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Modeling spatial transmission PAT of infectious diseases

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Content

- Training and career path
- Forecasting spatial spread of influenza (2016-2019)
- Modeling and inference for COVID-19 (2020-2023)
- Use of foot-traffic data in epidemic models



Pei 2020; CDC

Human mobility and spatial spread of infectious diseases





Can we predict the spatial spread of influenza in real time?



Forecasting spatial spread is challenging

- Mobility data are not available in real-time
- Parameter may change over time
- Limited disease data to validate (in 2017)
- A data-driven metapopulation model
- Influenza data from DoD healthcare system (35 states)





Spatial spread of 2009 H1N1 pandemic





Pei et al. 2018

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A humidity-driven SIRS model

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Day time transmission equations: SIRS model



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Model calibration and forecasting

- A high-dimensional system
- Ensemble Kalman filter (numerical weather prediction)



An example of ensemble forecasting using a local model



Parameter inference



Retrospective forecasting

• 2008-2012, 35 US states

- Weekly forecasting
 - Metapopulation model
 - Local model (Baseline)



Improvement of onset prediction for each individual state



Forecasts for peak week and peak intensity are also improved

A county-level model for respiratory viruses

- Optimal selection of surveillance sites (2018-2019)
- Influenza, human metapneumovirus, endemic coronavirus





Pei et al. (2021)

COVID-19 in 2020

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A pandemic?

Fast spatial spread, only ~900 cases

- Endemic coronavirus (229E, NL63, OC43, HKU1)
 - Infections with no/mild symptoms

How many infections were not detected? How infectious are the undetected infections?

• Potential for a pandemic?



Cumulative number of reported cases in 375 cities as of Jan 23. Wuhan has 454 cases.

Li et al 2020

What is the role of undetected infections?



Modeling SARS-CoV-2 spread in China

- Chunyun: travel during lunar New Year (3 billion trips in 40 days)
- Tencent location-based service data in 2018
- 375 cities, Jan 10 Jan 23, before Wuhan lockdown





Metapopulation SEIR model

- Susceptible (S), exposed (E), documented infection (Ir), undocumented infection (Iu), removed (R)
- Fraction of undocumented infection, relative contagiousness

$$\frac{dS_{i}}{dt} = -\frac{\beta S_{i}I_{i}^{r}}{N_{i}} - \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} + \frac{\beta \sum_{j} \frac{M_{ij}S_{j}}{N_{j} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}S_{i}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} - \frac{E_{i}}{Z} + \theta \sum_{j} \frac{M_{ij}E_{j}}{N_{j} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}E_{i}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} + \frac{\mu\beta S_{i}I_{i}^{u}}{Z} + \theta \sum_{j} \frac{M_{ij}E_{j}}{N_{j} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}E_{i}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} + \frac{\mu\beta S_{i}I_{i}^{u}}{Z} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{j} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}I_{i}^{u}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i}} + \frac{\mu\beta S_{i}I_{i}^{u}}{Z} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{j} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}I_{i}^{u}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i} - I_{j}^{r}} - \theta \sum_{j} \frac{M_{ji}I_{i}^{u}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i} - I_{j}^{r}} - \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i} - I_{i}^{r}} + \frac{\mu\beta S_{i}I_{i}^{u}}{N_{i} - I_{i}^{u}} + \frac{\mu\beta S_{i}I_{i$$

Parameter

Transmission rate (β , days⁻¹) Relative transmission rate (μ) Latency period (Z, days) Infectious period (D, days) Reporting rate (α) Basic reproductive number (R_e) Mobility factor (θ)

Within city transmission

Cross city migration

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A gamma-distributed reporting delay estimated using line-list data

Parameter inference

 Iterated filtering with ensemble adjustment Kalman filter

• Parameter identifiability?

 Connectivity improves identifiability!



Validation using synthetic outbreaks



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Inference results

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- 86% [82%, 90%] infections were undocumented before travel restrictions
- The transmission rate of undocumented infections was 55% [46%, 62%] of documented infections



Counterfactual simulations

• Assume undocumented infections are not contagious



"These findings explain the rapid geographic spread of SARS-CoV-2 and indicate that containment of this virus will be particularly challenging."

SARS-CoV-2 spread in the US

• A metapopulation model for 3142 US counties

• Commuting data from census

• Fit to county-level data from NYT



Early simulation in the US



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Communications with the public

The New York Times

Coronavirus Could Overwhelm U.S. Without Urgent Action, Estimates Say

By James Glanz, Lauren Leatherby, Matthew Bloch, Mitch Smith, Larry Buchanan, Jin Wu and Nicholas Bogel-Burroughs March 20, 2020



No control measures



Some control measures

Three scenarios for how the outbreak could spread.





Severe control measures



Making a Rare Vocal Le

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Poet Who Had 'Bandit' Fathe

| ew York | Overshadowed by Bach The music of Heinrich Schütz, a l century path breaker, is largely a known today but worth a listen. |
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Short on Beds and Ventilators,

New York Hospitals Face Surge

Decrees From New York and Illinois

- Virus Tightens Grip on Nation

By JULIE BOSMAN and JESSE MCKINI

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Mixed Signals

From President

Sow Confusion

a article is by Ketle Ropers

PLAY THE CROSSWORD

PRESSURE ON TRUMP AS MILLIONS ARE KEPT HOME How the Outbreak Could Spread Across ounties Under Three Social Control Scen

New data streams on human mobility

Aggregated mobility data shared by private companies
 SafeGraph, Cuebiq, Google, GPS, etc.

Unprecedented data for infectious disease modeling

- High-resolution foot-traffic data to understand contact patterns and mobility
 SafeGraph: points of interest (POIs) and mobility
- Potentials and challenges





POIs and mobility in NYC

 Place categories: Grocery & Pharmacy, Other Retails, Art & Entertainment, Restaurant & Bar, Education, Healthcare, Other Places.





MAILMAN SCHOOL OF PUBLIC HEALTH Grocery & Pharmacy, 1/31/2020, Friday



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Ongoing research

- Link behavior features with mobility change in different neighborhoods
 Temporal discounting, loss aversion, agency, normative decisions
- Develop a parsimonious model for NYC informed by foot-traffic data
 Represent population mixing in different settings
- Couple risk-driven behavior model with mobility-driven epidemic model

 Feedback, retrospective forecasting

Reflections

• More complex models do not necessarily work better in real-world applications

- Imperfect data, unrealistic assumptions, high computational cost
- Complexity versus Parsimony
- Real-world data are imperfect
 - Underreporting, reporting delay, large observational noise, non-stationary
 - Develop methods to deal with imperfect data
 - Avoid perfectionism
- Communicate with end-users
 - Understand real needs, think about how model will be used
 - Push for better data collection

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- China: Ruiyun Li, Zhanwei Du, Xiao-Ke Xu, Lin Wang, Renquan Zhang, et al.
- CDC FluSight challenge, COVID-19 forecasting hub, COVID-19 scenario hub





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Thank you!



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