

## Chapter 5. Case study: Measles in large and small towns

### Objectives

- ▶ To display a published case study using plug-and-play methods with non-trivial model complexities.
- ▶ To show how extra-demographic stochasticity can be modeled.
- ▶ To demonstrate the use of covariates in **pomp**.
- ▶ To demonstrate the use of profile likelihood in scientific inference.
- ▶ To discuss the interpretation of parameter estimates.
- ▶ To emphasize the potential need for extra sources of stochasticity in modeling.

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### Motivation: challenges in inference from disease dynamics I

- ▶ Understanding, forecasting, managing epidemiological systems increasingly depends on models.
- ▶ Dynamic models can be used to test causal hypotheses.
- ▶ Real epidemiological systems:
  - ▶ are nonlinear
  - ▶ are stochastic
  - ▶ are nonstationary
  - ▶ evolve in continuous time
  - ▶ have hidden variables
  - ▶ can be measured only with (large) error

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# Motivation: challenges in inference from disease dynamics

## II

- ▶ Dynamics of infectious disease outbreaks illustrate this well.
- ▶ Measles is the paradigm for a nonlinear ecological system that can be well described by low-dimensional nonlinear dynamics.
- ▶ A tradition of careful modeling studies have proposed and found evidence for a number of specific mechanisms, including
  - ▶ a high value of  $R_0$  (c. 15–20)
  - ▶ under-reporting
  - ▶ seasonality in transmission rates associated with school terms
  - ▶ response to changing birth rates
  - ▶ a birth-cohort effect
  - ▶ metapopulation dynamics
  - ▶ fadeouts and reintroductions that scale with city size
  - ▶ spatial traveling waves
- ▶ Much of this evidence has been amassed from fitting models to data, using a variety of methods.
- ▶ See Rohani and King (2010) for a review of some of the high points.

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Change eval to T if you want London-Liverpool-Hastings plot

## Outline

- ▶ We revisit a classic measles data set, weekly case reports in 954 urban centers in England and Wales during the pre-vaccine era (1950–1963).
- ▶ We examine questions regarding:
  - ▶ measles extinction and recolonization
  - ▶ transmission rates
  - ▶ seasonality
  - ▶ resupply of susceptibles
- ▶ We use a model that
  1. expresses our current understanding of measles dynamics
  2. includes a long list of mechanisms that have been proposed and demonstrated in the literature
  3. cannot be fit by existing likelihood-based methods
- ▶ We examine data from large and small towns using the same model, something no existing methods have been able to do.
- ▶ We ask: does our perspective on this disease change when we expect the models to explain the data in detail?
- ▶ What bigger lessons can we learn regarding inference for dynamical systems?

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### Data sets

- ▶ Twenty towns, including
  - ▶ 10 largest
  - ▶ 10 smaller, chosen at random
- ▶ Population sizes: 2k–3.4M
- ▶ Weekly case reports, 1950–1963
- ▶ Annual birth records and population sizes, 1944–1963

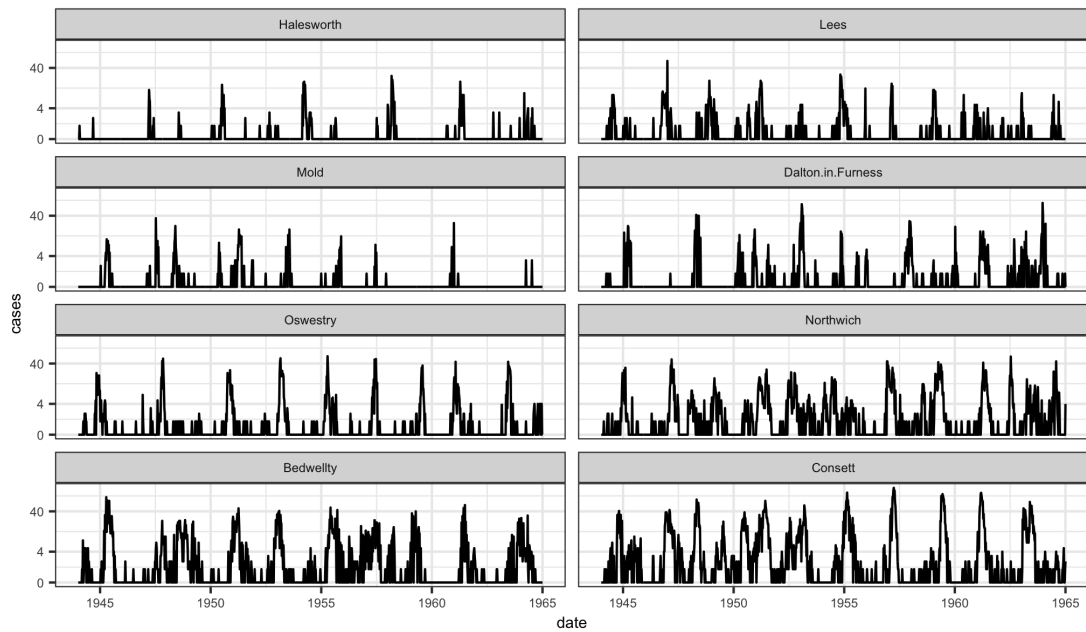
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### Map of cities in the analysis



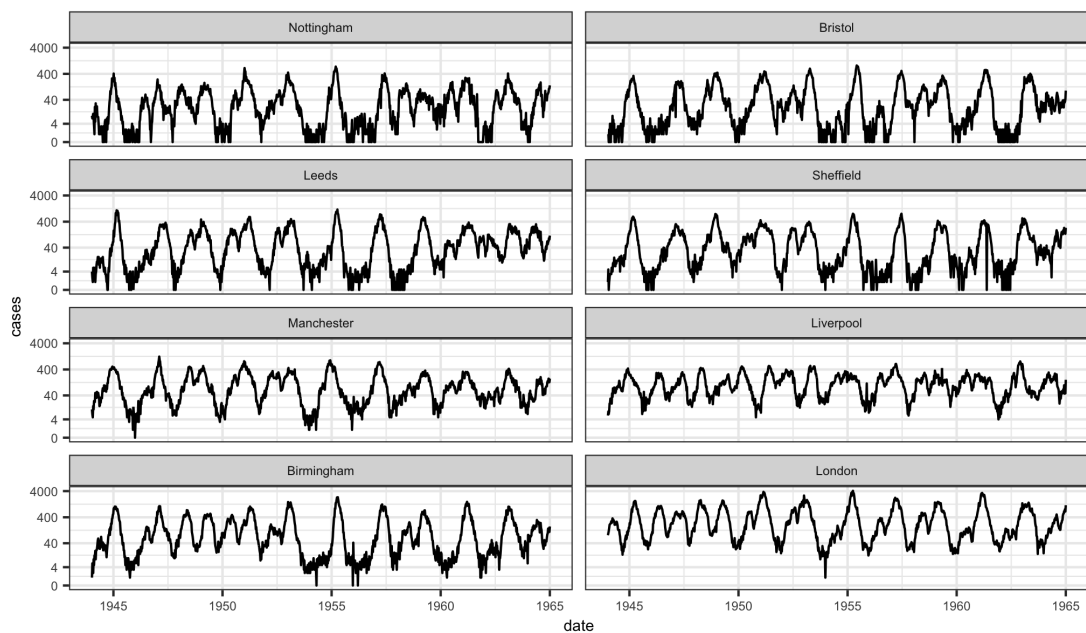
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## City case counts I: smallest 8 cities



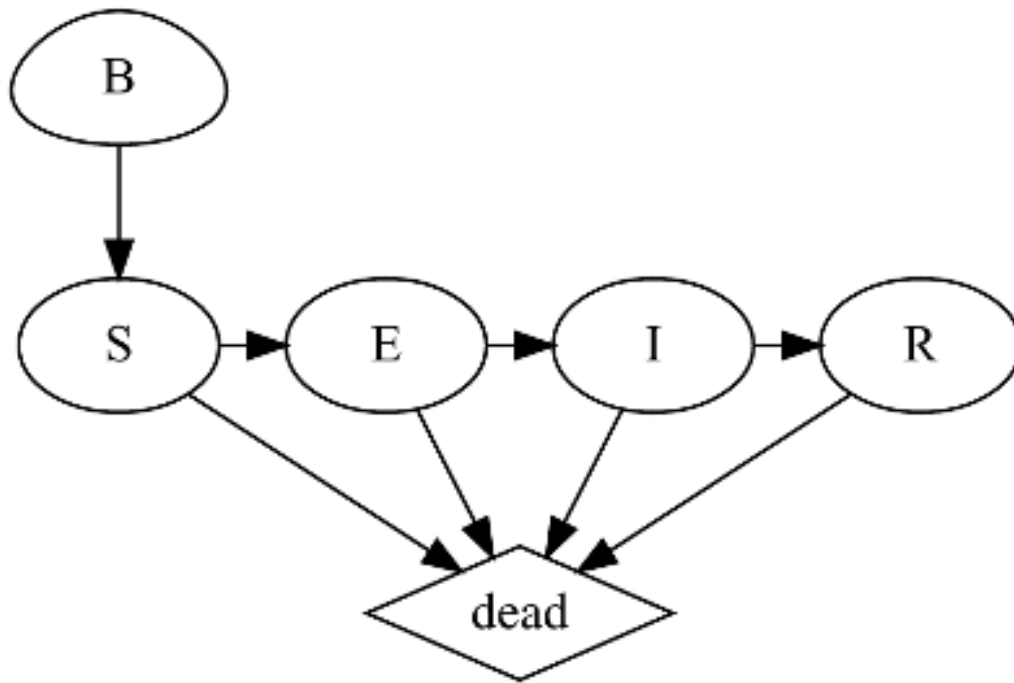
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## City case counts II: largest 8 cities



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## Continuous-time Markov process model



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## Continuous-time Markov process model I

- ▶ Covariates:
  - ▶  $B(t)$  = birth rate, from data
  - ▶  $N(t)$  = population size, from data
- ▶ Entry into susceptible class:

$$\mu_{BS}(t) = (1 - c) B(t - \tau) + c \delta(t - \lfloor t \rfloor) \int_{t-1}^t B(t - \tau - s) ds$$

- ▶  $c$  = cohort effect
- ▶  $\tau$  = school-entry delay
- ▶  $\lfloor t \rfloor$  = most recent 1 September before  $t$

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## Continuous-time Markov process model II

- ▶ Force of infection:

$$\mu_{SE}(t) = \frac{\beta(t)}{N(t)} (I + \iota) \zeta(t)$$

- ▶  $\iota$  = imported infections
- ▶  $\zeta(t)$  = Gamma white noise with intensity  $\sigma_{SE}$  [He et al. (2010); Bhadra et al. (2011)]
- ▶ school-term transmission:

$$\beta(t) = \begin{cases} \beta_0 (1 + a(1 - p)/p) & \text{during term} \\ \beta_0 (1 - a) & \text{during vacation} \end{cases}$$

- ▶  $a$  = amplitude of seasonality
  - ▶  $p = 0.7589$  is the fraction of the year children are in school.
  - ▶ The factor  $(1 - p)/p$  ensures that the average transmission rate is  $\beta_0$ .
- ▶ Overdispersed binomial measurement model:  
 $\text{cases}_t \mid \Delta N_{IR} = z_t \sim \text{Normal}(\rho z_t, \rho(1 - \rho) z_t + (\psi \rho z_t)^2)$

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## Implementation in **pomp**

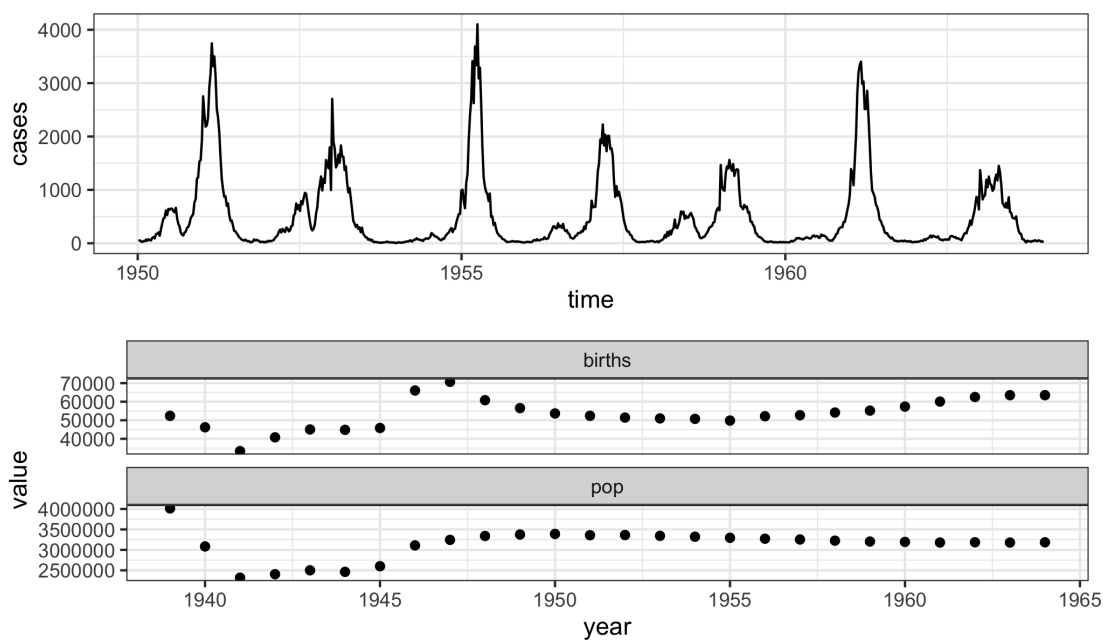
- ▶ We'll load the packages we'll need, and set the random seed, to allow reproducibility.
- ▶ Note that we'll be making heavy use of the **tidyverse** methods.
- ▶ Also, we'll be using **ggplot2** for plotting: see this brief tutorial.
- ▶ Finally, we'll use the convenient **magrittr** syntax, which is explained here.

## Data and covariates

- ▶ Now we'll load the data and covariates. The data are measles reports from 20 cities in England and Wales.
- ▶ We also have information on the population sizes and birth-rates in these cities; we'll treat these variables as covariates.
- ▶ We select the data for London and pre-process the measles and demography data.

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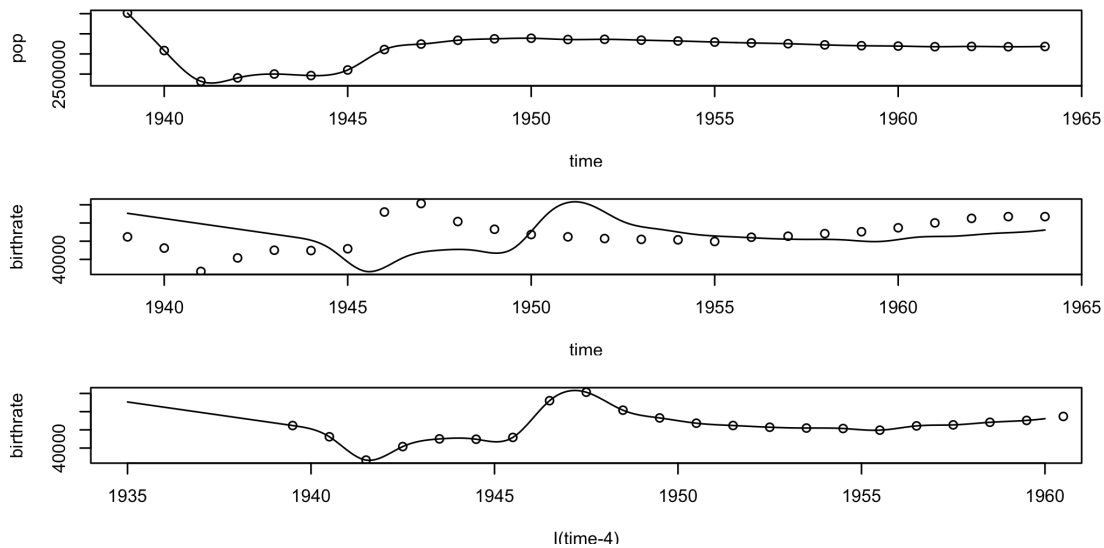
## Data and covariate plots I



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## Data and covariate plots II

Now, we smooth the covariates. Note that we delay the entry of newborns into the susceptible pool.



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## The partially observed Markov process model

We require a simulator for the BSEIR model. Notable complexities include:

1. Incorporation of the known birthrate.
2. The birth-cohort effect: a specified fraction (cohort) of the cohort enter the susceptible pool all at once.
3. Seasonality in the transmission rate: during school terms, the transmission rate is higher than it is during holidays.
4. Extra-demographic stochasticity in the form of a Gamma white-noise term acting multiplicatively on the force of infection.
5. Demographic stochasticity implemented using Euler-multinomial distributions.

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## Implementation of the process model I

```
double beta , br , seas , foi , dw , births ;
double rate[6] , trans[6];

// cohort effect
if ( fabs(t-floor(t)-251.0/365.0) < 0.5*dt)
    br = cohort*birthrate/dt + (1-cohort)*birthrate;
else
    br = (1.0-cohort)*birthrate;

// term-time seasonality
t = (t-floor(t))*365.25;
if ((t>=7 && t<=100) ||
    (t>=115 && t<=199) ||
    (t>=252 && t<=300) ||
    (t>=308 && t<=356))
    seas = 1.0+amplitude*0.2411/0.7589;
else
    seas = 1.0-amplitude;
```

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## Implementation of the process model II

```
// transmission rate
beta = R0*(gamma+mu)*seas;

// expected force of infection
foi = beta*pow(I+iota , alpha)/pop;

// white noise (extrademographic stochasticity)
dw = rgammawn(sigmaSE , dt);

rate[0] = foi*dw/dt; // stochastic force of infection
rate[1] = mu;        // natural S death
rate[2] = sigma;     // rate of ending of latent stage
rate[3] = mu;        // natural E death
rate[4] = gamma;     // recovery
rate[5] = mu;        // natural I death

// Poisson births
births = rpois(br*dt);
```

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## Implementation of the process model III

```
// transitions between classes
reulermultinom(2,S,&rate[0],dt,&trans[0]);
reulermultinom(2,E,&rate[2],dt,&trans[2]);
reulermultinom(2,I,&rate[4],dt,&trans[4]);

S += births - trans[0] - trans[1];
E += trans[0] - trans[2] - trans[3];
I += trans[2] - trans[4] - trans[5];
R = pop - S - E - I;
W += (dw - dt)/sigmaSE; // standardized i.i.d. white noise
C += trans[4];          // true incidence
```

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## Implementation of the process model IV

- ▶ The above code is in the C programming language. As shown in the remaining components (e.g. `rinit` below), we create an R string with these codes and pass the resulting string to the `Csnippet` function.
- ▶ In the above, the variable named `C` represents the true incidence, i.e., the number of new infections occurring over an interval.
- ▶ Since recognized measles infections are quarantined, we argue that most infection occurs before case recognition so that true incidence is a measure of the number of individuals progressing from the `I` to the `R` compartment in a given interval.

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## State initializations

We complete the process model definition by specifying the distribution of initial unobserved states. The following codes assume that the fraction of the population in each of the four compartments is known.

```
rinit <- Csnippet("  
  double m = pop/(S_0+E_0+I_0+R_0);  
  S = nearbyint(m*S_0);  
  E = nearbyint(m*E_0);  
  I = nearbyint(m*I_0);  
  R = nearbyint(m*R_0);  
  W = 0;  
  C = 0;  
")
```

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## The measurement model I

- ▶ We'll model both under-reporting and measurement error.
- ▶ We want  $\mathbb{E}[\text{cases}|C] = \rho C$ , where  $C$  is the true incidence and  $0 < \rho < 1$  is the reporting efficiency.
- ▶ We'll also assume that  $\text{Var}[\text{cases}|C] = \rho(1 - \rho)C + (\psi \rho C)^2$ , where  $\psi$  quantifies overdispersion.
- ▶ Note that when  $\psi = 0$ , the variance-mean relation is that of the binomial distribution. To be specific, we'll choose cases— $C \sim f(\cdot|\rho, \psi, C)$ , where

$$\begin{aligned} f(c|\rho, \psi, C) \\ = \Phi(c + \tfrac{1}{2}, \rho C, \rho(1 - \rho)C + (\psi \rho C)^2) - \\ \Phi(c - \tfrac{1}{2}, \rho C, \rho(1 - \rho)C + (\psi \rho C)^2) \end{aligned}$$

where  $\Phi(x, \mu, \sigma^2)$  is the c.d.f. of the normal distribution with mean  $\mu$  and variance  $\sigma^2$ .

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## The measurement model II

The following computes  $\mathbb{P}[\text{cases}|C]$ .

```
dmeas <- Csnippet("  
  double m = rho*C;  
  double v = m*(1.0-rho+psi*psi*m);  
  double tol = 1.0e-18;  
  if (cases > 0.0) {  
    lik = pnorm(cases+0.5,m,sqrt(v)+tol,1,0)-pnorm(cases-0.5,m,sqrt(v)+tol,1,0);  
  } else {  
    lik = pnorm(cases+0.5,m,sqrt(v)+tol,1,0)+tol;  
  }  
")
```

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## Case simulations

The following codes simulate  $\text{cases}|C$ .

```
rmeas <- Csnippet("  
  double m = rho*C;  
  double v = m*(1.0-rho+psi*psi*m);  
  double tol = 1.0e-18;  
  cases = rnorm(m,sqrt(v)+tol);  
  if (cases > 0.0) {  
    cases = nearbyint(cases);  
  } else {  
    cases = 0.0;  
  }  
")
```

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## Constructing the 'pomp' object

```
dat %>%
  pomp(t0=with(dat,2*time[1]-time[2]),
        time="time",
        rprocess=euler(rproc,delta.t=1/365.25),
        rinit=rinit,
        dmeasure=dmeas,
        rmeasure=rmeas,
        covar=covariate_table(covar,times="time"),
        accumvars=c("C","W"),
        statenames=c("S","E","I","R","C","W"),
        paramnames=c("R0","mu","sigma","gamma","alpha","iota",
                      "rho","sigmaSE","psi","cohort","amplitude",
                      "S_0","E_0","I_0","R_0")
  ) -> m1
```

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## Estimates from He et al. (2010)

He et al. (2010) estimated the parameters of this model. The full set is included in the R code accompanying this document, where they are read into a data frame called 'mles'.

We verify that we get the same likelihood as He et al. (2010).

Change eval to T

```
library(foreach)
library(doParallel)
library(doRNG)

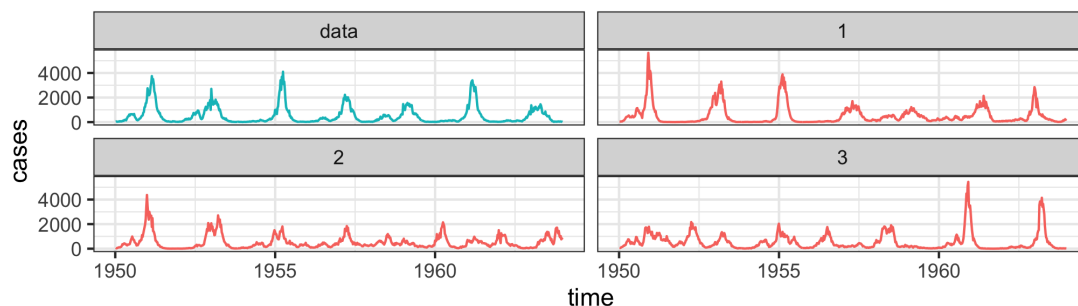
registerDoParallel()
registerDoRNG(998468235L)

foreach(i=1:4) %dopar% {
  library(pomp)
  pfilter(m1,Np=10000,params=theta)
} -> pfs
logmeanexp(sapply(pfs,logLik),se=TRUE)
```

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## Simulations at the MLE

```
m1 %>%  
  simulate(params=theta,nsim=3,format="d",include.data=TRUE) %>%  
  ggplot(aes(x=time,y=cases,group=.id,color=(.id=="data")))+  
  guides(color=FALSE)+  
  geom_line()+facet_wrap(~.id,ncol=2)
```



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## Parameter transformations

- ▶ The parameters are constrained to be positive, and some of them are constrained to lie between 0 and 1.
- ▶ We can turn the likelihood maximization problem into an unconstrained maximization problem by transforming the parameters.
- ▶ Specifically, to enforce positivity, we log transform, to constrain parameters to  $(0, 1)$ , we logit transform, and to confine parameters to the unit simplex, we use the log-barycentric transformation.

```
pt <- parameter_trans(  
  log=c("sigma","gamma","sigmaSE","psi","R0"),  
  logit=c("cohort","amplitude"),  
  barycentric=c("S_0","E_0","I_0","R_0")  
)  
m1 %>%  
  pomp(partrans=pt,  
    statenames=c("S","E","I","R","C","W"),  
    paramnames=c("R0","mu","sigma","gamma","alpha","iota",  
      "rho","sigmaSE","psi","cohort","amplitude"),
```

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## Results from He et al. (2010)

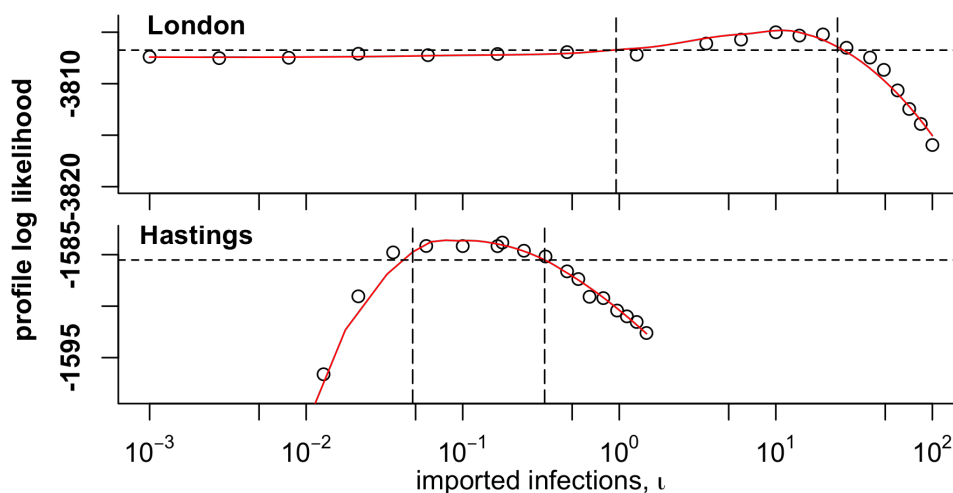
The linked document shows how a likelihood profile can be constructed using IF2. The fitting procedure used is as follows:

- ▶ A large number of searches were started at points across the parameter space.
- ▶ Iterated filtering was used to maximize the likelihood.
- ▶ We obtained point estimates of all parameters for 20 cities.
- ▶ We constructed profile likelihoods to quantify uncertainty in London and Hastings.

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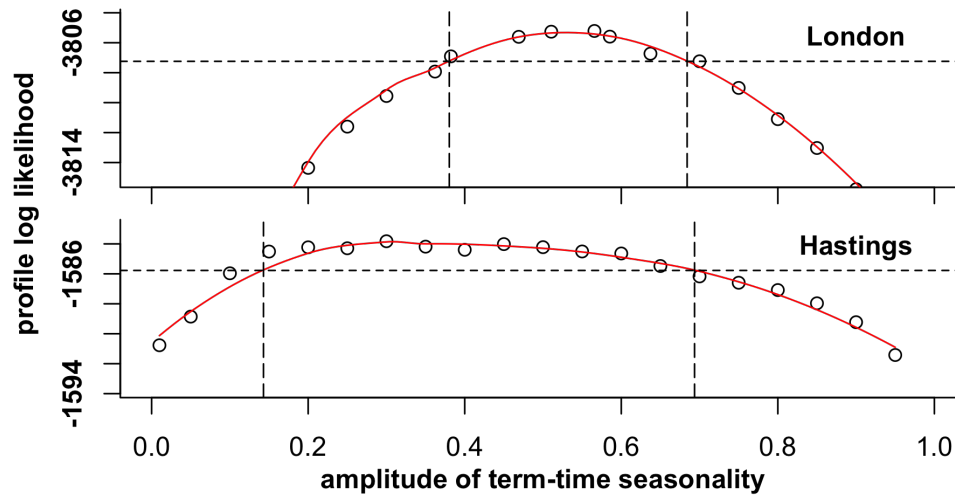
## Imported infections

$$\text{force of infection} = \mu_{SE} = \frac{\beta(t)}{N(t)} (I + \iota) \zeta(t)$$



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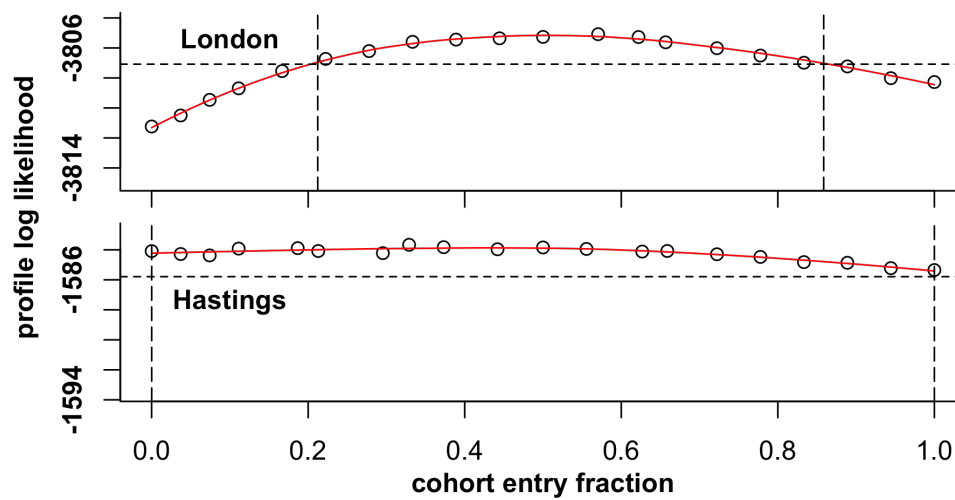
# Seasonality



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# Notable findings

## Cohort effect



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Notable findings

Birth delay

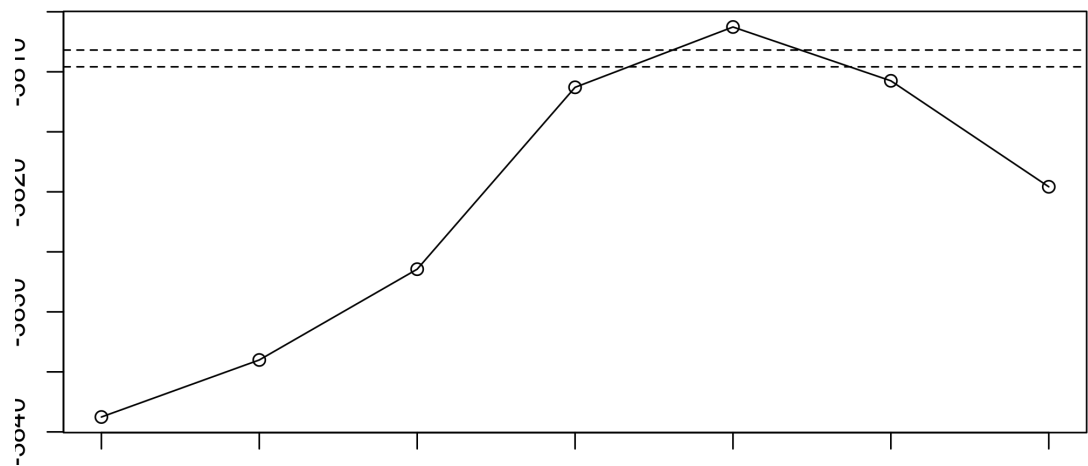
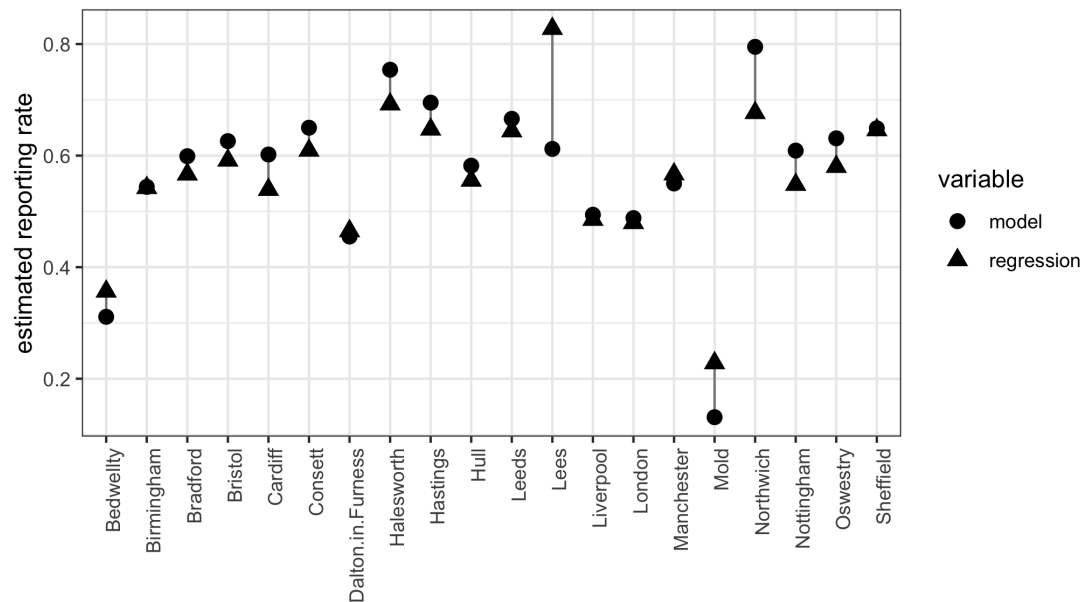


Figure: Profile likelihood for birth-cohort delay, showing 95% and 99% critical values of the log likelihood.

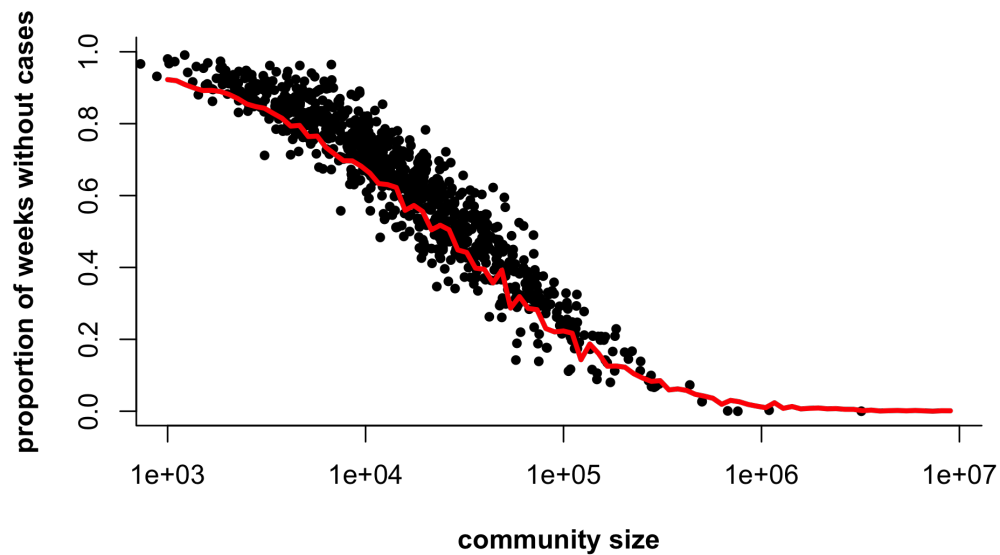
Notable findings

Reporting rate



## Notable findings

### Predicted vs observed critical community size

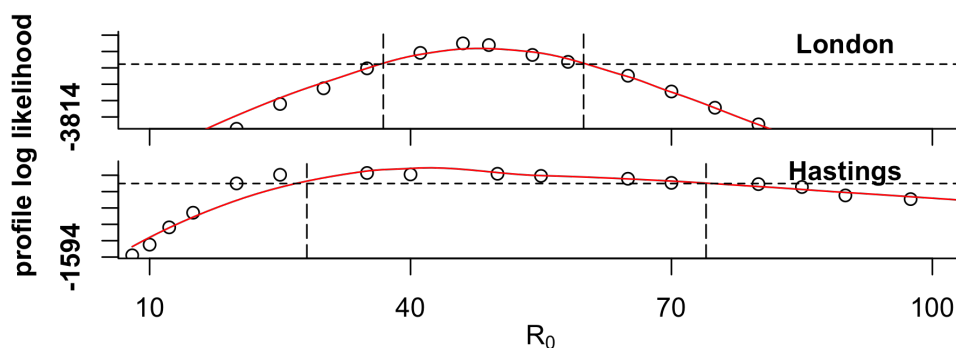


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## Problematic results

### $R_0$ estimates inconsistent with literature

- ▶ Recall that  $R_0$  : a measure of how communicable an infection is.
- ▶ Existing estimates of  $R_0$  (c. 15–20) come from two sources: serology surveys, and models fit to data using feature-based methods.



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## Problematic results

### Parameter estimates

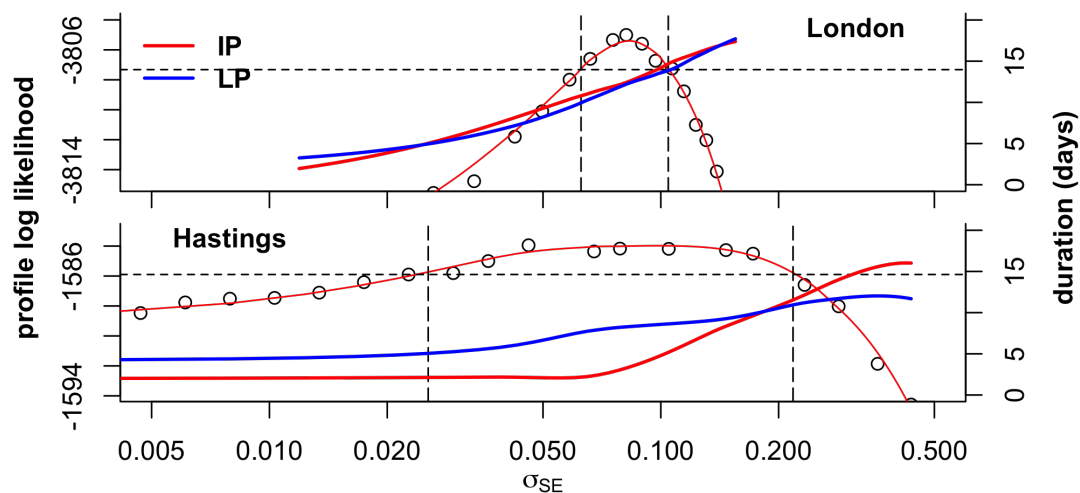
##	pop	R0	amplitude	LP	IP
## Halesworth	2170	33.100	0.381	7.870	2.290
## Lees	4250	29.700	0.153	8.510	2.050
## Mold	6410	21.400	0.271	5.930	1.780
## Dalton.in.Furness	10600	28.300	0.203	5.480	1.980
## Oswestry	11000	52.900	0.339	10.300	2.710
## Northwich	18300	30.100	0.423	8.510	3.020
## Bedwellty	28900	24.700	0.160	6.820	3.030
## Consett	39100	35.900	0.200	9.080	2.660
## Hastings	65700	34.200	0.299	7.000	5.440
## Cardiff	245000	34.400	0.223	9.870	3.090
## Bradford	294000	32.100	0.236	8.510	3.360
## Hull	302000	38.900	0.221	9.180	5.460
## Nottingham	307000	22.600	0.157	5.720	3.700
## Bristol	443000	26.800	0.203	6.190	4.940
## Leeds	510000	47.800	0.267	9.480	10.900
## Sheffield	515000	33.100	0.313	7.230	6.380
## Manchester	704000	32.900	0.290	11.100	6.940
## Liverpool	802000	48.100	0.305	7.900	9.800
## Birmingham	1120000	43.400	0.428	8.510	11.600
## London	3390000	56.800	0.554	13.100	12.500
## r	NA	0.455	0.301	0.322	0.946
##	alpha	iota	rho	psi	sigmaSE
## Halesworth	0.948	0.00912	0.754	0.641	0.0748
## Lees	0.968	0.03110	0.612	0.681	0.0802
## Mold	1.040	0.01450	0.131	2.870	0.0544

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## Problematic results

### Extrademographic stochasticity

$$\mu_{SE} = \frac{\beta(t)}{N(t)} (I + \iota) \zeta(t)$$



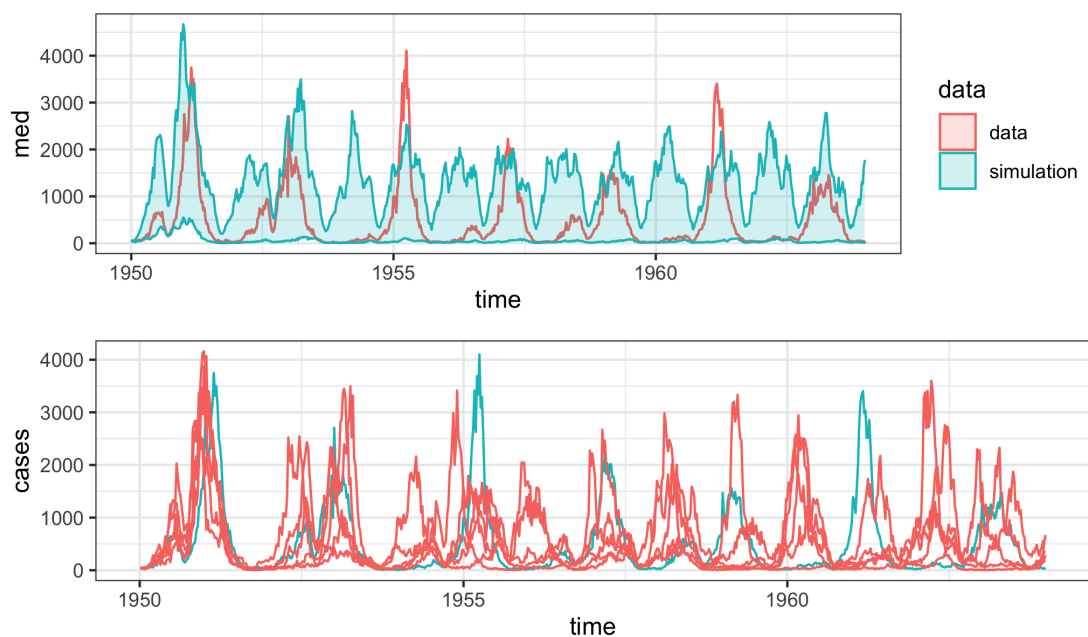
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## Questions

- ▶ What does it mean that parameter estimates from the fitting disagree with estimates from other data?
- ▶ How can one interpret the correlation between infectious period and city size in the parameter estimates?
- ▶ How do we interpret the need for extrademographic stochasticity in this model?

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## Simulations at the MLE



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## Exercises

### Exercise 1: Reformulate the model

- ▶ Modify the He et al. (2010) model to remove the cohort effect. Run simulations and compute likelihoods to convince yourself that the resulting codes agree with the original ones for 'cohort = 0'.
- ▶ Now modify the transmission seasonality to use a sinusoidal form. How many parameters must you use? Fixing the other parameters at their MLE values, compute and visualize a profile likelihood over these parameters.

### Exercise 2: Extrademographic

**stochasticity** Set the extrademographic stochasticity parameter  $\sigma_{SE} = 0$ , set  $\alpha = 1$ , and fix  $\rho$  and  $\iota$  at their MLE values, then maximize the likelihood over the remaining parameters.

- ▶ How do your results compare with those at the MLE? Compare likelihoods but also use simulations to diagnose differences between the models.

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## Acknowledgments

- ▶ Versions of this material have been presented at Summer Institute in Statistics and Modeling in Infectious Diseases (SISMID) in 2015-2018.
- ▶ Licensed under the <http://creativecommons.org/licenses/by-nc/4.0/>. Please share and remix noncommercially, mentioning its origin.



- ▶ Produced in R version 4.0.0 using **pomp** version 3.0.2.0.

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## References I

- Bhadra, A., Ionides, E. L., Laneri, K., Pascual, M., Bouma, M. and Dhiman, R. (2011). Malaria in Northwest India: Data analysis via partially observed stochastic differential equation models driven by Lévy noise, *Journal of the American Statistical Association* **106**: 440–451.
- He, D., Ionides, E. L. and King, A. A. (2010). Plug-and-play inference for disease dynamics: measles in large and small populations as a case study, *Journal of the Royal Society, Interface* **7**: 271–283.
- Rohani, P. and King, A. A. (2010). Never mind the length, feel the quality: the impact of long-term epidemiological data sets on theory, application and policy, *Trends in Ecology & Evolution* **25**(10): 611–618.