CLIMATE CHANGE AND ZOONOTIC INFECTIOUS DISEASES

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SUMMARY

KEY MESSAGES

- Many human actions can contribute, directly or indirectly, to pandemics such as the one we are currently experiencing.
- Anthropogenic climate change is a fact and a relevant risk factor.
- By strongly influencing the functioning of ecosystems, climate change can promote the spread of pathogens and of new epidemics.
- Fighting climate change, while protecting pristine ecosystems and restoring those deteriorated by man, is a proactive approach aimed at protecting the health and well-being of human communities and at preventing future pandemics.

INTRODUCTION

The human inability to foresee future scenarios and crucial issues in order to prevent global disasters and crises is, sadly, very evident. In the last **Global Risk Report of the World Economic Forum**[1] (which only recently has recognized the importance of climate and environmental risks), the risk of the spreading of infectious diseases was included among the factors with low probability of occurrence.

There are two possibilities: either it was a case of extreme misfortune, or we were not able to better assess and foresee systemic risks, including the risk linked to the onset of a pandemic (which had been predicted by many experts in the fields of virology, ecology and epidemiology in their scientific work, brilliantly summarized by scientific journalist David Quammen in his book "Spillover. The evolution of pandemics"[2]). Given the numerous studies that link the possibility of the development of infectious diseases to the dramatic anthropogenic changes made to our Planet, the second answer appears to be the most likely.

This document is aimed at summarizing knowledge from scientific publications that highlights connections between climate change and emerging diseases, based on the complex ecological relationships that link these dynamics. This will be done to enhance the perception of the risk that we ourselves have created and, above all, to contribute to the debate on how urgent it is to take all the necessary measures to stop climate change, halt the loss of natural ecosystems and protect biodiversity, and by doing so, to contain the spread of diseases.

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[1] https://www.weforum.org/reports/the-global-risks-report-2020

[2] Quammen, 2012. Spillover. The Evolution of Pandemics. Norton & co. ISBN 978-0393066807.

THE CLIMATIC CRISIS: AN UNDISPUTABLE FACT

Negative records on the ongoing climate change process keep accumulating, parallel with extreme events related to it. **2019 was the second hottest year ever recorded**, with an **average global temperature increase of about 1.1°C** compared to the pre-industrial era[3]. The figure is even more alarming because in the record year (2016), the warming was further amplified by El Niño, the periodic climatic phenomenon that starts off with a strong warming of surface waters in the Pacific Ocean, off the coast of Peru and Ecuador, and then moves on to influence global climate. The **last five years have been the five hottest years in history** and the last decade, 2010-2019, has also been the hottest in history (since the first reliable records of the Earth's average surface temperature). Since the 1980s, each decade has been warmer than any previous decade since 1850[4].

Arctic summer ice extension is decreasing at a rate of 12.8% per decade, compared to the average annual extensions measured during the 1981-2010 period. The ice caps, which cover Greenland and Antarctica, have also declined massively, at an annual average of 283 Gt (1 gigaton = 1 billion tons) in Greenland and 145 Gt in Antarctica. The melting of the **Earth's ice** caps is causing sea levels to rise. The new and worrying figure for 2019 is represented by the loss of large amounts of ice in Antarctica, in areas that until now were considered immune to melting.

Among the many significant climatic events registered in 2019, we should remember the worst **heatwave** ever recorded in Australia – with a record temperature of +49.9°C in Nullarbor, South Australia, on 19 December - accompanied and followed by **fires of** enormous proportions in a number of vast areas of the country, causing the direct and indirect destruction of species, habitats and settlements, and the loss of human lives; Europe also recorded numerous heat waves, with record temperatures in France (+46°C) and in many Northern European countries; Japan has been ravaged by two massive heat waves. Many countries have experienced **extraordinary droughts**, from Singapore to Laos. **Cyclones and hurricanes were** also very destructive in 2019. The northern hemisphere was hit by 72 tropical cyclones, compared to an average of 59, with catastrophic damage amounting to billions of dollars. Repeated extratropical systems have hit the Mediterranean region, from Spain to France and to the northern Adriatic sea.

The scientific community overwhelmingly considers **human activities** as responsible for the climate crisis, in particular due to the increase in greenhouse gases. The

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[3] WMO Statement on the state of the Global Climate, https://library.wmo.int/index.php?lvl=notice_display&id=21700%C2%A0#.XnyDpIhKjIU

[4] Global Climate Report 2019 NOAA https://www.ncdc.noaa.gov/sotc/global/201913

concentration of greenhouse gases in the atmosphere has reached record levels[5]: carbon dioxide has increased by 147% (CO_2), methane by 259% (CH_4) and nitrous oxide by 123% (N_2O) compared to pre-industrial levels (2018 data, trend confirmed in 2019). CO_2 in the atmosphere is currently estimated, on average, at 413 parts per million (by volume), a concentration that has never been recorded for at least 650 thousand years, but probably much more.

And these sudden changes may also have extremely significant implications for our health.

FROM CLIMATE TO HUMAN HEALTH: THE ZOONOSES

60% of human emerging infectious diseases (EIDs) derive from animals and the majority of these (71.8%) originate in wildlife[6]. They cause around one billion individual infections and millions of deaths each year[7].

In technical terms, they are referred to as **zoonoses**. In this paper, we will include in the term zoonoses all diseases that are transmitted from animals to humans, including both those most typically transmitted by vertebrate species and those mediated by insects and other arthropods, which are known in Anglo-Saxon scientific literature as *vector-borne diseases* (VBD).

Zoonoses include a heterogeneous group of infections that can be caused by viruses, bacteria, fungi, other organisms, unconventional transmissible agents or prions (such as the agent causing bovine spongiform encephalopathy, also known as "mad cow disease").

The known zoonoses are very numerous - over 200 according to the WHO - and their study represents one of the most interesting fields of human and veterinary medicine. Zoonoses include rabies, leptospirosis, anthrax, SARS (including the new pandemic caused by SARS-CoV-2), MERS, yellow fever, Dengue, HIV, Ebola, Chikungunya and Covid-19, Lyme disease, but also the widespread seasonal flu, only to name a few.

The annual report of the *European Centre for Disease Prevention and Control*[8] highlights zoonoses and food-related outbreaks affecting Europe: brucellosis, campylobacteriosis, congenital toxoplasmosis, echinococcosis, listeriosis, salmonellosis, *Escherichia coli* infections, trichinellosis, yersiniosis, but also Q fever, rabies, tularaemia, West Nile virus

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[5] Nasa, Climate Vital Signs https://climate.nasa.gov/vital-signs/carbon-dioxide/

[6] Jones *et al.*, 2008. Global trends in emerging infectious diseases. *Nature*, 451(7181, 990-993.

[7] Morse *et al.,* 2012. Prediction and prevention of the next pandemic zoonosis. *Lancet*, 380, 1956-1965.

[8] European Food Safety Authority and European Centre for Disease Prevention and Control, 2019. The European Union One Health 2018 Zoonoses Report. *EFSA Journal*, https://doi.org/10.2903/j.efsa.2019.5926

(WNV) infection and tuberculosis (TB, due to *Mycobacterium bovis* and *M. goats*). The most frequent zoonoses in the EU are campylobacteriosis and salmonellosis, followed by *Escherichia coli* infections (STEC) which produce Shiga toxins in humans and represent the third most frequent zoonosis. The number of cases of listeriosis and West Nile virus infections has increased. In total, there were 5,146 documented outbreaks in Europe in 2018.

Of all emerging diseases, **wild zoonoses could pose the greatest threat to the health of the world's population in the future**.

Many of these diseases may change in terms of their dangerousness as a result of global changes.

In this document, we will therefore discuss how the direct or indirect effects of climate change could influence the risk of the spread and transmission of these diseases, highlighting the possible implications for human health.

REGULATORY MECHANISMS

Each species can live permanently in a given territory if, within it, it can find suitable biological, ecological and physical-chemical resources and conditions. For example, *Edelweiss* will not survive at sea level (at intermediate latitudes) because the climatic conditions and soil characteristics would not allow it to, just as humans cannot dive to depths exceeding 300 metres, because our bodies would not be able to withstand the pressure.

Climate warming significantly affects the physical characteristics of the environment in which species live, both in terms of temperature variations, water availability and other factors, thus affecting metabolism, breeding, survival chances and, therefore, distribution in time and space. In a warming climate, in order to find suitable conditions, the species capable of migrating can progressively move towards higher latitudes (northwards in the northern hemisphere, southwards in the southern one), or towards higher altitudes. While some species are able to survive permanently and breed in diverse conditions, others, less adaptable, are forced to look for new areas. For migratory species, the adaptation can also take place by modifying the time spent in breeding or wintering areas. The first ones will usually be reached earlier and left later, as the average temperatures increase. Similarly, breeding periods for plants and animals can vary significantly as temperatures change.

Climate change can also have a significant impact on those species that harbour pathogens (reservoir species) or transfer them (vector species), and therefore on their ability to infect other species, including humans.

In the following chapter, we will present a number of climate-induced mechanisms that can ignite the onset or spread of zoonoses or other diseases affecting human health.

CHANGES IN THE RANGES OF HOST OR VECTOR SPECIES

As mentioned above, climate change can create favourable conditions for a species in areas where it was previously unable to settle permanently. In particular, climate warming can favour both the latitudinal shift of a given species' range and its altitudinal expansion. Below we will present the interesting analysis of a number of specific cases that may effectively illustrate the current trends.

The climate in northern regions is changing faster than the global average, making these areas more vulnerable to the risk of climate-sensitive infectious diseases (*Climate Sensitive Infections*), which threaten both wildlife and humans. In fact, 37 potential climate-sensitive infectious diseases have been identified for northern regions. Diseases transmitted by arthropods, in particular, are considered as having the potential to expand their ranges towards northern latitudes[9].

Changes in the geographical and altitudinal range of some vector species, caused by global warming, have been documented in Europe for ticks belonging to the *Ixodes ricinus* species, a vector for **Lyme** disease and **tick-borne encephalitis** (TBE); these changes have been associated with new outbreaks and increased incidence of TBE. Similarly, northward shifts have also been observed in North America for the *Ixodes scapularis* tick, a vector species **of Lyme disease** and **babesiosis**[10]. The latter is a disease of increasing importance to public health. Recent studies suggest that climate change will have a strong impact on the spread of the vector species in the future as well, increasing the diffusion of human babesiosis[11].

Similar trends have also been observed in the Arctic regions of Europe and Russia, where climate change is more pronounced and where the period of seasonal activity of ticks has lengthened[12]. However, the factors contributing to the spread of vector species and affecting contagion dynamics are multiple and tend to interact with each other[13].

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[9] Omazic *et al.*, 2019. Identifying climate-sensitive infectious diseases in animals and humans in Northern regions. *Acta Vet Scand*, 61*,* 53 https://doi.org/10.1186/s13028-019-0490-0
[10] Mills *et al.*, 2010. Potential Influence of Climate Change on Vector-Borne and Zoonotic Diseases: A Review and Proposed Research Plan. *Environ Health Perspect*, 118, 1507-1514, https://doi.org/10.1289/ehp.0901389
[11] Young *et al.*, 2019. Zoonotic Babesia: A scoping review of the global evidence. *PLoS ONE*, 14(12)*,* e0226781. https://doi.org/10.1371/journal.pone.0226781
[12] Revich *et al.*, 2012. Climate change and zoonotic infections in the Russian Arctic. *International Journal of Circumpolar Health*, 71*,* 1, DOI: 10.3402/ijch.v71i0.18792
[13] Rizzoli *et al.*, 2019. Parasites and wildlife in a changing world: The vector-host- pathogen interaction as a learning case. *Parasites and wildlife*, 9, 394-401. https://doi.org/10.1016/j.ijppaw.2019.05.011

Hantaviruses are a family of RNA viruses that can be transmitted to humans by zoonotic means, causing potentially fatal diseases such as **haemorrhagic fever with renal syndrome** (HFRS) and **hantavirus pulmonary syndrome** (HPS). In the United States, the hispid cotton rat (*Sigmodon hispidus*), acts as the reservoir species of the Black Creek Canal hantavirus, known to cause HPS, and other hantaviruses. The distribution of the rodent is limited by climatic factors, in particular the minimum temperature. Precisely for this reason, in recent decades the species has expanded both northwards and to higher altitudes, thus increasing the chances of transmission to humans.

Swimmer's itch (or cercarial dermatitis) is an inflammatory skin reaction caused by larvae of a family of flatworms known as schistosomes, whose adults live as parasites in waterfowl, such as ducks. The larvae, in turn, parasitize, as intermediate hosts, freshwater snails. In the next stage, however, instead of infecting birds again and restarting their life cycle, they can penetrate and develop also under human skin or under the skin of other mammals encountered in water, causing severe allergic reactions. This zoonosis has been reported as one of the emerging global diseases in many lake regions, including North America and Europe (France and Sweden), where numerous cases have been reported. Global warming has made the climate in these regions particularly mild, which in turn has made the migration of several populations of waterfowl unnecessary. The birds have thus become resident throughout the year, leading to an increase in the number of generations of parasites during each year, the density of larvae and, consequently, human infections[14].

Filariasis is a form of cardiopulmonary and subcutaneous parasitosis caused by nematode worms, such as *Dirofilaria immitis* and *Dirofilaria repens,* which affect dogs and cats in particular, all over the world. The parasitosis is transmitted by mosquitoes of the genera *Culex, Culiseta, Aedes, Anopheles* and *Coquilletidia*. Filarial worms can also pose a risk to humans, causing emerging diseases in some areas of the world. Unfortunately, the general trend of global warming is extending the duration of the active season and transmission season, as well as favouring the northward expansion of *D. immitis* infections from the endemic area in the Po Valley to the Alpine regions.

The **West Nile virus** is a flavivirus that was isolated for the first time in Uganda in 1937 and has now reached a widespread distribution worldwide. Also transmitted by mosquitoes, in particular of the genus *Culex,* it finds in many species of wild birds its natural reservoir, but is also capable of infecting amphibians, reptiles and mammals, including horses, for which it is particularly pathogenic, and man, causing neurological damage, paralysis, coma or lethal outcomes in less than 1% of the cases. For this reason, it poses a significant threat for health, with hundreds of cases registered in Europe only, in particular in southern areas, where it has spread through infected birds migrating from Africa. Warmer weather conditions make the life cycle of mosquitoes faster, decreasing their longevity but significantly increasing their springtime abundance in

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[14] Mas-Coma *et al*., 2008. Effects of climate change on animal and zoonotic helminthiases. *Rev. Sci. Tech. Off. Int. Epiz*., 27, 443-452.

southern Europe and their overall abundance in northern Europe. Warmer weather has also extended their active season and, therefore, the likelihood of transmission to humans. At the same time, the source populations of birds, more adapted to mild climates, have now extended their summer ranges northwards, thus favouring the expansion of the virus into areas that were not previously affected[15,16].

The range of tiger mosquitoes (*Aedes albopictus, syn. Stegomyia albopicta*) appears to be expanding in America, Europe and China due to climate change, and with it the diseases of which they are vectors, such as **Dengue** and **Chikungunya**[17]. Also, the *Aedes aegypti* mosquitoes, which can spread Dengue, Chikungunya, Zika, yellow fever and other pathogens, favoured by industrial agriculture, are expanding their range to degraded natural habitats, thus promoting further zoonoses. Global changes, combined with these factors, favour its expansion[18].

In North America, the **bubonic plague** (whose responsible bacterium, *Yersinia pestis*, relies on several rodent species as its reservoir) and **tularemia** (also a serious zoonosis caused by the bacterium *Francisella tularensis*, which is in turn hosted by rodents and transmitted by ticks or by ingestion of infected water or meat), are serious zoonotic diseases. Scholars who have assessed spatial transmission patterns since the 1960s have observed northward shifts of areas compatible with ongoing climate change dynamics. Fortunately, such expansions are still limited, and partly offset by a reduction in their southernmost range[19], but recent studies predict the possibility of climate change related expansion at higher latitudes[20].

CHANGES IN RAINFALL AND TEMPERATURE REGIMES

Climate change, in addition to altering the average temperatures of the atmosphere, earth's surface and seas, significantly influences rainfall and thus water availability in a given place at a given time, which in turn affects the dynamics of vegetation and the carrying capacity of ecosystems. With equal rainfall in a given year and in a specific area, for the species living in that territory, things can change dramatically when rain is concentrated in a single season or is evenly distributed during each month of the year. These variations can have significant effects also from the point of view of pathogens,

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[15] Rizzoli *et al.*, 2019. Parasites and wildlife in a changing world: The vector-host- pathogen interaction as a learning case. *Parasites and wildlife*, 9, 394-401, https://doi.org/10.1016/j.ijppaw.2019.05.011
[16] Greer *et al.*, 2008. Climate change and infectious diseases in North America: the road ahead. *Can Med Assoc J*, 178, 715-722, DOI: https://doi.org/10.1503/cmaj.081325
[17] Franch & Holmes, 2020. An Ecosystems Perspective on Virus Evolution and Emergence. *Trends in Microbiol*, 28, 3, https://doi.org/10.1016/j.tim.2019.10.010
[18] Wolfe *et al.*, 2007. Origins of major human infectious diseases. *Nature*, 447, 279-283, doi: 10.1038/nature05775
[19] Nakazawa *et al.*, 2007. Climate Change Effects on Plague and Tularemia in the United States. *Vector-Borne and Zoonotic Dis*, 7, 529-540, http://doi.org/10.1089/vbz.2007.0125
[20] Ma *et al.*, 2019. Potential for Hydroclimatically Driven Shifts in Infectious Disease Outbreaks: The Case of Tularemia in High-Latitude Regions. *Int J Environ Res Public Health*, 16, 3717, doi:10.3390/ijerph16193717

altering the probability of survival in the environment and the abundance of host or vector species, and therefore the possibility of spreading pathogens. Again, we wanted to highlight the many cases that best illustrate the connection between changes in rainfall and temperature regimes and the spread of zoonotic diseases.

The populations of mosquitoes of the genus *Aedes*, vectors of diseases such as **Rift Valley Fever** (RVF) in East Africa, increase dramatically in periods of high rainfall associated with the El Niño Southern Oscillation (ENSO). Similar increases have been observed in South America and southern Africa. An increase in **malaria** cases was also associated with higher rainfall and temperatures in Kenya[21], but some outbreaks were also registered in 2018 in Uganda, South Africa and Rwanda. Although RVF has never been reported in Europe, the emergence of a number of African viruses transmitted by mosquitoes outside the continent suggests that as a result of climate change this disease could spread to Europe and to higher latitudes[22].

Similarly, the increased rainfall caused by El Niño in North America in 1997 improved the quality of vegetation and, consequently, allowed for an increase in the deer mouse populations (*Peromyscus maniculatus*), a rodent of the hamster family, in the southwestern part of the United States. This increase preceded that of cases of **hantavirus pulmonary syndrome** (HPS) registered in the subsequent three years, following patterns already observed in Paraguay and Panama[11]. An association between rainfall and enteric disease has also been documented for ***Escherichia coli*** infections, which were particularly significant, for example, following the exceptional rainfall observed in Ontario in 2000[23].

Many fungi representing a threat for public health produce spores whose persistence in the environment is regulated by local climate and soil characteristics. The dry summers and high winter rainfall expected in North America create the ideal conditions for the dispersion of the spores of *Blastomyces dermatitidis,* the fungus responsible for **blastomycosis,** a severe disease affecting the skin, blood vessels, lungs and bones[22]. Milder temperatures and longer summers also contribute to multiply the replication cycles of **parasites**, such as *Trichinella* and *Echinococcus*, found in species utilized in human nutrition, typical of northern latitudes, and with them their infectious potential.

The current climate change scenario is also contributing to the emergence of new and known viral diseases such as **Chikungunya**, caused by the Chikungunya virus (CHIKV) spread by mosquitoes of the genus *Aedes,* which has rapidly spread globally since 2004, re-emerging in India after over 30 years, and causing serious epidemics in some states,

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[21] Mills *et al.*, 2010. Potential Influence of Climate Change on Vector-Borne and Zoonotic Diseases: A Review and Proposed Research Plan. *Environ Health Perspect*, 118, 1507-1514, https://doi.org/10.1289/ehp.0901389

[22] Simons *et al.*, 2019. Using species distribution models to predict potential hot-spots for Rift Valley Fever establishment in the United Kingdom. *PLoS ONE*, 14(12), e0225250. https://doi.org/10.1371/journal.pone.0225250

[23] Greer *et al.*, 2008. Climate change and infectious diseases in North America: the road ahead. *Can Med Assoc J*, 178, 715-722, DOI: https://doi.org/10.1503/cmaj.081325

favoured by favourable thermal conditions and changes in the rainfall regime[24]. Also in Italy, in recent years, starting from 2007, several cases of this disease have been recorded, in addition to cases of Dengue and Zika.

Temperature levels and rainfall are the most important abiotic factors affecting the prevalence of **Dengue** in Brazil, as well as widening the breeding areas of the vector mosquito[25].

In some regions, rising temperatures cause an increase in the sporulation of oocysts and the geographical distribution of hosts for ***Toxoplasma gondii***, producing higher infection rates. Increased rainfall also increases infection rates due to increased survival of oocysts[26]. **Zika**, a mosquito-borne zoonosis that exploded in South America in 2015, has also been declared an international health emergency by the World Health Organization. Some researchers pointed out that the risk of transmission in 2015 has been the highest since 1950, due to favourable temperatures that limited mosquito mortality rates while at the same time reducing their incubation period[27].

Tsetse flies, vectors of **trypanosomiasis**, represent a serious health and economic threat in sub-Saharan Africa. In Tanzania, a research group showed a close correlation between trypanosome prevalence and ambient temperature, which favoured the relative abundance of *tsetse* flies[28]. Moreover, human migrations caused by water scarcity may further promote infections, due to the gathering of people near water supply sites, where flies concentrate[29].

Both **haemorrhagic fever with renal syndrome** (HFRS) and **leptospirosis** are rodent transmitted infections, influenced by climate variability. In South Korea, an increase of 1°C in minimum temperatures was seen to correspond to a 17.8% increase in HFRS cases and a 22.7% increase in leptospirosis cases, also favoured by increased solar radiation[30].

One final example of how climate change (which is also affecting the oceans), poses a risk to human health is **cholera**, a global disease responsible for some 3-5 million cases

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[24] Shil *et al*., 2018. Rainfall and Chikungunya incidences in India during 2010-2014. *Virus Dis,* 29, 46-53, https://doi.org/10.1007/s13337-018-0428-6.
[25] Viana & Ignotti, 2013. A ocorrência da dengue e variações meteorológicas no Brasil: revisão sistemática. *Rev Bras Epidemiol*, 16 (2), https://doi.org/10.1590/S1415-790X2013000200002.
[26] Yan *et al*., 2016. Impact of environmental factors on the emergence, transmission and distribution of *Toxoplasma gondii*. *Parasites Vectors*, 9, 137, https://doi.org/10.1186/s13071-016-1432-6
[27] Caminade *et al.*, 2017. Global risk model for vector-borne transmission of Zika virus reveals the role of El Niño 2015. *PNAS*, 114, 119-124, http://www.pnas.org/cgi/doi/10.1073/pnas.1614303114.
[28] Nnko *et al*., 2017. Seasonal variation of tsetse fly species abundance and prevalence of trypanosomes in the Maasai Steppe, Tanzania. *J Vector Ecol*, 42, 24-33, https://doi.org/10.1111/jvec.12236.
[29] Mills *et al*., 2010. Potential Influence of Climate Change on Vector-Borne and Zoonotic Diseases: A Review and Proposed Research Plan. *Environ Health Perspect*, 118, 1507-1514, https://doi.org/10.1289/ehp.0901389
[30] Joshi *et al*., 2017. The influence of climatic factors on the development of hemorrhagic fever with renal syndrome and leptospirosis during the peak season in Korea: an ecologic study. *BMC Infect Dis*, 17, 406, https://doi.org/10.1186/s12879-017-2506-6

and 100.000-120.000 deaths every year and tragically increasing worldwide[31,32,33]. Its causative agent, the bacterium *Vibrio cholerae*, is naturally present in the marine environment, particularly in coastal and estuarine ecosystems. This pathogenic bacterium attaches itself to the exoskeleton of small crustaceans, the copepods. Survival and growth of these bacteria are based on the size of the plankton populations on which they reside and, accordingly, are influenced by environmental variables such as the surface temperature of the sea and the presence of freshwater supplies. Climate change and flooding promote the spread and development of epidemics[34].

Of particular importance are an unprecedented number of human infections that have occurred in northern European countries, associated with swimming and bathing in coastal waters[35,3637,38]. Most of these cases have been reported during heat waves (e.g. 1994, 1997, 2003, 2006, 2010), and are expected to increase in frequency and intensity as global warming increases. A recent study has in fact demonstrated that the increase in sea surface temperature is responsible for the long-term increase in the concentration of *Vibrio in* the ocean over the last 54 years, in turn associated with a recent increase in related diseases, which occurred at an unprecedented rate in Northern Europe and along the Atlantic coast of the United States[39].

The heating of water surface can also promote the coalescence of the so-called **marine mucilage**, large marine aggregates that represent an ephemeral and extreme habitat found in aquatic systems with altered environmental conditions. Mucilage is able to trap large quantities of a wide range of organisms, from phytoplankton to zooplankton, and is also an important deposit for prokaryotes, bacteria and viruses. These can show a concentration factor up to 100 times higher than the sea water surrounding the mucilage[40], thus increasing the likelihood of contact with **pathogenic bacteria** (of which the presence of *E. coli* is a common indicator). The abundance of such bacteria is consistent with the appearance of dermatitis and other syndromes associated with human contact with mucilage[41]. The results of a recent study suggest that if the

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31 WHO, 2015. Cholera: Fact Sheet No. 107. www.who.int/mediacentre/ factsheets/fs107/en/
32 Pascual *et al.*, 2000. Cholera dynamics and El Niño-Southern oscillation. *Science*, 289(5485), 1766-1769.
33 Martinez-Urtaza *et al.*, 2010. Climate anomalies and the increasing risk of *Vibrio parahaemolyticus* and *Vibrio vulnificus illnesses*. *Food Res Int*, 43(7), 1780-1790.
34 Harvell *et al.*, 1999. Emerging Marine Diseases-Climate Links and Anthropogenic Factors. *Science*, 285, 1505-1510.
35 Semenza *et al.*, 2012. Climate change impact assessment of food- and waterborne diseases. *Crit Rev Environ Sci Technol*, 42(8), 857-890.
36 Frank *et al.*, 2006. *Vibrio vulnificus* wound infections after contact with the Baltic Sea, Germany. *Euro Surveill*, 11(8), E060817.1.
37 Andersson *et al.*, 2006. Wound infections due to *Vibrio cholerae* in Sweden after swimming in the Baltic Sea, summer 2006. *Euro Surveill*, 11(8), E060803.2.
38 Schets *et al.*, 2006. *Vibrio alginolyticus* infections in the Netherlands after swimming in the North Sea. *Euro Surveill*, 11(11), E061109.3
39 Vezzulli *et al.*, 2016. Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. *PNAS*, 113(34), E5062-E5071.
40 Danovaro *et al*., 2009. Climate change and the potential spreading of marine mucilage and microbial pathogens in the Mediterranean Sea. *PLoS One*, 4, https://doi.org/10.1371/journal.pone.0007006
41 Kokelj *et al.*, 1994. Skin damage caused by mucilaginous aggregates in the Adriatic sea. *Contact Dermatitis*, 31, 257-259.

mucilage phenomenon continues to increase in frequency and duration in coastal areas of the Mediterranean Sea, it may be associated with increased outbreaks of disease caused by the potential release of large numbers of pathogenic bacteria from mucilage[42].

RELEASE OF PATHOGENS IN PREVIOUSLY FROZEN AREAS

Global warming can lead to the thawing of areas that have been frozen for a long time or to the retreat of ice in areas that were previously covered by it. This is the case with **permafrost**, the permanently frozen soil and rock layer of the Arctic regions, or the retreat of Alpine or Antarctic glaciers. These phenomena have also generated fears in public opinion about the possible release of pathogens that have remained trapped in ice for millennia, and to which the immune system of our species may no longer be able to respond adequately. But is that really the case? In fact, very few case studies have investigated thispossible relationship.

Among these, some have investigated **anthrax**, an acute infection commonly manifesting itself in wild and domestic herbivorous animals, but which can also affect humans. The infection is caused by the bacterium *Bacillus anthracis*, whose spores can survive in permafrost for decades. Epidemics of the past have left their traces in over 13,000 burial sites of infected animals, such as cattle and reindeer. The warming of the Russian Arctic due to climate change, particularly in regions such as Yacutia, could accelerate the melting of permafrost, including the burial sites, causing spores to be released in the soil and on surrounding vegetation. The spores could then be consumed by herbivores, ropening the cycle of contagion, which could extend to humans again[43].

Four new species of **giant viruses** have been discovered in recent years from permafrost samples dating back to the late Pleistocene (30,000 years ago), some of which are still able to replicate if inoculated inside host cells (such as the protozoon *Acanthamoeba castellanii*). Although no cases of infection are yet known for the human species, these studies confirm that other ancient species may re-emerge in the future from permafrost or melting polar ice[44].

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[42] Danovaro *et al.*, 2009. Climate change and the potential spreading of marine mucilage and microbial pathogens in the Mediterranean Sea. *PLoS One*, 4(9).
[43] Revich *et al.*, 2012. Climate change and zoonotic infections in the Russian Arctic. *Int J Circumpolar Health*, 71, 1, DOI: 10.3402/ijch.v71i0.18792
[44] Legendre *et al.* , 2015. In-depth study of *Mollivirus sibericum* giant virus. *PNAS*, 112(38), E5327-E5335; DOI: 10.1073/pnas.1510795112

OTHER SPREADING MECHANISMS OF ZOONOSES

Although the two types of relationship between climate change and zoonoses that we have seen so far are those mostly highlighted in the scientific literature, several other regulatory mechanisms can be hypothesized. Each species in nature is connected to many others, with which it establishes ecological relationships of many types (predation, commensalism, parasitism, competition, facilitation, etc.). Stressful conditions caused by climate change or even the loss of one or more species can have significant effects on the balance of many others, including pathogens, sometimes favouring their increase. In some cases, however, climate change may also have locally positive effects on the occurrence of old and new zoonoses.

The species of the genus *Brucella* are bacteria responsible for **brucellosis** that can develop in different substrates and environmental conditions over long periods of time. In Iran, there a significant negative correlation has been observed between the average air temperature and the incidence of brucellosis, which has been found to be lower at higher temperatures[45].

More in general, isolated outbreaks of zoonoses requiring the simultaneous presence of host and vector species could disappear if, due to climate change, some of them were forced to move and others were prevented from doing so. In such cases, the zoonosis could not develop because it would require the simultaneous presence of all three components (pathogen, host and vector) at the same site for sufficient time to complete the transmission cycle.

Undoubtedly, the effects of climate change will vary from region to region. The transmission of malaria may decline in areas characterised by lower rainfall, which will nonetheless compensated by areas where rainfall is increasing, particularly in regions at higher altitudes, also due to the lengthening of the critical seasons. Overall, therefore, it is believed that, as a result of climate change, human exposure to the agent responsible for malaria[46] will increase, particularly in southern and Mediterranean Europe, in part due to the creation of conditions favourable to the spreading of vectors[47]. Therefore, although climate change may have locally positive effects in some areas, in general the expected costs will far outweigh the benefits[48].

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[45] Dadar *et al.*, 2020. A primary investigation of the relation between the incidence of brucellosis and climatic factors in Iran. *Microb Pathog*, 139, 103858, https://doi.org/10.1016/j.micpath.2019.103858
[46] Haines *et al.*, 2008. Climate change and human health: impacts, vulnerability, and mitigation. *Lancet*, 367, 2101-2109.
[47] Hertig, 2019. Distribution of *Anopheles* vectors and potential malaria transmission stability in Europe and the Mediterranean area under future climate change. *Parasit Vectors*, 12, 18., https://doi.org/10.1186/s13071-018-3278-6
[48] https://www.who.int/news-room/detail/05-12-2018-health-benefits-far-outweigh-the-costs-of-meeting-climate-change-goals

OTHER EFFECTS OF CLIMATE ON HUMAN HEALTH

Climate change affects the social and environmental fundamentals of health: clean air, safe drinking water, sufficient food and safe shelter. **Between 2030 and 2050, climate change is expected to cause some 250,000 additional deaths per year due to** malnutrition, malaria, diarrhoea and heat stress; injuries and loss of life due to storms and floods; the onset of vector and waterborne diseases; the exacerbation of cardiovascular and respiratory diseases due to air pollution; stress and mental trauma due to forced displacement and loss of livelihoods and property. The **direct costs of health damage** (i.e. excluding costs in key health sectors such as agriculture, water and sanitation), are estimated at between **$2-4 billion per year by 2030**[49].

Most of the scientific community agrees that there is a correlation between climate change and **extreme climate events**[50], 68% of which are now more likely to happen or more intense due to global warming. Heat waves account for 43% of these events, droughts for 17% and heavy rainfall or flooding for 16%[51].

Among the many destructive effects, there is also the possible deterioration of water quality, and in some regions also the progressive reduction of water resources. Increasingly variable rainfall can affect the supply of drinking water. **Lack of safe water can compromise hygiene and increase the risk of diarrhoeal diseases, which kill more than 500,000 children under the age of five every year**. In extreme cases, water scarcity leads to drought and famine.

Northern Europe is getting much wetter and winter floods could become a recurring event. Urban areas, where 4 out of 5 Europeans live today, are exposed to heat waves, floods and rising sea levels, but are often not prepared to adapt to climate change. Extreme weather events can not only cause the huge spread of diseases through increased growth of vectors, pathogens, viruses and transmission routes, as we have seen, but also the collapse of public health infrastructures, loss of hygiene and sanitation, lack of drinking water and increased concentration of residents.

Lastly, heat and drought - closely linked to climate change - play a very important role in the fires that affect many parts of the world. Fire smoke can cover very large areas, exposing people to dangerous gases and particulate matter.

Within such a widespread impact, it is not surprising that healthcare professionals have taken a leadership role in demanding that the climate crisis be tackled urgently and effectively. UK medical and health practitioners' associations, for example, were among

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49 https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
50 https://sites.nationalacademies.org/BasedOnScience/climate-change-global-warming-is-contributing-to-extreme-weather-events/index.htm
51 https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world

the first to announce actions aimed at divesting their pension funds from the fossil fuels industry by joining the ***UK Health Alliance on Climate Change***. The Executive Director and Editorial Director of the prestigious *British Medical Journal*[52] have been leading the initiative. Richard Horton, editor of another of the world's most prestigious medical journals, *The Lancet*, has publicly encouraged[53] all health professionals to participate in civil disobedience aimed at fighting back climate change. Healthcare professionals know very clearly, among other things, that decarbonisation will not only bring direct benefits in preventing exponential increases in diseases, death and suffering caused by the impacts of climate change, but will also lead to many collateral benefits for many diseases of environmental origin or cause (e.g. the ones caused by pollution).

FOCUS: ITALY

Italy has just gone through the hottest decade in its history[54]. This has not only caused the increasing melting of our glaciers and threats to the survival of plant and animal species, in fact the current climate crisis undoubtedly poses a risk to public health.

Italy is in one of the countries with the highest life-expectancy rates in Europe. With a life expectancy at birth of 83.1 years in 2017, Italy is fourth highest globally and the second highest in the EU after Spain - approximately 2 years more than the average[55]. The "**Italian country profile"** regarding climate change and its impact on health highlights how Italy, due to its geographical position, its longitudinal extension and its orographic and hydrographic characteristics, the great heterogeneity of weather and climate, the widespread state of post-industrial pollution phenomena, combined with intrinsic hydro-geological and seismic vulnerability, is **particularly at risk**[56]. In particular, in our country due to climate change many climate hazards and extreme weather events, such as heat waves, heavy waves and coastal flooding could become more frequent and more intense, with an expansion of new species of disease vectors, a worsening of air quality and increased fire risk due to drought. Under a high emissions scenario, the number of days of warm spell [4] to increase from about 10 days in 1990 to about 250 days on average in 2100. If global emissions decrease rapidly, the days of warm spell are limited to about 75 on average.

In the international context of advanced countries, Italy already today presents the highest risk of additional mortality linked to **heat waves** and the overall increase in

[52] https://www.bmj.com/content/368/bmj.m167
[53] https://twitter.com/TheLancet/status/1204369232244412417?s=20
[54] https://www.cnr.it/it/nota-stampa/n-9151/con-il-2019-si-chiude-il-decennio-piu-caldo-di-sempre
[55] https://ec.europa.eu/health/sites/health/files/state/docs/2019_chp_it_italy.pdf
[56] WHO UNFCCC Climate and health country profile for Italy, https://apps.who.int/iris/bitstream/handle/10665/260380/WHO-FWC-PHE-EPE-15.52-eng.pdf;jsessionid=E7C4F7A194845595D437A6D920B4FB69?sequence=1

temperatures[57]. According to recent estimates in Italy, by 2100, the number of heat wave days is projected to increase drastically, from 10 days in 1990 to about 250 days on average per year, according to the high emission scenario[58]. From 1999 to 2018, Italy recorded 19,947 deaths due to **extreme weather events.** Italy was 26th overall in the ranking of countries affected most by the climate crisis. For year 2018 alone, Italy ranked at the 21st place[59]. The risk of mortality due to these causes affects, and will continue affecting especially the elderly and sick, but recent studies have shown an association between excess heat during pregnancy and pre-term mortality rates, thus shifting the focus towards these threatened groups[60].

Water-related and climate-dependent diseases, both transmissible and not, are one of the main killers in our Planet. In 2017 in the four main Italian river basins (Po, Adige, Tevere and Arno) the average annual flows decreased compared to the long term annual average (LTAA) 1981-2010, with an overall mean reduction of 40%. In 2017, six of Italy's 20 regions asked for the declaration of a state of emergency to address deep droughts and water shortages also in the drinking water sector, as a result of which supply interruptions and rationing occurred. Areas and communities historically never affected by water scarcity, have been affected by limitations of access to water and sanitation, and several other problems related to water quality, with potential health risks.

Climate change risks could also increase **food security** problems, problems that today mainly affect developing countries[61]. Enteric pathogens transmitted by water and food (such as *Salmonella*, *Campylobacter*, *E. coli, Shigella*, etc.) have a seasonal trend that could be altered, and even prolonged, byclimate changes[62]. The risk of food contamination by mycotoxins, that until a few years ago have not been signalled as a matter of concern for primary production in Italy, seems likely to increase: forecasting models of possible aflatoxin contamination of corn and wheat crops across Europe indicate Italy as one of the countries that are potentially most at risk[63]. Already in 2003 and 2012, years characterized by seasons with higher temperatures and lower than

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[57] Michelozzi *et al*., 2016. On the increase in mortality in Italy in 2015: analysis of seasonal mortality in the 32 municipalities included in the Surveillance system of daily mortality. *Epidemiol Prev*, 40(1), 22-28.
[58] WHO UNFCCC Climate and health country profile for Italy, https://apps.who.int/iris/bitstream/handle/10665/260380/WHO-FWC-PHE-EPE-15.52-eng.pdf;jsessionid=E7C4F7A194845595D437A6D920B4FB69?sequence=1
[59] Global Climate Risk Index (CRI) 2020: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2018 and 1999 to 2018; www.germanwatch.org/en/cri
[60] Toffol & Reali, 2017. Cambiamento climatico: effetto delle ondate di calore sulla natimortalità. *Quaderni ACP*, 24(6).
[61] Miraglia *et al*., 2009. Climate change and food safety: An emerging issue with special focus on Europe. *Food Chem Toxicol*, 47, 1009-1102.
[62] https://apps.who.int/iris/bitstream/handle/10665/260380/WHO-FWC-PHE-EPE-15.52-eng.pdf;jsessionid=E7C4F7A194845595D437A6D920B4FB69?sequence=1
[63] Battilani *et al*., 2016. Aflatoxin B1 contamination in maize in Europe increases due to climate change. *Sci Rep*, 6, 24328.

average rainfall in Italy, alarming contamination of these two crops by aflatoxins caused by *A. flavus*[64] have been registered.

Also as a consequence of climate change, our country there is registering the reappearance or resurgence of previously endemic **infectious agents** (including the poliovirus, present in neighbouring countries and the tuberculosis bacillus) and the arrival of new exotic transmissible diseases, such as Dengue, Chikungunya[65], Zika, Congo-Crimea Fever (CCHF, *Crimean-Congo Haemorrhagic Fever*), West Nile disease[66]. In recent years, outbreaks of Chikungunya have diagnosed in several Italian regions and the presence of the vectors of these viruses is now permanently reported in many Mediterranean regions[67]. A significant fact is that the ability to acquire viruses and transmit them to a susceptible host, for example the viruses responsible for Dengue fever carried and spread by the *Aedes albopictus* mosquito have increased by 50% in about 40 years. This means that the climatic suitability for viruses is increasing in Italy, i.e., if a mosquito infected with the virus reaches our country it will find the right environment to transmit the disease[68]. In some regions of northern Italy there have been cases of *tick-borne encephalitis* (TBE, *Tick-Borne Encephalitis*) never seen before in Italy. Numerous cases of meningitis or viral encephalitis have occurred in several regions of Italy. In central Italy, the little-known Tuscan virus (TOSV), which takes its name from the region where it was isolated in the early 1970s, and is transmitted by 2 species of sand-flies (*Phlebotomus perniciosus* and *P. perfiliewi*), and which has been associated with cases of meningitis and meningoencephalitis in humans, has[69]spread in central Italy.

The adverse effects of ongoing climate change also affect **air quality** (e.g. by encouraging stagnation in the atmosphere which prevents pollutants from dispersing upwards or leads to the formation of secondary pollutants such as ozone and fine particles), aggravating pollution levels that are already too high, particularly in urban contexts, and could also lead to changes in the distribution of local flora and fauna, with possible degradation of biodiversity. Italy still has the sad record in Europe of premature deaths (45,600 in 2016) from exposure to fine particulate matter (PM2.5) with an economic loss of over 20 million euros, putting Italy at the 11th at the global level[70].

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[64] http://old.iss.it/binary/efsa/cont/Aflatossine_Brera.pdf
[65] Rezza *et al*., 2007, Infection with Chikungunya Virus in Italy: an outbreak in a temperate region. *Lancet*, 370, 1840-1846.
[66]Toffol & Reali, 2018. Cambiamento climatico e salute in Italia: evidenze dal progetto Climate and Health Country Profile dell'Organizzazione Mondiale della Sanità. *Quaderni ACP*, 25(2).
[67] Reali, 2018. Cambiamenti climatici e malattie trasmesse da vettori. *Quaderni ACP*, 2, 51.
[68] Manica *et al*., 2016. Spatial and Temporal Hot Spots of *Aedes albopictus* Abundance inside and outside a South European Metropolitan Area. *PLoS Negl Trop Dis*, 10(6), e0004758. doi:10.1371/journal.pntd.0004758
[69] http://old.iss.it/emol/?lang=1d=125ipo=16
[70] Watt *et al*., 2018. The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come. *Lancet*, 392(10163), 2479-2514.

Lastly, in front an increase of 1°C, **mental health risk**, such as depression, anxiety, insomnia, fears, generalized psychic illnesses, could rise by 2%. The increased probability of catastrophic events due to climate (floods, fires, progressive loss of arable land, among others) could generate or exacerbate situations of psychological distress and the reactions of already fragile[71]individuals. In addition, the progressive reduction of animal and plant biodiversity, together with the variation of the usual seasonal atmospheric parameters, creates the perception of a state of imbalance that can induce or at least exacerbate even mild pathological conditions.

It is therefore clear that in our country, in order to preserve human health, specific actions of environmental protection, prevention, national policies and strategies for mitigation and adaptation to climate change are absolutely necessary.

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[71] Obradovich *et al*., 2018. Empirical evidence of mental health risks posed by climate change. *PNAS*, 115(43), 10953-10958, DOI: 10.1073/pnas.1801528115

CONCLUSIONS

Changes in climate, habitats and biodiversity are affecting the abiotic and biotic components of ecosystems, while at the same time social and economic changes (such as urbanization, the development of mega-cities and the movements of people and goods in a globalized world), offer multiple pathways for transferring and spreading species and diseases. Additional external factors increasingly facilitate "biological invasions", which pose a serious threat to biodiversity and ecosystems globally[72].

As we have seen, many zoonoses, as well as many other risks to human health, are strongly influenced by human-induced climate change. We have dwelt on infectious diseases, but in general, global warming could make some areas of the planet unsuitable and intolerable for our own body, for example by interfering with the temperature control systems that are stressed by the increase in extreme temperature periods[73].

It is increasingly evident that our health and well-being depend closely on how we relate to the Planet that hosts us, as evidenced by countless scientific sources. The human species is also subject to great risks as are other living species and our fate is connected to that of ecosystems, climate, i.e. the complex network that sustains life as it has developed on our Planet. Fighting climate change and preserving intact and balanced ecosystems is a far-sighted approach, capable of preventing the spread of new epidemics, both because biodiversity naturally regulates the presence of vectors of these diseases and because intact ecosystems do not allow the spread of these diseases in wild organisms and consequently their expansion through contact with humans.

Never before have we had the opportunity and the tools to address the health of the Planet and human health in an integrated way, on a solid scientific basis. After a long period of health benefits from industrialization and the use of fossil fuels, for decades we have begun to see the limits and the deep and destructive long-term damage; many clouds are hanging over our future. However, this is also a formidable opportunity to rethink our economy and our lifestyles at the root, the "ecological" root that is our common home, the Planet, to which we are all intimately linked.

The **choice is ours.**

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72 Altizer *et al.*, 2013. Climate change and infectious diseases: from evidence to a predictive framework. *Science*, 341, 514-519. doi:10.1126/science.1239401
73 Rexford, 2020. Global warming threatens human thermoregulation and survival. *J Clin Invest*, 130(2), 559-561, https://doi.org/10.1172/JCI135006.

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