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United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

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Workshop on Theoretical Ecology and Global Change

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Climate variability and epidemic cycles: from understanding the past to anticipating the future I

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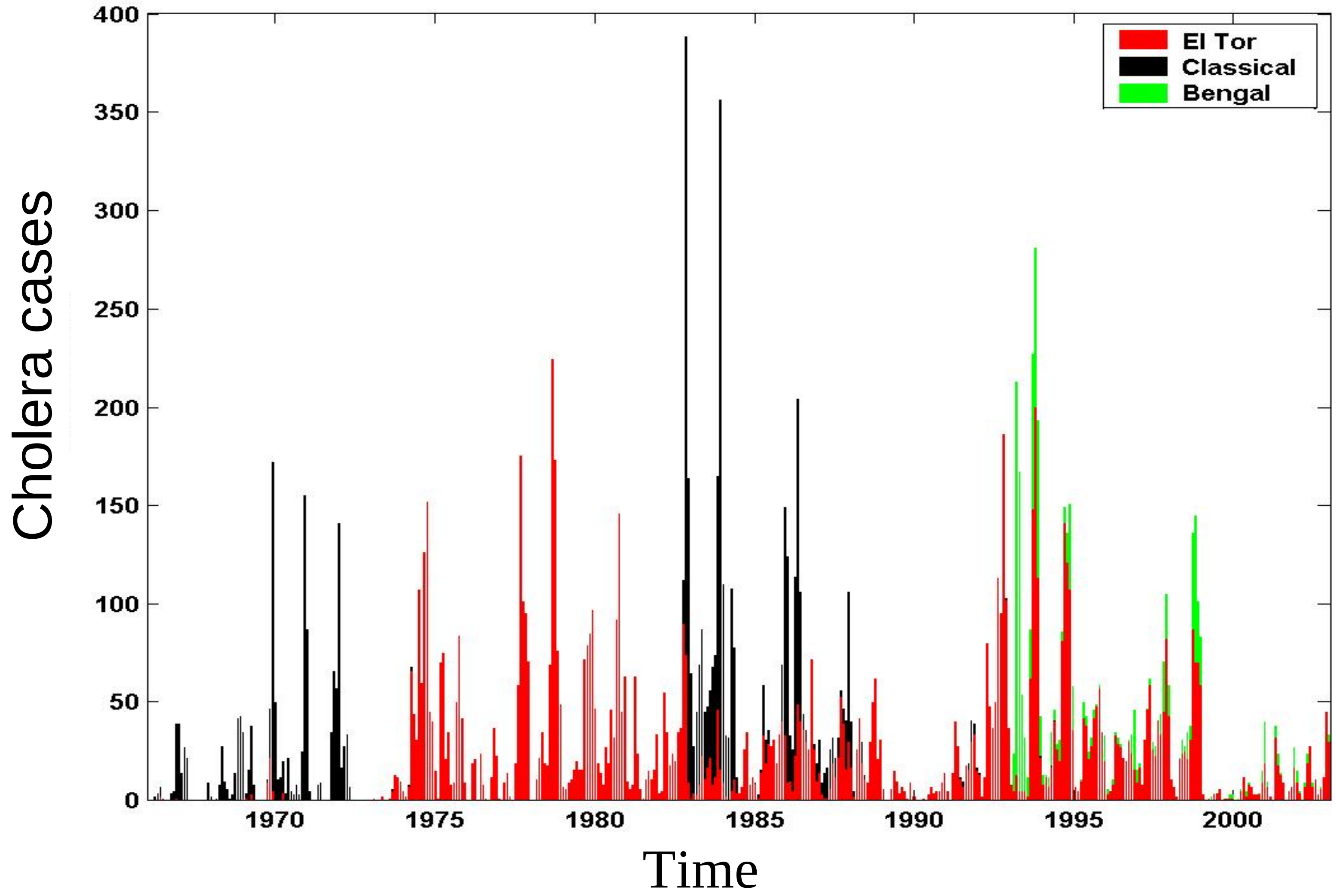
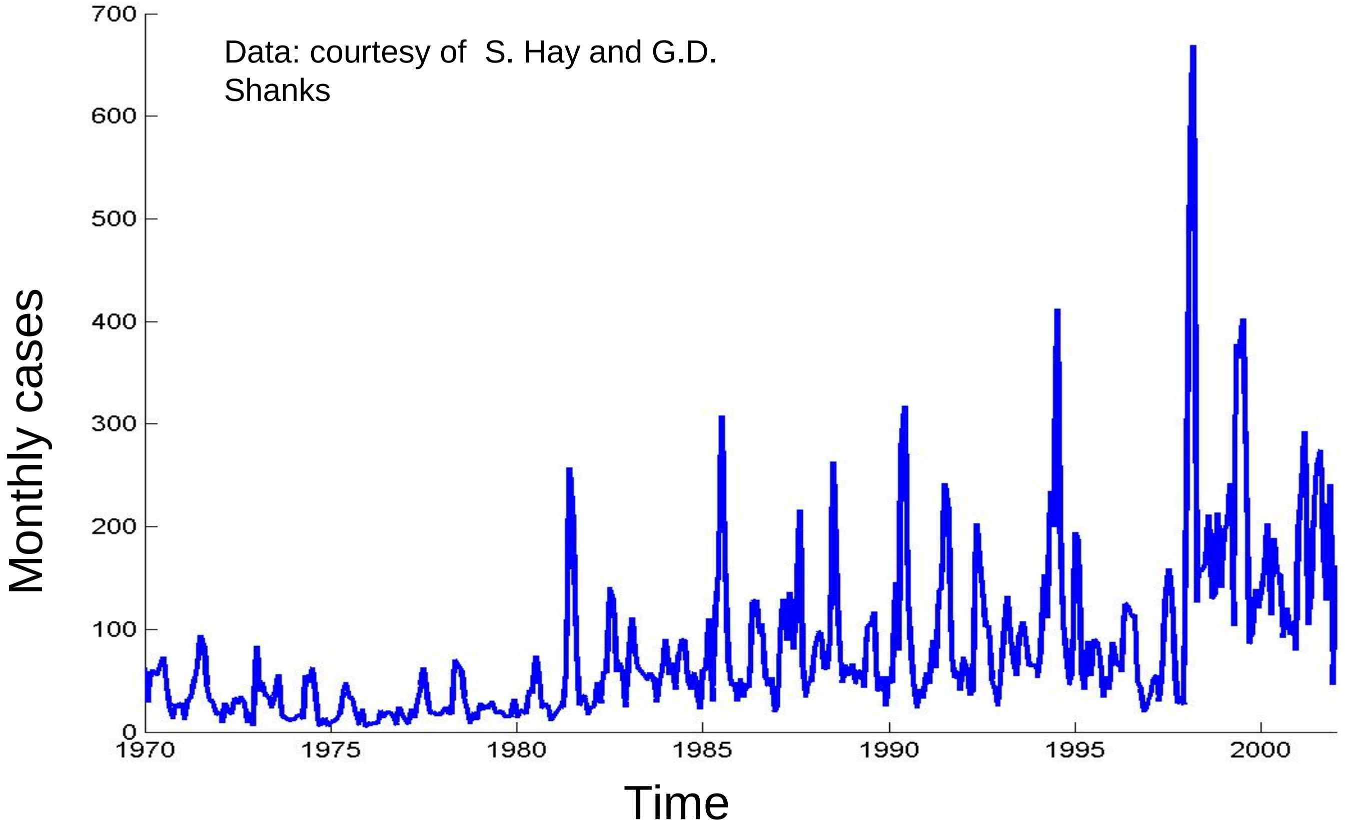
London, 1854


Bangladesh, 2000
courtesy ICDDR, B



El Tor
Classical
Bengal
400
350
300
250
200
150
100
50
0
1970
1975
1980
1985
1990
1995
2000
Cholera cases
Time

Malaria ward, Amana Hospital, in Dar es Salaam
Photograph / SAMANTHA APPLETON



Data: courtesy of S. Hay and G.D. Shanks
Monthly cases
0
100
200
300
400
500
600
700
1970
1975
1980
1985
1990
1995
2000
Time

METHODS OF DIVINATION

Traditional techniques of foretelling the future include:
Stars and planets (astrology)
Rolling dice/drawing lots (cleromancy)
Tarot cards (cartomancy)
Palm reading (chiromancy)
Crystal balls (crystallomancy)
Shape of head (phrenology)
Atmospheric conditions (aeromancy)
Dreams (oneiromancy)
Animal entrails (haruspicy)
Moles on the body (moleosophy)
Lightning and thunder (ceraunoscopy)
Smoke and fire (pyromancy)
Flight of birds (ornithomancy)
Neighing of horses (hippomancy)
Tea leaves or coffee grounds (tasseomancy)
Passages of sacred texts (bibliomancy)
Numbers (numerology)
I Ching
Guessing
To which we can add:
Mathematical models (meteorology/biology/economics)

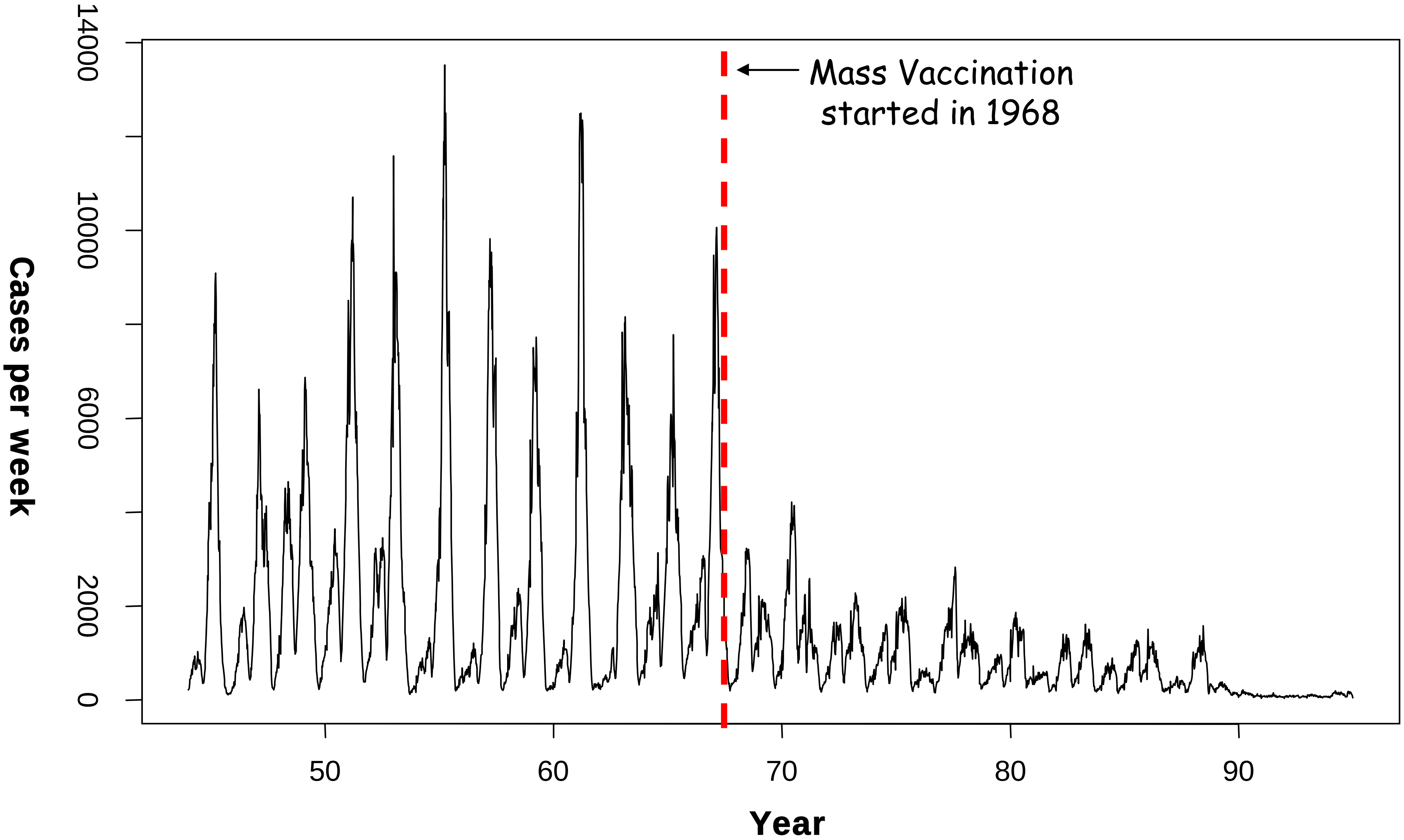
D. Orrell. The Future of Everything

Measles

- Airborne RNA virus
- Respiratory infection
- Mean latent period: 8 days
- Mean infectious period: 5 days
- Lifelong immunity after recovery
- Easy to diagnose

Still kills ~ 1 million people/year

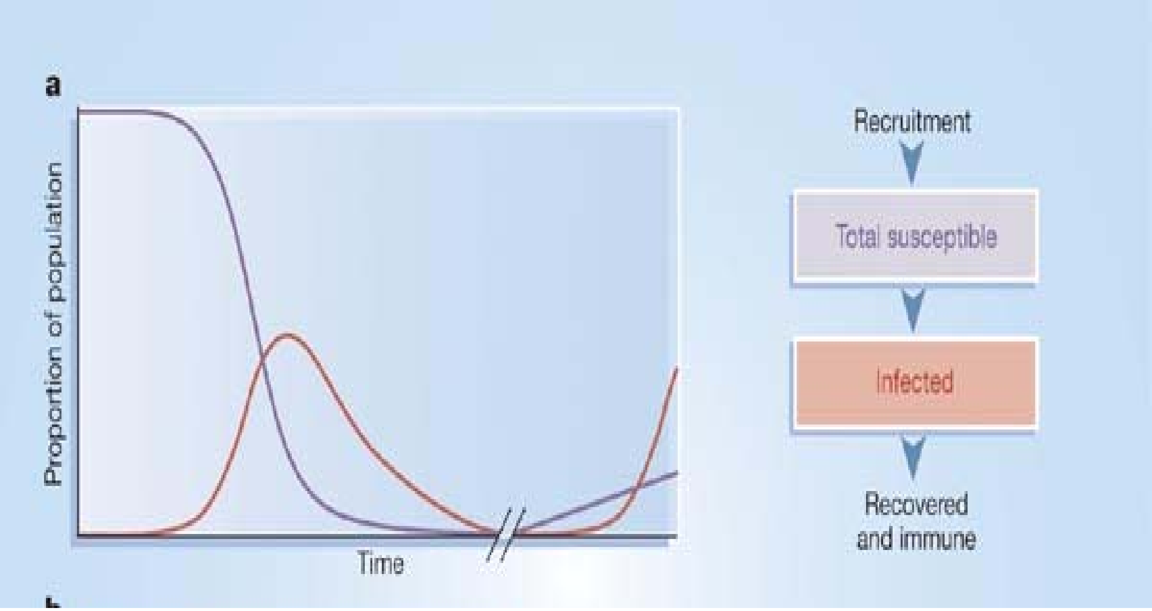
Measles in England & Wales 1945-1995



Outline

- Some general background on disease models (as "natural oscillators")
- Cholera cycles and climate variability (ENSO): disentangling intrinsic and extrinsic factors
- A detour into Wavelet Spectra to characterize patterns of variability
- An application to malaria and rainfall variability

Infectious diseases as forced "natural" oscillators



From Bryan Grenfell, Ottar Bjornstad (2004)

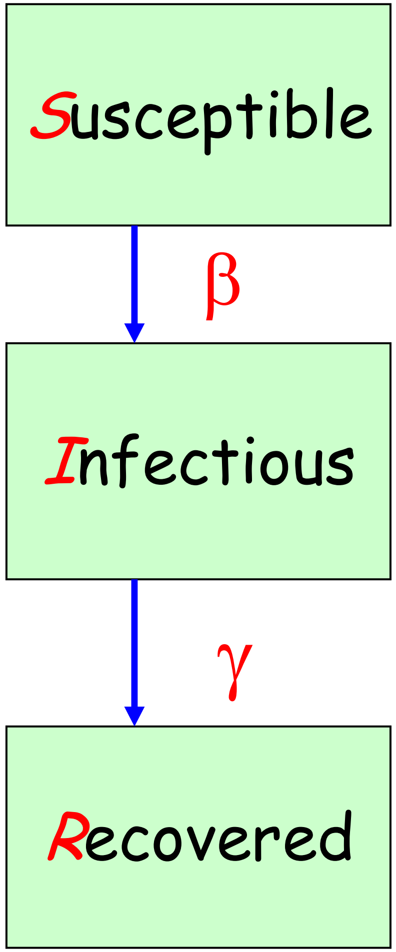
Courtesy: J. Vandermeer

SIR: basic model

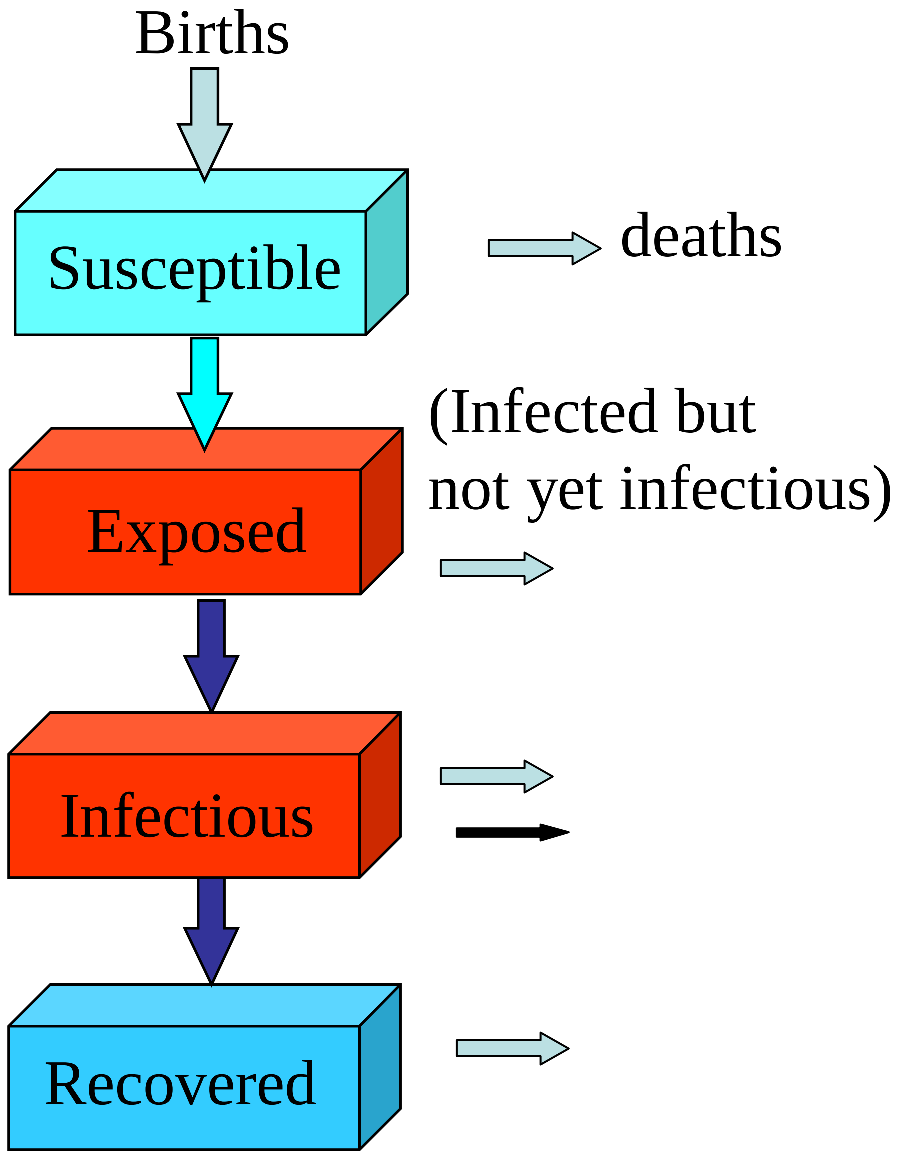
$$\frac{dS}{dt} = -\beta\, SI$$

$$\frac{dI}{dt} = +\beta\, SI - \gamma\, I$$

$$\frac{dR}{dt} = +\gamma\, I$$

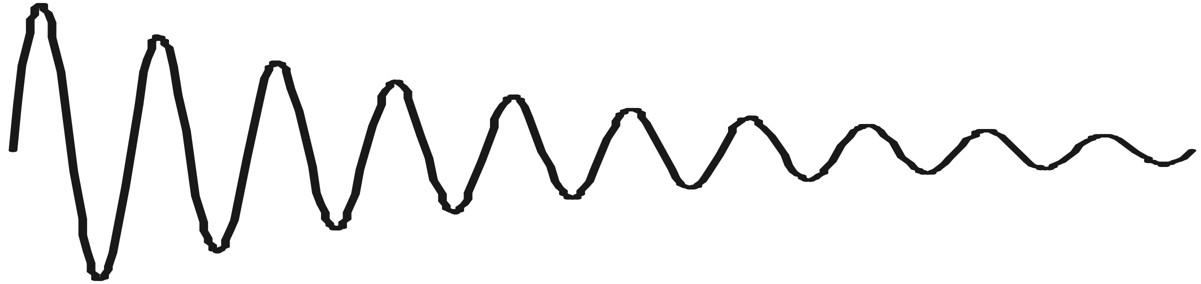


SEIR Model with demography



SEIR Model: Results

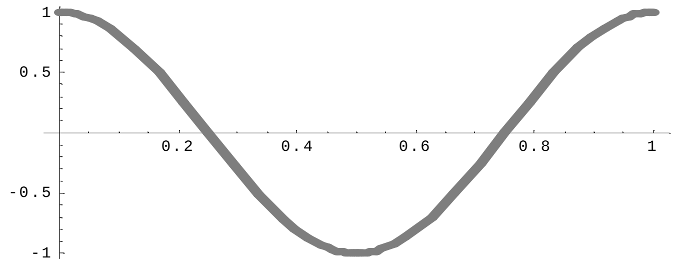
- *Endemic equilibrium*
- *Explains persistence*
- Equilibrium approached by *damped oscillations:* recurrent epidemics



- Does not explain *persistent* oscillations: add noise or seasonality

Intrinsic disease dynamics and seasonality

Natural cycles of the disease



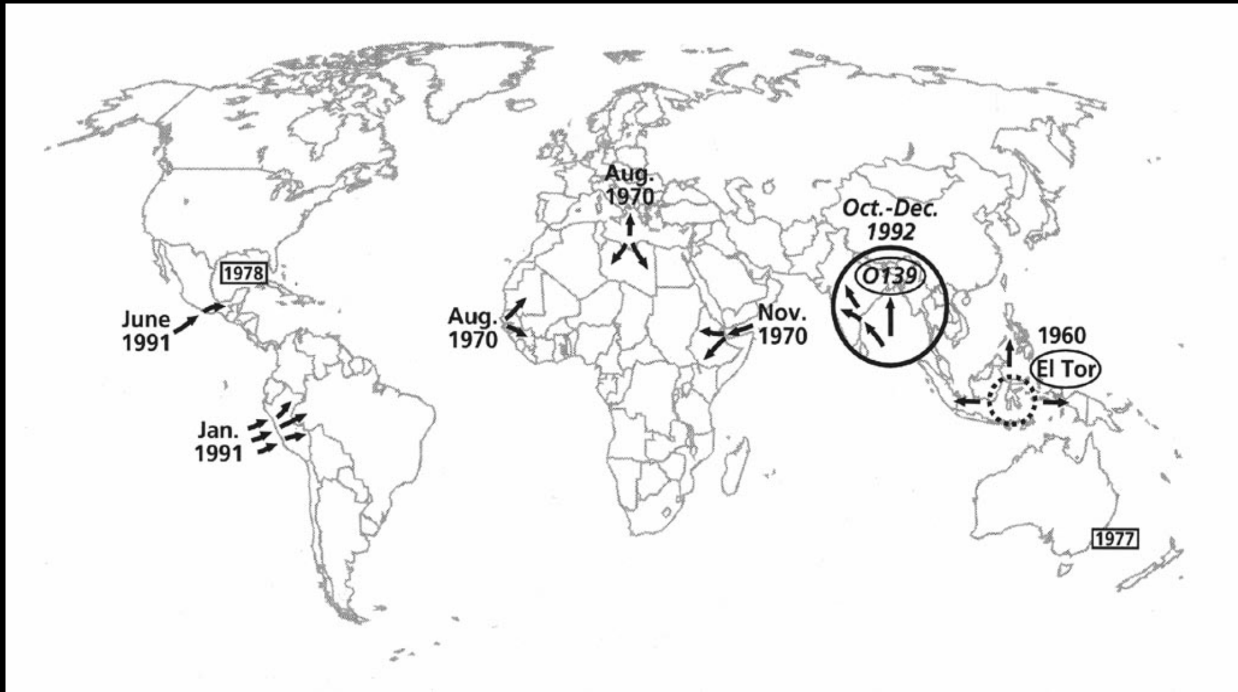
Seasonal transmission

Annual cycles

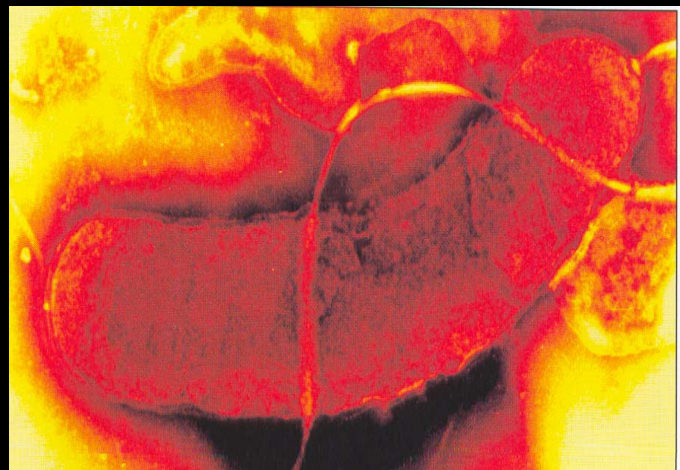
Biennial cycles or cycles of longer period

Multiple coexisting cycles

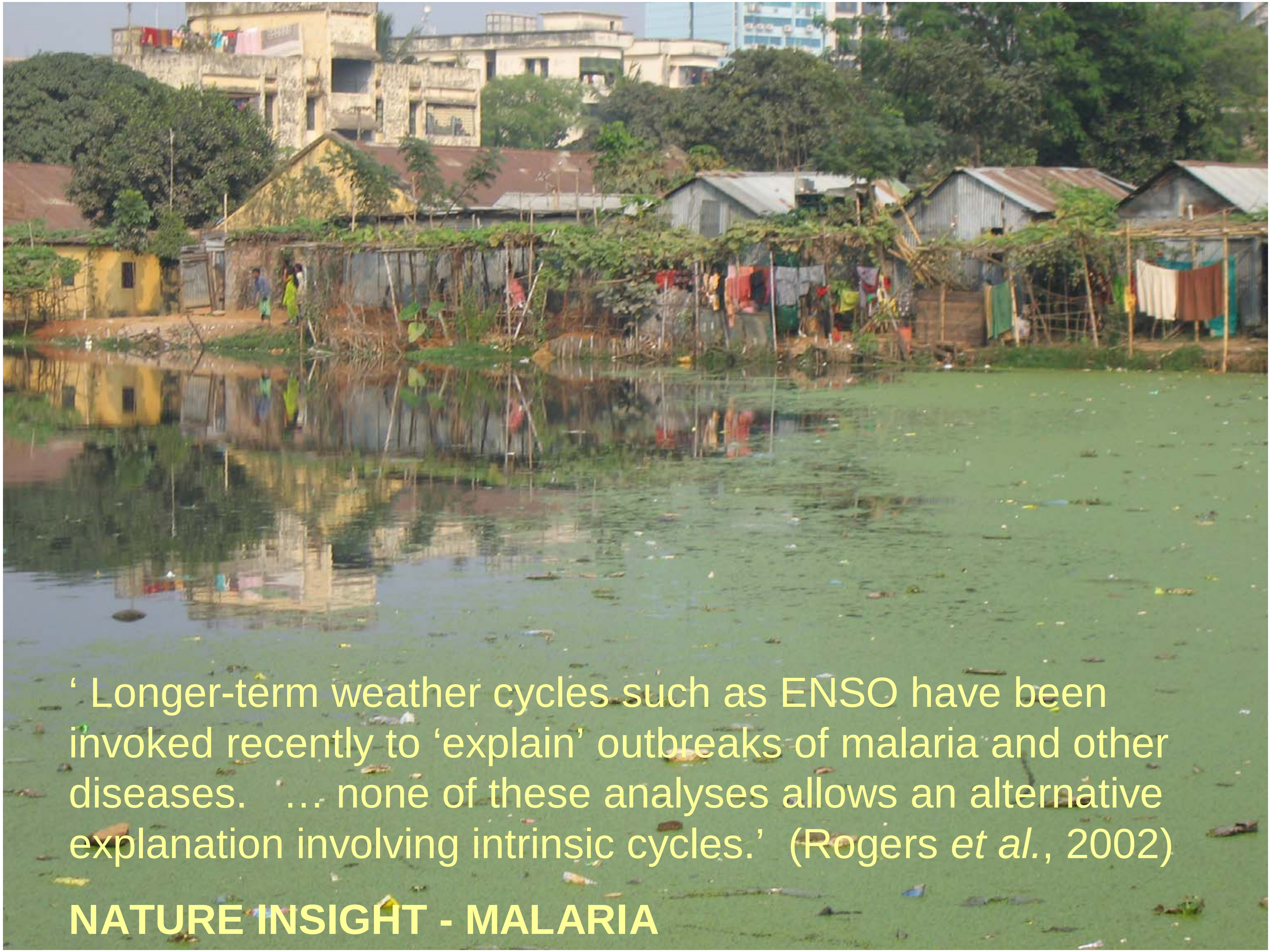
Chaos

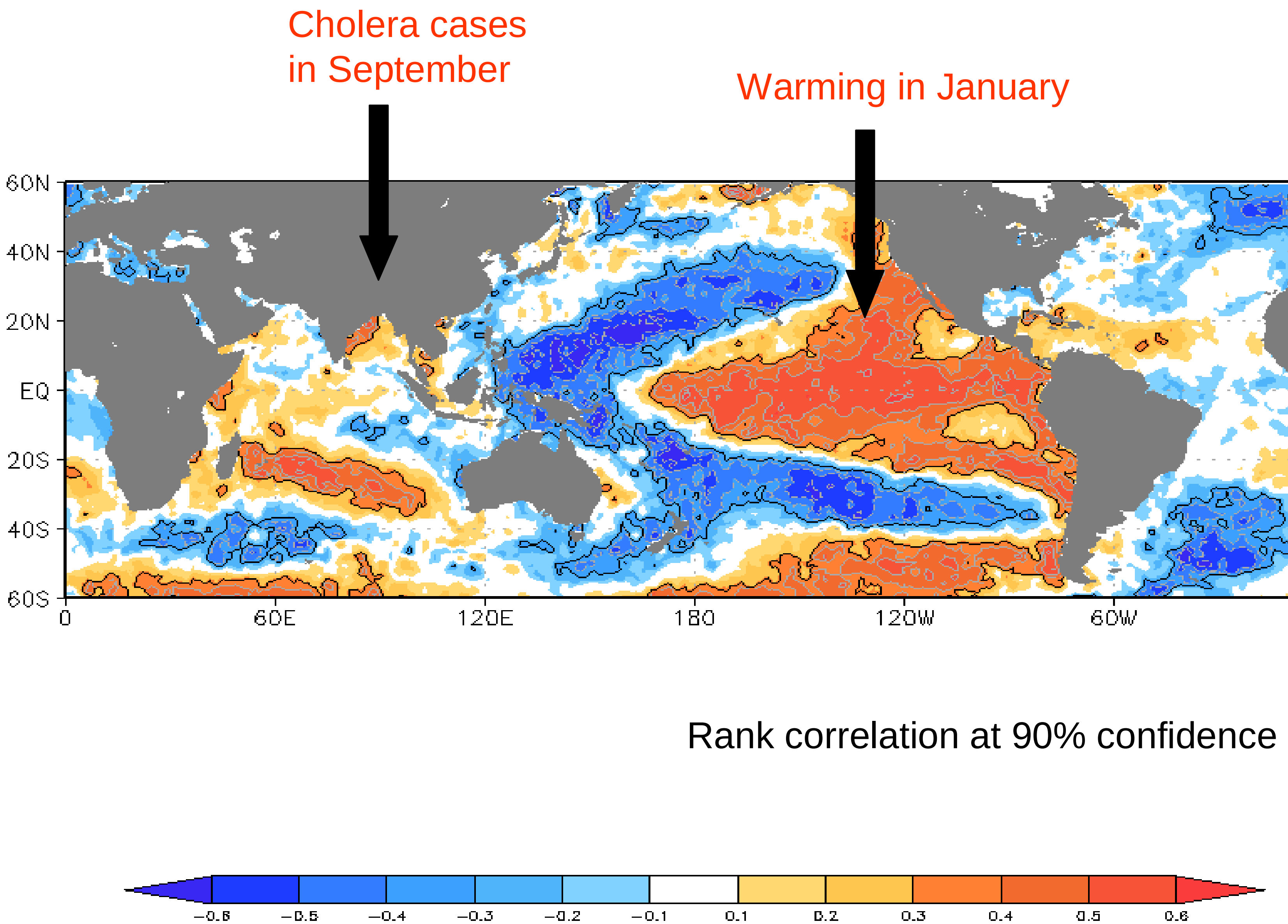


The pathogen, *Vibrio cholerae*, inhabits aquatic environments (brackish water and estuaries) (Colwell *et al.* 1981)



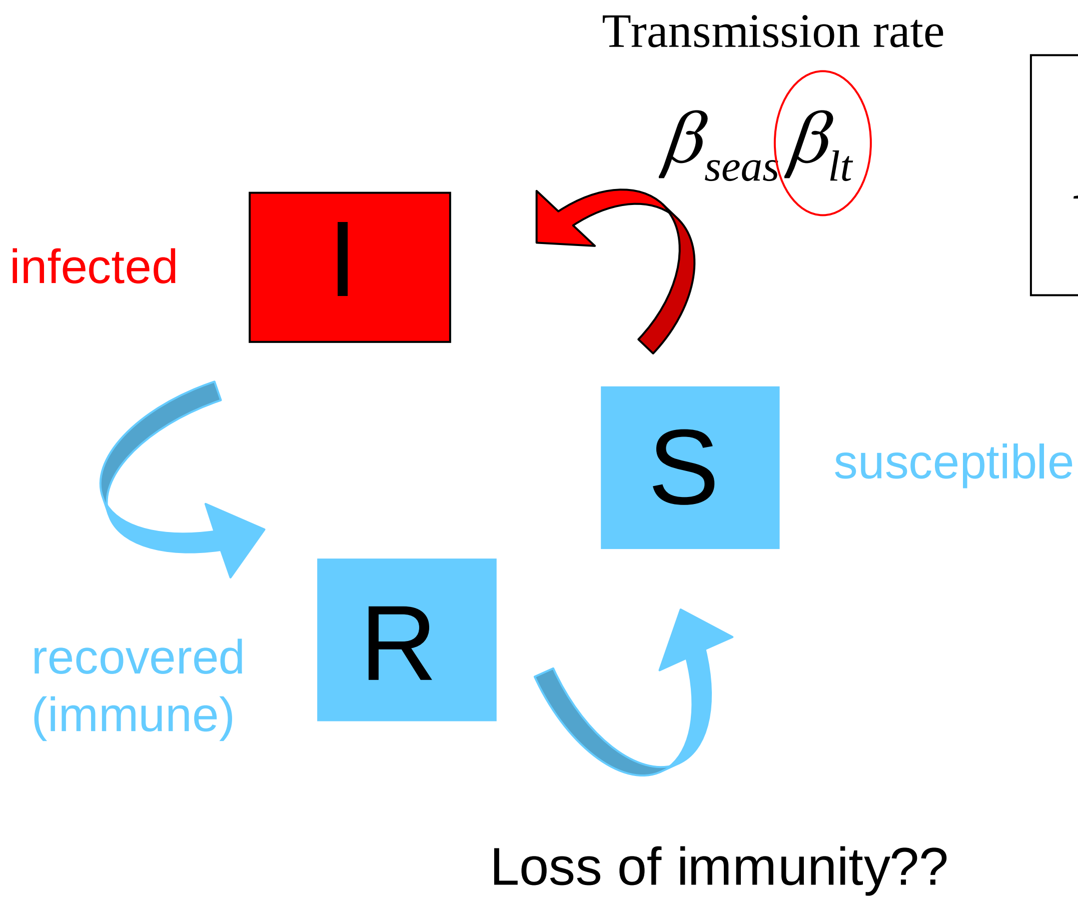

From National Geographic web site


‘ Longer-term weather cycles such as ENSO have been invoked recently to ‘explain’ outbreaks of malaria and other diseases. … none of these analyses allows an alternative explanation involving intrinsic cycles.’ (Rogers *et al.*, 2002)
NATURE INSIGHT - MALARIA



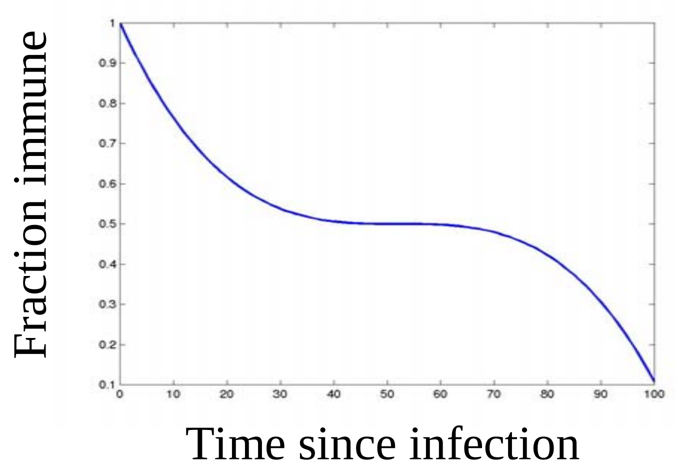
Pascual, Chaves, Rodo, Cash, Yunus
(Climate Research 2008)

Disease population model: TSIRS



$$I_{t+1} = \beta_{seas}\beta_{lt}\, I_t^{\alpha}\, \frac{S_t}{N_t}\, \varepsilon_t$$

$$S_t = N_t - \sum_{i=0}^{m} I_{t-i}\, k(i)$$



$$\ln(I_{t+1}) = \ln(\beta_t) + \ln(\beta_{seas}) + \alpha \ln(I_t) + \gamma \ln\left(\frac{S_t}{N_t}\right) + \ln(\varepsilon_t)$$

Smooth function of t:
semiparametric models
(Hastie and Tibshirani, 1990; Ellner *et al.*, 1998)

1- regression step
(weighted least square)

2- smoothing step
(smoothing the time series of residuals)

S_t ?

$$\Rightarrow \ln\frac{S_t}{N_t} \approx -\frac{R_t}{N_t} + O\left(\frac{R_t^2}{N_t^2}\right)$$

with $R_t = \sum_{i=0}^{m} I_{t-i} k(i)$

backfitting algorithm ...

Koelle and Pascual. Am. Nat. 2004

Observed patterns

I

cases

population model(s) +
statistical inference methods

1) Decay of immunity

2) Susceptibles

Intrinsic dynamics

3) Variability of transmission rate over time

Seasonal transmission rate

Long-term transmission rate

Residuals (unexplained variability)

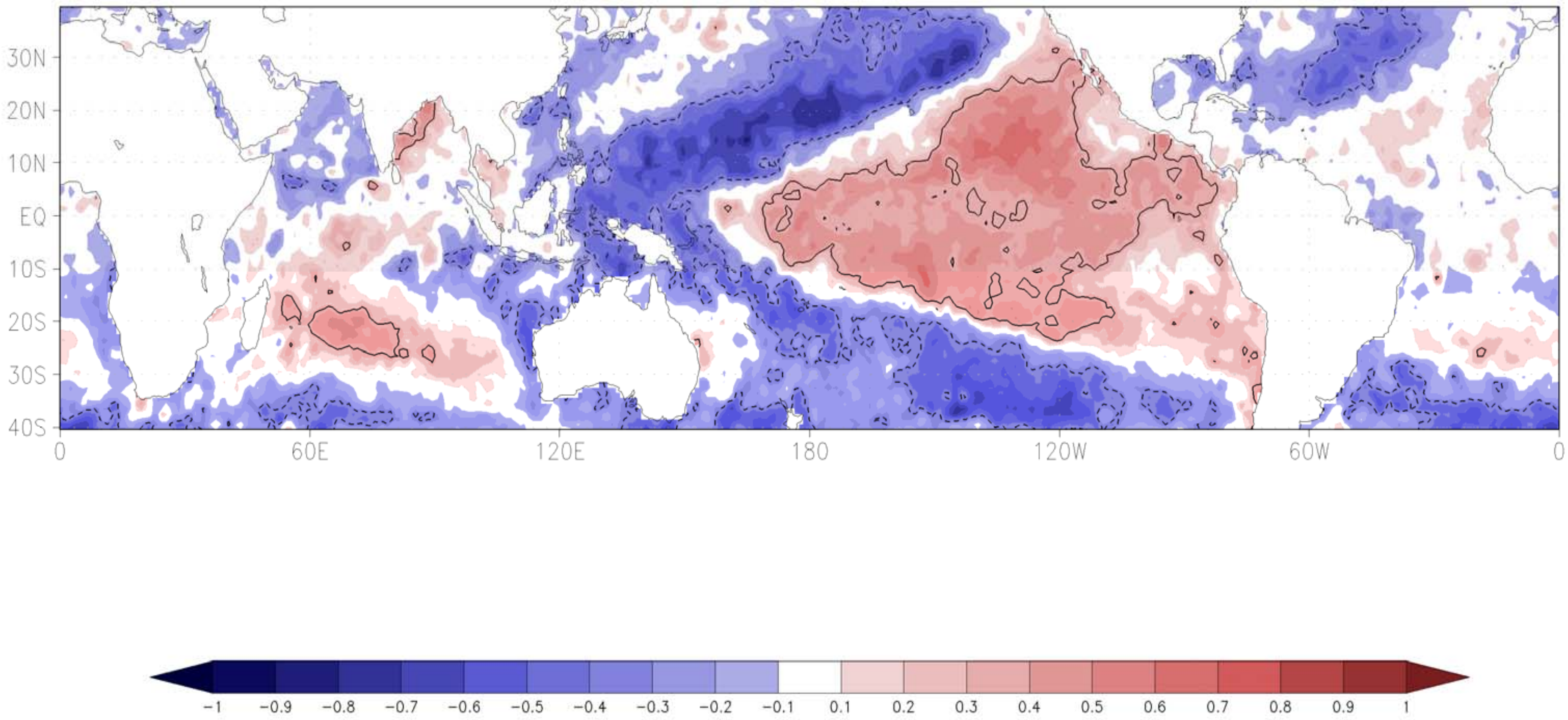
Extrinsic factors (e.g. climate)

Koelle and Pascual (Am. Nat. 2004)

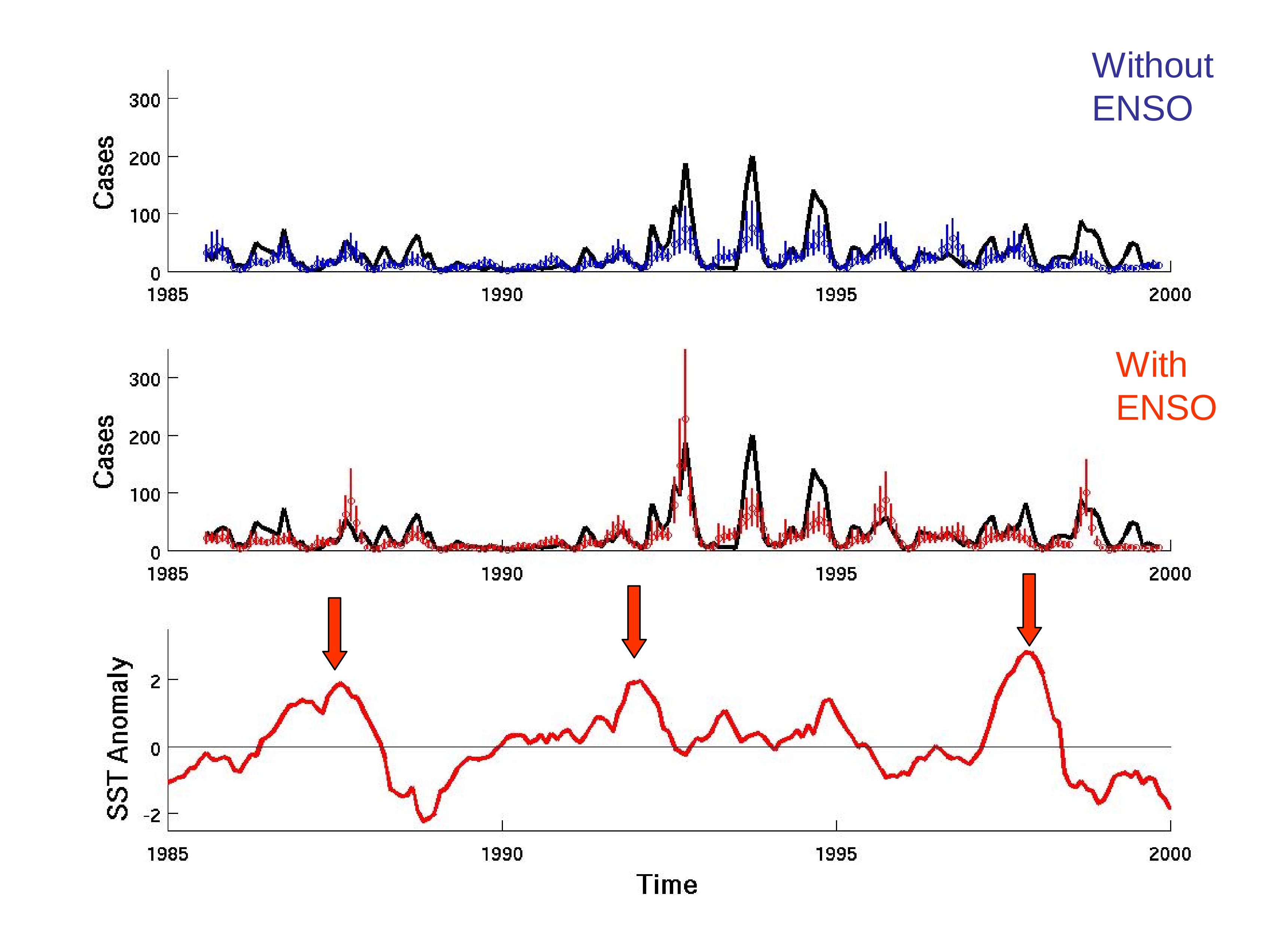
Koelle, Rodo, Pascual et al. (Nature 2005)

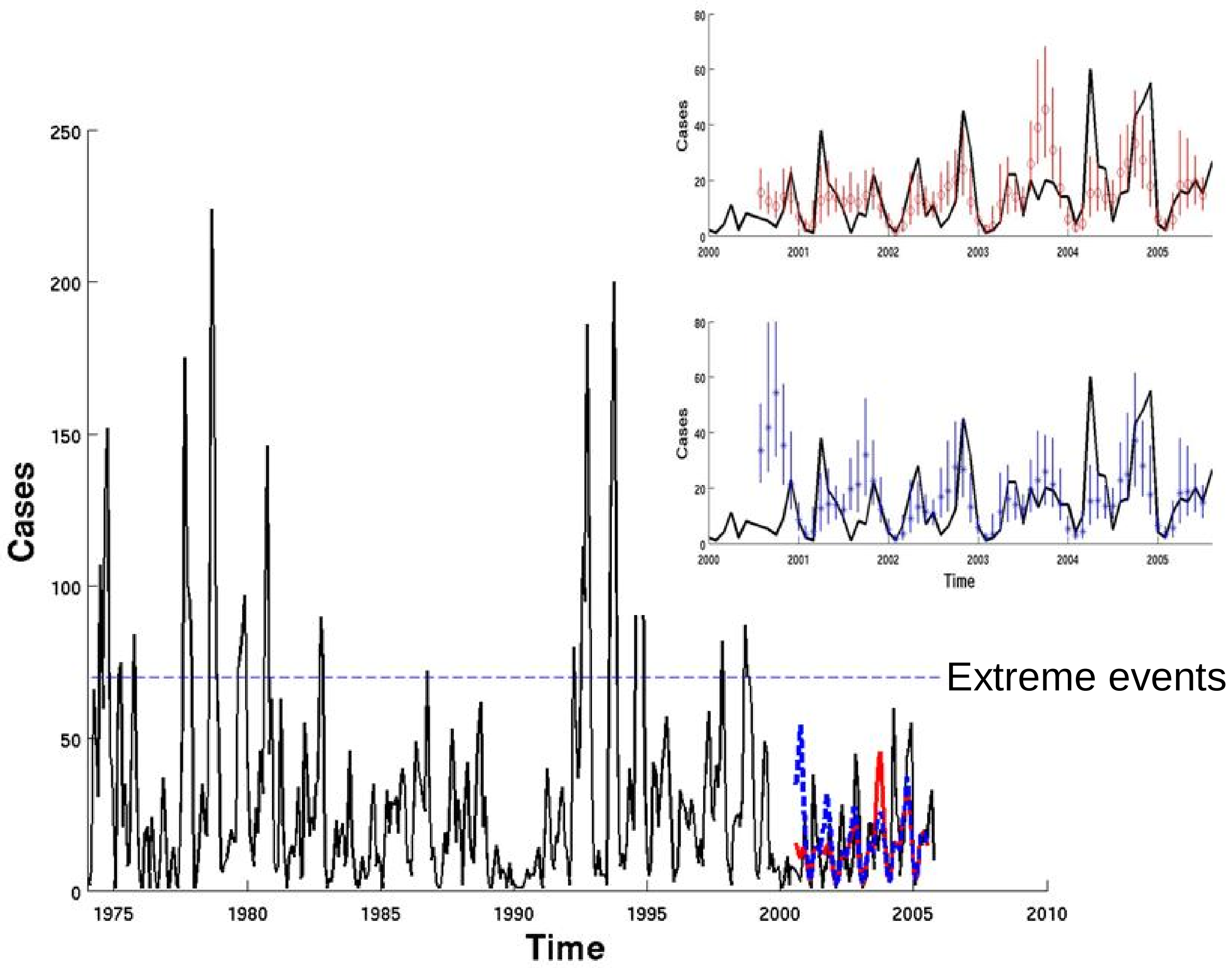
Pascual et al. (Climate Research 2008)

September residuals
and Sea Surface Temperature anomalies in January



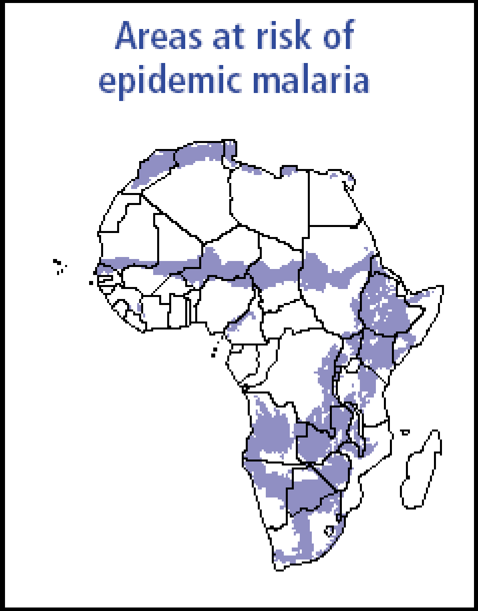
Refractory periods: 7-months lead (hindcast) predictions




Cases
Time
Extreme events

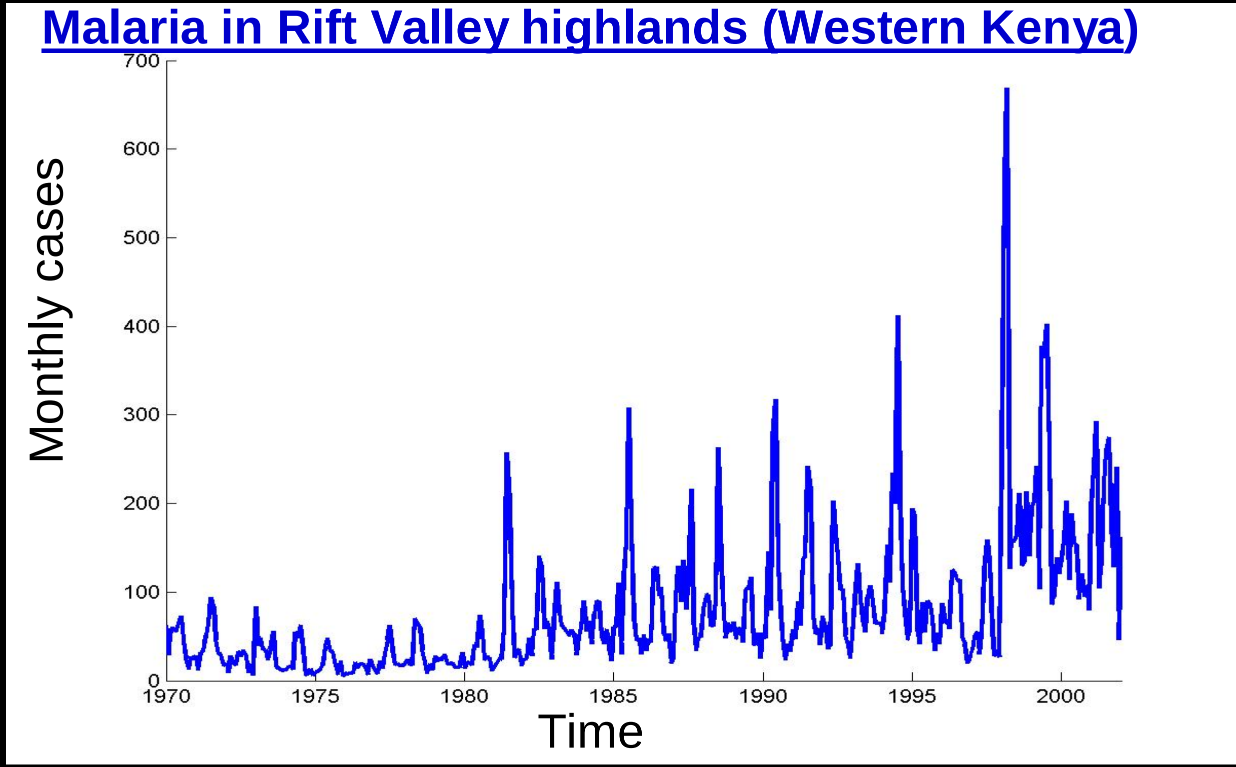
- Method(s) to disentangle extrinsic forcing from nonlinear feedbacks within a system with unobserved variables
- Climate variability (ENSO, rainfall) drives cholera dynamics but immunity is key to the response

- New statistical method (Ionides, Breto, and King, PNAS 2006, “MIF”) → continuous time, more flexible formulations, different types of noise, **allows model comparisons based on likelihoods**



~ 110 million people live in areas at risk of epidemic malaria in Africa

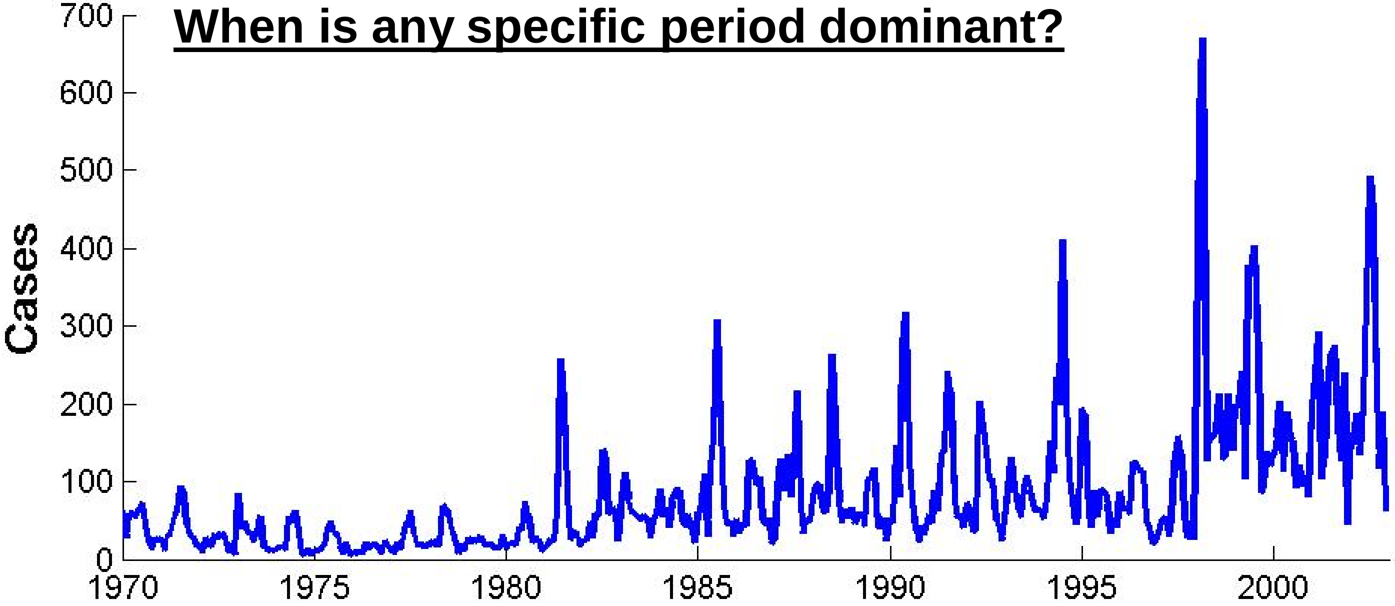
Estimated 110 000 deaths from epidemics each year (Africa Malaria Report, 2003)

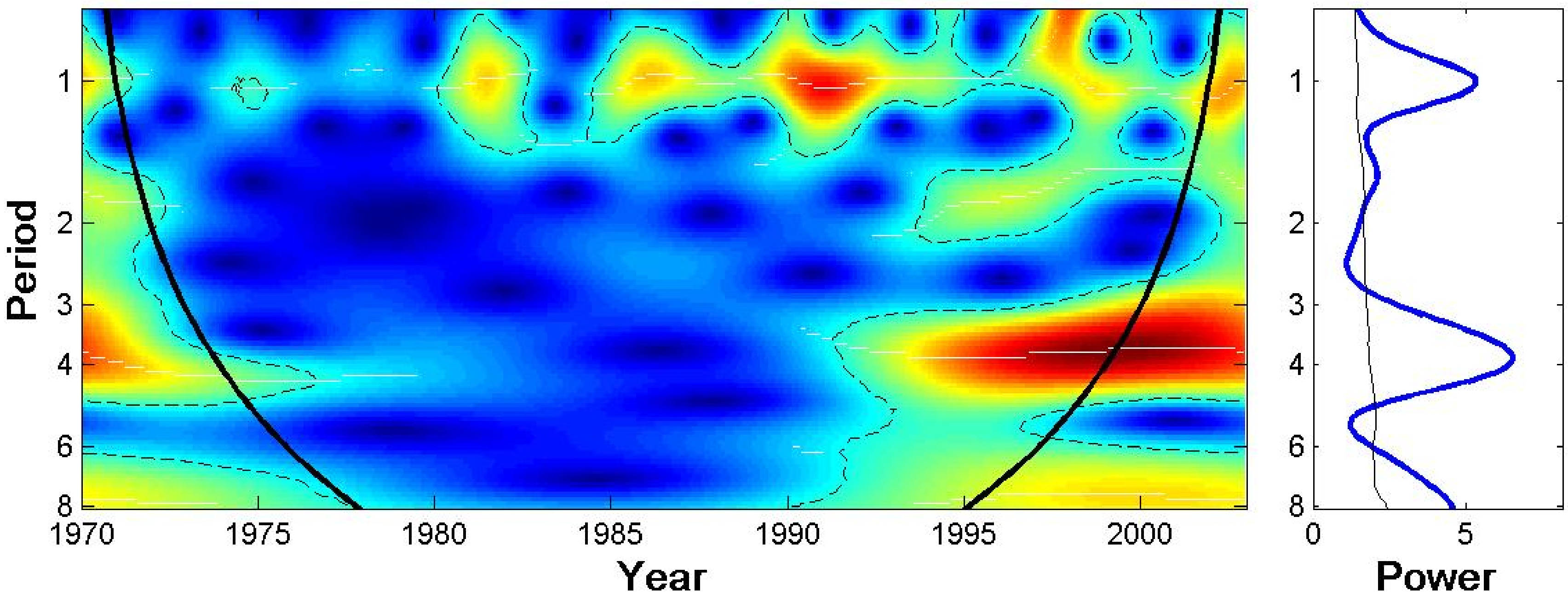


Data: courtesy of
S. Hay and G.D. Shanks

Which periods (or frequencies) are dominant in these dynamics?

When is any specific period dominant?

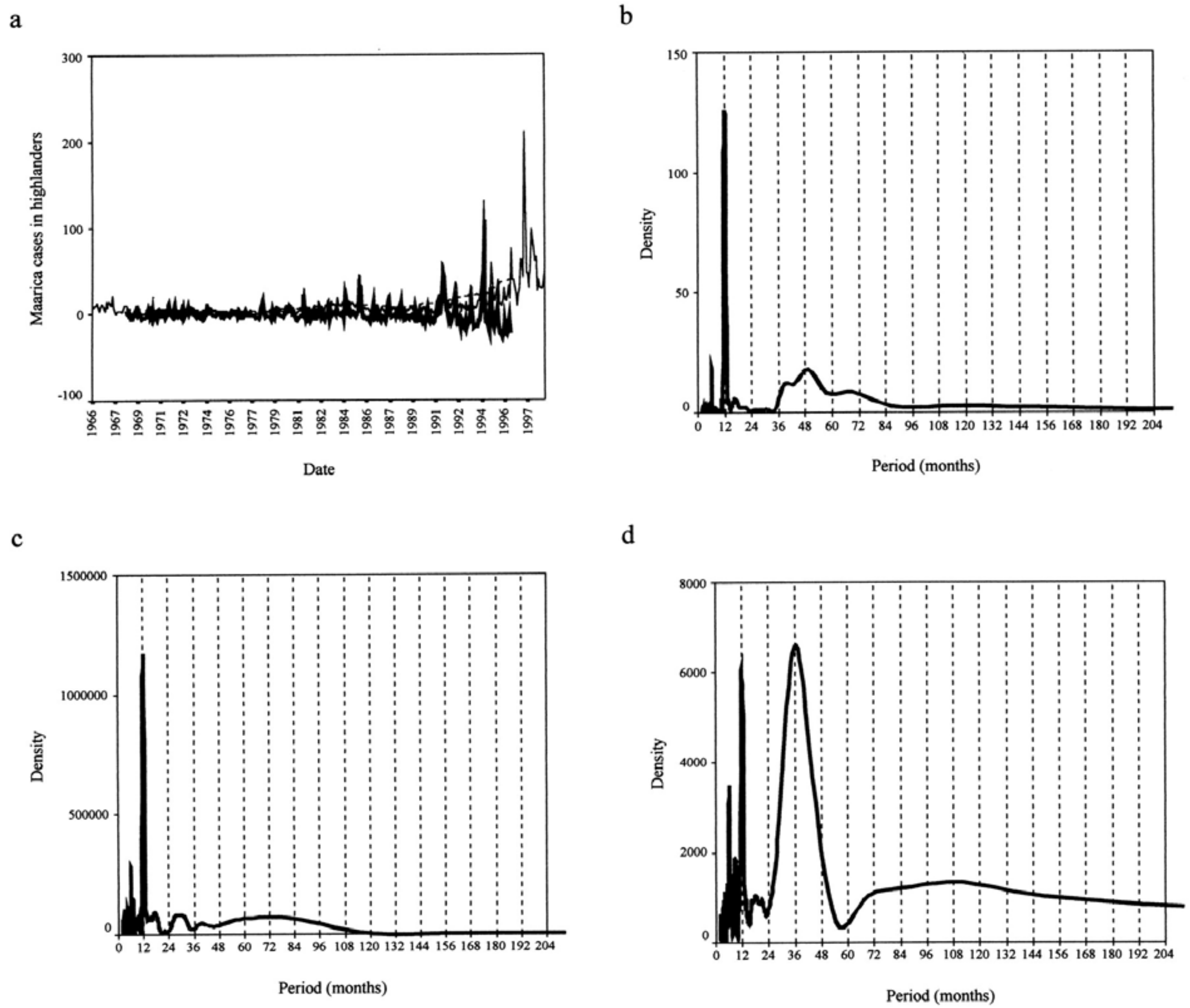




“Classical” time series: spectral techniques

- These seek to identify the dominant periodicities (or frequencies) in the data
- For example, power spectral analysis describes how the variance in the data is allocated to different frequencies
- However, this type of analysis is appropriate for data whose statistical properties do not vary with time (i.e. are stationary)

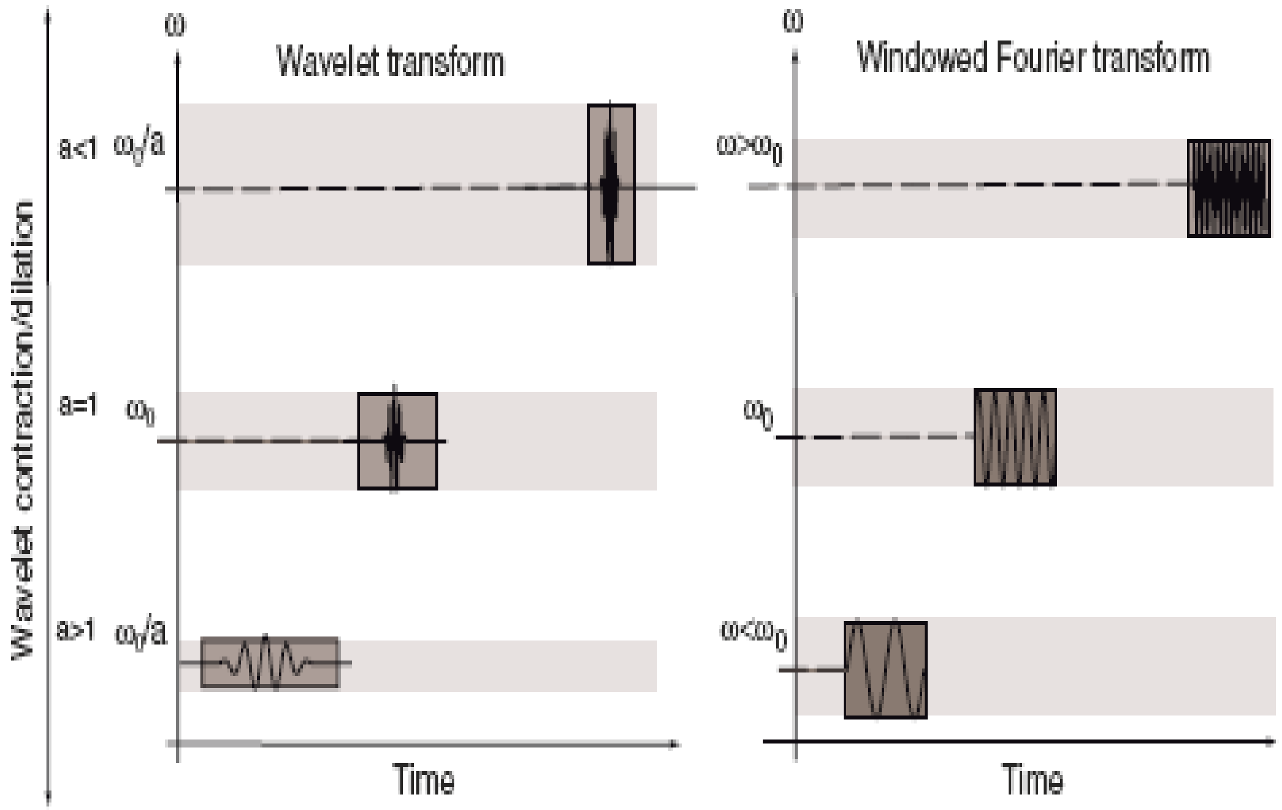
(a) A line graph showing the monthly incidence (cases per 100,000) of P. falciparum malaria incidence (cases per 100,000) in Kericho from January 1966 to December 1998



Hay S. I. et.al. PNAS 2000;97:9335-9339

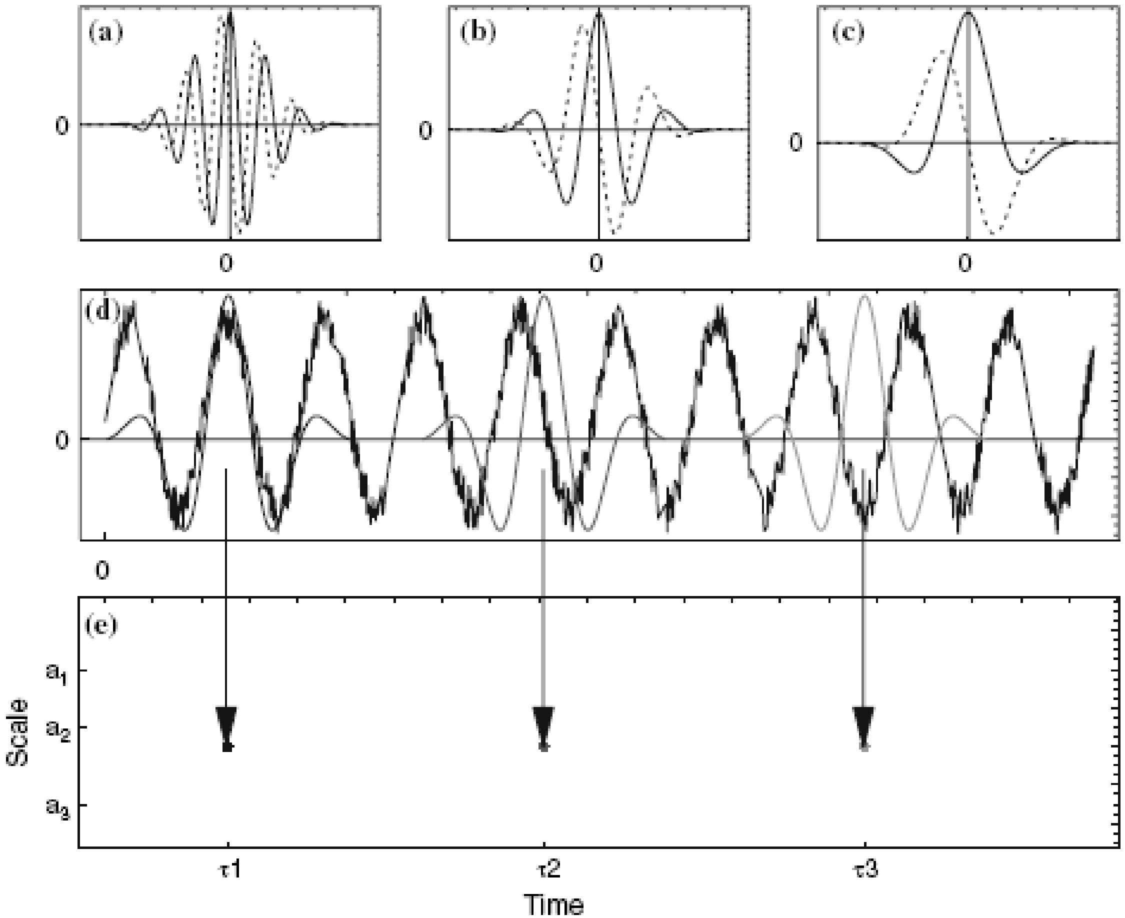
PNAS

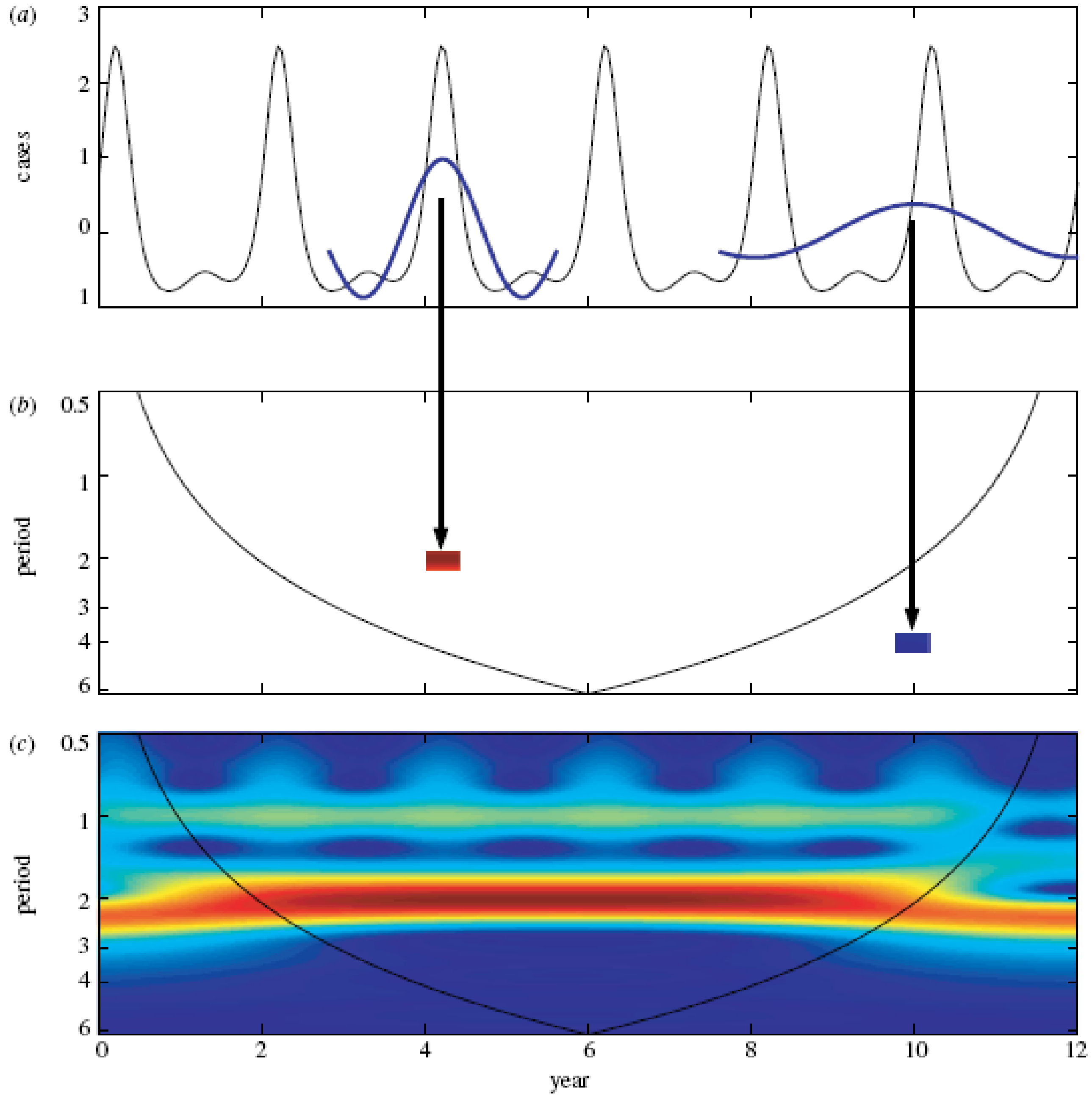
The periodogram …



From Cazelles et al. (2007)

The Wavelet Spectrum
tells us about local variability





(a)
3
2
1
0
1
cases
(b)
0.5
1
2
3
4
6
period
(c)
0.5
1
2
3
4
6
period
0
2
4
6
8
10
12
year

The Wavelet Transform

Decomposes signals over dilated and translated functions called “mother wavelets” that have two parameters, one for the time position, τ , the other for the scale, a (or f , with f~1/a).

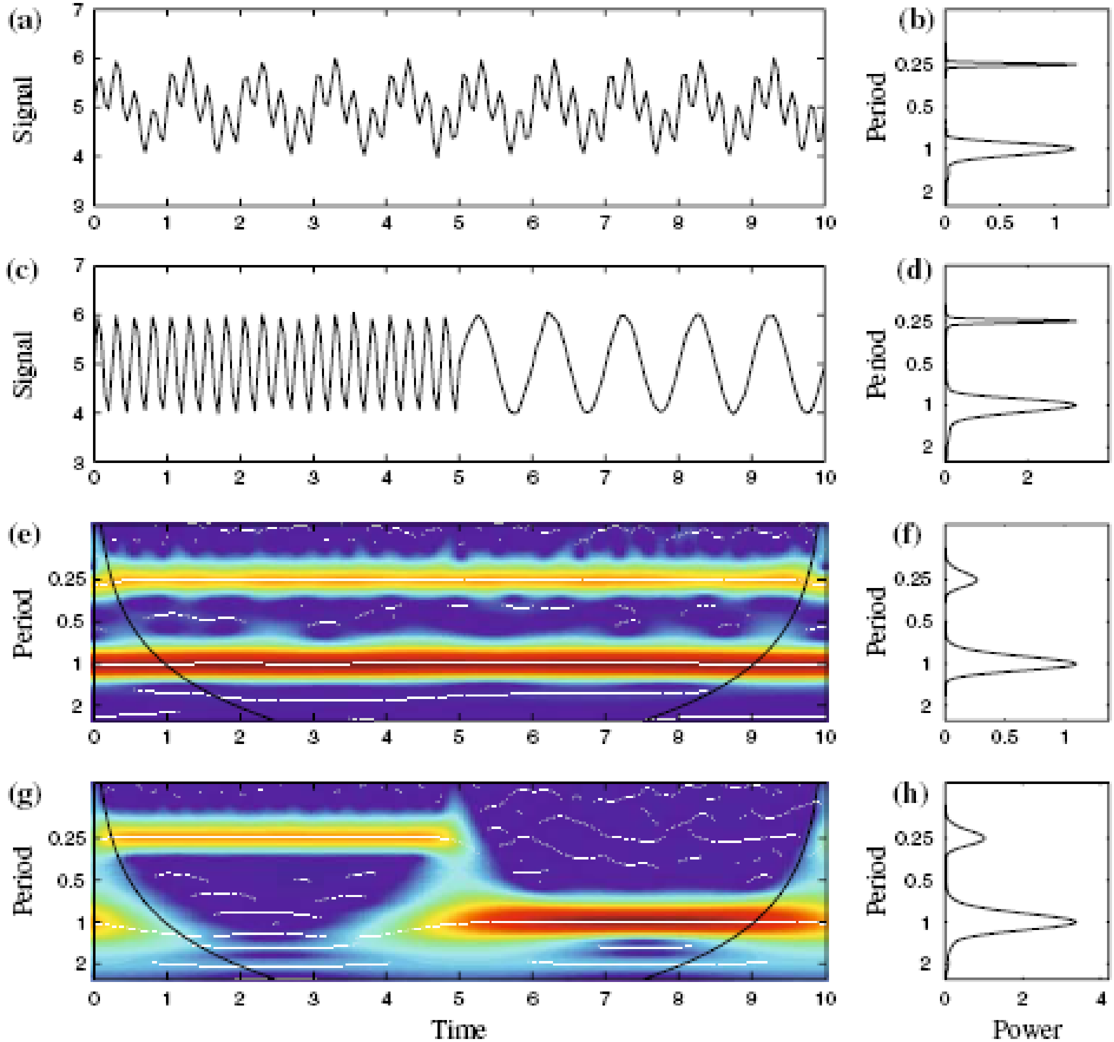
$$W(a,\tau) = \int_{-\infty}^{+\infty} x(t)\varphi^{*}\left(\frac{t-\tau}{a}\right) dt$$

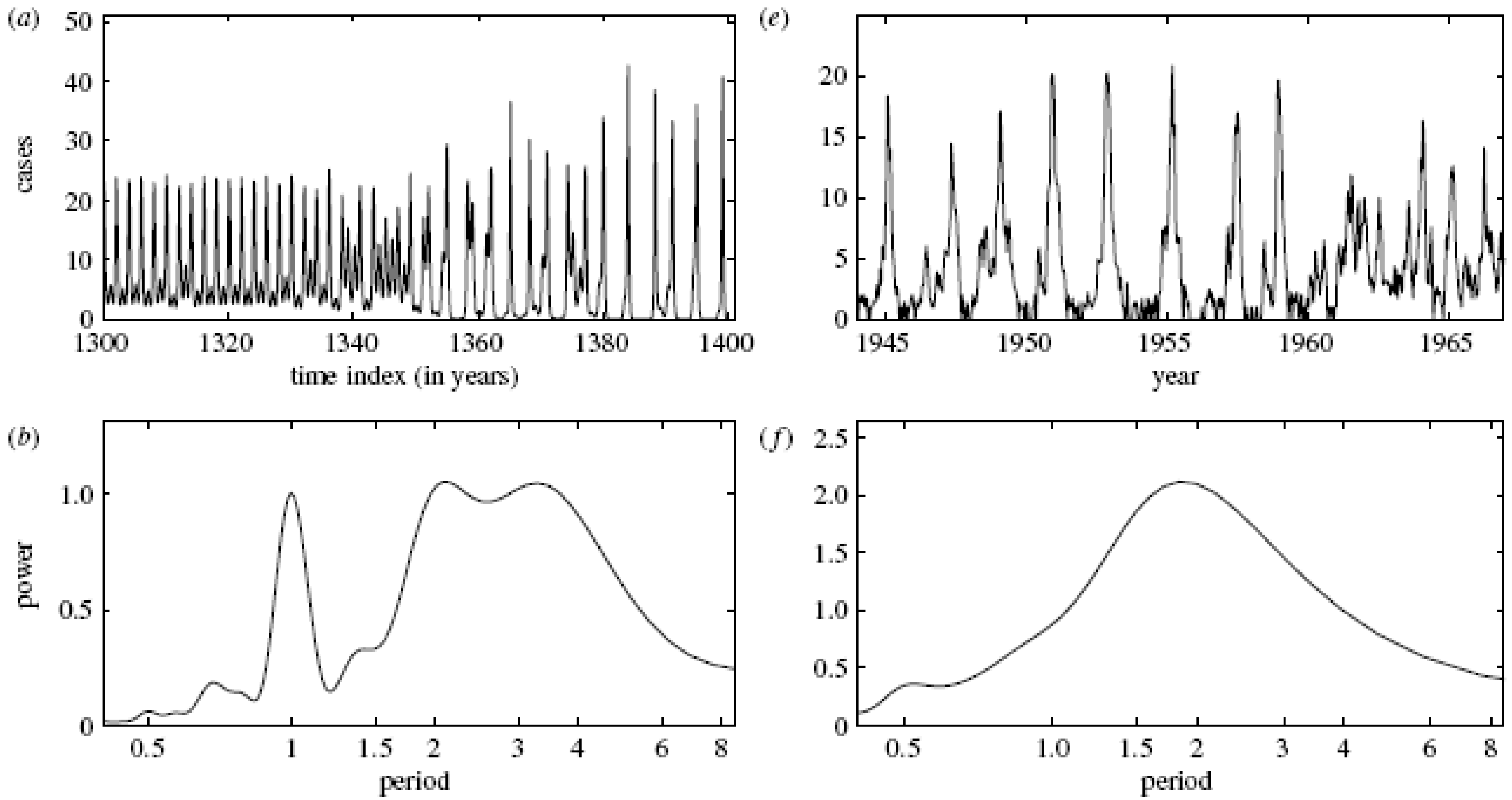
$$S(f,\tau) = \left\| W(f,\tau) \right\|^{2}$$

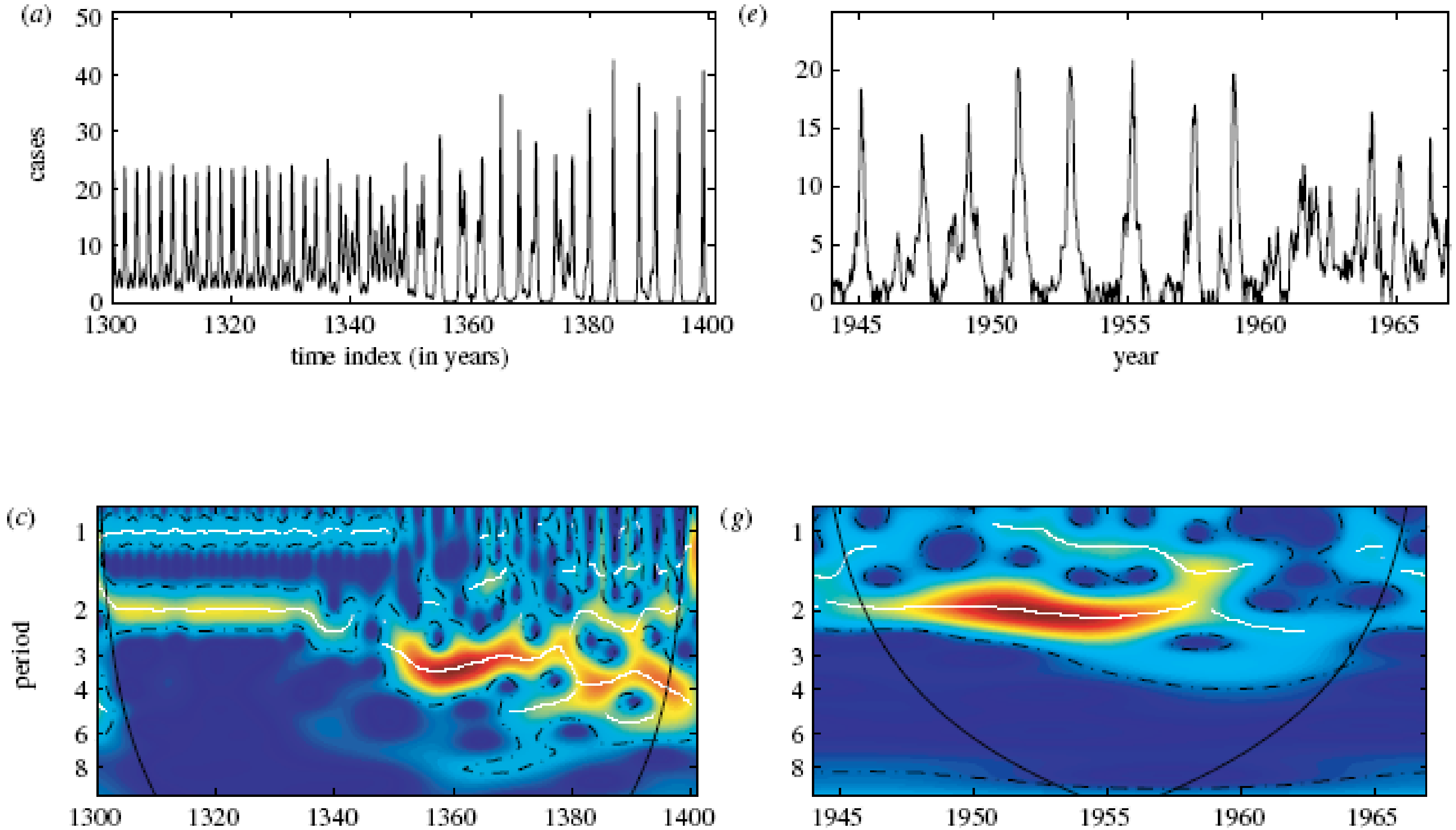
The “local power spectrum”

$$\phi(f,\tau) = \tan^{-1} \frac{\Im W(f,\tau)}{\Re W(f,\tau)}$$

The local phase

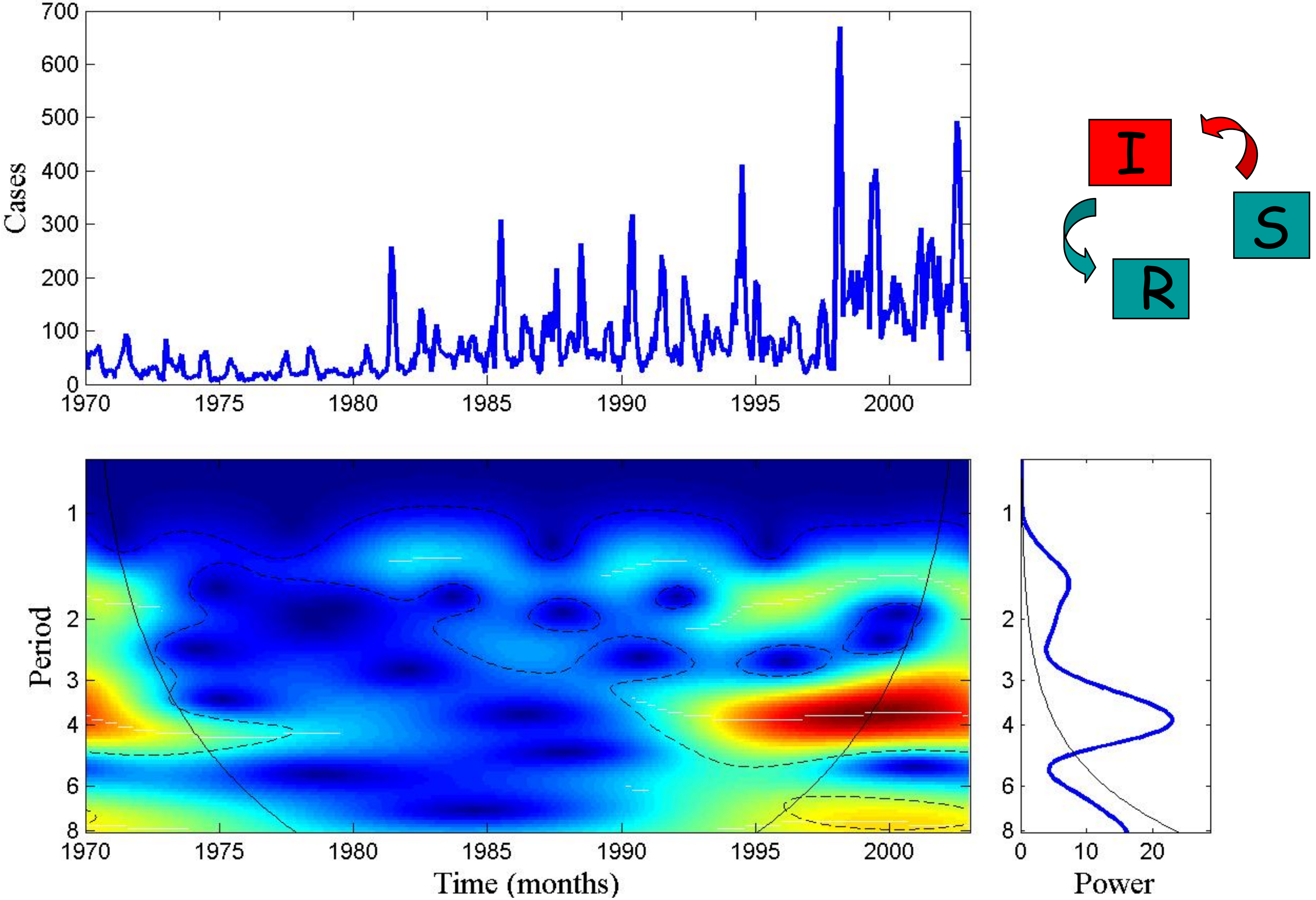

(a)
Signal
(b)
Period
(c)
Signal
(d)
Period
(e)
Period
(f)
Period
(g)
Period
(h)
Period
Time
Power


(a)
cases
time index (in years)
(b)
power
period
(e)
year
(f)
period



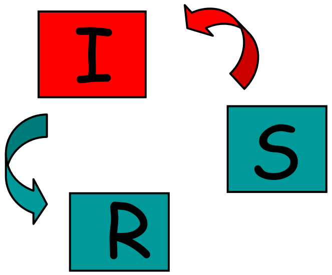
(a)
(e)
(c)
(g)
cases
time index (in years)
year
period

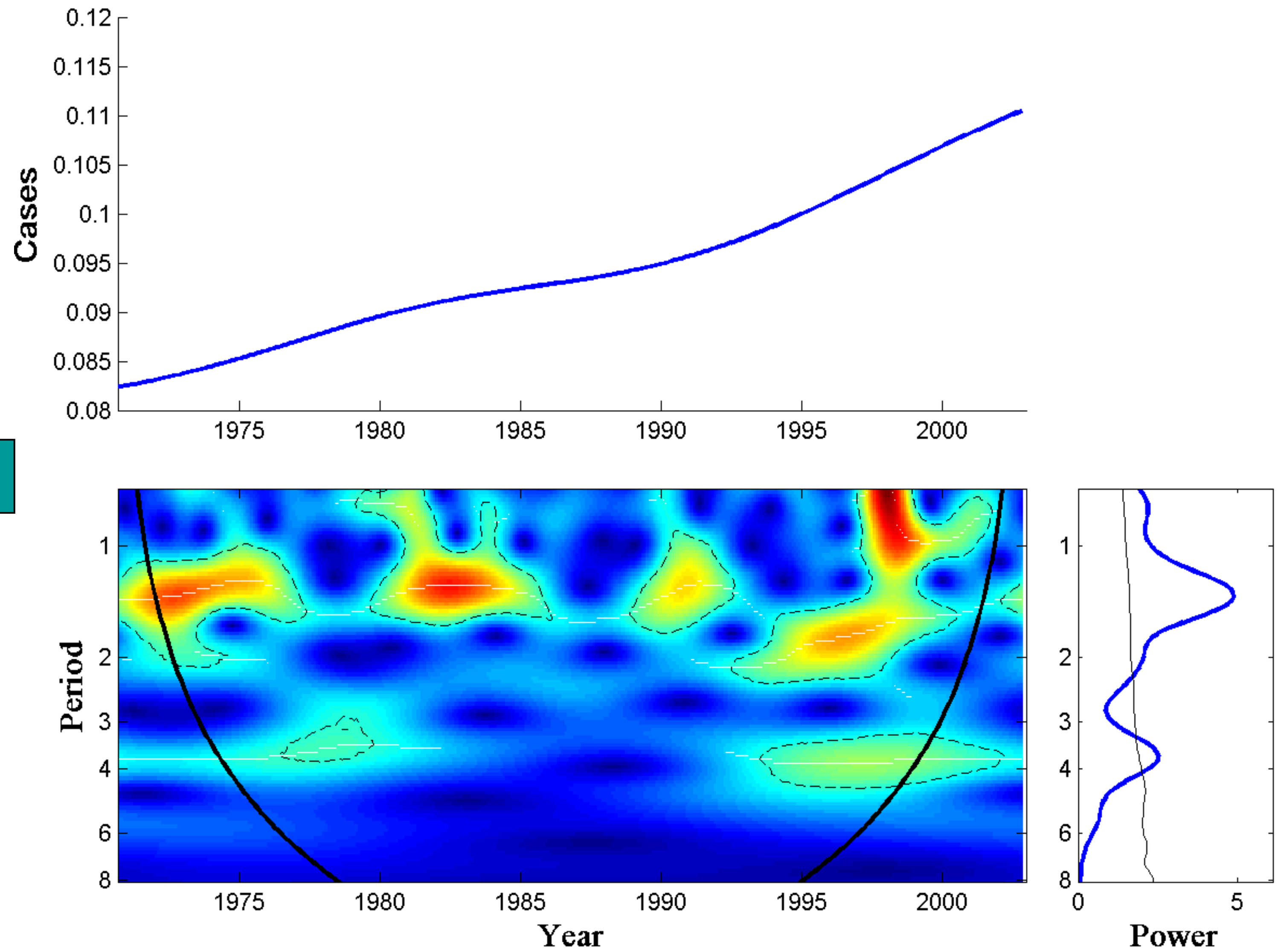
Back to unstable malaria in a Kenyan highland

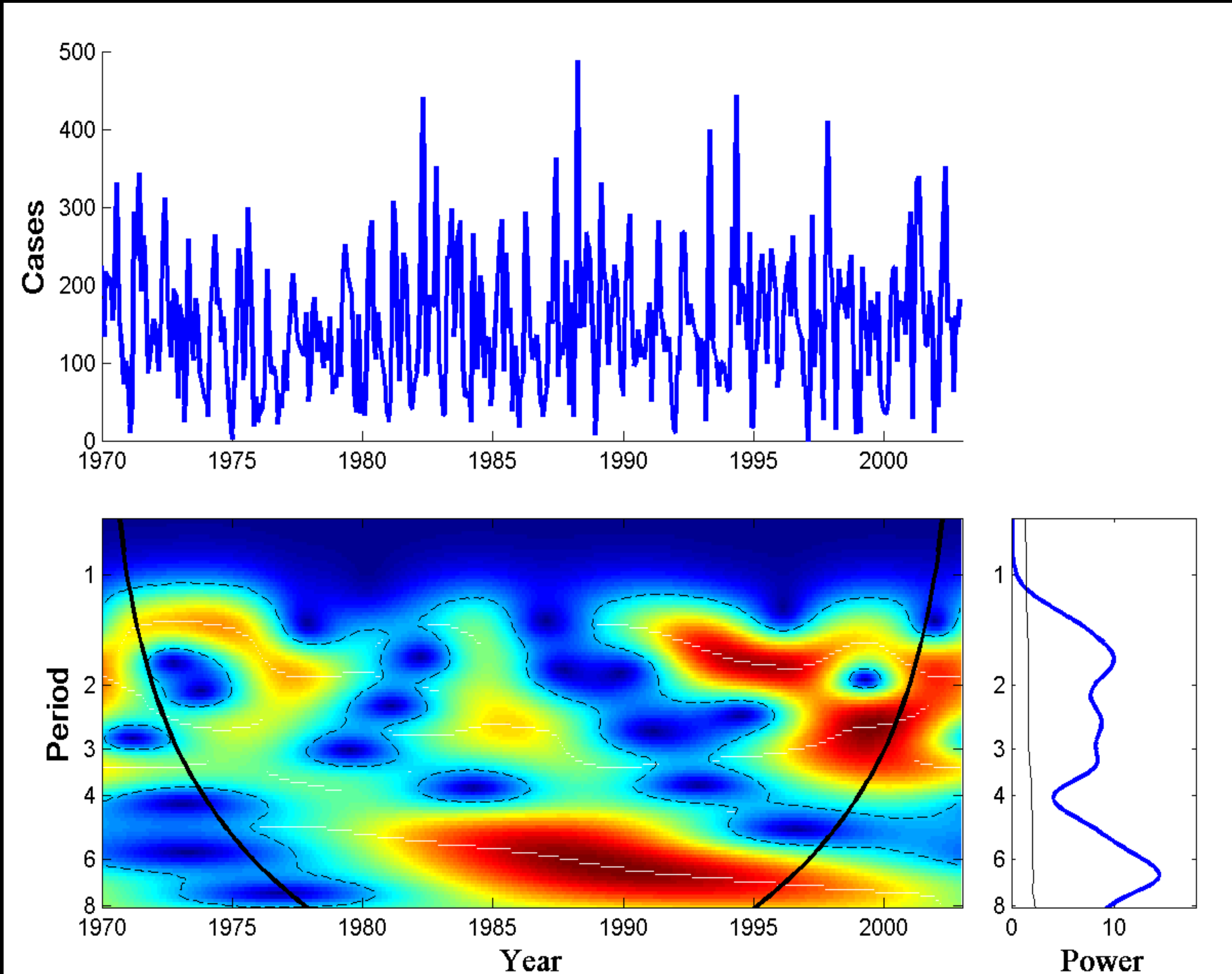


Pascual *et al.* (in prep.)

TSIR model: <u>does disease dynamics account for the cycles?</u> Yes and No

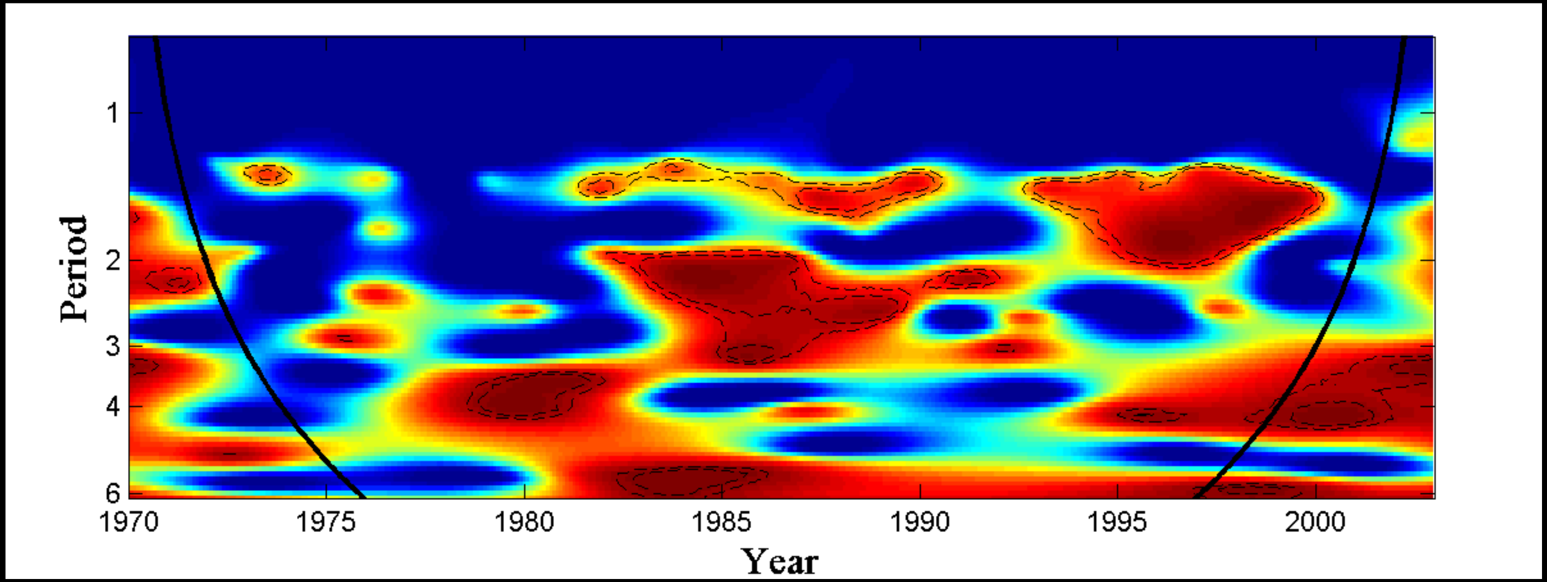


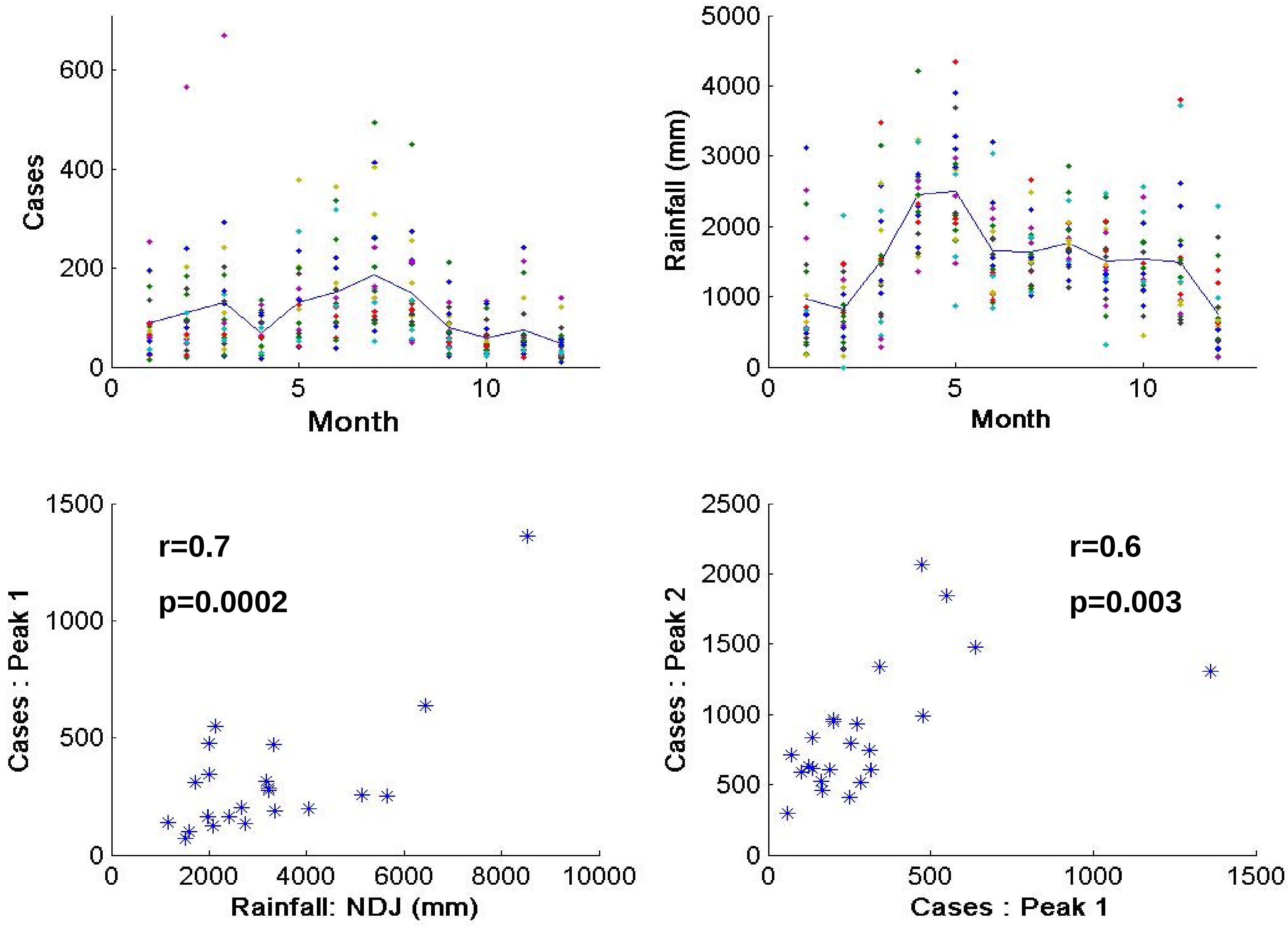




Cases
500
400
300
200
100
0
1970
1975
1980
1985
1990
1995
2000
Period
1
2
3
4
6
8
Year
0
10
Power

Coherence between rainfall and malaria:

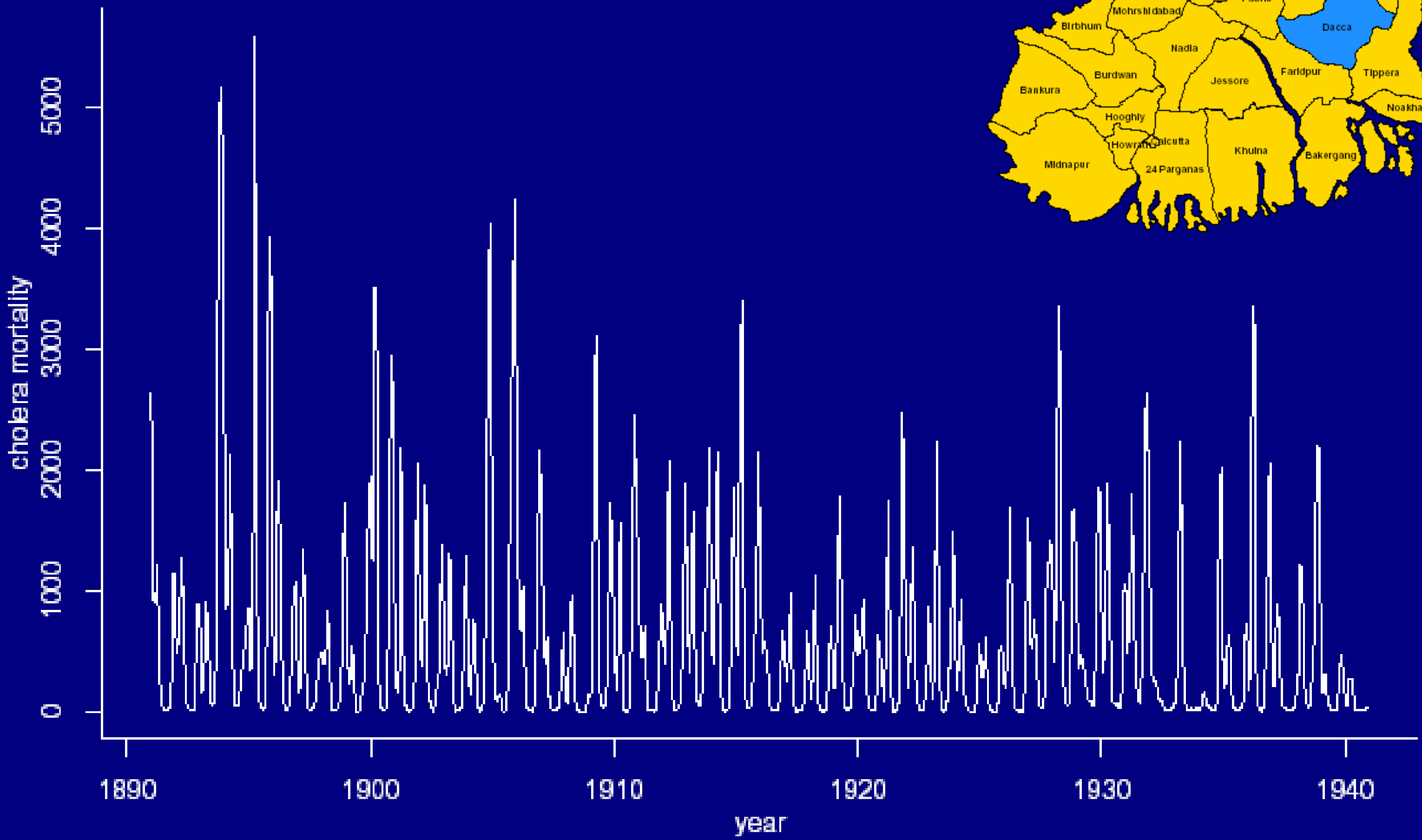




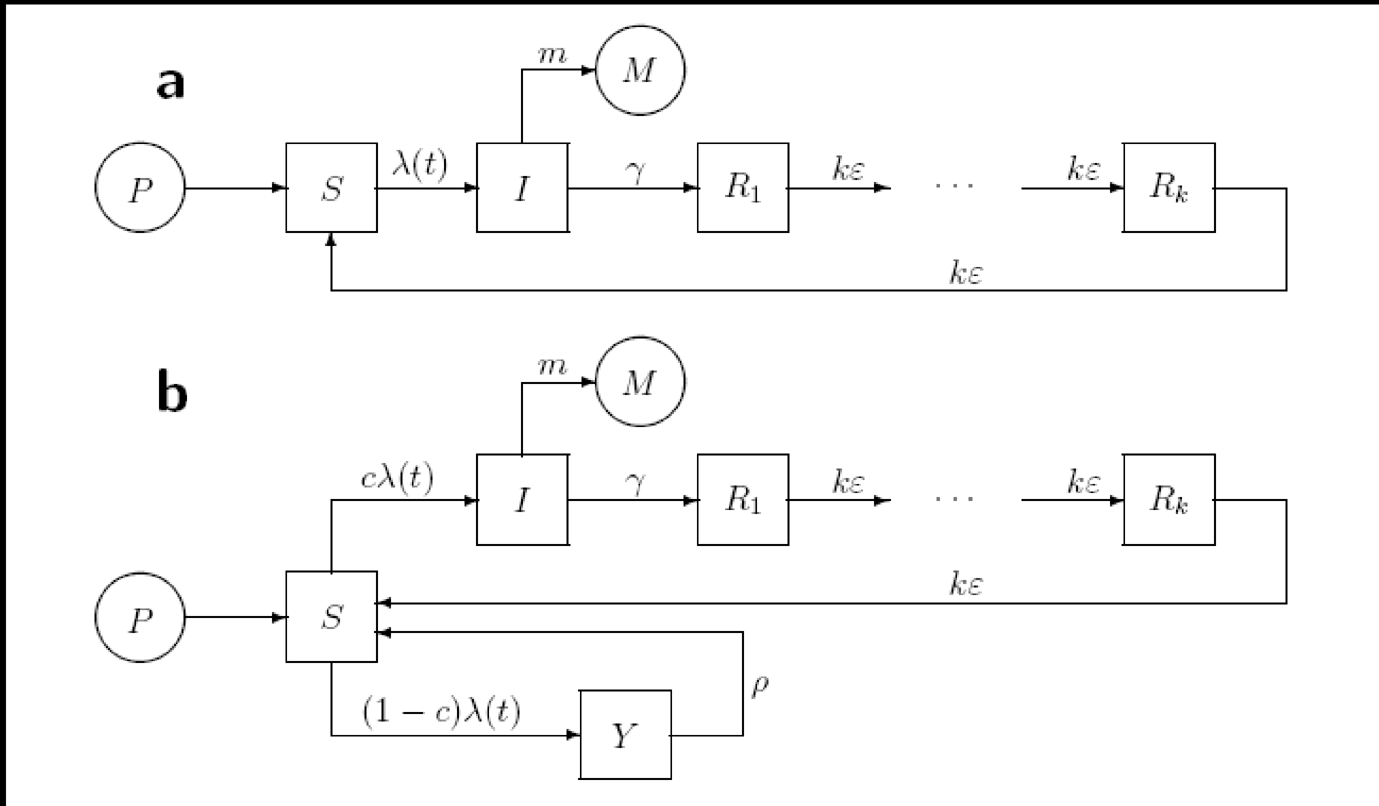
Cases
Month
Rainfall (mm)
Month
Cases : Peak 1
Rainfall: NDJ (mm)
r=0.7
p=0.0002
Cases : Peak 2
Cases : Peak 1
r=0.6
p=0.003

- Malaria dynamics exhibit cycles of period ~ 2 (and 3) years, as well as longer cycles of period ~ 4
- The shorter cycles appear to be extrinsic and driven by rainfall.
- Epidemic outbreaks are evident in the 80's and are particularly pronounced in the 90's, a pattern coincident with a long-term trend in transmission
- The shorter cycles can resonate with disease dynamics and contribute to oscillations at a longer period (4 years), a pattern that is enhanced by the trend in transmission

Historical cholera mortality



King, Ionides, Pascual, Bouma (Nature, *2008*)



King, Ionides, Pascual, Bouma
(Nature, *2008*)

Gracias

Bernard
Cazelles, CNRS

Katia Koelle (UM >> Duke Univ.)

Aaron King

(EEB, UM)

Ed Ionides

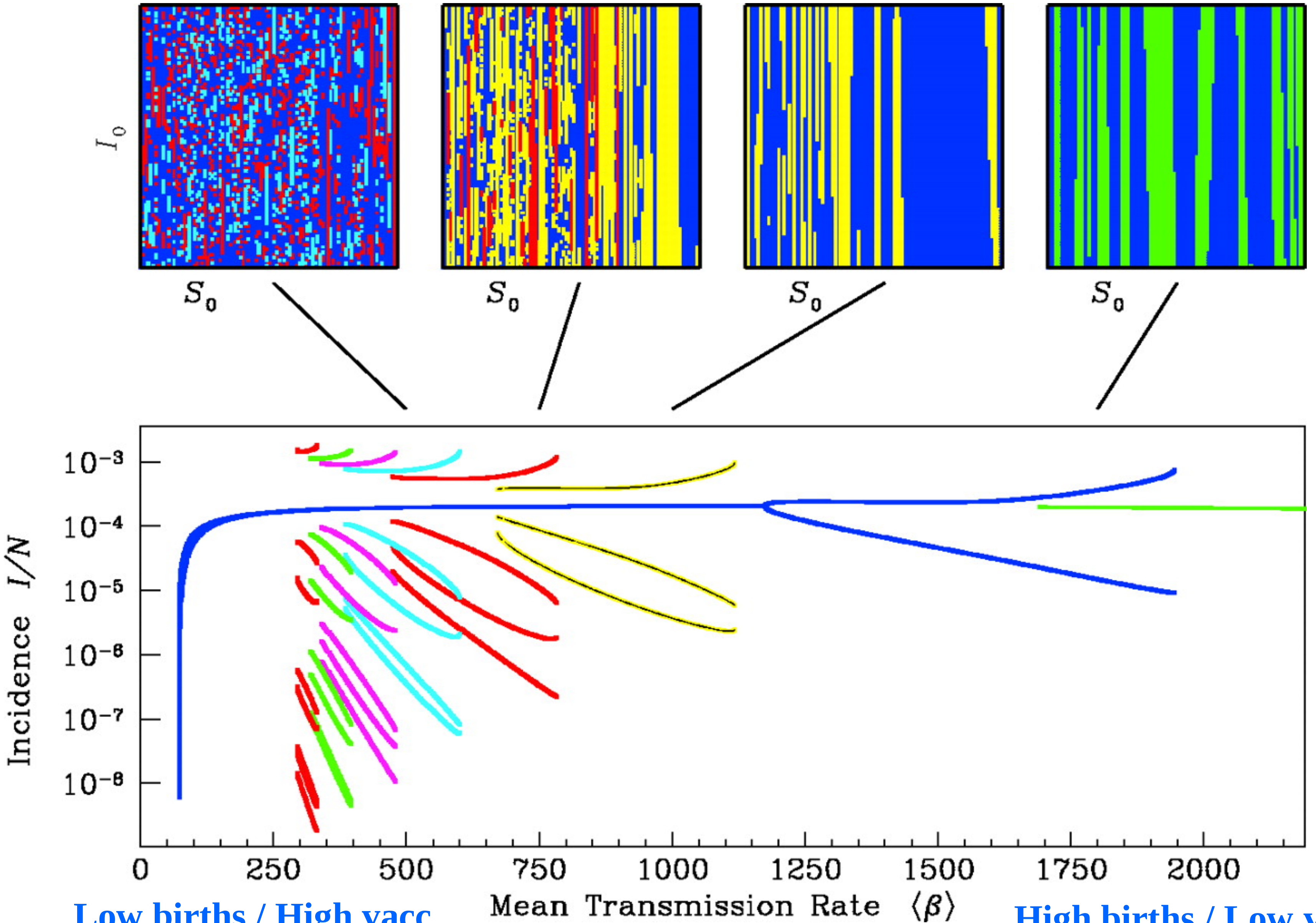
(Statistics, UM)

Menno Bouma (LSHTM)

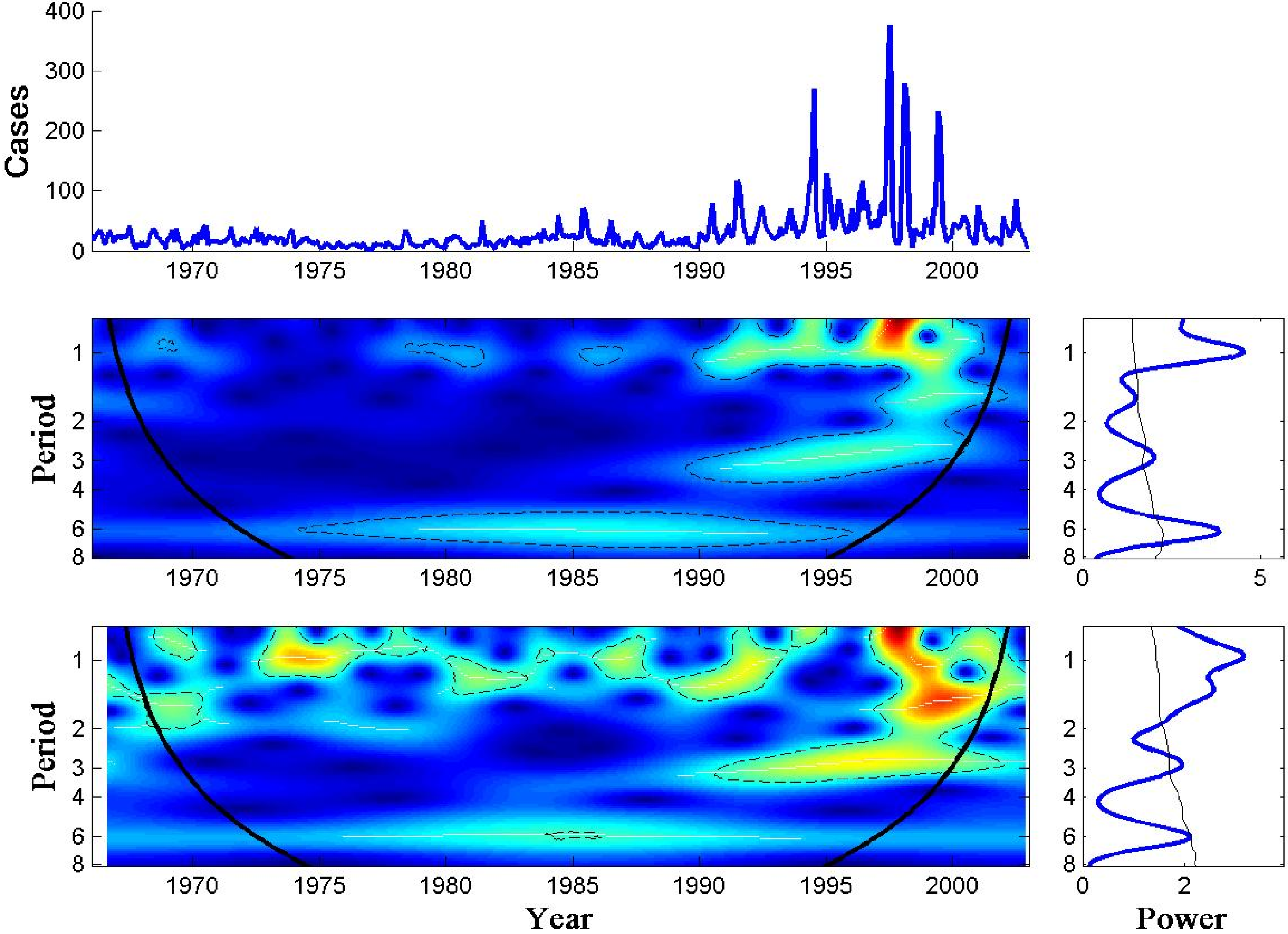
ICDDR, Bangladesh

Dr. Md Yunus

Earn, Rohani, Bolker, Grenfell, *Science* **287**, 667-670 (2000)

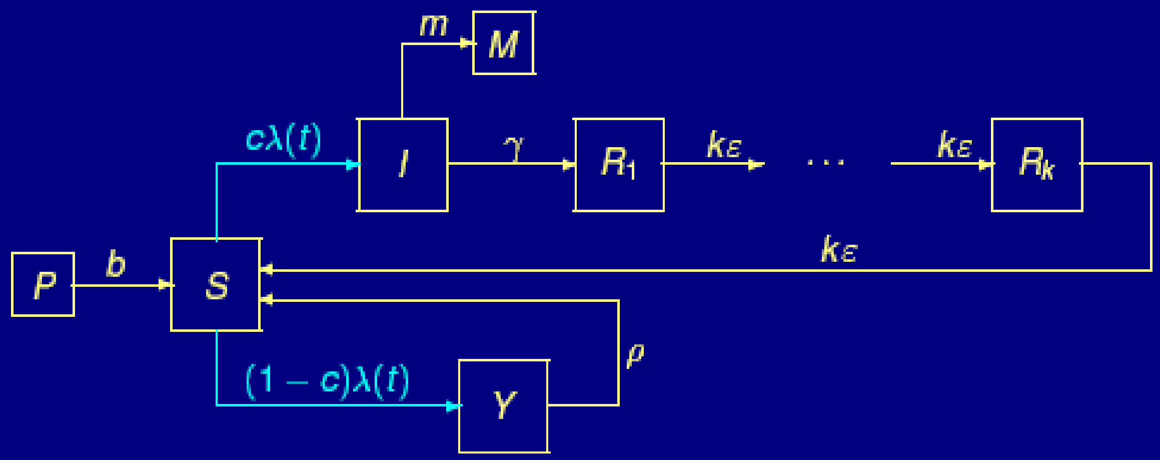


Low births / High vacc **High births / Low vacc**



Cases
400
300
200
100
0
1970
1975
1980
1985
1990
1995
2000
Period
1
2
3
4
6
8
0
5
2
Year
Power

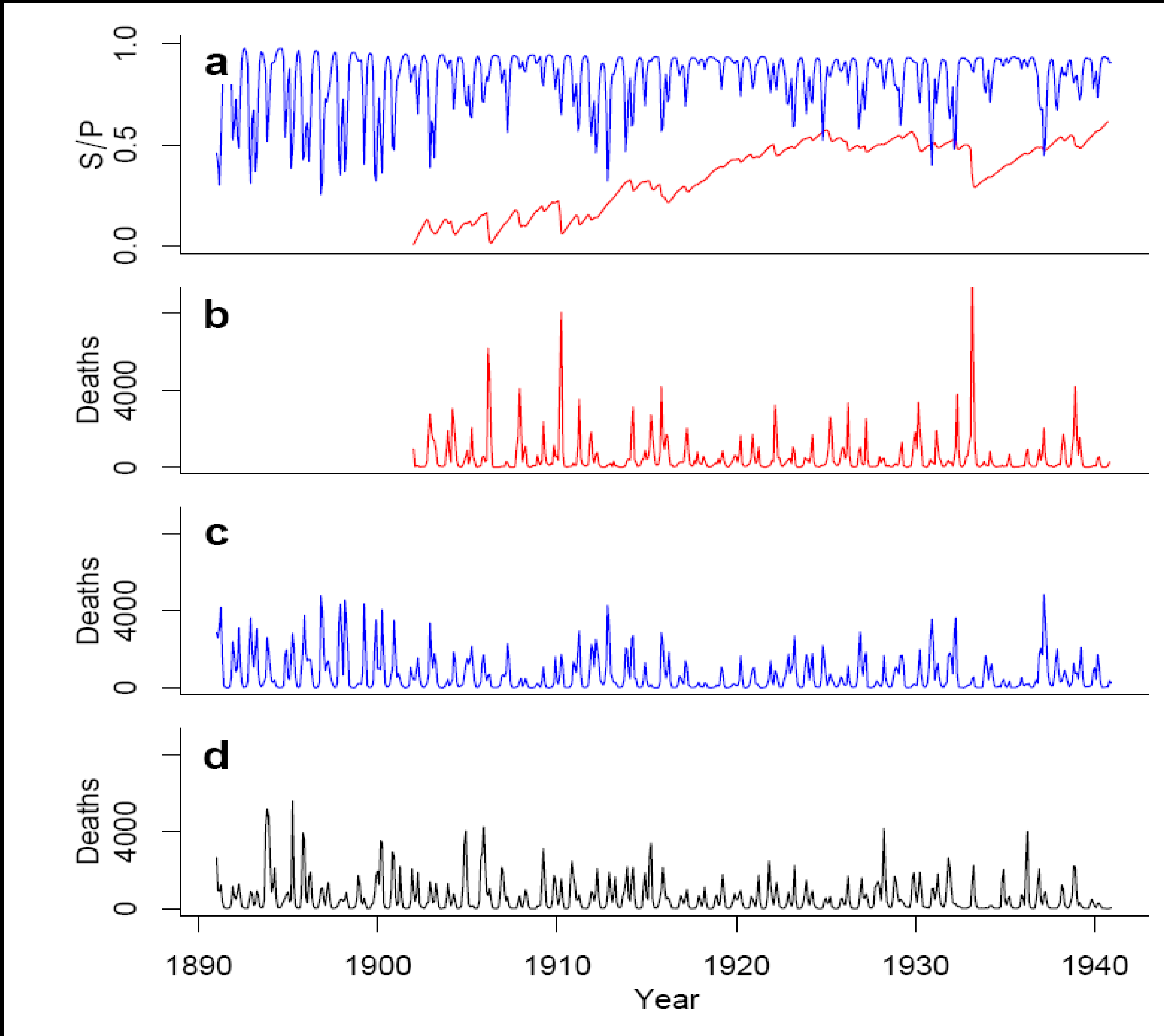
Two-path model



$$\lambda(t) = \left(e^{\beta_{trend}\, t}\, \beta_{seas}(t) + \xi(t)\right) \frac{I(t)}{P(t)} + \omega$$

ω = environmental reservoir

King *et al., (2008)*



TSIRS

Short immunity

Data

King *et al*. (Nature, *2008)*