Climate change and infectious diseases in Europe

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Concerted action is needed to address public health issues raised by climate change. In this Review we discuss infections acquired through various routes (arthropod vector, rodent, water, food, and air) in view of a changing climate in Europe. Based on an extensive review of published work and expert workshops, we present an assessment of the infectious disease challenges: incidence, prevalence, and distribution are projected to shift in a changing environment. Due to the high level of uncertainty on the rate of climate change and its impact on infectious diseases, we propose to mount a proactive public health response by building an integrated network for environmental and epidemiological data. This network would have the capacity to connect epidemic intelligence and infectious disease surveillance with meteorological, entomological, water quality, remote sensing, and other data, for multivariate analyses and predictions. Insights from these analyses could then guide adaptation strategies and protect population health from impending threats related to climate change.

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Introduction

Accelerating economic activity and fossil fuel combustion over the past century has precipitated an environmental impact of unprecedented proportions. Ecosystem decline, loss of biodiversity, stratospheric ozone depletion, and climate change are some of these environmental changes. Climate change is ascribed to natural processes and human activity altering atmospheric conditions.[1,2] Climate change is indeed tangible: the worldwide mean surface temperature has increased by 0·74°C (SD 0·18) over the past 100 years, while the worldwide sea level has risen by 1·8 mm per year since 1961, and the Arctic sea ice is retreating by 2.7% (SD 0.6) per decade. In addition, sea surface temperatures are warming, mountain glaciers are shrinking, oceans are becoming more acidic, and extreme weather events are increasing in frequency and intensity. These climatic changes have already had noticeable effects on many natural systems, including marine and terrestrial ecosystems, such as the timing of seasonal biological events and the distribution of animal and plant species.[3]

The transmission of infectious diseases is determined by many factors, including social, economic and ecological conditions, access to health care, and intrinsic human immunity.[4] Many infectious agents, vector organisms, non-human reservoir species, and pathogen replication rates are particularly sensitive to climatic conditions.[5] Numerous theories have been developed in recent years to explain the relation between climate change and infectious diseases: they include higher proliferation and reproduction rates at higher temperatures, extended transmission season, changes in ecological balances, and climate-related migration of vectors, reservoir hosts, or human populations.[6]

The relation between climate change and infectious diseases in Europe thus calls for careful assessment and analysis. In this Review we look at the evidence for climate-related changes in infectious disease incidence, distribution, localised outbreaks, and potential for the establishment of tropical vector species in Europe.[7] Based on this review of published work the European Centre for Disease Prevention and Control (ECDC) has identified the need to tackle the technical challenges by developing a blueprint for an environmental and epidemiological network that would link existing resources. Merging, integrating, and analysing such data will advance our understanding of the relation between climate change and infectious diseases in Europe and inform public health action (panel).[8,9]

Methods

Search strategy and selection criteria

Original research articles were retrieved from PubMed. The search strategies submitted (see webappendix) combined the concepts of "climate change" plus "climate variability" and specific infectious diseases covered by the disease-specific programmes at ECDC: food and water-borne diseases, vector-borne diseases, invasive bacterial infections, influenza, tuberculosis, and vaccine preventable diseases.[10] Keywords of the concepts and MeSH terms (when available) were used in the search strategies included articles in all languages from January, 1966, to April, 2009. Research reports from international organisations and grey literature were also included in our analysis.

See **Online** for webappendix

Expert workshops

Three international workshops on infectious diseases and environmental change were hosted by ECDC in Sweden, in collaboration with the WHO Regional Office for Europe, the European Commission's Joint Research Centre (JRC), and the European Environmental Agency (EEA). Scientists and public health practitioners from Europe, Canada, China, and the USA mapped out the current state of understanding of climate change and infectious diseases, and discussed potential solutions to these challenges. The discussion included findings from past and ongoing European-Community-funded research projects and disease networks. This Review includes insights from the review of published work and workshop discussions.

Vector-borne diseases

Vector-borne diseases are infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, triatomine bugs, sandflies, and blackflies.[11]

Arthropod vectors are cold-blooded (ectothermic) and thus especially sensitive to climatic factors. Weather influences the survival and reproduction rates of the vectors, in turn influencing habitat suitability, distribution, and abundance; intensity and temporal pattern of vector activity (particularly biting rates) throughout the year; and rates of development, survival and reproduction of pathogens within vectors.[12] However, climate is only one of many factors influencing vector distribution, such as habitat destruction, land use, pesticide application, and host density. Vector-borne diseases are widespread in Europe and are the best studied diseases associated with climate change, which is reflected in this Review.

Panel: Selected examples of public health functions as they relate to climate change and infectious diseases

Monitoring

Indicator-based surveillance—collection, (trend) analysis, and interpretation of data related to climate change

- Routine data analysis from mandatory notification (eg, the 49 infectious diseases and conditions notifiable at European Union level)
- Pharmacy-based monitoring of prescription and non-prescription drug sales or health-related data preceding diagnosis
- Sentinel surveillance (collection and analysis of high quality, accurate data at a geographical location—eg, tick-borne encephalitis, Lyme borreliosis, etc)
- Vector surveillance (monitor distribution of vectors—eg, *Aedes albopictus*)
- Real-time surveillance (instantaneous data collection with dynamic and sequential data analysis—eg, hospital admissions or dead-bird surveillance)
- Mortality from infectious diseases (monitor cause-specific deaths from infectious diseases based on medical records, autopsy reports, death certificates, etc)
- Syndromic surveillance (eg, monitor emergency room admissions for symptoms indicative of infectious diseases)

Event-based epidemic intelligence—early identification of infectious disease threats related to climate change

- Screening of (international) news media and other sources
- Case reports (eg, clinician-based reporting)
- Science watch (eg, screening scientific reports for discoveries and new findings)
- Interdisciplinary reporting on infectious disease threats (eg, from agriculture, industry, environment, etc)

Outbreak investigation and response

- Diagnose and investigate health problems (eg, newly emerging tropical diseases)
- Respond effectively and rapidly to prevent dispersion of outbreak (eg, though water boil notices or insecticide spraying)
- Multisectorial response (eg, public, private, commerce, faith-based, etc)
- Logistical support and adequate supplies (eg, provisions for unusual outbreaks including antivirals, medications, vaccines, etc)

Inform, educate, empower

- Develop communication strategies to disseminate timely, accurate, and well-organised information
- Health education and health promotion (eg, reduce occupational or recreational exposure to ticks through changes in behaviour)
- Food handling under hot weather conditions (eg, promote refrigeration, thorough cooking, use of uncontaminated water and food, separation of cooked and raw food, etc)
- Vector control measures (eg, integrated pest management, window screens, eliminate standing water)
- Personal vector protection (eg, bed nets, protective clothing, insecticide use)

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Mosquito-borne diseases

West Nile fever is caused by the West Nile virus, a virus of the family Flaviviridae that is part of the Japanese encephalitis antigenic group. West Nile fever mainly infects birds and infrequently human beings through the bite of an infected *Culex* spp mosquito. In numerous European countries the virus has been isolated in mosquitoes, wild rodents, migrating birds, hard ticks, horses, and human beings.[13] Since roughly 80% of cases are asymptomatic, the rate of West Nile virus infections in human beings remains largely unknown, and probably only some of the epidemics with tens or hundreds of West Nile fever cases have been documented.[14] Past entomological data have been linked to meteorological data to model a West Nile fever outbreak in southern France in 2000. The aggressiveness of the vector (*Culex modestus)* was positively correlated with temperature and humidity, and linked to rainfall and sunshine, which were particularly high during the epidemic period.[15] An outbreak in 1996–97 in southeastern Romania[16] resembled a subsequent outbreak in Israel in 2000, which was associated with a heat wave early in the summer with high minimum temperatures.[17] These observations are in agreement with a climatic model for West Nile virus with mild winters, dry springs and summers, heat waves early in the season, and wet autumns.[18] Dry spells favour reproduction of city-dwelling mosquitoes (eg, *Culex pipiens*) and concentrate vectors with their avian hosts around water sources, which leads to arbovirus multiplication.[19] Explanatory models have assisted public health practitioners in making decisions about the spraying of preventative larvicides.[20]

Dengue is the most important worldwide arboviral human disease; however, mainly due to nearly universal use of piped water, the disease has disappeared from Europe.[21] Dengue is frequently introduced into Europe by travellers returning from dengue-endemic countries, but no local transmission has been reported since it would also depend on the reintroduction of its principal vector, the mosquito *Aedes aegypti* (also the yellow fever mosquito), which is adapted to urban environments. However, over the past 15 years another competent vector *Aedes albopictus* (Asian tiger mosquito) has been introduced into Europe and expanded into several countries, raising the possibility of dengue transmission.[22]

Epidemiological studies have shown that temperature is a factor in dengue transmission in urban areas.[23] Climate change projections on the basis of humidity for 2085 suggests dengue transmission to shift the latitudinal and altitudinal range.[24] In temperate locations, climate change could further increase the length of the transmission season.[25] An increase in mean temperature could result in seasonal dengue transmission in southern Europe if *A aegypti* infected with the virus were to become established.

Chikungunya fever is caused by a virus of the genus Alphavirus, in the family Togaviridae, which is transmitted to human beings by the bite of infected mosquitoes such as *A aegypti* and *A albopictus*.

A confirmed outbreak of chikungunya fever was reported in August, 2007, in northeastern Italy, the first chikungunya outbreak on the European continent.[26–28] Vector surveillance in the vicinity of the cases identified large numbers of *A albopictus* mosquitoes in traps, but no sandflies or other vectors. While introductions of *A albopictus* and chikungunya virus into Italy were accidental events, a climatic model with five scenarios has been developed for possible further establishment of *A albopictus* in Europe with main variables such as mild winters, mean annual rainfall exceeding 50 cm, and mean summer temperatures exceeding 20°C.[29] Vector population density, an important determinant of the epidemic potential, is also linked to duration of the seasonal activity; therefore, the weeks between spring egg hatching and autumn egg diapause are also factored in. This model defines the potential for further transmission and dispersion of the vector under favourable climatic conditions in temperate countries, and outlines the geographical areas potentially at risk of future outbreaks.

Malaria is caused by one of four species of the *Plasmodium* parasite transmitted by female *Anopheles* spp mosquitoes. Historically malaria was endemic in Europe, including Scandinavia, but it was eventually eliminated in 1975 through a number of factors related to socioeconomic development.[30,31] Any role that climate played in malaria reduction would have been small. Nevertheless, the potential for malaria transmission is intricately connected to meteorological conditions such as temperature and precipitation.[32] For example, conditions for transmission in Europe have remained favourable as documented by sporadic autochthonous transmission of a tropical malaria strain by local vectors to a susceptible person.[33,34]

The potential for malaria and other tropical diseases to invade southern Europe is commonly cited as an example of the territorial expansion of risk due to climate change (socioeconomic, building codes, land use, treatment, capacity of health-care system, etc). Projections of malaria under future climate change scenarios are limited in Europe. An assessment in Portugal projected an increase in the number of days per year suitable for malaria transmission; however, transmission would depend on infected vectors being present.[35] For the UK, an increase in risk of local malaria transmission based on changes in temperature projected to occur by 2050 was estimated to be 8–14%, but malaria re-establishment is highly

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Foster interagency and community partnerships

- Connect different sectors (eg, civil engineering and sanitation for drinking water quality)
- Connect different disciplines (eg, entomologists with agronomist for vector surveillance and control)
- Reach out to stakeholders (eg, wildlife, fishing, or hunting clubs, etc)
- Media advocacy (eg, mass media vaccination campaign)
- Engage community leaders of susceptible populations

Develop policies

- Include climate sensitive infectious diseases on the list of notifiable diseases
- Land use and housing codes to minimise exposure
- Adaptation and mitigation strategies
- Emergency preparedness and management procedures at local, national, and international levels

Enforce laws and regulations

- International Health Regulations, 2005: early identification and reporting of events related to climate change that could constitute potential international crises
- Water protocol: Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE) calls upon countries to protect water resources, drinking water, human health, to provide sanitation, and to monitor water-borne disease outbreaks
- Enact regulations to minimise harmful exposures—eg, land use zoning (flood risk areas, habitat encroachment, etc), water-distribution systems, housing codes, introduction of non-native species and their pathogens, etc

Access to care

- Link infected patients to health services
- Treatment of infected patients to prevent outbreak propagation (eg, malaria treatment)
- Prevention (vaccination, prophylaxis, travel medicine)

Assure competent workforce

- Train health-care workforce (eg, ability to diagnose chikungunya fever)
- Implement emergency preparedness training across different sectors (eg, housing, social services, health, etc)
- Strengthen capacity of public health professionals

Evaluate

- Assess interventions to protect communities from adverse events related to climate change
- Evaluate effectiveness, accessibility, and quality of public health services

Research

- Basic and applied research on the relation between infectious diseases and climate (eg, establishment of baselines and longitudinal seroprevalence studies for trends)
- Mapping vector ecology and competence relative to a changing climate (eg, risk maps)
- Promote studies on susceptible populations in high-risk areas (eg, tick-borne encephalitis in hunters)
- Develop diagnostic tests, vaccines, and innovative solutions to vector abatement (eg, development, evaluation, and introduction of a dengue vaccine)
- Models of projections, in particular burden-of-disease studies under different climatic, developmental, and policy scenarios

UNECE=United Nations Economic Commission for Europe.

unlikely.[36] Thus, while climatic factors may favour autochthonous transmission, increased vector density, and accelerated parasite development, other factors (socioeconomic, building codes, land use, treatment, capacity of health-care system, etc) limit the likelihood of climate-related re-emergence of malaria in Europe.[37]

Sandfly-borne diseases

Leishmaniasis is a protozoan parasitic infection caused by *Leishmania infantum* that is transmitted to human beings through the bite of an infected female sandfly. Temperature influences the biting activity rates of the vector, diapause, and maturation of the protozoan parasite in the vector.[38,39] Sandfly distribution in Europe is south of latitude 45°N and less than 800 m above sea level, although it has recently shifted to a latitude of 49°N.[40,41] Historically, sandfly vectors from the Mediterranean have dispersed northwards in the postglacial period based on morphological samples from France and northeast Spain, and, more recently, sandflies have been reported in northern Germany.[42] The biting activity of European sandflies is strongly seasonal, and in most areas is restricted to summer months. Currently, sandfly vectors have a substantially wider range than that of *L infantum*, and imported cases of infected dogs are common in central and northern Europe. Once conditions make transmission suitable in northern latitudes, these imported cases could act as plentiful sources of infections, permitting the development of new endemic foci. Conversely, if climatic conditions become too hot and dry for vector survival, the disease may disappear in southern latitudes. Thus, complex climatic and environmental changes (such as land use) will continue to shift the dispersal of leishmaniasis in Europe.[43,44]

Tick-borne diseases

Tick-borne encephalitis (TBE) is caused by an arbovirus of the family Flaviviridae, and is transmitted by ticks (predominantly *Ixodes ricinus*) that act both as vectors and as reservoirs.[45] Similar to other vector-borne diseases, temperature accelerates the ticks' developmental cycle, egg production, population density, and distribution. It is likely that climate change has already led to changes in the distribution of *I ricinus* populations in Europe.[46] *I ricinus* has expanded into higher altitudes in the Czech Republic over the past two decades, which has been related to increases in average temperatures.[47–49] This vector expansion is accompanied by infections with TBE virus.[50,51] In Sweden, since the late 1950s all cases of encephalitis admitted in Stockholm County have been serologically tested for TBE. An analysis of the period 1960–98 showed that the increase in TBE incidence since the mid-1980s is related to milder and shorter winters, resulting in longer tick-activity seasons. In Sweden, the distribution-limit shifted to higher latitude;[52] the distribution has also shifted in Norway and Germany.[53,54]

Climate models with warmer and drier summers project that TBE will be driven into higher altitudes and latitudes, although certain other parts of Europe will be cleared of TBE.[55] However, these climatic changes alone are unlikely to explain the surge in TBE incidence over the past three decades, and it is endemic in 27 European countries today.[54] There is considerable spatial heterogeneity in the increased incidence of TBE in Europe, despite observed uniform patterns of climate change.[56] Potential causal pathways include changing land-use patterns, increased density of large hosts for adult ticks (eg, deer), habitat expansion of rodent hosts, alterations in recreational and occupational human activity (habitat encroachment), public awareness, vaccination coverage, and tourism.[57,58] These hypotheses can be tested epidemiologically and tackled through public health action.

Lyme borreliosis is caused by infection with the bacterial spirochete *Borrelia burgdorferi*, which is transmitted to human beings during the blood feeding of hard ticks of the genus *Ixodes*. In Europe, the primary vector is *I ricinus*, also known as the deer tick, and *Ixodes persulcatus* from Estonia to far eastern Russia. In Europe, Lyme borreliosis is the most common tick-borne disease with at least 85 000 cases yearly, and has an increasing incidence in several European countries such as Finland, Germany, Russia, Scotland, Slovenia, and Sweden. Although detection bias could explain part of this trend, a prospective, population-based survey of cases in southern Sweden has serologically confirmed such an increase.[59,60]

A shift toward milder winter temperatures due to climate change may enable expansion of Lyme borreliosis into higher latitudes and altitudes, but only if all of the vertebrate host species required by tick vectors are equally able to shift their population distribution. In contrast, droughts and severe floods will negatively affect the distribution, at least temporarily. Northern Europe is projected to experience higher temperatures with increased precipitation, although southern Europe will become warmer and drier, which will impact tick distribution, alter their seasonal activity, and shift exposure patterns.[61]

Crimean-Congo haemorrhagic fever (CCHF) is caused by an RNA virus of the Bunyaviridae family and transmitted by *Hyalomma* spp ticks from domestic and wild animals. The virus is the most widespread tick-borne arbovirus and is found in the eastern Mediterranean where there have been a series of outbreaks in Bulgaria in 2002 and 2003, and in Albania and Kosovo in 2001.[62–64] Milder weather conditions, favouring tick reproduction may influence CCHF distribution.[65] For example, an outbreak in Turkey was linked to a milder spring season (a substantial number of days in April with a mean temperature higher than 5°C) in the year before the outbreak.[66] However, other factors such as land use and demographic changes have also been implicated.[67]

There have been new records of spotted fever group rickettsioses with new pathogens such as *Rickettsia slovaca, Rickettsia helvetica, Rickettsia aeschlimannii,* and flea-borne rickettsioses (*Rickettsia typhi*, *Rickettsia felis*).[66,68,69] However, this emergence is most likely detection bias due to advancements in diagnostic techniques. Since ticks, fleas, and lice serve as vectors and reservoirs they might contribute to disease amplification under favourable climate change conditions. There has been a geographical expansion of rickettsial diseases throughout Europe,[70] and while underlying reasons for this expansion are still unclear, it is possible that wild bird migration could play a part.[71]

Human granulocytic anaplasmosis is caused by *Anaplasma phagocytophilum*, a bacterium usually transmitted to human beings by *I ricinus*. In Europe, this disease was known to cause fever in goats, sheep, and cattle until it emerged as a disease in human beings in 1996.[72] It has now shifted to new geographical habitats throughout Europe, and migrating birds have been implicated in its expansion.[73] Spatial models have been developed to project the geographical distribution under climate change scenarios for North America but not for Europe.[74,75]

Summary

Based on the vector-borne disease articles reviewed, it is clear that climate is an important geographical determinant of vectors, but the data do not conclusively demonstrate that recent climatic changes have resulted in increased vector-borne disease incidence on a pan-European level. However, the reports indicate that under climate change scenarios of the past decades ticks have progressively spread into higher latitudes in Sweden and higher elevation in the Czech Republic; they have become more prevalent in many other places and intensified the transmission season. Conversely, the risk for Lyme borreliosis is projected to be reduced in drought and flood-ridden locations. The articles reviewed do not support the notion that climate change has altered the distribution of sandflies and visceral leishmaniasis, but since sandfly vectors expand further than *L infantum* this hypothesis cannot be discounted. The risk of re-introduction of malaria into certain European countries is very low and determined by variables other than climate change. Introduction of dengue, West Nile fever, and chikungunya into new regions of Europe is a more immediate consequence of virus importation into competent vector habitats; climate change is one of many factors that influence vector habitat.

The lack of published articles for other vector-borne diseases makes an assessment difficult; for example, tick-borne relapsing fever caused by spirochaetes of the genus *Borrelia* could spread from its current endemic area in Spain since its tick vector is sensitive to climatic changes, but no climate models have been developed for this disease.[76] In the case of yellow fever, the existence of an effective vaccine makes its establishment in Europe very unlikely; conversely, an existing human vaccine for Rift Valley fever is not available (veterinary vaccines are used in Africa). These multifactorial events call for a case by case assessment and targeted interventions.

Rodent-borne diseases

Rodents are reservoirs of a number of human diseases. Rodents can act as both intermediate infected hosts and as hosts for arthropod vectors such as fleas and ticks. Rodent populations are affected by weather conditions. In particular, warm, wet winters and springs increase rodent populations, which have been observed in recent years.[77] Under climate change scenarios, rodent populations could be anticipated to increase in temperate zones, resulting in greater interaction between human beings and rodents and a higher risk of disease transmission, especially in urban areas. In some European countries breakdown in sanitation and inadequate hygiene are contributing to serious rat infestations.

Plague

Since the last major plague outbreak in 1720, plague is no longer circulating in Europe—neither in human beings nor in rodent populations. Plague is a zoonosis caused by the bacterium *Yersinia pestis* that is spread by fleas feeding on black rats (*Rattus rattus*). Milder weather conditions are favourable to rodent populations, while harsh weather conditions such as heat waves might drive rodents indoors in search of water and thus increase contact with human beings.[77] Fluctuations in the abundance of its main reservoir host have been linked to variation in plague incidence.[78] Climatic changes in central Asia favour conditions for the propagation of plague; it has been projected that only a 1°C increase in spring temperatures could result in a 50% increase in *Y pestis* prevalence in its reservoir host.[79] Plague epizootics may become more frequent in central Asia and pose a threat to eastern European countries.[80]

Hantavirus infections

Hantaviruses are rodent-borne viruses with four genotypes circulating in Europe, of which at least Puumala, Dobrava, and Saaremaa viruses are human pathogens.[81] Human beings are at risk of exposure through the inhalation of virus aerosols from the excreta of infected rodents. Excess proliferation of rodent populations related to climatic changes is of considerable international public health concern.[82,83] Hantavirus infection is sensitive to climatic conditions; for example, increased grass seed production following heavy precipitation has been linked to higher deer mouse densities that caused an outbreak in the Four Corners region (New Mexico) of the USA.[84–86] Similarly, bank vole populations in Belgium are linked to tree-seed production that in turn has been linked to high summer and autumn temperatures.[87] These climatic conditions are associated with hantavirus disease incidence, and can be used as early warning indicators of potential outbreaks. In other parts of Europe warm weather has also been associated with hantavirus, and it is anticipated that general warming of the European climate will increase the risk of infection.[88,89]

Summary

Rodent populations respond rapidly to conducive weather conditions, such as heavy precipitation events that can directly or indirectly propagate rodent-borne pathogens like leptospirosis, a zoonotic bacterial disease, with an unknown, but probably high human and veterinary prevalence in eastern Europe and the Mediterranean.[90,91] However, an increase in disease incidence is also related to a number of other variables such as rodent abatement strategies, human activities, and land use; the contribution of each ought to be quantified.

Water-borne diseases

Climatic systems display complex interactions of interconnected components, including the atmosphere, hydrosphere, cryosphere, bioshphere, and geosphere. Global climate change will interfere with these interactions and alter the hydrological cycle not only by altering mean meteorological measures but also by increasing the frequency of extreme events such as excessive precipitation, storm surges, floods, and droughts. These extreme weather-related events can affect water availability, quality, or access, posing a threat to human populations. Water-borne pathogens often act in concert through two major exposure pathways: drinking water and recreational water use. Therefore, we have not discussed water-borne diseases by pathogen but rather by pathway.

Recreational water use

Theoretical, simulation, and empirical data corroborate that increased water vapour, due to higher mean temperatures, triggers more intense precipitation events, even if the precipitation quantity remains constant.[92,93] Such events can result in run-off and loading of coastal waters with pathogens, nutrients, and toxic chemicals that may adversely affect aquatic life and public health. This is particularly true in coastal watersheds where human development and population increases have led to urbanisation of coastal areas. Storm surges greatly increase the risk and the amount of pollutants entering recreational coastal waters.[94] Climate variability can negatively impact public health: exposure to southern California coastal waters during an El Niño winter compared with a La Niña winter doubles the risk of symptoms related to infectious agents.[95] Risk of gastroenteritis and respiratory infections due to recreational water use are much higher during the rainy season rather than the dry season.[96] Precipitation is projected to increase in northern Europe, but no similar studies have been published for Europe so far. Conversely, extended periods of hot weather can increase the mean temperature of water bodies, which can be favourable for microorganism reproduction cycles and algal blooms. For example, *Vibrio* spp bacteria (including *Vibrio vulnificus* and *Vibrio cholerae* non-O1 and non-O139) indigenous to the Baltic and the North Sea, have displayed increased growth rates during unusually hot summers (eg, 2006) and infected open wounds that can necrotise and cause severe sepsis.[97–99]

Drinking water

Water-borne outbreaks have the potential to be rather large and of mixed aetiology, but the actual disease burden in Europe is difficult to approximate and most likely underestimated.[100] In 2006, only 17 water-borne outbreaks were reported by five countries, clearly substantially under-reported. These outbreaks involved 3952 patients, of whom 181 were hospitalised, afflicted by a number of causative agents including campylobacter, calicivirus, giardia, and cryptosporidium.[101]

Erratic and extreme precipitation events can overwhelm water treatment plants[102] and lead to cryptosporidium outbreaks due to oocysts infiltrating drinking-water reservoirs from springs and lakes and persisting in the water distribution system.[103,104] A study from England and Wales[105] found that 20% of water-borne outbreaks in the past century were associated with a sustained period of low rainfall, compared with 10% associated with heavy rainfall. Droughts or extended dry spells can reduce the volume of river flow possibly increasing the concentration of effluent pathogens, which might pose a problem for the clearance capacity of treatment plants.[106,107]

In Europe, flooding has rarely been associated with an increased risk of water-borne disease outbreaks, but a few exceptions exist in the UK,[108] Finland,[109] the Czech Republic,[110] and Sweden.[111] Cholera, caused by *Vibrio cholerae*, is an imported disease in Europe, with only 11 confirmed cases in 2006.[112] However, internationally, cholera outbreaks during the warmer months display a seasonal pattern in higher absolute latitudes, and climate change might influence the strength, duration, or appearance of such a seasonal pattern.[113]

Summary

Aging water treatment and distribution systems are particularly susceptible to weather extremes, posing a substantial vulnerability to the drinking water supply. Environmental pollutants can synergistically interact with climatic conditions and exacerbate exposure of human populations. Infrastructure improvements and environmental protection can attenuate potential negative consequences of climate change from water-borne diseases.

Airborne diseases

Climatic factors such as absolute humidity have been associated with the risk of lower respiratory tract infections.[114] Respiratory syncytial virus (RSV) is one of the most important viral respiratory pathogens, especially for infants. The epidemic activity of RSV infection is related to meteorological conditions and thus to latitude: persistently high temperature and humidity results in epidemic peaks in summer and early autumn, while in temperate climates RSV infection peaks in the winter.[115] A causal link with temperature seems inconsistent based on these climatic data, but the RSV infection season in England and Wales has ended earlier and its duration has shortened as the climate has become warmer.[116] Seasonality has been documented for a number of other respiratory infections including tuberculosis,[117] and seasonal fluctuations of the El Niño-southern oscillation in California are associated with the impact of influenza epidemics (hospital admissions or mortality profiles),[118–120] but a direct link to climate change has not been established. Furthermore, increased use of cooling towers during heat waves might increase the risk for exposure to *Legionella* spp, although appropriate public health measures should be able to contain this risk.[121]

On the basis of the articles reviewed here, it is not possible to draw conclusive inferences about the link between airborne diseases and climate change, but it might shorten the transmission season.

Food-borne diseases

Climatic factors influence the growth and survival of pathogens, as well as transmission pathways.[122] Higher ambient temperatures increase replication cycles of food-borne pathogens, and prolonged seasons may augment the opportunity for food handling mistakes—in 32% of investigated food-borne outbreaks in Europe "temperature misuse" is considered a contributing factor.[123]

Campylobacteriosis

Campylobacter is the most commonly reported gastrointestinal bacterial disease, and is caused by thermophilic *Campylobacter* spp bacteria. In 2007, the European Union incidence was 45·2 cases per 100 000 people (200 507 confirmed cases) and broiler meat and fresh poultry meat were the biggest identified sources of infections.[124] Colonisation of broiler-chicken flocks with campylobacter increases rapidly with rising temperatures. The risk of campylobacteriosis is positively associated with mean weekly temperatures, although the strength of association is not consistent in all studies.[125–128]

Salmonellosis

The second largest number of human food-borne diseases is caused by *Salmonella* spp bacteria. In 2007, the European Union incidence was 31·1 cases per 100 000 population (151 995 confirmed cases) with eggs being the biggest contributors to these outbreaks followed by fresh poultry and pig meat.[124] Higher ambient temperatures have been associated with 5–10% higher salmonellosis notifications for each degree increase in weekly temperature, for ambient temperatures above 5°C.[128–130] Roughly one-third of the transmission of salmonellosis (population attributable fraction) in England and Wales, Poland, the Netherlands, the Czech Republic, Switzerland, and Spain can be attributed to temperature influences.

Summary

Temperature has the most noticeable effect on salmonellosis and food poisoning notifications 1 week before disease onset, indicating inappropriate food handling and storage at the time of consumption. Indeed, an analysis of food-borne illnesses from England and Wales showed that the impact of the temperature of the

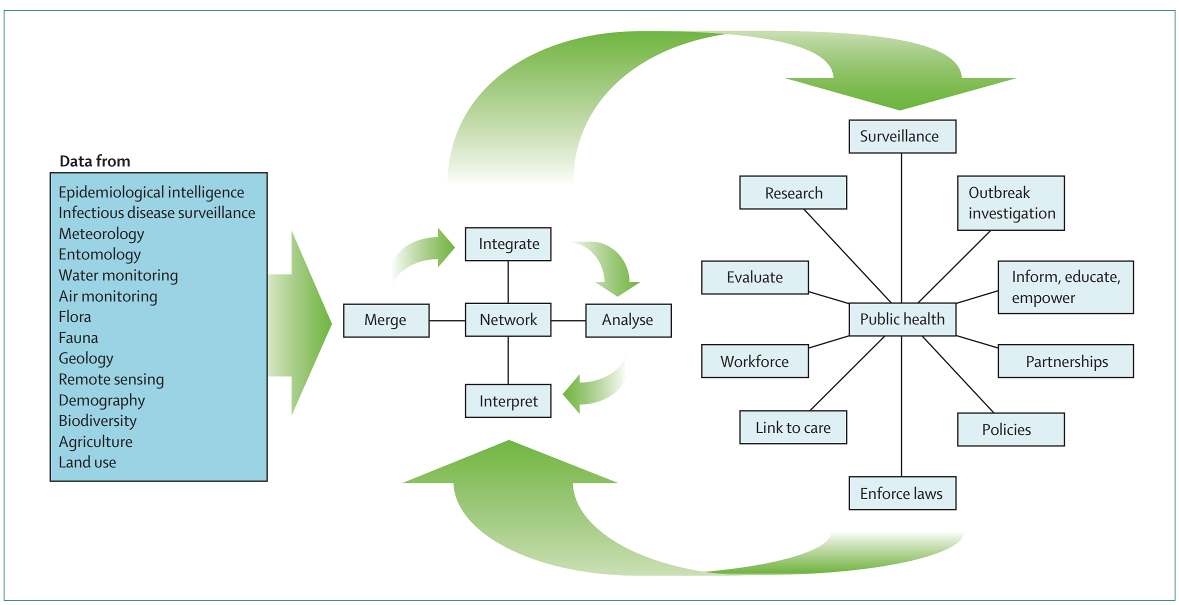

Figure: **Proposed diagram of an environment and epidemiology network**

Search strategy and selection criteria

These are described in detail in the Methods section.

current and preceding week has decreased over the past decades, indicating that the potential risk from elevated temperatures related to climate change can be counteracted through concerted public health action.[130] Thus, regardless of climatic factors, health-behaviour interventions and food-safety regulations should be able to attenuate possible negative consequences on public health. Indeed, bacterial enteric infections have recently started to decrease throughout Europe, in part due to control measures.

A proactive public health response

Despite a considerable body of research on the relation between climate and infectious diseases in Europe, substantial information gaps remain, such as the impact of climate change on the geographical distribution of vectors, vector–host relationships, new or re-emerging pathogens, transmission of food-borne pathogens, or the vulnerability of drinking water supplies. These research gaps are due partly to the multidisciplinary nature of this specialty and due partly to the complexity of many interacting factors that make analysis difficult. The contribution of socioeconomic development, urbanisation, land-use, migration, or globalisation to infectious disease transmission is in some cases more important than climate change, but quantification is intricate. In Europe, a large number of environmental data sets exist that could be linked with epidemiological data for multivariate analysis of climatic events.[131] For example, meteorological, entomological, ecological, or environmental data sets can be merged and integrated to analyse complex interactions and generate essential information to increase our understanding of these systems. Inferences can be drawn from such analyses to quantify risk, compute trends, delineate geographical exposure areas, identify clusters, or describe vulnerable populations. Identifying predictions would build the evidence base for strategic public health action, irrespective of climate change, whereas identifying short-term events linked to environmental conditions would help improve and accelerate early warning and response capabilities (figure).

On the basis of this review of published work and expert consultation, ECDC has recognised the need to develop an infrastructure coined the European Environment and Epidemiology (E³) Network. Under the ECDC work plan for 2009 a blueprint for the E³ Network will be designed to provide timely access to climatic and environmental data and infectious disease surveillance data that are collected by a variety sources. The hub could serve as a repository and would support data exchanges and sustained collaborations between member states, researchers, and other authorised users across geographical and political boundaries (figure). Such a network would promote Europe-wide quality standards for environmental data, leverage existing investments, and increase the use of available data sets. The E³ Network could provide technical support for the reporting, monitoring, analysis, and mapping of data and enhance the analytical capacity of existing resources in Europe. Results could then be disseminated to policy makers, public health practitioners, European Union and international agencies, other governmental sectors, and non-governmental organisations (figure).

This Review illustrates the inherent disciplinary difficulties, in which climatic conditions cannot be experimentally controlled and many complex factors interact. Thus, it is often difficult to draw causal links to actual climatic events. Therefore, ECDC plans to build the E³ Network as a resource for the public health research community; however, the E³ Network can only advance the specialty if it is built and maintained in a collaborative effort with input from a wide range of stakeholders. In the long-run the E³ Network could then support adaptation efforts with state of the art analyses and protect the public from impending climate change threats.

Conflicts of interest

We declare that we have no conflicts of interest.

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