The role of surface hydrology in some infectious diseases

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- Part 1 - Malaria transmission and the VECTRI model
- Part 2
  - Cholera
  - RVF
  - Schistosomiasis
  - Dengue

Malaria is a major disease affecting 500 million people a year.
Malaria deaths estimated at approx 1 million a year.
BBC headlines:

- 18 oct 2011 - malaria deaths fall by 20% over decade
- 13 nov 2011 - anti-malaria compound 'shows promise'
- 20 dec 2011 - potential new vaccine revealed by Oxford
- 2 feb 2012 - malaria deaths hugely underestimated - lancet
- 14 April 2013 - Malaria hotspots 'need new approach'
- 25 April 2013 - Malaria cases on rise in Nairobi
- 29 April 2013 - Parasite 'resistant to malaria drug artemisinin'


BBC News - Third of malaria dr...
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Third of malaria drugs 'are fake'

By Michelle Roberts
Health editor, BBC News online

A third of malaria drugs used around the world to stem the spread of the disease are counterfeit, data suggests.

Researchers who looked at 1,500 samples of seven malaria drugs from seven countries in South East Asia say poor-quality and fake tablets are causing drug resistance and treatment failure.

Data from 21 countries in sub-Saharan Africa including over 2,500 drug samples showed similar results.

SPL
Some species in Thailand and Vietnam spread a drug-resistant malaria strain

Related Stories

Malaria caused by the plasmodium parasite of which 6 species are known to infect man:

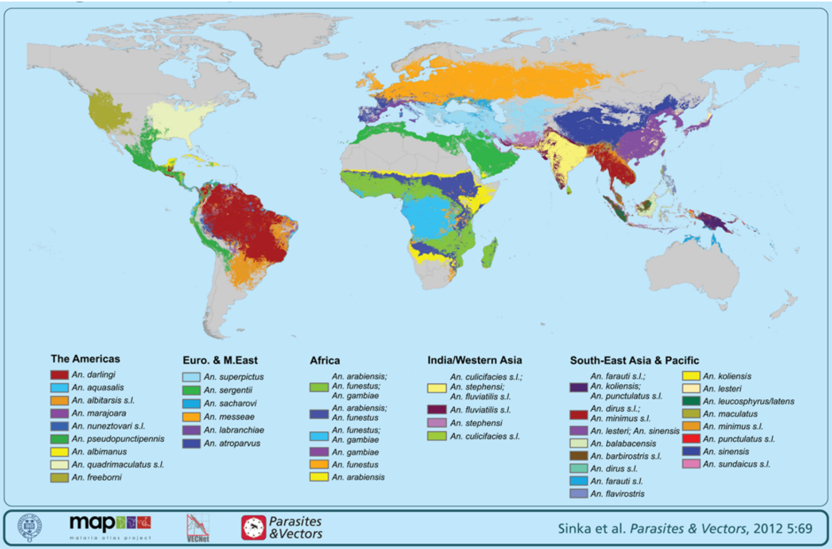
- P. falciparum
- P. Vivax
- P. Ovale (2)
- P. Malariae
- P. Knowlesi

falciparum and vivax are the most widespread, their vector is 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.

MAP analysis of vector species.



Many of these deaths from falciparum occur in Africa (Fig. 2), although this is a recent phenomenon. See *the making of a tropical disease* by Packard.

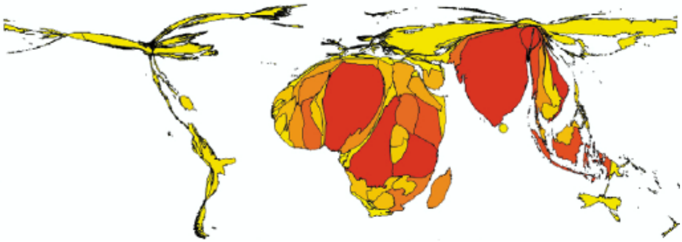


Figure: Cartogram of national prevalence of falciparum from Hay et al. (2004)

- Epidemic regions are usually found on the transmission fringes and are associated with temperature and/or rainfall seasonality (Fig. 3).
- 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.

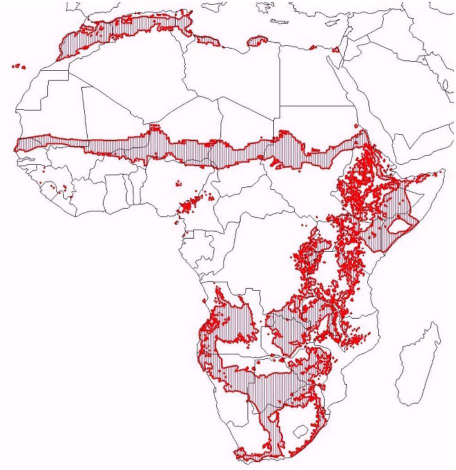


Figure: Malaria epidemic zones - from ?

- 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 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:

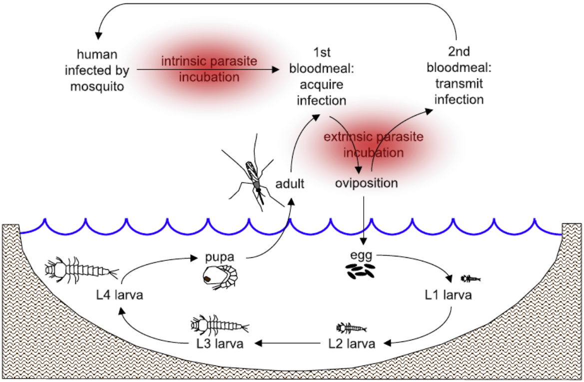
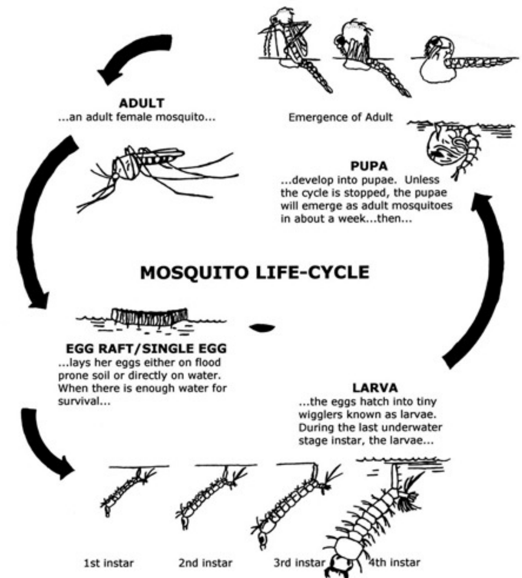


Figure: schematic of transmission cycle from Bomblies et al. 2008

What came first: the mosquito or the egg?



As temperature increases

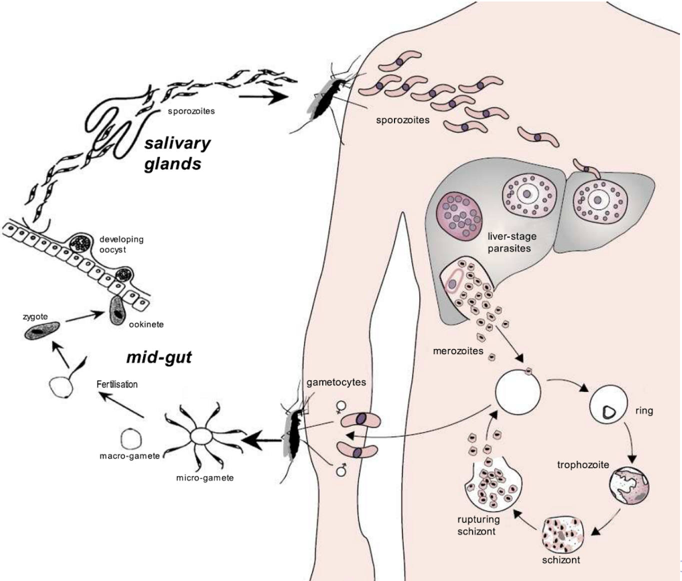
- Larvae development speeds up in warmer ponds
- Gonotrophic cycle: Eggs development in vector speeds up (Degree days concept)
- But high temperatures $> 39C$ kill vector
- And high water temperature $> 35C$ kill larvae

Cycle in host takes 10-26 days

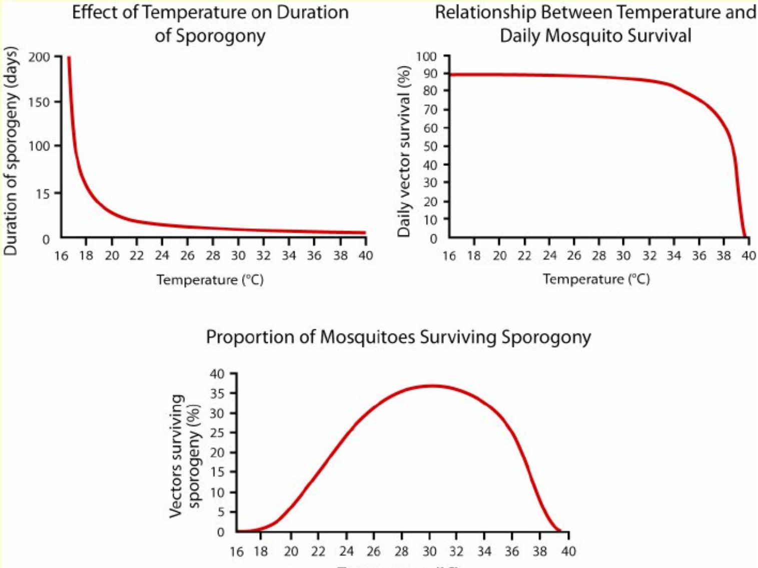
Sporogonic cycle

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%)



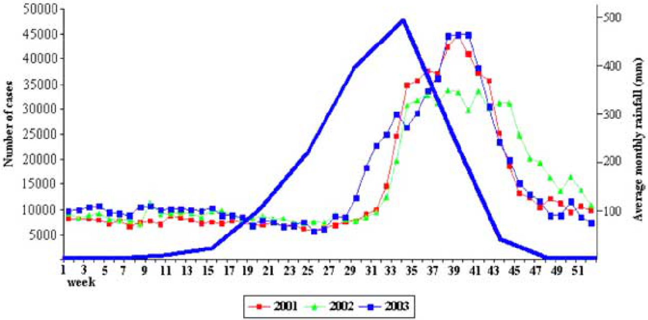
Sporogonic cycle



Rainfall

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

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



Blue - Rainfall
Dots - Malaria cases in 3 seasons

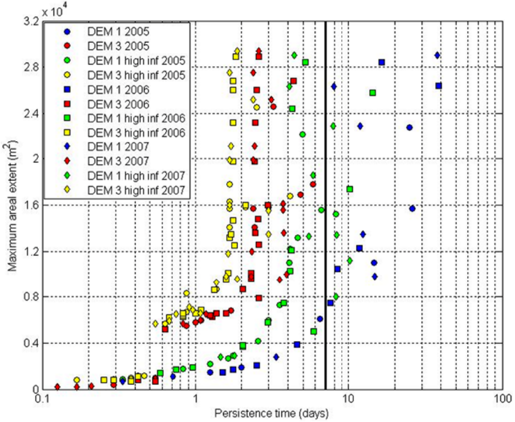
Breeding sites in Kumasi taken by E. Asare

Bomblies et al. (2009) Pond in S.W. Niger

pond persistence

Pond persistence times depends on the size, evaporation, and infiltration rates (which also depend on the size due to clogging).

Gianotti et al. (2009):



Diversity of breeding sites

Identifying the most productive breeding sites for malaria mosquitoes in The Gambia

Ulrike Fillinger*[1], Heleen Sombroek[2,3], Silas Majambere[4], Emiel van Loon[3], Willem Takken[2] and Steven W Lindsay[1]

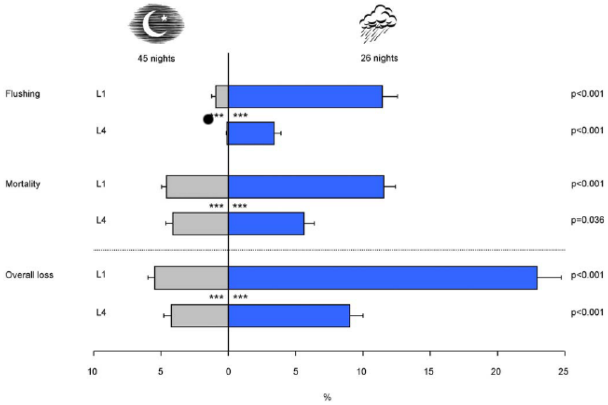
Table 3: *Anopheles* larvae species composition per habitat type

Habitat type	Total number of larvae sampled	Proportion of larvae identified in % (n)	*Anopheles* species composition based on identified specimen in %						
			gambiae s.l.	*gambiae s.s.**	*arabiensis**	*melas**	*coustani*	*pharaoensis*	*others*
Floodwater (n = 22)	95	34.7 (33)	21.2	6.1	0.0	15.2	30.3	18.2	30.3
Rice field (n = 21)	71	32.4 (23)	17.4	0.0	17.4	0.0	47.8	8.7	26.1
Stream fringe (n = 15)	76	39.5 (30)	10.0	6.7	3.3	0.0	53.3	20.0	16.7
Pool (n = 15)	213	21.1 (45)	53.3	6.7	46.7	0.0	28.9	11.1	6.7
Puddle (n = 6)	158	20.3 (32)	87.5	3.1	81.3	3.1	6.3	0.0	6.3
Man-made pits (n = 4)	95	16.8 (16)	87.5	6.3	75.0	6.3	0.0	0.0	12.5

*species of the *An. gambiae* complex summarized under *An. gambiae* s.l.

flushing of small larvae

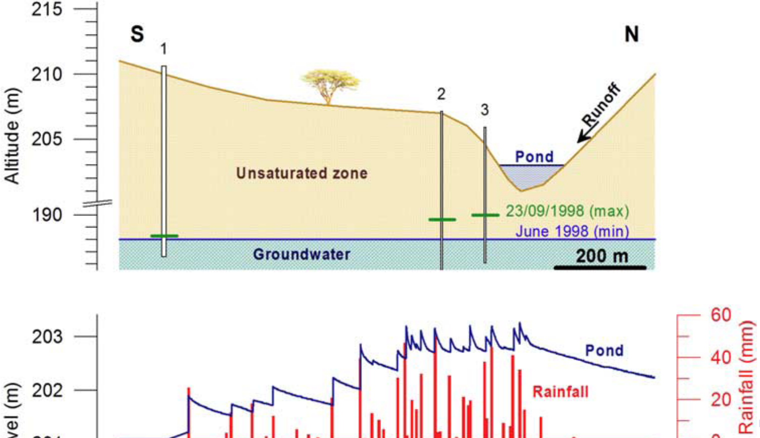
Intense rainfall cause larvae death as a expontial function of larvae growth stage after *Paaijmans et al.*(2007):



Catchment scales

A number of studies from the HARPEX-SAHEL and AMMA campaigns highlights the small km-scale of these depressions that collect run off into m-scale pools.

Favreau et al. 2009:



Relationship highly nonlinear and complex

- Rivers/Lakes provide pools at edges, local hazard may increase in drought period.
- Ponds/puddles increase in number and size with rains
- However, heavy rain can flush out (L1) larvae (Paaijmans et al. 2007)
- Large (long lived) ponds only contain larvae at edge - wave action/ preditors
- Irrigation and rice cultivation?

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- Large (long lived) ponds only contain larvae at edge - wave action/ preditors
- Irrigation and rice cultivation?
- *Impact of irrigation on malaria in Africa: paddies paradox JN Ijumba, SW Lindsay:* Irrigation may increase risk in epidemic regions, but in endemic regions associated little change or reduction - endophilic and anthropophilic malaria vector *funestus Giles* by *An. arabiensi*, irrigation communities often have greater use of bednets, better access to improved healthcare).

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.

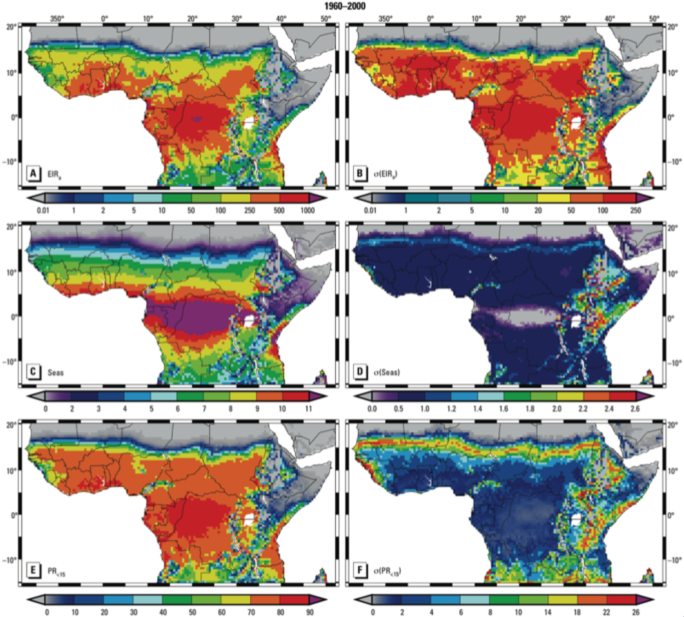
Liverpool Malaria Model LMM

- 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

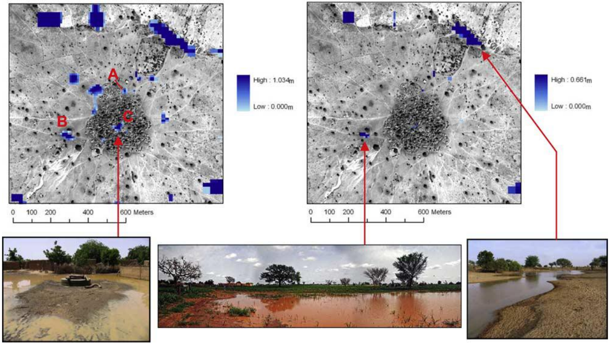
Bomblies model

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

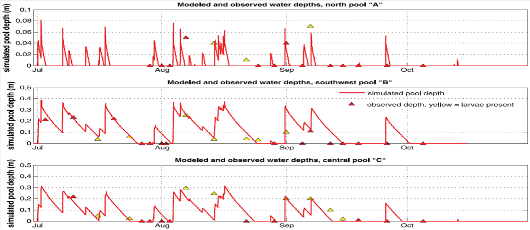
????



Example model simulation of present day malaria by Emert et al. EHP (2011)



Bomblies et al. 2008



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

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).

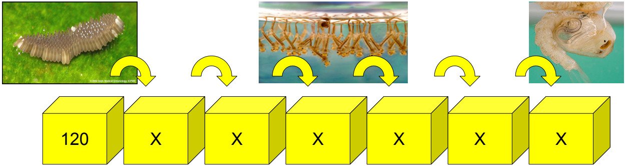
Uses:

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

Further info:

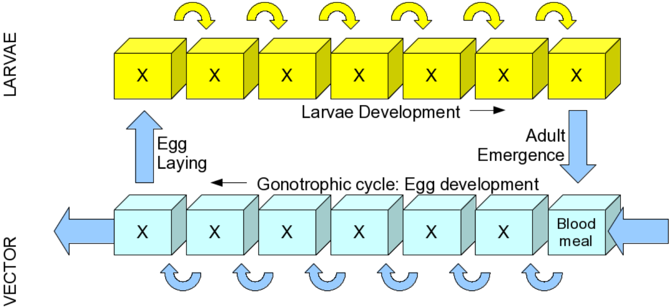
http://www.ictp.it/~tompkins/vectri Tompkins A.M. and Ermert V, 2013: *A regional-scale, high resolution dynamical malaria model that accounts for population density, climate and surface hydrology*, Mal. J., **DOI: 10.1186/1475-2875-12-65**

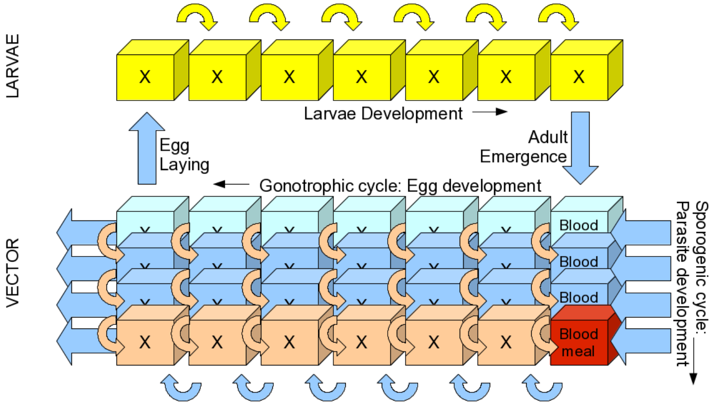
The larvae lifecycle is divided into stages or "bins". Each model timestep, larvae 'progress' from left to right, with the rate determined by temperature.



Larvae Development

We now add the subclasses for the vector gonotrophic cycle.




LARVAE
X
X
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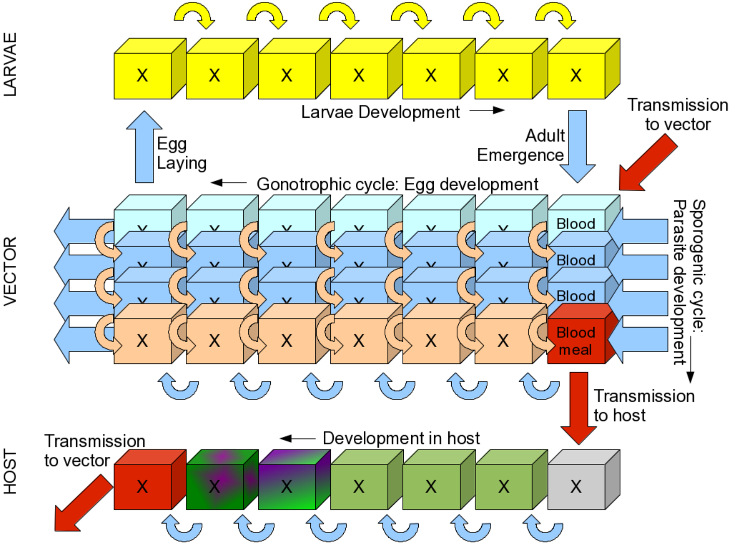
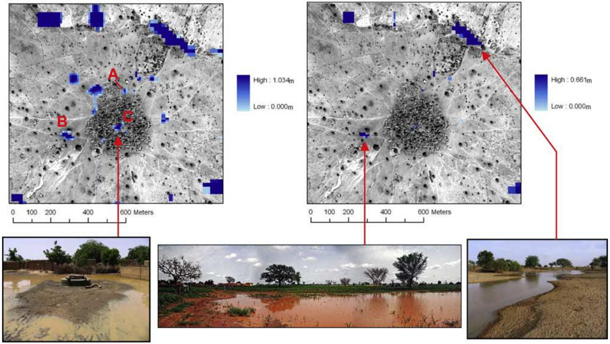
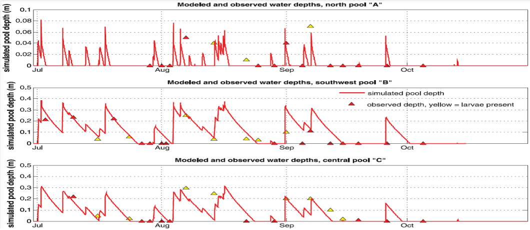
X
X
X
X
Larvae Development
Egg
Laying
Adult
Emergence
Gonotrophic cycle: Egg development
VECTOR
Blood
Blood
Blood
Blood
meal
X
X
X
X
X
X
Sporogenic cycle:
Parasite development

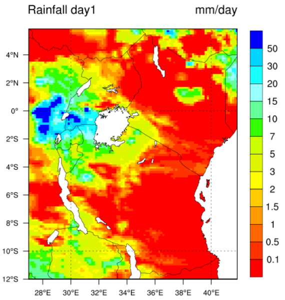

LARVAE
VECTOR
HOST
Larvae Development
Transmission
to vector
Adult
Emergence
Egg
Laying
Gonotrophic cycle: Egg development
Blood
Blood
Blood
Blood
meal
Sporogenic cycle:
Parasite development
Transmission
to host
Development in host
Transmission
to vector

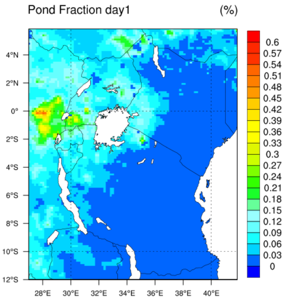


Bomblies et al. 2008



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





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.

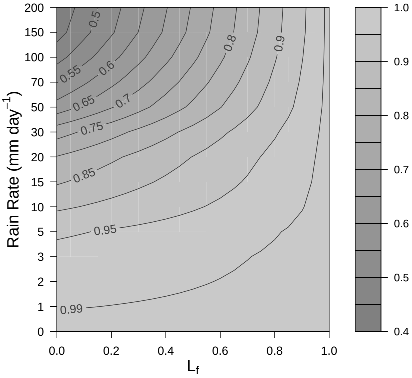
The rate of change of fractional pond coverage w_{pond} is given by

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

- 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)

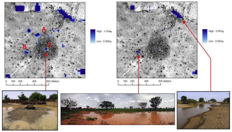
vectri flushing

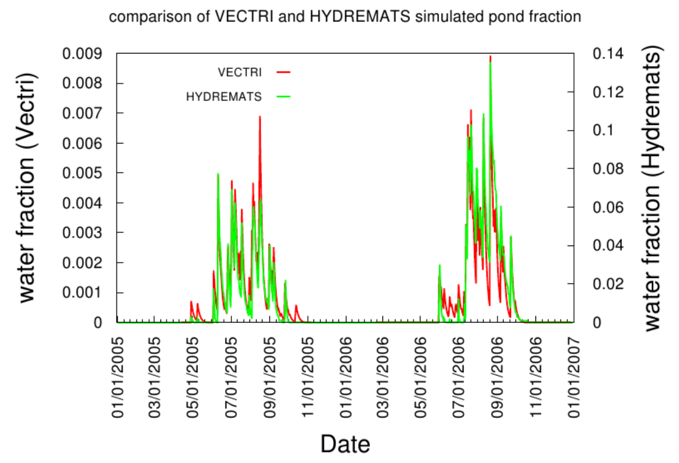
Flushing represented as simply as possible, with the effect increasing linearly with larvae mass, and an e-folding flushing rain rate set to 50 mm/day to approximate Paaijmans et al.



vectri Comparison to Bomblies

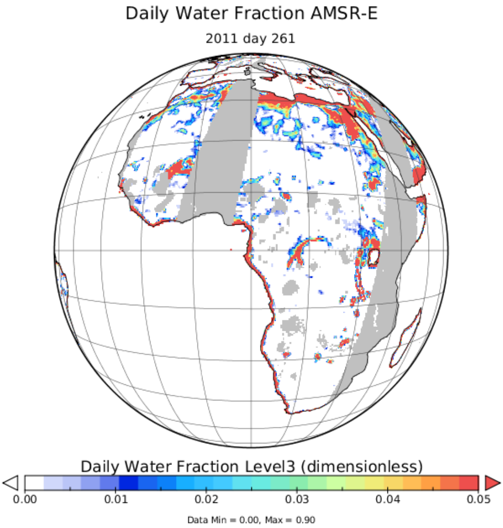
The two year integration of Hydremats at 10m resolution compared to VECTRI runs (Asare, Tompkins and Bomblies, 2013).





Use of TRMM similar, next step to evaluate with AMSR-E.

Use of AMSR-E


Daily Water Fraction AMSR-E
2011 day 261
Daily Water Fraction Level3 (dimensionless)
0.00
0.01
0.02
0.03
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0.05
Data Min = 0.00, Max = 0.90

Bayoh and Lindsay (2004) Survival tables for larvae of An. Gambiae s. s. taken from Lagos

Table 1. Summary of life table attributes of *Anopheles gambiae* larvae at different constant temperatures.

Temperature (°C)	Mean survival in days (95% confidence interval)	Range of larval mortality (days)	Proportion of terminal events occurring as larval mortality (%)
10	2.7 (2.6–2.8)	2–5	100.0
12	3.7 (3.6–3.9)	1–6	100.0
14	20.5 (19.3–21.8)	5–42	100.0
16	25.5 (24.4–26.5)	9–39	100.0
18	24.9 (23.8–26.2)	10–38	58.0
20	24.9 (23.6–26.4)	3–31	24.7
22	18.1 (17.5–18.6)	5–20	24.0
24	16.4 (15.9–16.8)	6–18	20.7
26	13.5 (13.2–13.9)	5–15	27.3
28	11.0 (10.6–11.4)	3–14	33.3
30	11.2 (10.8–11.5)	4–16	72.7
32	10.2 (9.9–10.5)	5–13	70.0
34	8.9 (8.5–9.3)	4–14	100.0
36	6.9 (6.8–7.2)	4–10	100.0
38	4.8 (4.6–4.9)	3–7	100.0
40	2.8 (2.6–2.9)	2–4	100.0

Water temperatures in Ghana

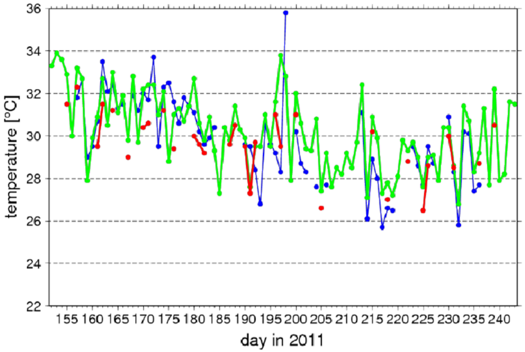
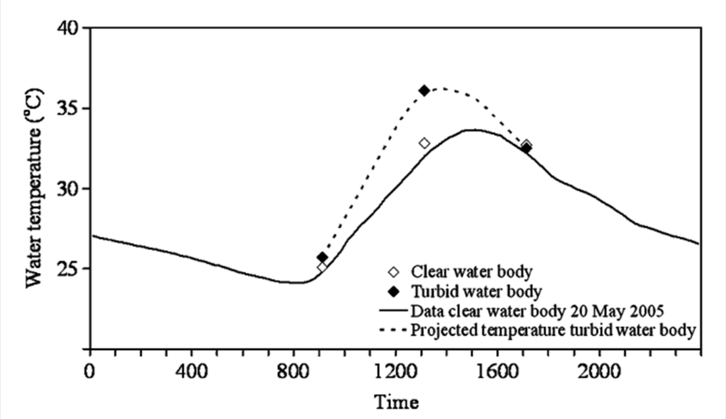


Figure 5: Water temperatures measured between June and August 2011 (Julian calendar) at 15 temporary water bodies within the Ayeduase and Kotei quarters of Kumasi during lunchtime (blue line and dots; 12:00-13:30 UTC) and maximum temperatures measured at the OwabiAWS (green line and dots) and at the Kumasi airport (red line and dots)

Water turbidity

The effect of water turbidity on the near-surface water temperature of larval habitats of the malaria mosquito *Anopheles gambiae*

K. P. Paaijmans · W. Takken · A. K. Githeko ·
A. F. G. Jacobs

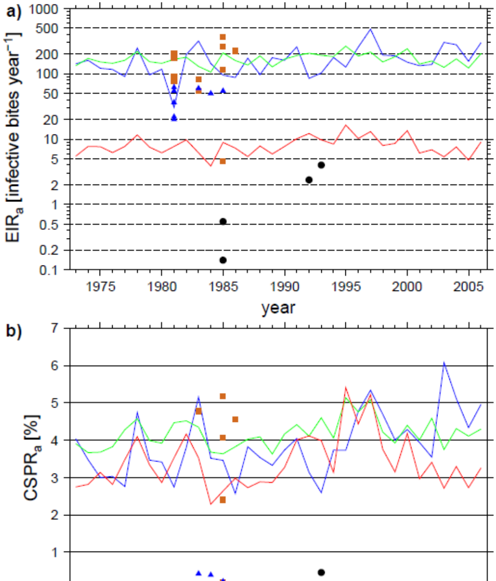


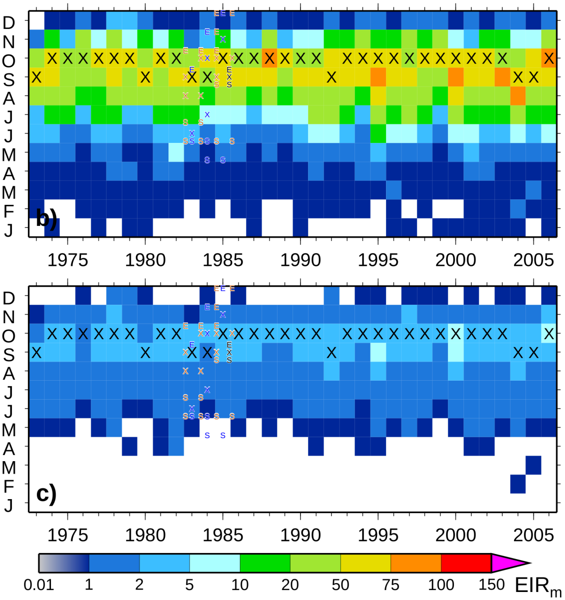
Turbidity affects the radiation balance and resulting peak temperatures

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).

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

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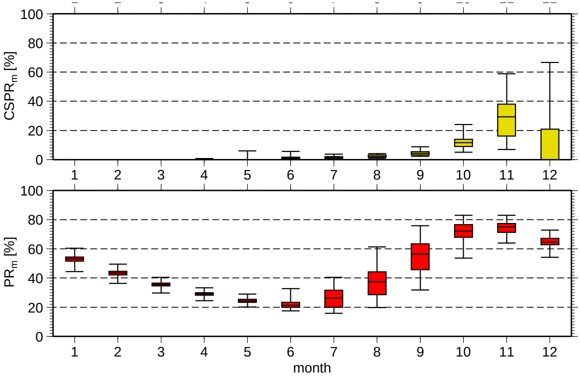
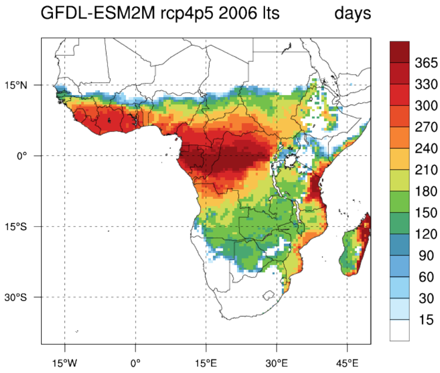
EIR_m

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

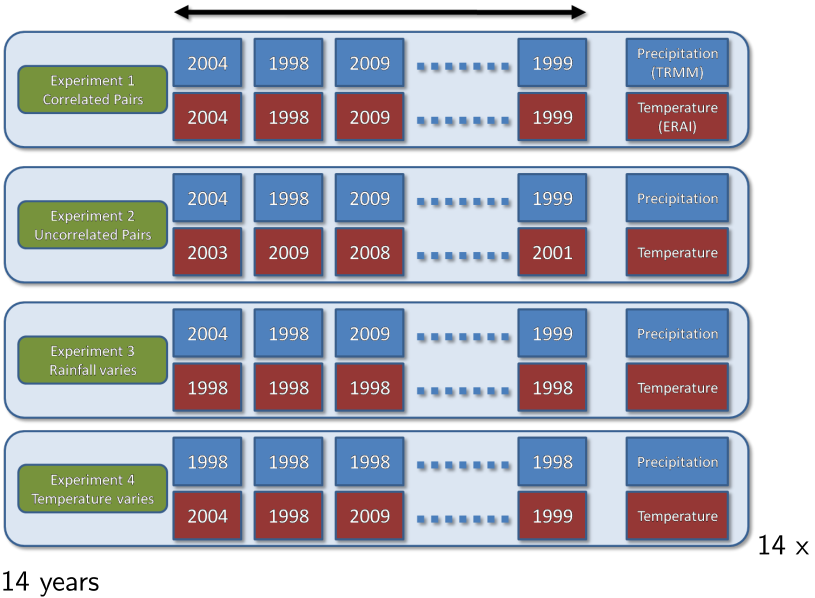
EIR=infectious bites pp per annum, PR=Parasite Ratio

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.





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


Experiment 1
Correlated Pairs
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2009
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Precipitation (TRMM)
2004
1998
2009
1999
Temperature (ERAI)
Experiment 2
Uncorrelated Pairs
2004
1998
2009
1999
Precipitation
2003
2009
2008
2001
Temperature
Experiment 3
Rainfall varies
2004
1998
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1999
Precipitation
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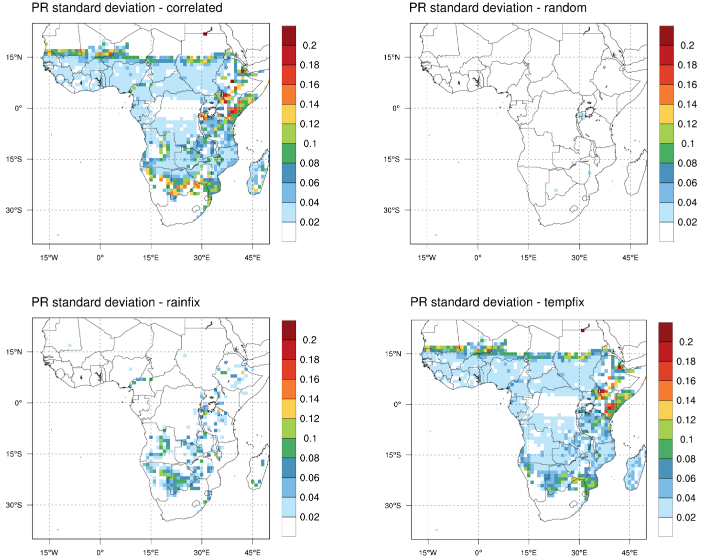
14 years


PR standard deviation - correlated
PR standard deviation - random
PR standard deviation - rainfix
PR standard deviation - tempfix
15°N
0°
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0.2
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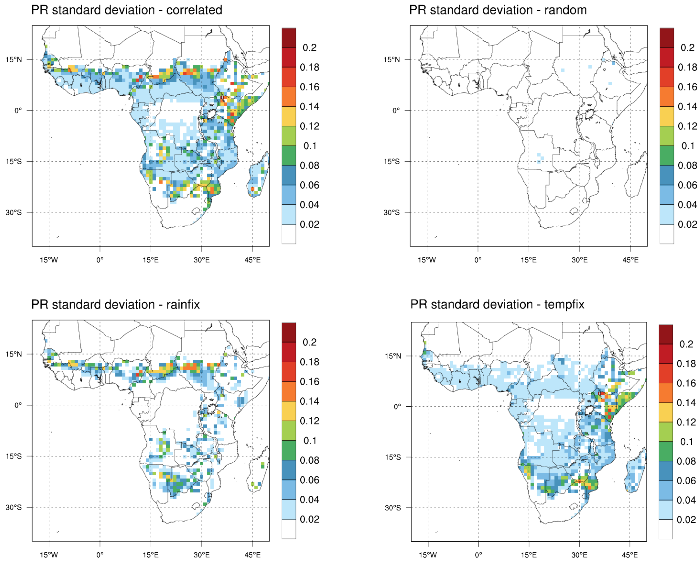
0.02

Bayoh and Lindsay (2004) Survival tables for larvae of An. Gambiae s. s. taken from Lagos

Table 1. Summary of life table attributes of *Anopheles gambiae* larvae at different constant temperatures.

Temperature (°C)	Mean survival in days (95% confidence interval)	Range of larval mortality (days)	Proportion of terminal events occurring as larval mortality (%)
10	2.7 (2.6–2.8)	2–5	100.0
12	3.7 (3.6–3.9)	1–6	100.0
14	20.5 (19.3–21.8)	5–42	100.0
16	25.5 (24.4–26.5)	9–39	100.0
18	24.9 (23.8–26.2)	10–38	58.0
20	24.9 (23.6–26.4)	3–31	24.7
22	18.1 (17.5–18.6)	5–20	24.0
24	16.4 (15.9–16.8)	6–18	20.7
26	13.5 (13.2–13.9)	5–15	27.3
28	11.0 (10.6–11.4)	3–14	33.3
30	11.2 (10.8–11.5)	4–16	72.7
32	10.2 (9.9–10.5)	5–13	70.0
34	8.9 (8.5–9.3)	4–14	100.0
36	6.9 (6.8–7.2)	4–10	100.0
38	4.8 (4.6–4.9)	3–7	100.0
40	2.8 (2.6–2.9)	2–4	100.0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PR standard deviation - random
PR standard deviation - rainfix
PR standard deviation - tempfix
15°N
0°
15°S
30°S
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30°E
45°E
0.2
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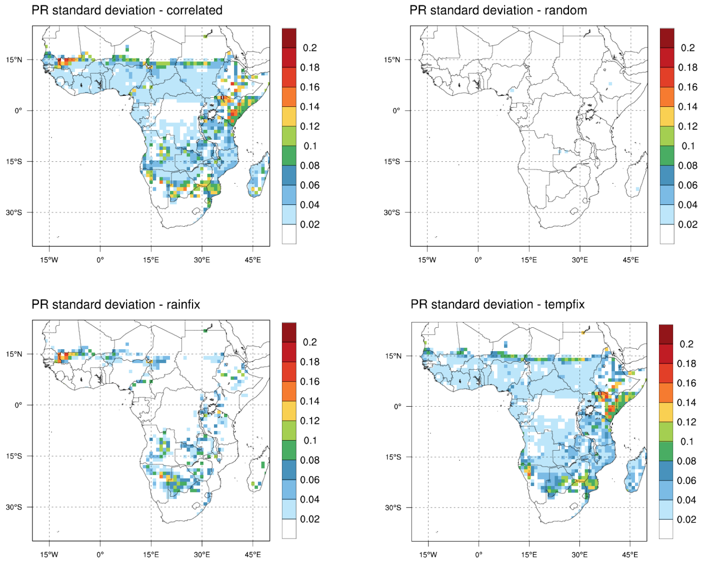
PR standard deviation - correlated
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15°N
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0.2
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0.14
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0.04
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- Hydrology very important for Malaria - defines general transmission season
- Complex Diverse relationships
- Permanent (Lakes, Dams, rivers, swamps) and temporary (pools, ponds, puddles) breeding sites
- Streams can provide more sites in drought conditions.
- Different preferences of breeding site according to vector species
- *Gambiae* prefers ponds and puddles
- timescale important, long enough for larva development, but short enough to avoid predators
- Irrigation and wetland cultivation complicated by socio-economic factors
- VECTRI dynamical model one the first regional malaria models to incorporate simple hydrology of ponds
- Compares well to Bomblies, but soil texture, slope and further evaluation required.

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Volker Ermert, University of Cologne, Germany - advice on parametrization schemes and literature.
Arne bomblies, Wisconsin, USA - provision of hydremats output.