Title

Socio-environmental predictors of Barmah Forest virus transmission in coastal areas,
Queensland, Australia

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Running title

Risk factors for Barmah Forest virus disease

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List of abbreviations

BFV - Barmah Forest virus

SEIFA - Socio-economic index

LGAs - Local Government Areas

MaxT - Maximum temperature

MinT - Minimum temperature

Rh - Relative humidity

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Abstract

Background

Barmah forest virus (BFV) disease is one of the most common mosquito-borne diseases in Australia, but little empirical information is available on the impact of social and environmental factors on its transmission.

Objective

To assess the socio-environmental predictors of BFV transmission in coastal areas, Queensland, Australia.

Methods

Data on BFV notified cases, climate, tidal levels and socioeconomic index for area (SEIFA) in six coastal cities, Queensland, for the period 1992-2001 were obtained from the relevant government agencies. Negative binomial regression models were used to assess the socio-environmental predictors of BFV transmission.

Results

The results show that maximum and minimum temperature, rainfall, relative humidity, high and low tide were statistically significantly associated with BFV incidence at lags 0 - 2 months. The fitted negative binomial regression models indicate a significant independent association of each of maximum temperature ($\beta = 0.139$, $p = 0.000$), high tide ($\beta = 0.005$, $p = 0.000$) and SEIFA index ($\beta = -0.010$, $p = 0.000$) with BFV transmission after adjustment for confounding variables.

Conclusions

The transmission of BFV disease in Queensland coastal areas seemed to be determined by a combination of local social and environmental factors. The model developed in this study may have applications in the control and prevention of BFV disease in these areas.

Introduction

Barmah Forest virus (BFV) is the second most common mosquito-borne disease in humans in Australia, and causes an epidemic polyarthritis-like disease known as BFV disease (Flexman *et al.* 1998; Mackenzie and Smith 1996). The symptoms of BFV include fever, arthritis, arthralgia and rash, and may include rheumatic pain in and around the joints and muscles, and difficulty in moving thus leading to polyarthritis (Flexman *et al.* 1998). The disease is non-fatal and affects all age groups irrespective of gender. The incubation period is about 7 to 10 days (Fraser and Cunningham 1980).

Barmah Forest virus was isolated in 1974 from *Culex annulirostris* Skuse mosquitoes collected in the Barmah Forest near the Murray River in northern Victoria (Marshall *et al.* 1982). It was then subsequently isolated from mosquitoes in Queensland in 1974, in Western Australia in 1989 (Lindsay *et al.* 1995), in Northern Territory in 1974 and 1976 (Standfast *et al.* 1984), and from a number of species between 1984 and 1992 (Whelan and Weir 1993a). It has also been isolated from numerous other mosquitoes, including the coastal salt marsh species *Ochlerotatus vigilax* (Skuse) (sub-tropics to tropics) and *Ochlerotatus camptorhynchus* (Thomson) (temperate). Barmah Forest virus was first shown to infect humans in New South Wales in 1986 (Vale *et al.* 1986) and was reported as a cause of clinical disease in humans in 1988 (Boughton *et al.* 1988). The first outbreak of BFV disease occurred at Nhulunbuy in the Northern Territory in 1992 (Merianos *et al.* 1992) and subsequent outbreaks have been reported from various parts of Australia (Doggett *et al.* 1999; Lindsay *et al.* 1995; Passmore *et al.* 2002). Australian native animals such as kangaroos, possums, marsupials (Kay *et al.* 2007; Kay *et al.* 1982) and some birds (Kay *et al.* 1982) are the main hosts for the transmission of BFV disease.

BFV is an increasing disease and notifications have now been reported in every state across Australia, particularly in subtropical and tropical regions (Jacups *et al.* 2008). During 1995 - 2007, there were 14 395 BFV notifications in Australia (national annual average incidence: 3.78/100,000 population), the majority of which were reported in Queensland (N =7272) (Queensland Department of Health 2008). Seasonality plays an important role in the disease transmission with a peak in summer and autumn, and lower transmission in winter and spring (Kay 2002).

The transmission cycles of BFV appear to be determined by many factors including the virus-carrying mosquitoes and its reservoir hosts, the vector population, the human population, and social and ecological conditions (Boughton *et al.* 1984; Hills and Sheridan 1997; Kramer *et al.* 1983; Lindsay and Mackenzie 1997; Mackenzie *et al.* 1994; Phillips *et al.* 1992; Russell 1995). Climatic factors such as temperature, rainfall and humidity, at local and regional levels, directly affect mosquito abundance, breeding and survival of mosquitoes and the extrinsic incubation period of the virus (Gatton *et al.* 2005; Hu *et al.* 2007; Kelly-Hope *et al.* 2004b; Tong *et al.* 2005; Woodruff *et al.* 2006). Tidal factors are also important in the transmission of BFV disease (Naish *et al.* 2006). However, other socio-economic factors including human behaviour and lifestyle as well as immunity levels may also be involved in the transmission of BFV disease (Gatton *et al.* 2005; Hu *et al.* 2007; Kelly-Hope *et al.* 2004b; Tong *et al.* 2005; Woodruff *et al.* 2006).

Previously, we have studied the potential linkages between environmental factors and BFV in the Gladstone region of Queensland, Australia (Naish *et al.* 2006). In this study, we extended the previous research to examine the impact of climate, socio-economic and tidal factors on the transmission of BFV disease in six coastal cities in Queensland, Australia.

Methods

Study area

Queensland is the second largest state of Australia (after Western Australia), located in the north-east of the country. It covers approximately 1 727 000 km², with 9 800 km of coastal line, including islands. Lying generally between 10° and 29° south of the equator, it ranges from the temperate and densely populated southeast to the tropical, sparsely populated Cape York Peninsula in the north. Its population was 3 904 532 on 31 July 2006. The study included six coastal cities in Queensland: Brisbane, Bundaberg, Cairns, Gladstone, Mackay and Townsville (Figure 1).

[Insert Figure 1 about here]

Data collection

The computerised data set of notified BFV cases in Queensland for the period January 1992 to December 2001 (10 years) was obtained from the Queensland Department of Health. Because of the typically low numbers of daily and weekly cases, we calculated the total monthly counts based on the daily data (Abeku *et al.* 2004; Hu *et al.* 2004). Climate data originally consisted of daily maximum and minimum temperature (°C), rainfall (cm) and relative humidity (%) at 9 am and was provided by the Australian Bureau of Meteorology. Semi-diurnal data on daily high and low tide (cm) were provided by Queensland Department of Transport. The tidal pattern is semi-diurnal usually with two high and two low tides in each period of 25 hours and 50 minutes. We calculated the average monthly high and low tides by aggregating the two daily high and low tides. Population data and values of a socioeconomic index for areas (SEIFA) for the study period and locations studied

were obtained from the Australian Bureau of Statistics (Australian Bureau of Statistics 2004; Australian Bureau of Statistics 2003). The SEIFA index, which includes information on socio-economic variables such as income, education, occupation, wealth and living conditions, is a measure of the socio-economic wellbeing of the Australian population and identifies areas of advantage and disadvantage (Australian Bureau of Statistics 2003). The SEIFA index for Local Government Areas (LGAs) (Australian Bureau of Statistics 2004) was used in this study.

Data analysis

An initial exploratory analysis of the BFV data, climate and tidal variables, SEIFA indexes and population factors was carried out to characterise each variable. The monthly incidence rates of BFV disease were calculated using monthly counts of BFV as the numerator and the population size (resident population estimate) in the middle of each year from the 2001 census as the denominator. Spearman correlation coefficients (Snedecor and Cochran 1989) were used to assess the relationships between the monthly incidence rates of BFV disease and each independent variable in the current month and also over a range of time lags as lag effects are likely to be important in relation to the influence of socio-environmental variables on BFV transmission (Hu *et al.* 2004; Naish *et al.* 2006; Tong and Hu 2001). The Spearman correlations showed that the incidence rates of BFV were statistically significantly associated with climate and tidal variables in the current month, and at lags of 1 and 2 months. Therefore, the correlations between the climate variables with a moving average of 1 - 2 months and BFV incidence were also calculated.

The relationship between climate variables and BFV was determined further by taking anomalies of all the variables from the annual cycle as there was a strong

seasonal cycle in the climate variables and BFV incidence. To remove the annual cycles, the monthly anomalies of each of the climate variables and monthly BFV cases for each city was calculated first (anomalies = observations – mean (calculated from the 10 years data available)) and then Spearman correlations were calculated between the anomalies of BFV incidence rates and climate variables. Similarly, monthly anomalies of each of the climate variables and monthly BFV cases for six coastal cities on average were calculated first and then Spearman correlations between the anomalies were calculated.

Generalised linear models (GLMs) using the negative binomial distribution with a log link function were used to explore the risk factors for the transmission of BFV disease as the BFV data were overdispersed (McCullagh and Nelder 1989). We used the original BFV cases (count) as the dependent variable and the seasonality (seasons of the year) and LGA (coastal city) as factors (both categorical). Population size was used as an offset in all the models. SEIFA value for each city was different which reflects the different state of socio-economic status in each city. However, SEIFA value does not change much from year to year in any city. We used the average annual SEIFA value for each city. The explanatory variables (predictors) included were the current month and a moving average of lags 1 - 2 months of climate and tidal variables (maximum and minimum temperature, rainfall, relative humidity high and low tides) and SEIFA index.

Multicollinearity between independent variables was assessed using Spearman rank correlation. Those variables with a Spearman rank correlation lower than 0.75 were included in the same model (Bland 2000; Gujarati 2003; Zar 1999). A series of different models were calculated using various sets of predictors.

A number of generalised linear models (GLMs) were calculated to find the model with the best fit to the data. The Akaike's Information Criterion (AIC) value was used to measure how well the model fitted the data - viz., the smaller the AIC value the better the model (Hair *et al.* 1998; Wuensch 2006). Pearson chi-square and deviance test statistics were calculated to measure the model's goodness-of-fit (Hair *et al.* 1998; Lawless 1987; McCullagh and Nelder 1989). The omnibus likelihood ratio test was also applied to check each model's fit (Spinelli *et al.* 2002). Data analyses were conducted using SPSS for Windows (version 16) (Statistical Package for Social Sciences 2008) and the statistical significance level was set at 5% for two tails.

Results

BFV transmission

Table 1 provides descriptive information about the incidence of BFV infection and climatic, tidal and seasonal variables. BFV infections appeared to vary with season, peak in autumn and were relatively infrequent in winter in these coastal areas.

[Insert Table 1 about here]

Figure 2 shows the monthly BFV counts (aggregated over the six cities), maximum temperature, high tide and rainfall in coastal areas in Queensland between 1992 and 2001.

[Insert Figure 2 about here]

Figure 3 shows that BFV transmission was low in 1992 and peaked in 1996. The patterns of BFV transmission appeared to be similar for all the six coastal cities, and therefore the data from each city were aggregated to assess the relationship between socio-environmental factors and BFV incidence.

[Insert Figure 3 about here]

Correlation between predictors and BFV incidence

Spearman correlation coefficients between the incidence of BFV and the climate variables were calculated. The results of these analyses show that all the climate and tidal variables except rainfall were positively and statistically

significantly associated with the monthly incidence of BFV at lags of 0 -, 1 - and 2 - months (Table 2) individually. Likewise, a positive and significant relationship was observed between the monthly incidence of BFV and the moving averages of lags 1- and 2 - months of all the climate and tidal variables (Table 2).

[Insert Table 2 about here]

Correlations among the climate and tidal variables (Table 3) indicate that maximum and minimum temperatures were highly positively ($r_s = 0.81$) correlated with each other. Similarly, high and low tides were highly negatively ($r_s = -0.80$) correlated with each other. Therefore, maximum and minimum temperatures and, high and low tides were included separately in the models to avoid multicollinearity. Correlations between all other predictor variables were not strong ($|r_s| \leq 0.54$).

[Insert Table 3 about here]

Correlations between the anomalies of incidence rates of BFV and climate and tidal variables of individual cities indicate that there were statistically significant relationships between some of the climate and tidal variables and BFV (Table 4). For example, in Brisbane, the anomalies of incidence rates of BFV were statistically significantly associated with relative humidity, low tide and high tide. When correlations were calculated for all the six cities on average, the anomalies of incidence rates of BFV were statistically significantly associated with maximum temperature, minimum temperature, relative humidity, low tide and high tide (Table 4).

[Insert Table 4 about here]

In addition, scatter diagrams were plotted to show the statistically significant relationships between BFV and the anomalies of climate and tidal variables, (i.e., maximum and minimum temperatures and, relative humidity, high and low tides) (Figure 4).

[Insert Figure 4 about here]

Generalised linear models

A series of models was explored to obtain the best-fit model for the BFV dataset with different sets of predictors, applying the backward selection method. The models included the number of BFV cases as the response variable and the climate and tidal variables in the current month and with a moving average of lags 1 - 2 months, and SEIFA index, as explanatory variables. All the models were checked and the best-fit model was selected based on the deviance reduction as measured with χ^2 statistic and the AIC value. The best-fit model for this data set (ie, the model with smallest AIC value and deviance) shows that BFV counts were positively and statistically significantly associated with maximum temperature ($\beta = 0.139$, $p = 0.000$) and high tide ($\beta = 0.005$, $p = 0.000$) and negatively and statistically significantly associated with SEIFA index ($\beta = -0.010$, $p = 0.000$), after adjustment for confounding effects of seasonality and population size. The goodness-of-fit test indicates that the model developed was the most parsimonious for this dataset with

AIC = 3532.97, Pearson χ^2 value of 1.05, deviance value = 0.95 and Omnibus likelihood ratio of 444.3 (Table 5).

[Insert table 5 about here]

Discussion

In this study, we assessed the key predictors of BFV transmission in six coastal cities, Queensland, Australia. The results of this study suggest that temperature, high tide and socio-economic conditions are key risk factors in the transmission of BFV disease. Hence, these variables may be useful for predicting the transmission of BFV disease in the Queensland coastal region.

We found that maximum temperature at a moving average of lags 1-2 months had a significant influence on the transmission of BFV disease. Higher temperatures can speed up the rate of larval development, with adults emerging faster than at lower temperatures (Doggett *et al.* 1999; Gatton *et al.* 2005; Hu *et al.* 2006; Jacups *et al.* 2008; Kelly-Hope *et al.* 2002; Kitron 2000; Naish *et al.* 2006; Patz *et al.* 2005; Tong *et al.* 2005; Woodruff *et al.* 2006), and this may increase the likelihood of transmission and BFV outbreaks. Previous studies have shown that mosquitoes exposed to higher temperatures after ingestion of virus become infectious more rapidly than mosquitoes of the same species exposed to lower temperatures (Hardy 1988; Jacups *et al.* 2008; Mackenzie *et al.* 1994; Naish *et al.* 2006; Russell 1995). In addition, temperature strongly influences the length and efficiency of mosquito incubation periods and the survival of adult mosquitoes (McMichael 2003; Naish *et al.* 2006; Reeves *et al.* 1994; Russell 1995; Russell 1998b).

Like other vector-borne diseases, the lagged effect is important in assessing socio-environmental predictors of BFV transmission. In this study, we found that the lags of 1 and 2 months were important. Such delays are consistent with the development of mosquitoes, the external period of incubation of BFV within mosquitoes, and the incubation period of the virus in the host (Lindsay and Mackenzie 1997; Mackenzie *et al.* 2000; Russell 1995; Russell 1998b; Russell and Kay 2004).

The existence of these lags will facilitate public health interventions to control and prevent BFV outbreaks.

Our results also indicate that high tide was positively and statistically significantly associated with BFV transmission. Tidal inundation of saltmarshes is a major source of water for breeding of the coastal saltmarsh mosquitoes, *Ochlerotatus vigilas* and *Ochlerotatus camptorhynchus*. Adult females of both species lay their eggs on soil, moist mud, and the bases of plants around the margins of their breeding sites. The eggs hatch when high tides subsequently inundate the sites. Large populations of adult mosquitoes can emerge as quickly as eight days after very high tides on salt marshes (Lindsay *et al.* 1995; Mackenzie *et al.* 2000; Russell 2002; Tong *et al.* 2002; Tong and Hu 2002; Tong *et al.* 2005). Our results corroborate findings from previous studies on tidal influence and mosquito distribution (Dale 2008; Dale and Knight 2008; Hu *et al.* 2007; Kelly-Hope *et al.* 2004b; Naish *et al.* 2006; Tong and Hu 2002; Woodruff *et al.* 2006)

Our results also indicate that SEIFA index was negatively and statistically significantly associated with BFV disease. SEIFA is an index that provides a populated weighted value for each LGA across Australia (Australian Bureau of Statistics 2004). The index values enable areas to be ranked and compared against one another. A low index value reflects relative disadvantage and occurs where there is a large proportion of low-income families, people with low skilled occupations and high proportions of the population with low educational attainment. A high value reflects the opposite situation (i.e, relative advantage where there are large proportions of high-income families, high-skilled occupants and low proportion of low education achieved people) (Australian Bureau of Statistics 2003). Despite some shortcomings (for example, reliability of SEIFA based on census data and collection of census data

only once every five years), SEIFA still remains an essential and most useful tool for assessing relative levels of socio-economic status across areas in Australia. The risk of transmission of vector-borne diseases has been shown to increase with decreasing socio-economic status (Hu *et al.* 2007). People in lower social classes are likely to have high incidence rates of BFV, because of their poorer housing conditions and low knowledge about disease prevention. Thus, a low SEIFA index may be an important indicator of risk of transmission of mosquito-borne diseases in Queensland.

There are three strengths in this study: (1) to the best of our knowledge, this is the first attempt to assess the predictors of BFV transmission using a range of socio-environmental factors; (2) this study included multiple locations from densely populated areas in Queensland; and (3) the model fitted the data quite well and may have implications for the control and prevention of BFV and other vector-borne diseases.

This study also has some limitations, including: (1) the data were collected from national disease surveillance system. The quality of the data may vary with time and place. Thus, this may impact the study results and cause some non-differential bias. (2) We were unable to analyse the association between socio-economic factors and BFV transmission in inland areas because tidal data are unavailable in these areas. (3) Further, climatic and social factors may be only part of the important parameters, and some other factors (eg, host, virus and mosquito species) may also be important. However, these data were not readily available.

In conclusion, our study shows that the climate and socio-economic factors were associated with transmission of BFV disease in coastal areas, Queensland. The models developed in this study may be used by disease surveillance and risk managers

as an additional tool in the control and prevention of BFV disease and other wide-spread mosquito-borne diseases.

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Conflicts of interests declared

There is no conflict of interest in this manuscript for any of the authors.

References

- Abeku TA, De Vlas SJ, Borsboom GJ *et al.* (2004) Effects of meteorological factors on epidemic malaria in Ethiopia: a statistical modelling approach based on theoretical reasoning. *Parasitology* **128**, 585-593.
- Australian Bureau of Statistics. Census of Population and Housing - Basic community profiles, Commonwealth of Australia, Canberra, ABS. 2004 [updated 2004; cited 23 September 2004]; Available from: www.abs.com.au.
- Australian Bureau of Statistics A. Socio-Economic Indexes for Areas, Australia, 2001. Canberra; 2003 [updated 2003; cited 2008]; Available from: www.census.abs.gov.au/ausstats/.
- Bland M (2000) An Introduction to Medical Statistics, 3rd edn. Oxford: Oxford University Press.
- Boughton CR, Hawkes RA, Naim HM (1988) Illness caused by a Barmah-Forest-like virus in New South Wales. *Medical Journal of Australia* **148**, 146-147.
- Boughton CR, Hawkes RA, Naim HM, Wild J, Chapman B (1984) Arbovirus infections in humans in New South Wales. Seroepidemiology of the alphavirus group of togaviruses. *Medical Journal of Australia* **141**, 700-704.
- Dale PER (2008) Large numbers of this species develop after very high tides or heavy rains on salt marshes *Wetlands Ecology and Management* **16**, 77-87.
- Dale PER, Knight JM (2008) Wetlands and mosquitoes: a review *Wetlands Ecology and Management* **16**, 255-276.
- Doggett SL, Russell RC, Clancy J, Hanriotis J, Cloonan MJ (1999) Barmah Forest virus epidemic on the south coast of New South Wales, Australia, 1994-1995: viruses, vectors, human cases, and environmental factors. *Journal of Medical Entomology* **36**, 861-868.

- Flexman JP, Smith DW, Mackenzie JS *et al.* (1998) A comparison of the diseases caused by Ross River virus and Barmah Forest virus. *Medical Journal of Australia* **169**, 159-163.
- Fraser JR, Cunningham AL (1980) Incubation time of epidemic polyarthrititis. *Med J Aust* **1**, 550-551.
- Gatton ML, Kay BH, Ryan PA (2005) Environmental predictors of Ross River virus disease outbreaks in Queensland, Australia. *Am J Trop Med Hyg* **72**, 792-799.
- Gujarati D (2003) Basic Econometrics (4th Edition). Hill M, editor. Boston.
- Hair JF, Anderson JR, Tatham RE, Black WC (1998) Multivariate data analysis (5th ed). Upper Saddle River, N.J., USA: Prentice-Hall.
- Hardy JL (1988) Susceptibility and resistance of vector mosquitoes. In: Monath TP, editor. The Arboviruses: Epidemiology and Ecology. Boca Raton, FL: CRC Press. p. 87-126.
- Hills SL, Sheridan JW (1997) The epidemiology of Barmah Forest Virus infection in Queensland. *Arbovirus Research Australia* **7**, 95-99.
- Hu W, Nicholls N, Lindsay M *et al.* (2004) Development of a predictive model for ross river virus disease in Brisbane, Australia. *American Journal of Tropical Medicine and Hygiene* **71**, 129-137.
- Hu W, Tong S, Mengersen K, Oldenburg B (2007) Exploratory spatial analysis of social and environmental factors associated with the incidence of Ross River virus in Brisbane, Australia. *American Journal of Tropical Medicine and Hygiene* **76**, 814-819.
- Hu W, Tong S, Mengersen K, Oldenburg B (2006) Rainfall, mosquito density and the transmission of Ross River virus: A time-series forecasting model *Ecological Modelling* **196**, 505-514

- Jacups SP, Whelan PI, Currie BJ (2008) Ross River Virus and Barmah Forest Virus Infections: A Review of History, Ecology, and Predictive Models, with Implications for Tropical Northern Australia. *Vector Borne Zoonotic Dis.*
- Kay BH, Boyd AM, Ryan PA, Hall RA (2007) Mosquito feeding patterns and natural infection of vertebrates with Ross River and Barmah Forest viruses in Brisbane, Australia. *Am J Trop Med Hyg* **76**, 417-423.
- Kay BH, Fanning ID, Carley JG (1982) Vector competence of *Culex pipiens quinquefasciatus* for Murray Valley encephalitis, Kunjin, and Ross River viruses from Australia. *Am J Trop Med Hyg* **31**, 844-848.
- Kay BHJ, C.D. (2002) Enhancement or modulation of the vector competence of *Ochlerotatus vigilax* (Diptera: Culicidae) for Ross River virus by temperature. *Journal of Medical Entomology* **39**, 99-105.
- Kelly-Hope LA, Kay BH, Purdie DM, Williams GM (2002) The risk of Ross River and Barmah Forest virus disease in Queensland: implications for New Zealand. *Australian and New Zealand Journal of Public Health* **26**, 69-77.
- Kelly-Hope LA, Purdie DM, Kay BH (2004b) Ross River virus disease in Australia, 1886-1998, with analysis of risk factors associated with outbreaks. *Journal of Medical Entomology* **41**, 133-150.
- Kitron U (2000) Risk Maps: Transmission and Burden of Vector-borne Diseases. *Parasitology Today* **16**, 324-325.
- Kramer LD, Hardy JL, Presser SB (1983) Effect of temperature of extrinsic incubation on the vector competence of *Culex tarsalis* for western equine encephalomyelitis virus. *American Journal of Tropical Medicine and Hygiene* **32**, 1130-1139.

- Lawless J, F. (1987) Lawless, Negative binomial and mixed Poisson regression.
Canad J Statist **15**, 209-225.
- Lindsay MD, Johansen CA, Smith DW, Wallace MJ, Mackenzie JS (1995) An outbreak of Barmah Forest virus disease in the south-west of Western Australia. *Medical Journal of Australia* **162**, 291-294.
- Lindsay MD, Mackenzie JS (1997) Vector-borne viral disease and climate change in the Australian region: major concerns and the public health response. In: Curson P, Guest, C., Jackson, E., editor. Climate change and human health in the Asia-Pacific region. Canberra, Australia: Australia Medical Association and Greenpeace International. p. 47-62.
- Lindsay MDA, Johansen CA, Broom AK, Smith DW, Mackenzie JS (1995) Emergence of Barmah Forest Virus in Western Australia. *Emerging Infectious Diseases* **1**.
- Mackenzie JS, Lindsay MD, and , Daniels PW (2000) The effect of climate on the incidence of vector-borne viral diseases: the potential value of seasonal forecasting. In: G.Hammer NN, and C.Mitchell, editor. Applications of seasonal climate forecasting in Agriculture and Natural Ecosystems - The Australian experience. The Netherlands: Kluwer Academic Publishers. p. 429-452.
- Mackenzie JS, Lindsay MD, Coelen RJ *et al.* (1994) Arboviruses causing human disease in the Australasian zoogeographic region. *Archives of Virology* **136**, 447-467.
- Mackenzie JS, Smith DW (1996) Mosquito-borne viruses and epidemic polyarthritis. *Medical Journal of Australia* **164**, 90-93.

- Marshall ID, Woodroffe GM, Hirsch S (1982) Viruses recovered from mosquitoes and wildlife serum collected in the Murray Valley of South-eastern Australia, February 1974, during an epidemic of encephalitis. *Australian Journal of Experimental Biology and Medical Sciences* **60**, 457-470.
- McCullagh P, Nelder JA (1989) Generalised Linear Models. Second ed. London/New York: Chapman & Hill.
- McMichael AJ (2003) Climate change and human health : risks and responses. McMichael AJ, Campbell-Lendrum DH, Corvalan CF, Ebi KL, Githeko A, Scheraga JD, Woodward A, editors. Geneva: World Health Organisation.
- Merianos A, Farland AM, Patel M, Currie B (1992) A concurrent outbreak of Barmah Forest and Ross River disease in Nhulunbuy, Northern territory. *Communicable Diseases Intelligence (Australia)* **16**, 110-111.
- Naish S, Hu W, Nicholls N *et al.* (2006) Weather variability, tides, and Barmah Forest virus disease in the Gladstone region, Australia. *Environmental Health Perspectives* **114**, 678-683.
- Passmore J, O'Grady KA, Moran R, Wishart E (2002) An outbreak of Barmah Forest virus disease in Victoria. *Communicable Diseases Intelligence* **26**, 600-604.
- Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. *Nature* **428**, 310-317.
- Phillips DA, Sheridan JW, Aaskov J (1992) Epidemiology of arbovirus infection in Queensland, 1989-1992. *Arbovirus Research in Australia* **6**, 245-248.
- Queensland Department of Health. National Notifiable Diseases Surveillance System, Communicable Diseases Australia, Department of Health and Ageing, Australian Government. 2008 [updated 2008; cited 26 September 2004]; Available from: www.health.gov.au/internet/wcms/publishing.nsf/content.

- Reeves WC, Hardy JL, Reisen WK, Milby MM (1994) Potential effect of global warming on mosquito-borne arboviruses. *Journal of Medical Entomology* **31**, 323-332.
- Russell RC (1995) Arboviruses and their vectors in Australia: an update on the ecology and epidemiology of some mosquito-borne arboviruses. *Review of Medical and Veterinary Entomology* **83**, 141-158.
- Russell RC (1998b) Mosquito-borne arboviruses in Australia: the current scene and implications of climate change for human health. *International Journal of Parasitology* **28**, 955-969.
- Russell RC (2002) Ross River virus: ecology and distribution. *Annual Reviews of Entomology* **47**, 1-31.
- Russell RC, Kay BH (2004) Medical entomology: changes in the spectrum of mosquito-borne disease in Australia and other vector threats and risks, 1972-2004. *Australian Journal of Entomology* **43**, 271-282.
- Snedecor GW, Cochran WG (1989) Statistical Methods, 8th edn. Ames, editor. IA.: Iowa State University Press.
- Spinelli JJ, Lockhart RA, Stephens MA (2002) Tests for the response distribution in a Poisson regression model *Journal of Statistical Planning and Inference* **108**, 137-154
- Standfast HA, Dyce AL, St George TD *et al.* (1984) Isolation of arboviruses from insects collected at Beatrice Hill, Northern Territory of Australia, 1974-1976. *Aust J Biol Sci* **37**, 351-366.
- Statistical Package for Social Sciences.2008. SPSS 16.0 Guide for data analysis. New Jersey: Prentice-Hall.

- Tong S, Bi P, Donald K, McMichael AJ (2002) Climate variability and Ross River virus transmission. *Journal of Epidemiology and Community Health* **56**, 617-621.
- Tong S, Hu W (2001) Climate variation and incidence of Ross river virus in Cairns, Australia: a time-series analysis. *Environmental Health Perspectives* **109**, 1271-1273.
- Tong S, Hu W (2002) Different responses of Ross River virus to climate variability between coastline and inland cities in Queensland, Australia. *Occupational and Environmental Medicine* **59**, 739-744.
- Tong S, Hu W, Nicholls N *et al.* (2005) Climatic, high tide and vector variables and the transmission of Ross River virus. *International Medical Journal* **35**, 677-680.
- Vale TG, Carter IW, McPhie KA, James GS, Cloonan MJ (1986) Human arbovirus infections along the south coast of New South Wales. *Australian Journal of Experimental Biology and Medical Sciences* **64 (Pt 3)**, 307-309.
- Whelan P, Weir RP (1993a) The isolation of alpha and flaviviruses from mosquitoes in the Northern Territory 1982-1992. Darwin: Northern Territory Government-Department of Health and Community Services; Contract No.: Document Number.
- Woodruff RE, Guest CS, Garner MG, Becker NE (2006) Early warning of Ross River Virus epidemics and combining surveillance data on climate and mosquitoes. *Epidemiology* **17**, 569-575.
- Wuensch KL. Logistic regression. 2006 [updated 2006; cited 2008 22 April]; Available from: <http://core.ecu.edu/psyc/wuenschk/MV/multReg/Logistic-SPSS.doc>.

Zar JH (1999) Biostatistical Analysis (4th Edition). Hall P, editor. New Jersey, USA:
Upper Saddle River.

Tables

Table 1: Descriptive statistics for the BFV, climate and tidal variables at Queensland coastal locations during the period 1992-2001 (n=720)

Variable	Mean	S.D.	Minimum	25% Percentile	Median	75% Percentile	Maximum
BFV incidence	5.69	10.04	0.00	0.78	2.02	5.61	92.71
Maximum temperature ($^{\circ}\text{C}$)	27.44	3.14	19.94	25.21	27.86	30.01	34.06
Minimum temperature ($^{\circ}\text{C}$)	18.52	4.15	7.37	15.42	19.18	22.02	26.11
Rainfall (cm)	99.61	134.79	0.00	23.40	57.20	121.60	1287.00
Relative humidity at 9 am (%)	68.7	134.79	45.35	63.98	68.82	73.83	85.66
High tide (cm)	266.94	118.07	122.40	187.00	204.06	96.08	511.43
Low tide (cm)	55.08	38.49	-10.00	23.13	44.49	360.55	157.83
<i>BFV incidence by Season</i>							
Summer	6.11	9.38	0.00	0.92	2.72	7.10	55.65
Autumn	8.22	13.14	0.00	1.61	3.38	8.61	70.53
Winter	3.54	5.86	0.00	0.16	1.53	3.86	37.10
Spring	4.88	9.92	0.00	0.71	1.82	4.79	92.71

Table 2: Spearman rank correlation coefficients between BFV incidence and climate variables at various lags and at a moving average of lags 1-2 months during the period 1992- 2001 for Queensland coastal cities (n=720)

Variable	Current month		Moving average	
	r_s	p	r_s	p
Maximum temperature ($^{\circ}\text{C}$)	0.16	0.000	0.22	0.000
Minimum temperature ($^{\circ}\text{C}$)	0.17	0.000	0.24	0.000
Rainfall (cm)	0.03	0.304	0.09	0.009
Relative humidity at 9 am (%)	0.15	0.000	0.14	0.000
High tide (cm)	0.32	0.000	0.31	0.000
Low tide (cm)	0.29	0.000	0.25	0.000
SEIFA	-0.38	0.000	-	-

r_s = Spearman rank correlation; p = significance level.

Table 3: Spearman rank correlation coefficients between predictor variables with a moving average of 1 & 2 months of lag for Queensland coastal cities during the period 1992 – 2001 (n=720)

Variables	MaxT	Rh	Rainfall	High tide	Low tide
MinT	0.93*	0.26*	0.60*	-0.03	0.03
MaxT		0.02*	0.44*	-0.17*	-0.12*
Rh			0.49*	0.23*	0.21*
Rainfall				0.02	0.08*
High tide					0.82*

MaxT = Maximum temperature; MinT = Minimum temperature; Rh = Relative humidity; * Significant at the 0.01 level

Table 4: Correlation coefficients between anomalies of BFV incidence rates and climate variables based on 1992-2001 monthly data of six Queensland coastal cities

	MaxT		MinT		Rainfall		Rh9am		Low tide		High tide	
	r_s	P	r_s	P	r_s	P	r_s	P	r_s	P	r_s	P
Brisbane	0.163	0.076	0.172	0.060	0.104	0.258	0.229*	0.012	0.201*	0.028	0.263*	0.004
Bundaberg	0.169	0.065	0.130	0.158	-0.052	0.569	-0.140	0.126	0.123	0.181	0.260*	0.004
Cairns	0.089	0.335	0.157	0.087	0.166	0.070	0.133	0.148	0.300*	0.001	0.403*	0.000
Gladstone	0.333*	0.000	0.353*	0.000	-0.120	0.215	0.214*	0.019	0.074	0.423	0.087	0.346
Mackay	0.077	0.402	0.113	0.218	0.194*	0.034	0.090	0.330	0.239*	0.009	0.124	0.179
Townsville	0.154	0.094	0.145	0.113	0.110	0.231	0.125	0.174	0.289*	0.001	0.290*	0.001
<i>All cities</i>	<i>0.159*</i>	<i>0.000</i>	<i>0.173*</i>	<i>0.000</i>	<i>0.040</i>	<i>0.287</i>	<i>0.108*</i>	<i>0.004</i>	<i>0.177*</i>	<i>0.000</i>	<i>0.182*</i>	<i>0.000</i>

r_s = Spearman rank correlation; p = significance level.

Table 5: Negative binomial regression model of climate variables on the BFV counts
in Queensland coastal cities (n=720)

Variables	β	SE	Wald χ^2	95% C.I.	p-value
Maximum temperature	0.139	0.023	36.056	0.093 to 0.184	0.000
High tide	0.005	0.000	153.596	0.005 to 0.006	0.000
SEIFA	-0.010	0.001	104.648	-0.012 to -0.008	0.000
AIC = 3532.97, Pearson χ^2 value = 1.05, Deviance = 0.95 and Omnibus likelihood ratio = 444.3					

Figure legends

Figure 1: Location of the coastal study areas in Queensland, Australia

Figure 2: Annual BFV cases, mean maximum temperature and high tide for coastal Queensland cities.

Figure 3: Monthly occurrences of BFV cases for six coastal cities during 1992 – 2001.

Figure 4: Scatter diagrams of the anomalies of BFV incidence and climate variables for the study areas: a) Brisbane, b) Bundaberg, c) Cairns, d) Gladstone, e)Mackay, f)Townsville and g) all cities (only significant results are shown here)

Figures

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a) Brisbane

b) Bundaberg

c) Cairns

d) Gladstone

e) Mackay

f) Townsville

g) Six coastal cities