Malaria models for Senegal and the role of climate in malaria predictability

Senegal malaria

Dielmo (all year round transmission, cohort 1)

Ndiop (seasonal transmission, cohort 2)
Malaria transmission: Stochastic differential equation model (VIC3 framework)

Flow diagram of the SDE model. Human classes are S1 (susceptible), E (exposed, carrying a latent infection), I1 (infected and infectious), I2 (asymptomatic infection which is minimally infectious) and S2 (recovered having some resistance to reinfection). Mosquito-parasite classes are λ (force of infection at previous time t-s) and λκ (force of infection at time t). The possibility of transition between class X and Y is denoted by a solid arrow, with the corresponding rate written as μ_{XY}. The dotted arrows represent interactions between the human and mosquito stages of the parasite. The model is formalized by equations (1–14).
The transmission rate $\mu_{S1E}$ is defined as:

$$\mu_{S1E}(t) = \int_{-\infty}^{t} \gamma(t-s)\lambda(s)d\Gamma(s)$$

$\lambda(s)$ is the force of infection at a previous time $s$ when the mosquito bites the infected human, $\gamma(t-s)$ is a delay distribution (for duration of parasite life cycle inside mosquito + vector survival) and $\mu_{S1E}(t)$ is the transmission at the current time $t$. 
The force of infection in VIC3

\[ \lambda(t) = b \alpha^2 c \frac{M}{N} \int_{t_0}^{t} \frac{I(s)}{N} x(s)p(t - s) \, ds \]

- \( x(s) \): the fraction of uninfected mosquitoes at time \( u \)
- \( M \): total number of mosquitoes (assumed constant)
- \( N \): total number of humans
- Uninfected mosquitoes become infected with malaria with a probability \( c \) when they bite (at a rate \( a \)) an infected human.
- \( I(s)/N \): fraction of infected humans at time \( s \).
- \( p(.) \): a delay distribution that describes the mosquito stage of the parasite life cycle and vector survival. We choose \( p(.) \) to be a \( \Gamma(n, \tau) \) density. \( n \)
- The infected mosquitoes then contribute to malaria infection in humans when they again bite an uninfected human (at a rate \( a \)) and infect with a probability \( b \).
How do we attempt to integrate climate in VIC3 framework

We expect the fraction of uninfected mosquitoes $x(s)$ to be seasonal, to have a dependence on climatic factors and to have a random component.

$$\lambda(t) = \left[ \frac{I_1(t) + q_f \times I_2(t) + s_f \times S_2(t)}{N(t)} \exp \left\{ \sum_{i=1}^{k} \beta_i s_i(t) + Z_t \beta \right\} \right]$$

Here, $q_f$ represents the fraction of asymptomatics capable to infect mosquitoes.

The seasonality of disease transmission is modeled by the coefficients $\{\beta_i\}$

$Z_t$ depends on rainfall and drug treatment in the form:

$$Z_t = \beta_r R(t) + \beta_{qui} D[t_{qui}] + \beta_{cla} D[t_{cla}] + \beta_{fan} D[t_{fan}] + \beta_{act} D[t_{act}]$$
Integrating drug treatment in VIC3

Drug periods Ndiop and Dielmo

- 29/05/90
- 01/01/94
- 01/01/97
- 01/01/00
- 01/01/03
- 01/01/06
- 31/12/08
Natural mortality rate estimation

\[ \rho(\alpha) = \mu_0 \frac{e^{-\mu_0 \alpha}}{1 - e^{-\mu_0 \alpha}} \]

- Fixed value for mortality as 0.03
- Lose of immunity
  \[ \mu_{S2S1} = \frac{\mu_{S1E}}{e^{\mu_{S1E}t_{S2S1}} - 1} \]
- Reinfection
  \[ \mu_{I2I1} = s_{i1}\mu_{S1E} \]
- Superinfection
  \[ \mu_{S2I2} = s_{i3}\mu_{S1E} \]

Density of people \( \rho \) at a given age \( \alpha \)
Relationship between cases and rainfall
Discrepancies among rainfall products
Preliminary fittings of SDE using MIF
(Including Population change, rainfall and drug treatment)
Preliminary fittings of SDE using MIF
(Including Population change, rainfall and drug treatment)
Preliminary fittings of SDE using MIF
*(Including Population change, rainfall and drug treatment)*

### Dielmo

**Parameters estimated**

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
<th>unit</th>
<th>estimated? (y/n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{X,Y}$</td>
<td>per-capita rate of transition from compartment X to Y, $X, Y \in {S1,E,I1,I2,S2}$</td>
<td>yr$^{-1}$</td>
<td>y</td>
</tr>
<tr>
<td>$\beta_i$</td>
<td>ith spline coefficient</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$\beta$</td>
<td>dimensionality constant</td>
<td>yr</td>
<td>n</td>
</tr>
<tr>
<td>$\tau$</td>
<td>mean development delay for mosquitoes</td>
<td>yr</td>
<td>n</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>standard deviation of the process noise</td>
<td>yr$^{1/2}$</td>
<td>y</td>
</tr>
<tr>
<td>$\rho$</td>
<td>reporting fraction of people in the transition from E to I</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>time step for stochastic Euler integration</td>
<td>day</td>
<td>n</td>
</tr>
<tr>
<td>$1/\delta$</td>
<td>average human life expectancy</td>
<td>yr</td>
<td>n</td>
</tr>
<tr>
<td>$\sigma_{o,b}$</td>
<td>standard deviation of the observation noise</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$X_0$</td>
<td>initial fraction of people in compartment $X, X \in {S1,E,I1,I2,S2}$</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$q_f$</td>
<td>infectivity of asymptomatic people</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$s_f$</td>
<td>infectivity of subp tart infected people</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>probability of becoming a symptomatic case</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$t_s$</td>
<td>fraction of successful transmits</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$s_{I1}$</td>
<td>fraction of force of infection for superinfection (from $I_2$ to $I_1$)</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$s_{I2}$</td>
<td>fraction of force of infection for superinfection (from $S_2$ to $I_1$)</td>
<td>-</td>
<td>y</td>
</tr>
<tr>
<td>$s_{I3}$</td>
<td>fraction of force of infection for superinfection (from $S_2$ to $I_2$)</td>
<td>-</td>
<td>y</td>
</tr>
</tbody>
</table>

Table 1: List of symbols for the malaria model. Fixed parameters are $\beta = 1$ yr, $n_\lambda = 2$, $\Delta = 1$ day, $1/\delta = 33$ yr and $f_t = 1$. 
Next steps: To include in the model
(Demography, age-incidence, EIR, more environment)
Next steps: To improve integration of extrinsic drivers and test the interplay with intrinsic factors

(New predictors? Where to integrate them? Are they given their actual weight?)

9 months before

New indices

4 months before

Adding skill
Next steps: To improve integration of extrinsic drivers and test the interplay with intrinsic factors

(New predictors? Where to integrate them? Are they given their actual weight?)
Incorporating climate predictions
(ECMWF System4, GPCP 2.5°, GHCN 0.5°, 1981-2010)

MAY

precipitation climatology in Senegal, May start

precipitation climatology in Senegal, Nov start

T2m

2m air temperature climatology in Senegal, May start

2m air temperature climatology in Senegal, Nov start
Incorporating climate predictions
(EMSWF System4, GPCP 2.5°, GHCN 0.5°, 1981-2010)

Local

precipitation climatology in Ndio-Nدلو, May start

precipitation climatology in Senegal, May start

2m air temperature climatology in Ndio-Nدلو, May start

2m air temperature climatology in Senegal, May start
Incorporating climate predictions
(EMWF System4, GPCP 2.5°, GHCN 0.5°, 1981-2010)

precipitation anomalies in Ndiop–Dielmo, May start
Incorporating climate predictions

NDIOP/DIELMO (*ECMWF System4, GPCP 2.5°, GHCN 0.5°, 1981-2010*)

**MAY**

**NOVEMBER**

**PRECIP**

precipitation anomalies in Ndiop–Dielmo, May start

**T2m**

2m air temperature anomalies in Ndiop–Dielmo, May start

precipitation anomalies in Ndiop–Dielmo, Nov start

2m air temperature anomalies in Ndiop–Dielmo, Nov start
Thank you!
Gràcies!
Asante Sana!