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ORIGINAL PAPER

Climate change and risk of arboviral diseases in the state of Rio de Janeiro (Brazil)

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Abstract
Arboviral diseases are a theme of high interest in the field of public and collective health worldwide. Dengue, Zika, and Chikungunya, in particular, have shown significant expansion in terms of morbidity and mortality in different portions of the ecumene. These diseases are of great interest in geographic studies due to the characteristics of their vector (*Aedes aegypti*), adapted to the environmental and unequal context of the urbanization process. Given this background, this study assesses the relationship between global climate change and the risk of arboviral diseases for the state of Rio de Janeiro. To this end, the characteristics of future climate susceptibility to vector proliferation in the scenarios RCP 4.5 and 8.5 (2011-2040 and 2041-2070) were assessed using two models: Eta HadGEM2-ES and Eta MIROC5, as well as the vulnerability conditions that favor the spread of arboviruses. The results indicate that the tendency of thermal and hygrometric elevation, in association with vulnerability, may have repercussions on the intensification and spatial expansion of the risk of arboviral diseases in the state of Rio de Janeiro, since there is a spatial and temporal expansion of the optimal environmental conditions for the development of the vector.

1 Introduction

Risk is an analytical category that comprises the notions of uncertainty and loss. They can be material, economic, about human lives, and related to extreme phenomena of natural, social or technological origin. To Nunes (2009), risk is the probability of harmful consequences caused by the interaction between a triggering event and the vulnerability conditions of the population and for IPCC (2014), trends in vulnerability and exposure are major drivers of changes in disaster risk, and of impacts when risk is realized. Considering this interaction between extreme triggering phenomena and the society exposed to them, Mendonça (2015) developed the notion of hybrid risk, which states that the degree of risk is changeable according to time and space and can be reduced (but never eliminated) by actions that allow people and institutions to be prepared to respond effectively to the harmful effects.

The first dimension of risk is susceptibility, which refers to the propensity of an area to be affected by a certain hazard for an indefinite period of time and must be assessed by the environmental predisposition factors for the occurrence of processes or actions (Julião et al. 2009). The second dimension is vulnerability, which incorporates the unequal production of space and the unjust reproduction of society; a model that encourages spatial differentiation and an unequal insertion of people, organizations and territories in the world system (Smith 1988; Harvey 1989, 2004; Santos 2008). Therefore, it regards the conditions that favor or facilitate the repercussion of a hazard. From this dimension, it is possible to apprehend that the diverse phenomena will materialize from the social, economic, and cultural heterogeneities.

In the field of human health, vulnerability and space can be conceived as social products, being subject to the logics and processes of structuration of society and, consequently, to the principles of socio-spatial reproduction. Such principles perpetuate inequalities, making some spaces and social organizations healthier than others, being very useful to the understanding of spatial logic, as well as the epidemiological profiles of health and disease (Barata 2009; Smith 1988).

In the context of climate change several risks are potentiated, among them the risk to human health (IPCC 2014).

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Arboviral diseases, including Neglected diseases (WHO, 2012) such as Dengue, Chikungunya, Zika, and others have aroused considerable concerns in the field of public health worldwide (Donalisio et al. 2017), especially because the incidence of diseases caused by arboviruses relevantly increased worldwide (Gould et al. 2017). This growth is explained by factors such as: intensive growth of global transport systems; adaptation of vectors to increasing urbanization; inability to contain the mosquito population; and changes in environmental factors (Gould et al. 2017).

In the Brazilian case, the history and model of territorial organization and urbanization have created fundamental conditions that favor the proliferation of diseases. While environmental changes, especially climatic ones, provide adequate conditions for the proliferation of the vector (Gregianini et al. 2017), the social determinants reveal the logic of epidemics, outbreaks and endemics, whose explanatory bases also lie in the unequal and corporate urbanization developing in Brazil (Santos 1993). Various communicable diseases have in the climate one of their conditioning factors for proliferation by the action of different vectors (Rouquayrol 1993); in order to face this problem, it is fundamentally important to deepen the understanding of the climate and monitoring techniques.

Regarding dengue, one of the main arboviral diseases and the focus of several studies (Oliveira 2019; Aleixo and Sant'Anna Neto 2011; Mendonca et al. 2011; Hayden et al. 2010; Consoli and Oliveira 1994), it is already possible to acknowledge the decisive role of climate for the understanding of its development process. *Aedes aegypti,* the vector of these arboviral diseases that affect the Brazilian population, is normally found in humid tropical and subtropical regions between latitudes 35° N and 35° S. They can also be found outside these limits, although very close to the mean annual isotherm of 20 °C or the winter isotherms of 10 °C, an evidence of the endemic condition the climate represents to the mosquito (Consoli and Oliveira 1994).

It is relatively well established in the scientific community that the climatic elements that influence living beings the most in the transmission process of arboviral diseases are air temperature, relative humidity and rainfall; nonetheless, wind speed also causes a small interference in the vector displacement. (Rouquayrol 1993).

Temperature and precipitation can influence the transmission of dengue, impacting the population of the vector. The abundance of *Aedes aegypti* is partially regulated by precipitation, creating breeding grounds and stimulating the development of eggs (Foo et al. 1985). Alternatively, temperature influences the mosquito's ability to survive and determines its development and reproductive rates (Johansson et al. 2009; Mendonça et al. 2011).

Mendonça (2003), Reiter (2004), Patz et al. (2005), and Confalonieri and Marinho (2007), among many others, have established important relationships between global climate change and human health. In their analyses, they highlighted the perspectives of global climate warming and their repercussions on health, pointing out that, in accordance with climatic scenarios for the near and long future, there will be an intensification of human morbidity and mortality as a result of the direct and indirect impacts of global climate change. Communicable diseases are expected to cause far more impacts in society than today. Therefore, it is imperative to develop studies and public policies to act in the present, but at the same time in a preventive way, regarding climate change and its regional and local repercussions.

Such findings are valuable because there is no clinical control for arboviral diseases, so monitoring environmental conditions and deepening the understanding of the correlation between vector and climate are essential for disease control. However, it is known that the control of diseases such as dengue is based on interventions throughout the epidemiological chain that are capable of interrupting it. Because of this, it is fundamental to analyze susceptibility (the climatic characteristics that favor the propagation of the vector) and vulnerability (those socio-territorial conditions that favor the propagation of the vector). Both of them associatively contribute to understanding the risk of arboviral diseases.

Data released by government agencies reinforce the urgency, topicality and relevance of arboviruses disease in Brazil, especially dengue fever (Table 1). According to data from the Brazilian Ministry of Health, in the last decade over 11 million people have been infected with arboviruses in the country, in particular dengue fever, responsible for 91% of these infections, largely explained by the recent circulation of other diseases in Brazil. The years of 2010, 2013, 2015, 2016, 2019, and 2020 were the most epidemic, suggestive of years of introduction of new serotypes of the disease. Rio de Janeiro state follows national trends, accounting for 7.6% of national notifications of dengue fever and 24.4% of notifications of Zika virus. It is important to note that there are no official reported cases of chikungunya fever for this state.

In view of the above, this article aims to analyze the impacts of climate change on the expansion of *Aedes aegypti,* responsible for the main arboviral diseases (Dengue fever, Zika virus and Chikungunya fever) in the state of Rio de Janeiro (Fig. 1).

2 Data and approach

2.1 Regional simulations of climate models

The Earth System Models (ESMs) are capable of representing biogeochemical processes that interact with the physical climate and alter its response to forcing, such as that associated with human-caused emissions of greenhouse gases (Flato 2011), having become fundamental for the environmental

Table 1 Arboviruses notification in Brazil e Rio de Janeiro between 2010 and 2020. Source: Brazilian Ministry of Health (2021)

Year	Arboviruses notification in Brazil			Arboviruses notification in Rio de Janeiro		
	Dengue fever	Chikungunya fever	Zika virus	Dengue fever	Chikungunya fever	Zika virus
2010	985,488			26,700		
2011	689,277			158,481		
2012	582,365			178,518		
2013	1,433,344			208,771		
2014	591,128			7,860		
2015	1,697,801			73,666		
2016	1,518,858		281,464	88,616		83,532
2017	243,336	247,692	32,684	11,035		2,962
2018	266,386	118,765	19,551	14,917		3,969
2019	1,556,595	178,500	30,500	32,276		2,862
2020	965,019	99,804	19,300	4,590		307
Total	10,529,597	644,761	383,499	805,430		93,632

planning of the territory. By simulating important physical and dynamic processes, it can represent the complex interactions that influence the climate, the interactions between the components of the terrestrial system (mainly atmosphere, biosphere and hydrosphere) and the feedback mechanisms, including changes in frequency and intensity of extreme events

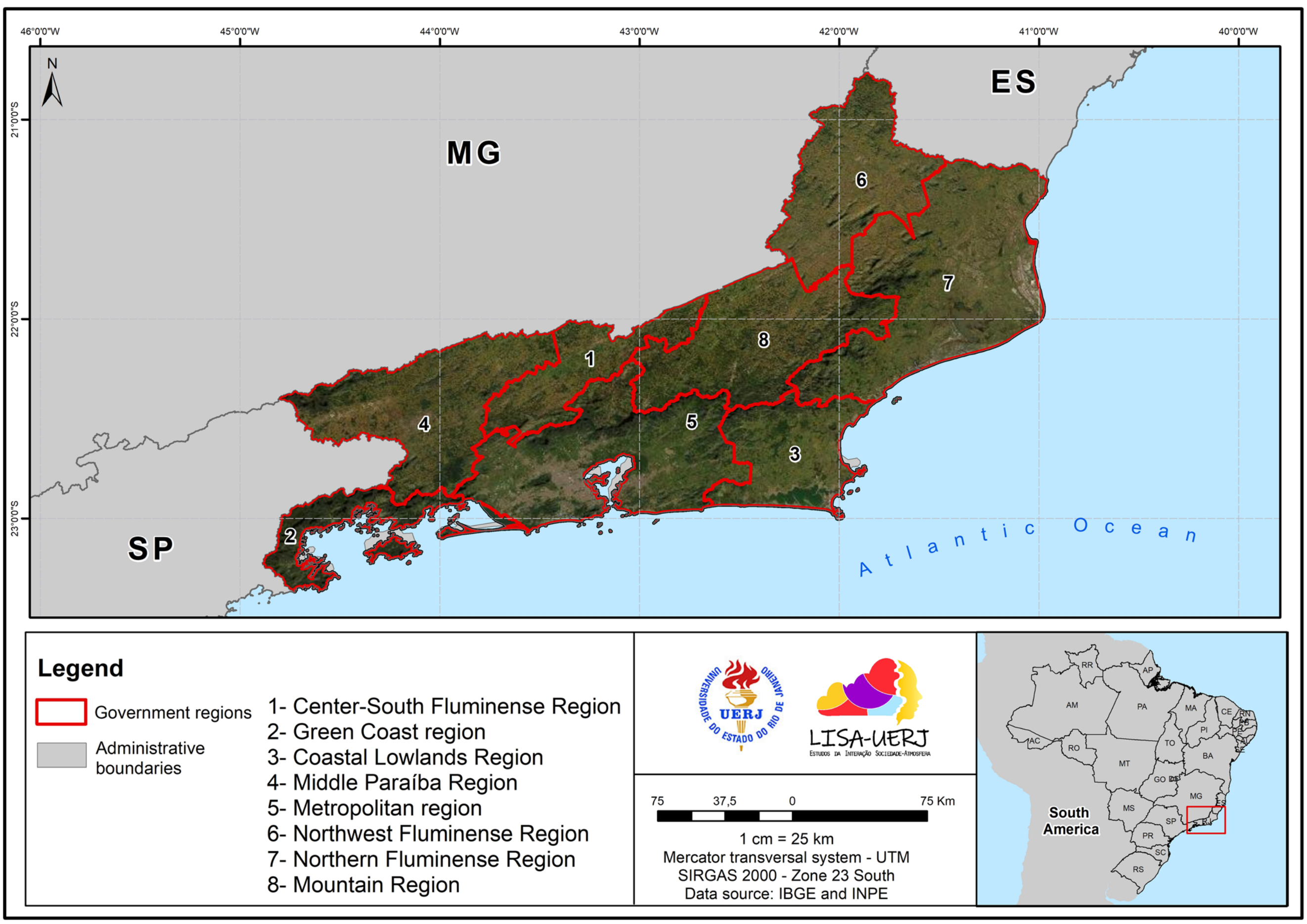

Fig. 1 State of Rio de Janeiro and government regions

(Gordon et al. 2000). In addition, ESMs can simulate future climates in response to changes in the concentration of greenhouse gases and aerosols.

Unlike weather forecasts, a climate change scenario is not a forecast (IPCC 2014). A climatic scenario is a plausible representation of the future, considering a specific set of assumptions, such as: socioeconomic conditions, greenhouse gas emissions, radiative forcing and the ability to represent the climate system numerically (Chou et al. 2014a, b). The climatic scenarios are based on dynamical downscaling, in other words, the use of high-resolution regional simulations to dynamically extrapolate the effects of large-scale climate processes to regional or local scales of interest. Such simulations are derived from global climate models and regionalization models, subject to considerable uncertainty, especially in regions with a lack of observational data (Torres 2014).

While these scenarios can be inexact, uncertainties are inherent to any projection of the future and are not limited to climate modeling. Currently, the best method to offset and quantify uncertainties in modeling is to use the largest set of models possible, i.e., an ensemble. An ensemble can help predict future climate projections using past and present day information, and help explain the "what ifs" by running multiple scenarios at once (IPCC 2014).

For the purpose of this article, the regional climate was simulated using the Eta model, from the Center for Weather Forecasting and Climate Studies / National Institute for Space Research (*Centro de Previsão de Tempo e Estudos Climáticos / Instituto Nacional de Pesquisas Especiais* - CPTEC/INPE), which proceeds from the original Eta model (Mesinger et al. 2012), developed at the University of Belgrade (Serbia) and operationally implemented by the US National Center for Environmental Prediction (NCEP) (Black 1994). The Eta model was chosen because it is satisfactorily used at the CPTEC/INPE. In addition, the vertical coordinate system used in this model is recommended in the South American continent, due to the presence of the Andes.

The regional scenarios resulting from the application of the Eta model, with spatial resolution of 20 km, were obtained from two Global Climate Models (GCM): HadGEM2-ES and MIROC5. According to Chou et al. (2014a) and Chou et al. (2014b), the climate change response of the Eta simulations nested in HadGEM2-ES is larger than the Eta nested in MIROC5. In austral summer, the reduction of precipitation in the southeastern part of the South America continent are common changes in these simulations. The Eta-MIROC5 expands the area of increase of precipitation in southern Brazil toward the end of the century. In austral winter, precipitation decreases in southeastern of the continent, limited to near the coastal region. The time series of temperatures show that warming trends are larger in the Eta-HadGEM2-ES than in the Eta-MIROC5 simulations. Heavier precipitation rates are projected in the Central-South of Brazil toward the end of the century.

At the moment of development of this research, these were the only two models with downscaling for Brazil, justifying their use. They were extracted using the monthly data for the summer (December, January, and February) and winter (June, July, and August) by means of the mean temperature, minimum temperature, relative humidity and total precipitation. The following climate indices, considering the base period, were also calculated from the daily data: TN90p—percentage of days with minimum temperature higher than the 90th percentile; and R10—days with precipitation higher than 10mm, selected due to the biological dependence of the vector lavas at a minimum range of temperature and water availability.

The period from 1961 to 2005 (base period) was used as a reference period and these data are important as a control member of this study, allowing quantifying and qualifying the changes. The future climate represented in this article refers to two distinct time periods: 2011–2040 and 2041–2070, considering both the RCP 4.5 scenarios (realistic scenario with stabilization of greenhouse gas emissions; in this case, a stabilization of the increase in radiation due to anthropogenic forcing) and RCP 8.5 (pessimistic scenario of greenhouse gas emissions, with a constant increase in radiation due to anthropogenic radioactive forcing). The reference climatology is the 1961–2005 period, obtained for both models. For a better understanding of the representative concentration pathways (RCPs), we suggest Vuuren et al. (2011).

2.2 Calculation of the risk of arboviral diseases in the face of climate change

The evaluation of the potential impact on the distribution of arbovirus infections associated with *Aedes Aegypti* was performed through geostatistical relationships and the combination of the distribution of parameters of climatic susceptibility, using the data from the models mentioned above, the vulnerability, the occurrence of diseases and the vector throughout the territory.

The first stage focused on the elaboration of the General Potential Index - GPI to the proliferation of the vector, calculated with the combination of three potentials:

1 *Potential for vector generations (α):* based on the contribution of Farnesi et al. (2009), it uses the mean data of the monthly air temperature—°C—(Tmean), the base temperature (Tbase)—which is the lower thermal limit necessary for the development of the vector—and the thermal constant (*K*)—which relates the duration of the development of any phase as a function of the accumulated temperature in degrees day—according to Eq. 1 below:

$$\alpha = \text{number of days}\ \frac{(Tmean - Tbase)}{K} \quad (1)$$

2 *Egg hatching potential*: uses a multiple linear regression equation, based on Vianello et al. (2006), in which the meteorological parameters were treated as an independent variable, with the percentage of positive ovitraps (egg traps to monitor the mosquito population) as the dependent variable. Therefore, the variable Yi represents the expected percentage of positive ovitraps, depending on the relative humidity of the air—%—(X1i), mean temperature (X2i)—°C—and accumulated rainfall—mm—(X3i) as shown in Eq. 2 below:

$$Yi = -162,3230 + 1,3089X1i + 4,8921X2i + 0,0436X3i \quad (2)$$

3 *Infection potential (Pi):* based on Lambrechts et al. (2011), it represents the time needed for incubation of the virus in the vector *Aedes aegypti*, and is sensitive to temperature. The probability of infection increases linearly with temperature and remains at 1 at temperatures higher than 26.1 °C. The regression coefficients were derived from the linear part of the model, according to Eq. 3:

$$Pi = (0,0729{*}Tmean) - 0,9037 \quad (3)$$

The previous potentials were articulated in a General Potential Index-GPI (Eq. 4), which points to greater or lesser ease of development of *Aedes aegypti,* vector of Dengue, Zika, and Chikungunya:

$$GPI = (0,4{*}Yi) + (0,3{*}\alpha) + (0,3{*}Pi) \quad (4)$$

From a climatic point of view, one of the main determining factors in mosquito survival and reproduction is temperature, particularly the minimum temperature (Viana and Ignotti 2013). The amount and frequency of rain are also factors related to the distribution of the vector, but with less correlation, as it increases the humidity of the air (Cassab et al. 2011). Rain showers can define new breeding sites, hence favoring their overflow and hindering the establishment and hatching of eggs.

Capturing these aforementioned climate interferences, the Climate Index-CI (Eq. 5) was proposed, based on Vianello et al. (2006), to assess the greater or lesser ease for the mosquito's survival and reproduction, and is based on the data: RH— relative humidity; TN90p—annual percentage of days with minimum temperature higher than the 90th percentile; R10—days in the year with precipitation higher than 10mm. The weights were distributed according to the contribution of Viana and Ignotti (2013).

$$CI = (0,2{*}RH) + (0,3{*}TN90p) + (0,1{*}R10) + (0,4{*}Tmin)^{18} \quad (5)$$

The combination of the General Potential Index and the Climate Index reflects the General Indicator of Susceptibility-GIS (Eq. 6), which allows the establishment of a metric for the assessment of climatic susceptibility to vector development, proliferation, reproduction and infection.

$$GIS = 0,4{*}GPI + 0,6{*}CI \quad (6)$$

Furthermore, the literature points out that factors related to the low quality of basic sanitation, access to potable water and garbage collection are relevant to the distribution of diseases such as dengue (Hayden et al. 2010; Fullerton et al. 2014; Mendonça et al. 2019; Confalonieri and Marinho 2007). Such social variables are presented in the Water Associate Disease Index (WASI), used to map the vulnerability to dengue on a global scale. Based on data from the Brazilian Demographic Census (IBGE 2010), it was possible to build a Sanitation Index-SI (Eq. 7) that reflects the percentage of households, per census sectors, without access to sanitation, piped potable water and garbage collection service and weights were distributed according to WASI (Fullerton et al. 2014).

$$SI = 0,3{*}sanitation + 0,6{*}water + 0,1{*}garbage \quad (7)$$

Through the health database of the Brazilian Ministry of Health (DATASUS), we obtained data on hospitalizations associated with Dengue, Zika, and Chikungunya between 2010 and 2020, broken down by municipality. When related to population density (IBGE 2010), it resulted in the construction of the index on cases of arboviral disease (Eq. 8).

$$Cases = 0,8{*}occurance + 0,2{*}population\ density \quad (8)$$

The articulation between the Sanitation Index and the arboviral disease cases index resulted in the Vulnerability Indicator-VI (Eq. 9), a gauge for quantifying and assessing the social predisposition to the proliferation of the vector and diseases.

$$VI = 0,2{*}SI + 0,8{*}cases \quad (9)$$

Finally, the risk of arboviral diseases (Eq. 10), a synthesis that provided the impetus for subsequent analyses, was obtained from the equation between the General Indicator of Susceptibility (GIS) and the Vulnerability Indicator. It is about the integration of two geospatialized indicators with fundamental dimensions (climatic, social and epidemiological) that explain the vector's potential for destruction and, consequently, of arboviral diseases in the face of the climate change scenarios. The risk classes were defined based on interquartile ranges.

$$\text{Risk of arboviral diseases} = 0,6*GIS + 0,4*VI \tag{10}$$

3 Results and discussion

According to Silva and Dereczynski (2014), based on data from 1961 to 2012, minimum temperatures in the state of Rio de Janeiro range from 9.5 to 11°C (15.5 to 17°C). Higher temperatures occur mainly on the coast, where the average minimum temperatures range between 17 and 18.5°C (21.5 and 23°C) in the winter (summer). The lowest average maximum temperatures oscillate between 21.5 and 23°C (26 and 27.5°C) in winter (summer) in the Serrana region and the highest values are found in the Metropolitan region and in the North/Northwest Fluminense, fluctuating between 26 and 27.5°C (32 and 33.5°C) in winter (summer). The annual precipitation presents maximums in the high areas (about 2500 to 2800 mm per year) and minimums over the lowland and coastal regions (between 700 and 1300 mm per year).

Chou et al. (2016), comparing the results of both models with the present climate, found that the simulations capture the seasonality of temperature well over the study area, identifying patterns, both in Eta HadGEM2-ES and Eta MIROC5, in agreement with the climatological pattern for the four seasons.

Regarding the mean temperature, the projected temperature anomaly varies between 1.5°C and 4.5°C; as for the minimum temperature between 0.1 and 2.5°C. Spatially, the most significant anomalies occur in the inland of the state, especially in the Mountain Region and in the Center-South of Rio de Janeiro to the detriment of the coast. Silva and Dereczynski (2014) corroborate the same tendency of warming based on observational data, using the period of analysis from 1961 to 2012.

In accordance with the results for mean and minimum temperature, both models project an increase in frequency of the warm nights (TN90p). The prospect is for an increase of between 100 and 600% on nights with temperatures above the 90th percentile until 2070. The result of the index helps to comprehensively understand the persistent increase in temperature for the study area, indicating a greater heat stock due to the radiative forcing. In physical terms, this result indicates that in the daytime phase of short waves there will be greater availability of energy, resulting in a greater storage and, consequently, greater heating at nighttime.

In the study by Lyra et al. (2017) for Rio de Janeiro, São Paulo and Santos, both observational (1961–1990) and climate modeling data pointed to a significant increase in warm nights; in the study, between 60 and 90% of the nights are already warm, that is, above 20°C. In Silva and Dereczynski (2014) the Metropolitan, Center-South, Mountain and Northern/Northwest regions (Fig. 1) exhibited the highest rates of increase in warm nights in the state, demonstrating that these regions are already experiencing marked extreme hot events, which continue to intensify.

The regions pointed out by Silva and Dereczynski (2014) are the same that stand out in terms of heating in the results presented in this article. With the exception of the Metropolitan Region, the other ones (Center-South, Mountain and Northern-Northwest) are fundamentally controlled by altitude and continentality (Nimer 1979), that is, while presenting the highest thermal amplitudes, they also register the lowest temperatures, making them less favorable to the development of *Aedes aegypty*, whose optimal thermal is between 19 and 30 °C (Mendonça et al. 2011).

According to an analysis developed by the Health Department of the Rio de Janeiro state, the municipalities located in the Coastal Lowlands of the state are those with the highest risk for arboviral diseases (Rio de Janeiro 2019). According to the report by the state department, the highest infestation rates of *Aedes aegypti* occur in this sector, not coincidentally the hottest and most humid sector in the state. In contrast, in Center-South, Mountain and Northern/Northwest Fluminense regions, both the infestation and the number of cases are rarefied.

Regarding rainfall, there is a divergence in both models: while the Eta HadGEM2-ES model points to rainier winters and less rainy summers, the Eta MIROC5 model projects the opposite. This divergence of results between the models signals the high degree of uncertainty about how rainfall will behave in the face of climate change.

Chou et al. (2016) concludes that Eta-HadGEM2-ES showed an underestimation of rainfall in the Southeastern Brazil, mainly due to the difficulty of the model to represent the rainfall produced by the South Atlantic Convergence Zone - ZCAS (Kousky 1988). According to the authors, this is due to the poor representation of some components of the hydrological cycle (vegetation cover, soil moisture, surface flows) and the parameterization of convection (Chou et al. 2016).

For precipitation, Lyra et al. (2017) indicate a reduction in rainfall for metropolises in southeastern Brazil; for Rio de Janeiro, the authors point to a reduction of up to 50% in the volume of annual rainfall. Contrastively, Silva and

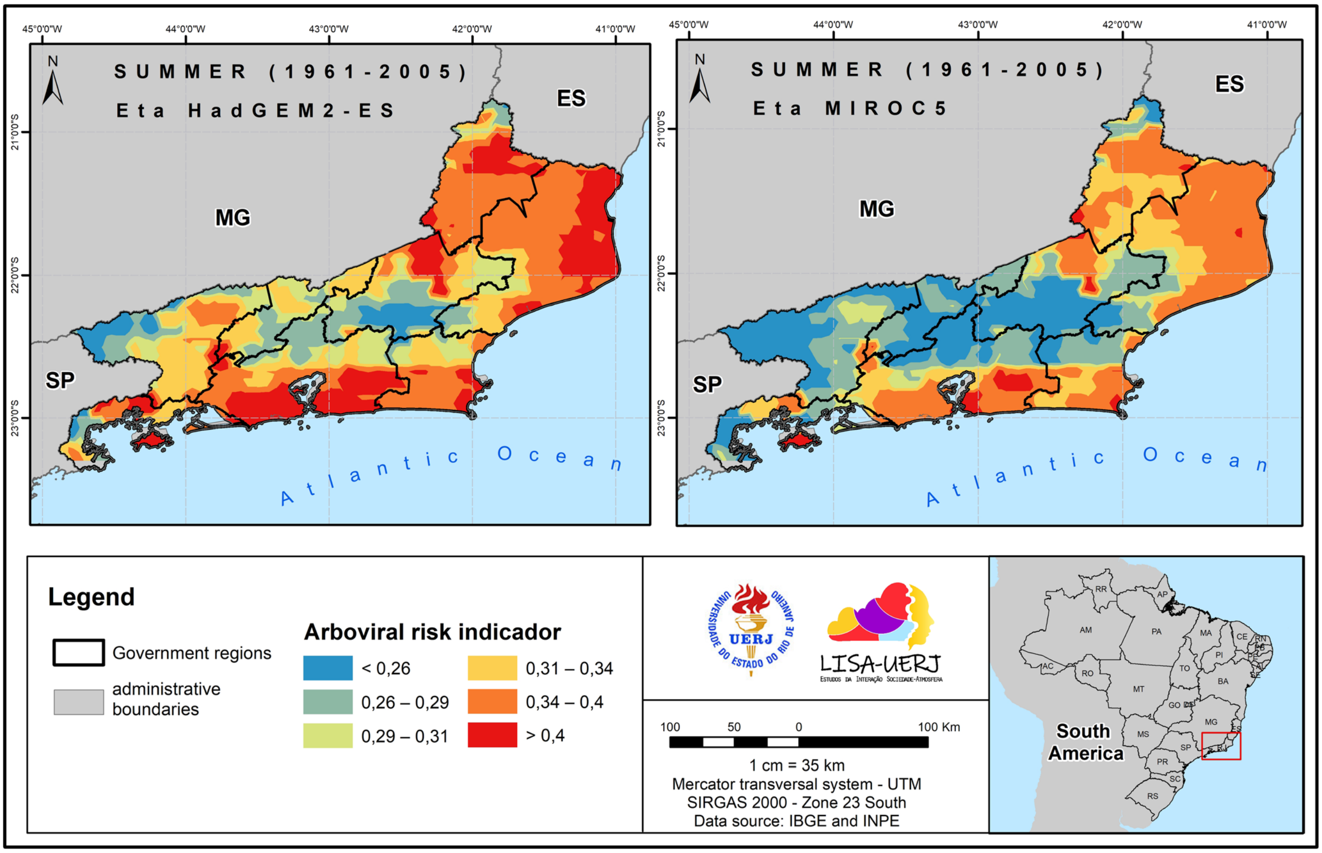

Fig. 2 Rio de Janeiro/Brazil-Risk of arboviral diseases for the summer, according to the Eta HadGEM2-ES and Eta MIROC5 models, considering the historical period (1961–2005)

Dereczynski (2014) found a statistically significant upward tendency of rainfall totals in the state, especially in Coastal Lowlands region.

In both, the data and the literature, divergences are observed in relation to the variability of rainfall, indicating the high degree of uncertainty regarding this parameter. However, for vector development purposes, variability is predominant, mainly concerning minimum temperature (Câmara et al. 2007); for precipitation, the existence of accumulated water predominates (Câmara et al. 2007; Mendonça et al. 2011), either from natural processes or the urban social infrastructure.

In summary, the climatic models and observational data signal, above all, the temperature increase in the state of Rio de Janeiro, directly impacting the greater climatic susceptibility to the development of *Aedes aegypti* (Gould et al. 2017). Such environmental susceptibility combined with the expressive regional limitations and disparities in access to basic sanitation (UN 2019) promote the intensification of the risk of arboviral diseases in the state.

Data from IBGE (2019) (Brazilian Institute of Geography and Statistics) show that, in the state of Rio de Janeiro, only 35% of households have sewage treatment, 89.3% have access to treated water and 76.4% have access to garbage collection; most of the households well served by sanitation infrastructure are located in the Metropolitan Region. Access to inadequate sanitation infrastructure increases the population's exposure to various diseases, including arboviral ones, since it favors, above all, the appearance of breeding sites, where mosquito eggs develop (Fullerton et al. 2014; Mendonça et al. 2019).

In the following sub-items, we present the results of the risk assessment for arboviral diseases in two contrasting seasonal situations: austral summer and austral winter. Several contributions point to the preponderance of diseases related to *Aedes aegypti* in the summer season, precisely because of the high temperatures and greater availability of water from rain (Gomes et al. 1992; Câmara et al. 2007; Reis et al. 2010). However, based on the possible repercussions of climate change, especially on air temperature, the seasonality of the disease may be affected (Sousa et al. 2018).

3.1 Summer

Figure 2 shows the results of the risk of arboviral diseases between 1961 and 2005 for the summer in the state of Rio de Janeiro, considering both models used in this study; it is the data projected for the present climate that serve as a reference for the analyzes. The result of the indicator reinforces the

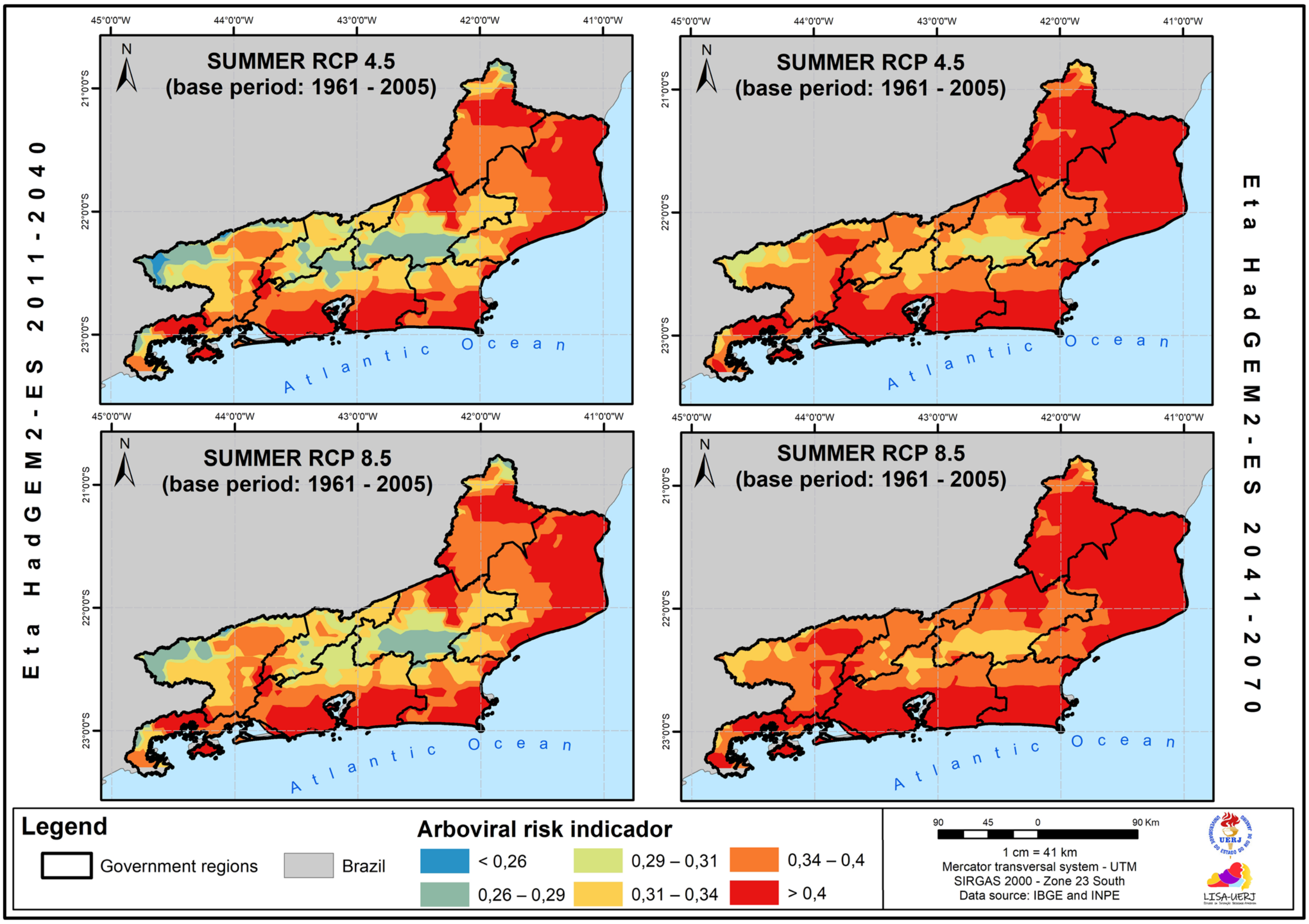

Fig. 3 Rio de Janeiro/Brazil-Risk of arboviral diseases for the summer, according to the Eta HadGEM2-ES model, considering the periods 2011–2040 and 2041–2070, RCP 4.5 and 8.5

seasonal expression of diseases related to *Aedes aegypti*, pointing to a high risk of arboviral diseases in a significant area of the state; direct relationship with greater warming and increased rainfall, except in the highest areas of the relief, regulated thermo-pluviometrically by altitude.

Both the Eta HadGEM2-ES and the Eta MIROC5 point more consistently to greater risk of arboviral diseases in the coast and northwest of Rio de Janeiro, explained by the greater heat stock, given the tropical position of the state which guarantees high insolation in this period of the year, and lastly the predominance of lowlands that enhance this warming. Likewise, the proximity to the ocean, combined with high temperatures, ensures a static instability in the study area, allowing the generation of convective cells, which provide the necessary water for the development of mosquito eggs.

In addition to the environmental conditions that explain the greater risk of arboviral diseases, especially on the coast of Rio de Janeiro, it is important to consider the complexity of the urbanization process developed in the state. The main and most complex cities in the state are located in this coastal strip, contributing both to the enhancement of environmental and social changes, enabling the proliferation of the vector and the disease (Mendonça et al., 2009).

Comparing both models, the greater intensity of risk of arboviral diseases is notorious for the Eta HadGEM2-ES model, with greater spatial expression of the high-risk classes (greater than 0.4 and between 0.34 and 0.4); while the Eta MIROC5 model presents a greater spatial domain of the class below 0.26. This result stems from the greater tendency of heating presented by the Eta HadGEM2-ES model (Chou et al. 2014a, b), indicating intensification of the risk since the mosquito prefers higher temperatures. As highlighted by Mendonça et al. (2011), the optimal climate for the development of *Aedes aegypti* is between 19 and 30°C, which explains the spatial pattern of the risk.

Figure 3 refers to the summer projection of the model Eta HadGEM2-ES RCP 4.5 and RCP 8.5 for the periods 2011–2040 and 2041–2070. The maps signal both scenarios (RCP 4.5 and 8.5) and reinforce the aforementioned spatial pattern, thus reinforcing the expressive risk to which Coastal regions and the Northwest Fluminense are subjected. Especially for the period 2041–2070, there is an intensification of risk in the

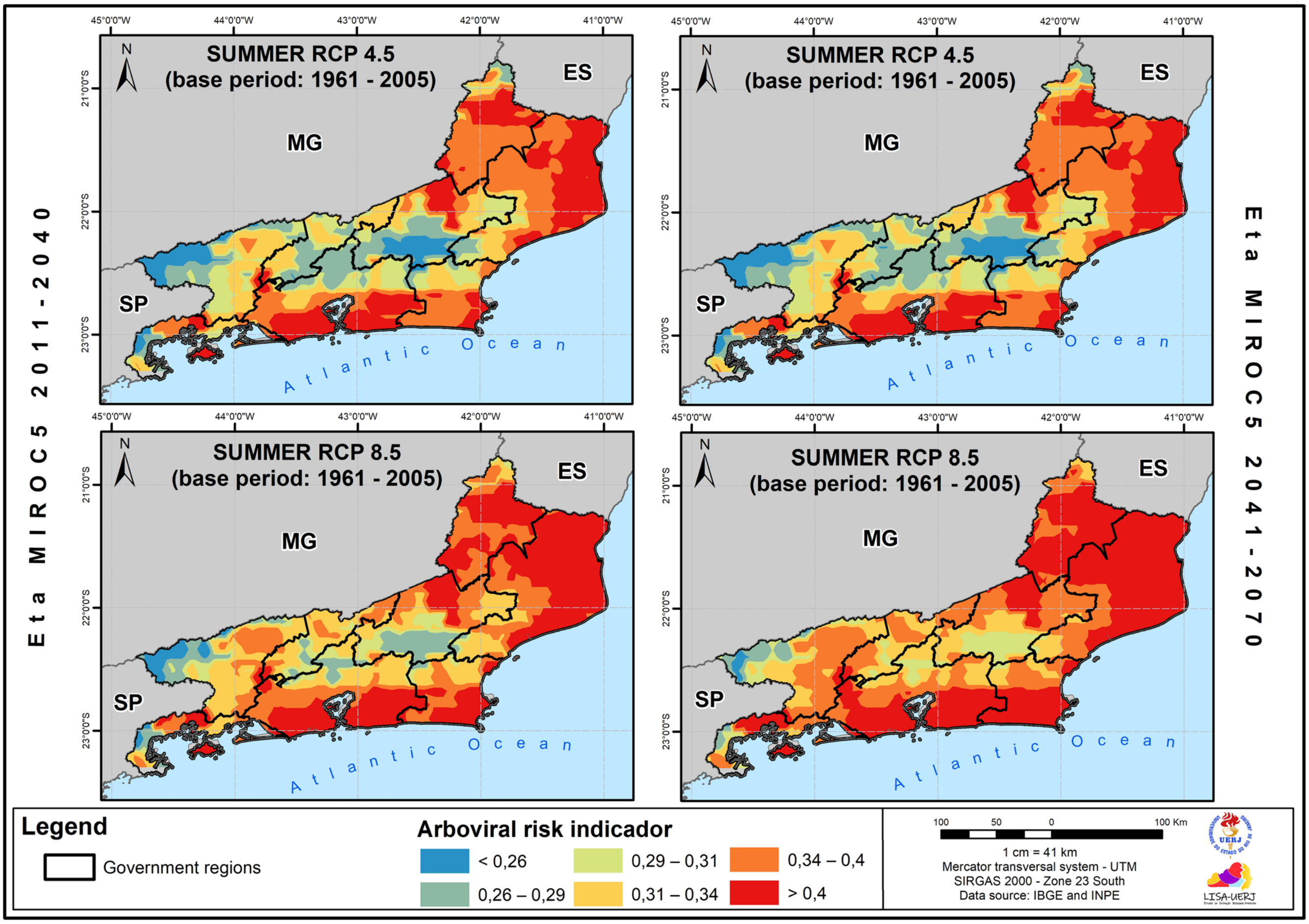

Fig. 4 Rio de Janeiro/Brazil-Risk of arboviral diseases for the summer, according to the Eta MIROC5 model, considering the periods 2011–2040 and 2041–2070, RCP 4.5 and 8.5

entire state of Rio de Janeiro, including in the Mountain region and Middle Paraíba region, a clear repercussion of the increased warming of the atmosphere.

In the context of the urban network of southeastern Brazil, Middle Paraíba region has a prominent position because it is located between the metropolises of Rio de Janeiro and São Paulo, developed on the margins of the country's main highway (Rodovia Presidente Dutra), the main axis of the Brazilian megalopolis. Although it is the third most important region in the state in terms of structural investments aimed at industrial development, its urban infrastructure does not meet the demand generated by the rapid population concentration (Marafon et al. 2011). This is a revealing consideration for understanding the context in which the risk develops. After all, Aedes aegypti is a vector, eminently urban and is already expressive in the number of cases in current climatic conditions (Rio de Janeiro 2019; Gomes et al. 1992).

Figure 4 refers to the summer projection of the model Eta MIROC5 RCP 4.5 and RCP 8.5 for the periods 2011–2040 and 2041–2070. Once again, it is clear that the lower heating trend presented by Eta MIROC5 (Chou et al. 2014a, b; Chou et al. 2016) interferes with the result of the arboviral risk indicator throughout the state. Nevertheless, the spatial patterns are reinforced, placing the Coast and Northwest Fluminense in prominence.

As in the Eta HadGEM2-ES model, in RCP 8.5 of MIROC5 there is a gradual tendency to increase the risk of arboviral diseases in the higher areas of the study area, especially the Serrana region, indicating that the temperature anomalies predicted in this scenario imply the spatial expansion of areas susceptible to the development of the vector, most likely resulting in an increase in cases of Dengue, Zika, and Chikungunya. Pereira et al. (2014), analyzing the municipality of Nova Friburgo, highlight the worsening of Dengue in the municipality mainly due to climatic extremes.

3.2 Winter

Figure 5 presents the results for the risk of arboviral diseases in the state of Rio de Janeiro for the period 1961-2005 in the seasonal winter situation using the Eta

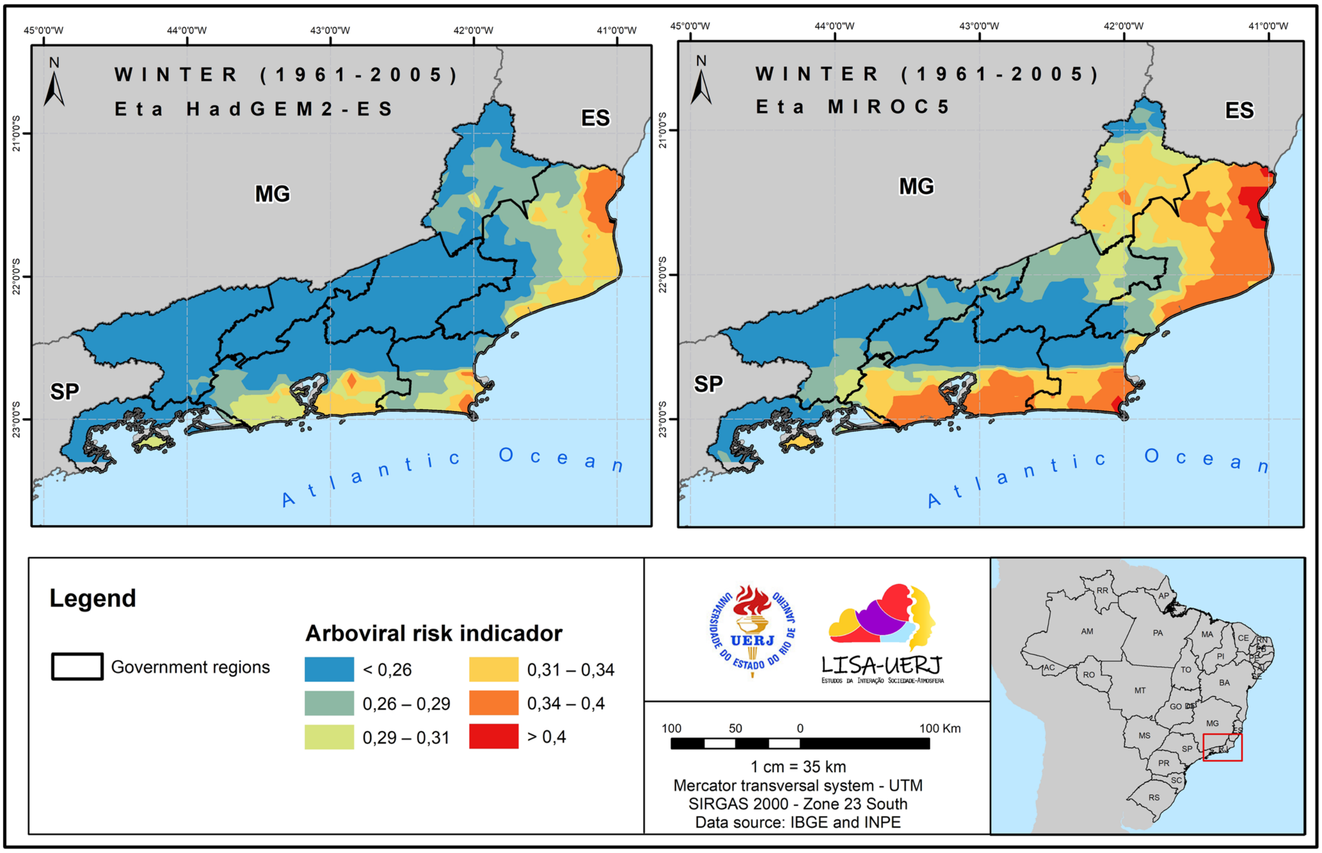

Fig. 5 Rio de Janeiro/Brazil-Risk of arboviral diseases for winter, according to the Eta HadGEM2-ES and Eta MIROC5 models, considering the historical period (1961–2005)

HadGEM2-ES and Eta MIROC5 models. Given the characteristics of reduced temperature and rainfall, there is a very low risk of arboviral diseases in the winter. Only in portions of the Coast is this risk higher (between 0.29 and 0.4), most likely due to the thermal regulation exercised by the ocean, keeping such environments warm.

However, as pointed out by Vianello et al. (2006) and Collischonn et al. (2018), despite the lower occurrence of arboviral diseases in winter given the decrease in temperatures and rainfall, there is still circulation of the vector, fundamentally due to the dynamics of the types of weather. As pointed out by the Brazilian government, these colder months should be treated not as a truce, but as an opportunity to take preventive measures to reduce mosquito breeding sites.

Unlike the summer results, in the winter situation the Eta MIROC5 model presents a higher degree of risk of arboviral diseases (but without any novelty regarding the spatial distribution of this risk). This intensification stems from the projections for winter precipitation; although it shows a decrease tendency of the total, it signals the temporal concentration, changing the distribution of rains in this season.

Changes in the characteristics of rainfall distribution must be carefully analyzed, as it may favor the development of the mosquito. Given the exclusion of most households from the sanitation system, mainly piped water (UN 2019), individual water storage strategies are cultural in Rio de Janeiro, an excellent situation for the development of mosquito breeding sites.

Figure 6 refers to the winter projection of the Eta HadGEM2-ES RCP 4.5 and RCP 8.5 model for the periods 2011–2040 and 2041–2070. The result for the 2011–2040 period of RCP 4.5 is very similar to the present climate, except for some intensification of risk in Northern Fluminense. In RCP 8.5 of the 2041–2070 period, it is possible to observe an intensification of risk in Northern Fluminense, Metropolitan Region and in Coastal Lowlands, as well as the spatial expansion of the high-risk classes to the Northwest Fluminense and the Mountain region.

The winter results indicate that, due to climate change, optimal conditions for the development of the vector will be more frequent in the winter period. This arises, fundamentally, from the increase in the minimum temperature, offering favorable conditions for extending the infestation period, consequently extending the contamination period. In terms of public health and epidemiology, these results most likely indicate that arboviral diseases will become prominent in the state throughout the year, demanding

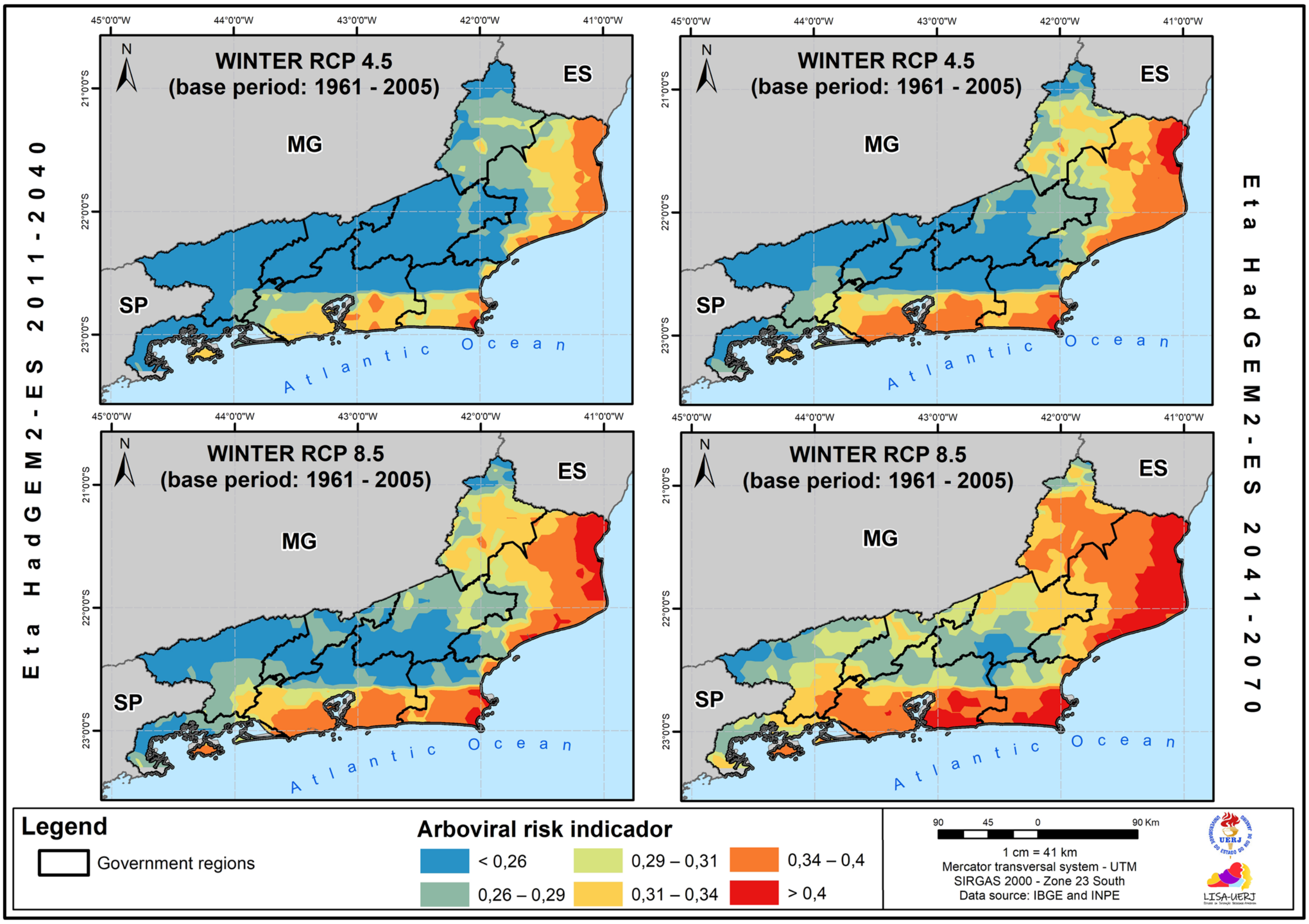

Fig. 6 Rio de Janeiro/Brazil-Risk of arboviral diseases for winter, according to the Eta HadGEM2-ES model, considering the periods 2011–2040 and 2041–2070, RCP 4.5 and 8.5

new strategies for tackling them, increasing demand for the public health service and costs (Pereira et al. 2014).

Figure 7 refers to the winter projection of the model Eta MIROC5 4.5 and RCP 8.5 for the periods 2011–2040 and 2041–2070. In comparison to the results of Fig. 6, for Eta HadGEM2-ES, there is a high degree of agreement between the models regarding the risk of arboviral diseases in the winter for the state of Rio de Janeiro. The results point to the intensification of the disease over time, mainly on the coast, confirming the importance of coastal climate controllers in the spatial understanding of the distribution of arboviral diseases.

The Mountain, Green Coast, Middle Paraíba, and Center-South regions, with considerable altimetric control, may have a low risk of Dengue, Zika, and Chikungunya in the winter period. With regard to the Northwest Fluminense region, an intensification of the risk of arboviral diseases is observed. This intensification was consistently pointed out in all models both for summer and winter, due to the more accentuated characteristics for warming by the dynamics of local winds, which are derived from their leeward position in relation to the Sea Ridge (locally called Serra dos Órgãos) (Bernardes 1953).

4 Summary and conclusions

This study analyzed the impacts of climate change on the expansion of *Aedes aegypti,* responsible for the main arboviral diseases (Dengue, Zika, and Chikungunya) in the state of Rio de Janeiro. These diseases have high rates of morbidity and mortality throughout Brazil. Due to the influence of the climate, the air temperature in particular, the projected warming tendency may have an impact on the optimization of environmental conditions for *Aedes aegypti*, expanding the areas of influence of the mosquito, as well as altering the seasonal behavior of the disease. Such findings affect, above all, public health strategies, which are still based on the prevalence of the disease in summer and autumn.

Both models used (Eta HadGEM2-ES and Eta MIROC5) point to an intensification of the risk of arboviral diseases in all government regions of the state of Rio de Janeiro. This intensification results mainly from the gradual increase of the

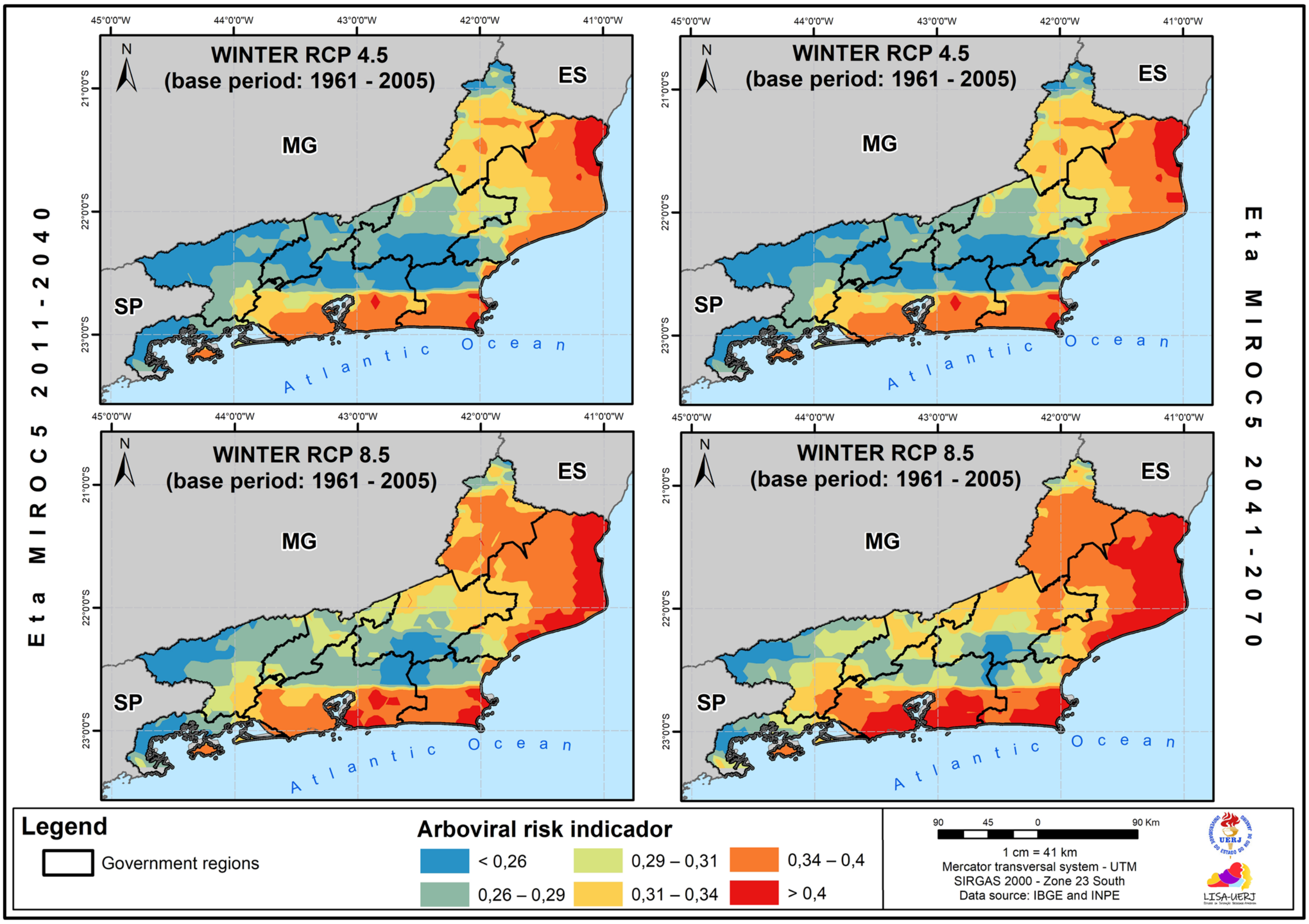

Fig. 7 Rio de Janeiro/Brazil-Risk of arboviral diseases for the winter, according to the Eta MIROC5 model, considering the periods 2011–2040 and 2041–2070, RCP 4.5 and 8.5

minimum temperature and warm nights over the future periods. These are important conditions for the spread of the disease, since they favor the development of the vector-mosquito. However, the complexity of the production of urban space that develops in different government regions, with indelible marks of socio-spatial segregation and exclusion from urban infrastructure, also impacts the health-disease process, and must not be disregarded.

In the summer situation, the projection points to a greater risk of proliferation of the vector and, consequently, of arboviral diseases to the higher regions of the state, controlled by altitude. Given the projections of warming, the Mountain region will probably be the main area of expansion of arboviral diseases, with repercussions on the increase of people exposed to Dengue, Zika and Chikungunya in the state.

In the winter situation, the projections indicate that the warming caused by global climate change will cause the expansion of the infection period by arboviruses. The diseases contemplated here will no longer be restricted to summer and autumn: the development of an optimum environmental condition for the persistence and development of the mosquito will impact the possibility of an increase in cases and occurrence throughout the year.

As summarized in Fig. 8, a qualitative map showing the intersections of classes of susciptibility to arboviruses in the state until 2070, in all RCP models and scenarios, the Metropolitan, Coastal Lowlands and Northern Fluminense regions will present a high risk of arboviral diseases, deserving the attention of health agencies to develop strategies for tackling the diseases and adapting to the impacts of climate change. The characteristics of these regions (tropical domain, lowland environment and proximity to the oceans) are fundamental to guarantee high temperatures and humidity, conditions conducive to the ecology of the vector.

Pondering the importance of arboviral diseases for Brazil, especially for Rio de Janeiro, the results show that climate change will most likely intensify the impact of Dengue, Zika, and Chikungunya on human health, with the potential to intensify impacts on the public health of the country in the near future. In this sense, acknowledging the absence of clinical control for these diseases, the development of universal

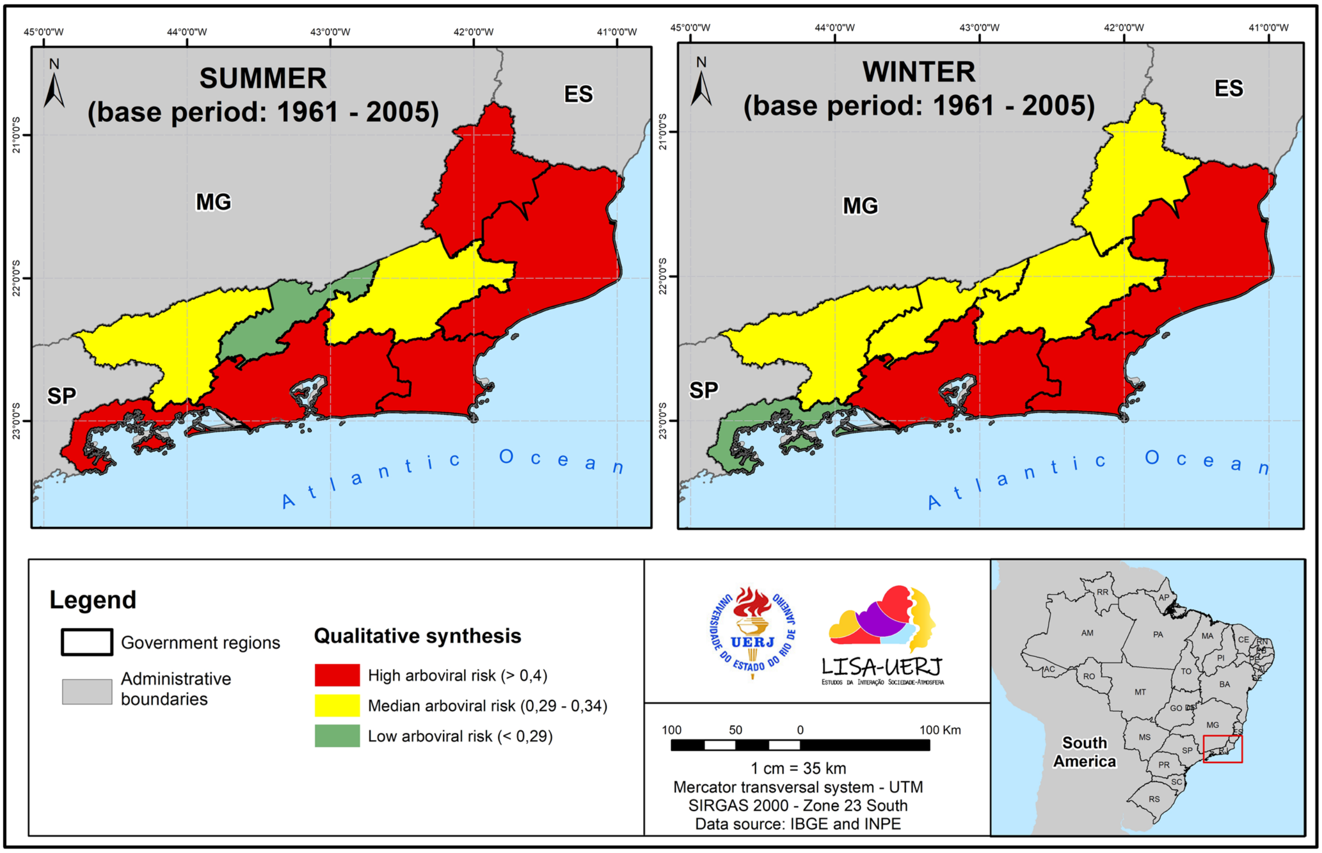

Fig. 8 Rio de Janeiro/Brazil-Qualitative synthesis of the risk to arboviral diseases in the state of Rio de Janeiro for summer and winter until 2070, according to the Eta HadGEM2-ES and Eta MIROC5 models

access strategies to basic sanitation is essential and a priority, in order to directly interfere in the epidemiological cycle.

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Code availability No applicable

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Data availability Arbovirus data available at DATASUS (http://www2.datasus.gov.br/DATASUS/index.php), database sustained by Ministry of Health of Brazil and climate modeling data available by National Institute for Space Research (INPE). All data used are in public domain.

Declarations

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Consent to participate No applicable

Consent for publication No applicable

Competing interests The authors declare no competing interests.

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