A regional suitable conditions index to forecast the impact of climate change on dengue vectorial capacity

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Abstract

Background

The mosquitoes Aedes aegypti and Ae. albopictus are the primary vectors of dengue virus, and their geographic distributions are predicted to expand further with economic development, and in response to climate change. We aimed to estimate the impact of future climate change on dengue transmission through the development of a Suitable Conditions Index (SCI), based on climatic variables known to support vectorial capacity. We calculated the SCI based on various climate change scenarios for six countries in the Asia-Pacific region (Australia, China, Indonesia, The Philippines, Thailand and Vietnam).

Methods

Monthly raster climate data (temperature and precipitation) were collected for the period January 2005 to December 2018 along with projected climate estimates for the years 2030, 2050 and 2070 using Representative Concentration Pathway (RCP) 4·5, 6·0 and 8·5 emissions scenarios. We defined suitable temperature ranges for dengue transmission of between 17·05–34·61 °C for Ae. aegypti and 15·84–31·51 °C for Ae. albopictus and then developed a historical and predicted SCI based on weather variability to measure the expected geographic limits of dengue vectorial capacity. Historical and projected SCI values were compared through difference maps for the six countries.

Findings

Comparing different emission scenarios across all countries, we found that most South East Asian countries showed either a stable pattern of high suitability, or a potential decline in suitability for both vectors from 2030 to 2070, with a declining pattern particularly evident for Ae. albopictus. Temperate areas of both China and Australia showed a less stable pattern, with both moderate increases and decreases in suitability for each vector in different regions between 2030 and 2070.

Interpretation

The SCI will be a useful index for forecasting potential dengue risk distributions in response to climate change, and independently of the effects of human activity. When considered alongside additional correlates of infection such as human population density and socioeconomic development indicators, the SCI could be used to develop an early warning system for dengue transmission.

Keywords

Aedes, Climate change, Dengue, SCI, Vectors, Prediction

1. Introduction

Dengue fever is recognised as the most important, and fastest spreading arboviral disease of humans in the world, now present in 129 countries (Bhatt et al., 2013; Brady et al., 2012). It is caused by infection with dengue virus, a mosquito-borne Flavivirus that is primarily spread by Aedes vectors (Guzman et al., 2016). Dengue virus is transmitted primarily in tropical and subtropical regions but has a high potential for geographic spread to new areas (Gubler 2011; Bhatt et al., 2013). The Asia-Pacific region has a particularly high burden of infection, with up to 70% of global infections recorded in Asia alone, and increasingly frequent epidemics occurring in the Pacific region (Shepard et al. 2013; Bhatt et al., 2013; Roth et al., 2014). These figures reflect the large-scale re-emergence of dengue fever in the region facilitated by urban growth, globalisation and socioeconomic factors (Gubler 2011) and the geographic expansion of the two major vectors of dengue, Aedes aegypti and Ae. albopictus (Kraemer et al., 2015).

A key determinant of the distribution and vectorial capacity of these vector species is climate (Fouque and Reeder 2019; Reinhold et al. 2018). The presence or absence of suitable climate conditions including temperature ranges, precipitation levels, and extreme weather events can affect viral amplification, vector reproduction and survival, and human biting rate(Liu-Helmersson et al., 2014; Reinhold et al. 2018; Mordecai et al., 2019). During this century, global mean temperature is projected to increase between 1·1–6·4 °C (IPCC 2013). Anticipated changes in both temperature and precipitation under climate change scenarios are likely to affect the biology and ecology of both virus and vectors, and consequently the risk of dengue transmission (Reinhold et al. 2018; Fouque and Reeder 2019; Zhu et al. 2020). Transmission risk may also expand beyond current transmission zones to non-immune human populations that are more vulnerable to infection (Barcellos and Lowe 2014). Hence, understanding how a changing climate might affect future dengue epidemic patterns is important for risk prediction and the targeting of mitigation strategies.

Previous studies have projected future dengue infection risk using estimated dengue incidences, climate variables alone, or combined with human population distributions, and ecological variables (Messina et al., 2015). Estimations of dengue incidence used in previous research is expected to have spatial uncertainty in different countries and thus these projections of dengue distribution need to be further validated and improved. Moreover, fewer studies have attempted to develop a vector suitable index based on experimental data for dengue virus transition at high spatial resolution (Benedict et al., 2007; Khormi and Kumar 2014; Kraemer et al., 2015; Kamal et al., 2018; Messina et al., 2019). Previous research has either been on a global scale, or focused on one country or region, and often has not allowed relative comparisons of vector suitability across multiple countries and time points at fine scales. Additionally, most studies use mean temperatures to predict vector distributions rather than optimal temperature ranges for vectorial capacity (Messina et al., 2019; Liu-Helmersson et al., 2019).

We report on the suitability for dengue vector survival and virus transmission in six countries: Australia, China, Indonesia, Thailand, the Philippines, and Vietnam, where climate regions and dengue endemicity levels are diverse. Our study uses climatological data together with known parameters for virus transmission by vectors (such as biting rate, adult development and survival, extrinsic incubation rate), to develop a Suitable Condition Index (SCI). The SCI ranks geographic regions by likelihood that their climates will provide suitable conditions for the two primary vectors, Ae. aegypti and Ae. albopictus, to transmit dengue. We then use the SCI to predict future spatial patterns of climate suitability for vectorial capacity under different climate change scenarios, with a view to informing further development of early warning systems for dengue virus transmission.

2. Methods

2.1. Study sites

We chose six countries from the Asia-Pacific region to include in our study: Australia, China, Indonesia, the Philippines, Thailand and Vietnam where a range of climate and socioeconomic variables that influence dengue transmission are present. Four of the countries are geographically based in South East Asia (SEA) and have largely tropical climates along with high incidences of dengue fever, while Australia and China have more diverse climate types, and report periodic outbreaks confined to specific regions; for example, in the southern Chinese province of Guangdong, and in the north-eastern state of Queensland in Australia. However, the latter two countries both have suitable environments for dengue transmission to flourish and are vulnerable to imported cases from SEA. Our previous research suggested that imported dengue cases trigger and enhance local outbreaks only under favourable weather conditions, particularly in Cairns, Australia.

2.2. Data collection

Shapefiles delineating geographical boundaries for each SEA country were collected at administrative level 2 from the Humanitarian Data Exchange, developed by the UN Office for the Coordination of Humanitarian Affairs (OCHA) (OCHA 2020). The Australian shapefile was obtained at the equivalent scale, Statistical Area 2 (SA2), from the Australian Statistical Geographic Standard available from the Australian Bureau of Statistics (ABS) (ABS 2016).

Gridded historical climate data for the period 2005–2018 were collected for the six countries from the TerraClimate dataset (Abatzoglou et al., 2018). The TerraClimate database combines three datasets to maximise spatial resolution (0·04°, approximately 4 km). For the same countries, gridded projected climate data for 2020, 2050 and 2070 were sourced from the “CERA” database (0·04°, approximately 4 km), created by Navarro and colleagues using their CCAFS-CMIP5 Delta Method Downscaling for monthly averages and bioclimatic indices of four Representative Concentration Pathway (RCP) emissions scenarios (Navarro et al., 2019).

Climate data were extracted from TerraClimate and CERA using RStudio software (version 3·4·2) for 8980 administrative areas. Data were unavailable for 2/8980 administrative areas (<0·01%). Historical values for average monthly precipitation, maximum and minimum temperature from 2005 to 2018 were extracted from the TerraClimate dataset in raster format through a zonal function using the exact_exctract R package (Baston 2020). Projected values for precipitation, maximum and minimum temperature were similarly extracted from the CERA database for projections of 2030, 2050 and 2070 years based on RCP emissions scenarios of 4·5, 6·0 and 8·5. RCP Scenario 8·5 has been described as “business as usual”, with current global emissions currently following this trajectory (van der Zande et al., 2020).

This study was approved by the University Human Research Ethics Committee of Queensland University of Technology (Ref: 1,800,000,058).

2.3. Calculation of SCI

A climate-based SCI was developed to define potential distributions of Ae. aegypti and Ae. albopictus based on forecasts of local climate conditions that support vectorial capacity. We determined suitable temperature ranges for dengue vectorial capacity based on those identified by Mordecai et al., (2017) which synthesized previous empirical results of temperature suitability for vector and pathogen survival, and used a mechanistic approach to ascertain suitable temperatures for vector capacity in the transmission of dengue fever. This approach used a temperature-dependent transmission model to estimate the basic reproduction number R0(T), suggesting a conservative estimate of transmission risk R0(T) > 0 for identifying an optimum temperature range for transmission by Ae. aegypti and Ae. albopictus. This approach used mechanistic generalized linear models to assess whether the predicted relationship between temperature and transmission was consistent with observed human dengue cases. It then further adjusts for mosquito abundance based on temperature. Using this approach, Mordecai et al. determined temperature ranges affecting vectorial capacity using published empirical data on the interaction between temperature and key mosquito and pathogen traits.

These temperature ranges were between 17·05 and 34·61 °C for Ae. aegypti and between 15·84 and 31·51 °C for Ae. albopictus. While vector survival and transmission can occur outside of these ranges, they reflect conditions where adult female survival, density, biting rate, extrinsic incubation period, and larval development will support high dengue transmission intensity, as indicated by empirical data and probability models (Mordecai et al., 2017; Reinhold et al. 2018; Liu-Helmersson et al., 2014; Benedict et al., 2007). We initially developed an index based on these temperature ranges alone and then combined this with average monthly rainfall, which is known to influence vectorial capacity in some regions, but for which there is no clear transmission threshold (Liu et al., 2019).

Based on the extracted monthly temperature and precipitation values from the TerraClimate gridded dataset for each administrative area (2005–2018), we calculated the number of months per year where the monthly minimum and maximum temperature were within the range considered suitable for each species. To obtain the SCI, we multiplied the number of suitable months per year by the average monthly precipitation (weight variable) in the same location (n = 8980 administrative areas). Rainfall was included based on hypotheses from previous ecological and modelling research that rainfall could be an important influence on vector capacity (Thai and Anders 2011; Fouque and Reeder 2019; Naish et al., 2014). Unfortunately, empirical data on suitable rainfall ranges for dengue transmission are unavailable; therefore, the monthly average was used to account for the influence of this variable on vectorial capacity. Annual SCI values were then averaged for the years 2005–2018 for each location to obtain baseline SCI estimates for each species. The projected climate data from the CERA database were similarly extracted and manipulated to estimate suitability for Ae. aegypti and Ae. albopictus within the six countries for 2030, 2050 and 2070, using emissions scenarios of RCP 4·5, 6·0 and 8·5.

2.4. Mapping transmission suitability by dengue vectors

Baseline (2005–2018) and projected (2030, 2050 and 2070) climate suitability for dengue transmission by Ae. aegypti and Ae. albopictus were mapped at administrative level 2 scale for all countries using ArcGIS Geographical Information System software (version 10·5, Esri USA). The administrative level 2 boundaries used can be viewed in Supplementary Fig. 1. Difference maps were then created by subtracting the current SCI value from the projected SCI values for each administrative region for 2030, 2050 and 2070.

3. Results

3.1. Baseline patterns of transmission suitability

Baseline suitable conditions for dengue transmission across the six countries are shown in Fig. 1 and Supplementary Table 1. These indicate that of all six countries, the SEA countries currently have the most suitable climate conditions to support dengue transmission by each vector. The highest suitability values were found in the Philippines and Indonesia. Moderately high values were observed in southern Thailand and Vietnam, particularly for Ae. aegypti. Large parts of Australia and China were relatively unsuitable, except for certain tropical and sub-tropical regions in the north and south of each country, respectively. Our baseline suitability maps for Ae. aegypti and Ae. albopictus in China indicated that transmission suitability was highest in the southern provinces of Yunnan, Guangxi and Guangdong, with gradually reducing suitability moving further north. In Australia, suitability for both vectors were highest in the state of Queensland.

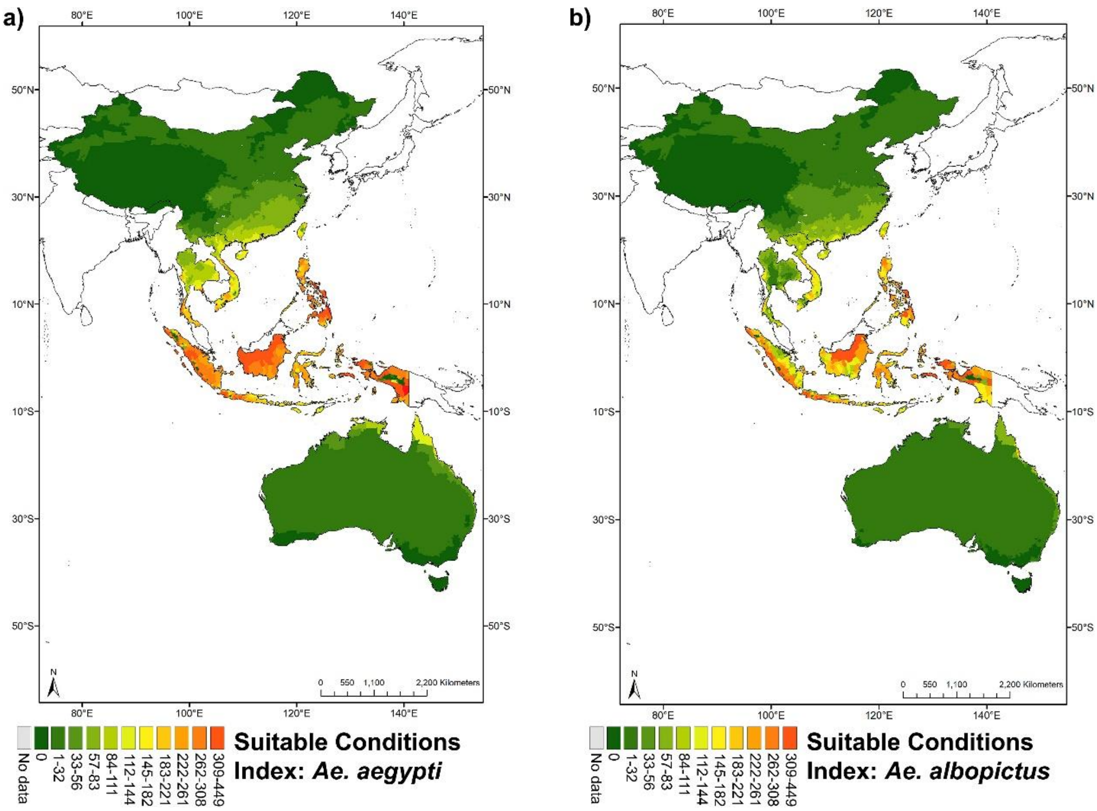

Fig. 1. Baseline vector suitability for countries included in the study.

The Suitable Conditions Index for a) Ae. aegypti and b) Ae. albopictus are shown for the six countries selected for the study included Australia, China, Indonesia, the Philippines, Thailand, and Vietnam. The index ranks relative transmission suitability based on the number of months between 2005 and 2018 where climate and rainfall conditions were conducive for each vector to transmit dengue.

The distribution of high transmission suitability areas for Ae. aegypti was more widespread than that for Ae. albopictus, with suitability for dengue transmission by Ae. aegypti being especially high throughout SEA countries. The baseline vector suitability distribution indicated by the SCI appears to correlate well with known populations at risk of dengue, and with recently reported dengue incidence patterns for the six countries, which indicate that the Philippines and Indonesia have the highest incidence rates of all countries (Supplementary Fig. S2). Similarly, countries where our vector suitability values were comparatively lower, such as Australia and China (Supplementary Fig. S3), report lower dengue incidence rates.

3.2. Projected patterns of transmission suitability

Comparison of the difference maps across countries showed that each country exhibited distinct patterns in the projected changes in SCI between the current transmission suitability present for each vector and projected scenarios for 2030, 2050 and 2070 (Supplementary Table 2). Projection data based on the worst-case RCP 8·5 emissions scenario are shown below (Fig. 2, Fig. 3, Fig. 4), while maps for RCP 4·5 and 6·0 emissions scenarios can be found in Supplementary Figures S4 and S5, respectively. Under each scenario, differential increases and decreases in vector suitability were projected across countries compared to current suitability. Overall, there were distinctly different patterns in the SEA countries, where climates are primarily tropical, compared to patterns in Australia and China which have a higher proportion of either temperate or arid climate regions. Projected changes in SCI for both vectors were generally more extreme in SEA countries for each future time point (both extreme increases and decreases present) compared to Australia and China where the degree of change was more moderate. Further specific observations for the South East Asian countries, China and Australia under scenario RCP 8·5 are outlined below.

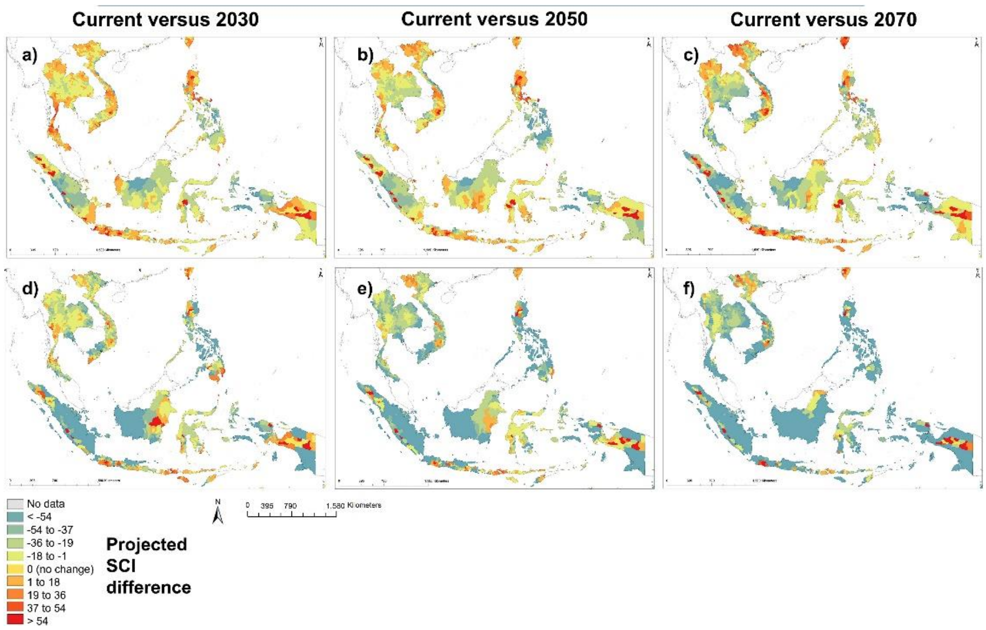

Fig. 2. Difference map of vector suitability in South East Asian countries.

Projected differences in current and future SCI values are shown for 4 countries of South East Asia: Indonesia, Thailand, The Philippines and Vietnam. For Ae. aegypti (top panel), differences in SCI projections are shown for a) current SCI versus 2030 projections, b) current SCI versus 2050 projections and c) current SCI versus 2070 projections. Similarly, for Ae. albopictus (bottom panel), projections are shown for d) current SCI versus 2030 projections, e) current SCI versus 2050 projections and f) current SCI versus 2070 projections. All projections used the RCP 8·5 emissions scenario. State boundaries of each country are also indicated.

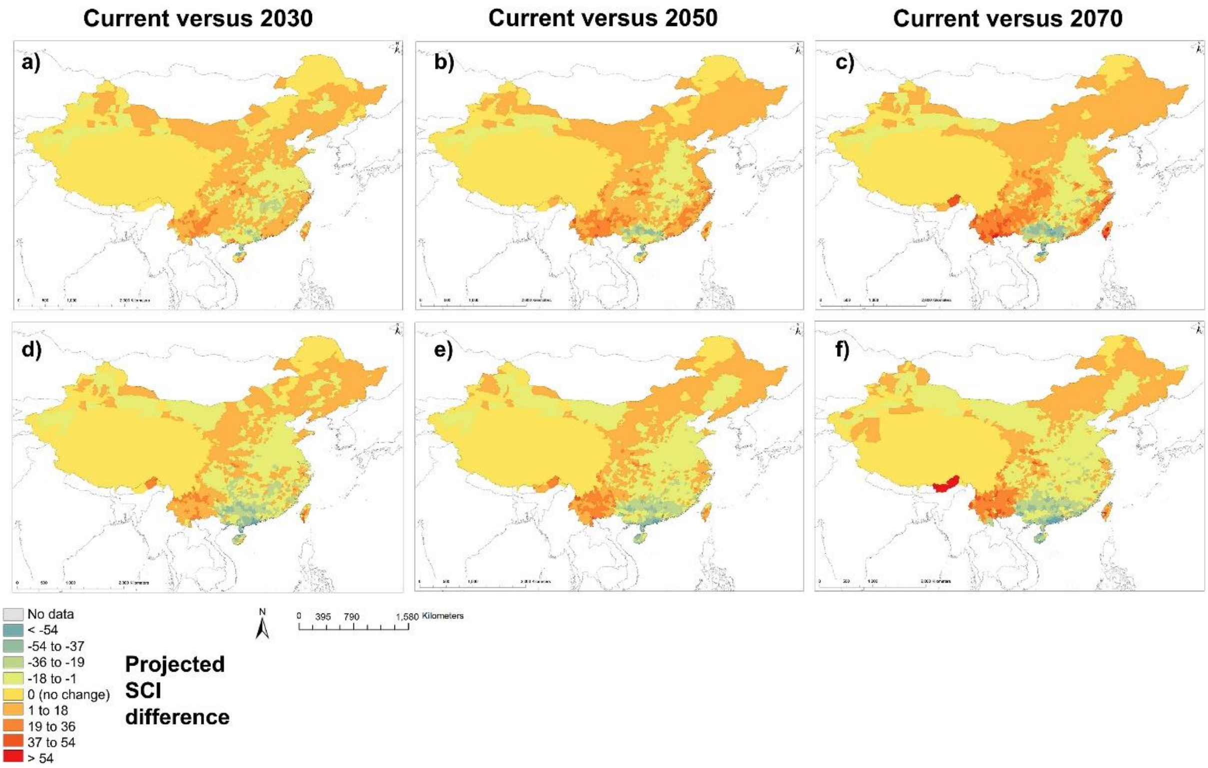

Fig. 3. Difference map of vector suitability in China.

Projected differences in current and future SCI values in China are shown for each dengue vector. For Ae. aegypti (top 3 panels), differences in SCI values are shown for a) current SCI versus 2030 projections, b) current SCI versus 2050 projections and c) current SCI versus 2070 projections. Similarly, for Ae. albopictus (lower 3 panels), projections are shown for d) current SCI versus 2030 projections, e) current SCI versus 2050 projections and f) current SCI versus 2070 projections. All projections used the RCP 8·5 emissions scenario. State boundaries of China are also indicated.

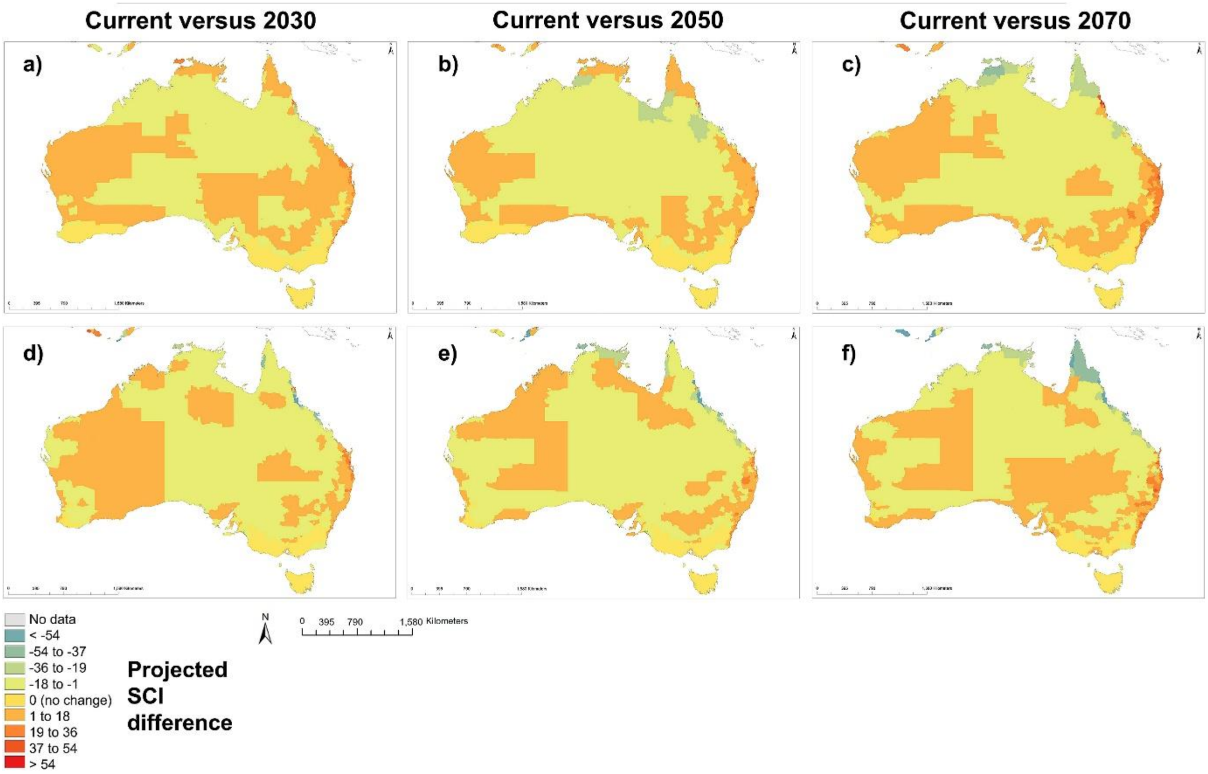

Fig. 4. Difference map of vector suitability in Australia.

Projected differences in current and future SCI values in Australia are shown for each dengue vector. For Ae. aegypti (top 3 panels), differences in SCI values are shown for a) current SCI versus 2030 projections, b) current SCI versus 2050 projections and c) current SCI versus 2070 projections. Similarly, for Ae. albopictus (lower 3 panel), projections are shown for d) current SCI versus 2030 projections, e) current SCI versus 2050 projections and f) current SCI versus 2070 projections. All projections used the RCP 8·5 emissions scenario. State boundaries of Australia are also indicated.

3.2.1. South East Asia

In the SEA region, widespread decreases in suitability for both vectors to transmit dengue were projected to occur from 2030 onwards in most countries in the region (Fig. 2). For Ae. aegypti, decreases in SCI were evident in many regions of Thailand, Vietnam and western Indonesia between 2030 and 2070, while increases were also projected in several regions. Increases were most evident in outer border regions of Thailand and Vietnam, and in southern and western Indonesia. For Ae. albopictus, widespread decreases in vector suitability were projected at each future time point across many regions of each country, alongside substantial increases in some regions of Indonesia, and in isolated pockets of the Philippines. Increases in SCI for both vectors were noted particularly in the northern Philippines, and southern and western Indonesia.

3.2.2. China

In China, the difference map shows both increases and decreases in SCI are projected across different regions of the country (Fig. 3). Much of the currently cold and arid regions in China's north-western mainland are projected to experience either no change in suitability, or a slight decrease for both vectors. However, widespread increases in SCI were also observed for both vectors throughout central and north-eastern regions where climate regions are currently temperate, or where temperate areas overlap with regions currently considered as cold climate. For Ae. aegypti, SCI values appear to gradually increase in most areas between 2030 and 2050, particularly in the southern provinces of Yunnan and Guizhou. The trend is similar for Ae. albopictus, although its suitability appears to be most consistent in the southern provinces. For both vectors, SCI increases are projected to overlap in Yunnan, Taiwan, and the north east.

3.2.3. Australia

In Australia, the difference map shows both moderate increases and moderate decreases in SCI for both vectors, across much of the country (Fig. 4). Many arid regions of central Australia will continue to be unsuitable for both vectors between 2030 and 2050. For Ae. aegypti, increased suitability is projected for much of eastern and western Australia between 2030 and 2050. Patterns fluctuate particularly for Queensland state between 2030 and 2070, with both increases and slight decreases projected. Slight to substantial increases were projected particularly along some, but not all, of the highly populated eastern coaster regions of Queensland and New South Wales. Suitability for Ae. albopictus is projected to increase in large parts of Western Australia between 2030 and 2050, with more sporadic increases and decreases in other states. The far north coastal areas of Queensland, which are currently highly susceptible to invasion by Ae. albopictus, are projected to experience continually decreasing suitability for this vector. For both vectors, increases in suitability tend to overlap along the eastern coastal regions, around the cities of Brisbane and Sydney, along with parts of Western Australia including the city of Perth, while the trend remains largely stable in the southern states of Victoria and Tasmania.

4. Discussion

Future changes in climate are predicted to influence the geographic distribution of dengue vectors and therefore potentially expose new populations to infection. The presence or absence of suitable climate conditions sets the spatial parameters for dengue transmission. This is the first predictive climate model to evaluate dengue transmission probabilities using a suitability index for both dengue vectors across multiple countries at a fine spatial scale. The SCI we developed, combined with climate projection data for various emissions scenarios, enabled us to project both current and future climate suitability for Ae. aegypti and Ae. albopictus for dengue transmission in the six countries studied.

4.1. Baseline suitability

Our baseline SCI maps detail patterns of dengue risk that are concordant with recent disease patterns (Ryan et al., 2019; Messina et al., 2019) and known vector distributions (Liu-Helmersson et al., 2019; Kamal et al., 2018). These comparisons indicate that our estimates of current vector suitability match predictions from other studies using alternative data and methods (Ryan et al., 2019; Messina et al., 2019; Liu-Helmersson et al., 2019; Stanaway et al., 2016; Kraemer et al., 2015; Bhatt et al., 2013). In SEA countries, the Philippines and Indonesia showed the highest baseline transmission suitability for both vectors, which correlates well with their dengue incidence rates being highest of all the countries studied, and among the highest in South East Asia (Edillo et al., 2015; Nadjib et al., 2019). Baseline suitability maps for Australia and China were also well-matched with published distributions of dengue epidemic risk in these countries (Akter et al., 2019). In Australia, local transmission of dengue has most recently been restricted to tropical north Queensland where the vector Ae. aegypti is present, although it previously had a more widespread distribution (Akter et al., 2020). Ae. albopictus is subject to a quarantine program which restricts it to the Torres Strait Islands of north Queensland, despite the presence of suitable conditions across coastal Australia. However it is regularly intercepted at Australian ports (Russell et al., 2005). While our predictions differ from the actual distribution of vectors in Australia, the relevant SCI showcases a theoretical feasibility for the vector to thrive, should it become established. In China, Ae. aegypti has a limited distribution while Ae. albopictus is more extensively distributed (Liu et al., 2019). Dengue case distributions tend to be focused in coastal provinces of southern China and provinces adjacent to Southeast Asia, where human populations are larger and travel and trade connections are greater (Wu et al., 2010; Yue et al., 2019).

Agreement between our SCI predictions and the known dengue distributions in the countries we studied is unsurprising given that almost all dengue fever transmission is mediated by Ae. aegypti and Ae. albopictus (Moncayo et al., 2004; Vasilakis and Weaver 2008). However, given the complexity of sociodemographic and behavioural factors that influence dengue transmission, our approach focussing solely on climate appears to be accurate while being relatively simple and replicable by public health departments. We also employed a similar geographic scale (administrative level 2) to that commonly used to map dengue case patterns, compared to more complex multivariate models that have been developed which use a less granular scale. Other recent models have used different combinations of human (cases, population) and environmental data (climate, landscapes) to predict future dengue risk (Khormi and Kumar 2014; Kamal et al., 2018; Liu-Helmersson et al., 2019; Messina et al., 2019; Liu et al., 2019). Of these, climate factors have been correlated to varying degrees with human dengue incidence, through their influence on both viral replication and mosquito vector density (Mordecai et al., 2019; Fouque and Reeder 2019). The continuing influence of climate on vector density may contribute to a widening of the current geographic distribution of populations at risk of dengue (Lee and Farlow 2019; Ryan et al., 2019; Tran et al., 2020). However, the contribution of climate factors to expanding dengue case distributions will also be substantially influenced by socioeconomic and human behavioural factors.

4.2. Future suitability

Our future projections of dengue vector suitability indicated both expanding and contracting trends within and between different Asia-Pacific countries. Particularly for the SEA countries both increases and decreases in SCI values were projected for each vector at each future time point. The increased future suitability observed for Ae. aegypti in the Philippines and in parts of Indonesia is particularly concerning, especially where these overlap with increased suitability for Ae. albopictus, given the very high existing burdens of dengue in these countries, along with rising population density and urbanisation levels. For China and Australia, variable increases and decreases in SCI values were projected though climate suitability was still lower than the SEA countries. However, in both Australia and China locations with increased suitability also occurred where densely populated cities are currently located. Assuming that increased climate suitability projected by our SCI translates to increases in dengue transmission, there are likely to be increased costs for disease surveillance and conventional vector control (larval source management, adulticiding using insecticides) unless other long term, sustainable control measures are in place (e.g. Wolbachia, or a vaccine) (Shepard et al. 2013; Bouzid et al., 2016). This emphasises the importance of biosecurity controls and other prevention measures for reducing the risk of vector expansion and the subsequent burdens of dengue.

4.3. Strengths

Our SCI approach could be applied to estimate potential distributions of all Aedes-borne diseases. However, while there is general agreement that climate change will alter the current distribution of vector species, there is disagreement on the degree and direction of the consequent impact on virus transmission for different countries (Banu et al., 2011; Fouque and Reeder 2019; Li et al., 2018; Williams et al., 2016). Previous global studies of dengue risk in response to climate change are either out of date, having been performed before the introduction of RCPs or limited in scope in that they only project forward to one point in time or assuming one scenario (Xu et al., 2020a; Patz et al., 1998). Similarly, studies comparing multiple future time points tend to predict either global changes at a large focal scale or are limited to individual countries, and only one vector, which make it difficult to draw detailed comparisons across countries (Ryan et al., 2019; Liu-Helmersson et al., 2019; Khormi and Kumar 2014). Predictions made using different variables and modelling methodology also complicate comparisons (Xu et al., 2020b; Messina et al., 2015).

The temperature limits used for this study are from Mordecai et al. (Mordecai et al., 2019), who synthesized previous studies that have determined suitable temperatures for vector survival, breeding and transmission rates as well as pathogen survival and prevalence. Those results were then mechanistically analysed to identify temperature ranges which are suitable for dengue transmitting vector capacity. This allows for extrapolating future climate effects on vector capacity and characterising the effects of climate on transmission across broad geographical ranges. Our approach draws on this previous work linking temperature with vectorial capacity and builds upon it by adjusting for rainfall to produce a more accurate suitability index. This index is then used to compare multiple projection scenarios and timescales at equivalent administrative units across countries. Further, mapping SCI by administrative units could enable direct linkage with reported dengue surveillance data collected by health departments.

4.4. Limitations

Temperature and rainfall have substantial impact on vector development and propagation and subsequent dengue virus transmission. Other climate factors (e.g. humidity, wind speed and solar radiation etc) could be important factors for dengue transmission. However, such data were unavailable in the present study. In future research, the factors could eventually be included to further improve the predictive models. A range of socioeconomic, human behavioural and environmental variables that are largely independent of climate may influence dengue transmission, such as human movement and behaviour, urban development and microclimates, the provision of aquatic habitat, and public health and vector control practices (Gubler 2011; Fouque and Reeder 2019). These variables may have equivalent, or greater, impacts on dengue infection risk than climate or vector distributions. In addition, transmission dynamics and bionomic responses vary between mosquito populations and dengue virus serotypes, (Bara et al. 2013; Alto et al., 2014; Soni et al., 2020; Whitehorn et al., 2015; Pongsiri et al., 2014), and can also be influenced by short-term fluctuations in weather patterns(Carrington et al., 2013; Lambrechts et al., 2011). Therefore, while the patterns obtained using our SCI tool appear to correlate well with others' observations, there are additional factors that can contribute to dengue transmission that we have not accounted for. For example, human population size and economic development are two key covariates to any projection of future dengue prevalence, and are known to have a strong influence on dengue vector breeding capacity (e.g. by providing a source of multiple blood meals, and through water storage practices). We also did not do a specific validation of SCI and any of the additional factors known to influence dengue prevalence, such as known case or vector distributions. Particularly in some tropical regions, where temperature fluctuations have a weaker correlation with dengue fever transmission (Stoddard et al., 2014), additional factors aside from precipitation could be incorporated with the SCI to increase predictive efficacy.

4.5. Future directions

Although research suggests that the geographical limits of dengue transmission are strongly determined by climate, it is not the sole determinant (Morin et al. 2013; Xu et al., 2020a). Predicting infection dynamics should also consider the broader range of influencing factors on dengue incidence. Our SCI provides a baseline platform to understand the impact of climate change on vectorial capacity alone which, used in combination additional drivers of future dengue risk, could contribute to creation of early warning systems for dengue surveillance and response. For example, the inclusion of dengue incidence and socioeconomic data could also be explored for its capacity to further refine dengue predictions. Ideally, data for dengue cases, climate variables and socioeconomic drivers would be well-matched at appropriate spatial and temporal scales, accessible in real-time and combined into analytical models that enable timely input into public health decision making.

4.6. Conclusions

This study used climate data to project suitable conditions for transmission of dengue by its two principal vectors across a range of RCP emissions scenarios. It is the first to assess transmission suitability for both vectors across multiple countries at a comparable spatial scale. The study found that the suitability for vector distribution in south east Asian countries will maintain a similarly high or slightly decreased suitability. This is especially true for the Aedes albopictus breed which shows a substantial decrease in suitability throughout the south east Asian countries in this study. Conversely, the arid regions of Australia and China show both moderate increases and slight decreases in suitability across the two countries. Assessment of other climate factors such as relative humidity, wind speed and solar radiation, alongside additional data of dengue drivers such as urbanisation, microclimate, and human population density and behaviour may further develop the efficacy of the SCI. Given that climate is likely to exert a key influence on dengue infection risk in decades to come, additional research on the relative contribution of climate is warranted to support improved dengue preparedness.

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Role of the funding source

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Credit author statement

WH conceived and supervised the project. CD carried out the analyses and co-wrote the manuscript with AM. Both CD and AM verified the underlying data. HB, GD, FF, LY, XH, ZL, WY, GW and WH provided input to writing and aided interpretation of results. All authors had full access to all the data in the study and had accept responsibility for publication. All authors reviewed and revised the final manuscript and agreed to its submission.

Declaration of competing interest

The authors have no competing financial interests or non-financial conflicts of interest to declare.

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