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CLIMATE IMPACTS ON DISASTERS, INFECTIOUS DISEASES AND NUTRITION

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> Whoever wishes to investigate medicine properly, should proceed thus: in the first place to consider the seasons of the year, and what effects each of them produces for they are not at all alike, but differ much from themselves in regard to their changes. Then the winds, the hot and the cold, especially such as are common to all countries, and then such as are peculiar to each locality.
>
> On Airs, Waters, and Places *by Hippocrates c. 400BC*

2.1 Introduction

The Zika virus epidemic that emerged in northeast Brazil in 2015 occurred during an unusually warm and dry year. Both natural climate variability as well as long-term trends were responsible for the extreme temperatures observed[1] and these climate conditions are likely to have contributed to the timing and scale of this devastating epidemic. Knowledge of this climate context is derived from analyses of large-scale global climate datasets and models, which provide policy-makers with broad insights into changes in hydro-meteorological extremes. However, societal response to epidemics works at multiple levels. For instance, policies and resource commitments may be developed at international and national levels, while targeted prevention and control efforts are managed at local levels by district health teams and community leaders. Adaptation to climate change also needs to be developed at multiple levels. National level information may be needed for planning, but an understanding of the local weather and climate that individuals and communities experience is also required. Once specific climate-sensitive health risks are identified, information on the past, present or future climate can be used to help mitigate risks and identify new opportunities for improved health outcomes. This information needs to be provided as a routine service if it is to support operational decision-making.

Climate services for health are an emerging technical field involving both the health and climate communities.[2] The Climate Services for Health Case Study Project showcases 40 studies that can help readers better understand what, how and why health-tailored climate services can support health solutions in managing climate risks. The publication emanating from the World Health Organization/World Meteorological Organization (WHO/WMO) Joint Office on Climate and Health presents a shared framework for developing climate services for health and highlights common needs and good practices.[i] A conceptual framework for the development of services is also emerging[3] along with relevant terminology (see Box 2.1).

However, to-date there is little concrete information on the value of such services and a significant gap remains between the potential for climate services to deliver actionable information routinely to health decision-makers and on the ground experience.

As our primary focus is human health it is helpful to consider *what is health*? In 1948, the WHO defined health in its Constitution with a phrase that is still used today: '*Health is a state of complete physical, mental and social well-being and not merely*

BOX 2.1 TERMINOLOGY FOR CLIMATE SERVICES[3]

- **Climate service coordinating bodies**, including the Global Framework for Climate Services, work to increase connections between climate information users and providers and to support the development of climate services in particular contexts.
- **Climate service users** employ climate information and knowledge for decision-making; they may or may not participate in developing the service itself. In some cases, climate information users may also pass information along to others, making them both users and providers.
- **Climate service providers** supply climate information and knowledge. Climate service providers may operate on international, national, regional or local levels and in a range of different sectors; they may be public or private, or some mixture of both.
- **Climate impact monitoring groups** meet to monitor and discuss evolving climate impacts and implications of forecasts for decision-making in particular contexts, especially with regard to health (e.g., Climate and Health Working Groups that monitor the incidence of climate-sensitive diseases) and food security. They generally include decision-makers, sectoral experts and representatives from practitioner communities.
- **Climate services** involve the direct provision of knowledge and information to specific decision-makers. They generally involve tools, products, websites or bulletins.

TABLE 2.1 Health impacts of hydro-meteorological events

	Health impact
Environmental	
Flood (general floods, flash floods and coastal floods)	The immediate health impacts of floods include drowning, injuries, hypothermia and animal bites. Vector-borne and water borne infectious diseases. Nutritional deficiencies through crop/livestock loss, livelihood disruption. In the medium-term, infected wounds, complications of injury, poisoning, respiratory problems from moulds, poor mental health, are indirect effects of flooding. Coastal floods may result in salt-water intrusion to drinking, hypertension, eclampsia.
Mass Movement (rockfall, landslide, avalanche, subsistence) often precipitated by high rainfall or warmer temperatures	The immediate health impacts of mass movement include loss of life, crush injuries. These may be followed by loss of livelihoods and mental health issues.
Meteorological	
Storm (hurricane, typhoon, cyclone) or local storm	The immediate health impacts of major storms include wind related crush injuries and loss of life. Further impacts may relate to flooding from associated rainfall (see above), infrastructure damage or sea surge.
Climatological	
Wildfire (forest fire, land fire)	Burns, respiratory morbidity, loss of life, cardiovascular, ophthalmic, loss of livelihoods, mental health problems. May increase mudslide risk.
Drought	Nutrition-related effects (including general malnutrition and mortality, micronutrient malnutrition, and anti-nutrient consumption (e.g., cassava)); water-related diarrhoeal diseases, airborne and dust-related disease (including meningococal meningitis); vector borne disease (including arboviral diseases transmitted by *Aedes aegypti* such as dengue and Zika); mental health effects.
Climate Extremes	
Heat wave	Heat stress, exhaustion, stroke.
Cold wave	Hypothermia, cardiovascular and respiratory health conditions, frost bite.
Extreme winter conditions	Snow, ice, frost, may result in increased car accidents, loss of life and injury.
Extreme humidity	High humidity may result in high levels of fungi and molds in the domestic environment which promote allergies including asthma. It may also result in fungal (e.g., aflatoxin) contaminated food stuffs with associated negative health consequences.

the absence of disease or infirmity'. More recently the Meikirch Model of Health posits that: '*Health is a state of wellbeing emergent from conducive interactions between individuals' potentials, life's demands, and social and environmental determinants*'.[4] The latter definition implies that there are multiple impact pathways for health.

In this chapter we introduce the three climate and health impact pathways that are central to our discussions throughout this book: i) the health outcomes of hydro-meteorological disasters such as floods, droughts and heatwaves (Table 2.1); ii) infectious diseases of humans and animals such as malaria, Zika, cholera and Rift Valley Fever (Table 2.2); iii) nutrition (Figure 2.1).

While there is clear overlap between all three pathways the stakeholder communities that are engaged in setting policy and responding in practice may differ substantially (Table 2.3).

TABLE 2.2 Climate sensitive infectious diseases

Transmission mechanism	*Type of pathogen*	*Disease*	*Pathogen*	*Epidemic potential*	*Transmission mechanism*	*Climatic or environmental transmission drivers*
Air-borne	Bacterial	Meningococcal meningitis	*Neisseria meningitides*	yes	Airborne aerosol	Aridity, dust, low relative humidity, temperature
Air-borne	Viral	Influenza	H1N1	yes	Airborne aerosol	Humidity, temperature
Food-borne	Bacterial	Gastroenteritis	*Salmonella* spp	no	Inappropriate food handling	Temperature
Vector-borne	Bacterial	Lyme Disease	*Borrelia burgdorferi*	no	Ticks *Ixodes* sp.	Rainfall, temperature, NDVI
Vector-borne	Filarial	Onchocerciasis / River Blindness	*Onchocerca volvulus*	no	Blackflies: *Simulium* sp.	Rainfall, temperature, NDVI, wind, river discharge
Vector-borne	Filarial	African Eye Worm	*Loa loa*	no	*Chrysops* sp. Forest canopy,	Forest soils, NDVI
Vector-borne	Parasitic	Malaria	*Plasmodium* sp.	yes	Mosquitoes *Anopheles* sp.	Rainfall, humidity, temperature, surface water puddles, river margins, irrigation, altitude, NDVI
Vector-borne	Parasitic	Schistosomiasis / Bilharzias	*Schistosoma* sp.	no	Snails e.g., *Bulinus Africanus*	Surface water, NDVI, temperature, rainfall, elevation

(*Continued*)

TABLE 2.2 (Continued)

Trans-mission mechanism	*Type of pathogen*	*Disease*	*Pathogen*	*Epidemic potential*	*Transmission mechanism*	*Climatic or environmental transmission drivers*
Vector-borne	Parasitic	African Trypanosomiasis / Sleeping Sickness, Ngana	*Trypanosoma brucei gambiensis*		Tsetse *Glossina* sp.	Gallery forests, savannah wood-land, temperature, NDVI
Vector-borne	Viral	Yellow Fever	*Flavivirus*	yes	Mosquitoes *Aedes, Haemagogus* and *Sabethes* sp.)	Rainfall, temperature
Vector-borne	Viral	Rift Valley Fever	*Phlebovirus*	yes	*Mosquitoes Aedes* and *Culex* sp.	Rainfall, humidity, surface water, temperature, NDVI
Vector-borne	Viral	Dengue and Dengue Hemorrhagic Fever	*Flavivirus*	yes	Mosquitoes *Aedes* sp.	Temperature, rainfall, humidity
Vector-borne	Viral	Zika	*Flavivirus*	yes	Mosquitoes *Aedes* sp.	Temperature, rainfall, humidity
Vector-borne	Viral	Chikungunya	*Flavivirus*	yes	Mosquitoes *Aedes* sp.	Temperature, rainfall, humidity
Water-borne	Bacterial	Cholera	*Vibrio cholerae*	yes	Faecal/oral route and filth flies e.g., *Musca* sp. via mechanical transmission	Water and air temperature, water depth, rainfall and conductivity, algal blooms, flooding, sunlight, SST
Water-borne	Viral	Gastroenteritis	*Rotavirus*	yes	Faecal/oral route and filth flies e.g., *Musca* sp. via mechanical transmission	Humidity, cool/winter, dry months, low rainfall, water shortages, flood
	Bacterial	Trachoma	*Chlamydia trachomatis*	no	Flies e.g., *Musca sorbens* via mechanical transmission	Aridity, dust, low relative humidity, temperature

Abbreviations: NDVI, Normalized Difference Vegetation Index; SST, Sea Surface Temperature.

TABLE 2.3 Stakeholder communities for different climate impacts on health pathways

	Hydro-meteorological disasters of public health importance	*Infectious diseases epidemics/pandemics*	*Nutritional crisis*
Government	Multi-institutional disaster response (Office of the President)	Infectious disease departments or specific vertical programmes/Health Security Committee	Nutrition department, food security agency
National NGOs	National Society of the Red Cross Red Crescent	Local health NGOs	
International bilateral agencies	Infrastructure, engineering,	International partners responding to International Health Regulations e.g., WHO and CDC	World Food Programme/ FEWSNET/ SUN
Private sector	Insurance	Diagnostics	Food supplements
Academia	Engineering, public health/nursing/ emergency medicine	Public health, tropical medicine	Nutrition, food security
Specialist organizations	International Federation of the Red Cross Red Crescent Military	WHO, CDC, Military	World Food Programme, FAO

Abbreviations: CDC, Center for Disease Control; FAO, Food and Agriculture Organization; FEWSNET, Famine Early Warning System Network; NGOs, non-governmental organizations; SUN, Scaling up Nutrition; WHO, World Health Organization.

Other important pathways that are not significantly covered in this book include the direct health impacts of increases in atmospheric carbon dioxide on allergens[5] and air pollution. Nor do we cover the indirect impact of climate variability and change on economic growth and income inequalities[6] that affect the ability of governments to provide health services, and individuals to support a healthy lifestyle and, when necessary, to seek care.

2.2 Hydro-meteorological disasters

Hydro-meteorological disasters (droughts, floods, heatwaves, storms, etc.) are significant causes of mortality as well as of acute and chronic health issues.[7,8] The 1931 Central China flood disaster, which followed a period of extreme weather events, is the largest recorded disaster of the 20th century. The initial death toll was put at 150,000 from drowning; however, the total associated mortality is thought to have exceeded two million people, most of whom died from flood-related disease.[9] While much has been done in China to manage riverine flood disasters they remain a significant challenge for the population and government.[10]

The World Bank identified three investment areas for disaster mitigation: early warning, infrastructure and environmental buffering.[11] A common argument justifying investments in early warning is that early interventions are more cost-effective in reducing suffering and economic losses from disasters than late responses. It is therefore essential that early warning systems are tied to an effective early response. Forecast based Financing (FbF) is an innovative new approach to disaster risk reduction that seeks to scaffold disaster preparedness planning. Pre-allocated funding (necessary for rapid mobilization of pre-defined early action) is triggered to support 'just enough, just in time' preparedness, based on scientific (climate) forecasts. FbF is being promoted by the Red Cross Red Crescent (RCRC) Climate Centre to assist the mainstreaming of the early warning–early action model into RCRC disaster management worldwide.[12] Ability to demonstrate economic value from such early warning–early response systems is important to help ensure their long-term sustainability. Assessment of value requires the development of a counterfactual – an assessment of what would have happened if the forecast had not been available.

Measuring the impact of disasters on human and economic outcomes is important because it allows the humanitarian response to be based on concrete information on the type and scale of resources needed as well as to demonstrate the economic and social value of an early, organized response. Actions to measure the predicted or actual health impact of hydro-meteorological disasters pose a significant challenge (Table 2.1) and an agreed set of indicators are needed. According to the United Nations International Strategy for Disaster Reduction,[ii] primary indicators of disasters are: *deaths, missing, injured, exposed* and *economic loss,* with all five indicators taken as cumulative estimates without distinguishing between direct or indirect impacts. Secondary indicators provide greater refinements, for instance, identifying population movements and displacements such as *homeless*, *relocated* or *evacuated*, or other characterizations of the exposed population. By using these secondary indicators, the effects of disasters are counted in terms of the increased exposure of populations to additional morbidity and mortality, such as those derived from impacts on water and sanitation, vector-borne diseases, access to health care, depression, etc., as well as immediate lost lives and injury.

The impact of different types of disasters on health can be complex. Floods, for example, vary in their characteristics (see Box 6.6) and the vulnerabilities of affected populations may also differ. Areas at greatest risk of riverine flooding are low-lying flood plains or river beds located downstream from large catchment areas or dams. Areas at risk of flash floods include densely populated mountainous slopes such as those surrounding Freetown, Sierra Leone, where an estimated 1000 people were killed in a mudslide in August 2017 following an exceptional downpour in a deforested area. Coastal flooding is of greatest concern to countries like Bangladesh where a third of the country was underwater in the summer of 2017 following an unusually heavy monsoon. Many low-lying coastal areas globally are at risk of permanent flooding from sea-level rise in coming decades as a result of climate change.

People are often shocked to learn the extent of the toll on human life exacted by extreme heat each year. Heat waves were responsible for four of the ten deadliest natural disasters worldwide in 2015,[13] and remain the leading cause of declared weather-related disasters in Europe and the United States, outpacing hurricanes, floods and other dramatic weather-events that are usually considered more newsworthy.[14] However, definitions of heat waves and their impact vary from region to region depending on what temperatures the population normally experience; analysis of local health and weather data is necessary to understand temperature thresholds above which action should be taken. In practice, daily temperatures or apparent temperature (an index which describes the 'feels-like temperature' by also incorporating humidity [see Box 4.2[15]]) are most often used, although there are variations in approach.[14] For instance, temperature or apparent temperature are used for forecasts in the United States, Canada and in many European countries.

Hot nights have been associated with increased mortality in some of the most deadly heat waves, so thresholds for high night-time temperatures are often used as an indication of temperature mortality risk (for example in England, Montreal city and Poland). In some countries synoptic circulation systems associated with high heat-related mortality are used to supplement threshold-based heat forecast systems. To have a significant impact on mortality and health events hazardous hot conditions may be required to persist for two to three days to qualify for a heat wave. Once the characteristics of a heat wave at a particular location can be identified then there is the potential to create a locally relevant heat early warning system (see Case Study 7.2). Although heatwaves result in significant short-term health crises, outside of the tropics, seasonally cold weather kills 20 times as many people as hot weather.[16] Cold extremes are much less important in overall winter mortality than milder but non-optimum weather.

Drought disasters differ markedly from other natural hazards such as floods and heat waves – they are slow-onset events, which manifest over months or even years, over spatially diffuse areas, long before their many downstream impacts are felt.[8] Central to most definitions of drought is a deficit of water from a 'norm' for a given spatial area. However, the complexities of drought are reflected in its numerous definitions (over 150 according to researchers concerned with the issue).[17] These definitions differ according to the way drought is measured.

- *Meteorological drought* is defined based on the degree of dryness and the duration of the dry period due to less precipitation than normal.
- *Hydrological drought* is based on the impacts of precipitation shortages on surface or sub-surface (groundwater) water supplies.
- *Agricultural drought* links characteristics of meteorological or hydrological drought to agricultural impacts, where the amount of moisture in the soil no longer meets the needs of a particular crop.
- *Socioeconomic drought* occurs when the demand for a particular economic good exceeds supply as a result of weather-related shortfall in water supply and when water shortages begin to affect people.

The impact of drought on health outcomes may be wide-ranging, and involve multiple pathways including physical (e.g., dust inhalation) as well as nutritional and economic routes.

The disaster community treats epidemics of notifiable diseases (i.e., those reported to WHO) as disasters in their own right – whether or not the origin of the disaster is an unusual weather or climatic event. As a result, epidemics are included under 'natural hazards' in the Emergency Events Database (EM-DAT) that is run by the Centre for Research on the Epidemiology of Disasters (CRED) based at Université Catholique de Louvain (UCL) in Brussels, Belgium (www.emdat.be). Initiated with the support of WHO and the Belgian Government, EM-DAT has become a major global resource for the humanitarian community to rationalize decision-making for disaster preparedness. It also provides an objective base for vulnerability assessment and priority setting.

2.3 Infectious diseases

Epidemics of infectious diseases are those caused by other living organisms such as bacteria, viruses, worms, fungi or parasites living in or on human bodies. Many such organisms may normally be harmless, but under certain circumstances they become pathogenic and may cause mild to severe disease or even death.

Infectious diseases can be transmitted from person to person through a number of routes such as: i) in utero; ii) exchange of bodily fluids (e.g., during sex or blood transfusions); iii) via airborne aerosols (e.g., cough droplets); iv) via disease vectors (such as insects, ticks or snails); or v) through contaminated food or water. Climate may play a significant role in the transmission of many infectious diseases (Table 2.2). However, the importance of its role will depend on characteristics of the pathogen and its mode of dispersal.

In general, the rate at which infections may spread through a human (or animal) population can be captured by two quantities: the *basic reproductive ratio* (R_0), or number of secondary infections produced by a typical case of an infection in a population that is totally susceptible, and the *generation time*, or time between a case becoming infected, and causing other infections.[18] For dengue, R_0 has been estimated at around 5 while the generation time has been estimated at around two weeks. Using these values, if dengue was introduced into an urban population with little immunity, each infection would cause five new cases, so that in four weeks there would be 25 new cases, in six weeks, 125 – and rapid exponential growth will occur until immunity within the population restricts the pathogen's spread. Conversely, if R_0 were less than 1, the infection would go locally extinct: its continued occurrence is only possible from inward migration of infected individuals.

Both R_0 and generation time depend on innate characteristics of the pathogen itself and its mode of transmission, and human behaviour. For directly transmitted pathogens, the rate of contacts between individuals, as well as the probability of transmission on each contact, shape R_0; how long infected individuals tend to be infectious modulates both R_0 and the generation time. Climatic effects on these underlying features thus have the potential to modulate infection spread. Taking the dengue example above, if climatic conditions change to speed up mosquito life cycles, more frequent biting will increase the effective patterns of contact between individuals, thus increasing R_0, and that initial phase of exponential growth could be amplified.

Pathogens that cause epidemics in response to unusual climate conditions are characterized by high R_0 and short generation times, with vectors, pathogens and human hosts each responding quickly to changes in environmental characteristics. A single infective bite of a malaria transmitting mosquito may be sufficient to cause severe disease, even death, in a non-immune individual within two weeks. In epidemic malaria, disease and mortality statistics may be tightly correlated with changing environmental conditions. Rapid transmission cycles are the norm for bacterial, parasitic and viral infections. However, filarial worms, such as lymphatic filariasis (the cause of elephantiasis) or onchocerciasis (the cause of river blindness), have a much slower development rate in the human body and multiple infective bites are needed to infect a host sufficiently to cause disease. As a consequence, while climate drivers may significantly impact filarial worm transmission the relationship with human cases may be obscured by long and uncertain lags between infection and cases.

Climate and infectious disease analysis is dependent on accurate, long-term, historical disease data (either incidence or event data). Measuring the size and scale of infectious disease epidemics is challenging. A recent review identified over 1730 outbreaks/epidemics that have been reported in the WHO African region in the period 1970 to 2016.[19] There are, however, major inconsistencies in the epidemic records used in the report, which limit the use of this database for trend analysis. Challenges include: inconsistent definitions and thresholds for epidemics and outbreaks, inconsistencies between major epidemic databases and poor access to original epidemic reports. Data sources post-1980 indicate a marked improvement over earlier years, but changes in reporting and diagnosis continue to occur. Thus, extreme caution must be exercised when interpreting the trends in disease outbreaks and epidemics in Africa and in other data-poor regions. Painstaking efforts are needed to collate, manage and analyse historical disease data in relation to environmental data. Such analyses have been performed for meningococcal meningitis epidemics in Africa.[20] The Malaria Atlas Project (MAP, www.map.ox.ac.uk), initiated to support ongoing malaria control and elimination activities, has generated an extensive list of data sources that are publicly available and can be used in climate-malaria analyses. Historical records of infectious diseases in domesticated and wild animals are even more problematic than information on human cases. This makes assessment of zoonotic and emerging disease risk from changing patterns of climate and livestock farming in lower and middle-income countries particularly challenging (see Box 2.2).

BOX 2.2 CLIMATE AND LIVESTOCK

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Most of the world's farmed animals are kept by smallholders and pastoralists living in poverty in low and middle-income countries. Between 0.75–1 billion smallholders are concentrated in Asia and Africa.[21] Most are agro-pastoralists, integrating crops and livestock to harness ecological processes such as nutrient recycling and use of crop by-products. On the other hand, pastoralists rely mainly on livestock and use mobility to track scarce and shifting resources. Pastoralists are found from the drylands of Africa to the highlands of Latin America and the plains of Central Asia. They occupy around 25% of the global land area influencing ecosystems and contributing significantly to livestock products and economies.[22] Poverty, livestock keeping and infectious diseases are strongly and positively correlated. Around 60% of all human diseases and around 75% of emerging infectious diseases are zoonotic, that is, transmissible between humans and animals.[23] Impoverished livestock keepers and the consumers of the products they sell and produce bear a disproportionate burden of zoonosis and foodborne diseases.[24]

The high level of poverty and disease experienced by smallholders and pastoralists inevitably increases vulnerability to weather and climate through both direct and indirect effects. Direct effects include reduced livestock capacity to mount a response to infection (e.g., due to heat stress) as well as increased development rates of pathogens and vectors. Indirect effects, on the other hand, are associated with climate-driven ecosystem changes or socio-cultural and behavioural adaptations that could also amplify vector and pathogen development, or increase vector–pathogen–host contact. For example, drought-driven livestock movements have led to large increases of death from diseases to which the animals had no previous exposure.[25] Thirty-eight region-specific climate-sensitive diseases of high priority to poor people have been identified.[26] Among the most important diseases, food-and-waterborne zoonosis were prominent. Also notable were the parasitic endemic diseases that impose a high burden on productivity, water-transmitted leptospirosis and soil associated anthrax. Zoonoses play a prominent role in emerging infectious diseases and a number have been highlighted by the WHO as being amongst the most likely to cause severe outbreaks in the future (Table 2.4). Assessing, mapping and measuring climate-sensitive animal diseases is a pre-requisite to their better management using a 'One health' approach where veterinary, medical and public health professionals work together to prevent the spread of infection.[27]

TABLE 2.4 Emerging infectious diseases that pose a significant risk to health security[28] (many of these diseases are vector borne and/or zoonotic)

Disease	*Transmission*
Crimean Congo hemorrhagic fever virus	Ticks and livestock
Filo virus diseases (Ebola and Marburg)	Bats, person to person (respiratory)
Highly pathogenic emerging coronaviruses relevant to humans (Middle-East Respiratory Syndrome: MERS, coronaviruses and severe acute respiratory syndrome coronavirus)	Person to person
Lassa fever virus	Rats (urine, faeces) and person to person (blood/fluids)
Nipah virus	Bats to pigs to person (contaminated meat)
Rift Valley Fever virus	Mosquitoes (*Aedes* and *Culex* spp.)
Chikungunya virus	Mosquitoes (*Aedes* spp.)
Severe fever with thrombocytopenia syndrome	Ticks and person to person (infected blood/fluids)
Zika virus	Mosquitoes (*Aedes* spp)

2.4 Nutrition

Good nutrition underpins good health. Maternal and infant nutrition depend on ready access to appropriate nutritious foods and the absence of diseases (such as those causing diarrhoea) that reduce the body's capacity to benefit from the food. Both dietary intake and disease are the result of broader drivers including household food security, the adequacy of care and feeding practices (e.g., breast feeding) as well as household environments and the quality of health services (Figure 2.1). Thus, nutritional status, which ranges across a spectrum from healthy to underweight/obese and nutrient deficient, is the result of a large number of basic, underlying and immediate causes, each of which may be climate sensitive.[29]

Consumption of nutritious foods (including all relevant micronutrients) is required to maintain the composition and function of an otherwise healthy individual within the normal weight range. At its most basic level, human health is sustained by vital vitamins and minerals that support normal cellular and molecular functions. Deficiencies in iron, iodine, folate, vitamin A and zinc are widespread and are common contributors to poor growth, intellectual impairments, perinatal complications and increased risk of morbidity and mortality,[31] particularly for women and children. Iron deficiency is the most common and widespread nutritional disorder in the world. As well as affecting a large number of children and women in developing countries, it is the only nutrient deficiency that is also significantly prevalent in developed countries. Over 30% of the world's population are anaemic, many due to iron deficiency in resource-poor areas. Anaemia is frequently

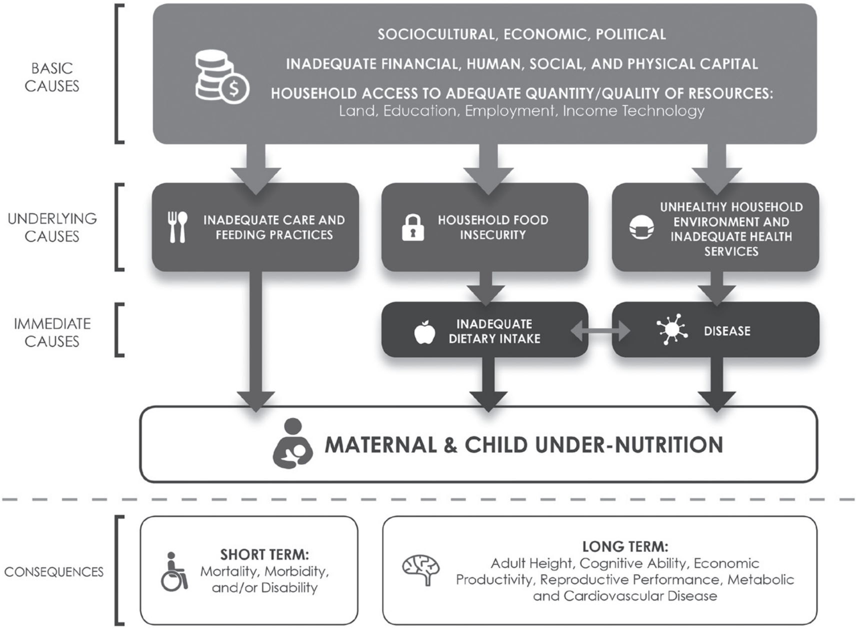

FIGURE 2.1 Basic, underlying and immediate causes of nutrition outcomes. Adapted from the United Nations Children's Fund (UNICEF)[30]

exacerbated by infectious diseases that interfere with iron absorption (e.g., malaria) or directly cause blood loss (e.g., hookworm).

Many factors influence the nutrient and calorific needs of individuals including age, gender, growth, disease states and genetic makeup. At any time, nutritional status may change rapidly as a result of loss in food consumption (e.g., due to loss in nutritious food availability or entitlement), an increase in nutritional requirements (e.g., due to exercise load or pregnancy) or a change in the body's capacity to absorb and metabolize necessary nutrients (e.g., infection with parasites, HIV, cancers, etc.).

Because of its complexity, nutritional status is measured using a range of clinical, social and anthropometric tools. For children, who are the most at risk of protein-energy malnutrition (PEM), anthropometric measures of weight and height have been used for many decades as indicators of malnutrition and potential mortality.[32] When nutritional disequilibrium occurs, it may be followed quickly (e.g., hours to days) by an alteration in processes that are associated with protein and energy metabolism (e.g., resulting in muscle fatigue) and subsequently manifests in changes over days/weeks in a bodyweight that is inappropriate for the child's height (wasting). Chronic malnutrition will result in bodyweights that are inappropriate for the child's age (stunting). 'Underweight' is also sometimes used as an indicator for malnutrition, but as a composite indicator of both stunting and wasting, it may be difficult to interpret. An important but often overlooked nutritional indicator is the weight of a child at birth. Low birthweight (LBW) is a strong indicator of infant morbidity and mortality as well as long-term health issues (see Case Study 2.1).

CASE STUDY 2.1 LOW BIRTHWEIGHT

Madeleine C. Thomson

Low birthweight (LBW) is defined by the WHO as a birthweight of less than 2500 g regardless of gestational age. The prevalence of LBW is 15.5% globally; 96 .5% of which is found in developing countries. Poor maternal nutrition (including iron deficiency) before and during pregnancy is a significant cause of LBW.[33] Other causes include risk factors, such as multiple births, smoking, indoor air pollution and parasitic infections, such as malaria. Measuring LBW is challenging in many settings as births may occur at home in the absence of trained midwives.

In areas of endemic transmission, malaria in pregnancy is associated with severe maternal anaemia and LBW babies. Malaria in pregnancy is commonly associated with placental infection which is highest in prima-gravidae (women who are pregnant for the first time); hence it is their babies who are at highest risk of LBW. The differential birthweight between prima and multi-gravidae can been used to assess the levels of malaria endemicity in a region.[34] In epidemic prone regions, where endemicity is low, both prima-gravidae and multi-gravidae have similar responses to infection and the birthweight differential is minimal, however in endemic regions the birthweight differential can be significant.

For example, a dramatic impact of the El Niño – Southern Oscillation (ENSO) on the LBW differential of prima-gravidae and multi-gravidae coming from an endemic region, Kagera can be observed in hospital records in Tanzania pre and post the 1997 El Niño. Data obtained from the delivery ward in Ndolage hospital, Kagera for the years 1990–1999 showed a significant increase in this differential (155 g) ($P = 0.001$) during April–August 1998, five months after the malaria epidemic which followed the exceptionally heavy short rains of 1997; the biggest ENSO event recorded at that time.[35]

The availability of nutritious foods is dependent on agricultural production, the nutritional content of crops and food safety; each of which may be affected by climate variability, trends and weather extremes. In the absence of irrigation, rainfall is needed to grow crops and even short drought periods at critical growth times can severely affect the harvest. Post-harvest processing may be significantly impacted by insects and pathogenic microbes (such as aflatoxins) that increase in warm and humid environments.[36] High temperatures may reduce the zinc and magnesium content of certain crops.[37]

The impact of climate on agriculture manifests in access to local, home-grown produce or changes in the price of food stuffs grown far away. Reduced production can ricochet throughout trade networks with severe consequences for prices and

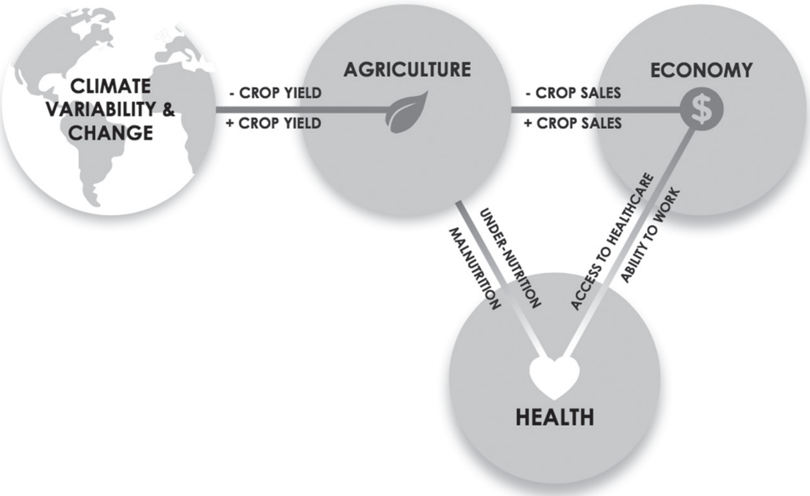

FIGURE 2.2 Relationships between climate, agriculture, economy, nutrition and health in lower and middle-income countries (LMICs)

availability. For example, droughts in Australia and Ukraine in 2007–2008 suppressed grain production and contributed to price spikes in many countries.[38] Significant price hikes for staple crops can have a major impact on nutritional status as families cut back on more nutritious foods to ensure that basic calorie needs are met.[39] Thus, in addition to direct effects, associated with food security and disease, the price of food and the capacity to purchase food, add significant new pathways to climate impacts on nutrition (Figure 2.2).

In response to these direct and indirect climate-related risks a renewed focus on traditional cereals is emerging, which could both achieve nutritional benefits and promote climate-resilient agriculture (see Box 2.3).

The nutritional value of a crop may also be impacted by pests and diseases that are weather sensitive. For example, many important food staples, e.g., maize and peanuts, are prone to contamination by mycotoxins. One example is aflatoxins, toxic secondary metabolites mainly produced by fungal pathogens *Aspergillus flavus* and *A. parasiticus*. Aflatoxins are known to cause liver cancer, and chronic exposure has been linked to other adverse health outcomes including growth faltering in children and kwashiorkor, a severe PEM disease.[44] The population potentially exposed to dietary aflatoxins is an estimated 4.5 billion people, predominantly those living in developing countries, with many chronically exposed at high levels.[45] Conditions that promote the production of the aflatoxin are hot weather and drought stress especially during the flowering and early grain-filling stages and heat and humidity during post-harvest storage. Other

BOX 2.3 CLIMATE AND CROPS

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Production of cereals, which globally provide almost half of the world's calories and cover more than half of all cropland area,[40,41] is vulnerable to drought, floods and other climate extremes. Cereals that are less sensitive to climate variability buffer against such shocks, as well as reduce vulnerability of small-scale farmers to fluctuations for home consumption.

Traditional cereals, such as millet and sorghum, which are grown and consumed in the sub-tropics, evolved in dry conditions with a C4 photosynthetic pathway that is more resilient to drought compared with C3 cereals such as rice and wheat (see below).[42] For instance, sorghum is highly nutritious in terms of iron, zinc and protein particularly when compared with rice.[43] C3 and C4 crops also respond differently to CO_2 fertilization that occurs in association with climate change, with possible consequences for nutritional content (see Chapter 9). Traditional crops such as sorghum and millet were substantially replaced by high-yielding rice and wheat following the Green Revolution beginning in the 1960s. Now, there is a renewed interest in traditional crops because of their nutritious value and climate resilience.

For example, farmers in the Central Highlands of India have recently demonstrated a renewed interest in traditional crops. The territory is characterized by a hot, sub-humid (dry) climate with a highly seasonal monsoon season. Fifty-four million people populate this agricultural region; nearly 70% of whom practice small-scale, rain-fed farming for subsistence and market. As in the rest of India, micro-nutrient deficiencies including iron and zinc are pervasive. The Central Highlands are highly vulnerable in terms of climatic variability and food security. Rice, the dominant monsoon crop in the region, is highly sensitive to climate variability and has the lowest content of protein and iron, when compared with traditional crops (e.g., sorghum and millet). A switch from rice to traditional coarse cereals could potentially provide more nutrition and improve climate resilience although many obstacles, such as production technologies, government subsidies, low yields, cooking habits and consumer preferences, complicate implementation of this win-win solution.[42]

- **C3 plants** are the most common (representing 95% of global plant biomass) and the most efficient at photosynthesis in cool, wet climates. They are most likely to benefit from increased growth due to CO_2 fertilization (see Chapter 9). Their growth becomes limited in hot and water stressed environments. C3 plants include key food staples such as rice, wheat, barley and soya bean.

- **C4 plants** are most efficient at photosynthesis in hot, sunny climates. They are less sensitive to CO_2 fertilization C4 plants are include maize, sorghum, sugarcane, tef and millet.
- **CAM plants** are adapted to avoid water loss during photosynthesis so they are best in deserts. A commercially grown example is agave. As they are adapted to hot and dry environments there is increasing interest in understanding how they can be better exploited for food and fibre in a warmer world.

weather-dependent food safety issues that may undermine nutritional status include *Salmonella* and *Campylobacter*.[46]

Floods may also impact on the underlying causes of poor nutrition by disrupting the availability and access of food to vulnerable groups, changing household activities (e.g., parents seek work away from home) resulting in reduced care for infants and children and changing the environment to increase exposure to disease. Floods may also limit access to health services. Major floods can significantly disrupt local and national economies impacting on household budgets and the tax revenues of governments used to support health systems.

Climate and other seasonal drivers (such as population movement, immune response, school holidays) may have an important effect on health outcomes in human populations. For infectious diseases, even small changes in seasonal drivers can drive large seasonal fluctuations in disease incidence, as a result of the amplifying effects of the inherent non-linear dynamics.[47] Considering the importance of such non-linear effects and the range of potential seasonal drivers, it is essential to distinguish the specific drivers of the seasonal pattern of disease if we are to understand the role of climate (see Box 2.4). The seasonality of the climate is described in detail in § 5.3.3 in Chapter 5.

BOX 2.4 SEASONALITY

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Seasonality drives all aspects of life in rural communities[48] including seasonal changes in nutritional status in populations that rely on household production and local markets. The ‘hungry season’ has long been identified as a period of severe stress to poor rural families that are unable to maintain body weight and function throughout the year. As nutrition is the foundation for health writ large, understanding how seasonal climate drives nutritional status is important for understanding many health issues.

A diversity of infectious pathogens, ranging from influenza to malaria, show clear seasonal fluctuations in incidence, with large numbers of cases concentrated at particular times of year.[49] Such seasonal patterns provide a uniquely repeatable probe for evaluating the association between climate drivers and health outcomes. Yet using this repeatable process to build evidence on climates role in driving disease is complicated by the diversity of ways by which health outcomes can be affected seasonally. For infectious diseases, the effects of seasonal fluctuations can range from direct effects of climatic conditions on pathogen transmission, indirect effects as a result of seasonal human biology or behaviour (including travel) and seasonal timing (with greater investment in control efforts) or disruption (e.g., floods or cyclones) of health system functioning.

Direct effects of climate variables on pathogen transmission

For directly transmitted infections (influenza,[50] chicken pox,[51] meningitis[52]) where transmission substantially relies on airborne movement between hosts (e.g., sneezing), seasonal fluctuations in incidence may emerge because humidity, or other climatic variables, shapes the way in which infectious particles fall out of the air. The onset of increased wintertime influenza-related mortality in the United States is associated with anomalously low absolute humidity levels during the prior weeks.[50] For food or water-borne pathogens, such as cholera or typhoid, seasonality of rainfall, which facilitates contamination, can shape seasonal incidence.[53] Cholera seasonality can also be formed by the biology of copepods whose association with the cholera bacteria is sensitive to seasonally fluctuating environmental variables.[54] Similarly, for *vector-transmitted infections* (malaria, dengue, Lyme disease), the biology of underlying insects or ticks, and their dependence on seasonal fluctuations, is key to understanding how climate seasonality modulates transmission[55]; the same is true of the seasonal biology of non-human reservoir species for some zoonotic pathogens (e.g., mice for hantavirus[56]). Finally, pathogenic species often interact, and although a focal pathogen might not, itself, be climate-sensitive, its abundance might depend on another species which is. For example, seasonally sensitive influenza increases the risk for invasive disease caused by *Streptococcus pneumoniae*,[57] but this latter pathogen might not, itself, be affected by seasonal drivers.

Indirect effects via human biology or behaviour

Many aspects of human biology relevant to health status are seasonal. Seasonality in immune function (e.g., associated with vitamin D metabolism and sunlight[58]) is perhaps the most obvious driver of seasonal fluctuations in human health status. In the ‘meningitis belt’ in Africa, seasonal dust storms which occur during the protracted dry season have been suggested as an important driver of meningitis outbreaks. The proposed mechanism which underpins this relationship is that damage to the human pharyngeal mucosa from the dry and dusty weather eases bacterial invasion[52] (see Chapter 7). The ‘hungry season’ may also affect susceptibility to infection. Poor nutrition prior to the harvest season has been suggested as a possible driver of respiratory syncytial virus (RSV) seasonality in the Philippines, for example.[59] Less directly, conception is seasonal all around the world, for reasons which remain poorly characterized. Since the resulting seasonality in births will result in a seasonality in the replenishment of individuals with no immunity to infection, birth seasonality could allow greater spread of immunizing infections at particular times of the year.[60] A strong relationship between influenza prevalence in the month of birth and prematurity in part accounts for the seasonality of the length of gestation: infants conceived in the USA in May have the shortest gestation, they are likely to be due in mid-February, which is the height of the flu season.[61] Pre-term neonates are also likely to be of low birthweight. Thus seasonality in births interacts with seasonality in infection risk to shape the burden of disease.

Human behaviour is also seasonal in ways that can shape exposure to infectious diseases. A classic example is schooling, known to be a key driver of transmission of directly transmitted childhood infections like measles, as transmission is magnified when children aggregate in schools during term times.[62] Seasonal migration linked to agriculture, fisheries and pastoralism[63] is also widespread, and may shape measles[64] and meningitis[65] dynamics in sub-Saharan Africa. Travel associated with seasonal holidays has also been found to impact the speed at which pathogens are introduced to new communities.[66]

Health system functioning

One of the largest footprints on many infectious diseases’ incidence globally is the impact of control efforts. Since control efforts tend to focus on time periods in which transmission is most intense (e.g., indoor residual spraying may be concentrated during the season of greatest mosquito abundance) timing of interventions is an important consideration in evaluating seasonality in infectious disease incidence. Conversely, events such as hurricanes or flooding may reduce the functionality of health systems during particular times of the year, with roads impassable and health care delivery intractable. The timing of vaccination weeks in Madagascar illustrates this well. Here the timing of interventions, when mothers and children receive many important health care components, is set to be either side of the hurricane season. The timing of vaccination may modulate seasonality in health outcomes.[67]

Observations of seasonal effects on health status have revealed astonishing impacts and intriguing new drivers of human morbidity and mortality. For example, rural Gambian children born during the rainy season are up to ten times more likely to die prematurely in young adulthood than those born in the dry season.[68] Nutrition-related epigenetic regulation in the early embryo may be a highly plausible mechanism for this seasonality in mortality.[69] Epigenetic processes describe changes to the genome that can alter gene expression without changing the underlying DNA sequence and there is strong evidence that these changes can be influenced by a diverse array of intrinsic and environmental factors, including age, disease, stress, exposure to pollutants and nutrition.

Given the importance of seasonality in the climate and other factors in driving disease any study of climate and health interactions should start with an exploration of seasonal drivers.

2.5 Beyond the seasonal climate cycle to multiple timescales

Beyond the cyclical seasonal structure weather and climate vary on multiple timescales, from specific weather events (minutes to hours) to daily, seasonal, decadal and long-term climate change timescales. The best studied example of the way the climate interacts with society on multiple timescales is the African Sahel (Case Study 2.2). These different timescales will be discussed in greater detail in Chapters 5–9.

CASE STUDY 2.2 DROUGHT IN THE SAHEL

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The majority of the rains in the African Sahel fall between July and September. The amounts vary considerably from year to year, but are potentially predictable given the proven influence of global sea surface temperatures, including those in the Central and Eastern tropical Pacific associated with ENSO events.

Extreme drought years occurred in 1972 and 1982–1984 (Figure 2.3). These droughts, which were embedded in a longer drought cycle, resulted in widespread food insecurity and severe malnutrition, population movement and loss of traditional livelihoods as the herds of pastoralists were decimated. Human mortality due to famine was rife.[70] The longer (decadal) drought cycle is also associated with sea surface temperatures, only this time in the oceans around Africa, including the warming Indian Ocean.[71] The observable long-term drying trend for the region might suggest that the climate change signal for the region is towards reduced rainfall.

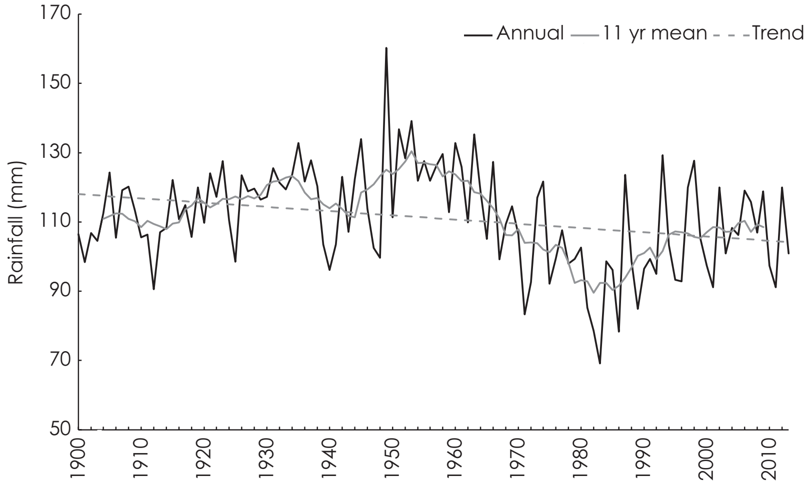

FIGURE 2.3 Rainfall variability in the Sahel at multiple timescales. Rainfall data from UEA/.CRU/.TS3p23

However, there is now compelling evidence that the 1970s–1980s' drought was in part due to the impact of aerosols from industrialized societies on the North Atlantic Ocean sea-surface temperatures.[72] These multiple timescale influences on seasonal climate have significant implications for climate change attribution. The recent recovery of rainfall in the Sahel, after the devastating droughts, may be in part a natural decadal cycle with origin in internal oceanic processes, in part attributable to the reduction in aerosols due to pollution control. One outcome of the drought was a greater than 80% decline in malaria prevalence in the semi-arid areas of northern Senegal and Niger from the early 1960s to the mid 1990s.[73] The drought, and associated land use changes, resulted in a loss of vector breeding sites, lower vector survivorship and ultimately the disappearance of the malaria vector species *Anopheles funestus*. The overall result was a shortening or reduction in intensity of the malaria transmission season.

The idea that modification of sea surface temperatures (SSTs) by anthropogenic emissions is the driving force behind late 20th century drought contrasts dramatically with earlier perceptions. Prior to the focused climate research, responsibility for these regional drought disasters had been put predominantly upon the shoulders of local peasant farmers, whose overuse of the land was deemed to have resulted in reduced vegetation cover, the advance of the desert and localized impacts on the regional climate regime.[74] Emerging evidence relating drought to anthropogenic aerosols shifts the blame to industrialized countries while indicating that the Sahel's future might be wetter under climate change in the absence of aerosols.

Different external drivers are associated with these timescales – weather, for instance is predominantly associated with atmospheric influences whereas seasonal and decadal changes in the climate are driven primarily by changes in the temperatures of the oceans. Long-term trends in climate, consistent with climate change impacts, are strongly influenced by anthropogenic forcing, including carbon emissions. Predictability at different timescales varies according to these underlying drivers (see Table 5.1).

2.6 Population vulnerability

Some groups of people are inherently more vulnerable to the impacts of weather and climate events and associated environmental hazards than others. The elderly or very young, the sick, and the physically or mentally challenged are vulnerable. A number of physiological, psychological, cultural and socioeconomic factors contribute to this vulnerability including poverty and social marginalization, Women, who globally are socially and economically disadvantaged, may be vulnerable to weather and climate extremes through reproductive factors (pregnancy and lactation) as well as sexual and domestic violence, which commonly follow disasters.[75] Their greater responsibilities as care-givers to other vulnerable groups (elderly parents, children and the sick) also increases women's vulnerability to disasters and in part explain their higher risk of dying.[76] Older adults have a higher prevalence of certain diseases, medical conditions and functional limitations that put them at risk of hydro-meteorological events; these include increased social isolation, poverty and higher sensitivity to extreme heat.[77] The effect of hot weather on the human body is determined not only by temperature, but by humidity, wind speed, cloud cover and night-time vs day-time conditions. Heat exhaustion may be followed by heat stroke when temperatures are extreme. Hot and humid nights are particularly associated with increased mortality as individuals' ability to stay cool may be limited. Children are also particularly vulnerable to excessive heat because of their small size and dependency on others.

2.7 Conclusions

Natural climate variability has always been important in human development. While year-to-year variations in rainfall and temperature cause significant challenges to many aspects of human health and well-being the stark seasonality of the climate in rural areas in many developing countries is the primary source of climate impacts on health. Here populations undergo seasonal (i.e., highly predictable) dramatic changes to health and well-being including hunger, nutritional deficiencies, disease, livelihood loss, migration and debt. Seasonal forecasts may indicate likely shifts in the probable outcome of the rainy season but the underlying season will still dominate the health response. Climate change may impact on the length and intensity of the rains, but the underlying seasonal patterns will remain as these are determined by factors that are not amenable to significant change. Even in urban areas in developed countries seasonality governs many aspects of health, from the timing of epidemic flu and heat-associated cardiovascular crises to the risk of fractures from falls on ice. The occurrence of extreme events, such as those precipitated by hurricanes or cyclones, has a marked seasonality to their occurrence. Hippocrates' statement, over 2000 years ago, that medical students should understand the importance of seasonality when considering health issues[78] is still relevant today. In the context of a changing climate seasonal challenges will continue to be significant while new threats to health emerge.

In Chapter 2 we have explored some of the many ways in which climate impacts on health; focusing on the health outcomes of hydro-meteorological disasters, infectious diseases and nutrition. Having identified a problem that is climate-sensitive, the subsequent chapters in this book should help the reader to consider how, when, where and why climate information might be used to mitigate some of the risks and improve the health of vulnerable populations.

Notes

i https://public.wmo.int/en/resources/library/climate-services-health-case-studies.
ii www.irdrinternational.org/wp-content/uploads/2015/03/DATA-Project-Report-No.-2-WEB-7MB.pdf.

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