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Possible spread of African horse sickness on the wind

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SUMMARY

Analyses of outbreaks of African horse sickness showed that movement of infected *Culicoides* midges on the wind was most likely responsible for the spread of the disease over the sea from Morocco to Spain in 1966, from Turkey to Cyprus in 1960, and from Senegal to the Cape Verde Islands in 1943. The pattern of spread of the epidemic in the Middle East in 1960 could have been laid down by the infected midges carried on spells of south-east winds, and analyses of outbreaks in Algeria in 1965 and India in 1960 also suggested windborne spread of the disease. Each spread occurred when the presence of virus, host and vector coincided either with a spell of winds unusual for a particular time of year (Spain, Cyprus, Cape Verde Islands and Algeria) or with a series of disturbances usual at that time of the year (Middle East and India). Inferred flight endurance of the midge varied up to at least 20 h and flight range from 40 to 700 km. Flight occurred when temperatures were likely to have been in the range of 15–25 °C if it was at night or 20 to about 40 °C if it was by day.

It is suggested that likely movements of midges on the wind can be estimated from synoptic weather charts, and should be taken into account when planning control of the disease in the face of an outbreak. Such control includes a ban on movement of horses, vaccination and spraying of insecticide.

The risk of spread to countries outside the endemic areas should be assessed by reference to possible wind dispersal of infected midges.

INTRODUCTION

African horse sickness (AHS) is a virus disease of horses, mules and donkeys transmitted by blood sucking insects. The disease is endemic in west, central, east and southern Africa (Bourdin, 1972) but at intervals epidemics occur when the disease is introduced to other areas, for example in 1959 and 1960 in the Middle East and the Indian subcontinent, and in 1965 and 1966 in North Africa and Spain. During these and other epidemics, spread took place which could not be accounted for by the movement of horses, mules or donkeys, either because the disease crossed seas or deserts or because it spread too quickly. The spread of other diseases transmitted by biting insects, e.g. potato leaf roll, sugar beet yellow, myxomatosis and bovine ephemeral fever, has been shown to be associated with dispersal of infected insects on the wind (Johnson, 1969; Ratcliffe, Myers, Fennessy & Calaby, 1952; Seddon, 1938; Murray, 1970; Newton & Wheatley, 1970). The following analyses of six examples of disease spread strongly suggest that AHS can be spread by windborne movement of the infected vector.

HOST AND VECTOR

Host

Mammalian hosts are horses, mules and donkeys, and in some areas zebras. Horses are more affected by the disease than mules and donkeys and death is more likely. In endemic areas the disease is mild (horsesickness fever) or subclinical, but if horses are introduced from outside, rapid and fatal disease results, as has happened in West Africa from the nineteenth century to the present (Gaubert, 1936; Best, Abegunde & Taylor, 1975). If the virus spreads outside the endemic area, the disease is severe and readily noticed by the local population. Disease has not been seen in zebras, but antibodies indicating previous infection have been detected (Mirchamsy & Hazrati, 1973; Davies & Lund, 1974).

The incubation period of the disease in horses is usually from 5 to 9 days (Howell, 1963), but 12 and 16 days have also been recorded (Maurice & Provost, 1967; Alexander, 1948). Virus is present in the blood 4 days before the signs of the disease and 2 days after (Goldsmit, 1968) and may reach a titre of $10^{6\cdot8}$ LD 50 per ml (Ozawa, Salama & Dardiri, 1972). Virus persists at low titre in the blood in the presence of antibody for long periods after recovery from the disease. Death, if it is going to happen, takes place 4–5 days after the first clinical signs. The amount of virus in the blood for a midge to become infected is $10^{4\cdot0}$ LD 50 per ml or higher and this level occurs for 4–5 days at the most around the time that clinical signs are apparent.

Vector

The main vector of AHS virus is the midge *Culicoides imicola* (*C. pallidipennis*). Du Toit (1944, and 1949 quoted by Wetzel, Nevill & Erasmus, 1970) isolated the virus from the midge and subsequently in 1949 transmitted the disease by *Culicoides* bite from an infected horse to a susceptible one 12 days after the midge had taken blood. McIntosh (1958) recorded that AHS virus was isolated on two occasions from *Culicoides* in 1949. E. M. Nevill, B. J. Erasmus & O. J. B. Hübschle (personal communication, 1976) fed wild-caught *C. imicola* on blood containing AHS virus and isolated virus 12 days later. Boorman, Mellor, Penn & Jennings (1975) and Mellor, Boorman & Jennings (1975) demonstrated the multiplication of the virus in *C. variipennis* after feeding and showed that the midge would transfer the virus from infected to non-infected chick embryos. (*C. variipennis* does not occur outside America, where it is the main vector of bluetongue virus, but its role corresponds to that of *C. imicola*, which is the main vector of bluetongue virus in Africa as well as of AHS).

Mosquitoes are unlikely to be vectors of AHS virus, although some species remained infective for 7 days after feeding on infected horses (Nieschulz, Bedford & Du Toit, 1934; Nieschulz & DuToit, 1937). Survival of the virus in *Anopheles* *stephensi* and *Culex pipiens*, and possible multiplication in *Aedes aegypti*, with transmission to horses was found (Ozawa & Nakata, 1965; Ozawa, Nakata, Shaddel & Navai, 1966).

Midges lay eggs 2–6 days after a blood meal (Jones, 1967; Boorman, 1974) in damp muddy areas containing plants or detritus (Walker, 1977*a*). The eggs hatch in 2–3 days and the larval stages usually last 12–16 days. Adults emerge 2–3 days after pupation and take a blood meal 1 day later. Subsequently they may take a blood meal every 3–4 days. This life-cycle was found in the laboratory at temperatures 23–25 °C, but the length of the cycle varies with the temperature. Mating occurs within 12–24 h of emerging and sperm can be stored for fertilization of several egg batches.

If the blood meal is infective the virus multiplies in the midge and reaches a high titre (10^6 LD50 per midge) on the 5th day. Transmission of virus has been shown on the 7th, 12th and 13th days after feeding, and the midge remains infective with high titre of virus for the rest of its life (Boorman *et al.* 1975; Mellor *et al.* 1975; du Toit, 1949 quoted by Wetzel *et al.* 1970). Thus a midge infected at the first bite could have transmitted the virus on the 8th day of its life and as many as five times at the 20th day. Walker (1977*b*) calculated a daily survival rate of 0·8 for *C. imicola*, which meant that after 18 days for example 1·8 % of a given population had survived. At the time of taking a blood meal a midge may feed more than once on the same or a different host until it is engorged and so increase the chance of being infected or of passing on infection (Murray, 1975).

With an incubation period in horses of 7 days (range 5–9 days) and a minimum period in midges of 7 days, the shortest period between a midge biting an affected horse and the disease being seen later in another horse bitten by that midge could be from 12 to 16 days with a mean of 14 days.

Movement of host and vector

African horse sickness spreads by movement of host or vector. Unless they are driven hard, horses are unlikely to move more than 60 km in a day, and 30 km would be the upper limit of a day's march in a mixed caravan of donkeys, mules, sheep and goats. Greater distances would be covered if the animals were transported by ship, vehicle or aircraft.

Unlike those of horses, the numbers of midges vary widely throughout the year. In endemic areas, midges breed all the year, but for example in West Africa (J. Boorman, personal communication, 1976) a peak is reached at the end of the rains in August and September. In epidemic areas such as Israel (Braverman & Galun, 1973) there are two peaks: a smaller one between March and June, and a larger one between August and November. Adults are present in small numbers during the winter. Increase in midge population is important in the spread and maintenance of an epidemic, since given a daily survival rate of 0·8 and a low infection rate the chance of infecting further hosts would be small without large numbers of midges.

Midges may fly at any time of the day or night, but most are caught between dusk and dawn (Murray, 1975), the period when the hosts of *C. imicola*, horses, cattle and sheep, are bitten (Nevill & Anderson, 1972). Such biting flight is likely to be in calm or in light, night-time winds near the ground, where midges can find and settle on their hosts, but it may not be typical of flight at other times during the life-cycle. Thus, *Culicoides* have been collected at various heights up to 4000 m, *C. variipennis* having been found at 170, 340 and 1700 m (Glick, 1939; Glick & Noble, 1961; Bowden & Gibbs, 1973).

The air speed of midges has not been measured, but with a wing-span × body-length of 4·65 mm^2 a mean air speed of 40 cm s^{-1} can be expected (Lewis & Taylor, 1967). Because the air speed of *C. imicola* is likely to be small compared with most wind speeds, the track of a midge should often be the same as the track of the air in which it is flying. Track length is the product of wind speed and flight endurance, but the latter is unknown. Winds of speed 7–8 m s^{-1} took *C. furens* for 3–5 km (Breeland & Smith, 1962), and the same species was carried more than 6 km at a height of 400 m (Williams, 1962). Evidence for movement over much greater distances is presented here, and may well also happen in Australia, for example, if it is accepted that *Culicoides* species are the vectors of bovine ephemeral fever (Murray, 1970).

Track direction may be calculated, in principle, from a map of the wind field, but since the wind field changes progressively from hour to hour and from day to day, in practice the track is not easy to find, the more so where there are large day-to-night wind changes near coasts and mountains on scales of tens or hundreds of kilometres. Day-to-day changes are due to readily recognizable developments in the wind field on scales of thousands of kilometres, easily seen on weather maps based on observations made routinely at networks of places kept by national meteorological services. In the case studies that follow, weather maps are used to help show the speed and track of flying midges, bearing in mind the effects of likely but largely unknown smaller-scale disturbances in the wind field. Where the date of an outbreak is reported, a period of 5–16 days before has been taken as the most likely time for midges to be brought in on the wind. This allows an incubation period of 7 days in the midge and 5–9 days in the horse.

The temperature range for night biting flight is 20–32 °C in the tropical endemic areas (Dipeolu, Durojaiye & Sellers, 1974), 13–32 and 10–32 °C in Colorado and California respectively (Jones, 1965; Nelson & Bellamy, 1971) and not less than 17 °C in Kenya (Walker, 1977*a*), but the threshold for down-wind flight is unknown.

EXAMPLES OF DISEASE SPREAD

Six examples were examined (Fig. 1). In the first three, Spain, Cyprus and Cape Verde Islands, the possibility of spread by movement of horses was unlikely, since the outbreaks were separated by the sea from their likely origin. In the fourth example, the Middle East, a more complex situation is analysed, and in the last two examples, Algeria and India, where epidemiological data were sparse, the findings from the first four examples are used to help in the analysis. It is recognized that in some of the areas where AHS occurred the date of the outbreaks may not be precise. However, in the first two examples the countries had been aware of the risk for some time before AHS arrived and were prepared for its immediate

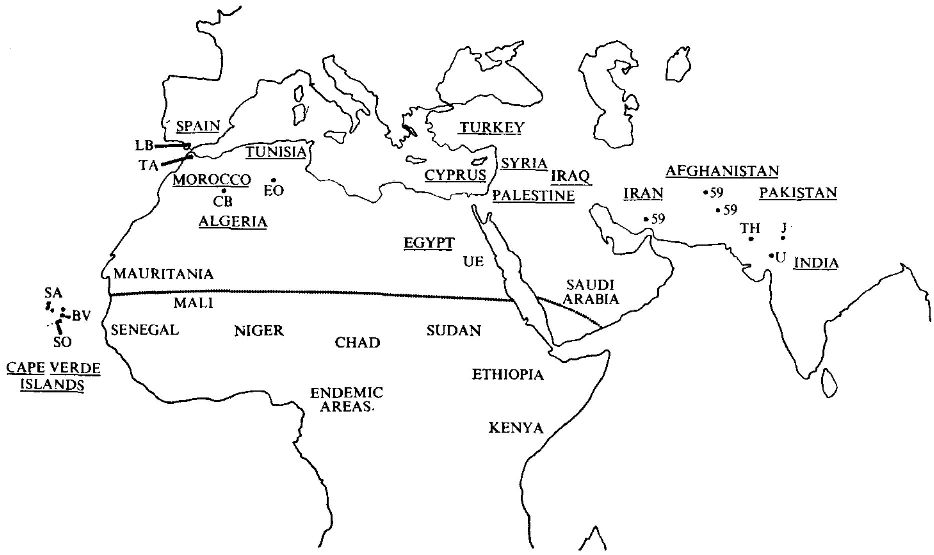

Fig. 1. Location map showing outbreaks discussed in this paper (countries underlined). SA, Santo Antao; BV, Bôa Vista; SO, San Tiago; CB, Colomb Bechar; EO, El Oued; TA, Tanger; LB, Los Barrios; UE, Upper Egypt; TH, Tharparkar; J, Jaipur; U, Udaipur; 59, Sites of first outbreaks of AHS in 1959 (Iran, Afghanistan and Pakistan).

recognition and control. Similarly in the Middle East there had been a warning in 1959 of what to expect. In addition in all these countries the horse is a valuable animal and greater attention would have been paid to disease in it than in man and other animals.

Spain – October 1966

During 1966 there was an epidemic of AHS in Morocco, and from the end of August to the end of October outbreaks were occurring in the provinces of Nador, Al Hoceima, Tetouan and Tanger (Laaberki, 1969). In the Tanger area a peak was reached from 25 to 30 September (Montilla & Marti, 1968). On 13 October 1966 the disease had spread to Spain: it was seen in a horse at a farm 4 km north-west of Los Barrios and 11 km north-north-west of Algeciras. On the same day it occurred at La Linea just north of Gibraltar. There were three outbreaks on 14 October, two on 15 October, near Los Barrios, and the final outbreak was on 16 October, 11 km south-east of the first at Los Barrios and 13 km north of Tarifa (Montilla & Marti, 1967, 1968). The outbreak at La Linea was linked to the first at Los Barrios since the two mules affected had been at the Los Barrios farm during the night of 8 October.

Strict precautions against the entry of AHS into Spain had been taken since August 1966. The entry of live animals from North Africa was banned and all vehicles arriving at Algeciras from North Africa were disinfected and treated with insecticide. Thus the disease was unlikely to have entered by the introduction of infected horses. The two more likely possibilities are entry of infected midges by a port other than Algeciras, and carriage of infected midges on the wind from

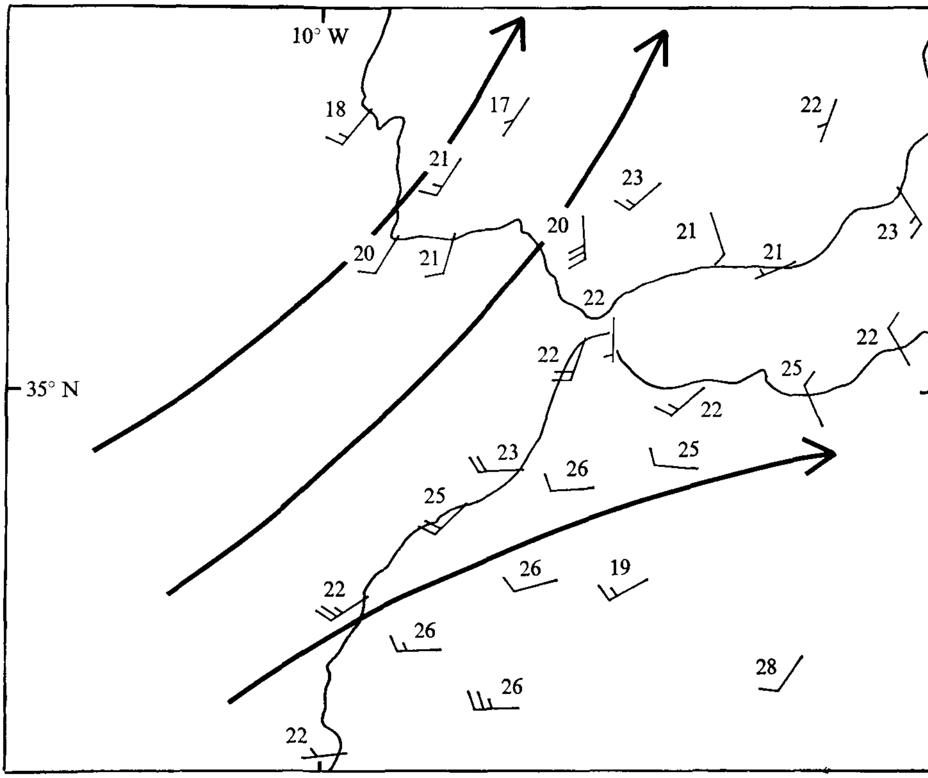

Fig. 2. Synoptic weather chart for 1800 GMT 3 October 1966, showing south to south-west winds that probably brought infected midges from Morocco to Spain. Winds and temperatures are shown at a selection of reporting stations. Arrows show the direction of the large scale wind flow. Surface winds: < 2·5 m s^{-1}; < 5 m s^{-1}.

Morocco. Entry of infected midges through La Linea is possible but unlikely, since the mules at La Linea had apparently been infected at Los Barrios. The interval between the first case and the last was 3 days, which implies a common source. The initiation of eight outbreaks would have required more midges than are likely to have been carried on ship.

As the first case was on 13 October 1966 the most likely period for arrival of midges was 27 September to 8 October, and the nearest source was Morocco. Winds around the Gibraltar Straits can be strongly modified by topography – both from mountains acting as barriers, and from coasts causing sea and land breezes. Such topographic effects could greatly hinder midges crossing the Straits, but winds at 900 m, a standard reporting height, are likely to have been largely unaffected. From 27 September to 15 October, the 900 m winds over Gibraltar (recorded in the British Daily Weather Reports, Overseas Supplement) were from between west-south-west and east-north-east, through north, on all days but one – the 3rd. On that day there were south to south-west winds at both 900 m and near sea level, and with speeds of about 10 m s^{-1} they were the strongest of the period. Thus, the most likely day for midges crossing from Morocco to Spain was 3 October, a day when minimum temperatures were 15–20 °C, and maxima 20–25 °C. The

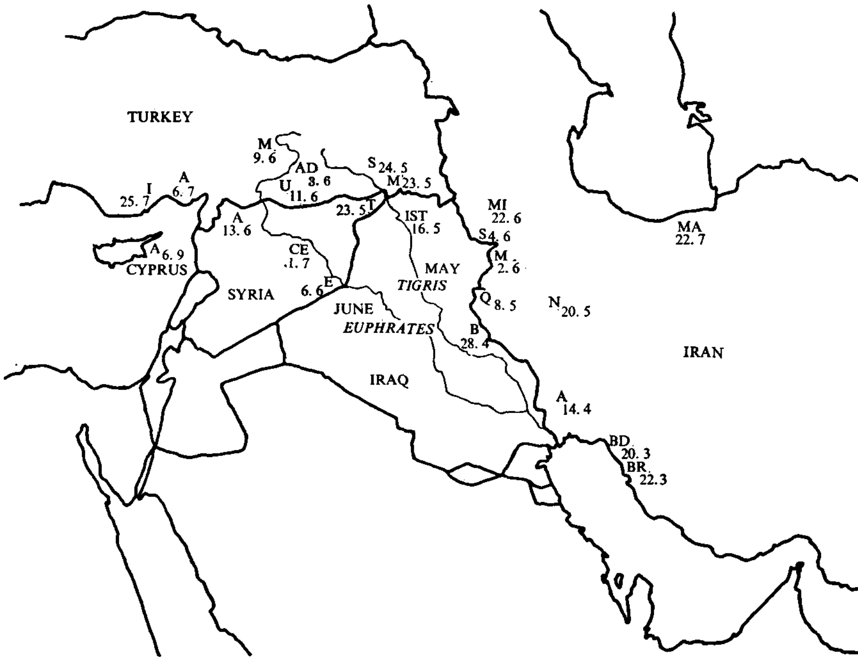

Fig. 3. Location map showing dates of outbreaks over the Middle East in 1960. *Iran*: BD, Bandar Daylum; BR, Bandar Rig; A, Ahwaz; Q, Qasr Shirin; N, Nahawand; M, Marivan; S, Sardasht; MI, Miandowab; MA, Mazendaram. *Iraq*: B, Badra; IST, Iraq–Syria–Turkey border. *Syria*: T, Tigris border; E, Euphrates border; A, Aleppo; CE, Central Euphrates. *Turkey*: M, Mardin; S, Siirt; AD, Adiyaman; M, Malatya; U, Urfa; A, Adana; I, Icel. *Cyprus*: A, Arnadhi.

crossing would have taken 2–4 h. These strong south-westerlies were blowing ahead of the eastward-moving cold front of a deep, slow-moving depression near 50° N to south-west of the British Isles (Fig. 2).

Cyprus – September 1960

The epidemic of AHS which started in Iran in March 1960 (Fig. 3, Table 1) reached Turkey and Syria in May and was present in southern Turkey from July onwards (Durusan, 1961).

The first outbreak in Cyprus was seen in the village of Arnadhi in Famagusta district on 6 September (Orhan, 1961). From 7 September to 13 September the disease was reported in ten other villages within 34 km and in Nicosia. Further affected villages were not reported until 21 September. It is likely that the outbreaks from 6 to 13 September came from a common source, since the 7 days interval between the first and last is too short for a horse–midge–horse cycle to elapse. Strict precautions had been taken in Cyprus from the time when the epidemic reached Turkey. No horses, mules or donkeys were imported. Aircraft were treated with insecticide, and watch was kept at the ports for anything unusual. Once the disease had been confirmed, the movement of horses, mules and donkeys was banned.

AHS could have entered Cyprus in a number of ways: (i) illicit entry of an infected horse, mule or donkey (this is unlikely since smuggling would have been

Table 1. *Outbreaks of African horse sickness in Iran, Iraq, Turkey, Syria and Cyprus, March–June* 1960

	Date of outbreak	Possible dates of infection of horse	Latest possible dates of infection of midge
Iran			
Bandar Daylum	20 Mar.	11–15 Mar.	4–8 Mar.
Ahwaz	14 Apr.	5–9 Apr.	29 Mar.–2 Apr.
Iraq			
Badra	28 Apr.	19–23 Apr.	12–16 Apr.
Iran			
Qasr Shirin	8 May	29 Apr.–3 May	22–26 Apr.
Iraq			
Turkish–Syrian border	16 May	7–11 May	30 Apr.–4 May
Iran			
Nahawand	20 May	11–15 May	4–8 May
Turkey			
Mardin	23 May	14–18 May	7–11 May
Syria			
Tigris border	23 May	14–18 May	7–11 May
Turkey			
Siirt	24 May	15–19 May	8–12 May
Hakkari	27 May	18–22 May	11–15 May
Iran			
Shahr Kord	29 May	20–24 May	13–17 May
Iraq			
All provinces lying on or east of river Tigris affected by 31 May			
Iran			
Marivan	2 June	24–28 May	17–21 May
Turkey			
Van	2 June	24–28 May	17–21 May
Adiyaman	3 June	25–29 May	18–22 May
Iran			
Sardasht	4 June	26–30 May	19–23 May
Turkey			
Diyaribakir	5 June	27–31 May	20–24 May
Syria			
Euphrates border	6 June	28 May–1 June	21–25 May
Turkey			
Bingöl	8 June	30 May–3 June	23–27 May
Elazig/Malatya	9 June	31 May – 4 June	24–28 May
Bitlis/Urfa	11 June	2–6 June	26–30 May
Tunceli	12 June	3–7 June	27–31 May
Erzincan	13 June	4–8 June	28 May–1 June
Syria			
Aleppo	13 June	4–8 June	28 May–1 June
Turkey			
Sivas	16 June	7–11 June	31 May–4 June
Konya	18 June	9–13 June	2–6 June
Gaziantep	20 June	11–15 June	4–8 June

Table 1. (*Cont.*)

	Date of outbreak	Possible dates of infection of horse	Latest possible dates of infection of midge
Iran			
Miandowab	22 June	13–17 June	6–10 June
Turkey			
Maras	25 June	16–20 June	9–13 June
Adana	6 July	27 June–1 July	20–24 June
Hatay	9 July	30 June–4 July	23–27 June
Icel	25 July	16–20 July	9–13 July
Antalya	19 Sept.	10–14 Sept.	3–7 Sept.
Cyprus			
Arnadhi	6 Sept.	28 Aug.–1 Sept.	21–25 Aug.

detected); (ii) the carriage of infected midges on ships entering Famagusta harbour (however, the number of midges would probably have been insufficient to set up the extent of infection); (iii) the wind carriage of infected midges from Turkey before 1 September.

To investigate the third possibility, winds and temperatures during August were examined. We may take the broad-scale wind flow across Cyprus to be represented by the 1200 GMT winds at Nicosia, for on most days at that time they are unaffected by the usual afternoon 5–8 m s^{-1} sea breeze from Morphou Bay. Moreover, daytime convective mixing to heights of 3–5 km at that time of year should largely remove the channelling effects of mountains. During August 1960 the 1200 GMT Nicosia winds (recorded in the British Daily Weather Report, Overseas Section) were mostly from between west and north, less than 4 m s^{-1}, but on some days the wind was from between east and south-east. In the period 23–29 August, however, there was a spell of north winds, 4–6 m s^{-1}; and from 23 to 25 August there were north-east winds at 0600 GMT, a time of day when winds are usually from between west and north, or calm. On these same 3 days there were 0600 GMT north-easterlies of 5–10 m s^{-1} at Morphou Bay, contrasting with the often calm winds there at that time of day. North to north-east winds, 5–7 m s^{-1}, returned to both places at 0600 GMT on 28 and 29 August, and the only other spell of such winds in August was on 11th and 12th, although speeds then were only 3–5 m s^{-1}. These north-easterly spells brought cool weather, the more so on 23rd and 24th when daily maximum temperatures at Nicosia were 31 and 32 °C, contrasting with 35–40 °C on most other days in the month.

Thus, the inferred flight dates corresponded remarkably with a spell of strong north to north-east winds, blowing from a known source of the disease, and the most likely date was 28 August. Fig. 4 is a weather map showing the wind flow at 1200 GMT on that date; it is representative of the period 23–29 August. The sea crossing of 150–250 km would have taken 4–15 h on the 5–10 m s^{-1} winds likely to have been blowing between Turkey and Cyprus. With such wind speeds, afternoon on-shore sea breezes were unable to form along parts of the Turkish coast; flying midges would have been swept seawards by day as well as night for much of the period 23–29 August. Air temperatures near the sea surface would have been about 20–25 °C.

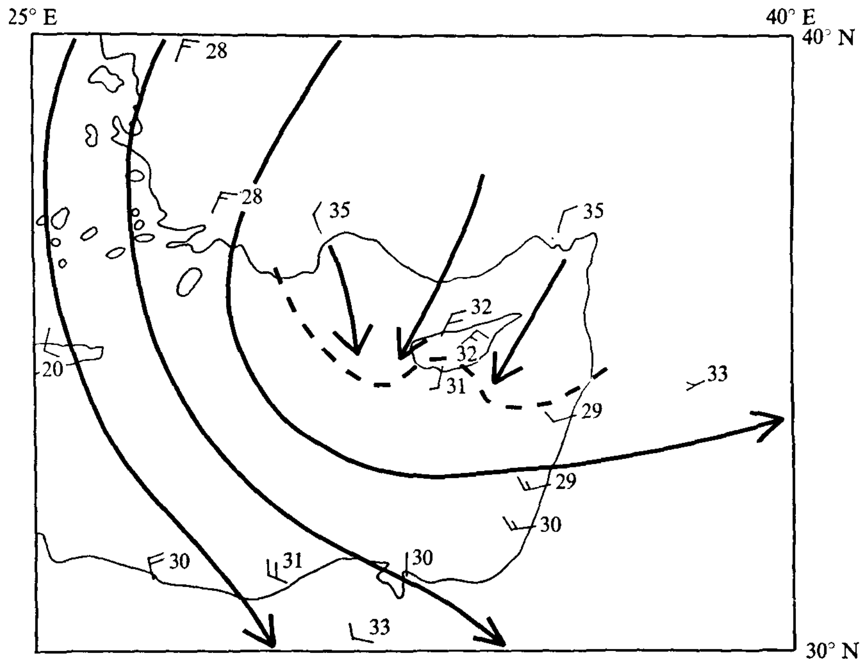

Fig. 4. Synoptic weather chart for 1200 GMT 28 August 1960, during a spell of north to north-east winds that probably brought infected midges from Turkey to Cyprus. The broken line shows the likely boundary between the north-westerly flow that has come around the western end of the mountains of Turkey, and the north-easterly flow that has crossed the mountains. Surface winds: Y 2·5 m s^{-1}; < 5 m s^{-1}.

The winds on these days in late August could have brought midges to the eastern parts of Cyprus. The midges would also have bitten cattle and sheep in addition to horses, mules and donkeys, and it was only in those areas where there was the densest population of horses that the disease was seen.

Cape Verde Islands – January 1944

In January 1944 there was a severe epidemic of AHS in the Cape Verde Islands (Palmeiro, 1946). It started simultaneously on the north-west of Santo Antao island, on Bôa Vista island and on the island of San Tiago. Santo Antao lies 150 km north-west and San Tiago 100 km south-west of Bôa Vista. The islands are about 600–700 km west of Dakar, Senegal (Fig. 1). The horses, mules and donkeys on Santo Antao were the most affected and their numbers were severely reduced, with greatest losses on the north-west of the island. The epidemic reached its peak in February and died away at the end of April, to reappear in November in a less virulent form. The disease was also seen in the last 4 months of 1945 in Santo Antao and the neighbouring San Vicente island, as well as in San Tiago. The disease had previously occurred in the islands in 1918, one year after the importation of horses from Senegal, and recrudescences of the disease in 1926–7 and in 1933 had been recorded (Palmeiro, 1946). The nearest source of African horse sickness in 1943 was Senegal, where the disease was endemic. Outbreaks have been reported in imported horses from 1885 to 1965, and most disease occurred between September and January (Mornet & Gilbert, 1968).

There are four possibilities for the origin of the epidemic in 1944: (i) introduction of horses from Senegal or West Africa; (ii) introduction of infected midges on ships or aircraft; (iii) recrudescence; (iv) carriage of infected midges on the wind from Senegal.

Palmeiro (1946) did not refer to the introduction of horses although he associated the 1918 epidemic with introduction of horses the previous year. Carriage of infected midges on ships or aircraft seems unlikely since on Santo Antao there are only poor landing places and no airport. Palmeiro (1946) described the outbreaks as a 'recrudescence', and it is true that the disease died away at the end of April, to reappear in November. It also reappeared in late 1945 indicating that the virus might persist for 2 years on the islands. However, before 1944 the previous outbreak was in 1933 and recent work in Cyprus (Parker, 1974) indicates that AHS is unlikely to persist in epidemic areas for periods as long as 10 or 11 years. The horse population of the Cape Verde Islands is about 4000 or 1 per km^2 compared with 6 per km^2 in Cyprus, and this seems insufficient to maintain the virus over that number of years. The high mortality at the time of the 1944 epidemic suggests there was little protection against the virus.

African horse sickness started in January, but the date was not given by Palmeiro. If it is presumed to be 1 January, the most likely period of midge movement would be from 15 to 26 December 1943. A midge movement from Senegal would need a wind from east-south-east. The daily Historical Weather Maps for the 3 months November 1943 to January 1944 show that 20 December was the only day when the wind was about east-south-easterly, although these maps are only marginally suitable for estimating wind directions because the Islands are near the southern edge of the area of analysis. On all other days the wind blew from either east or north-east (i.e. from Mauritania or Spanish Sahara), or it had a long track over the ocean without crossing the African coast. The coincidence of timing again suggests a windborne movement of midges, but a 700 km flight over sea in the observed 10 m s^{-1} winds implies an endurance of 20 h in a single flight (although winds would have been stronger at heights of a few hundred metres). Air temperatures near the sea surface were about 20 °C. If midges crossed to the Islands on 20 December, the disease almost certainly was present by the end of the year, although perhaps not reported until the first week in January.

Middle East – 1960

The analysis of the spread of AHS from Morocco to Spain, Turkey to Cyprus, and Senegal to the Cape Verde Islands has shown that transport of infected midges on the wind is likely, that a flight endurance of up to 20 h by day or night may be possible, and that temperatures at the time of flight can be between about 20 and 35 °C if flight is assumed to take place by day, but between about 15 and 25 °C if it is at night. These deductions are used in the following analysis of disease spread in the Middle East, where movements of both horses and midge populations are concerned.

An epidemic of AHS of unknown origin broke out in Southern Iran, Afghanistan and Pakistan in the autumn of 1959 (Rafyi, 1961). During the winter the disease disappeared but in Iran it recurred in Bandar Daylum on 20 March 1960. It subsequently spread into Iraq at the end of April, and to Turkey and Syria by the last week of May. There were severe losses among the horse population in all these countries during the summer. Spread also took place northwards and north-eastwards in Iran during the same period. Places and dates are shown in Table 1 and Fig. 3.

In south-western Iran and Iraq from March to May, the main direction of spread was north-west along the Tigris in the areas between the river and the eastern mountain chain. In Iraq during June, the main direction was west-north-west along the Euphrates, and west into the provinces west of the Tigris and the Euphrates. The initial north-west spread in Iraq over a distance of 550 km was covered in 18 days, and according to accounts at the time (Doghramachi & Ayar, 1961; FAO/OIE, 1961) this surprised the veterinarians since it seemed as though the disease had travelled 200 km in one day and crossed three rivers.

A number of reasons could be put forward to explain the rapid and extensive spread in the area. These are: (i) the movement of people, especially nomads, and their animals; (ii) the movement of horses on vehicles or trains; (iii) the movement of infective midges on vehicles or trains; (iv) the carriage of infected midges on the wind.

Nomadic movement in Iraq and Iran takes place in April and May. In Khouzestan (Iran), and on the eastern borders of Iraq the movement is from the lowlands north-eastwards or eastwards to the high pastures in the mountains. On the western border of Iraq west of the Euphrates, the movement is westwards in the desert. In other parts of Iraq the movement is local. Thus there is no nomadic movement in the north-west direction, and movement on foot is likely to be not more than 30 km a day. If the spread was due solely to movement of horses, the disease would have been expected to be seen along the Euphrates and on the road to Rutba earlier than June, when it did arrive. Movement by rail or vehicles would have taken horses rapidly to the Syrian and Turkish border. However, the first outbreaks in both Syria and Turkey were at villages beside the river Tigris and not where the road and rail cut through north-eastern Syria. Spread by infected midges on vehicles or trains is a possibility but it is doubtful whether sufficient numbers would be carried in that way. Winds over the Euphrates–Tigris valley were examined to see if the spread of AHS could be attributed to windborne spread of midges.

Spring-time winds over the area are mostly from the north-west, but at irregular intervals of 5–10 days there are spells of a few days with south-east winds. A change from north-west to south-east usually takes place with a day of light and variable winds, whereas a reverse change is often sudden and takes the form of a windshift line moving across country from the north-west at speeds of 10–20 m s^{-1}. Highest temperatures, allowing for changes between day and night, are in the south-easterlies just ahead of the windshift line, whereas the lowest are a day or two later. Because of the temperature contrast between south-easterlies and north-

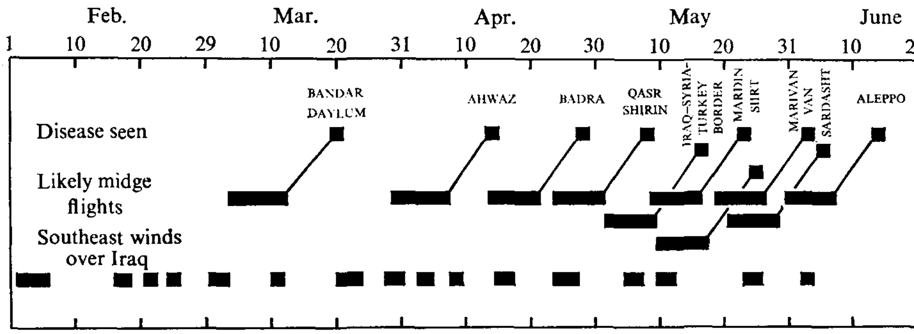

Fig. 5. Inferred dates of midge flight and spells of south-east winds over the Euphrates–Tigris valley, February to June 1960.

westerlies, midges are likely to have been carried furthest in the south-easterlies – at least during the first half of spring, when the north-westerlies may often be too cold for flight. Movement is therefore expected to be towards the north-west (i.e. *against* the usual wind direction), in just the direction so clearly shown by the successive outbreaks of AHS. Moreover, this movement is likely to be in short spells when south-east winds are blowing, and would account for sudden apparent jumps in the incidence of the disease.

Fig. 5 compares the periods with south-east winds over the Euphrates–Tigris valley during the spring of 1960 with the most likely periods when midges were flying, inferred from dates when AHS was seen. It shows that, for March, April, and early May, each period of likely flight coincided with at least one spell of south-east winds; but later in May and in June, with more disease reports and hence overlapping periods of likely flight, any relationship between such flight and spells of south-east winds is not clear. Speeds of the south-east winds (5–10 m s^{-1}) and displacements between successive reports of disease during March and April over Iran and Iraq (150–300 km) give an estimated flight endurance of about 10 h. Flight need not be in one stage, however, nor even on one day. The first report of disease in the spring of 1960, at Bandar Daylum on 20 March, followed the first two spells with 1200 GMT temperatures near 30 °C (25–26 February and 5 March). However, the source of the midges bringing the disease was not known. Temperatures at 1200 GMT (near the mid-afternoon maximum) in the subsequent spells of south-easterlies were greater than 30 °C, whereas the north-westerlies were cooler than that until the beginning of May (by which month the south-easterlies were warmer than 40 °C). The absence of flight when spells of south-easterlies had afternoon temperatures less than about 30 °C suggests that flight across the Middle East in 1960 took place mostly at night; otherwise flight might have been expected earlier in the year on those days when afternoon temperatures were less than 30 °C, for flight seems to be possible at temperatures as low as 20 °C – as shown by the flights over sea discussed in the three previous examples.

Disease spread was most rapid over the open plains. Among the foothills of north-west Iran and south-east Turkey spread was slower, perhaps because south-easterly winds were lighter and more irregular in direction there than over the plains, rather than because temperatures were significantly lower. Spread on to the western plateau of Iran probably did not take place until 9 May, for that was the first day when 1200 GMT temperatures went above 30 °C. This date is consistent with diseased horses being seen in 20 and 22 May. Spread across northern Syria and south-eastern Turkey probably took place on 2 June, the final spell of south-easterlies. Further spread north and west across Turkey may have been in part caused by the movement of animals, and in part by movement of the vector, for winds among the mountains during the summer would have been mostly northerly. This summer spread has not been examined.

Thus, although spread through movement of horses over short distances no doubt took place, the main pattern of spread was laid down by the spells of south-east winds. These spells coincided with the spread of the disease, and with the large population of midges at that time of the year, when water levels in the irrigation channels from the Tigris–Euphrates system were at their highest.

Algeria – September 1965

In the remaining two examples to be examined, AHS suddenly appeared among horses separated from the possible origin of disease by desert. Epidemiological data are sparse, so winds and temperatures are analysed to help find the origin and spread.

There was an epidemic of AHS in Algeria from September to December 1965 and during the following summer (Anon, 1967). The epidemic also occurred in Morocco from December 1965 to the end of 1966, and in Tunisia from June 1966 (Fassi-Fehri, Mouslifi & Nguyen Thanh Cac, 1967; El Fourgi, 1967).

In Algeria the epidemic started in two areas simultaneously: near Colomb Bechar in the west and at El Oued 1000 km to the east (Fig. 1). There are reports of a disease being present earlier in southern Algeria and south of Morocco (Sers, 1967; Rabah, 1966) where it was considered to be equine influenza. In the initial outbreaks in September in Algeria, African horse sickness was confused with anthrax because of the many sudden deaths among horses and mules.

The date of the first outbreak was not given (Anon, 1967) but it appears from a report by a veterinary official that disease was around Colomb Bechar by 28 September and possibly in mid-September (Sers, 1967). The origin of the virus is not known for certain. In 1961 African horse sickness of the same type was diagnosed in Chad (Doutre & Leclercq, 1962) and was present there in 1965 (Maurice & Provost, 1967). It is also believed that it was present in Niger and Mali from 1962. After the epidemic in Algeria antibodies to African horse sickness were demonstrated in donkeys living around Adrar, Tamanrasset and Djanet in southern Algeria (Pilo-Moron, Vincent, Ait-Mesbah & Forthomme, 1969). The most likely origin was therefore south of the Sahara.

The disease could have been introduced through infected donkeys, by carriage of infected midges on the wind, or by a combination of both. Horses and mules are not kept in Algeria south of 32° N latitude, since the desert conditions are unsuitable (Pilo-Moron, Vincent, Ait-Mesbah & Forthomme, 1969). Donkeys are mainly kept around the oases and movement of donkeys over long distances on foot is limited. Rapid crossing of the Sahara is normally by vehicle.

Winds in the lowest kilometre of the atmosphere over Algeria south of the Atlas Mountains at that time of year are mostly east or north-east, having come across the Mediterranean Sea east of about 10° E. Sometimes there are spells of hot south-west winds, which weather maps show come across the Sahara after recurving from more persistent east or south-east winds over southern Algeria and neighbouring countries near 20° N, just north of the Intertropical Convergence Zone (ITCZ).

The year 1965 had a particularly disturbed August and September over Algeria; there were spells of south-west winds 9–12, 22–24, 27–28 August, and 2–4, 10–11, 24 September. The first two spells in September coincided with inferred periods of midge flight, but in the absence of disease reports from other places, it is possible only to speculate on the origin of the midges.

Over south-eastern Algeria, including the Hoggar Mountains, winds from between south-west and south-east blew on many days, often being separated from east or north-east winds over the remainder of Algeria south of the Atlas Mountains by an almost stationary windshift line lying from north-western Libya to the west of the Hoggar Mountains, and bringing several spells of scattered rain and thunderstorms over and to the north of the Hoggar Mountains between 7 and 12 August, and between 30 August and 22 September. The earlier rains may well have led to suitable conditions where midges could have developed and later, after feeding on infected donkeys, been carried northwards to the southern Atlas Mountains on the spells of winds that reached there. It is not known whether the disease was present in the Hoggar Mountains, but the reports of equine influenza in southern Algeria may well have referred to the horse sickness fever characteristic of the mild form of African horse sickness. If not, infected midges of earlier generations could have come there from Niger on south-east winds north of the ITCZ.

It must be admitted these midge movements are highly speculative, but the unusually frequent southerly winds and widespread rains in August and September 1965 over and around the Hoggar Mountains may not have been just a coincidence, for they could have provided both opportunities for movement and places for breeding where these do not usually exist at that time of the year.

India – April 1960

AHS was diagnosed among horses and mules at Jaipur and Udaipur (Fig. 1) on 22 April 1960, so the most likely period of any midge movement was 6–17 April, and the only known source was Pakistan. The disease had been reported in Pakistan in the last few months of 1959, but it disappeared over winter, and reappeared at the end of March in Tharparkar, where it stayed until May (FAO/OIE, 1960, 1961; OIE, 1961). The simultaneous outbreaks at two places 320 km apart suggests movement of the disease by midges rather than by horses or mules, although at Jaipur the outbreak was attributed to gypsies (Howell, 1960). During the northern spring, winds over Pakistan and northern India vary from day to day owing to the eastward passage of 'western disturbances'. In the period 15 March *to 17 April 1960 there were six disturbances, bringing west or south-west winds* from Pakistan to Jaipur and Udaipur: 19, 21–22 and 26–27 March, and 3–4, 7–8, 12–13 April. The last two disturbances are the most likely on which midges could have been carried. By that time there would have been an increase in midge population in the area of the disease in Pakistan, and more midges would have become infected. However, between the outbreak in Pakistan and that in India, two horse–midge–horse cycles are possible, and earlier disturbances may have been responsible for carrying infected midges part of the distance, as may have happened in Algeria. The total distance is about 550 km; with observed wind speeds of 5–10 m s^{-1} at heights up to 1 km above sea level, the time taken would have been 15–30 h. Daytime maximum temperatures near the ground were about 40 °C, and night minima about 15–20 °C.

DISCUSSION

The analyses show strongly that wind dispersal of infected midges could have been responsible for the spread of African horse sickness to Spain, Cyprus and the Cape Verde Islands, and across the Middle East; the evidence for North Africa and India is less convincing. Similar analyses can also be used to exclude the possibility of wind dispersal on other occasions. For example, outbreaks of African horse sickness have started on four occasions in Upper Egypt. For three outbreaks near Aswan (Kom Ombo in July 1928 and July 1943; Edfo in September 1971), the Egyptian Daily Weather Report shows there were persistent winds from the north and north-west (as expected for that time of year), with no chance of midges being moved downwind from the south or east – i.e. from Sudan or Ethiopia, where the disease is endemic, or from western Saudi Arabia, where it has been seen. On the other hand, before the outbreak in Upper Egypt in January 1953 there were two spells of east or south-east winds (5–9 December and 2–3 January) and a spell of variable winds 18–20 December. There were no other breaks in the otherwise northerly winds over Aswan during December and January. Both spells came with depressions moving eastwards across the Middle East. The most likely source would have been the Red Sea coasts.

An unexplained jump of disease also occurred in August 1944, when AHS which was present at that time in the Suez Canal Zone in Egypt broke out at Gaza and at Lydda in Palestine (Alexander, 1948). There were no spells of south-westerly winds that would have been needed to interrupt the very persistent north to north-west winds typical of that time of the year, and the disease may have spread by illicit movement of infected donkeys or by carriage of infected midges in vehicles or aircraft.

Epidemiological data were lacking in many of the outbreaks examined. It is important that the dates when sick animals were seen are carefully recorded if the most likely inferred dates of midge movement are to be calculated and the winds on those dates found from synoptic weather maps. Midges have been shown in this paper to be carried for distances of 40–700 km over periods up to at least 20 h. Flight may have been mostly at night, at temperatures between 15 and 25 °C. During an outbreak, when the chances of spreading are being assessed, the possibility should be kept in mind that infected midges might be carried on the wind for such distances on one day or a succession of days. Synoptic weather maps should be examined for the occurrence of suitably warm winds, the timing, speed and direction of which will give some idea of when and where new outbreaks could occur.

This knowledge would be applied to control measures in the field. First, the movement of horses into or out of the suspected area could be banned. Second, if vaccine was to be given, the areas to get priority would be chosen partly on the numbers of horses and partly on the risk from windborne dispersal of midges. Third, measures could be taken against the midge population, but such control is expensive and less likely to be successful. In the outbreaks of Venezuelan equine encephalitis in Texas, U.S.A., in 1971, the mosquito population was reduced by 90% for 7–10 days by ultra-low volume spraying (Sudia *et al.* 1975) and this may have helped to delay the virus cycle in the vector. Treatment of breeding sites would be unlikely to have an immediate effect. In many countries where epidemics of African horse sickness have occurred, the initial outbreaks have been in places where communications are poor and control measures difficult to enforce.

In the past, epidemics of African horse sickness have taken place every 10–20 years, probably due to the coincidence at any one time and place of a number of factors such as the presence of virus, large populations of hosts and vectors, together with suitable winds and temperatures. From the analyses made here it is apparent that if the disease is present in south-western Iran in spring, then, owing to winds usual at that time of year, Iraq, Turkey and Syria are at risk. Similarly, India is at risk from eastern Pakistan. North Africa would only be at risk on occasions when unusual winds coincided with the presence of disease south of the Sahara. It therefore should be possible, from knowledge of the winds and temperatures at particular times of the year, to assess the risk of animals in a country being affected by a midge-borne disease, should it be in a neighbouring area.

From the meteorological data it has been possible to make some tentative deductions about time and endurance of flight, and temperatures at the time of flight. The latter agree with those observed at ground level in biting flight. However, investigation of the biology of the midge, especially its migratory behaviour, flight and animal attack, is still required so that, as with locusts and aphids, further and better control measures can be devised.

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