Impact of the climatic changes on animal diseases spread

Claudia Cianci (Università degli Studi di Firenze)
Rafael Granero Belinchón (Universidad Autónoma de Madrid),
Rocio Picado Álvarez (Universidad Complutense de Madrid)
Francisco Javier Pino Carrasco (Universidad Complutense de Madrid)
Nuria Rodrigo Campos (Universidad Complutense de Madrid)
Elena Tamayo Mas (Universitat Politècnica de Catalunya)

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1 Introduction

The climatic change is affecting the ecosystem and many of the factors associated with human and animal diseases. The clearest example of this has been observed in Europe in relation to bluetongue virus (BTV), a disease of ruminants transmitted by mosquitoes (*Culicoides* spp.), which traditionally occurs only below parallel 40 and now it has been spread further North.

It has been described that there is a positive directed relationship between increases on temperatures and *Culicoides* abundance. Furthermore the presence of more insects due to the increase of temperature amplify the probability that these insects are transported by the wind. Previous studies suggest that *Culicoides* spp. could be transported by the wind up to distances of 170 km ([Gloster]).

In Spain this introduction of *Culicoides* by the wind has not been formally proved, but there is evidence suggesting this possibility. Knowing locations and time periods at higher risk for introduction of mosquitoes and their survival once has been introduced it would help to allocate prevention and control measures to the reduced future BTV outbreaks.

The aim of the model is to forecast the number of mosquitoes introduced by the wind and their survival in Spain.

In the following sections we explain the advection-diffusion, deposition and *Culicoides*-survival models we consider to quantify the number of *Culicoides* entering in Spain and the numerical schemes.

2 Model description

2.1 Data

Data regarding temperature, winds, dust deposition and capture of *Culicoides* was used in this model.

Data on winds and temperature are provided by the State Agency of Meteorology (AEMET). Data consisted on wind speed (km/h) and direction (tens of degrees Celsius), temperature (maximum and minimum) and relative humidity of 58 Spanish regions per day during

2005. Latitude and longitude of those locations were also available. Two considerations were made before using the available data. Firstly, we ruled out the last seven regions (*i.e.* Canary Islands) to provide a better interpolation of any point of Spain. Secondly, we considered the arithmetic mean of the direction and speed of wind, which were taken at certain times of day (00h, 07h, 13h and 18h Universal Time Coordinated) to get one value per day.

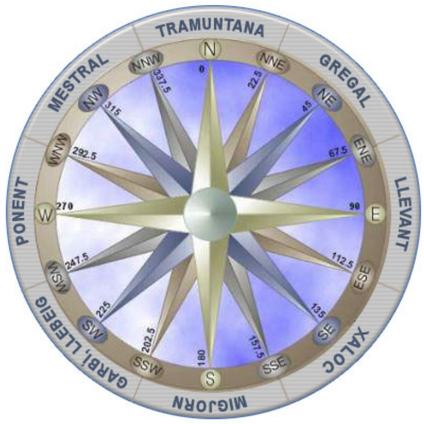

Figure 1: A wind direction of 36 tens of degrees (*i.e.* 360 degrees) is a north wind and a wind direction of 9 tens (90 degrees) is heading east.(Source: www.clubmaritimocastelldefels.com).

Data regarding dust deposition was provided by the Dust Regional Atmospheric Model (DREAM). The assumption made was that deposition of dust particles coming from North Africa could be a good approximation to estimate the deposition of *Culicoides*. Information consisted on the surface concentration of dust per m^2 per day during 2005 in 21 regions of Spain, for which northern and eastern coordinates were available. The surface concentration measures the concentration of dust at 1000 meters height.

Information about captures of *Culicoides imicola* was provided by the Ministry of Environment and Rural and Marine Affairs (MARM) (courtesy of Javier Lucientes). Data consisted on the number of mosquitoes caught in 168 Spanish municipalities (including its coordinates) per day during 2005.

2.2 Advection model

We are interested in $c(x,t)$, the quantity of *Culicoides imicola* females, which are the only ones acting as vectors of BTV. This mosquito is a bad flying one and very small (1-3 mm), which mathematically implies that its movement is mainly by the wind, $\mathbf{w}(x,t)$.

We consider only 2D-spatial model (without high) in order to simplify the model.

We have two potential models to be used (both described below) although we finally used the Model 1 for the simulations.

Model 1:

Our main model is based in an advection-diffusion PDE:

$$\frac{\partial c(x,t)}{\partial t} = \frac{\varepsilon^2}{2}\Delta c(x,t) + \nabla \cdot c(x,t)\mathbf{w}(x,t) \ \text{ if } \ x \in \Omega, \quad c(x,t) = 0 \ \text{ if } \ x \in \partial\Omega \tag{1}$$

where Ω is a big enough domain to consider that all mosquitoes are inside. Spain, Morocco and Algeria are contained inside Ω. We need a initial value function, $f(x)$, the initial population of mosquitoes.

We have wind data each day for 2005, and using interpolation techniques we have $\mathbf{w}(x,t)$ for all points.

Model 2:

This model is based in a stochastic diffusion (Itô diffusion) with transport. We have the same initial data $f(x)$, but now, for simplicity, we have an unbounded domain[1].

We consider, in the previous notation, the SDE

$$d\mathbf{X} = \mathbf{w}(x,t)dt + \varepsilon d\mathbf{B}, \quad \mathbf{X}(0) = x \tag{2}$$

where $\mathbf{B}$ is a brownian motion. We note $X_0^t(x)$ the solution of the previous SDE, which exists if $\mathbf{w}$ is Lipschitz.

We know ([Ku, O]) that a classical solution of a parabolic (or elliptic) PDE can be described like the expectation (in the Wiener sense) of some Itô diffusion[2]. The interpretation is that we have $f(\mathbf{X}_0^t(x))$ mosquitoes which move with the wind and a very small diffusion and the movement ends in x. The reason to understand the *inverse* diffusion, this is with *initial* point $\mathbf{X}_0^t(x)$ and final point x (quite the opposite in the 2) is the inverse sense of time in the Itô's formula ([O, Ku]). The mosquitoes' trajectories are independent. The expectation *kills* the randomness.

[1] We can consider also a bounded one, but this gives us an additional term.

[2] Which is non-unique, but the induced measure is.

To summarize,

$$T_t f(x) = E_x[f(\mathbf{X}_0^t(x))]$$

is a contraction semigroup on L^∞, associated to the elliptic operator

$$A = \frac{\varepsilon^2}{2}\Delta + \mathbf{w}(x,t)\cdot\nabla$$

so, we have that

$$c(x,t) = T_t f(x)$$

solves the parabolic PDE

$$\frac{\partial c(x,t)}{\partial t} = \frac{\varepsilon^2}{2}\Delta c(x,t) + \nabla c(x,t)\cdot \mathbf{w}(x,t), \quad c(x,0) = f(x)$$

We suppose that $f(x) \in L^\infty$ and $\mathbf{w}(x,t)$ is Lipschitz.

This second model is quite different from the previous one. In this stochastic formulation we suppose that the wind is a solenoidal field (divergence free). The second model provides us an useful intuition for the mosquitoes' movement and the posibility of a Monte-Carlo scheme for the simulations. With this model we don't need the deposition model inside Spain.

The two equations are the same if we suppose the air is incompressible.

As we stated before, we use Model 1 for simplicity.

2.3 Deposition model

The aim of the deposition model is to study the number of *Culicoides imicola* that, coming from the North of Africa, finally fall to the soil. This model would depend on the number of *Culicoides* in the cloud, size and weight of the *Culicoides* and speed of the wind. The number of *Culicoides* in the cloud was assumed to be the same than the number of particles of dust (*i.e.* surface concentration). Size and weight of the *Culicoides* were assumed to be 1 mm and 0,5 microgram, so they are sensitive to the prevailing wind. This way, we can assume that the mosquito falls to the surface since the dust would do on having been taken by the wind. Therefore, we will base on a model for prediction of desert dust cycle. This model is the Eta/NCEP model ([Ni]).

We consider a cloud of powder of 1000 meters of height and we will study the quantity of mosquitoes that fall for m^2 to the surface. Besides the speed of the wind, also it is necessary to bear other information in mind as the weight of the mosquito (0,5 μg), the viscosity of the air (1,78*10 $^{-5}$ kg / (m*s)) and the gravity force (-9,8 m*s^2).

The Eta/NCEP model maintains monotonicity in the calculation of the vertical advection of d, the total concentration. Through a number of readjustment iterations for a given time step, the vertical profile of d is represented by piecewise linear segments. The slope of the d-line segment is never adjusted in layers that the contain local extremes. This results in no new minima or maxima created in the vertical profile of d. Given the values of d on the layer interfaces, the change in d due to the vertical advection is computed according to:

$$\frac{\partial d}{\partial t} = -W\frac{\partial d}{\partial z} = -\frac{\partial (dW)}{\partial z} + C\frac{\partial W}{\partial z}$$

$W = w - v_g$ is the relative vertical velocity of concentration, where w is the air velocity and v is the gravitational settling velocity calculated from the Stokes formula:

$$v_g = \frac{2g\rho R^2}{9\nu}$$

With ρ to be the midge density, R the midge's radius, ν the air viscosity, and g the gravitation acceleration.

2.4 Survival model

Once the *Culicoides imicola* have been introduced into Spain by the wind, the most interesting aspect is to quantify how many would survive and potentially could transmit BTV. As widely reported in the literature, see for example [Gloster], the temperature is the most important factor for the survival of *Culicoides imicola*, although there are other aspects such as relative humidity and precipitation that also affect their survival. More explicitly, *Culicoides imicola* are not able to survive neither with very low temperatures nor with very high ones. The optimal temperature for their survival is considered to be between 18ºC and 38ºC.

We use data on *Culicoides imicola* captures provided by MARM (courtesy of Javier Lucientes) to estimate the relationship between temperature and amount of *Culicoides imicola*. For example, in Figure 2, we can see the relationship between the amount of *Culicoides* captures (plotted in black crosses) and the maximum and minimum temperature (in red and in blue) respectively. The peak of captures occurs when temperatures were between 20 and 30°C. These results are in agree with the ones in [BRFB].

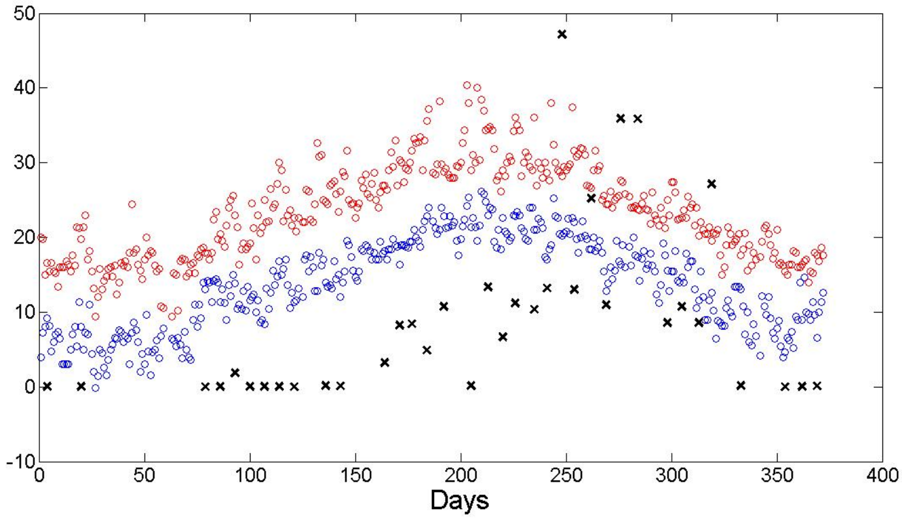

Figure 2: Relationship between temperature minimum (blue circles) and maximum (red circles) and captures (black crosses) of *Culicoides imicola*.

In order to formulate a more realistic survival model, other factors such as relative humidity and precipitation may be considered. Nevertheless, as reported in [BRFB], these aspects may be neglected, so we decide not to include it in order to simplify the model. Therefore, only temperature is took into account. More explicitly, the following assumptions are considered:

- For a period of 3 days at temperature of 0 degrees, *Culicoides imicola* die.
- For a period of 10 days at temperature of 10 degrees, *Culicoides imicola* die.

Assuming these two facts, the linear law, see Figure 3, is obtained. Using this linear law, it is very easy to know the number of *Culicoides imicola* in one day, if the temperature and the number of them in the previous day are known. In Table 1 the number of *Culicoides imicola* are calculated assuming a initial population of 10000 *Culicoides imicola*.

The results are as expected: at temperatures of 10°C (or less), the population of *Culicoides imicola* decrease while at optimal temperature, they are able to survive.

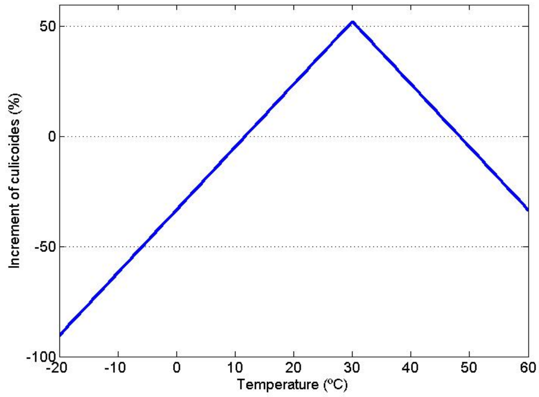

Figure 3: % of increment in population of *Culicoides imicola* versus temperature.

Table 1: Number n of *Culicoides imicola* ($n_0 = 10000$)

T	-10ºC	0ºC	10ºC	20ºC	30ºC
n	3810	6667	9524	12381	15238

3 Numerical experiments

3.1 Interpolation

The data on wind and temperature were only available for certain regions of Spain, but within the model we need to know the wind and temperature for each particular location at time t. Therefore, to achieve winds and temperatures of any point of the study area, interpolation methods were used.

Since our domain is not rectangular and our interpolation nodes are not uniformly distributed over a Cartesian grid, the interpolation problem is difficult to solve. So that, we had to move four nodes to get a rectangular domain and with a software application we also made a grid getting the nodes uniformly distributed. The method that we have used en is Interpolary Cubic Splines.

Interpolatory Cubic Splines are particularly significant since:

- They are the splines of minimum degree that yield C^2 approximations.
- They are sufficiently smooth in the presence of small curvatures.

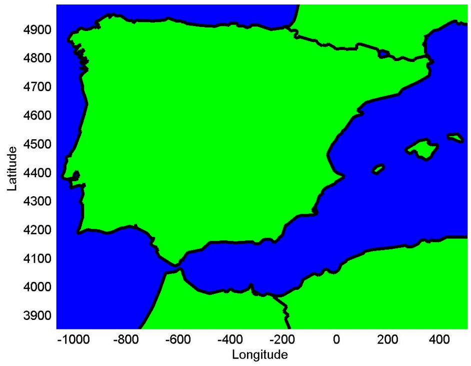

Figure 4: Study domain

Several packages exist for dealing with interpolating splines. In the case of cubic splines, we have used the command *griddata* with the method 'cubic' of Matlab ([QSS]).

3.2 Advection model

The model 1 for the mosquitoes' transport is approximated with a finite volume scheme ([Glow]).

The model 2 (the stochastic one) for the transport is a Monte-Carlo scheme ([GKMPPT]). This second approach is a very useful for difficult equations or very high dimensions, but for this simple equation 1 the finite volume is better.

3.3 Deposition model

To solve 2.3 we use an implicit numerical scheme.

3.4 Results

The highest number of *Culicoides* introduced by the wind and surviving during 2005 from North of Africa to Spain was concentrated in the South part of Spain and mainly in the months of "April to July ". In a few years the temperature will increase due to the climatic change. Supposing that the temperature increases 5 degrees, according to our model, the average number of Culicoides will increase considerably.

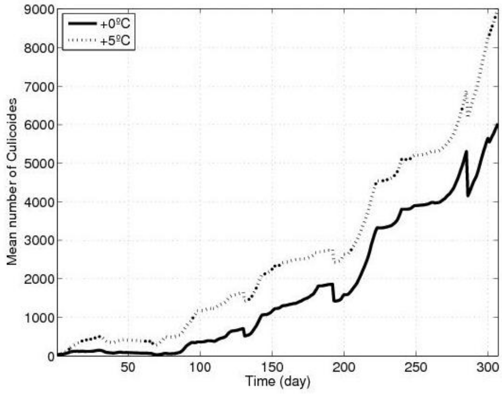

Figure 5: An increase on temperature would produced an increase of *Culicoides* population.

3.5 Validation

The 90% of the primary outbreaks occurring during 2005 were located in the areas identified by the model to be at higher risk of introduction/survival of *Culicoides*.

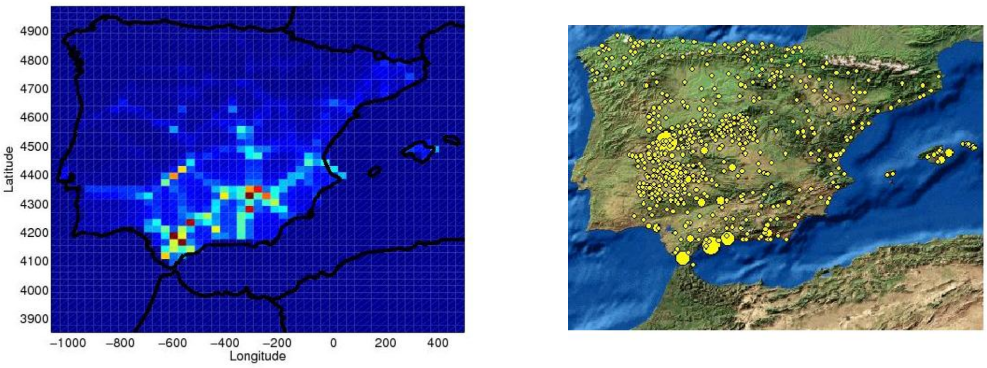

Figure 6: Solution given by the experiment and data obtained in 2005.

4 Concluding remarks

The methods and results presented in this work would be useful to identify areas and periods at higher risk of introduction of *Culicoides* from the Nort of Africa, which ultimately would help in the prevention and control of future incursions of BTV in Spain.

5 Acknowledgements

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References

[BRFB] Braverman, Y., Rechtman, S., Frish, A., Braverman, R. Dynamics of biting activity of C. Imicola kieffer (diptera:Ceratopogonidae) during the year. *Veterinary Medicine*, **58**(2-3), 2003

[GKMPPT] C.Graham, T.Kurtz, S.Meleard, P.Protter, M.Pulvirenti, D.Talay, *Probabilistic Models for Nonlinear Partial Differential Equations*, Lecture Notes in Mathematics **1627**, Springer-Verlag, 1996.

[Gloster] Gloster, J., Mellor, P.S., Burgin, L., Sanders, C. and Carpenter S., Will bluetongue come on the wind to the United Kingdom in 2007? *Vet Rec 2007*;**160**:422–6.

[Glow] R.Glowinski, *Numerical methods for fluids, part 3*, North-Holland, 2003.

[Ku] H.Kunita, *Stochastic differential equation and stochastic flows of diffeomorphism*, Lecture Notes in Math. vol 1097, Springer, 1984.

[Ni] S.Nickovic, *A model for prediction of desert dust cycle in the atmosphere*, Journal of geophysical research. Vol 106, August 27, 2001.

[O] B.Oksendal, *Stochastic differential equations: an introduction with applications, fifth edition*, Springer-Verlag, 2000.

[QSS] A. Quarteroni, R. Sacco, F.Salieri, *Numerical Mathematics*, Text in Applied Math. vol 37, Springer, 2000.