

Climate change could threaten blood supply by altering the distribution of vector-borne disease: an Australian case-study

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Background: Climate change is expected to promote more intense and prolonged outbreaks of vector-borne disease, and alter the geographic boundaries of transmission. This has implications for the safety and supply of fresh blood products around the world. In Australia, a recent outbreak of dengue fever caused a prolonged regional shortage in the supply of fresh blood products.

Objective: To highlight the potential for climate change to affect the safety and supply of blood globally through its impact on vector-borne disease, using the example of dengue in Australia as a case-study.

Design: We modelled geographic regions in Australia suitable for dengue transmission over the coming century under four climate change scenarios, estimated changes to the population at risk and effect on blood supply.

Results: Geographic regions with climates that are favourable to dengue transmission could expand to include large population centres in a number of currently dengue-free regions in Australia and reduce blood supply across several states.

Conclusion: Unless there is strong intergovernmental action on greenhouse gas reduction, there could be an eight-fold increase in the number of people living in dengue prone regions in Australia by the end of the century. Similar impacts will be experienced elsewhere and for other vector-borne diseases, with regions currently on the margins of transmission zones most affected. Globally, climate change is likely to compound existing problems of blood safety and supply in already endemic areas and cause future shortages in fresh blood products through its impact on transmission of vector-borne disease.

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Climate change over coming decades is expected to have a number of adverse human health consequences. In Australia, these impacts include increases in the incidence of vector-borne disease and in the size of geographic regions affected, as well as a greater number of deaths and hospitalisations from heat exposure and more cases of bacterial gastroenteritis (1).

A recent outbreak of dengue fever in the north of the Australian state of Queensland highlights another probable, but less direct, human health outcome with global public health consequences: reduced availability of fresh blood products due to more intense, more frequent and

more geographically widespread outbreaks of vector-borne disease. Such events could exacerbate existing shortfalls in blood supply and compromise transfusion safety, especially in developing countries.

Dengue fever is caused by infection with one of four serotypes of dengue virus. It is transmitted between humans by the urban freshwater mosquito *Aedes aegypti*. Dengue infection causes fever, general aches and occasional minor bleeding. Subsequent infection with another of the dengue serotypes can cause dengue haemorrhagic fever, a life-threatening complication (2). Local transmission of dengue occurs in most years in northern Queensland but the virus is

not yet endemic in Australia. Instead, outbreaks commence when a mosquito bites an infected traveller and transmits the virus to a resident.

The transmission of dengue virus through blood transfusion has been documented in Hong Kong (3) and Singapore (4). It is neither known if other cases have occurred, nor what level of viraemia causes infection (5), but the potential risk to blood supplies in endemic countries is high (6, 7).

The Australian Red Cross Blood Service (ARCBS) collects blood across Australia from non-remunerated volunteer donors. Approximately 26,000 blood donations are required each week, or more than 1.35 million per year (8). For Australia's population of 22 million, this is 0.06 units used for each person per year. Currently there is no screening test available for the dengue virus; red cells and platelets collected in an outbreak area (or from recent visitors to that region) cannot be used, even if donated by an asymptomatic person as they may unknowingly carry the virus. Plasma collected from affected areas is still used for the manufacture of blood products once it has been through the fractionation process (Anthony Keller, ARCBS, personal communication).

From 1991 to 2007, there were 3,385 confirmed cases of locally acquired dengue fever in Australia (9). On average, there are 200 cases per year and another estimated 120 sub-clinical cases (cases where symptoms are minor and do not result in a consultation with a general practitioner) (10), giving a ratio of clinical to sub-clinical cases of approximately 1:0.6. There were five deaths attributed to dengue during this period. Dengue outbreaks in non-endemic regions like northern Australia

are sporadic; in some years case numbers are very high, while other years may be free of cases.

Outbreaks have, however, become more regular in recent years with five major and many smaller outbreaks recorded between 1992 and 2004 (9). In contrast, the five known outbreaks prior to 1992 occurred over a 90-year period (11). Increasing international travel into north Queensland and a global amplification in dengue activity are proposed as principal reasons for this increase, and sustained education and mosquito control programmes instituted by public health authorities may have averted what could have been even larger epidemics (Scott Ritchie, Far North Queensland Health Service, personal communication).

By 6 May 2009, more than 900 cases had been recorded during the outbreak in Cairns and Townsville in northern Queensland (with a likely additional 540 sub-clinical cases) (Fig. 1). This caused a prolonged 14% reduction in Queensland's collection of red cells and platelets, as deferral of donors resident in or who have visited the region continued for several months. The outbreak prompted the ARCBS to call for extra donations from other parts of Queensland to ensure that demand for blood supplies continued to be met (Anthony Keller, personal communication). During an outbreak, the ban on using fresh blood from affected areas remains in place until there are no new cases for at least three months (Anthony Keller, personal communication).

This is neither the first time a dengue outbreak has caused a reduction in Queensland's blood collections, and nor will it be the last. We modelled changes to transmission-risk areas and estimated the population at risk of dengue in the future to investigate whether associated

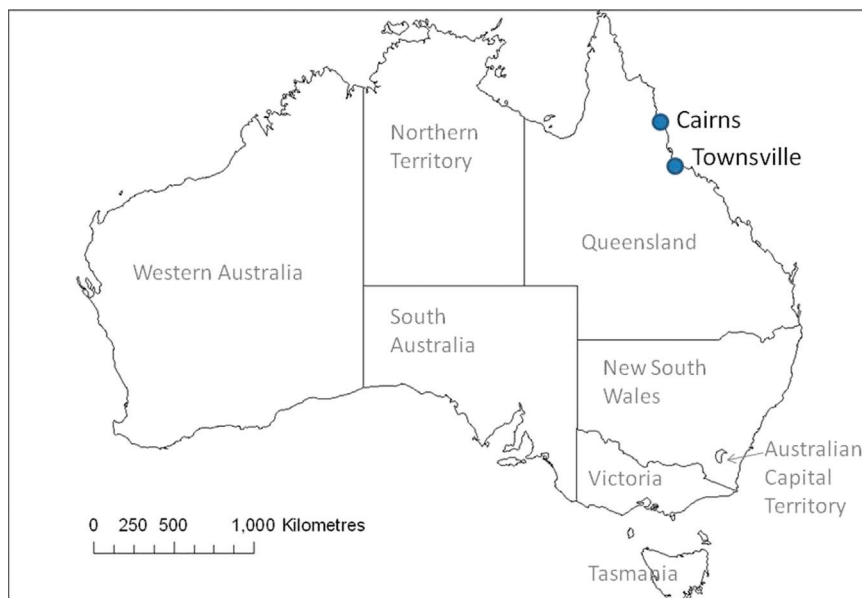


Fig. 1. Map of Australian States and Territories showing the location of the 2009 dengue outbreak centred around the towns of Cairns and Townsville.

blood supply shortages may become more severe as a result of climate change.

Methods

Regions at risk

We employed an empirical model of the relationship between climate and dengue based on the known global distribution of dengue (12). The climate factor that predicts the presence of dengue most accurately is the long-term average humidity of a region, expressed as ‘average annual vapour pressure’, which is an expression of both humidity and temperature. Mosquito survival is strongly dependent on moisture and humidity levels; longer mosquito lifespans increase the likelihood of multiple blood feeds and hence transmission of dengue. Warmer temperatures also facilitate dengue transmission through speeding up replication rate of the virus within the vector, reducing the extrinsic incubation period and thus time to infectivity. The model does not attempt to predict the current or potential geographic range of the vector itself, which may extend beyond regions where virus transmission is currently observed.

We used this climate–disease relationship to model the regions in Australia that are at high risk of becoming suitable for dengue transmission under four different climate change scenarios (Box 1). From annual average vapour pressure and temperature baseline data for each Statistical Division (SD) (13) for the period 1961–1990 (14), we calculated relative humidity by using standard meteorological conversion formulae. We calculated the probability that one (or more) epidemics of dengue fever could occur, defining regions to be ‘at risk’ of dengue where the model indicated a greater than 50% probability of transmission.

Population at risk

We estimated the future population at risk using population projections for each SD in the national census data (16, 17). We obtained the estimates for the capital cities and ‘rest-of-state’ areas for each State and Territory between 2004 and 2100. The capital city estimates from this dataset were used for the entire period; the rest-of-state estimates were adjusted to reflect predicted trends in the SDs within them. For this we used an earlier set of SD population predictions from 2004 to 2019 (18) to interpolate SD populations from 2020 to 2049 to the Australian Bureau of Statistics (ABS) estimate for 2050 (19, 20). In the absence of sub-state level projections from the ABS from 2050 to 2100, we made the simplifying assumption that the proportional contribution each SD made to the rest-of-state totals up to 2050 would remain for the rest of the century. On this basis, we estimated the rest-of-state population totals for the period 2051 and 2100, taking the ABS 2100 values as the endpoint.

To estimate numbers of annual infections in the future, a minimum expected average annual incidence of dengue infection was derived from baseline using notifications between 1991 and 2007 (10, (Scott Ritchie, Far North Queensland Health Service, personal communication)) (i.e. not including the most recent and unusual 2008–2009 epidemic) and population resident in the at risk region. An upper incidence estimate for future infections was derived from numbers of infections during the most recent outbreak (N.B. Even this upper estimate is conservative as it does not take into account likely changing transmission intensity in the future).

Effect on blood supply

We used the current proportions of ‘regular’ donors from each state to estimate future percentage declines in

Box 1. Climate scenarios

The four climate scenarios used were produced by Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the Australian Government’s *Garnaut Climate Change Review* (15).

Three of the scenarios assume ‘no action’ is taken to reduce emissions; emissions remain high and continue to rise, mean global temperature increase is around 4.5°C by 2100. These scenarios differ according to anticipated changes to humidity and precipitation.

The fourth scenario assumes ‘strong action’ is taken; emissions are significantly reduced over coming decades, CO₂ stabilises at 420 ppm by 2100, and mean global temperature increase is around 2°C.

Scenario	No action			Strong action
	1 Hot and dry	2 Hot, median humidity	3 Hot and wet	4 Warm
Global average temperature increase (°C)	~4.5	~4.5	~4.5	~2
Humidity	Low	Median	High	Median

national blood supply based on modelled dengue transmission areas, ‘population at risk’ and projected incidence of infection. This current pattern of blood donation by state was estimated from a recent national survey of over 2,000 adults (methods described elsewhere (21)) where response was ‘usually donate at least every six months’.

Other public health and economic impacts

We estimated that the annual public health and health care cost of dengue is approximately \$2.82 per person living in transmission-risk areas. This is comprised of:

- *Surveillance and control:* \$2.56 per person, for vector surveillance and control, health education, case ascertainment and follow-up, and training of specialist staff (Scott Ritchie, Far North Queensland Health Service, personal communication).
- *Diagnostic costs:* 19c per person. Approximately three times the number of diagnostic tests are conducted for dengue and associated viruses as the number of confirmed tests. Routine testing during the year might result in another 50 tests being conducted – 650 in all. Approximately half these are PCR (@\$75) and the other half IgM ELISA (@\$180) ((Scott Ritchie, Far North Queensland Health Service, personal communication), (Russell Simmons, Queensland Health Scientific Services, personal communication)).
- *Treatment costs:* 7c per person, from an average of two visits to a general practitioner (one to seek a test, and

another to get the results) and additional follow-up checks for approximately 10% of cases. A standard Level B general practice consultation is \$55. Assuming all confirmed cases and 50% of unconfirmed cases attend a general practice 2.1 times in an average year, this makes 546 visits at baseline at a cost of approximately \$30,000 (Scott Ritchie, Far North Queensland Health Service, personal communication).

- *Hospital costs:* Deaths to date have been rare and generally occur before protracted hospital stays incur notable system costs.

Time off work due to dengue illness or caring for a sick child is an additional economic cost that we have estimated previously (1) to be 0.005 days per year per person living in a dengue transmission region.

Results

Regions at risk

Under each of the three ‘no emissions action’ scenarios, there is an increase in the geographic spread and hence the number of SDs that are favourable to dengue transmission (Fig. 2). In Scenario 3 (Hot and wet), the geographic region suitable for the transmission of dengue is expected to extend far to the south and west from its current distribution. The regions at risk include all coastal areas of Queensland and into New South Wales, northern Western Australia and the Northern Territory. In Scenarios 1 (Hot and dry) and 2 (Hot, median humidity), dengue

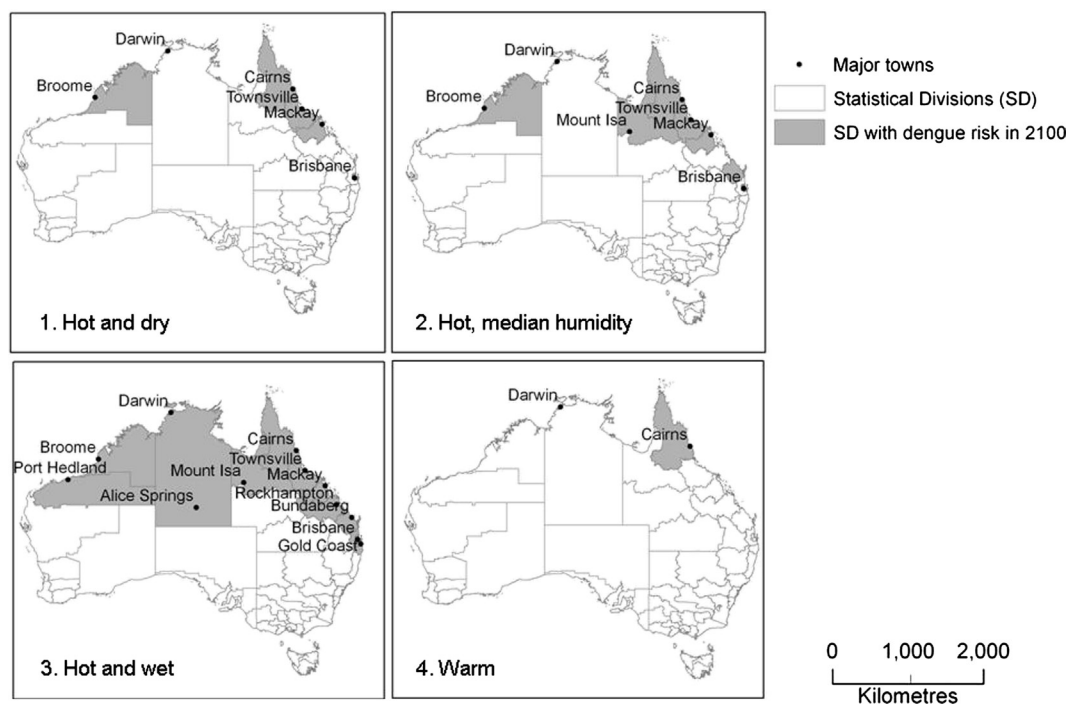


Fig. 2. Areas suitable in Australia for dengue transmission in 2100 under four climate change scenarios (>50% likelihood of transmission).

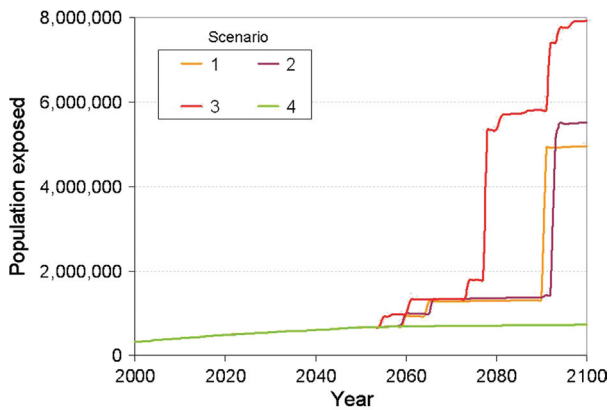


Fig. 3. The number of people living in regions in Australia at high risk (>50%) of dengue transmission under four climate change scenarios. Scenarios: 1, Hot (dry); 2, Hot (median humidity); 3, Hot (wet); 4, Warm (strong mitigation).

transmission areas extend south in Queensland to include Brisbane (and west to Mt Isa in Scenario 2), and into Broome in Western Australia. In contrast, under emissions mitigation (the ‘strong action’ Scenario 4 (Warm)), dengue transmission-suitable areas remain limited to northern Queensland and to Darwin.

Population at risk

The number of people at risk from dengue (i.e. the population living in transmission-risk areas) estimated under each scenario in coming decades is shown in Fig. 3, and the percentage changes are represented in Table 1.

Annual rates of confirmed infection are estimated to be between 47/100,000 and 230/100,000 in dengue susceptible regions, with a further 28/100,000–138/100,000 sub-clinical infections likely. Table 2 shows the range estimate for the number of people to be infected with dengue based on the exposed population and these current rates of infection. About 63% of these infections will be ‘clinical’ and require treatment.

The increase in number of people at risk and hence the potential infections observed over the next four decades is gradual and due solely to expected population growth in existing dengue regions rather than to a geographic expansion of transmission-suitable areas. Around mid-century, however, step-changes occur under each of the three ‘no action’ scenarios as a result of geographic

expansion incorporating new population centres. By the end of the century, strong mitigation action could reduce the number of people living in dengue transmission zones in Australia by between 80 and 90%, depending on how regional climates respond to increased carbon concentrations (becoming dryer or wetter, respectively).

Effect on blood supply

The regional contributions to Australia’s blood supply, estimated by current self-report of ‘regular’ donation and the percentage of Australia’s population in each state and territory is shown in Table 3. The estimated future proportion of the state’s population living in transmission-risk areas in selected years is shown in Table 4.

As reduction in blood supply during an outbreak is geographically determined, the proportion of the population in each state living in transmission-risk zones relates directly to the potential decline in blood supply in each state during an outbreak (assuming that blood donors are evenly distributed throughout the population of each state). We estimated the percentage of donors in each state that are likely to be at least periodically affected by dengue outbreaks by multiplying the proportion of each state’s population in transmission-risk zones by each state’s percentage contribution to national blood supply (Table 5).

Blood supply in the state of Queensland will be most affected as it can expect declines of at least between 61 and 93% of its blood supply by the end of the century (and at least 15% in the decades before then), which will occur at least periodically if transmission patterns do not intensify.

Other public health and economic impacts

Estimates of the average annual economic costs to public health and surveillance are shown in Table 6 and estimated annual number of work days lost are shown in Table 7.

Discussion

In coming decades in Australia, the geographic regions favouring dengue transmission are expected to expand across a number of states and encompass new populations unless strong mitigation action is taken.

Table 1. Percentage change in numbers of people living in transmission-risk areas, selected years

Year	Hot (dry)	Hot (median)	Hot (wet)	Warm (strong mitigation)
2020	+55	+55	+55	+55
2050	+114	+114	+114	+114
2070	+313	+332	+332	+124
2100	+1,500	+1,680	+2,500	+133

Table 2. Estimated annual numbers of new dengue infections under the four climate scenarios^a

Year	Hot (dry)	Hot (median)	Hot (wet)	Warm (strong mitigation)
2020	360–1,766	360–1,766	360–1,766	360–1,766
2050	495–2,429	495–2,429	495–2,429	495–2,429
2070	960–4,710	1,005–4,931	975–4,784	525–2,576
2100	3,720–18,253	4,140–20,314	5,948–29,182	540–2,650

^aUsing 'population at risk' projections (Fig. 3). Lower estimate is calculated from average annual incidence rate 1991–2007; upper estimate is calculated from the much larger 2008–2009 outbreak.

Note. These upper estimates are likely to be conservative in a climate changed future as they do not consider changes to transmission intensity or a shift from an epidemic to endemic pattern of disease.

If no or insignificant action is taken to reduce global carbon emissions, the distribution of dengue transmission-suitable areas could, at the very least, progress southward along the Queensland coast and include the northernmost parts of Western Australia. If conditions are wetter, transmission-suitable areas could extend into New South Wales along the east coast, as far south as Port Hedland in Western Australia and throughout the Northern Territory. In terms of numbers of people affected, up to eight times as many people could be at risk compared to scenarios based on strong mitigation. If several dengue outbreaks were to occur spontaneously in different areas or spread between the newly transmission-suitable regions, blood collections – and potentially the supply of fresh blood products – could be greatly reduced across Australia.

People living in towns and cities never before exposed to dengue would be especially susceptible during outbreaks. Large numbers of people could become infected, increasing the amount of virus circulating in the population and furthering risk of transmission. For example, in 1993, an estimated 26% of the population were infected in one outbreak that occurred in the Queensland town of Charters Towers (22).

The predictive model we employed to estimate changes to dengue transmission regions is conservative. It predicts

current global dengue presence with an accuracy of 89% based on areas deemed to have a greater than 50% chance of transmission (12). This means that some regions returning a lower than 50% probability estimate in the model could still be suitable for dengue transmission, and dengue will, on occasion, occur outside these areas. Such is the case with Townsville which was affected by the most recent Australian outbreak.

Importantly, this model does not predict *vector* distribution but rather regions suitable for future virus transmission, based on current known transmission regions. Vectors do exist, and have existed in the past, in regions in Australia where transmission does not currently occur (23). The model is thus influenced by human behaviour, such as surveillance programmes that have kept dengue from being more widespread in recent years than it otherwise might be, and is informed by current urban features and infrastructure. For example, near universal water reticulation in non-remote areas of Australia has reduced domestic storage and thus *A. aegypti* breeding sites. Such behavioural factors and infrastructure are not static; Beebe et al. have suggested that human adaptation to climate change may cause further spreading of the *Aedes* mosquito in Australia and more intense epidemics as recent prolonged water shortages have already, in some urban areas, led to the re-installation of domestic water storage facilities (23).

The altered distribution of dengue modelled here is predicted to reduce Queensland's blood supply by between 61 and 93% by the end of the century, unless strong mitigation action is taken. Such reductions may remain periodic, unless dengue becomes endemic to an area. Although changing transmission intensity was not modelled here, it is a likely outcome of climate change, especially in regions that become more humid or where minimum temperatures (night-time or winter-time) are not sufficiently low to disrupt either vector activity or replication of the virus (24). Again conservatively, we estimate that blood supply in the Northern Territory could be reduced by more than double the current potential periodic loss, and Australia's national supply could be reduced by up to 20%. Larger reductions in

Table 3. Australia's blood donors by state/territory and population distribution

State/Territory	Australia's 'regular' donors (%)	Australian population (%)
New South Wales	36.5	33.7
Victoria	22.1	24.8
Queensland	18.8	18.8
Western Australia	6.6	7.7
South Australia	10.4	9.9
Tasmania	1.7	2.4
Australian capital territory	2.7	1.0
Northern Territory	1.0	1.6

Table 4. Proportion of the population within each dengue-risk state living in transmission areas under the four scenarios

Scenario	State/Territory	Proportion of state/territory population living in dengue risk areas			
		2020	2050	2070	2100
Hot and dry	Queensland	0.06	0.06	0.15	0.61
	Western Australia	–	–	0.02	0.02
	Northern Territory	0.46	0.46	0.46	0.46
Hot (median humidity)	Queensland	0.06	0.06	0.15	0.69
	Western Australia	–	–	0.02	0.02
	Northern Territory	0.46	0.46	0.46	0.46
Hot and wet	Queensland	0.06	0.06	0.15	0.93
	Western Australia	–	–	0.02	0.04
	Northern Territory	0.46	0.46	0.46	1.00
	New South Wales	–	–	–	0.03
Strong mitigation	Queensland	0.06	0.06	0.06	0.06
	Northern Territory	0.46	0.46	0.46	0.46

Note: This proportion is extrapolated from the current pattern of residence and no allowances have been made for future contributions from internal migration.

Queensland's blood supply are likely to occur earlier than modelled here as some years will most certainly experience outbreaks outside these boundaries.

Under all but the strong mitigation scenario, the potential economic costs of dengue to Australia are considerable; up to \$22 million annual public health costs in today's terms, and 40,000 work days if transmission intensity remains unchanged. The costs of other vector-borne disease not modelled here are also likely to be affected by climate change in a similar manner.

We used costs from 2006 to 2008 and did not account for any variation in costs over time. We assumed, conservatively, that the cost per person will remain the

same in future, and that the pattern of dengue in Australia will also remain the same (i.e. epidemic). If, however, changing transmission patterns mean that dengue becomes established in Australia, the associated health system costs are likely to increase substantially above our estimated baseline per person amount. First, unlike the present, there would no longer be years with few or even no cases of dengue recorded. Second, a much larger campaign of mosquito eradication would be needed across the endemic towns and cities. This would involve trained personnel, broad scale and intensive community education, and mosquito spraying. Currently this work is only focused on 'hot spots' – the local areas

Table 5. Projected decline in blood supply in Australian States and Territories with high risk transmission regions, and nationally

Scenario	State/Territory	Decline in state's blood supply during an outbreak (%)				Total national decline in blood supply (%)			
		2020	2050	2070	2100	2020	2050	2070	2100
Hot and dry	Queensland	6	6	15	61	2	2	3	12
	Western Australia	–	–	2	2				
	Northern Territory	46	46	46	46				
Hot (median humidity)	Queensland	6	6	15	69	2	2	3	14
	Western Australia	–	–	2	2				
	Northern Territory	46	46	46	46				
Hot and wet	Queensland	6	6	15	93	2	2	3	20
	Western Australia	–	–	2	4				
	Northern Territory	46	46	46	100				
	New South Wales	–	–	–	3				
Strong mitigation	Queensland	6	6	6	6	2	2	2	2
	Northern Territory	46	46	46	46				

Table 6. Average annual public health costs (millions \$AUS) under the four scenarios for selected years, based on cost per person living in regions at risk

Year	Hot (dry)	Hot (median)	Hot (wet)	Warm (strong mitigation)
2020	1.35	1.35	1.35	1.35
2050	1.87	1.87	1.87	1.87
2070	3.61	3.78	3.78	1.96
2100	13.99	15.57	22.36	2.04

(usually sections or suburbs) where cases have been identified in a particular season.

We made no assumptions about future tourism patterns and how these may affect the introduction of dengue cases. At present, all outbreaks in Australia begin with an infected person who enters from another country. If tourism were to increase markedly (especially to and from dengue-endemic countries), this might result in more outbreaks in Australia. The opposite is also the case. As well, the introduction of other serotypes of dengue (and hence the risk of the more serious complication of dengue haemorrhagic disease) will also come from residents returning or foreign tourists. This is a random event, and we have not modelled the possible consequences and costs involved.

Globally, the severity of dengue symptoms varies enormously. Factors that affect disease severity include ethnicity, age, nutritional status, the sequence of two different dengue infections, the genotype of the infecting virus, and the competence of the clinical and laboratory surveillance systems. We assumed that Australia's future health system, demographic, social and environmental influences on disease severity will broadly represent those of today.

Currently, there are very few deaths due to dengue fever in Australia (about 0.3 deaths per year). The number of deaths from exposure to different dengue serotypes is, however, likely to increase if dengue transmission becomes more intense and the virus becomes endemic as the risk of sustaining multiple infections in a lifetime increases. We have assumed that the average number of dengue haemorrhagic fever cases is not likely to increase in future. Australian cases that occurred between 2003 and 2004 were aged 32–70 years, but in Southeast Asia, dengue haemorrhagic fever predomi-

nantly occurs among children. A possible explanation for the older age of patients in northern Queensland is the long period between the dengue 1 and 2 epidemics in this region, which means that only older people or those who had been infected previously while overseas were susceptible to dengue haemorrhagic fever. If outbreaks of different dengue serotypes occur more frequently in future (due to random chance, increased global virus activity or higher tourism numbers), or if dengue became established locally, this would probably change the age profile of haemorrhagic fever towards younger people (24).

Worldwide, the warmer temperatures associated with climate change are expected to enhance transmission in already affected areas and to increase the likelihood of its emergence in new areas (25). Scenario-based modelling using global climate models and average temperature increases has consistently projected increases to the latitudinal range of dengue transmission and increased transmission intensity in already affected areas, and predicts that the dengue virus will become established in areas that are currently marginal for transmission. For example, over the coming decades dengue is predicted to spread into new areas further south in South America and Africa as well as Australia (12, 24), further North into the USA (12), while parts of India, the Middle East and Southeast Asia classified as low risk will become high risk (12). These models found that transmission intensity is expected to increase not only in northern Australia, but also across India and Thailand, eastern and northern Africa, and in South and Central America. The epidemic potential of dengue virus is expected to increase in a number of major cities even with only a small increase in average temperature (26, 27), and new patterns of year

Table 7. Average annual number of lost workdays under the four scenarios, based on days per person living in regions at risk

Year	Hot (dry)	Hot (median)	Hot (wet)	Warm (strong mitigation)
2020	2,400	2,400	2,400	2,400
2050	3,300	3,300	3,300	3,300
2070	6,400	6,700	6,700	3,500
2100	24,800	27,600	39,700	3,600

round transmission occurring in some regions, including northern Australia (24).

The modelling of dengue and blood supply in Australia thus highlights what is most certainly a global problem; climate change induced blood shortages and impacts on safety could become a significant and long-term issue, especially in regions already struggling to control vector-borne disease or those that are presently on the margins of current disease distribution, and even more so in countries which already struggle to meet their blood supply needs. Such changes are probably already well underway; the incidence of dengue is observed to be increasing in parts of the Americas and Asia (28, 29).

The potential for climate change to reduce future blood supply extends to a number of other vector-borne pathogens. The transfusion-transmissibility of other vector-borne viruses of importance to Australia, including Ross River virus, Barmah Forest virus and Murray Valley Encephalitis is currently unknown (30). These viruses are also expected to increase in incidence, intensity and geographic distribution as conditions become more favourable to mosquitoes and virus replication, a situation that could have further detrimental impacts on Australian blood supply.

Climate change impacts could further contribute to future blood shortages across the world as other globally important vector-borne diseases are similarly affected. While the modelling presented here examines average trends across coming decades for a single virus, there is considerable evidence that transmission of a number of vector-borne diseases is already intensifying and expanding geographically. For example, the recent emergence of Chikungunya in northern Italy caused a reduction in blood supply and plasma for manufacture (31), while this and other vector-borne diseases such as West Nile virus are becoming established in previously unaffected regions (32, 33).

The increasing global movement of blood and blood products adds another dimension to future blood safety; transfusion-transmission risk is not geographically contained in an already affected region and could potentially lead to local transmission in a previously unaffected area, while any contaminated supplies are becoming more difficult to trace and recall.

In the modelling of future reductions in blood supply, a possible change to the use of blood products was not taken into account. The annual rate of IVIg use in Australia has increased approximately 57% since 2003 and platelet use has increased approximately 13%, while plasma-derived factor VIII and factor IX have declined in favour of recombinant technology over the same period (34). It is not possible to speculate reasonably on whether the net therapeutic need for blood will increase or decrease in coming decades.

By mid-century, rather than merely increasing the frequency or amplitude of outbreaks in already affected areas as seems to be occurring, the impact of climate change on expanding dengue-transmission regions in Australia will become obvious. By then, it is possible that medical therapies will no longer rely on donated blood, or that dengue has become a readily treatable or curable infection, or that an accurate and reliable screening test has become available. The development of an effective dengue vaccine and/or the future application of pathogen reduction technology to blood components may also mitigate the risks. However, there remain a large number of other vector-borne pathogens, and possibly some emerging ones, that will also be affected by climate change. If the current situation for screening and vaccination, and our reliance on blood products holds for the future, we expect the safety and availability of blood products around the world to be compromised by climate change unless blood collections can be adequately increased in non-affected areas. Other countries already intensely affected by dengue may experience much earlier increases in the transmission range and intensity of vector-borne disease than is expected for Australia, and will be thus be subject to contemporary medical technology and therapy.

With its national control of blood component inventory, Australia is well prepared to be able to move blood components into areas of need as required (Anthony Keller, personal communication). Many other regions of the world do not have such a safety net that can be invoked when outbreaks occur, and with climate change expected to affect a number of vector-borne infections worldwide, periodic or even continuous shortfalls in blood supply should be expected and planned for.

Climate in Australia and elsewhere over coming decades will be shaped by future global carbon emissions. The level of global emissions will be heavily dependent on the action taken by national governments, especially those of currently high polluting countries, such as Australia, and those with large populations that are rapidly industrialising, such as India and China.

While some climate change is 'already in the pipeline', strong emission reductions are needed to avert global average warming of greater than 2°C, the threshold of 'dangerous' and irreversible climate change (35). It is estimated that a 50% global reduction in emissions by 2050 is required in order to stabilise CO₂ concentration below 450 ppm and warming below 2°C (35), equivalent to the 'strong mitigation' scenario that was used here.

International action on emissions at this level could help safeguard future blood supply around the world, as demonstrated here for dengue transmission in Australia. However, both the virus and the vectors are highly sensitive to climate, thus even a much smaller increase

in global mean temperature will affect – and may already be affecting – the transmission of vector-borne disease.

Importantly, and perhaps as demonstrated by the recent epidemic of dengue in Australia, outbreaks of vector-borne disease will become more difficult to control as the climate changes. Regions that are currently under disease surveillance may need to expand rapidly and control measures implemented swiftly. Regulatory action to reduce potential breeding habitats should be considered well in advance, such as adequate screening of water tanks to inhibit oviposition by mosquitoes, even if global warming is kept to a minimum by strong emission reductions.

It is difficult when assessing the impacts of climate change on any health outcome to predict precise changes in occurrence or distribution. This is especially true for vector-borne diseases, where innumerable environmental, human and other animal behaviours and physiologies are affected (36). The example presented here of how climate change could affect the supply of blood in Australia by extending the range of dengue-favourable environments illustrates what should be a global concern, and highlights the importance of considering what may be a less obvious climate impact on health.

Conflict of interest and funding

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