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CLIMATE CHANGE IMPACTS FOR UKRAINE

Acknowledgements

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Front cover	The Southern Bridge across the Dnieper in Kiev, the capital of Ukraine. (Shutterstock 1178833933).
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Back cover	Pink rhododendron flowers on a sunny day. Location Carpathian Mountains, Ukraine, Europe. (Shutterstock 1854809887).

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Acronyms

AR5	IPCC 5th Assessment Report
AR6	IPCC 6th Assessment Report
CMIP	Coupled Model Intercomparison Project
CORDEX	CoOrdinated Regional climate modelling Downscaling EXperiment
COVID	Coronavirus-19
ECMWF	European Centre for Medium-range Weather Forecasts
EU	European Union
EURO-CORDEX	European branch of the CORDEX initiative
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
FCDO	Foreign, Commonwealth & Development Office (UK Government)
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contributions
ODI	Overseas Development Institute
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

Preface

At the request of the British Embassy Kyiv and funded by the UK's Foreign, Commonwealth and Development Office (FCDO), this report builds on work published by the Met Office in 2010 on the impacts of climate change for Ukraine [1], which described impacts on the key sectors of water and food security, energy and infrastructure, and the natural and built environment. This report provides updated projections on climate change impacts in Ukraine associated with future global warming and new information on the impacts of climate change across sectors, including on human health and in Ukraine's cities.

The content and format of the report has been informed by engagement with the Government of Ukraine, including a stakeholder consultation workshop in May 2021 with government ministries, the Ukrainian Hydrometeorological Institute, Odessa State Environmental University, and Ukrainian think tanks. The report is intended to inform climate policy and risk management in priority economic sectors in Ukraine. The headline messages were provided to the British Embassy Kyiv for sharing with key stakeholders to support negotiations at the 26th Conference of the Parties (COP26) of the United Nations Framework Convention on Climate Change (UNFCCC).

Headline Climate Statements	
Temperature	• Ukraine and the surrounding region have warmed by almost 1.5°C over the last 30 years. 2020 was Europe's and Ukraine's hottest year on record. • Annual mean temperatures are projected to increase by 1.2°C to 3.0°C by mid-21st century and by 1.6°C to 3.5°C by late-21st century under a moderate greenhouse gas concentration scenario (RCP4.5), compared to the late-20th century. • Annual mean temperatures are projected to increase by 1.7°C to 4.1°C by mid-21st century and by 3.4°C to 6.2°C by late-21st century under a high greenhouse gas concentration scenario (RCP8.5), compared to the late-20th century.
Extreme Temperature	• The number and severity of heatwaves have increased in Ukraine in recent decades and are projected to further increase in the future. In a 4°C warmer world, heatwaves which previously occurred once-in-50 years may occur nearly every year. • The number of days of frost is projected to decrease, with some areas no longer experiencing any frost days by the late-21st century.
Precipitation	• Annual rainfall is variable across Ukraine, with large year-to-year variability leading to some very wet years and some very dry years. This variability is expected to continue into the future. • There is potential for large decreases in summer rainfall, especially for southern and south-eastern Ukraine, by the late-21st century. • There is potential for an increase in winter rainfall, especially across northern Ukraine. Despite increasing winter precipitation, projections show potential for decreased snow cover extent and snow pack and reduced runoff from less available water during the Spring melting season in western mountainous regions in a warmer climate.
Extreme Precipitation	• The frequency and intensity of very heavy rainfall events is projected to increase by 10% to 25% by the late-21st century.

Headline Impact Statements	
Agriculture and food	• Increasing temperatures and projected increases in winter season rainfall may increase the productivity of agricultural production, though productivity increases only apply to lower warming levels associated with lower greenhouse gas concentration scenarios. • Increasing temperatures and projected decreases in summer season rainfall are likely to result in increasing aridity and heat stress, negatively affecting agriculture and food systems over the 21st century.
Water	• Water-stressed regions in Ukraine are experiencing more prolonged heatwaves and a longer summer season than in the 20th century. • Increased water scarcity in southern and eastern Ukraine will increase pressure on existing waterways exposing more of the population to contaminated water supplies. • Projected decreases in snow pack in the future are likely to change the timing and amount of runoff from mountainous areas, that may reduce the risk of river flooding in some basins.
Health	• More intense and frequent heat extremes, together with declining air quality, will increase the risk of heat-related mortality and productivity losses.
Ecosystems	• Marine ecosystems and biodiversity in the Black Sea and Sea of Azov are under threat from climate change. Waters have warmed by more than 1°C in the last 20 years and under a high greenhouse gas concentration scenario warming of up to 5°C is plausible by the end of the 21st century, further threatening marine ecosystems. • Deforestation and increasing temperatures have been linked to increased fire risk, with fires occurring more often and being more intense. Fire risk will continue to increase in the future as temperatures rise, particularly in scenarios where summer rainfall decreases.
Energy and infrastructure	• Projected increases in temperature, water scarcity and extreme events are expected to both increase demand for energy and threaten supply through placing infrastructure under stress. • Increases in the frequency of heavy rainfall events are expected to increase the risk of flash flooding events which damage infrastructure and properties.
Changes over time	• Most negative climate change impacts projected for the 21st century are expected to be greater under higher greenhouse gas concentration scenarios. • Impacts from climate change will be affected by a complex range of other factors, such as planning decisions and demographic change.

1 Introduction

Ukraine is already experiencing a changing climate. 2020 was Europe's and Ukraine's hottest year on record, at 2.8°C above average, and each of the last 20 years in Ukraine were warmer than the long-term average (see Figure 1) [2]. Since 2010 Ukraine has experienced a range of climate-related impacts such as severe drought, extensive flooding, and devastating fires, resulting in loss of life and livelihoods, and negatively impacting GDP [3].

Ukraine's primary exports are agricultural goods, especially wheat, as well as iron ore and steel. Ukraine is also an important transit country for the Eastern European energy market and is one of the region's largest hydrocarbon producers [4]. All key socio-economic sectors are currently exposed to climate-related extreme events such as extreme heat events, fires, and flooding, and many communities are vulnerable to expected future changes in climate over the coming decades [5]. At the same time, improved information and knowledge about the nature of expected changes provides Ukraine with opportunities to adapt, enhancing agricultural productivity and transforming the energy sector, with improved outcomes for the natural environment and for human health and well-being.

The projected climate impacts detailed in this report are intended to educate and inform the Government of Ukraine as well as the wider public and businesses about the range of impacts Ukraine can expect under a warming climate. The aim is to motivate and inform national climate change adaptation planning, as well as broader economic policies and initiatives to build Ukraine's climate resilience.

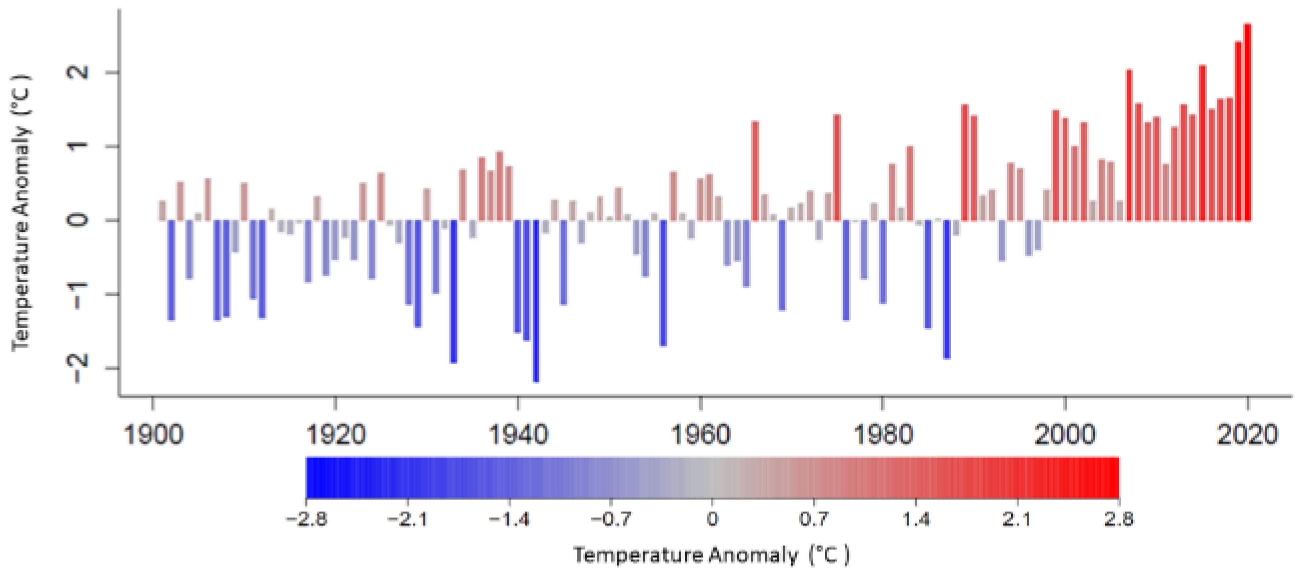


Figure 1 *Change in annual temperature for Ukraine since 1901; warmer than average years are shown as red bars, cooler than average years with blue bars. The larger the bar the greater the difference from an average year, where the reference period for the anomalies is 1961 – 1990. The data comes from the [Berkeley Earth temperature dataset](http://berkeleyearth.lbl.gov/auto/Regional/TAVG/Text/ukraine-TAVG-Trend.txt)[i].*

[i] Berkeley Earth temperature dataset: http://berkeleyearth.lbl.gov/auto/Regional/TAVG/Text/ukraine-TAVG-Trend.txt

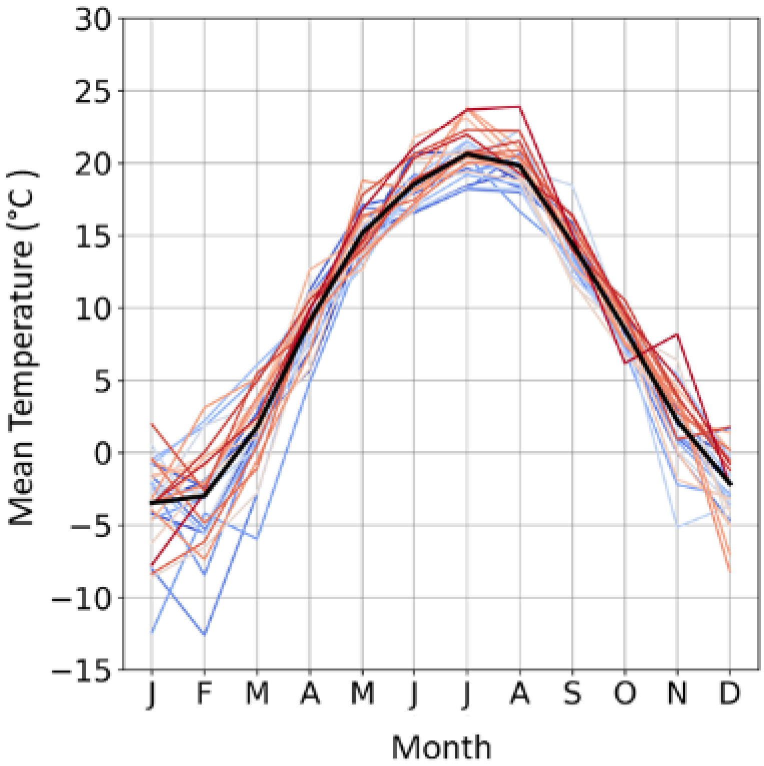
2 Current Climate of Ukraine

Ukraine experiences a largely temperate climate with cold winters and warm summers. The southern coastal regions along the Black Sea and Sea of Azov having a subtropical Mediterranean climate. Average summer (May-August) temperatures range from 18°C to 22°C across the country (Figure 2, temperature), with the warmest average temperatures in the Crimean Peninsula. Average winter (December-March) temperatures range from -5°C to 2°C across the country, with the coldest temperatures experienced in the northeast [3]. Precipitation is experienced all year-round with higher precipitation amounts in the summer in northern regions and southern regions experiencing higher precipitation in winter (Figure 2, precipitation). The mountainous north and western areas are the wettest regions of Ukraine, characterised by heavy summer season precipitation with annual totals up to 1600mm in the Carpathian region and heavy snowfall during the winter months, whilst the south and southeast of the country experience very little precipitation in summer months [3,6,7]. A large network of rivers crosses the country flowing into the Black Sea, with significant rivers including the Dnipro, which provides an estimated two thirds of all water resources to Ukrainian agriculture and industry as well as supporting more than 30 million people, and the Pripyat and Desna, which flow into the Dnieper Estuary and provide an important source of hydropower [8,9].

2.1 Observed Trends

Climate change has resulted in a number of observed changes in the central-eastern European region, including Ukraine, with annual air temperatures increasing by almost 1.5°C over the last 30 years [10] and the last decade seeing an acceleration in the rate of warming [11]. Warming is also unevenly distributed, with rates of warming fastest over Ukraine compared to surrounding regions. Figure 2 shows that temperatures have risen over time, with recent years (coloured in red) warmer than the earlier years (coloured in blues), while no trend is visible for precipitation. For temperature, variability from year-to-year is small, with the greatest variability during the winter season. For precipitation, year-to-year variability is much more pronounced, with large differences in monthly totals.

The frequency of hot extremes is increasing and the frequency of cold extremes is decreasing in central-eastern Europe, including Ukraine, because of climate change, against a background of increasing annual mean temperatures and changing rainfall patterns [12,13]. This is increasing the prevalence of heatwaves, water stress, and weather-related disruptions to transport and energy networks, as well as impacts from increasing frequency of flooding on sectors such as agriculture, infrastructure, and human health [14,15].



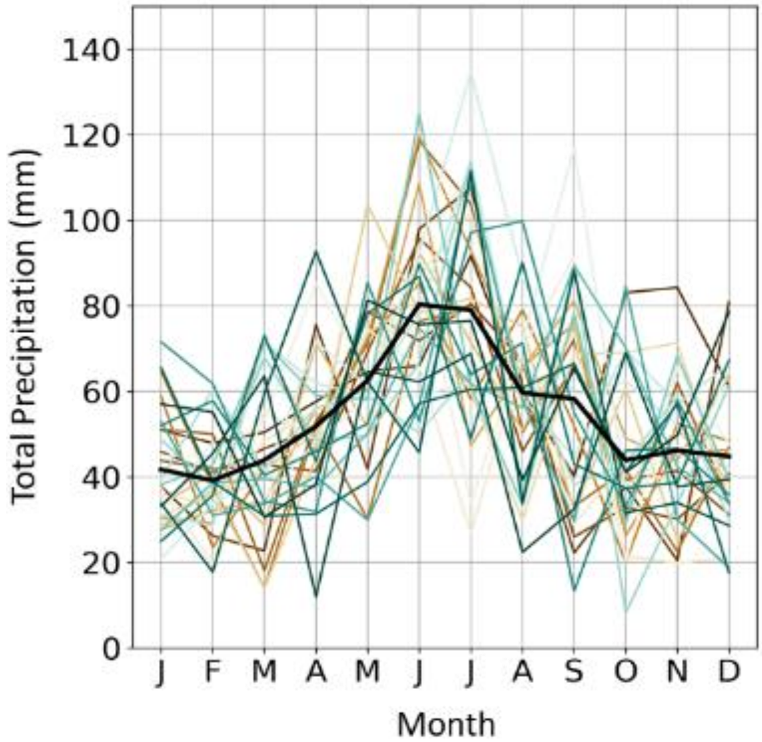


Figure 2 *Observations for Ukraine from the ERA5[i] reanalysis dataset [16] for the 30-year baseline period 1981 – 2010, which is the period used in this report to describe the average climate of Ukraine. Plots show (left) average daily temperature (°C); and (right) total monthly precipitation (mm). Each year is represented by a single line, coloured from earliest in the time period to most recent (blue to red for temperature, brown to green for precipitation). The bold black line indicates the 30-year average.*

2.2 Recent High Impact Events

Ukraine is highly vulnerable to riverine, pluvial, and coastal flooding with impacts including flooding of agricultural and urban areas, mudslides and mudflows, and changes to the landscape. Whilst reduced snow cover and spring snow melt from warmer winters has contributed to a decrease in extreme riverine flooding across the region including and surrounding Ukraine [17], Ukraine has experienced several devastating floods in recent decades (in 1998, 2001 and 2008) [18]. In July 2008 one of the biggest and most destructive floods on record occurred in the Carpathian region, resulting in 47 fatalities and the evacuation of ~40,000 people [19,20]. In June 2020, floods in Western Ukraine resulted in over 14,000 homes being damaged [21], along with major infrastructure damage; an estimated 500km of roads were damaged and some routes were destroyed [22].

Regions previously unaffected by droughts are recording drought conditions driven by increased water demand and increasing water scarcity, including the northern and north-eastern agricultural regions [23]. Most recently in the period since September 2019, warmer than average temperatures and a prolonged rainfall deficit have placed the south-west and central Ukraine into drought [24,25], with expected reductions in crop yields [26,27]. In 2003 and 2007, drought events generated losses in grain production estimated at ~€3 billion [28,29]. Drought also has significant impacts on soil erosion and degraded soil conditions, health and hygiene, and the economy. Increasing temperatures are also reducing the number of spring frosts positively impacting cereal crop yields such as spring wheat in the agricultural sector [30].

Increases in the number of dry days, combined with increasing heat, has increased the risk of wildfires in Ukraine over the last decade [31]. In the decade since 2007 the average annual burned area of Ukraine's forests has increased from 4.4 thousand hectares to 5.9 thousand hectares compared to the previous decade [32], consistent with the increase in fire risk observed across Europe [33]. The rate of destruction of Ukraine’s forests from fire is increasing, with the 2020 fire season burning three times the average annual burned area. In 2020 a warm and dry winter and strong spring winds contributed to the spread of wildfires in the Chernobyl exclusion zone which burnt through almost 11.5 thousand hectares [34,35].

Ongoing military conflict in eastern Ukraine has resulted in destruction of forests and agricultural land, potentially exacerbating the severity and impact of wild fires [36]. Military conflict has also placed communities in the region under considerable stress through compromised water quality and availability from destruction to mineral extraction mines [37]. In 2020 firefighters struggled to contain the spread of wildfires in the Luhansk conflict zone, which destroyed properties and caused the evacuation of many villages [38]. Ongoing military conflict further reduces resources available for responding to high impact weather events when they do occur, reducing adaptive capacity and eroding resilience.

3 Future climate projections for Ukraine

There is now a substantial evidence base for understanding future climate change in Ukraine, developed through successive rounds of modelling studies included in the Intergovernmental Panel on Climate Change (IPCC) assessment reports [39], most recently in the Sixth Assessment Report (AR6) in 2021 [5], as well as regional modelling studies such as EURO-CORDEX [40]. These studies look at the response of the climate system, as represented in complex climate models, to differing rates of change in atmospheric greenhouse gas (GHG) concentrations, typically called concentrations scenarios[ii].

Over the past decade there have been considerable advances in scientific understanding and representation of processes in climate models, as well as significant technological improvements to the supercomputing infrastructure making models run faster and at higher resolutions. Improvements to global climate models mean that the impacts at regional scales, such as for Ukraine, can be better understood by scientists. With these advances has come a better understanding of the sensitivity of our climate to changes in factors that influence the climate (e.g., GHGs), and the latest generation of climate models used to provide results in the IPCC AR6 report indicate that impacts may be more extreme, or be experienced sooner, than previously thought [41]. For decision makers this means that there is a more urgent need to plan for these more extreme potential futures.

3.1 What are climate projections?

A climate projection is the simulated response of the climate system to a future scenario of changing GHG concentrations and other factors that influence the climate (e.g., pollutants in the atmosphere). Climate projections are produced using climate "models"; complicated mathematical models of the atmosphere, ocean and land system run using high-performance computers.

Future changes in atmospheric GHG concentrations depend on the choices made and implemented by governments and people around the world (e.g. demographic and socioeconomic development, technological change) [39], and how natural systems such as the oceans and forests cope with increased GHGs. Scientists deal with this uncertainty by modelling different plausible future GHG and aerosol (airborne particles, such as dust or smoke) emissions scenarios in climate model experiments. Typically, climate projections sample a range of future scenarios, including scenarios where efforts are made to substantially curb human-caused GHG emissions (e.g. in line with the Paris Agreement of the UNFCCC [42]), and scenarios in which emissions continue to increase or are reduced very slowly.

Representative concentration pathways (RCPs) – used in the climate model experiments reported here – are time-series of changing concentrations of GHGs, aerosols and chemically active gases, resulting from emissions and changes to land-use [43]. The word representative signifies that each RCP provides only one of many possible emissions and land-use scenarios that would lead to a specific "radiative forcing" (i.e., change in energy flux in the atmosphere, measured in Watts per square metre) produced by the end of the 21st century due to an increase in GHGs. There could potentially be many different emissions scenarios resulting in a single RCP.

Projections are typically reported as changes in the statistics of future climate, such as the change in the average (or mean) temperature calculated for a 30-year period in the future, relative to a baseline climate for a 30-year period in the recent past. Because of natural variations from year to year (e.g., a hot summer can be followed by a cooler summer), standard 30-year climatological periods are used to calculate averages in

[ii] For more information on greenhouse gas concentration scenarios please see the Met Office Guide to Representative Concentration Pathways: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---representative-concentration-pathways.pdf

temperatures, precipitation, and other variables. Additional statistics, such as the number of heatwaves experienced over a 30-year period, are also calculated for comparison over time. These 30-year climate statistics can be calculated at any spatial scale (e.g., local, national or global levels) both for historical periods, known as 'baselines', as well as for future periods at time horizons of interest to decision-makers. The World Meteorological Organization (WMO) defines standard historical baseline periods to assist in the coordination and comparability of research and reporting globally [44]. The IPCC defines future periods of interest for projections, updating them for successive rounds of IPCC Assessment Reports. To date, most peer reviewed literature examining climate change impacts has been published using the 1981-2010 baseline, used by the WMO and in the IPCC Fifth Assessment Report containing climate projections using different RCPs.

3.2 Projected Changes in Ukraine's Climate

In this report, projected changes in temperature and rainfall for Ukraine are primarily taken from climate models that were used in the IPCC Fifth Assessment Report (AR5) – model simulations conducted for phase 5 of the Climate Model Intercomparison Project (CMIP5)[iii]. The results are accompanied by new insights synthesised from assessments of the latest generation of climate model projections, used in the IPCC AR6, at global and regional scales.

***Table 1** Projected annual and seasonal changes in surface air temperature for Ukraine. Changes are from a baseline period of 1981-2010 and are given as a range of the 10th and 90th percentiles from an ensemble of 31 CMIP5 climate models, calculated as spatially averaged means for Ukraine for the RCP4.5 (shaded blue) and RCP8.5 (shaded red) GHG concentration scenarios. Changes are reported for two future time periods, a mid-century period denoted 2050s (average over the period 2041-2070) and a late-century period denoted 2080s (average over the period 2071-2100).*

Temperature changes (°C)				
Season	2050s, RCP4.5	2050s, RCP8.5	2080s, RCP4.5	2080s, RCP8.5
Dec - Feb	+0.7 to +3.3	+1.6 to +4.2	+1.6 to +4.3	+3.5 to +7.3
Mar - May	+0.8 to +2.9	+1.5 to +3.8	+1.3 to +3.3	+2.7 to +5.7
Jun - Aug	+1.3 to +3.5	+1.7 to +4.9	+1.4 to +4.5	+3.3 to +7.7
Sep - Nov	+1.1 to +2.8	+1.8 to +3.9	+1.6 to +3.4	+3.4 to +6.2
Annual	+1.2 to +3.0	+1.7 to +4.1	+1.6 to +3.5	+3.4 to +6.2

Projected changes are reported for mid-21st century (2050s, a 30-year period from 2041 to 2070) and late-21st century (2080s, a 30-year period from 2071 to 2100) under a moderate GHG concentration scenario (RCP4.5) and a high GHG concentration scenario (RCP8.5), relative to a 30-year baseline of 1981-2010. While the exact amount of warming is dependent on both the amount of GHGs emitted and the rate of emissions reductions throughout the century [45], the high GHG concentration scenario is broadly consistent with late-21st century global warming of between 3°C and 5°C, and the moderate GHG concentration scenario with global warming of between 2.5°C and 3°C [46]. An additional GHG concentration scenario (RCP2.6) is associated with strong mitigation to reduce emissions results in late-century global warming of 1.7°C to 1.8°C, in line with ambitions to limit global warming to well below 2°C [47]. Regional assessments of the impacts of climate change for this scenario are limited but information has been included in the report where evidence is available in the literature.

Results for temperature changes in Ukraine are shown in Table 1 and precipitation changes are shown in Table 2. To demonstrate the regional differences in spatial patterns across Ukraine, output from four selected

[iii] For details of the CMIP5 models and analysis conducted for Ukraine in this report please see the Appendix of the joint Met Office, ODI and the FCDO Risk Reports, available from https://www.metoffice.gov.uk/services/government/international-development/climate-risk-reports

climate models under a high GHG concentration scenario (RCP8.5) are shown in Figure 3 – selected as they broadly span the range of potential futures, not because the models are more or less reliable than others.

3.2.1 Changes to average and extreme temperatures

By the 2050s, average temperatures across Ukraine are projected to increase from 1.2°C to 3.0°C under a moderate GHG concentration scenario (RCP4.5), and from 1.7°C to 4.1°C under a high GHG concentration scenario (RCP8.5), compared to the end of the 20th century (see 'Annual' row, Table 1). By the 2080s, average temperatures are projected to increase from 1.6°C to 3.5°C under a moderate GHG concentration scenario (RCP4.5), and from 3.4°C to 6.2°C under a high GHG concentration scenario (RCP8.5), compared to the end of the 20th century (see 'Annual' row, Table 1).

***Table 2** Projected annual and seasonal changes in rainfall for Ukraine for all seasons and calculated annually. Changes are from a baseline period of 1981-2010 and are given as a range of the 10th and 90th percentiles from an ensemble of 31 CMIP5 climate models, calculated as spatially averaged means for Ukraine for the RCP4.5 (shaded blue) and RCP8.5 (shaded red) GHG concentration scenarios. Changes are reported for two future time periods, a mid-century period denoted 2050s (average over the period 2041-2070) and a late-century period denoted 2080s (average over the period 2071-2100).*

Precipitation changes (%)				
Season	2050s, RCP4.5	2050s, RCP8.5	2080s, RCP4.5	2080s, RCP8.5
Dec - Feb	-1 to +15	-2 to +17	0 to +20	0 to +28
Mar - May	-5 to +22	-4 to +22	-2 to +23	-6 to +27
Jun - Aug	-20 to +14	-26 to +10	-19 to +10	-44 to +6
Sep - Nov	-8 to +11	-13 to +13	-11 to +15	-17 to +11
Annual	0 to +10	-6 to +10	+1 to +12	-7 to +14

Figure 3 shows spatial changes projected for Ukraine, associated with different levels of global warming. It shows that central and northern Ukraine are projected to experience the highest rates of warming, while coastal regions experience lower increases due to the moderating effect of the Black Sea and Sea of Azov.

The frequency and intensity of heat extremes is also projected to increase over the 21st century under all GHG concentration scenarios, with more very hot days and warm nights, as well as increasing warm spells [39,48,49]. For example, in a high GHG concentration scenario, the Donetsk region is projected to experience an increase in the number of hot days warmer than 35°C [50]. Currently, the Donetsk region experiences 1 such day per year on average. However, this is projected to increase to almost 20 days each year by late-century.

Warming temperatures over coming decades are projected to result in decreases in the number of frost days, with some areas becoming frost-free [49,51]. The timing at which these thresholds are reached is dependent upon the rate of warming, with thresholds reached sooner at higher GHG concentration scenarios. The reduction in days of frost by the 2080s under a high GHG concentration scenario is over 1.5 times more rapid than for a moderate GHG concentration scenario [50].

3.2.2 Changes to average and extreme precipitation

Projected rainfall changes for Ukraine vary between seasons, and seasonal changes may not easily be distinguished from existing year-to-year variability by the mid-21st century. Most models show potential for large decreases in summer rainfall for southern and south-eastern Ukraine by the 2080s and an increase in winter rainfall across northern Ukraine for all GHG concentration scenarios (see seasonal changes in Table 2, and spatial changes in Figure 3), though little to no change in rainfall for these seasons is also possible. Evidence shows more confidence of decreasing rainfall towards the coastal regions and the greatest potential for increases in the north of Ukraine in a warmer world (Figure 3).

Despite the range of plausible future changes in average rainfall, rainfall extremes in all seasons are projected to become more intense [49,52], and are associated with projected increases in surface water and flash flooding under all GHG concentration scenarios [51]. Late-century increases in the wettest-day in a year of between 10% and 25% are plausible under all GHG concentration scenarios, with the larger increases occurring under the higher scenario [49,50].

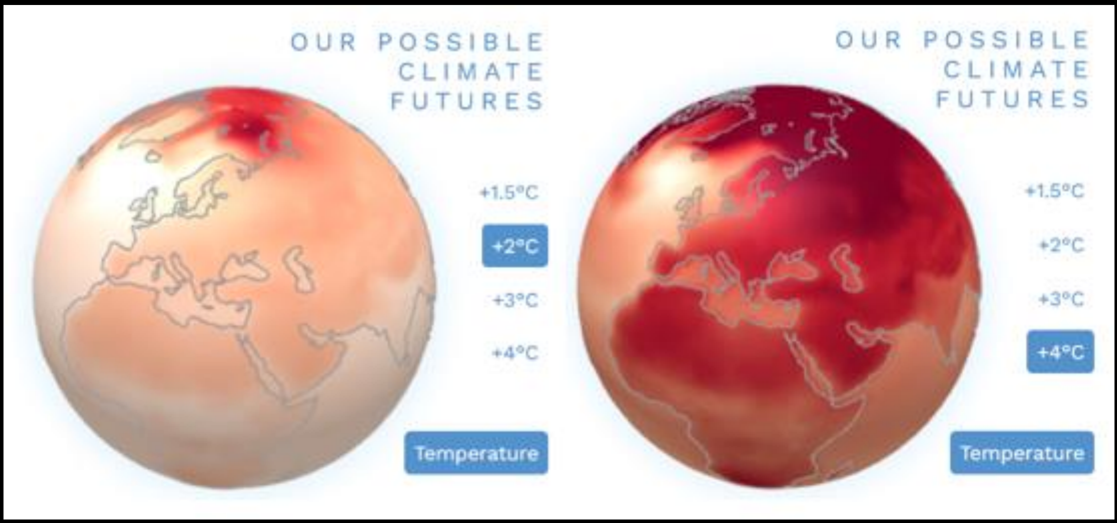
3.2.3 Hydrological changes

A reduction in average total rainfall driven by large reductions in summer rainfall, as well as decreases in snowpack which will change the timing and amount of runoff from mountainous areas, would lead to a decreasing risk of river floods [17,49,52]. Runoff and ground water recharge are also projected to decline in most GHG concentration scenarios, associated with reductions in annual rainfall, and evapotranspiration rates that are projected to increase with increasing temperatures [51]. This would lead to reductions in soil moisture content and further degradation of land and steppes across Ukraine, as well as potential for longer duration and more severe drought conditions [53,54].

3.2.4 Fire risk

Weather conditions most suitable for the ignition and persistence of fires is projected to increase [51], with an expansion of the proportion of the year when conditions are most conducive to wildfires associated with increasing temperatures and a drying landscape. The projected increases in the number of hot days, along with projected changes in rainfall patterns in Ukraine will have a significant impact on increased fire risk in the future. Recent studies have identified several regions in Ukraine which are vulnerable to forest fires including Kherson, Luhansk, Kyiv, Donetsk, Zaporizhzhia and Dnipropetrovsk [31,55].

3.3 What would a 2°C or 4°C warmer world look like for Ukraine?

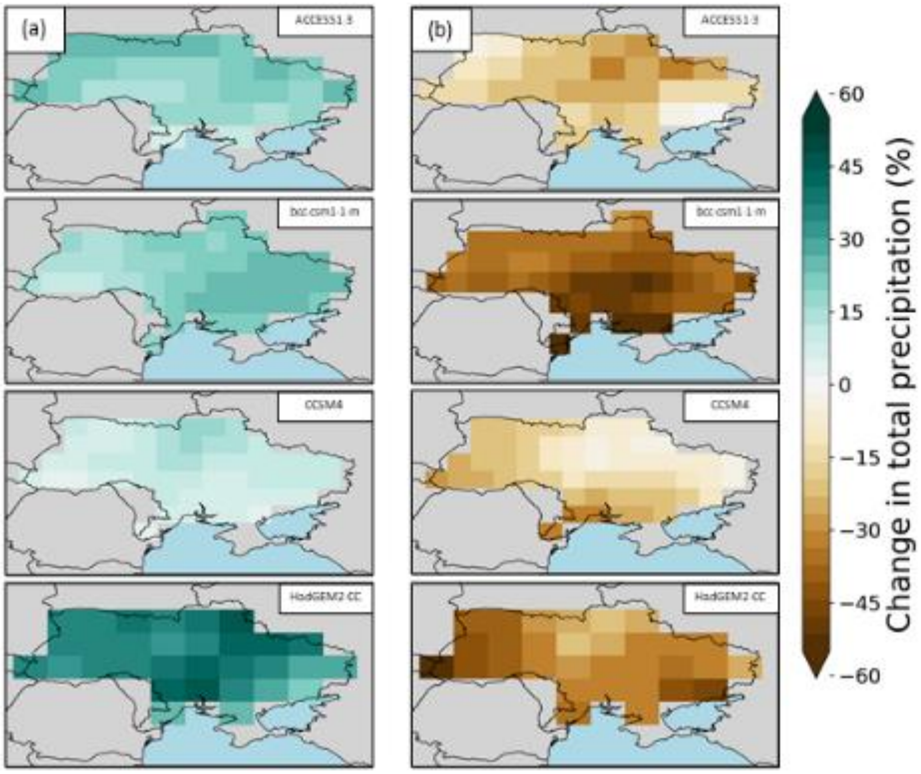


Images taken from IPCC AR6 Interactive Atlas: https://interactive-atlas.ipcc.ch/

As temperatures increase, the impacts are not spread uniformly across the globe. In recent decades eastern-central Europe has experienced greater warming than surrounding regions, with Ukraine in particular experiencing a higher level of warming. Under the UNFCCC Paris Agreement governments have committed to limit global warming to well below a 2°C threshold compared to pre-industrial levels, but the latest IPCC reports and assessments of expected emissions show that current ambitions are insufficient to rule out warming exceeding 4°C [124]. It is therefore important to consider how a global average temperature rise of 2°C or 4°C would impact Ukraine.

Research indicates that in a 2°C warmer world eastern-central Europe will experience higher warming than the global average, including up to 3°C warmer during winter, as well as more intense and frequent heat extremes [125]. Analysis of model results indicates that in a 4°C warmer world, regional patterns of warming and seasonal rainfall changes will be further amplified, with heat events which previously occurred once-in-50-years occurring nearly every year [5]. Migration of geographical zones of up to 400km poleward are possible in a 4°C world, severely impacting Ukraine's unique mountain ecosystems, and resulting in mass disruptions to ecosystem health and biodiversity [126,127].

(a) Percentage change in total winter precipitation (Dec-Feb) under RCP8.5 for the 2080s relative to 1981-2010.
(b) Percentage change in total summer precipitation (Jun-Aug) under RCP8.5 for the 2080s relative to 1981-2010.



(c) Change in mean winter temperature (Dec-Feb) under RCP8.5 for the 2080s relative to 1981-2010.
(d) Change in mean summer temperature (Jun-Aug) under RCP8.5 for the 2080s relative to 1981-2010.

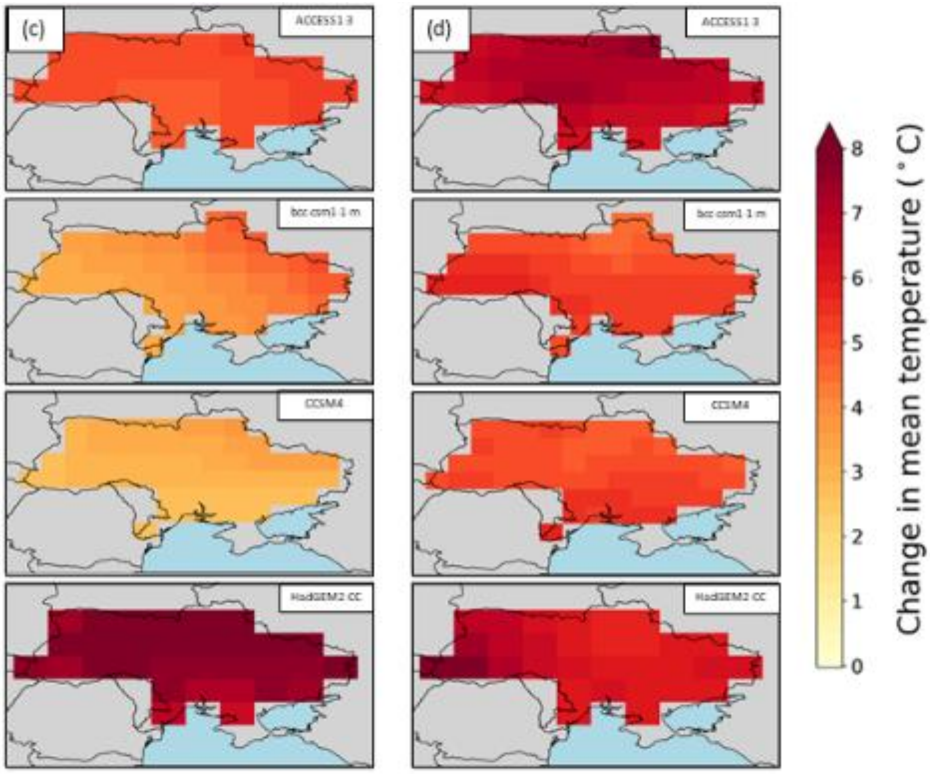


Figure 3 *Maps showing projected changes under a high greenhouse gas concentration scenario (RCP8.5) for winter and summer precipitation (figures a and b) and temperature (figures c and d) for Ukraine from 4 selected CMIP5 models, as representative examples of plausible future spatial variability. Changes are reported for the late-21st century period denoted 2080s (average over the period 2071-2100), relative to the 1981-2010 reference period.*

4 Past and future climate impacts on key sectors

This section of the report synthesises information from the current literature on past and future climate change impacts in Ukraine and the surrounding region for key sectors. Where possible results relating specifically to Ukraine have been drawn from literature. Where country-specific results are not available, relevant findings from the wider central and eastern European region encompassing Ukraine have been described. Headline impacts for each sector are summarised at the beginning of this report.

Adaptation to climate change impacts is critical to protect society and vulnerable communities. Whilst recommendations on specific adaptation options for Ukraine are beyond the scope of this report, examples of adaptation efforts gathered from the UK and elsewhere have been included in each section to demonstrate how the impacts described are being addressed, albeit in different contexts.

4.1 Agriculture & Food Security

Ukraine is an important exporter of grain, particularly wheat, and other agricultural goods to Europe and the rest of the world. The agricultural sector is a major employer, primarily in the agricultural regions to the south-east. Projected increases in temperature may increase productivity in the near term, i.e. lengthen the growing season for some cereal crops and increase yield in the north [56]. However, these benefits may be outweighed once important warming thresholds for individual crops are exceeded. Under a warmer climate there will be increased frequency of heat extremes, and these combined with the increase in frequency and severity of droughts in the south, could have a negative impact overall [57,58]. Research has demonstrated that irrigation can address the increased demand for water for agriculture from rising temperature extremes and increasing evapotranspiration [30], though this strongly depends on the availability of water resources.

Throughout the 2010s, agricultural production in Ukraine was repeatedly hit by serious harvest failures in vegetable plants and grain crops due to low rainfall and severe droughts and this is projected to continue into the future, with serious implications for global food security [58]. The already dry and warm southern regions of Ukraine are warming faster than the rest of the country and have already experienced significant changes to seasonal rainfall variability, with increases in winter season rainfall totals and reductions in summer season totals [59]. These changes in seasonal rainfall variability combined with increasing temperatures are driving increases to evapotranspiration and creating a water deficit [60], making irrigation-dependent farming more difficult in areas that experience low rainfall and frequent extreme summer temperatures which cause water and heat stress. Water stress during hot and dry periods, and water erosion from flooding events as well as wind erosion of bare soils, is already affecting more than one third of agricultural land in Ukraine [61]. Reduced availability of water to plants through increased aridity and decreases in soil nutrients may limit potential productivity gains available from increased CO_2 fertilisation [62], although this remains are area of active research [63]. Future climate projections of decreased summer rainfall and increasing temperatures, combined with increasing frequency of heat extremes would exacerbate these risks to agricultural production.

Addressing climate change impacts on agriculture and food security requires adaptation actions taken at different scales, from national scale policy to local household interventions. As an example, in the Climate Science for Service Partnership China (CSSP China) [64] the Met Office is providing information the current drought risk to maize yield in the Northeast Farming Region, showing that current drought risk is higher than previously estimated [65]. Farmers and local governments are using this understanding to make plans for addressing drought risk by using more efficient irrigation technologies or planting drought resistant crop varieties. The irrigation technologies employed differ and depend on local environmental conditions, source of water (i.e. proximity to rivers), crop varieties, and the socio-economic and local community context.

4.2 Water Resources and Flood Risks

A warming climate is expected to alter the seasonal river flow across Ukraine, with decreases in runoff relative to current flow possible in spring months and increases in autumn and summer months. For example, modelling of runoff in the Southern Bug Basin under future warming indicates a reduction in spring-time runoff of up to 50% [66]. This is consistent with expected decreases in spring runoff across eastern-central and eastern European river basins related to decreased snow amount during warmer winter months and decreases in rainfall during the summer half of the year [17,67]. To the south, the highly irrigated crop-farming Kherson Oblast is becoming increasingly exposed to potential increases in aridity (decreasing rainfall, increasing temperature, increasing evapotranspiration) [68]. Regions across Ukraine already experiencing water stress and reductions in annual rainfall totals are seeing increases in the frequency of prolonged heatwaves with an expanding summer season and reductions in the dominant wet season rainfall totals, and reductions in groundwater recharge [6,12,69].

While seasonal changes in rainfall vary across the country, extreme rainfall is projected to increase everywhere [52], with more intense rainfall expected to increase the frequency of flash flooding events. Across Europe, annual flood losses are expected to increase up to five-fold by the 2050s and as much as seventeen-fold by the 2080s, highlighting the need for nations to build flood resilience [70]. Changes in rainfall across Ukraine's vast networks of rivers, catchments, and aquifers, can result in high-risk flooding scenarios. In Ukraine, river flooding currently poses a serious risk, with potential for damaging and life-threatening river floods across the country, however projected future decreases in spring snow melt is expected to lead to a reduction in the intensity of 1-in-100-year river flooding events [17]. Continued urbanisation accompanied by the intensification of rainfall patterns due to climate change will likely exacerbate pluvial (direct rainfall-related flooding) flood risks, so action is needed to manage pluvial floods to minimize damage to the economy, environment, and society from both direct (e.g., damage to infrastructure, threat of life) and indirect (e.g., businesses shutting down and people moving away) losses.

Climate change impacts across multiple climate and ecosystems are also acting to exacerbate existing threats. For example in the Carpathian Mountains, even though decreases in summer season rainfall has led to greater water scarcity in the region, more intense rainfall during the winter and decreases in snow cover have simultaneously increased the risk of flooding and associated impacts such as landslides and erosion in the area [71].

Management of water resources at basin-scales requires strategic planning and coordination between multiple partners representing water users. In the Danube Basin, which spans 19 countries including Ukraine, the Climate Adaptation Strategy for the Danube River Basin brings together the latest scientific understanding of how climate change may impact water security and water quality and sets out possible adaptation measures [72]. The plan has been adopted by the International Commission for the Protection of the Danube River (ICPDR) and includes recommendations for improvements to early warning systems in response to expected increases in hydrological extremes such as flooding, as well as basin-wide measures for reducing the impact of flood events and building drought resilience such as restoration of water-sensitive ecosystems [73].

4.3 Human health

Climate change is already adding additional stress on health systems. Loss of life, illness, and productivity losses associated with heat waves and cold snaps, fires, drought, and flooding events, will continue to increase with global warming. A clear relationship exists between extreme hot and cold temperatures and mortality rates [74]; climate change is decreasing the frequency of cold extremes and increasing the frequency of hot extremes. The temperature extremes disproportionately affecting the elderly and those with low incomes who are vulnerable to poor housing and the cost of fuel to be used for cooling [74]. Diseases commonly associated with tropical regions, such as mosquito-borne Malaria and Dengue Fever will move into new regions as climate zones change with increasing temperatures [75], posing new threats to human health in Ukraine. At a national level, decision-makers will need to adapt to interconnected risks associated with impacts affecting water and air quality, moving disease vectors affecting human health, as well as threats to water supplies and crops. Health outcomes will be a combination of these climate related impacts and actions towards building resilience through social factors, such as through advances to disease treatment and improvements to housing and air quality.

The number of people exposed to heat-humidity extremes of days where the wet-bulb globe temperature (a measure of heat stress in direct sunlight) exceeds 33°C will increase with global warming, with high humidity reducing people's ability to cool themselves and leading to heat stress [76]. Rising habitation of urban environments will expose more people to worsening air quality issues with the need to adapt heating and cooling of buildings which are currently ill-adapted to expected future conditions. Many of the most vulnerable groups including women, outdoor workers, people on low-incomes, and the homeless, will be increasingly exposed to poor health outcomes associated with temperature extremes [77].

In Ukraine, poor air quality and air pollution has had a considerable impact on human health. Air pollution related mortality represents ~6% of total mortality (~27,000 excessive deaths per year) [78], with Ukraine ranked 4th highest for European death rates resulting from all types of pollution, of which air pollution is the predominant type [79]. Climate change is expected to impact human health outcomes directly through increasing fine particulates and pollutants, and indirectly, through production of secondary pollutants including ozone, which can have a detrimental effect on crop yields [80]. Contributors to poor air quality in Ukraine include pollution from power generation, aging industrial infrastructure and coal mining, and smoke from forest fires which contributes to higher levels of air pollution during the summer fire season [81].

To build resilience in cities, decision makers need locally relevant information about present day hazard as well as future heat impacts in order to inform policy and adaptation responses. In the UK, city councils are resource constrained and many do not have a dedicated adaptation officer, or staff with the scientific background to interpret national climate information for their local area. Urban fact sheets, co-produced by the Met Office with several UK city councils in the form of "city packs" [82], have been designed for use by city councils to raise awareness of the current and future climate hazards relevant to their cities and provide headline messages on hazards such as heat, rainfall and sea-level rise and how they could change in the future across all scenarios. Councils are working with city health authorities to develop early warning systems which alert citizens ahead of forecast periods of extreme heat to reduce heat stress, as well as looking into passive adaptation strategies such as increasing tree canopy and green spaces to cool city environments.

4.4 Cities & Urban environments

Approximately two thirds of Ukraine's population reside in cities and urban areas [83], which experience unique challenges from climate change. For example, urban environments contain impermeable surfaces which can increase flood risk. Urban areas are also affected by the urban heat island effect, which results in higher temperatures compared to surrounding rural areas. Heatwaves[iv], high temperatures, and associated heat islands and their effects such as heat stress are a major health risk in Ukrainian cities. The occurrence of summertime heatwaves has increased in Ukraine in recent decades [84]. For example, in Kyiv the number of summertime heatwaves has increased by 142% (from 7 to 17 events) in the 30 years since 1991 [85]. Health-related illnesses include heat stroke, heat fatigue, and heat exhaustion, and vulnerable people such as those with underlying health conditions, the elderly, and children are particularly at risk of heat related illnesses. More research is needed to understand the future vulnerability of cities and urban areas to increasing temperatures and more heatwaves.

Flash flooding exacerbated by increased urbanisation and heavy rainfall events are likely to become a major problem for cities in Ukraine and across central and eastern Europe [86]. Flooding can also have a significant effect on water quality, human health issues, disruptions to industry and transport, and destruction of infrastructure.

Adaptation in cities is needed across a range of climate hazards. For example, in the Thames Estuary in the UK, which includes London, flooding can occur when high tides coincide with low-pressure weather systems [87]. Areas of low-lying land (floodplains) in the estuary would be at significant risk of flooding if flood defences did not protect them. The Thames Estuary houses critical infrastructure including the London Underground and the area contributes £250 billion annually to the UK economy, making it an important centre of commerce. To build resilience to rising sea levels and increasing tidal flood risk in the Thames estuary, the UK Government has developed an adaptation plan to monitor and manage risks to this infrastructure through to the end of this century [88]. This includes a program to monitor and upgrade flood defenses such as flood walls and embankments. The flood walls and embankments are an intrinsic part of the Thames landscape. As flood defence works are carried out there will be other opportunities. These include creating better access for communities to the river, creating habitat and enhancing the social, economic and commercial benefits the river provides.

[iv] Here a heatwave is defined as an extended period of hot weather relative to the expected conditions of the area at that time of year, which may be accompanied by high humidity.

4.5 Ecosystems & Biodiversity

Ukraine is a globally important agricultural producer, as well as home to ecologically significant forest and forest steppe regions. The health of ecosystems, especially of forests, is vital for ensuring both productivity and function of agricultural land and waterways, as well as having benefits for human health [61,89]. The proportion of forested areas affected by pests and diseases in Ukraine has increased recently. Between 2001-2010 5–6% of the total forested area was affected, increasing to 8% between 2011-2020 [90]. These increases can be partly attributed to rising temperatures, changes to rainfall, and additional factors which are placing forests and other ecosystems under stress, as the climate changes beyond their ability to adapt. For example, decreases in snow-cover associated with climate change in combination with shifting land use practices in the Carpathian Mountain region is having a detrimental impact on rare alpine plant species [91]. The Carpathian Mountains has also recorded increases in both summer heat and winter cold waves, which when combined with increasing frequency, duration, and intensity of drought events can threaten the unique biosphere [92]. A major man-made threat to Ukrainian forests is deforestation, for agricultural cultivation or as a result of conflict. Deforestation has been linked to increased occurrence and damage from flooding and fire events, both of which are also projected to increase as a result of climate change [93,94]. Marine ecosystems and biodiversity in the Black Sea and Sea of Azov are also under threat from climate change, warming more than 1°C in the last 20 years, and warming up to 5°C plausible by late-century, disrupting existing system function [95].

In other mountain ecosystems which support unique flora and fauna, adaptation efforts have centred around building resilience to climate change through reforestation and increases to biodiversity. In the Queuña forests of the Vilcanota range, Peru, local communities manage reforestation of the region with native tree species [96]. Native species are already adapted to the conditions of the region and allow for the natural retention of water and its gradual discharge to the surrounding environment, providing water resources throughout seasons. A co-benefit is promoting ecotourism in the region which brings in additional resources, raises awareness of the challenges the region faces, and enhances the unique cultural value of the communities.

4.6 Energy & Infrastructure

Ukraine has an important resources sector, is a key transit country for distribution of natural gas, and also hosts a large manufacturing and processing sector, especially in the production of steel. Extreme events including flooding and heat waves reduce productivity and disrupt transport networks, delaying movement of goods, increasing costs, and putting pressure on supply chains. Ports and supply chains are also vulnerable to increasing frequency of storm surges, extreme rainfall events, and rising sea levels associated with climate change [97].

Limiting global temperature rise to 'well below 2°C' as per the Paris Agreement requires all countries to substantially reduce their carbon emissions [42]. Ukraine is a significant European producer of hydrocarbons and has pledged to reduce emissions by 65% of 1990 levels by 2030 [98]. The Ukrainian Government recently joined the Powering Past Coal Alliance, and is negotiating a timeframe for a phase out of coal and a significant reduction in nuclear generation [99–101]. Coal based and nuclear generation of energy in Ukraine consumes large volumes of water for cooling, and in regions which are already experiencing water scarcity [102]. Expected increases in water stress with rising global temperatures and reduced rainfall places pressure on energy production, both in terms of efficiency of thermoelectric generation and also in the sectors role as a significant water consumer [103]. For example, power generation from steam turbines reduces by about 0.2–0.3% per degree, and the efficiency reduction for nuclear power is even greater at 0.4–0.6% per degree, requiring significant additional production to meet demand [104]. Reductions in the efficiency of existing energy infrastructure such as cooling towers have already been observed during heat waves, compounded by increased demand for energy to power cooling. Much of Ukraine's housing stock and other infrastructure is aging and would benefit from efforts to improve energy efficiency with the dual benefits of reduced energy consumption and increased resilience to both heat and cold waves and extremes.

Decades of mining has had an impact on the water security and quality in Ukraine, with flooding and pollution from open and disused mines impacting ground water supplies and domestic water quality. For example, the Donbas region has already experienced groundwater and river water contamination, as well as soil contamination, from the regions heavy industry and the impacts from continuing hostilities [105]. Climate change acts to exacerbate these current issues: under a warming future increasing water scarcity in Donbas and surrounding regions will increase pressure on existing waterways, exposing more of the population to contaminated water supplies.

Water scarcity as a result of climate change will require effective management of water resources and strategic planning to manage water-dependent energy infrastructure such as hydropower and nuclear generation. In California water scarcity is already impacting energy supply through reduced hydropower generation, as ongoing drought reduces water supply and water management strategies priorities water for irrigation [106]. To improve the resilience of the energy sector to future drought conditions California has increased the amount of solar and wind generation as part of the energy grid [107]. Adoption of technologies such as solar and wind energy generation not only enhances drought resilience of energy supply but also reduces demand on water supply for other uses including for human consumption and for agricultural projection.

5 Cross-cutting Issues

5.1 Economic costs of climate change

Climate change will result in economic costs over the coming decades, as countries both have to cope with new climatic conditions and events, and undertake pre-emptive mitigation and adaptation actions. Macroeconomic impacts of climate change will also increase with increasing severity of GHG concentration scenario [108]. Adaptation efforts can substantially reduce direct losses resulting from climate change impacts, through upgrading infrastructure and defences to be more resilient, by adopting policies and initiatives to reduce exposure, as well as increasing the nation's capacity to respond and bounce back from disasters. There is strong evidence that adaptation activities targeted towards building adaptive capacity and resilience in the construction sector and other energy and capital-intensive industries will result in the avoidance of the greatest losses [109]. An assessment of European climate change impacts and vulnerability highlighted that in central and eastern Europe climate-related damage to critical infrastructure in the energy and transport sectors, and damages to the environment, including the Carpathians, and tourism will be most affected [86]. Ukraine is strongly positioned: the nation ranks amongst the countries with the lowest global exposure and vulnerability to multi-sector development and climate change hotspots, in a recent assessment [110]. This indicates that building resilience will benefit Ukraine both regionally and globally, providing opportunities for growth and enhancing Ukraine's regional performance.

5.2 Role of military conflict and gender in exacerbating climate impacts

Climate impacts on society, and responses to deal with these impacts now and in the future, are gender-sensitive, and there is evidence that women and girls are disproportionately affected by climate change [48,111]. In eastern-central Europe an increasingly aging population, displacement related to military conflict, and continued economic migration out of country may reduce the resources and capacity for adaptation and resilience [112,113]. Climate change is already acting to amplify challenges faced by communities who are experiencing or displaced by conflict, reducing resources available for maintaining essential services including justice, education, and health, decreasing women's access to child and family health services, and increasing vulnerability to sexual violence [37]. Gendered roles and societal expectations of women and men in communities and in decision-making processes can lead to the impacts of disasters being disproportionately experienced by those who are subject to inequality [114]. Eastern Europe has improved representation of women in international delegations to UNFCCC (for example), acting as a regional leader; however representation of women in positions of authority and on company boards globally remains very low [114]. In Ukraine action is being taken to increase the proportion of women involved in peace talks [37]. Involvement of women in the resolution of military conflict and the peace building process is recognised by the Human Rights Council as a crucial element of success, and participation of women in negotiations and decision making can assist in military conflict prevention [115].

6 Initiatives Relevant to Climate Action in Ukraine

Ukraine is a part of several regional initiatives aimed at understanding and responding to new and emerging climate risks, as well as identifying and seizing opportunities. In July 2021 Ukraine's government approved a new 2030 climate target: reducing GHG emissions by 65% in comparison to 1990 levels [116]. The EU4Climate[v] initiative is supporting the implementation of NDCs in Ukraine, focused on innovations in the energy sector [117]. Ukraine has been identified as a key partner in the European Clean Hydrogen Alliance with the possibility for hydrogen to act to transform the Ukrainian energy sector [118]. Alongside energy reform Ukraine is participating in the UNDP Climate Promise[vi] programme strengthening political and societal will for climate change action and promoting transparency and accountability. Domestically, the Ukrainian government has commenced a dialogue with the EU on Ukraine's opportunities under the European Green Deal to build a greener Ukrainian economy, including not only energy reform but also forest conservation, agricultural productivity increases and improved human health outcomes.

Organisations and think tanks operating in Ukraine are active in raising awareness of the impacts of climate change on lives and livelihoods, and recent efforts have highlighted the importance of effective communication with the public and at local authority levels [119]. Shared vulnerabilities and risks arising from increasing frequency of extreme events, such as the recent devastating forest fires in Chernobyl and Luhansk during 2020 [34,36], provides common ground for peace negotiations along the disputed territories.

The impact of COVID on Ukraine's GHG emissions for 2020 is estimated to be a reduction of 11% lower than predicted [98]. Many countries including Ukraine are using the social and industrial changes resulting from the pandemic as an opportunity to 'build back greener' through economic stimulus investment in green policies and technologies. The cost of inaction, and the benefits of early adaptation are clear: economic assessments of the costs demonstrate that peak costs are greater and reached sooner if action is delayed [120].

7 Knowledge & Research Gaps to Support a Resilient Ukraine

This report summarises existing knowledge on climate change trends and impacts in Ukraine, relevant to climate change adaptation and mitigation. However, there are variety of knowledge and research gaps that require attention to enable effective and timely national and sub-national actions to address current and emerging climate risks.

Preparing for and responding to extreme events and climate-related disasters requires effective monitoring and early warning systems that are integrated into emergency management and services, as well as long-term adaptation planning integrated into economic decision-making. Stable and ongoing resourcing of environmental monitoring networks is a key element of building preparedness and in launching rapid and efficient responses. Understanding the current and future impacts on Ukrainian citizens requires up-to-date information on population demographics (where people are living, how they are affected) as well as reliable data on the state of Ukraine's natural resources [121]. This can assist the Ukrainian Government to implement policy responses which build resilience and reduce risk across the country. The dual benefits of comprehensive environmental monitoring combined with demographic information are that citizens benefit from timely disaster responses, minimising loss of life and livelihoods, and that policy initiatives are strategic and targeted to the regions and groups where they can be most effective. For example, monitoring air quality, air

[v] EU4Climate: https://eu4climate.eu/ukraine
[vi] UNDP Climate Promise: https://www.undp.org/climate-promise

temperature, and humidity can provide information for early warning systems and public health messages to mitigate the impacts of heat waves.

Research in Ukraine indicates that more must be done to engage policymakers at local scales on existing threats, and to coordinate a consistent national approach to climate action [119]. The latest IPCC report notes that while global emissions reductions to limit global warming to 1.5°C are still within reach it is not possible to rule out warming of 4°C or more [122]. Therefore, countries must ensure that adaptation planning considers these higher levels of warming as part of their risk assessment and climate change response. Failure to do so may result in considerable losses from the impacts of climate change, and the sooner action is taken the greater the reduction in this risk [123].

Learning from the gathering of evidence for this report demonstrates a need for more tailored climate projections and impacts work focused specifically on Ukraine. Detailed national climate change risk assessments are required to provide information across regions and sectors to raise awareness of risks and guide adaptation decision-making. This requires investment and coordination in national science and research capabilities across climate science, modelling, and multi- and inter-disciplinary research encompassing diverse related fields (e.g., economics, hydrology, ecology and engineering), potentially mirroring areas of focus in the IPCC assessment reports – i.e., physical science, vulnerability of socio-economic and natural systems, and options for mitigation and adaptation. Furthermore, to better understand and assess impacts at local scales, there is a need to develop climate services capabilities. Nationally mandated institutions, such as the Ukrainian Hydrometeorological Institute, have a key role to play, as well as other organisations positioned to expand climate change impacts research.

Finally, education on climate change science, impacts and potential responses is needed at all levels, from schools and the general public to business leaders and government officials. Increasing the understanding of climate changes issues across society will help inform appropriate responses. The media have an important role to educate, inform and stimulate debate [119], as well as other organisations and platforms that promote awareness and education on climate and environmental change.

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