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# Modelling the regional impact of climate change on the suitability of the establishment of the Asian tiger mosquito (*Aedes albopictus*) in Serbia

**M. Petrić**[1] **· B. Lalić**[2] **· E. Ducheyne**[3] **· V. Djurdjević**[4] **·**
**D. Petrić**[5]

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**Abstract** The Asian tiger mosquito, *Aedes albopictus*, is one of the world's most dangerous invasive species. It has vector competence for a wide range of arboviruses such as chikungunya, dengue, Zika and Rift Valley fever viruses. The vector originated in Asia but has recently spread to the temperate regions of Europe and North America. Further spread to the north and the east and a shift to higher altitudes could be expected as a result of climate change. This makes modelling the regional climatic suitability for the establishment of *A. albopictus* in naïve regions a pressing issue. The future suitability and subsequent seasonal activity of the vector were investigated using three mechanistic models, with climatic data from the Eta Belgrade University-Princeton Ocean Model regional climate model. The results showed that after a slight decrease in suitability for the first part of the century, most of Serbia would become significantly more suitable for the establishment of *A. albopictus*. This is due to the simulated rise in seasonal and annual temperatures by the end of the twenty-first century. This study allows for the incorporation of regional heterogeneity in vector modelling. The spatial resolution of the

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✉ M. Petrić
petricmina9@gmail.com

[1] Department of Physics, Faculty of Sciences, University of Novi Sad, Trg Dositeja Obradovića 3, Novi Sad 21000, Serbia

[2] Department of Field and Vegetable Crops, Faculty of Agriculture, University of Novi Sad, Trg Dositeja Obradovića 8, Novi Sad 21000, Serbia

[3] Avia-GIS, Risschotlei 33, 2980 Zoersel, Belgium

[4] Institute of Meteorology, Faculty of Physics, University of Belgrade, Dobračina 16, Belgrade 11000, Serbia

[5] Laboratory for Medical and Veterinary Entomology, Faculty of Agriculture, University of Novi Sad, Trg Dositeja Obradovića 8, Novi Sad 21000, Serbia

maps obtained from a regional analysis is much higher than that acquired by a global model, allowing for detailed risk assessment and planning of surveillance focused on the habitats where the main introduction routes and climatic suitability are coupled. This work should be applied to all countries in the region with the risk of introduction or further spread of *A. albopictus*.

## 1 Introduction

The Asian tiger mosquito, *Aedes albopictus*, represents a rising threat to human and animal health in Europe. It has a vector capacity/competence for a wide range of viruses, including chikungunya, Zika (Wong et al. 2013; Grard et al. 2014), dengue and Rift Valley fever viruses, as well as *Dirofilaria immitis* and *Dirofilaria repens* filarial worms (Shroyer 1986). A viraemic dengue primary infection caused by the dengue virus 3 genotype imported from Cuba was reported in Serbia on the 29th of September 2015 (Petrović et al. 2016). *D. immitis* and *D. repens* have been present in Serbia since their first detection in 1999 (Savić et al. 2015). There have so far been no reported cases of Zika, chikungunya or Rift Valley fever in Serbia. However, chikungunya outbreaks have been reported in Italy (ECDC 2007), and dengue has been reported in neighbouring Croatia (Gjenero-Margan et al. 2011). The risk of introduction and transmission of these and other emerging and re-emerging vector-borne diseases (VBDs) emphasizes the need to develop detailed vector distribution models as a necessary precursor for targeted surveillance of invasive *A. albopictus* and associated vector-borne pathogens.

The Asian tiger mosquito originates in the subtropical regions of Southeast Asia. In recent decades, it has spread to many countries worldwide. Larvae develop in transient water in natural and human-made containers. This preference, together with the ability of females to lay desiccation-resistant eggs, has enabled them to survive intercontinental transport. The most likely form of transport for *A. albopictus* eggs is the used tire trade. In addition, the mosquito could also be globally transported by plant trade; it was introduced in California (Madon et al. 2003) and the Netherlands (Scholte et al. 2007) by containerized oceanic shipments of *lucky bamboo* (*Dracaena* spp.) from Southeast Asia (China and Taiwan). The rate of spread of the vector was found to be proportional to the increase in international trade (Ficher et al. 2011). The spatial distribution of *A. albopictus* was confined to parts of Asia, India and several islands in the Pacific Ocean until the second half of the twentieth century. Since then, it has spread to Europe, North America, South America, Africa and the Middle East. Coastal regions with suitable climates are the trade-driven hot spots for establishment in Europe. However, ports are not the final destination for the vector, as tires with eggs or adult mosquitoes are usually transported further inland, where unsuitable climatic conditions could be a major limiting factor in future spread.

Temperate strains of *A. albopictus* have developed the ability to induce photoperiodic egg diapause, allowing overwintering in temperate regions and further assisting its establishment in more northerly latitudes (Hawley 1988). The environmental parameters limiting the establishment and seasonal activity of *A. albopictus* are rainfall, temperature and photoperiods, most significant being the annual and seasonal temperatures, mean monthly temperature of the coldest month, annual precipitation and frequency of rainy days (Kobayashi et al. 2002; ECDC 2009; Caminade et al. 2012). Hatching is influenced by the spring photoperiod and temperature; however, the overall activity and abundance of *A. albopictus* depends on the June-July-August air temperatures and annual precipitation (Medlock et al. 2006). The northern range of the vector is limited by winter temperatures and annual precipitation (Kobayashi et al. 2002).

Several studies address the topic of modelling the climatic suitability of the establishment of *A. albopictus* in Europe (e.g. Medlock et al. 2006; ECDC 2009; Fischer et al. 2011; Roiz et al. 2011; Caminade et al. 2012; Koch et al. 2015; Roche et al. 2015). Only one of these studies concentrates on the influence of climate change on the future distribution of climatically suitable habitats on a local level (Roiz et al. 2011).

The existing models for the assessment of climatic suitability for *A. albopictus* can be methodologically grouped into two categories: mechanistic and correlative (niche) models. Mechanistic models do not require presence/absence vector data. Most are based on the construction of *overlay* functions for relevant climatic factors in GIS-based environments according to empirically set thresholds (Medlock et al. 2006; ECDC 2009; Caminade et al. 2012). On the other hand, correlative environmental models rely on a stochastic approach based on the relationship between vector occurrence and various abiotic variables (ECDC 2009; Roiz et al. 2011; Fischer et al. 2011; Koch et al. 2015; Roche et al. 2015).

In Serbia, vector surveillance has been conducted by ovitraps at the most frequent border crossings to the countries where *A. albopictus* is established (Petrić et al. 2012). The eggs were collected from the end of July to September every year since 2009, when it was first detected. Henceforth, the presence of *A. albopictus* was recorded for six consecutive years at the border of Croatia (2009–2015) (Petrić et al. 2012; Petrić, unpublished) and from 2014 to 2016 at the border of Montenegro (Petrić, unpublished).

We used three mechanistic models to evaluate the climatic suitability for the establishment and the seasonal activity of *A. albopictus* based on the multi-model approach by Caminade et al. (2012). The models were as follows: a GIS-based model (model 1) developed by Kobayashi et al. (2002), a multi-criteria decision analysis model (model 2) developed by the European Centre for Disease Prevention and Control (ECDC 2009) and a seasonal activity model (model 3) developed by Medlock et al. (2006). The first two models were used to examine the climatic suitability for the establishment of *A. albopictus* in Serbia (model 1 and model 2) while the third model (model 3) was used to explore potential adult mosquito activity, which was defined by the number of weeks between spring hatching and the laying of diapausing eggs in autumn. The multi-model approach allows for the assessment of the variability in the simulated distribution and the evaluation of the differences that arise due to the use of different abiotic factors for suitability assessment.

The primary objective of this study was to assess the impact of climate change (CC) on the climatic suitability for the establishment and seasonal activity of *A. albopictus* in Serbia, based on outputs from a regional climate model. The continuing interception and seasonal presence of *A. albopictus* in Serbia (Petrić et al. 2012; Petrić, unpublished) encouraged us to model how the simulated CC would affect suitability for the establishment of the vector and whether its seasonal occurrence would be long enough to cause a significant biting nuisance and potentially influence the transmission of VBDs in Serbia. The incorporation of precise, regional vector suitability modelling can provide missing support to medical entomologists and public health specialists, enabling a targeted interdisciplinary approach to surveillance of invasive mosquitoes and the diseases they transmit.

## 2 Materials and methods

### 2.1 Datasets

Temperature and precipitation values were derived from two sources of climate data. The database of the Republic Hydrometeorological Service of Serbia (RHMSS) was used for the observed climate data from the 1971–2000 reference period. It consists of meteorological data from 16 sites (Fig. 1), with daily values for mean air temperature (°C) (measured at 2 m) and daily total precipitation (mm). Daily values for photoperiod (h) were calculated for each location using the CBM model developed by Forsythe et al. (1995).

Climate projections were used from the Eta Belgrade University (EBU)-Princeton Ocean Model (POM) model for the A2 scenario over the 2001–2030 and 2071–2100 integration periods (Djurdjević and Rajković 2012) for 30 sites (Fig. 1). The EBU-POM is a two-way, coupled regional climate model. The atmospheric part is the Eta/National Centers for Environmental Prediction (NCEP) limited area model (resolution 0.25° × 0.25° on 32 vertical levels; centred at 41.5° N, 15° E, with boundaries at

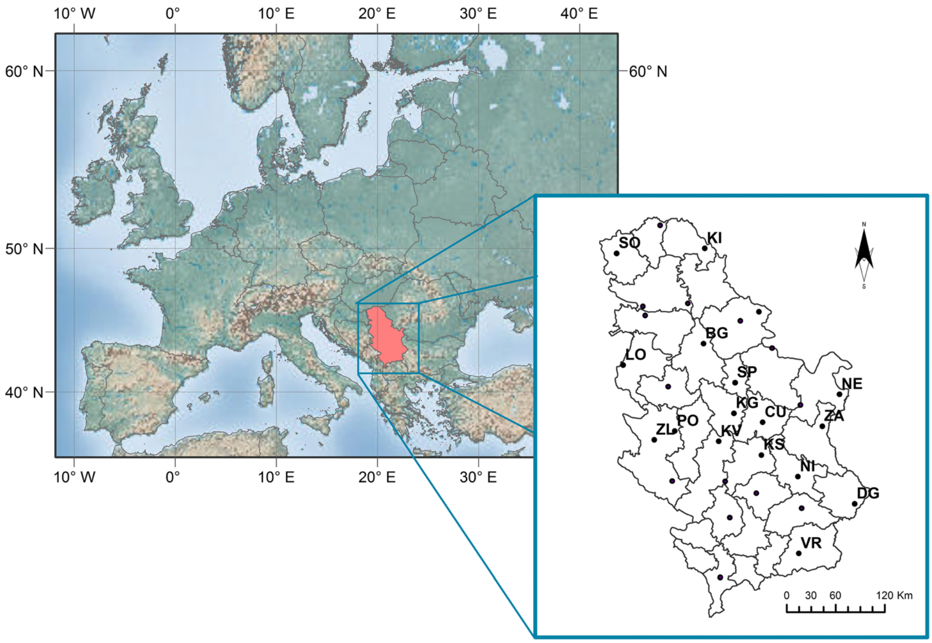

**Fig. 1** The 16 sites used in the study. *SO* Sombor, *KI* Kikinda, *LO* Loznica, *BG* Belgrade, *KG* Kragujevac, *SP* Smedervska Palanka, *NE* Negotin, *ZL* Zlatibor, *PO* Požega, *KV* Kraljevo, *KS* Kruševac, *CU* Ćuprija, *NI* Niš, *ZA* Zaječar, *DG* Dimitrovgrad, *VR* Vranje. Unlabelled sites indicate 14 additional locations used in the analysis of future suitability for 2001–2030 and 2071–2100 (EBU-POM)

±19.9° W–E and ±13.0° S–N; defined on the Arakawa E-grid), while the oceanic part is the POM (resolution 0.20° × 0.20° on 21 vertical levels). The coupling was performed with a 6-min time step. The driving global circulation model (GCM) is the ECHAM5 (ECMWF Hamburg Atmospheric Model 5) model (Roeckner et al. 2003) coupled with the Max Planck Institute Ocean Model (MPI-OM) (Jungclaus et al. 2006). The atmospheric component is defined on the Gaussian grid. The model physics package includes turbulence, large-scale precipitation and convection. Specifically, the EBU-POM uses a Goddard radiation scheme, Mellor-Yamada-Janjić turbulence scheme, Monin-Obukhov PBL scheme with viscous sublayer, NOAH land surface parameterization scheme and Betts-Miller-Janjić convective adjustment scheme. A statistical method of bias correction was applied to surface air temperatures and daily precipitation with calibration functions that are derived using observations on these locations over the period 1961–1990 and model results from historical run over the same time period. Calibration functions are derived following the methodology presented in Dettinger et al. (2004) and Piani et al. (2010) for each station and each month separately.

The datasets for temperature, precipitation and photoperiod were assembled in R project and ArcGIS. The values for the mean annual temperature ($T_a$), mean January temperature ($T_{Jan}$) and mean temperature for June, July and August ($T_{JJA}$) were calculated by averaging the daily temperature data for the model projections as well as the historical period. Total annual precipitation ($H_a$) was calculated from daily precipitation values. Weekly temperature values for a 13-week period in spring ($T_{Spr}$) and autumn ($T_{Aut}$) were also calculated and used together with daily photoperiod values in spring ($S_{pp}$) and autumn ($C_{pp}$) to derive a weekly activity of *A. albopictus*. Table 1 shows the simulated change in annual temperature and precipitation, as well as the change in the mean January temperature with respect to the reference period (1971–2000) for the 16 representative sites considered in this study.

**Table 1** Change in annual precipitation ($\delta H_a$), annual temperature ($\Delta T_a$) and the mean January temperature ($\Delta T_{Jan}$) for 2001–2030 and 2071–2100 projections

| Site | Abbreviation | Long (° E) | Lat (° N) | Alt (m) | (2001–2030) | | | (2071–2100) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $\delta H_a$ (%) | $\Delta T_a$ (°C) | $\Delta T_{Jan}$ (°C) | δHa (%) | $\Delta T_a$ (°C) | $\Delta T_{Jan}$ (°C) |
| Sombor | SO | 19.08 | 45.78 | 88 | 8.44 | 0.47 | −0.62 | −2.51 | 4.07 | 4.85 |
| Kikinda | KI | 20.47 | 45.85 | 81 | 10.62 | 0.43 | −0.70 | 0.47 | 4.05 | 5.05 |
| Loznica | LO | 19.22 | 44.55 | 121 | 6.37 | 0.49 | −1.03 | −10.28 | 4.27 | 4.76 |
| Beograd | BG | 20.46 | 44.8 | 132 | 8.36 | 0.46 | −0.74 | −7.82 | 4.14 | 4.86 |
| Kragujevac | KG | 20.93 | 44.03 | 197 | 9.47 | 0.55 | −0.62 | −8.90 | 4.33 | 5.14 |
| Smederevska Palanka | SP | 20.95 | 44.37 | 122 | 8.44 | 0.53 | −0.72 | −9.23 | 4.31 | 5.15 |
| Negotin | NE | 22.55 | 44.23 | 42 | 3.14 | 0.69 | 0.15 | −17.22 | 4.21 | 4.90 |
| Zlatibor | ZL | 19.72 | 43.73 | 1028 | 3.65 | 0.58 | −0.73 | −15.24 | 4.35 | 4.72 |
| Požega | PO | 20.03 | 43.83 | 310 | 6.74 | 0.58 | −0.72 | −11.39 | 4.12 | 4.35 |
| Kraljevo | KV | 20.7 | 43.72 | 215 | 7.88 | 0.61 | −0.55 | −11.86 | 4.09 | 4.38 |
| Kruševac | KS | 21.35 | 43.57 | 166 | 10.24 | 0.65 | −0.48 | −10.45 | 4.26 | 4.79 |
| Ćuprija | CU | 21.37 | 43.93 | 123 | 9.36 | 0.68 | −0.41 | −8.96 | 4.35 | 4.61 |
| Niš | NI | 21.9 | 43.33 | 201 | 7.83 | 0.68 | −0.36 | −10.03 | 4.22 | 4.49 |
| Zaječar | ZA | 22.28 | 43.88 | 144 | 13.36 | 0.66 | −0.19 | −7.02 | 4.30 | 5.05 |
| Dimitrovgrad | DG | 22.75 | 43.02 | 450 | 8.37 | 0.76 | −0.24 | −8.99 | 4.16 | 4.27 |
| Vranje | VR | 21.9 | 42.48 | 432 | 7.64 | 0.69 | −0.28 | −11.01 | 4.04 | 4.11 |

For the creation of a gridded dataset, we used a Cokriging spatial interpolation algorithm with an elevation layer from the SRTM30 dataset, aggregated to 30-s resolution (CGIAR-CSI 2008).

## 2.2 Models

### *2.2.1 Climatic suitability for the overwintering of A. albopictus*

The overwintering criterion was constructed using the annual precipitation sum ($H_a$) and mean January temperature ($T_{Jan}$). The models were used to create a zone where overwintering was possible. Suitable climatic conditions for the overwintering of *A. albopictus* were defined with $H_a$ over 700 mm and $T_{Jan}$ over 2 °C (Medlock et al. 2006). The less favourable conditions in which eggs could still survive were classified into three categories: medium suitability ($1\ °C \le T_{Jan} < 2\ °C$, $600\ mm \le H_a < 700\ mm$), low suitability ($0\ °C \le T_{Jan} < 1\ °C$, $500\ mm \le H_a < 600\ mm$) and unsuitable conditions ($T_{Jan} < 0\ °C$, $H_a < 500\ mm$) (Medlock et al. 2006). For a more detailed analysis, see Online Resource 1.

### *2.2.2 Mechanistic GIS-based model for evaluating the climatic suitability for establishment of A. albopictus*

A mechanistic GIS-based model (model 1) was designed to incorporate the overwintering criterion together with the mean annual temperature ($T_a$) to obtain the climatic suitability for the establishment of *A. albopictus*. Maximum suitability was defined by $T_a$ over 12 °C following the finding of Kobayashi et al. (2002). The $T_a$ intervals that defined three suitability scenarios were 11–12 °C (high risk), 10–11 °C (medium risk) and 9–10 °C (low risk). The overwintering condition ($T_{Jan} < 0\ °C$, $H_a < 500\ mm$) was used as a cut-off criterion for determining the areas where a mosquito would not be expected to overwinter. For the areas where overwintering was possible, suitability was calculated as a linear combination of the three overwintering scenarios and $T_a$, rescaled to a 0–100 scale for easier interpretation.

### *2.2.3 Mechanistic multi-criteria decision analysis model*

Model 2 was a mechanistic model used for the analysis of the climatic suitability for the establishment of *A. albopictus*. Sigma fuzzy membership functions for three climatic variables were developed: total annual precipitation ($H_a$); the mean temperature for the period June, July and August ($T_{JJA}$); and the mean January temperature ($T_{Jan}$). The membership function is a curve that defines how each value of the environmental variable is mapped to a membership value corresponding to suitability. More specifically, it is a continuous, smooth, sigma function defined by maximum and minimum empirically determined threshold values. This model did not incorporate the overwintering criterion but considered vector overwintering through the $T_{Jan}$ sigma function.

Membership functions were constructed based on empirical criteria and expert advice for the selected variables. This process-based mechanistic approach was analogous to that followed by ECDC (2009) and explored in Caminade et al. (2012). For total annual precipitation, the minimum suitability was defined as $H_a$ <450 mm, and the maximum was defined by precipitation values over 800 mm. The sigmoid for January temperatures was defined by threshold values of −1 and 3 °C. The symmetric membership function for $T_{\mathrm{JJA}}$ was constructed as a combination of two sigma functions, such that the maximum suitability lies in the interval of 20–25 °C, and the minimum suitability was defined for temperature values less than 15 °C and over 35 °C. The final suitability was calculated as a linear combination of these three functions with equal statistical weight. This value was standardized to the 0–100 scale.

### *2.2.4 Seasonal activity model*

Model 3 is a GIS mechanistic model that assessed the ability for overwintering eggs to survive and predicts the hatching of spring eggs and the subsequent production of diapausing eggs in autumn. It combined the overwintering criterion with the mean weekly temperatures for the hatching period in spring (March 1st–May 30th) and autumn (September 23rd–December 22nd) and daily photoperiod values to model the number of weeks in the annual active season for *A. albopictus*. Seasonal activity is calculated for two scenarios with different critical autumn photoperiods ($C_{\mathrm{pp}}$). For scenario 1, the spring criterion was set with a temperature threshold of 10–11 °C ($T_{\mathrm{Spr}}$) and a critical photoperiod above 11–11.5 h ($S_{\mathrm{pp}}$). The date for the laying of diapausing eggs in autumn was determined by temperatures at 9–10 °C ($T_{\mathrm{Aut}}$) and a critical photoperiod below 13–14 h ($C_{\mathrm{pp}}$) (Medlock et al. 2006). Scenario 2 uses the same values for $T_{\mathrm{Spr}}$, $T_{\mathrm{Aut}}$ and $S_{\mathrm{pp}}$ as Scenario 1 but employs a decreased critical photoperiod ($C_{\mathrm{pp}}$). This scenario was used to explore the effect of an 11–12 h threshold, which agrees with the findings of Kobayashi et al. (2002).

High-, medium- and low-risk cases in both scenarios were considered to assess the way in which variability in $T_{\mathrm{Spr}}$ and $T_{\mathrm{Aut}}$ and day length affected the annual activity of the vector. More precisely, both scenarios consider three categories: high risk ($T_{\mathrm{Spr}} > 10$ °C, $T_{\mathrm{Aut}} < 9.5$ °C, $S_{\mathrm{pp}} > 11$ h), medium risk ($T_{\mathrm{Spr}} > 10.5$ °C, $T_{\mathrm{Aut}} < 9.5$ °C, $S_{\mathrm{pp}} > 11.25$ h) and low risk ($T_{\mathrm{Spr}} > 11$ °C, $T_{\mathrm{Aut}} < 10$ °C, $S_{\mathrm{pp}} > 11.5$ h). Autumn $C_{\mathrm{pp}}$ is defined for Scenario 1 as high risk ($C_{\mathrm{pp}} < 13$ h), medium risk ($C_{\mathrm{pp}} < 13.5$ h) and low risk ($C_{\mathrm{pp}} < 14$ h), and it is defined for Scenario 2 as high risk ($C_{\mathrm{pp}} < 11$ h), medium risk ($C_{\mathrm{pp}} < 11.5$ h) and low risk ($C_{\mathrm{pp}} < 12$ h). The medium risk scenario represents the median of each interval and was used as the most likely scenario (see Online Resource 1).

## 3 Results

### 3.1 Past climatic suitability for the establishment of *A. albopictus* (climatology 1971–2000)

When considering model 1, the northern parts of central Serbia, an area on the western boarder and part of southern Serbia, could support the establishment of *A. albopictus* from 1971 to 2000 (Fig. 2a). On the other hand, the highlands in western Serbia and the Karpatian region on the east appeared unsuitable. This was related to low $T_{\mathrm{Jan}}$ values in these regions that did not meet the overwintering threshold of 0 °C. Similar results were highlighted using model 2, with the most suitable regions around the capital, Belgrade, and the southern border (Fig. 2b). However, model 2 gave a different suitability pattern

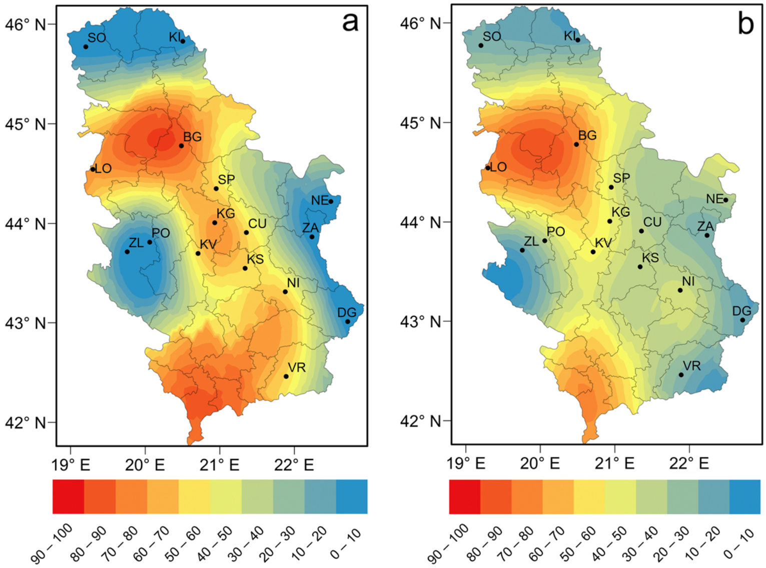

**Fig. 2** Climatic suitability for the establishment of *A. albopictus* based on model 1 (**a**) and model 2 (**b**) for the 1971–2000 reference period

for the remainder of southern Serbia and a significantly lower suitability for central and south-eastern Serbia.

Figure 3a shows the weeks of adult mosquito activity for 1971–2000 under the medium risk scenario for model 3. *Aedes albopictus* had the longest annual activity in the northern belt, east and west from Belgrade and the south of Serbia (Fig. 3a). If introduced, the Asian tiger

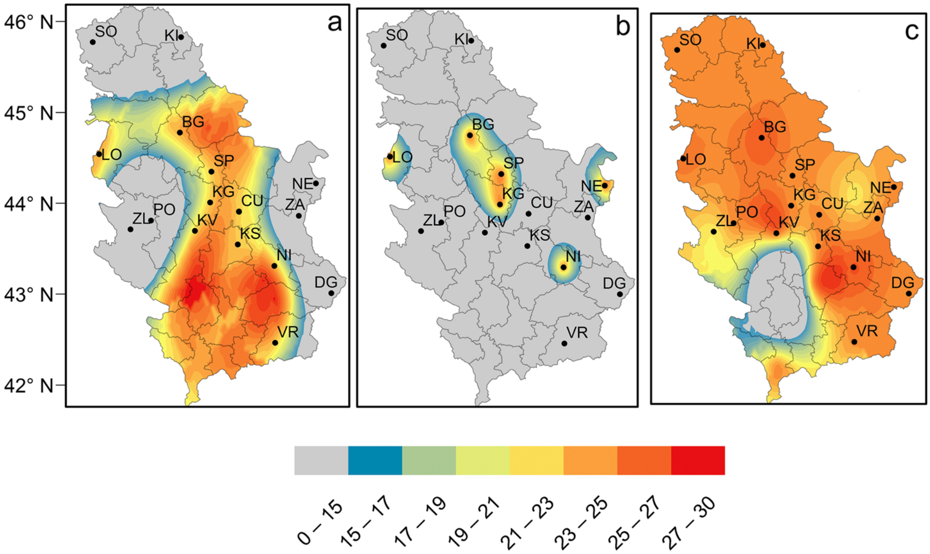

**Fig. 3** Seasonal activity of *A. albopictus* based on Model 3 for the periods 1971–2000 (a), 2001–2030 (b) and 2071–2100 (c)

mosquito would be active for up to 25 weeks, from spring hatching to the autumn production of diapausing eggs.

## 3.2 Climate change impact on climatic suitability for the establishment of *A. albopictus*

### *3.2.1 Climatic suitability and seasonal activity of A. albopictus for 2001–2030*

Models 1 and 2 both simulate a slight decrease in suitability for 2001–2030 (Fig. 4). These changes were chiefly related to the fact that most areas other than certain parts of central Serbia and areas near the eastern border were unsuitable for the overwintering of *A. albopictus* due to a simulated decrease in $T_{\mathrm{Jan}}$ (Table 1).

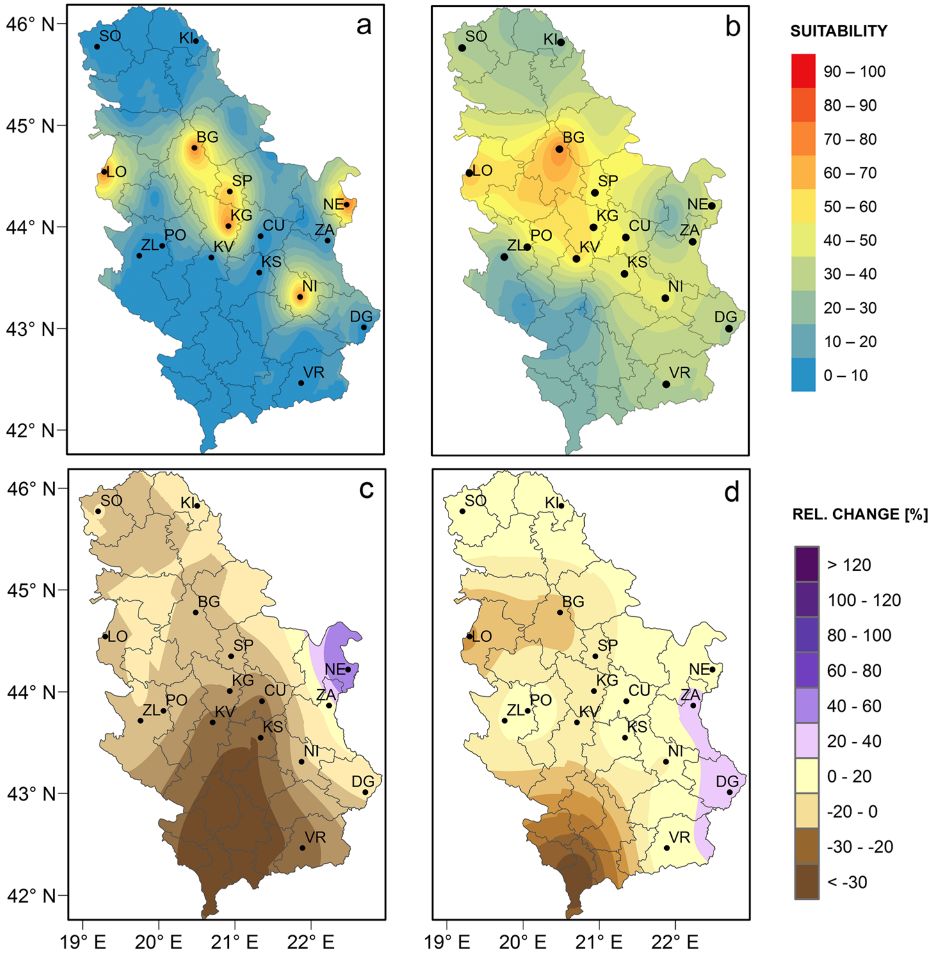

**Fig. 4** Climatic suitability for the establishment of *A. albopictus* for the 2001–2030 integration period according to model 1 (**a**) and model 2 (**b**) and the relative change in climatic suitability for 2001–2030 with respect to the 1971–2000 reference period for model 1 (**c**) and model 2 (**d**)

For this period, the hot spots for the establishment of *A. albopictus* were restricted to central Serbia, areas on the eastern border and the southeast. The relative change of the climatic suitability was negative for most areas of Serbia, with a simulated increase only for areas near the eastern border (Fig. 4c). The simulated suitability was higher according to model 2 (Fig. 4b), in which no strict overwintering criterion was included; only highlands above 1000 m a.s.l. were unsuitable for the establishment of *A. albopictus*. Moreover, the simulated suitability pattern was different that in model 1, with the highest suitability tied to central and western Serbia. The remainder of the country exhibited a moderate suitability for the establishment of the mosquito during 2001–2030. There is an increase in suitability only on the eastern border (Fig. 4c, d). This increase was related to the simulated increase in $T_a$, $T_{JJA}$ and $H_a$.

Under the medium risk scenario for model 3 (Fig. 3b), the mosquito would be active for up to 24 weeks over parts of central and western Serbia and a small region on the eastern border. The activity window would generally be shorter for most parts of Serbia compared to the 1971–2000 period. This slight decrease in activity was related to the poor overwintering conditions calculated for the climate model projections for 2001–2030. Specifically, a decrease in projected $T_{Jan}$ values (Table 1).

### *3.2.2 Climatic suitability and seasonal activity of A. albopictus for 2071–2100*

The climatic suitability for the establishment of *A. albopictus* for 2071–2100 is shown in Fig. 5. A significant increase in suitability is simulated for the end of the century. The area around the western border has the highest suitability for the establishment of the mosquito under both models (Fig. 5a, b). Furthermore, a shift of suitability to higher altitudes is emphasized. Highland regions with altitudes up to 1038 m a.s.l. would be hot spots for establishment by the end of the century. Northern Serbia is simulated to become highly suitable for *A. albopictus* under both models. Moreover, there is a noticeable increase over areas in the north and the eastern border with respect to 1971–2000 for both projections (Fig. 5c, d). However, a significant decrease is simulated for the southern part of the country. This decrease is due to drier conditions in the south and southeast. Although these parts would also experience an increase in $T_{Jan}$, $T_{JJA}$ and $T_a$, the suitability is most affected by a negative relative change in $H_a$ of up to 11% (Table 1).

The future suitability pattern simulated by model 2 was similar to the results from model 1 (Fig. 5b). The biggest increase in suitability was simulated in the northern, north-western and western parts of the country (Fig. 5d). As in model 1, there is a decrease in suitability in the southern part of the country under model 2 due to the projected decrease in $H_a$.

The hot spots defined by model 2 for 1971–2001 and 2001–2030 shifted from the central part of Serbia and the urban and peri-urban areas around Belgrade towards the west (Fig. 5b). This was related to a significant rise in $T_{JJA}$ for the urban area, which would actually exceed the upper threshold for optimal mosquito activity for the continental strain of *A. albopictus* as defined by model 2, making it less suitable for establishment.

Model 3 (Fig. 3c) showed that the simulated number of active weeks for *A. albopictus* under the medium risk scenario would increase over most of Serbia, with up to 28 weeks of mosquito activity. The main factor driving this change is the simulated increase in the mean weekly temperatures during the spring period when hatching occurs, as well as the simulated increase in the mean weekly temperatures in autumn, which would lead to a delay in the production of diapausing eggs and thus prolonged mosquito activity. Areas near the western border and parts of central Serbia had the longest simulated mosquito activity. The most significant increase (up to 4 weeks) could be observed over central, southern and south-eastern Serbia.

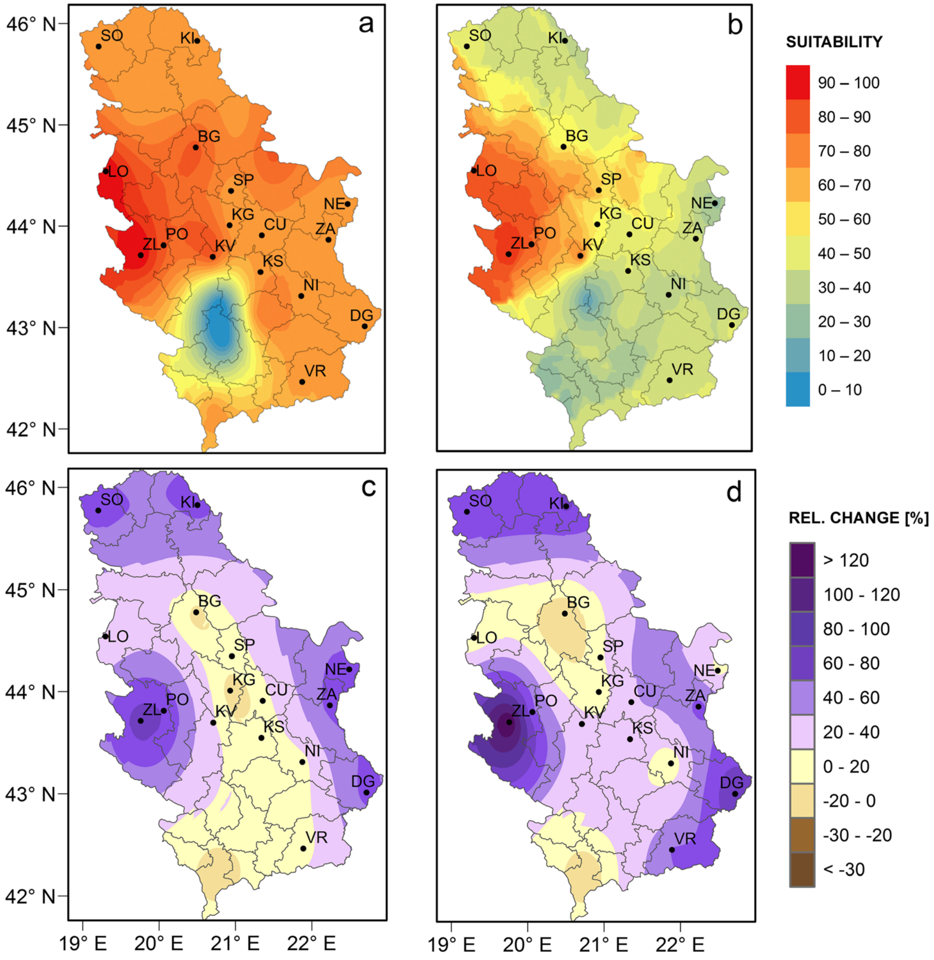

**Fig. 5** Climatic suitability for the establishment of *A. albopictus* for the 2071–2100 integration period according to model 1 (**a**) and model 2 (**b**) and relative change of climatic suitability for 2071–2100 with respect to the 1971–2000 reference period for model 1 (**c**) and model 2 (**d**)

## 4 Discussion

This study is, to our knowledge, the first analysis of climatic suitability for the establishment and subsequent activity of *A. albopictus* in the Balkans. The continuing interception and seasonal presence of *A. albopictus* at the borders of Serbia (Petrić et al. 2012) led us to analyse whether the seasonal occurrence would be long enough for the mosquito to cause a significant biting nuisance and support transmission of VBD in Serbia. This study provides essential information for the establishment of targeted countrywide surveillance of *A. albopictus* and the pathogens it transmits, lowering the future threat of VBDs. A similar approach could be used by other countries under the risk of establishment or spread of *A. albopictus* or other invasive and native vector and pest species.

Three models were used to assess the variability in the simulated distribution and evaluate differences due to the use of various abiotic factors for suitability assessment. There was some spread in comparing the output of model 1 and model 2 regarding the 2001–2030 period, while the model outputs were very well correlated in the projected suitability for 2071–2100. The difference in modelling in the near future was mainly related to simulated changes in $T_{\mathrm{Jan}}$ and the fact that model 2 did not have a strict overwintering criterion. This allowed for compensation from favourable annual precipitation and $T_{\mathrm{JJA}}$ values in areas that were below the 0 °C threshold.

Recent climate change in Serbia (Djurdjević and Rajković 2012) might favour the establishment of *A. albopictus* in 1971–2000. However, the probability of the mosquito being introduced at that time is unlikely, considering it was first observed in Montenegro in 2001 (Petrić et al. 2001), in Croatia in 2004 (Klobučar et al. 2006) and in Bosnia and Herzegovina in 2005 (ECDC 2006). In Serbia, *A. albopictus* was intercepted in two districts in the western and south-western part of the country. It has been present for the past 7 years (2009–2015) on the Croatian border (Batrovci, northwest of Serbia) (Petrić et al. 2012) and on the Montenegro border (Dobrakovo, southwest of Serbia) since 2014 (http://ecdc.europa.eu/en/healthtopics/vectors/vector-maps/Pages/VBORNET_maps.aspx). In 2016, during the VectorNet field study, *A. albopictus* was found established at one site in the northwest of Serbia (Petrić, unpublished). These observations were consistent with the hot spots simulated on the western border in our 2001–2030 model.

An accurate comparison of these results with previous studies of future climatic suitability for the establishment of *A. albopictus* in Europe (ECDC 2009; Fischer et al. 2011; Caminade et al. 2012) cannot be made, as there were clear differences regarding the selected periods, time steps and spatial resolution across models. Nonetheless, a rough qualitative assessment can be made. For instance, ECDC (2009) used ensemble forecasting for 2010 (short term) and 2030 (long term), which was run with different climate scenarios to examine minimum and maximum impact scenarios. Because we used climatic averages over longer time periods, the results cannot be directly compared. However, a qualitative assessment can be made. The minimal impact 2030 simulated trends were in agreement with our findings, showing a decrease in suitability in the Balkan zone, with parts of Romania and Bulgaria becoming unsuitable (ECDC 2009). The decrease in suitability across Serbia was also depicted in the expert knowledge-based model by Fischer et al. (2011) for the near future. However, they predicted a further decrease of climatic suitability for the establishment of *A. albopictus* for the end of the century, which was inconsistent with our results. In contrast, the globally driven statistic-based model employed in the same study (Fischer et al. 2011) failed to simulate a decrease in the near future. However, it showed a significant increase in the end-of-century climatic suitability for Serbia, consistent with our 2071–2100 model results.

Regional climate models produce outputs at a higher spatial resolution than driving models. This is particularly important in CC impact studies, where small-scale heterogeneity must be considered. Vector surveillance is costly; high-resolution models can be of pivotal importance to target crucial areas. Caminade et al. (2012) used an ensemble of ten RCMs from the ENSEMBLES framework (Linden and Mitchell 2009).

Naturally, the presence of the pathogen and its mosquito vector in a given region is a precondition for the existence of VBD. However, if both are available, the likelihood of disease transmission is positively correlated with mosquito abundance and prolonged annual activity. Given the recent outbreak of chikungunya in Italy in 2007, with over 200 people infected (ECDC 2007) and an annual activity estimated at 24 weeks (Caminade et al. 2012), efforts should definitely be made to conduct surveys for *A. albopictus* in future hot spots in Serbia because the simulated activity window for 2071–2100 was up to 28 weeks.

The biggest increase in climatic suitability was simulated for the north, north-west and west of the country, with a significant shift to higher altitudes. This was consistent with the modelled suitability of the species and anticipated changes for the Balkans for short-term and long-term climate change scenarios, as highlighted by ECDC (2009) and Caminade et al. (2012). Extreme cold events in winter and drier conditions resulting from the simulated decrease in annual precipitation may constrain the establishment of the vector in Serbia. On the other hand, one could argue that low precipitation is unlikely to significantly impact the establishment of *A. albopictus* because many human-made containers in urban and peri-urban areas are suitable breeding sites for the vector and will be provided with sufficient water through anthropogenic activities. For example, suitability models tend to under-predict the spatial range of *A. albopictus* around the dry eastern coast of Spain (ECDC 2009, Caminade et al. 2012), while the VectorNet 2016 field study (http://ecdc.europa.eu/en/healthtopics/vectors/vector-maps/Pages/VBORNET_maps.aspx) shows that the Asian tiger mosquito is spreading all along the coast, which can be due to specific water use habits and irrigation practices.

Future work should focus on developing correlative, stochastic models using presence/absence or abundance data in regions that were previously sampled systematically. Detailed knowledge of the current species distribution is crucial for suitability forecasting and for understanding environmental parameters that influence establishment. However, presence/absence data for Serbia is not dense enough, resulting in species distribution information that is inadequate for the development of better suitability models. Future research will focus on applying the same modelling approach to Montenegro, where it can be trained with plentiful presence/absence data for the south part of the country. The model will then be validated through targeted surveillance in the north, where no surveillance has yet been conducted (Pajović, I., personal communication).

Steps should also be taken to model *A. albopictus*-related disease emergence. Vector-borne infections are nonlinear in nature, which makes mechanistic modelling difficult and inadequate for effective intervention. Stochastic models can help explain the dynamics and spread of VBD. Finally, future work should also contemplate the effect of international traffic density and frequency on the spread of *A. albopictus*, while these and other socio-economic factors (water storage habits) have a major influence on the future spread of the vector.

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