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

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Key Points:

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

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 *Aedes albopictus* 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 *Ae. albopictus* 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° C, along with large tropical-cyclone-related rainfall events accumulating 10-15 mm per event, the modeled *Ae. albopictus* 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 of rainfall for the Dec-Jan period in Réunion are 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 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.

Plain Language Summary

During the end of 2017 and the beginning of 2018, there was a large outbreak of dengue in the French overseas department of Réunion. Tropical-cyclone-related rainfall events and higher-than-average temperatures played a role in the dengue outbreak, which could have been forecast four weeks in advance. The size of the *Ae. albopictus* mosquito population in Réunion was 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 mosquito model, for one to four weeks prior to the target date of January 8^{th}, to better understand if the increased mosquito population could have been calculated in advance. Due to abnormally warm temperatures hovering around 25° C, along with large rainfall events accumulating 10-15 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, model results suggest accurate prediction of the onset and size of the outbreak two weeks in advance, with some accuracy three to four weeks in advance, which could have provided enough time to enhance preparedness measures.

1 Introduction

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% 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).

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

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, 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 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 (Hawley, 1988; Jia et al., 2016; Dieng et al., 2012; Waldock et al., 2013; Reinhold et al., 2018). Favorable ambient climatic conditions enhance viral replication within vectors and lead to increased transmission in a vulnerable population (Liu-Helmersson et al., 2016).

2 Data and Methods

2.1 Climate attribution

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-year baseline: 2000-2017. Our climate analysis used observed station-based gridded rainfall data (CPC-Unified; see Chen et al., 2008), and temperature and atmospheric circulation variables 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 calibrated models of *Ae. albopictus* (Jia et al., 2016; Metelmann, 2019), and of *Ae. aegypti* (Liu-Helmersson et al., 2019). See supplement for further details. The model was validated to local Breteau index observations from Reunion (Boyer et al., 2014) exhibiting skillful results (supplement).

The model was then run for the baseline period on a "perfect prognosis" mode, i.e., using climate observations of daily temperature and rainfall to generate past adult vector population from four 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 European Centre for Disease Control (ECDC).

2.2 Sub-seasonal Skill Assessment

Additionally, we wanted to understand if the events leading to the outbreak could have been forecast in advance. Seasonal forecasts provide a first layer of information to assess if suitable conditions for an outbreak will happen in a coming season, but cannot be specific enough as to 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., 2017). Using sub-seasonal climate forecasts produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) model, available through the Seasonal to Sub-seasonal Prediction Project Database (Vitart et al., 2017; WMO, 2020), we analyzed if and how many weeks in advance the outbreak could have been forecast.

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 (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, 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, Dec 18 2017 and Dec 11 2017, respectively. The week of Jan 8 was selected due to its proximity 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.

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 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 initializations available in the 4 weeks prior to the initialization of the forecast. Since the 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.

The skill assessment process involved a cross-validation procedure for two key forecast 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). The cross-validation analysis used a leave-5-out moving window, and was conducted using PyCPTv1.6 (Muñoz et al., 2020), a set of Python libraries designed to interface and enhance IRI's Climate Predictability Tool (CPT; Mason et al., 2020). PyCPT automatically downloads from the IRIDL the necessary hindcasts and observations to perform the skill assessment analysis.

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 calibration was conducted beyond the mean and variability bias corrections.

4 Results

3.1 Climate Attribution

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, even during most of the austral winter (in red in Figure 1). The average daily rainfall between 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 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 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.

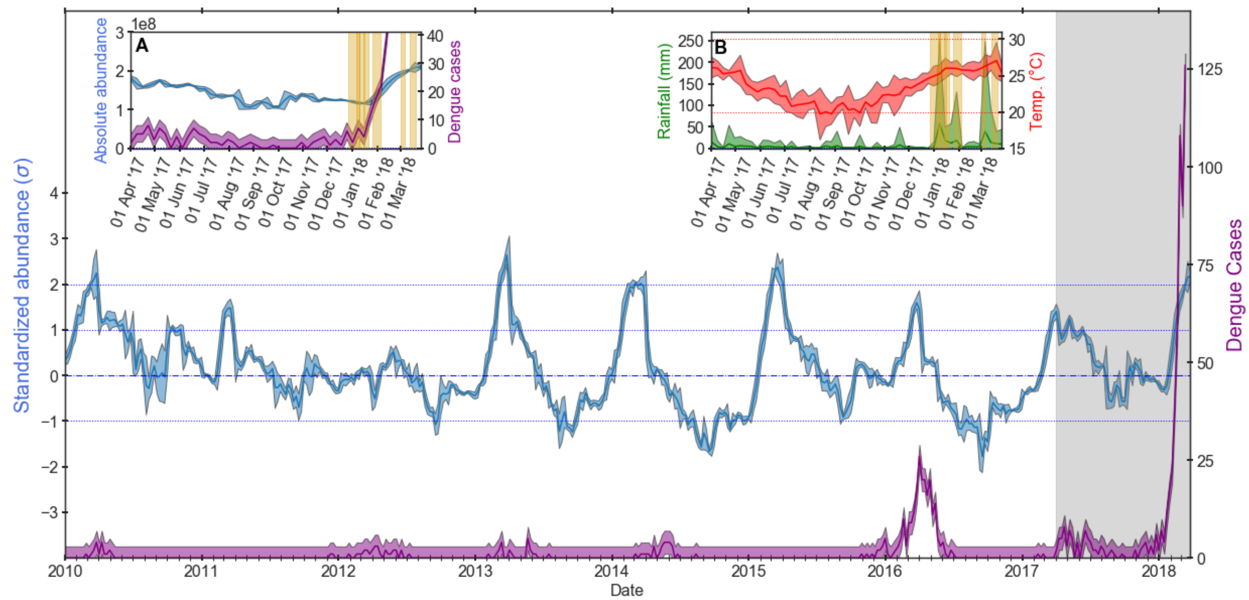

Figure 1. *Main panel*: Simulated weekly standardized abundance of *Aedes albopictus* adult population in Réunion (blue curve, units in standard deviations, σ), overlaid with weekly number of reported dengue cases by ECDC (purple curve). *Panel A:* as in the main panel, but for the period highlighted in grey: April 1st, 2017 – March 26th, 2018. Vertical scale for dengue cases ranges from 0 to 40 to better visualize variations before December 2017. *Panel B:* weekly rainfall amounts (green curve) and temperature values (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 one of the seven tropical storms/cyclones referred to in the main text. Base period for standardization is 2001-2016. Shading represents uncertainty for each curve: for standardized vector abundance and dengue cases it corresponds to ±1σ, for rainfall and temperature it is defined by the weekly maxima and minima.

This is reflected in the reported number of dengue cases in Réunion in 2017, as they did not drop 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. Vector population, in turn, grew from a relative minimum in June to exceptionally high levels during October and November 2017 (almost constant at 2 standard deviations, σ; see blue curve in Figure 1), concurrent with the initiation of the outbreak. A decrease occurred during most of December, followed by an abrupt increase during the end of that month and beginning of 2018. Hence, we posit that sustained high levels of mosquito population co-occurring with an actively circulating DEN2 serotype virus set up the scenario for the present epidemic, and that it was triggered by a combination of climate factors at the end of 2017 and the beginning of 2018.

3.2 Sub-seasonal Skill Assessment

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 for surface temperature, not shown, was also high up to six weeks ahead of time; temperature tends to vary little during the analyzed season (Figure 1B), which makes it far easier to predict than rainfall. Specifically, by using forecasts for one to four weeks (Figure 3) preceding January 8th 2018, the targeted week of one of the larger rainfall events, we found that models were able to forecast above normal rainfall over Réunion three weeks in advance, corresponding to the initialization of December 18th 2018. The forecasts predicted an anomalous amount of 10-15 mm 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 that the forecast model has improved skill over the baseline (based on the long-term rainfall average for the period under consideration, commonly known as “climatology”) for all weeks analyzed. Further research should consider if and how spatially-calibrated calibrated model 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.

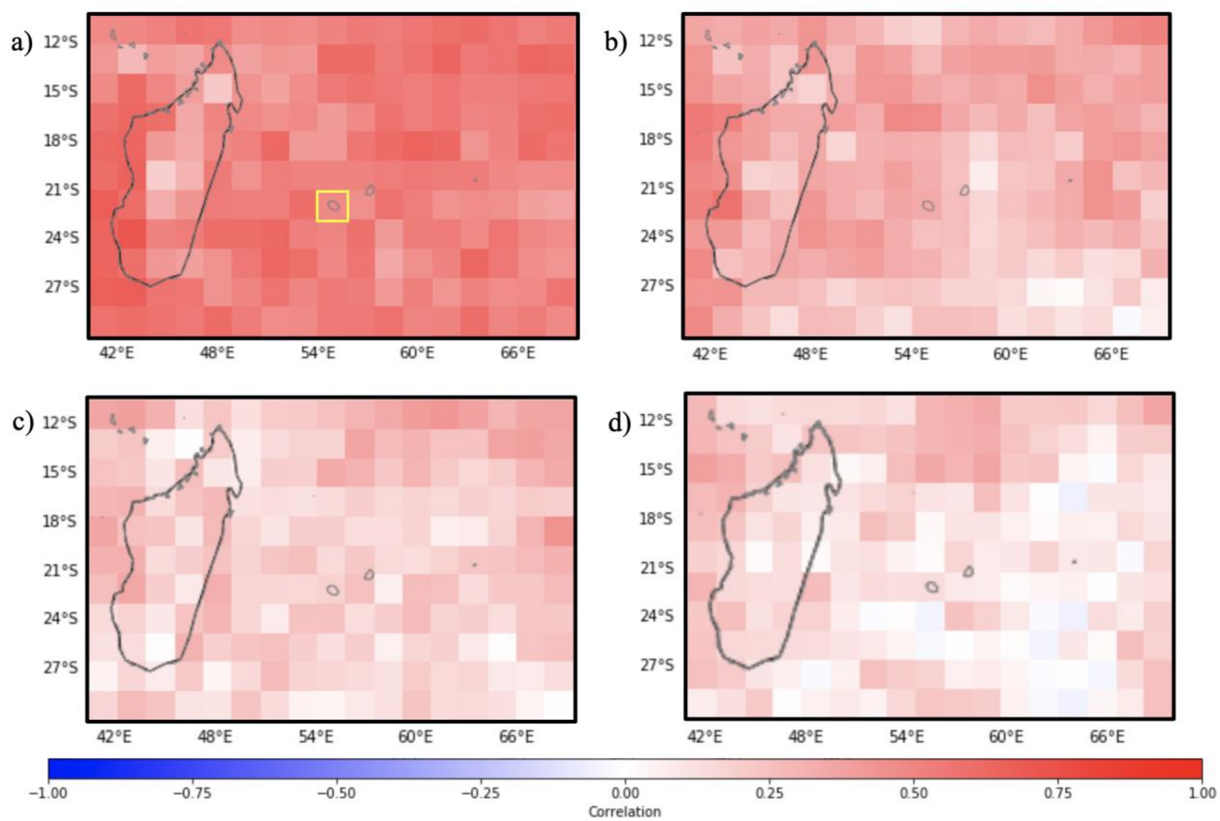

Figure 2. Forecast skill, measured by the Spearman rank correlation, for lead times a) one, b) two, c) three, and d) four weeks preceding the target week starting on January 8th, 2018. A yellow square shows the location of Réunion.

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 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 improvement in the Week 3 forecast (Figures 4c).

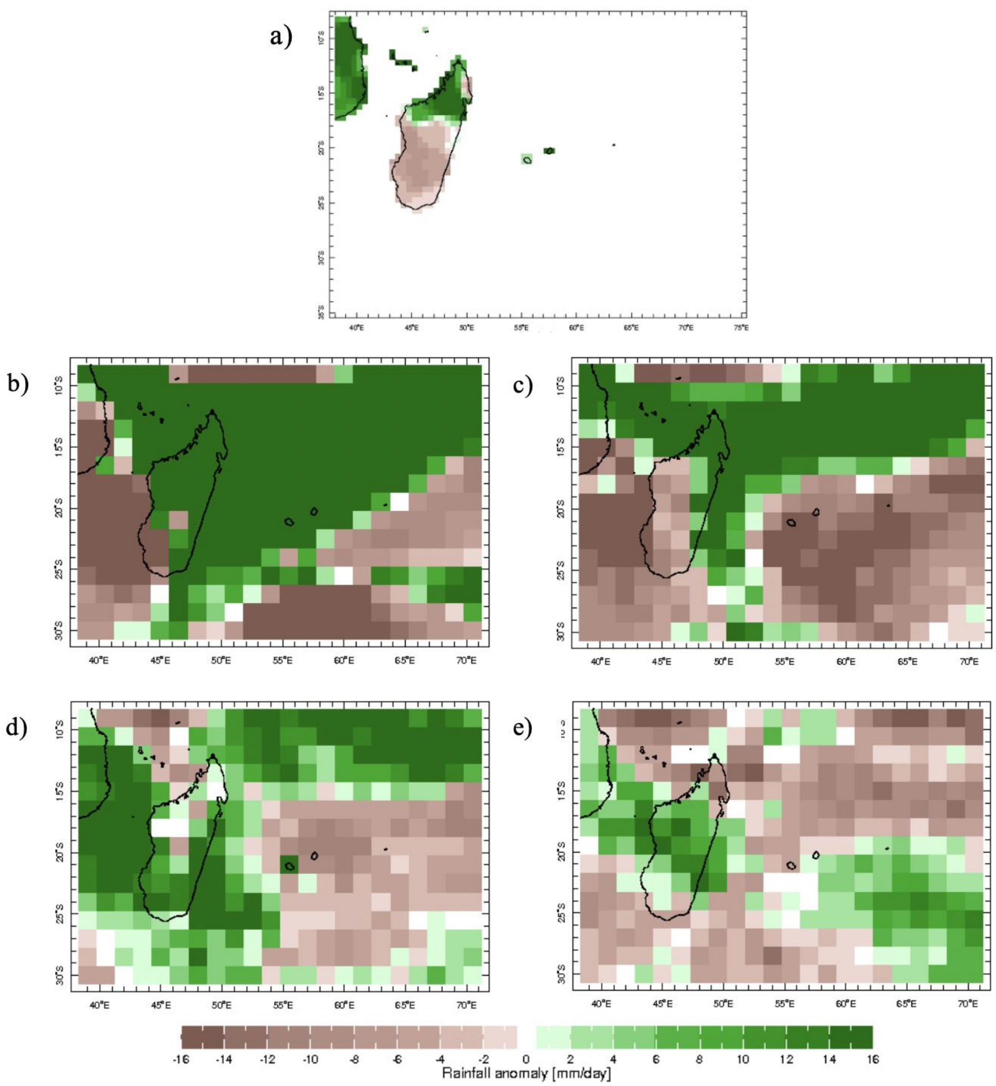

Figure 3. Observed (a) and forecast rainfall anomaly (mm/day) produced (b) one, (c) two, (d) three, and (e) four weeks preceding the target week of January 8th, 2018.

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.

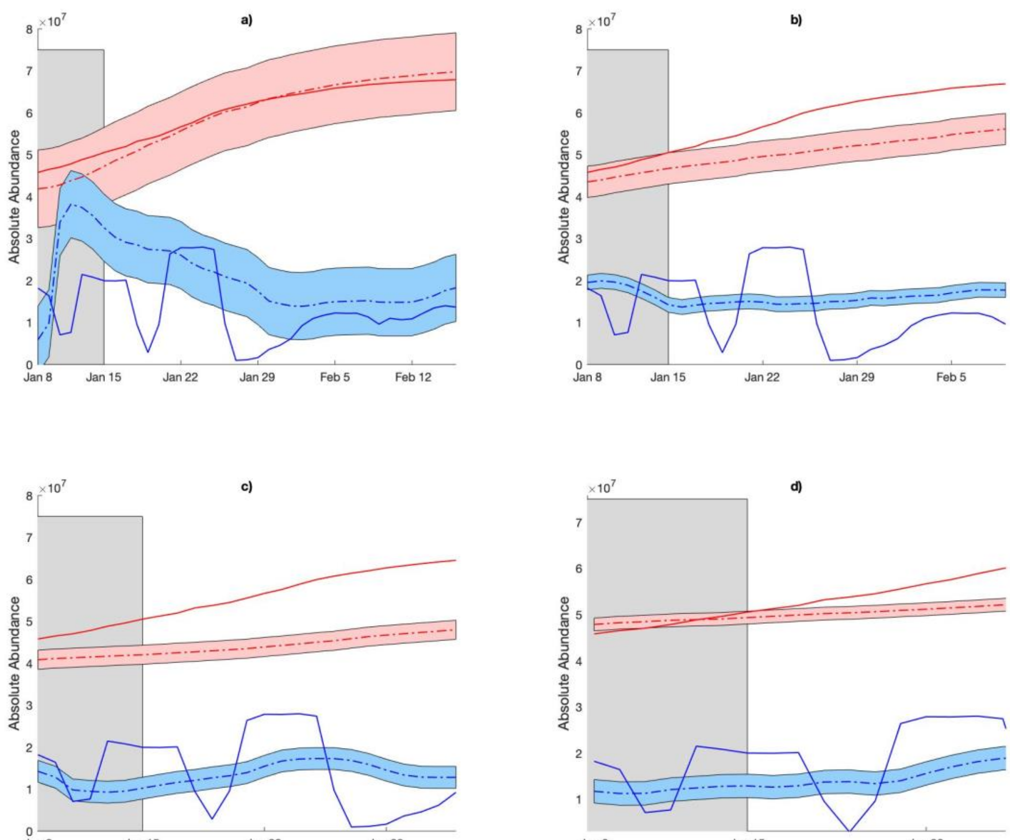

Figure 4. Forecast (dashed, with standard deviation shading) and reference (simulation used observed climate data; solid) adult (red) and larvae (blue) mosquito abundance, produced (a) one, (b) two, (c) three, and (d) four weeks preceding the target week of January 8th, 2018. Each forecast was produced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

5 Discussion and Concluding Remarks

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 replication rate above average levels during the second half of 2017. Most importantly, we contend that this particular epidemic event could have been successfully predicted using models such as the one used in this study, forced by seasonal and sub-seasonal climate forecasts (L'Heureux et al., 2015; Barnston et al., 2011; Vitart et al., 2017; Kirtman et al., 2014). In this particular example, the International Research Institute for Climate and Society's seasonal forecast system predicted above-normal rainfall conditions over Réunion for the November 2017-January 2018 season since at least October 2017 (IRI, 2019). Given this, and the warmer-than-normal temperatures observed during the year, it would have been possible to establish an early warning status of a potential dengue outbreak, targeting the end of 2017. Skillful predictions in this context could have provided public health authorities with sufficient time to initiate an early response strategy to try to minimize the impact of this epidemic event.

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 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 monetary costs. The information generated by such assessments can be used to inform preparedness and response planning under uncertainty.

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

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