The Abdus Salam International Centre for Theoretical Physics

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School on Modelling Tools and Capacity Building in Climate and Public Health

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VECTRI: A high resolution dynamical regional model for malaria transmission - Overview and uses

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VECTRI: A high resolution dynamical regional model for malaria transmission - Overview and uses

School on Climate and Health
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- Malaria - brief overview of climate drivers
- VECTRI - a new community model for malaria transmission
- USES - from seasonal forecasting to climate change
- CONCLUSIONS - where next?

Malaria caused by the plasmodium parasite, of which 4 species are known to infect man. Two are wide-spread and particularly dangerous, falciparum and vivax. It is spread by the anopheles genus of mosquito (Fig. 1).

Figure: anopheles gambiae vector

Vivax can lie dormant in the liver for weeks to years and cause frequent relapses, while falciparum has wide-spread drug resistance and causes the most fatal cases due to the potential cerebral complications.

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Many of these deaths from falciparum occur in Africa (Fig. 5), although this is a recent phenomenon. See *the making of a tropical disease* by Packard.

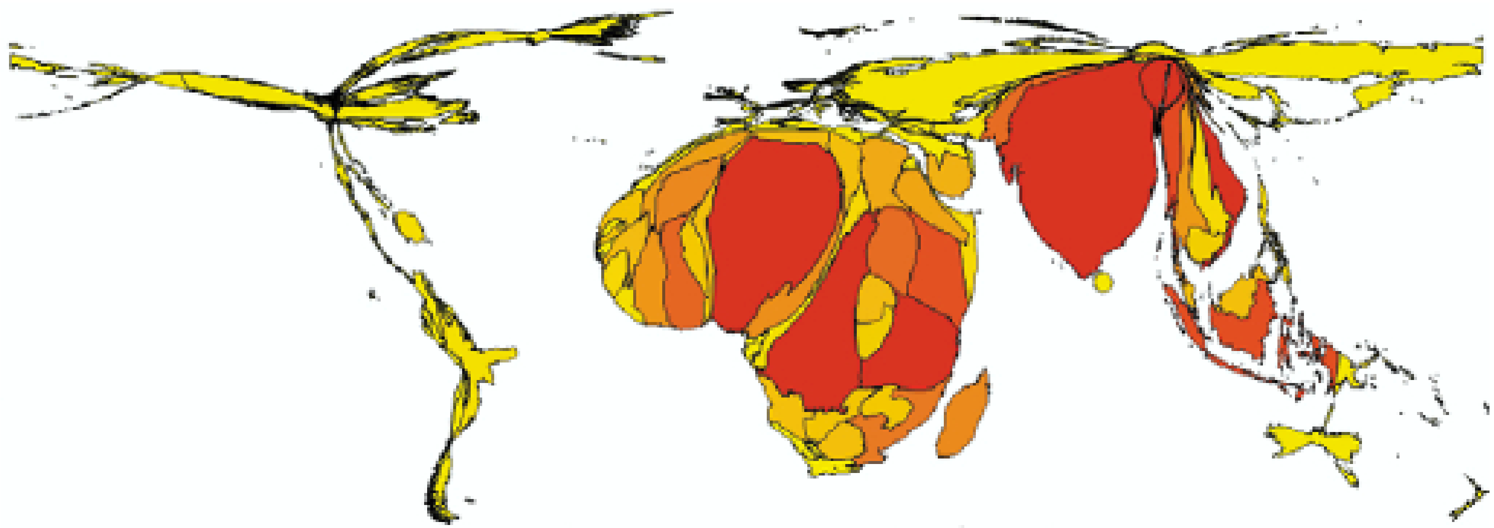


Figure: Cartogram of national prevalence of falciparum from Hay et al. (2004)

Malaria endemicity definitions

Endemicity	PR	Definition
Holoendemic	0.75-1.0	all year round
Hyperendemic	0.5-0.75	all year with dry season pause
Mesoendemic	0.1-0.5	regular but seasonal transmission
hypoendemic	0-0.1	very intermittent transmission (Epidemics)

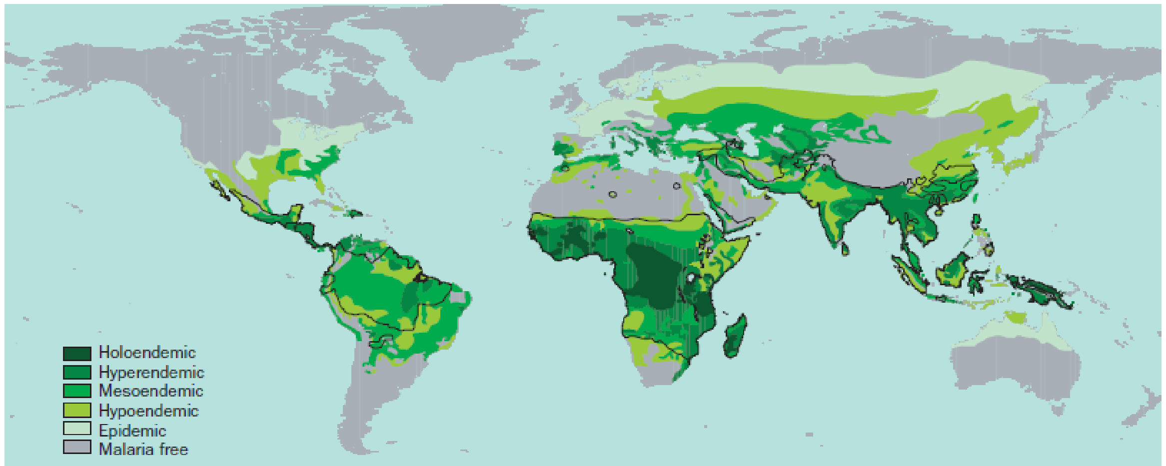


Figure: Lysenko malaria epidemic zones from Hay et al.

- Epidemic regions are usually found on the transmission fringes and are associated with temperature and/or rainfall seasonality (Fig. 4).
- Epidemic areas - low immunity, whole population at risk - forecasts potentially very useful for early warning.
- Epidemic belt on the Sahel fridge is associated with rainfall variability, while cold temperatures reduce or eliminate malaria incidence at high altitudes over eastern Africa.

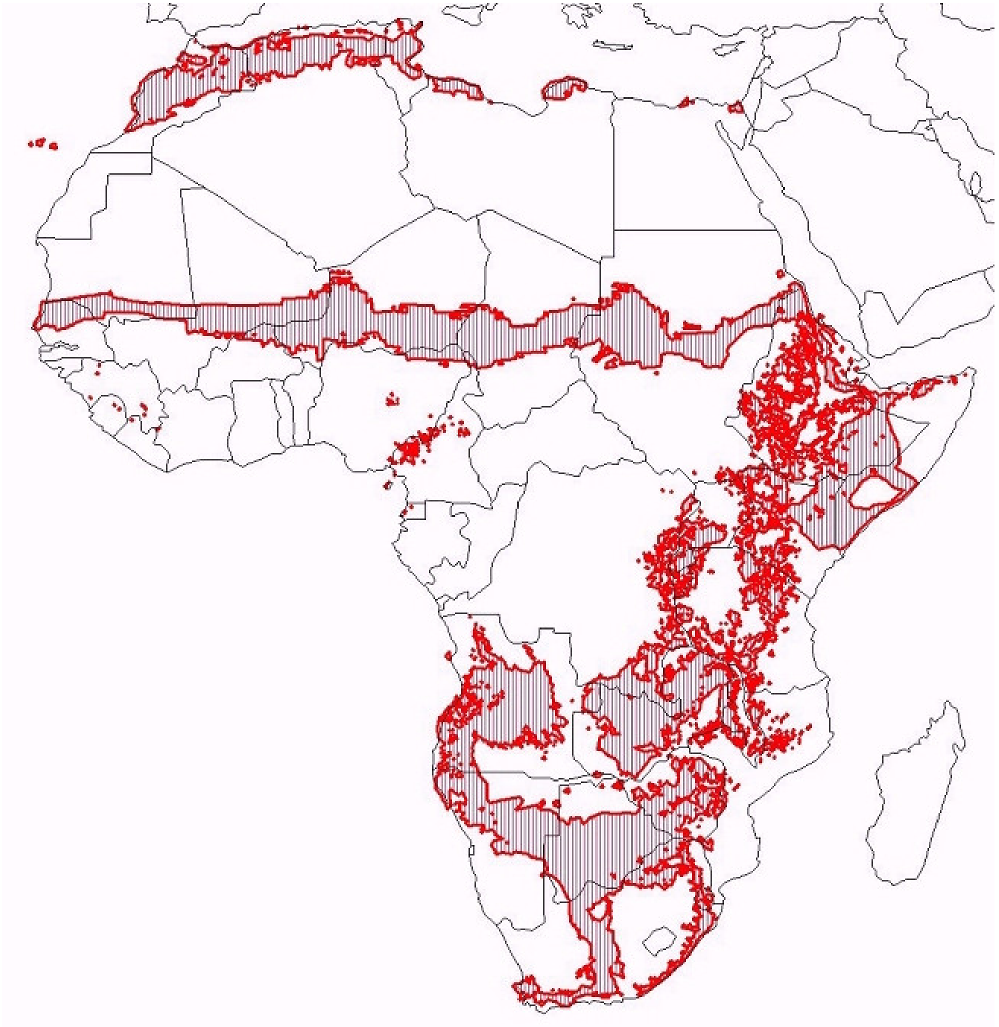


Figure: Malaria epidemic zones - from ?

Force of infection and EIR

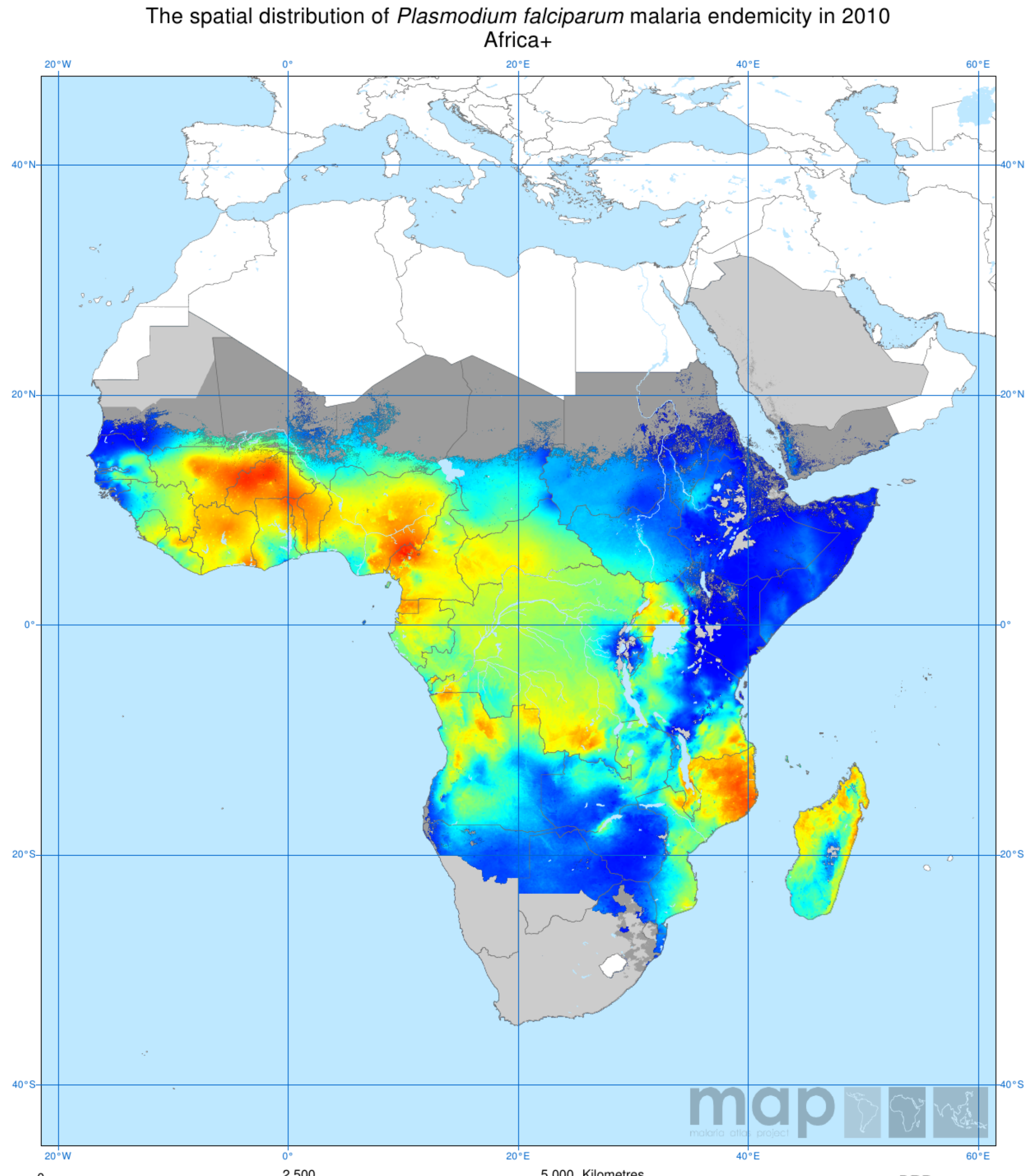
Generally the division between epidemic and endemic regions is governed by the force of infection.

entomological inoculation rate

A good measure of the force of infection is the entomological inoculation rate (EIR) which is the number of infected bites per person per unit time.

An EIR of around 10 infected bites per year marks the division between epidemic and endemic areas.

Another metric is the parasite ratio (PR) shown in this statistical model analysis of MAP (Malaria Atlas Project) (Fig. 5).
Immunity is higher in endemic regions, where under 5s are most at risk. Immunity is still poorly understood.



- Vector borne diseases such as malaria have a “climatic niche”
- Both the vector and parasite are influenced by weather

However many other factors can alter the disease range:

- land use changes such as drainage or wetland cultivation, rice cultivation, irrigation.
- interventions: bed nets, spraying, treatment
- socio-economic factors: access to health facilities, population density, migration, poverty
- vector predators, competition and dispersion limits

Figure: pond spraying

Climate variability may offer some potential predictability therefore to help planners:

- short-medium term: prediction of outbreaks in epidemic areas
- short-medium term: potential prediction of seasonal onset in endemic areas
- decadal timescales: potential shift of epidemic areas to higher altitudes [**?**,], shifts in response to rainfall, and associated changing epidemic and endemic patterns.

Role of climate change relative to socio-economic factors and interventions remains controversial.

Climate drivers of malaria

- Rainfall : provides breeding sites for larvae.
- Temperature: larvae growth, vector survival, egg development in vector, parasite development in vector.
- Relative Humidity : dessication of vector.
- Wind : Advection of vector, strong winds reduce CO_2 tracking.

>2 bites are required to pass on the disease:

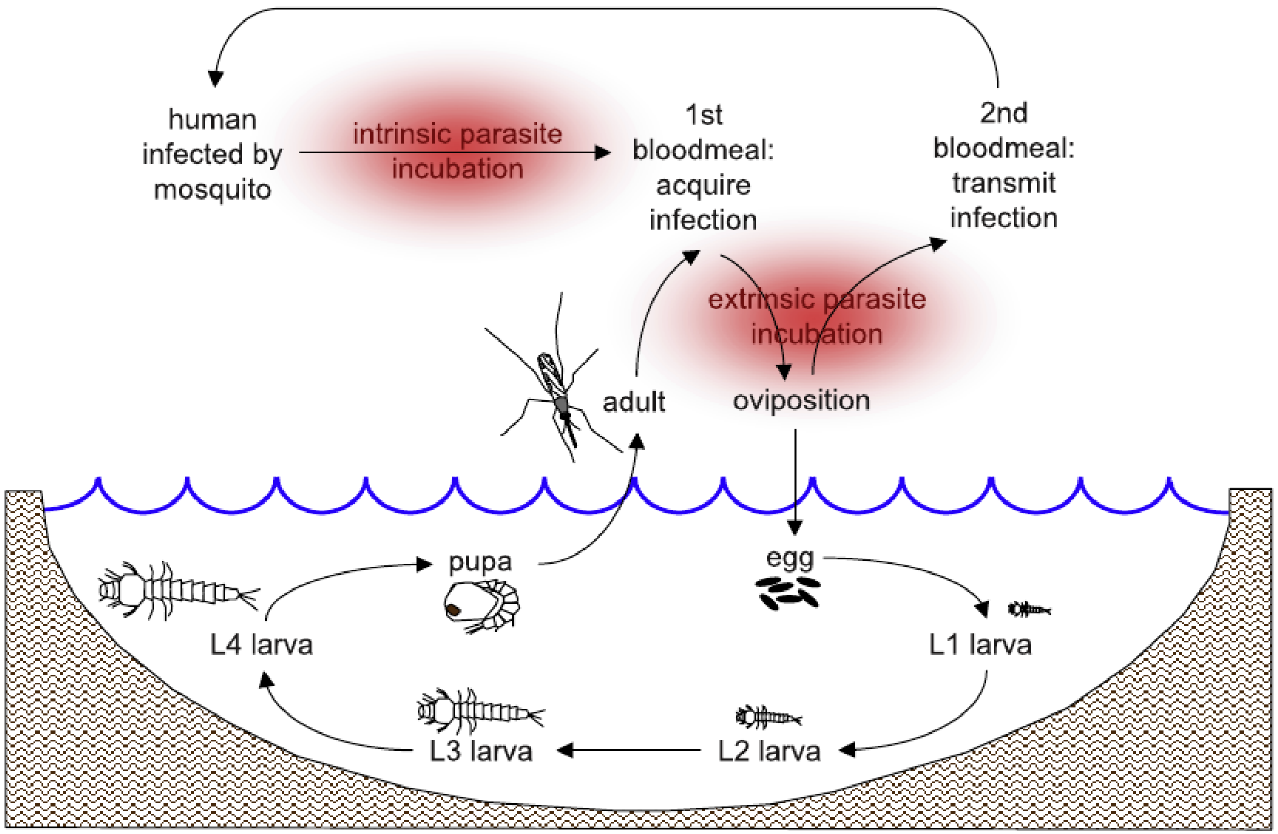
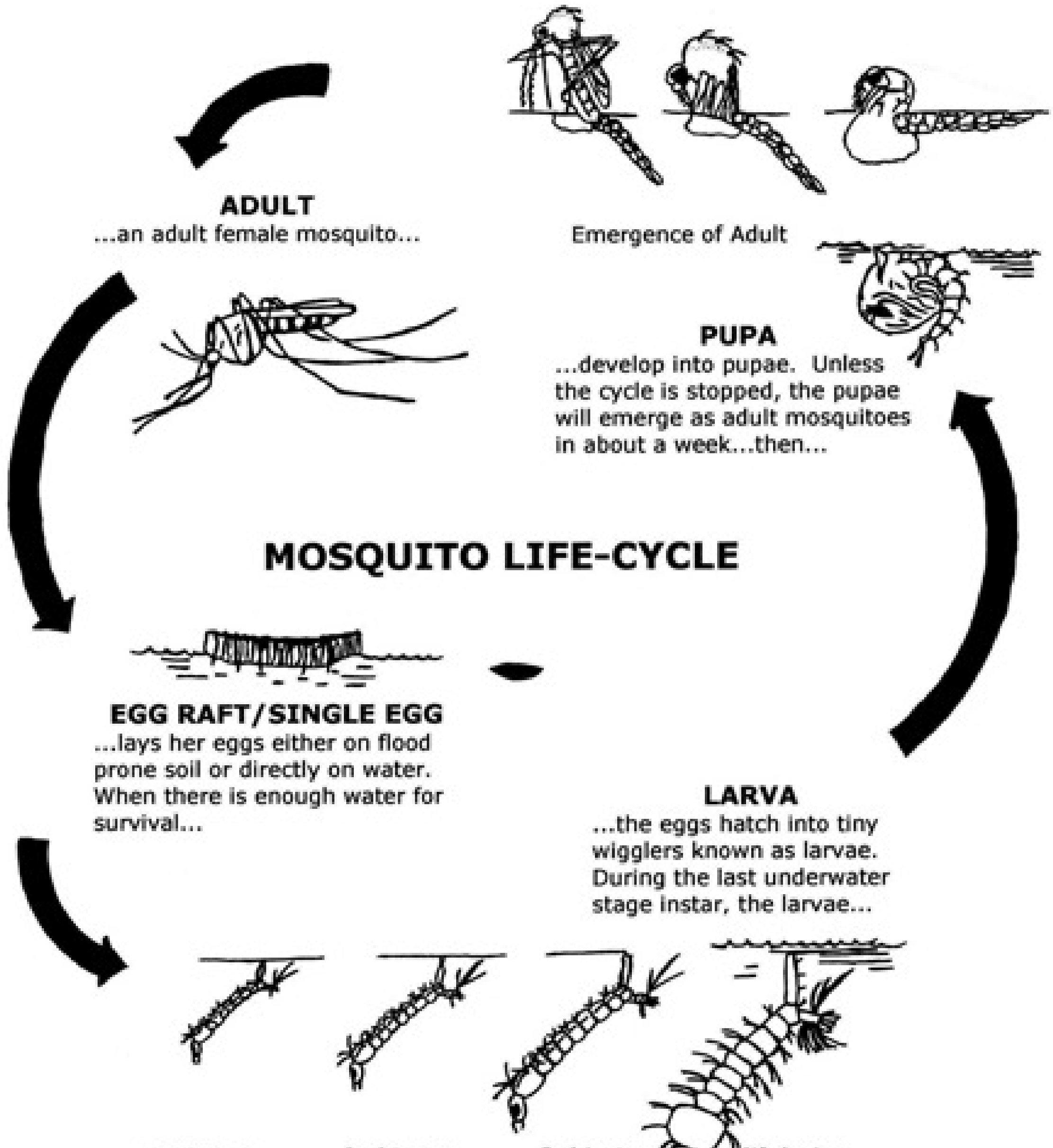


Figure: schematic of transmission cycle from Bomblies et al. 2008

What came first: the mosquito or the egg?



As temperature increases

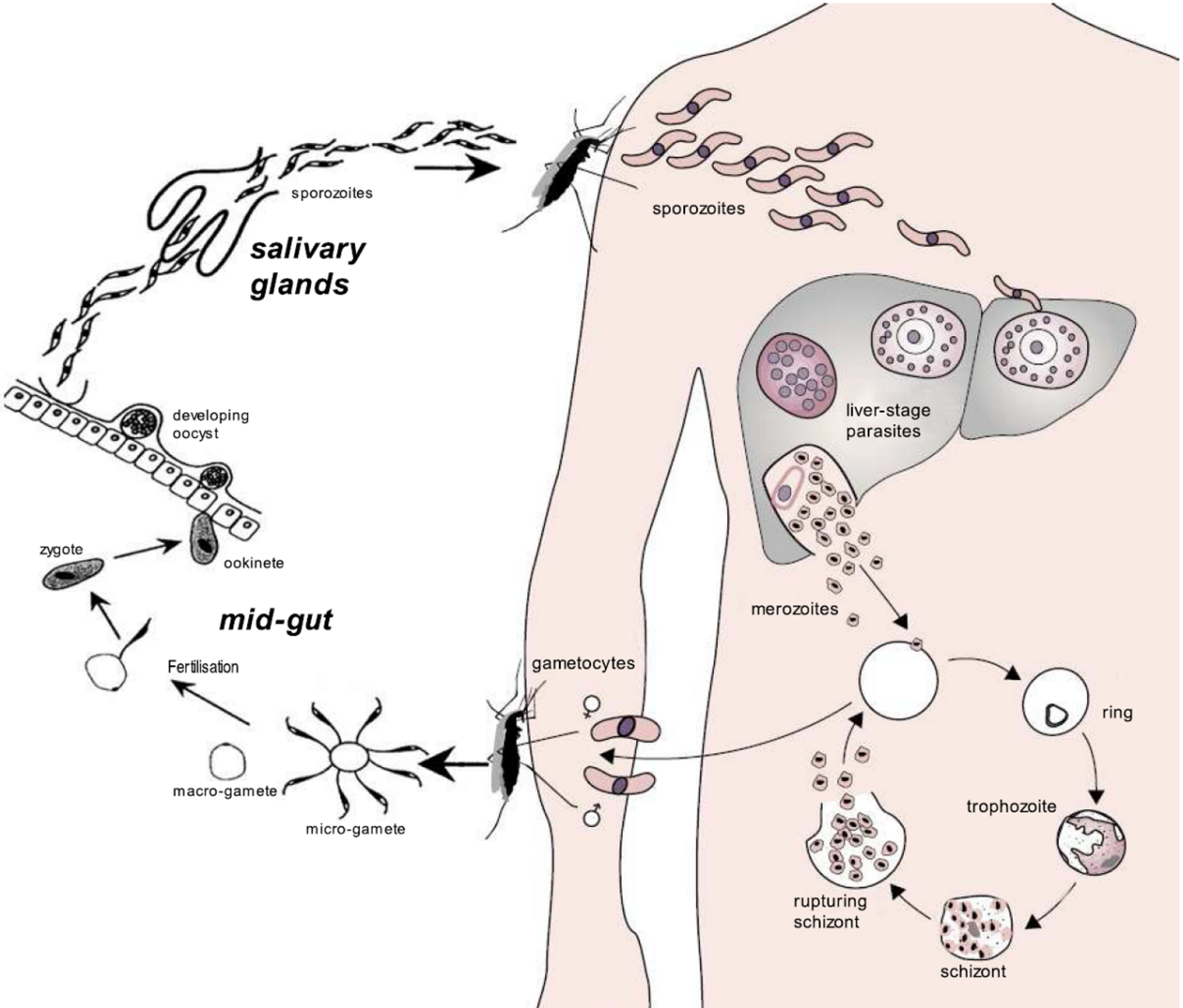
- Larvae development speeds up in warmer ponds
- Gonotrophic cycle: Eggs development in vector speeds up (Degree days concept)
- But high temperatures $> 39C$ kill vector
- And high water temperature $> 35C$ kill larvae

Cycle in host takes 10-26 days

Sporogonic cycle

Cycle in vector is temperature dependent (threshold 16-18C, 111 degree days)

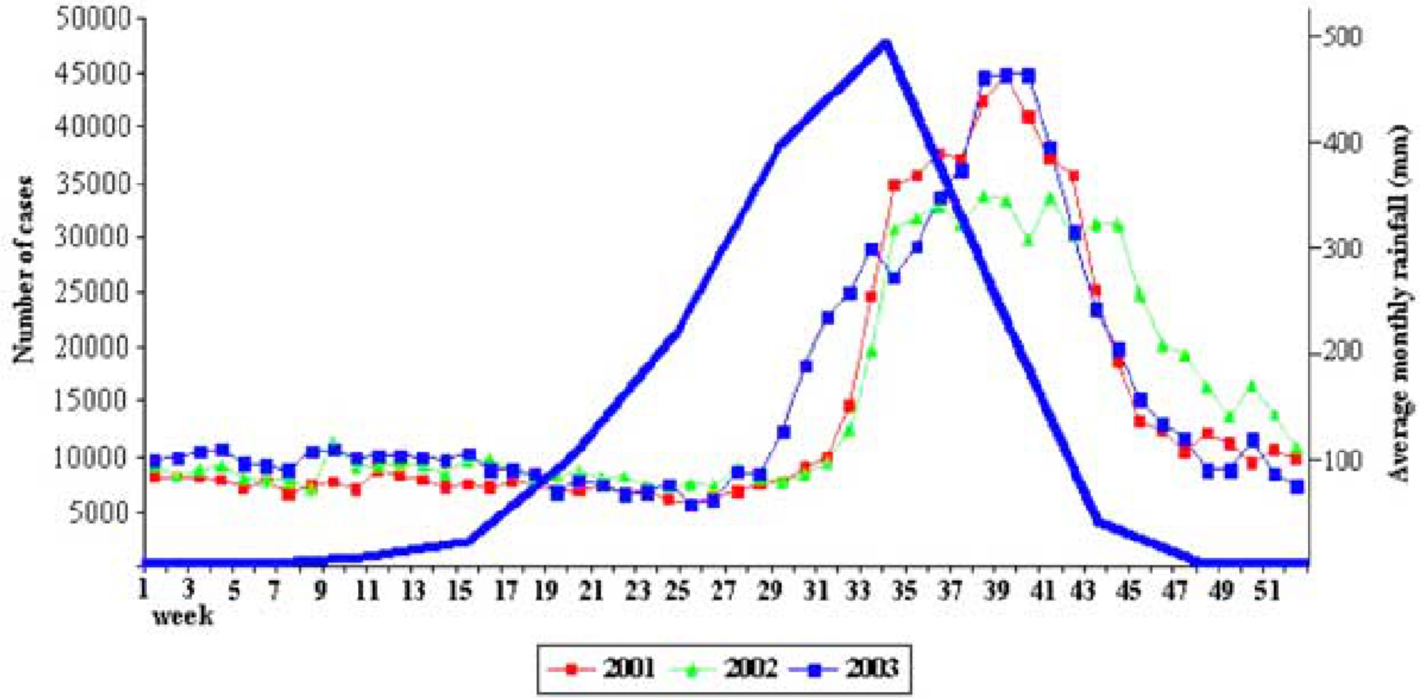
Not all bites on infective host or by infected vector lead to transmission (probability estimated at 20-30%



Rainfall

- Water required for breeding.
- Anopheles Gambiae prefers natural sunlit puddles.
- highly nonlinear relationship (flushing)

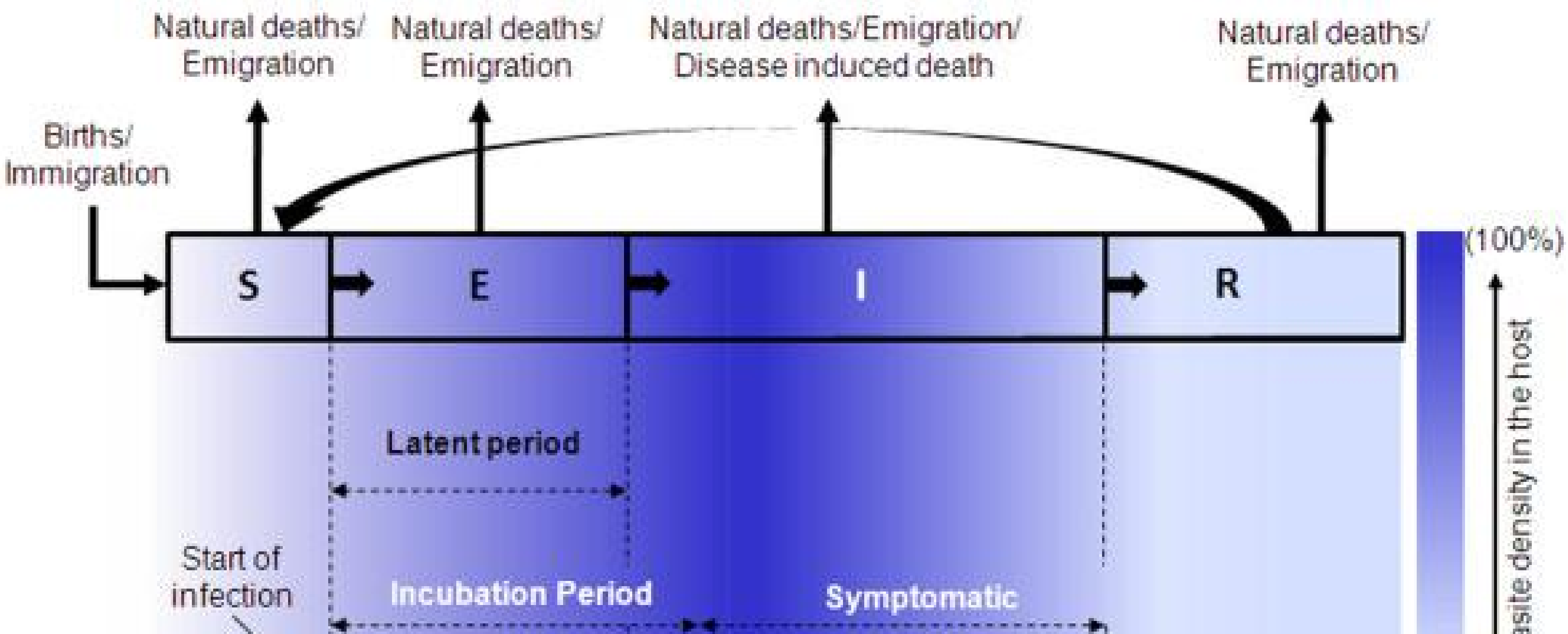
Example from village in SW Niger from Bomblies et al. (2008)

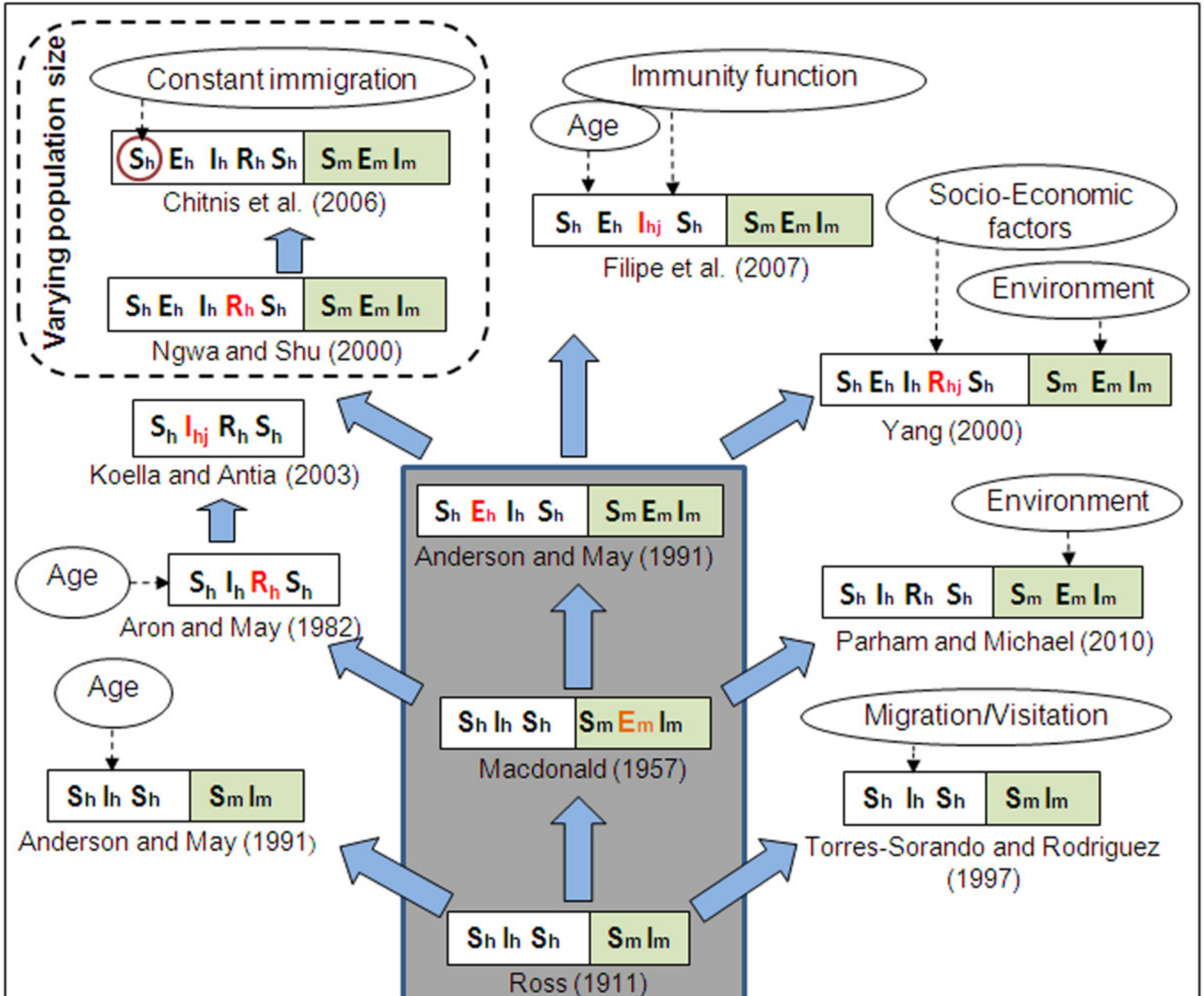


Blue - Rainfall
Dots - Malaria cases in 3 seasons

Epidemiological compartment models focus on the disease transmission and progression in human populations, dividing human status into some or all of the following categories

S	fraction of host population that is **S**usceptible to infection
E	**Exposed** fraction of population individuals infected by pathogen, but not capable of passing it on to others during latent period
I	fraction of **I**nfectious individuals, who are capable of passing on transmission to others
R	**R**ecovered fraction that have acquired temporary or permanent immunity




Varying population size
Constant immigration
Sh Eh Ih Rh Sh Sm Em Im
Chitnis et al. (2006)
Sh Eh Ih Rh Sh Sm Em Im
Ngwa and Shu (2000)
Immunity function
Age
Sh Eh Ihj Sh Sm Em Im
Filipe et al. (2007)
Socio-Economic factors
Environment
Sh Eh Ih Rhj Sh Sm Em Im
Yang (2000)
Sh Ihj Rh Sh
Koella and Antia (2003)
Sh Eh Ih Sh Sm Em Im
Anderson and May (1991)
Environment
Sh Ih Rh Sh Sm Em Im
Parham and Michael (2010)
Age
Sh Ih Rh Sh
Aron and May (1982)
Sh Ih Sh Sm Em Im
Macdonald (1957)
Migration/Visitation
Sh Ih Sh Sm Im
Torres-Sorando and Rodriguez (1997)
Age
Sh Ih Sh Sm Im
Anderson and May (1991)
Sh Ih Sh Sm Im
Ross (1911)

Modelling malaria: Some existing dynamical models

Some models have divided the categories into many sub-categories, or *bins*, or order to try and model delays in e.g. adult emergence, and have been applied to spatial modelling. Two examples of existing models: represent the 'bounds', run on coarse (100km) and very fine (10m) resolutions.

Liverpool Malaria Model LMM

- Rainfall affects larvae birth/death rate
- Temperature affects sporogonic/gonotrophic cycles and vector death rate
- 100 humans per grid cell, tuned for rural locations on coarse grid-cells

Bomblies model

- Similar temperature and rainfall relationships
- Runs on village scale with 10m resolutions
- tracks every human and mosquito!

VECTRI: VECtor-borne disease community model of ICTP, TRIeste

A model for the impact of weather on malaria, with:

- daily timestep
- surface hydrology
- regional to global scales with resolution down to 5km
- incorporating population interactions (migration, immunity) and interventions (spraying, drugs, bednets).

Uses:

- Community model
- Research and operational tool
- Seasonal forecasting
- Climate projections

Further info:

http://www.ictp.it/˜tompkins/vectri Tompkins A.M. and Ermert V, 2013: *A regional-scale, high resolution dynamical malaria model that accounts for population density, climate and surface hydrology*, Mal. J., **DOI: 10.1186/1475-2875-12-65**

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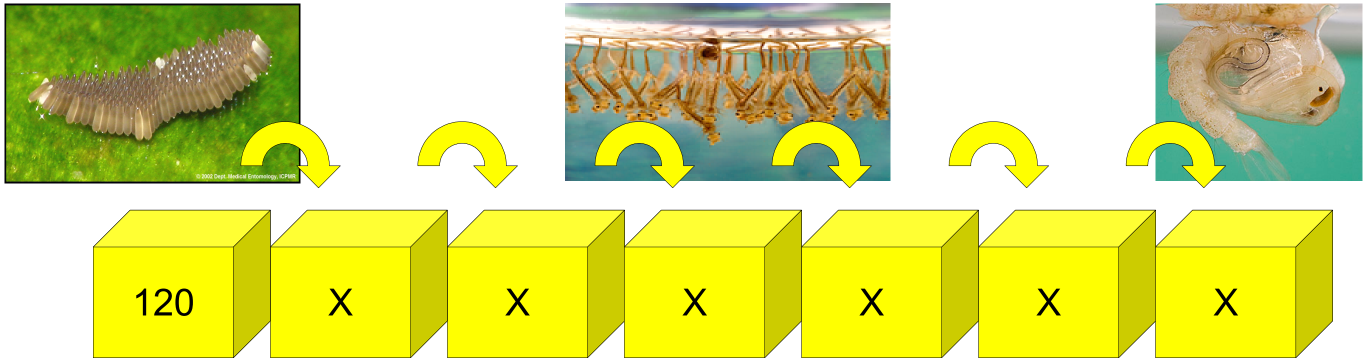
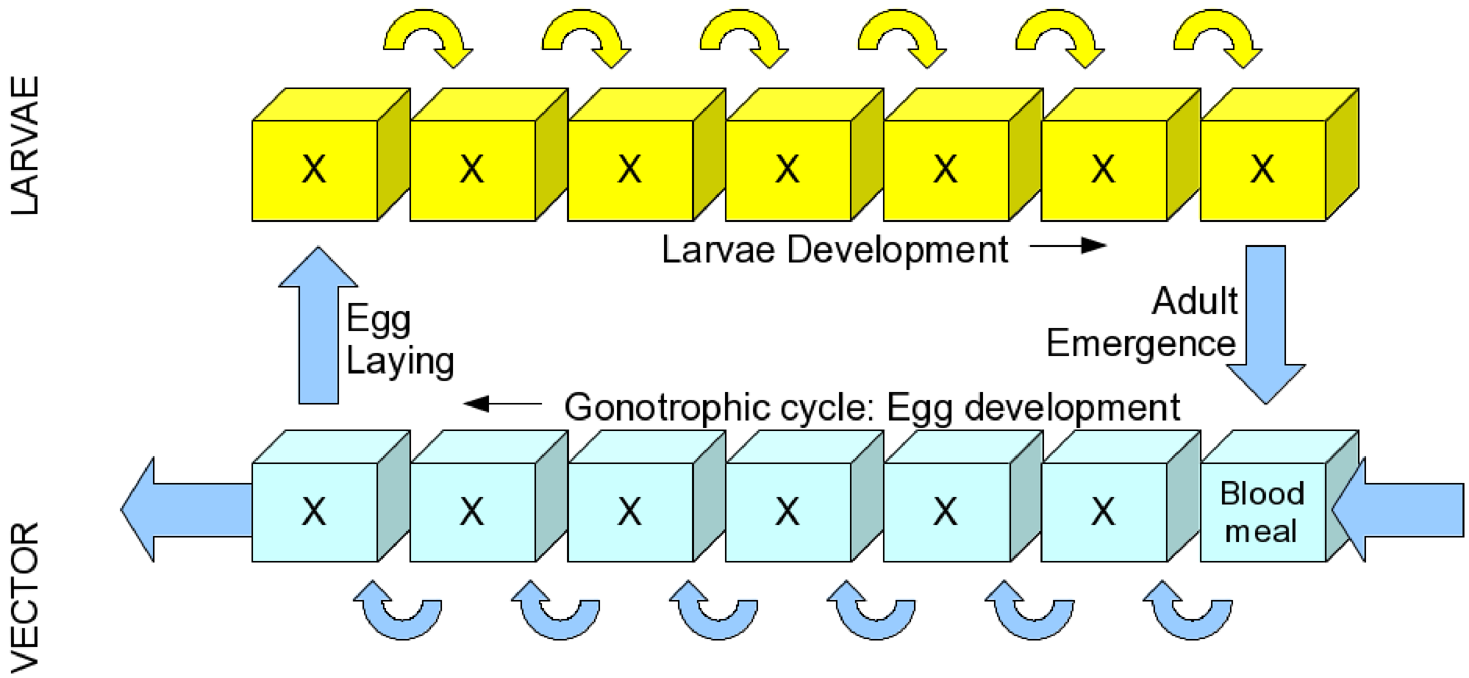
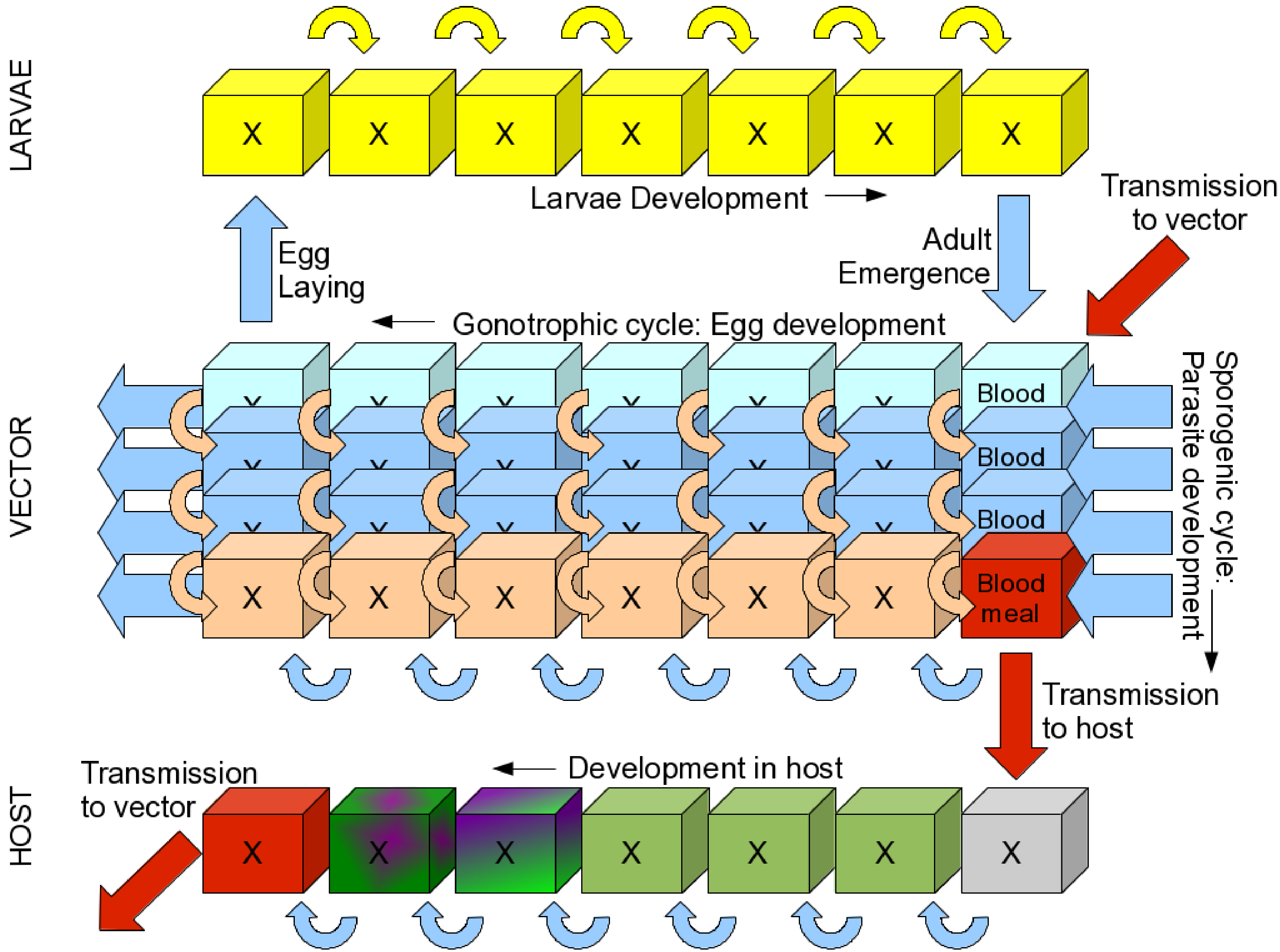
The larvae lifecycle is divided into stages or “bins”. Each model timestep, larvae ’progress’ from left to right, with the rate determined by temperature.

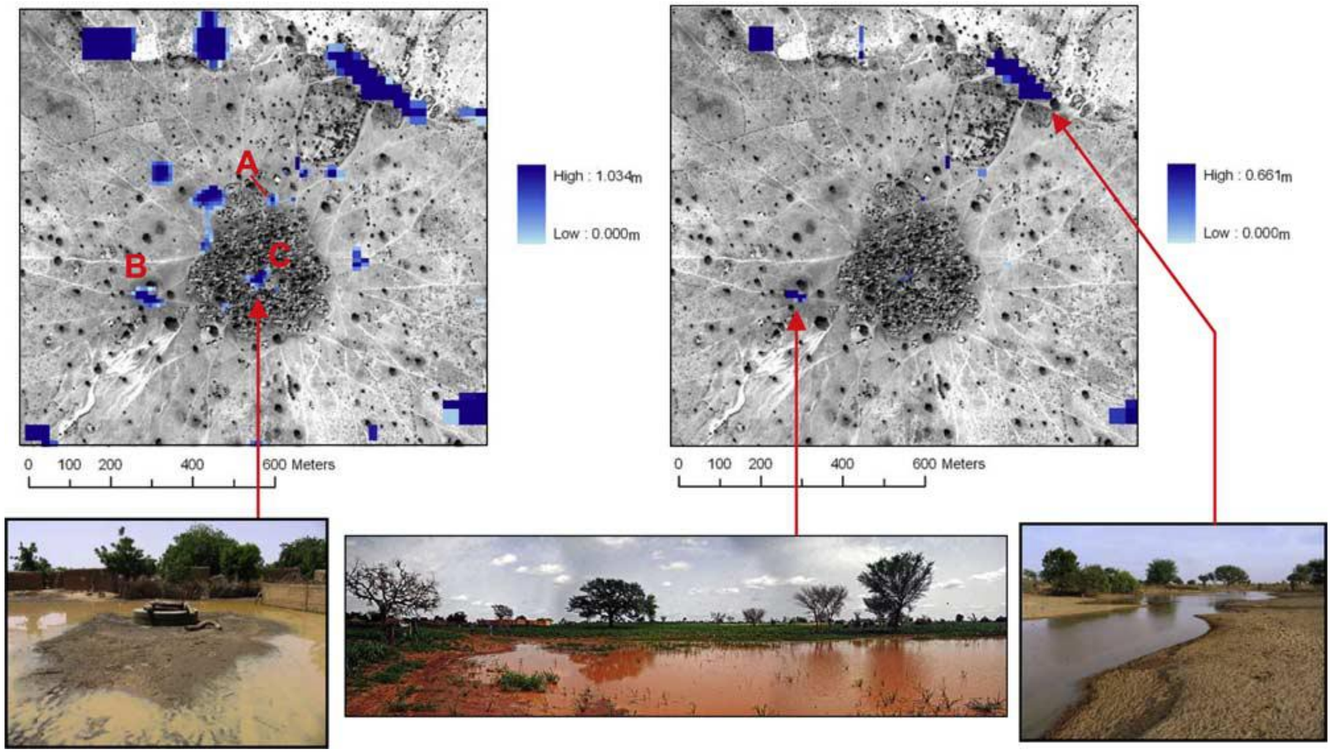


Larvae Development

We now add the subclasses for the vector gonotrophic cycle.

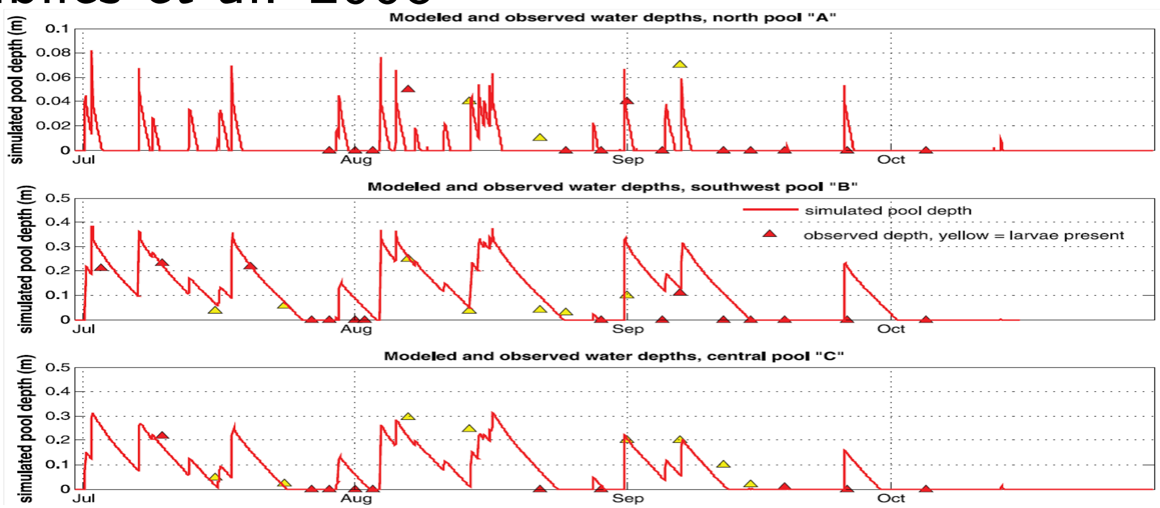


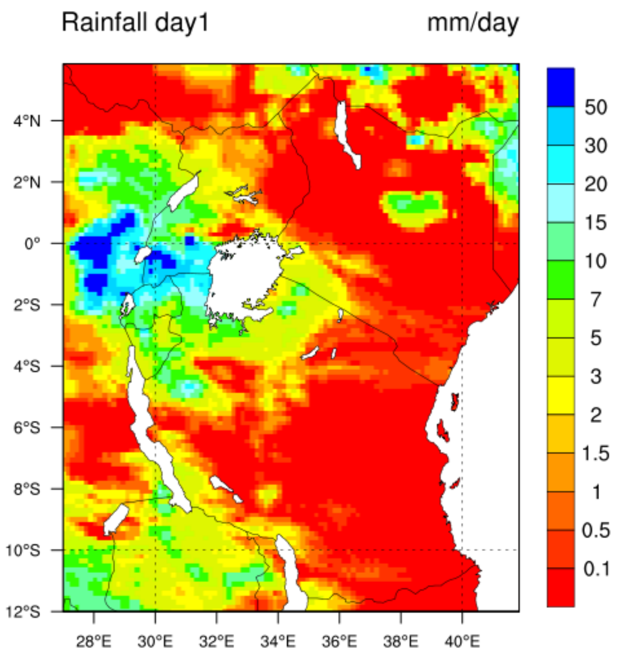

LARVAE
VECTOR
HOST
Larvae Development
Egg Laying
Adult Emergence
Transmission to vector
Gonotrophic cycle: Egg development
Blood
Blood
Blood
Blood meal
Sporogenic cycle: Parasite development
Transmission to host
Development in host
Transmission to vector
X

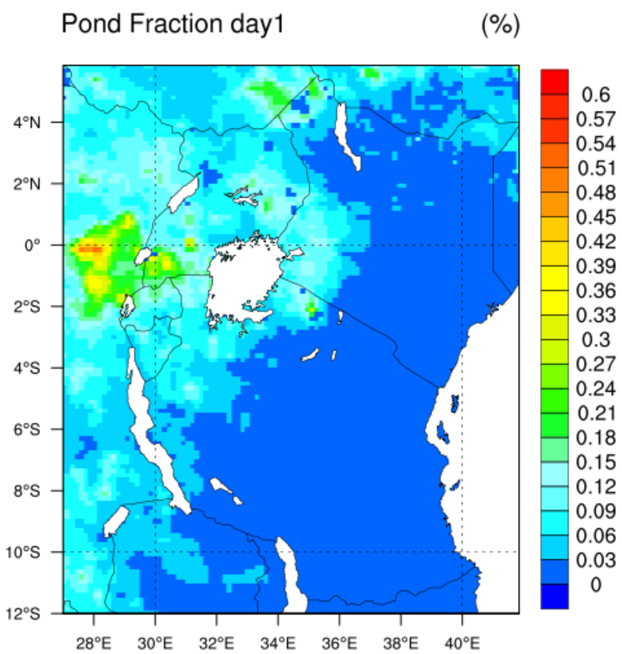


Modelled pond behaviour - However the aggregated effect of these small water bodies could be represented by a pond parametrization in a coarser scale model

Bomblies et al. 2008







Breeding sites are divided into a permanent breeding fractions plus a temporary 'pond' fraction $w = w_0 + w_{pond}$. A competition factor limits larvae biomass to 300 mg m^{-2}, while intense rainfall flushes out larvae.

The rate of change of fractional pond coverage w_{pond} is given by

$$\frac{dw_{pond}}{dt} = K_w \left(P(w_{max} - w_{pond}) - w_{pond}(E + I) \right). \quad (1)$$

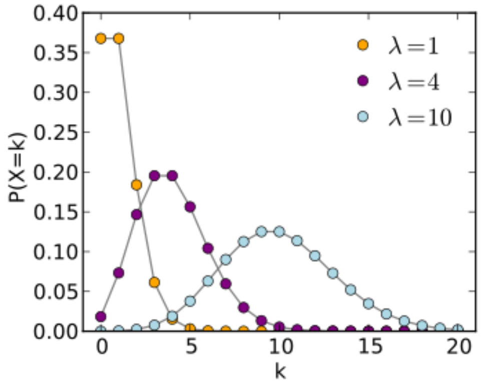
- P is the precipitation rate
- K_w is related to the aggregate pond geometry
- I Infiltration rate
- E Evaporation rate
- w_{max} Collection area = Maximum coverage (overflow losses)

- Mean number of bites per human $B = V_b/D$ biting vectors density/population density
- Assume random distribution (all people equal)
- bednet (BN) use can be accounted for.
- single-bite malaria transmission probability is integrated over Poisson distribution to give transmission probability

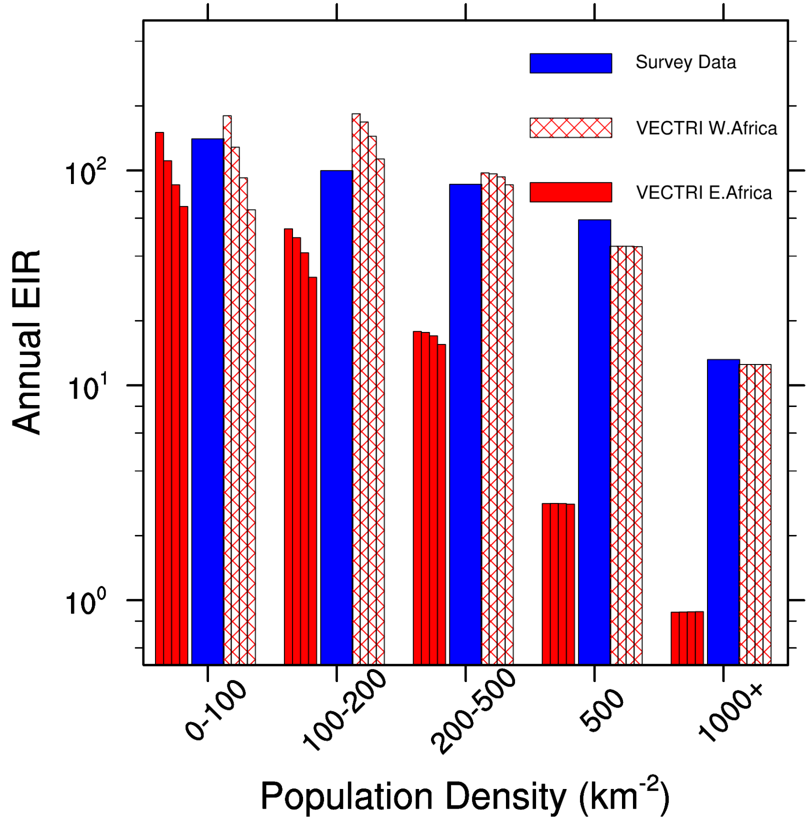
$$P_{vh} = (1 - P_{bednet}) \sum_{n=1}^{\infty} G_{B*}(n) P_{v_i h}^{n} \qquad (2)$$

where G_B is the Poisson distribution for a mean bite rate B^*

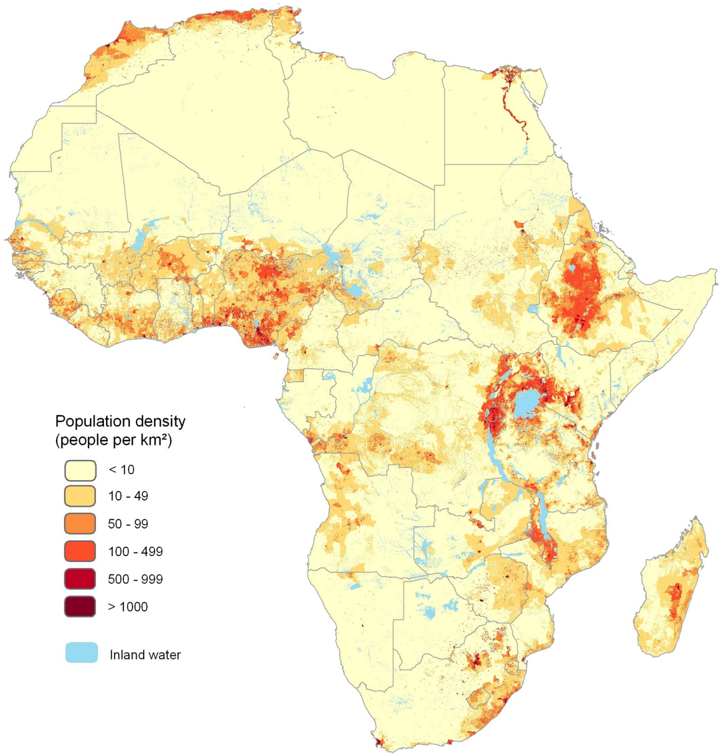
Poisson distributions:



VECTRI EIR compared to survey data:



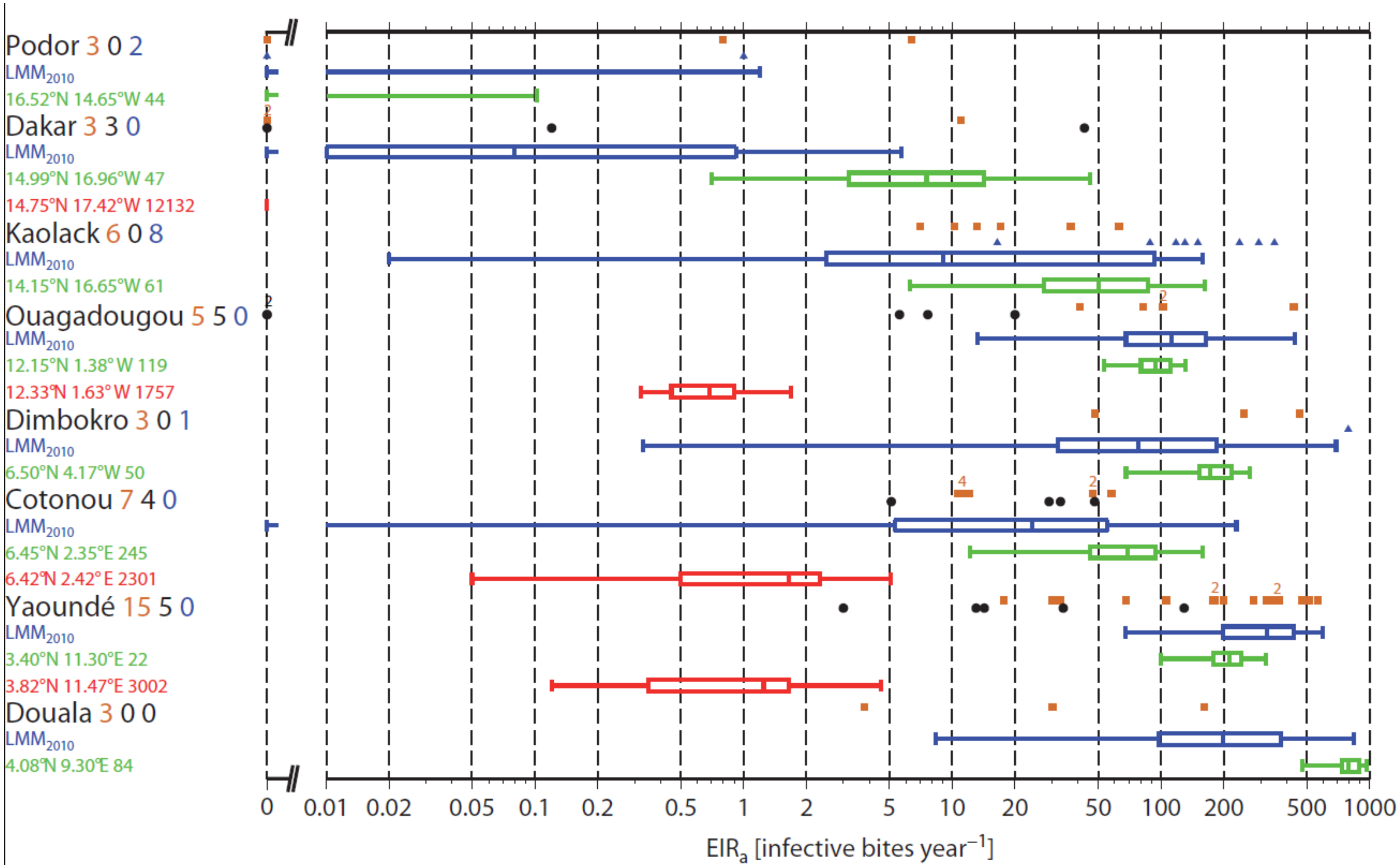
VECTRI: biting rate



- AFRIPOP data used on a 1km grid (thanks Dr. Catherine Linard) or GRUMP on 5km grid (global)
- Present day maps for seasonal forecasting purposes
- For future scenarios, GRUMP/AFRIPOP scaled by AR5 SSP country growth scenarios (no urbanisation trends).
- Data on migration will be extremely important for incorporation in VECTRI (in-country records, lights, mobile phone statistics)

Long term runs with station data

- An extensive literature search was conducted (Volker Ermert) to document studies measuring malaria parameters in Africa:
  - Malaria cases
  - Infected bite rates (EIR)
  - Ratio of infected to total vectors (CSPR)
- For each study location (many tens), if meteorological station data available nearby ($<$ tens of km) this was used to drive the vector models for multiple decades.
- The population density is remapped for a 5x5km cell around the *study site* (i.e. not the station).

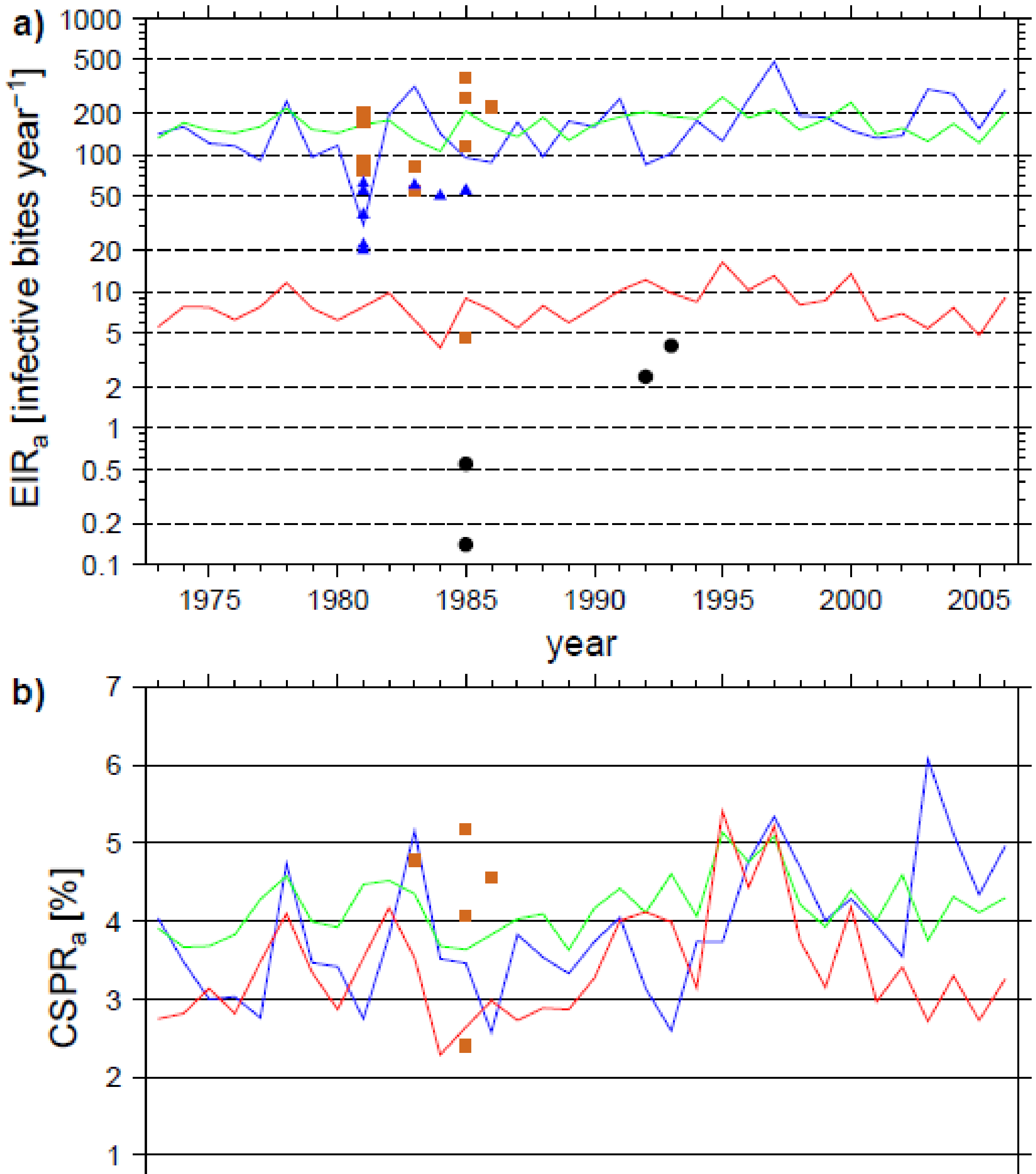


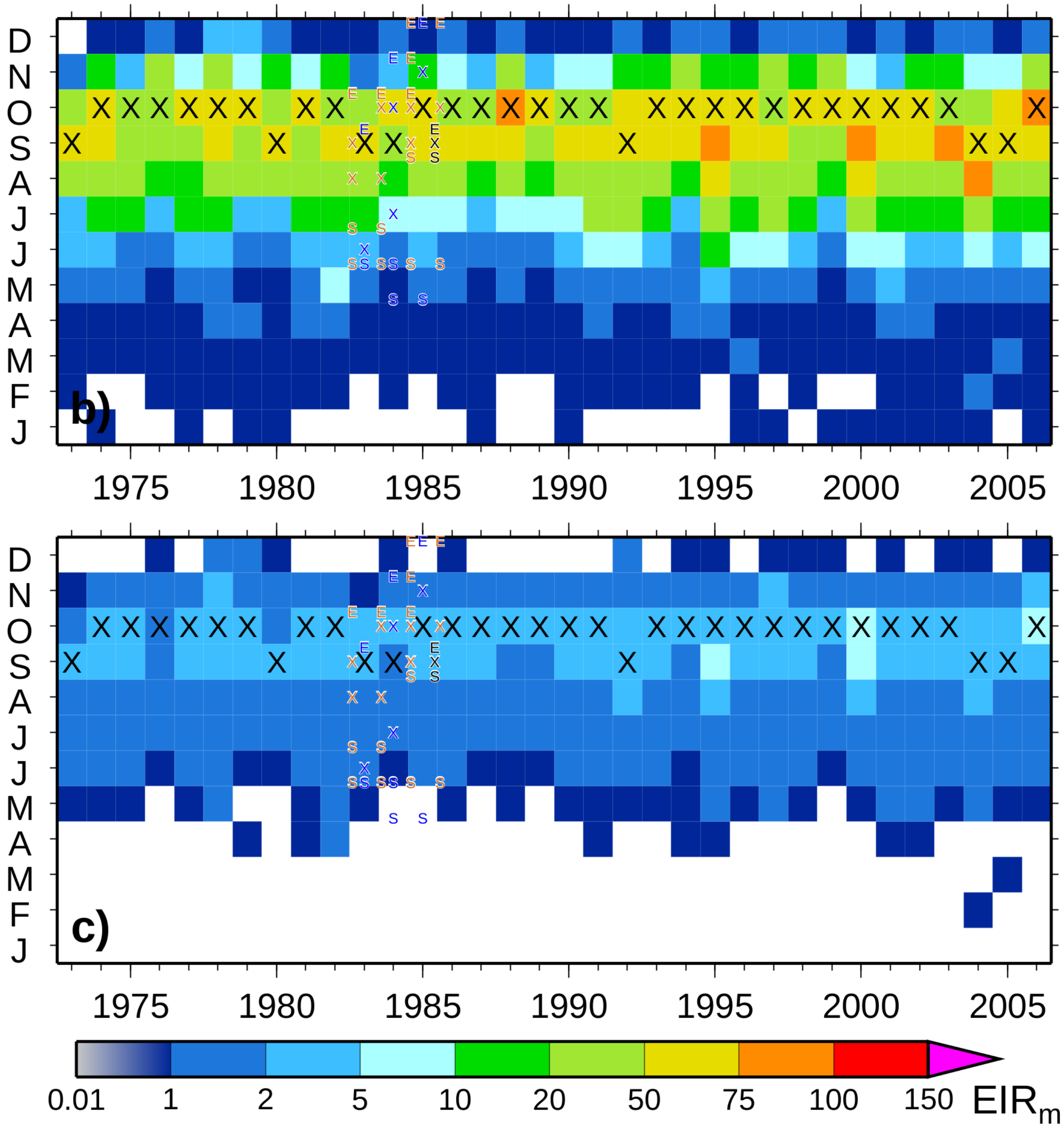
Symbols represent field campaign measurements.

Brown square: urban location

black dots: rural location (non-zero)

VECTRI Bobo-dioulasso - population 1037/41 km^{-2}





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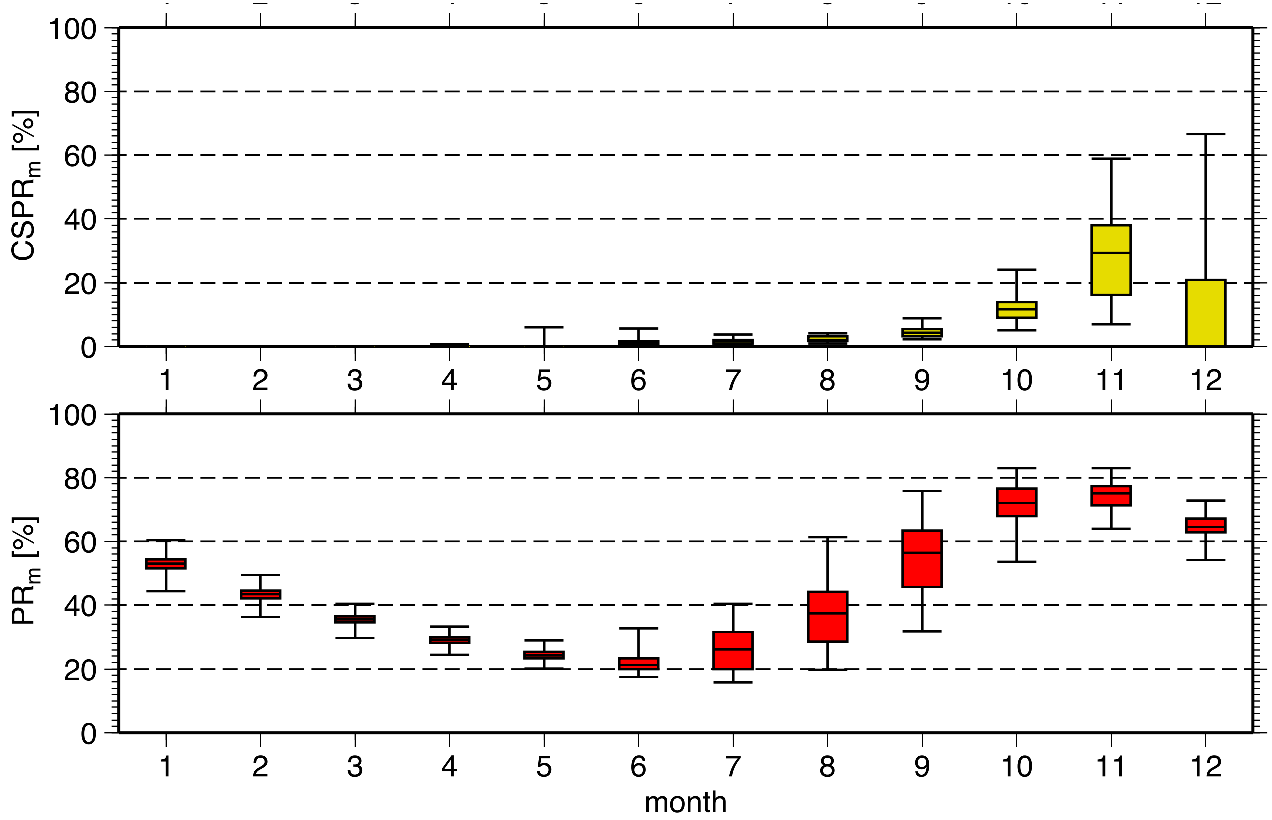
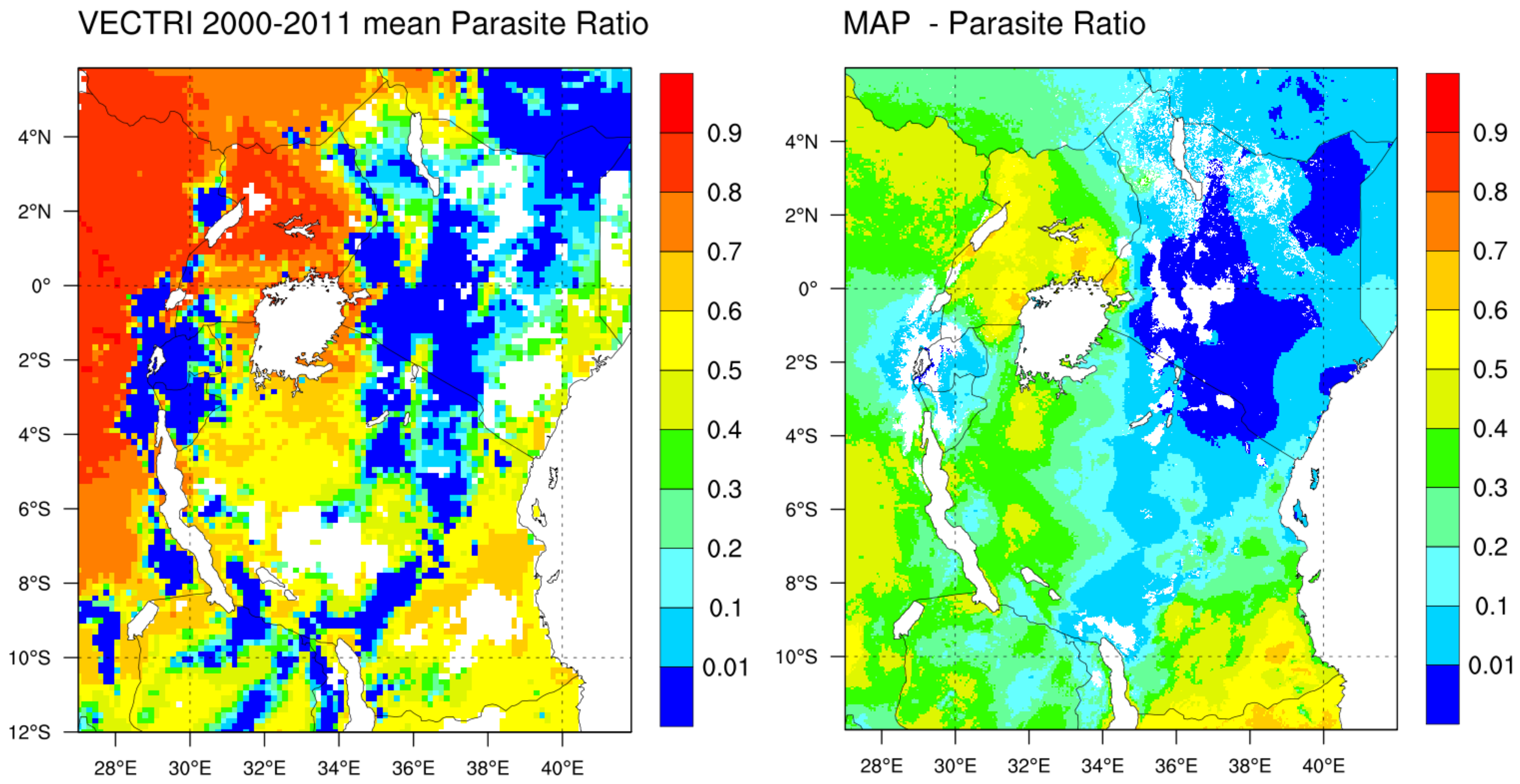
Bobo-dioulasso (SW BF) - population 1037 km^{-2}

EIR=infectious bites pp per annum, PR=Parasite Ratio

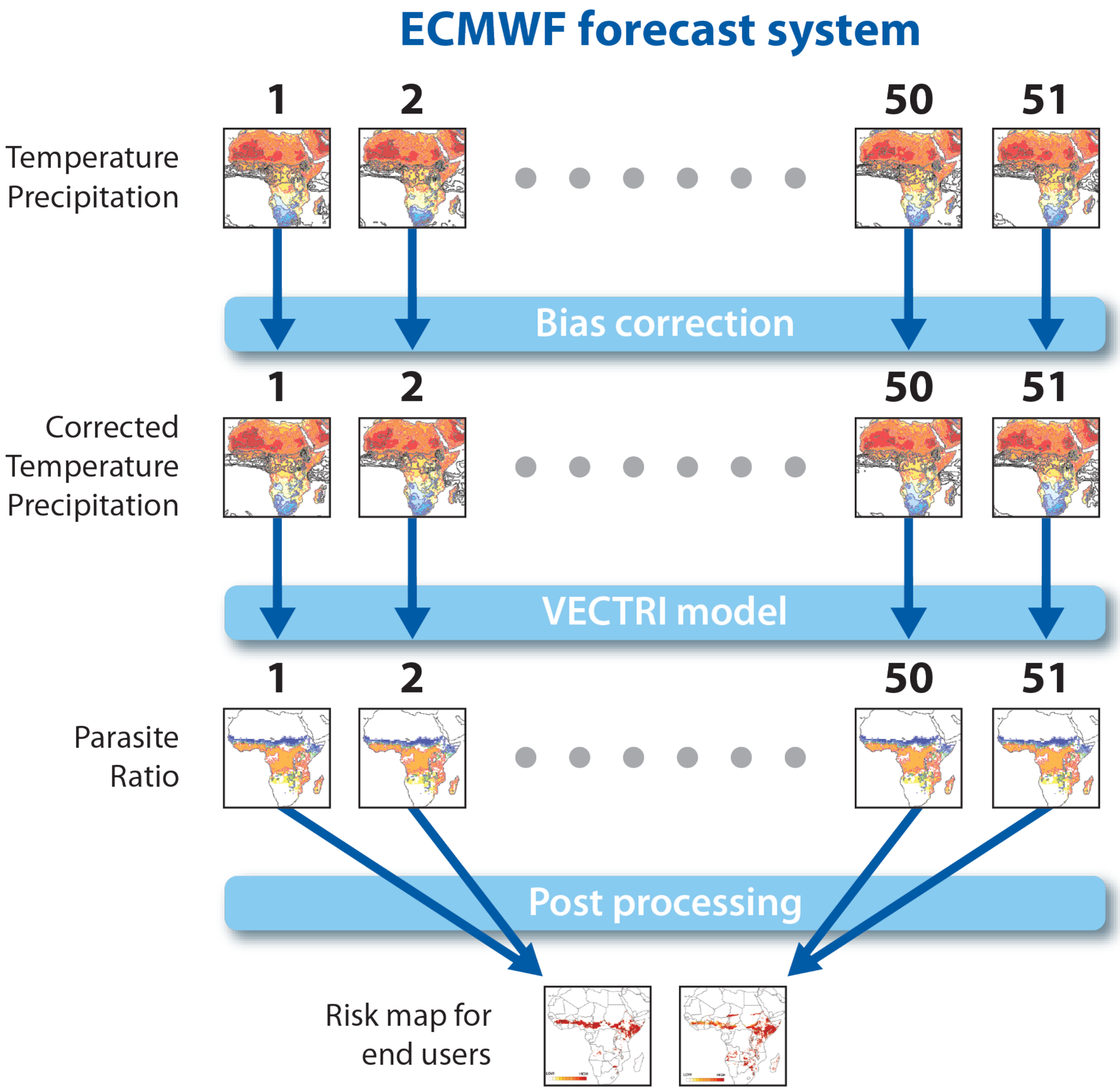
Onset period most variability in infection rates of host - seasonal forecast potential. This is because peak PR is "saturated", reducing sensitivity to the late season climate.



VECTRI vs MAP Parasite Rates (PR)



MAP data from http://www.map.ox.ac.uk/

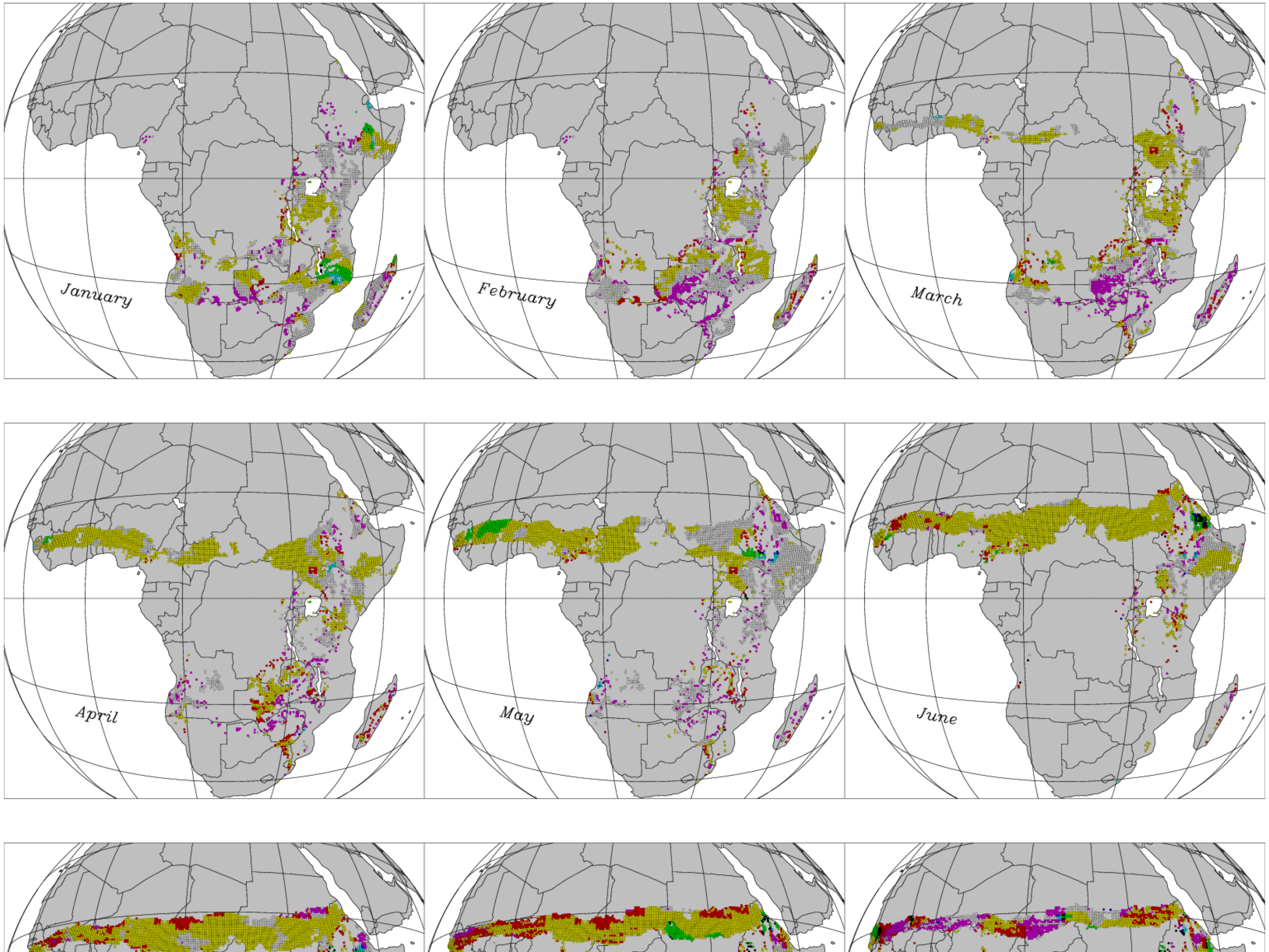


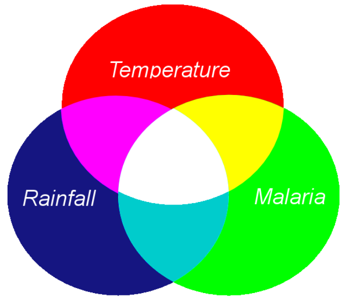
The ECMWF-ICTP dynamical Malaria Early Warning System

- Risk maps in terms of PR/EIR.
- hybrid system needed for case predictions
- see later talk for details

http://nwmstest.ecmwf.int/products/forecasts/d/inspect/catalog/research/qweci/

Skill in predicting temperature, rainfall and malaria PR at month 1 lead in areas of high variation. Black=no skill. (Tompkins and Di Giuseppe, submitted).





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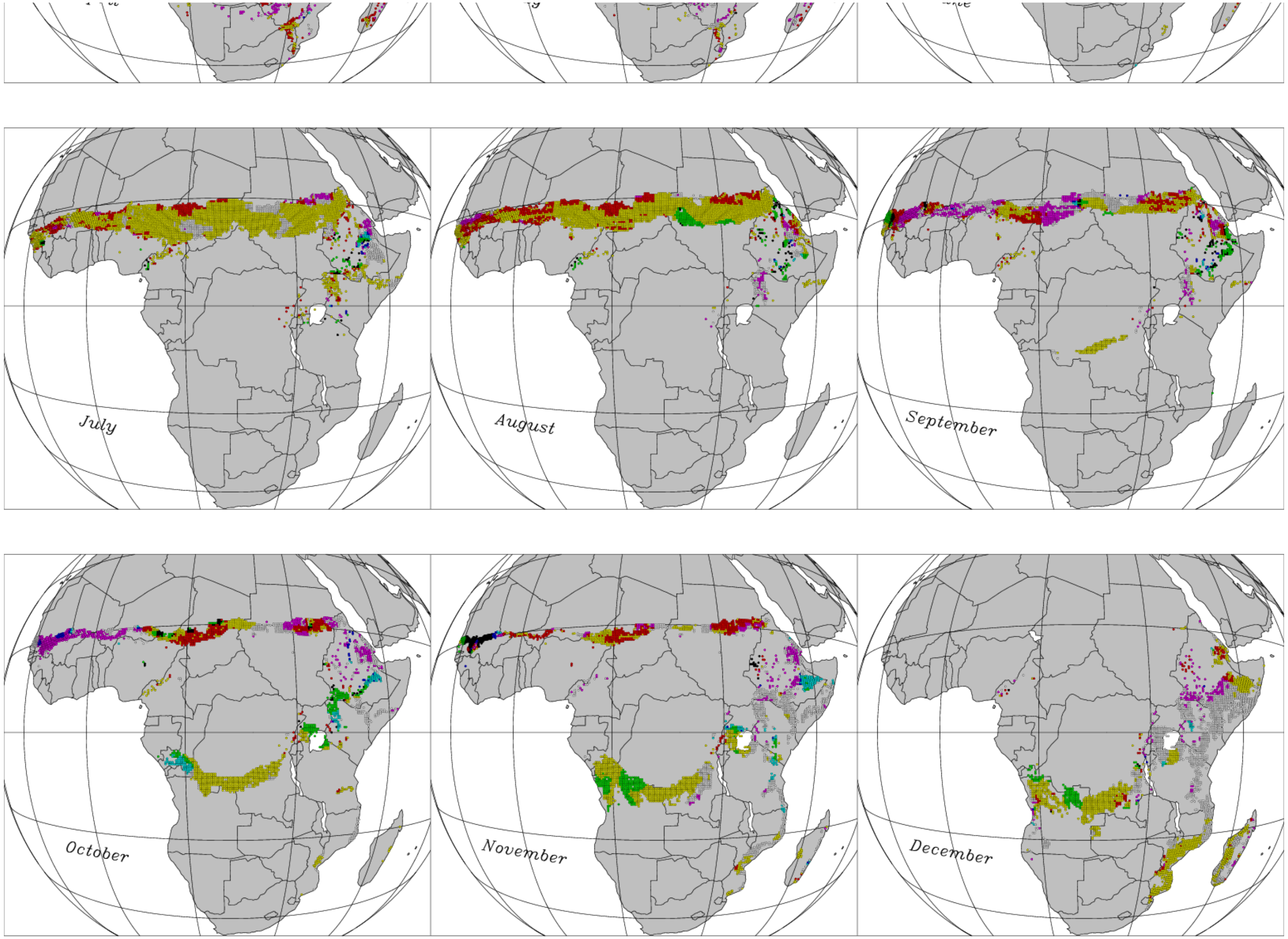
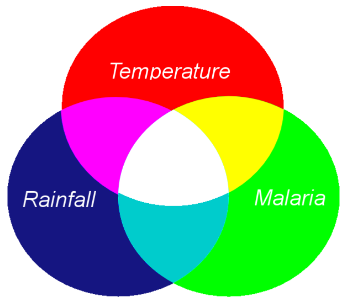
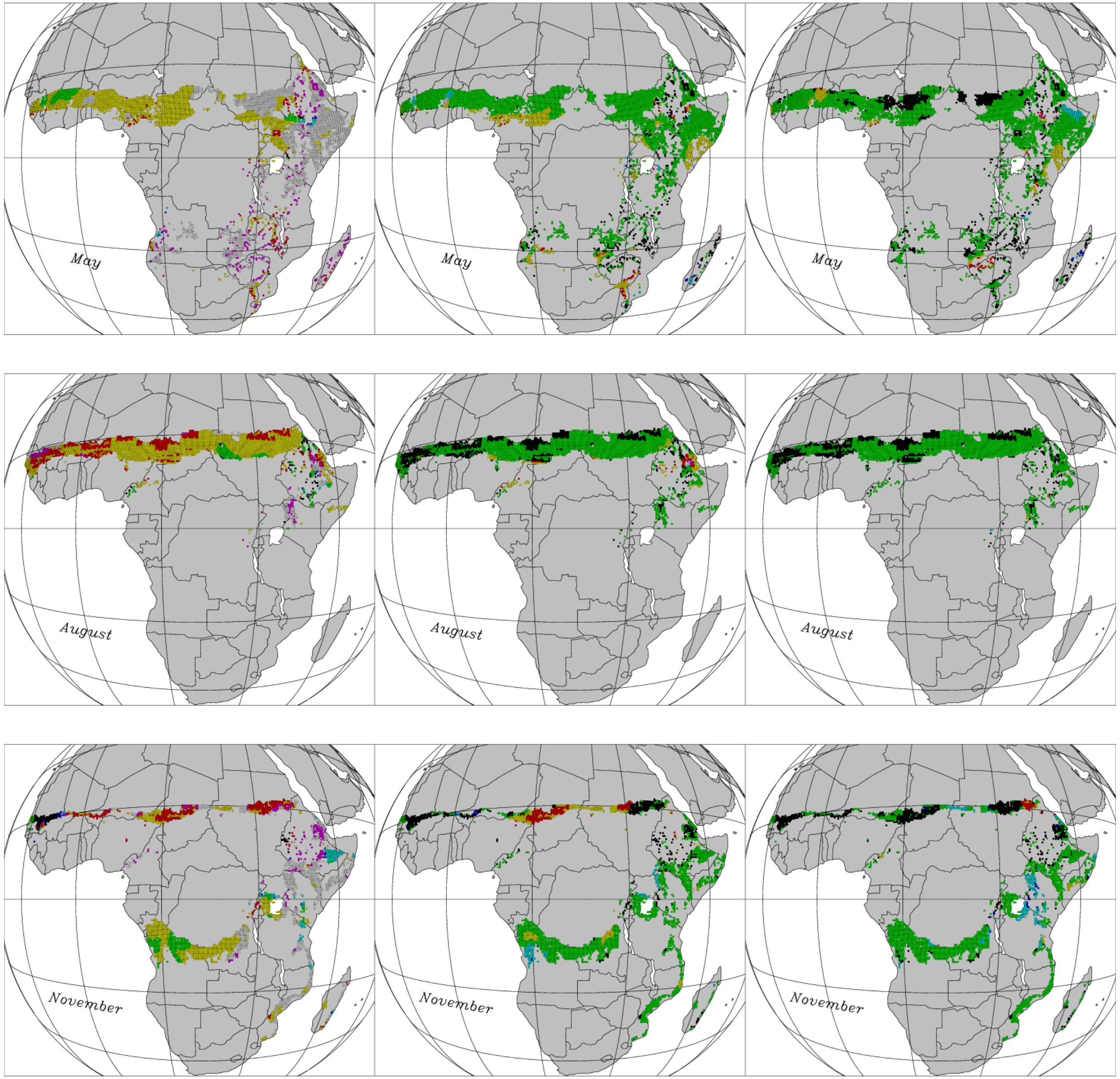
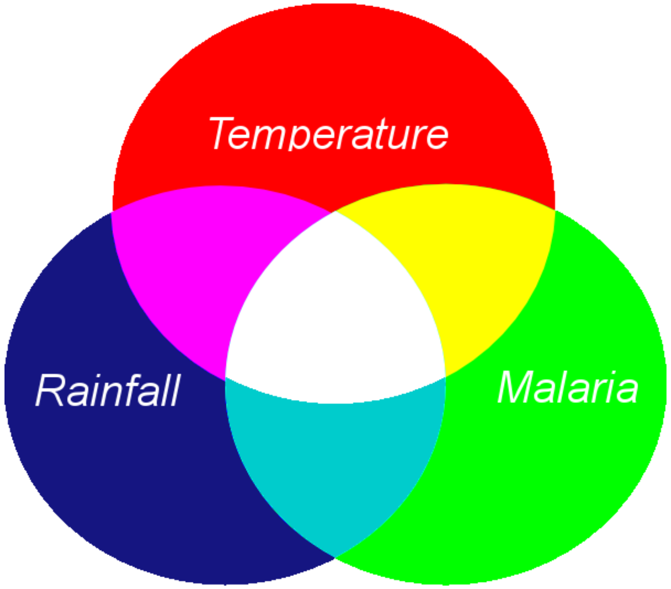




Skill in predicting temperature, rainfall and malaria PR at lead 1-3 months





ISIMIP

Impacts model intercomparison project (led by PIK)

- Aims to feed directly into IPCC 5th assessment report - providing five (so far) CMIP5 global models with the same bias correction technique applied to all models for rainfall/temperature.
- Covers several sectors: water, agriculture, health.
- Health only concerns falciparum malaria and contains 3 statistical malaria models, a monthly means version of LMM, and VECTRI.

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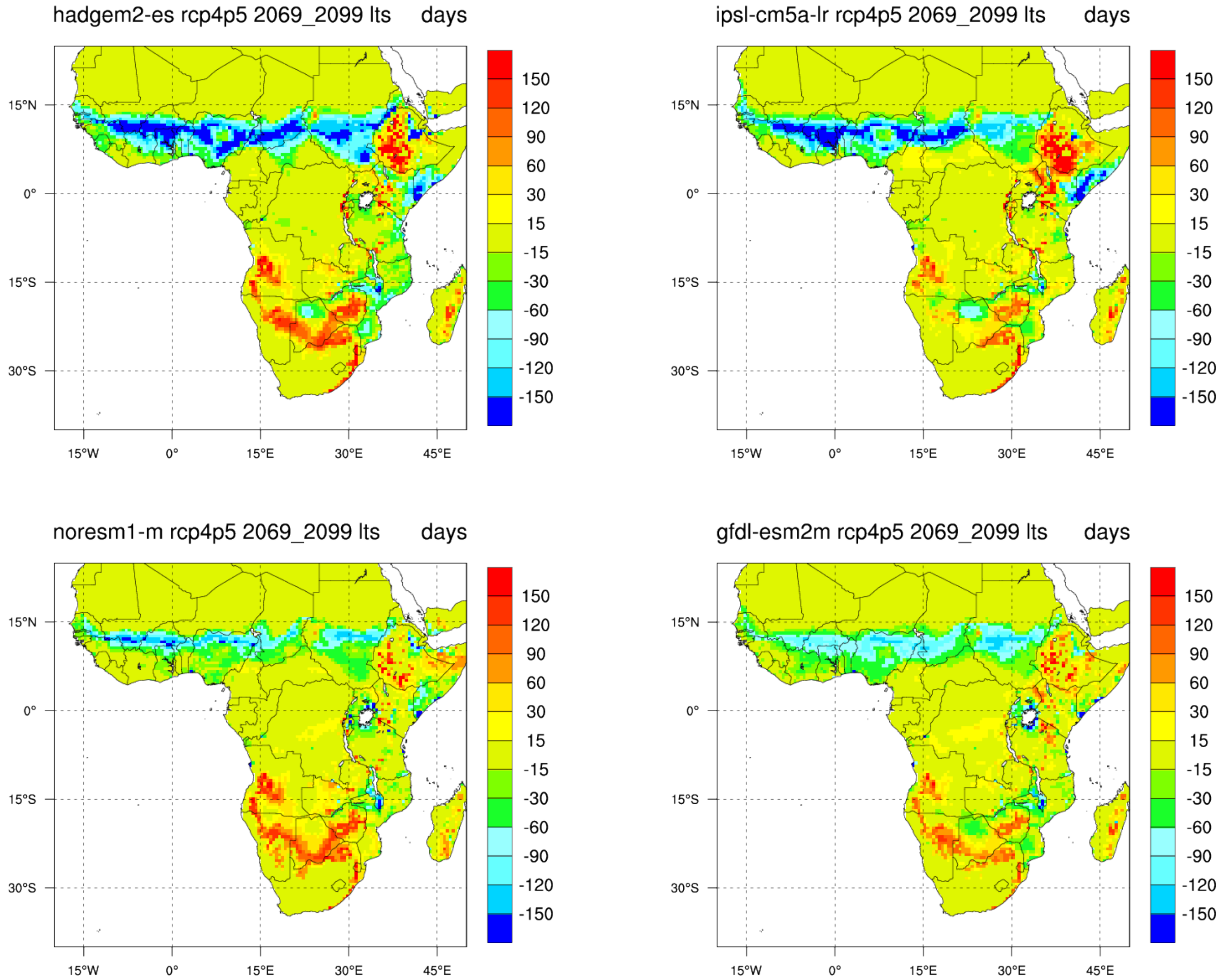
hadgem2-es rcp4p5 2069_2099 lts days
ipsl-cm5a-lr rcp4p5 2069_2099 lts days
noresm1-m rcp4p5 2069_2099 lts days
gfdl-esm2m rcp4p5 2069_2099 lts days
15°N
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0°
15°E
30°E
45°E
150
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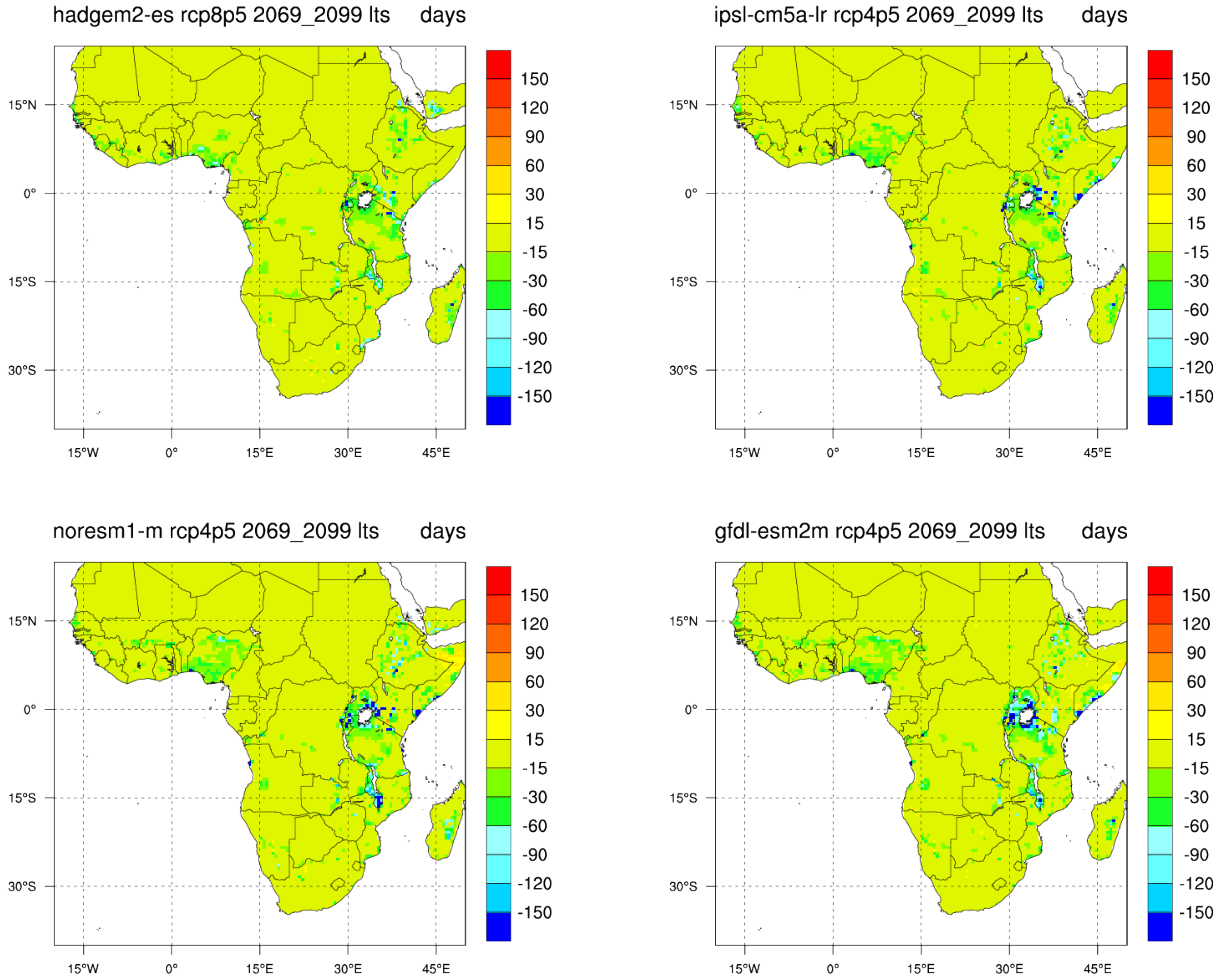
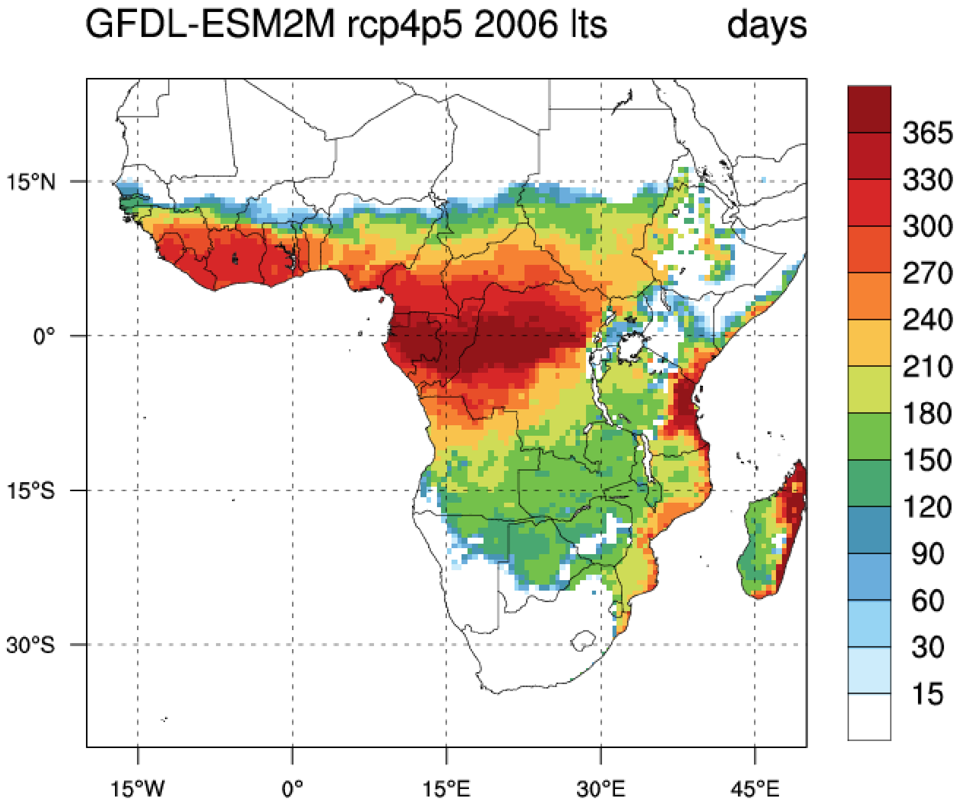
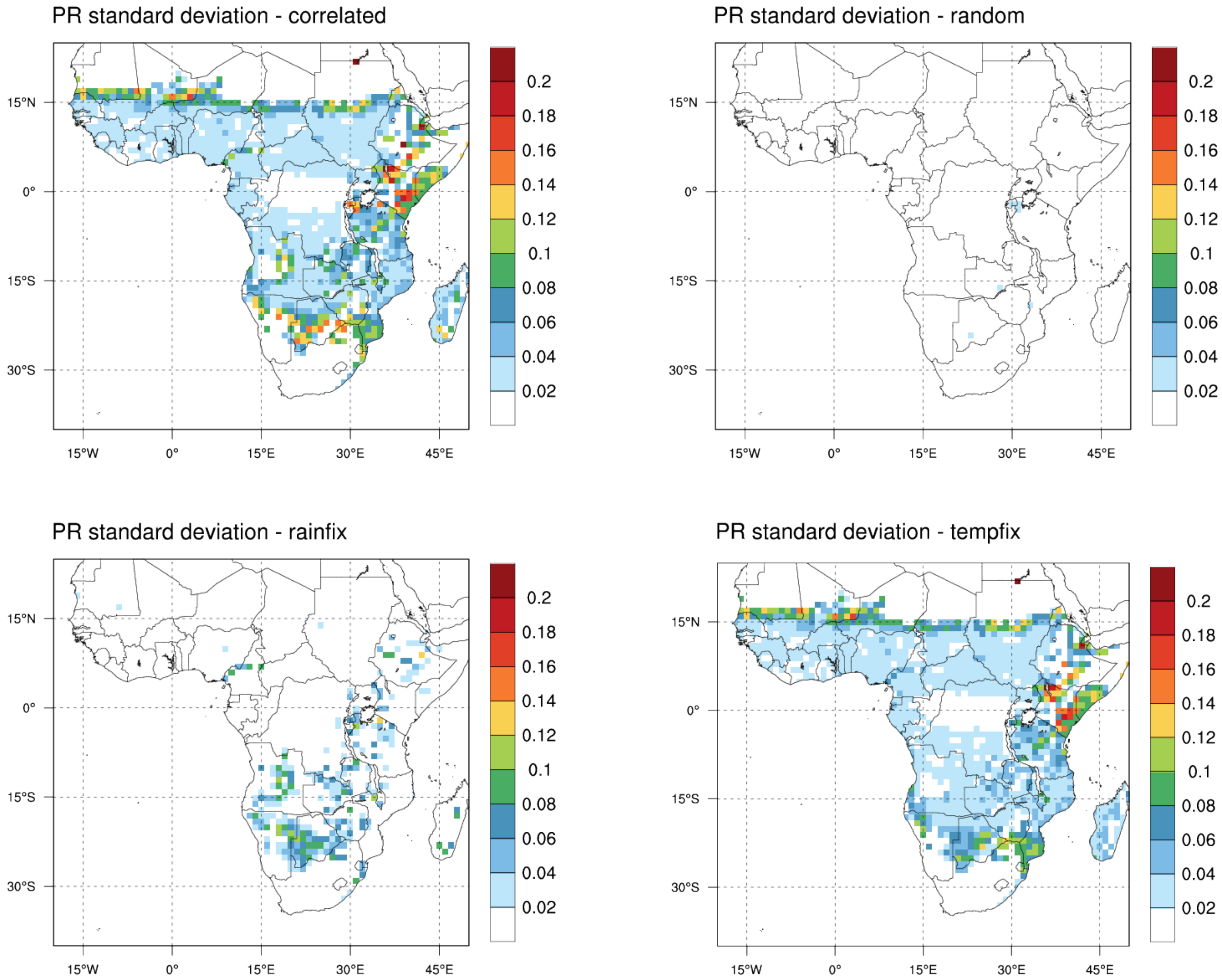
15
-15
-30
-60
-90
-120
-150

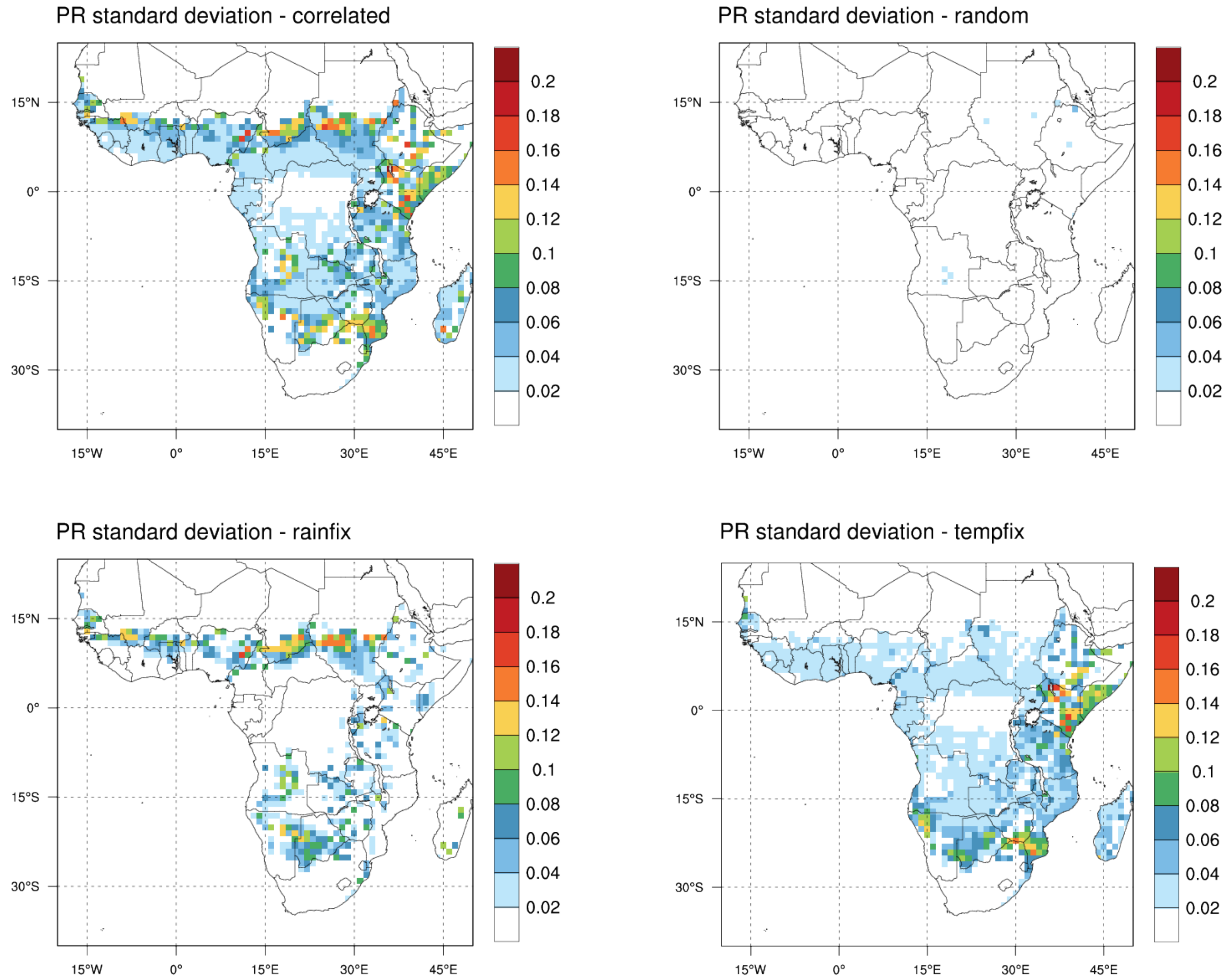
population dilution effect - end of 21st century minus present



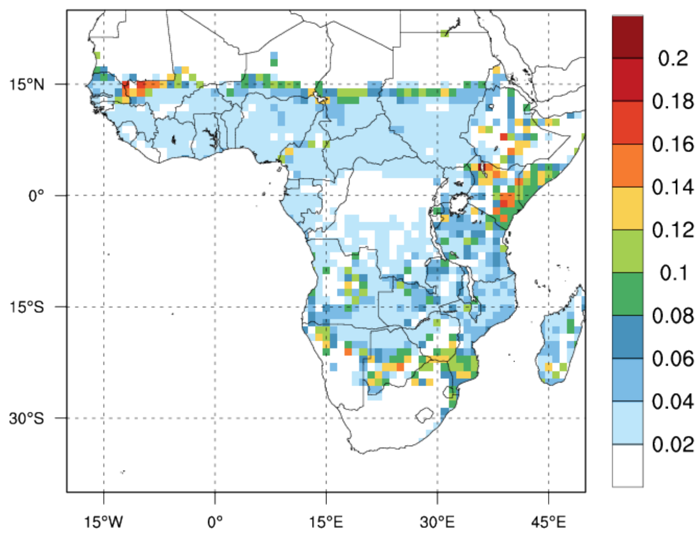


- malaria in West Africa too far south - fault of climate model or malaria model?
- significant interannual variability
- shifts in zone with time

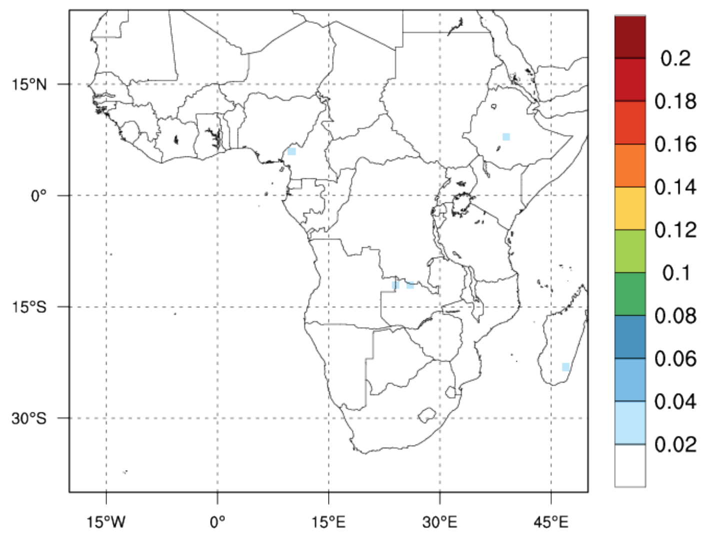

PR standard deviation - correlated
PR standard deviation - random
PR standard deviation - rainfix
PR standard deviation - tempfix
15°N
0°
15°S
30°S
15°W
0°
15°E
30°E
45°E
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02


PR standard deviation - correlated
PR standard deviation - random
PR standard deviation - rainfix
PR standard deviation - tempfix
15°N
0°
15°S
30°S
15°W
0°
15°E
30°E
45°E
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02

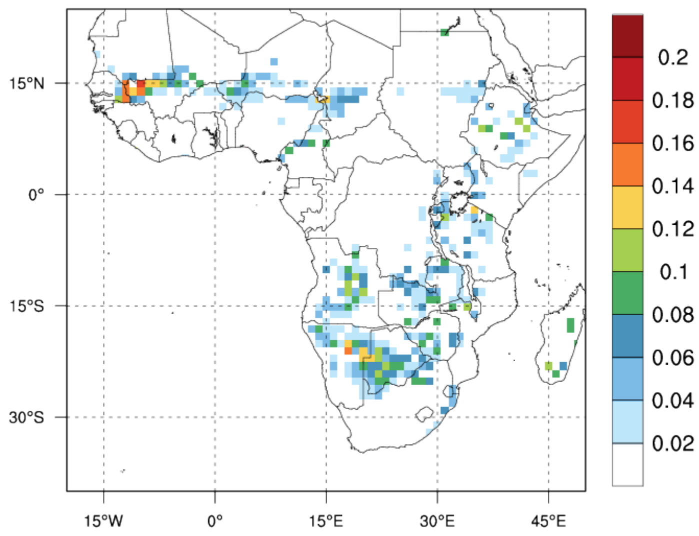
PR standard deviation - correlated



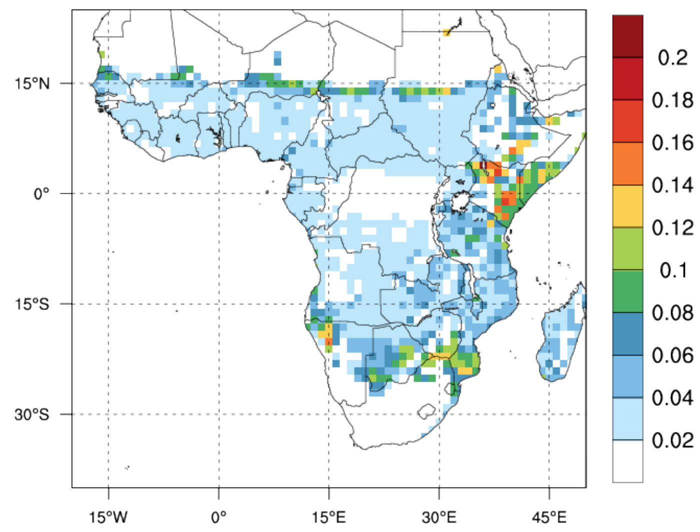
PR standard deviation - random



PR standard deviation - rainfix



PR standard deviation - tempfix



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- Introduced the VECTRI dynamical malaria modelling system
  - community model
  - easy to set up for a single location
  - schools at ICTP, Addis, Arusha.
  - ICTP open to collaboration for system evaluation
- Uses in monthly to seasonal prediction - new pilot MEWS with ECMWF
- understanding impact of climate variability on malaria transmission, but stochastic variation of parameters required.
- Extension to include: migration, immunity, interventions, improved hydrology underway.