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INFECTIOUS DISEASE

Malaria mosquitoes go with the flow

The rapid return of mosquitoes to African semi-desert regions when the dry season ends was an unsolved mystery. A surprising solution to the puzzle is the long-range migration of mosquitoes on high-altitude winds.

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During the long dry season in the semi-desert region of Africa known as the Sahel, malaria transmission ceases because the mosquitoes that can transmit the disease (termed malaria mosquitoes or vectors) disappear, along with the surface water required for the development of the next generation of mosquitoes. Yet with the first rains that end the dry season, adult numbers surge more quickly than can be explained by resumed breeding in newly rain-filled sites. Evidence to explain this adult population boom has remained elusive for decades. Writing in *Nature*, Huestis *et al.*[1] report high-altitude sampling of malaria vectors in the Sahel, which revealed data consistent with long-range wind-borne migration of mosquitoes.

Insect flight typically occurs close to the ground, in a habitat patch that provides all of the insect's essential resources such as food, shelter, mates and breeding sites. Among malaria vectors, this type of foraging flight rarely exceeds a distance of five kilometres[2]. By contrast, during long-distance migration, insects ascend to altitudes as high as 2–3 km, where fast air currents transport them downwind for hundreds of kilometres in a few hours[3]. This behaviour is beneficial[3] for insects moving in seasonally favourable directions.

The migration of monarch butterflies (*Danaus plexippus*) between North America and Mexico is one of the most widely known insect migrations, but the extent to which other insects engage in long-distance migration is under-appreciated, because these high-altitude flights are undetectable without technology such as radar. The type of radar that can detect larger insects (those heavier than 10 milligrams) had been mainly used to track just a few agricultural pests, until a 2016 study of the southern United Kingdom[4] used such radar to investigate insect migration in general. This study revealed that an estimated 16.5 billion insects migrate annually at high altitude (defined in this case as a height of more than 150 metres) above the 70,000 km^2 study area, indicating that wind-borne insect migration can occur on a strikingly large scale.

Current radar technology does not detect small insects (lighter than 10 mg) such as mosquitoes, which must instead be tracked by sampling using aerial nets. In the UK study[4], such insect capture provided evidence that three trillion small insects undertake high-altitude migrations, a number that substantially exceeds that of the larger radar-tracked insects in the same area. These migrations, termed mass seasonal bioflows[4], involve representatives of all major insect orders[3], including Diptera, to which mosquitoes belong. Seasonal patterns in the direction of high-altitude winds can enable consistent routes for these bioflows (Fig. 1).

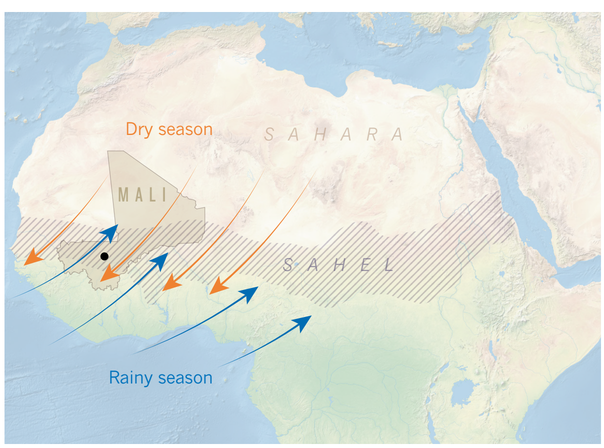

Figure 1 | High-altitude winds enable the seasonal migration of African mosquitoes. Huestis *et al.*[1] report that certain types of mosquito that can transmit malaria undergo long-distance wind-borne journeys. The authors studied sites in Mali (region marked with a black circle) in a semi-desert region of Africa called the Sahel. In the rainy season, there is a sudden rapid rise in the number of mosquitoes in the Sahel. The seasonal patterns of high-altitude wind directions (coloured arrows) are consistent with rainy-season winds transporting mosquitoes into the Sahel from southerly sites, where mosquitoes reside throughout the year. During the dry season, winds from the north blow into the Sahel, which could transport mosquitoes southwards.

Huestis and colleagues studied four villages in the Sahel region of Mali. The possibility that wet-season mosquito populations are re-established there by adults flying from the nearest year-round populations was excluded in a previous study[5] by this team. This is because the distance of more than 150 km to such sites is prohibitively long for self-powered mosquito flight.

A second possibility is that mosquitoes maintain a local presence and survive during the dry season, hidden away in a state of dormancy termed aestivation. Important, albeit indirect, support for this hypothesis came from extensive population time-series analysis from that earlier study[5], which showed beyond reasonable doubt that a mosquito vector species called *Anopheles coluzzii* persists locally in the dry season in as-yet-undiscovered places. However, the data were not consistent with this outcome for other malaria vectors in the study area — the species *Anopheles gambiae* and *Anopheles arabiensis* — leaving wind-powered long-distance migration as the only remaining possibility to explain the data[5].

Both modelling[6] and genetic studies[7] support the idea of long-distance migration to explain the seasonal dynamics of malaria mosquitoes in the Sahel, but many researchers have instead long discounted this phenomenon as being rare, accidental and inconsequential. This entrenched attitude has been difficult to dispel given the challenge of obtaining compelling direct evidence.

Huestis *et al.* met this challenge through aerial sampling of insects using sticky nets tethered to helium-filled balloons stationed in the villages that they studied. Nets suspended at set altitudes ranging from 40 to 290 metres above ground were launched at night (malaria mosquitoes are nocturnal), for about 10 consecutive nights each month over a span of 22–32 months. During a total of 617 sampling nights, 461,100 insects were caught, which included 2,748 mosquitoes. Careful controls by the authors enabled them to conclude that the insects were captured at altitude and not during balloon deployment near the ground.

Among the mosquitoes captured were *A. gambiae* and *A. coluzzii*, as well as four other species of malaria vector. Comparable distributions of species across villages and years, and consistent peaks in insect captures in the mid to late rainy season, indicate that high-altitude migration of malaria vectors is deliberate rather than accidental. Moreover, the annual malaria vector bioflow predicted to cross a hypothetical 100-km line joining the authors' sampling sites exceeds 50 million insects, suggesting that high-altitude migration is common rather than rare. Simulated migratory trajectories for these vectors yield maximal distances of around 300 km, assuming one 9-hour high-altitude journey.

From this work and their previous study[5], Huestis and colleagues have finally resolved in broad outline the 'dry-season paradox' in favour of two non-mutually exclusive strategies: long-distance migration and local persistence. Yet many knowledge gaps remain.

Perhaps the most important of these is whether wind-borne migration includes malaria mosquitoes infected with malaria-causing parasites. The authors make much of the fact that female insects (only females transmit malaria) outnumber males by a ratio of more than 4:1 in the mosquitoes they captured, that more than 90% of the females had taken at least one blood meal before their flight, and that 31% of those meals were from humans, implying possible mosquito exposure to malaria parasites and the potential to spread infection over great distances.

However, the authors failed to detect parasite infections in their aerially sampled malaria vectors, a result that they assert is to be expected given the small sample size and the low parasite-infection rates typical of populations of malaria vectors. A problem with this argument is that the typical infection rates they mention are based on one specific mosquito body part (salivary glands), rather than the unknown but undoubtedly much higher infection rates that would be obtained if whole mosquito bodies were used to test for parasite infection. Further research will be required to flesh out this and many other fundamental issues raised by Huestis and colleagues' study.

If it is confirmed that there are wind-borne mosquitoes infected with the malaria-causing parasite, the implications of this would include the possibility of the reintroduction of disease into places where malaria has been previously eliminated, as well as the potential for the long-distance spread of drug-resistant parasites. Wind-borne malaria vectors, whether or not they are infected with parasites, could also profoundly affect the success of vector-control efforts. For example, migration could foster the long-distance spread of insecticide-resistant mosquitoes, worsening an already dire situation, given the current spread of insecticide resistance in mosquito populations. This would be a matter of great concern because insecticides are the best means of malaria control currently available[8]. However, long-distance migration could facilitate the desirable spread of mosquitoes for gene-based methods of malaria-vector control. One thing is certain, Huestis and colleagues have permanently transformed our understanding of African malaria vectors and what it will take to conquer malaria. ■

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