

# Time, travel and infection

**Andrew Cliff\*** and **Peter Haggett†**

\**Department of Geography, University of Cambridge, Cambridge* and †*Institute for Advanced Studies, University of Bristol, Bristol, UK*

The collapse of geographical space over the last 200 years has had profound effects on the circulation of human populations and on the transfer of infectious diseases. Three examples are used to illustrate the process: (a) the impact of the switch from sail to steamships in importing measles into Fiji over a 40-year period; (b) changes in measles epidemic behaviour in Iceland over a 150-year period; and (c) changes in the spread of cholera within the United States over a 35-year period. In each case, the link between time, travel and disease has been an intimate one.

Over the last 200 years, the earth's human population has grown seven-fold from less than a billion to over six billion. Half of that increase has come in the last 40 years. Striking as this is, still more impressive has been the growth in the spatial mobility or volatility of the expanding population as transport barriers have been reduced. In western countries this has increased mobility 1000-fold with half the rise coming since 1960. If we combine the two increases of population numbers ( $\times 7$ ) and mobility (up to  $\times 1000$ ), we arrive at the notion of population *flux* which is probably in the range 3000 to 7000 increase in just two centuries.

The medical literature abounds with examples of the ways in which infectious diseases may be swept along in this Brownian tide of interacting humanity—as cultures mix, so diseases are shared too. Increasing contacts with the Levant at the time of the Crusades, the New World contacts following the Columbus voyages, and Muslim pilgrimages to Mecca in the 19th century all brought major consequences for disease distribution. In recent decades the tropical haemorrhagic diseases have provided some striking instances. For example, in the summer of 1967, the export of green monkeys from Uganda *via* London to hospital laboratories in Dusseldorf, Marburg and Frankfurt, and the export a few weeks later of a further consignment to Belgrade, brought in August and the following months a sequence of 32 serious illnesses (including seven deaths) from what was eventually recognized as a viral disease, Marburg fever<sup>1</sup>.

Correspondence to:

Prof. AD Cliff,  
Department of  
Geography,  
University of Cambridge,  
Downing Place,  
Cambridge CB2 3EN, UK

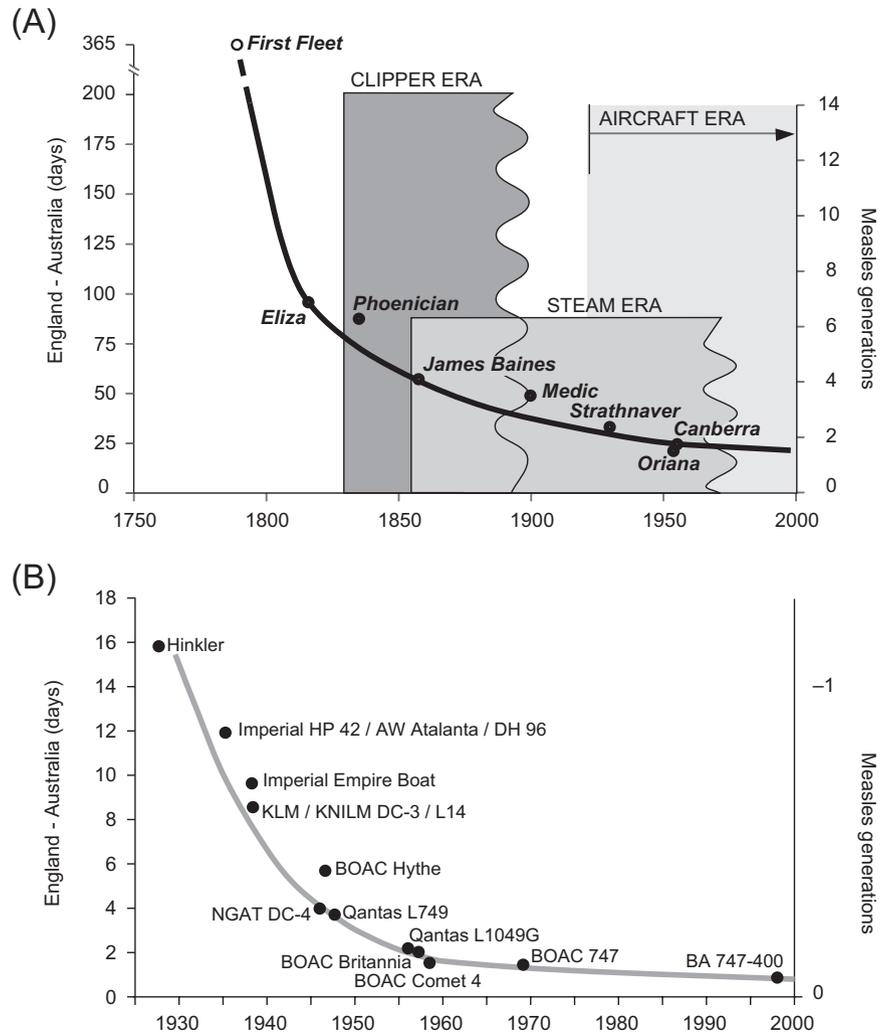
In this chapter, we try to establish the main trends in the contraction of geographical space brought about by burgeoning population flux, a space within which the human population is born, lives and dies. First, we identify the changes in technology which brought about revolutions in marine travel in the 19th century and in air travel in the 20th. Second, we illustrate how these changes appear to have brought about modifications in disease patterns. For the most part, we concentrate on old infections (notably measles and cholera) where we can be fairly sure that, unlike influenza, historical changes are not due simply to new agent strains or transformations in virulence. The impact of newly-emerging diseases (including HIV–AIDS) is a separate theme which we have treated at length elsewhere<sup>1</sup> and which we do not attempt to cover here. Third, we reflect on the general implications of travel in causing increased transfer of infections.

For the 200 years covered by this paper, two developments in transport technology were dominant: the succession of steam over sail in the 19th century, and the growth of civil aviation in the 20th. We identify the characteristic trends in both.

### *Changes in sea transport*

Summaries of the history of steam navigation and its succession over sail in the 19th century are provided by Fletcher<sup>2</sup> and Rowland<sup>3</sup>. They show that, although the practical use of steamships can be traced to the early years of the century, the prototypes were slow, inefficient and largely designed for river and canal transport. A number of fundamental advances from 1860 increased dramatically the speed and efficiency of ocean-going steamers. These included the commercial adoption of the compound steam engine, the succession of steel over iron hulls, introduction of the screw propeller and production of twin-screw vessels, development of the triple expansion steam engine and, from the 1890s, the steam turbine. The impact of these improvements on voyaging times is shown in Figure 1A<sup>4</sup>. This plots the changes in travel times between England and Australia since the First Fleet in 1788. The vertical axes of the graph have two scales, measuring travel times in days (left-hand vertical axis) and—as an epidemiological exemplar—measles generations (right-hand vertical axis). We define a measles generation (or serial interval) as 14 days, the average time between the observation of symptoms of measles in one case and the observation of symptoms in a second case directly infected from the first.

The solid line in Figure 1A depicts an exponentially-declining time trend in voyage times. As the early decades of the 19th century passed, so the size and speed of ships on the England–Australia route increased;



**Fig. 1** Changes in the travel times between England and Australia. (A) Sea transport 1788–2000. (B) Air transport 1925–2000. The solid lines show the exponential decline in travel times. A measles generation is defined as 14 days. Based on research by Cliff *et al*<sup>4</sup> and Davies<sup>5</sup>.

the periods encompassing the clipper era (1830s–1890s) and the steam era (from the 1850s) are indicated for reference. By 1840, clippers had reduced the voyage time to 100 days and, by the first decade of the 20th century, steamers had halved the voyage time again. In terms of measles virus generations, the reduction was from six to three, greatly increasing the chance of infections surviving on board and of infectives causing outbreaks in Australia.

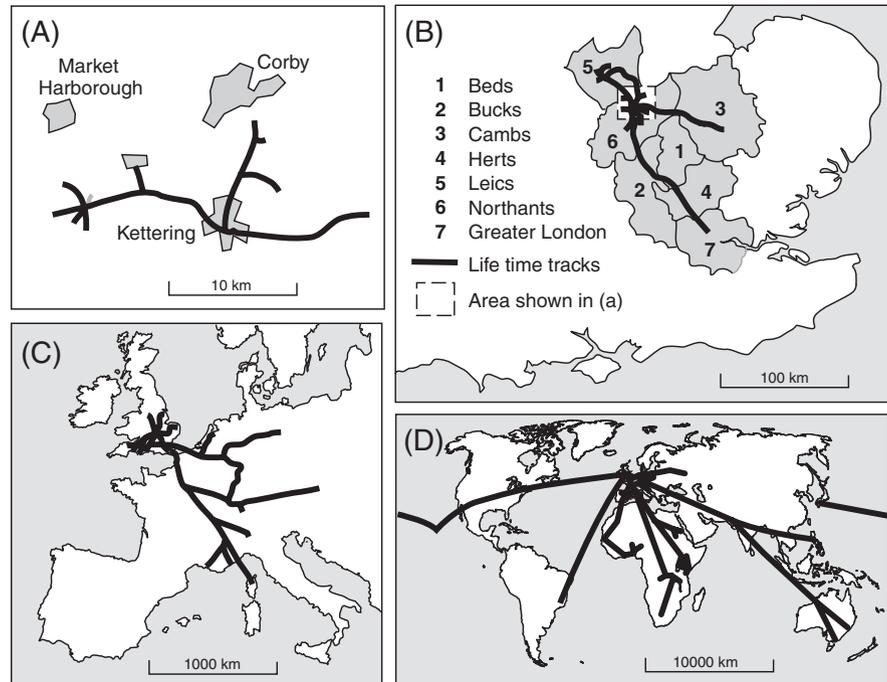
### *Changes in air transport*

If steamships accelerated global interaction in the second half of the 19th century, parallel inventions for aircraft were to do the same again in the second half of the 20th. Spurred by the technological advances that accompanied the Second World War, including the development of high-precision navigational aids and the gas turbine (jet) engine, passenger aircraft increasingly replaced ships as the international carrying medium. Figure 1B<sup>5</sup> charts the decline in flight times on the England–Australia run since 1925. Like travel times by sea, the graphs tell a similar story of exponentially diminishing journey times, with exponentially increasing speeds and carrying capacities.

Taking both parts of the figure together, it is evident that, by the year 2000, England–Australia journey times had collapsed from a year in 1788 to around 24 h. However, the collapse of geographical space has not been uniform. It is the distance between major centres, notably the world's great cities, that has been cut most dramatically. The ability of long-distance aircraft to 'overfly' those locations (often islands) which previously served as necessary refuelling places along the route has now made these relatively less accessible. Thus the shrinking world is marked by (i) reducing travel times between major centres, balanced by (ii) unchanging or reducing accessibility for minor centres off the well-beaten transport tracks.

### *Impact on population movements*

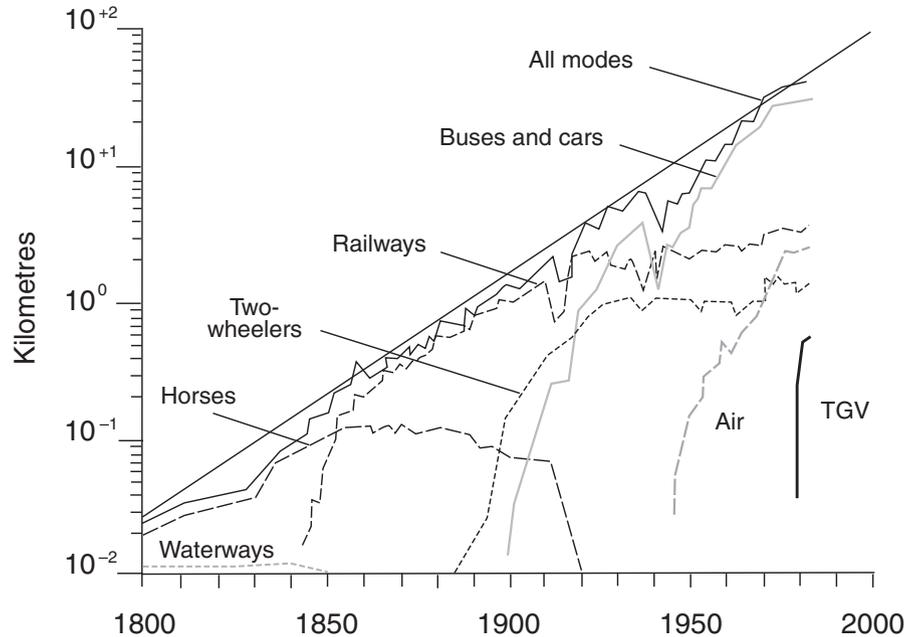
Ways in which travel patterns have changed for the host population over recent generations have been shown in an interesting way by the distinguished epidemiologist, David Bradley<sup>6</sup>, when he was at the London School of Hygiene and Tropical Medicine. Bradley compared the travel patterns of his great-grandfather, his grandfather, his father and himself (see Figure 2). The life-time travel track of his great-grandfather around a village in Northamptonshire could be contained within a square of only 40 km side. His grandfather's map was still limited to southern England, but it now ranged as far as London and could be contained within a square of 400 km side. If we compare these maps with those of Bradley's father (who travelled widely in Europe) and Bradley's own sphere of travel, which is worldwide, then the enclosing square has to be widened to sides of 4000 km and 40,000 km, respectively. In broad terms, the spatial range of travel has increased 10-fold in each generation so that Bradley's own range is 1000 times wider than that of his great-grandfather.



**Fig. 2** Bradley's record of increasing travel over four male generations of the same family<sup>6</sup>. (A) Great-grandfather. (B) Grandfather. (C) Father. (D) Son. Each map shows in a simplified manner the individual's 'life-time tracks' in a widening spatial context, with the linear scale increasing by a factor of 10 between each generation.

Against this individual cameo, we can set some broader statistical trends from recent years. One indicator of the dramatic increase in spatial mobility appears in Figure 3<sup>7</sup>. This plots for France over a 200-year period the average kilometres travelled daily by people both by particular transport mode and by all modes. Since the vertical scale is logarithmic the graph demonstrates that, despite changes in the mode used, average travel increased exponentially over the period, broken only by the two World Wars—a rise of over 1000 in mobility.

The precise rates of flux or travel of population both within and between countries are difficult to catch in official statistics. But most available evidence suggests that the flux over the last few decades has risen at an accelerating rate. While world population growth rate since the middle of the 20th century has been running at between 1.5% and 2.5% per annum, the growth in international movements of passengers across national boundaries has been between 7.5% and 10% per annum. One striking example is provided by Australia: over the last four decades, its resident population has doubled whereas the movement of people across its international boundaries (that is, into and out of Australia) has increased nearly 100-fold.



**Fig. 3** Increased spatial mobility of the population of France. Changes over a 200-year period, 1800–2000. The vertical scale is logarithmic so that growth in average travel distance has increased exponentially over time. Based on Haggett<sup>7</sup>.

## Contraction and disease spread

In this second section, we take three examples of the ways in which spatial contraction has had an influence on the spread of infectious diseases.

### *Intercontinental spread: the example of Fiji (1879–1920)*

Fijian sugar plantations provide a classic example of the way in which a change in transport technology—from sailing ship to steamship—brought about the end of natural isolation as a defensive barrier to disease importation. We consider measles as our exemplar disease.

In the late 19th century, Fiji in the Pacific was one of a series of tropical islands (others included Trinidad in the Caribbean and Mauritius in the Indian Ocean) whose climate and soils were ideal for growing sugar cane, a crop in soaring demand in Europe. But all three islands were short of suitable local labour. In the post slavery period, the import of slave plantation labour from Africa was banned. A new source area (India) and a new form of bondage (indentured labour<sup>a</sup>) provided a solution.

Between 1879 and 1920, Indian immigrant ships made 87 voyages to Fiji carrying nearly 61,000 indentured emigrants<sup>8</sup>. The main routes followed are mapped in Figure 4A. This illustrates an important distinction between voyages by sailing ships (used between 1879 and 1904) and steamships (used between 1884 and 1916). To take advantage of prevailing winds, sailing ships followed the route south of Australia and took about 70 days for the voyage. Steamships used the Torres Strait north of Australia and halved the sailing ship times; they were also able to carry a larger number of immigrants.

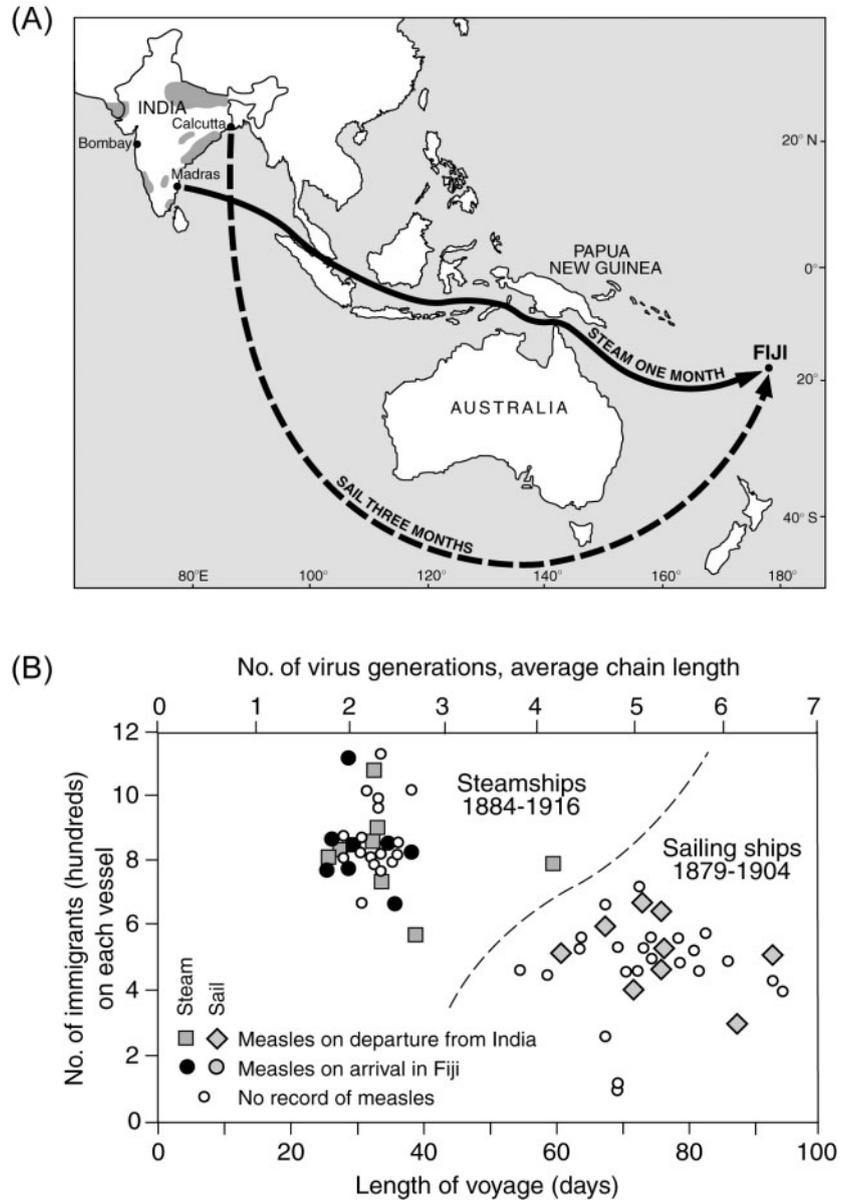
The health and welfare of the immigrants were the responsibility of the Surgeon-Superintendent who accompanied each ship and whose report was incorporated into the Annual Reports on Indian Immigration published regularly as Official Papers of Fiji's Legislative Council. Study of these papers by Cliff and Haggett<sup>9</sup> shows how the transition from sail to steam dramatically altered the ways in which infectious diseases were transmitted between India and Fiji.

Since measles was an endemic disease in India, it is not surprising that cases were recorded on departure, although there were checks in the camps both at Calcutta and Madras (the two exit ports) before embarkation: the evidence in the Fijian annual reports shows a 1:3 probability of measles being detected on board on departure from India, and this proportion of 'infected' voyages remained constant over the period. These are shown in Figure 4B in which each voyage is plotted in terms of the time taken and the passenger size of each vessel.

For the smaller and slower sailing ships, one-third of the voyages left India with infections but the measles virus did not survive the journey. By the end of the voyage those infected had either recovered or died and the sequence of measles generations (up to six on slower voyages) was broken. But for the faster and larger steamships, Figure 4B shows the situation was different. One in three voyages were still infected on departure and, in 11 cases, the virus continued to thrive on arrival in Fiji. The larger susceptible population and shorter travel times (as few as two generations on the fastest voyages) ensured the virus persisted to pose a potential threat at the receiving end. Only intensive quarantine guaranteed that the experience of the disastrous 1875 measles epidemic in Fiji was not repeated.

### *Island epidemics: the example of Iceland (1840–1990)*

A second example of an infectious disease responding to transport changes is provided by the sub-Arctic island of Iceland. Because of its exceptional epidemiological records, Iceland has been intensively studied by epidemiologists<sup>10</sup>. Over the 150-year period from 1840 to 1990, some



**Fig. 4** Measles transfer from India to Fiji. (A) Routes from India to Fiji via sailing ships and steamships. (B) Vessels carrying indentured immigrants between India and Fiji, 1879–1916, categorized by length of voyage in days and in measles virus generations (14-day periods), type of vessel and measles status. Based on archival research by Cliff and Haggett<sup>9</sup>.

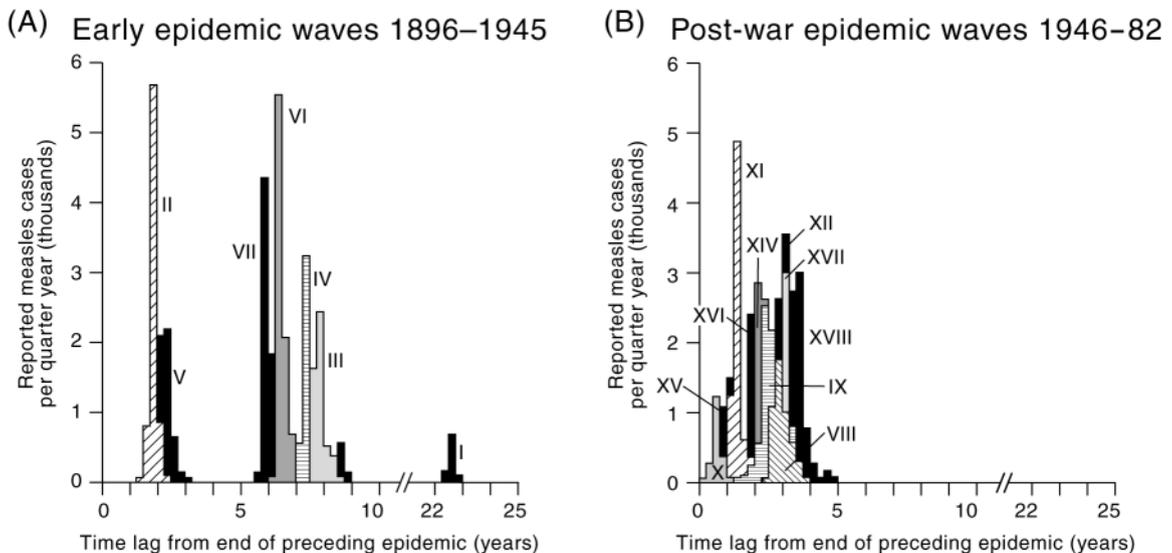
93,000 cases of measles were recorded in Iceland. Over 99% of these occurred in 19 distinct epidemic waves. The Icelandic doctors kept detailed written accounts of the geographical pattern of spread of many of these epidemics. The early waves frequently diffused from one community to

another as infectives travelled coastwise by boat. In addition, Iceland has always had too small a population to maintain measles permanently, and introductions of the disease into Iceland at the start of each wave was, until the end of the Second World War, exclusively by ship. After 1945, both measles introductions and the subsequent spread of the disease within Iceland became dominated by movements of infectives by air rather than by boat. Virus introductions also became more frequent as population flux in Iceland increased.

The impact of more frequent virus introductions is shown in Figure 5. The spacing of Iceland's measles waves became shorter over time as the island's population grew and contacts with the outside world became more frequent. The average gap between waves in the period 1896 to 1945 was more than 5 years; from 1946 to 1982 it had fallen to a year and a half. More frequent virus introductions also meant there was less time for the susceptible population to increase and so epidemics became smaller as well as more closely spaced.

#### *Intracontinental spread: cholera in the United States (1832–1866)*

The 19th century saw six major pandemics in which cholera exploded from its base in the Indian subcontinent into other parts of Eurasia. The increased volume of shipping and the falling travel times across the Atlantic made it all but inevitable that the United States and Canada

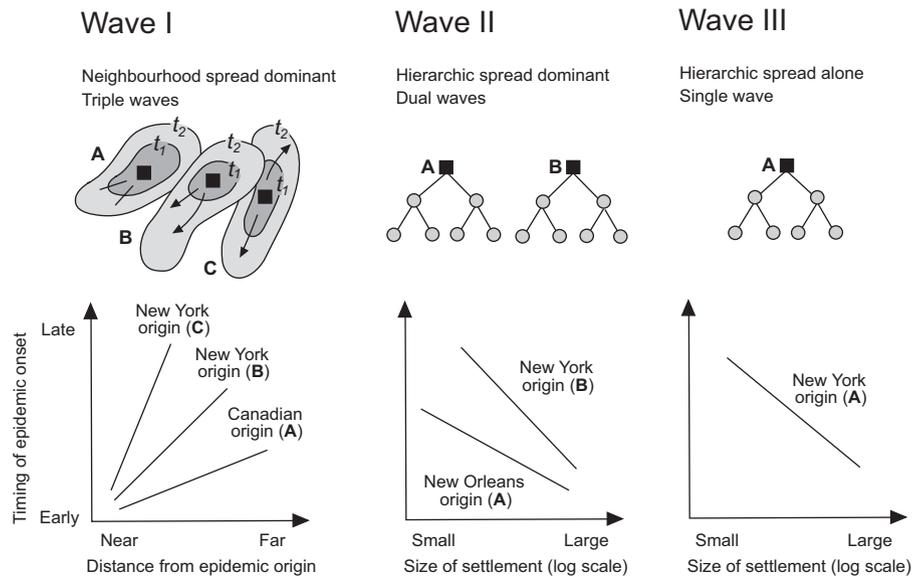


**Fig. 5** Time intervals between epidemic waves in Iceland. The diagram shows contrasts between earlier and later measles epidemics between 1896 and 1982. The horizontal axis gives the time in months since the preceding epidemic. Based on research by Cliff *et al*<sup>10</sup>.

would not escape the pandemics that were engulfing Europe. In fact it was affected by three, with the disease introduced in June 1832 (a 6-month outbreak), December 1848 (9 months) and May 1866 (5 months). Pyle<sup>11</sup> has plotted the progress of the three waves, city by city, charting the day of first reporting of the disease in each place. Over that critical period of 35 years, the North American transport system had been revolutionized with canal transport being largely replaced by the rapidly-expanding railroad system.

Figure 6 gives a generalized diagram of Pyle's results. Wave I (1832) had three spatial components, (a) a Canadian pulse (starting in the St Lawrence valley and moving *via* the Great Lakes), (b) an interior waterways pulse (starting at New York City and moving *via* the Hudson into the Ohio river system) and (c) a coastal waterways pulse (also starting at New York City but moving up and down the Eastern seaboard).

In contrast Wave II (1848–9) had a simpler two-fold structure; an interior waterways pulse based on cholera imported into New Orleans, and an Eastern seaboard pulse fuelled by cholera imported into New York City. By the time of Wave III (1866), the pattern of spread was simpler still with a single national system emanating from New York City. Pyle went on to show that the shifts in the way cholera spread in the three epidemics reflected the evolving economic and political structure of the United

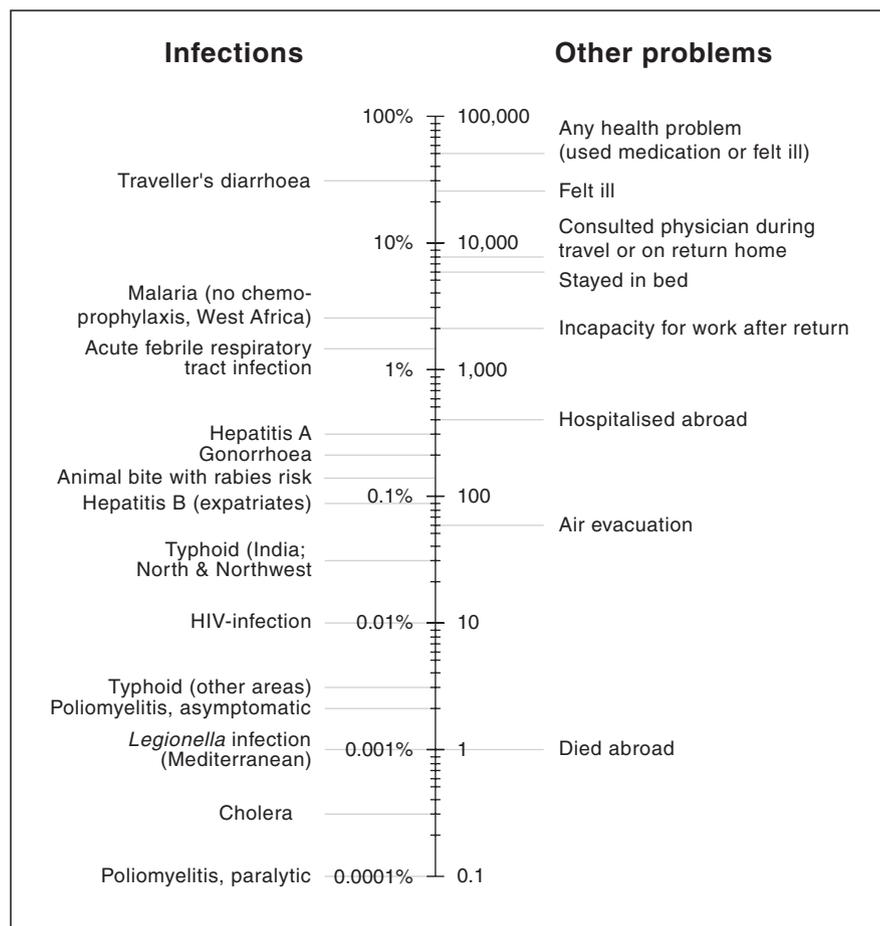


**Fig. 6** Schematic diagram of Pyle's<sup>11</sup> ideas on the changing spread of cholera in the United States, 1832–66. Wave I (1832) spread in three pulses mainly by contagious diffusion from two points of introduction. Wave II (1848–9) spread in two pulses mainly by hierarchic diffusion from two centres; it was reinforced by local contagious diffusion. Wave III spread in a single pulse by hierarchic diffusion from a single centre.

States. As the railways (with their east–west grain) replaced the inland waterways (with their south–north grain) and the political economy became more integrated (a United States replaced the Confederate South and Unionist North), so cholera diffusion became less dependent upon local and regional contact (transport) networks and ever more driven through intercity links in the urban metropolitan hierarchy.

## Some general implications of travel for disease spread

The implications of increased travel are two-fold: short-term and long-term. First, an immediate and important effect is the possible exposure of the travelling public to a greater range of diseases than they might meet in their home country. The relative risks encountered in tropical areas by travellers coming from western countries (data mainly from North America and Western Europe) have been estimated by Steffen<sup>12</sup> and are given in Figure 7.



**Fig. 7** WHO estimates<sup>12</sup> of relative disease threats to travellers in tropical areas. Note that the scale is logarithmic.

These suggest a spectrum of risks from unspecified “traveller’s diarrhoea” (a high risk of 20%) to paralytic poliomyelitis (a very low risk of less than 0.001%). Another way in which international aircraft from the tropics can cause the spread of disease to a non-indigenous area is seen in the occasional outbreaks of tropical diseases around mid-latitude airports. Typical are the malaria cases that appeared within 2 km of a Swiss airport, Geneva–Cointrin, in the summer of 1989<sup>7</sup>. Cases occurred in late summer when high temperatures allowed the in-flight survival of infected *anopheles* mosquitoes which had been inadvertently introduced into the aircraft while at an airport in a malarious area. The infected mosquitoes escaped when the aircraft landed at Geneva to cause malaria cases among several local residents, none of whom had visited a malarious country.

A second short-term factor with modern aircraft is their increasing size in terms of passenger numbers. Bradley<sup>6</sup> postulates a hypothetical situation in which the chance of one person in the travelling population having a given communicable disease in the infectious stage is 1 in 10,000. With a 200-seat aircraft, the probability of having an infected passenger on board ( $x$ ) is 0.02 and the number of potential contacts ( $y$ ) is 199. If we assume homogenous mixing, this gives a combined risk factor ( $xy$ ) of 3.98. If we double the aircraft size to 400 passengers, then the corresponding figures are  $x = 0.04$ ,  $y = 399$  and  $xy = 15.96$ . In other words, *ceteris paribus*, doubling the aircraft size increases the risk from the flight four-fold, although in practice such probabilities would be modulated by the air circulation technology used. Thus the new generation of wide-bodied jets presents fresh possibilities for disease spread, not only through their flying range and their speed, but also from their size.

On a longer time-scale, increased travel brings some possible long-term genetic effects. With more travel and longer range migration, there is an enhanced probability of partnerships being formed and reproduction arising from unions between individuals from formerly distant populations. As Khlát and Khoury<sup>13</sup> have shown, this can bring advantages from the viewpoint of some diseases. For example, the probability of occurrence of multi-factorial conditions such as cystic fibrosis or spinal muscular atrophy is reduced; the risk of these conditions is somewhat higher in children of consanguineous unions. Conversely, inherited disorders such as sickle cell anaemia might become more widely dispersed.

## Conclusion

The collapse of distance brought about by changes in transport technology over the last 200 years, linked to massive increases in personal mobility, has affected the transfer of communicable diseases. The geographical

extent of many has increased; they appear more frequently in different locations, but they generally occur today as small outbreaks rather than as the massive epidemics witnessed in the 19th and early 20th centuries. In addition, greater international population flux carries genetic implications for population mixing.

## Notes

- a Indentured labour means work under a restrictive contract of employment for a fixed period in a foreign country in exchange for payment of passage, accommodation and food.

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