

1 Forecasting the future risk of dengue epidemics facing climate change in New Caledonia, South
2 Pacific.

3

4 This paper is dedicated to the memory of our brilliant colleague Elodie Descloux, who passed away far
5 too soon.

6

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25

26 **Abstract**

27 **Background**

28 Dengue dynamics result from the complex interaction between the virus, the host and the vector, all
29 being under the influence of the environment. Several studies have explored the link between climate
30 and dengue outbreaks in New Caledonia. None of them have explored the evolution of the dengue
31 outbreak risk facing climate change.

32 **Methodology/Principal Findings**

33 In this study we chose the threshold time dependent reproduction number (R_t) as the modeling target to
34 focus on time frames suitable for outbreak growths. A weekly statistical model of dengue outbreak risk
35 (i.e. dengue outbreak probability) based on climate variables was developed using support vector
36 machines (SVM) and then used in combination with CMIP5 projections of rainfall and temperature to
37 estimate the future evolution of seasonal weekly risk and the inter-annual yearly risk of dengue
38 outbreak up to the year 2100. The weekly risk of dengue outbreak is estimated using the number of
39 days with maximal temperature exceeding 30.8°C during 80 days preceding the predicted week and the
40 mean of precipitation during 60 days preceding the predicted week. According to the SVM model and
41 to the worst greenhouse gas emission scenario projection (RCP8.5), the time frame suitable for
42 epidemic growth will gain one month starting in November instead of December and the yearly risk of
43 dengue outbreak occurrence increases regularly up to 2100 and reach a probability of 1 around 2080,
44 making the dynamic of dengue fever endemic in New Caledonia.

45 **Conclusions/Significance**

46 A complete method to assess seasonal and inter annual variability of the risk of dengue outbreaks with
47 respect to climate change is proposed. We conclude that climate change is likely to increase the risk of
48 dengue in New-Caledonia (the other non climatic parameters remaining constant) in terms of both
49 frequency of outbreak and temporal spread of the outbreak.

50 **Author summary**

51 Dengue virus is transmitted to human through the bite of an *Aedes* mosquito vector. Dengue fever is a
52 worldwide public health concern, especially on tropical and subtropical countries. Over the last decade,
53 the toll of dengue fever has increased in New Caledonia, raising questions about the future of the
54 disease in this French island territory located in the South Pacific. Climate has a strong influence on
55 dengue through its influence on the ecology of the vector and the viral cycle. Several studies have
56 explored the link between climate and dengue in New Caledonia, with the aim of explaining and
57 predicting dengue outbreaks. None of these studies have explored the possible outcome climate change
58 will have on the risk of dengue fever in New Caledonia. This is the goal of this study, through
59 projections of rainfall and temperature and the selection of an appropriate prediction target for our
60 statistical model, we assess the climate-induced risk of dengue outbreaks up to the 2100 horizon. We
61 prove that the inter-annual risk of dengue outbreaks in New Caledonia will raise, according to all the
62 greenhouse gas emission scenarios and according to the high emission scenario, dengue fever will
63 become an endemic disease in New Caledonia.

64 **Introduction**

65 Dengue fever is a disease caused by a *Flavivirus* which is transmitted to human by an *Aedes* genus
66 female mosquito. Dengue virus (DENV) are divided in 4 serotypes (DENV-1 to -4). Infection with one

67 serotype provides life-long protection from reinfection with the same serotype, but does not prevent
68 secondary infection by another serotype. Most clinical infections are unapparent or exhibits mild-
69 febrile illness symptoms, but sever form of dengue can occur with hemorrhagic manifestations or shock
70 syndrome, with a possible fatal outcome. Dengue is a worldwide public health concern with 390
71 millions persons affected each year and 4 billions considered at risk in tropical and subtropical
72 countries [1,2]. New Caledonia faces recurrent dengue epidemics which is propagated by a single
73 *Aedes vector, Aedes aegypti*. Dengue profile in New Caledonia and its association with environmental
74 variables has been documented in previous studies for the past 30 years thanks to a long record of
75 quality surveillance data [3–6]. Before the year 2000, dengue outbreaks displayed a 4-5 years cyclical
76 pattern of occurrence with outbreaks due to a single DENV serotype followed by a different one during
77 the next outbreak. Seasonally epidemics were confined to the austral summer season while cases were
78 absent during winter [3]. However, this epidemiological profile evolved from ~2008-2019, with an
79 unusual persistence of DENV-1, the co-circulation of other DENV serotypes and the episodic
80 appearance or/other arboviruses such as Zika and chikungunya virus. Recent years were also marked
81 by uninterrupted virus circulation with few cases in austral winter rendering the epidemic profile more
82 endemic. These changes of circulation dynamics raise the question of whether environmental changes
83 may be acting to produce such modifications. Dengue outbreaks are due to a complex interaction
84 between viruses, hosts and vectors all of these being influenced by the environment. Among all known
85 factors impacting dengue dynamics, climate and socio-economic conditions can sustain epidemics in
86 New Caledonia [3,5].

87 Climate can influence dengue ecology by affecting virus replication and transmission, vector life cycle
88 and vector/human interactions. Variables such as temperature, humidity and water vapor pressure have
89 been identified as influencing dengue incidence rates in several dengue endemic areas around the world
90 [7]. For instance, temperature increases are associated with a faster rate of viral replication within the

91 vector and a shorter extrinsic incubation period (EIP; the time required for DENV to become
92 transmissible to another host after initial infection of a mosquito). Egg, immature mosquito
93 development, ovarian development and survival at all stages of the *Ae. aegypti* life cycle are governed
94 in part by temperature with reduced gonotrophic cycle time and more frequent blood meals (i.e.
95 chances of infection) at high temperatures. On another hand, rainfall is required to create and maintain
96 breeding sites and humidity is important for adult survival rates [8].

97 In order to understand how the multiple factors influence dengue epidemics, statistical modeling is
98 efficient. Nevertheless, the interactions between climate factors and dengue epidemiology are complex
99 and the role of the climate variables may vary from place to place, depending on the specific climate,
100 vector species and the cultural and socio-economic environment. Several studies aimed at modeling at
101 a regional scale the risk of dengue occurrence based on climate variables using either data driven
102 models [7], or mechanistic models [9,10]. No common set of optimal climatic variables has been
103 identified. Moreover, the modeling approaches differ in terms of target output of the model (number of
104 cases, incidence rate, risk of outbreak, basic reproduction number) and in terms of type of models
105 (Poisson regression, (S)ARIMA, semi parametric model, non parametric model...). Among those
106 approaches, few have tried to project dengue outbreaks risks facing climate change. Indeed, it is very
107 likely that a disease with such a strong relationship with the climatic parameters like dengue fever will
108 be affected by the ongoing global changes in earth's climate [11]. Especially given the fact that we
109 already reported +1,2°C over the last 40 years in New Caledonia [12].

110

111 The objectives of the present study were i) to set a method for assessing the current weekly risk of
112 dengue outbreak for a specific location based on climate variability; ii) to estimate the inter- and
113 seasonal risk of dengue outbreak during the next century in the face of climate change. To reach these
114 objectives, a complete process is presented, from data collection to data pre-processing, model

115 designing, variable selection and application to future climate projections. We address a number of
116 methodological issues such as the importance to define an adapted model target output (time dependent
117 reproduction number) and the processing of potential non-linearities between epidemiological data and
118 climate variables.

119 **Methods**

120 **Study area**

121 This study takes place in New Caledonia, a French overseas territory located in the southwest Pacific
122 between 19°S and 23°S about 1,200km east of Australia and 1,500 km north of New Zealand. This
123 archipelago of 18,575 km² is made up of a main mountainous island elongated northwest-southeast
124 400km length and 50–70 km wide, the Loyalty Islands (Mare, Lifou, and Ouvea), and several smaller
125 islands (e.g. Isle of Pines). Located near the Tropic of Capricorn, New Caledonia is subject to both
126 tropical and temperate influences depending on the season [13]. There are two main seasons: The hot
127 season is centered on the first quarter. The tropical influence is predominant and the weather is
128 punctuated by variations in the position of the South Pacific Convergence Zone (SPCZ) as well as by
129 the trajectories of tropical depressions. Precipitation is abundant and average temperatures are high
130 although extremes are limited by the maritime influence and the trade winds. In the cool season, from
131 June to September, the SPCZ shifts to the northeast. Disturbances in the temperate regions move
132 northward and can trigger rain spells and so-called “westerly blows”. These disturbed episodes
133 punctuate generally dry and cool weather with relatively low minimum temperatures in some areas.
134 The transition between these two seasons is not always easy to distinguish: the dry season, from August
135 to November, is the link between the cool season and the hot season. This part of the year is
136 characterized by very low rainfall and increasingly high daytime temperatures. Forest fires spread

137 easily over dehydrated vegetation under the action of a trade wind reinforced by breezes. The return of
138 rainfall is therefore eagerly awaited but can be dramatically delayed during El Niño episodes. At the
139 end of the warm season/start of the cool season, the seawater temperature is still warm and can favor
140 the formation of important rainy/stormy episodes or even subtropical depressions. The average rainfalls
141 range from 700 mm.year⁻¹ on the western side of New Caledonia to 5000 mm.year⁻¹ on its eastern
142 coasts due to the orographic effect. The population was estimated in January 2020 to be 271,407.
143 Approximately half of inhabitants are concentrated in the southeast region of the main island in
144 Noumea, the main city and its suburbs [14].

145 **Epidemiological data**

146 Demographic data come from general population census of New Caledonia made by the Institut de la
147 Statistique et des Etudes Economiques (ISEE). Times series of population have been made by linear
148 interpolation of the general population census: 1969, 1976, 1983, 1989, 1996, 2004, 2009, 2014 and
149 2019 [15].

150 In New Caledonia , dengue is a notifiable disease. Monthly number of dengue cases from 1973 to 2019
151 have been retrieved from the Public Health Authorities of New Caledonia. Dengue cases are defined as
152 clinical or confirmed. A clinical case is an evocative dengue case without diagnosis. A confirmed case
153 has been confirmed by direct detection of dengue virus by reverse-transcriptase polymerase chain
154 reaction (RT-PCR using a pandengue technique) and/or serological assay (IgM detection by indirect
155 immunofluorescence or ELISA) [3].

156 **Meteorological data**

157 Daily rainfall (RR) and maximal temperature (TX) were measured by a weather station of Météo-
158 France from 1970 to 2020 at Faubourg Blanchot, Nouméa. A moving average on TX and RR was

159 computed in order to create climate-based indices. The time windows of the moving average varied
160 from 50 days to 80 days preceding each current week w for TX and 30 days to 70 days for RR.
161 Additionally, number of days where these variables exceeded a panel of given threshold (e.g, number
162 of days where TX exceeded 32°C) were computed as Descloux et al., [3] indicated that such thresholds
163 on temperatures and rainfall were most pertinent for predicting outbreaks. We thus obtain a large panel
164 of climate indices. Before computation RR was log-transformed and added 1 to normalize its
165 distribution for better predictions.

166 **Climate change scenarios data**

167 To obtain projections of temperature and rainfall under different global warming scenarios, we
168 retrieved historical (1970-2004) and projections (2005-2100) of daily maximum temperature and
169 rainfall simulated by eight coupled ocean-atmosphere models from the 5th Phase of the Coupled Model
170 Intercomparison Project – Assessment Report 4 (CMIP5 – AR4) experiments [16]. The eight selected
171 models were “CanESM2”, “CNRM-CM5”, “inmcm4”, “IPSL-CM5A-MR”, “IPSL-CM5B-LR”, “MPI-
172 ESM-LR”, “MRI-CGCM3” and “NorESM1-M”. They were selected based on their capacity to
173 reproduce the observed climate in the South Pacific [17]. Three scenarios of emission (greenhouse
174 gases and aerosols) – referred to as “Representative Concentration Pathways” (RCPs) – were chosen:
175 the RCP8.5 for a high emission scenario, RCP4.5 for a midrange mitigation emission scenario and
176 RCP2.6 for a low emission scenario. These data are thereafter referred to as "historical" covering 1971-
177 2004 and “projections” (RCP2.6, RCP4.5 and RCP8.5) covering 2005-2100. For each model, we
178 selected time-series from the spatial point closest to Nouméa. A statistical downscaling based on a
179 quantile-quantile correction was also applied to correct the distribution of the modeled time series to fit
180 the distribution observed time series over the historical period [18]. This correction is then applied to

181 projections to correct accordingly their distributions as in [18]. That allowed avoiding a part of model
182 biases while keeping their climate change trends.

183 **Modeling the weekly risk of dengue outbreaks**

184 The risk of dengue outbreaks was estimated through the time-dependent reproduction number R_t
185 defined as the number of secondary infections caused by a primary case at time t . If $R_t > 1$ the number
186 of cases increases with time, R_t must be < 1 for an outbreak to decline [19]. R_t was estimated
187 according to a method proposed by Wallinga & Teunis [20,21]. This method allowed to transform a
188 time series of number of cases in a time series of estimated values of R_t . The method is based on the
189 “Generation Time” i.e. the time lag between infection in a primary case and a secondary case. The
190 generation time distribution should be obtained from the time lag between all infectee/infecter pairs. As
191 it cannot be observed directly, it is often substituted with the serial interval distribution that measures
192 time between symptoms onset. Based on the extrinsic incubation period of the virus within the
193 mosquito (2 to 15 days at 30°C) – and intrinsic incubation period of the virus within human (3 to 9
194 days) [22], we assumed the generation time distribution was ‘lognormal’ with a mean of 14 days and a
195 standard deviation of 7 days. We relied on those values and assumed that mosquito to human and
196 human to mosquito transmission were negligible compared to the two incubation periods. Then this
197 method computes time-dependent reproductions numbers by averaging over all transmission networks
198 compatible with observations. Given observation of (N_0, N_1, \dots, N_t) incident cases over consecutive time
199 units, and a generation time distribution w . The probability p_{ij} that case i with onset at time t_i was
200 infected by case j with onset at time t_j is calculated as $p_{ij} = N_i w \frac{(t_i - t_j)}{\sum_{i \neq k} N_i w(t_i - t_k)}$. The effective
201 reproduction number for case j is therefore $R_j = \sum p_{ij}$, and is average as $R_t = \frac{1}{N_t} \sum R_j$ over all cases with
202 the same date of onset.

203 R_t was computed only when incidence rates (per 1000 inhabitants) were superior to the 8th decile and
204 set to 0 otherwise in order to avoid high values of reproduction number with low circulation of the
205 virus. With these choices, periods when outbreaks developed were detected satisfactorily.

206 In contrary to the standard reproduction number R_0 which is defined as the number of secondary
207 infections from a primary case in an entirely naive population, $R_t > 1$ is defined as the real number of
208 secondary cases from a primary case and thus may reflect the impact of the immunity status of the
209 population and control measures during outbreaks. Those factors are not considered in our evaluation
210 of the risk of dengue outbreaks.

211 To avoid multi-collinearity between explanatory variables and consider the possible existence of
212 complex non-linear links between the explanatory variables and the response variable, we chose to use
213 Support Vector Machines (SVM) to model the weekly risk of dengue outbreak [23]. When training our
214 SVM model, to compensate for the under-representation of epidemic weeks (175) versus non epidemic
215 weeks (2269) in our data set, an oversampling method was applied. We sampled with replacement in
216 the pool of epidemic weeks in order that the number of epidemics weeks match the number of non
217 epidemic weeks (i.e. adjust the class distribution) during the training phase. To determine the model
218 with the best prediction performance (i.e. “best model”), a model was created for each combination of
219 one or two computed climate indices as inputs (i.e. explanatory variables). Then after training, the
220 models performance were compared on a test set in a 5 fold Leave-Time-Out Cross Validation (LTO-
221 CV) [24]. The method consists in dividing the time series of data in 5 continuous equal parts
222 (approximately 10 years each for our data) to account for the time nature of the data. The model is
223 trained on four parts and test on the fifth. Estimated probability of dengue outbreaks for the current
224 week (between 0 and 1) were compared to the actual state of the week (1 if epidemic, 0 otherwise) then
225 the performances were compared in terms of averaged mean squared errors (MSE). The software R and

226 packages R0, e1071 [21,25], were used for all the simulations. In the end, the model provides a
227 probability for each week w , that $R_t > 1$ (i.e. weekly risk of dengue outbreak).

228 **Forecasting inter- and seasonal dengue outbreak risk variability**

229 Then the evolution of the risk of dengue outbreak under climate change is explored by feeding the
230 “best model” with computed climate indices up to 2100 from the projections : RCP2.6, RCP4.5 and
231 RCP8.5. A year was considered epidemic if for at least one week during that year, the probability was
232 greater than a set threshold. Thresholds were chosen with the aim of matching the number of predicted
233 epidemic years by the model fed with the input from the observed climate data and the model fed with
234 the modeled climate data. Thresholds were fixed to 0.6 for the model fed with the input from the
235 observed climate data and 0.8 for the model fed with the modeled climate data. Then the inter-annual
236 risk variability was assessed for the entire period 1973-2100 for the three warming scenarios. To
237 highlight the long-term trend of this risk and estimate a sliding probability of dengue outbreak
238 occurrence, a central moving average of 11 years was then applied.

239 In parallel the seasonal risk variability was assessed by averaging for each of the 52 weeks in a year,
240 the modeled estimated risk over the time frames 1973-2004, 2020-2040, 2050-2070 and 2080-2100.
241 Confidence intervals were also estimated based on the variance of the eight climate models forecasts
242 for each week over each studied time frame. This way, the seasonal risk distributions of the outbreak
243 risk of these four-time frames can be compared in terms of amplitude and spread.

244 **Results**

245 For the period 1973-2019, the time frames suitable for outbreak were detected ($R_t > 1$) based on the
246 number of cases evolution. These time frames are depicted by the dashed green line in the Figure 1.

247

248 **Fig 1. SVM prediction of weekly dengue outbreak risk during 1973-2020 in New Caledonia.**

249 The dashed red line depicts the model probability of dengue outbreak each week (w) according to the number of days with
250 maximal temperature exceeding 30.8°C during a period of 80 days preceding w and the logarithm of mean precipitation
251 during a period of 60 days preceding w . Normalized weekly incidence rate is in solid blue line. Periods prone to dengue
252 outbreaks ($R_t > 1$) according to the Wallinga & Teunis method are in dashed green line.)

253

254 The dashed red line is the model probability that the current week is epidemic. The most effective SVM
255 model for classifying each week w , as a period suitable for epidemic growth was obtained using the
256 number of days with maximal temperature exceeding 30.8°C during a period of 80 days preceding w
257 and the logarithm applied to the mean of precipitation during a period of 60 days. The SVM model
258 used a polynomial kernel of degree 3, hyper parameters were cost = 1 and gamma = 1. Feeding the
259 model with projections of temperature and rainfall under the global warming scenarios: RCP2.6,
260 RCP4.5 and RCP8.5, we were able to estimate the smoothed yearly risk of dengue. Figure 2 is the risk
261 modeled with input from the weather station (i.e. observed climate data) and the mean of risk modeled
262 from the 8 CMIP5 models (i.e. modeled climate data). The outputs are processed in a similar way:
263 central moving average (11 years) of the yearly time series series where the value for each year is 1 if
264 an outbreak is observed, 0 otherwise. Over the historical period, the inter-annual variability of the
265 dengue probability of outbreaks occurrence is similar for both the model fed with input from the
266 observed and modeled climate data (Figure 2).

267

268 **Fig 2. Evolution of the inter-annual dengue outbreak risk according to different RCP scenarios up to the year 2100.**

269 Plain lines denotes the yearly mean of dengue risk outbreak estimated by the model based on the 8 selected CMIP5 models
270 for the historical period and the three scenarios. Black lines depicts the historical period, green line depicts the low
271 greenhouse gas emission scenario (RCP2.6), blue line depicts the medium emission scenario (RCP4.5) and red line depicts
272 the high emission scenario (RCP8.5). The risk is computed as a central moving average (11 years) of the epidemic year time

273 series; with epidemic year (i.e. a year where at least one week was estimated epidemic) coded as 1 and non epidemic year
274 coded as 0. For each lines, the corresponding colored region depicts the confidence interval (± 1 standard deviation of the 8
275 selected models). Processed in a similar way, the dashed black line denotes the risk estimated based on the weather station
276 records during the contemporary period (1973-2020).

277

278 From 0,20 in 1980 (i.e. 1 outbreak every 5 years) the risk of outbreak occurrence increases to 0,6 in
279 2000 (i.e. 3 outbreaks every 5 years) before decreasing to 0,4 approaching 2020 (i.e. 2 outbreak every 5
280 years). According to the SVM model and the climate projections, the yearly probability of dengue
281 outbreak occurrence increases regularly up to 2100 and converges toward, 0.8 for RCP4.5 scenario and
282 1 for the RCP8.5 scenario. According to the RCP2.6 scenario, it increases up to 2050 and then
283 decreases and converges to 0.7 in 2100. In other words, in 2100 the model predicts 7 outbreaks every
284 10 years considering the lowest emission scenario and one outbreak each year considering the high
285 emission scenario. Figure 3 depicts the evolution of the seasonal risk distribution corresponding to 4
286 distinct time frames.

287

288 **Fig 3. Evolution of the seasonal dengue outbreak risk according to different RCP scenarios up to the year 2100.**

289 From left to right, each frame depicts the seasonal dengue outbreak risk according to (a) the low greenhouse gas emission
290 scenario (RCP2.6), (b) the medium emission scenario (RCP4.5) and (c) the high emission scenario (RCP8.5) respectively.
291 Dotted lines are the mean of the weekly dengue risk outbreak estimated by the model based on the 8 selected CMIP5
292 models and colored region denotes the confidence interval around that mean (± 1 standard deviation of the 8 selected
293 models) averaged for the period 1973-2004 in green, 2020-2040 in light blue, 2050-2070 in pink and 2080-2100 in orange.

294

295 Here the risk is computed as the average probability that a week is epidemic given by the model for
296 each week of each year for the 4 distinct time frames. The results show that the amplitude of the risk
297 given by the modeled climate data on the time frame 1973-2004 is over-estimated compared to the

298 observed climate data. Nevertheless period for both set of inputs are consistent. The amplitude of the
299 risk corresponding to the future time frames (2010-2030, 2040-2060, 2080-2100) significantly
300 increases to reach almost 0.7 in February/March in 2100 for the low scenario (RCP2.6), 0.9 for medium
301 scenario (RCP4.5) and 1 for the high scenario (RCP8.5). Moreover, period of the year during which an
302 outbreak may occur will gain one month starting in November instead of December according to worst
303 scenario (RCP 8.5) in the 2080-2100-time frame.

304 **Discussion**

305 In this work, we propose a complete process to assess the climate-based inter-annual and seasonal risk
306 of dengue outbreak during the next century facing climate change for a specific location where high-
307 quality and long term time series are available at a fine temporal scale: monthly for the epidemiological
308 data, daily for the climate data. The first step was to develop a reliable weekly explanatory model able
309 to estimate the risk of dengue outbreak based on contemporary climate. The model is based on two
310 climatic variables: one regarding the maximal temperature (the number of days where the maximal
311 temperature was higher than 30.8°C during a period of 80 days preceding w) and one regarding
312 precipitations (the logarithm of the mean of precipitations during a period of 60 days preceding w).
313 Those climatic conditions are coherent with other climate-based predictive models, reviewed in Naish
314 et al., [7].

315 Using this model, most of the period of epidemic growths are detected (Figure 1) but fail to detect
316 important outbreaks like 1989, 2003, 2013, 2017 and 2019. For those “double outbreaks” (i.e. spread
317 on two years) 1989-1990,2003-2004, 2012-2013, 2016-2017 and 2018-2019, the model predicts a high
318 risk either the first or the second year. It is interesting to note that these outbreaks could be related to
319 new serotype introductions, genotypic displacements or serotypic replacement. For example, the year
320 1989 is the first time DENV-3 is reported in New Caledonia during our period of study, 2003 is the

321 first time DENV-1 is reported in New Caledonia in 12 years, 2012-2013 is the DENV-1 “Asia”
322 genotypic displacement over the DENV-1 “Pacific” and 2017 is the DENV-2 serotypic replacement
323 over DENV-1 [26]. For these outbreaks, immunity may play a bigger role in the outbreak dynamic,
324 diminishing the role of climate factors. Some periods are also estimated at risk despite nil or low
325 dengue virus circulation: at low level for 1982, 1983, 1985, 1992, 2001, 2005, 2015 and at high level
326 for 2002 and 2011. In these cases, immunity could prevail or weakens climatic influences. Feeding this
327 model with climate projections, we can clearly see a trend that climate change will increase the inter-
328 annual risk of dengue outbreak in the future in the three considered scenarios. Also if we consider the
329 seasonal risk of dengue outbreak evolution (see Figure 3), we observe that the period of the year in
330 which an outbreak can occur does extend. However the seasonality remains well marked with zero risk
331 of dengue outbreak during July to November. Isolating the effects of climate on dengue outbreak
332 dynamic is not an easy task because the establishment and spread of this disease is a complex
333 phenomenon with many interacting factors, e.g., the environment in which the virus and hosts are
334 situated, the population and its characteristics (e.g. the susceptibility), the virus and its characteristics.
335 One of the key features introduced here is the use of the threshold time dependent reproduction number
336 ($R_t > 1$ vs $R_t < 1$) to focus on time frames suitable for outbreak growths. There are several advantages
337 in using this variable as target for the model. First the time lag between climate condition and outbreak
338 dynamic due to the duration of extrinsic incubation in mosquitoes and the intrinsic incubation in
339 humans is directly considered through the generation time distribution. Second, this variable focuses on
340 the time frames suitable for outbreak growth without considering the amplitude of the increase or
341 decrease of the dengue outbreak which may be more sensitive to non-climatic factors such as the size
342 of the susceptible population or the behavior of the human host population.

343 In this study, we used a statistical estimate of the real-time production number (R_t) based on [21]
344 without the possibility of separating the environmental effects from the depletion of the susceptible
345 population. To overcome this issue, an estimate of the basic reproduction number (R_0) could be
346 investigated by other methods (Exponential Growth, Maximum Likelihood, Attack Rate, Sequential
347 Bayesian and compartmental model) but information about the dynamic of the size of susceptible
348 population is needed and this information is difficult to obtain (usually estimated from a seroprevalence
349 survey).

350 Another key feature concern the non-linearities of the relation between climate and dengue dynamic
351 that has been observed in several studies [3,27,28]. These results are consistent with our findings and
352 suggest that it is worthwhile to use a type of model such as SVM which is a non-parametric supervised
353 learning algorithm and can be used to model non-linear links without any prior knowledge of the shape
354 of the relationship [29]. In our climate model projections, rainfall does not change in the future
355 whatever the scenario considered (not shown) while temperature projection show a robust increase
356 within climate models which intensity depends on the scenario considered. For instance, in RCP8.5
357 (resp. RCP2.6) a mean increase of 0,82°C (resp. 0,68°C) is found in 2020-2040 and 2,98°C (resp.
358 0,82°C) in 2080-2100 in comparison to our historical period 1973-2004. Given the absence of rainfall
359 changes, the projected risk increase is solely due to the temperature increase with climate change. It is
360 worth to note however, that a limit of our study is the use of these CMIP5 climate models, because they
361 have a poor horizontal resolution (~100-200km), that is not *a priori* adapted to simulate the climate of a
362 mountain island such as New-Caledonia. While the amplitude of temperature changes simulated by
363 these CMIP5 models is robust among models (Fig S1) and reasonable compared with projections
364 performed with an atmospheric regional model at the island scale [30], it is known that projections of
365 precipitation in the South Pacific and at island scales in CMIP5 models are not reliable according to

366 Dutheil et al. [31]. These authors used a very high resolution (~4km) atmospheric model to show, a
367 possible strong reduction of precipitation over New Caledonia at the end of 21st century in the RCP8.5,
368 confirming doubts on CMIP5 rainfall projections. That study highlights the need for further regional
369 climate projections at the appropriate island scales prompting further work to re-assess the risk of
370 dengue outbreak using such high resolution climate data for the next century.

371 Another limit to our study is given one of the two variable selected by the model : the number of days
372 where maximal temperature is higher than 30.8°C during a period of 80 days preceding the current
373 week (*w*), thus the risk of a dengue outbreak increases as the projected temperature increase. However
374 it may be that temperatures too high may be no more suitable for the ecology of the vector (e.g.
375 evaporation of breeding sites, decrease of survival in adults), indeed a review of fifty mark-release-
376 recapture has shown that the survival and longevity of *Aedes aegypti* mosquitoes is highly reduced
377 when temperatures exceed a threshold, which might be around 35°C [32].

378 Finally the last limit in the design of the study is that we extrapolate data from one weather station of
379 Nouméa, the capital city, to conceive a climate-based explanatory model of the risk of dengue outbreak
380 in the whole island of New Caledonia. However, Nouméa is the main urban pole of New Caledonia and
381 account for the majority of New Caledonia's inhabitants. Furthermore, it has been shown that either
382 epidemics start in Nouméa or the capital city is affected in the weeks following the report of first cases
383 in New Caledonia [33]. In addition to this, for the last 50 years, Nouméa was affected by all reported
384 outbreaks.

385 The aim of this study is to assess the climate-based risk of dengue outbreaks in the face of climate
386 change but factors such as the emergence of new strains or serotypes, human population immunity
387 status, urbanization and new control methods cannot be ignored in the dynamics of dengue fever
388 outbreaks.

389 As an end note, Noumea has joined the World Mosquito Program (WMP), which is likely to
390 profoundly transform the epidemiological profile of dengue in New Caledonia. This program consists
391 of releasing *Aedes aegypti* mosquitoes colonized by the endosymbiotic bacterium *Wolbachia*. The
392 *Wolbachia*-mosquitoes released lose their ability to transmit arboviruses and will gradually replace the
393 wild mosquito population. Nouméa is assumed to be covered by the end of 2021 and become a dengue-
394 free zone. It is difficult to anticipate how this change will impact the dengue dynamic in the whole
395 country and if the temperature (i.e. climate change) will have an adverse impact on the strategy. Indeed
396 it has been shown that temperature regimes significantly altered the *Wolbachia* density in *Aedes*
397 *aegypti* carrying the bacteria [34].

398 We showed that dengue outbreaks in New Caledonia can reasonably be explained with variables
399 regarding temperature and precipitations. Given CMIP5 projections of temperature and rainfall, down-
400 scaled to fit New Caledonia climate we estimated that seasonally, periods conducive to epidemics will
401 be higher according to every greenhouse gas emission scenarios. Inter-annually, the risk of dengue
402 outbreak will increase until the year 2100 with 7 outbreaks every 10 years according to the low
403 greenhouse gas emission scenario and 1 every year according to the high emission scenario. Making in
404 the latter case, the dynamic of dengue, endemic in New Caledonia.

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407 **Supporting information**

408 **S1 Fig. Evolution of maximal temperatures according to different RCP scenarios up to the year**
409 **2100.**

410 **References**

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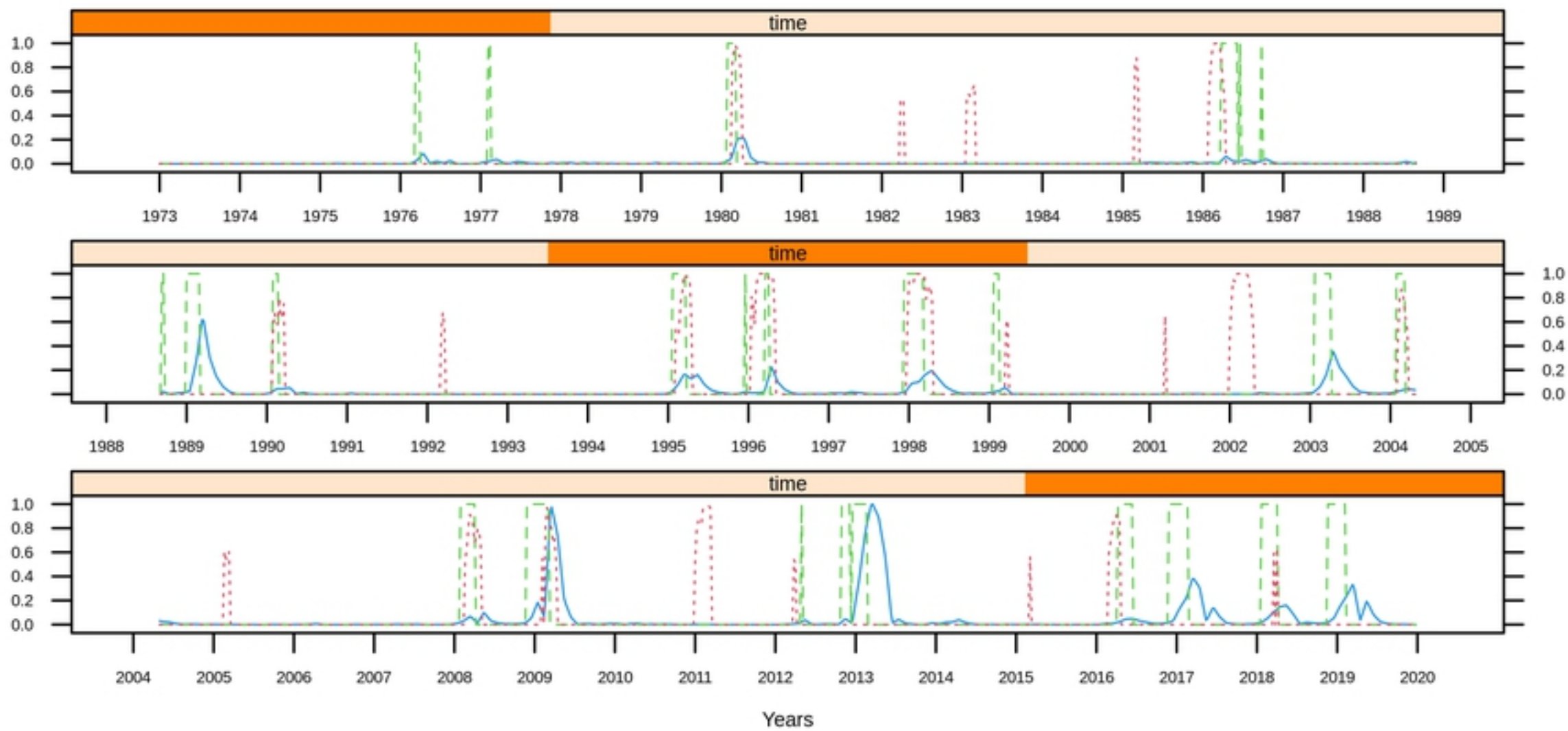


Figure 1

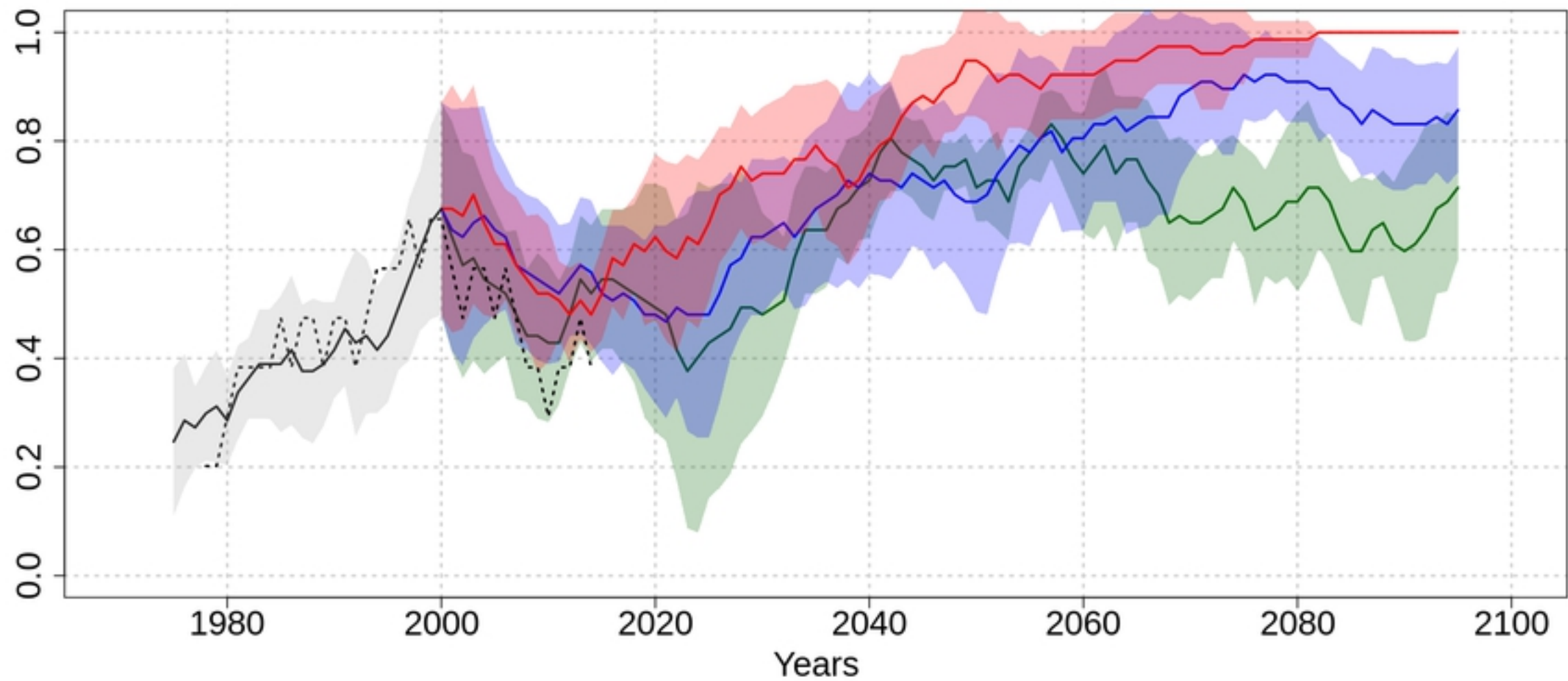


Figure 2

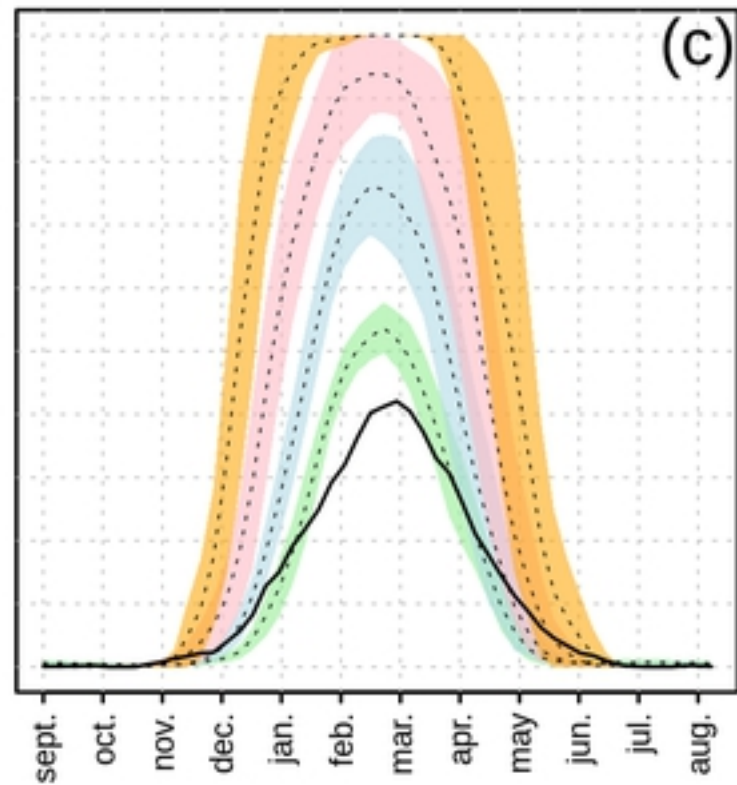
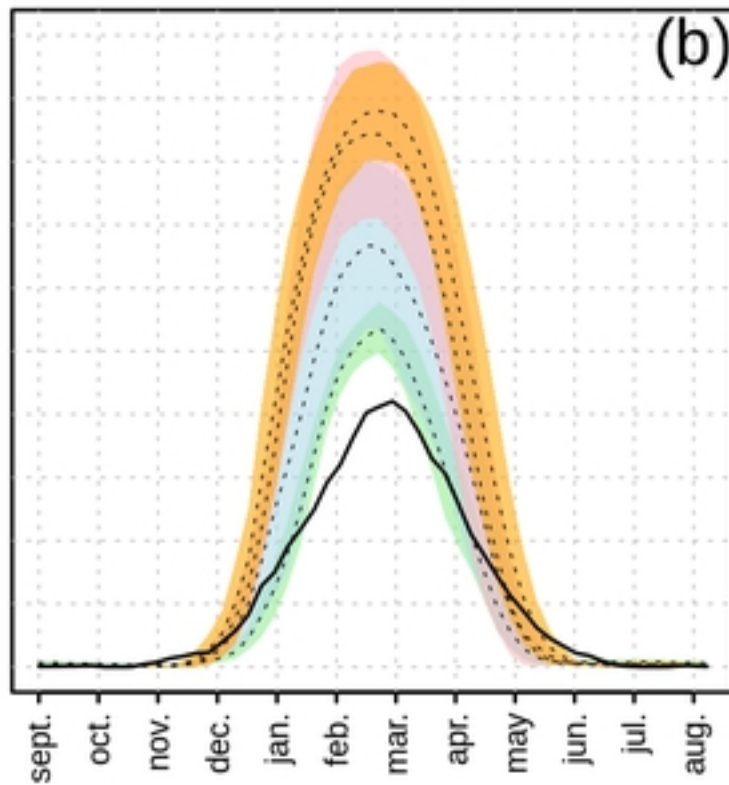
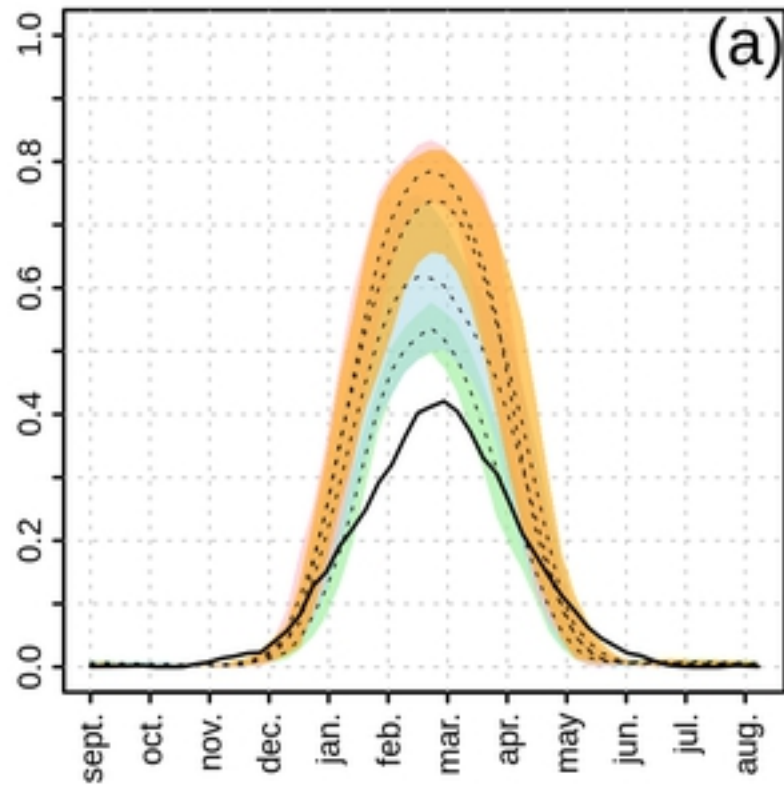


Figure 3