The Mosquito, the Virus, the Climate: An Unforeseen Réunion in 2018

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Abstract

The 2018 outbreak of dengue in the French overseas department of Réunion was unprecedented in size and mobility across the island. This research focuses on the cause of the outbreak, asserting that climate played a large role in both the proliferation of the mosquitoes, which transmitted the disease, and the vulnerability of the island's occupants. Additionally, this study analyses if this outbreak could have been forecast in the sub-seasonal time scale. A stage-structured model was run using observed temperature and rainfall data to simulate the lifecycle and abundance of the mosquito. Further, the model was forced with uncalibrated sub-seasonal forecasts to determine if the event could have been forecast up to four weeks in advance. With unseasonably warm temperatures remaining above 25 degrees C, along with large tropical-cyclone-related rainfall events accumulating 10-15 mm per event, the modeled mosquito abundance did not decrease during the second half of 2017, contrary to the normal behavior, likely contributing to the large dengue outbreak in early 2018. Although sub-seasonal forecasts two weeks in advance, which along with seasonal forecast information could have provided enough time to enhance preparedness measures. Our research demonstrates the potential of using state-of-the-art sub-seasonal climate forecasts to produce actionable sub-seasonal dengue predictions. To the best of the authors' knowledge, this is the first time sub-seasonal forecasts have been used this way.

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15	Key Points:
16	• Unseasonably warm temperatures and increased tropical-cyclone-related rainfall led to
17	the large 2018 dengue outbreak in Réunion.
18	• A combination of seasonal and subseasonal forecasts can be used to predict temperature
19	and rainfall events, up to four weeks in advance.
20	• This can provide enough lead time for decision makers to activate early warning systems,
21	vector control strategies and medical readiness.

Abstract 22

The 2018 outbreak of dengue in the French overseas department of Réunion was unprecedented 23 in size and mobility across the island. This research focuses on the cause of the outbreak, 24 asserting that climate played a large role in both the proliferation of the Aedes albopictus 25 mosquitoes, which transmitted the disease, and the vulnerability of the island's occupants. 26 Additionally, this study analyses if this outbreak could have been forecast in the sub-seasonal 27 28 time scale. A stage-structured model was run using observed temperature and rainfall data to simulate the lifecycle and abundance of the Ae. albopictus mosquito. Further, the model was 29 forced with uncalibrated sub-seasonal forecasts to determine if the event could have been 30 forecast up to four weeks in advance. With unseasonably warm temperatures remaining above 31 25° C, along with large tropical-cyclone-related rainfall events accumulating 10-15 mm per 32 event, the modeled Ae. albopictus mosquito abundance did not decrease during the second half 33 of 2017, contrary to the normal behavior, likely contributing to the large dengue outbreak in 34 early 2018. Although sub-seasonal forecasts of rainfall for the Dec-Jan period in Réunion are 35 36 skillful up to four weeks in advance, the outbreak could only have been forecast two weeks in advance, which along with seasonal forecast information could have provided enough time to 37 enhance preparedness measures. Our research demonstrates the potential of using state-of-the-art 38 sub-seasonal climate forecasts to produce actionable sub-seasonal dengue predictions. To the 39 best of the authors' knowledge, this is the first time sub-seasonal forecasts have been used this 40 way.

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Plain Language Summary 43

During the end of 2017 and the beginning of 2018, there was a large outbreak of dengue in the 44 French overseas department of Réunion. Tropical-cyclone-related rainfall events and higher-45 than-average temperatures played a role in the dengue outbreak, which could have been forecast 46 47 four weeks in advance. The size of the Ae. albopictus mosquito population in Réunion was 48 modeled with temperature and rainfall data to replicate the size that would have been present during the time of the outbreak. Forecast rainfall and temperature data were input into the 49 mosquito model, for one to four weeks prior to the target date of January 8th. to better understand 50 if the increased mosquito population could have been calculated in advance. Due to abnormally 51 warm temperatures hovering around 25° C, along with large rainfall events accumulating 10-15 52 53 mm per event, the mosquito population did not diminish towards the end of 2017 - contrary to normal behavior - likely contributing to the large dengue outbreak in early 2018. Additionally, 54 model results suggest accurate prediction of the onset and size of the outbreak two weeks in 55 advance, with some accuracy three to four weeks in advance, which could have provided enough 56 time to enhance preparedness measures. 57

58

59 **1 Introduction**

60 Despite heightened levels of attention and the mobilization of intensive vector control efforts

over the last several decades, Réunion, an island in the Indian Ocean, experienced an

unprecedented epidemic of dengue during the early months of 2018. A total of 1388 cases were

reported between 1 January and 15 April 2018, and 6942 cases by the end of the year, a 6000%

64 increase from 2017 (Kles et al., 1994; WHO, 2019; Kreisel, 2018). The first dengue epidemic

occurred in Réunion between 1977-78. Between 2004 and 2016, small dengue outbreaks have

been observed on the island, with an average number of cases ranging from one to 281. In 2017,

a larger outbreak was observed, with 1086 cases reported; however, even compared to this

outbreak, the magnitude of the 2018 event was unusual in size (Kreisel, 2018).

69 Globally, dengue is a significant public health concern, estimated to cause nearly 100 million

⁷⁰ symptomatic cases per year, but tends to be confined to urban areas in tropical and subtropical

regions, where the principal mosquito vector, *Aedes aegypti*, is endemic (Bhatt et al.,

2013). However, in Réunion this mosquito is only found in the larvae form (WHO, 2019). The

island is home to the secondary dengue vector, *Aedes albopictus*, which has rarely been

associated with large dengue outbreaks, such as the one observed in 2018 (Lambrechts et al.,

2010). Unlike the primary dengue vector Ae. aegypti, Ae. albopictus is endemic in temperate

regions of the globe, such as North America, Europe and China (Kraemer et al., 2015).

77 The underlying causes for the sudden and unusual upsurge in cases of the 2018 outbreak have

not been investigated in detail thus far. High susceptibility to dengue virus among the population,

79 or genetic adaptation of the dengue virus to *Ae. albopictus* are plausible hypotheses (Kles et al.,

1994). In addition, we hypothesize here that optimal temperatures for the vector and the virus,

- and tropical-cyclone-related rainfall created favorable climatic conditions that contributed to
- ⁸² unusual vector abundance beyond the epidemic level in the island. Previous research suggests
- that the combination of above normal rainfall and temperatures is a prerequisite for the

reproduction of ectotherm vectors such as *Ae. albopictus*, leading to high vector abundance

- 85 (Hawley, 1988; Jia et al., 2016; Dieng et al., 2012; Waldock et al., 2013; Reinhold et al., 2018).
- 86 Favorable ambient climatic conditions enhance viral replication within vectors and lead to

87 increased transmission in a vulnerable population (Liu-Helmersson et al., 2016).

88 **2 Data and Methods**

89 2.1 Climate attribution

90 In order to examine the contribution of climatic conditions to the 2018 dengue outbreak in

Réunion, we analyzed the preceding climatic conditions and contextualized them using an 18-

92 year baseline: 2000-2017. Our climate analysis used observed station-based gridded rainfall data

93 (CPC-Unified; see Chen et al., 2008), and temperature and atmospheric circulation variables

- 94 from the European Re-Analysis Interim project (Dee et al., 2011). We developed a process-based
- stage-structured model of the mosquito-vector *Ae. albopictus* by drawing on previously
- 96 calibrated models of Ae. albopictus (Jia et al., 2016; Metelmann, 2019), and of Ae. aegypti (Liu-
- 97 Helmersson et al., 2019). See supplement for further details. The model was validated to local
- 98 Breteau index observations from Reunion (Boyer et al., 2014) exhibiting skillful results
- 99 (supplement).

100

- 101 The model was then run for the baseline period on a "perfect prognosis" mode, i.e., using climate
- 102 observations of daily temperature and rainfall to generate past adult vector population from four
- 103 compartments (i.e., emerging, blood feeding, gestating, and ovipositing); the approach is
- designed to help diagnose the role of climate in the present epidemic event, and also as a
 measure of the maximum predictive skill provided by such a model (often called "perfect-
- prognosis approach"). The adult *Ae. albopictus* abundance was standardized over time in order to
- visualize statistical anomalies in vector population driven by climate factors. We obtained
- epidemiological data of dengue from Réunion from 2010 up to April 2018, provided by the
- 109 European Centre for Disease Control (ECDC).

110 2.2 Sub-seasonal Skill Assessment

- Additionally, we wanted to understand if the events leading to the outbreak could have been
- 112 forecast in advance. Seasonal forecasts provide a first layer of information to assess if suitable
- 113 conditions for an outbreak will happen in a coming season, but cannot be specific enough as to
- 114 indicate when *within that season* the epidemic could occur. Nonetheless, the relatively new sub-
- seasonal forecasts have the potential to provide that kind of information (Vitart et al.,
- 116 2017). Using sub-seasonal climate forecasts produced by the European Centre for Medium-
- 117 Range Weather Forecasts (ECMWF) model, available through the Seasonal to Sub-seasonal
- 118 Prediction Project Database (Vitart et al., 2017; WMO, 2020), we analyzed if and how many
- 119 weeks in advance the outbreak could have been forecast.
- 120 We conducted a sub-seasonal forecast skill assessment analysis for both temperature and rainfall,
- as described below, paying special attention to sub-seasonal rainfall forecast skill to see if the
- heavy rainfall episodes that occurred at the end of December 2017 and beginning of 2018
- 123 (yellow sections in 1A and 1B) could have been forecast. Four different lead time forecasts were
- used, each 45 days in length, for one to four weeks before the target week starting on Jan 8,
- 125 2018. For simplicity, we refer to each sub-seasonal forecast as Week 1, Week 2, Week 3 and
- Week 4 prior to the target week, corresponding to the initializations of Jan 1 2018, Dec 25 2017,
- 127 Dec 18 2017 and Dec 11 2017, respectively. The week of Jan 8 was selected due to its proximity
- 128 within the various tropical-cyclone-related rainfall events hypothesized to be partially
- responsible for the observed steep increase in dengue cases during and after that week.

- 130 For each of the 4 sets of 45-day-long forecasts, a large set of 160 ECMWF hindcasts was
- downloaded from the Subseasonal-to-Seasonal Database at the International Research Institute
- 132 for Climate and Society's Data Library (IRIDL). Hindcasts are forecasts made with exactly the
- same model configuration for the same 45 forecast days in the past 20 years. For example, for
- the Jan 1 2018 initialization, the forecasts consist of daily predictions from Jan 1 to Feb 14 2018,
- and the hindcasts (or "reforecasts") consist of the same days for the years 1998-2017. A 20-year
- record does not provide a statistically robust sample for skill analysis; hence, we used all
- 137 initializations available in the 4 weeks prior to the initialization of the forecast. Since the
- 138 ECMWF model provides two initializations per week (every Monday and Thursday), we used a
- total of 160 hindcasts (20 hindcasts x 2 initializations/week x 4 weeks), as indicated above.
- 140 The skill assessment process involved a cross-validation procedure for two key forecast
- 141 attributes: association, measured by the Spearman rank correlation, and discrimination, measured
- by the two-alternative forced choice metric, or 2AFC (supplement; Mason and Weigel, 2009).
- 143 The cross-validation analysis used a leave-5-out moving window, and was conducted using
- 144 PyCPTv1.6 (Muñoz et al., 2020), a set of Python libraries designed to interface and enhance
- 145 IRI's Climate Predictability Tool (CPT; Mason et al., 2020). PyCPT automatically downloads
- 146 from the IRIDL the necessary hindcasts and observations to perform the skill assessment
- 147 analysis.
- 148 For each set of sub-seasonal hindcasts, we corrected for mean and amplitude biases present in the
- temperature and rainfall time series. To do this, we shifted the mean and rescaled the standard
- deviation for each variable and forecast initialization, and then used this corrected daily
- temperature and rainfall time series to run the vector model in forecast mode. No climate forecast
- 152 calibration was conducted beyond the mean and variability bias corrections.

153 **4 Results**

- 154 3.1 Climate Attribution
- 155 During 2017, then the warmest year on record without an El Niño event (Harrabin, 2018), daily
- average surface temperature in Réunion provided suitable conditions for vector proliferation,
- 157 even during most of the austral winter (in red in Figure 1). The average daily rainfall between
- 158 May and the end of November on the island was around 2-3 mm/day, providing suitable
- conditions for mosquito reproduction. Starting on December 27th, a total of seven (European
- 160 Commission, 2018) large-scale atmospheric systems in the South-West Indian Ocean one
- tropical depression, one tropical storm, and five tropical cyclones, denoted by yellow sections in
- 162 Figure 1- produced important rainfall events over Réunion (in green in Figure 1). Rainfall
- associated with these tropical systems are likely responsible for the increase in vector population
- during the end of 2017 and beginning of 2018, due to an increased number of larvae habitats, but
- also to the hampering of vector control activities.



Figure 1. Main panel: Simulated weekly standardized abundance of Aedes albopictus adult population in 167 Réunion (blue curve, units in standard deviations, σ), overlaid with weekly number of reported dengue 168 cases by ECDC (purple curve). Panel A: as in the main panel, but for the period highlighted in grey: April 169 1st, 2017 – March 26th, 2018. Vertical scale for dengue cases ranges from 0 to 40 to better visualize 170 variations before December 2017. Panel B: weekly rainfall amounts (green curve) and temperature values 171 172 (red curve) for the period highlighted in grey; horizontal red lines indicate suitable temperatures for the vector: 20-30°C. Periods highlighted in yellow in panels A and B indicate the timing and duration of each 173 one of the seven tropical storms/cyclones referred to in the main text. Base period for standardization is 174 175 2001-2016. Shading represents uncertainty for each curve: for standardized vector abundance and dengue cases it corresponds to $\pm 1\sigma$, for rainfall and temperature it is defined by the weekly maxima and minima. 176 177

This is reflected in the reported number of dengue cases in Réunion in 2017, as they did not drop 178 179 off to typical levels observed in previous years (see Figure 1, purple line); after a bimodal peak of dengue reports with maxima between April and June, the cases decreased but did not subside. 180 Vector population, in turn, grew from a relative minimum in June to exceptionally high levels 181 during October and November 2017 (almost constant at 2 standard deviations, σ ; see blue curve 182 in Figure 1), concurrent with the initiation of the outbreak. A decrease occurred during most of 183 December, followed by an abrupt increase during the end of that month and beginning of 2018. 184 Hence, we posit that sustained high levels of mosquito population co-occurring with an actively 185 circulating DEN2 serotype virus set up the scenario for the present epidemic, and that it was 186 triggered by a combination of climate factors at the end of 2017 and the beginning of 2018. 187

188 3.2 Sub-seasonal Skill Assessment

189 Skill assessment for the beginning of the outbreak shows (Figure 2, and Supplemental Figure 1) the uncalibrated rainfall predictions to be skillful even four weeks ahead of time. Forecast skill 190 for surface temperature, not shown, was also high up to six weeks ahead of time; temperature 191 tends to vary little during the analyzed season (Figure 1B), which makes it far easier to predict 192 193 than rainfall. Specifically, by using forecasts for one to four weeks (Figure 3) preceding January 8° 2018, the targeted week of one of the larger rainfall events, we found that models were able to 194 forecast above normal rainfall over Réunion three weeks in advance, corresponding to the 195 initialization of December 18th 2018. The forecasts predicted an anomalous amount of 10-15 mm 196 197 of above average rainfall for Réunion and the surrounding region, consistent with the pass of tropical cyclones Ava and Berguitta (European Commission, 2018; Bouhet, 2018). We found 198 that the forecast model has improved skill over the baseline (based on the long-term rainfall 199 average for the period under consideration, commonly known as "climatology") for all weeks 200 analyzed. Further research should consider if and how spatially-calibrated calibrated model 201 202 output (e.g. Munoz et al., 2017), addressing mean, variability and spatial biases, may be able to further improve the forecast skill with additional lead times at the sub-seasonal time scale. 203



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Figure 2. Forecast skill, measured by the Spearman rank correlation, for lead times a) one, b) two, c)

three, and d) four weeks preceding the target week starting on January 8th, 2018. A yellow square shows
 the location of Réunion.

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209 Upon integrating this forecast information into the mosquito model (Figure 4), there is potential

- for the use of subseasonal forecasts in predicting mosquito vector abundance, especially for adult
- 211 mosquitos, up to four weeks in advance, and perhaps also for larvae in the case of the Week 1
- forecast (Figure 4). Indeed, always focusing on the week starting on Jan 8th, 2018, the Week 1
- forecast shows (Figure 4a) that as larvae reach a peak, adult abundances grow a few days after
- that, as expected, and although the timing is not perfect in the larvae forecast, the adult
- abundance matches almost perfectly the simulated one. The match between the simulated and
- forecast adult population abundance is weaker for the Week 2 and Week 4 forecasts (Figure 4b
- and 4d, although still of potential use for decision makers. Nonetheless, there is room for
- 218 improvement in the Week 3 forecast (Figures 4c).



- Figure 3. Observed (a) and forecast rainfall anomaly (mm/day) produced (b) one, (c) two, (d) three, and
- (e) four weeks preceding the target week of January 8th, 2018.
- 222

223 Though the subseasonal rainfall forecasts indicate that, up to three weeks out, there is a positive

- rainfall amount tendency, there is not a clear translation of this behavior into an increase in adult
- mosquito abundance. However, the subseasonal forecasts in this study are spatially uncalibrated,
- therefore creating a potential for increased skill and accuracy in mosquito abundance at a lead
- time of three to four weeks in future analysis. This suggests that it is and was possible even with
- the uncalibrated forecasts, to create and utilize an early warning system in an effort to protect the
- citizens of Réunion.



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Figure 4. Forecast (dashed, with standard deviation shading) and reference (simulation used observed climate data; solid) adult (red) and larvae (blue) mosquito abundance, produced (a) one, (b) two, (c) three, and (d) four weeks preceding the target week of January 8th, 2018. Each forecast was produced forcing

the vector model with output from the ECMWF model (51-member ensemble mean), and has an horizon

of 45 days. The analysis focuses on the week starting on January 8th, 2018 (gray shading).

236 **5 Discussion and Concluding Remarks**

237 Based on this analysis, we posit that climate factors substantially contributed to the onset and magnitude of the present outbreak of dengue in Réunion, by increasing vector activity and viral 238 replication rate above average levels during the second half of 2017. Most importantly, we 239 contend that this particular epidemic event could have been successfully predicted using models 240 such as the one used in this study, forced by seasonal and sub-seasonal climate forecasts 241 (L'Heureux et al., 2015; Barnston et al., 2011; Vitart et al., 2017; Kirtman et al., 2014). In this 242 particular example, the International Research Institute for Climate and Society's seasonal 243 forecast system predicted above-normal rainfall conditions over Réunion for the November 244 245 2017-January 2018 season since at least October 2017 (IRI, 2019). Given this, and the warmerthan-normal temperatures observed during the year, it would have been possible to establish an 246 early warning status of a potential dengue outbreak, targeting the end of 2017. Skillful 247 predictions in this context could have provided public health authorities with sufficient time to 248 initiate an early response strategy to try to minimize the impact of this epidemic event. 249

Additionally, utilizing subseasonal outbreak predictions allows for the assessment of expected

- costs and benefits, in regards to the implementation of early-warning systems and other response
- activities. One of the largest challenges for using these predictions derives from uncertainty in
- the forecasts. Due to the inherent uncertainties in prediction and local circumstances that shape
- high-transmission events, false alarms may occur. Benefits from this analysis include the
- 255 potential to allow decision makers to avoid otherwise unexpected health system costs or
- experience other burdens due to the disease in the event of an outbreak. Identifying the net
- benefit, by taking the difference of the benefits and costs, allows for the comparison of response
- strategies and makes explicit the trade-offs between forecast skill, response effectiveness, and
- 259 monetary costs. The information generated by such assessments can be used to inform
- 260 preparedness and response planning under uncertainty.

For future research, we recommend that sub-seasonal hindcasts be spatially calibrated using 261 pattern-based Model Output Statistics to minimize biases in the mean, variability and spatial 262 patterns Additionally, we suggest that future studies investigate whether this particular outbreak 263 co-occurred with the adaptation of the virus to the vector, a possibility that cannot be ruled out 264 by this analysis. Adaptability, along with human mobility, can pose a great threat to other 265 countries that are otherwise unexposed to these diseases. As a consequence, from this and future 266 outbreaks, areas across the world with high connectivity to Réunion, or other high-risk areas, are 267 likely to receive viraemic travelers. If the timing is right to the local receptivity of the vector, this 268 transmission could initiate epidemics outside the island and pose a great threat to other 269 vulnerable populations. 270

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- 276 forecast or historical data can be found at the IRI Data Library (Vitart et al, 2017). The authors
- 277 declare no conflict of interests.
- 278

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