

Simulation of climate-change scenarios to explain Usutu-virus dynamics in Austria

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ABSTRACT

The emergence and spread of infectious diseases in mid-latitudes, so far mainly observed in the tropics, considerably increase under the current situation of climate change. A recent example is the Usutu virus (USUV) outbreak in Austria. USUV is closely related to the West Nile virus in the U.S. and caused mass mortalities mainly of blackbirds (*Turdus merula*). The USUV flavivirus persists in a natural transmission cycle between vectors (mosquitoes) and host reservoirs (birds) and leads – once endemic in a population – to periodic outbreaks. In an epidemic model to explain the USUV dynamics in Austria 2001–2005, USUV dynamics were mainly determined by an interaction of bird immunity and environmental temperature. To investigate future scenarios, we entered temperature predictions from five global climate models into the USUV model and also considered four different climate-warming scenarios defined by the Intergovernmental Panel on Climate Change, IPCC (20 different model-scenario combinations). We downscaled the 20 time series of predicted temperatures (through the year 2100) to represent the region around Vienna. Our simulations predict that USUV will persist in the host population after the epidemic peak observed in 2003. USUV-specific annual blackbird-mortality time series predict that the outbreak frequency increases successively from the beginning to the end of the century. Simulations of worst-case scenarios result in an endemic equilibrium with a decline of the blackbird population of about 24%. Additionally we calculated the annually averaged basic reproduction number for the period 1901–2100. The latter depict that undetected major outbreaks before 2000 were unlikely, whereas it is likely that the USUV becomes endemic after 2040.

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1. Introduction

The incidence and spread of previously tropical infectious diseases considerably increased under the current situation of climate change (Harvell et al., 2002). A recent example is the Usutu virus (USUV), which was detected the first time outside Africa during 2001 in Austria (Weissenböck et al., 2002). USUV is a rather unknown member of the flaviviridae family of the Japanese encephalitis virus complex. It is closely related to the more common West Nile virus (WNV), dengue virus (DENV), Japanese encephalitis-virus (JEV) and yellow-fever virus (YFV) (Weissenböck et al., 2002). USUV caused mass mortalities of birds, especially blackbirds (*Turdus merula*) and great grey owls (*Strix nebulosa*), in and around the capital city of Austria, Vienna. The established monitoring program of the University of Veterinary Medicine Vienna confirmed that USUV overwintered in Austria (Chvala et al., 2007). Although the initial number of dead blackbirds was very low in 2001 and 2002, an epidemic peak was observed during the extraordinary hot summer 2003 (Schönwiese et al., 2004). In the meantime, USUV was also observed in other Central European countries such as Switzerland, Hungary, and Northern Italy (Nowotny et al., 2007).

Arthropod-borne viruses (arboviruses), like USUV, persist in a natural transmission cycle between vectors

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(here, mosquitoes of the *Culex pipiens* complex) and avian hosts. Once endemic, it might cause periodic disease outbreaks. Rubel et al. (2008) developed a new epidemic model for explaining the multi-seasonal dynamics of the USUV infection in Austria. This model considers both the density-dependent seasonal dynamics of mosquitoes and birds and the USUV bird–mosquito infection cycle. The dynamics of the mosquito population and the virus reproduction rate depend strongly on the environmental temperature. Efficient USUV transmission requires warm temperatures (which increase the reproduction and biting rates of mosquitoes and decrease the extrinsic incubation period). To demonstrate the relationship between warm temperatures and USUV, Fig. 1 depicts the total number of dead blackbirds associated with USUV infections (period 2001–2005) together with the spatial distribution of the average number of hot days (days with temperature $\geq 30^\circ\text{C}$) in Austria. Conspicuously, the emergence of USUV infections is mainly related to those regions around Vienna where the number of hot days exceeds 10 days/year. Most of the dead birds were found in the most populated region in the district of Lower Austria, and only few in the surrounding agricultural areas. A more detailed discussion on the dead-bird monitoring is in Weissenböck et al. (2003) and Chvala et al. (2007).

In this paper we asked: How might USUV around Vienna develop in response to global warming? Should we expect large-scale declines in several bird populations as observed for the related WNV in North America (LaDeau et al., 2007)? We applied the USUV model of Rubel et al. (2008), which calculates (once initialized with some USUV-positive mosquitoes and exclusively forced by environmental temperature) time series of bird and mosquito populations of various health states. We used a dataset comprising temperature predictions from five different climate models, to incorporate the uncertainty across climate models. However, each model was based on

the same initial conditions. We used a combination of these five climate models with the four emission scenarios (defined by the Intergovernmental Panel on Climate Change, IPCC) resulting in a total of 20 temperature predictions for the period 2006–2100 to force our USUV model. The results of these multiple model runs are interpreted like results from a stochastic model. Finally, we used temperature observations from a weather station in Vienna to run the USUV model for the period 1901–2005.

2. The epidemic model

Our SEIR (susceptible, latent, infectious, recovered) model (Rubel et al., 2008) simulates the seasonal lifecycles of blackbirds (*Turdus merula*) and mosquitoes (*Culex pipiens*) and the inter-species USUV infection cycle between birds and mosquitoes. The model has nine compartments (i.e. health states): susceptible birds (S_B), latent-infected birds (E_B), infectious birds (I_B), recovered or immune birds (R_B), dead birds (D_B), mosquito larvae (L_M), susceptible mosquitoes (S_M), latent-infected mosquitoes (E_M) and infectious mosquitoes (I_M). The dynamics of these bird and mosquito health states is mathematically formulated by nine ordinary differential equations, which are solved numerically.

The movements between health states are defined by 13 parameters, of which seven depend exclusively on the environmental temperature. These are the birth and mortality rates of mosquito larvae (b_L , m_L) and adult mosquitoes (b_M , m_M), the virus-transmission rates between infectious mosquitoes and susceptible birds (β_M) and vice versa (β_B), and the reciprocal of the extrinsic incubation period (i.e. the virus-reproduction rate within the mosquitoes; γ_M). Further parameters are the birth rate of birds (b_B) and the proportion of mosquitoes non-diapausing (δ_M), which are functions of the Julian calendar day and the geographic latitude. Constant parameters are

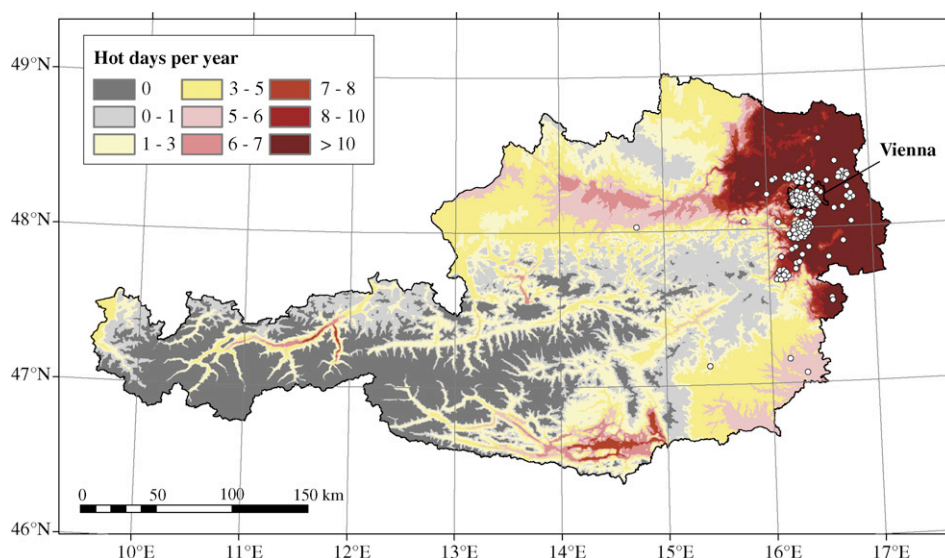


Fig. 1. Spatial distribution of the average number of hot days per year in Austria for the climate reference period 1961–1990 (Auer et al., 2001) and blackbirds died from USUV (white dots; Chvala et al., 2007). Among some other species, about 140 blackbirds died from USUV infections have been collected between 2001 and 2005.

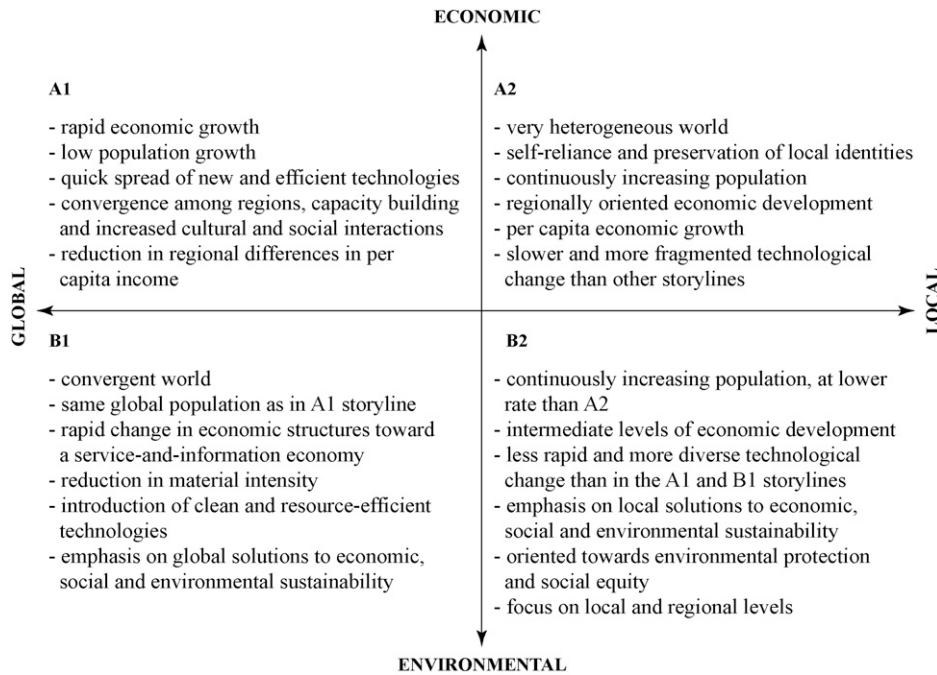


Fig. 2. Brief characterization of the main *Special Report on Emission Scenarios* (SRES) storylines after IPCC (2000) and Arnell et al. (2004).

the mortality rate of birds (m_B), the reciprocal of the intrinsic incubation period (i.e. the rate of transition within birds from latently infected to infectious; γ_B), the immunization rate of birds (α_B) and the proportion birds dying due to infection (δ_B). For more details on parameter definition and estimation see Rubel et al. (2008).

The model has been calibrated using observations from the Austrian dead-bird-monitoring program (Chvala et al., 2007), which was established for the period 2001–2005. For the model development and calibration, air-temperature data measured by the automatic weather station located at the University of Veterinary Medicine Vienna (*Veterinärmedizinische Universität Wien*, VUW) were used. Contrary to this previous study, we used climate model predictions in this study presented here to project the USUV dynamics onto the future period 2006–2100.

3. Climate-prediction data

To force the USUV model, we selected the Tyndall Centre for Climate Change Research dataset, TYN SC 2.0 (Mitchell and Jones, 2005). It is based on four scenarios defined by IPCC and described in the *Special Report on Emission Scenarios* (SRES). This dataset provides the five climate parameters temperature, diurnal temperature range, precipitation, water-vapor pressure, and cloud cover—but we only used the temperature data. Information is presented on a 0.5° grid, equidistant in geographical latitude and longitude that covers the world land surface and is available with a monthly time-step for the period 2001–2100. Thus, the TYN SC 2.0 dataset comprises a total of 20 climate-change model runs, combining four possible future worlds using SRES scenarios with five state-of-the-art climate models (Mitchell et al., 2004).

The emission scenarios (Fig. 2) were developed in the mid 1990s and are based on four different narrative storylines to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification (IPCC, 2000). The four SRES storylines represent different world futures in two dimensions: a focus on economic or environmental concerns, and global or regional development. The variables in each model include population growth, economic development, energy use, efficiency of energy use, and mix of energy technologies, respectively. The TYN SC 2.0 dataset considers the scenarios A1,¹ A2, B1 and B2. On the other hand, five general circulation models were used to simulate climatic changes: The Hadley Centre Coupled Model Version 3 (HadCM3), the National Centre for Atmospheric Research-Parallel Climate Model (NCAR-PCM), the Second Generation Coupled Global Climate Model (CGCM2), the Industrial Research Organization – Climate Model Version 2 (CSIRO2) and the European Centre Model Hamburg Version 4 (ECHam4).

We used only time series of monthly temperatures of the grid-point 392/277 of the TYN SC 2.0 dataset (“grid-point Vienna”), which is representative for the geographical region between 16.0–16.5° longitude and 48.0–48.5° latitude. Fig. 3 depicts time series of the average annual temperature for the grid-point Vienna, grouped by scenarios (upper panel) and climate models (lower panel). All predicted temperatures show a clear trend toward warming. The average predicted increase of the temperature during the 100-year period, calculated from the linear trend, ranged from 2.6 °C to 6.1 °C (across emission

¹ Note that the abbreviation A1 is used for the scenario with additionally intense use of fossil fuels, A1FI.

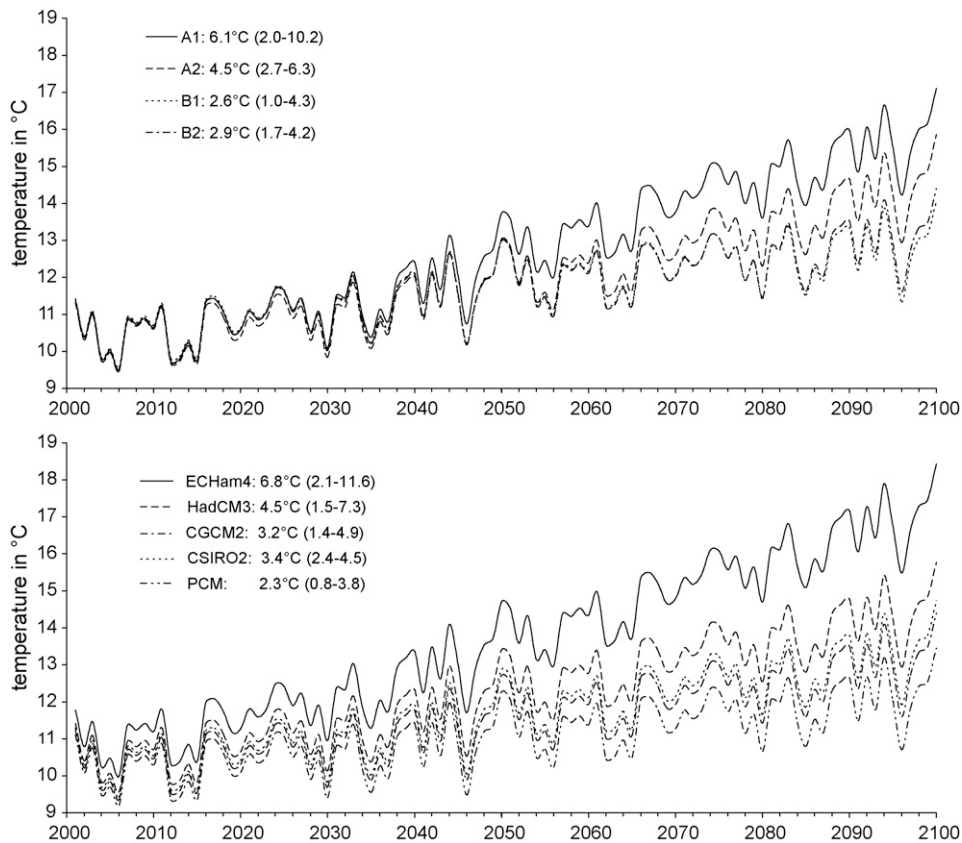


Fig. 3. Time series of average annual temperature predictions for different emission scenarios (upper panel) and climate models (lower panel). Numbers in brackets denote the temperature range predicted by different climate models (upper panel) and different emission scenarios (lower panel). Grid-point Vienna, period 2001–2100.

scenarios) and from 2.3 °C to 6.8 °C (across climate models). For the 20 model-scenario combinations, the range in average annual predicted warming across the century was 0.8 °C (PCM model with B1 scenario) to 11.6 °C (ECHam4 model with A1 scenario). The lowest temperature increase of 2.3 °C (0.8–3.8 °C) is simulated by the B1 scenario. It represents an environmentally oriented world with emphasis on global solutions to economic, social and environmental sustainability.

4. Downscaling climate data

Two specific features of climate model predictions have to be considered when using it to study the evolution of biological systems (e.g. epidemic outbreaks). Firstly, climate predictions for the next 100 years merely simulate a possible temperature based on a scenario which is also a prediction. Uncertainties of these climate predictions are made evident by the range of prediction, depending on the scenario and model used. Secondly, climate models are representative for a specific spatial resolution, here of 0.5° equidistant in geographical latitude and longitude. Thus, the temperature at grid point Vienna is representative for an area of about 70 km × 50 km with a mean height above sea level of 261 m. The grid-point Vienna comprises, for example, the foothills of the Alps, the Vienna Forest, and

planes like the *Tullner Feld* (i.e. the resolution is too coarse for our study area). USUV cases have been observed only in the flat country where temperatures are high. The temperatures were measured by the weather station VUV, which is representative for the flat country (Rubel et al., 2008). It is located at 153 m above sea level. Therefore, temperatures simulated by climate models must be downscaled to describe this small-scale region.

Fig. 4 depicts two examples for the relationship between monthly temperatures representative for regions where USUV cases have been observed and temperatures predicted for grid-point Vienna. For the period 2001–2005 (for which both observed and predicted temperatures are available), the predicted annually averaged temperatures are 0.02–1.00 °C lower than the observed. This is consistent with meteorological considerations, where a dry-adiabatic temperature decrease with height of 1 °C/100 m is defined for the so-called “standard atmosphere”. Moist-adiabatic temperature gradients, depending on the air humidity, are significantly lower. Thus, the systematic lower temperatures predicted by the climate models may be completely explained by the height of the grid-point Vienna. It is about 100-m higher than the height of the region where USUV infections have been observed.

The downscaling approach we applied is a simple correction of the systematic deviations of the monthly

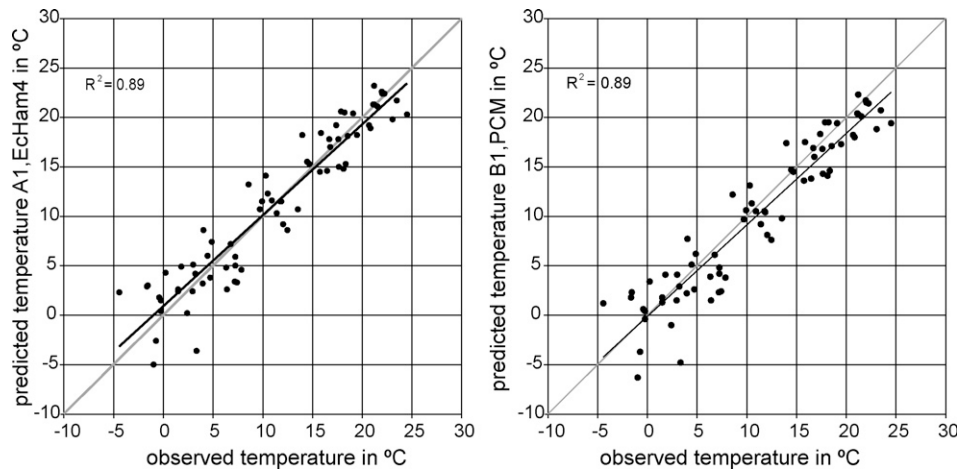


Fig. 4. Relation between monthly temperatures observed at weather station VUW and predicted by ECHam4 model with A1 scenario (left) and PCM model with B1 scenario (right). Period 2001–2005. The biases of the predictions are depicted by regression lines and corrected with Eq. (1).

temperatures predicted by climate models. The following transfer function, derived from linear regression, was used to correct the temperature data of all climate model runs

$$T_{\text{downscaled}} = \frac{T - i}{s} \quad (1)$$

whereas T is a temperature value predicted by a climate models, i is the axis intercept and s is the slope. The axis intercepts and the slopes were estimated separately for each of the 20 climate model predictions and are given in Table 1. Note that it is essential to use the (generally slightly higher) downscaled temperature predictions $T_{\text{downscaled}}$ instead of the original temperature predictions T to force the USUV model. Otherwise the effect of the climate warming signal would be compensated by the underestimation of the temperatures predicted by the large-scale climate models.

5. Simulation results

The time series of predicted annually numbers of birds dead because of USUV is depicted in Fig. 5. The upper

Table 1

Axis intercepts i and slopes s for correcting systematic temperature deviations of climate model predictions by Eq. (1) (downscaling based on regression of observed vs. predicted temperatures; period 2001–2005)

Scenario	ECHam4	HadCM3	CGCM2	CSIRO2	PCM
A1					
Intercept	0.905	0.032	−0.069	−0.028	−0.144
Slope	0.919	0.945	0.932	0.923	0.927
A2					
Intercept	0.397	0.055	−0.062	0.204	−0.126
Slope	0.922	0.940	0.932	0.919	0.926
B2					
Intercept	0.550	−0.048	−0.005	0.200	−0.110
Slope	0.911	0.943	0.928	0.919	0.924
B1					
Intercept	1.105	0.098	−0.024	0.111	−0.130
Slope	0.901	0.939	0.928	0.927	0.924

panel shows the predictions forced by temperatures from the five climate model for the worst-case emission scenario A1, the lower panel for the best-case scenario B1 (results for other scenarios are not shown). The main result is that USUV was predicted to survive in almost all model simulations except those simulations where the USUV model is driven by temperatures from PCM using the A1 and A2 scenarios. After the epidemic peak 2003, only minor outbreaks are simulated until the next major outbreak in 2019. The amplitude of the outbreaks, here the annually accumulated proportions of dead blackbirds, vary accordingly to the temperatures predicted by the climate models. Using temperatures from climate models predicting an intense warming (ECHam4 and HadCM3 with A1 scenario) lead to the highest predicted annual USUV-specific mortality risk in the blackbirds. Moreover, forcing the USUV model with temperatures from these two climate models result in an endemic situation with a constant level of about 11% dead birds in the year 2050. Typically, a cyclic annual mortality pattern was predicted through the years, but the predicted amplitude of the cycle of annual mortality decreases later in the century for some of the climate model predictions and especially with the A1 emission scenario. For the latter on average 59.3% of all birds acquire immunity until the end of the century. But also for the best-case scenario B1, a proportion of 49.1% of the birds acquire lifelong immunity (Table 2).

A summary of all simulations results for the period 2076–2100, comprising susceptible birds S_B , immune birds R_B and total birds N_B , is presented in Table 2. Annually accumulated dead birds D_B are given in Table 3. Note that all proportions of birds are related to the carrying capacity K_B (Rubel et al., 2008). Thus, a total proportion of $N_B < 100\%$ indicate a reduction of the blackbird population due to the emergence of USUV. Table 2 depicts for example, that USUV model simulations predict a possible reduction of blackbirds in the last quarter of the century between 12.4% (PCM, B1) and 23.7% (ECHam4, A1). Additionally, the proportion of infected

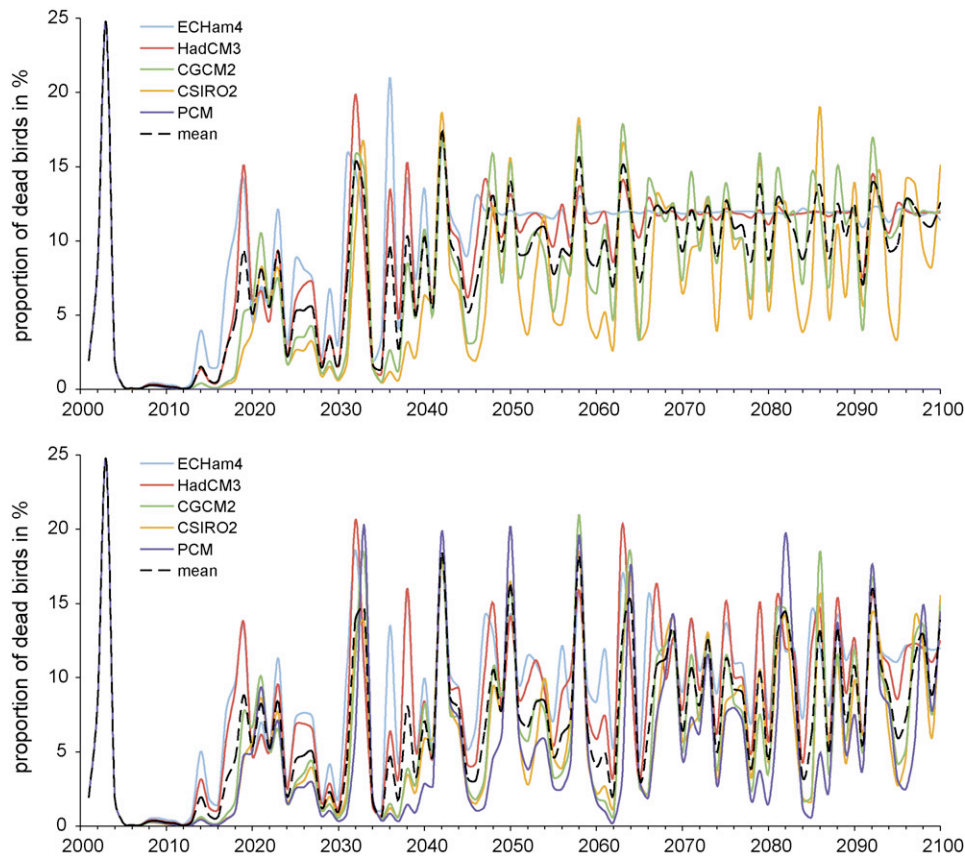


Fig. 5. Time series for the predicted annual USUV-specific mortality risk for blackbirds around Vienna, Austria (dotted line is the mean). Emission scenario A1 (upper panel) and B1 (lower panel).

and infectious birds ($E_B + I_B$) may be calculated as residuum from $E_B + I_B = N_B - S_B - R_B$.

Additionally, we depict the USUV dynamics by the annual basic reproduction number $\bar{R}_0$ as derived and

discussed by Rubel et al. (2008):

$$R_0 = \sqrt{\left[\frac{\delta_M \gamma_M(T) \beta_M(T)}{(\gamma_M(T) + m_M(T)) m_M(T)} \frac{N_B}{K_B} \right] \left[\frac{\delta_M \gamma_B \beta_B(T)}{(\gamma_B + m_B)(\alpha_B + m_B)} \frac{N_M}{K_B} \right]} \quad (2)$$

Fig. 6 shows the time series of $\bar{R}_0$ for the period 1901–2100. While IPCC scenarios have been used to predict the future, observed temperature values were taken to calculate a projection to the past. Major outbreaks may only occur for $\bar{R}_0 > 1$, firstly calculated for the observed USUV epidemics 2001–2005. Thus, our backward prediction using observed temperatures shows that USUV was not able to cause major outbreaks in the past. Nevertheless,

Table 2

Average percentages of susceptible (S_B), immune (R_B) and total birds (N_B) during the period 2076–2100 as simulated with temperature data from five climate models using four emission scenarios

Scenario	ECHam4	HadCM3	CGCM2	CSIRO2	PCM	Mean	±95% CI
A1							
S_B	12.3	13.6	18.0	30.2	NA	18.5	13.0
R_B	63.3	62.7	59.8	51.4	NA	59.3	8.8
N_B	76.3	77.0	78.6	82.3	NA	78.5	4.2
A2							
S_B	13.6	14.6	22.4	27.2	NA	19.5	10.4
R_B	62.8	62.1	56.8	53.5	NA	58.8	7.0
N_B	77.1	77.5	79.9	81.4	NA	79.0	3.2
B2							
S_B	18.0	19.2	30.0	34.2	41.4	28.6	12.4
R_B	59.9	59.1	51.5	48.6	43.3	52.5	8.8
N_B	78.6	79.0	82.1	83.4	85.3	81.7	3.5
B1							
S_B	16.8	21.3	37.2	40.9	50.3	33.3	17.3
R_B	60.7	57.7	46.3	43.8	36.8	49.1	12.3
N_B	78.2	79.6	84.2	85.2	87.6	83.0	4.9

Values for worst-case scenario (ECHam4, A1) and best-case scenario (PCM, B1) in bold, “NA” for virus-free scenarios (PCM, A1 and A2).

Table 3

Average percentages of annually accumulated dead birds (D_B) during the period 2076–2100 as simulated with temperature data from five climate models using four emission scenarios

Scenario	ECHam4	HadCM3	CGCM2	CSIRO2	PCM	Mean	±95% CI
A1	11.9	11.8	11.2	9.8	NA	11.2	1.5
A2	11.8	11.7	10.7	10.2	NA	11.1	1.2
B2	11.2	11.1	9.8	9.4	8.4	10.0	1.5
B1	11.4	10.8	8.9	8.5	7.3	9.4	2.1

Values for worst-case scenario (ECHam4, A1) and best-case scenario (PCM, B1) in bold, “NA” for virus-free scenarios (PCM, A1 and A2).

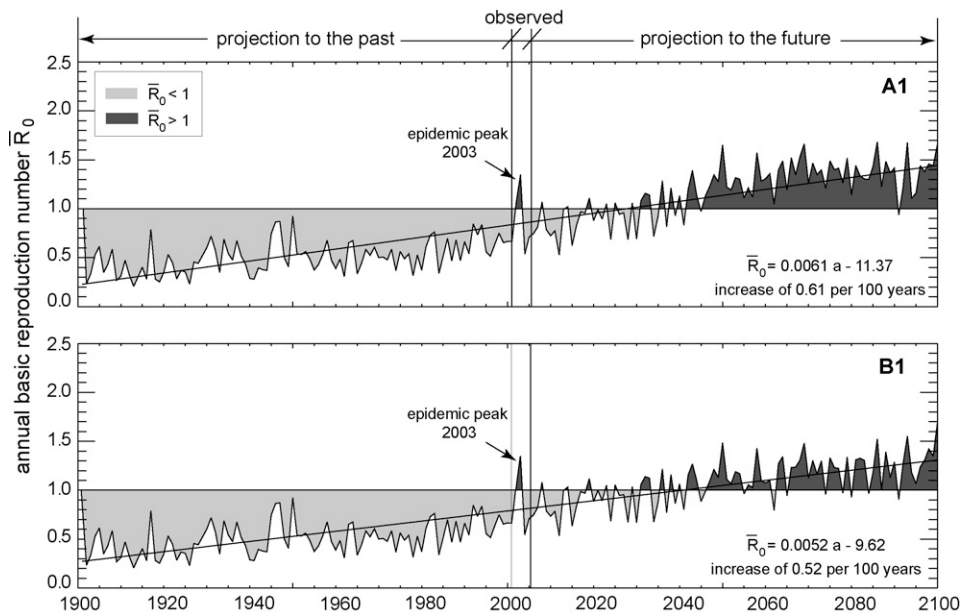


Fig. 6. Mean annual basic reproduction numbers for the IPCC worst-case scenarios A1 (upper panel) and best-case scenarios B1 (lower panel). Linear trends for the period 1901–2100 indicate an increase of $\bar{R}_0 = 0.61$ per 100 years for the A1 and $\bar{R}_0 = 0.52$ per 100 years for the B1 scenario.

minor outbreaks below some detection threshold were possible, because of the annual cycle of $\bar{R}_0$ (not shown).

6. Discussion

From 20 scenario-model combinations we examined, only two were predicted to lead to extinction of USUV (PCM, A1 and A2 scenarios). The other 18 combinations lead to endemicity in Central Europe through the end of the century. It is therefore very likely, that the virus survives in Central Europe until the end of the century. We do not further investigate the possibilities for local extinction because we assume that the USUV is continuously introduced by migratory birds. Thus, the most important epidemiological quantity determining major outbreaks is the basic reproduction number $\bar{R}_0$. It predicts optimal environmental conditions for USUV outbreaks due to global warming in about 10 years. On the other hand, undetected USUV outbreaks before the observed outbreak in 2003 are very unlikely.

Our estimations seem realistic when compared to the observed large-scale declines in the bird populations caused by WNV infections in North America (LaDeau et al., 2007). Possible effects of global warming concerning bird and mosquito populations due to changes in land cover, availability of food or other environmental factors have not been considered; i.e. the carrying capacity of birds K_B and mosquitoes K_M were assumed to be constant during the investigation period 2001–2100.

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