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# Environmental drivers of Ross River virus in southeastern Tasmania, Australia: towards strengthening public health interventions

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## SUMMARY

In Australia, Ross River virus (RRV) is predominantly identified and managed through passive health surveillance. Here, the proactive use of environmental datasets to improve community-scale public health interventions in southeastern Tasmania is explored. Known environmental drivers (temperature, rainfall, tide) of the RRV vector *Aedes camptorhynchus* are analysed against cumulative case records for five adjacent local government areas (LGAs) from 1993 to 2009. Allowing for a 0- to 3-month lag period, temperature was the most significant driver of RRV cases at 1-month lag, contributing to a 23·2% increase in cases above the long-term case average. The potential for RRV to become an emerging public health issue in Tasmania due to projected climate changes is discussed. Moreover, practical outputs from this research are proposed including the development of an early warning system for local councils to implement preventative measures, such as public outreach and mosquito spray programmes.

**Key words**: Alphavirus, environmental drivers, predictive model, Ross River virus, Tasmania.

## INTRODUCTION

Ross River virus (RRV) is the most common and widespread mosquito-borne disease in Australia [1]. By law, all RRV cases must be reported to local, state, and national health authorities [2] and lodged in the National Notifiable Disease Surveillance System (NNDSS). This passive surveillance system is used to inform mosquito control programmes, identify patterns in the disease and areas at risk, as well as to develop public health interventions [3]. Major outbreaks, epidemics, small case clusters, and incidental cases have previously been reported from all Australian states and territories [4, 5].

When compared to the national annual average (~5000 cases) [1], Tasmania experiences relatively low numbers of RRV cases, although case numbers can fluctuate substantially from year to year. Between 1994 and 2008, annual RRV cases ranged from 4 to 117, with above average years (>baseline rate of 0·8–5·9 cases/100 000) recorded in 1996, 1999, 2002 and 2008 [6, 7]. The largest outbreak, in 2002, was attributed to higher than average densities of *Aedes camptorhynchus* Thomson (Diptera: Culicidae)

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mosquitoes, with spring tides and unusually high rainfall thought to be likely environmental factors responsible [6]. Regular mosquito abundance monitoring was recommended as a proactive biological indicator of imminent RRV outbreaks; a practice endorsed by state health authorities across Australia [6, 8]. However, further investigation into the specific environmental drivers of RRV in Tasmania remains to be undertaken.

A considerable evidence base exists linking natural and anthropogenic environmental drivers to mosquito productivity and subsequent case rates of RRV [9–17]. In much of Australia, rainfall is considered the most important factor driving RRV prevalence [9] due to mosquitoes' reliance on water to complete their life-cycle. Temperature and tides have also been positively correlated with mosquito abundance and rates of RRV [13, 18] – in the presence and absence of rainfall [9, 10, 19]. Such variability in research findings infers that environmental drivers of mosquito productivity in Australia are not ubiquitous for all species in space or time [1]. In Tasmania, the absence of a distinct wet/dry season, and low rainfall variability, provides an opportunity to help elucidate the true influence of other environmental drivers on RRV prevalence.

The ecology of local vectors, the virus, and the importance of macropod reservoir hosts should also be considered when investigating environmental drivers of RRV case numbers [20–22]. For example, abundances of freshwater mosquito species are known to be influenced by changes in rainfall intensity, while abundances of saltmarsh mosquito species are influenced by both rainfall and tidal variations [14, 15, 18, 23]. However, the reasons for an outbreak occurring are complex and are not necessarily triggered by environmental factors only. Development rates of local mosquitoes and the virus incubation periods in both hosts and vectors may also be important contributing factors [13, 20, 21].

In the context of climate change and its impending impact on the environmental drivers of mosquito distribution and abundance, the potential exists for RRV to become an emerging public health issue in Tasmania [1]. Tasmania is predicted to have an increase in mean temperature from 1·6 °C to 2·9 °C, depending on greenhouse gas emissions, and while it is not projected to experience dramatic changes in total annual rainfall, it is expected that seasonal and spatial rainfall patterns will vary [24]. Accordingly, this study explores the influence of climatic and tidal drivers on RRV in Tasmania, in order to: (1) establish a baseline body of work on vector populations and environmental drivers of RRV in southeastern Tasmania; (2) examine the influence of mosquito populations and environmental drivers on RRV prevalence in Sorell Council and surrounds, and; (3) explore the use of environmental datasets as predictors of RRV to improve community-scale public health interventions.

## METHODS

In Tasmania, RRV is a notifiable disease under the Public Health Act 1997 with all case data reported to the Director of Public Health. Confirmation of RRV cases requires positive serological testing, and mandatory reporting is required at local, state and national levels [22]. Relevantly, in 2002, an unusually high outbreak occurred in Tasmania with 89% of RRV cases reported from southeastern coastal areas: 65% resided in the adjoining local government areas (LGAs) of Clarence and Sorell (see Fig. 1) [6]. The adjacent LGAs of Brighton, Clarence, Glenorchy, Hobart, and Sorell make up 71·2% of the total cases for Tasmania for the period of all available LGA specific case data (1991–2009) and 45·5% of total cases for Tasmania for the time period used in this study (1993–2009).

Given this history of high RRV infection, our investigations targeted the southeastern coastal region of Tasmania comprising these same five LGAs. Sorell Council was chosen as the primary study area due to the availability of historic longitudinal mosquito surveillance data [6], although some sampling sites extend across adjacent LGA boundaries. We prioritized the use of climate and tidal data acquired proximal to Clarence and Sorell to best represent environmental conditions experienced at and around the time of reported RRV cases.

### Study area

Located approximately 25 km east of Hobart (see Fig. 1), Sorell Council is characteristic of Tasmania's temperate maritime climate with considerable annual rainfall. The long-term average (1887–2010) annual rainfall for Sorell is 546·8 mm with rainfall not restricted to a wet season, but consistent throughout the year [25]. The annual mean minimum temperature is 8·1 °C and the annual mean maximum temperature is 17·5 °C (1958–2010), with the hottest days occurring

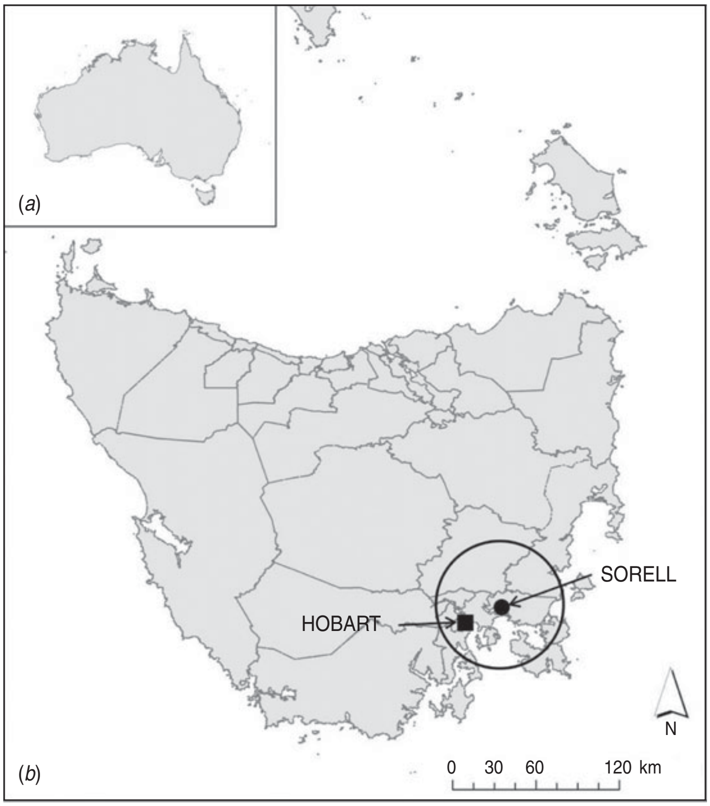

**Fig. 1.** Study area: southeastern Tasmania, Australia [using ArcGIS (GIS software), version 9.3, USA, Environmental Systems Research Institute]. The primary study area, Sorell Council, is located in the southeastern part of Tasmania, 25 km from Hobart. RRV case data were considered from five adjacent local government areas (Brighton, Clarence, Glenorchy, Hobart, Sorell), contributing to 71·2 % of the total cases for Tasmania from 1991 to 2009.

from December to March [25]. The major land uses in the Sorell Council area are rural (70·9 %), forestry (25·3 %), residential (3·6 %), open space (1·7 %), and business and commercial (0·3 %) (G. Robertson, personal communication, 2010).

## Case data

Monthly RRV case totals for Tasmania were extracted from the NNDSS, which is based on the date of diagnosis, for the 1993–2009 study period [7]. Monthly RRV cases for the southeastern Tasmania study area were obtained from the Tasmania Department of Health and Human Services (DHHS) for the 1993–2009 study period using the specimen date (date of blood sample collection) to categorize cases. Where a discrepancy occurred between the two data sources, the Tasmanian DHHS data were prioritized. Monthly case averages were then calculated across all years to examine patterns across months and look for evidence of seasonality. For Tasmania data, outbreak years were defined as those with case rates greater than the normal baseline rate (0·8–5·9 cases/100 000), consistent with the rates presented in the NNDSS database.

## Mosquito larval surveillance

Available mosquito data collected by Sorell Council are presented here to establish a baseline for future work and examine seasonality and any correlations with high RRV years. These data were not analysed alongside environmental data due to temporal sampling design constraints (e.g. two of the outbreak years occurred before the programme began, preventing meaningful statistical analyses). However, recommendations for study design improvements are presented to allow for future investigations alongside environmental data.

Larval data for the period 2000–2009 were collated from six Sorell Council reports, as well as additional raw data files. A total of 45 sites were sampled within a 30 km radius of Sorell – some extending across adjacent LGA boundaries. The complete dataset reflects surrounding regional mosquito populations, including: *Aedes camptorhynchus, Ae. notoscriptus, Ae. australis, Anopheles annulipes*, and *Culex molestus*. Only *Ae. camptorhynchus* data were extracted from the database for use in this study, due to being recognized as the key vector responsible for the transmission of RRV in the Sorell region [1, 26].

Larvae were collected by Sorell Council using a mosquito dipper (Australian Entomological Supplies Pty Ltd., Australia) and preserved in 80% ethanol. Specimens were counted under a dissecting microscope and species were identified using the larval key of Russell [27]. Abundance data were standardized per dipper to account for variability in sampling effort within and between sites. Average larval abundances per month were calculated for each sampling location and then a mean was taken across the entire dataset (2000–2009) to illustrate seasonal variation in species populations. Years were defined as the period 1 July to 30 June of the following year to reflect the seasonal rain year and to allow comparison with similar research efforts [28, 29]. If pools were dry on subsequent sampling occasions, then values were listed as zero. If re-sampling on subsequent visits could not occur due to unsuitable habitat or restricted access, then values were listed as null (not zero).

## Climate and tidal data

Rainfall and temperature data for the period 1993–2009 were obtained from the Australian Bureau of Meteorology (BOM) [25], comprising: total monthly rainfall records from Sorell (Whitlea) station (BOM site no. 94063); and monthly mean maximum temperature records from Hobart Airport station (BOM site no. 94008). Where data were missing (e.g. rainfall for June 2008 and November 2008), respective monthly averages (1993–2009) were inserted as surrogate values. Average monthly values were calculated across all years (as defined above). Above-average rainfall years were defined as years with total rainfall above the historical mean (546·8 mm).

Tide data were obtained from the National Tidal Centre (July 1993–September 2007) [Hobart; Port no. 61220; latitude 42° 53′ S, longitude 147° 20′ E; lowest astronomical tide (LAT)] and the Australian Hydrographic Service (October 2007 to June 2009) [Hobart; Port no. 61220; latitude 42° 53′ S longitude 147° 20′ E; 0·89 m below mean sea level (MSL)]. Missing data in January 1999, May 2004, and October 2006 were treated as per climate values before monthly maximum tide averages were calculated for each month across the 1993–2009 period. The historical mean maximum tide was calculated across all available data – which extended back to 1960.

## Analyses

Data analyses were conducted using Statistical Analysis Software (SAS) version 9.2 (SAS Institute Inc., USA).

Fisher's exact test was conducted on state-wide RRV outbreaks and above-average rainfall years in Tasmania to validate exploring regional-scale relationships between RRV cases and other environmental drivers. The analyses confirmed a relationship (see Results section) and justified undertaking more detailed statistical analyses for RRV cases in south-eastern Tasmania, including those on other climatic variables and tidal data.

Environmental drivers (rainfall, temperature, tide) were analysed against case records for the study area, including Brighton, Clarence, Glenorchy, Hobart, and Sorell councils, from 1993–2009.

Spearman's correlation was used to conduct a bivariate analysis of three potential environmental drivers (rainfall, temperature, tide) and the study area RRV cases over sequential lag periods (0–3 months), including all possible combinations of time lags between RRV cases and drivers. RRV cases from months during the peak season were also analysed alongside temperature. The correlation analysis was used to determine which variables should be included in the subsequent analysis.

Negative binomial regression was used to: model study area RRV case data; assess rainfall, temperature, and tide as potential environmental drivers of RRV, and; establish at what lag period (0–3 months) these drivers are most significant. Rainfall, temperature, and tide were all given the same lag time against RRV cases. Projected percentage increases in cases were determined by taking the average of RRV cases for the five LGA areas during the study period and dividing by the model estimate to obtain the magnitude of change. To assess the degree of multicollinearity, the variance inflation factor (VIF) was examined for all independent variables. Note that lag periods were chosen based on the findings of similar research efforts [14, 30–32] and to allow comparisons with these studies.

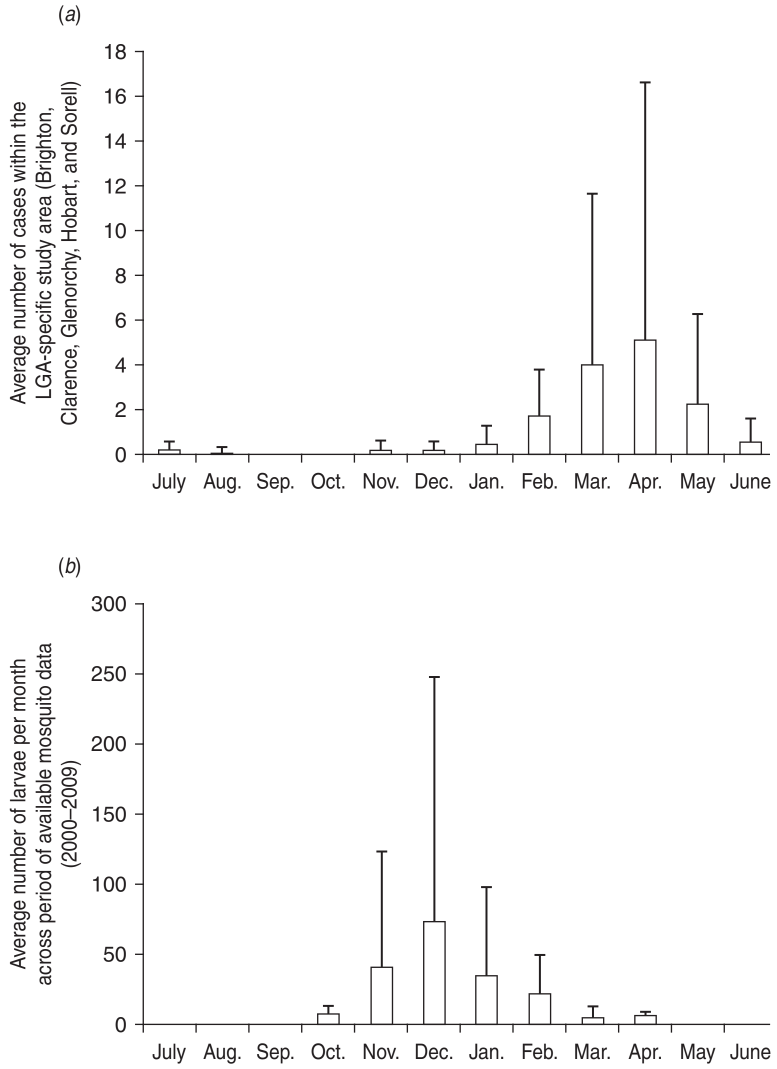

**Fig. 2.** Seasonality in RRV cases and *Ae. camptorhynchus* larvae in southeastern Tasmania, 2000–2009: (*a*) RRV cases from the local government area (LGA)-specific study area, including Brighton, Clarence, Glenorchy, Hobart, and Sorell councils (average across years for each month); (*b*) Sorell Council, *Ae. camptorhynchus* larvae (average across years for each month). Each graph displays the mean values with standard deviation. Only upper standard deviation bars are shown for graphical clarity.

## RESULTS

### RRV cases

Monthly RRV case data, reported in NNDSS for Tasmania, show variability in case numbers and outbreak occurrences within and between years. Over the study period, the normal baseline rate for RRV cases in Tasmania ranged from 0·8 to 5·9 cases/100 000, with outbreak years occurring in 1996 (16·0/100 000), 1999 (14·2/100 000), 2002 (24·5/100 000), and 2008 (15·3/100 000) (Supplementary Table S1, available online). For LGA-specific data, cases were highest in 1995 (9·79/100 000), 1996 (28·73/100 000), 1999 (25·83/100 000), 2002 (53·19/100 000), and 2008 (8·06/100 000) (Supplementary Table S1). There was a clear seasonal pattern in monthly RRV case data for the LGA study area, with a peak in case numbers evident in March and April (Fig. 2*a*).

### Mosquito larvae data

*Ae. camptorhynchus* data show variability in both sampling effort and larval abundances over the 9-year study period (Supplementary Table S2, online), with a regular sampling regimen established post-2003 comprising 5–6 months of data collection for each year up to 2008. *Ae. camptorhynchus* abundances were highest for the years 2005 and 2006 and for the respective

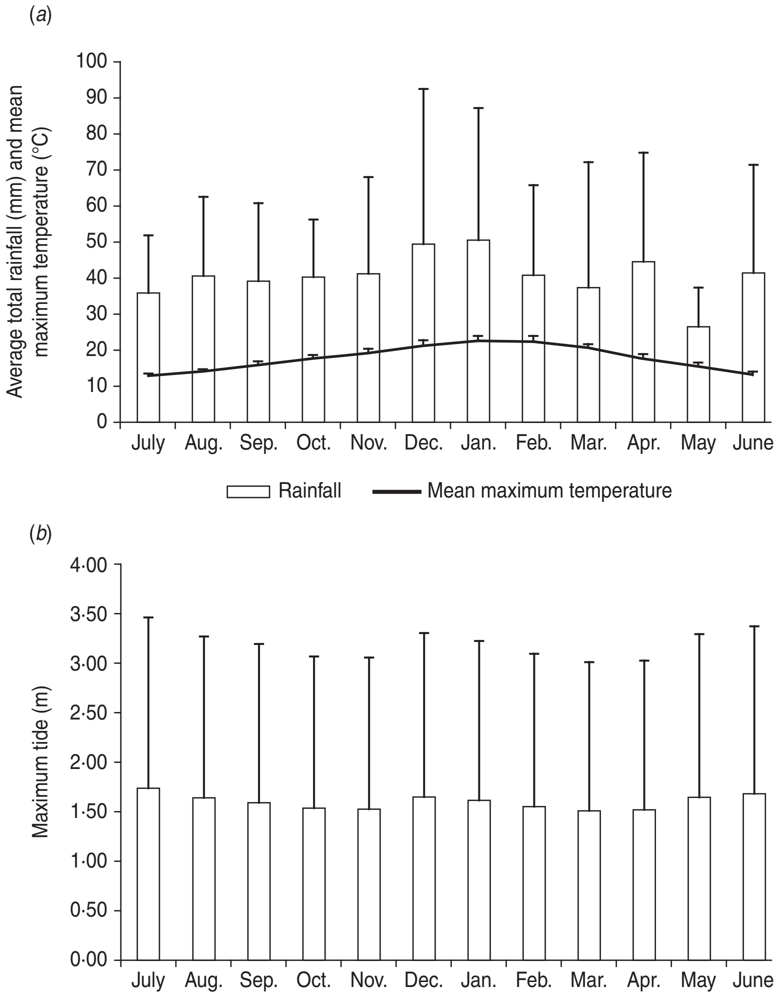

**Fig. 3.** Climatic and oceanic data for the 1993–2009 survey period: (*a*) Sorell area monthly means for total rainfall and mean maximum temperature; (*b*) Sorell area monthly means for maximum tide. Both graphs present mean values with standard deviation. Only the upper standard deviation bars are presented for ease of interpretation.

months of November and December. There is a clear seasonal pattern in the average monthly distribution of larvae populations, with peaks in November, December, and January (Fig. 2*b*).

### Climate and tidal data

Climate data for Sorell (1993–2009) are presented in Figure 3*a*. Monthly average total (±S.D.) rainfall peaks are evident in December (49·2±43·1 mm) and January (50·7±36·5 mm). Mean maximum temperatures are highest in January (22·6±1·2 °C) and February (22·4±1·4 °C). Over the 16-year sample period above-average rainfall years occurred in 1996, 1999, and 2002. Above-average mean maximum temperature years (defined as above the historical mean, which is 17·5 °C) were experienced for much of the sampling period 1993–1994, 1998–2003, and 2005–2009 [25].

Tide data for Sorell (1993–2009) are presented in Figure 3*b*. Average maximum tide demonstrates a cyclic pattern, with peaks in June and July (1·68±0·17 m, 1·73±0·16 m) and again in December and January (1·65±0·13 m, 1·61±0·16 m). Average maximum tide is lowest in March and April (1·50±0·09 m, 1·51±0·09 m). Consecutive years of above-average tidal conditions were also experienced in 1994–1996, 1999–2000, 2002–2004, and 2006.

### Relationship between environmental variables and RRV cases

Years with above-average rainfall were significantly correlated with (Tasmania-wide) RRV outbreak years

Table 1. *Spearman's correlation coefficients between RRV cases in five local government areas and environmental variables for 0-, 1-, 2-, and 3-month lag periods [significance at the 0·05 level (two- tailed)], N = 192*

| | | Cases | Rain | Temp. |
|---|---|---|---|---|
| 0-month lag | | | | |
| Rain | CC | 0·002 | — | — |
| | *P* value | 0·987 | — | — |
| Temp. | CC | **0·144** | −0·073 | — |
| | *P* value | **0·047** | 0·314 | — |
| Tide | CC | −**0·146** | 0·055 | −**0·296** |
| | *P* value | **0·043** | 0·45 | <**0·0001** |
| 1-month lag | | | | |
| Rain | CC | −0·0499 | — | — |
| | *P* value | 0·492 | — | — |
| Temp. | CC | **0·339** | −0·073 | — |
| | *P* value | <**0·0001** | 0·314 | — |
| Tide | CC | −**0·166** | 0·055 | −**0·296** |
| | *P* value | **0·022** | 0·45 | <**0·0001** |
| 2-month lag | | | | |
| Rain | CC | 0·132 | — | — |
| | *P* value | 0·067 | — | — |
| Temp. | CC | **0·399** | −0·073 | — |
| | *P* value | <**0·0001** | 0·314 | — |
| Tide | CC | −0·045 | 0·055 | −**0·296** |
| | *P* value | 0·536 | 0·45 | <**0·0001** |
| 3-month lag | | | | |
| Rain | CC | **0·247** | — | — |
| | *P* value | **0·0006** | — | — |
| Temp. | CC | **0·372** | −0·073 | — |
| | *P* value | <**0·0001** | 0·314 | — |
| Tide | CC | −0·09 | 0·055 | −**0·296** |
| | *P* value | 0·213 | 0·45 | <**0·0001** |

Rain, Total rainfall; Temp., mean maximum temperature; Tide, maximum tide; CC, correlation coefficient.
—, Value equals 1·00
Bold values indicate a significant correlation ($P<0{\cdot}05$).

(Fisher's exact analysis, two-sided, $P=0{\cdot}0071$). Of the four outbreak years, three years (1996, 1999, 2002) had above-average rainfall compared to the historical mean annual rainfall.

Due to the consistency between results from the peak season and the full dataset analyses, the dataset was analysed as a whole. Correlations between the five LGA RRV cases and three key environmental variables separately varied for 0-, 1-, 2- and 3-month lag periods (Table 1). Rainfall was significantly correlated with RRV cases in a positive relationship at the 3-month lag period, although this was a weak correlation. Temperature was positively correlated with RRV cases across all lag periods and tide was significantly correlated with RRV cases in a negative relationship for the 0- and 1-month lag periods (Table 1). While these variables produced a significant relationship over various lag periods, no variables demonstrated a strong correlation with RRV cases. Mean maximum temperature and maximum tide are inter-dependent due to a negative correlation (correlation coefficient across all lag periods = −0·29575, $P\leqslant 0{\cdot}0001$). This is the only significant relationship between two of the environmental variables.

Monthly rainfall and mean maximum temperature were important predictors of RRV in the southeastern Tasmania region (five LGA study area), including the interactions between them (Table 2). The only significant relationships between the environmental predictors and RRV cases fell within the single 1-month lag period (Table 2). No independent variables demonstrated a high degree of multicollinearity (VIF <1·5 over all lag periods).

The parameter estimates showed that with a 1 unit increase (tide 1 m, rainfall 1 mm, temperature 1 °C), tide has the greatest impact on RRV disease burden (near significant trend) by resulting in an additional 32·9 cases (Table 2). The significant predictor that has the greatest impact on RRV disease burden in the southeastern area is temperature, projecting a 23·2% increase in RRV cases over the long-term average of 13·8 cases per unit increase in temperature (Table 2). There was also a significant positive relationship between the amount of rainfall and number of RRV cases (Table 2).

## DISCUSSION

The objectives of this study were to: (1) establish a baseline body of work on vector populations and environmental drivers of RRV in southeastern Tasmania; (2) examine the influence of mosquito populations and environmental drivers on RRV prevalence in Sorell Council and surrounds, and; (3) explore the use of environmental datasets as predictors of RRV to improve community-scale public health interventions. The results of the study show that climatic drivers are significant predictors of RRV cases in southeastern Tasmania. However, locally, the principal driver/s can differ from those presented in other Australian studies. The significance of these findings for local council management practices is both relevant and timely – especially when considered in the context of global climate change.

Table 2. *Negative binomial regression parameter estimates, 95% Confidence interval (CI), and P values for environmental predictor variables at 0-, 1-, 2-, and 3-month lag periods within five specified local government areas. A one unit increases equates to specific units for rainfall, temperature, and tide: 1 mm, 1 °C, and 1 m, respectively*

| | 0-month lag | | | 1-month lag | | | 2-month lag | | | 3-month lag | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Estimate | 95% CI | *P* value | Estimate | 95% CI | *P* value | Estimate | 95% CI | *P* value | Estimate | 95% CI | *P* value |
| Rain | 0·92 | −0·09 to 1·93 | 0·076 | 1·36 | 0·18 to 2·53 | 0·024 | 0·94 | −0·3 to 2·19 | 0·14 | 0·18 | −1·02 to 1·38 | 0·77 |
| Temp. | 2·25 | −0·65 to 5·15 | 0·128 | 3·22 | 0·41 to 6·04 | 0·025 | 2·23 | −0·97 to 5·44 | 0·17 | −0·25 | −3·1 to 2·6 | 0·87 |
| Rain × Temp. | −0·05 | −0·106 to 0·007 | 0·083 | −0·069 | −0·123 to −0·0095 | 0·023 | −0·05 | −0·12 to 0·01 | 0·12 | −0·017 | −0·08 to 0·04 | 0·58 |
| Tide | 20·18 | −12·01 to 52·37 | 0·219 | 32·9 | −0·996 to 66·8 | 0·057 | 23·06 | −15·04 to 61·15 | 0·24 | −5·29 | −41·79 to 31·20 | 0·78 |
| Rain × Tide | −0·56 | −1·19 to 0·063 | 0·078 | −0·85 | −1·62 to −0·09 | 0·029 | −0·60 | −3·17 to 0·83 | 0·25 | −0·099 | −0·86 to 0·66 | 0·80 |
| Temp. × Tide | −1·34 | −3·14 to 0·46 | 0·145 | −1·84 | −3·61 to −0·064 | 0·042 | −1·17 | −3·17 to 0·83 | 0·25 | 0·37 | −1·42 to 2·17 | 0·68 |
| Rain × Temp. × Tide | 0·031 | −0·004 to 0·065 | 0·087 | 0·044 | 0·005 to 0·08 | 0·026 | 0·03 | −0·008 to 0·075 | 0·12 | 0·01 | −0·03 to 0·05 | 0·58 |

Rain, Total rainfall; Temp., mean maximum temperature; Tide, maximum tide.
Shaded areas indicate a significant correlation ($P < 0·05$).

## Larvae and RRV case data

Seasonality is evident in both larvae and the LGA-specific RRV case data with a 2- to 3-month lag time between a peak in the larval numbers and the onset of RRV cases (Fig. 2*a*, *b*). Along the southeastern coastal areas of Tasmania, Robertson *et al.* [6] suggest that high densities of *Ae. camptorhynchus* may be responsible for RRV outbreaks. Russell [33] found that *Ae. camptorhynchus* demonstrates seasonality with more activity in the cooler months before summer.

For the purpose of developing proactive public health interventions for vector-borne disease, it is ideal to also consider environmental drivers on vector populations that might influence virus–host relationships (S. Carver, unpublished observations). However, in this instance, collated mosquito larval data were insufficient to permit analyses with selected climatic and tidal drivers: largely due to temporal limitations of the study design (e.g. insufficient sequential monthly data for an entire year and/or consecutive years). Moreover, meaningful interpretation within a public health context was limited given that two of the four outbreak years occurred prior to the commencement of mosquito surveys. Nevertheless, the current dataset as presented provides a starting point for future studies in this area.

## Rainfall, tide and temperature as key drivers of RRV incidence

The influence of rainfall, temperature, and tide on *Aedes* spp. and/or RRV case numbers in Australia is variable on geographical and temporal scales [1, 14, 21, 30, 34]. Accounting for a 0–3 month lag period, our studies identified temperature, rainfall, and tide as having significant correlations with RRV cases (Table 1). Correlations varied in which lag periods were significant and if the relationship was positive or negative, but all of the correlations produced demonstrated only a weak relationship between the variable and RRV cases. Further, tide and temperature were the only two environmental variables that were significantly correlated.

Results from this study are consistent with existing knowledge on the *Ae. camptorhynchus* biology and RRV incubation periods. During typical spring/summer temperatures of 15–25 °C, development of *Ae. camptorhynchus* can take 20–37 days [35]. However, large populations can emerge in as little as

8 days if the conditions are suitable [34]. The lifespan of an average female mosquito is 2–3 weeks, while males have a shorter lifespan [36]. RRV generally takes 7–9 days to incubate, but can take as little as 3 days or as long as 21 days [21]. Other studies have found that a lag of 1 to 2 months is plausible due to mosquito biology and virus incubation periods [14, 31].

Similar research efforts to correlate RRV cases with potential environmental drivers have yielded variable results. In a Queensland-based study, Bi & Parton [30] found a lag time of up to 4 months with temperature, rainfall, and tide and RRV case notification with the main vector species being *Ae. vigilax*. For a lag period of 0–5 months, Tong & Hu found no significant correlation between rainfall and RRV incidence in Gladstone [37]. Within the same study, a significant positive correlation was evident at a 3-month lag in Mackay and at a 4-month lag in Bundaberg; however, this too was a weak correlation [37]. Other studies showed a significant correlation for a 1-month lag in Brisbane for *Culex annulirostris* and *Ae. vigilax* vectors [14], as well as 2- and 4-month lag times in Townsville and Toowoomba for *Ae. vigilax* [30]. The latter study also found a relationship between maximum temperature and RRV infection in Queensland – similar to those reported here for Tasmania. The negative relationship between tide and RRV cases at 0 and 1 months is novel to this study.

The absence of a distinct wet/dry season, as well as difference in the main vector species, in Tasmania may explain differences within and between previous research findings in Queensland, and those presented here. In particular, we refer to the contributing influence of rainfall on RRV case presentations. Compared to more consistent rainfall patterns experienced in Tasmania, Queensland is characterized by a subtropical climate with high-volume summer rainfall events followed by comparatively dry winter months [38]. Thus, considering the geographical extent of the Queensland study area, it seems plausible that the degree of rainfall variance experienced at each study location might explain the observed variability in correlations with RRV cases. Indeed, by extracting above-average rainfall years from the Tasmania-wide dataset and analysing them with reported RRV outbreak years, we too yielded a significant correlation – providing rudimentary support to such a hypothesis.

The weak correlation between rainfall and case data may also reflect the relative influence of competing or cumulative environmental drivers on *Ae. camptorhynchus* populations [32]. Females lay desiccant resistant eggs in saltmarsh areas, with tidal inundation thought to facilitate hatching in the absence of rainfall [32]. This phenomena is especially prevalent in coastal marshes during summer when shallow habitats would normally be dry [30]. The combination of high tides and higher temperatures probably prolongs suitable conditions for mosquitoes to breed; allowing mosquito populations to develop more rapidly, reach higher densities faster, and be maintained for longer periods [39]. The continued longevity of shallow tidal pools due to successive rainfall can also create extended periods of potential habitats for mosquitoes to complete development – and potential exposure to the virus. Intuitively, when lower than normal tides are experienced, it would be expected that rainfall would play a more significant role in determining RRV vector populations. This hypothesis is supported by our finding of a significant interaction of rainfall and tide with RRV cases.

In our study, tide and temperature were found to be the only two environmental variables that were significantly correlated (Table 1). A similar correlation has been reported in other studies over longer time periods [40], but not the short-term negative correlation found here.

## Rainfall, tide and temperature as predictors of RRV cases

Another objective of this study was to examine the predictive capability of each variable and their interactions with negative binomial regression (for 0–3 months). Results show that mean maximum temperature and rainfall are significant predictors of RRV cases (Table 2). However, the different environmental variables predict the burden of RRV disease by varying degrees. For example, RRV cases are projected to increase 23·2% over the long-term average per unit increase in temperature, whereas cases are projected to increase 9·9% over the long-term average per unit increase in rainfall. In addition to finding that mean maximum temperature and rainfall are significant predictors of RRV cases, accounting for lag periods is also important. The most significant predictors from the negative binomial regression model fell under the 1-month lag period. Neither predictors nor their interactions were significant at the 0-, 2-, and 3-month lag periods (Table 2). It appears that it would not be as beneficial for public health interventions to consider lag periods of

$\geqslant 3$ months. Others have also suggested that lag periods of $\geqslant 4$ months may not be relevant [31].

While tide is not a significant predictor ($P = 0{\cdot}057$ from Table 2) of RRV cases in this model, it should be noted the degree by which this result exceeds this threshold value is marginal. Thus, it could be argued there is potential to utilize tide as an environmental predictor of RRV cases in southeastern Tasmania. Certainly, in a short-term context (< 10 years), the use of tide as a predictor of RRV cases is limited due to the scale of change required to invoke an increase in case numbers. For example, it is more likely that a 1 unit increase in rainfall (1 mm) or temperature (1 °C) would occur within 1 month, compared to 1 m increase in tide (as shown in the year-to-year environmental variable ranges (Supplementary Table S3, online). However, the magnitude of disease burden forecast by tide in this model (1 m = 32·9 cases = 238·4%) may warrant further investigation over the longer term in the context of the forecast influence of climate change on local coastal marsh areas due to rising sea levels.

In southeastern Tasmania, a cooperative approach between Sorell and adjacent LGAs could see rapid advances in information to strengthen local interventions for RRV. The creation of a predictive model using environmental datasets and RRV case data could prove a simple, yet cost-effective way of improving the capacity of public health services to forecast and reduce future disease burden of RRV in southeastern Tasmania. Mosquito monitoring data is more expensive to collect, time-consuming, and gives a shorter time period to implement interventions and issue warnings to the public about potential RRV risks. However, a simple yet proactive tool for predicting and triggering public health interventions for RRV could aid local health authorities in issuing warnings before vector populations boom and help focus mosquito control measures, such as mosquito spraying [29, 41].

Developing a proactive tool with predictive modeling will include challenges that will need to be accounted for including: variable lag times that are relative to environmental drivers; factors that regulate mosquito populations such as predation, competition for space, habitat conditions and available food resources; and potentially surrounding land-use practices and population proximity to humans, as well as reservoir hosts. However, a model that integrates these data, while accounting for uncertainties, is an exciting new research opportunity for improving the sensitivity of existing public health practices to better predict and prevent RRV cases.

## Strengths and limitations

This study examines specifically the southeast of Tasmania, so that extraneous cases (i.e. those from the northeast) are excluded, and utilizes environmental and NNDSS data which are routinely collected, easy to obtain, and inexpensive. However, the use of a passive surveillance system like the NNDSS may also introduce limitations if: (*a*) RRV notifications are underestimates of true incidence [1], or, (*b*) notification records do not accurately reflect the location of disease acquisition [42]. In addition, it is possible that during outbreak years residents may be more alert, resulting in increased numbers of cases being reported.

It is difficult to ascertain exactly how many RRV cases reported in this study may have been contracted outside residential postcodes. Limited follow-up surveys undertaken by local health professionals suggest that those cases potentially acquired externally to the patient's residential address were probably restricted to nearby postcodes, and are therefore covered by the collective study area. As such, we consider this potential source of error to be relatively minor with findings remaining indicative of the dynamics of RRV at the locations evaluated. However, any future analysis should aim to exclude cases of infection where the infection was known to have been acquired outside the study area (other parts of Australia or overseas). Confirmed cases of RRV are based on laboratory definitive evidence and only confirmed cases should be reported. While cases are based on the defined case definition, on occasion there may be misdiagnosis from other causes of arthritis or due to false-positive results from clinically compatible cases. In addition, IgM antibodies, which are tested to aid in confirmation of a case, can persist for long periods and may only be used as presumptive evidence of a recent infection [43]. However, it is difficult to know how often misdiagnosis occurs. Although this is a potential limitation of the study, the data used are consistent with numerous other epidemiological investigations of RRV in Australia [14, 30, 32, 39].

Tasmanian data are based on specimen collection date, while the NNDSS data are based on the date of disease diagnosis, which is equivalent to the disease onset date. However, where this date is unknown, the date of the earliest specimen collection, the notification date, or the notification received date can be used instead. While the two datasets are based on different dates, there is general consistency between them, so any discrepancies are assumed to be minor.

The impacts of climate change and its potential influence on environmental drivers and increased numbers and/or intensity of outbreaks has been raised. However, further studies are warranted to account for climate variation at local scales. It is anticipated that new data sources soon to be released by the Australian Bureau of Meteorology, including 7-day and 3- to 6-month climate forecasts at 3 $km^2$ resolution, may indeed enable public health actions to be developed at LGA scales. Future studies might consider the use of local scale temperature projections as a tool to identify, classify, and rank those communities most at risk of exposure to reproductive viable vector populations and subsequent virus transmission.

The predicted changes in temperature for Tasmania range from a 1·6–2·9 °C increase in mean temperature (under low to high greenhouse gas emission models), with projected changes in the incidence of extreme temperature days [24]. Models show that total annual rainfall is likely to remain consistent, but there are projected changes with respect to extremes and spatial distribution, including increased rainfall over coastal areas [24]. In this climate context, our results suggest that RRV cases are likely to pose an increased public health threat in southeastern Tasmania. These predictions need to be tempered against an understanding of the role of hosts in the ecology of RRV transmission, which is currently underdeveloped [1, 17, 20, 21].

In order to fully analyse relationships between potential environmental drivers of *Ae. camptorhyncus* populations, and subsequent RRV case data, a more robust dataset using standardized methods and a study area that expands across adjacent LGA boundaries from Sorell is required.

## CONCLUSION

This research serves as an initial study of environmental drivers of RRV in specific southeastern LGAs in Tasmania. Future research directions include examining which of these environmental drivers contribute most to RRV cases, or which may be the best predictor of RRV cases, with a stepwise logistic regression analysis. However, such a study requires collection and integration of other data on how hosts factor in to RRV transmission, as well as examining additional environmental drivers, like larger scale oscillations, humidity, and salinity. Anthropogenic drivers, such as land use, are also important to include as these may affect mosquito and host populations, thus affecting the number of RRV cases. Further statistics might include investigating interactions with effect modification analyses. Using these results for future studies and modelling to develop warning systems for local councils could prove very valuable. Implementing these early warning systems might help to prioritize funding towards interventions such as mosquito spray programmes and/or public outreach campaigns. These steps will help to further guide public health policy and public health officials to reduce the overall disease burden.

## NOTE

Supplementary material accompanies this paper on the Journal's website (http://journals.cambridge.org/psm).

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## DECLARATION OF INTEREST

None.

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