ABSTRACT

One hypothesis to explain the southern extension of Japanese encephalitis (JE) virus from Papua New Guinea into the Torres Strait islands in 1995 and to mainland Australia in 1998 is the dispersal of infected mosquitoes, particularly Culex annulirostris Skuse from which JE virus has been isolated repeatedly. To investigate whether this species disperses in this manner, mosquitoes were identified from 368 aerial kite trap collections operated at 50–310 m (altitude) at inland New South Wales between November 1979 to December 1984. Forty samples (9 during daylight and 31 at night) contained mosquitoes, of which 221 could be identified as Culex australicus Dobrotworsky & Drummond (35.8%), Culex annulirostris (21.3%), Anopheles annulipes Walker s.l. (10.4%), Aedes theobaldi (Taylor) (7.2%), Aedes rudibitorax (Macquart) (1.4%), and Aedes sugger (Skuse) (<0.9%). During the night, mosquitoes were found in 22.6% of the collections at a mean density (±SD) of 91.3 ± 151.7/10^6 m^3 of air sampled. During the day, only 3.8% were positive at a mean density 125.3 ± 152.1. When examined in relation to possible flying time and wind speed, mean ± SD dispersal distances by day and night were 23.9 ± 15.3 km and 152.4 ± 116.3 km, respectively. These data provide circumstantial evidence that aerial carriage southward ~200 km from Papua New Guinea to Cape York peninsula is feasible, but that southern dispersal of Murray Valley encephalitis virus infected mosquitoes from tropical to temperate Australia is unlikely.

KEY WORDS Culex annulirostris, mosquito dispersal, epidemiology, Japanese encephalitis, Murray Valley encephalitis.
and MVE viruses. The position of this zone, where southerly winds from the Southern Hemisphere meet northerly winds from the Northern Hemisphere, moves north and south during the northern and southern summers, respectively. The zone is associated with rains and warm winds, and in some years it may move further north or south than during other years. However, this zone rarely extends far enough south in Australia to transport insects over the distances postulated by Sellers.

As a preliminary test of these hypotheses, i.e., that dispersing mosquitoes, especially Cx. annulirostris, can ascend into the atmospheric boundary layer, we examined 368 kite trap collections of microinsects, carried out by the Commonwealth Scientific and Industrial Research Organization (Commonwealth Scientific and Industrial Research Organization) Division of Entomology from November 1979 to December 1984 at Trangie, Hay, and Hillston in inland New South Wales. Such localities were situated on a possible flight path of MVE virus-infected mosquitoes into temperate Australia. Our article details the first aerial collections of mosquitoes including Cx. annulirostris from Australia, and considers this means of dispersal in relation to the likely mode of southern transport of JE and MVE viruses into tropical and temperate Australia, respectively.

Materials and Methods

Trangie (32° 02’ S, 147° 59’ E), Hillston (33° 29’ S, 145° 32’ E) and Hay (34° 30” S, 144° 51” E) are inland rural towns in New South Wales. Between October 1979 and February 1984, 310 aerial samples were obtained during field trips to Trangie, 198 by day and 112 by night. During November 1984, 24 collections were made at Hillston (16 by day, 8 by night) followed by 34 collections at Hay in December 1984 (17 each by day and night).

When wind conditions were suitable, a kite was launched and allowed to ascend to a predetermined altitude in the planetary boundary layer using methylenecrilate foam. A net of 1 m² cross section with a detachable terylene bag 50 cm long was attached to the kite line by a pulley and allowed to ascend by natural wind pressure in a non-horizontal position below the kite by a radio-controlled release device, which also caused the collecting bag to be shut off preventing any contamination during the descent.

Total numbers of arthropods and mosquitoes were counted and the latter were sorted by sex and identified at the Queensland Institute of Medical Research (QIMR) laboratory. Catches were expressed as density per 10⁶ m³ for arthropods (Farrow and Dowse 1984) and for mosquitoes as catch per unit area per volume of air sampled. The number of arthropods caught per sample depends on the rate of dispersal, i.e., the number of arthropods passing through a unit area in a unit of time (e.g., m²/s), and the duration of sampling. Dispersal rate is, in turn, a function of aerial density and the net air speed of the arthropods. It generally is expressed on the basis of the interaction between wind speed and direction and the arthropod’s flying speed and heading. Because of the small size and flying speed of mosquitoes, the flight vector was ignored in these estimations and the wind vector used. The minimum time airborne and hence minimum distance traveled assumes that a mosquito taking off at dusk was caught at the beginning of the sampling period. Maximum distance assumes that it was caught at the end of the sampling period. Distance traveled was calculated from the wind speed at the sampling height (determined by pilot balloon ascent) and the time airborne. Meteorological data were measured on site and it was assumed that the wind speed was the same as that for areas where dispersal originated.

Results

Forty of 368 collections from Trangie, Hillston, and Hay contained mosquitoes. Of the 97,315 arthropods collected, 294 were mosquitoes (Table 1). The average densities of mosquitoes from both day (125 ± 152.1) and night (91.3 ± 151.7) collections were similar (t = 0.6, df = 37, P = 0.56) and ranged from 0.36 to 0.30% of the total arthropod catch, respectively. The mean density of mosquitoes in comparison with that for total arthropods was 99 and 28,606/10⁶ m³, and mosquito and total arthropod dispersal rates were 970 and 356,660/10⁶ m²/s, respectively.

Specimens from six mosquito taxa (Table 2) were collected, and 221 of the 294 were identified to species, Culex australicus Dobrotworsky & Drummond (58.5%), Cx. annulirostris (21.3%), Anopheles annulipes Walker s.l. (10.4%), Aedes theobaldi (Taylor) (7.2%), Aedes rubithorax (Macquart) (1.4%), and Aedes sagax (Skuse) (0.9%). Of these, 71 and 150 were males and females, respectively. Cx. annulirostris conformed to the description of Edwards (1924).

Distance traveled or displacement (Table 1) ranged from a low estimate of 0 km to a maximum of 648 km; 10 of 40 samples had estimated maximum distances of >200 km. Mean distance traveled by day and night respectively was 23.9 ± 15.3 and 152.4 ± 116.3 km (t = 3.3, df = 37, P < 0.01). Of the 12 collections that contained Cx. annulirostris, most displacements were in the order of ≤150 km, but those from Hay on the nights of 8, 10, and 11 December 1984 ranged from 162 to 396, 216 to 594 and 144 to 396 km, respectively.

Discussion

These data demonstrated that Cx. annulirostris and other mosquito species ascend from surface air into the planetary boundary layer. The geostrophic winds, which descend at dusk to the top of the planetary boundary layer, can transport dispersing insects over long distances at night because of their speed and constancy.

This is not unexpected because its Asian counterpart, Cx. tritaeniorhynchus (and other banded probos-
cis Culex), has been collected in aerial samples some 500 km from land in the northwest Pacific (Asahina 1970) and in aerial samples in China and West Bengal (Ming et al. 1993, Reynolds et al. 1996). Their conclusions, although based on circumstantial evidence, are consistent with the reintroduction of JE virus-infected Cx. tritaeniorhynchus into temperate China from warmer southern parts of Asia, but does not rule out other modes of transport, particularly viremic birds or local maintenance by a variety of methods. Humans are regarded as ‘dead end’ hosts for both JE and MVE viruses (Burke and Leake 1988, Marshall 1988).

Because of stable airflow, night is considered more favorable than day for long-range continental movements by small insects (Farrow 1982), including mosquitoes. In our study, although mosquitoes comprised 0.3% of the total catch by both day and night, comparable to recoveries in northeast India (Riley et al. 1995), estimated displacements were sixfold higher at night averaging 152 km, because of the strength of the geostrophic air flow in inland Australia and the coincidence of flights with strong prefrontal airflows. Provided conditions are warm enough, mosquitoes such as those collected with crepuscular-nocturnal activity patterns may take off after dusk and rapidly ascend into the upper air.

Table 1. Summary of aerial collections positive for mosquitoes at localities in inland New South Wales, Australia

<table>
<thead>
<tr>
<th>Date</th>
<th>Altitude, m</th>
<th>Mosquito catch/total (%)</th>
<th>Mosquito density (10^3/m²)</th>
<th>Mosquito dispersal rate (10^3/m²/s)</th>
<th>Estimated min./max flying time, h</th>
<th>Wind speed and direction (m/s)</th>
<th>Min./max displacement, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26/11/79</td>
<td>220</td>
<td>2/130 (0.7)</td>
<td>62</td>
<td>309</td>
<td>1</td>
<td>10.0 S</td>
<td>36</td>
</tr>
<tr>
<td>25/9/80</td>
<td>150</td>
<td>1/268 (0.5)</td>
<td>28</td>
<td>265</td>
<td>1</td>
<td>14.5 N</td>
<td>52</td>
</tr>
<tr>
<td>25/8/83</td>
<td>177</td>
<td>1/292 (0.3)</td>
<td>25</td>
<td>167</td>
<td>1</td>
<td>8.5 NE</td>
<td>31</td>
</tr>
<tr>
<td>23/9/83</td>
<td>140</td>
<td>1/376 (0.3)</td>
<td>55</td>
<td>180</td>
<td>1</td>
<td>3.5 N</td>
<td>13</td>
</tr>
<tr>
<td>24/9/83</td>
<td>100</td>
<td>3/792 (0.4)</td>
<td>71</td>
<td>347</td>
<td>1</td>
<td>4.4 S</td>
<td>16</td>
</tr>
<tr>
<td>6/12/83</td>
<td>100</td>
<td>1/311 (0.3)</td>
<td>444</td>
<td>976</td>
<td>1</td>
<td>10.0 W</td>
<td>36</td>
</tr>
<tr>
<td>1/2/84</td>
<td>150</td>
<td>1/41 (2.4)</td>
<td>330</td>
<td>1157</td>
<td>1</td>
<td>3.5 SW</td>
<td>13</td>
</tr>
<tr>
<td>25/11/84</td>
<td>50</td>
<td>1/232 (0.4)</td>
<td>68</td>
<td>272</td>
<td>0.1</td>
<td>4.0 NE</td>
<td>0-14</td>
</tr>
<tr>
<td>9/12/84</td>
<td>90</td>
<td>1/615 (0.2)</td>
<td>37</td>
<td>112</td>
<td>1</td>
<td>10.0 NE</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 2. Numbers of mosquitoes collected from aerial sampling at localities in inland New South Wales, Australia

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>An. annulipes</td>
<td>7</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>Ae. rubitubus</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Ae. sagax</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ae. theobaldi</td>
<td>1</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Cx. annulirostris</td>
<td>15</td>
<td>32</td>
<td>47</td>
</tr>
<tr>
<td>Cx. austrolevis</td>
<td>5</td>
<td>85</td>
<td>130</td>
</tr>
<tr>
<td>Total</td>
<td>71</td>
<td>150</td>
<td>221</td>
</tr>
</tbody>
</table>
Previous radar observations of micro-insect populations over western New South Wales (Farrow 1982) indicated that small insects, possibly including some mosquitoes, progressively concentrated during the night into a layer at 100–300 m altitude, corresponding to the top of the nocturnal temperature inversion and the planetary boundary layer. This layer of migrating insects persisted for some hours after dawn but was broken up by thermal convection. Therefore, some nocturnal migrants may experience displacement periods of ≥12 h, depending on their behavior during daylight. However, warm temperature and low relative humidity would not favor their survival aloft. These effects probably are more important in determining the duration of flight and their ultimate displacement than their maximum endurance, as indicated by Asahina’s (1970) recoveries in the China Sea that he estimated as ≤37 h on the basis of surface wind speeds. This is an overestimate because dispersal is likely to have occurred in the faster geostrophic airflow at higher altitude and mosquitoes were more likely to have flown for only 18–24 h, in keeping with other estimates (Hocking 1953).

Approximately 11% of our 368 aerial samples contained up to six taxa of mosquitoes, but mainly Cx. australicus (59%) and Cx. annulirostris (21%), at densities averaging 99/106 m2, which is the same order of magnitude as found in both northeast India (Reynolds et al. 1996) and China (Ming et al. 1993). At moderate wind speeds of 10–15 m/s, our maximum estimated displacements, including those involving Cx. annulirostris, extended to 594–648 km. Previously, maximum dispersal of Cx. annulirostris at ground level by mark-release-recapture studies were 7–12 km (Russell 1986, Bryan et al. 1992).

The localities in our study are relevant to the introduction of MVE virus into temperate Australia, as suggested by the Miles–Anderson hypothesis. In temperate Australia where wind speeds are generally much higher than in the tropics, insects such as the plague locust Chortoicetes terminifera Walker and several species of noctuid moth may cover distances of 500 km or more in a single night (Farrow 1975, McDonald et al. 1991), whereas in the United States, mosquitoes have been displaced 360 km (Horsfall 1954). In North America, Sellers and Maarouf (1988, 1990, 1993) have analyzed wind trajectories and suggested that both eastern and western equine encephalomyelitis viruses may have been transported distances ranging from 1,250 to 1,350 km by windborne mosquitoes.

Dispersal between tropical and temperate latitudes of Australia in a 24-h period requires a mean wind flow of 80 km h−1 over 1,800 km. Sequential flights, involving refueling, although reducing the length of individual flight also depend on the maintenance of a favorable airflow direction over several days, and on persistent migratory activity by the mosquito. Given that the dominating influence on the Australian climate is a ridge of descending high-pressure air between the tropical and temperate latitudes, a series of flights seems more likely, if it occurs at all. In contrast to the southern spread of bovine ephemeral fever virus by windborne Calicivores from September 1967 to March 1968 (Murray 1970), clinical cases or even seroconversions to MVE virus are not known to follow a temporal progression southward in Australia. Although our data do not support southern transport of MVE virus by infected mosquitoes, neither do they rule it out.

In contrast, our findings lend circumstantial support for the hypothesis that JE virus may be introduced from Papua New Guinea into the Torres Strait islands and even onto mainland Australia via infected mosquitoes, particularly Cx. annulirostris. We have no way of estimating how often this may happen or how many mosquitoes, if infected, may arrive alive. It does suggest, however, that a similar study should be done in the Torres Strait-Cape York peninsula region during the period of the northwest monsoon.

Acknowledgments

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