Vol. 42: 1–11, 2010
doi: 10.3354/cr00861

CLIMATE RESEARCH
Clim Res

Published online May 20

Changes in dengue risk potential in Hawaii, USA, due to climate variability and change

Korine N. Kolivras*

Department of Geography, Virginia Tech, Blacksburg, Virginia 24061, USA

ABSTRACT: Climate variability brought about by the El Niño-Southern Oscillation has been linked to outbreaks of infectious diseases, such as hantavirus pulmonary syndrome, cholera, and malaria. Additionally, climate change affects the distribution of diseases, causing some regions to become more or less favorable for the transmission of certain pathogens. Mosquitoes in particular are sensitive to climate change, and mosquito-borne diseases may become more common at higher latitudes and elevations under warmer conditions. This study examined the potential changes in dengue risk in Hawaii, USA, in response to climate variability and change using GIS. Dengue, transmitted by mosquitoes of the genus *Aedes*, is considered to be an emerging disease and almost half of the world's population is at risk of infection. Previous research has identified mosquito habitat and potential dengue risk areas in Hawaii based on average climate conditions, and this study incorporated notions of climate variability and change to that model and determined the population at risk under different scenarios. Dengue risk areas generally contract during El Niño-induced droughts and expand as a result of increased precipitation received during La Niña events. Future climate scenarios predict warmer temperatures and wetter summers in Hawaii over the next 25 yr, which will cause an expansion of mosquito habitat and potential dengue risk areas. The results of this study contribute to the overall understanding of climate–dengue relationships and will aid public health officials in efforts to determine where to concentrate resources for mosquito and dengue surveillance, given certain current or forecast climate conditions.

KEYWORDS: Dengue · Climate change · ENSO · Mosquito-borne disease · Health · GIS · Hawaii

1. INTRODUCTION

As an island state, Hawaii is vulnerable to the effects of climate variability and change. In particular, sea level rise, an increase in extreme events, and decreased access to potable water during droughts offer challenges for residents of the islands (Shea et al. 2001). Additionally, the potential exists for a greater susceptibility to mosquito-borne disease outbreaks under warmer and/or wetter conditions (Shea et al. 2001). An important driver of climate variability in Hawaii is the El Niño-Southern Oscillation (ENSO), which modifies precipitation regimes across the islands (Taylor 1984, Chu 1995, Kolivras & Comrie 2007) and affects vulnerability to mosquito-borne diseases. This vulnerability is exemplified by an outbreak of dengue fever in Hawaii in 2001–2002 (see Fig. 1). The outbreak, which was focused on the island of Maui and partially mediated by weather conditions (Napier 2003), highlights the potential for mosquito-borne diseases to impact Hawaii's residents and economy.

Dengue fever, caused by one of 4 different strains of the dengue virus, is transmitted by mosquitoes of the genus *Aedes*. Most commonly, dengue viruses are transmitted by *Ae. aegypti*; however, *Ae. albopictus* plays a less important but increasing role in the disease's spread and was implicated in the Hawaiian outbreak (Clark et al. 2002, Effler et al. 2005). *Ae. albopictus* is less peri-domesticated than *Ae. aegypti* and more likely to prefer outdoor habitats, and is therefore more sensitive to climate variability (Kuno 1997, Rodhain & Rosen 1997). Additionally, there is a strong rela-

*Email: korine@vt.edu

tionship between mosquito density and precipitation in locations where the intentional storage of water by humans is minimal (Moore et al. 1978), such as in a developed area like Hawaii.

Globally, there are tens of millions of dengue infections per year and, while few people die from a dengue infection, the case fatality rate ranges from 1 to 5% for a severe form of the disease, dengue hemorrhagic fever (DHF) (Centers for Disease Control and Prevention 2007). DHF appears to be linked to subsequent infection with a different strain of the virus (Guzman & Kouri 2002), making prevention and control of dengue in Hawaii of critical importance; those infected during the 2001–2002 outbreak could be at increased risk of contracting DHF should a different strain of the virus be introduced. A global resurgence of dengue and DHF has occurred over the past 3 decades as the range of the mosquito vector has expanded and the virus has been transferred to a greater number of locations. One factor that has been implicated in the emergence of dengue is climate variability and change (Morse 1995, Gagnon et al. 2001).

While other studies have examined the relationship between dengue risk and climate variability and change at the global scale (Hopp & Foley 2001, Hopp & Foley 2003) and within specific countries (e.g. de Wet et al. 2001, Gagnon et al. 2001), such analyses have not been conducted at a relatively fine scale for the Hawaiian Islands, even though they were described as a priority by the Pacific regional report for the US National Assessment (Shea et al. 2001). Additionally, spatial analyses of dengue risk are sparse in the literature when compared to the number of studies focusing on temporal patterns. Given the role that precipitation variability has played in dengue outbreaks, an examination of the ways in which climate variability and change can affect mosquito habitat across the islands will contribute to our understanding of spatial patterns of dengue risk and will address needs related to disease surveillance and control. The goals of the research presented here were to: (1) apply a previously developed conceptual framework and model that incorporates a dynamic approach to evaluating the impacts of climate variability and change on mosquito-borne disease (Kolivras 2006), and (2) examine the ways in which climate variability and change affect mosquito habitat and the human population at risk in Hawaii under different scenarios. In an applied sense, the present study considered shifts in mosquito habitat in order to aid in outbreak prevention or control by health department officials. While it is well known that *Aedes albopictus* is able to breed in the artificial containers provided around human habitation (Hawley et al. 1987), the present study seeks to examine the habitat of *Ae. albopictus* away from humans; that is, the areas where the mosquito is able to breed in natural sites, such as tree holes, rock holes, or bromeliads, given favorable climate conditions. So while the mosquito also breeds in water dishes and planters in homes, the focus here is on rain-filled breeding areas. Human behavior with respect to water storage can be modified, particularly in developed countries that tend to have more effective public health education campaigns to limit artificial breeding sites than less developed countries.

2. CLIMATE–DENGUE RELATIONSHIPS

Changes in vector-borne disease patterns have been noted to have a clear, albeit indirect, relationship with climate patterns given that climate variability and change can increase human disease risk by improving the environmental conditions needed for disease reservoirs or vector breeding and survival. Over a decade of research on climate and dengue risk at various spatial scales suggests that the spatial extent of endemic areas will increase under future warmer climate conditions. This body of research also shows that climate variability will lead to fluctuations in epidemics temporally and spatially. Much research has evaluated temporal relationships between dengue and climate, but fewer studies have focused on spatial patterns and those that have are mainly at the global scale. Generally, both spatial and temporal models examining changes in dengue transmission with climate variability and change indicate that the disease is very sensitive to even minor temperature fluctuations (Patz et al. 1998, McMichael et al. 2004).

Research examining the temporal relationship between climate and dengue reveals the presence of a time lag, the length of which varies according to location, between precipitation and incidence. In 5 study areas in Puerto Rico, the peak in dengue infections followed peak precipitation by roughly 2 mo (Moore et al. 1978), and a similar time lag was seen in research specifically focused on San Juan, Puerto Rico (Schreiber 2001). A time lag was also present when comparing an El Niño-induced drought to dengue in Indonesia, with outbreaks occurring immediately after the drought given connections with local water storage (Gagnon et al. 2001). A broad comparison of the annual number of dengue epidemics from 1970 to 1995 across the south Pacific and the Southern Oscillation Index found a positive correlation between the 2 variables, indicating that climate variability plays some role in the onset of dengue epidemics (Hales et al. 1996).

Temperature has also been recognized as an important variable in studies predicting the occurrence of mosquito-borne disease. The time between when a mosquito acquires a pathogen and when that mosquito can transmit it to others (extrinsic incubation period [EIP]) is important for dengue transmission models, which predict temporal fluctuations in transmission, because the EIP is shortened at warmer temperatures (McMichael et al. 1996). Therefore, mosquitoes are able to transmit the virus to a susceptible person in a shorter period of time as compared to the transmission rate during cooler times. Temperature also affects mosquito survival, which is limited at temperature extremes. The viable temperature range in which *Aedes albopictus* is able to survive and reproduce is ~10 to 40°C (Delatte et al. 2009).

Jetten & Focks (1997) and Patz et al. (1998) were among the first to examine the relationship between climate change and dengue incidence. The studies, which focused specifically on the transmission of dengue viruses to humans rather than mosquito habitat, recognized an increased risk of dengue transmission under warmer climate conditions using output from general circulation models. Additional research (e.g. Hales et al. 2002) has corroborated the findings that dengue risk could potentially increase substantially under warmer conditions at the global scale. Hopp & Foley (2001) modeled population dynamics and densities of *Aedes aegypti* temporally and spatially based on climate conditions at the global scale, and they then applied that model to an examination of worldwide dengue cases (Hopp & Foley 2003). While human factors such as urbanization and water storage are also tied to dengue emergence (Morse 1995, Gubler et al. 2001), the results of the above described studies confirm the presence of a relationship between climate conditions and dengue, and highlight the importance of local-scale studies.

Local- or regional-scale studies permit a more detailed analysis of climate–dengue relationships and are likely more useful to public health officials than broad, global-scale studies. Specifically, finer-scale analyses allow for greater incorporation of local features and characteristics and may provide a greater opportunity for intervention and response, given that public health programs are typically applied at the regional or local level. For example, the results of Schreiber's (2001) study of the temporal variation of dengue in San Juan, Puerto Rico, can contribute to an early warning system for the city using moisture variables to predict future outbreaks. Dengue risk maps developed for New Zealand based on current and future warmer climate scenarios can be used by public health officials for outbreak prevention and control should *Aedes aegypti* or *Ae. albopictus* become established in New Zealand (de Wet et al. 2001).

The conceptual framework applied in the present study, outlined in detail in Kolivras (2006), recommends the incorporation of a dynamic perspective in the modeling of vector-borne disease risk. In particular, studies of climate and health frequently neglect to consider the dynamic nature of the interaction between climate and human health. Static, average risk models are typically created using average climate conditions to define human risk. However, temperature and precipitation are not frequently average (due to ENSO and other drivers of climate variability) and, therefore, an understanding of the expansion and contraction of vector habitats and dengue risk with climate variability and change is crucial to outbreak prevention and control. By incorporating forecast weather conditions or climate change scenarios within an integrated assessment of disease risk, surveillance and education efforts, which are typically funded by limited public health resources, can be effectively concentrated in the areas most likely to experience an outbreak.

3. STUDY AREA

The Hawaiian Islands are located in the North Pacific Ocean, between 19 and 22° N and 155 and 160° W. The elevation of the island chain ranges from sea level to 4205 m at the top of Mauna Kea on the Big Island of Hawaii, leading to varied temperature and precipitation regimes across the islands. The eastern windward sides are dominated by tropical easterlies and receive precipitation throughout the year. The western sides of the islands receive rain seasonally; summers are typically dry, and winter precipitation results from the occasional passage of low pressure systems (Kona lows) and fronts extending from extratropical low pressure systems (Sanderson 1993). A study of mosquito pest complaints on Oahu during the 1990s revealed that mosquito populations appear to fluctuate along with seasonality in rainfall, with a lag present in the data. Complaints were highest during the winter, spring, and summer months (Leong & Grace 2009); on the leeward side of the island in particular, mosquito populations likely 'bloom' following receipt of winter and spring rainfall, prompting mosquito pest complaints in the months that follow, and population numbers likely slowly decline during the summer as breeding sites desiccate during the dry season.

As noted earlier, an important source of climate variability in Hawaii is ENSO. Drought conditions typically occur with an El Niño event, while La Niña events are associated with above-average rainfall (Lyons 1982, Chu 1989, Sanderson 1993, Chu & Chen 2005). As experienced in other locations, the impact of ENSO events on precipitation in Hawaii can be near average or very extreme. For example, during the strong 1997–1998 El Niño, many stations in Hawaii recorded between 10 and 23 % of normal precipitation (Pierce 1998, Western Drought Coordination Council 1998). La Niña tends to have a less extreme impact on Hawaii's precipitation, which is typically near or above average during La Niña events, although some stations do report greater variation. The 2008–2009 La Niña resulted in rainfall totals ranging from 84 to 209 % of normal from October through December (Pacific ENSO Applications Climate Center 2009).

With respect to the impacts of climate change on Hawaii, climate change scenarios generally indicate that Hawaii will experience warmer temperatures and changed precipitation patterns in the future, although there is uncertainty in model estimates. The Pacific Islands Regional Assessment Group summarized the results of models attempting to predict future climates for Hawaii. Given that Canadian model results were very similar to Hadley results and climate processes relevant for the Pacific Islands such as ENSO 'were better resolved in the Hadley model' (Shea et al. 2001, p. 23), the assessment group's report focused particularly on Hadley Centre model (HadCM2) results. Those results indicate that by 2025–2034, the temperature in Hawaii is expected to increase by 1°C, and seasonal variations in precipitation are expected: there will be minimal change in winter precipitation in Hawaii, but summer rainfall is expected to increase by roughly 1.5 mm d^{-1} (45 mm mo^{-1}). These estimates are generally corroborated by Timm & Diaz (2009), although they examined changing rainfall patterns for the end, rather than the middle, of the 21st century. Timm & Diaz (2009) applied statistical downscaling to rainfall projections of the Intergovernmental Panel for Climate Change's Fourth Assessment Report for Hawaii and found that winter rainfall is likely to decrease by 5 to 10 % and summer rainfall is likely to increase by approximately 5 %.

4. DATA AND METHODS

The present study employed GIS to determine dengue risk in Hawaii under varied and changed climate conditions. Previous research has demonstrated that GIS is an effective tool for the delineation of areas at increased risk of vector-borne disease outbreaks, including Lyme disease (Nicholson & Mather 1996) and malaria (Martin et al. 2002). Additionally, dengue risk maps have been developed using GIS at the global scale (Hopp & Foley 2003), as well as for Argentina (Carbajo et al. 2001) and New Zealand (de Wet et al. 2001). Finally, Napier (2003) developed a risk model and map for Hawaii using GIS with a different approach and different variables than those included here.

The approach used to delineate average dengue risk, summarized here, was demonstrated in a previous study and is applied in the present study to consider climate variability and change. Kolivras (2006) combined temperature and precipitation data with entomological knowledge of the survival thresholds of *Aedes albopictus* to delineate the generalized boundaries of average habitat for the mosquito species in Hawaii using GIS. These same data sets were applied in the present study to improve and build upon the previous work by adjusting the average habitat area based on precipitation variability and a potential climate change scenario, and the population at risk was calculated with the use of gridded population data.

To develop the base model, monthly and annual PRISM (parameter-elevation regressions on independent slopes model) temperature and precipitation data, available at a resolution of 450 m for Hawaii and averaged over 1961–1990, were acquired from the PRISM Climate Group (www.prism.oregonstate.edu/; the model has been re-run for the present study using the 1971–2000 data that are now available for Hawaii). Station measurements of weather variables were combined with expert knowledge and topographic information using regression in order to create gridded PRISM layers; data sets were verified through the use of other spatial data sets and error statistics (Daly et al. 2002). Climate data layers were incorporated into the GIS, along with broad thresholds for *Aedes albopictus* survival summarized in Mitchell (1995), to develop the average habitat map. Generally speaking, more than 500 mm of annual rainfall is conducive to *Ae. albopictus*' establishment in a location, and a minimum temperature of 10°C during the coldest month is the approximate value for larvae survival (Mitchell 1995); tropical strains of *Ae. albopictus* are non-diapausing, meaning they are more sensitive to cold temperatures (Hawley et al. 1987). These cut-offs were used during initial model development to create Hawaii's average risk map. Additionally, a seasonal precipitation value of 40 mm during June, the driest month, was added to the model because conditions on the drier, leeward sides of the islands are less conducive to overall mosquito survival; 40 mm roughly represents one-twelfth of the total annual cut-off of 500 mm. Therefore, if a location experienced considerable seasonality in rainfall with very dry conditions during summer, that area was excluded from the general average habitat area defined in the present study. While fine-scale and short-term extremes clearly affect mosquito survival (Tsuda & Takagi 2001), the goal was to develop generalized mosquito habitat areas, thus broad-scale and longer-term data were used to develop this initial model.

Areas meeting precipitation and temperature thresholds were combined in an overlay analysis in the GIS using constraints, which are limitations placed on a model. Using Mitchell's (1995) description of *Aedes albopictus*' broad survival thresholds as constraints, 3 layers were created: one layer delineated areas in Hawaii that received more than 500 mm of rainfall annually, the second layer delineated areas with a minimum February temperature greater than 10°C, and the final layer delineated areas that received over 40 mm of rainfall during June. Areas meeting the threshold for each layer were assigned a '1' and those areas not meeting the threshold were assigned a '0'. Through the overlay analysis, areas had to meet all 3 survival thresholds in order to be delineated as habitat area; in other words, if a location met the 2 precipitation thresholds but experienced February temperatures below 10°C, it was not designated as an area that would support mosquito survival and/or reproduction.

The final average habitat area that met the 3 mosquito survival thresholds totaled 8385 km^2 (50.3% of Hawaii's area). Since spatially representative mosquito data were unavailable for validation, case locations from the 2001–2002 outbreak in Hawaii were used to validate the final mosquito habitat area map; 13 of the 20 communities with cases during the outbreak, representing 93% of the total number of cases, were located within the defined habitat area (Fig. 1).

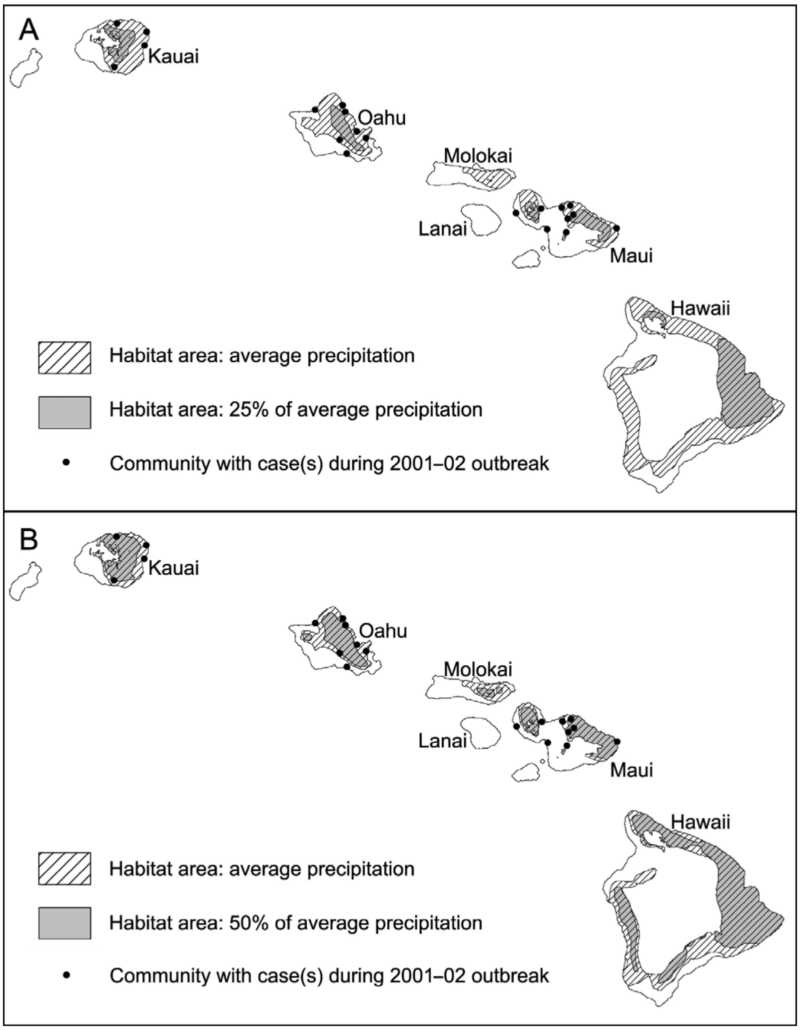

Fig. 1. Habitat area of *Aedes albopictus* at (A) 25% and (B) 50% of average precipitation. Communities with cases (case totals) during the 2001–2002 dengue fever outbreak were located on the following islands: Maui: Haiku (4), Hana area (77), Kihei (1), Kula (1), Lahaina (2), Makawao (1), Paia (1), Pukalani (1), and Wailuku (1); Oahu: Aiea (1), Haleiwa (1), Hauula (4), Honolulu (1), Kailua (3), Kaneohe (11), and Laie (5); and Kauai: Anahola (1), Hanalei (1), Kalaheo (1), and Kapaa (1)

In the present study, this initial average model was adjusted based on precipitation variability and a climate change scenario. Risk to humans was determined by calculating the population at risk under the different conditions. To represent precipitation receipt during a drought (e.g. during the typical El Niño), the model calculated the habitat area under 25 and 50% of average rainfall; above-average precipitation, such as that received under La Niña conditions, is represented by incorporating 125 and 150% of average rainfall into the model. To evaluate mosquito habitat and dengue risk in Hawaii under a climate change scenario, the initial model was shifted to incorporate a 1.5 mm precipitation increase per day (an additional 45 mm per month) and a 1°C temperature increase, as suggested by HadCM2 for 2025–2034 (Shea et al. 2001). The mid-21st century estimates were selected for the present study given that the results are thought to be more reliable than long-term estimates, and the present study seeks to estimate dengue risk changes in the coming decades rather than in the more distant future. The human population at risk under each scenario was calculated using gridded population data, based on US Census Bureau data from the 2000 census, acquired from the Socioeconomic Data and Applications Center (http://sedac.ciesin.columbia.edu/usgrid).

5. RESULTS

5.1. Climate variability

Variation in precipitation causes an expansion or contraction of the *Aedes albopictus* habitat area (Table 1). Under drought conditions, the habitat area contracts as compared to average conditions. With the receipt of 25 % of average precipitation, such as during a strong El Niño event, the mosquito habitat area represents 17.3 % of Hawaii's total land area, and roughly 180 000 people (of 1.2 million total residents) reside within the defined zone. The zone is mainly focused on the eastern windward sides of the islands, as well as mid-elevation areas on Kauai and western Maui; no areas on Lanai, which is in Maui's rain shadow, support mosquito habitat (Fig. 1A). When 50 % of average precipitation is received, the mosquito habitat area encompasses roughly one-third of Hawaii's land area, with 287 000 people located within the zone. *Ae. albopictus*' habitat remains concentrated mainly on the wetter windward sides of the islands, but some suitable areas for the mosquito's reproduction and survival are also present on the leeward sides, particularly on the island of Hawaii (Fig. 1B).

With above-average precipitation, the habitat area expands beyond the zone under average conditions, but not greatly (Fig. 2). The slight expansion mainly occurs on the leeward sides of the islands; however, many leeward areas are still too dry to support reproduction and survival of *Aedes albopictus*. With the receipt of 125 % of average precipitation, the habitat area encompasses just over one-half of Hawaii's land area and approximately 569 000 residents. The receipt of 150 % of average rainfall results in a modest expansion of the habitat area, which then covers 59 % of the islands and includes just over 744 000 residents.

The specific mechanisms that result in an expansion or contraction of *Aedes albopictus*' habitat under varied climates are related to mosquito breeding and survival characteristics. Female *Ae. albopictus* typically lay their eggs at or just above the water line in a natural or artificial container (Sota 1993), with rainfall raising the

Table 1. Size of the habitat area of *Aedes albopictus* and the population at risk under various climate conditions (percent of average precipitation, and climate change scenario)

Precipitation (%)	Area (km^2)	% Hawaii's total area	Population[a]
25	2879.7	17.3	179 851
50	5473.9	32.9	287 005
100	8385.4	50.3	532 036
125	9091.3	54.6	569 222
150	9807.4	58.9	744 206
Climate change	12 786.6	76.8	1 181 770

[a]Hawaii's total population was estimated at 1 211 538 during the 2000 Census (http://quickfacts.census.gov/qfd/states/15000.html)

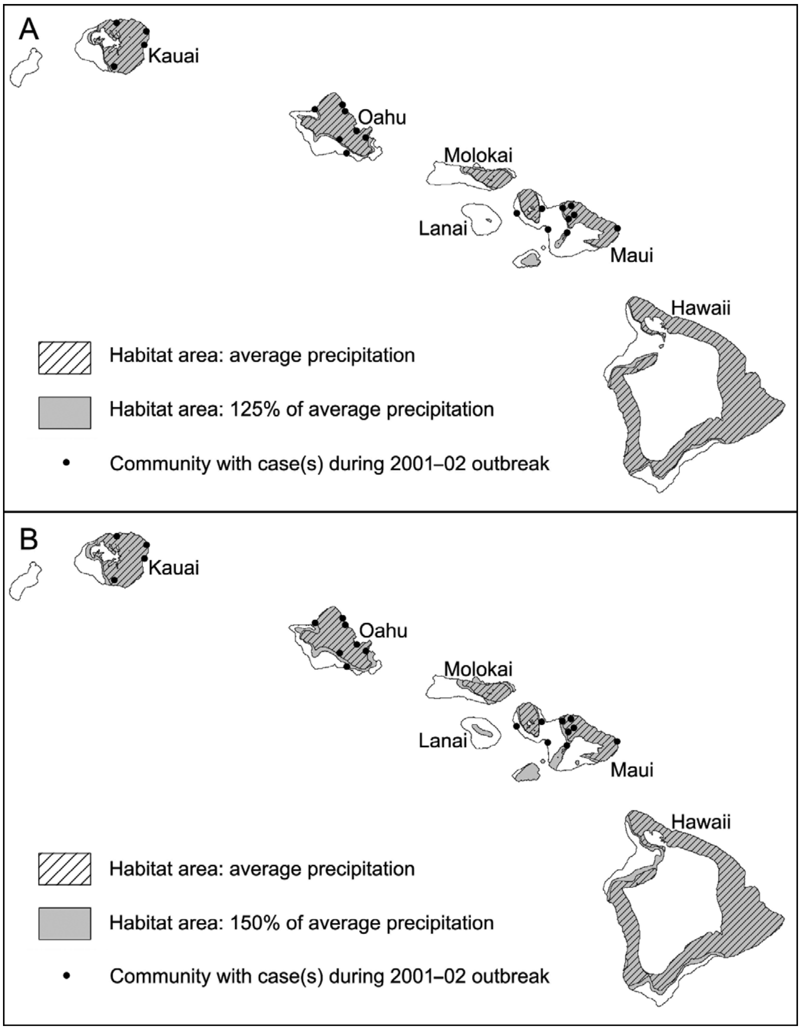

Fig. 2. Habitat area of *Aedes albopictus* at (A) 125 % and (B) 150 % of average precipitation. See Fig. 1 for number of dengue cases in each community

water level to provide the needed moisture so the eggs can then hatch. Depending on temperature and humidity conditions, eggs can survive a period of desiccation greater than 4 mo and are able to then hatch when inundated (Sota 1993). Therefore, during periods of below-average rainfall, adult mosquito populations will die, but the eggs can remain viable for a considerable time period. When moisture conditions return to optimal levels, the eggs can then hatch and the area will experience a mosquito 'bloom' several weeks after the rainfall event. In that way, the mosquito habitat areas delineated in the present study will contract under drought conditions and expand following precipitation receipt. Given that tropical populations of *Ae. albopictus* are non-diapausing (Hanson et al. 1993), they do not enter a period of dormancy that would allow them to survive cold temperatures. This lack of cold-hardiness limits mosquitoes to warmer middle and low elevations in Hawaii, and cold high-elevation areas are excluded from the defined habitat zones.

5.2. Climate change

The most dramatic change in *Aedes albopictus*' habitat area occurs under the climate change scenario. Given that models indicate favored conditions for mosquito survival in the future (i.e. warmer temperatures and greater summer rainfall), there is a considerable expansion of the habitat area as compared to average conditions (Fig. 3). Nearly all low- and mid-elevation areas on both the windward and leeward sides of the islands will support the survival of *Ae. albopictus*. Additionally, given the relatively low elevations on Oahu, Molokai, and Lanai as compared to the other islands, mosquito survival will not be limited by temperature at any location on those 3 islands. Small areas on the leeward sides of all islands are excluded from the habitat area given low summer precipitation receipt, and high elevation areas on Kauai, Maui, and Hawaii are limited by temperature. Under the climate change scenario, over three-quarters of Hawaii's land area and 1.1 million residents will be within *Ae. albopictus*' habitat area. It is also important to note that there will be continued fluctuations of mosquito habitat with climate variability under changed climate conditions. So while the climate change scenario indicates a single, static habitat zone, the drivers that currently result in an expansion or contraction of mosquito habitat will, with climate variability, also operate in a future, changed climate and cause fluctuations in the habitat zone.

The same biological mechanisms that support fluctuations in mosquito habitat under climate variability will contribute to the expansion of mosquito habitat under the climate change scenario. The temperature increase expected in the next several decades will permit the survival and reproduction of mosquitoes at higher elevations. Increased summer rainfall predicted for Hawaii will not affect mosquito habitat on the windward sides of the islands, as those areas already receive enough rainfall to support mosquito habitat; however, rainfall on the drier leeward sides will provide sufficient moisture for mosquito eggs to hatch.

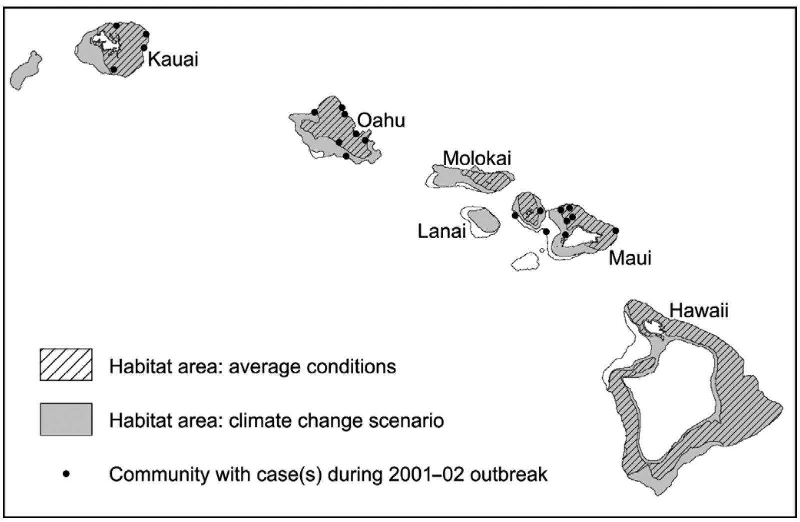

Fig. 3. Habitat area of *Aedes albopictus* under a climate change scenario with a 1°C temperature increase and increased summer precipitation. See Fig. 1 for number of dengue cases in each community

6. DISCUSSION AND CONCLUSIONS

The goals of the present study were to examine the expansion and contraction of *Aedes albopictus*' habitat area in Hawaii using mosquito survival thresholds under varied and changed climate conditions, and to determine the population at risk for dengue based on residence in the defined habitat area. This study built on a previously developed framework to examine the relationship between *Ae. albopictus* and climate conditions by adding notions of variability and change to an average, static habitat model. While *Ae. albopictus* also breeds in artificial containers near human habitation, this study delineated areas with climate conditions that would allow the mosquito to breed in natural sites, such as rockholes and vegetation. The approach contributes to the overall understanding of climate–dengue relationships, and the results elucidate areas to focus on as a starting point for dengue prevention and control and for further fine-scale, in-depth analyses. The research represents a case study that demonstrates how information on climate and mosquito ecology can be combined to develop disease risk maps, and generally advances our understanding of data needs and methodological issues when mapping vector-borne disease risk.

In a broad sense, the present study responds to the need to evaluate fluctuations in health risks based on climate variability and change to help public health decision-makers react to forecast conditions (Shea et al. 2001). The results of the present study confirm that the habitat area of *Aedes albopictus* and the population at risk for dengue in Hawaii will expand and contract under varied and changed climate conditions. Under drought conditions, such as during an El Niño event, the area of the defined habitat region and the number of residents at risk decrease, while both values increase when above-average precipitation is received, such as under La Niña conditions. Under a future warmer and wetter climate, the habitat area expands considerably. This expansion puts nearly all residents of Hawaii at risk for dengue transmission, given that the state's population is concentrated at low and middle elevations where temperature and precipitation conditions will be suitable for mosquito survival. It is important to note that the model can be used by public health officials to develop projections that account for the transient states between and beyond the projections presented here; for example, rainfall greater than 150% of normal will result in a further expansion of the habitat area, while rainfall below 25% of normal will lead to a contracted habitat zone. Similarly, different climate change scenarios can be used to shift the scenario presented here. If temperatures warm in excess of 1°C by 2025–2034, then higher elevations that are currently excluded from the habitat area under the climate change scenario will experience temperatures that are warm enough to support mosquito survival and reproduction.

In an applied sense, the results of the present study can be used to shape mosquito control efforts and identify vulnerable populations based on forecast weather conditions. While dengue is not considered to be endemic to Hawaii, the presence of *Aedes albopictus* and contact between Hawaii and endemic locations in East Asia and the South Pacific mean that another outbreak could occur in the future. The findings provide a starting point for targeting dengue surveillance, should the virus be reintroduced to the mosquito population, and mosquito control and public education efforts can be concentrated in specific areas once an outbreak is initiated. In this sense, often scarce human and financial public health resources can be used most efficiently and directed to the areas with the greatest need based on a forecast La Niña or El Niño, or under a future warmer, wetter climate. In their review of the use of risk maps and spatial modeling to operationalize dengue control, Eisen & Lozano-Fuentes (2009) link the results of research studies with vector control programs, noting that the use of such techniques can specifically be used by public health officials to target priority areas for vector control through the generation of static or dynamic dengue risk maps.

Given that no vaccine is currently available for dengue, although a considerable amount of research currently focuses on vaccine development (Stephenson 2005), prevention can only be accomplished through mosquito control, which can be concentrated in the right place and at the right time based on climate forecasts and the results of the present study. While any individual can provide breeding sites for *Aedes albopictus* if water is stored in artificial containers near the home, and the presence of mosquitoes on the drier, leeward sides of islands confirms that human activity provides such breeding sites (Leong & Grace 2009), these sites can be eliminated with effective public health education programs and individual efforts to remove standing water. By identifying areas where climate conditions would allow mosquitoes to breed in natural sites, such as treeholes or vegetation, which are more difficult to control than human-provided breeding sites, the present study determined locations where the risk of contracting dengue would be more difficult to minimize during an outbreak.

While most other studies are at a broader scale or for a different region of the world, the findings of the present study agree with the general results of other studies of dengue risk potential. At the global scale, Hopp & Foley (2003) also found precipitation to be a limiting factor under drought conditions, such as during El Niño in Hawaii, and saw an increase in modeled mosquito habitat when rainfall receipt increased. At a regional scale, studies that used GIS to examine *Aedes albopictus* habitat or dengue risk in a non-endemic area were conducted in New Zealand (de Wet et al. 2001) and Japan (Kobayashi et al. 2002). Given that both are located in the mid-latitudes rather than the tropics, the results are not easily compared to those of the present study; however, there are links that can be established, particularly since the study areas are islands. In Japan, where temperature is the main limiting factor for mosquito survival, *Ae. albopictus* appears to be confined to low-elevation areas where the annual mean temperature is above 11°C (Kobayashi et al.

2002). Furthermore, the range of *Ae. albopictus* is expected to expand latitudinally under warmer conditions, reaching the northern Japanese island of Hokkaido by 2100 (Kobayashi et al. 2008), which is similar to the altitudinal expansion found in the present study. The suitable area for *Ae. albopictus* survival in New Zealand, where temperature is also an important controlling factor, will similarly expand under warmer conditions, and a considerable portion of the low-elevation areas will be at increased risk for dengue transmission by 2100 (de Wet et al. 2001).

When comparing the results to studies of dengue risk in tropical island locations, the findings are comparable. In a study of mosquito populations in Puerto Rico, Moore et al. (1978) found variation in *Aedes aegypti* populations and dengue across the island; seasonal rainfall patterns had a clear relationship with mosquito populations. In drier areas of Puerto Rico, a higher number of containers had larvae during the rainy season than during the dry season, while in locations with less seasonality in rainfall, such as along the wetter north coast, there was a corresponding lack of seasonality in larval populations. The model created by Napier (2003) indicated that tropical rainforest areas with annual rainfall in the 1500 to 5000 mm range are within the defined dengue threat area for Hawaii. Mosquito survival thresholds were not included as input in the study, rather environmental characteristics of areas with cases during the 2001–2002 outbreak, along with climate data at a coarser resolution than incorporated here, were used to train the model. Generally, the high risk areas identified by Napier (2003) are comparable to those identified in the present study.

Future iterations of the model can be improved with more detailed mosquito survival information achieved through long-term mosquito surveillance, the inclusion of human behavioral factors, and analyses at multiple spatial scales. A long-term, spatially representative record of mosquito data will also support the verification of the risk maps created in the present study. As with other vector-borne diseases, climate is only one factor involved in the transmission of dengue, although the present and other studies clearly show that it is an important factor. Specifically, the relationship between vector-borne disease and climate is complicated by human activity and socio-economic status (Comrie 2007). Non-climatic factors, such as human behavior, sanitation (e.g. storage of tires and the proper disposal of garbage), and water storage, all play a role in transmission as well. It is significant to note, though, that these human behaviors can be improved through public health campaigns. We can adapt to and prepare for increased disease risk by modifying behaviors based on forecasts combined with predictive models, such as the model presented here.

The scale of analysis also complicates the examination of dengue risk given that there are different mechanisms operating at different spatial scales. At the relatively coarse island-wide scale examined in the present study, El Niño typically brings drought and likely results in a decrease of mosquito habitat in trash or containers left outside and within natural breeding sites. However, at the fine scale, streams may nearly dry up and leave behind pockets of standing water; larvae were identified in standing pools that had formed in streams during the 2001–2002 outbreak in Hawaii (Napier 2003). So while above-average precipitation typically provides breeding sites broadly across the islands, droughts could actually result in the formation of localized breeding sites. Given processes occurring at different spatial scales, future work will include analyses at multiple scales, including a fine-scale analysis of potential stream habitats.

Several areas remain to be explored using GIS to improve our understanding of mosquito habitat and dengue risk. Since human activity plays a clear role in dengue incidence, future studies could incorporate human behavior and climate impacts at multiple scales using a mixed methods approach. Qualitative data regarding water storage practices and the perception of disease risk gathered during surveys and interviews could be combined with environmental data to create a more holistic model of dengue risk. Also, other studies have noted a time lag with respect to precipitation and the appearance of dengue cases, so future work can consider the timing of the spatial shifts identified in the present study; such research should include spatio-temporal impacts on dengue viruses, given that the reproduction and transmission of the viruses are influenced by temperature variability and the EIP will be shortened at the warmer temperatures expected under future climate scenarios. Finally, the protocol developed here can be applied to the study of how climate variability and change can affect the distribution of other vector-borne diseases.

Dengue risk is generally highest in tropical, less-developed locations, given the interaction between environmental characteristics and human behavior with respect to water storage (Phillips 2008); however, recent outbreaks in Hawaii and Brownsville, Texas, USA (Brunkard et al. 2007), illustrate the vulnerability of developed regions of the world when the dengue virus is introduced to established populations of *Aedes albopictus* or *Ae. aegypti*. Additionally, poor regions within developed countries are at greater risk than wealthier areas (Brunkard et al. 2007, Phillips 2008). Isolated locations, such as Hawaii, may have viewed distance as a protective factor with respect to public health in the past (Woodward et al. 1998). However, Hawaii's 2001–2002 dengue outbreak and the continued risk illustrated by the present study show that our increased inter-connectedness, via trade and human travel, along with environmental variability, allow diseases to easily overcome the barrier of distance. Dengue and other infectious diseases are spreading globally, exposing more people to infection, so concentrating limited public health resources in the right areas is critically important to rapidly identifying an outbreak and controlling the spread of disease.

Acknowledgements. I thank the anonymous reviewers for helpful suggestions, and C. Luebbering for technical assistance.

LITERATURE CITED

Brunkard JM, Lopez JLR, Ramirez J, Cifuentes E and others (2007) Dengue fever seroprevalence and risk factors, Texas-Mexico border, 2004. Emerg Infect Dis 13:1477–1483

Carbajo AE, Schweigmann N, Curto SI, de Garín A, Bejarán R (2001) Dengue transmission risk maps of Argentina. Trop Med Int Health 6:170–183

Centers for Disease Control and Prevention (2007) Dengue fever. Available at: www.cdc.gov/ncidod/dvbid/dengue/index.htm

Chu PS (1989) Hawaiian drought and the Southern Oscillation. Int J Climatol 9:619–631

Chu PS (1995) Hawaii rainfall anomalies and El Niño. J Clim 8:1697–1703

Chu PS, Chen H (2005) Interannual and interdecadal rainfall variations in the Hawaiian Islands. J Clim 18:4796–4813

Clark GG, Rigau-Perez JG, Vorndam V, Hayes JM (2002) Imported dengue — United States, 1999 and 2000. Morb Mortal Wkly Rep 51:281–283

Comrie A (2007) Climate change and human health. Geogr Compass 1:325–339

Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P (2002) A knowledge-based approach to the statistical mapping of climate. Clim Res 22:99–113

de Wet N, Ye W, Hales S, Warrick R, Woodward A, Weinstein P (2001) Use of a computer model to identify potential hotspots for dengue fever in New Zealand. NZ Med J 114: 420–422

Delatte H, Gimonneau G, Triboire A, Fontenille D (2009) Influence of temperature on immature development, survival, longevity, fecundity, and gonotrophic cycles of *Aedes albopictus*, vector of chikungunya and dengue in the Indian Ocean. J Med Entomol 46:33–41

Effler PV, Pang L, Kitsutani P, Vorndam V and others (2005) Dengue fever, Hawaii, 2001–2002. Emerg Infect Dis 11: 742–749

Eisen L, Lozano-Fuentes S (2009) Use of mapping and spatial and space-time modeling approaches in operational control of *Aedes aegypti* and dengue. PLoS Negl Trop Dis 3: e411

Gagnon AS, Bush ABG, Smoyer-Tomic KE (2001) Dengue epidemics and the El Niño Southern Oscillation. Clim Res 19:35–43

Gubler DJ, Reiter P, Ebi KL, Yap W, Nasci R, Patz JA (2001) Climate variability and change in the United States: potential impacts on vector- and rodent-borne diseases. Environ Health Perspect 109:223–233

Guzman MG, Kouri G (2002) Dengue: an update. Lancet Infect Dis 2:33–42

Hales S, Weinstein P, Woodward A (1996) Dengue fever epidemics in the South Pacific: Driven by El Niño Southern Oscillation? Lancet 348:1664–1665

Hales S, de Wet N, Maindonald J, Woodward A (2002) Potential effect of population and climate changes on global distribution of dengue fever: an empirical model. Lancet 360: 830–834

Hanson SM, Craig JPJPM, Jr GB, Novak RJ (1993) Reducing the overwintering ability of *Aedes albopictus* by male release. J Am Mosq Control Assoc 9:78–83

Hawley WA, Reiter P, Copeland RS, Pumpuni CB, Craig GB Jr (1987) *Aedes albopictus* in North America: probable introduction in used tires from northern Asia. Science 236: 1114–1116

Hopp MJ, Foley JA (2001) Global-scale relationships between climate and the dengue fever vector, *Aedes aegypti*. Clim Change 48:441–463

Hopp MJ, Foley JA (2003) Worldwide fluctuations in dengue fever cases related to climate variability. Clim Res 25: 85–94

Jetten TH, Focks DA (1997) Potential changes in the distribution of dengue transmission under climate warming. Am J Trop Med Hyg 57:285–297

Kobayashi M, Nihei N, Kurihara T (2002) Analysis of northern distribution of *Aedes albopictus* (Diptera: Culicidae) in Japan by geographic information system. J Med Entomol 39:4–11

Kobayashi M, Komagata O, Nihei N (2008) Global warming and vector-borne infectious diseases. J Disaster Res 3: 105–112

Kolivras KN (2006) Mosquito habitat and dengue risk potential in Hawaii: a conceptual framework and GIS application. Prof Geogr 58:139–154

Kolivras KN, Comrie AC (2007) Regionalization and variability of precipitation in Hawaii. Phys Geogr 28:76–96

Kuno G (1997) Factors influencing the transmission of dengue viruses. In: Gubler DJ, Kuno G (eds) Dengue and dengue hemorrhagic fever. CAB International, New York, p 61–88

Leong M, Grace JK (2009) Occurrence of distribution of mosquitoes (Diptera: Culicidae) of public health importance on the island of Oahu. Proc Hawaii Entomol Soc 41:57–70

Lyons SW (1982) Empirical orthogonal function analysis of Hawaiian rainfall. J Appl Meteorol 21:1713–1729

Martin C, Curtis B, Fraser C, Sharp B (2002) The use of a GIS-based malaria information system for malaria research and control in South Africa. Health Place 8:227–236

McMichael AJ, Haines A, Slooff R, Kovats S (eds) (1996) Climate change and human health. World Health Organization, Geneva

McMichael AJ, Campbell-Lendrum D, Kovats S, Edwards S and others (2004) Global climate change. In: Ezzati M, Lopez AD, Rodgers A, Murray CJL (eds) Comparative quantification of health risks: global and regional burden of disease due to selected major risk factors. World Health Organization, Geneva

Mitchell CJ (1995) Geographic spread of *Aedes albopictus* and potential for involvement in arbovirus cycles in the Mediterranean basin. J Vector Ecol 20:44–58

Moore CG, Cline BL, Ruiz-Tiben E, Lee D, Romney-Joseph H, Rivera-Correa E (1978) *Aedes aegypti* in Puerto Rico: environmental determinants of larval abundance and relation to dengue virus transmission. Am J Trop Med Hyg 27:1225–1231

Morse SS (1995) Factors in the emergence of infectious diseases. Emerg Infect Dis 1:7–15

Napier M (2003) Application of GIS and modeling of dengue risk areas in the Hawaiian Islands. 30th Int Symp Remote Sens Environ, Honolulu, HI

Nicholson MC, Mather TN (1996) Methods for evaluating Lyme disease risks using geographic information systems and geospatial analysis. J Med Entomol 33:711–720

Pacific ENSO Applications Climate Center (2009) Pacific ENSO Update, 1st Quarter 2009 Vol. 15 No. 1. Available at http://www.soest.hawaii.edu/MET/Enso/peu/2009_1st/hawaii.htm

Patz JA, Martens WJM, Focks DA, Jetten TH (1998) Dengue fever epidemic potential as projected by general circulation models of global climate change. Environ Health Perspect 106:147–153

Phillips ML (2008) Dengue reborn: widespread resurgence of a resilient vector. Environ Health Perspect 116: A382–A388

Pierce RV (1998) Monthly precipitation summary. Available at www.wrcc.dri.edu/monitor/hawaii.9802

Rodhain F, Rosen L (1997) Mosquito vectors and dengue virus–vector relationships. In: Gubler DJ, Kuno G (eds) Dengue and dengue hemorrhagic fever. CAB International, New York, p 45–60

Sanderson M (1993) Prevailing trade winds. University of Hawaii Press, Honolulu, HI

Schreiber KV (2001) An investigation of relationships between climate and dengue using a water budgeting technique. Int J Biometeorol 45:81–89

Shea EL, Dolcemascolo G, Anderson CL, Barnston A and others (2001) Preparing for a changing climate: the potential consequences of climate variability and change. Pacific Islands. East-West Center, Honolulu, HI

Sota T (1993) Response to selection for desiccation resistance in *Aedes albopictus* eggs (Diptera: Culicidae). Appl Entomol Zool 28:161–168

Stephenson JR (2005) Understanding dengue pathogenesis: implications for vaccine design. Bull W H O 83:308–314

Taylor GE (1984) Hawaiian winter rainfall and its relation to the Southern Oscillation. Mon Weather Rev 112: 1613–1619

Timm O, Diaz HF (2009) Synoptic-statistical approach to regional downscaling of IPCC twenty-first-century climate projections: seasonal rainfall over the Hawaiian Islands. J Clim 22:4261–4280

Tsuda Y, Takagi M (2001) Survival and development of *Aedes aegypti* and *Aedes albopictus* (Diptera: Culicidae) larvae under a seasonally changing environment in Nagasaki, Japan. Environ Entomol 30:855–860

Western Drought Coordination Council (1998) Western climate and water status, April 1998: quarterly report. Available at www.drought.unl.edu/wdcc/quarterly/wcws9804/wcws9804.html

Woodward A, Hales S, Weinstein P (1998) Climate change and human health in the Asia Pacific region: Who will be most vulnerable? Clim Res 11:31–38

Editorial responsibility: Nils Chr. Stenseth, Oslo, Norway

Submitted: November 2, 2009; Accepted: March 30, 2010
Proofs received from author(s): April 22, 2010