Climate change and disorders of the nervous system

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Summary

Anthropogenic climate change is affecting people's health, including people with neurological and psychiatric diseases. Currently, making inferences about the impact of climate change on neurological and psychiatric diseases is challenging because of an overall sparsity of data, differing study methods, paucity of detail regarding disease subtypes, absence of consideration of the impact of individual and regional population genetics and widely differing geographical locations with the potential for regional influences. However, there is evidence that for many conditions, such as stroke, neurological infections and mental health disorders, their incidence, prevalence, and severity are clearly affected by climate change. The data demonstrate broad and complex adverse effects of climate change, and especially of unaccustomed temperature extremes and wide diurnal temperature fluctuations. Protective measures might be possible through local forecasting. Few studies project the future effects of climate change on brain health, hindering policy developments. We urgently need robust studies of threats from changing climate for people who have, or are at risk of developing, disorders of the nervous system.

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Introduction

Climate change is already challenging the health and survival of people in every country. The Earth's mean surface temperature has risen by 1·48°C since the industrial revolution started[1], with significant increases in the number of extreme weather events (e.g storms, droughts, heatwaves, wildfires, floods), leading to rising losses of life, and threatening wellbeing and livelihoods globally. 2023 was the warmest year on record[2]. Fulfilment of nationally-determined 2030 contribution targets collated at the COP28 climate negotiations would still result in an average 2·4-2·8°C temperature rise by 2100.[3] High humidity and temperatures will extend the regions and durations of time for which normal human thermoregulatory tolerance will be exceeded outdoors. These increases in humidity and temperature are already causing significant loss of outdoor labour and, in the future, will impact food production and security. A huge body of scientific literature now describes the potential health consequences of climate change at the level of populations:[4] the number of annual heat-related deaths in adults over 65 years old increased by 85% from 1991-2000 to 2013–22, an increase that would have been 38% (due to secular changes) if temperatures had not risen.[4] However, detailed consideration of disease-specific effects of climate change is sparse.

Neurological disorders are the leading causes of disability-adjusted life years and the second leading cause of death globally, and contribute substantially to societal inequalities.[5] Mental health disorders affect over 10% of the global population[6]; severe mental illnesses generate a mortality gap (18-year average life expectancy reduction).[7] To understand effects of climate change on neurological and psychiatric disorders, we consider the literature on the most burdensome neurological conditions in order of their age-standardised DALY ranking in the Global Burden of Neurological Disorders (2019).[5] We also consider the effects of climate change on common psychiatric diseases, in light of the high incidence of comorbidity with neurological diseases.[8] We do not include effects thought to be mediated entirely by pollution alone, aspects covered in a recent review.[9] We provide an interpreted synthesis of the published literature, emphasising the major findings, and stating the difficulties of such work and the gaps that remain.

Effects of heating on the brain

Climate change has pervasive, systemic consequences. In particular, rising temperatures have health impacts through multiple mechanisms, challenging the human capacity for maintaining body temperature within a narrow range, which is essential to preserve vital functions (panel 1). Heat can have direct effects on molecular function, particularly that of ion channels (panel 2).

Neurological diseases, and their treatments, can undermine all aspects of thermoregulation: adaptation to longer-term rising temperatures and acute temperature elevations (eg in heatwaves) may be compromised. Conversely, disease pathophysiology may itself be aggravated by normal thermoregulatory responses. For most diseases, the underlying mechanisms have not yet been well studied, but there are plausible links between climate change-related drivers, such as higher temperatures, and consequent generation or disruption of pathophysiology, based on current understanding of how heat affects the human body.

Neurological and psychiatric disorders and climate change

The scale of potential impacts of climate change on neurological diseases is likely to be considerable. In the 2003 European heatwave, there were 14,539 excess deaths in France, of which 3,377 (23.2%) were due to heatstroke, hyperthermia, 'nervous system diseases' (ICD10 codes G00-H95) or 'mental disorders' (ICD10 codes F00-F99).[11] Conditions of major interest are considered below, with details of contributing references provided in the Supplementary Table.

Stroke

Stroke is the second-leading cause of death and a leading cause of disability worldwide.[5] The impact of climate change on stroke is likely to be particularly important given the increasing burden of stroke-related disability in low-and-middle income countries and its disproportionate effect on elderly people, who are vulnerable to temperature changes through impaired temperature perception and disordered thermoregulation, comorbidities or medication use. Climate change might influence the incidence or outcome of stroke, but data are complex and show bimodality: studies from the US and South Korea showed an increased incidence of ischemic stroke with increasing temperature[12,13] and extremes of relative humidity, whereas others found increased stroke admissions with lower temperatures[14,15] Increased rates of admission, mortality or disability for stroke have been associated with higher ambient temperatures or heatwaves in most,[16,17] but not all, studies, as have increased diurnal temperature ranges[18] or temperature extremes[19]. Stroke incidence has been associated with cold spells or days.[20] Post-stroke mortality and morbidity are increased by higher temperatures.[17]

Importantly, stroke is a heterogenous condition due to either ischaemia (caused by athero-thrombo-embolism, cardiac embolism or small vessel occlusion) or intracerebral haemorrhage (caused mainly by small vessel rupture): many reports of the influence of temperature on stroke do not differentiate between stroke types, one reason underlying apparently discordant results. In addition, pre-existing cardiovascular risk factors and treatments might increase the risk of stroke associated with climatic variables.[21] The underlying mechanisms for ischaemic stroke being most consistently associated with higher temperature and humidity extremes are not known, but might include dehydration (from sweating and increased skin blood flow) increasing blood viscosity, osmolality and cholesterol levels, as well as endothelial dysfunction[22] which could increase the risk of thrombosis. By contrast, low temperatures or cold spells have been most consistently linked to the risk of intracerebral haemorrhage; higher barometric pressure might also contribute;[23] one explanation for the observed association is that cold ambient temperatures might activate the sympathetic and renin-angiotensin system causing short-term increased blood pressure, leading to vascular rupture. Interventions against climate change will thus need to address both hot and cold extremes, in the context of existing disease characteristics and risk factors.

Migraine and Tension-type headache

Although some patients might overestimate the role of weather,[24] research increasingly supports patient reports that warming temperatures trigger migraine episodes. An emergency department study found a 7·5% higher migraine admission risk per 5°C ambient temperature rise.[25] Temperature fluctuations are also linked with migraine severity, duration, and frequency; studies to date, however, have generally been small and are potentially underpowered in their attempts to evaluate multiple weather factors[26] such as sunlight and pollution, which itself is worsened by climate change. Overall, worsening climate conditions, including rising temperatures, extreme weather patterns, and escalating pollution, are likely to lead to a twofold impact on migraine: heightened attack frequency in existing sufferers and an upsurge in the overall occurrence of migraine. Impacts on tension-type headache seem more complex, with some studies finding weather changes (such as sunshine duration, ultraviolet index) trigger attacks whereas others do not.[26]

Alzheimer's disease and other dementias

Globally, about 55 million people have dementia, >60% living in low-and-middle income countries. As populations age, these numbers are projected to increase to ~150 million by 2050 with highest rates of increase in countries expected to experience the most significant effects of climate change.[27] People with dementia are exceptionally vulnerable to harm from extremes of temperature (eg heat-related illness, hypothermia) and weather events (eg flooding or wildfires), as cognitive impairment limits ability to adapt behaviour to environmental changes. Reduced awareness of risk is combined with a diminished capacity to seek help or to mitigate potential harm, from not drinking more in hot weather to not adjusting clothing to heat or cold. This vulnerability is compounded by frailty, multi-morbidity and psychotropic medications.[28] Accordingly, greater temperature variation, hotter days and heatwaves have been shown to increase dementia-associated admissions and mortality[29,30]: in New England, a 1·5°C increase in summer mean temperature increased dementia-associated admissions by 12%;[31] in Madrid, a 23% increase in Alzheimer's disease-related admissions followed a daily temperature maximum >1°C higher than the heatwave threshold temperature (34°C);[32] in the UK, a 4·5% increase was observed for each 1°C above 17°C.[28] Effects are complex, might be bimodal, and influenced by local factors: some studies suggest that cooler than average temperature,[29,31] or either extreme of temperature, raises numbers of admissions[30] or deaths; cumulative exposure to abnormal temperatures might also be important.

Meningitis and encephalitis

The identification of climate-sensitive infections is crucial for mitigating the effects of future epidemics and pandemics. WHO lists the following as potential pandemics or pandemic organisms – SARS-CoV-2, Crimean Congo Haemorrhagic fever, Ebola and Marburg viruses, Lassa fever, MERS, SARS, Nipah virus, Rift Valley fever and Zika virus and pathogens yet to emerge.[33] Climate change affects the transmission of many infectious diseases,[34] by altering life cycles[35] and behaviour of pathogens, vectors, and non-human reservoirs. Sociodemographic consequences of climate change will influence incidence of many infections due to migration, social disruption, famine, wars and urbanisation, compounded by both pre-existing and aggravated inadequacies of sanitation, clean water, nutrition, and healthcare provision. The latitudinal range of infections is changing: regional climate change-related weather conditions have been associated with extensive mosquito-borne disease outbreaks and the spread of tick-borne encephalitis; outbreak causation typically involves other (eg sociopolitical, geographical) factors. The arboviruses dengue, Zika, yellow fever and chikungunya are transmitted by *Aedes* mosquito species; the environmental suitability for their transmission is influenced by temperature, humidity and rainfall, all of which are affected by climate change. Dengue, which can cause encephalitis or encephalopathy, is currently the fastest-spreading tropical infection.[36] *Aedes albopictus* has already adapted to temperate climates and carries chikungunya and dengue: autochthonous transmission of both diseases has occurred in the US and France.[37] Zika virus infection causes congenital microcephaly, Guillain-Barre syndrome and meningoencephalitis, and its transmission is influenced by rainfall and temperature.[4] West Nile virus spread has been associated in many countries with changing environments and higher temperatures in most[38-40] (but not all) studies, with heatwave, drought and urban heat island effects, leading to disease occurring, or being predicted to occur, in naïve populations. The ranges of Lyme disease and tick-borne encephalitis have, or will, also spread,[41] with evidence of locality-specific effects, though more data are needed. Daily rates of diagnosis of viral meningitis rose modestly with an increase (1·05 fold/°C) in daily average temperature, with similar sized reductions in incidence with increased humidity, in a nationwide study in Kazakhstan.[42] Japanese B encephalitis (JEV), transmitted by the *Culex* mosquito, is endemic in South-East Asia and the Western Pacific. In more temperate Asian regions, JEV is transmitted in the warm season, whilst all-year transmission occurs in the tropics. Seasonal or climate change-related temperature or rainfall variations can have a significant effect on JEV infection rates, with some studies pointing in opposite directions.[43] Some viral infections are becoming less common, possibly due to vaccination or climate change-related alterations in vectors. In the Northern and Arctic regions, where climate change-induced temperature increases are over twice the global rate, animal migration to the North Pole will bring new micro-organisms which might infect humans, though obviously the populations of this region is small. Disease correlations may be temperature-related (eg borreliosis, cryptosporidiosis, leptospirosis) or water-related (eg Puumala virus infection, tick-borne encephalitis, Q fever and cryptosporidiosis). Rates of aseptic meningitis rose with higher temperature (11·4%/1°C) in South Korean urban settings. Local heating due to climate change was associated with an increased meningitis incidence in a South African setting, with additional contributions from socio-economic and other environmental factors. Observation and modelling both show climate change impacts are complex,[44,45,47] for example with high airborne dust concentrations or economic conditions compounding the risk of bacterial meningitis associated with high temperatures, and latitude-related seasonal effects (eg wind speed, oceanic oscillations) having important local influences on risk of disease. Combining global meningitis data with temperature variability (the difference between the maximum local temperature associated with the lowest incidence of meningitis and the observed absolute maximum local temperature) showed each logarithmic unit increase in temperature variability was associated with an increased overall global meningitis risk of 4·8%; low carbon emission scenarios would be associated with significantly reduced future meningitis incidence.[46,47]

Epilepsy

Approximately 60 million people have epilepsy. Most epilepsies share features likely to be aggravated by climate change, such as a sensitivity to sleep deprivation as a precipitant for seizures: sleep is, and will be, compromised by climate change, especially heatwaves. Ranges of infections causing or aggravating symptomatic seizures or epilepsy will likely extend under most climate scenarios. Most studies are small or anecdotal. Data indicate a bimodal relationship: heatwaves have been associated with increased admissions for febrile seizures or epilepsy, as have warmer days compared with colder days;[48,49] other studies report an increased risk of emergency visits with lower temperatures,[50,51] or negligible association.[52,53] Higher relative humidity and lower atmospheric pressure have also been associated with increased seizure risk. In common with many neurological diseases, epilepsy encompasses a wide variety of conditions which, despite sharing the common manifestation of seizures, are caused by a wide variety of underlying mechanisms. Most reports do not take this spectrum of disease biology into account, nor the effect of climate variables on other aspects around disease, such as the potential influence of seasonal factors on antiseizure medication levels in blood, emphasising the need for more granular data.

Multiple Sclerosis

The prevalence of multiple sclerosis increases with latitude globally[54] and within countries, such as the USA.[55] Additionally, there is an association between increasing multiple sclerosis severity and higher latitude in temperate zones, which might be caused by low UVB exposure[56] and low vitamin D levels[57] contributing to both susceptibility and severity. However, once multiple sclerosis has developed, warmer outdoor temperature is associated with worse multiple sclerosis symptoms. Up to 80% of people with multiple sclerosis complain of heat sensitivity, with temporary exacerbation of fatigue, motor, sensory and cognitive symptoms by exercise-induced or environmental (eg due to heatwaves[58,59]) skin or core temperature elevation. Temperature-related symptom aggravation, the Uhthoff phenomenon, can follow acute temperature elevation of just 0·5°C. Temperature-related symptom worsening can cause short-lasting pseudo-relapses, without neuroradiological changes: anomalously warm weather (defined as months >1·5°C warmer than the long-term average) was associated with increased risk of hospital emergency visits, especially in older patients (56-64 years of age).[60] Higher diurnal temperature ranges, or anomalously warm weather, increased emergency hospital attendance and admissions,[60,61] but other temperature-related variables did not aggravate the condition.[61] Sudden temperature increases, especially with simultaneously increased relative humidity across up to 30 preceding days, most strongly predicted increased risk of clinic visits, with additional variation by climate zones, in a large US study.[62] Subjective experience of heat and cold, mediated by discomfort and fatigue, rather than actual core temperature changes, might drive intolerance of ambient temperature.[63]

Psychiatric Disorders

Seasonal fluctuations in presentations of serious mental illness have been recorded for centuries. Recent data from around the world consistently show increased acute presentations of disorders with increased ambient temperature; weaker evidence suggests that both high and low extremes in temperature may exert similar effects. Incidence, hospital admissions and mortality risk for many mental health disorders are associated with increased ambient temperature,[64,65] diurnal temperature fluctuation, or both extreme hot and cold temperatures[29,66-76]. A few studies did not find these effects on mood disorders,[77,78] and additional factors, such as atmospheric pollution, might compound or modulate the links with temperature. Mean diurnal temperature ranges >3·2°C were associated with an increased admission risk for schizophrenia in Taiwan. Daily temperature excursion (5·6°C increase in mean apparent temperature within one day) was associated with increased (4·8-7·9%) hospital visits for any mental health disorder, self-harm, and intentional injury or homicide.[76] In Bern, Switzerland, time-series data on nearly 90,000 psychiatric hospitalisations between 1973 and 2017 showed a 4% increase for every 10°C increase in daily temperature, more so for people with neurodevelopmental disorders and schizophrenia.[68] In the USA, health insurance claims on nearly 3.5 million mental health-related emergency department visits between 2010-19 showed an increase on days of extreme heat with an incidence rate ratio of 1.08 (95% CI, 1.07-1.09) for any mental health condition.[70] Extreme weather events (eg winter storms, flooding, wildfires) can lead directly to acute and chronic disorders, including anxiety, post-traumatic stress, depression and suicidal ideation, and might even affect people who were exposed prenatally.[79] Birth season, urban settings, pollution, local climate zone effects, reduced sunshine exposure, and humidity show complex influences on climate change effects. A representative UK sample of patients with psychosis, dementia or substance misuse showed an overall 4.9% increase in risk of death per 1°C rise in temperature on the hottest days above the 93rd percentile of the annual temperature distribution.[80] Temperature-related deaths amongst patients with severe mental disorders are significantly higher than equivalent estimates in the general population, thus aggravating the excess and premature mortality already seen in people with severe mental disorders.[7] Signals from generally small studies show that many other climate-related factors might have an influence on psychiatric disorders too, indicating the need for comprehensive prospective studies.

Other neurological conditions

Prevalence, deaths, or DALYs for Parkinson's disease are elevated with higher temperature[81] and in countries with higher average temperatures and higher warming indices; this did not hold for motor neurone disease, a condition used in one study as a comparator.[82] Others conditions, such as the neuropathic complications of diabetes, might be aggravated by climate change[83]. For dermatomyositis, diurnal temperature ranges, humidity extremes and low temperatures were associated, with different lag intervals each, with increased risk of hospital attendance, demonstrating again the complexities of climate impacts on disease.[84]

Neurological conditions with early onset are especially important as children will be particularly affected by climate change, potentially compromising health and normal brain development in childhood[,4,85] and aggravating existing ill-health. Indeed, many neurogenetic and neurometabolic conditions of childhood onset are triggered or exacerbated by fever and intercurrent illness (for example mitochondrial disorders, aminoacidopathies, organic acidurias, *GNAO1*-related disease) and as such, these could possibly be worsened by climate change. For example, evidence from other species (European perch) suggests that climate change might induce adaptive changes in mitochondria as they adjust to a warmer environment, but with a higher risk of oxidative stress;[86] future studies in patients with mitochondrial disease will be important in defining the effects of climate change on mitochondrial function, both in health and disease. Detailed experimental studies in small groups of people have shown disordered thermoregulation,[87,88] and worsening spasticity with low temperatures,[89] in people with existing spinal cord injury.

Complexities of climate change impacts on neurological and psychiatric disorders

Despite the growing number of publications on climate change and neurological diseases (Figure 1), we note an overall lack of data for neurological and psychiatric diseases, for which there are several reasons. Interpretations are constrained by complexities, such as disease heterogeneity (eg different stroke or epilepsy types), effects of, and on, existing treatments, differing definitions of disease and climate parameters and reporting standards, varying methods (eg modelling lagged effects or not). In addition, there is a global disparity between regions most affected by climate change now and in the future, and regions from which the majority of publications come (Figure 2). Given that populations around the world have undergone genetic adaptation to their local climate over millenia, there are also potentially important individual and population genetics influences yet to be explored. An enormously complicated human civilisation sits within a hugely complex global ecology, which we are altering at rates beyond those seen over historic timescales: comprehending the resulting interplay between climate change and neurological disease is challenging, especially given limited pathobiological understanding for most neurological diseases. Thus, for example, the list of variables noted to influence the effects of climate change on neurological and psychiatric disorders include: cold and hot extremes, and daily temperature excursions; urban-rural differences; the built environment; oceanic cycles; local geographies (eg rivers, green cover), local agricultural practices and wildlife and vector changes; human behaviours, seasonal or otherwise; socioeconomic deprivation; and vaccination strategies and immunity. Interactions between multiple factors are likely, for example for sequential weather events, or drug abuse and climate-related admissions to hospital for psychiatric disorders, or vector range extension and sociopolitical upheaval; pollution is also likely to compound climate effects.[4,9] The complexity of interactions will necessitate systems approaches for the management of neuropsychiatric conditions under climate change, to produce the best outcomes, capitalise on co-benefits of climate mitigation and adaptation, and avoid unintended consequences. Few studies address this considerable complexity of climate change impacts. Several potentially confounding biases apply to every study reported (panel 3). However, bias due to researcher knowledge of patient exposures, the direction of causality, misclassification of diseases were largely unlikely given the nature of the question in hand and the sources of data employed. These considerations influence the quality of detailed conclusions drawn in most of the reviewed studies, but are unlikely to call into question the underlying signals suggesting there is an effect of climate change, especially for conditions, such as stroke and infectious diseases, for which there are large numbers of publications from different regions of the world. The risks of bias noted will be important to consider when future studies are designed and interpreted.

Notably, older and newer studies, which sometimes appear to generate opposing findings, might not be directly comparable due to progressive global warming between reports, with some studies already showing secular changes in the impacts of climate change.[66] Publication bias is inevitable: diseases of economic importance occurring in developed countries are over-represented, whilst regions of the world where humanity is most affected by climate change are under-served by research and health infrastructures (Figure 2). Neurological communities differ in their approaches: most studies not on infectious diseases report climate effects on incidence, admissions or mortality, whilst neuroinfection studies concentrate on climate or seasonality effects on infection rates. Few studies address effects on patients with established neurological diseases, or unreported symptom aggravation. Data regarding the particular impact of heatwaves are sparse for most conditions. Global or regional studies projecting health outcomes under various climate models are few.[28,46,90-93] Currently, there are no well-established strategies for managing neurological diseases under climate change, yet health effects are likely even in heat-adapted cities, underscoring the urgent need for research and policy development. The limitations of the existing literature constrain the inferences that can be derived and thus the strength of the policy changes for which we can advocate.

Areas for further research

Prospective systematic disease focussed models of how climate change projections will affect the nervous system are urgently needed. As a parallel, COVID-19 has neurological complications; the SARS-CoV-2 pandemic illustrated the importance of quantitative modelling in shaping public health policies and mitigating healthcare burdens. Generative modelling—originally used to estimate neuronal activity spread in epilepsy—was repurposed to model population-level viral spread, testing hypotheses about factors underlying viral spread and pathogenicity, specifically related to temperature and seasonality.[94] These COVID-related initiatives suggest that the fusion of sociobehavioural modelling, epidemiological modelling and climate-related pathogenicity has the potential to be an important public health tool for forecasting and scenario projections. Notably, COVID-19 vaccination advice was tailored for people with neurological diseases: as projections of the temperature and humidity effects of climate change become more detailed at the local level, climate-related health projections will also need to be developed to a level of granularity that is directly useful to individuals with neurological diseases.

Whilst meta-analyses have the capacity to offer important insights in general, the substantial heterogeneity, and other limitations listed above, of existing data on neurological and psychiatric diseases make such necessary analyses impossible or extremely challenging currently. In stroke, where appropriate data do exist, one meta-analysis (including >2 million events) reported short-term mean ambient temperature increases were associated with increased ischaemic stroke risk (1.2%/°C);[95] a meta-analysis of registry studies (476,511 participants) found no link between ambient temperature and admission for ischaemic stroke, the authors also suggesting that increases in the preceding 24 hours were more important than absolute temperature.[16]

People are already taking their own actions: caregivers of people with the rare severe epilepsy Dravet syndrome reported that both warm weather and reduced ambient temperatures were seizure precipitants, that warm weather was avoided, and cooling measures employed, to avoid seizures ((personal communication – Galia Wilson, Chair of Trustees, Dravet Syndrome UK and parent to a 16-year-old with Dravet Syndrome). Anecdotally, people with some neurological diseases (eg alternating hemiplegia of childhood, rare epilepsies, multiple sclerosis), or their carers, report rapid symptom onset soon after exposure to altered ambient temperatures, suggesting direct mediation by cutaneous sensory and effector mechanisms, rather than through changes in core temperatures that would take much longer periods of time. Moreover, subjective experiences of ambient temperature might contribute to intolerance of extreme ambient temperatures. These observations require further study, and might offer novel approaches for management to challenging temperature exposures.

Children are frequently listed as one of the groups most vulnerable to climate change. But as is apparent from our work, and as detailed in the Supplementary Material, data specifically related to child neurological and psychiatric health in the context of climate change are very sparse, emphasising the need for much more research in this area, especially given that levels of climate anxiety are the highest amongst children and young people.[96]

It is also important to note that almost all the published data considered here uses information on temperature gathered from existing weather monitoring stations that record outdoor temperature. The built environment can have important effects on aggravating the heat impacts of outdoor temperatures, for example retaining heat overnight leading to higher night time temperatures that can disrupt sleep with attendant detrimental effects on neurological or psychiatric conditions, or being designed for colder temperatures. Outdoor temperature recordings are likely to be particularly relevant for countries with populations that have agrarian economies. For most high income countries where typically populations spend the majority of their lives indoors, indoor temperature data will be important to collect in future studies.

Emerging Themes

The effects of climate change might be most marked not at absolute temperature or humidity values, but when those variables differ most (and diverge rapidly) from local historical means.[97-103] People adapt to local historical climatic parameters, raising the possibility of future shorter-term adaptation to forecast local weather changes: whether 'climate training'[104] (eg anticipatory acclimatisation) could be beneficial and widely implemented is unknown. Other adaptations are possible: air conditioning use may help,[105,106] but its monetary and carbon cost preclude widespread deployment; sustainable, passive cooling strategies include increasing urban green and blue spaces and nature-based solutions, implementation of cool, reflective rooves and pavements, and behavioural interventions. Climate monitoring,[107] projection models,[108] logic[109] and forecasting systems,[110-117] identifying especially vulnerable sub-populations,[118] and reliable extreme weather event warning systems, might reduce exposure and accompanying risks.[119] The lag often observed between climate events and associated disease outcomes could offer a useful intervention window, as might the apparently protective effect of night-time relief from higher temperatures.[120,121]

The mental health consequences of climate change are important. Climate change creates new psychological challenges, notably 'climate anxiety', which is a chronic sense of doom related to helplessness around the climate crisis,[122] evoking emotions including worry, fear, anxiety, grief, and anger.[123] Worry about climate change is experienced by over two-thirds of the adult population of the USA.[124] Whilst a reasonable response to climate change realities,[122] climate anxiety can be unconstructive.[125] People with neurological conditions are already more likely to experience anxiety and depression and are more vulnerable to mental health consequences of climate change than the general population.[126-128] Clinical services will need to implement interventions that increase patients' perceptions of control over aspects of their disease that are within their scope of change (eg indoor temperature control) and foster resilience skills (eg mindfulness).[128] Patient support organisations can engender resilience through communications bolstering adaptive coping and encouraging activities (eg proactive pro-environmental behaviours) reducing anxious responses to climate change.[122]

Conclusions and Future Directions

Global heating mandates new approaches to nervous system diseases. Patients might need to adopt new (eg treatments), modified (eg avoiding exercise during heat), intensified (eg drinking more) or adapted (eg pacing for fatigue) behaviours to manage their condition. Such behaviours, and the cognitive, interpersonal and emotional regulation skills influencing their expression, constitute changes to self-management,[129] and have the potential to reduce the effects of climate change on neurological outcomes. Carers and healthcare professionals will also need to adapt how they support and manage affected individuals. Responding effectively will thus require coordination of complex interventions of people with the condition, families, carers and health and social care providers within their encompassing systems. The UK Medical Research Council recommends a systematic, theory- and evidence-based approach to designing interventions to change self-management and practice behaviours.[130] Use of behavioural science principles and frameworks will be essential for creating effective change.

Just before COP26, 233 health journals simultaneously demanded urgent governmental action against 'catastrophic harm to health' from climate change.[131] In 2023, another powerful editorial was published across a large number of health journals. Coordinated global action is possible, at individual and societal levels, exemplified by the SARS-CoV-2 response, for which we needed cognitive function (individual behaviour change, modelling-led policies, vaccine invention). Healthcare professionals are trusted authorities for information about climate-related health impacts:[132] their duty of care must encompass planning for a changing climate and advocating for health solutions.[133] Neurologists can take action to help reduce their own impact on the climate and to provide more guidance for people with neurological disorders.[134] In addition, there is a pressing need for more research on the health impacts of climate change on neurological and psychiatric disorders (panel 4), as recognised by funding agencies such as the Wellcome Trust and UK Research and Innovation governmental body. Unless we pay attention to the danger to health from climate change, we risk losing many of the gains being made in improving human health.[4]

Contributors

Sanjay M Sisodiya, Medine I Gulcebi, Francesco Fortunato, James D. Mills and Ethan Haynes undertook literature searches. Medine I Gulcebi, Francesco Fortunato, James D. Mills and Ethan Haynes prepared the Tables and Figures. Sanjay M Sisodiya wrote the original draft with contributions from Elvira Bramon, Paul Chadwick, Olga Ciccarelli, Anthony S David, Kris De Meyer, Nick C Fox, Joanna Davan Wetton, Martin Koltzenburg, Dimitri M Kullmann, Manju A Kurian, Hadi Manji, Mark A Maslin, Manjit Matharu, Hugh Montgomery, Marina Romanello, David J Werring, Lisa Zhang, Karl Friston, and Michael G Hanna, who reviewed and edited the manuscript. Sanjay Sisodiya and Michael Hanna conceptualised the manuscript.

Declaration of Interests

HMo chairs Dyson's Scientific Advisory Board. He chairs the Lancet Countdown on Health and Climate Change. He holds a patent relating to a means to improve patient hydration in hospitals. HMo is a member of UK Climate and Health Council and co-founder of Real Zero. HMo is a member of UK Climate and Health Council and co-founder of Real Zero (a non profit company helping decarbonise healthcare). He has received honoraria in the past for talks on the subject of climate change, but none for talks related to the topic of this article**.**. NCF is the member of the Research Strategy Council of Alzheimer's Society (UK). DW has received: grant funding from the Stroke Association and British Heart Foundation; speaking honoraria from Bayer; speaking and chairing honoraria from Alexion and NovoNordisk; and consultancy fees from Alnylam, Bayer and NovoNordisk. He has participated on a data safety monitoring board for OXHARP, and the TICH-3, RESTART, MACE-ICH and PLINTH Trial Steering Committees. MaK has received payments from Bloomsbury Genetic Therapies, and PTC and holds shares in Bloomsbury Genetic Therapies, which is not relevant to this work as involvement pertains to the development of gene therapies for rare neurometabolic disorders. MaK also has leadership or fiduciary role in LifeArc grants committee, not relevant to this work as this membership pertains to the review of grants and allocation of funding through the Philanthropic fund, and is NIHR GOSH BRC ANT theme lead, and has patents, issued or pending for DTDS viral vector. OC reports speaking honoraria from Merck and Biogen, and for participation on a data safety monitoring board

or advisory board for Novartis (DSM Board). MaM has grants or contracts from Ehlers Danlos Society, Abbott, and Medtronic, and reports consulting fees from AbbVie (Institution), Kriya (Institution), TEVA (Institution), Lundbeck (Institution), Eli Lilly (Institution), Salvia (Institution), and Pfizer (Institution). MaM reports payment or honoraria for lectures, presentations, speakers bureaux, manuscript writing or educational events from AbbVie, Pfizer, and Eli Lilly. MaM reports patents, planned, issued or pending: WO2018051103A1: System and method for diagnosing and treating headaches. MaM is the president of medical advisory board of CSF Leak Association, and a board member of the Anglo Dutch Migraine Association (ADMA). All other authors declare no conflicts of interest.

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Search strategy and selection criteria

References for this Personal View were identified by searches of PubMed, Ovid MEDLINE, EMBASE, and PsycINFO between 01/01/1968 and 30/09/2023 for publications that reported potential effects of extreme climate events or temperature fluctuations on nineteen different nervous system conditions chosen based on the Global Burden of Disease 2016 study, supplemented by common, serious psychiatric disorders. We searched for papers on stroke, migraine and tension-type headache Alzheimer's disease and other dementias, meningitis and encephalitis, epilepsy, multiple sclerosis, psychiatric disorders; anxiety, depression, and schizophrenia, and other neurological conditions (Parkinson's disease, motor neuron disease, traumatic brain injury, peripheral neuropathy, myopathies, spinal cord injury, brain cancer, and tetanus) selecting papers for which the paper was available as a full-text version, in English, a primary research article, provided information on extreme climate events or temperature fluctuations and involved humans. As this is a new area of study, we included all studies that met the inclusion criteria, without selection based on individual study quality: we note that all studies contain important risks of bias, detailed in the Discussion. For references discussed in the main text, we focussed mainly on articles published in the past five years about the direct aspects of climate change, further informed by a detailed review of the published literature dating from 1968. Further details about our search can be found in Supplementary Material pages 1-2. We have grouped together migraine and tension-type headache, and meningitis and encephalitis, as from the climate change perspective the relevant studies and mechanisms are best reviewed together. Some conditions (spinal cord injury, Parkinson's disease, and motor neuron disease) for which literature is sparse are considered together under "Other neurological conditions"; for other conditions (traumatic brain injury, brain and other CNS cancers, and tetanus) we found too little relevant literature to include them in this Personal View.

Figure legends

Figure 1: Publication dates of included articles.

The x-axis indicates the year from 1960 until 2023. The y-axis indicates the number of included articles published each year. The line graph is overlayed with climate “warming stripes”. Here the yearly global temperature means are presented as temperature anomalies (degrees Celsius), the yearly mean temperature deviation relative to the mean temperature from 1961-1990. The dataset used was taken from the Met Office Hadley Centre/Climatic Research Unit global surface temperature data set (HadCRUT5).[137] The date of the Paris Agreement, a key event in climate policy which set out boundaries for safe rises in global temperatures, is indicated. The number of publications exploring the potential impact on brain health due to climate change was very low until the year 2004, since when there has been a notable growth in the number of published articles.

Figure 2: Global map comparing country-specific vulnerability to climate disruption against sources of papers included in this review.

The Notre Dame-Global Adaptation Index (ND-GAIN) vulnerability score summarises a country’s vulnerability to climate change.[138] ND-GAIN brings together over 74 variables to form 45 core indicators to measure vulnerability and readiness of 192 UN countries from 1995 to the present. Of the 332 articles included in this review, 308 reported data from a specific country. The red circles indicate the number of articles that report the impact of climate change in each specific country. The USA and China have published the most articles related to climate and neuropsychiatric diseases, with 67 and 65 published articles respectively. The majority of the other studies focus on the impact of climate change throughout Europe. The number of articles from countries in South America, Africa and South/Southeast Asia are low: these are the regions predicted to be most vulnerable to climate change.

Panel 1: Effects of heat on the body

Thermoregulation requires balancing heat loss against its generation from basal metabolism and physical activity. Skin and core temperature elevation induce cooling responses through behavioural (eg seeking shade, adjusting clothing) and physiological (eg sweating, cutaneous vasodilation) responses. When air temperature exceeds skin temperature (normally ~25-35°C), heat loss can only occur through evaporation, itself compromised as humidity rises or with activity-related heat generation. Sweat production, even in fit acclimatised individuals, cannot exceed 3-4 L/hour, limiting its thermoregulatory scope. Moreover, this sweat rate surpasses maximal enteric water absorption rate (<1·5 L/hour), which increases the risk of dehydration, and poses a further intrinsic limit to thermoregulatory capacity. If cooling cannot match heat generation, the resulting core temperature elevation (‘hyperthermia’) can harm health and prove fatal. Initial core temperature rises compromise voluntary muscle activity, through effects on the central and peripheral nervous systems and on muscles. Further core temperature elevation impairs physical function through heat cramps, caused by dehydration and electrolyte losses. Heat exhaustion, the inability to continue exercising, is more common in people who are not heat-acclimatised, and results from further dehydration, electrolyte losses, and psychological intolerance of heat. Heat exhaustion is characterised by tachypnoea, tachycardia, hypotension, cutaneous flushing, paradoxical thermal responses (goosebumps, shivering), and neurological symptoms (eg light-headedness, dizziness, headache, irritability, lethargy). Heat stroke, a medical emergency from failed thermoregulation (core body temperature

>40·5°C), manifests with encephalopathy, hot dry skin and circulatory instability; seizures, loss of consciousness and associated circulatory collapse can prove fatal, with adults over 65 most vulnerable.

Prolonged sub-lethal heat exposure generates physiological adaptations, enhancing thermal tolerance;10 ~75% of acclimation occurs within 4-7 days, but adaptations are transient, gradually disappearing without consistent heat exposure. Heatwaves – extended periods of hot weather relative to expected local seasonal averages – can also be accompanied by high humidity, limiting heat loss from sweating and thus compounding temperature effects. Typically, health consequences result before acclimation occurs.

Panel 2: Temperature and ion channels

In the nervous system, the fundamental properties of signalling and communication require ion channel gating in response to electrochemical stimuli. The conformational transitions that underlie ion channel opening and closing, the balance between which determines ion flux, are typically steeply dependent on temperature. The temperature coefficient (Q10), defined as the ratio of a rate constant at two temperatures separated by 10°C, for ion flux generally falls in the range 1·5–2, although some (eg TRP) channels generally have Q10 values far outside this range, making them exquisitely temperature-sensitive. Active trans-membrane transport also shows high sensitivity to temperature. The extent to which nervous system complications of hyperthermia result from direct temperature effects on ion channels, synapses and axonal function is incompletely understood. It is known, for example, that the properties of voltage-gated sodium channels are influenced by temperature, a phenomenon contributing to worsening conduction failure in demyelinating diseases with rising temperatures. Altered channel function might contribute directly to acute neurological manifestations of hyperthermia, such as seizures.

Panel 3: Risk of bias

- the lack of individual patient-level weather exposure data and the use of locality, rather than individual accommodation-level, climate parameters (eg temperature, humidity and their localised sampling intervals and time-varying properties; some buildings retain heat more than others after a heatwave), leading to mis-measurement bias
- the lack of information on measures taken by patients to combat individual weather events and their individual resources to be able to do so
- for disease symptoms (eg increased seizure frequency) that might not lead to patients seeking medical advice, or when weather events prevented patients seeking medical attention, the risk of under-ascertainment and missing data;
- lack of information presented about the weather context within which a given weather event took place, which is important as, for example, acclimation occurs after 4-7 days of exposure to higher temperatures.

Panel 4: Research priorities

There is a need for more data on the impacts of climate change across neurological diseases, from the individual to the epidemiological level. This need is both urgent and challenging, as the climate continues to change, necessitating care in the interpretation of data collected during previous years, even if the relevant studies were undertaken relatively recently (eg over the last 40 years). There is a place for 'responsive' studies that collect data around the time of adverse weather events, again challenging to organise and undertake, but potentially providing valuable information in short order. Research will also require appreciation of the complexity of climate impacts, as highlighted here, in a global environment that continues to warm due to climate change, and will need systems thinking to ensure the multiple interacting factors that can affect disease are all considered. Most importantly, disease area experts need to engage with the concept that the impacts of climate change are important in neurological and psychiatric diseases, and human health in general, and choose to undertake relevant global transdisciplinary research that directly involves people with neurological and psychiatric conditions, and can be incorporated into global initiatives such as the Intersectoral Global Action Plan on epilepsy and other neurological diseases[136].