statement

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Climate change and infectious diseases in Europe

Foreword

The impact of climate change on health has received comparatively little public or political attention by contrast with the concentration on environmental and economic aspects of climate change. This is a deficiency that must be remedied.

This Statement is the latest in a series of publications from the European Academies Science Advisory Council (EASAC; all publications are on www.easac.eu) on issues that policy-makers need to consider when addressing the public health challenges associated with infectious disease. Our Statement describes some of the scientific evidence available to characterise the impact of climate change on the transmission and distribution of human and animal infectious disease in Europe.

There is much still to be done to clarify and quantify this impact. There is difficulty in assessing the net public health consequences, because there are uncertainties in the current and projected assessments of changes in climate. Furthermore, this difficulty is compounded by gaps in the evidence base, by a weak integration of human–animal interfaces in research and surveillance, and by uncertainties about the impact of climate and other environmental change on human behaviour.

Although it is difficult to predict the consequences of climate change on infectious disease, particularly the emergence of new infectious diseases in Europe, and we know that there will be surprises, nonetheless impact is inevitable. To prepare for and respond to this impact there is need for concerted action by the policy-makers at both European Union (EU) and national levels because infectious disease, like climate change and economic disruption, does not stop at borders. But the imperative to raise the visibility of these issues does not apply only to the policy-making community. There is also relatively low awareness in the scientific and medical communities so we must do more to inform and educate ourselves about the importance of the health consequences of climate change.

EASAC's Statement recommends several areas for improved public health surveillance coupled with more intensive study of animal hosts, vectors and pathogens. We identify some research priorities across a broad front of molecular biology, epidemiology, ecology and the social sciences, but we also emphasise the importance of using the research advances more effectively to inform policy and to drive innovation for new approaches to tackle infection. Identifying the health priorities is also highly relevant to other domains of EU policy-making, for example in developing policies with neighbouring regions and for migration.

Our Statement draws on the presentations and discussion at a scientific meeting co-organised by the German Academy of Sciences Leopoldina with the Indian National Science Academy. I thank the experts who contributed to that meeting and to subsequent debate of the issues. I also thank my colleagues on the Council of EASAC who were responsible for organising the independent review of the draft paper and its approval for publication.

EASAC welcomes further discussion on any of the issues that we have raised. We recognise that the impact of climate change on health is a much broader topic than the specific points that we have reviewed for infectious disease in Europe. EASAC Academy members and other Academies worldwide are very interested in helping to explore the issues for the broader global health impact. Therefore we also welcome feedback to identify key matters that should be studied in future work.

Volker ter Meulen
President, German Academy of Sciences Leopoldina and Chairman, EASAC

Summary

Climate exerts both direct and indirect effects on the appearance and spread of human and animal infectious diseases. The impact of climate change on the transmission and geographical distribution of vector-borne diseases, including zoonoses (infections transmissible between vertebrate animals and humans), has been associated with changes in the replication rate and dissemination of pathogen, vector and animal host populations, which are sensitive to changing temperature and rainfall. The available evidence indicates the potential for an increasing challenge to European public health from arboviral (arthropod-transmitted) diseases such as tick-borne encephalitis (TBE), West Nile fever (WNF), chikungunya, diseases caused by rodent-borne hantaviruses, and parasitic diseases such as dirofilariasis and leishmaniasis. Climate change is also increasing the threat of infections, such as bluetongue virus (BTV), in domesticated animals.

Although the evidence base is fragmented and it is also important to take account of the other various determinants of changes in ecosystems and in human, animal and microbial behaviour, the fundamental influence of climate change on infectious diseases in Europe is beginning to be discerned. And although the World Health Organization (WHO), the World Organisation for Animal Health (OIE) and the European Commission and its agencies are already active in monitoring and evaluating some infections, there is much more to be done to fill gaps in the evidence base, prepare public health authorities and raise the political profile of the issue, without being alarmist—to alert to the possible emergence of new threats as well as the expansion of diseases already present in Europe.

Our assessment of the available evidence, predominantly for vector-borne diseases, leads us to make several recommendations directed to EU and national decision-makers, with the objectives of identifying and supporting the necessary adaptation responses to what is unavoidable in climate change:

- It is vital to modernise surveillance, based on trans-European early warning systems that have the capability to integrate epidemiological and environmental data.

- This also requires integration of data collection and analysis for human and veterinary health, to include surveillance of wildlife populations and new molecular techniques to assess vectorial competence—the ability to transmit the infection.

- The health and environment research agendas should be co-ordinated to develop a broad understanding of key determinants of the spread of vector-borne disease. It is also important to integrate research in social and biological sciences to understand and quantify the human response to climate change. Research-funding agencies need to consult with the scientific community to develop a more strategic and sustained approach to define priorities and to train the next generation of researchers in the face of impending skills shortages in critical disciplines.

- Attending to the research gaps is only a first step in addressing the health risks of climate change. In addition, the growing evidence base must be used to inform the preparedness and responsiveness of public health systems and to develop better predictive modelling to allow more robust projections for future climate impact. It is equally essential to use the scientific outputs as a resource to sustain the search for new and better diagnostics, vaccines and therapeutics, and to ensure that science-based policy facilitates the best use of these innovative products and services for the benefit of human and animal health.

- The goals for the EU cannot be considered in isolation from the rest of the world. EU policy-makers must take account of the issues relating to climate change and infectious disease when progressing regional initiatives, for example for European Neighbourhood Policy and for the Euro-Mediterranean Union. EU actions in surveillance, research and innovation must also be appropriately integrated with global needs, priorities and strategies.

- Climate change is likely to affect human migration as well as the mobility of animal hosts, vectors and pathogens. The potential future impact of climate change on human migration to the EU requires further study within the context of improving procedures to identify and quantify the current impact of migration on the infectious disease burden in Europe. In addition to filling these knowledge gaps, it is important to improve co-ordination of public health screening and follow-up practices for high-risk groups across Europe.

Introduction: the emerging policy focus

Climate change could be the biggest global health threat of the 21st century (Campbell-Lendrum et al. 2009). The work of the Intergovernmental Panel on Climate Change (IPCC) has assembled overwhelming evidence that humans are affecting the global climate, with numerous significant implications for human health[1]. Climate variability causes death and disease through natural disasters such as heat wave, flood and drought. In addition, many vector-borne and other infectious diseases are highly sensitive to changes in temperature and precipitation. Much of the political and research focus on climate change until now has been on ways to mitigate the change, especially by effecting the transition to a low-carbon economy. However, it is also increasingly recognised as vitally important to identify and support the necessary adaptation responses to what is unavoidable in climate change.

The impacts of climate change on human health will not be evenly distributed globally. Populations in developing countries are considered to be particularly vulnerable[2]. However, WHO emphasises that climate change is also likely to cause changes in ecological systems that will affect the risk of infectious diseases in the European region, including the seasonal activity of local vectors and the establishment of (sub-)tropical species (Menne et al. 2008). The General Assembly of the World Organisation for Animal Health has highlighted that climate change will also have considerable impact on the (re-)emergence of infectious diseases in animals[3].

The European Commission recently published a White Paper, 'Adapting to climate change: Towards a European framework for action'[4] that, taken together with the detailed Staff Working Paper, discusses the steps necessary to reduce the EU's vulnerability to the impact of climate change. In describing the profound effects expected on human and animal health, the White Paper reinforces the conclusions of WHO and OIE about the probable spread of serious infectious diseases, including zoonoses. The White Paper and its accompanying documents also review the activities underway to improve EU capacity and resilience to react to climate change; they propose some general objectives for the EU Health Programme and Community Health Strategy, covering public health capacity and financing, co-operation between sectors and co-ordination in policy development and collaboration with countries outside Europe.

Uncertainties in the evidence base

Climate exerts both direct and indirect influences on the transmission and geographical distribution of many infectious diseases in humans and animals (Institute of Medicine (IOM) 2008). Direct effects can be mediated by pathogen replication rate, pathogen dissemination, the movement and replication of vectors and abundance of animal hosts. Additionally there are relevant indirect effects of climate on local ecosystems (for example, density of vegetation beneficial to vectors) and human behaviour (for example, resulting in more exposure to local habitat). As the IOM has noted, the influences are complex and inter-related, '*Climate interacts with a range of factors that shape the course of infectious disease emergence, including host, vector and pathogen population dynamics; land use, trade and transportation; human and animal migration …*', and these interactions complicate the attribution of effects. In addition to the confounding effects and competing explanations, there are acknowledged methodological difficulties in ascribing the changes in the range and incidence of transmissible diseases to climate change, primarily because of the weakness and fragmentation of health information systems and the limited sources of long-term data sets.

Notwithstanding the methodological difficulties, improving European preparedness and responsiveness relies on collecting firm evidence at the local, national and regional levels of the influence of climate change on established diseases, while also being alert to the emergence of new communicable disorders. In aggregate, there is a major research agenda to be

1 www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf.
2 www.who.int/globalchange/climate/en/index.html. This WHO information resource reviews the implications for developing countries in detail. A resolution of the Sixty-First World Health Assembly, 'Climate Change and Health' (WHA 61.19, May 2008), identifies the continuing responsibility of WHO, with countries, to raise awareness of the issues, to develop capacity to assess risks and to implement effective response measures.
3 OIE, May 2009, press release 'Climate change has a considerable impact on the emergence and re-emergence of animal diseases' available at www.oie.int/eng/press/en_090525.htm.
4 April 2009, COM (2009) 147/4 available at www.ec.europa.eu/health/ph_threats/climate/docs/com_2009_147_en.pdf. A Commission Staff Working Document provides further detail on 'Human, Animal and Plant Health, Impacts of Climate Change', SEC (2009) 416.

pursued – encompassing epidemiology, microbiology, ecology, clinical and veterinary medicine – and there is a concomitant collective responsibility for the scientific community to ensure that the research evidence is used to inform policy-making in the public health and veterinary sectors.

EASAC work on infectious diseases

In a series of reports on infectious disease policy published since 2005, EASAC has examined EU priorities for public protection and for innovation in health system preparedness, responsiveness and control. EASAC recommendations have covered current and future needs for infrastructure, skills, investment in fundamental science and the generation of novel healthcare products and services. Although not addressing the impact of climate change in detail, several of our previous projects have alluded to some of the issues, most notably the studies on zoonoses (EASAC 2008) and on human migration (EASAC 2007a), which is likely to be one significant consequence of global climate change (Institute of Medicine 2008). Although there are many reasons for migration to the EU and it is important not to generalise about migrants or infectious diseases, it seems probable that one impact of climate change will be to increase human migratory flows worldwide. In our previous work (EASAC 2007a), we noted the need to do more to identify those communicable diseases most relevant to migration, to fill current gaps in quantifying the health burden in different groups, the nature of the health inequalities and any population health risk attributable to migration. As part of the preparedness for climate change, it is vital now to improve the evaluation and sharing of information on current migrant screening practices and health system follow-up, and to co-ordinate strategies for high-risk groups across the EU.

The present EASAC Statement takes account of our previous work and draws on the output from an international meeting co-organised by the German Academy of Sciences Leopoldina, a founder member of EASAC, to provide an independent view of the accumulating scientific evidence, with a particular focus on vector-borne diseases. We indicate where there are gaps in the evidence base but emphasise that filling these gaps is only a first step in tackling the health risks of climate change (Campbell-Lendrum et al. 2009). It is not our purpose to provide a detailed account of this research domain but rather to clarify where policy-makers at both the EU and Member State levels must focus in formulating and monitoring policy. In this context, we welcome the recent initiative by the European Commission in its White Paper and the increasing commitment made by key agencies, in particular the European Centre for Disease Prevention and Control (ECDC). We also welcome the priority assigned by successive Presidencies of the EU Council to policy associated with infectious disease; an intended future focus on climate change and zoonoses is particularly timely. However, there is much more to be done to raise political awareness in the European and national parliaments, to make clear that a major justification for taking action on climate change is to protect and enhance human (Neira et al. 2008) and animal health.

What is the evidence from recent research in Europe?

The scientific discussion meeting in Greifswald, Germany (Appendix 1), evaluated research findings documenting the impact of climate change on communicable diseases for human and animal health. In recent years, numerous vector-borne and other zoonotic diseases have emerged or re-emerged in Europe (Jones et al. 2008) with major health and socio-economic consequences[5]. There is growing evidence that these new threats can be associated with global and local changes, resulting from climate influences (hotter summers, warmer winters, varying precipitation patterns). These changes can be either abrupt and unanticipated or gradual and protracted.

As detailed in Appendix 1, presenters at the Greifswald meeting provided case-study analysis of a wide range of human infectious diseases that pose a current or future threat to Europe: rodent-borne viruses (for example, hantaviruses), arboviral diseases (for example, TBE, chikungunya, WNF) and parasitic diseases (for example, dirofiliarasis and leishmaniasis). There was also extensive discussion of infectious diseases in domesticated animals, in particular that caused by BTV, but also Rift Valley fever (RVF) and African swine fever (ASV), and of the potential importance of wildlife hosts as a reservoir for infection. The appearance and spread of human and animal diseases can, in some cases, be associated with specific changes in vector, host or pathogen populations,

[5] The broader issues for surveillance, management of risk, international co-operation, research, education and innovation are discussed in the EASAC report on zoonoses (EASAC 2008).

which are sensitive to the effect of temperature and precipitation.

Taken together, these case studies represent a critical mass of observations consistent with the growing influence of climate change, and of biologically plausible effector mechanisms. However, the evidence base is still fragmented and it is vital to continue considering other determinants of changes in habitat and human behaviour that may confound an understanding of the impact of climate change. It is particularly important to appreciate the considerable uncertainty in the present data when attempting to predict the future impact of climate change. Therefore, more research is needed to obtain larger data sets, to explore causality and test hypotheses, and to provide a stronger basis to extrapolate for projections and predictions. Nonetheless, fundamental influences of climate change on infectious disease can already be discerned and it is likely that new vectors and pathogens will emerge and become established in Europe within the next few years. The spread of pathogens to new habitats and their interaction with new potential hosts may additionally offer new evolutionary opportunities and lead to the emergence of pathogens with distinctive virulence (Pallen & Wren 2007). It is no longer prudent to assume that some infectious diseases are irrelevant for Europe—anything may be possible.

Tackling the challenge: recommendations from EASAC

Based on the outputs from the Greifswald meeting taken together with other recent literature and previous EASAC work, our conclusions and recommendations can be summarised as follows.

1. Surveillance

The weaknesses noted in the present surveillance capabilities across Europe are a concern not only for monitoring the impact of climate change but also for the satisfactory delivery of public health in the EU more generally. As a recent editorial in the journal *Nature* remarked, '*… surveillance of human diseases that originate in animals remains in the nineteenth century … and is chronically underfunded. Animal- and public-health bodies must now step up and fund a serious joint initiative in this area.*' (Anon 2009). This imperative for increased, more coherent, longer-term effort in surveillance must extend to vectors and hosts as well as pathogens. Discussion of the agenda for surveillance and epidemiology research that must be pursued in public health has been pioneered by the ECDC (Box 1).

There is an acknowledged need to improve monitoring and investigation of outbreaks, which must be accompanied by further initiatives to foster interagency partnerships and influence new policy (for example, on land use). These and other roles for the public health authorities are discussed further by Semenza & Menne (2009). The objectives of creating health system responsiveness must also be accompanied by efforts to raise public and professional awareness about the impending challenges.

Box 1 European Centre for Disease Prevention and Control activities focused on climate change

ECDC has identified climate change as a priority health topic and has started a wide range of work aimed at assessing its potential impact on communicable disease transmission in the EU:

- Hosting three international workshops to collect, synthesise and disseminate expert opinion. The most recent workshop (September 2009) was the first meeting of the ECDC Expert Group on Climate Change[6].

- Launching an extensive risk assessment of the potential impact of climate change on food- and water-borne diseases in the EU. This project, in collaboration with the WHO Collaborating Centre for Health Promoting Water Management and Risk Communication, is expected to release its findings in 2010.

- Conducting (with members of the EDEN project) an extensive risk assessment (V-Borne) on the future challenges related to vector-borne diseases. After V-Borne, ECDC launched a series of risk maps looking principally at the *Aedes albopictus* mosquito and its expansion in Europe. The first series of maps (TigerMaps) was published in 2009[7] and the second set, focusing on dengue, is scheduled to be released in 2010.

- Developing a handbook for EU Member States, to be published in 2010, to facilitate vulnerability assessments and the design of adaptation strategies to climate change.

[6] www.ecdc.europa.eu/en/publications/Publications/Forms/ECDC_DispForm.aspx?ID=455.
[7] www.ecdc.europa.eu/en/activities/Pages/Programme_on_emerging_and_vector-borne_diseases_maps.aspx

EASAC very much welcomes the growing activities of ECDC relating to human disease. However, it is important for the EU also to ensure equivalent coverage in the veterinary field. We emphasise that it is essential that epidemiology is accompanied by fundamental molecular biological and ecological research to provide the necessary correlates of human disease with vectors, animal hosts and pathogens. For example, where appropriate, new detailed surveillance studies should include the following: (1) the scientific characterisation of that (probably small) proportion of vectors with a high infectious load, responsible for transmission of infection; (2) long-term surveillance of human cases in previously disease-free areas to correlate with the appearance of new vectors, hosts or pathogens; and (3) long-term surveillance and characterisation of wildlife populations, including those in urban areas (for example, foxes, bats and wild boars).

2. Research funding and prioritisation

Ecological research on climate change and infectious disease raises some contentious issues (Lafferty 2009). It is important neither to generalise about the impacts nor to exaggerate the implications (Randolph 2009). However, although we agree that there is need to do much more research to understand the dynamics of infectious diseases at a population level, we do not share the view (Dobson 2009) that such research could replace molecular research.

We welcome the introduction in the Seventh Framework Programme of the collaborative Health and Environment interdisciplinary research topics that will facilitate the integrated investigation of determinants in the spread of vector-borne disease. The complexity of the ecosystems involved mandates multidisciplinary perspectives. Such work must have broad scope, covering Europe and Africa, among other regions, and supporting research that ranges from the study of the impact of environmental and climate factors to a better understanding of vector biology and population dynamics. It is also necessary to understand the social dimensions, in particular the nature of human responses to climate change.

For Europe, there are various specific impacts of climate change to consider: for example, drought stress in the Mediterranean, flooding in northern Europe and warming seas. The impact on ecological systems in Europe will be complicated by the potential for social and economic disruption. Moreover, the EU has a humanitarian responsibility to tackle the issues on a global scale, but even if viewed solely in terms of interests within Europe, it is important for the EU to contribute to the understanding of the global impact of climate change so as to slow the advance of infectious diseases into Europe. There is much work to be done on better predicting, assessing and mitigating the detrimental health consequences globally. One priority is to develop better models to predict which diseases will emerge after severe weather events.

Although we do not now specify the research priorities in any detail, we draw attention to the importance of developing and delivering a broad research strategy with multiple objectives, which we now describe.

Integration and synergy

A course of action for applied research to address the global challenges has been discussed in detail in the recent WHO initiative (Campbell-Lendrum et al. 2009). Therefore, it is important that research funded at the EU or Member State level is well integrated with the global agenda and capitalises on those new methodologies that are being developed elsewhere. For example, in the social sciences, the economic assessment of the costs and benefits of climate-change adaptation decisions will help to provide impetus to attempts to raise political awareness in the EU.

Proactivity and sustainability

Learning the lesson from previous lack of anticipation, all funders need to understand that research must be done in advance of a crisis. For example, since the outbreak of BTV, more money is now available for entomological research, but this research would have been much more effective in steering policy if it had been started earlier. The research agenda must also be understood as long term. Individual projects such as EDEN (see Appendix 1) are excellent initiatives but it is necessary to consider how interdisciplinary activities and networks can be sustained after project funding finishes.

Skill development

Research funders must also be made aware that many of the current generation of skilled researchers in areas such as epidemiology, microbiology and entomology are nearing retirement. Although we cannot be certain about the future impact of climate change on infectious diseases, we can be sure that whatever happens we will need skilled researchers and flexible systems. It is important to do more to train the next generation of researchers. One way of doing this would be to create multidisciplinary centres of excellence in infectious disease research offering master's and Ph.D. programmes.

Projections and predictions

Surveillance and other data (for example, on vectorial competence and capacity) must also be used effectively to develop better predictive modelling capabilities, according to different climatic, developmental and policy scenarios. It may not, of course, be feasible to predict the emergence of specific new diseases in Europe, although we can be sure that some will emerge, but it is important to draw on all resources for early intelligence on new threats, in particular the study of susceptible groups and sentinel animal species. Modelling and simulation tools, incorporating data from the social as well as the biological sciences, will provide new methods to test hypotheses, anticipate developments and inform the policy debate.

Connecting research with innovation

All of the research streams are important in providing the scientific resource to underpin the search for new and better diagnostics, vaccines and therapies. The challenges in capitalising on new research to develop novel products and services and the imperative to support both the public and private sectors in responding to new challenges for innovation have been discussed in detail in previous EASAC reports (EASAC 2006, 2007b)[8].

3. Collaboration between the sectors

There are important research dimensions to the need to improve collaboration between the public health and veterinary sectors at both EU and Member State levels to work towards the 'one health' strategy (EASAC 2008). An integrated research agenda across human and veterinary medicine requires efforts to develop integrated databases for disease surveillance, with meteorological monitoring, and the collection of entomological and remote sensing data.

There are also many other elements to this necessary intersectoral collaboration, for example to promote an understanding of the issues and requirements of companion-animal medicine alongside human travel (see Appendix 1).

4. Preparing for the future

Given the current weaknesses in the evidence base, public policy-makers may be tempted to focus on seemingly more pressing problems. However, climate change is already, and will increasingly, influence infectious disease in Europe so policy-makers need to be prepared. In addition, the impact of climate change on infectious diseases should be considered in developing EU strategies for the European Neighbourhood Policy (ENP) and the Euro-Mediterranean Union. Although the ENP strategy, for example, already recognises the relevance of public health capacity in the objectives for social cohesion and poverty reduction, it is necessary to agree on concrete actions. Capacity-building in the collection and use of surveillance data is one priority, and specific actions to develop clinical laboratory and research services in neighbouring countries for (re-) emerging infectious diseases could be developed, by analogy with those recommended in the recent EASAC report on tuberculosis (EASAC 2009a). It is also vital to build and integrate surveillance networks for animal disease.

Climate change is likely to increase human migration as well as that of animal hosts, vectors and pathogens. The public health implications of migration have received comparatively little attention in EU policy development, although previous EASAC work (2007a) recommended priority actions for collection of epidemiological data and implementation of good practice in migrant health screening and access to healthcare. These priorities continue to be important: tackling them and filling the current information gaps on the burden of disease in high-risk populations will help to develop robust systems in preparation for climate change.

In conclusion, the scientific community must help policy-makers to recognise that climate change could have a very significant impact on human and animal infectious diseases in Europe. There is need to strengthen the evidence base and to appreciate that much of the adaptation that is needed to respond to the impact of climate change is basic preventive public health. It is important to modernise surveillance with trans-European early warning systems and to install preventive measures, including those focusing on high-risk groups in the population. The EU can capitalise on its science base to build the

[8] Pharmaceutical approaches to tackling pathogens should also be accompanied by commitment to better chemical approaches for vector control, for example as represented by the public–private partnership Innovative Vector Control Consortium (www.climate.bayer.com).

necessary interdisciplinary linkages – particularly across epidemiology, ecology and molecular biology with the social sciences – to address the current fragmentation in knowledge. However, there is also need to use the research findings already available for risk assessment as part of improved preparedness. There is an important role for the European Commission and European agencies, with Member State public health authorities, to achieve this capability to respond to current threats and as a basis for improved modelling and prediction for future impact. In addition, there are vital innovation objectives to develop cost-effective diagnostics, preventions and treatments, and to ensure that the EU works with neighbouring countries to support the responses needed in the global context.

Our immediate goal must be to raise awareness that a significant problem exists, that its causes can be understood, and that collectively we have the capability to influence the situation. However, effective response requires increased political will: we look to successive Presidencies of EU Council and to the European Parliament to take the lead in demonstrating commitment to mobilise the necessary resources.

Appendix 1: Summary of points from the international conference in Greifswald, Germany, 'Climate change and infectious diseases', May 2009

This meeting brought together experts from the fields of climate research, human and veterinary medicine and biology to discuss recent scientific evidence relating to the potential influences of climate change on communicable diseases. Presentations at this meeting provided case studies for a wide range of threats to human and animal health.

Dynamics of rodent-borne human viral diseases

Hantaviruses, which belong to the *Bunyaviridae* family, are unique in being transmitted by rodents; all other genera in this family are arthropod-borne[9]. There is evidence to show that hantavirus global epidemiology is driven by local rodent population dynamics (the main rodent species in Europe are the yellow-necked mouse and the bank vole). For example, there is accumulating information that the dynamics of haemorrhagic fever with renal syndrome (HFRS, caused by *Puumala* hantavirus) in Finland, where there has been a dramatic increase in clinical incidence since 1990, can be attributed to changes in the geographical synchrony of vole cycles.

Rodent population dynamics are influenced both by direct and indirect climatic effects on local biodiversity in Europe, for example changes in seasonality and precipitation patterns associated with the North Atlantic Oscillation (a large-scale pattern of natural climate variability in the North Atlantic Ocean). Recent research from literature cited at the Greifswald meeting (Ims et al. 2008) identifies climate forcing as the underlying cause for collapsing population cycles in voles. However, interpretation of the experimental data remains challenging because only short time-series observations are available and there is imperfect understanding of the time-lag between environmental change and clinical infection. In addition, any attempts to predict the temporal and spatial risk of climate change on hantavirus infection in temperate and boreal Europe must recognise that the complex fluctuations in rodent population dynamics are also influenced by predator populations (in turn also subject to climate change impact), changes in landscape and variations in distribution of different virus carrier species. Moreover, although warming will affect the distribution and dynamics of rodent carrier species and their food supply, the assessment of any hantavirus infection also needs to take account of changes in human behaviour (such as rural tourism) and governmental policy (particularly relating to housing and agriculture in rural areas) that will increase human exposure to the vector and host in forest habitats.

Clinical emergence of arboviral diseases

Arthropod-borne viruses (arboviruses) cause more than 130 human diseases, for example WNF, Japanese encephalitis, TBE, chikungunya and dengue, with mosquitoes, ticks and sand-flies serving as the principal vectors. The basic transmission cycle involves arthropod–animal host amplification, with humans acting as a dead-end host (whose viraemia (presence of virus in the blood) does not achieve a sufficiently high level to infect arthropods). Experimental studies show that increasing temperature variably influences the survival rates of immature and mature forms of the vector but consistently shortens the extrinsic incubation period (the interval between initial receipt of infective agent and attainment of infectiousness).

[9] Further details on hantaviruses are available at www.ecdc.europa.eu/en/Health_Topics/Hantavirus/factsheet.aspx.

West Nile virus and other flaviviruses

In response to a relatively small increase in temperature, a markedly decreased West Nile virus (WNV) incubation period for the mosquito *Culex tarsalis* allows significantly increased vectorial capacity. It is probably significant that WNV endemicity was achieved in the USA coincident with the hottest summer on record, an observation that is consistent with the explanation for other outbreaks in Russia and Romania, although collection of longer time-series data would aid interpretation.

Evidence is being collected to document the emergence and spread of mosquito-borne flaviviruses in central Europe. Globally, WNV is the most widespread flavivirus. However, despite a long-term presence in Europe, it has rarely been associated with clinical symptoms. However, in 2008 a relatively large outbreak occurred in northern Italy, affecting humans as well as birds and horses; and in Hungary, spreading into Austria, there was an extensive outbreak of the virus in birds of prey, sheep and horses with some human infection (mild meningitis). The evidence suggests that the virus is now overwintering as a resident pathogen and that climate warming will spread the infection such that Europe could face a situation with WNF similar to that in the USA. To prepare public health authorities for this possibility, it is important to institute a European lineage-specific WNV surveillance programme covering birds, mosquitoes and horses as well as humans. This requires increased collaboration between the human health and veterinary sectors.

The emergence of other new flaviviruses in Europe is exemplified by Usutu virus, never previously observed outside (sub-)tropical Africa but associated in 2001 with an outbreak of avian mortality in Austria. This virus spread in bird populations within Austria up to 2003 and then declined, possibly attributable to the development of herd immunity. Although no human encephalitis was detected, there were cases of rash and specific antibodies measured in a significant number of asymptomatic individuals. The same viral strain has also now been found in Hungary, Switzerland and Italy. The conclusions drawn from this case study were that Usutu virus too could survive the Austrian winter, has adapted to European mosquito species and established effective transmission between local mosquitoes and birds. It has become a resident pathogen that might spread further.

There is less evidence to conclude that climate change can explain other recent global trends in arboviral distribution and incidence. Modelling studies suggest that the spread of dengue in the Americas might be explained by increases in temperature and rainfall subject to the influence of the underlying climate. If the climate is already hot and wet, further change may have little influence on dengue transmission[10]. The interpretation of the epidemiology of Japanese encephalitis is also complex: although there has been some expansion into south Asia, rates in Japan have declined, perhaps because of vaccination.

Chikungunya

The increased incidence and geographical distribution of chikungunya, most recently in Italy, might be interpreted more easily as a result of globalisation, specifically the trade in used tyres, a good breeding ground for the vector *Aedes albopictus*, than as a specific consequence of climate change. However, a rapid spread of *Ae. albopictus* has been documented in the Balkans, France, Spain and Greece as well as Italy. Further insight on the impact of climate change will emerge from better mapping of vector distribution[11]. There is also concern about the possible introduction into Europe of the mosquito *Aedes aegypti*, another important vector for the chikungunya virus as well as other arboviruses such as dengue and yellow fever, which has already appeared in Madeira. It is noteworthy that perhaps one hundred cases of chikungunya occurred in Italy before reaching medical and public awareness. There is room to do much better in early signal detection, education and communication; this requires better networking among international public health bodies and with Member State authorities.

[10] There is little equivalent modelling data yet for Europe, although that will be produced by ECDC (Box 1). The last documented dengue outbreak in Europe was in Greece in 1927–8, when there were perhaps one million cases and one thousand deaths.

[11] The initial work of ECDC and WHO in risk assessment for chikungunya, based on the epidemiological situation in Italy, was completed in 2007. The work of the ECDC consultation group (Straetemans 2008) was cited in the Greifswald meeting: this group recommended further work on clarifying the current distribution and the potential for expansion subject to climatic factors. The group also advised the development of European standards for vector surveillance methods (particularly trapping techniques) to improve comparability of data between countries. A recent ECDC Technical Report (Development of *Aedes albopictus* risk maps, May 2009) provides detailed analysis of the potential spread even in the IPCC minimum impact model.

Thus, although the interpretation of the heterogeneous pattern of disease trends of these different arboviruses does not yet necessarily indicate a consistent impact of climate change that can be differentiated from other determinants, there is need to explore further. There is a strong biological basis for expecting that climate change will alter the distribution and incidence of these infections. Discussants at the meeting agreed on the need for more epidemiological, molecular biological and ecological research, including long-term surveillance for the appearance of human cases in previously disease-free areas to correlate with the appearance of new vectors, hosts or pathogens.

Tick-borne viruses

There is also an increasing body of information in support of a correlation between climate change, tick activity and tick-borne disease in Europe (Suss & Kahl 2008), although confounding factors again render the precise and quantifiable attribution of causality difficult. Between 1990 and 2007, 157,000 cases of TBE were documented in 27 European countries (50,000 of the cases were outside Russia). TBE is endemic in 19 European countries. *Ixodus ricinus* is the vector for 95% of tick-transmitted pathogens in Europe, mainly TBE and Lyme borreliosis[12]. There is significant evidence accruing for northward and westward movement of the tick population in Europe, with occurrence at increasingly higher altitudes. However, further systematic study of the life cycle of *I. ricinus* and other ticks is needed to understand the potential for geographical expansion of the populations and their link to disease.

Leishmaniasis

In Europe, two species of *Leishmania* cause endemic human disease: *L. tropica* (cutaneous leishmaniasis) in Greece and Turkey, and *L. infantum* (visceral leishmaniasis) in the Mediterranean area[13]. *Leishmania* species are transmitted by *Phlebotomus* sand-flies. Disease rates are currently low and the disease is often relatively neglected by European public health authorities. Infections are usually asymptomatic (up to half the rural population in southern Europe are skin-test positive) unless there is immunosuppression; for example, clinical symptoms are associated with HIV co-infection. *L. infantum* is a zoonosis, and cats and dogs can be a major reservoir in Europe, with wild animals (jackals and foxes): up to 35% of the rural dog population in southern Europe is seropositive. Although there is relatively little evidence yet to indicate an impact of climate change, there are data to show that *Leishmania* infections are spreading into temperate zones in Europe, being detected north of the Alps for the first time in 1999. The EU-funded EDEN project (Box 2) is investigating leishmaniasis as an example of a threat to southern Europe.

Box 2 EDEN: Emerging Diseases in a changing European eNvironment

- EDEN was funded by the Sixth Framework Programme with aims to identify and catalogue those European ecosystems and environmental conditions that can influence the spatial and temporal distribution and dynamics of human pathogens. Twenty-four European countries are involved in fieldwork.
- Diseases were chosen either because they are already present in Europe, were found previously or may re-emerge: leishmaniasis; tick-borne viruses; rodent-borne viruses; WNV; malaria; Africa-source diseases (including RVF). Horizontal integration of the disease-specific work groups enables the development and sharing of tools for remote sensing, disease modelling and biodiversity assessment.
- For each disease, the research comprises the study of patterns and processes for landscape, vectors and host/reservoir characteristics.
- This co-ordinated European approach is expected to provide predictive emergence and spread models (global and regional) for public-health early warning and surveillance goals.
- It is clear from the interim outcomes of EDEN that many of the observed changes in disease occurrence are driven by complex multifactorial determinants, not simply related to temperature, in particular socio-economic factors that affect human behaviour and contact between host, vector and pathogen.

www.eden-fp6project.net

[12] In addition to the research published in the volume edited by Suss & Kahl (2008), a review by CDC authors (Gage et al. 2008) discusses the literature on the potential effects of climate change for Lyme borreliosis in Europe, whose distribution, like TBE, has increased at higher latitudes and elevations. Although the explanations are, again, probably complex, the authors conclude, *'Regardless of any uncertainties about whether climate change will occur or how this process will affect human health, the public health community needs to be prepared for such challenges, should they occur'*.

[13] The ECDC provides detailed information on clinical features, transmission and management, available at www.ecdc.europa.eu/en/health_Topics/Leishmaniasis/factsheet.aspx. Spatio-temporal modelling of leishmaniasis emergence in climate change models is reviewed by Ready (2008).

The work within EDEN includes mapping *Leishmania* environments in Europe, comparing endemic with non-endemic sites to identify key variables, using standardised sampling techniques to study the distribution of species of sand-fly vectors, using climate variables to map predicted vector risk and collecting time-series data to model transmission from canine hosts. This comprehensive approach to studying human and animal populations should help to quantify the northward migration of *Leishmania* species and their sand-fly vectors. In turn this will help to ascertain the relative contributions made by vectorial and non-vectorial transmission (the latter perhaps mediated by tourists' companion dogs returning home from holiday).

More generally, one of the lessons from the EDEN project has been a confirmation that the changing distribution of vectors and vector-borne diseases in Europe may not necessarily be explained by a single factor acting in isolation (for example, a change in temperature or precipitation) but rather by an interplay of factors (including changes in land use and human behaviour) that may also be influenced by climate change.

Dirofilariasis

Mosquito-borne *Dirofilaria repens* is the most frequent zoonotic infection in Europe and Asia. There is evidence for a growing clinical problem in northeast Europe because it appears that the parasite is now able to mature to the adult stage in humans whereas previously it had not usually done so. The public health problem is often not sufficiently appreciated but the epidemiology in Europe is complex. There is evidence that infections of *D. repens* decreased in some areas, for example in Italy during the past 20–30 years, but that *D. repens* is spreading throughout many other European countries and that animal and human infections, in some cases very severe, are increasing. In addition, infections of *Dirofilaria immitis* are dramatically increasing and extending to previously unaffected areas such as Switzerland.

The changes in disease incidence are attributed to effects of temperature on the parasite itself, on the density of the vector population (and the emergence of *Ae. albopictus* as a competent vector) and to changes in human exposure. Recent research demonstrates that temperature dictates the development of *Dirofilaria* larvae in the vector, with a threshold below which development will not proceed and consequently determines the seasonal occurrence of heartworm transmission in temperate latitudes. Modelling studies predicting the potential for transmission to humans map the seasonal duration of risk across Europe and indicate that areas formerly free of the infection are now endemic[14]. Tackling the issues requires, again, better co-ordination between public health and veterinary health authorities, particularly to advise on the value of preventing infection in companion animals[15].

Plague epizootics

Human plague, caused by the bacterium *Yersinia pestis*, has endemic foci in Africa (for example, Madagascar, the Democratic Republic of Congo and Tanzania), Asia and America. Since the beginning of the 1990s, the disease has reappeared in various countries where no cases were reported for decades. Some of these countries (for example, Jordan, Algeria, Libya) are close to Europe. The threat of the re-emergence of plague foci on the European continent is unclear. More than 200 species of rodents can act as reservoirs of plague, and more than 80 species of fleas may be vectors of the disease. Climate definitely plays a role in the annual seasonality of plague. The potential effects of temperature rise and drought (or abundant rains) associated with climate change on flea survival and reproduction and on rodent prevalence are likely to be complex. Although changes in the current geographical plague foci have to be expected, these changes may have opposite effects (a decrease or extension of current foci, an extinction or emergence of the disease in new areas) depending on local environmental conditions. Therefore, how climate change will affect plague foci globally cannot yet be predicted but it will most likely have an impact, and this impact will vary in different parts of the world. This should be a stimulus for new research.

[14] Although not discussed in detail at the meeting, work was cited on the spatial modelling of another mosquito species, *Anopheles atroparvus*, previously responsible for tertian malaria in Lower Saxony, where the disease was extinguished in the 1950s. A slight rise in ambient temperature and rainfall can extend the duration of the season for mosquito vectors to transmit malaria. Spatial and temporal temperature changes drive malaria transmission when modelled using both the IPCC best and worst case possibilities for climate change (Schroder & Gunther 2008). The conclusion, suggesting a significant extension of the theoretical risk period in this region, highlights the need for vector monitoring.

[15] Guidelines for the control of parasitic insects and ticks in dogs and cats are available at www.esccap.org.

Animal diseases[16]

Bluetongue virus

There are 19 orbiviral species, the most important being BTV and African horse sickness virus. The main vectors are *Culicoides* species. Although the main vector of BTV in Africa, *C. imicola*, has extended its range across the Mediterranean in the past decade, which may be a direct consequence of climate change[17], the outbreak of BTV-8 in central Europe demonstrated vector competence of Palaearctic, local midge populations.

Thus, although the impact of climate change on the introduction and establishment of BTV-8 in central Europe is unclear, higher temperatures extend the range of some vectors (*C. imicola*), accelerate virus development in the vector, increase the proportion of a vector population that is able to transmit, and extend the ability to transmit to additional *Culicoides* species. In consequence, after the initial spread, BTV may become established as an endemic disease in western Europe and serotypes other than BTV-8 may also become important. There is a continuing requirement to be alert in monitoring entry paths for pathogens, vectors and infected animals. There is also now the opportunity in research to use molecular biology to identify and monitor those vectors with the highest virus load (perhaps only 2% of the total vector population) responsible for transmission.

Rift Valley fever

RVF is another zoonotic arbovirus. Although human symptoms are usually mild there can be haemorrhagic complications and encephalitis[18]. RVF is currently confined to Africa, with severe economic impact, and Saudi Arabia but is listed by OIE as second of the priority diseases whose incidence and distribution could be affected by global warming. An impact of climate change on RVF outbreaks might be anticipated to be mediated by the influence of increased rainfall on the habitat for vector mosquitoes but use of remote sensing satellite imagery to map rainfall and vegetation has achieved only partial success in predicting disease patterns across Africa. It seems likely that the interpretation of effects induced by climate change must take account of other variables, chiefly the effect of temperature on vector competence. What is clear is that the geographical range of RVF has spread over the past 20 years, and it is possible that RVF may do the same as West Nile and bluetongue diseases in establishing in newly affected areas, including Europe (Senior 2009).

African swine fever

ASF African genotypes are highly virulent, inducing an acute form of the disease, and there is increasing risk that virulent ASF will enter the EU and infect domestic pig and wild boar populations. Episodes of ASF spreading from Africa to Europe in the 1990s can be attributed to the movement of infected live pigs, pig products and contaminated feed. The role of soft ticks as a vector is variable: it was important in the Iberian peninsula but not in Sardinia. The activity of ticks is dependent on temperature and humidity. Currently, the major problem is in the Caucasus, where ASF probably emerged because of weakened veterinary services for diagnosis and control of imports, a consequence of the breakdown in infrastructure following political instability rather than an effect of climate change. It is important to seek further information on the means by which the disease entered Caucasian countries in 2007 and its subsequent spreading.

Wildlife hosts and their pathogens

Both the public health and veterinary communities need to pay more attention to wildlife pathogens. By contrast with good knowledge about the effect of predators on wildlife, there are many gaps in the ecological characterisation of the effect of pathogens. However, the methodological challenges involved in collecting and assessing the data should not be underestimated. There are few baseline data, and multiple changes in habitat[19] confound the identification of specific climate influences. Data are

[16] A large amount of relevant information is provided in the special issue of the Scientific and Technical Review of OIE (de la Rocque et al. 2008), cited during the Greifswald meeting. For example, a review by Dufour et al. (2008) describes a method for prioritising animal health risks in France in consequence of global change, including global warming. In that work, six priority diseases were identified: BTV, RVF, WNV, visceral leishmaniasis, leptospirosis and African horse sickness. A consistent need was identified to develop epidemiological surveillance and to increase knowledge of vector and host life cycles, to support research on new diagnostics and vaccines and to pool cross-border efforts in control.

[17] This impact has been well characterised, for example by the research cited in Greifswald conducted by the Institute of Animal Health in the UK (www.iah.bbsrc.ac.uk/events/docs/Climate_Change_BTV.pdf). Information on European Community controls on BTV and latest situation on the distribution of serotypes is available at www.ec.europa.eu/food/animal/diseases/controlmeasures/bluetongue_en.htm. Co-ordinated EU effort on BTV has also been facilitated by the Framework Programme 6 Network of Excellence, Epizone. More generally, Epizone provides an expert risk-assessment framework to identify and prioritise potential animal disease threats to Europe as a result of climate change (www.epizone-eu.net/Paginas/Themes/Theme%207.aspx).

[18] Further details on clinical features, human transmission mechanisms and prevention and control measures are available at www.who.int/mediacentre/factsheets/fs207/en.

[19] The examples of Nipah, Hendra and Ebola viruses indicate the primary importance of changes to farming and other habitats.

usually correlative at best, and there is need for more insight on mechanisms whereby climate change may affect vector biology and host physiology. Nonetheless, there are established examples of both direct effects of climate change, for example on pneumonic pasteurellosis in southern Norway and parasitic disease in musk oxen in Greenland, and indirect effects, for example distemper in common seals arising from migration stress combined with algal-bloom-induced immunosuppression. Reinforcing points made previously, there needs to be long-term monitoring of free-ranging wildlife populations and accurate identification of their pathogens. Currently, there is more research done on wildlife populations in Africa than in Europe and there is a particular gap in the study of the urban environment for wildlife in Europe. In building this research capacity, it is important to appreciate the role of skilled veterinary scientists in zoos, enabling a focus on sentinel populations for signal detection—exemplified by the work of the Bronx Zoo in discovering WNV in the USA.

The options for controlling pathogens in wildlife are limited. The well-managed use of rabies vaccine in foxes in Europe is an example of best practice. However, too often control strategies have been ineffective because they do not take proper account of the ecological and evolutionary relationship of pathogen to host. For example, control of severe acute respiratory syndrome (SARS) in China targeted an accidental host, the Asian palm civet, missing the actual primary host, fruit bats. Preventive measures must take better account of ecohealth[20] in planning and developing habitat change, coupled with better controls on illegal importation of animals.

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[20] Other recent work by EASAC on ecosystem services (EASAC 2009b) reviews the collective benefits provided by the environment that include the influence of biodiversity in controlling disease: part of the ability of resilient ecosystems to resist invasion by novel pathogens may be related to the structure and complexity of the ecosystem.

List of abbreviations

ASF	African swine fever
BTV	Bluetongue virus
CDC	Centers for Disease Control and Prevention
ECDC	European Centre for Disease Prevention and Control
ENP	European Neighbourhood Policy
HFRS	Haemorrhagic fever with renal syndrome
HIV	Human immunodeficiency virus
IOM	Institute of Medicine
IPCC	Intergovernmental Panel on Climate Change
OIE	World Organisation for Animal Health
RVF	Rift Valley fever
SARS	Severe acute respiratory syndrome
TBE	Tick-borne encephalitis
WHO	World Health Organization
WNF	West Nile fever
WNV	West Nile virus

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