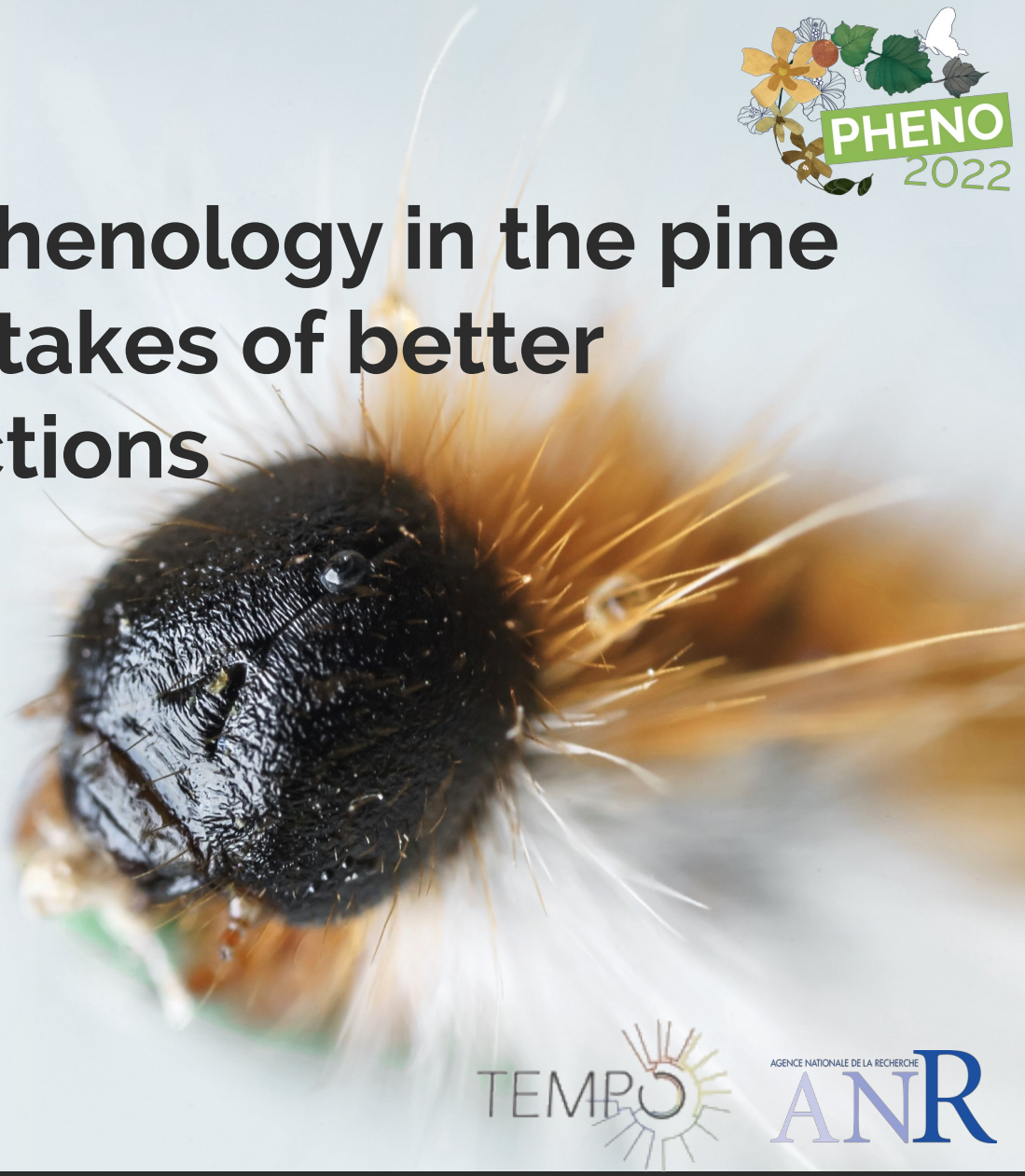
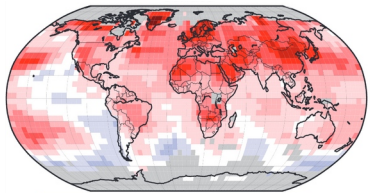
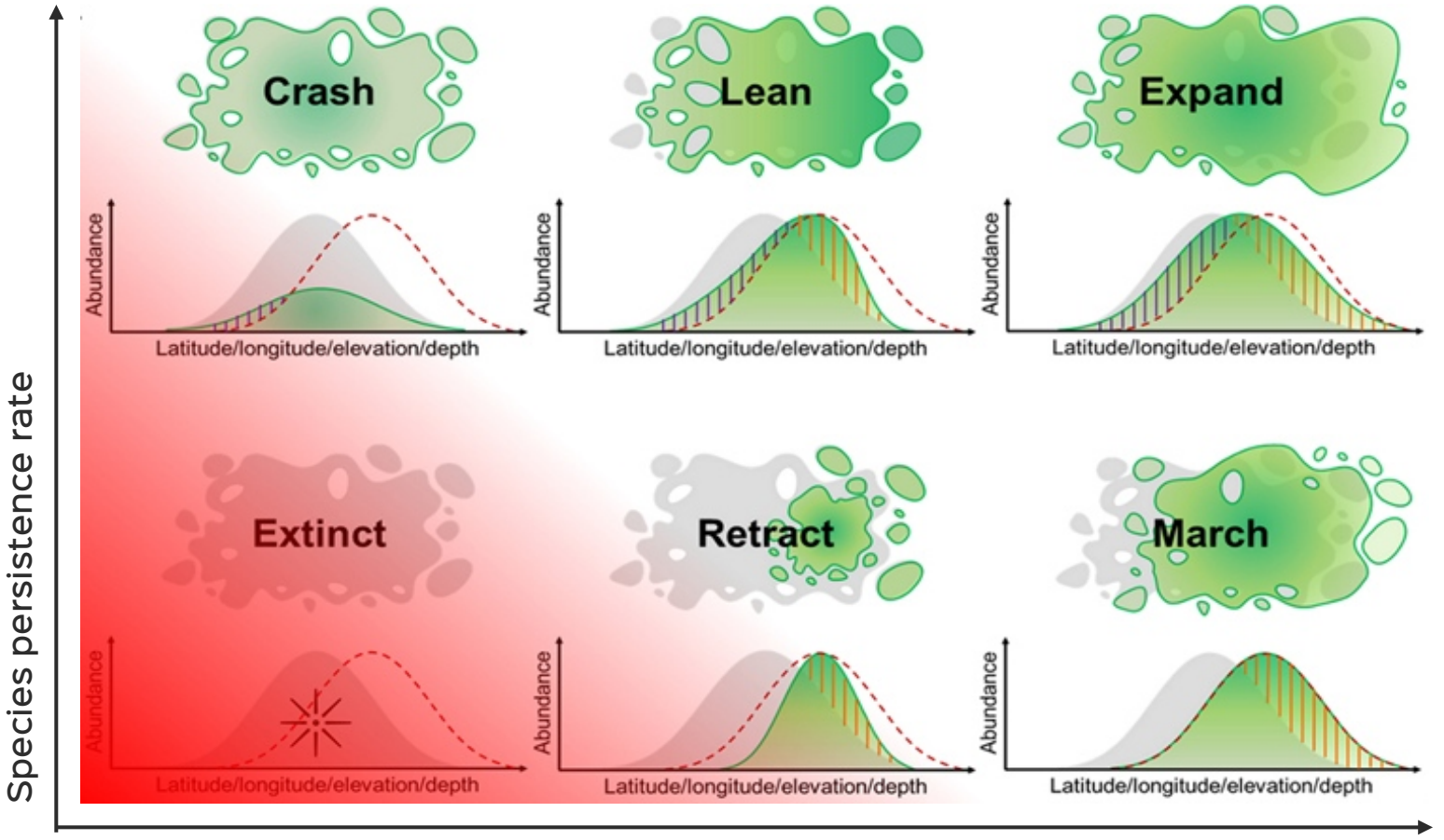
Climate change and phenology in the pine processionary moth: stakes of better monitoring and predictions



Mathieu Laparie, Laura Poitou, Jérôme Rousselet,
Sylvain Pincebourde, Christelle Suppo, Christelle Robinet

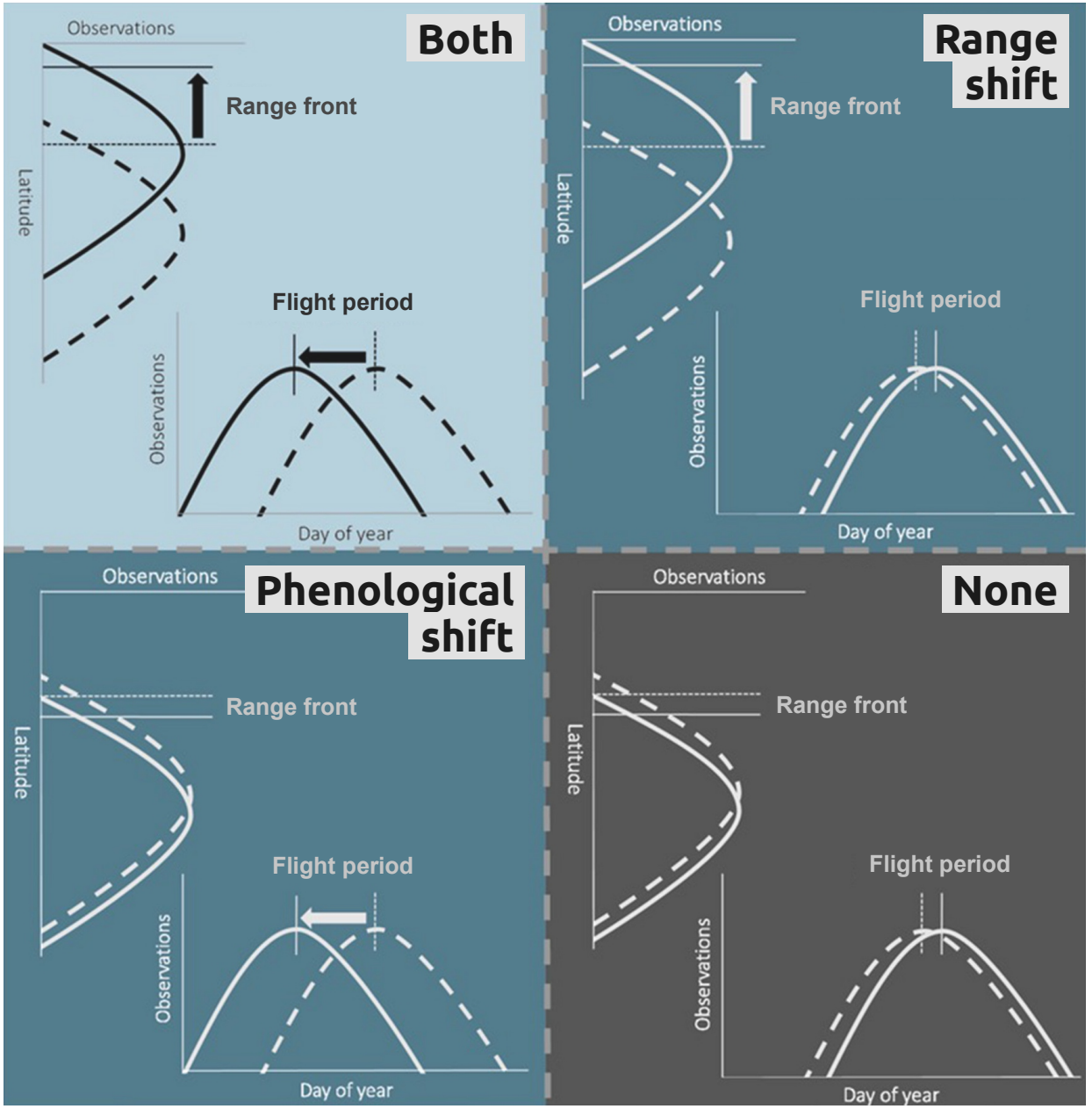


Climate change and range shifts



Lenoir & Svenning 2014

Spatial and time shifts are not mutually exclusive



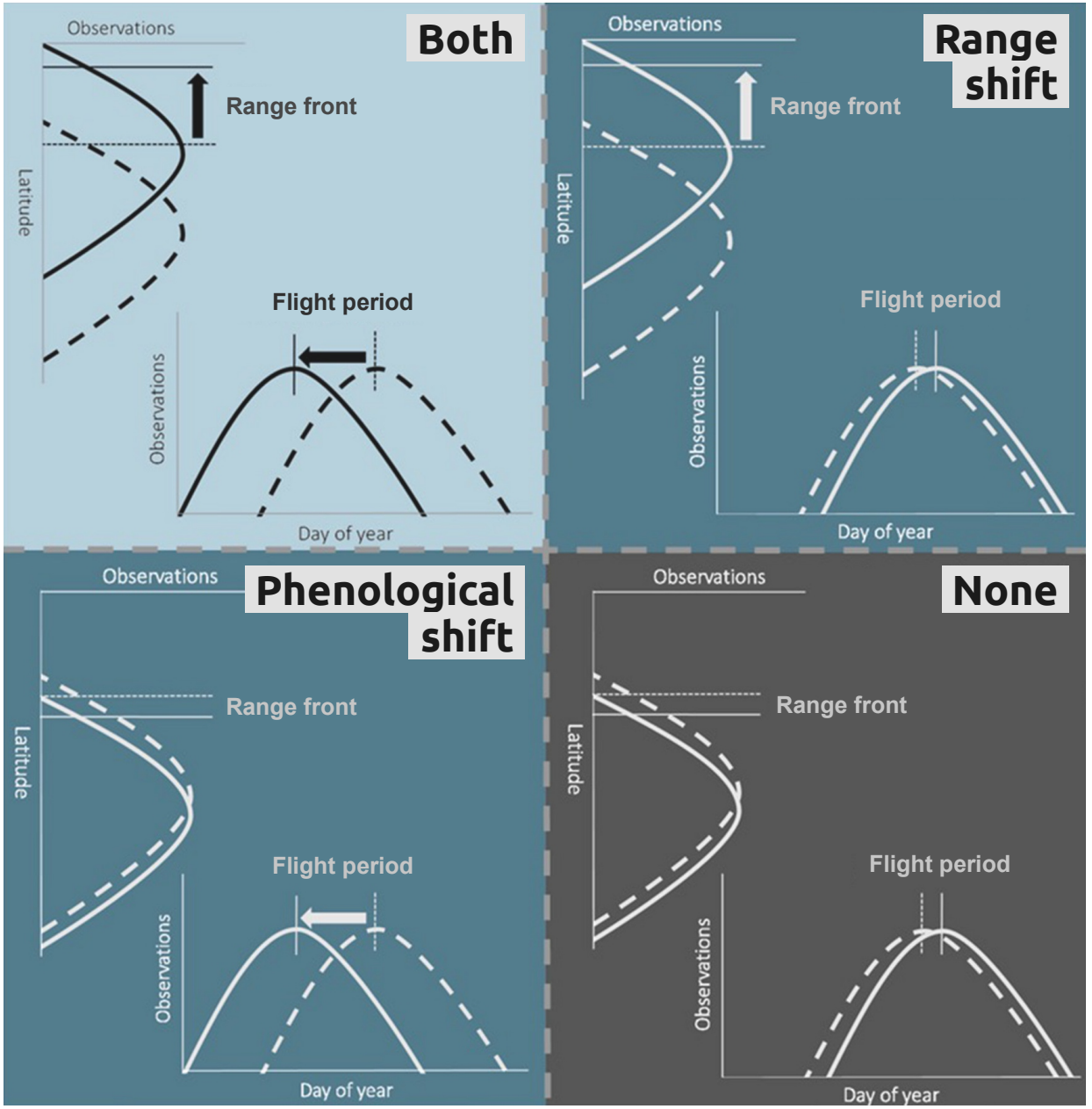
ECOLOGY LETTERS

Combining range and phenology shifts offers a winning strategy for boreal Lepidoptera

Maria H. Hällfors[1,2] | Juha Pöyry[3] | Janne Heliölä[3] | Ilmari Kohonen[4] | Mikko Kuussaari[3] | Reima Leinonen[5] | Reto Schmucki[6] | Pasi Sihvonen[4] | Marjo Saastamoinen[1,2,7]

Hällfors et al. 2022

Spatial and time shifts are not mutually exclusive



ECOLOGY LETTERS

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"Species can adapt to climate change by adjusting in situ or by dispersing to new areas, and these strategies may complement or enhance each other."

Hälifors et al. 2022

The pine processionary moth (PPM)

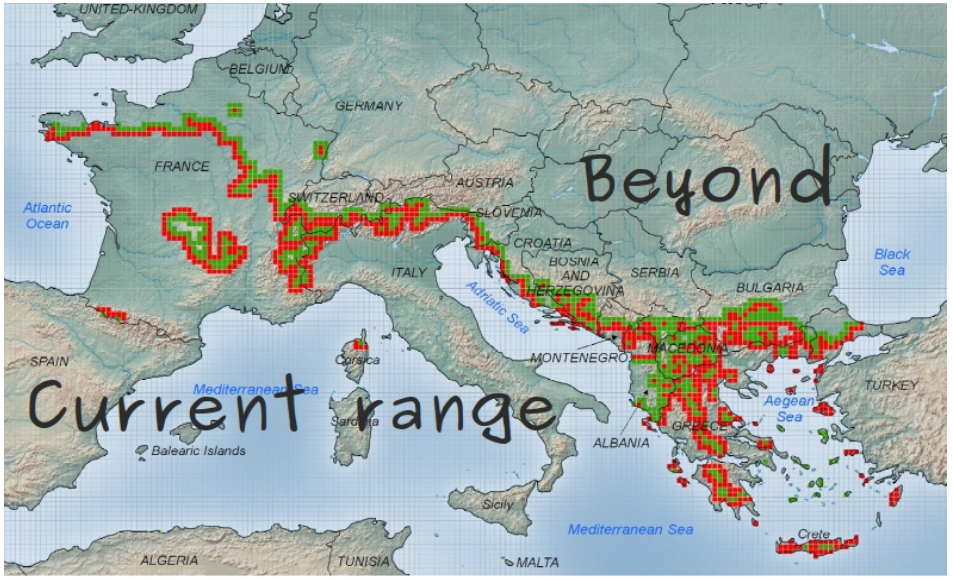
Thaumetopoea pityocampa

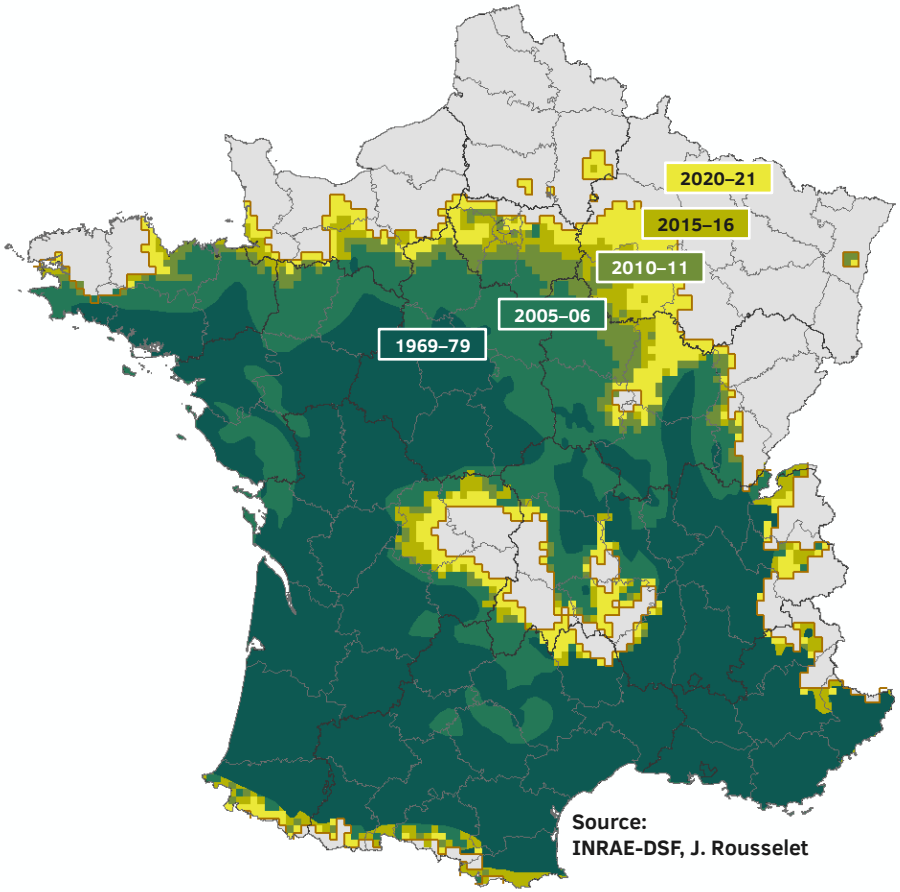
Range response to climate change well documented

Northern front determined in 2012 (16×16 km grid)

Known expansion history in France (8×8 km grid)

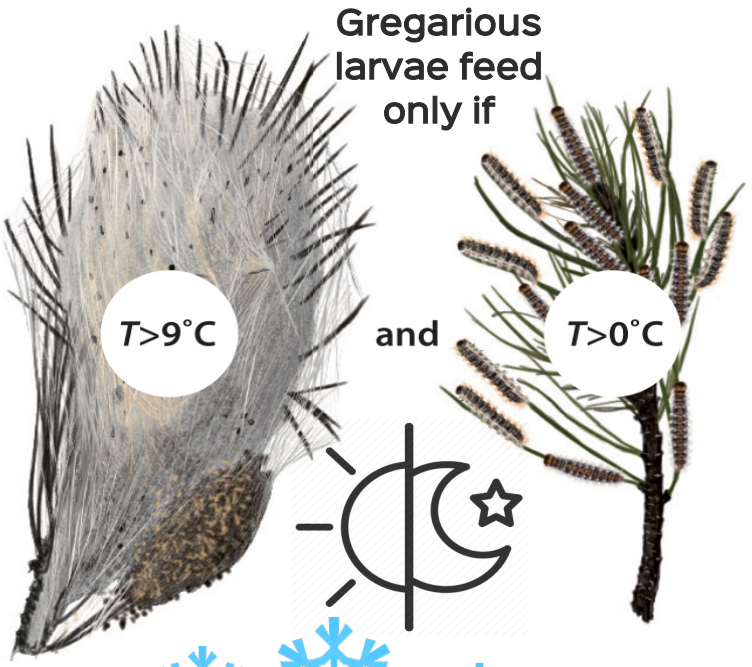
Phenology monitored in France since the 1970s



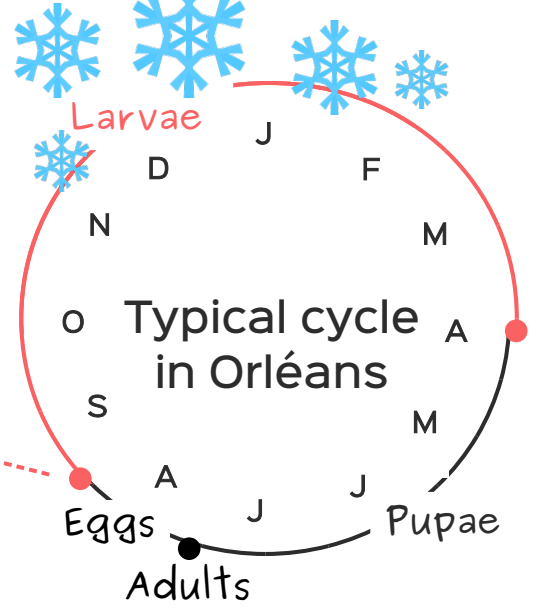


Battisi et al. 2006, 2017, Robinet et al. 2007, Robinet & Rousselet 2015, Rossi & Rousselet 2016

PPM larvae develop through winter



Newly hatched larvae

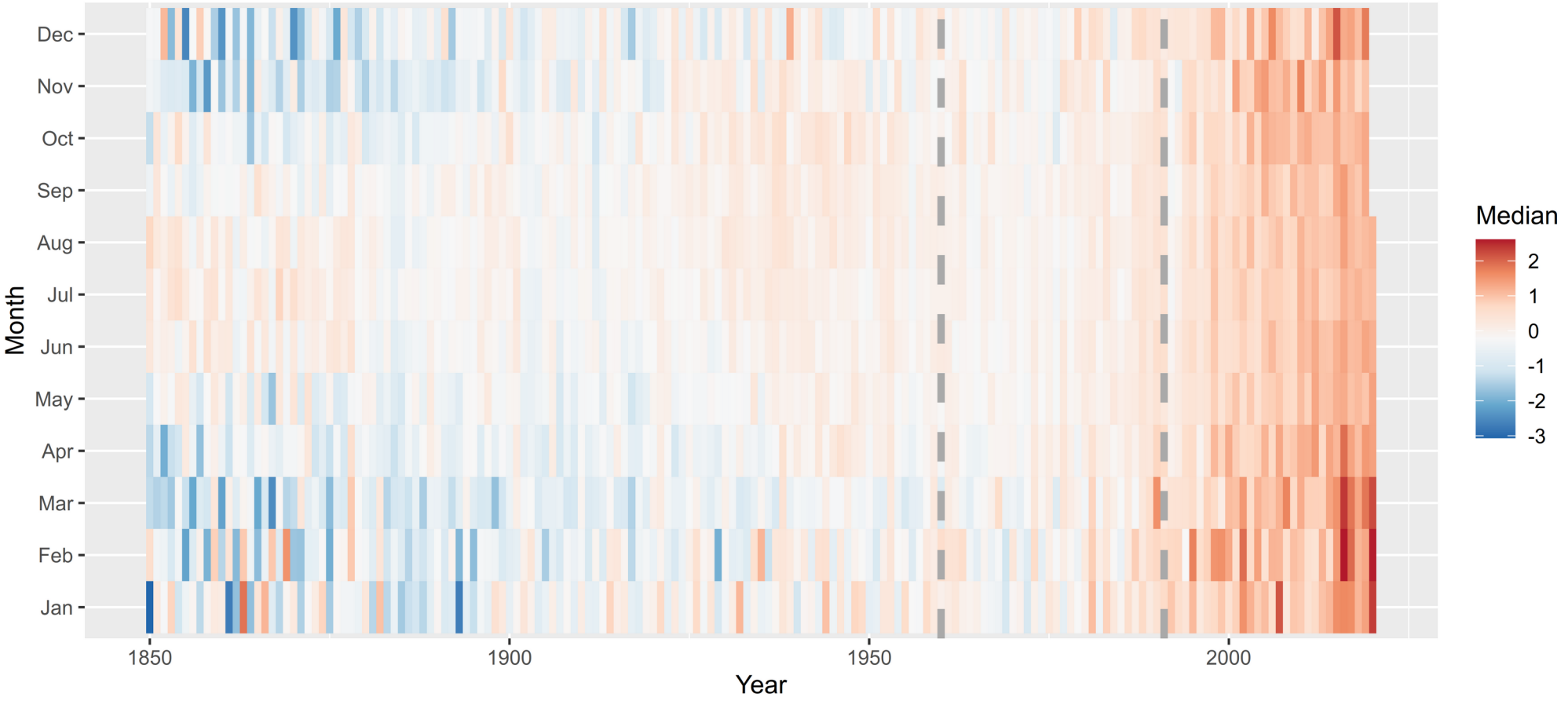


Battisi et al. 2005, 2017

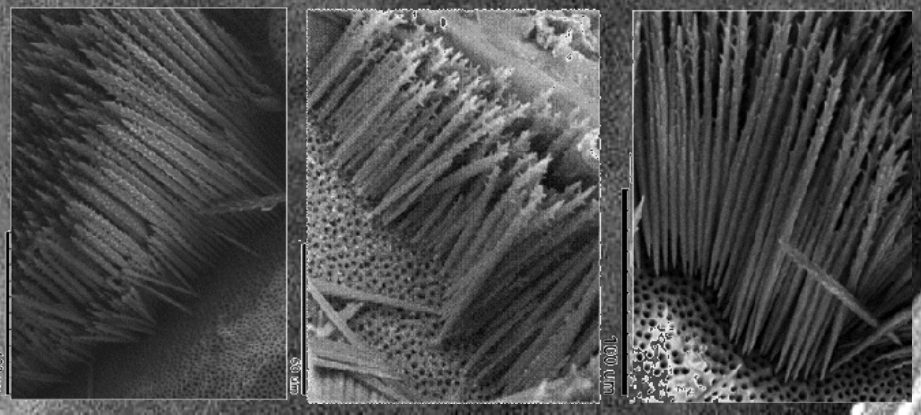
Winter warming in the Northern hemisphere

Land surface temperature anomalies relative to the 1960-1991 average, Northern hemisphere)

CRUTEM4 data



~1,000,000 per 5th instar larva

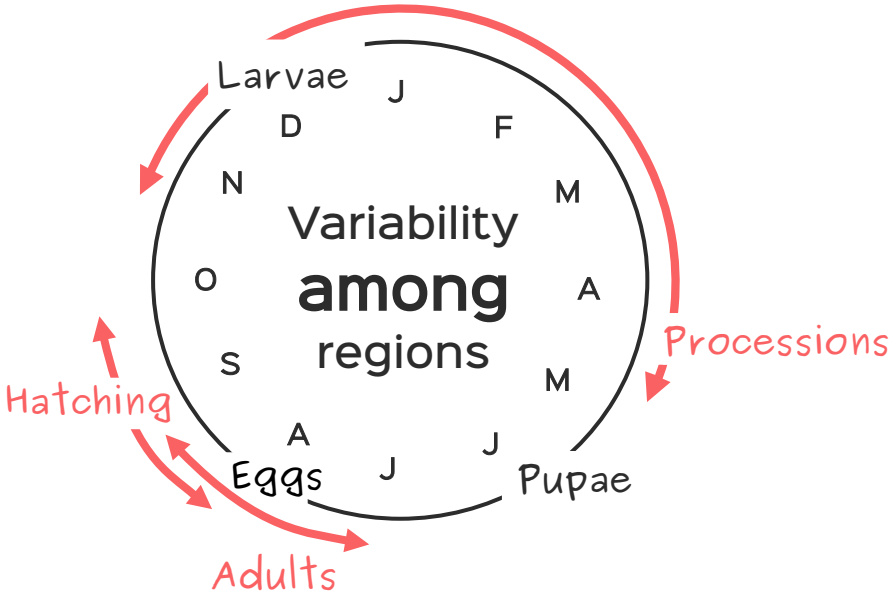


Toffolo et al. 2012, Rodriguez-Mahillo et al. 2012


VIVEONIS
BR-751-KR

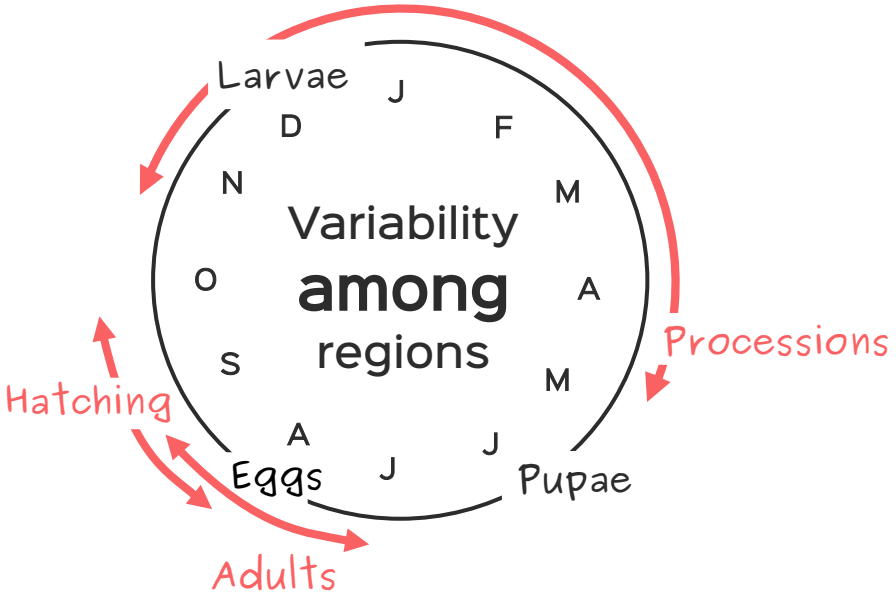
Pupation processions: high health hazard

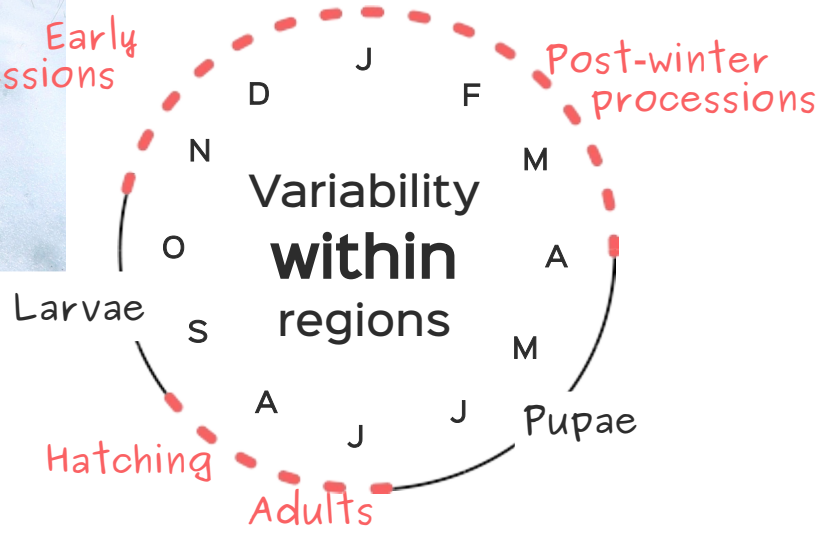
Problem: phenological variability



Battisti et al. in Roques (ed) 2015, Robinet et al. 2015

Problem: phenological variability

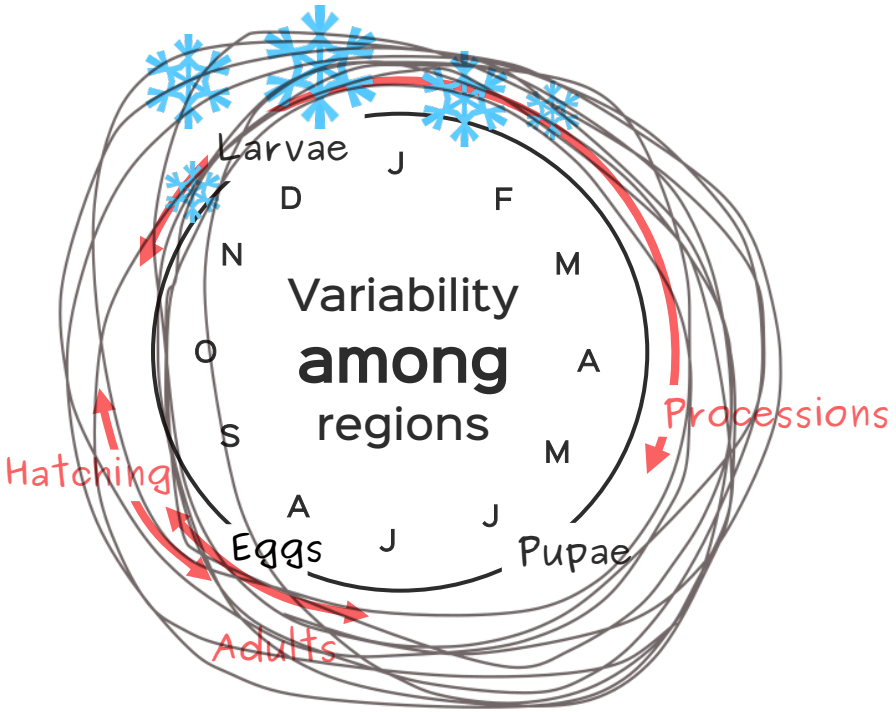


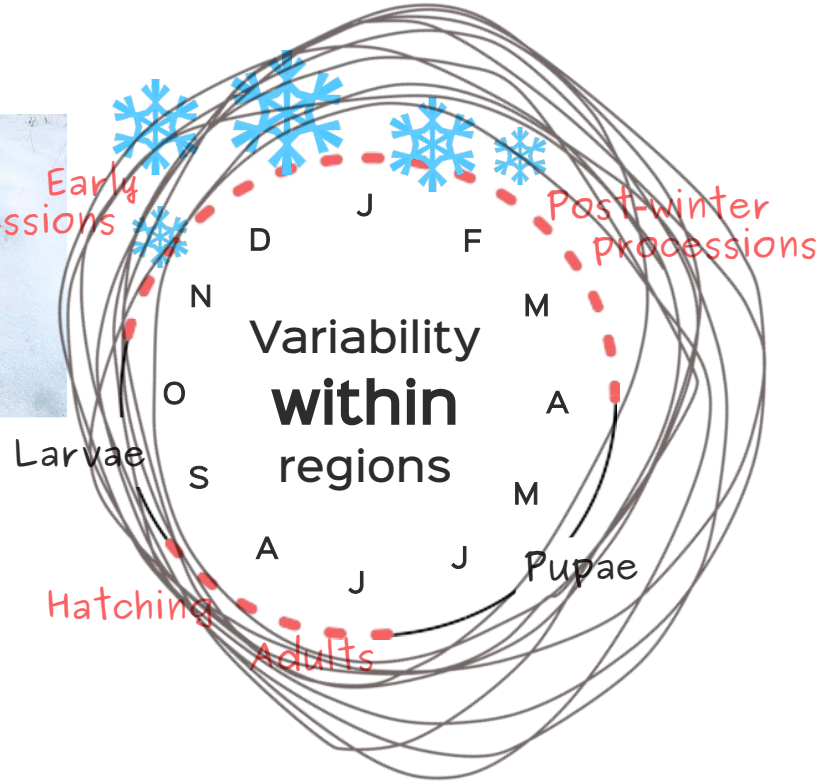


- prolonged and unpredictable urtication hazards
- difficult planning of stage-specific pest control

Battisti et al. in Roques (ed) 2015, Robinet et al. 2015

Problem: phenological variability





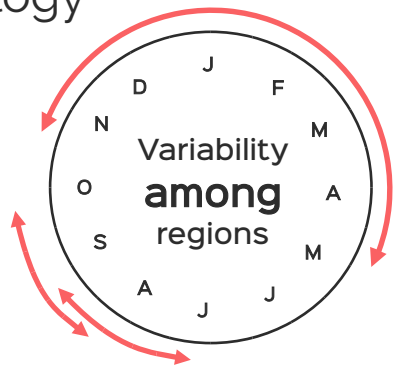
- prolonged and unpredictable urtication hazards
- difficult planning of stage-specific pest control
- extra variability due to prolonged diapause up to 9 years (bet-hedging)

Battisti et al. in Roques (ed) 2015, Robinet et al. 2015, Salman et al. 2019

Why modelling PPM larval phenology?

Laura Poitou's PhD project

Understanding spatial differences in phenology



Battisti et al. in Roques (ed) 2015, Robinet et al. 2015

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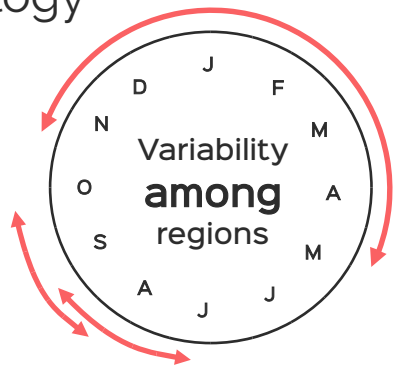
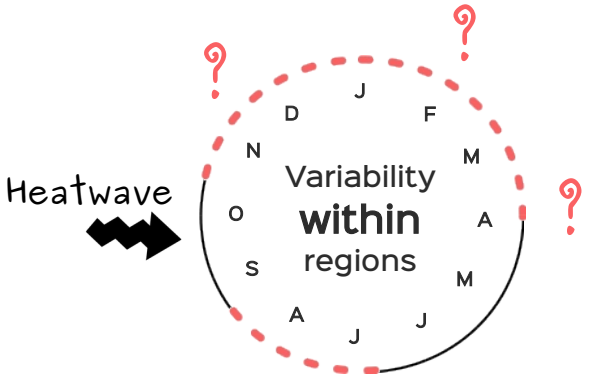
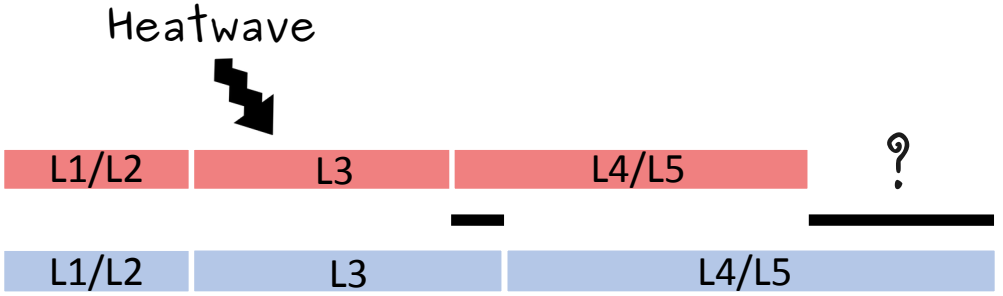


Predicting consequences of stochastic climatic events: lethality, cascading effects?





Model construction

1 Experimental data on development rate

Egg and larval cultures at multiple temperatures

2 Data analyses

Thermal performance equations

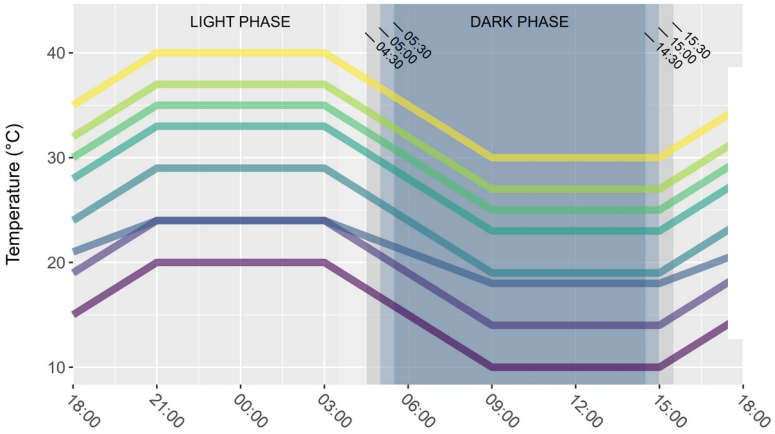
3 Modelling development

Percentage of larvae per instar per day

Model construction

Insect cultures at multiple temperatures

1 Experimental data on development rate



Mar-Jun — Collection of pupae

Mar-Jun — Adult rearing

Jul-Aug — Matings

Aug-Sep — Hatching monitoring at different temperatures

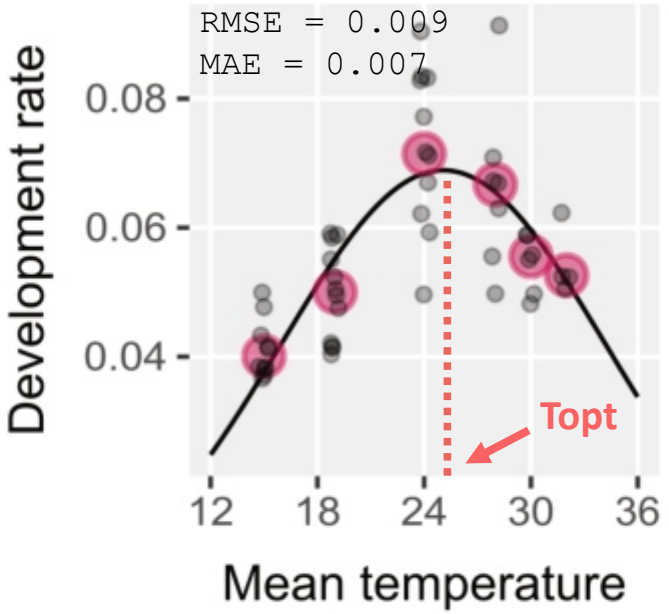
Sep-Dec — Insect cultures at different temperatures

Taylor_81
Analytis_77
beta_16
beta_95
bieri1_83
briere2_99
briere1_99
campbell_74
damos_08
damos_11
davidson_44
harcourtYee_82
hilbertLogan_83
janisch_32
kontodimas_4
lactrn1_95
lactrn2_95
lam_92
logan10_76
logan6_76
perf2_11
poly2
poly4
ratkowsky_82
ratkowsky_83
regniere_12
rootsq_82
schoolfieldHigh_81
schoolfieldLow_81
schoolfield_81
sharpeDeMicheke_77
shi_11
stinner_74
wagner_88
wangengel_98
wang_82

Model construction

Thermal performance equations

2 Data analyses



40 non-linear equations tested for each instar

Taylor selected using RMSE (*Root Mean Square Error*) and MAE (*Mean Absolute Error*)

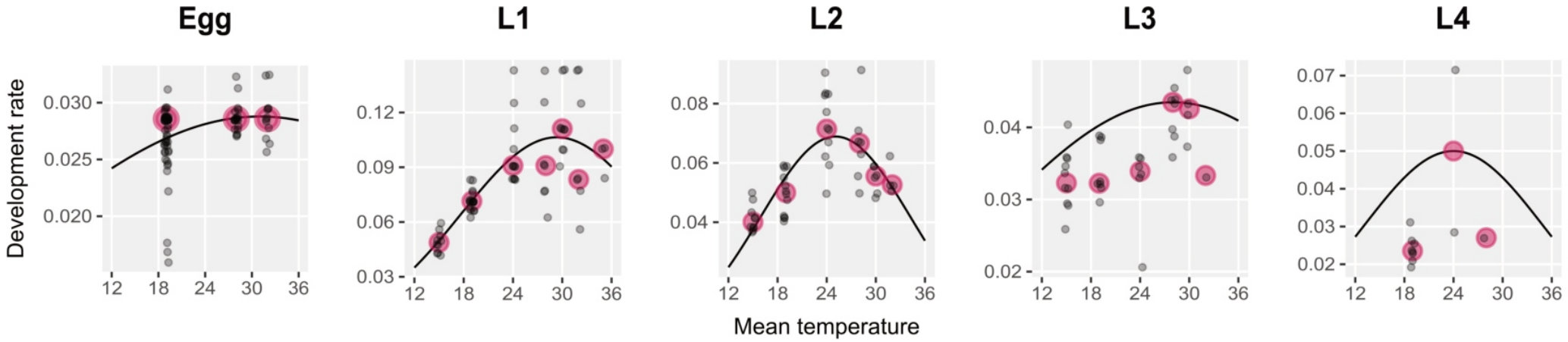
Parameters estiated using NLS (*Non-linear Least Squares*)

Rebaudo et al. 2018, Rebaudo & Rabhi 2018

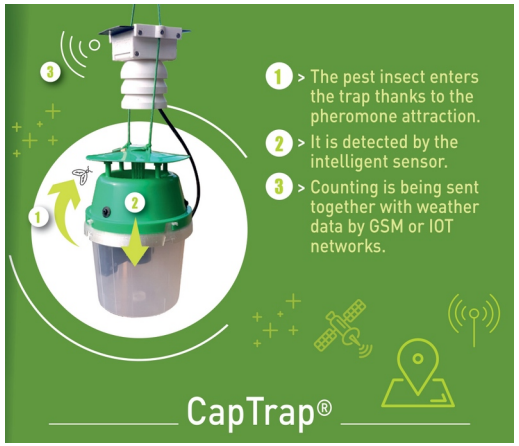
Model construction

Thermal performance equations

2 Data analyses

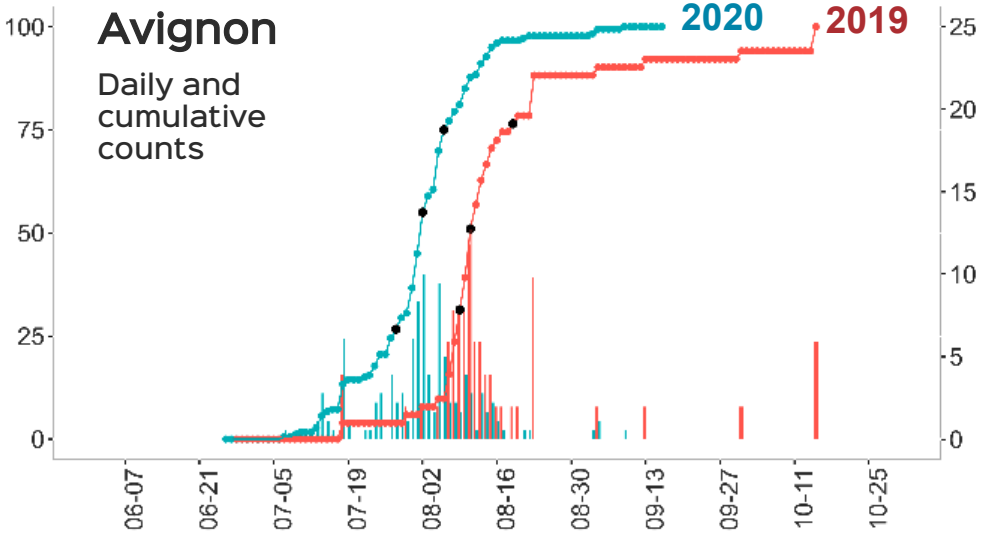


Rebaudo et al. 2018, Rebaudo & Rabhi 2018



Model construction

Development



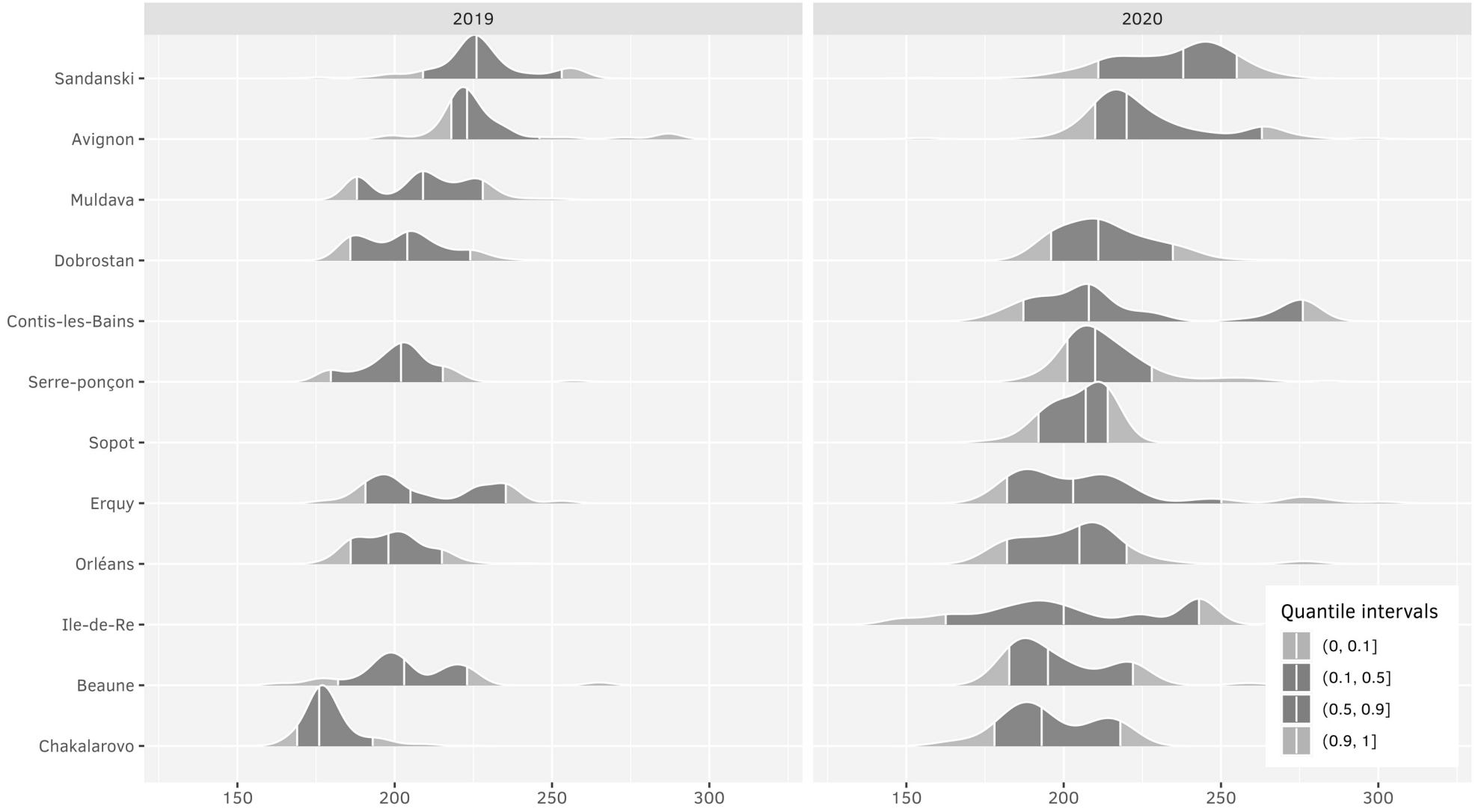
3 Modelling development

Inputs:
- flight monitoring (egg laying),
- air temperature

Outputs:
- beginning, end and average duration of instars,
- relative proportions of instars across time

Model construction

Development



Standardized flight curve for each site, sorted from earliest to latest flight peak (DOY)

Model construction

Development

Development rate is cumulated every day starting from egg laying. The instar is completed when development rate reaches 1.

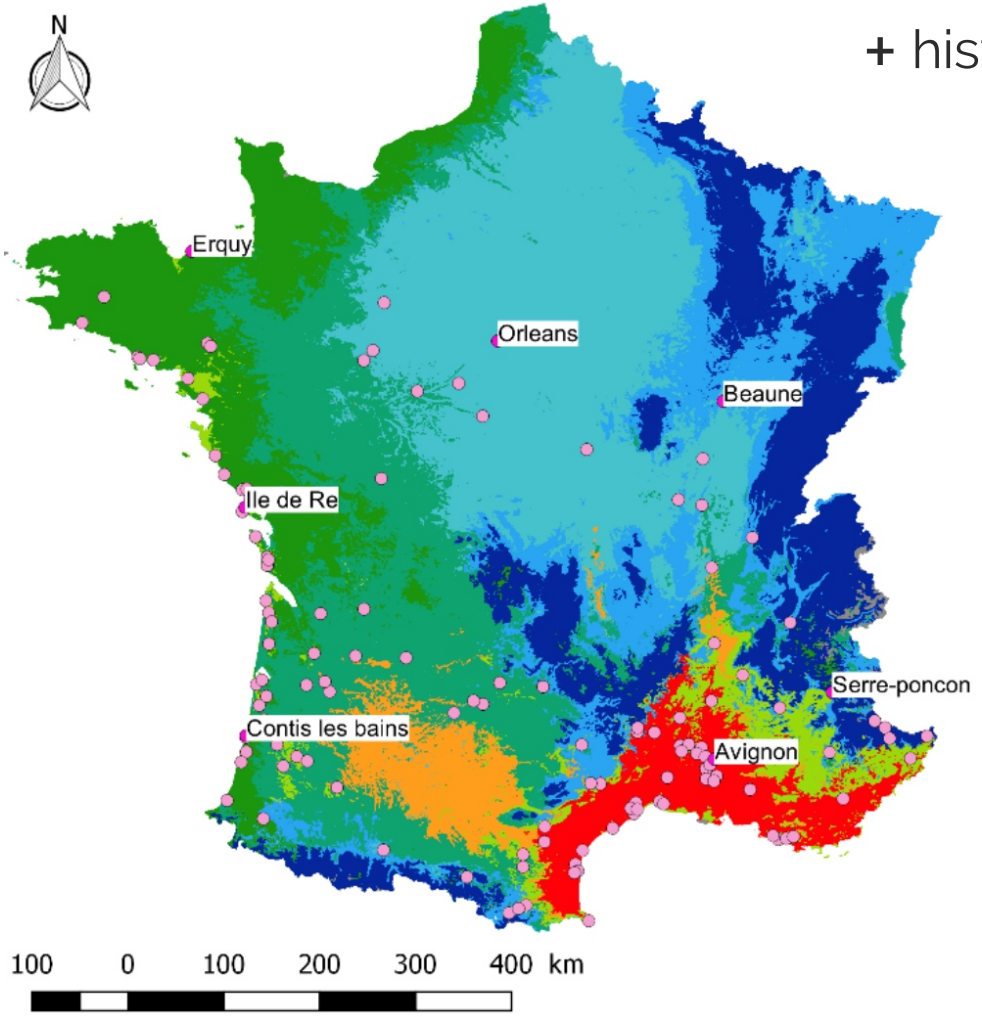
The same calculation is done for all prepupal stages with their respective equations.

The beginning, end, average duration of instars and their relative proportions each day are simulated.

Model validation

Simulations vs. observations

Actual larval phenology checked fortnightly on the field in 7 bioclimatic regions



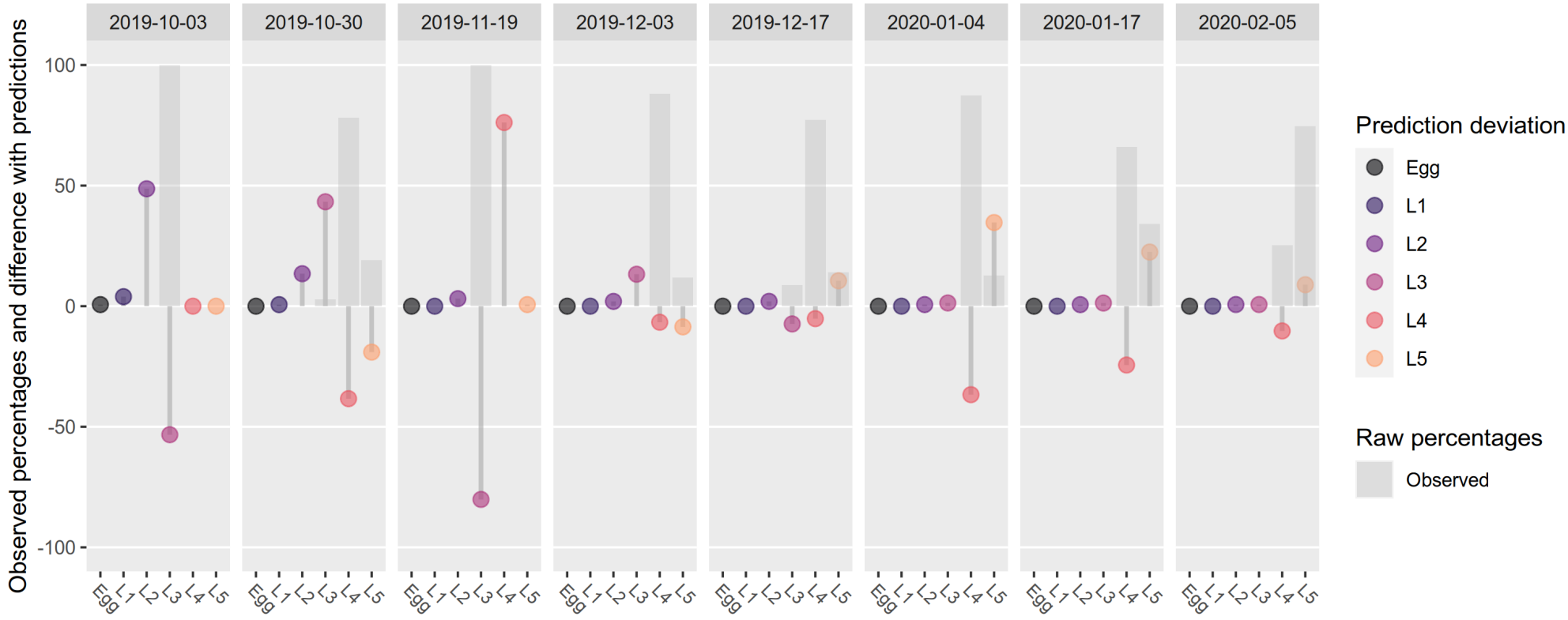
+ historic monitoring sites (processions only)

Model validation

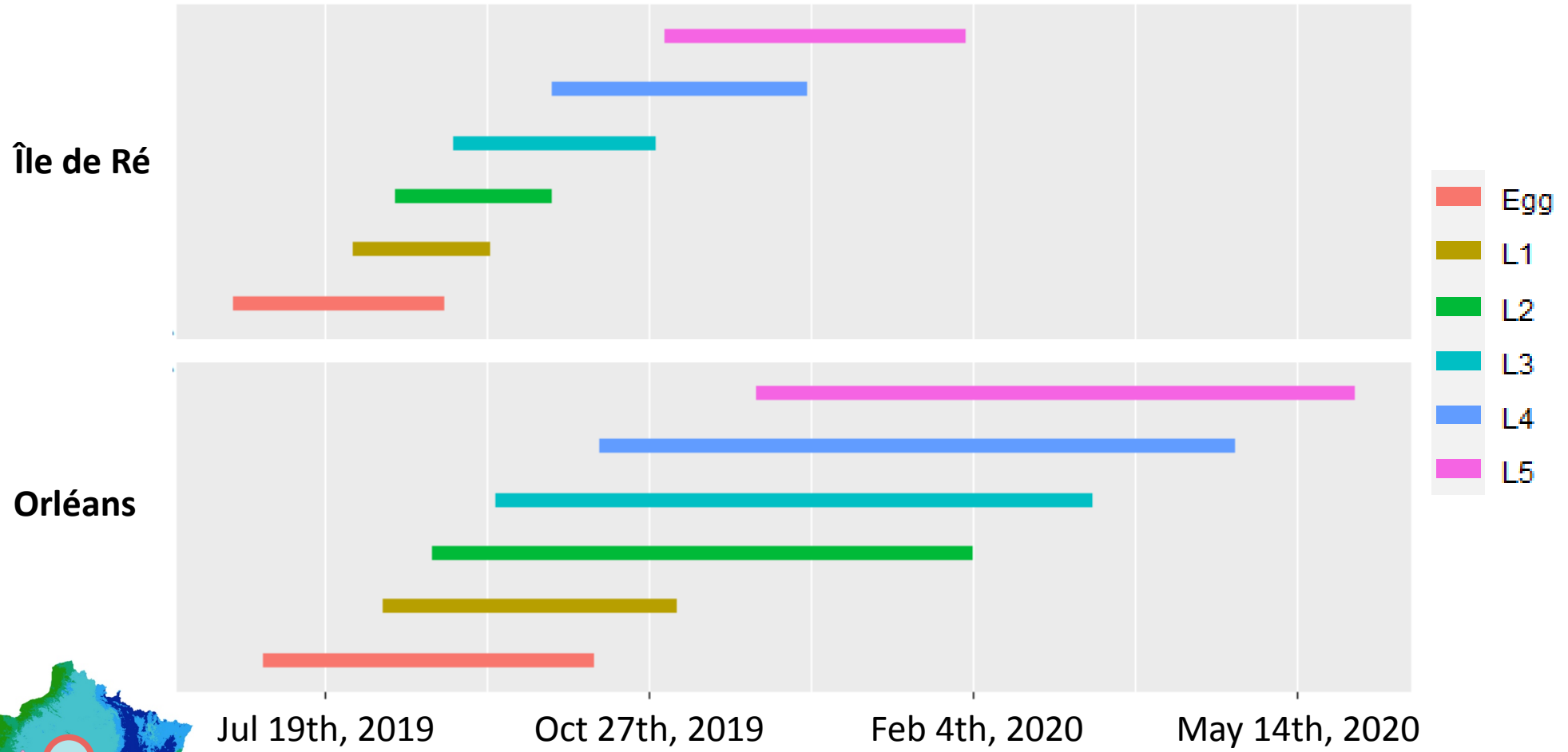
Simulations vs. observations

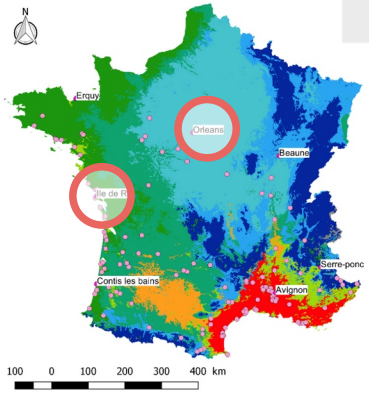
Actual larval phenology checked fortnightly on the field in 7 bioclimatic regions

e.g., Orléans



Inter- and intra-population variations are correctly simulated

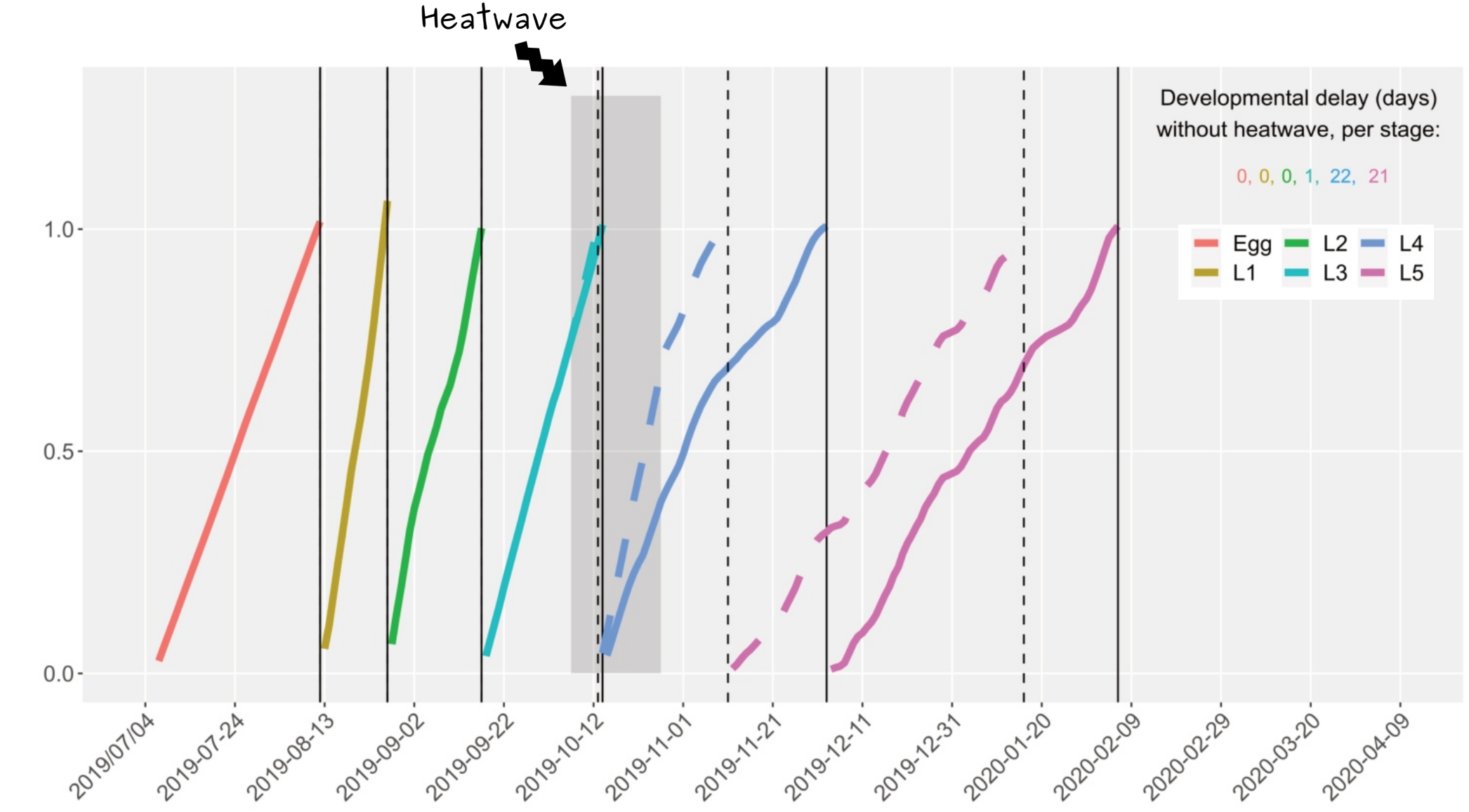




Pupation procession predicted from Dec. 18th to Feb. 2nd in **Île de Ré**
Pupation procession predicted from Jan. 27th to June 1st in **Orléans**

Poitou et al. 2021

Autumnal heatwaves: no cascading effects found (yet)



Poitou et al. 2022

Simulations under warmer and cooler scenarios

Delta in simulated conditions relative to meteorological records in Orléans:

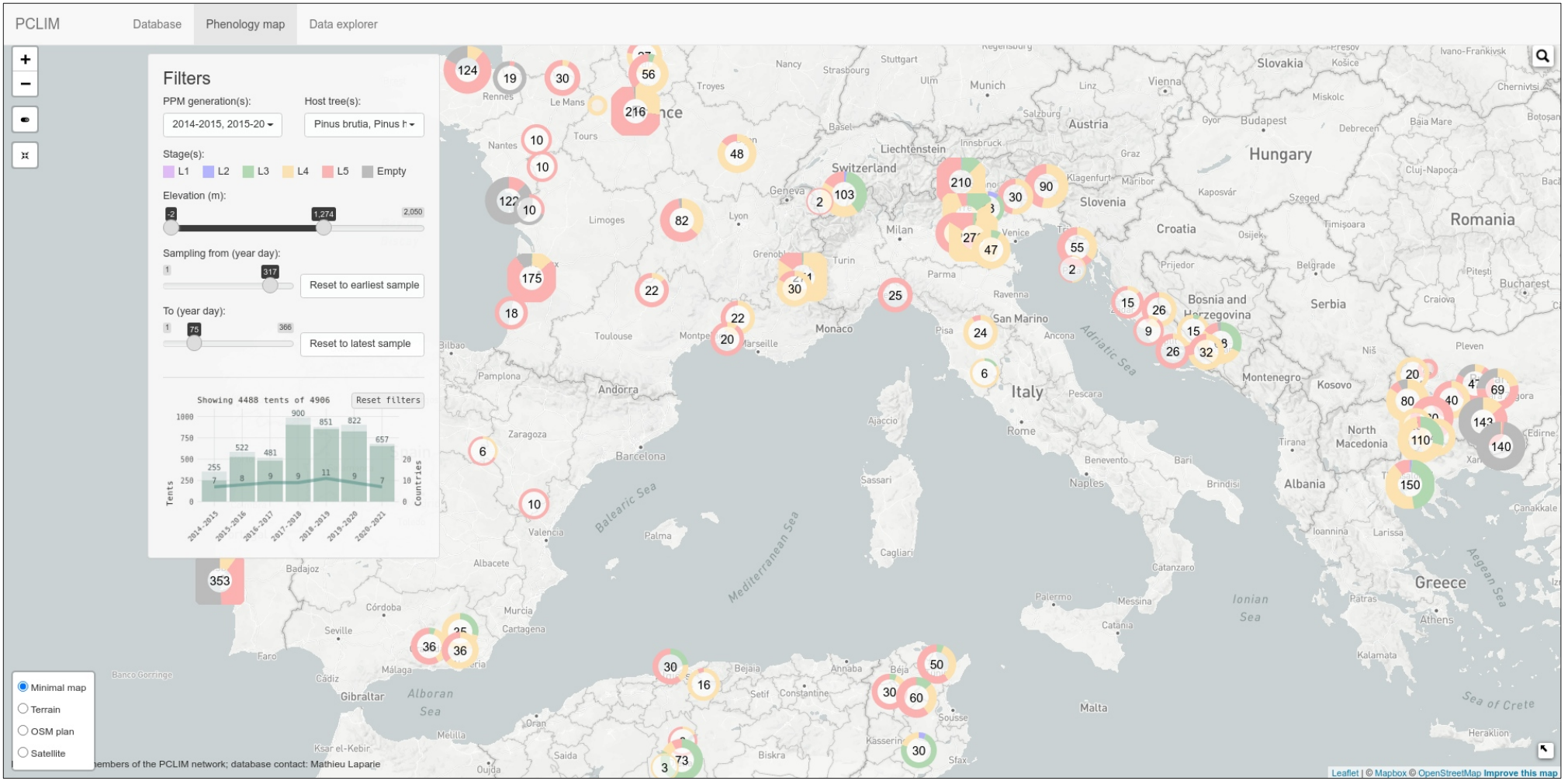
Scenario	Egg (days)	L1 (days)	L2 (days)	L3 (days)	L4 (days)	L5 (days)	Total (days)
−3°C	+2	+6	+39	+7	+23	−9	+68
−2°C	+1	+4	+17	+5	+20	−1	+46
−1°C	+1	+2	+7	+2	+10	+2	+24
+1°C	0	−1	−3	−2	−8	−5	−19
+2°C	0	−2	−6	−3	−16	−10	−37
+ 3°C	−1	−3	−8	−4	−22	−15	−53

Evidence of non-additive effects due the long cycle spanning multiple seasons.

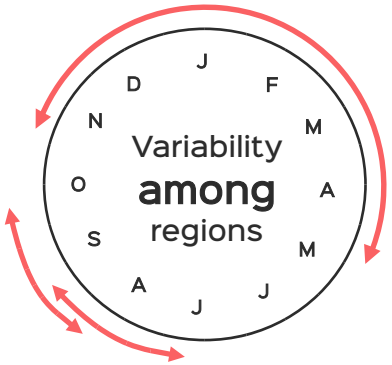
Poitou et al. 2022

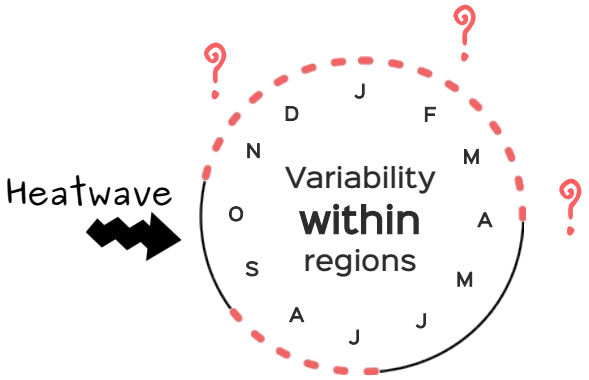
The PCLIM monitoring network:
an opportunity to challenge the model at large scale

Interactive map showing yearly phenological snapshots across the range of the species since 2014:



The model can help better understanding variations in space and time to...





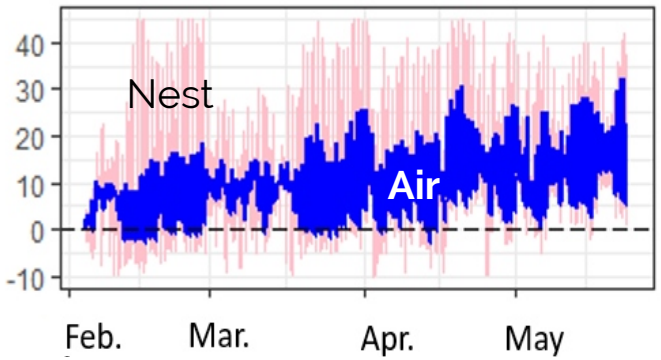
(i) better assess the impacts of climate change on the species,

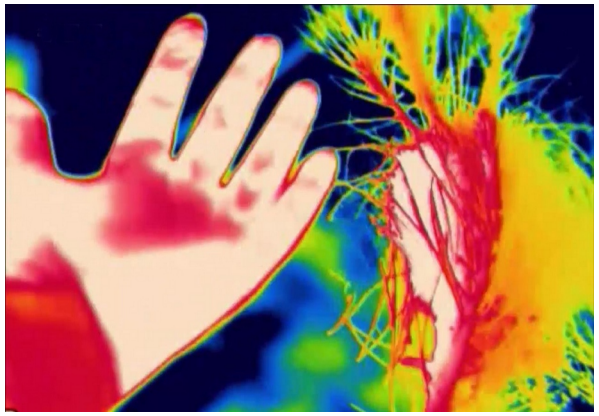
(ii) compare the expansion potential among populations (stress phenological avoidance),

(ii) optimize stage-specific control methods to mitigate health hazards.

Pooitou et al. 2022, Bourougaaoui et al. 2022

Ongoing improvements

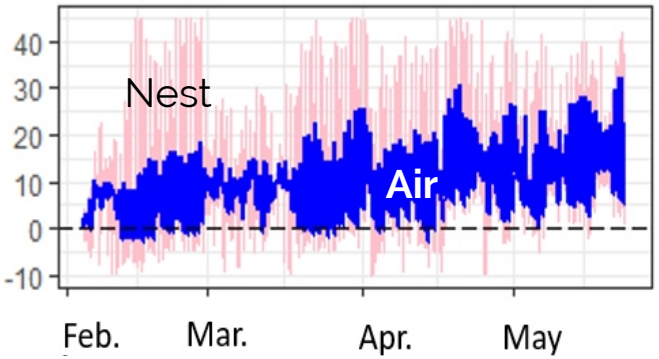


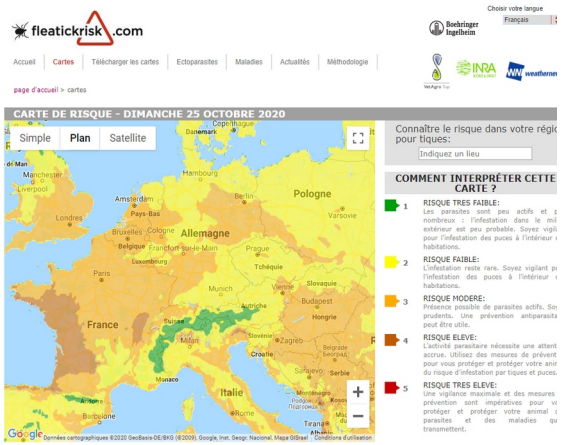


Replacing air temperature with nest temperature using **Poitou et al. 2021**'s microclimate biophysical model

Integrating phenological constraints and mortality factors

Ongoing improvements





Replacing air temperature with nest temperature using **Poitou et al. 2021**'s microclimate biophysical model

Integrating phenological constraints and mortality factors

Production of health hazard maps in real time

→ Clément Bourgade's work (URZF)

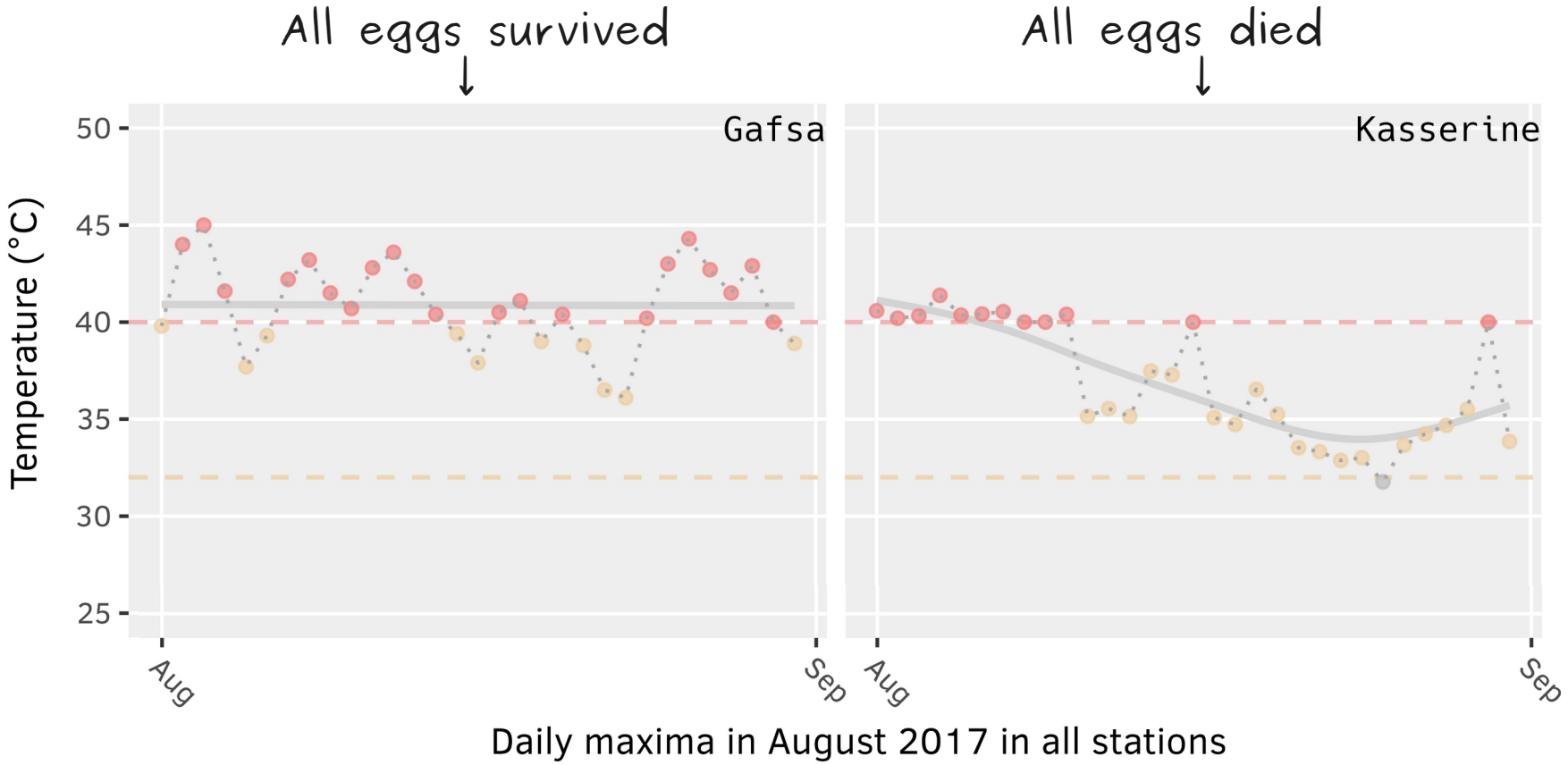
Thanks

And thanks to

Antonin Ageorges,
Alexis Bernard,
Thierry Fanjas-Mercere,
Louis Gross,
Benoît Nusillard,
Patrick Pineau,
…

Local adaptation and phenological avoidance

Example of a historic heatwave in two Tunisian regions in August 2017:



Bourougaaoui et al. 2022

Local adaptation and phenological avoidance

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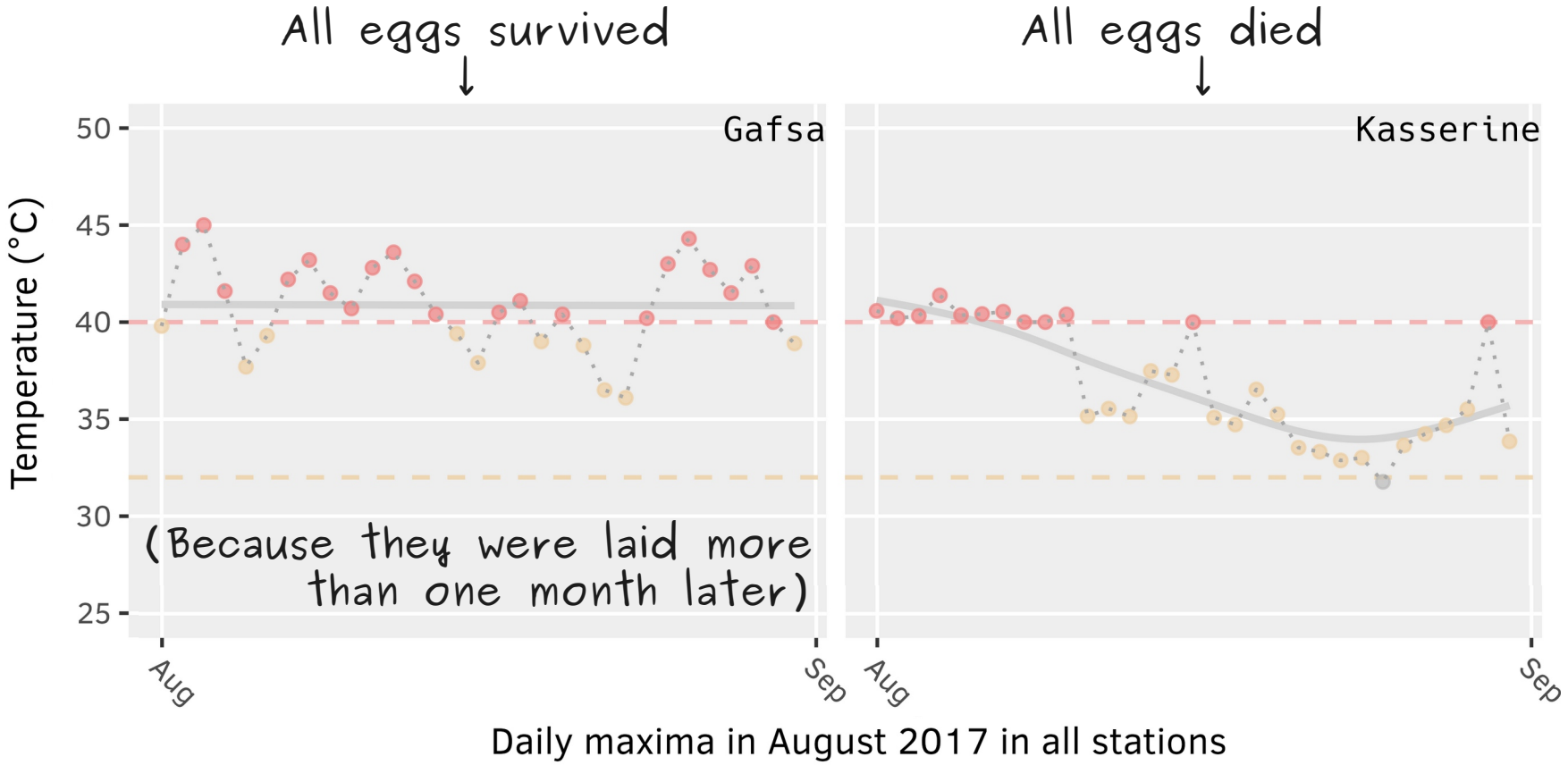
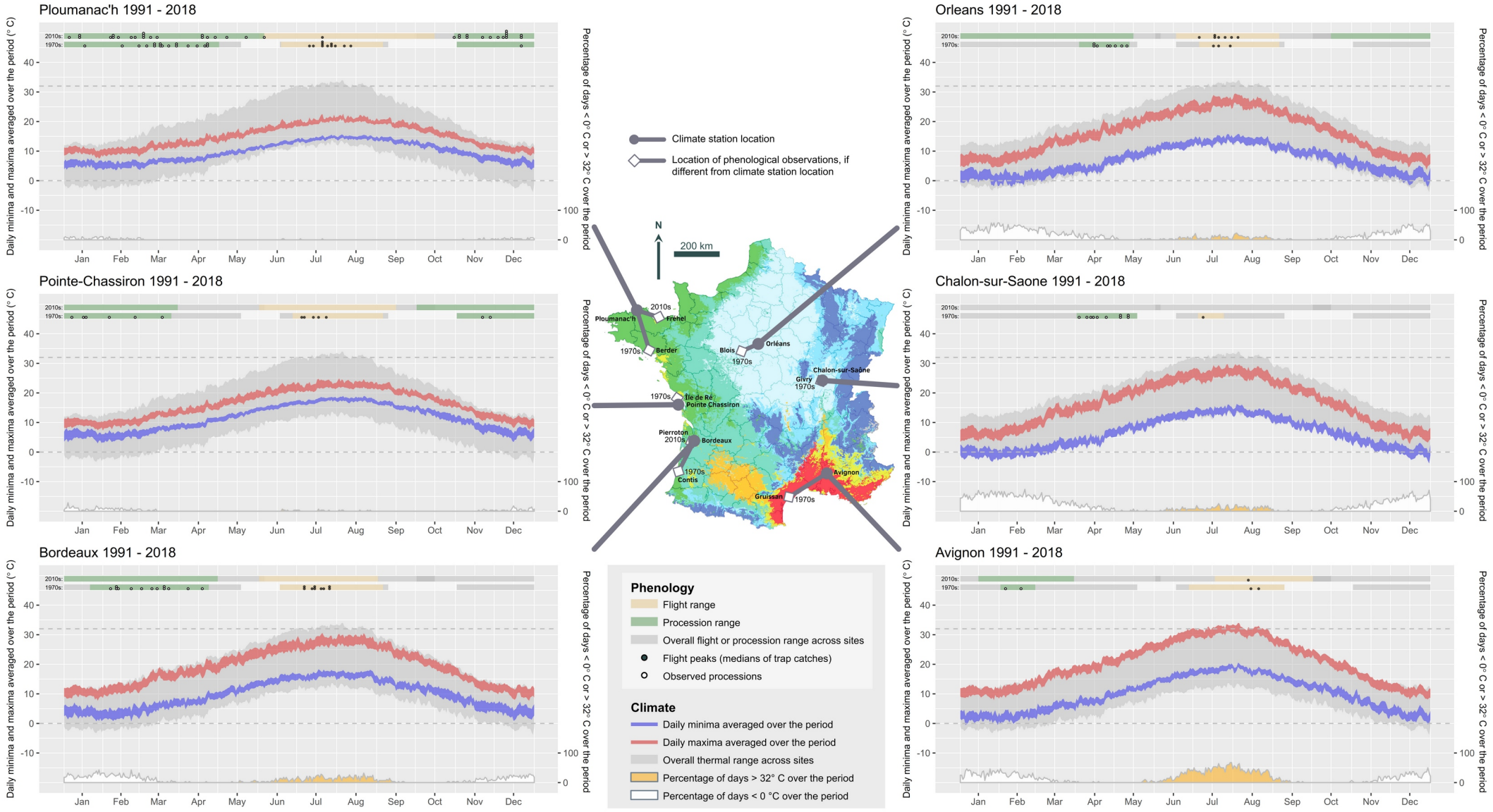


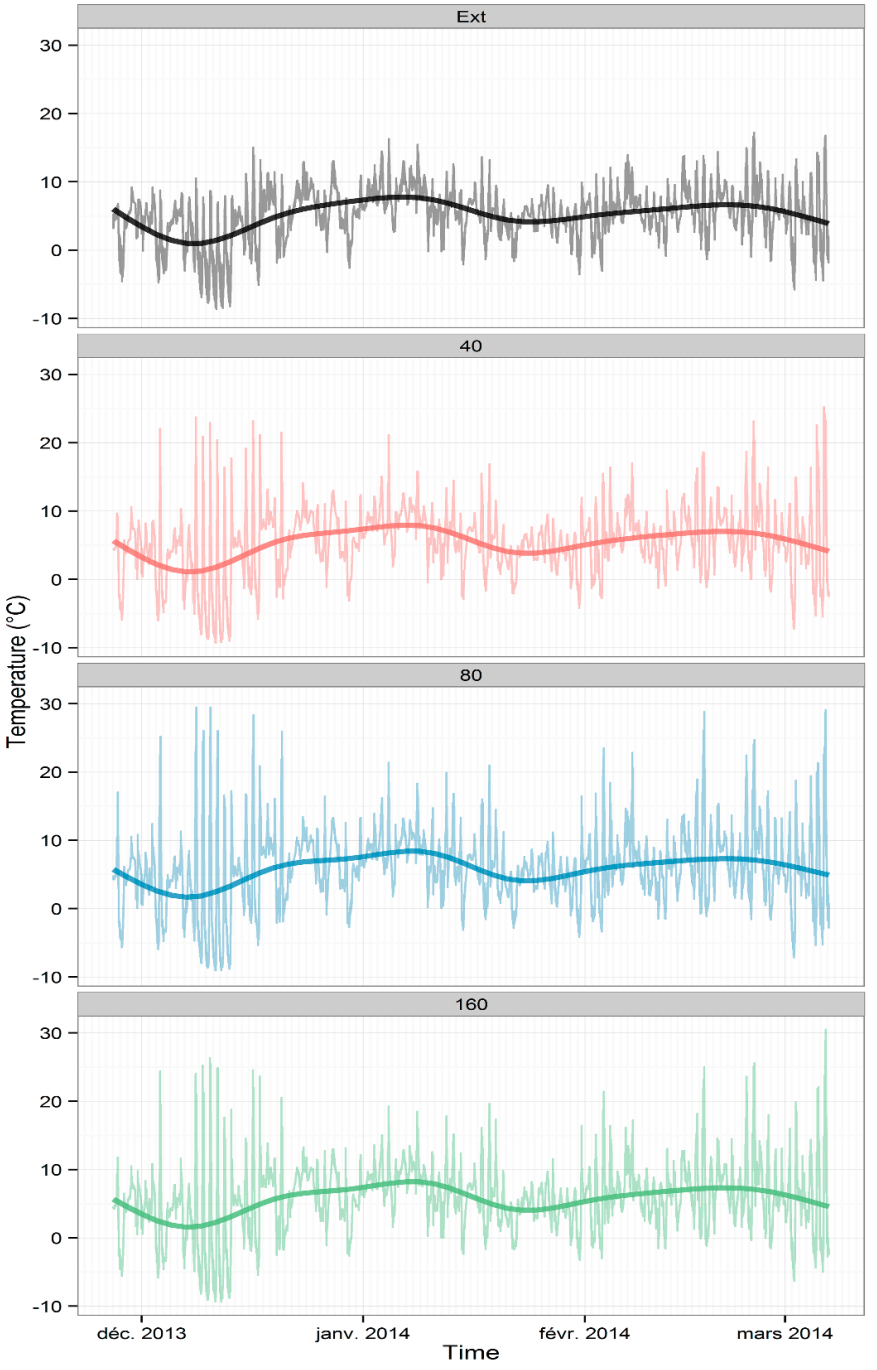
Climate vulnerability might not stand where one expects it.

Bourougaaoui et al. 2022

Stress avoidance



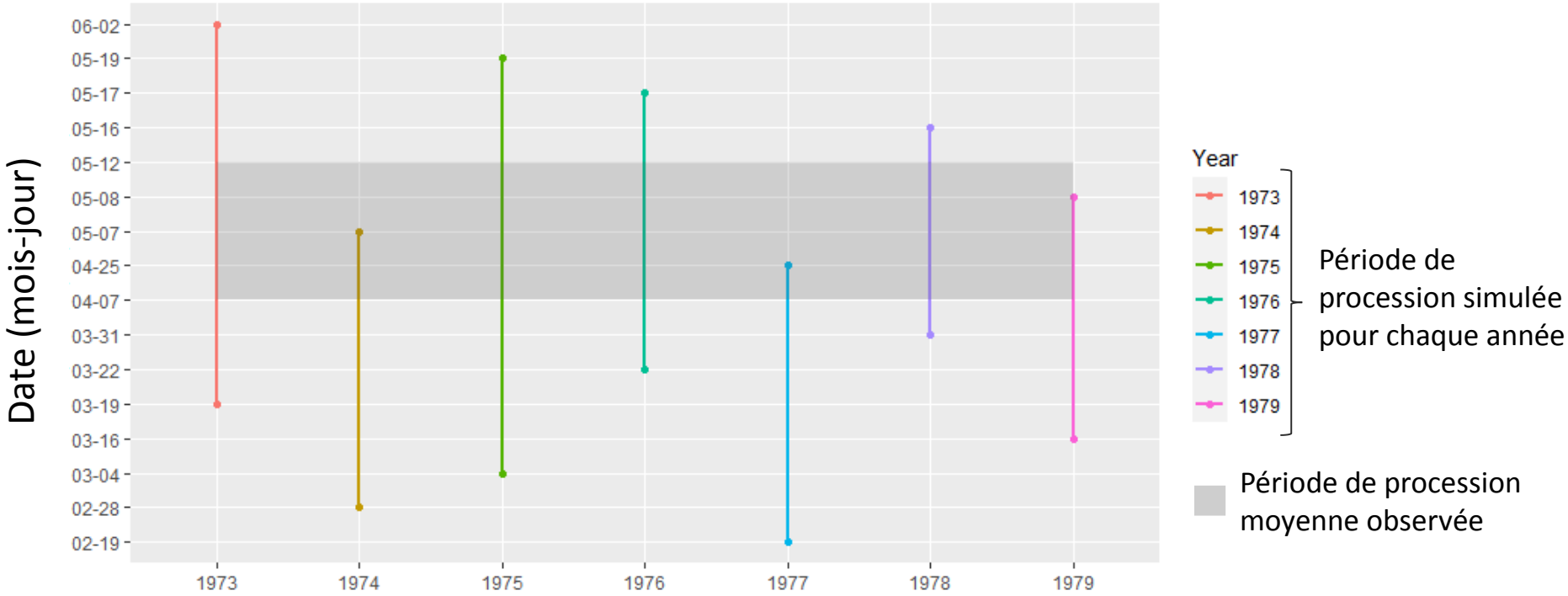
DENSITÉ	MOY	MIN	MAX
EXT	5.2	-8.6	17.3
40	5.4	-9.3	25.3
80	5.8	-9.1	29.5
160	5.7	-9.4	30.5



Validation du modèle

Simulations *vs.* observations

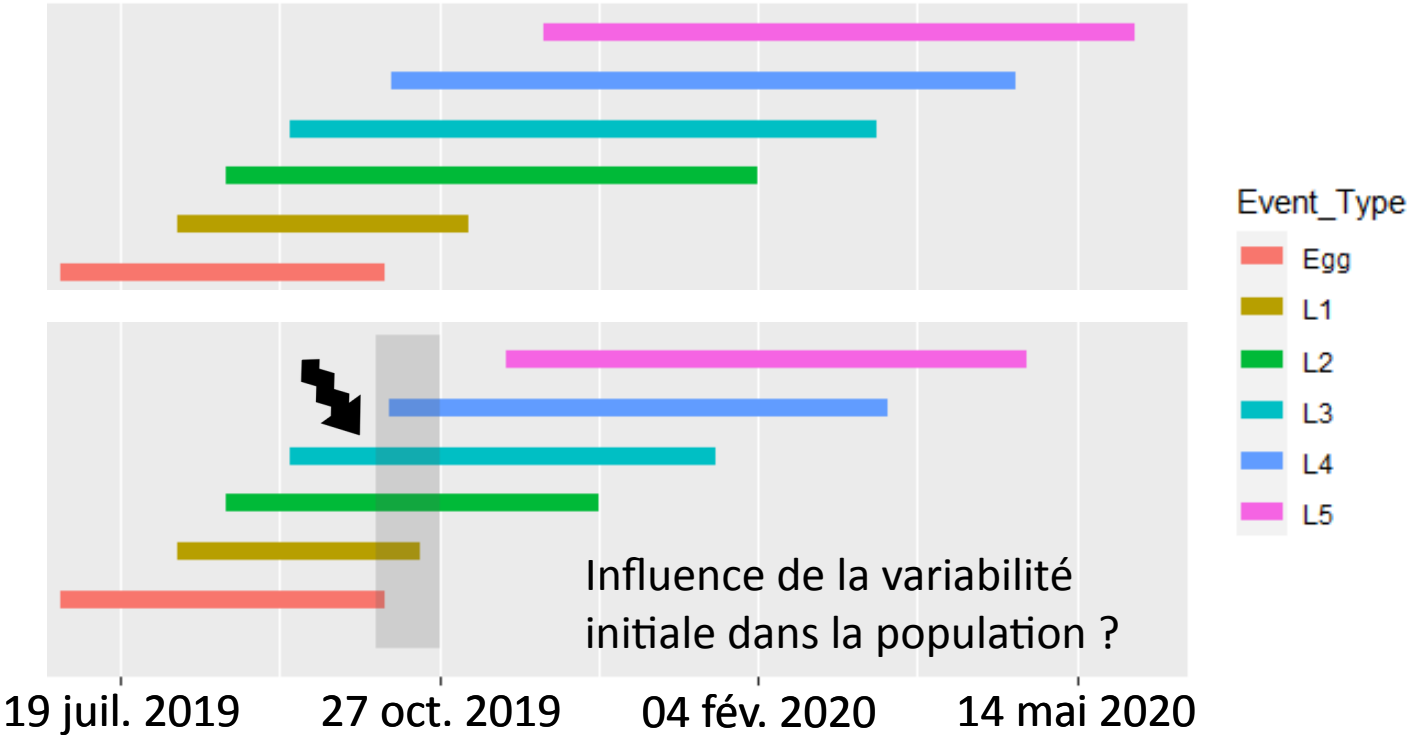
Données historiques de Lodève (méditerranéen franc)



Périodes moyenne de procession observée (gris foncé, 7 avril au 12 mai) et simulées (11 mars au 13 mai) entre 1973 et 1979

Simulation de vague de chaleur

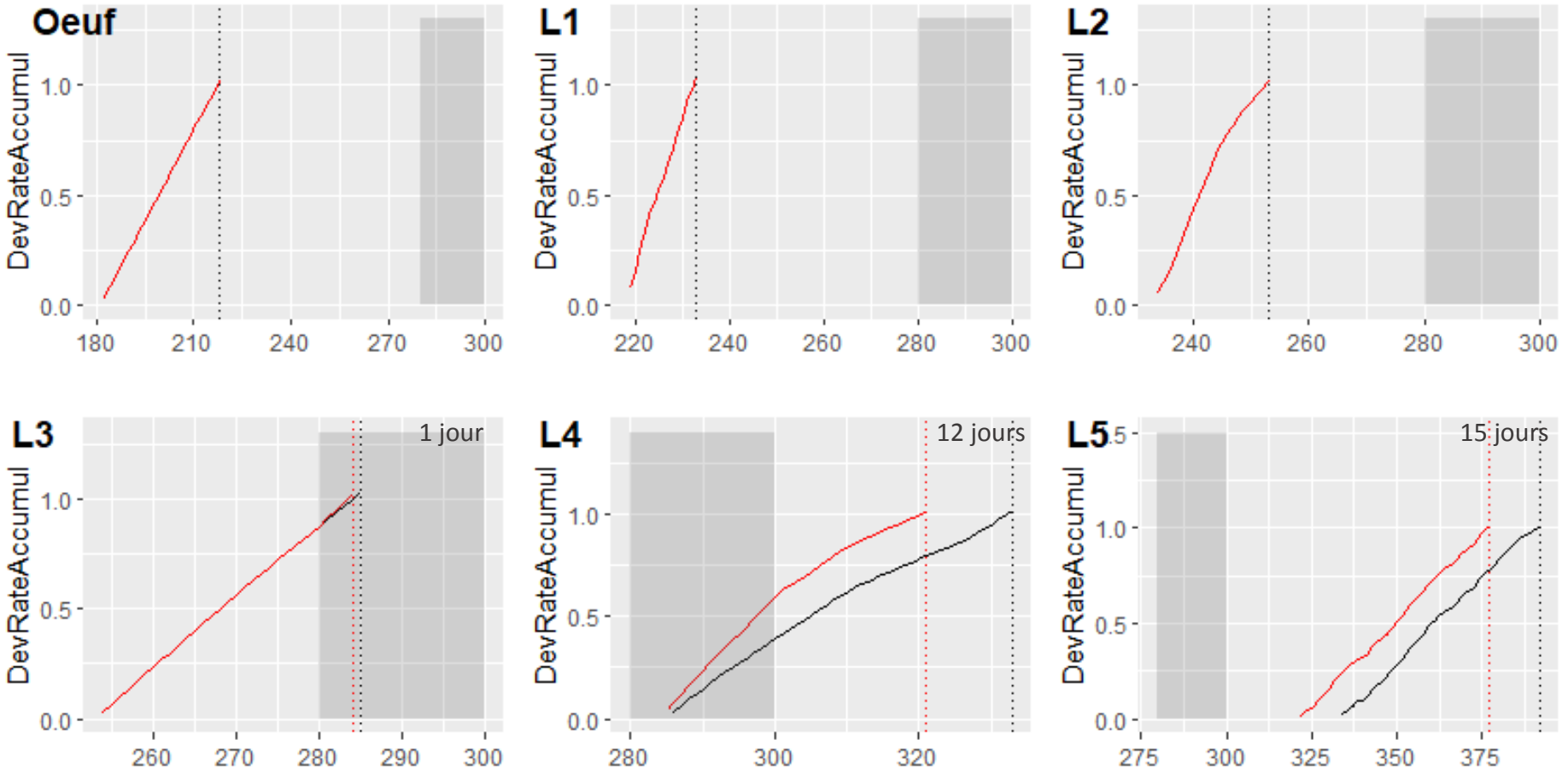
+ 10°C du 7 au 27 octobre, population orléanaise :



Période de procession prédite **sans** vague de chaleur : 27 janvier au 1 juin
Période de procession prédite **avec** vague de chaleur : 12 janvier au 28 avril

Simulation de vague de chaleur

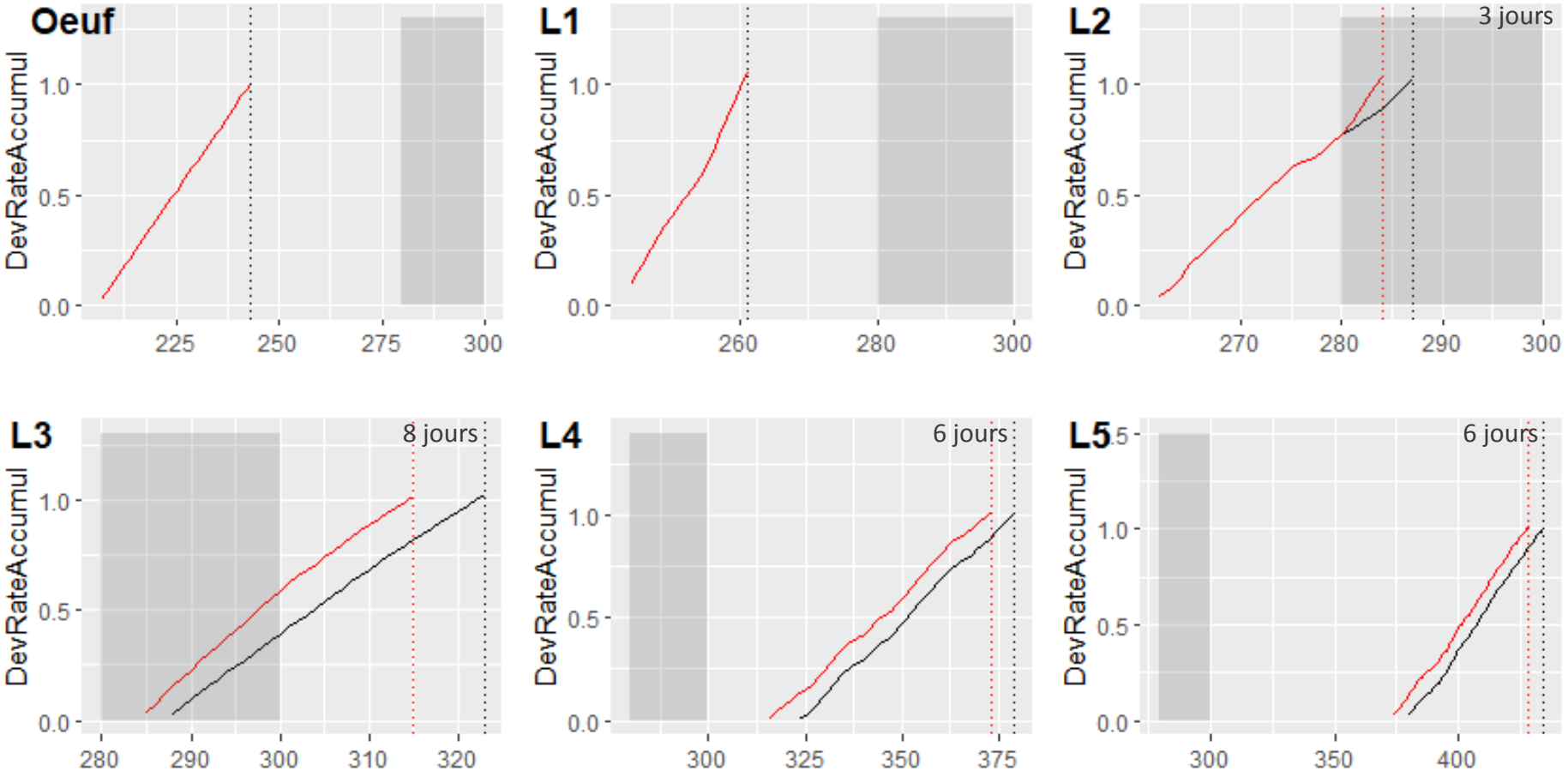
+ 10°C du 7 au 27 octobre :
Individus issus d'une ponte précoce à Orléans (30 juin 2019)



Procession prédite :
12 janvier avec vague de chaleur
27 janvier sans vague de chaleur

Simulation de vague de chaleur

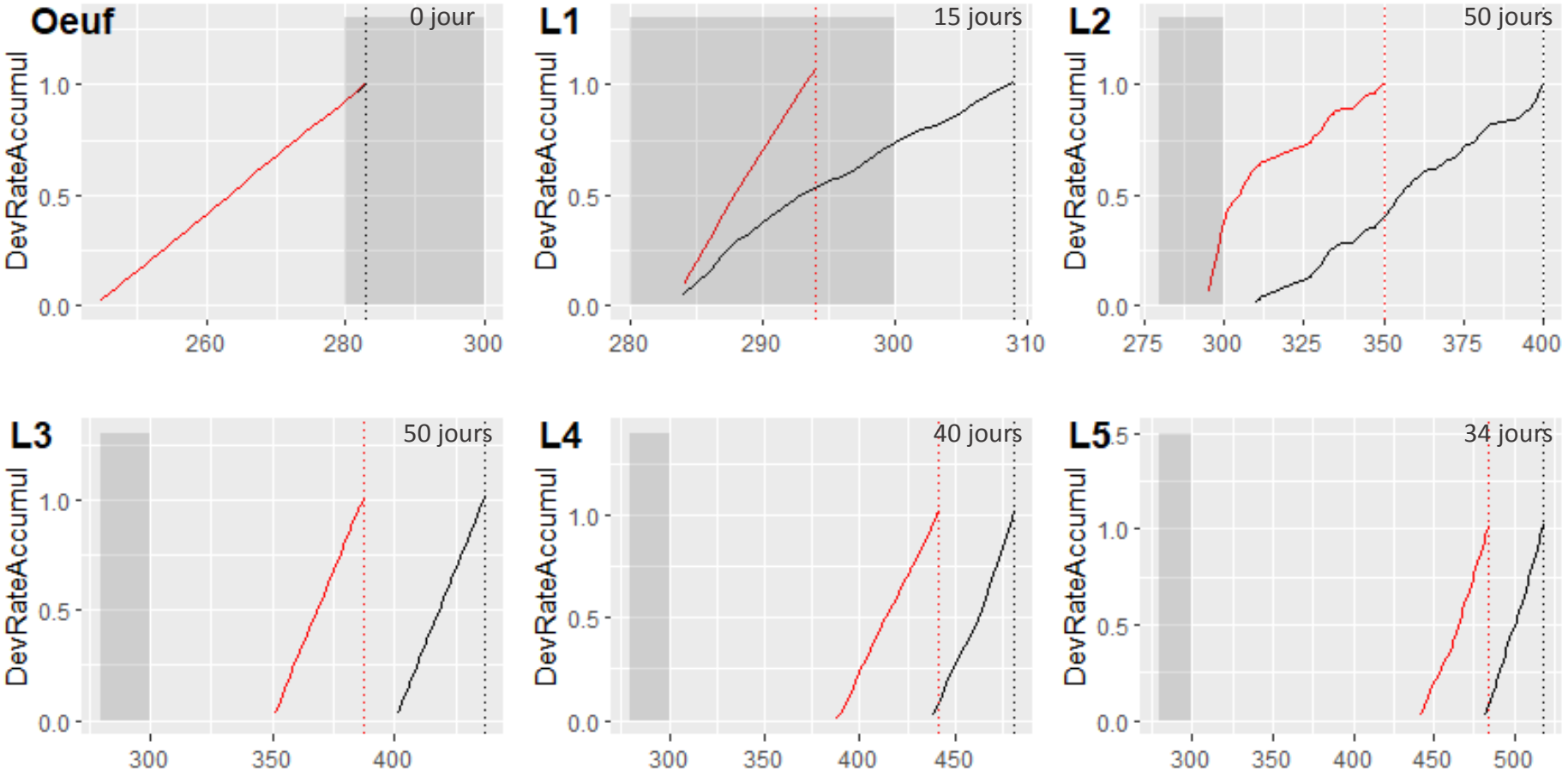
+ 10°C du 7 au 27 octobre :
Individus issus d'une ponte médiane à Orléans (5 juillet 2019)



Procession prédite :
3 mars avec vague de chaleur
9 mars sans vague de chaleur

Simulation de vague de chaleur

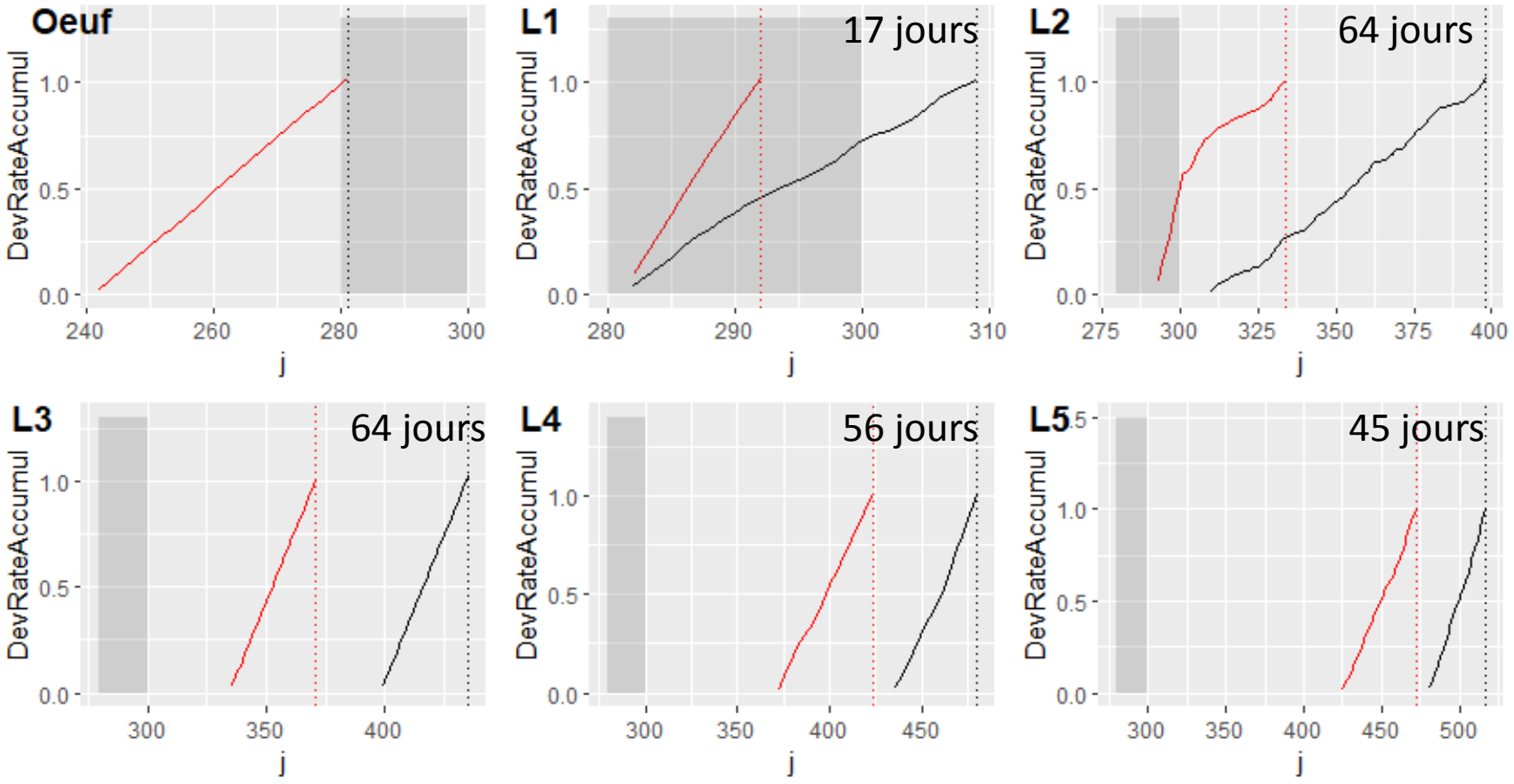
+ 10°C du 7 au 27 octobre :
Individus issus d'une ponte tardive à Orléans (5 sept. 2019)



Procession prédite :
28 avril avec vague de chaleur
1 juin sans vague de chaleur

Simulation de vague de chaleur

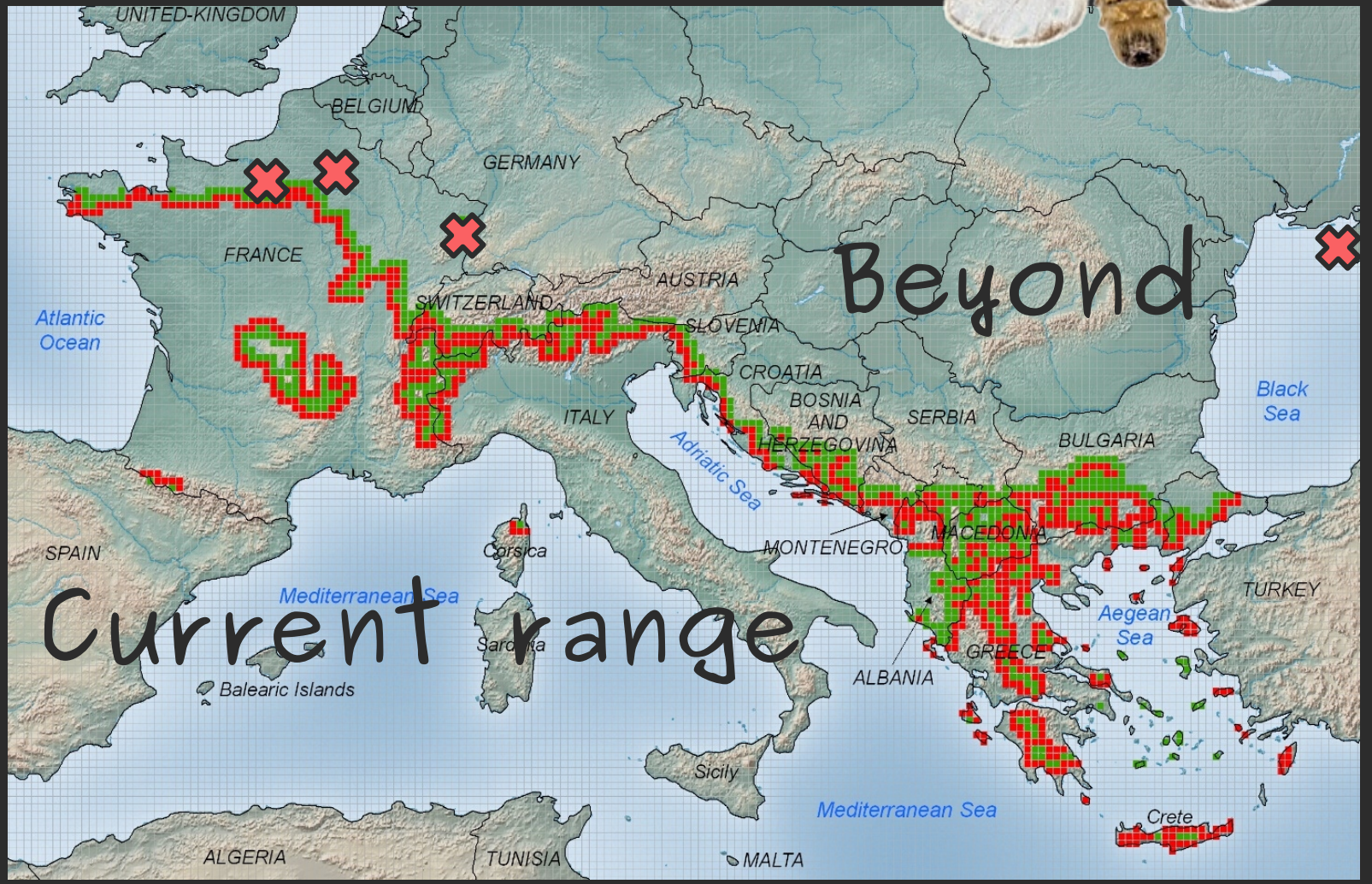
+ 10°C du 7 au 27 octobre :
Individus issus d'une ponte médiane à Erquy (27/08/2019)



Jours

Procession prédite :
16 avril avec vague de chaleur
31 mai sans vague de chaleur

RANGE EXPANSION OF THE PINE PROCESSIONARY MOTH



✖ Accidental introductions

Roques et al. 2013