Foresight

Infectious Diseases: preparing for the future

OFFICE OF SCIENCE AND INNOVATION

T8.5: Traffic in Disease Vectors: 2005, 2015 and 2030

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Abstract:

Climate change may make ports and airports in the UK more inviting to mosquito species responsible for serious diseases such as malaria, yellow fever and dengue. This study examined weather conditions at major ports and airports, both now and as they might evolve with climate change until 2030. The more similar the conditions are between ports and airports in the tropics and the UK destinations they serve, the more likely it is that disease-carrying mosquitoes arriving in ships and aircraft will be able to survive and potentially infect people. On current climate models, the risk of 'airport malaria' and other diseases will grow until 2015 and then ease as the climate of the UK diverges from those in tropical countries. There is very little chance of the mosquitoes or the diseases for which they are the vector becoming permanently established in the UK. The risk is of single cases or limited outbreaks of disease in and around airports and seaports.

This review has been commissioned as part of the UK Government's Foresight project, Infectious Diseases: preparing for the future. The views expressed do not represent the policy of any Government or organisation.

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1 Summary for Policy Makers

Method. The risk of disease vector invasion is related to climatic similarity and traffic volumes between origin and destination. An ecological–economic framework, applied previously to describe the historical spread of *Aedes albopictus* (Tatem et al. 2006a, 2006b), and the temporary establishment of *Anopheles gambiae* (Tatem et al. 2006b, 2006c), was extended to incorporate climate simulations for 2015 and 2030 derived from atmosphere–ocean general circulation models.

Climate predictions encompassing temperature, rainfall and humidity were used to provide estimates of the climate regimes at major seaports and airports around the world for 2005, 2015 and 2030. Measures of similarity between the climates at seaports and airports in the UK and those across the rest of the globe were calculated for each year. For three principal mosquito vectors of disease, *An. gambiae, Ae. albopictus* and *Ae. aegypti*, the change in climatic similarities between seaports and airports within the current distribution of the vector and those of London were examined.

For *An. gambiae*, known cases of airport malaria were used to define the timing and level of climatic similarity between airports sufficient to enable temporary invasion. Climatic similarities across the global air network were clustered and summarised using a dendrogram, and the airport malaria-defined threshold applied to extract air routes and months at greatest risk of temporary *An. gambiae* UK invasion. Incorporation of air-traffic volumes enabled refinements of these risks to account for propagule pressure.

Results. In terms of predicted future climate, spatial and temporal aspects of the risk of disease vector invasion to the UK will not change uniformly over the next 25 years. Examination of predicted climate at London's ports and airports and those within the current geographical ranges of three principal vectors of disease, *An. gambiae*, *Ae. albopictus* and *Ae. aegypti* show differing levels of similarity in 2015 and 2030, relative to today.

The likelihood today and in the next 25 years of more than a very temporary establishment of *An. gambiae* in the UK remains low. Any growth of travel to Africa presents a negligible risk of establishing malaria in the UK. However, results here suggest that the risks of temporary *An. gambiae* invasion, leading to possible airport malaria cases, may increase by 2015, before decreasing again by 2030. By 2015, more *An. gambiae*-endemic airports than today will have a comparable level of climatic similarity to those London airports that resulted in airport malaria cases, with August being the most similar month. Predicted climatic shifts for 2030 will result in this number falling again.

Predictions suggest that many seaports and airports in areas with *Ae. albopictus* and *Ae. aegypti* will become climatically more similar to London's seaports and airports by 2015, increasing any risk of invasion. This trend is, however, predicted to reverse by 2030 as climatic regimes diverge.

Conclusions. It must be emphasised that this exploratory study examines only predicted future climatic links within the global transport network. Nevertheless, results suggest that, in climatic terms, the risk of importation of disease vectors to the UK in the next 25 years will not change uniformly in space or time, and that vector-specific assessments are required. Specific research avenues are suggested to extend this work by: (i) using a complete database of all sea and air movements; (ii) incorporating predictions on future changes to global travel network architectures and traffic volumes; and (iii) examining additional aspects such as vector preferences, control policies, land transport and populations at risk.

Although the sheer volume of air traffic to the UK means that exotic mosquitoes will continue to arrive by air, the greatest risk of actual vector establishment in the UK must be through incoming sea traffic, due to the ability of modern container ships to carry large numbers of mosquitoes and their eggs. Vigilance over monitoring import risk should be maintained accordingly.

2 Technical Summary

We have outlined novel approaches to examining the risks of initial dispersal and the possible establishment of mosquito vectors of human disease. An ecological–economic framework, applied previously to describe the historical spread of *Aedes albopictus* (Tatem et al. 2006a, 2006b) and the temporary establishment of *Anopheles gambiae*, (Tatem et al. 2006b, 2006c), was extended to incorporate climate simulations for 2015 and 2030 derived from atmosphere–ocean general circulation models. These scenarios were used to estimate changes in climatic similarity between principal UK seaports and airports and those within the geographical ranges of *Ae. albopictus, An. gambiae* and *Ae. aegypti.* Results suggest that, in terms of predicted future climate, disease vector invasion risk to the UK will not change uniformly, either spatially or temporally, in the next 25 years. For *An. gambiae*, climatic convergence in the summer months with parts of Africa may increase the risks of temporary UK invasion by 2015, but reduce them below current levels by 2030.

Predictions suggest that many seaports and airports in areas inhabited by *Ae. albopictus* and *Ae. aegypti* will also become climatically more similar to London's seaports and airports by 2015, increasing the risk of invasion. This trend will, however, reverse by 2030 as climatic regimes diverge. The context of these results and the overall risk of UK invasion for each mosquito species are discussed, as are the different aspects of the seaborne and airborne transport of disease vectors. Finally, future research directions for improving this work are outlined, including the incorporation of future transport network predictions and the consideration of factors such as vector preferences, control policies, land transport and populations at risk.

3 Introduction

Throughout history, the opening of new travel and trade routes between countries has been accompanied by the spread of disease pathogens and their vectors (Diamond 1998). The current reach, volume and speed of travel are unprecedented, so that human spatial mobility has increased in high-income countries over 1,000-fold since 1800 (Wilson 1995; Wilson 2003). Aviation in particular has expanded rapidly as the world economy has grown, though worries about its potential for spreading disease have a history comparable to the duration of commercial aviation (Massey 1933). Passenger numbers have risen by nearly 9% per annum since 1960 and are expected to increase at more than 5% p.a. for at least the next 10 years, with airfreight traffic showing similar figures (Upham et al. 2003). Similarly, globalisation of the world economy has also resulted in a shipping traffic increase of over 27% since 1993 (Zachcial and Heideloff 2003). The global growth of economic activity, tourism and human migration has led to increasing movement of disease vectors and the pathogens they carry. Pathogens and their vectors can now move further, faster and in greater numbers than ever before, overcoming previous geographical barriers to their spread.

Aircraft and ships are believed to be directly responsible for rapid expansion in the range of many plants and animals via inadvertent transport (Perrings et al. 2005). Studies of the invasion process and the spread of exotic species have increased considerably in the past 15 years (Puth and Post 2005; Williamson 1996). Invasion is a multi-step process comprising three phases: (i) initial dispersal, where an organism moves from its native habitat to a new one, outside its previous range; (ii) establishment, where populations become self-sustaining within the new habitat; and (iii) spread, when these self-sustaining populations expand their ranges within the new habitat (Leung et al. 2002; Williamson 1996). The contingent nature of this process makes initial dispersal the phase with the greatest effects on other, later stages, yet it remains by far the least studied (Puth and Post 2005).

Non-indigenous vectors that disperse, establish and spread have, throughout recorded history, fomented epidemics of diseases such as malaria, yellow fever and typhus. Since the 15th century, successive invasive waves of the disease vector mosquitoes *Ae. aegypti, Culex pipiens* and recently, *Ae. albopictus*,[*] have been facilitated by global shipping (Lounibos 2002). Propagule pressure (Lockwood et al. 2005), previous success and level of adaptation to human habits and habitats, appear to favour successful invasion by vectors of disease (Lounibos 2002). The establishment of a vector-borne disease in a new area from an endemic region can be caused either by movement of an infected host and availability of competent vectors in the new area, or by the invasion, if only temporarily, of an infected vector.

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[*] Recent work has suggested the reclassification of *Ae. aegypti* and *Ae. albopictus* to *Stegomiyia aegypti* and *Stegomiyia albopicta*, respectively (Reinert et al. 2004). This has been contested. To prevent confusion while this taxonomic dispute is resolved, we follow the guidelines set by Weaver (2005) and maintain usage of the traditional names.

Here, we focus our attention on the changing risks to the UK, in terms of predicted climatic similarity to seaports and airports within their current distributions, of invasion by three of the world's principal mosquito disease vectors: *Anopheles gambiae*, vector of *Plasmodium falciparum* malaria in Africa*; Aedes albopictus*, a competent vector of 22 arboviruses; and *Aedes aegypti*, the principal vector of both dengue and yellow fever viruses. The approaches outlined in this report are not restricted to these mosquitoes, however, and can be applied to the risk of introduction of a range of other vectors of disease. Since arthropod disease vectors exploit a diversity of ecological niches and have unique, species-specific environmental preferences and distributions, these analyses need to be repeated for each and every vector species of interest.

3.1 Anopheles gambiae

An. gambiae is the most efficient vector of *P. falciparum* malaria. It resides solely in sub-Saharan Africa and has only escaped from its traditional range to establish and breed elsewhere twice in recorded history. The most devastating escape was from Senegal to north-eastern Brazil in 1930, either by steamship or plane. The resulting *P. falciparum* malaria epidemics cost 16,000 lives (Killeen et al. 2002) before they were eradicated by an effective, yet costly control programme (Soper and Wilson 1943). Comparable high mortality rates were seen in Mauritius, when the accidental introduction of *A. gambiae* in 1866 also changed malaria transmission from low to epidemic (Lounibos 2002). The rapid expansion in air travel to and from malaria-endemic regions has been reflected in the temporary movement of malaria and its vectors, especially from Africa. For example, in one three-week period in 1994, it was estimated that between 2,000 and 5,000 anopheline mosquitoes were imported into France on 250–300 aircraft arriving from malaria-endemic regions of Africa: a rate of 8–20 anopheline mosquitoes per flight (Gratz et al. 2000). Increased travel to malarious regions has also resulted in many cases of autochthonous malaria transmission, principally clustered around international airports: so called 'airport malaria' (Isaäcson 1989; Muentener et al. 1999). This occurs principally through the transport of infected anopheles mosquitoes that can survive for long enough to continue malaria transmission at their destination (Isaäcson 1989). Tatem *et al.* (2006b, 2006c) outlined a methodology to examine monthly risks of *P. falciparum* malaria-infected *An. gambiae* importation by plane from Africa, with the potential to cause consequent autochthonous transmission. Here, we extend this methodology to examine future risks to the UK. Although, globally, the movement of *P. vivax* malaria-infected mosquitoes may occur more frequently and pose more of an invasion risk to many regions, it is the movement of *P.-falciparum*-infected mosquitoes that has resulted in numerous recorded airport malaria cases. Due to its rapid clinical onset and the often associated development of life-threatening complications in non-immune individuals, it is the *P. falciparum* malaria parasite that has the most serious potential public health consequences for the UK population.

3.2 Aedes albopictus

The Asian tiger mosquito, *Ae. albopictus,* is a competent vector of 22 arboviruses, including West Nile, dengue and yellow fever viruses (Gratz 2004; Gubler 2003). Although *Ae. aegypti* is the principal vector of dengue fever, recent outbreaks of the disease in the absence of *Ae. aegypti* have implicated *Ae. albopictus* as a further competent vector (Effler et al. 2005; Gratz 2004). The range expansion of *Ae. albopictus* from its Old World distribution across temperate and tropical east Asia over the past 75 years is perhaps the best documented of any disease vector. The mosquito spread from its ancestral range initially to the Pacific Islands (Gratz 2004) in the 1930s and then, within the last 20 years, to other countries in both the Old and New Worlds (Gratz 2004; Moore and Mitchell 1997). This is thought to have been driven by ship-borne transportation of their eggs and larvae in tyres (Reiter 1998; Reiter and Sprenger 1987). The spread of *Ae. albopictus* throughout eastern USA from its discovery in Harris County, Texas, in 1985 has been monitored extensively (Moore 1999; Moore and Mitchell 1997), as have further invasions across central and South America, Africa and Europe (Gratz 2004; Gubler 2003).

3.3 Aedes aegypti

Ae. aegypti is a known vector of numerous human pathogens and is the principal vector of both yellow and dengue fever viruses. Though the mosquito is now established throughout the tropical and subtropical regions of the world, it was located solely in west Africa until the 15th century (Lounibos 2002). The insect adapted to anthropogenic breeding sites, including water-storage jars in ships (Lounibos 2002). This ability facilitated its spread with the growing slave trade from west Africa to reach the New World and to invade Portugal and Spain before proliferating elsewhere on European ships. *Ae. aegypti* consequently became established across the tropical and temperate regions of the Americas, causing severe yellow fever epidemics at port cities (Haggett 2000).

Intensive control and eradication schemes in the 1950s and 1960s reduced the geographical extent of *Ae. aegypti* considerably (Gubler 2004). However, gradual resurgence following the end of these control campaigns resulted in the species once again becoming widespread across the Americas and associated with the emergence of dengue and dengue haemorrhagic fever (Gubler and Clark 1995). Yellow fever has largely been contained by vaccination in modern times. *Ae. aegypti* also invaded tropical Asia where its dispersal has again been associated with a rise in the incidence of dengue and dengue haemorrhagic fever (Gubler and Clark 1995).

3.4 Aims

This report aims to examine two specific areas of future disease traffic risk to the UK:

1. Changes in global climatic similarity between UK seaports and airports and those of the rest of the world. This will focus specifically

on changes related to these seaports and airports within the current geographical ranges of *An. gambiae*, *Ae. albopictus* and *Ae. aegypti*, and thus enable assessment of the changing climatic risks.

2. Incorporation of air-traffic data to examine any changes in the risk of imported *An. gambiae* mosquitoes to the UK from Africa by air. Insufficient data from African ports precluded this being undertaken for sea traffic.

4 Methods

4.1 Data

4.1.1 Future climate

We used the HadCM3 coupled atmosphere–ocean general circulation model (AOGCM) (www.meto.gov.uk/hadleycentre/models/HadCM3.html) developed at the Hadley Centre for Climate Prediction and Research (www.mad.zmaw.de/IPCC_DDC/html/SRES_TAR/index.html, downloaded on 7 July 2005) that has a similar $2.5^{o} \times 3.75^{o}$ (latitude by longitude) spatial resolution to HadCM2 (Gordon et al. 2000; Hulme et al. 1999; Pope et al. 2000). We chose the medium–high A2 emission scenario. This choice has little consequence on results as the difference between the projected impacts of emission scenarios before 2030 are tiny (Stott and Kettleborough 2002). Since the HadCM3 AOGCM simulates weather, individual years can be noisy. Therefore, 11-year averages centred on 2005 (2000–2010) for the baseline, and 2015 (2010–2020 inclusive) and 2030 (2025–2035 inclusive) for future climate, were used. Moreover, we also chose to use the average of the A2a, A2b and A2c ensemble member runs, each of which were initialised with very small differences in their starting conditions, to obtain a more representative climatology. The specific meteorological variables used were mean surface air temperature (K) at 2m, total precipitation (mm/day) and relative humidity (%) for the years 2000–2035 inclusive. These three variables provide a basic representation of the climatic regime of an area (Rogers and Randolph 2003), and mosquito disease vectors are sensitive to all three (Craig et al. 1999; Rogers 2000).

A number of caveats must be highlighted when using climate simulations from an AOGCM. Firstly, while the HadCM3 model provides the finest spatial resolution output of any AOGCM, the climate simulations are undertaken within $2.5^{o} \times 3.75^{o}$ grid cells so that and any local variations that may occur at a finer scale than this (e.g. the increased rainfall across the western UK from the Gulf stream) are not simulated. Past studies have attempted to engineer finer spatial resolution estimates by interpolating the AOGCM output and subtracting a fine resolution known meteorologically-based baseline surface from them to provide fine-resolution change estimates. Such approaches would here add unnecessary uncertainty and make it difficult to tease out interpolation artifacts from possible climate change, and were therefore not used. See Hay et al. (2006) for a further discussion of these issues.

4.1.2 Seaports, airports and traffic

Data on the 243 most visited international seaports in 2000 (Drake and Lodge 2004) yielded a total of 29,403 routes. Flight data on total passenger numbers moving between the world's major airports in the year 2000, using statistics supplied by all scheduled airlines, were obtained from OAG Worldwide Ltd. The database contained data on the world's top 100 airports by traffic (100% aircraft capacity was assumed), plus the principal airport of 143 other countries. Data on a total of 7,129 routes between 278 international airports in the year 2000 were therefore available. Data on predicted changes in traffic volumes or the opening/closing of routes were not available, but may be available for future iterations of this work, as will also more comprehensive and contemporary seaport and airport data. This report is focused principally, therefore, on changes in climatic similarities that are predicted to occur within the existing global transport networks for which we have data. Where transport data was incorporated for Aim 2, the hypothetical situation of no changes in traffic volume or network structure was assumed.

4.1.3 Disease vector distributions

To provide an estimate of malaria endemicity and the presence of *An. gambiae* at each airport, the MARA fuzzy climate suitability (FCS) model (Craig et al. 1999) and predictions from Rogers et al. (2002) were used. To provide information on which seaports and airports are located within the current geographical range of *Ae. albopictus*, a range of data sources was consulted (Gratz 2004; Lounibos 2002; Moore 1999; Snow and Ramsdale 2002). To provide information on which seaports and airports are located within the current geographical range of *Ae. aegypti*, maps from the CDC *Traveler's Health Yellow Book* (www2.ncid.cdc.gov/travel/yb/) were used. We assume here that the vector distributions in 2015 and 2030 will remain as they are today. Future work will attempt to incorporate predicted changes in distributions into analyses.

4.2 Climate signatures

To estimate the risk of disease vector importation, it was assumed that mosquitoes breeding in the vicinity of the origin port or airport were most likely to be transported accidentally by ship or aircraft. Therefore, the climatic similarity between origin and destination seaports and airports determined principally whether the mosquito would survive, even temporarily, in the region of the destination port.

The locations of the 243 ports and 278 airports were superimposed onto the monthly climatology surfaces and each grid square covering the seaport and airport location identified. Seaports and airports located in areas too small to be represented by the climatology surfaces were eliminated from the analysis, thereby reducing the sample size to 233 seaports and 222 airports. The grid squares identified in each of the three climatology surfaces thus formed climate 'signatures' for each month, for each seaport and airport. The coarse resolution of the climate signatures meant that, in certain cases, grid squares encompassed more than one seaport and airport, for example, London

Heathrow/Gatwick airports. In such cases, these seaports and airports were analysed together, leaving a total sample size of 206 unique signatures for the seaports and 209 for the airports.

4.3 Distance measures and climate dissimilarity matrices

The lack of sufficient variance in the majority of climatic signatures dictated that only simple Euclidean distance could be used as a measure of climatic similarities. Euclidean distances between each signature centroid and the centroids of every other signature were calculated to derive separate monthly climate 'dissimilarity' matrices. Tests using those signatures that did facilitate the use of more sophisticated distance measures revealed that the relative distances produced were very similar to those derived from Euclidean distances (results not shown). This point represents the extent to which the methodology was followed for Aim 1. For Aim 2, the extended methodology, first outlined in Tatem et al. (2006b, 2006c), was followed and adapted, and is described briefly.

4.4 Clustering and dendrograms

The climate dissimilarity matrices were subject to hierarchical clustering using an agglomerative algorithm. The clustering results were then translated into dendrograms based on centroid linkage using Phylip v3.63 (University of Washington, USA), for each month of the year. In simple terms, this creates a climate-based version of a phylogenetic tree, which groups within its branches clusters of seaports and airports sharing similar climatic characteristics.

4.5 Climatic similarity thresholds

In terms of Aim 2, to define how similar airport climates need to be to permit the temporary survival of imported anopheles and the possible continued transmission of *P. falciparum* malaria, confirmed examples of where such events have occurred previously were used. Cases of airport malaria confirm that, at the time of year of the case, the climate in the vicinity of the origin and destination airports were similar enough for infected anopheles survival and malaria transmission at the destination. Interestingly, in no suspected cases of airport malaria has the exact origin of imported anopheles or malaria been confirmed unambiguously, though in almost all cases, Africa is known to be the origin. It was assumed, therefore, that the origin was the African airport or region most climatically similar with the destination in the 2005 data, during its primary transmission season.

Figures 1(a) and 1(b) show that, in the last 30 years, the vast majority of probable airport malaria cases have occurred in the months of July and August, in the vicinities of Paris Charles De Gaulle, London Heathrow/Gatwick and Brussels airports (Gratz et al. 2000). All routes linking these to airports in malaria-endemic African countries with transmission in July and August were identified. The routes were located on the relevant dendrograms and the branch height joining the most similar origin and destination airports in question noted. The height of the highest branch joining airport malaria origin to destination airport was then taken as the climatic similarity limit for temporary anopheles survival, once imported. This limit was then applied across all dendrograms for 2005, 2015 and 2030.

The locations of the African airports in the database were overlaid on the MARA FCS map and assigned as either ‘endemic’ or ‘non-endemic’. Those non-malarious airports linked by a dendrogram branch lower than the airport malaria-defined climatic limit to a malarious airport were identified. These airports were identified as being similar enough climatically to produce a risk of temporary malarious mosquito invasion, and consequent autochthonous transmission.

4.6 Risk matrices

To obtain a monthly measure of malaria movement risk to those airports identified as being at-risk within the dendrogram, the monthly Euclidean environmental distances and traffic data were used. In using this traffic data for 2015 and 2030 predictions, we assume that the flight routes operating today will remain and that relative passenger numbers also remain unchanged. While these allow us to isolate climate effects, the global air transport network is likely to continue its rapid evolution in scope and capacity. We therefore also analysed climatic similarity changes with malaria endemic airports in Africa as part of Aim 1 and calculated details of numbers of malaria-endemic airports linked within the airport malaria-defined dendrogram threshold to estimate the origin of risks should new flight routes open from Africa.

The Euclidean distances between malarious African airports and other airports were rescaled linearly by dividing through by the maximum Euclidean distance in the climate dissimilarity matrix, and inverted to lie between 0 and 1. Therefore, the most climatically similar airport pairs had a value close to 1, and those distinctly different a value close to 0. Similarly, the air-traffic data was also rescaled, resulting in the airports with the most traffic running between them in a year taking a value close to 1, while those routes with little or no traffic a value close to or at 0. It was assumed that passenger numbers on each route remained consistent year-round and that routes and relative passenger volumes would remain static up to 2030. For each month and route between malarious African airports and other airports, the rescaled climatic and traffic measures were then multiplied together to provide a simple monthly measure of temporary malarious mosquito importation and risk of consequent autochthonous transmission.

5 Results

In terms of risks to the UK, results were calculated for all of the UK’s international seaports and airports, but, for the sake of brevity, only the results involving the busiest ports and airports (London ports and London Heathrow/Gatwick airports) are reported here. In general, however, the results for London’s ports and airports were very similar to those for the rest of the UK.

5.1 Changes in global climatic similarity between UK seaports and airports and those of the rest of the world

Figure 2 shows the 2005 climatic similarities between (a) London ports and all other ports, and (b) London Heathrow/Gatwick airports and all other international airports. Figure 3 shows the magnitude and direction of predicted climatic similarity change with London's ports and airports from the 2005 baseline (Figure 2) to 2015. The direction and magnitude of predicted climate similarity changes from 2005 to 2030 are shown in Figure 4.

5.1.1 Seaports and airports within the current geographic range of An. gambiae

Figure 5(a) shows the 2005 monthly variations in average climatic similarity by region between those airports within the current geographical range of *An. gambiae* and London Heathrow/Gatwick airports. Figure 6 demonstrates how these climatic distances are predicted to change for 2015 and 2030. Finally, Table 1 lists the most climatically similar ports and airports, within the current geographical range of *An. gambiae,* to London Heathrow/Gatwick airports per month for 2005, 2015 and 2030.

5.1.2 Seaports and airports within the current geographical range of Ae. albopictus

Figures 5(b) and 5(c) show the 2005 monthly variations in average climatic similarity by region between those seaports and airports within the current geographical range of *Ae. albopictus* and London's ports and airports. Figures 7 and 8 demonstrate how these climatic distances are predicted to change for 2015 and 2030. Finally, Tables 2 and 3 list the most climatically similar ports and airports, within the current geographical range of *Ae. albopictus*, to London's ports and airports per month for 2005, 2015 and 2030.

5.1.3 Seaports and airports within the current geographical range of Ae. aegypti

Figures 5(d) and 5(e) show the 2005 monthly variations in average climatic similarity by region between those ports/airports within the current geographical range of *Ae. aegypti* and London's ports and airports. Figures 9 and 10 demonstrate how these climatic distances are predicted to change for 2015 and 2030. Finally, Tables 4 and 5 list the most climatically similar ports and airports within the current geographical range of *Ae. aegypti,* to London's ports and airports per month for 2005, 2015 and 2030.

5.2 Changes in the risk of imported *An. gambiae* mosquitoes to the UK from Africa by air

Table 6 shows, for 2005, 2015 and 2030, the number of airports within the geographical range of *An. gambiae* that are connected to London Heathrow/Gatwick airports on climatic dendrograms below the threshold defined by airport malaria cases. Table 7 shows the results of incorporating data on current air-traffic routes and volumes to extract the top 10 risk routes for 2005, 2015 and 2030.

6 Discussion

6.1 Future global climatic similarity

In interpreting Figures 3 and 4, the 2005 baseline climatic similarities shown in Figure 2 should be taken into account. From 2005–2015, Figure 3 shows that those seaports and airports located in southern, central-east and north-west USA, south-west Canada, south-east Australia, northern New Zealand, northern and south-west Africa, central Asia and central Europe are all predicted to become climatically more similar to London's ports and airports. This suggests that, focusing simply on climatic factors, disease vectors residing in these regions have an increased possibility of UK invasion in 2015 should sufficient transport links exist, compared to 2005.

Interestingly, the direction of climatic similarity changes predicted for 2005–2015 reverses for 2005–2030 (Figure 4) at many ports and airports. For example, south-west USA, east Africa, northern Europe and north-east Asia are all predicted to become less climatically-similar to London by 2015, but, by 2030, become more similar than today. Such changes suggest that disease vector invasion risk to the UK will not change uniformly in space or time over the next 25 years. This spatial and temporal heterogeneity suggests that the application of the approaches outlined to vectors of disease, other than the three chosen in this report, will produce varying and unique conclusions for each vector species. For brevity, only the predicted climatic similarity changes are examined here. For quantitative information on predicted climatic shifts for the UK and elsewhere (e.g. temperature, precipitation levels), readers are referred to the range of publications from the Intergovernmental Panel on Climate Change (www.ipcc.ch/pub/pub.htm).

6.2 An. gambiae

Figure 5(a) shows clearly the seasonal changes in climatic similarity between London Heathrow/Gatwick and airports within the range of *An. gambiae*, with summer in the UK producing the lowest average Euclidean distances for west, east and central Africa. Figure 6 shows that, for both west and central African airports, the climatic similarity to London's airports is predicted to change little, apart from in January when climates become less similar, and July when climates in 2015 are anticipated to become more similar. East Africa shows larger changes predicted for the UK winter and summer periods. Climate regimes at London airports and across east Africa are predicted to become less similar in June, but more similar in September. Table 1 reflects these changes, while Table 6 shows that, by 2015, more *An.-gambiae*-endemic airports than today will be within a comparable level of climatic similarity to London airports that result in airport malaria cases, with August the most similar month. Predicted climatic shifts for 2030 result in this number falling again by 2030.

In relation to the same air routes between sub-Saharan Africa and the UK remaining in operation, with similar relative passenger numbers on each route, Table 7 shows that the principal risk routes and months will change little. The large numbers of people currently travelling on both the Lagos to London Gatwick and Lagos to London Heathrow routes, combined with the relative climatic similarity of Lagos to London in the UK summer months, make this consistently the top risk route for *An. gambiae* temporary invasion. However, the predicted changes in climatic similarity result in overall higher risks in 2015.

It should be emphasised that the likelihood now and over the next 25 years of more than a very temporary establishment of *An. gambiae* in the UK remains low. Unsuitable year-round climate, low shipping volumes from Africa (Tatem et al. 2006a, 2006b), *An. gambiae's* intolerance of the urban habitat (Hay et al. 2005) surrounding many ports and airports, and competition from local mosquitoes that are less efficient vectors of *P. falciparum* all provide barriers to establishment. Malaria caused by *P. vivax* and vectored predominantly by *An. atroparvus* was a common cause of death in the marshes or wetlands of England during the 19th and 20th centuries (Kuhn et al. 2003), with the last autochthonous cases reported in 1953 (Crockett and Simpson 1953). Although malaria has been eradicated in the UK, re-introduction is theoretically possible.

This risk is negligible, however, as most of the former habitats of *An. atroparvus* have disappeared, and returning travellers are rapidly diagnosed and treated. In any case, they rarely live in suitable vector habitats (Kuhn et al. 2003). This is supported by the fact that not one of the 52,000 imported malaria cases reported since 1953 has led to a secondary case. Any growth of travel to Africa therefore presents a negligible risk of establishing malaria in the UK, but results here suggest that the risks of temporary *An. gambiae* invasion, leading to possible airport malaria cases, may increase by 2015, before decreasing again by 2030.

6.3 Ae. albopictus

The current distribution of *Ae. albopictus* has been shown to be made up of both temperate (diapausing) and tropical (non-diapausing) races (Hawley et al. 1987; Lounibos et al. 2003). The tolerance of the temperate race to cooler, wetter climates makes *Ae. albopictus* the most obvious candidate of the three disease vectors examined here for UK establishment and spread. Recent discoveries of breeding populations in southern France, northern Spain and Belgium (Gratz 2004) highlight this risk. Focusing solely on climatic factors, Figures 5(b) and 5(c) show that, of the ports and airports within the current distribution of *Ae. albopictus*, those in Europe are the closest to London climatically. In terms of sea transport, May represents the most similar month to European ports, with Table 2(a) indicating Genoa as the port with the lowest Euclidean distance. Elsewhere, climatic similarity peaks in different months, depending on the origin ports, with air travel showing similar patterns for 2005.

Analysis of predicted future climate change in terms of the climatic similarity of London’s seaports and airports to seaports and airports within the current range of *Ae. albopictus*, reveals a mixed picture. For 2015, the predicted climatic similarity for both ports and airports in Africa, Asia and the Americas generally increases, especially in the summer months of the northern hemisphere (Figures 7 and 8) when climatic distances are lowest. This is not the case for European seaports and airports, however.

Looking in the long term, to 2030, climatic similarity actually decreases relative to 2005 between London seaports and airports and those around the world within the current range of *Ae. albopictus*. There are noteworthy exceptions, e.g. Africa in July, Asia and North America in September and South America in August. Overall, the results suggest, climatically at least, that the risk of *Ae. albopictus* establishment in the UK may be lower than at present by 2030. This is reflected in Table 2, with climatic distances from the closest ports increasing from 2005 levels by 2030, though the closest linked ports climatically change from 2005 to 2015 to 2030 in certain cases.

6.4 Ae. aegypti

The preference of *Ae. aegypti* for more tropical climatic conditions, relative to *Ae. albopictus*, is reflected in the overall larger Euclidean distances shown in Figures 5(d) and 5(e) and Tables 4 and 5. However, the shifts in climatic similarity shown in Figures 9 and 10 match closely those described above for *Ae. albopictus*. With the exception of those seaports and airports in Africa and the Middle East, there exists a general trend for London’s ports and airports to become climatically more similar to seaports and airports within the range of *Ae. aegypti* in 2015, compared to 2005, then less similar by 2030, particularly during June–September. Tables 4 and 5 reflect these trends, with some of the smallest climatic Euclidean distance values occurring in 2015, especially for Africa and South America in August. The tropical climate preferred by *Ae. aegypti* makes the likelihood of establishment of the species in the UK low, but results here suggest that, should it become accidentally introduced during the UK’s summer months, the climatic similarities with certain seaports and airports within the mosquito’s current range mean temporary establishment could be possible.

Predictions suggest that many seaports and airports in *Ae. aegypti* infested regions will become climatically more similar to London’s seaports and airports by 2015, increasing the risk of temporary invasion. As with seaports and airports within the range of *Ae. albopictus*, however, this trend will reverse by 2030 as climatic regimes diverge.

6.5 Sea versus air travel

The most successful mosquito invaders in recorded history have generally arrived by ship. Of 40 instances of culicid invaders surveyed by Lounibos (2002), only five instances of aircraft introductions are known. The strong relationship between release size and probability of invasion success is thought to be behind this (Drake and Lodge 2004; Levine and D'Antonio 2003; Lockwood et al. 2005). Though surveys have found mosquitoes surviving flights in wheelbays and luggage compartments (Russell 1987, 1989), generally only a few adult individuals arrive as a result of aircraft introduction. Modern container ships are, however, capable of carrying large numbers of mosquitoes and their eggs, especially through the global used-tyre trade which is thought to be the cause of numerous recent mosquito invasions (Reiter 1998; Reiter and Sprenger 1987).

Therefore, although the sheer volume of air traffic arriving in the UK means that exotic mosquitoes will continue to arrive by air, the risk of actual vector establishment in the UK must be considered greater through incoming sea traffic. This is restricted to those species that can survive and breed in transit; generally anthrophilic species. Vigilance in monitoring import risk should be maintained accordingly and inspection and control policies from other countries reviewed. For example, in Australia and New Zealand, despite a greater risk from tropical disease vector invasion, protection measures have proved successful to date.

6.6 Future research priorities

We stress that the exploratory study outlined here merely examines predicted future climatic links within the global transport network and that levels of uncertainty are not quantified. Numerous other, more complex and intangible factors determine the success or failure of dispersal, establishment and spread of vectors of disease. However, recent work on retrospective predictions on disease vector traffic (Tatem et al. 2006a, 2006b, 2006c) has shown that the combination of climate and traffic data can yield surprisingly accurate estimates of invasion risk.

To extend and improve on the work outlined here, predictions on future sea- and air-traffic volumes should be incorporated, as well as predicted changes to network architecture and disease vector distributions. Additional factors for possible incorporation include data on disinsection, monitoring and fumigation policies, transport predictions, populations at risk, land transport, vector adaptations to local environments, breeding habitat availability, vector preferences, intra-species competition and the relative importance of both sea versus air transport and climate versus propagule pressure. The use of more detailed environmental data, such as from recent satellite imagery (Tatem et al. 2004), should also aid extension of this work.

Finally, while this review has focused primarily on mosquito invasion, the approaches described could be applied to any disease vector that is sensitive to climate. These may include, for example, specific species of sandflies (vectors of leishmaniasis) (Desjeux 2001), midges (vectors of African horse sickness and bluetongue) (Mellor and Hamblin 2004; Tatem et al. 2003) or ticks (vectors of tickborne encephalitis) (Randolph 2000).

7 Acknowledgements

Thanks to Dr Daithi Stone for advice on the appropriate choice, use and interpretation of the HadCM3 atmosphere–ocean general circulation model. We are grateful especially to John Drake for the generous supply of sea-traffic data. SIH and AJT are funded by a Research Career Development Fellowship from the Wellcome Trust (#069045, to SIH).

8 Glossary

Airport malaria	Malaria cases in people who live near airports in countries that have no malaria.
Baseline	Contemporary climate from which change is measured.
Climate	Weather averaged in time.
Climate change	Long-term changes in the climate, natural or man-made.
Climatology	Average climate of a region, usually over 30 years.
Climate model	Process-based model of physical processes that determine the weather.
Dendrogram	A 'tree-like' diagram that summaries the process of clustering. Similar cases are joined by links whose position in the diagram is determined by the level of similarity between the cases.
Disinsection	The process of eradicating insects from an enclosed space, most commonly used to describe the application of insecticide aerosol sprays to aircraft interiors.
Euclidean distance	Commonly called ‘straight-line distance’ or ‘distance as the crow flies’. Using Cartesian co-ordinates, the distance between points (x, y) and (x', y') is given by the formula in accordance with the Pythagorean theorem.
Propagule	Any organism that can give rise to a new individual and aids in dispersal of the species.
Propagule pressure	The number of propagules entering a new environment.

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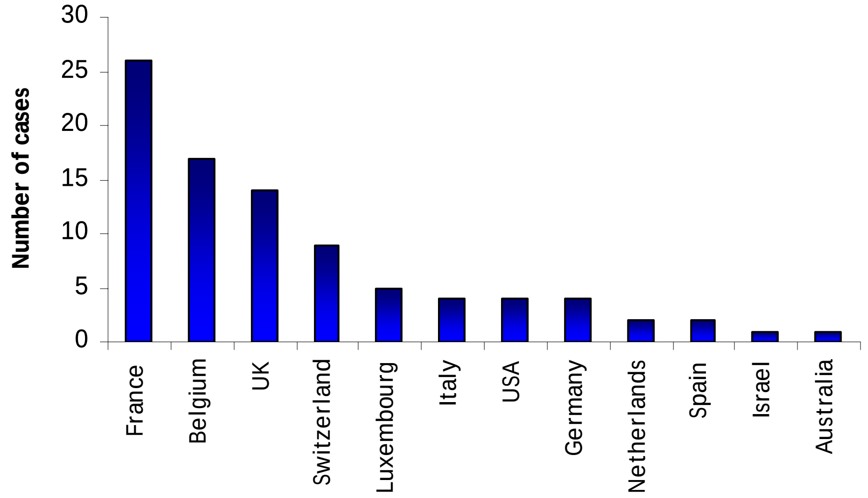
Figure 1: (a) *Countries in which confirmed or probable cases of airport malaria have been reported since 1969. Data taken from Gratz (2000);*
(b) *month in which European airport malaria cases occurred (where date is provided).*



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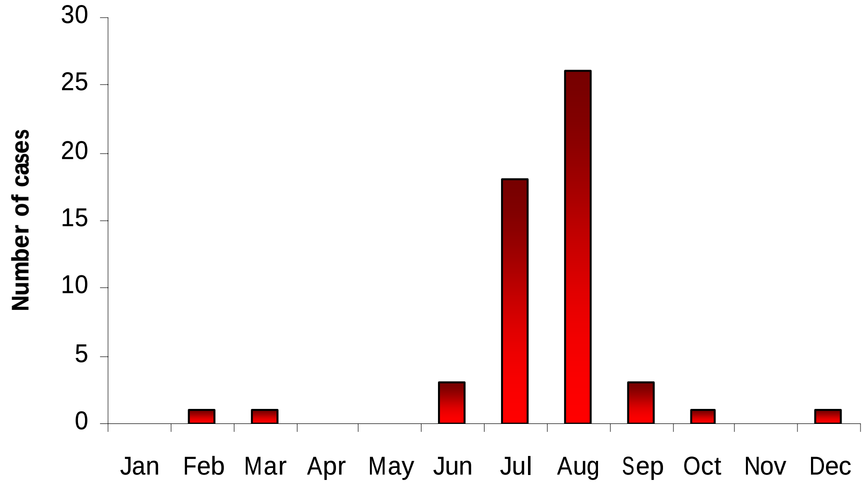
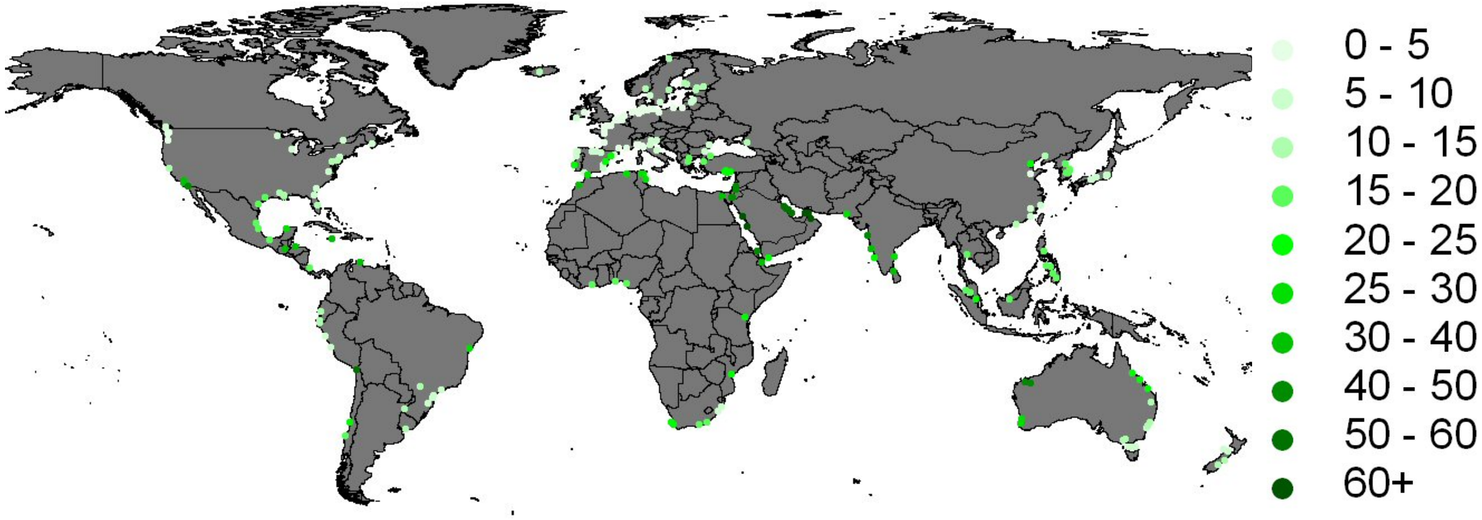


(b)

Figure 2: *Euclidean climatic distance in 2005 between:* ***(a)*** *London ports and all other ports;* ***(b)*** *London Heathrow/Gatwick airports and all other international airports.*



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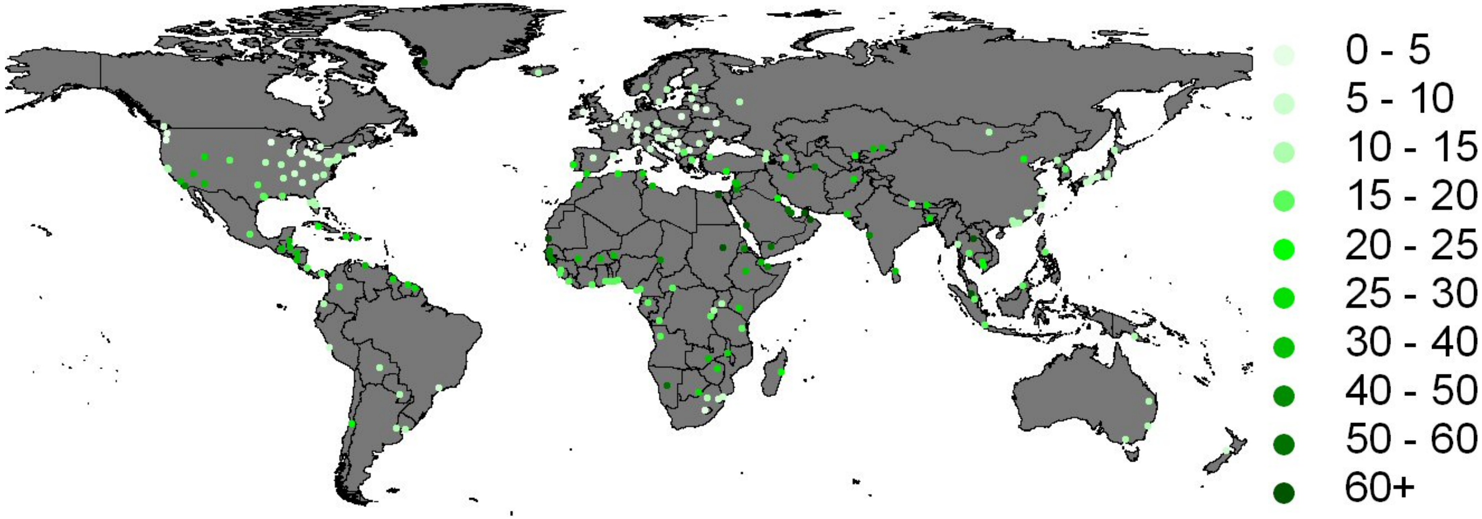

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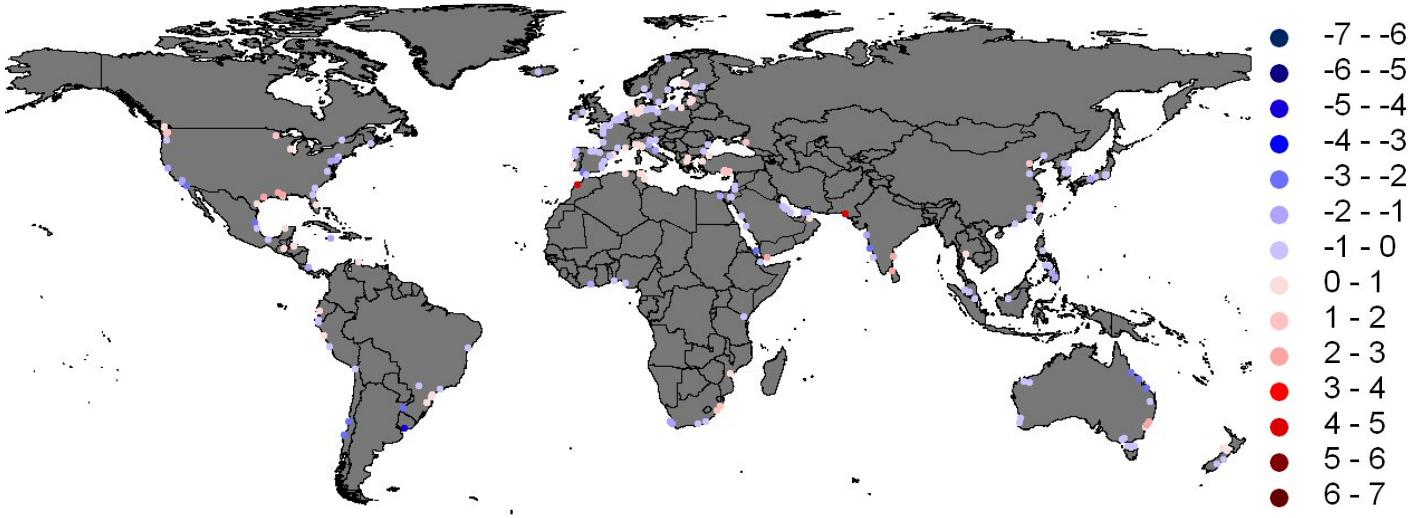
Figure 3: *Euclidean climatic difference in 2015 from 2005 baseline between:* ***(a)*** *London ports and all other ports;* ***(b)*** *London Heathrow/Gatwick airports and all other international airports.*



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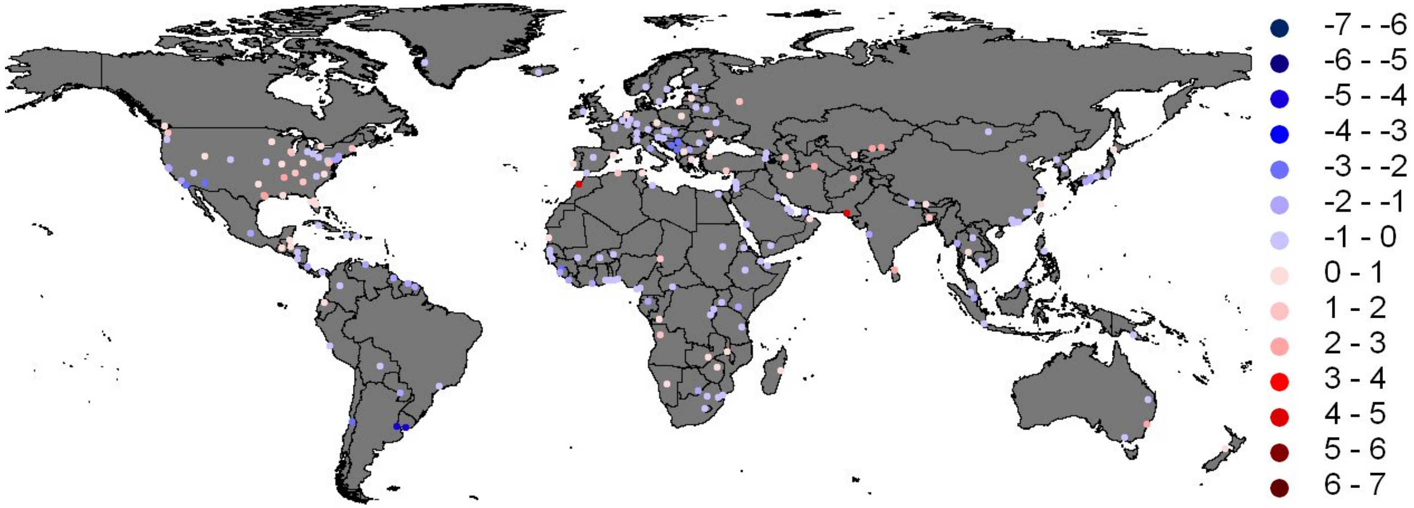

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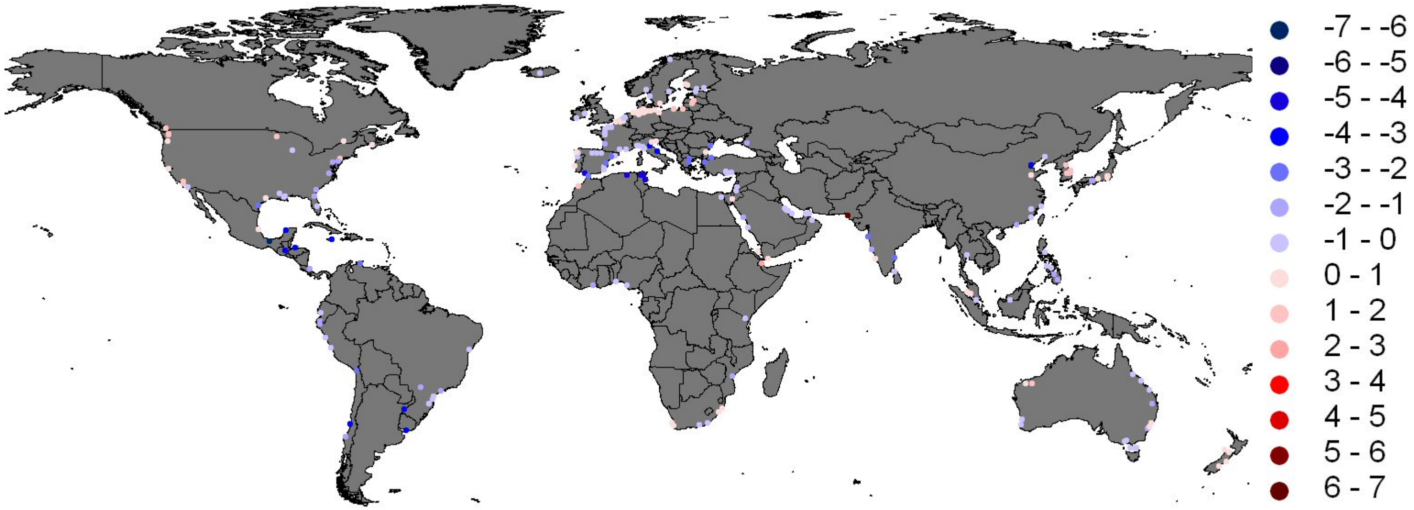
Figure 4: *Euclidean climatic difference in 2030 from 2005 baseline between:* ***(a)*** *London ports and all other ports;* ***(b)*** *London Heathrow/Gatwick airports and all other international airports.*



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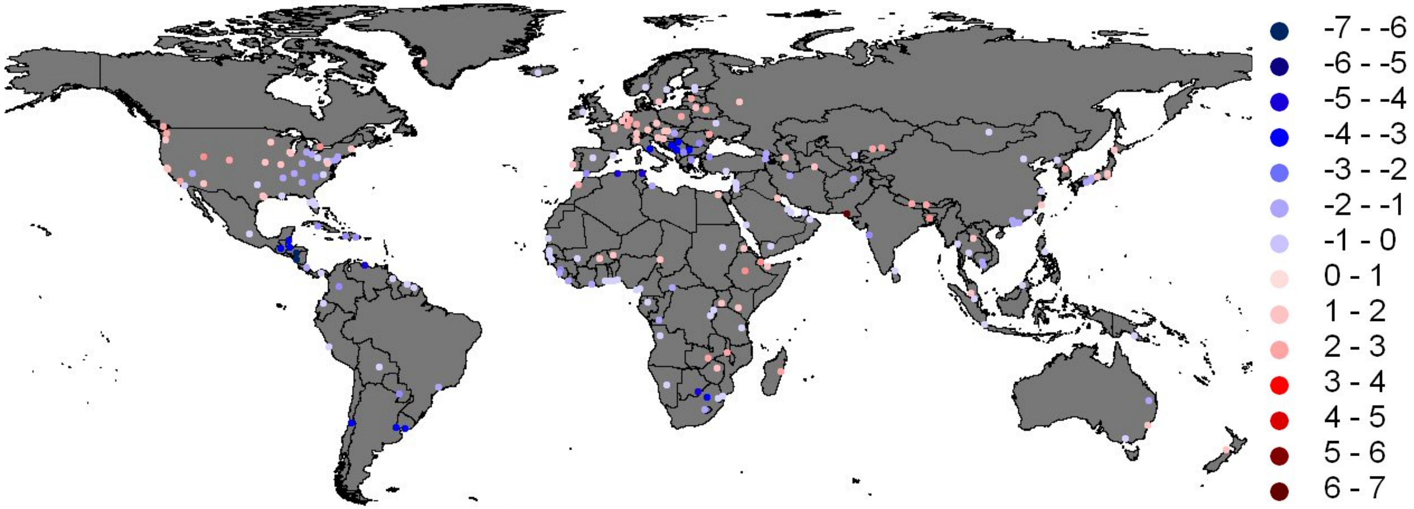
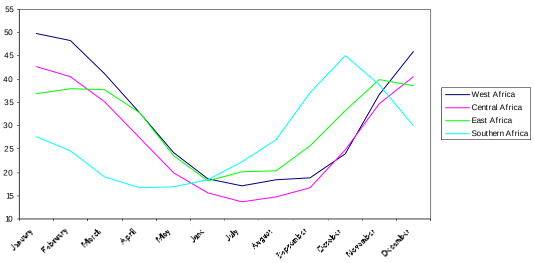


(b)

Figure 5: *Average monthly climatic similarities in 2005 between:* ***(a)*** *P. falciparum endemic airports across Africa and London Heathrow/Gatwick airports;* ***(b)*** *seaports within the current range of Ae. albopictus and London seaport;* ***(c)*** *airports within the current range of Ae. albopictus and London Heathrow/Gatwick airports;* ***(d)*** *seaports within the current range of Ae. aegypti and London seaport; and* ***(e)*** *airports within the current range of Ae. aegypti and London Heathrow/Gatwick airports. (In each graph, Euclidean distance is on the y-axis.)*



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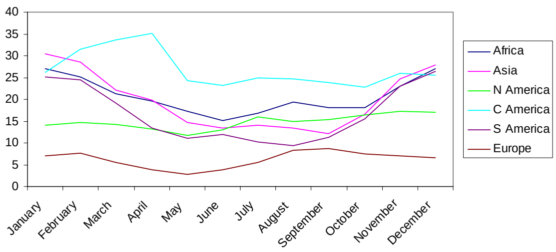

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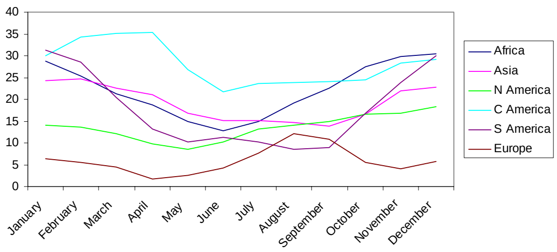

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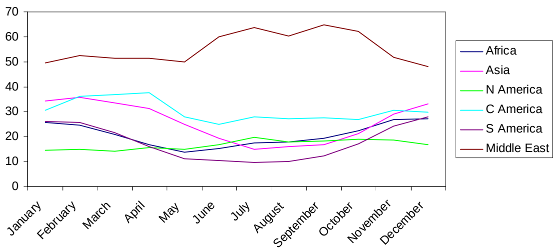

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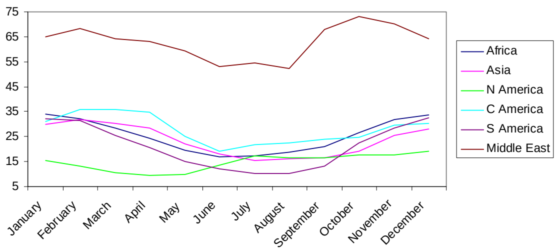
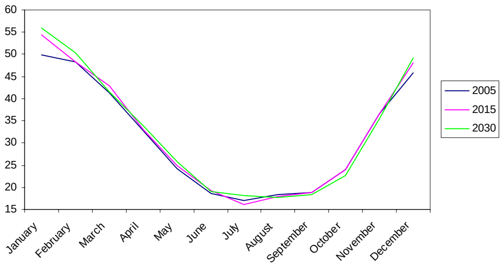


(e)

Figure 6: *Average monthly climatic similarities in 2005, 2015 and 2030 between London Heathrow/Gatwick airports and P. falciparum malaria endemic airports in:* ***(a)*** *west Africa;* ***(b)*** *central Africa;* ***(c)*** *east Africa; and* ***(d)*** *southern Africa. (In each graph, Euclidean distance is on the y-axis.)*



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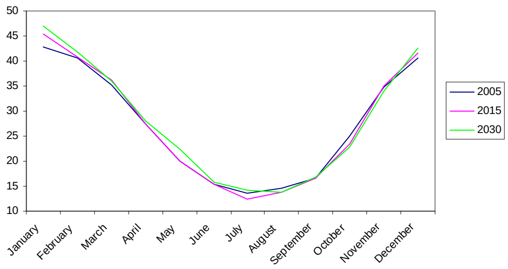

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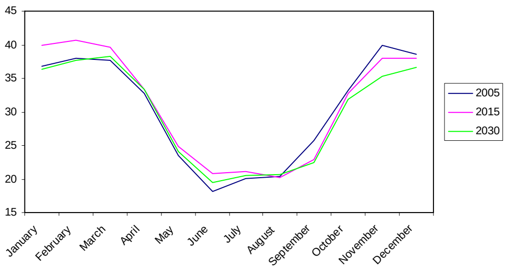

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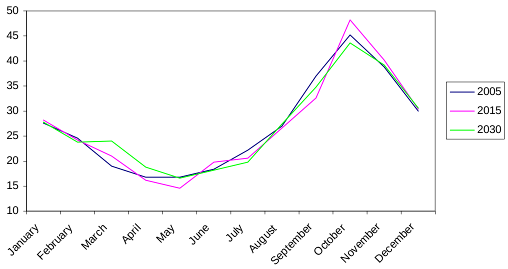
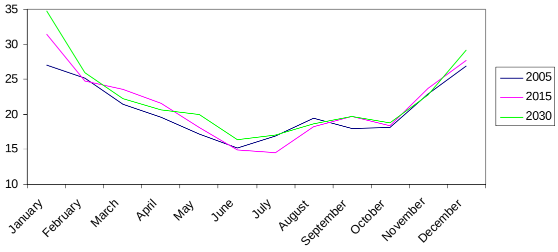


(d)

Figure 7: *Average monthly climatic similarities in 2005, 2015 and 2030 between London seaport and seaports within the current geographic range of Ae. albopictus in:* ***(a)*** *Africa;* ***(b)*** *Asia;* ***(c)*** *North America;* ***(d)*** *Central America;* ***(e)*** *South America; and* ***(f)*** *Europe. (In each graph, Euclidean distance is on the y-axis.)*



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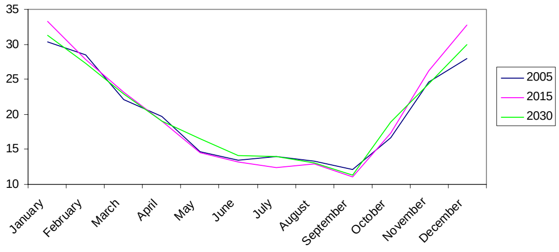

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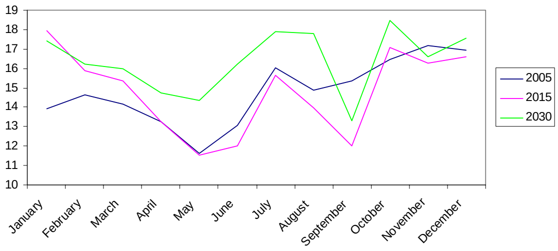

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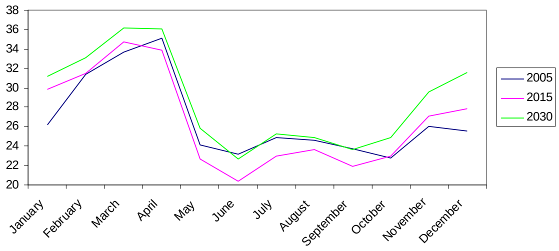
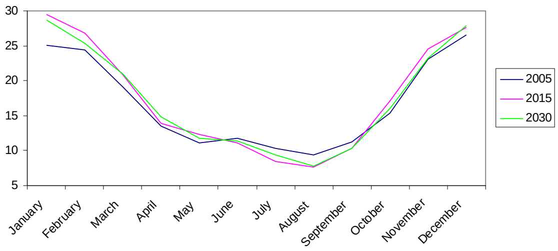
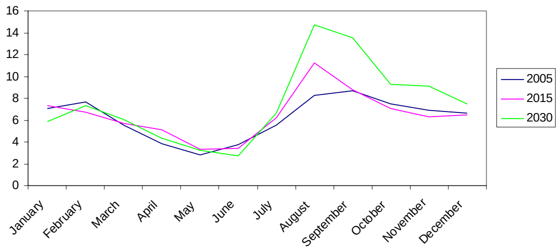


(d)



(e)



(f)

Figure 8: *Average monthly climatic similarities in 2005, 2015 and 2030 between London Heathrow/Gatwick airports and airports within the current geographic range of Ae. albopictus in:* ***(a)*** *Africa;* ***(b)*** *Asia;* ***(c)*** *North America;* ***(d)*** *Central America;* ***(e)*** *South America; and* ***(f)*** *Europe. (In each graph, Euclidean distance is on the y-axis.)*

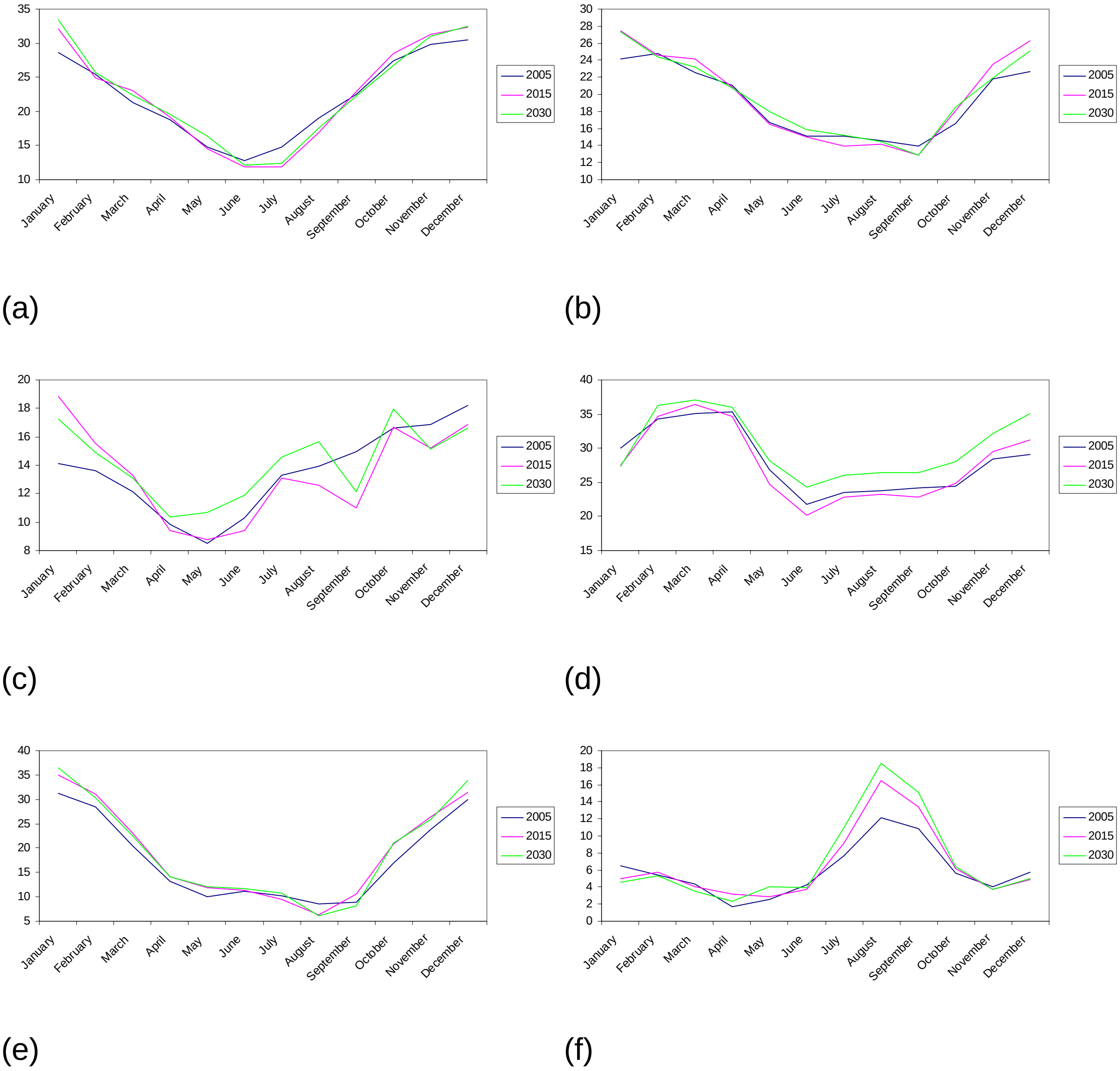
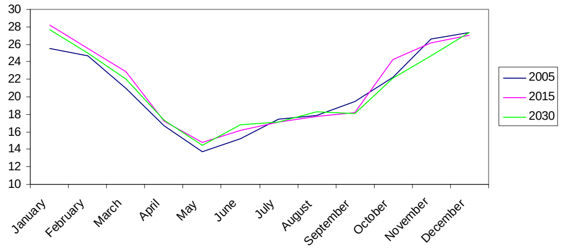
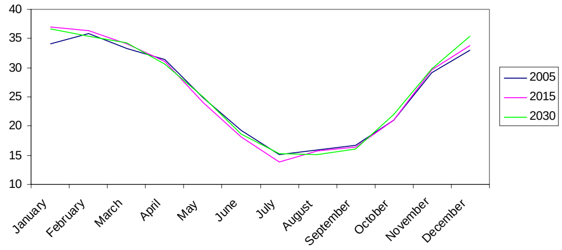


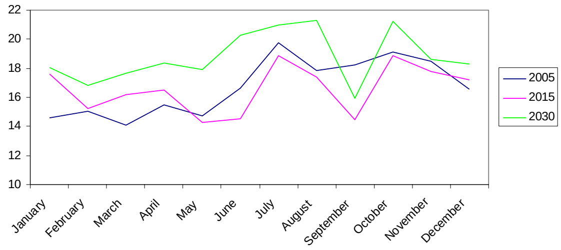
Figure 9: *Average monthly climatic similarities in 2005, 2015 and 2030 between London seaport and seaports within the current geographic range of Ae. aegypti in:* ***(a)*** *Africa;* ***(b)*** *Asia;* ***(c)*** *North America;* ***(d)*** *Central America;* ***(e)*** *South America; and* ***(f)*** *the Middle East. (In each graph, Euclidean distance is on the y-axis.)*



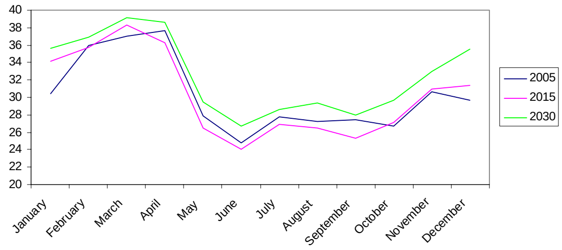
(a)



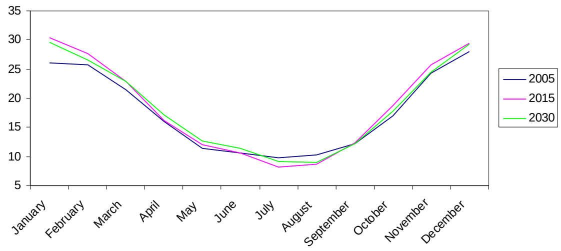
(b)



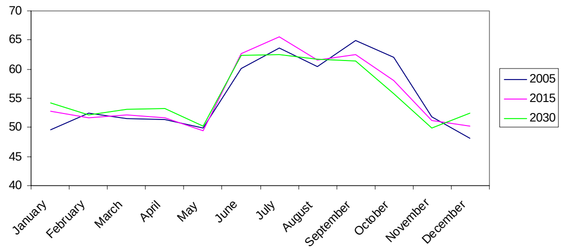
(c)



(d)

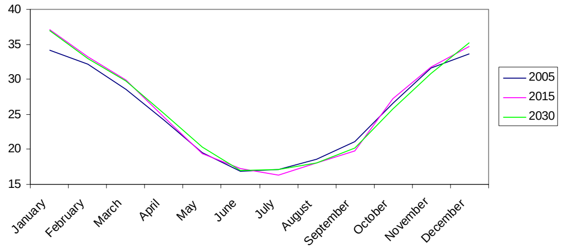


(e)

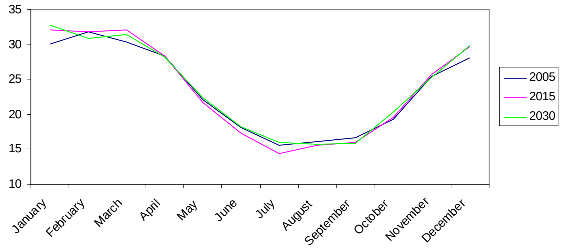


(f)

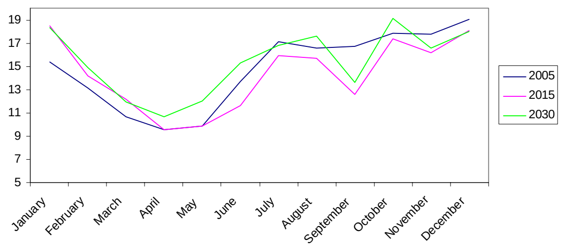
Figure 10: *Average monthly climatic similarities in 2005, 2015 and 2030 between London Heathrow/Gatwick airports and airports within the current geographic range of Ae. aegypti in:* ***(a)*** *Africa;* ***(b)*** *Asia;* ***(c)*** *North America;* ***(d)*** *Central America;* ***(e)*** *South America; and* ***(f)*** *the Middle East. (In each graph, Euclidean distance is on the y-axis.)*



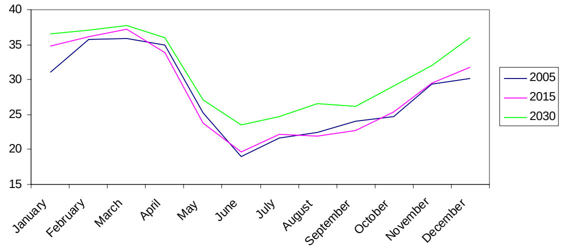
(a)



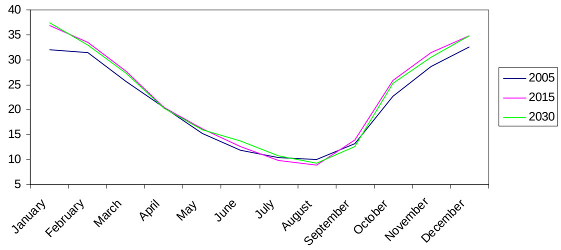
(b)



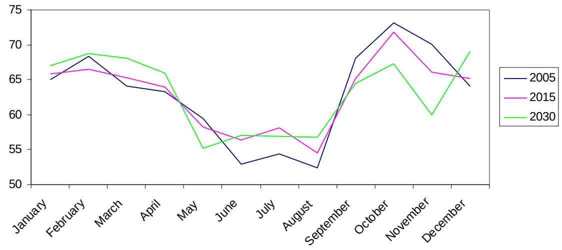
(c)



(d)



(e)



(f)

Table 1: The most climatically similar airports (within the range of *An. gambiae* in the four major regions of sub-Saharan Africa) to London Heathrow/Gatwick airports and the Euclidean distance between the two for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

2005	West Africa		Central Africa		East Africa		Southern Africa	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Freetown/Monrovia	27.3	Libreville	23.8	Kigali	17.7	Maputo	16.6
February	Freetown/Monrovia	23.4	Libreville	23.1	Kigali	17.7	Maputo	14.2
March	Freetown/Monrovia	21.2	Pointe Noire	20.8	Kigali	15.7	Maputo	11.9
April	Freetown/Monrovia	18.1	Pointe Noire	17.9	Kigali	11.6	Maputo	5.7
May	Freetown/Monrovia	14.2	Pointe Noire	13.6	Kigali	6.1	Maputo	4.2
June	Conakry	9.2	Pointe Noire	10.9	Entebbe	4.5	Antananarivo	7.9
July	Niamey	12.4	Pointe Noire	10.7	Entebbe	5.1	Luanda	8.7
August	Niamey	12.4	Pointe Noire	10.0	Kigali	2.2	Luanda	7.3
September	Conakry	14.4	Pointe Noire	13.9	Kigali	7.3	Maputo	12.2
October	Freetown/Monrovia	17.3	Libreville	18.1	Kigali	11.8	Maputo	16.7
November	Freetown/Monrovia	22.5	Libreville	22.4	Kigali	16.4	Maputo	15.1
December	Abidjan	26.9	Libreville	23.5	Kigali	19.0	Maputo	16.8

(a)

2015	West Africa		Central Africa		East Africa		Southern Africa	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Freetown/Monrovia	32.0	Libreville	25.7	Kigali	19.0	Maputo	18.5
February	Freetown/Monrovia	25.3	Douala/Malabo	24.7	Kigali	18.5	Maputo	16.0
March	Freetown/Monrovia	23.4	Pointe Noire	21.6	Kigali	17.1	Maputo	13.7
April	Freetown/Monrovia	19.2	Pointe Noire	18.7	Kigali	12.7	Maputo	9.5
May	Freetown/Monrovia	14.3	Pointe Noire	14.0	Kigali	6.3	Maputo	4.2
June	Freetown/Monrovia	10.6	Pointe Noire	10.5	Entebbe	5.9	Antananarivo	5.8
July	Bamako	10.5	Pointe Noire	8.7	Entebbe	4.4	Antananarivo	6.6
August	Banjul/Dakar	11.2	Pointe Noire	10.0	Kigali	1.7	Luanda	6.4
September	Bamako/Ouagadougou	14.2	Pointe Noire	11.2	Kigali	8.1	Maputo	5.2
October	Conakry	16.6	Libreville	18.3	Kigali	12.7	Maputo	22.4
November	Freetown/Monrovia	23.1	Libreville	23.2	Kigali	17.3	Maputo	16.2
December	Abidjan	28.2	Libreville	24.8	Kigali	19.2	Maputo	16.9

(b)

2030	West Africa		Central Africa		East Africa		Southern Africa	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Freetown/Monrovia	33.4	Libreville	25.5	Kigali	19.1	Maputo	17.1
February	Freetown/Monrovia	24.2	Libreville	23.1	Kigali	16.6	Maputo	13.1
March	Freetown/Monrovia	22.4	Douala/Malabo	22.2	Kigali	16.6	Maputo	11.7
April	Freetown/Monrovia	19.3	Pointe Noire	18.4	Kigali	13.0	Maputo	9.22
May	Freetown/Monrovia	15.0	Pointe Noire	15.4	Kigali	8.1	Maputo	6.1
June	Conakry	10.5	Pointe Noire	11.2	Kigali	4.9	Antananarivo	3.6
July	Niamey	12.2	Pointe Noire	10.6	Kigali	5.2	Antananarivo	3.3
August	Banjul/Dakar	11.9	Pointe Noire	8.3	Kigali	3.0	Maputo	5.4
September	Ouagadougou	13.7	Pointe Noire	12.6	Kigali	7.1	Maputo	8.1
October	Conakry	16.6	Libreville	17.1	Kigali	11.6	Maputo	14.4
November	Freetown/Monrovia	22.9	Libreville	22.3	Kigali	16.7	Maputo	17,0
December	Abidjan	29.2	Libreville	24.9	Kigali	19.9	Maputo	17.7

(c)

Table 2: The most climatically similar ports (within the range of *Ae. albopictus*) to London port and the Euclidean distance between the two for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

2005	Africa		Asia		North America		Central America		South America		Europe	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Escravos	27.00	Kobe	8.54	Jacksonville	6.40	Limon-Moin	21.28	Santos	19.10	Naples	5.00
February	Escravos	25.10	Keelung	7.14	Jacksonville	7.48	Limon-Moin	23.94	Santos	17.72	Naples	6.78
March	Escravos	21.38	Quingdao	2.45	Jacksonville	8.06	Limon-Moin	26.93	Paranagua	15.00	Naples	3.61
April	Escravos	19.54	Quingdao	4.24	Milwaukee	5.10	Limon-Moin	26.25	Santos	10.68	Genoa	0.98
May	Escravos	17.15	Shenzhen	1.00	Milwaukee	3.00	Limon-Moin	13.34	Rio Grande	7.00	Genoa	0.87
June	Escravos	15.17	Busan	4.24	Milwaukee	2.24	Limon-Moin	18.03	Rio Grande	7.35	Genoa	3.32
July	Escravos	16.88	Shenzhen	6.40	Milwaukee	4.58	Limon-Moin	16.55	Rio Grande	2.45	Genoa	1.41
August	Escravos	19.42	Shenzhen	6.32	Milwaukee	6.40	Limon-Moin	16.91	Itaqui	5.83	Genoa	3.32
September	Escravos	18.03	Kobe	4.47	Milwaukee	4.69	Limon-Moin	15.81	Itaqui	2.45	Genoa	5.48
October	Escravos	18.14	Keelung	7.28	Milwaukee	5.48	Limon-Moin	16.52	Paranagua	8.54	Trieste	5.10
November	Escravos	22.91	Keelung	7.21	Milwaukee	7.35	Limon-Moin	19.42	Paranagua	15.52	Trieste	5.10
December	Escravos	26.93	Keelung	5.92	Port of Virginia	6.78	Limon-Moin	21.31	Santos	19.21	Naples	4.24

(a)

2015	Africa		Asia		North America		Central America		South America		Europe	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Escravos	31.46	Keelung	10.20	Jacksonville	9.54	Limon-Moin	24.78	Santos	20.54	Naples	6.48
February	Escravos	24.74	Keelung	6.71	New York	7.35	Limon-Moin	26.48	Santos	18.36	Naples	5.83
March	Escravos	23.56	Quingdao	3.74	New York	8.77	Limon-Moin	28.34	Santos	15.94	Naples	3.32
April	Escravos	21.61	Quingdao	6.40	Milwaukee	3.74	Limon-Moin	25.48	Itaqui	11.87	Genoa	1.41
May	Escravos	18.06	Busan	3.16	Milwaukee	3.74	Limon-Moin	14.56	Itaqui	8.31	Genoa	1.00
June	Escravos	14.87	Shenzhen	3.16	Milwaukee	2.83	Limon-Moin	15.03	Rio Grande	5.92	Genoa	1.41
July	Escravos	14.53	Shenzhen	6.08	Milwaukee	4.58	Limon-Moin	14.59	Rio Grande	2.24	Genoa	1.41
August	Escravos	18.25	Shenzhen	5.10	Milwaukee	4.36	Limon-Moin	16.40	Santos	1.41	Genoa	3.61
September	Escravos	19.70	Busan	2.24	Milwaukee	2.24	Limon-Moin	16.06	Itaqui	3.32	Genoa	3.61
October	Escravos	18.38	Nagoya	8.31	Milwaukee	7.28	Limon-Moin	17.58	Paranagua	9.54	Trieste	5.20
November	Escravos	23.69	Keelung	9.22	Milwaukee	5.00	Limon-Moin	21.61	Paranagua	17.35	Naples	4.12
December	Escravos	27.73	Keelung	9.27	Port of Virginia	8.31	Limon-Moin	23.85	Paranagua	20.47	Naples	5.92

(b)

2030	Africa		Asia		North America		Central America		South America		Europe	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Escravos	34.71	Keelung	9.00	New York	9.70	Limon-Moin	25.88	Santos	20.81	Naples	4.36
February	Escravos	25.96	Keelung	5.20	New York	7.35	Limon-Moin	26.98	Santos	17.49	Naples	5.92
March	Escravos	22.23	Quingdao	2.45	New York	8.49	Limon-Moin	30.48	Santos	14.70	Genoa	4.58
April	Escravos	20.64	Quingdao	4.12	Milwaukee	3.32	Limon-Moin	27.66	Santos	12.85	Genoa	1.41
May	Escravos	20.02	Busan	4.36	Milwaukee	3.74	Limon-Moin	15.56	Itaqui	6.48	Genoa	1.73
June	Escravos	16.43	Shenzhen	4.00	Milwaukee	3.46	Limon-Moin	13.19	Rio Grande	6.63	Genoa	2.24
July	Escravos	17.00	Shenzhen	6.40	Milwaukee	5.92	Limon-Moin	15.62	Rio Grande	4.12	Genoa	1.00
August	Escravos	18.71	Shenzhen	6.40	Milwaukee	4.90	Limon-Moin	13.08	Santos	1.41	Genoa	7.07
September	Escravos	19.75	Busan	3.32	Milwaukee	2.83	Limon-Moin	13.64	Itaqui	3.00	Trieste	7.35
October	Escravos	18.81	Nagoya	8.25	Milwaukee	5.92	Limon-Moin	16.79	Paranagua	8.60	Trieste	5.20
November	Escravos	22.72	Keelung	8.06	Milwaukee	7.14	Limon-Moin	23.71	Paranagua	16.28	Naples	6.32
December	Escravos	29.17	Keelung	8.06	Port of Virginia	9.22	Limon-Moin	26.15	Paranagua	20.71	Naples	5.10

(c)

Table 3: The most climatically-similar airports (within the range of *Ae. albopictus*) to London Heathrow/Gatwick airports and the Euclidean distance between the two for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

2005	Africa		Asia		North America		Central America		South America		Europe	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Douala	27.00	Fukuoka	8.54	Cincinnati	6.32	San Jose	21.28	Sao Paulo	19.10	Rome	5.00
February	Douala	25.10	Taipei	9.49	Cincinnati	8.12	San Jose	23.94	Sao Paulo	17.72	Milan	4.47
March	Antananarivo	21.12	Shanghai	6.40	Washington	7.00	Panama City	22.49	Sao Paulo	15.10	Tirana	3.00
April	Antananarivo	17.32	Shanghai	6.71	Washington	5.20	Panama City	19.52	Sao Paulo	10.68	Milan	0.87
May	Antananarivo	10.20	Seoul	2.24	Baltimore	3.74	San Jose	13.34	Buenos Aires	7.00	Milan	0.66
June	Antananarivo	7.87	Seoul	4.24	Washington	3.74	Managua	13.93	Sao Paulo	7.55	Tirana	3.00
July	Antananarivo	10.63	Seoul	10.63	Mexico City	3.16	Managua	16.31	Sao Paulo	4.12	Ljubljana	5.10
August	Antananarivo	18.47	Seoul	7.28	Mexico City	4.36	San Jose	16.91	Santa Cruz	4.24	Ljubljana	9.27
September	Douala	18.03	Fukuoka	4.47	Washington	4.47	San Jose	15.81	Buenos Aires	2.24	Ljubljana	7.68
October	Douala	18.14	Fukuoka	7.28	Washington	8.06	San Jose	16.52	Sao Paulo	11.70	Milan	2.45
November	Douala	22.91	Taipei	11.05	Chicago	10.10	San Jose	19.42	Sao Paulo	17.46	Milan	3.00
December	Douala	26.93	Fukuoka	9.49	Cincinnati	6.40	San Jose	21.31	Sao Paulo	19.21	Milan	3.74

(a)

2015	Africa		Asia		North America		Central America		South America		Europe	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Douala	31.46	Fukuoka	14.90	Cincinnati	8.60	San Jose	24.78	Sao Paulo	20.54	Tirana	3.16
February	Douala	24.74	Fukuoka	9.85	New York	7.35	San Jose	26.48	Sao Paulo	18.36	Tirana	5.00
March	Antananarivo	22.02	Shanghai	6.00	Washington	6.00	Panama City	25.50	Sao Paulo	15.94	Tirana	2.45
April	Antananarivo	14.32	Shanghai	5.74	Washington	3.00	Panama City	20.27	Buenos Aires	10.30	Milan	1.41
May	Antananarivo	7.35	Seoul	3.16	Washington	3.46	San Jose	14.56	Buenos Aires	6.08	Milan	1.00
June	Antananarivo	5.83	Seoul	4.24	Washington	3.32	San Jose	15.03	Santa Cruz	8.54	Milan	1.41
July	Antananarivo	6.63	Seoul	6.78	Mexico City	2.00	San Jose	14.59	Sao Paulo	6.71	Ljubljana	2.24
August	Antananarivo	14.35	Seoul	6.40	Mexico City	3.00	San Jose	16.40	Sao Paulo	1.41	Ljubljana	5.39
September	Douala	19.70	Seoul	2.24	Washington	3.32	San Jose	16.06	Buenos Aires	9.27	Ljubljana	6.78
October	Douala	18.38	Fukuoka	10.20	Washington	10.05	San Jose	17.58	Sao Paulo	13.19	Milan	2.45
November	Douala	23.69	Shanghai	11.70	Chicago	6.16	San Jose	21.61	Sao Paulo	17.72	Tirana	2.45
December	Douala	27.73	Fukuoka	12.41	Washington	6.71	San Jose	23.85	Sao Paulo	20.54	Tirana	3.61

(b)

2030	Africa		Asia		North America		Central America		South America		Europe	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Antananarivo	30.63	Fukuoka	13.42	Cincinnati	8.66	San Jose	25.88	Sao Paulo	20.81	Milan	3.74
February	Antananarivo	25.32	Taipei	8.60	New York	7.35	San Jose	26.98	Sao Paulo	17.49	Tirana	4.00
March	Douala	22.23	Shanghai	5.74	Chicago	6.48	Panama City	23.77	Sao Paulo	14.70	Tirana	1.41
April	Antananarivo	17.61	Seoul	7.14	Washington	4.47	Panama City	19.44	Buenos Aires	10.82	Tirana	1.00
May	Antananarivo	9.27	Seoul	4.36	Baltimore	5.74	San Jose	15.56	Buenos Aires	6.08	Milan	1.73
June	Antananarivo	3.61	Seoul	5.92	Washington	3.74	San Jose	13.19	Sao Paulo	7.87	Milan	2.24
July	Antananarivo	3.32	Seoul	7.48	Mexico City	4.12	San Jose	15.62	Sao Paulo	4.36	Ljubljana	6.08
August	Antananarivo	15.33	Seoul	7.55	Washington	5.39	San Jose	13.08	Sao Paulo	1.41	Ljubljana	7.14
September	Douala	19.75	Seoul	3.32	Washington	4.58	San Jose	13.64	Buenos Aires	3.61	Ljubljana	7.62
October	Douala	18.81	Fukuoka	9.22	Washington	14.00	San Jose	16.79	Sao Paulo	13.08	Milan	2.45
November	Douala	22.72	Shanghai	10.00	Cincinnati	8.31	San Jose	23.71	Sao Paulo	17.12	Tirana	2.00
December	Douala	29.17	Fukuoka	11.40	Washington	6.48	San Jose	26.15	Sao Paulo	21.00	Milan	4.12

(c)

Table 4: The most climatically similar ports (within the range of *Ae. aegypti*) to London port and the Euclidean distance between the two for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

2005	Africa		Asia		North America		Central America		South America		Middle East	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Durban	16.76	Belawan	21.31	Jacksonville	6.40	Limon-Moin	21.28	Paita	18.92	Aden	14.04
February	Durban	15.17	Belawan	21.59	Jacksonville	7.48	Limon-Moin	23.94	Santos	17.72	Aden	14.07
March	East London	11.40	Cagayan de Oro	20.49	Jacksonville	8.06	Limon-Moin	26.93	Paranagua	15.00	Aden	17.06
April	Durban	5.48	Cagayan de Oro	18.22	Jacksonville	7.35	Limon-Moin	26.25	Santos	10.68	Aden	14.90
May	Durban	4.69	New Mangalore	14.70	Jacksonville	9.06	Limon-Moin	13.34	Montevideo	7.00	Aden	13.04
June	Mombasa	3.61	Karachi	12.04	Miami	11.58	Limon-Moin	18.03	Paita	4.58	Aden	44.33
July	Mombasa	3.00	Bombay	11.22	Miami	12.65	Limon-Moin	16.55	Rio Grande	2.45	Aden	50.20
August	Mombasa	3.74	Madras	10.77	Jacksonville	11.40	Limon-Moin	16.91	Itaqui	5.83	Aden	45.63
September	Mombasa	10.44	Karachi	12.65	Jacksonville	12.53	Limon-Moin	15.81	Montevideo	2.24	Aden	46.97
October	Mombasa	8.12	Kuching	18.38	Jacksonville	12.81	Limon-Moin	16.52	Paranagua	8.54	Aden	33.90
November	Durban	15.39	Cagayan de Oro	21.95	Jacksonville	10.86	Limon-Moin	19.42	Paranagua	15.52	Aden	14.04
December	Durban	18.14	Bankok	23.41	Jacksonville	7.68	Limon-Moin	21.31	Santos	19.21	Aden	15.33

(a)

2015	Africa		Asia		North America		Central America		South America		Middle East	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Durban	18.14	Belawan	23.85	Jacksonville	9.54	Limon-Moin	24.78	Santos	20.54	Aden	15.17
February	Durban	17.03	Belawan	22.41	Brake	8.77	Limon-Moin	26.48	Santos	18.36	Aden	15.81
March	East London	13.00	Cagayan de Oro	21.79	Jacksonville	9.43	Limon-Moin	28.34	Santos	15.94	Aden	16.97
April	East London	7.87	Cagayan de Oro	18.44	Jacksonville	8.25	Limon-Moin	25.48	Montevideo	10.30	Aden	19.26
May	Durban	4.58	Belawan	15.00	Jacksonville	9.11	Limon-Moin	14.56	Montevideo	6.08	Aden	14.18
June	Beira	4.24	Karachi	11.87	Miami	10.25	Limon-Moin	15.03	Paita	5.39	Aden	47.11
July	Beira	3.74	Mormugao	10.05	Jacksonville	10.39	Limon-Moin	14.59	Rio Grande	2.24	Aden	52.96
August	Mombasa	3.74	Madras	11.18	Jacksonville	10.86	Limon-Moin	16.40	Santos	1.41	Aden	45.20
September	Mombasa	10.20	Mormugao	13.15	Jacksonville	10.39	Limon-Moin	16.06	Itaqui	3.32	Aden	42.95
October	Mombasa	8.66	Karachi	12.08	Miami	14.80	Limon-Moin	17.58	Paranagua	9.54	Aden	23.37
November	Mombasa	15.07	Karachi	19.21	Jacksonville	12.04	Limon-Moin	21.61	Paranagua	17.35	Aden	15.81
December	Durban	18.14	Belawan	23.73	Jacksonville	9.17	Limon-Moin	23.85	Paranagua	20.47	Aden	15.84

(b)

2030	Africa		Asia		North America		Central America		South America		Middle East	
Month	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance	Port	Euclidean distance
January	Durban	17.83	Belawan	23.11	Jacksonville	10.05	Limon-Moin	25.88	Guayaquil	20.05	Aden	15.17
February	Durban	14.04	Belawan	21.86	Jacksonville	7.68	Limon-Moin	26.98	Santos	17.49	Aden	12.41
March	Durban	12.37	Belawan	21.31	Jacksonville	10.20	Limon-Moin	30.48	Santos	14.70	Aden	17.03
April	Durban	8.54	Cagayan de Oro	18.68	Jacksonville	9.11	Limon-Moin	27.66	Montevideo	10.82	Aden	18.89
May	Durban	3.00	New Mangalore	17.12	Miami	12.08	Limon-Moin	15.56	Montevideo	6.08	Aden	18.79
June	Mombasa	4.58	Karachi	12.57	Jacksonville	12.45	Limon-Moin	13.19	Paita	5.48	Aden	47.47
July	Beira	3.74	Bombay	11.22	Jacksonville	12.41	Limon-Moin	15.62	Rio Grande	4.12	Aden	50.58
August	Mombasa	2.24	Madras	9.54	Jacksonville	11.45	Limon-Moin	13.08	Santos	1.41	Aden	47.43
September	Durban	14.14	Bombay	10.25	Jacksonville	11.09	Limon-Moin	13.64	Itaqui	3.00	Aden	43.84
October	Mombasa	10.05	Karachi	11.58	Miami	14.42	Limon-Moin	16.79	Paranagua	8.60	Aden	24.06
November	Mombasa	15.07	Karachi	21.73	Jacksonville	12.08	Limon-Moin	23.71	Paranagua	16.28	Aden	16.16
December	Durban	17.97	Belawan	23.54	Jacksonville	9.43	Limon-Moin	26.15	Paranagua	20.71	Aden	15.56

(c)

Table 5: The most climatically-similar airports (within the range of *Ae. aegypti*) to London Heathrow/Gatwick airports and the Euclidean distance between the two for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

2005	Africa		Asia		North America		Central America		South America		Middle East	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Manzini	16.61	Yangon	13.56	Atlanta	8.60	San Jose	21.28	Quito	18.44	Jeddah	64.97
February	Manzini	14.18	Taipei	9.49	Dallas/Fort Worth	8.25	San Jose	23.94	Sao Paulo	17.72	Jeddah	68.10
March	Maseru	9.43	Taipei	10.05	Dallas/Fort Worth	7.87	Panama City	22.49	Sao Paulo	15.10	Sanaa	62.37
April	Maseru	5.10	Taipei	12.45	Raleigh/Durham	5.92	Panama City	19.52	Sao Paulo	10.68	Sanaa	58.56
May	Manzini	4.24	Taipei	12.45	Charlotte	6.40	San Jose	13.34	Buenos Aires	7.00	Sanaa	52.92
June	Kampala	4.47	Karachi	12.04	Charlotte	7.68	Port au Prince	11.75	Quito	5.92	Sanaa	41.77
July	Kampala	5.10	Mumbai	11.22	Charlotte	8.60	Havana	15.84	Sao Paulo	4.12	Sanaa	42.77
August	Kigali	2.24	Taipei	14.35	Charlotte	8.25	Havana	14.25	Asuncion	1.41	Sanaa	41.77
September	Maseru	6.40	Karachi	12.65	Charlotte	9.17	San Jose	15.81	Buenos Aires	2.24	Sanaa	64.34
October	Kigali	11.83	Taipei	10.30	Raleigh/Durham	13.08	San Jose	16.52	Sao Paulo	11.70	Sanaa	71.41
November	Manzini	15.07	Taipei	11.05	Atlanta	13.93	San Jose	19.42	Quito	16.88	Jeddah	67.71
December	Manzini	16.76	Yangon	15.00	Atlanta	11.09	San Jose	21.31	Sao Paulo	19.21	Jeddah	62.62

(a)

2015	Africa		Asia		North America		Central America		South America		Middle East	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Manzini	18.49	Yangon	16.25	Atlanta	12.21	San Jose	24.78	Quito	19.87	Jeddah	65.15
February	Maseru	15.94	Taipei	10.30	Dallas/Fort Worth	8.54	San Jose	26.48	Sao Paulo	18.36	Sanaa	66.25
March	Maseru	11.58	Fukuoka	12.53	Chicago	6.78	Panama City	25.50	Sao Paulo	15.94	Dubai	63.25
April	Maseru	7.87	Taipei	14.07	Raleigh/Durham	6.16	Panama City	20.27	Buenos Aires	10.30	Sanaa	62.65
May	Manzini	4.24	Taipei	13.34	Charlotte	7.00	San Jose	14.56	Buenos Aires	6.08	Sanaa	52.24
June	Antananarivo	5.83	Karachi	11.87	Charlotte	6.40	Havana	14.80	Quito	5.74	Sanaa	45.65
July	Kampala	4.36	Mumbai	10.34	Charlotte	8.49	San Jose	14.59	Asuncion	3.74	Sanaa	48.55
August	Kigali	1.73	Kaohsiung	13.49	Charlotte	9.00	Havana	13.75	Sao Paulo	1.41	Sanaa	43.43
September	Maseru	4.24	Taipei	12.45	Charlotte	5.48	Havana	15.81	Asuncion	6.40	Sanaa	60.42
October	Kigali	12.73	Taipei	12.04	Charlotte	13.93	San Jose	17.58	Sao Paulo	13.19	Sanaa	70.64
November	Manzini	16.16	Taipei	14.56	Atlanta	11.36	San Jose	21.61	Sao Paulo	17.72	Jeddah	65.28
December	Manzini	16.88	Yangon	16.67	Atlanta	10.20	San Jose	23.85	Quito	19.75	Sanaa	64.79

(b)

2030	Africa		Asia		North America		Central America		South America		Middle East	
Month	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance	Airport	Euclidean distance
January	Manzini	17.12	Yangon	15.39	Dallas/Fort Worth	12.08	San Jose	25.88	Quito	18.92	Sanaa	64.36
February	Manzini	13.08	Taipei	8.60	Atlanta	10.25	San Jose	26.98	Quito	17.20	Sanaa	68.48
March	Maseru	10.05	Fukuoka	13.30	Washington	7.14	Panama City	23.77	Sao Paulo	14.70	Sanaa	66.25
April	Maseru	6.40	Taipei	12.37	Raleigh/Durham	6.08	Panama City	19.44	Buenos Aires	10.82	Sanaa	62.39
May	Maseru	4.47	Taipei	15.17	Charlotte	9.06	San Jose	15.56	Buenos Aires	6.08	Sanaa	47.76
June	Antananarivo	3.61	Karachi	12.57	Charlotte	7.62	San Jose	13.19	Quito	6.32	Sanaa	47.84
July	Antananarivo	3.32	Mumbai	11.22	Charlotte	9.54	Havana	15.39	Sao Paulo	4.36	Sanaa	49.74
August	Kigali	3.00	Bangkok	13.96	Charlotte	8.31	San Jose	13.08	Asuncion	1.41	Sanaa	48.52
September	Kigali	7.07	Mumbai	10.25	Charlotte	9.49	San Jose	13.64	Buenos Aires	3.61	Sanaa	61.20
October	Kigali	11.58	Karachi	11.58	Fort Lauderdale	14.42	San Jose	16.79	Quito	13.04	Sanaa	65.54
November	Kigali	16.67	Taipei	12.08	Atlanta	10.95	San Jose	23.71	Sao Paulo	17.12	Sanaa	58.01
December	Manzini	17.72	Yangon	16.28	Memphis	12.08	San Jose	26.15	Quito	20.64	Jeddah	68.48

(c)

Table 6: The monthly number of sub-Saharan African airports (within the geographical range of *An. gambiae*) climatically as similar to London Heathrow/Gatwick airports as the climatic difference which has resulted previously in cases of airport malaria.

	2005	2015	2030
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0	2	1
June	17	23	18
July	19	23	19
August	25	25	23
September	4	4	2
October	0	0	0
November	0	0	0
December	0	0	0

Table 7: Top 10 predicted air travel risk routes for *P.-falciparum*-infected *An. gambiae* invasion and subsequent autochthonous transmission for: **(a)** 2005; **(b)** 2015; and **(c)** 2030.

	From		To		Risk value
Rank	Airport	Country	Airport	Month	2005
1	Lagos	Nigeria	Gatwick	June	0.004461
2	Lagos	Nigeria	Gatwick	July	0.004148
3	Lagos	Nigeria	Gatwick	September	0.003855
4	Lagos	Nigeria	Gatwick	August	0.003719
5	Lagos	Nigeria	Heathrow	June	0.003448
6	Lagos	Nigeria	Heathrow	July	0.003206
7	Entebbe/Kampala	Uganda	Gatwick	June	0.003087
8	Nairobi	Kenya	Gatwick	June	0.003085
9	Nairobi	Kenya	Gatwick	August	0.002996
10	Lagos	Nigeria	Heathrow	September	0.002979

(a)

	From		To		Risk value
Rank	Airport	Country	Airport	Month	2015
1	Lagos	Nigeria	Gatwick	June	0.004921
2	Lagos	Nigeria	Gatwick	July	0.00468
3	Lagos	Nigeria	Heathrow	June	0.003803
4	Lagos	Nigeria	Gatwick	September	0.003637
5	Lagos	Nigeria	Heathrow	July	0.003617
6	Lagos	Nigeria	Gatwick	August	0.003596
7	Entebbe/Kampala	Uganda	Gatwick	July	0.003168
8	Nairobi	Kenya	Gatwick	August	0.003161
9	Nairobi	Kenya	Gatwick	July	0.002864
10	Lagos	Nigeria	Heathrow	September	0.002811

(b)

	From		To		Risk value
Rank	Airport	Country	Airport	Month	2030
1	Lagos	Nigeria	Gatwick	June	0.004117
2	Lagos	Nigeria	Gatwick	August	0.003855
3	Lagos	Nigeria	Heathrow	June	0.003818
4	Lagos	Nigeria	Gatwick	July	0.003719
5	Nairobi	Kenya	Gatwick	July	0.003278
6	Lagos	Nigeria	Heathrow	August	0.002979
7	Nairobi	Kenya	Heathrow	June	0.002919
8	Lagos	Nigeria	Heathrow	July	0.002874
9	Nairobi	Kenya	Gatwick	August	0.002757
10	Entebbe/Kampala	Uganda	Gatwick	July	0.002058

(c)

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First published April 2006. Department of Trade and Industry. www.dti.gov.uk