A Dynamical Model to Forecast Seasonal Respiratory Epidemics

David Champredon

York University (Toronto, Ontario)
University of Western Ontario (London, Ontario)
McMaster University (Hamilton, Ontario)

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Background & Outline

Advances in Forecasting Epidemics

- Support public health efforts during outbreaks
- Critical mass of scientists
- Theoretical advances
- Data collection and access

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Epidemics are ripe for forecasting!

Modelling framework and results when applied in "real-time" to seasonal influenza in Ontario

Renewal Equation for Forecasting Epidemics

Renewal Equation for Epidemics

Euler (1767), Lotka (1907), Kermack & McKendrick (1927)

$$
\begin{aligned}
i(t) &= S_t \, \mathcal{R}_0 \int_0^\infty g(\tau) i(t-\tau) \, \mathrm{d}\tau \\
dS_t/dt &= -i(t)
\end{aligned}
$$

$i(t)$	:	incidence at time t
S_t	:	susceptible at time t
$\mathcal{R}_0$	:	basic reproduction number
g	:	generation interval distribution
τ	:	age of infection

Renewal Equation for Epidemics

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\end{aligned}
$$

- model cohorts of infectious individuals
- focus on incidence
- simple, well adapted to forecasting

Different Framework?

Compartmental SE^mI^nR

$$\begin{cases} \dot{S} &= -\beta SI \\ \dot{E}_1 &= \beta SI - m\sigma E_1 \\ \dot{E}_\ell &= m\sigma E_{\ell-1} - m\sigma E_\ell \\ \dot{I}_1 &= m\sigma E_m - n\gamma I_1 \\ \dot{I}_k &= n\gamma I_{k-1} - n\gamma I_k \\ \dot{R} &= n\gamma I_n \end{cases}$$

with $2 \leq \ell \leq m$ and $2 \leq k \leq n$

Renewal Equation

$$i(t) = \mathcal{R}_0 S_t \int_0^\infty i(t-\tau) g(\tau) \, \mathrm{d}\tau$$

$$\boxed{SE^mI^nR \Leftrightarrow RE(g_{SE^mI^nR})}$$

Champredon et al. *in* SIAM Journal on Applied Mathematics, 2018 (vol 78)

Uncertainty

Aaron King et al. *Avoidable errors in the modelling of outbreaks of emerging pathogen*.
Proc. Roy. Soc. B, 2015 (vol. 282)

Standard practices: over-confident forecasts

Sources of randomness:

- transmission
- observation/reporting

Uncertainty Propagation

$$\begin{aligned}
i(n) &\sim \text{Poisson}\left(\mathit{mean} = S_n \, \mathcal{R}_0 \sum_{k=1}^{n} g(k)\, i(n-k) \right) \\
y(n) &\sim \text{NegBinom}\left(\mathit{mean} = i(n)\, ;\, \mathit{dispersion} \right) \\
\mathit{Data} &: \; y_1, y_2, \dots, y_n
\end{aligned}$$

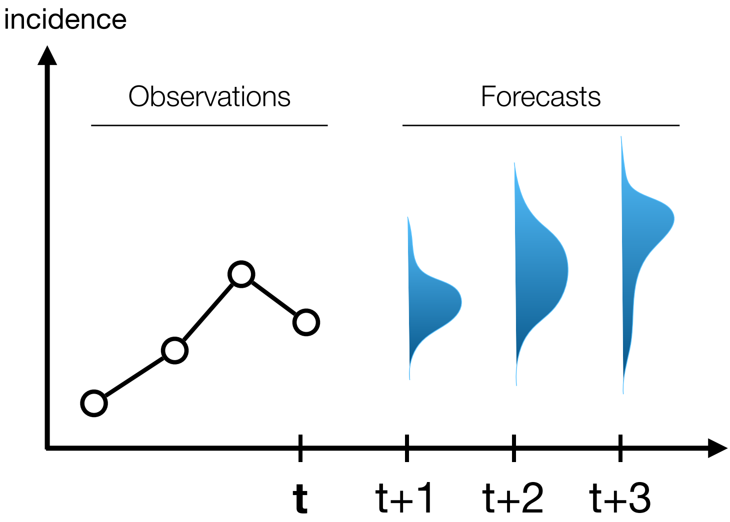
- i : "true" /unobserved incidence *(transmission process)*
- y : observed incidence *(observation process)*
- Posterior distribution for unobserved model parameters in Bayesian framework (e.g., MCMC, ABC, ...)

Forecasting

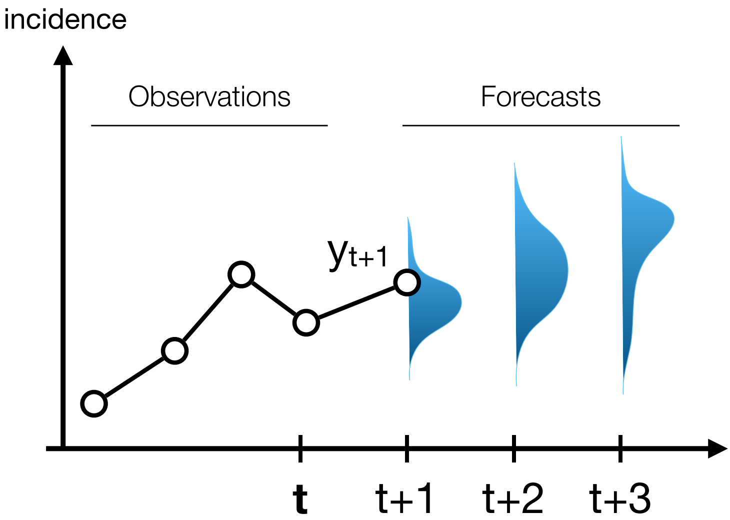
Forecasting = Two-Step Process

1. Fit model parameters on observed incidence $y_1, y_2, \cdots, y_n$
2. Simulate forward from last observation date

Forecasts Embrace Uncertainty



Assessing Forecasts



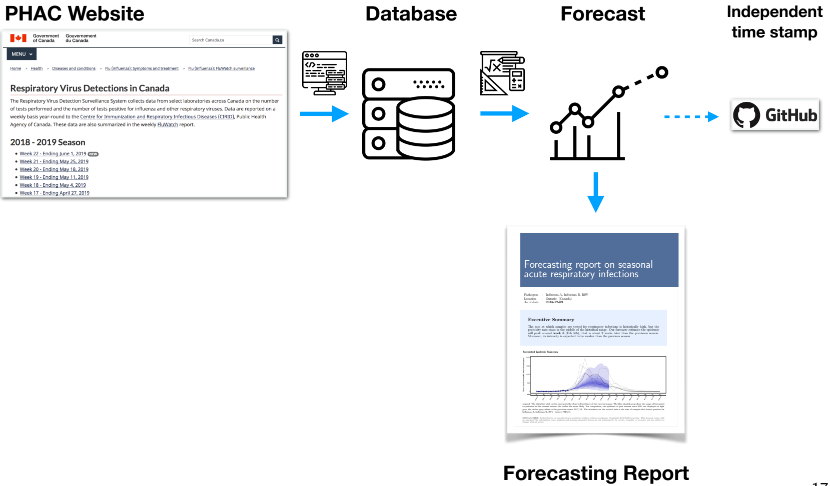
Application:

Forecasting Seasonal Epidemics of Acute Respiratory Infections in Ontario during the 2018/19 Season

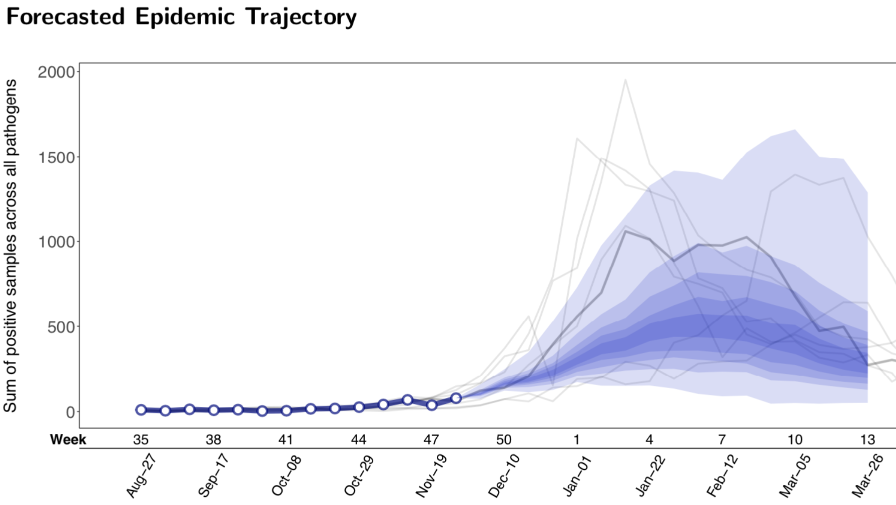
Acute Respiratory Infections in Ontario

- Influenza A,B & Respiratory Syncytial Virus (RSV)
- Weekly number of laboratory tests positive for a specific virus (1-2 week lag)
- 2018/19 season in Ontario in “real-time”

Weekly Forecasting Process



Forecasting Report



Forecasting Report

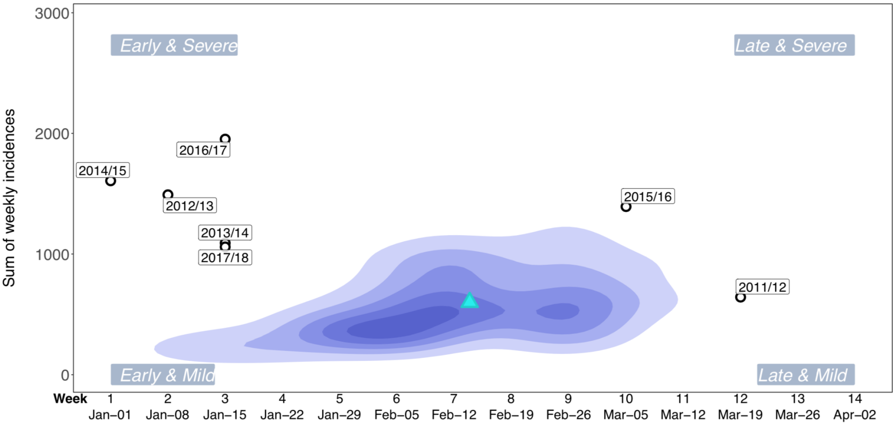
Probabilistic outputs:

Compared to the previous season:

Probability the peak will be *earlier*	:	5.5 %
Probability the peak incidence will be *higher*	:	8.5 %
Forecasted mean *peak week* timing	:	later by 3 weeks (80%CI: later
Forecasted mean *peak incidence* intensity	:	smaller by 43 % (80%CI: small

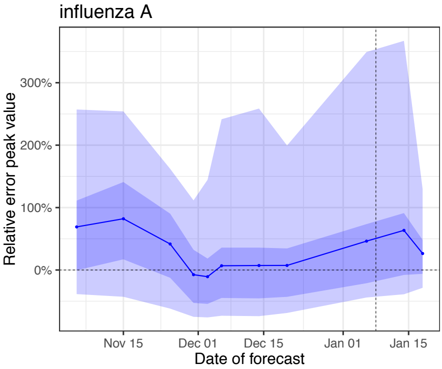
Forecasting Report

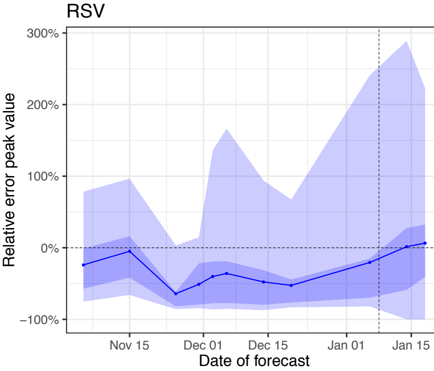
2-dimensional density of epidemic peak timing and value:



Forecasting Assessement

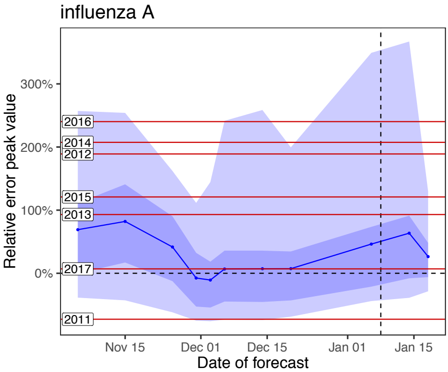
Relative error of epidemic peak value compared to realized value:

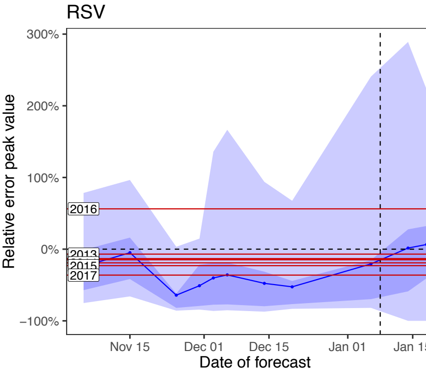




Forecasting Assessement

Relative error of epidemic peak value compared to previous seasons:





Future Directions

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- Current performance can be improved
- Improve modelling and statistical inference
- Incidence time series only not enough
- Include additional information

Future Directions

- Real-time data from hospitals emergencies in Ontario: early warning?
  - no lag, actual real-time
  - not specific

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- Real-time data from hospitals emergencies in Ontario: early warning?
  - no lag, actual real-time
  - not specific
- Genetic sequences: genetic/antigenic distance and epidemic severity? ("Genome to Biome")
  - timely
  - for influenza only
  - help very early in the season

Conclusion

Take Home Messages

- Real-time forecasting of seasonal epidemics is possible (proof of concept with ARI Ontario)
- Renewal Equation well adapted for forecasting
- Must quantify uncertainty
- How similar to/different from previous seasons (cannot pinpoint precise trajectory)
- Time series only not enough: complementary information

Thank you!