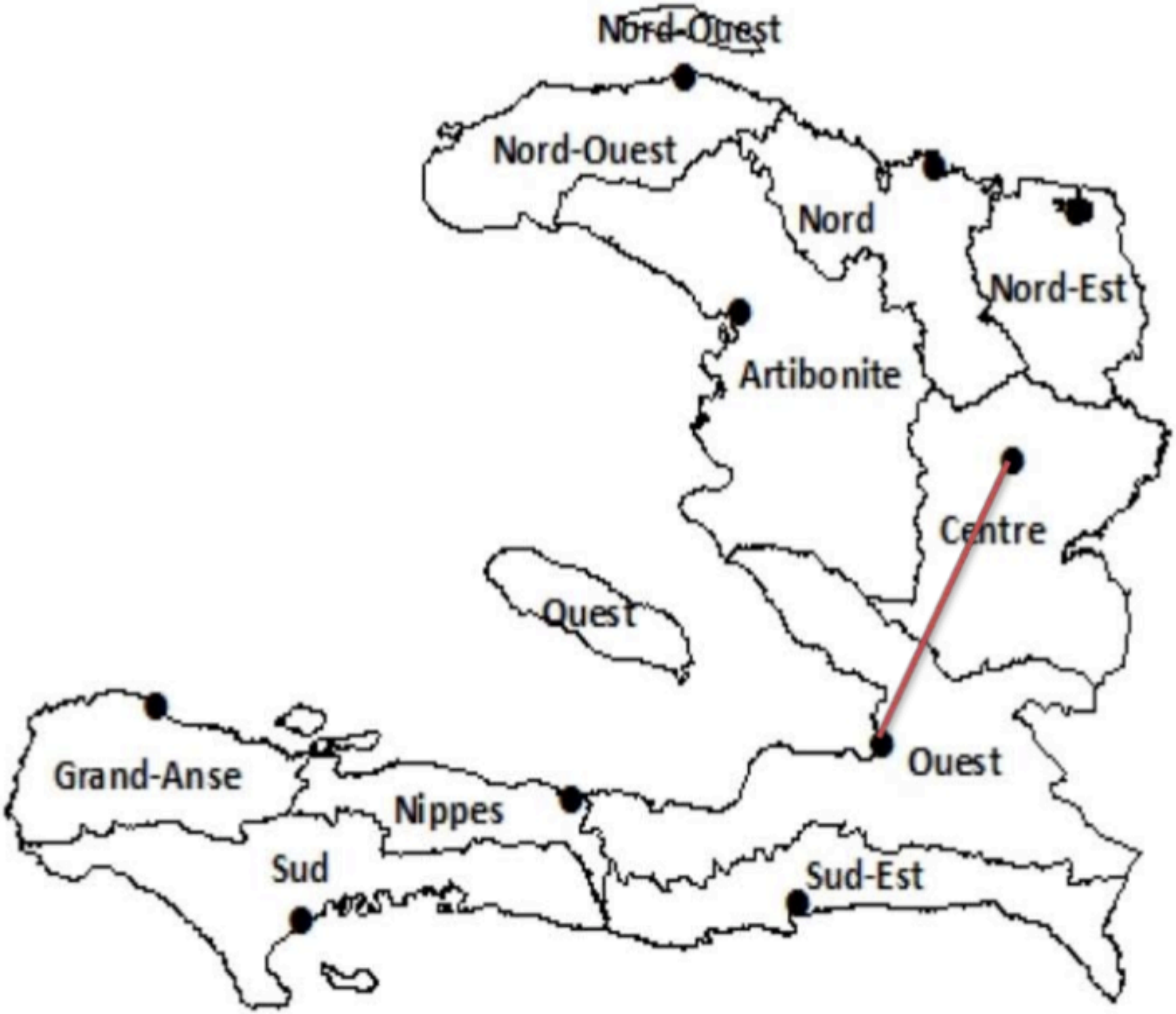
Sud-Est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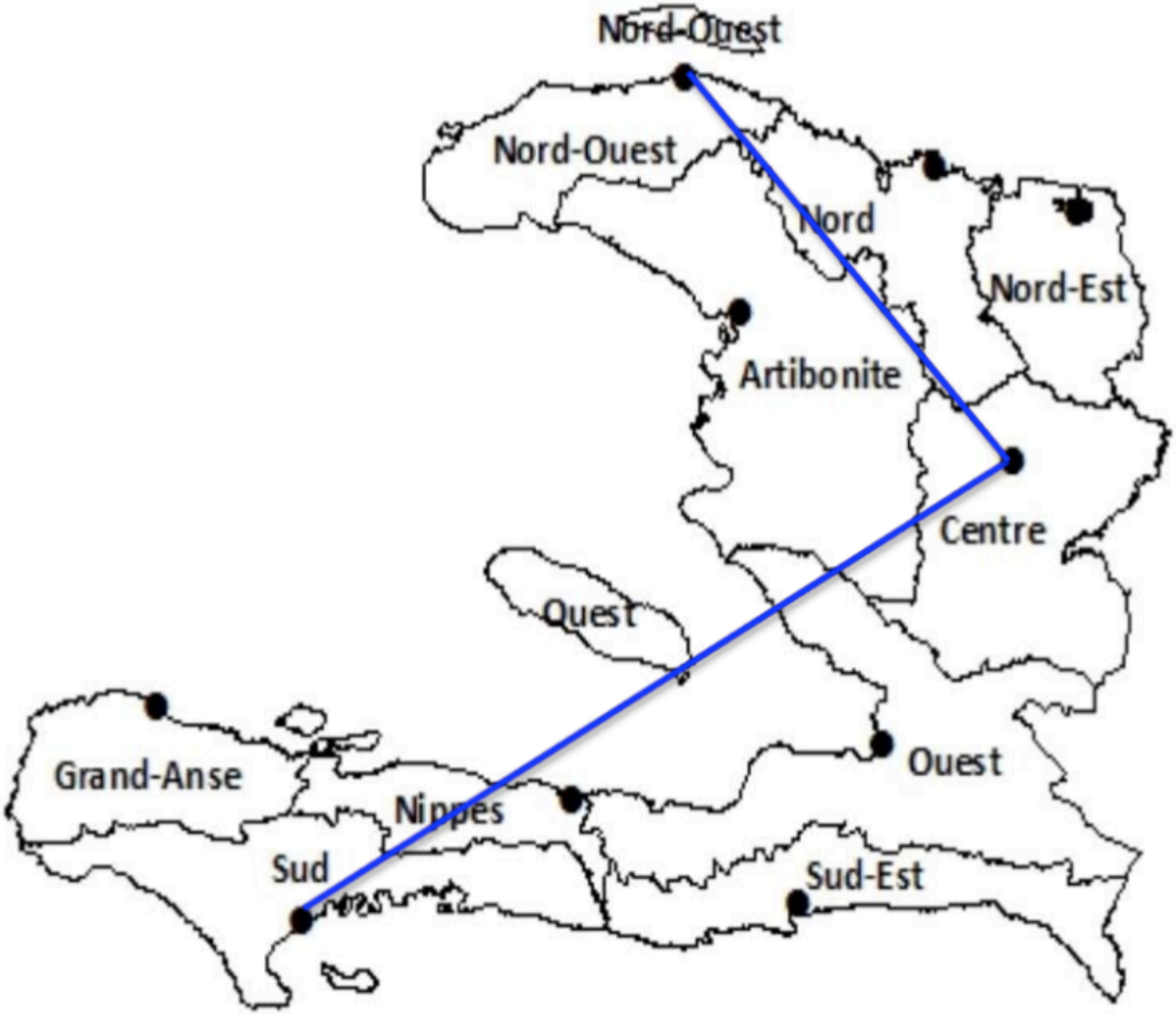

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Sud-Est

Modeling Spatial Spread in Haiti

- Fits overall epidemic dynamics well
- Predicts department ordering & initial cases well (Spearman ρ = 0.97, 0.92)
- Useful for examining effect of interventions so far, evaluating additional interventions
- Mechanistic coupling: what drives the spread of cholera? Environment? Rainfall? Seasonality?

Tuite, Tien, Eisenberg, et al. 2011 (*Annals of Int Med*)


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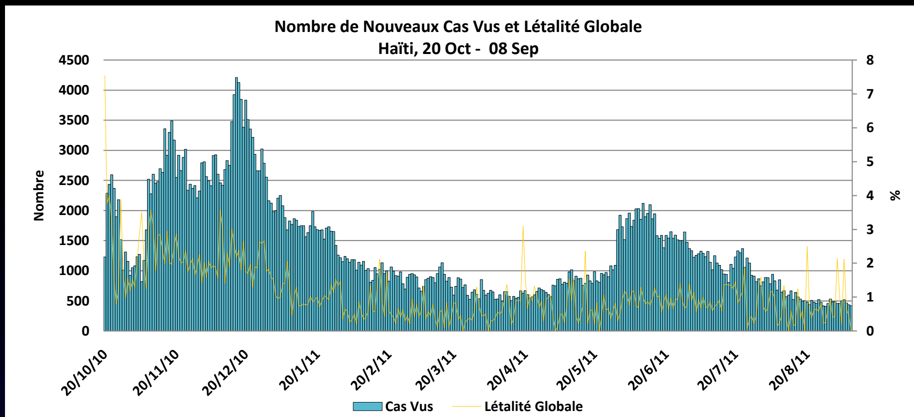
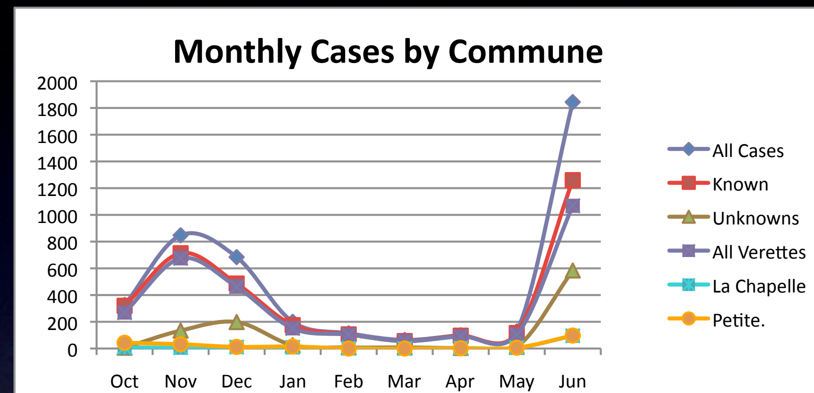
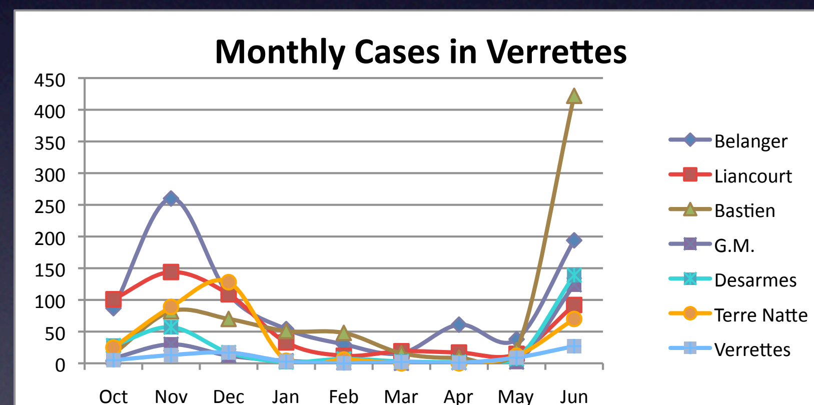
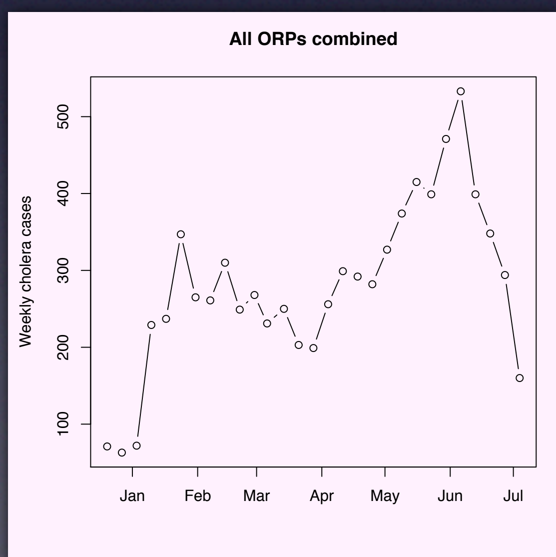
Case Data





Country, department, commune





Hôpital Albert Schweitzer
Artibonite Valley

Displaced person camps

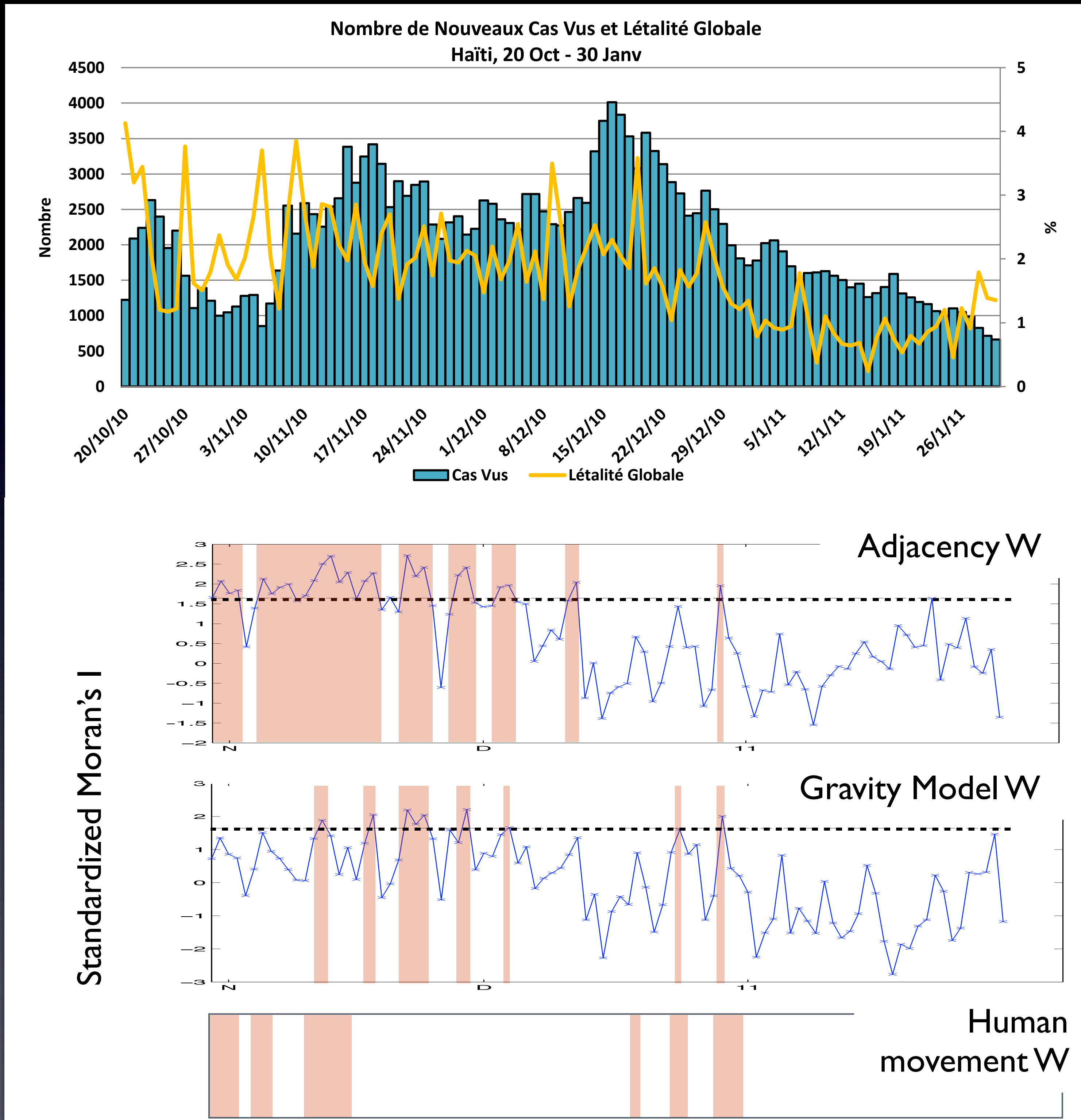
Spatial Patterns & Moran's I

- Measure of spatial clustering/patterns

$$I = \frac{n}{S_0} \sum_{i,j} W_{ij} \left(x_i - \bar{x} \right)\left(x_j - \bar{x} \right)$$

$$S_0 = \sum_{i,j} W_{ij}$$

- W = connectivity matrix
  - Human movement - cell phone data
  - Water movement - adjacency
  - Gravity model connectivity?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Nombre
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19/1/11
26/1/11
Cas Vus
Létalité Globale
Standardized Moran's I
Adjacency W
Gravity Model W
Human movement W

IDP Camp WASH Data

- Case data from >1000 camps across 13 communes
- Presence/absence data for toilets, water provision, bathing facilities, and waste management
- Chorine residuals in drinking water

Table 1: Descriptive statistics of IDP camps reporting weekly cholera cases at ORPs

Characteristic	Count (%)	Range	Mean
Presence of toilets	58 (82.9)	…	…
Presence of water provision	35 (50.0)	…	…
Presence of bathing facilities	29 (41.4)	…	…
Presence of waste management	14 (20.0)	…	…
Number of people at IDP camp	…	65 – 24500	1279
Population density of IDP camp (individuals per square meter)	…	0.9 – 117.9	17.9
Area of IDP camp	…	649.2 – 116242.2	10486.3
Cumulative number of cholera cases reported at IDP camp	…	5 - 346	82

NOTE. IDP, Internally Displaced Person.

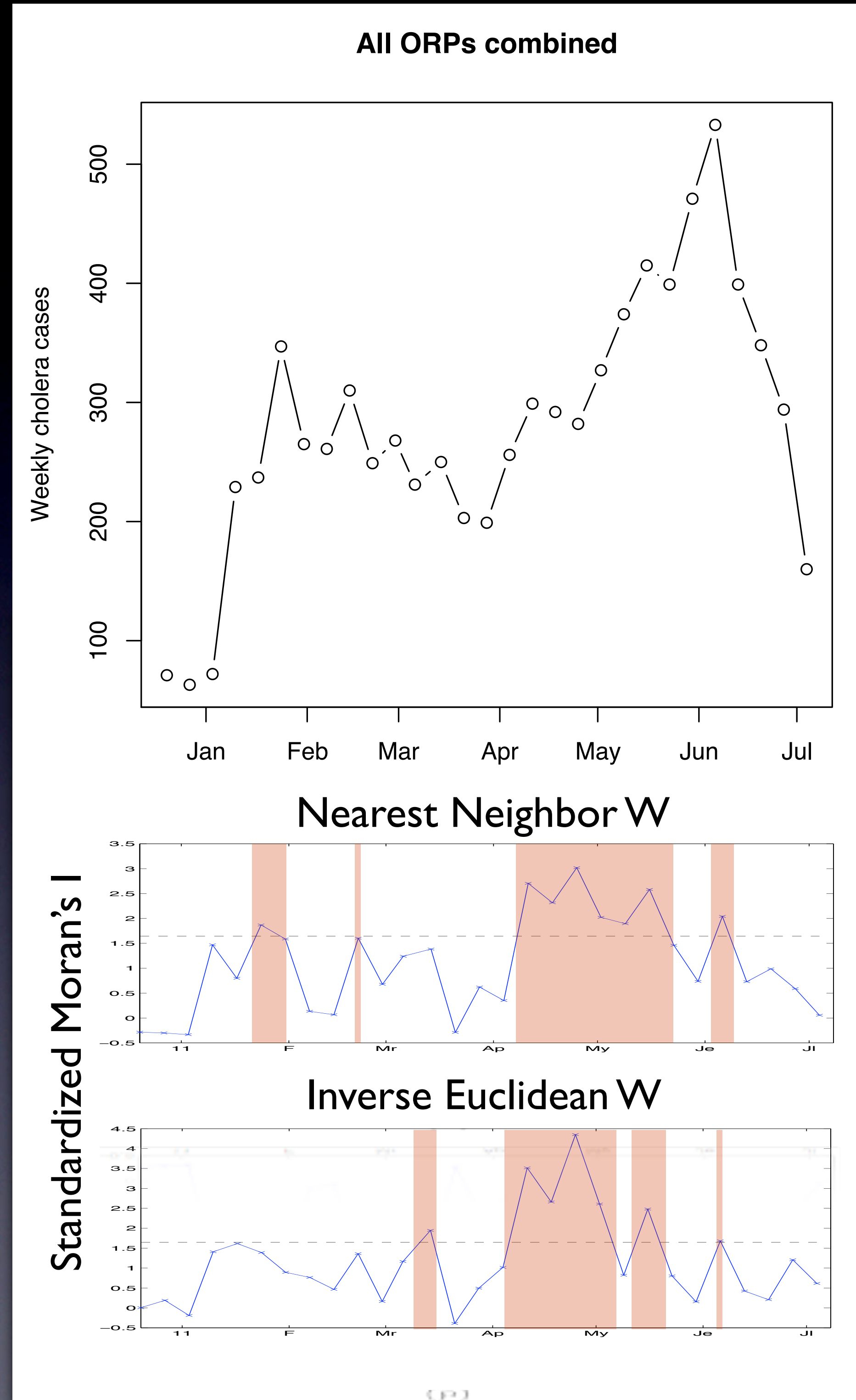

Te Roche Camp, Tabarre – June 2011

IDP Camp Wash Data

- IDP Camp cases - cholera risk
  - decreases with clean water, toilet availability, waste management
  - increases with bathing (why?)
- Kuhn-Kuenne Centroid shows initial invasion period in first months of disease

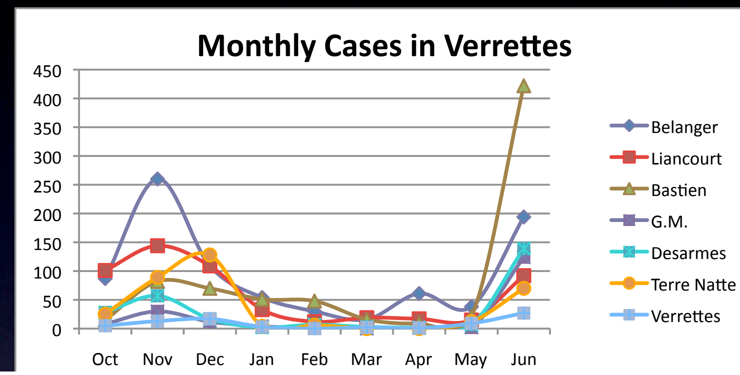
IDP Camp Moran's I

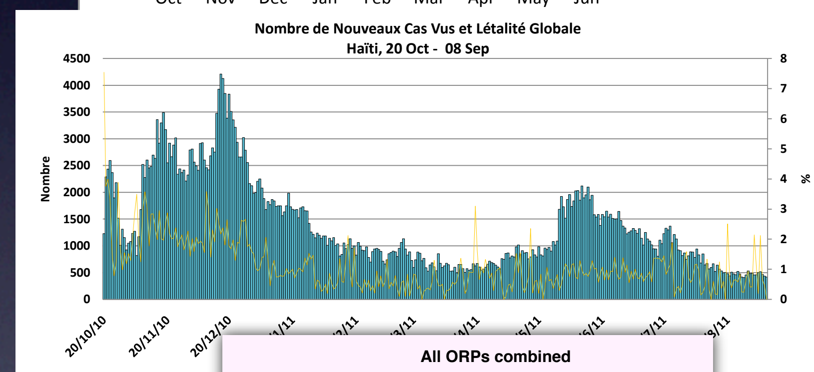
- Spatial autocorrelation/ clustering appears later
- IDP camps spared early wave of cholera, likely due to early intervention efforts of WASH NGOs

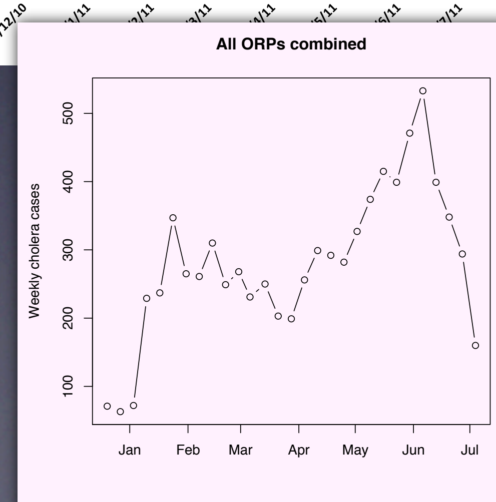


Preliminary Results

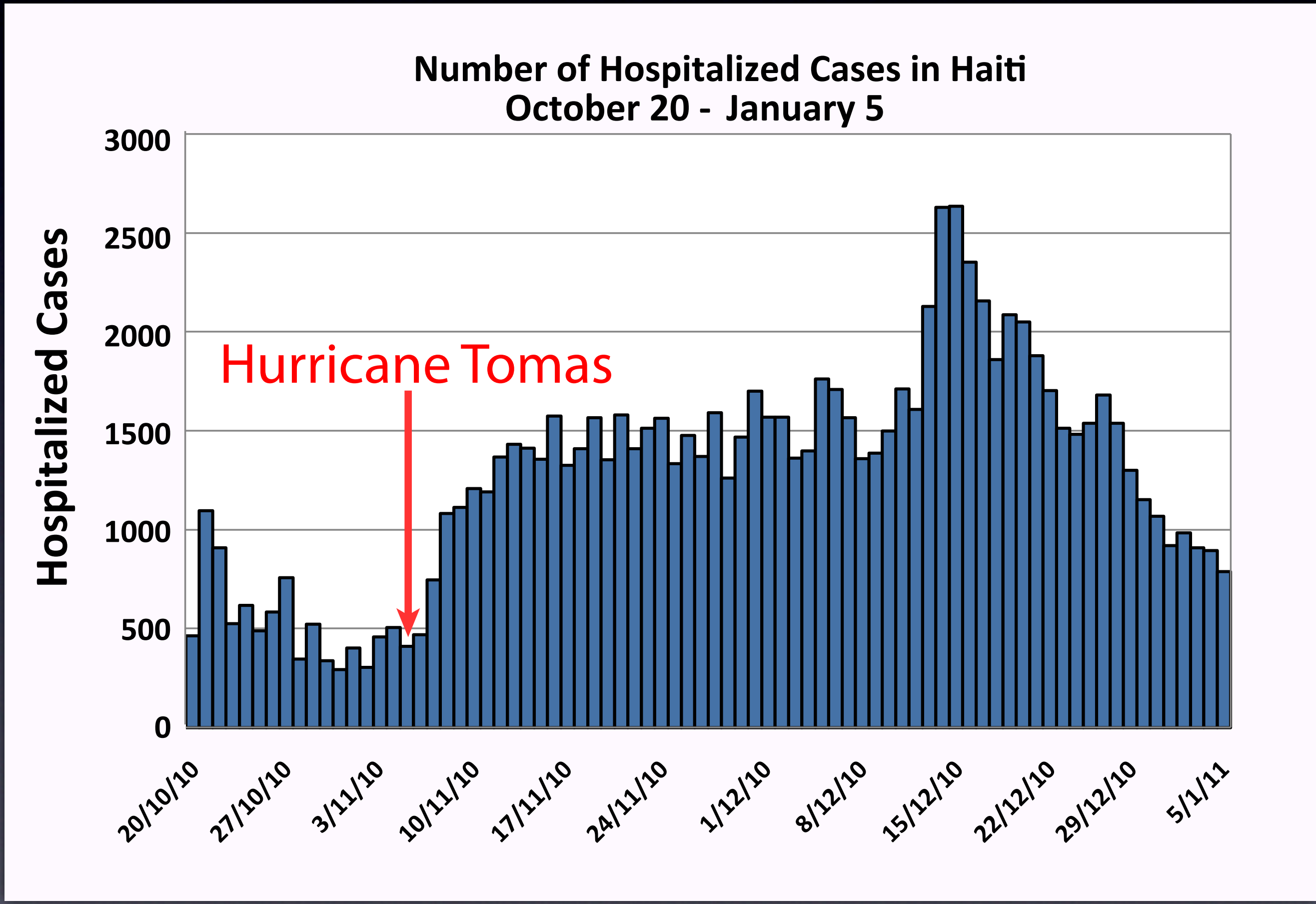
- Initial pattern of spatial spread during first weeks/months
  - Both water movement & human movement may play a role
- Summertime surge in cases seen at all levels
- Later cases - environment, rainfall important?





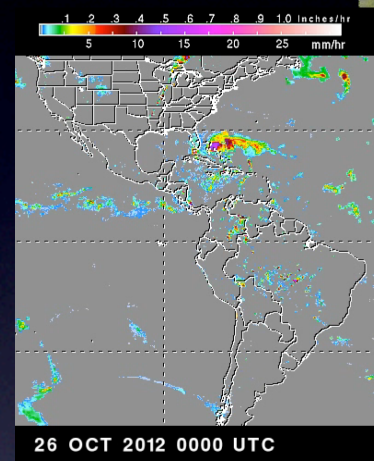


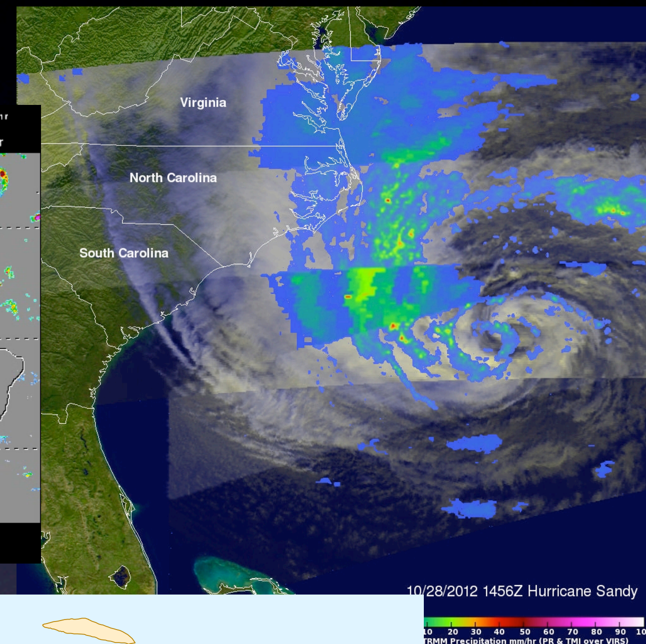
Cholera & the environment



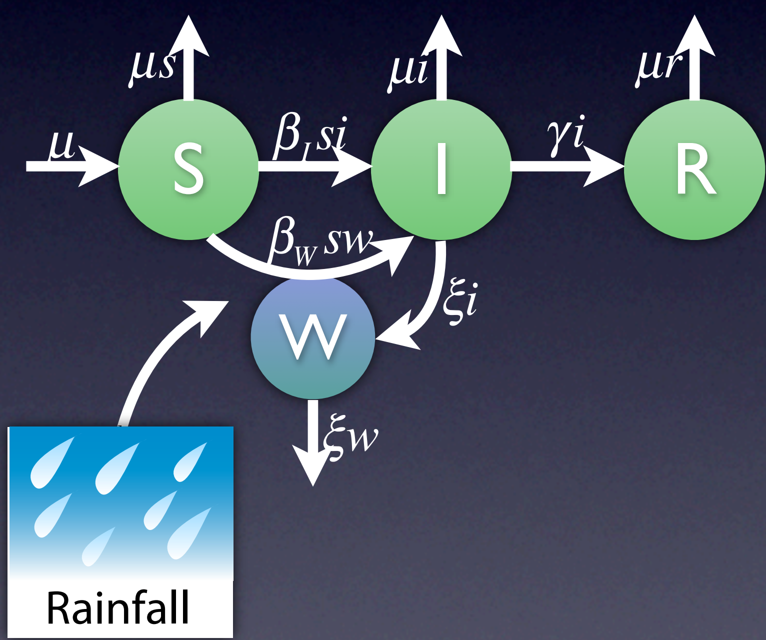
Rainfall Data

- NASA TRMM Data - satellite precipitation data (resolution 0.25° × 0.25°) averaged over each area
- USGS Rain Gauges in the Morne Gentilehomme and Foret de Pins regions





SIWR Model & Rainfall



$$\frac{ds}{dt} = \mu - \beta_W f_{rain}(t) ws - \beta_I si - \mu s$$

$$\frac{di}{dt} = \beta_W f_{rain}(t) ws + \beta_I si - \gamma i - \mu i$$

$$\frac{dw}{dt} = \xi(i - w)$$

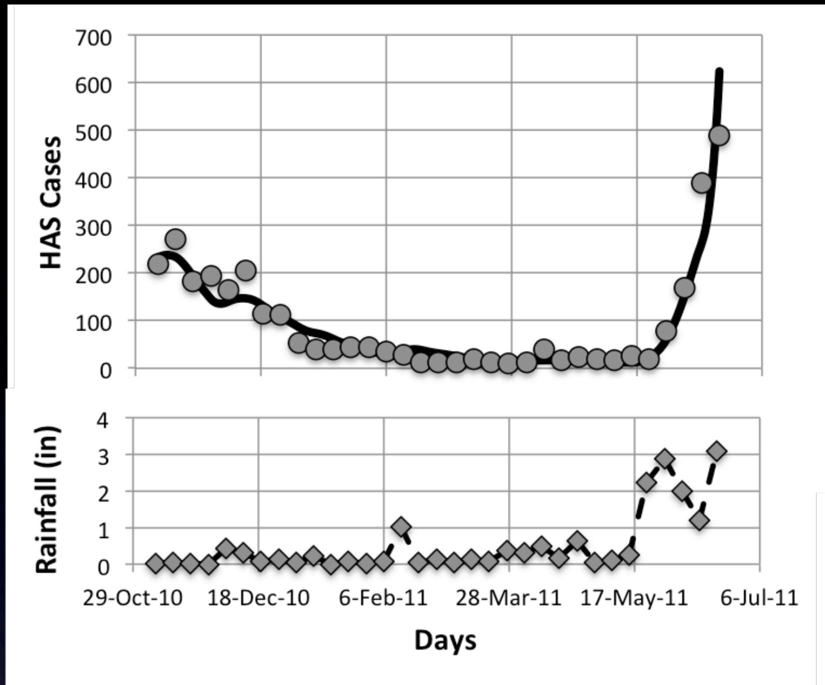
$$\frac{dr}{dt} = \gamma i - \mu r$$

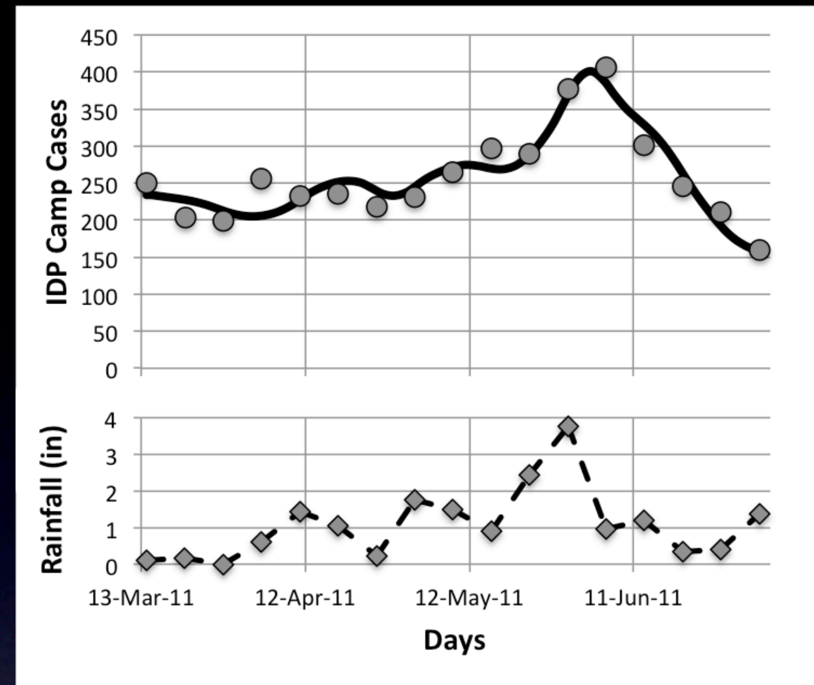
$$y = ki$$

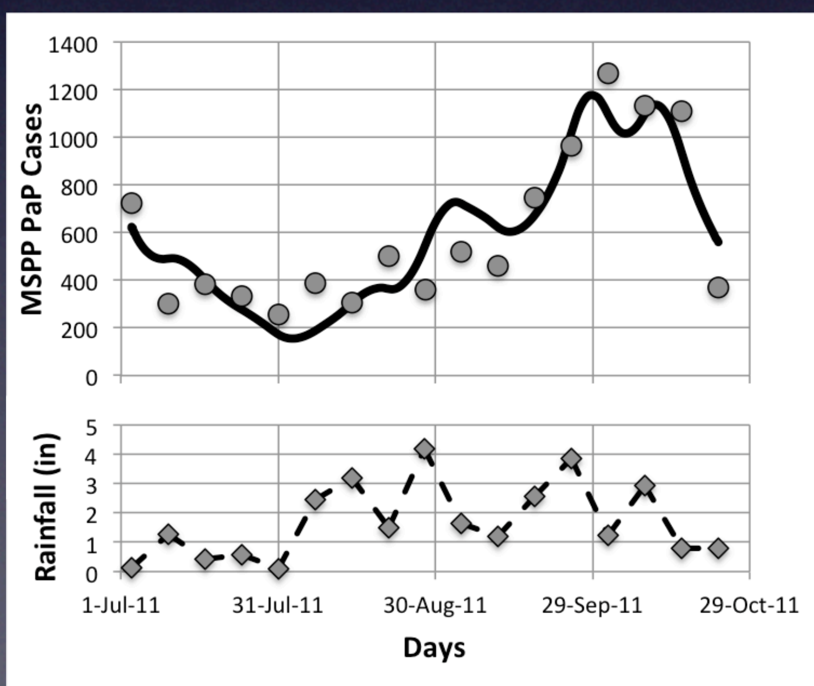
Eisenberg, Kujbida, Tuite, Fisman Tien 2012 (*Submitted*)

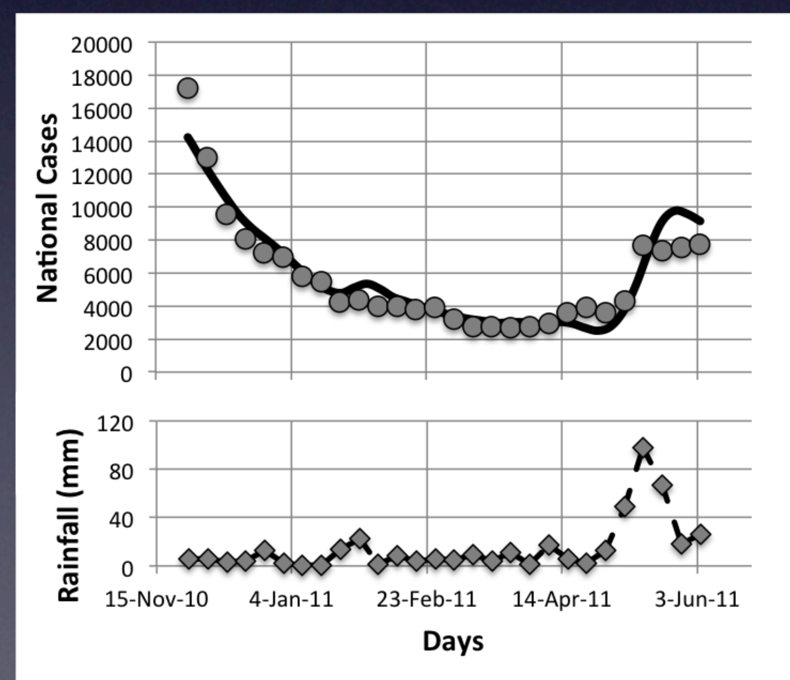
Rainfall Forcing & Identifiability

- Adding the rainfall forcing function corrects the structural identfiability problem when $\xi \rightarrow \infty$
- Allows β_W and β_I to be estimated separately
- Can also improve practical identifiability

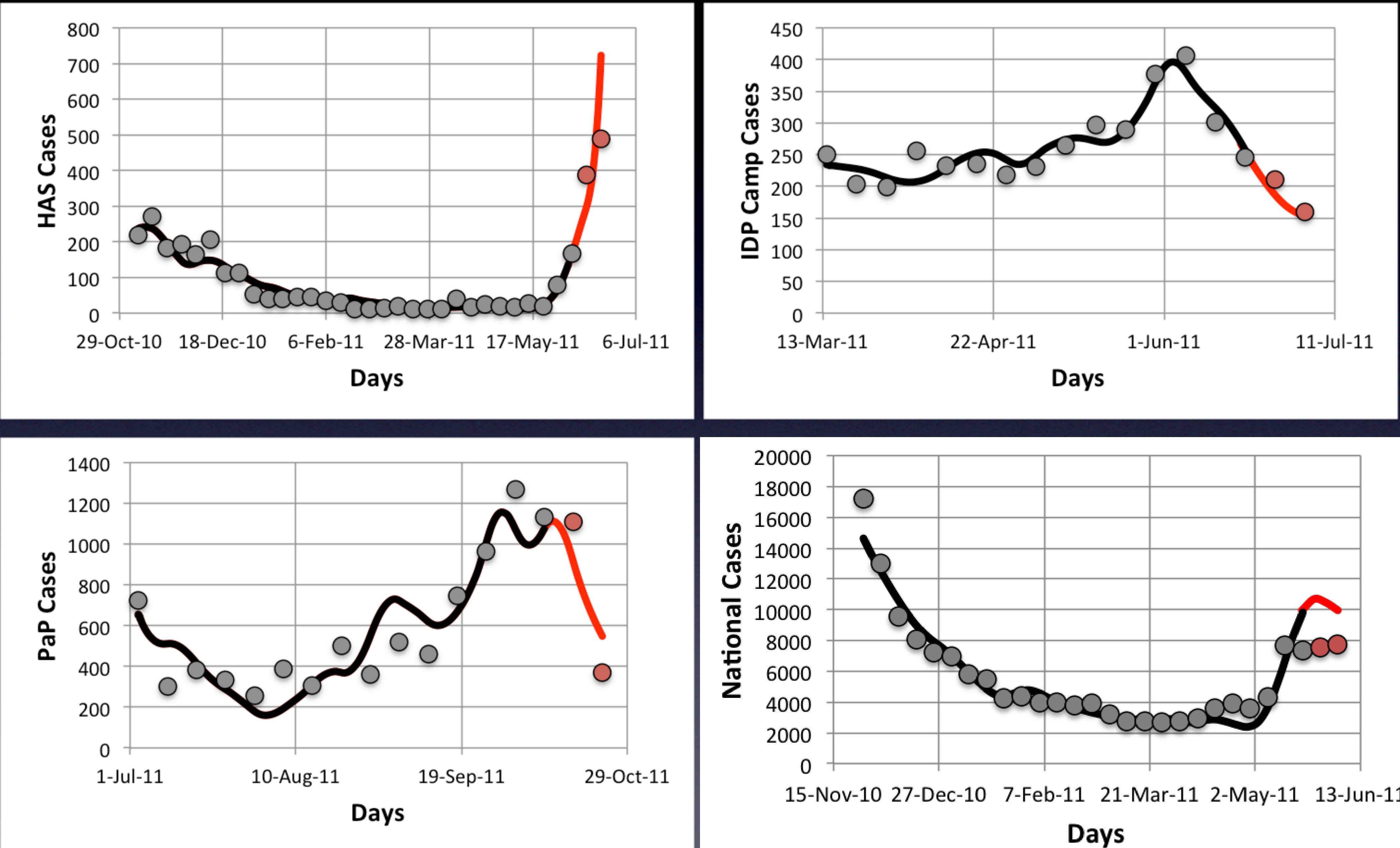








Eisenberg, Kujbida, Tuite, Fisman Tien 2012 (*Submitted*)



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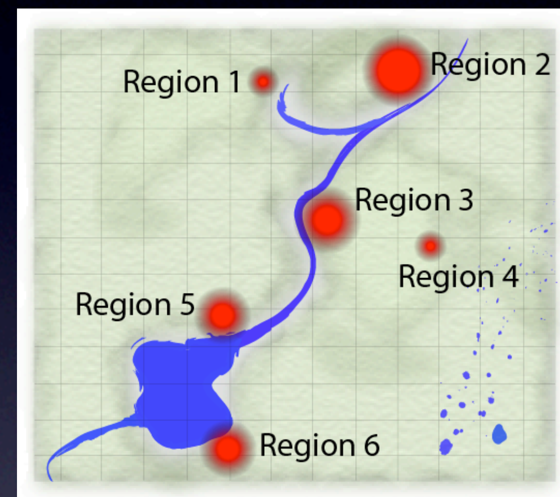
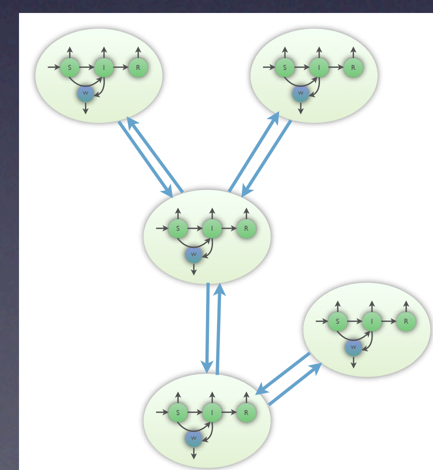
Ongoing Work: Hotspots, Disease Risk & Spatial Spread

- How does the arrangement of good/bad patches affect disease spread? (hotspots)



- Water movement among patches - pathogen decay vs. water movement
  - decay ≫ movement - patches decouple
  - movement ≫ decay - weighted average accounting for network topology



Conclusions

- Range of modeling approaches & data sets
- Initial invasion phase with spatial clustering
  - Spatial spread depends on both human & water movement
- Rainfall & environment are key factors for capturing cholera dynamics going forward
  - Water & rainfall information can improve identifiablity
  - Rainfall-based predictions?

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Thank you!

- Collaborators
  - Joe Tien (OSU)
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  - Greg Kujbida, Ashleigh Tuite, David Fisman (UofT)
  - David Earn (McMaster)
  - Pauline van den Driessche, Zhisheng Shuai, Junling Ma
- Hôpital Albert Schweitzer, Haiti
- UN WASH Cluster, CDC
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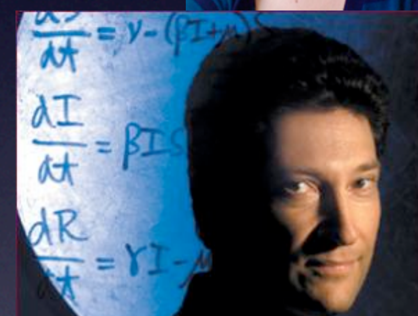

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WHERE DISCOVERIES BEGIN

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at The Ohio State University