Wind-Blown Mosquitoes and Introduction of Japanese Encephalitis into Australia

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Backtrack simulation analysis indicates that wind-blown mosquitoes could have traveled from New Guinea to Australia, potentially introducing Japanese encephalitis virus. Large incursions of the virus in 1995 and 1998 were linked with low-pressure systems that sustained strong northerly winds from New Guinea to the Cape York Peninsula.

Japanese encephalitis (JE) is a recently emerged disease in Australia (1). Two major incursions have occurred, in 1995 and 1998; the earlier outbreak caused three human cases on Badu Island in Torres Strait (2,3). In 1996-97, JE virus activity was limited to Saibai Island, the northernmost island in Torres Strait (3). The 1998 incursion was more widespread, with JE activity from the Torres Strait south to the Mitchell River on Cape York Peninsula (3). Human serosurveys in the Western Province of Papua New Guinea, which–along with Irian Jaya–is considered a probable source of the virus in the Australian incursions (4), indicate that JE virus was not confirmed in the region before 1989 (1). Thus, the incursions of JE virus into Australia are novel. The *Culex annulirostris* mosquito is likely the primary vector (5).

JE virus may have been introduced into Australia by infected birds (2), frugivorous bats (J. Mackenzie, pers. comm.), or mosquitoes (2,3). However, the widespread, sudden appearance of JE virus in the Torres Strait and Cape York Peninsula suggests that it was an episodic incursion potentially mediated by mosquitoes (2,3). *Cx. tritaeniorhynchus*, an Asian JE virus vector, is migratory in China (6) and has been collected at altitudes >100 m in India and China (6,7). In New South Wales, Australia, *Cx. annulirostris* has been collected at heights up to 310 m with an estimated flight range of 594 to 648 km, well beyond the 160 km from New Guinea to northernmost Cape York Peninsula (8). Similar incursions of bluetongue virus into northern Australia (9) are thought to be mediated by wind-blown, exotic *Culicoides* midges from Indonesia (10).

The Study

We used computer simulation to investigate whether winds were sufficient to have carried mosquitoes from New Guinea to the Torres Strait and Cape York Peninsula, potentially introducing JE virus into northern Australia. The *Helicoverpa* migration model incorporates wind speed and direction to simulate migratory flights for *Helicoverpa* spp. noctuid moths in Australia (11). We used wind speed and direction generated by the Regional Assimilation and Prognosis System (1995-96) and the Limited Area Prediction System (1996-97 onwards) of the Australian Bureau of Meteorology Research Centre (Melbourne). Backtrack simulations were used to map flight paths of mosquitoes from a focus of JE virus activity back to their potential source. Simulation parameters used were a) flight time: 20:00 Australian Eastern Standard Time; b) flight duration: 0-11 hours; c) flight altitude: 100-400 m; and d) flight speed: 0 meters/second. Flight duration and height were randomly sampled from uniform probability distributions in Monte Carlo simulations of 1,000 replicates (mosquitoes) each. The estimated flight paths are conservative; trajectories would have been longer if we had included the mosquito downwind flight speed (an estimated 5 to 7 km/hr [12]) and a longer flight time.

Backtrack simulations were run from December to March for the 1995-96 and 1997-98 seasons, encompassing the monsoon season, when westerly to northwesterly winds dominate. In 1994-95, simulations were limited to January 16-20 and February 8 to March 31, 1995; flight trajectories on other days were estimated from maps of wind speed and direction provided by the Tropical Area Projection System (Bureau of Meteorology, Darwin, Australia). Simulations were run for Badu Island in the Torres Strait, the northern peninsula area, and the mouth of the Mitchell River on Cape York Peninsula. These sites are 100 km, 160 km, and 675 km from the New Guinea mainland, respectively (Figure 1). Badu Island had JE virus activity in March-April 1995 and February-March 1998, while activity was limited to February-May 1998 in the Cape York Peninsula sites.

The simulations indicate that winds sufficient to transport mosquitoes from New Guinea frequently reach Badu Island (mean 14.2% [Table]). No association with JE activity has been confirmed. In 1994-95, the year of the initial incursion, only eight nights (6.6%) had favorable winds. Conversely, in the 1995-96 and 1996-97 seasons, JE virus activity was limited to islands within 5 km of Papua New Guinea (3) despite favorable winds for transport to Badu Island on 17% of nights (Table). Both Cape York Peninsula locations had fewer nights with favorable winds (Table). Only on December 27, 1997, were winds sufficient to carry mosquitoes from New Guinea to the mouth of the Mitchell River (Figure 2).

Weather conditions before the 1995 and 1998 JE outbreaks suggest that low-pressure systems west of Cape York Peninsula could have carried mosquitoes from New Guinea to the study sites. On January 19, 1995, a large monsoonal

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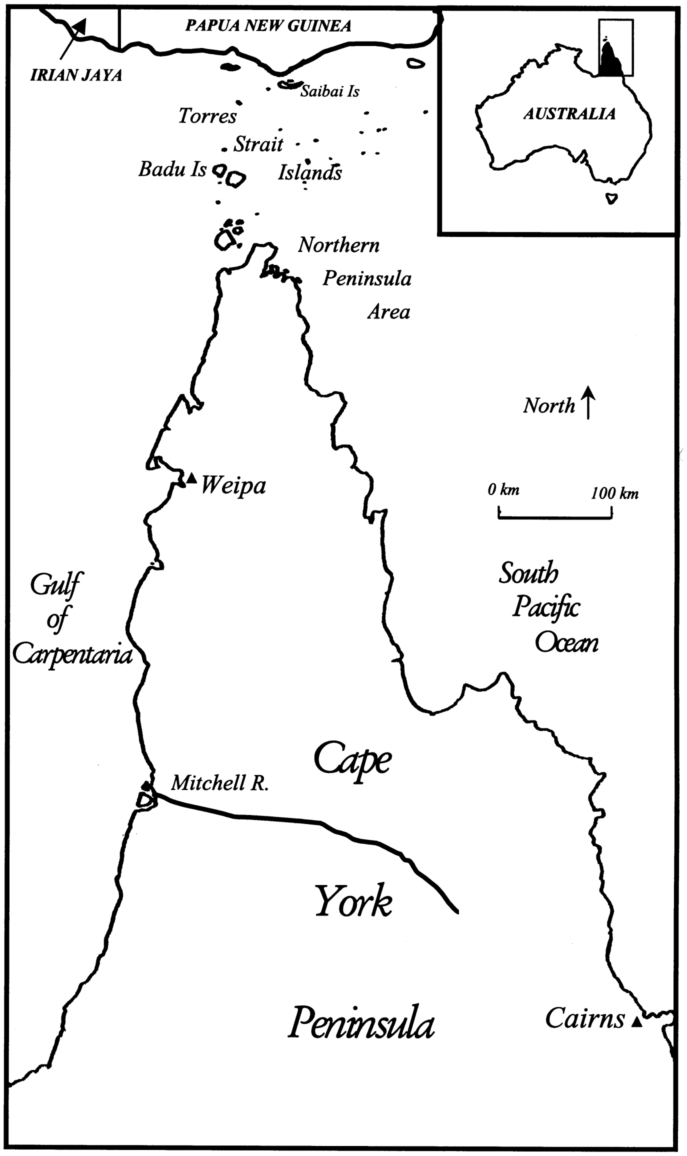

Figure 1. Map showing location of Japanese encephalitis foci (Badu Island in the Torres Strait, the northern peninsula area, and the mouth of the Mitchell River in Cape York) used in backtrack simulations.

low in the Northern Territory sustained 15 to 20 km/hour northerly winds from southern Papua New Guinea across the Torres Strait into northernmost Cape York Peninsula. The weather preceding the widespread JE outbreak in 1998 was especially noteworthy. In December 1997, Tropical Cyclone Sid in the Gulf of Carpentaria west of Cape York Peninsula produced northerly winds of 36 to 72 km/hour, which were capable of carrying mosquitoes from New Guinea to the Northern peninsula area on December 27 (Figure 2). Furthermore, the system persisted in the area, sustaining northwesterly winds capable of carrying mosquitoes from New Guinea to Badu Island and the northern peninsula area for 11 of 14 days and 8 of 14 days, respectively, from December 26, 1997, to January 8, 1998.

The arrival dates of migrating mosquitoes in 1995 and 1997 would have allowed sufficient time for amplification of JE virus in vertebrate hosts and subsequent spillover into humans. In Japan, two cycles of JE viral amplification occur in pigs, with human cases peaking approximately 2 months after pigs are infected (13). Thus, for Badu Island, where human JE cases occurred in late March 1995 and in late February 1998, JE virus was likely introduced in late January 1995 and late December 1997, respectively. These dates correspond to the weather events described above.

Conclusions

Backtrack simulations indicate that winds sufficient to transport mosquitoes from New Guinea to Badu Island occurred frequently (Table). However, many favorable wind conditions were not followed by JE virus activity (e.g., 1995-96 [Table]), suggesting that other factors influence incursions of JE virus.

Several conditions would have to be met to permit a large incursion of windblown, infected mosquitoes from New Guinea into Australia. First, there would have to be a sufficient amount of JE virus at the potential source of migrant mosquitoes. Results of human serologic tests indicate that JE virus has been active in southern Papua New Guinea since 1989 (4), especially in late 1997 and early 1998, when multiple human cases were reported (1). Second, large populations of JE virus-infected mosquitoes must be present. The southern part of New Guinea (approximately 160,000 km^2)

Table. Number of days when winds could have carried mosquitoes from New Guinea to Badu Island in the Torres Strait and to the northern peninsula area and the mouth of the Mitchell River on Cape York Peninsula[a]

Year	No. of days[b]	Badu Island (Torres Strait) days (%)	Northern peninsula area (Cape York) days (%)	Mouth of Mitchell River (Cape York) days (%)
1994-95	121	8 (6.6)	0 (0)	0 (0)
1995-96	122	21 (17.2)	7 (5.7)	0 (0)
1996-97	121	20 (16.5)	8 (6.6)	0 (0)
1997-98	121	20 (16.5)	11 (9.1)	1 (0.8)
Mean	121	17.3 (14.2)	6.5 (5.4)	0.25 (0.2)

[a]Based on backtrack simulations done during the monsoon season (December to March) for the seasons 1994-95 through 1997-98.
[b]Backtrack-simulated flight path with one or more pixels completely within the New Guinea mainland (e.g., Figure 1B).

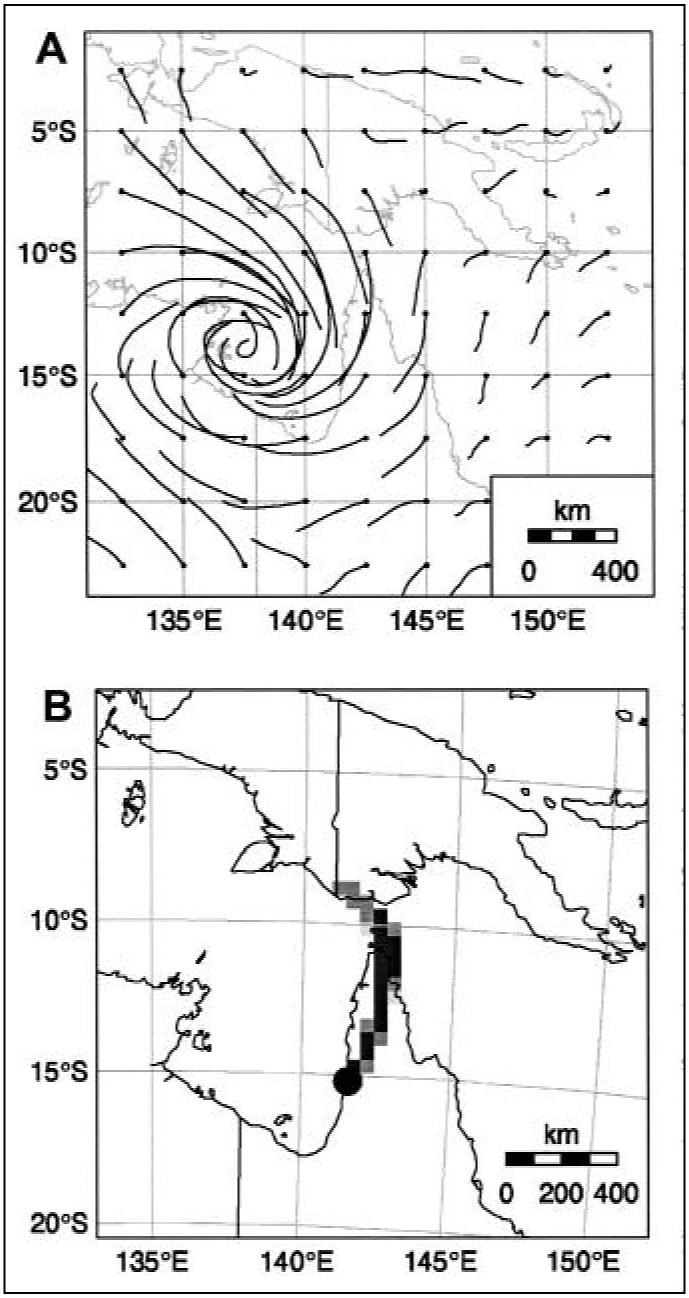

Figure 2. The estimated flight trajectories at 100 m (A) and back-track simulations (B) of mosquitoes from the Mitchell River for December 27, 1997. Shading represents the number of back trajectory endpoints per km^2 per million simulated mosquito trajectories, with white = 0, light = <10, medium 10 to 20, and dark >20.

is dominated by lowland swamps and lakes. In late 1997 and early 1998, a severe drought created stagnant wetlands, producing high populations of *Cx. annulirostris* (3). In February 1998, 39% of 26 light trap collections in the southeastern part of the Western Province of Papua New Guinea contained >10,000 female *Cx. annulirostris* (C. Johansen, unpub. data), and JE virus was isolated from them. Third, substantial numbers of the *Cx. annulirostris* vector must exploit high winds in the atmospheric boundary layer for long-distance travel. Female *Cx. annulirostris* have been collected at altitudes $\leq$310 m in western New South Wales at densities comparable with those of mosquitoes collected in India and China (8). Finally, wind speed and direction must be capable of carrying the vector to the area in question.

Our results suggest that the necessary wind conditions occur annually in the Torres Strait but only rarely beyond the northern peninsula area of Cape York Peninsula (Table). Monsoonal winds are typically westerly to west-northwesterly in the Torres Strait; mosquitoes carried from New Guinea by these winds would bypass all but the northernmost Torres Strait islands. The rarity of JE virus incursions deep into Cape York Peninsula indicates that it is an extreme, episodic event. Our simulations link the 1995 and 1998 JE virus incursions with tropical low-pressure systems west of Cape York Peninsula. These large systems can sustain northerly winds capable of carrying mosquitoes from New Guinea or even Badu Island into Cape York Peninsula. In addition, the convergent winds and unstable atmosphere of these low-pressure systems would enhance entrainment of mosquitoes into the upper boundary layer. Associated storms with heavy rain would aid mosquitoes' descent to land. Large-scale migration of insects, including mosquitoes, is often associated with large-scale weather systems with extensive wind fields (14), such as tropical low-pressure systems.

Direct evidence confirms that *Cx. annulirostris* travel from Papua New Guinea into northern Australia. Electrophoretic analysis of *Cx. annulirostris* populations collected from 1996 to 1998 in Papua New Guinea, the Torres Strait, and Cape York indicates substantial gene flow, indicating dispersal between the populations (H. Chapman and S. Ritchie, unpub. data).

Despite evidence that windborne mosquitoes could have introduced JE virus into northern Australia, additional field studies should be conducted. Northerly winds originating from New Guinea can be sampled for *Culex* mosquitoes and other potential vectors. Other incursion mechanisms, such as the movement of viremic birds and fruit bats, need to be investigated, as well as their ability to infect *Culex* mosquitoes.

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