Early warning signals anticipate critical transitions in empirically-based simulations of measles dynamics in Niger

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Abstract

Forecasting the trajectory of infectious disease outbreaks over time is a fundamental challenge facing society.

Introduction

- Theory shows that epidemic transitions can be anticipated by trends in the statistical properties of disease
- 3 time series (AERO papers). The existence of statistical trends in the data that precede critical transitions,
- 4 so-called 'early warning signals' (EWS), imply that we may be able to anticipate disease emergence and
- outbreaks. The end goal is a model-independent detection system, where statistical properties of disease
- 6 surveilence data can trigger warnings of impending outbreaks without the need to fit mechanistic models of
- disease transmission (Han and Drake 2017).
- However, there is currently a gap between the theoretical work, which has relied on knowing the underlying
- 9 disease dynamics, and the eventual goal of applying EWS in real-world situations where the underlying
- disease dynamics may be unknown. Theoretical development of EWS has focused on anticipating when the
- population becomes supercritical, when $\Re_0 > 1$, after which an outbreak is inevitable, perhaps with some
- bifurcation delay (Dibble et al. 2016). Knowing the value of \mathcal{R}_0 through time makes it possible to test the
- accuracy of EWS that are estimated from state variables alone. Empirical application of EWS does not
- require knowing the value of \Re_0 through time, meaning that "tests" require making assumptions about when
- 15 critical transitions occur. Whether EWS track and/or anticipate underlying dynamics of real disease time
- series remains unknown, and is a critical knowledge gap that must be filled before EWS can confidently be
- 17 deployed.
- To fill this gap we will fit a mechanistic model to incidence data of measles in Niger to estimate the temporal
- 19 epidemiology of the disease, yielding the very same parameters that are known in data-free modeling studies.
- 20 In particular, we are interested in the correlation between EWS and the time-varying repreoductive ratio,
- known as the effective reprodutive ratio (\mathcal{R}_E) . If EWS and \mathcal{R}_E are significantly and positively correlated,
- then we have empirical evidence that EWS are applicable in real-world settings. If EWS and \mathcal{R}_E are
- negatively correlated or not significantly posivitely correlated, then we have evidence that EWS may not be
- 24 applicable in certain settings.

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25 Materials and Methods

26 Data

- ²⁷ We used weekly measles case report data from four Nigerien cities, collected over an 11 year period
- 28 (1995-2005) (Figure 1). These data are ideal for stress testing EWS because each city has different
- 29 population sizes, has different dynamics in terms of size of outbreaks and length of inter-epidemic periods,
- and each time series has different amounts of demographic stochasticity due to differences in population size.
- The data come from [somewhere/someone], and used here with permission from [somewhere/someone].

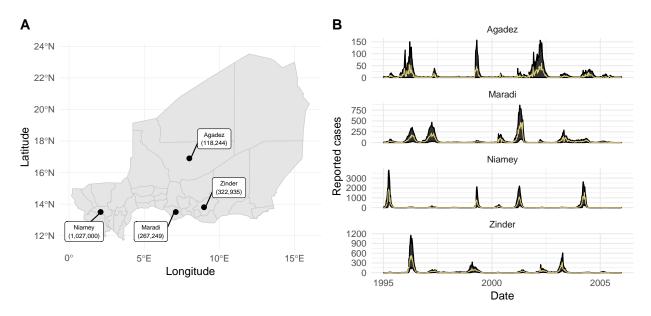


Figure 1: (A) Locations and population sizes (in parantheses) of our four focal cities in Niger. (B) Time series of reported cases (yellow solid lines) and the 95% prediction intervals for one-step-ahead forecasts from our fitted SEIR models for each city.

32 Stochastic SEIR model

- 33 The model is a discrete-time approximation of a continuous-time SEIR model with limited demography,
- specified as a set of difference equations,

$$S_{t+dt} = n_{S,t} - n_{E,t} \tag{1}$$

$$E_{t+dt} = n_{E,t} - n_{I,t} \tag{2}$$

$$I_{t+dt} = n_{I,t} + n_{O,t} - n_{R,t}, (3)$$

where \mathbf{n}_t are random variables representing the number of individuals transitioning into or out of each class

- at each timestep $t \to t + dt$. n_S is the number of births, n_E is the number of newly infected individuals that
- have the disease but are not infectious, n_I is the number of newly infectious individuals, n_O is the number of
- n_R is the number of newly recovered individuals who are no longer infectious and
- have life-long immunity. The stochastic random variables are specified as follows:

$$n_{S,t} \sim \text{Poisson}(\mu_t N_t \times dt)$$
 (4)

$$n_{E,t} \sim \text{Binomial}(\lambda_{E,t}, S_t)$$
 (5)

$$n_{l,t} \sim \text{Binomial}(\lambda_{l,t}, E_t)$$
 (6)

$$n_{O,t} \sim \text{Poisson}(\psi \times dt)$$
 (7)

$$n_{R,t} \sim \text{Binomial}(\lambda_{R,t}, I_t),$$
 (8)

- where μ_t is the birth rate at time t, ψ is the rate of imported infections, and λ_E , λ_I , and λ_R are the probabilities of exposure, becoming infectious, and recovery, respectively. These probabilities reflect the processes of
- transmission, transition from the latent period to the infectious period, and recovery, which we model as:

$$\lambda_{E,t} = 1 - e^{-\frac{\beta_t I_t dt}{N_t}} \tag{9}$$

$$\lambda_{I,t} = 1 - e^{-\eta E_t dt} \tag{10}$$

$$\lambda_{R,t} = 1 - e^{-\gamma I_t dt},\tag{11}$$

where β_t is time-varying rate of transmission, η is time-invariant rate from the exposed class to the infectious class, and γ is time-invariant recovery rate. We model rate of transmission as:

$$\beta_t = \beta \left(1 + \sum_{i=1}^6 q_i \xi_{i_t} \right) \Gamma_t. \tag{12}$$

 β is the mean transmission rate, ψ accounts for measles infections from external sources that are not part of the local dynamics, and the term $\sum_{i=1}^{6} q_i \xi_{i_t}$ is a B-spline to model seasonality in transmission. The B-spline bases (ξ_{i_t}) are periodic with a 1 year period. The transmission rate (β_t) is also subject to stochastic process noise at each time step, Γ_t , which we model as a gamma-distributed white (temporally uncorrelated) noise with mean 1 and variance σ^2 (Bretó and Ionides 2011).

We do not include a death process in the model because the rate of infection is much faster than the rate of death. Excluding deaths means we can avoid making further assumptions about demographic rates – we are already making assumptions about birth rates (e.g., the rate is the same across cities, but with city-specific population size). We model demographic stochasticity in births and imported infections by drawing time-specific values from Poisson distributions. Transitions in the model are shown in Table 1. In this model, the effective reproductive ratio at time t is: $\mathcal{R}_E(t) = \frac{\beta_t}{\gamma} \frac{S_t}{N_t}$.

We assume observed case reports (y) are drawn from a Negative Binomial distribution subject to a constant reporting fraction (ρ) and dispersion parameter τ ,

$$y_t \sim \text{Negative Binomial}(\rho I_t, \tau)$$
. (13)

Table 1: Transitions in the SEIR model. We show the determinstic transmission rate for clarity, but our model uses the stochastic transmission rate.

Transition	$(\Delta S, \Delta E, \Delta I)$	Propensity
birth	(1,0,0)	$N_t \mu_t$
transmission	(-1, 1, 0)	$SI\beta_t/N_t$
(deterministic)		
transmission (stochastic)	(-k, k, 0)	$\frac{S}{k}\sum_{j=0}^{k} {k \choose j} (-1)^{k-j+1} \tau_{\mathbf{f}}^{-1} \ln(1 + (\beta_t I/N_t)) \tau_{\mathbf{f}}(S-j)$
symptomatic	(0, -1, 1)	$E\eta$
(infectious)	, , , ,	·
imported infections	(0,0,1)	ψ_t
recovery	(0,0,-1)	$I\gamma$

58 Model fitting and inference

- ⁵⁹ We fit the SEIR model to time series of case reports from each of our focal cities using Maximization by
- 60 Iterated particle Filtering (MIF) in the R package pomp. We estimated 14 parameters for each city: six
- seasonal transmission parameters (q_i) , mean transmission rate (β) , three initial conditions
- $(S_{(t=0)}, E_{(t=0)}, I_{(t=0)})$, the number of imported infections (ψ) , reporting rate (ρ) , one parameter accounting
- 63 for process noise, and one parameter accounting for measurement noise. To ensure identifiability, and to
- make the model easier to fit, we assumed the infectious period was fixed at $1/\eta = 8$ days and the recovery
- period was fixed at $1/\gamma = 5$ days.

66 Model simulations

67 Early warning signals

- We considered ten candidate early warning signals (EWS; Table 3). EWS were calculated using the function
- spaero::get_stats() (O'Dea 201x) in R (R Core Team 201x).

Table 2: List of candidate early warning signals and their estimating equations. Note that b denotes the bandwidth. See Brett et al. (2018) for details.

EWS	Estimator	Theoretical Correlation with $\mathcal{R}_E(t)$
Mean	$\mu_t = \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} rac{X_s}{2b-1}$	Positive
Variance	$\sigma_t^2 = \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} \frac{(X_s - \mu_s)^2}{2b-1}$	Positive
Coefficient of variation	$CV_t = rac{\sigma_t}{\mu_t}$ $ID_t = rac{\sigma_t^2}{\mu_t}$	Null
Index of dispersion	$ID_t = \frac{\sigma_t^2}{\mu_t}$	Positive
Skewness	$S_t = rac{1}{\sigma_t^3} \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} rac{(X_s - \mu_s)^3}{2b-1}$	Positive
Kurtosis	$K_{t} = \frac{1}{\sigma_{t}^{4}} \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} \frac{(X_{s} - \mu_{s})^{4}}{2b-1}$ $ACov_{t} = \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} \frac{(X_{s} - \mu_{s})(X_{s-\delta} - \mu_{s-\delta})}{2b-1}$	Positive
Autocovariance	$ACov_t = \sum_{s=t-(b-1)\delta}^{t+(b-1)\delta} \frac{(X_s - \mu_s)(X_{s-\delta} - \mu_{s-\delta})}{2b-1}$	Positive

EWS	Estimator	Theoretical Correlation with $\mathcal{R}_E(t)$
Autocorrelation Decay time First differenced variance	$egin{aligned} & \operatorname{AC}_t = rac{\operatorname{ACov}_t}{\sigma_t \sigma_{t-\delta}} \ & \overline{ au}_t = -\delta/\ln\left[\operatorname{AC}_t(\delta) ight] \ & \Delta \sigma_t^2 = \sigma_t^2 - \sigma_{t-\delta}^2 \end{aligned}$	Positive Positive Positive

70 Results

The fitted models adequately reproduced observed dynamics (Figure 1), with R^2 s ranging from 0.54 to 0.89 (Figure 2).

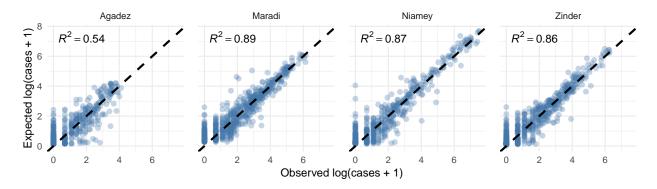


Figure 2: Comparison of in-sample model predictions and observations for each city. Expected cases are one-step-ahead predictions from the fitted models. The dashed line shows 1:1.

Stochastic simulations from sub-critical ($\mathscr{R}_{E(t)} \ll 0$) to near-critical dynamics ($\mathscr{R}_{E(t)} \approx 1$) differed among

the four cities (Figure 3).

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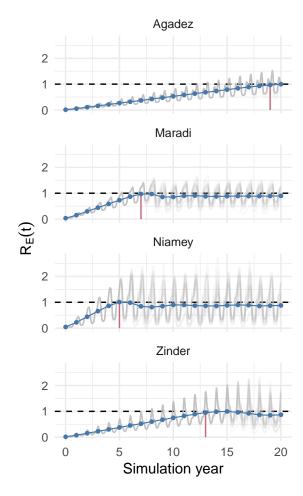


Figure 3: Yearly average $\mathscr{R}_{E(t)}$ (blue lines) across 500 models simulations at the MLE parameters and 20 representations simulations (grey lines) for each city. The horizontal dashed line shows where $\mathscr{R}_{E(t)} = 1$. The vertical solid red lines show the time point at which yearly average $\mathscr{R}_{E(t)} \geq 1$. The time periods before the red line for each city were used for testing early warning signals.

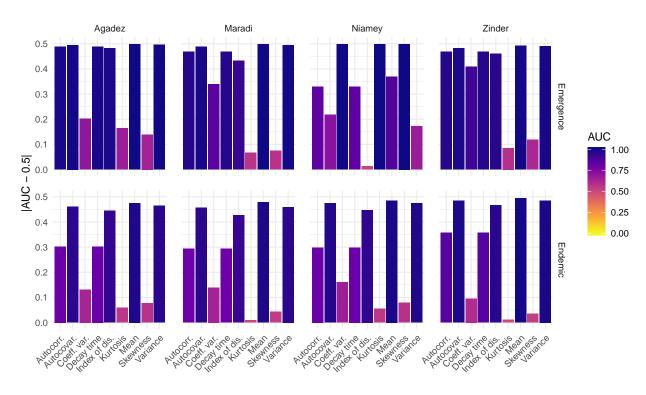


Figure 4: Performance of EWS calculated over two windows (far from and near $\mathcal{R}_{E(t)} = 1$) from the time series of 500 simulated dynamics. The two windows were defined as equally-sized windows over the course of the time series up to $\mathcal{R}_{E(t)} = 1$ (red lines in Figure 3)