J Vector Borne Dis 59, June 2022, pp. 115–126

Spatio-temporal distribution of vector borne diseases in Australia and Papua New Guinea vis-à-vis climatic factors

Yuriy Kuleshov[1–3], Yufei Wei[4], Kasis Inape[5] & Gang-Jun Liu[2]

[1]Bureau of Meteorology, Melbourne, Victoria 3008, Australia; [2]School of Science, The STEM College, Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Victoria 3000, Australia; [3]School of Mathematics and Statistics, The University of Melbourne, Melbourne, Victoria 3001, Australia; [4]Maison des Sciences Humaines, University of Luxembourg, L-4366 Esch-sur-Alzette, Luxembourg; [5]Papua New Guinea National Weather Service, Port Moresby, Papua New Guinea

ABSTRACT

Background & objectives: Weather and climate are directly linked to human health including the distribution and occurrence of vector-borne diseases which are of significant concern for public health.

Methods: In this review, studies on spatiotemporal distribution of dengue, Barmah Forest Virus (BFV) and Ross River Virus (RRV) in Australia and malaria in Papua New Guinea (PNG) under the influence of climate change and/or human society conducted in the past two decades were analysed and summarised. Environmental factors such as temperature, rainfall, relative humidity and tides were the main contributors from climate.

Results: The Socio-Economic Indexes for Areas (SEIFA) index (a product from the Australian Bureau of Statistics that ranks areas in Australia according to relative socio-economic advantage and disadvantage) was important in evaluating contribution from human society.

Interpretation & conclusion: For future studies, more emphasis on evaluation of impact of the El Niño-Southern Oscillation (ENSO) and human society on spatio-temporal distribution of vector borne diseases is recommended to highlight importance of the environmental factors in spreading mosquito-borne diseases in Australia and PNG.

Key words Vector-Borne Diseases; Climate Change; Socioeconomic Factors; Dengue; Barmah Forest Virus; Ross River Virus; Malaria

INTRODUCTION

Vector-borne diseases are of significant concern for society and the economy: they account for more than 17% of all infectious diseases, and more than 700,000 people die annually from vector-borne diseases, including malaria and dengue[1]. Vector-borne diseases are sensitive to weather and climate conditions. As climate is rapidly changing on a global scale, manifesting in continuing temperature increase, changes in rainfall patterns, and increase in frequency and severity of extreme weather and climate events, this leads to changes in geographical distribution of vector-borne diseases. In addition to climatic factors, human society factors are equally important in affecting spread of vector-borne diseases. It should be noted that resistance to insecticides also is a problem for increasing the vector-borne diseases. In this review, studies of mosquito-borne diseases in Australia and Papua New Guinea (PNG) under the influence of climate change and human society were analysed providing recommendations for future implementation of Climate Risk and Early Warning Systems (CREWS) activities in the health sector.

Developing countries, least developed countries (LDCs) and small island developing states (SIDS) are particularly vulnerable to impact of climate change and climate extremes, and at the same time, vector-borne diseases are more common and widespread in these countries compared with developed countries. Recognising the urgency of enhancing early warning systems to assist vulnerable countries with climate change adaptation, CREWS international initiative was established in 2015. Key priorities for CREWS are aligned with the priority areas of the Global Framework for Climate Services: agriculture and food security; disaster risk reduction; energy; health; and water. Weather and climate are directly linked to human health including the distribution and occurrence of various diseases; climate variability affects the environment favourable for proliferation of communicable vector-borne diseases. As such, the role of climate services in developing reliable health and climate-related tools for various time scales - from weeks to months to seasons and longer - in order to support public health is paramount. In this way, climate services will support health priorities such as improving disease surveillance and extending the lead-time to prevent and prepare for climate related disease outbreaks.

In particular, CREWS in PNG develops improved monitoring and sub-seasonal to seasonal prediction of rainfall that can foster better decision-making for agriculture, health, water management and other climate-sensitive sectors aiming to create end-to-end early warning systems. As the abundance of mosquitoes is correlated with rainfall, CREWS climate monitoring and prediction products, including rainfall products, could be valuable for assessment of malaria risk. On the other hand, to create effective early warning systems, knowledge about the spatiotemporal patterns of mosquito-borne diseases are essential, together with the understanding of the combined impacts of climate change and human society on the distribution of vectors. In this review, we focused on analysing studies of vector-borne diseases prevalent in two neighbouring countries in the Asia-Pacific region-Australia and PNG.

Mosquito-borne diseases in Australia and Papua New Guinea (PNG)

Mosquito-borne diseases are continuous concerns in Australia[2], especially in the tropical regions[3–4]. As one of the most common arboviral human diseases in tropical and subtropical regions[5–6], dengue fever has spread in Australia mainly by *Aedes aegypti* (Diptera: Culicidae)[7] carrying one of at least four serotypes of dengue virus[8–9] since 1879[10]. While dengue is not an endemic disease in Australia because travellers from overseas bring most of the cases[11], the real number of cases is usually underestimated[10]. Additionally, local mosquitoes become vectors of dengue fever biting overseas travellers infected with the virus[12]. Continual annual dengue outbreaks in Queensland in 1990–2014 were originally from infected overseas travellers[13].

Ross River Fever is the most common arboviral human disease in Australia[14] caused by Ross River virus (RRV). More than 40 species of mosquito are the potential vectors of RRV[15]. Although RRV disease is a non-fatal human disease, it has significant impact on the Australian society with annual health care cost estimated at US$4.1–US$4.7 million[16–23]. More efforts should be put into monitoring and predicting RRV disease since the number of reported RRV cases can be very high in some years, e.g., 9544 in 2015 and 6928 in 2016[24]. Barmah Forest virus (BFV) disease is the second most prevalent arboviral human disease in Australia caused by mosquitoes such as *Aedes vigilax* (Diptera: Culicidae) and *Culex annulirostris* (Diptera: Culicidae) with BFV[25]. No known deaths have been caused by BFV, however, some of the infected population may have symptoms as arthralgia and myalgia up to a year[26–27].

The complicated relationships among the environment, climate change, human society, mosquito-borne diseases and vectors led to the changing spatiotemporal patterns of mosquito-borne diseases in Australia. Due to human mobility and convenient transport[28], dengue fever was prevalent among capital cities and fast-growing cities[29–30], although the maximum travel distance of *Ae. aegypti* was 512m and 77% of the *Ae. aegypti* experimental sample moved no further than one house from indoor[31]. The spatiotemporal distribution of dengue fever and its vectors has changed in accordance with the socioeconomic development in Australia. In the past, the geographical distribution of dengue vectors expanded to the coastal cities of New South Wales and Queensland by roads, railways and coastal steamers[32]. However, the usage of piped-water networks rather than household rainwater tanks, introduction of fridges to replace water-cooled 'Coolgardie' safe, and transition from steam to diesel locomotives could confine the dissemination of dengue virus and reduce the population quantity of dengue vectors[10].

Traditionally, RRV disease was prevalent in rural areas across Australia[22] because *Culex annulirostris* was the main inland rural vector living in natural reservoirs[21]. Nevertheless, since the 1980s, RRV cases have appeared in Australian metropolitan cities such as Sydney and Melbourne[33–36] due to the expansion of housing[37] and exposure to infected mammals[21] during urbanization. Human intervention in wetlands and irrigation practices also led to an increasing trend of BFV cases around Australia in recent years[2, 38–39]. Some studies considering socioeconomic influence on the risk of mosquito-borne diseases utilised Socio-Economic Indexes for Areas (SEIFA) - a product from the Australian Bureau of Statistics that ranks areas in Australia according to relative socio-economic advantage and disadvantage[40].

Meanwhile, the risk of mosquito-borne diseases was influenced by survival and propagation of both the viruses and the vectors, which in turn are affected by climatic factors[41]. For example, increased air temperature extended altitudinal and latitudinal range of mosquitoes[42]. Tropical climate pattern facilitated the silent transmission of dengue virus after detectable epidemic happened years ago[43–44]. Studies suggested that dengue fever existed in places with at least 16°C annual mean temperature[45], which conformed to the well-known facts of dengue virus[46–47]. Increased rainfall (mean monthly rainfall of about 400 mm during wet season months of January, February and March) was associated with the increase of *Ae. aegypti* population, but excessive rainfall was associated with decreased population of *Ae. aegypti* due to the flushing of breeding sites[48]. Additionally, state of the El Niño-Southern Oscillation (ENSO) has become a popular predictor for forecasting the influence of climate on occurrences of vector-borne diseases[49–50]. ENSO is a significant contributor to climate variability on a global scale and one of the most important drivers of annual climate variability in Australia[51]. The ENSO manifests in the periodic changes in sea surface temperatures, atmospheric pressure, sea level and patterns of precipitation in most regions of the equatorial Pacific Ocean. Warm phase of the ENSO known as El Niño is characterised by above average sea surface temperatures in the equatorial central Pacific; on the other hand, the ENSO's cold phase - La Niña, brings cooler than average waters to this region. However, the geographical distribution of mosquito-borne diseases in Australia is difficult to forecast using the ENSO state as a sole independent predictor due to the complex interaction between the environment and human society. The relative importance of climatic, environmental and socioeconomic drivers in assessing mosquito-borne diseases such as dengue remained a topic of continuous research[52–54].

In PNG, the major malaria transmission vectors are members of the *An. punctulatus* group[55–58]. Malaria transmission varies across environmentally diverse zones of PNG, ranging from intense perennial transmission in the northern coastal lowlands to seasonal moderate transmission in the southern coast and unstable transmission at higher altitudes[59]. With increasing altitude, malaria transmission decreases significantly, becoming unstable at an altitude of 1300–1600m (i.e., changes in incidences are large and uneven, and the occurrence of outbreaks/epidemics is relatively common) whilst intense transmission is normally limited to local epidemics which tend to follow the rainy season (November–March). Above 1700m, the temperature becomes too cold inhibiting malaria transmission. Furthermore, Mueller *et al*.[60–61] also showed that substantial heterogeneities exist across broad environmental gradients and within villages short distances apart. This variation may be due to the topography of the highlands region as they contain step gradients and deep inter-montane valley bottoms[62] and basin-like depressions than in the hills, therefore become major breeding sites for malaria transmission.

Malaria incidence in PNG has decreased dramatically in recent years due to consistent preventive efforts including widespread distribution of bednets[58, 63] and improvements in diagnosis and treatment of malaria[64]. Prevalence in the general population for *Plasmodium spp.* decreased from 14% in 2009 to below 7% in 2011[65]. Since 2004, the incidence of malaria in PNG dropped from 400 cases per 100,000 population to 200. The incidence of malaria admissions to public health facilities dropped by 83% and malaria death rates in health facilities fell by 76% between 2009 and 2015. However, malaria risk is still present throughout the country at the altitude of below 1800 meters, including urban areas.

Similar to its influence on Australian climate, the ENSO is one of the key drivers of interannual climate variability in PNG. During El Niño events, cooler than average ocean waters and shift in atmospheric circulation/convection towards the central equatorial and eastern Pacific often results in severe rainfall deficit leading to drought conditions across the country. On the other hand, during La Niña events opposite changes in oceanic and atmospheric conditions occur (i.e., warmer than average ocean waters and enhanced convection over the Maritime continent) which typically results in extreme precipitation over PNG often leading to flooding. These climate extremes take a severe toll on PNG people and the economy, and to some extent have an impact on malaria incidence.

The first aim of this review is to compare and assess previous studies of evaluating and predicting the spatiotemporal distribution of mosquito-borne diseases (i.e., dengue fever, RRV and BFV diseases in Australia and malaria in PNG) under the influence of climate change and human society from the perspective of location, risk factors, statistical methods, and outcomes. The second aim of this review is to provide recommendations for further research directions and in this way to produce research outcomes that are useful for assisting government officials to control and prevent mosquito-borne diseases in Australia and PNG, and in this way assist CREWS with implementation of its activities to enhance early warning systems for the health sector.

RESULTS

A comprehensive literature search was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Search engine (Bing academic) and major academic database and indices including Academic Search Complete, Complementary Index, JSTOR Journals, MEDLINE, Science Citation Index, ScienceDirect, Scopus and Supplemental Index were used to select studies on the spatiotemporal distribution studies of vector borne diseases. The following terms were used during the literature search process: Australia, Barmah Forest Virus, climate anomalies, climate change, climate model, climate variability, dengue, dengue fever, ENSO, El Niño, land cover change, land use change, malaria, modelling, PNG, population density, regression analysis, risk factors, Ross River Virus, socioeconomic drivers, spatiotemporal models, water storage practice. Only articles that were published in the past two decades were considered. The selected research papers included 11 dengue studies, 10 BFV studies and 23 RRV studies including 13 papers on influence of human society. Among them, 2 papers were focused on the spatiotemporal studies of both BFV and RRV[66–67] and 1 study on the evaluation of geographical distribution of dengue, BFV and RRV in Australia[68]. Regarding the study area, of the 40 studies, 25 studies were focused on Queensland, 4 studies on Western Australia, 2 studies on the Northern Territory, 2 studies on South Australia, 1 study on Victoria and 1 study on New South Wales. Two studies examined occurrences of vector-borne diseases in contiguous areas of the New South Wales, Victoria and South Australia and 1 study in four epidemic-prone cities across Australia. Only 2 studies were focused on the spatiotemporal distribution of mosquito-borne diseases in all the Australian states[68–69]. Twenty-one papers on malaria in PNG have also been reviewed.

The spatiotemporal distribution of mosquito-borne diseases in Australia was influenced by various risk factors led by climate change and human society. Rainfall and temperature were the top most common risk factors in dengue, BFV and RRV studies. Tides were the second and the third most common risk factor in the studies of BFV and RRV respectively. Relative humidity was the second common factor in dengue and RRV studies only, and SEIFA index, a socioeconomic risk factor, was at the third place in BFV studies. Among the studies of three mosquito-borne diseases, RRV studies had the most diverse risk factors from residents' feedback[70] and living habits[71] to soil salinity[72] and sea surface temperature[73–74]. However, only 2 studies were focused on only socioeconomic factors[69–71]. As a result, the impact of human society on dengue, BFV and RRV was not fully investigated.

Various statistical methods were used in the studies of the spatiotemporal distribution of mosquito-borne diseases in Australia. Poisson regression and the AutoRegressive Integrated Moving Average (ARIMA) model with its variation with an additional seasonal effect - Seasonal AutoRegressive Integrated Moving Average (SARIMA) models, appeared most in the time-series analyses, to forecast the relationship between weather, sea levels and outbreaks[68, 75–83]. Negative binomial regression and logistic regression models involved inclusive independent variables[67, 72–73, 84–89] from river flow and vegetation cover, to ethnic groups and population density[84–89]. Most of linear regression and Bayesian Conditional Auto Regressive (CAR) models concentrated on the impacts of SEIFA and cases brought from overseas combined with influence from local temperature and rainfall conditions, on the spatiotemporal distribution of mosquito-borne diseases[69, 90–92]. Spatial analyses were performed in GIS software such as ArcGIS, QGIS and SaTScan to find the potential incidence of diseases and mosquito biting around wetlands, introduced cases, and residents' complaints[25, 37, 70, 93]. The degree of spatial autocorrelation of mosquito-borne diseases was calculated by classic Moran's I statistic[67, 92, 94–96] and spatial regression models[92] in some studies. There were 2 studies that used graphical models[97–98] and models for epidemiology[71, 99] respectively as well.

Major findings from dengue studies revealed that dengue cases brought from overseas and human movements affected the spatiotemporal distribution of autochthonous dengue cases[69, 88, 91, 97–100]. From December to February in the following year, overseas-acquired dengue virus was carried by Australian overseas travellers from Southeast Asia, Africa and the Americas to northern, western and eastern coastal Queensland cities, and was influenced by rainfall and SEIFA index[69, 91]. This imported dengue virus caused the highest dengue incidence ratio in the 20-49 years-old group, between January and April[88] and determined the continuation and the size of subsequent autochthonous dengue cases[99]. However, local dengue outbreaks and transmissions could be triggered in wet seasons and the periods with increased rainfall, temperature, and relative humidity only[91, 97, 99–100]. Other environmental factors, such as the Southern Oscillation Index (SOI) and wind directions were predictors of magnitude and direction of dengue outbreaks as well[82, 93]. However, studies showed that short extrinsic incubation period of dengue virus instead of warm weather and human movements led to the large dengue outbreak between 2008 and 2009 in Queensland[101]. In addition, studies indicated that prompt, intense vector control actions were effective in decreasing future mosquito population and dengue risks[93, 101].

As an Australian mosquito-borne endemic, none of the BFV studies contained international tourism and human movements as risk factors in the examined literature. SEIFA index was the only socioeconomic factor that positively associated with BFV outbreaks[85, 87, 92]. Temperature, rainfall, tides and relative humidity were significantly associated with BFV outbreaks with a lag of 0-5 months[66, 79, 85, 92]. Other environmental factors such as wetlands and climate zones were also significant contributors of BFV cases[25]. In addition, the SOI index could predict BFV outbreaks 3 months in advance. By monitoring monthly abundance of mosquito, BFV endemic could be forecasted before 0-4 months, depending on mosquito species[66]. Studies showed that the highest BFV incidence often appeared from January to May[68, 85, 96] and occurred mainly in central Queensland, inland and northern Queensland coastal cities[96]. However, most of BFV studies were focused on Queensland as the study area; no reports incorporated human intervention as risk factors.

The annual temporal patterns of RRV outbreaks were similar to the one of BFV cases, although RRV was a more powerful infectious disease than BFV[67–68]. Temperature, rainfall, tides, and relative humidity were significantly associated with future RRV cases[66–68, 73–78, 80–83, 86, 89–90, 102–104], however, the relative impact of these factors varied in different cities[103], catchment areas[104], and spatial scales[76], and were differed between coastal and inland regions as well[77]. Aside from the SOI index[81, 84], more oceanic and atmospheric factors that related to the ENSO state such as sea surface temperature[73] and vapour pressure[89] linked to the increased amount of RRV cases. In addition, Normalised Difference Vegetation Index (NDVI) was a predictor for RRV outbreaks at a lag of up to 24 months[74]. Nevertheless, studies showed that salinity and water logging in soil[72], and SEIFA index[90] were not associated with RRV cases because of the inappropriate selection of spatial scale, short study period[90] and insufficient density of RRV cases[72]. RRV studies that included the impact from human society suggested that lower-education population, labour workers and indigenous population had highest RRV risks comparing with other groups[84]. Ensuring residents live at least 1 km away from mosquito breeding sites and reducing camping will control the RRV risk to the lowest level, although mosquito-repelling tools and light-colored clothing decreased the risk by 3-fold at most[37, 71]. Complaints from residents living in high RRV risks areas were also used to assess spatial clustering patterns of RRV diseases and mosquitos' population[70].

Numerous studies on malaria in PNG demonstrate progress in combating this mosquito-borne disease in recent years[59, 105–109]. However, PNG's mountainous terrain and poor transport infrastructure creates challenges in assessing risk of and providing treatment for malaria, particularly in remote communities. While the malaria situation in the coastal lowlands has been studied in detail, the current malaria situation in the highland communities has not been studied in depth since the 1960s. Recently, an assessment of the epidemiology of malaria in the PNG highlands has been conducted[60–61, 110–114]. As a result of these comprehensive studies, importance of local factors in risk of malaria in highlands was emphasised.

Survey conducted in 24 villages in Western Highlands Province of PNG (Fig. 1) demonstrated strong correlation of malaria with altitude, ranging from 1.6% at altitudes of 1500–1800 m to over 30% in villages below 900 m; malaria outbreaks were observed at the end of the rainy season[60]. In Eastern Highlands Province of PNG the epidemiology of malaria was characterised by generally very low-level or no local malaria transmission but a considerable risk of epidemics[61].

Within Simbu Province of PNG, two very distinct malaria zones were found[111]. The north of the province was characterised by the absence or very low level of local malaria transmission, but there was a considerable risk of epidemics prevalent in the lower-lying parts. On the other hand, in south Simbu Province malaria was clearly endemic with an overall prevalence of 35%, combined with a strong age-dependence of infections i.e., the malaria epidemiology in south Simbu was more similar to the lowlands than to other highlands areas[111]. The authors concluded that epidemic prevention, surveillance and response in the north, and bednet distribution and strengthening of curative services in the south, should be the priorities for malaria control in Simbu Province.

Of all Papua New Guinea provinces, Enga has the largest proportion of people living at altitudes that preclude malaria transmission. A series of surveys conducted in both wet and dry seasons showed that lower-lying valleys to the north and east of the province were the main areas in Enga with high risk of malarial infection[112]. However, over the last decades the risk of malarial infection has increased substantially in areas < 1200 m (from 10% to 37–41%) while in areas above 1200 m overall prevalence rates (0–9%) have not changed[112]. Sleeping under a bednet was associated with a significant reduction in risk of malaria infection. It was concluded that malaria control in malarious areas of Enga province could therefore be based on the distribution of bednets in combination with health education of population[112].

A series of malaria surveys in Morobe province which encompasses large highlands areas of Aseki, Menyamya and Wau-Bulolo conducted in both the wet and dry seasons found malaria to be clearly endemic in areas below 1400 m in Menyamya and Wau-Bulolo, with overall prevalence rates in the wet season (25.5%) greatly exceeding those in the dry season (8.3%); a low prevalence of malaria was found in the Aseki area[113]. As a result of this survey, it was recommended that all villages below 1500-1600 m in Morobe Province should be included in malaria control activities.

Madang, predominantly a lowland province, also includes highland areas such as Simbai and Bundi. A series of recent surveys found that the malaria situation has changed little since the 1960s in both Simbai and Bundi. In the Simbai area there was little malaria transmission in villages above 1400 m, with prevalence rates of 2.5–4.2%, and moderate to high transmission (8.6–24.7%) - below 1400 m; prevalence rates of malaria infection were low in all Bundi villages (2.5–8.5%)[114]. In 2003-2005, a

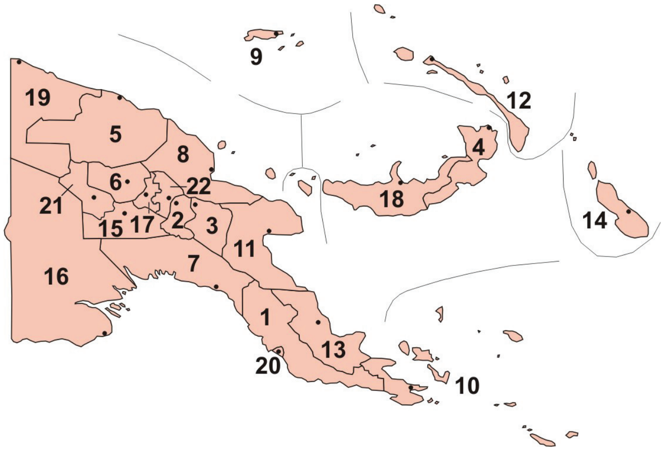

Fig. 1: Province-level division of PNG: 1. Central; 2 Chimbu (Simbu); 3 Eastern Highlands, 4 East New Britain; 5 East Sepik; 6 Enga; 7 Gulf; 8 Madang; 9 Manus; 10 Milne Bay; 11 Morobe; 12 New Ireland; 13 Northern (Oro Province); 14 Bougainville (autonomous region); 15 Southern Highlands; 16 Western Province (Fly); 17 Western Highlands; 18 West New Britain; 19 West Sepik (Sandaun); 20 National Capital District (Port Moresby); 21 Hela; 22 Jiwaka.

series of rapid malaria surveys was conducted in different parts of Southern Highlands Province. Malaria was found to be highly endemic in Lake Kutubu (prevalence rate 17–33%), moderate to highly endemic in Erave (10–31%) and moderately endemic in low-lying parts (< 1500 m) of Poroma and Kagua (12–17%), but was rare or absent elsewhere[115]. Based on the surveys' results, areas of different malaria epidemiology were delineated and options for malaria control in each area suggested.

PNG is a country with fragmented malaria surveillance because of its large area, complex terrain and difficult accessibility of remote areas; application of modern technology such as Geographical Information Systems (GIS) is of great assistance for public health system. GIS mapping is an important part of spatial epidemiology as it not only provides an efficient and unique method for displaying distributions of phenomena in space but more so in revealing spatial patterns that are quite difficult to detect by a tabular or statistical form. In PNG, very few epidemiological studies have addressed the importance of the spatial dimensions of public health problem such as malaria at the local or national level.

One of the few studies was mapping the prevalence of malaria in rural PNG using a GIS[116]. The application of GIS technology to malaria surveillance presents an opportunity for focusing intervention and prevention activities in the areas most affected. In this study, GIS technology was used to map the prevalence of malaria in the Wosera Health and Demographic Surveillance Site, East Sepik Province of PNG between 2001 and 2003. Malaria, demographic and GIS data were collected, aggregated and analysed; the results suggested that malaria was endemic with high prevalence as observed across the three surveyed years[116]. The dependence of malaria transmission on rainfall and temperature factors is well known and accepted fact due to their significant roles in influencing population dynamics of mosquito vectors. Furthermore, apart from temperature and rainfall, humidity and land use[117] together with hydrology, all affect mosquito population and influence malaria transmission in many ways[118]. Unfortunately, the omission of these important environmental factors in the above studies makes it difficult to critically assess and evaluate the link between malaria transmission and the climatic factors. In recognition of this oversight, Namosha *et al.*[116] has strongly recommended the inclusion, particularly elevation, rainfall, temperature and humidity as major factors influencing the ecology of mosquitoes and the distribution of the disease. This would greatly enhance the quality of such a study. The study demonstrated that optimised implementation of GIS can be highly beneficial in assessment of risk of malaria in PNG.

Recently, strengthening the National Health Information System (NHIS) in PNG has been achieved using mobile technologies and GIS to provide timely, high quality, geo-coded, case-based malaria data required for malaria elimination. Since 2015, 160,750 malaria testing records, including village of residence, have been reported to the NHIS; the system maps malaria to the village level in near real-time as well as the availability of treatment and diagnostics to health facility level[119]. In summary, significant progress has been achieved in assessment, prevention and treatment of malaria in PNG; however, more dedicated efforts are still required to improve control of this dangerous vector-borne disease across the country.

DISCUSSION

The first aim of this review is to compare and assess studies on evaluating and predicting the spatiotemporal distribution of mosquito-borne diseases (i.e., dengue fever, RRV and BFV diseases in Australia and malaria in PNG) under climate change and human society from the perspective of location, risk factors, statistical methods, and outcomes.

The geographical location of study areas of mosquito-borne diseases in Australia was not evenly distributed. More than half of the studies (i.e., 25 of 40) were focused on Queensland as the study area. Meanwhile, only 4 studies were concentrated on New South Wales and Victoria where two largest populated cities (i.e., Sydney and Melbourne) are located. There is a great demand for future detailed BFV studies in New South Wales since there 121 BFV notifications occurred in that state in 2017, which accounted for more than one fourth of total national cases[120].

More oceanic and atmospheric risk factors and indices such as vapour pressure, the SST and the SOI index that related to the ENSO state should be included in the future studies of mosquito-borne diseases in Australia. Although most of the examined studies that considered environmental factors utilised temperature, rainfall and relative humidity as predictors for outbreaks of mosquito-borne diseases, their relative importance varied considerably[76–77, 103–104] and further investigations are required to determine the key factors.

Similarly, impact of the ENSO should be thoroughly investigated. The ENSO is a powerful driver of annual climate variability in Australia, e.g., 90% of driest winter-spring periods were associated with El Niño in eastern Australia[51]. In southern Australia, El Niño contributed to warmer-than-average temperatures in the spring and summer months; the warmer temperatures were further exacerbated by the decreased cloud covers during El Niño events[51]. Warmer temperature may allow mosquitos to survive in winters, to reach maturity faster, and to have RRV with shorter extrinsic incubation periods[121]. Examined studies also confirmed that the outbreak of BFV in the coastal cities of New South Wales in 1994 was a result of large numbers of mosquitoes propelled by above-average rainfall and high tides[96]. The forecast of mosquito-borne diseases influenced by environmental factors could be improved by incorporating ENSO changing patterns[73].

Regarding the risk factors from human society, currently, only SEIFA index was widely used as a socioeconomic index[69, 85, 87, 90–92] but the future SEIFA index was unavailable in mosquito-borne disease studies[87]. Investigating demographic information and daily activities will help to find the most vulnerable groups and the most effective way to prevent mosquito-borne diseases[71, 84].

Although various statistical methods were found in this review, the outcomes of the studies may be highly affected by the combined effects of data, risk factors and statistical methods due to relatively short study period[71, 84, 90–101, 122], limited risk factors [67– 68, 82, 96, 103, 122], and complicated models[101]. It is also necessary to distinguish the primary species of mosquitoes in transmitting RRV and BFV to get an accurate judgment as well[66].

The second aim of this review is to provide recommendations for further research directions and in this way to produce research outcomes that could be useful to assist government officials to control and prevent mosquito-borne diseases in Australia and PNG.

Results of this review for Australia highlights that (i) Queensland is a vulnerable state to mosquito-borne diseases, and (ii) BFV received the least attention among mosquito-borne diseases. It is also necessary to derive spatiotemporal patterns of the diseases in more populated areas and across Australia using both environmental and socioeconomic risk factors. Although temperature, rainfall and relative humidity were common predictors to forecast outbreaks, impact of the ENSO state was underestimated, and socioeconomic factors were not fully investigated. The evolution of the ENSO and Australian climate patterns were monitored and skillfully forecasted by the Australian Bureau of Meteorology providing stakeholders with nationwide seasonal prediction of both the ENSO[123] and associated precipitation in Australia[124]. In 2018, the introduction of a new dynamical climate model with an improved spatial resolution of about 60 km over the Australasian region – the Australian Community Climate Earth-System Simulator (ACCESS)[125] significantly strengthened operational capacity of the Australian Bureau of Meteorology in providing sub-seasonal (multi-week) to seasonal climate forecasts. Consequently, more long-term, nationwide models should be developed to predict spatiotemporal patterns of mosquito-borne diseases incorporating impacts of the ENSO, climate change and human society.

Moreover, remotely sensed data acquired from satellites and aerial photographs can derive the relations between mosquito-borne diseases and earth surface conditions such as land use types[126–127] or assess the key determinants and the spatiotemporal characteristics of mosquito-borne diseases[74, 128–129]. The interaction between human society and mosquito-borne diseases can be gained by field surveys of control measures and land-use change, and interviews among residents and travellers from overseas of personal opinions, living habits, and population mobility. All seasonal climatic patterns and socioeconomic factors should be parameterised into a model and tested by historical notifications of mosquito-borne diseases. The evaluation and prediction results of mosquito-borne diseases can be published online finally to promote public health protection strategies.

Analysis of studies for malaria in PNG indicates complexity of influencing factors on outbreaks of the disease including global climate impact and local conditions. Historically, malaria in PNG was considered as a major health problem for populations in most coastal, lowland and foothill areas[130–131]; malaria at higher elevations above 1500 m was considered intermittent[115]. However, global climate change results in warmer temperatures e.g. the 20 warmest years on record have been in the past 22 years, with the top four in the past four years, according to the

World Meteorological Organization[132].

Rapidly changing climate creates the environment in PNG highlands which could be favourable for breeding malaria-transmitting vectors. In one such study, it was notable that the increasing trend of malaria incidence was prominent in the highlands region of PNG with corresponding increases in rainfall and temperature[133]. This in turn could lead to malaria outbreaks due to the low level of naturally acquired immunity in highland populations. Climate change also manifests in increase in frequency and severity of extremes such as drought and heavy precipitation. Droughts typically affect PNG during El Nino events[134]. Drought conditions usually result in substantial increase of pools of standing water in areas that are normally associated with fast-flowing water permitting rapid increase in population of malaria-transmitting vector. Droughts lead to water and food shortages contributing to increased demographic movement and population's exposure to highrisk malaria endemic lowlands. In addition, malaria outbreaks may be further exacerbated by the population's compromised nutritional status because of severe shortages of staple foods.

Local weather factors could be equally important as the global climate change factors. After examining the association between malaria and local and global climate variability in five regions in PNG, it has been shown that malaria incidence was associated with local weather factors in most regions but at the different lag times and in directions; there were also trends in associations with global climate factors by geographical locations of study sites[135]. All these influencing factors, global and local, as well as *Plasmodium spp*. resistant to antimalarial drug need to be taken into consideration when dealing with prevention of malaria.

CONCLUSION

Through this review, we attempt to provide recommendations for climate research and services community assisting with understanding public health needs and challenges of the health community to interpret and apply available climate information. Studies on spatiotemporal distribution of dengue, BFV and RRV in Australia and malaria in PNG under the influence of climate change and/or human society conducted in the past two decades were analysed and summarised. Environmental factors such as temperature, rainfall, relative humidity and tides were main contributors from climate change, and the SEIFA index was important in evaluating contribution from human society. However, insufficient evaluation of impacts of the ENSO and human society, and short study periods confined conclusions about relative importance of the environmental factors in spreading mosquito-borne diseases in Australia and PNG. It is recommended for future studies to further investigate the spatiotemporal patterns of mosquito-borne diseases, specifically considering the combined impacts from climate change and human society, and include ENSO effects and comprehensive socio-economic factors to build a solid surveillance and forecast system of mosquito-borne diseases in Australia and PNG. This is an important recommendation for future development of CREWS international initiative for improving early warning systems to protect the most vulnerable populations against hydro-meteorological hazards and implementing the initiative's activities to enhance early warning systems for the health sector.

Conflict of interest: None

ACKNOWLEDGEMENTS

Climate Risk and Early Warning Systems (CREWS) international initiative and the World Meteorological Organization (WMO) provided support for this study.

REFERENCES

1 Vector-borne diseases. Geneva: World Health Organization 2020. Available from: *https://www.who.int/en/news-room/fact-sheets/detail/vector-borne-diseases* (Accessed on March 29, 2021).

2 Russell RC. Mosquito-borne disease and climate change in Australia: Time for a reality check. *Austral Entomol* 2009; *48*(1): 1–7.

3 Jacups SP, Whelan PI, Currie BJ. 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* 2008; *8*(2): 283–97.

4 Van Den Hurk AF, Craig SB, Tulsiani SM, Jansen CC. Emerging tropical diseases in Australia. Part 4. Mosquitoborne diseases. *Ann Trop Med Parasit* 2010; *104*(8): 623–40.

5 Hales S, Edwards SJ, Kovats RS. Impacts on health of climate extremes. Geneva: World Health Organization 2003. Available from: *http://www.who.int/globalchange/publications/climatechangechap5.pdf* (Accessed on March 29, 2021).

6 Farrar J, Focks D, Gubler D, Barrera R, Guzman G, Simmons C, *et al*. on behalf of the WHO/TDR Dengue Scientific Working Group. Editorial: Towards a global dengue research agenda. *Trop Med Int Health* 2007; *12*(6): 695–99.

7 Beebe NW, Whelan PI, Van Den Hurk AF, Ritchie SA, Cooper RD. Genetic diversity of the dengue vector Aedes aegypti in Australia and implications for future surveillance and mainland incursion monitoring. *Commun Dis Intell* 2005; *29*(3): 299–304.

8 Normile D. Surprising new dengue virus throws a spanner in disease control efforts. *Science* 2013; *342*(6157): 415.

9 Dwivedi VD, Tripathi IP, Tripathi RC, Bharadwaj S, Mishra SK. Genomics, proteomics and evolution of dengue virus. *Brief*

Funct Genomics 2017; *16*(4): 217–27.

10 Mackenzie JS, La Brooy JT, Hueston L, Cunningham AL. Dengue in Australia. *J Med Microbiol* 1996; *45*(3): 159–61.

11 Increasing notifications of dengue in Australia related to overseas travel, 1991 to 2012. Canberra: Department of Health 2013. Available from: *https://www.health.gov.au/internet/main/publishing.nsf/Content/cda-cdi3701f.htm* (Accessed on March 29, 2021).

12 Dengue fact sheet. Canberra: Department of Health 2016. Available from: *http://www.health.gov.au/internet/main/publishing.nsf/Content/ohp-dengue-fs.htm* (Accessed on March 29, 2021).

13 Gyawali N, Bradbury RS, Taylor-Robinson AW. Knowledge, attitude and recommendations for practice regarding dengue among the resident population of Queensland, Australia. *Asian Pac J Trop Biomed* 2016; *6*(4): 360–66.

14 Horwood CM, Bi P. The incidence of Ross River virus disease in South Australia, 1992 to 2003. Canberra: Department of Health 2005. Available from: *http://www.health.gov.au/internet/main/publishing.nsf/Content/cda-cdi2903i.htm* (Accessed on March 29, 2021).

15 Claflin SB, Webb CE. Ross River virus: Many vectors and unusual hosts make for an unpredictable pathogen. *Plos Pathog* 2015; *11*(9): e1005070.

16 Mackenzie JS, Smith DW. Mosquito-borne viruses and epidemic polyarthritis. *Med J Aust* 1996; *164*(2): 90–3.

17 Selden SM, Cameron AS. Changing epidemiology of Ross River virus disease in South Australia. *Med J Aust* 1996; *165*(6): 313–17.

18 Russell RC. Mosquito-borne arboviruses in Australia: The current scene and implications of climate change for human health. *Int J Parasitol* 1998; *28*(6): 955–69.

19 Tong S, Bi P, Parton K, Hobbs J, McMichael AJ. Climate variability and transmission of epidemic polyarthritis. *Lancet* 1998; *351*(9109): 1100.

20 Mackenzie JS. Emerging viral diseases: An Australian perspective. *Emerg Infect Dis* 1999; *5*(1): 1–8.

21 Harley D, Sleigh A, Ritchie S. Ross River virus transmission, infection, and disease: A cross-disciplinary review. *Clin Microbiol Rev* 2001; *14*(4): 909–32.

22 Russell RC. Ross River virus: Ecology and distribution. *Annu Rev Entomol* 2002; *47*: 1–31.

23 Woodruff R, Bambrick H. Climate change impacts on the burden of Ross River virus disease. *Garnaut Climate Change Review* 2008; *115*: 1–15.

24 Number of notifications of Ross River virus infection, Australia, in the period of 1991 to 2020 and year-to-date notifications for 2021. Canberra: Department of Health 2021. *Available from: http://www9.health.gov.au/cda/source/cda-index.cfm* (Accessed on March 29, 2021).

25 Naish S, Mengersen K, Hu W, Tong S. Wetlands, climate zones and Barmah Forest virus disease in Queensland, Australia. *T Roy Soc Trop Med H* 2012; *106*(12): 749–55.

26 Kostyuchenko VA, Jakana J, Liu X, Haddow AD, Aung M, Weaver SC, *et al*. The structure of Barmah Forest virus as revealed by cryo-electron microscopy at a 6-angstrom resolution has detailed transmembrane protein architecture and interactions. *J Virol* 2011; *85*(18): 9327–33.

27 Barmah Forest virus control guideline. New South Wales: Ministry of Health 2016. Available from: *http://www.health.nsw.gov.au/Infectious/controlguideline/Pages/barmah-forest.aspx* (Accessed on March 29, 2021).

28 Mutheneni SR, Mopuri R, Naish S, Gunti D, Upadhyayula SM. Spatial distribution and cluster analysis of dengue using self-organizing maps in Andhra Pradesh, India, 2011- 2013. *Parasite Epidemiol Control* 2018; *3*(1): 52–61.

29 Banu S, Hu W, Hurst C, Guo Y, Islam MZ, Tong S. Space-time clusters of dengue fever in Bangladesh. *Trop Med Int Health* 2012; *17*(9): 1086–91.

30 Liu C, Liu Q, Lin H, Xin B, Nie J. Spatial analysis of dengue fever in Guangdong Province, China, 2001-2006. *Asia-Pac J Public Health* 2014; *26*(1): 58–66.

31 Harrington LC, Scott TW, Lerdthusnee K, Coleman RC, Costero A, Clark GG, *et al*. Dispersal of the dengue vector Aedes aegypti within and between rural communities. *Am J Trop Med Hyg* 2005; *72*(2): 209–20.

32 Russell RC, Lee DJ, Stanislas Y. Aedes aegypti (L.) (Diptera: Culicidae) in New South Wales. *Gen Appl Ent* 1984; *16*: 9–16.

33 Amin J, Hueston L, Dwyer DE, Capon A. Ross River virus infections in the north-west outskirts of the Sydney Basin. *Commun Dis Intell* 1998; *22*(6): 101–2.

34 Russell RC. Vectors vs. humans in Australia--Who is on top down under? An update on vector-borne disease and research on vectors in Australia. *J Vector Ecol* 1998; *23*(1): 1– 46.

35 Brokenshire T, Symonds D, Reynolds R, Doggett S, Geary M, Russell R. A cluster of locally-acquired Ross river virus infection in outer western Sydney. *NSW Public Health Bulletin* 2000; *11*(7): 132–34.

36 Ross River virus disease in Australia. Atlanta: Centres for Disease Control and Prevention 2017. Available from: *https://wwwnc.cdc.gov/travel/notices/watch/ross-river-virus-disease-australia* (Accessed on April 11, 2017).

37 Jardine A, Neville PJ, Lindsay MD. Proximity to mosquito breeding habitat and Ross River virus risk in the Peel region of Western Australia. *Vector Borne Zoonotic Dis* 2015; *15*(2): 141–6.

38 Gould EA, Higgs S. Impact of climate change and other factors on emerging arbovirus diseases. *T Roy Soc Trop Med H* 2009; *103*(2): 109–21.

39 Lafferty KD. The ecology of climate change and infectious diseases. *Ecology* 2009; *90*(4): 888–900.

40 Pink B. Technical paper - Socio-economic indexes for areas (SEIFA) 2011. Canberra: Bureau of Statistics 2013. Available from: *https://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/22CEDA8038AF7A0DCA257B3B00116E34/$File/2033.0.55.001%20seifa%202011%20technical%20paper.pdf* (Accessed on March 30, 2021).

41 Wang X, Wang L, Ma J. The applications and developments of remote sensing and geographical information system technology in malaria research. *Zhonghua Liu Xing Bing Xue Za Zhi* 2009; *30*(4): 410–2.

42 Elliott M, Winslow M, Hoerner A. African Americans and climate change: An unequal burden. Washington DC: Congressional Black Caucus Foundation 2004. Available from: *http://rprogress.org/publications/2004/CBCF_REPORT_F.pdf* (Accessed on March 30, 2021).

43 Kuno G. Review of factors modulating dengue transmission. *Epidemiol Rev* 1995; *17*(2): 321–35.

44 Teixeira MD, Barreto ML, Costa MD, Ferreira LD, Vasconcelos PF, Cairncross S. Dynamics of dengue virus circulation: A silent epidemic in a complex urban area. *Trop Med Int Health* 2002; *7*(9): 757–62.

45 Machado-Machado EA. Empirical mapping of suitability to dengue fever in Mexico using species distribution modeling. *Appl Geogr* 2012; *33*: 82–93.

46 Koopman JS, Prevots DR, Vaca Marin MA, Gomez Dantes H, Zarate Aquino ML, Longini Jr IM, et al. Determinants and predictors of dengue infection in Mexico. *Am J Epidemiol* 1991; *133*(11): 1168–78.

47 Halstead SB. Dengue virus-mosquito interactions. *Annu Rev Entomol* 2008; *53*: 273–91.

48 Duncombe J, Clements A, Davis J, Hu W, Weinstein P, Ritchie S. Spatiotemporal patterns of Aedes aegypti populations in Cairns, Australia: Assessing drivers of dengue transmission. *Trop Med Int Health* 2013; *18*(7): 839–49.

49 Nicholls N. A method for predicting Murray Valley encephalitis in southeast Australia using the Southern Oscillation. *Immunol Cell Biol* 1986; *64*(Pt 6): 587–94.

50 Kovats RS, Bouma MJ, Hajat S, Worrall E, Haines A. El Niño and health. *Lancet* 2003; *362*(9394): 1481–9.

51 What is El Niño and what might it mean for Australia? Melbourne: Bureau of Meteorology 2014. Available from: *http://www.bom.gov.au/climate/updates/articles/a008-el-nino-and-australia.shtml* (Accessed on March 30, 2021).

52 Reiter P. Climate change and mosquito-borne disease. *Environ Health Persp* 2001; *109*(suppl 1): 141–61.

53 Erickson RA, Presley SM, Allen LJS, Long KR, Cox SB. A dengue model with a dynamic Aedes albopictus vector population. *Ecol Model* 2010; *221*(24): 2899–908.

54 Erickson RA, Hayhoe K, Presley SM, Allen LJS, Long KR, Cox SB. Potential impacts of climate change on the ecology of dengue and its mosquito vector the Asian tiger mosquito (Aedes albopictus). *Environ Res Lett* 2012; *7*: 034003.

55 Cooper RD, Waterson DG, Kupo M, Foley DH, Beebe NW, Sweeney AW. Anopheline mosquitoes of the western province of Papua New Guinea. *J Am Mosq Control Assoc* 1997; *13*(1): 5–12.

56 Ebsworth P, Bryan JH, Foley DH. Ecological distribution of mosquito larvae of the Anopheles punctulatus group on Niolam (Lihir) Island, Papua New Guinea. *J Am Mosq Control Assoc* 2001; *17*(3): 181–5.

57 Beebe NW, Cooper RD. Distribution and evolution of the Anopheles punctulatus group (Diptera: Culicidae) in Australia and Papua New Guinea. *Int J Parasitol* 2002; *32*(5): 563–74.

58 Reimer LJ, Thomsen EK, Koimbu G, Keven JB, Mueller I, Siba PM, *et al*. Malaria transmission dynamics surrounding the first nationwide long-lasting insecticidal net distribution in Papua New Guinea. *Malaria J* 2016; *15*: 25.

59 Müller I, Bockarie M, Alpers M, Smith T. The epidemiology of malaria in Papua New Guinea. *Trends Parasitol* 2003; *19*(6): 253–9.

60 Mueller I, Taime J, Ivivi R, Yala S, Bjorge S, Riley ID, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 1. Western Highlands Province. *PNG Med J* 2003; *46*(1-2): 16–31.

61 Mueller I, Bjorge S, Poigeno G, Kundi J, Tandrapah T, Riley ID, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 2. Eastern Highlands Province. *P N G Med J* 2003; *46*(3-4): 166–79.

62 Minakawa N, Atieli F, Mushinzimana E, Zhou, G, Githeko AK, Yan G. Spatial distribution of anopheline larval habitats in Western Kenyan highlands: Effects of land cover types and topography. *Am J Trop Med Hyg* 2005; *73*(1): 157–65.

63 Bockarie MJ, Tavul L, Kastens W, Michael E, Kazura JW. Impact of untreated bednets on prevalence of Wuchereria bancrofti transmitted by Anopheles farauti in Papua New Guinea. *Med Vet Entomol* 2002; *16*(1): 116–9.

64 Genton B, Anders RF, Alpers, MP, Reeder JC. The malaria vaccine development program in Papua New Guinea. *Trends Parasitol* 2003; *19*(6): 264–70.

65 Betuela I, Maraga S, Hetzel MW, Tandrapah T, Sie A, Yala S, *et al*. Epidemiology of malaria in the Papua New Guinean highlands. *Trop Med Int Health* 2012; *17*(10): 1181–91.

66 Barton PS, Weaver HJ. Mosquito (Diptera: Culicidae) and rainfall associations with arbovirus disease in eastern Victoria. *Trans R Soc S Aust* 2009; *133*(2): 257– 64.

67 Pelecanos AM, Ryan PA, Gatton ML. Spatial-temporal epidemiological analyses of two sympatric, co-endemic alphaviral diseases in Queensland, Australia. *Vector Borne Zoonotic Dis* 2011; *11*(4): 375–82.

68 Stratton MD, Ehrlich HY, Mor SM, Naumova EN. A comparative analysis of three vector-borne diseases across Australia using seasonal and meteorological models. *Sci Rep* 2017; *7*: 40186.

69 Huang X, Yakob L, Devine G, Frentiu FD, Fu SY, Hu W. Dynamic spatiotemporal trends of imported dengue fever in Australia. *Sci Rep* 2016; *6*: 30360.

70 Ryan PA, Alsemgeest DH, Gatton ML, Kay BH. Ross River virus disease clusters and spatial relationship with mosquito biting exposure in Redland Shire, southern Queensland, Australia. *J Med Entomol* 2006; *43*(5): 1042–59.

71 Harley D, Ritchie SA, Bain C, Sleigh AC. Risks for Ross River virus disease in tropical Australia. *Int J Epidemiol* 2004; *34*(3): 548–55.

72 Jardine A, Speldewinde P, Lindsay MD, Cook A, Johansen CA, Weinstein P. Is there an association between dryland salinity and Ross River virus disease in southwestern Australia? *Ecohealth* 2008; *5*: 58–68.

73 Woodruff R, Guest CS, Garner MG, Becker N, Lindesay J, Carvan T, *et al*. Predicting Ross River virus epidemics from regional weather data. *Epidemiology* 2002, *13*(4): 384–93.

74 Ng V, Dear K, Harley D, McMichael A. Analysis and prediction of Ross River virus transmission in New South Wales, Australia. *Vector Borne Zoonotic Dis* 2014; *14*(6): 422–38.

75 Tong S, Hu W. Climate variation and incidence of Ross River virus in Cairns, Australia: A time-series analysis. *Environ Health Persp* 2001; *109*(12): 1271–3.

76 Tong S, Bi P, Donald K, McMichael AJ. Climate variability and Ross River virus transmission. *J Epidemiol Commun H* 2002; *56*: 617–21.

77 Tong S, Hu W. Different responses of Ross River virus to climate variability between coastline and inland cities in Queensland, Australia. *Occup Environ Med* 2002; *59*: 739–44.

78 Tong S, Hu W, McMichael AJ. Climate variability and Ross River virus transmission in Townsville Region, Australia, 1985-1996. *Trop Med Int Health* 2004; *9*(2): 298–304.

79 Naish S, Hu W, Nicholls N, Mackenzie JS, McMichael AJ, Dale P, *et al*. Weather variability, tides, and Barmah Forest virus disease in the Gladstone Region, Australia. *Environ Health Persp* 2005; *114*(5): 678–83.

80 Tong S, Hu W, Nicholls N, Dale P, MacKenzie JS, Patz J, *et al*. Climatic, high tide and vector variables and the transmission of Ross River virus. *Intern Med J* 2005; *35*(11): 677–80.

81 Bi P, Hiller JE, Cameron AS, Zhang Y, Givney RC. Climate variability and Ross River virus infections in Riverland, South Australia, 1992-2004. *Epidemiol Infect* 2009; *137*: 1486–93.

82 Hu W, Clements A, Williams G, Tong S. Dengue fever and El Niño/Southern Oscillation in Queensland, Australia: A time series predictive model. *Occup Environ Med* 2010; *67*: 307–11.

83 Mciver L, Xiao J, Lindsay MD, Rowe T, Yun G. A climate-

based early warning system to predict outbreaks of Ross River virus disease in the Broome Region of Western Australia. *Aust N Z J Public Health* 2010; *34*(1): 89–90.

84 Hu W, Tong S, Mengersen K, Oldenburg B. Exploratory spatial analysis of social and environmental factors associated with the incidence of Ross River virus in Brisbane, Australia. *Am J Trop Med Hyg* 2007; *76*(5): 814–9.

85 Naish S, Hu W, Nicholls N, Mackenzie JS, Dale P, McMichael AJ, *et al*. Socio-environmental predictors of Barmah Forest virus transmission in coastal areas, Queensland, Australia. *Trop Med Int Health* 2009; *14*(2): 247–56.

86 Jacups SP, Whelan PI, Harley D. Arbovirus models to provide practical management tools for mosquito control and disease prevention in the Northern Territory, Australia. *J Med Entomol* 2011; *48*(2): 453–60.

87 Naish S, Mengersen K, Hu W, Tong S. Forecasting the future risk of Barmah Forest virus disease under climate change scenarios in Queensland, Australia. *Plos One* 2013; *8*: e62843.

88 Viennet E, Ritchie SA, Faddy HM, Williams CR, Harley D. Epidemiology of dengue in a high-income country: A case study in Queensland, Australia. *Parasites Vectors* 2014; *7*: 379.

89 Cutcher Z, Williamson E, Lynch SE, Rowe S, Clothier HJ, Firestone SM. Predictive modelling of Ross River virus notifications in southeastern Australia. *Epidemiol Infect* 2017; *145*(3): 440–50.

90 Hu W, Clements AC, Williams GM, Tong S, Mengersen K. Bayesian spatiotemporal analysis of socio-ecologic drivers of Ross River virus transmission in Queensland, Australia. *Am J Trop Med Hyg* 2010; *83*(3): 722–8.

91 Hu W, Clements AC, Williams GM, Tong S, Mengersen K. Spatial patterns and socioecological drivers of dengue fever transmission in Queensland, Australia. *Environ Health Persp* 2011; *120*(2): 260–6.

92 Naish S, Mengersen K, Tong S. Spatial analysis of risk factors for transmission of the Barmah Forest virus in Queensland, Australia. *Geospat Health* 2013; *8*(1): 289– 99.

93 Vazquez-Prokopec GM, Kitron U, Montgomery BL, Horne P, Ritchie SA. Quantifying the spatial dimension of dengue virus epidemic spread within a tropical urban environment. *Plos Neglect Trop D* 2010; *4*(12): e920.

94 Moran PAP. The interpretation of statistical maps. *J Roy Stat Soc B* 1948; *10*(2): 245–51.

95 Moran PAP. Notes on continuous stochastic phenomena. *Biometrika* 1950; *37*(1/2): 17–23.

96 Quinn HE, Gatton ML, Hall G, Young M, Ryan PA. Analysis of Barmah Forest virus disease activity in Queensland, Australia, 1993-2003: Identification of a large, isolated outbreak of disease. *J Med Entomol* 2005; *42*(5): 882–90.

97 Huang X, Clements AC, Williams GM, Milinovich GJ, Hu W. A threshold analysis of dengue transmission in terms of weather variables and imported dengue cases in Australia. *Emerg Microbes Infect* 2013; *2*(1): e87.

98 Ho SH, Speldewinde P, Cook A. Predicting arboviral disease emergence using Bayesian networks: A case study of dengue virus in Western Australia. *Epidemiol Infect* 2017; *145*(1): 54–66.

99 Bannister-Tyrrell M, Williams CR, Ritchie SA, Rau G, Lindesay J, Mercer G, *et al*. Weather-driven variation in dengue activity in Australia examined using a process-based modelling approach. *Am J Trop Med Hyg* 2013; *88*(1): 65–72.

100 Huang X, Williams GM, Clements AC, Hu W. Imported dengue cases, weather variation and autochthonous dengue incidence in Cairns, Australia. *Plos One* 2013; *8*(12): e81887.

101 Karl S, Halder N, Kelso JK, Ritchie SA, Milne GJ. A spatial simulation model for dengue virus infection in urban areas. *Bmc Infect Dis* 2014; *14*: 447.

102 Whelan PI, Jacups SP, Melville L, Broom A, Currie BJ, Krause VL, *et al*. Rainfall and vector mosquito numbers as risk indicators for mosquito-borne disease in central Australia. *Commun Dis Intell* 2003; *27*(1): 110–6.

103 Kelly-Hope LA, Purdie DM, Kay BH. Differences in climatic factors between Ross River virus disease outbreak and nonoutbreak years. *J Med Entomol* 2004; *41*(6): 1116–22.

104 Williams CR, Fricker SR, Kokkinn MJ. Environmental and entomological factors determining Ross River virus activity in the River Murray Valley of South Australia. *Aust N Z J Public Health* 2009; *33*(3): 284–8.

105 Moir J, Garner P. Malaria control through health services in Papua New Guinea. *P N G Med J* 1986; *29*(1): 27–33.

106 Reilly Q. The Control of Malaria in Papua New Guinea. *P N G Med J* 1986; *29*: 3–4.

107 Montanari RM, Pyakalyia TR, Ake IN. The malaria control program in Papua New Guinea: Epidemiological surveillance and a look into the future. *P N G Med J* 1992; *35*(4): 233–42.

108 Ataka Y, Inaoka T, Ohtsuka R. Knowledge, attitudes and practices relevant to malaria control in remote island populations of Manus, Papua New Guinea. *Trop Med Int Health* 2011; *39*(4): 109–17.

109 Feterl M, Graves P, Seehofer L, Warner J, Wood P, Miles K, *et al*. The epidemiology of malaria in Kutubu, Southern Highlands Province, Papua New Guinea, before and during a private sector initiative for malaria control. *Trop Med Infec Dis* 2017; *2*(1): 2.

110 Mueller I, Taime J, Ibam E, Kundi J, Lagog M, Bockarie M, *et al*. Complex patterns of malaria epidemiology in the highlands Region of Papua New Guinea. *P N G Med J* 2002; *45*(3-4): 200–5.

111 Mueller I, Kundi J, Bjorge S, Namuigi P, Saleu G, Riley ID, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 3. Simbu Province. *P N G Med J* 2004; *47*(3-4): 159–73.

112 Mueller I, Ousari M, Yala S, Ivivi R, Sie A, Reeder JC. The epidemiology of malaria in the Papua New Guinea highlands: 4. Enga Province. *P N G Med J* 2006; *49*(3-4): 115–25.

113 Mueller I, Sie A, Ousari M, Iga J, Yala S, Ivivi, R, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 5. Aseki, Menyamya and Wau-Bulolo, Morobe Province. *P N G Med J* 2007; *50*(3-4): 111–22.

114 Mueller I, Yala S, Ousari M, Kundi J, Ivivi R, Saleu G, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 6. Simbai and Bundi, Madang Province. *P N G Med J* 2007; *50*(3-4): 123–33.

115 Maraga S, Plüss B, Schöpflin S, Sie A, Iga J, Ousari M, *et al*. The epidemiology of malaria in the Papua New Guinea highlands: 7. Southern Highlands Province. *P N G Med J* 2011; *54*(1-2): 35–47.

116 Namosha E, Mueller I, Kastens W, Kiele R, Kasehagen L, Siba PM. Mapping the prevalence of malaria in rural Papua New Guinea using a geographic information system. *P N G Med J* 2010; *53*(1-2): 5–14.

117 Beck-Johnson LM, Nelson WA, Paaijmans KP, Read AF, Thomas MB, Bjornstad ON. The importance of temperature fluctuations in understanding mosquito population dynamics and malaria risk. *Roy Soc Open Sci* 2017; *4*: 160969.

118 Bomblies A. Modeling the role of rainfall patterns in seasonal malaria transmission. *Climatic Change* 2011; *112*: 673–85.

119 Rosewell A, Makita L, Muscatello D, John LN, Bieb S, Hutton

R, *et al*. Health information system strengthening and malaria elimination in Papua New Guinea. *Malaria J* 2017; *16*: 278.

120 Number of Notifications of Barmah Forest virus infection, received from state and territory health authorities in the Period of 1991 to 2020 and year-to-date notifications for 2021. Canberra: Department of Health 2021. Available from: *http://www9.health.gov.au/cda/source/rpt_4.cfm* (Accessed on March 30, 2021).

121 Kay BH, Aaskov JG. Ross River virus (epidemic polyarthritis). In: Monath TP, editor. The arboviruses: Epidemiology and ecology. Boca Raton: CRC Press 1991; 93–112.

122 Bi P, Tong S, Donald K, Parton K, Hobbs J. Southern Oscillation Index and transmission of the Barmah Forest virus infection in Queensland, Australia. *J Epidemiol Commun H* 2000; *54*(1): 69–70.

123 Hudson D, Alves O, Hendon H, Wang G. The impact of atmospheric initialization on seasonal prediction of tropical Pacific SST. *Clim Dynam* 2011; *36*: 1155–71.

124 Cottrill A, Hendon HH, Lim E, Langford S, Shelton K. Seasonal forecasting in the Pacific using the coupled model POAMA-2. *Weather Forecast* 2013; *28*(3): 668–80.

125 Hudson D, Alves O, Hendon HH, Lim E, Liu G, Luo JJ, *et al*. ACCESS-S1: The new Bureau of Meteorology multi-week to seasonal prediction system. *J South Hemisphere Earth Syst Sci* 2017; *67*(3): 132–59.

126 Ostfeld RS, Glass GE, Keesing F. Spatial Epidemiology: An emerging (or re-emerging) discipline. *Trends Ecol Evol* 2005; *20*(6): 328–36.

127 Syed M, Saleem T, Syeda U, Habib M, Zahid R, Bashir A, *et al*. Knowledge, attitudes and practices regarding dengue fever among adults of high and low socioeconomic groups. *J Pak Med Assoc* 2010; *60*(3): 243–47.

128 Fuller DO, Troyo A, Beier JC. El Niño Southern Oscillation and vegetation dynamics as predictors of dengue fever cases in Costa Rica. *Environ Res Lett* 2009; *4*: 140111–8.

129 Buczak AL, Koshute PT, Babin SM, Feighner BH, Lewis SH. A data-driven epidemiological prediction method for dengue outbreaks using local and remote sensing data. *BMC Medical Inform Decis Mak* 2012; *12*: 124.

130 Cooper RD, Frances SP. Malaria vectors on Buka and Bougainville Islands, Papua New Guinea. *J Am Mosq Control Assoc* 2002; *18*(2): 100–6.

131 Pluess B, Mueller I, Levi D, King G, Smith TA, Lengeler C. Malaria--a Major health problem within an oil palm plantation around Popondetta, Papua New Guinea. *Malaria J* 2009; *8*: 56.

132 World Meteorological Organization. WMO climate statement: Past 4 years warmest on record. Geneva: World Meteorological Organization 2018. Available from: *https://public.wmo.int/en/media/press-release/wmo-climate-statement-past-4-years-warmest-record* (Accessed on March 30, 2021).

133 Park JW, Cheong HK, Honda Y, Ha M, Kim H, Kolam J, *et al*. Time trend of malaria in relation to climate variability in Papua New Guinea. *Environ Health Toxicol* 2016; *31*: e2016003.

134 McGree S, Schreider S, Kuleshov Y. Trends and variability in droughts in the Pacific islands and northeast Australia. *J Climate* 2016; *29*: 8377–97.

135 Imai C, Cheong HK, Kim H, Honda Y, Eum JH, Kim CT, *et al*. Associations between malaria and local and global climate variability in five regions in Papua New Guinea. *Trop Med Int Health* 2016; *44*: 23.

Correspondence to: Yuriy Kuleshov, Bureau of Meteorology, 700 Collins Street, Melbourne, Victoria 3008, Australia.
E-mail: yuriy.kuleshov@bom.gov.au

Received: 05 February 2020 *Accepted in revised form:* 14 January 2022