United in Science 2022

A multi-organization high-level compilation of the most recent science related to climate change, impacts and responses

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WORLD METEOROLOGICAL ORGANIZATION · UN environment programme · GLOBAL CARBON project · Met Office · ipcc INTERGOVERNMENTAL PANEL ON climate change · UNDRR UN Office for Disaster Risk Reduction

This report has been compiled by the World Meteorological Organization (WMO) under the direction of the United Nations Secretary-General to bring together the latest climate science-related updates from key global partner organizations – WMO, Global Carbon Project (GCP), UN Environment Programme (UNEP), Met Office (United Kingdom), Urban Climate Change Research Network (UCCRN), UN Office for Disaster Risk Reduction (UNDRR), World Climate Research Programme (WCRP, jointly sponsored by WMO, IOC-UNESCO and the International Science Council (ISC)) and the Intergovernmental Panel on Climate Change (IPCC). The content of each chapter is attributable to each respective organization.

The report is available electronically at: https://public.wmo.int/en/resources/united_in_science

Cover Illustration: A man works on a destroyed house in the aftermath of Cyclone Batsirai in the town of Mananjary, Madagascar, 8 February 2022 (REUTERS/Alkis Konstantinidis).

Lead authors and contributors: Overall coordination and editing by WMO - Lauren Stuart, Jürg Luterbacher, Laura Paterson, Rose Devillier and Sylvie Castonguay (Editor)

Atmospheric Greenhouse Gas Concentrations (WMO Global Atmosphere Watch): Oksana Tarasova (WMO), Alex Vermeulen (Integrated Carbon Observation System (ICOS) Carbon Portal, Lund University, Sweden), Jocelyn Turnbull (GNS Science, New Zealand/Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, USA), Luciana V. Gatti (National Institute for Space Research, Brazil)

Global Greenhouse Gas Emissions and Budgets (Global Carbon Project): Josep G. Canadell (Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia), Robert B. Jackson (Stanford University, USA), Robbie M. Andrew (Centre for International Climate and Environmental Research (CICERO), Norway), Philippe Ciais (Laboratoire des Sciences du Climat et de l'Environnement (LSCE), France), Steven J. Davis (University of California, USA), Pierre Friedlingstein (University of Exeter, UK), Corinne Le Quéré (University of East Anglia, UK), Zhu Liu (Tsinghua University, China), Glen P. Peters (CICERO, Norway)

State of the Global Climate: 2018–2022 (WMO): Omar Baddour (WMO), John Kennedy (Met Office, UK), Peter Siegmund (principal author, Royal Netherlands Meteorological Institute, Netherlands).

Global Climate Predictions: 2022–2026 (Met Office, UK/WMO/World Climate Research Programme (WMO/International Science Council/IOC-UNESCO)): Leon Hermanson (Met Office, UK), Adam Scaife (Met Office, UK; University of Exeter, UK), Melissa Seabrook (Met Office, UK), Doug Smith (Met Office, UK)

Emissions Gap (UN Environment Programme): Anne Olhoff (CONCITO, Denmark's Green Think Tank), John Christensen (CONCITO, Denmark's Green Think Tank), Joeri Rogelj (Imperial College London, UK; International Institute for Applied Systems Analysis, Austria), Maarten Kappelle (UNEP), Jian Liu (UNEP)

Tipping Points in the Climate System (WMO/World Climate Research Programme (WMO/International Science Council/ IOC-UNESCO)): Thomas F. Stocker (University of Bern, Switzerland), Gabriele C. Hegerl (University of Edinburgh, UK) James W. Hurrell (Colorado State University, USA), Timothy M. Lenton (University of Exeter, UK), Sonia I. Seneviratne (ETH Zürich, Switzerland), Ricarda Winkelmann (PIK Potsdam, Germany)

Climate Change and Cities (Urban Climate Change Research Network): Cynthia Rosenzweig (NASA Goddard Institute for Space Studies and Columbia University, USA), William Solecki (City University of New York – Hunter College, USA), Maria Dombrov (Columbia University, USA)

Extreme Weather Events and Socioeconomic Impacts (WMO World Weather Research Programme): Estelle De Coning (WMO), Lauren Stuart (WMO), Andrew King (University of Melbourne, Australia), Ram Dhurmea (Mauritius Meteorological Service, Mauritius), Peter Bissolli (Deutscher Wetterdienst, Germany), Marvin Manus (Deutscher Wetterdienst, Germany), Stefan Rösner (Deutscher Wetterdienst, Germany), Andrea Kreis (Deutscher Wetterdienst, Germany)

Early Warning Systems: Supporting Adaptation and Disaster Risk Reduction (WMO/UN Office for Disaster Risk Reduction): Laura Paterson (WMO), Lauren Stuart (WMO), Animesh Kumar (UNDRR), Serena Odianose (WMO), Lorena Santamaria (WMO), Victoria Alexeeva (WMO)

IPCC boxes: content taken from the Summary for Policymakers (SPM) reports from the most recent IPCC 6th Assessment Report, including Working Group I: The Physical Science Basis, Working Group II: Impacts, Adaptation and Vulnerability and Working Group III: Mitigation of Climate Change.

Foreword by Antonio Guterres, Secretary-General of the United Nations

Rapidly accelerating climate disruption means that no one is safe from disasters such as floods, droughts, heatwaves, extreme storms, wildfires or sea level rise. The answer lies in urgent climate action, yet we continue to feed our fossil fuel addiction and to compromise the livelihoods of future generations.

In the Paris Agreement on climate change, governments pledged to limit global temperature rise to 1.5 degrees and to build climate-resilient communities. This year's United in Science report shows that we are way off track. It is time to turn pledges into action.

We need a renewable energy revolution to bring down carbon emissions. We must also double investment in adaptation. A first necessary step, which is both quick and cost-effective, is early warning.

Early warnings save lives and livelihoods from climate threats. Yet, many developing countries still lack such systems. Ensuring early warnings is essential to help people prepare for extreme weather events, droughts and other climatic impacts. I am pleased that the World Meteorological Organization is developing a plan to ensure universal global early warning coverage within the next five years.

However, we need much more if we are to rise to the existential climate challenge. I urge all leaders to heed the facts in this report, to unite behind the science and to take ambitious urgent climate action.

A. Guterres, Secretary-General UN

Foreword by Prof. Petteri Taalas, Secretary-General of the World Meteorological Organization

The science is unequivocal: we are going in the wrong direction.

Greenhouse gas concentrations are continuing to rise, reaching new record highs. Fossil fuel emission rates are now above pre-pandemic levels. The past seven years were the warmest on record. Cities, which contribute 70% of global emissions, are highly vulnerable to climate impacts.

These trends will continue if we do not act urgently to reduce fossil fuel emissions. Ambition of emissions reduction pledges for 2030 needs to be seven times higher to meet the 1.5 °C goal of the Paris Agreement.

The combined effects of higher temperatures and humidity in some regions could have dangerous consequences for human health in the next few decades. This could lead to physiological tipping points beyond which outdoor human labor is no longer possible without technical assistance. Research on this and other climate tipping points, such as the melting of polar ice sheets, will help society better understand the costs, benefits and potential limitations of climate mitigation and adaptation in the future.

Climate science is increasingly able to show that many of the extreme weather events that we are experiencing have become more likely and more intense due to human-induced climate change. It is more important than ever that we scale up action on early warning systems to build resilience to current and future climate risks in vulnerable communities.

I thank the many expert teams involved in creating this report for their collaboration, uniting the climate science community to deliver the latest essential information, in these unprecedented times.

Prof. P. Taalas, Secretary-General WMO

Summary

United in Science provides an overview of the most recent science related to climate change, impacts and responses from the World Meteorological Organization (WMO) and partner organizations. At a time when urgent action to address climate change is needed, the report provides unified scientific information to inform decision-makers and highlights some of the physical and socioeconomic impacts of the current and projected climate.

According to the WMO Global Atmosphere Watch, atmospheric greenhouse gas (GHG) concentrations continue to rise, despite emissions reductions in 2020 resulting from the COVID-19 pandemic lockdowns. The Global Carbon Project also notes that, in 2021, global fossil CO_2 emissions returned to 2019 pre-pandemic levels after a large, but temporary, absolute drop in emissions due to widespread lockdowns. These conditions are leading to increasing global surface temperature and other climatic changes, as highlighted by the WMO *State of the Global Climate 2021* report, which found the most recent seven years, 2015 to 2021, to be the warmest on record.

Looking forward, the Met Office (UK), in partnership with the World Climate Research Programme, found that there is a 48% chance that, during at least one year in the next five years, annual mean temperature will temporarily be 1.5 °C higher than in 1850-1900. Additionally, there is a 93% chance that at least one year in the same time period will be the hottest on record.

The UN Environment Programme's latest *Emissions Gap Report* found that the full implementation of mitigation pledges made by countries (as of 4 November 2021) is insufficient and will not keep global warming below 1.5 °C above pre-industrial levels. The report also found that the ambition of these pledges would need to be four times higher to keep global temperature rise below 2 °C above pre-industrial levels and seven times higher to limit warming to 1.5 °C. Enhanced mitigation action is needed to prevent the goals of the Paris Agreement from slipping out of reach.

Without ambitious action, the physical and socioeconomic impacts of climate change will be devastating. Irreversible physical changes in the climate system, known as tipping points, can not be ruleld out and could have significant global and regional consequences. According to the Urban Climate Change Research Network, cities – responsible for up to 70% of human-caused emissions – will face increasing climate impacts that will intersect with socioeconomic inequalities. Additionally, the WMO World Weather Research Programme highlights that it is the world's most vulnerable populations that will suffer the most, as has already been observed during recent extreme weather events.

Billions of people around the world are highly vulnerable to the impacts of climate change. As a result, adaptation and disaster risk reduction are crucial to lower the risks to climate impacts. According to WMO and the UN Office for Disaster Risk Reduction, early warning systems not only save lives and reduce losses and damages, but also contribute to disaster risk reduction, and support climate change adaptation. However, less than half of all countries in the world have these crucial systems and coverage is particuarly low in vulnerable countries. To address this issue, the United Nations Secretary-General António Guterres called for new action to ensure every person on Earth is protected by early warning systems in the next five years.

Additionally, the Intergovernmental Panel on Climate Change recently released highly anticipated Working Group reports covering *The Physical Science Basis*; *Impacts, Adaptation and Vulnerability*; and *Mitigation of Climate Change*, which are an integral part of its Sixth Assessment Report. These important reports identify the strength of scientific agreement in these different areas as well as where further research is needed.

The science is clear – urgent action is needed to mitigate emissions and adapt to our changing climate. The United Nations system, along with its partners, will continue to provide world-leading science to inform decision-making and support global climate action.

Key messages

- **Atmospheric greenhouse gas (GHG) concentrations continue** to rise and fossil fuel emissions are now above pre-pandemic levels after a temporary drop due to lockdowns associated with the COVID-19 pandemic in 2020 and 2021
- **Recent years saw record high temperatures and ocean heat.** Looking forward, there is a 48% chance that, during at least one year in the next five years, annual mean temperature will temporarily be 1.5 °C higher than in 1850-1900
- **Mitigation pledges are insufficient to achieve the Paris Agreement.** Enhanced action is needed to prevent the continued warming that is increasing the likelihood of irreversible changes in the climate system, known as tipping points
- **Billions of people around the world are exposed to climate change impacts.** Cities – responsible for up to 70% of human-caused emissions – will face increasing socioeconomic impacts and the world's most vulnerable populations will suffer most, as seen in recent extreme weather events
- **Adaptation is crucial to lower the risks to climate impacts.** Early warning systems can save lives, reduce losses and damages, contribute to disaster risk reduction and support climate change adaptation.

Atmospheric Greenhouse Gas Concentrations

WMO Global Atmosphere Watch

WORLD METEOROLOGICAL ORGANIZATION

Key messages

- Concentrations of the major GHGs continued to increase in 2021 and the first half of 2022
- Overall emissions reductions in 2020 did not have a substantial impact on the annual increase of the atmospheric concentrations of long-lived GHGs
- The role of carbon uptake by the biosphere in achieving carbon neutrality would be better understood if supported by more robust atmospheric observations.

Global levels of GHGs

Levels of atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) continue to rise. Preliminary analysis of the data from a subset of the GAW GHG observational network demonstrated that CO_2 concentrations exceeded 410 parts per million (ppm) during the whole of 2021. Additionally, concentrations[1] during the seasonal peak of 2022 in the northern hemisphere reached 430 ppm at some background locations.

A full analysis of the three main GHGs (Figure 1) shows the globally averaged atmospheric concentrations of CO_2 at 413.2 ± 0.2 ppm, CH_4 at 1889 ± 2 parts per billion (ppb) and N_2O at 333.2 ± 0.1 ppb for 2020 (respectively 149%, 262% and 123% of pre-industrial levels in 1750). The increase in CO_2 from 2019 to 2020 was slightly lower than that observed from 2018 to 2019, but higher than the average annual growth rate over the last decade. This is despite a fall in global energy-related CO_2 emissions of 5.4% in 2020 due to restrictions related to the coronavirus (COVID-19) pandemic (See chapter: *Global Greenhouse Gas Emissions and Budgets*). For CH_4 and N_2O, the increases from 2019 to 2020 were higher than those observed from 2018 to 2019 and also higher than the average annual growth rate over the last decade (WMO, 2021).

Final global average figures for 2021 will not be available until the second half of 2022, but data from all global locations, including flagship observatories – GAW stations at Mauna Loa (Hawaii, USA) and Cape Grim (Tasmania, Australia) –

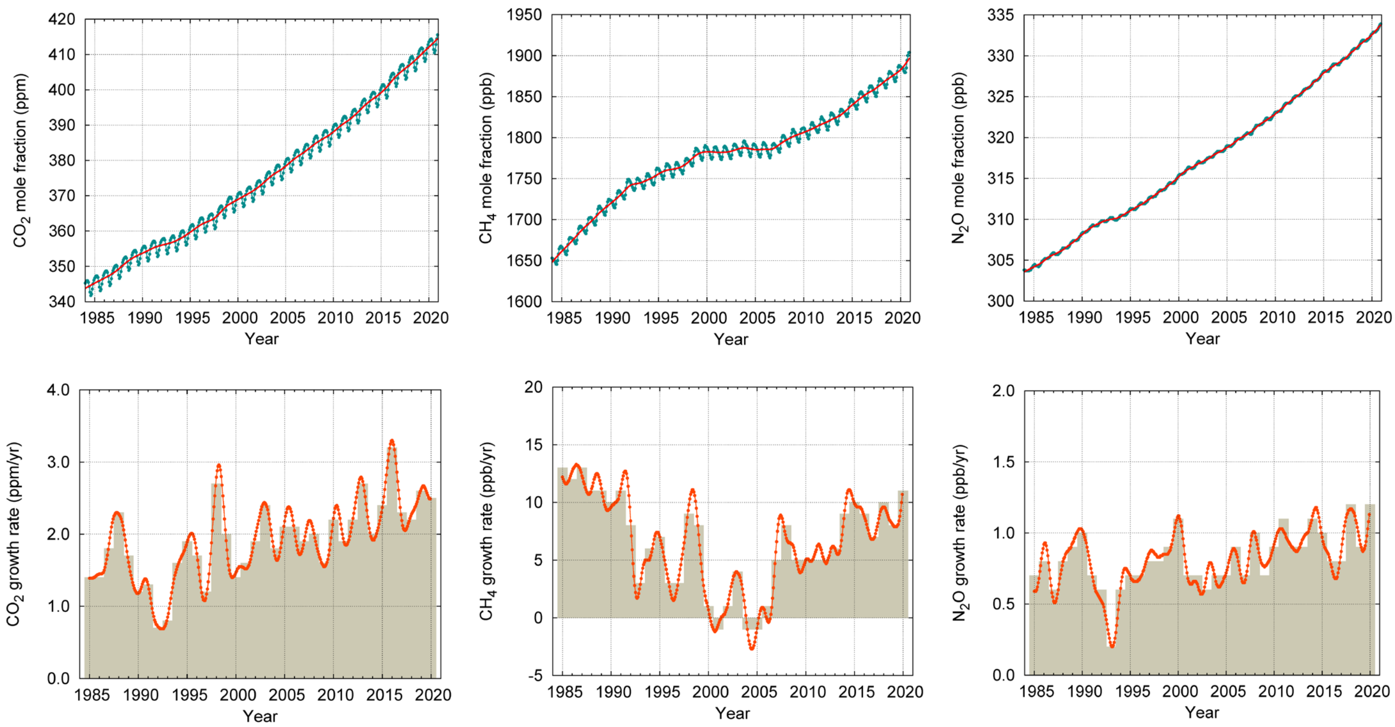

Figure 1. (upper row) Globally averaged CO_2, CH_4 and N_2O mole fraction in ppm (CO_2) and ppb (CH_4; N_2O, respectively) and its growth rate (lower row) from 1984 to 2020. Observations from 139 stations were used for the CO_2 analysis, 138 stations for the CH_4 analysis and 105 stations for the N_2O analysis. The red line (top row) is the monthly mean with the seasonal variation removed; the blue dots and line depict the monthly averages. Increases in successive annual means are shown as the shaded columns (bottom row).

[1]In this section, the physical quantity related to the amount of gases in the atmosphere (dry mole fraction) is referred to as "concentration".

indicate that levels of CO_2 continued to increase in 2021 and 2022 (Figures 2 and 3). In June 2022, CO_2 concentration at Mauna Loa and Cape Grim reached 420.99 ppm and 414.12 ppm, respectively. The comparative figures for June 2021 were 418.94 ppm, and 411.64 ppm.

Use of atmospheric observations to improve knowledge of biosphere GHG fluxes

The most ambitious mitigation scenarios assessed by the Intergovernmental Panel on Climate Change (2022) call for net negative emissions in the second half of this century. Afforestation and reforestation may have an important role in increasing carbon sinks, which are the uptake of carbon by the biosphere. At the same time, net anthropogenic CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) are subject to large uncertainties and high annual variability with low confidence, even in the direction of the long-term trend. Natural CO_2 fluxes are also subject to substantial interannual variability. Atmospheric observation and analysis can play an important role in improving quantification of total CO_2 biosphere fluxes, as shown in the examples below.

Tracking progress towards emissions targets in New Zealand

Estimates of forest carbon uptake remain highly uncertain in New Zealand. The National Inventory Report, which tracks progress against emissions targets under the United Nations Framework Convention on Climate Change (UNFCCC), uses measurements of tree diameter and height at a national network of sites to estimate forest carbon uptake (New Zealand Ministry for the Environment, 2021). Independent estimates from atmospheric CO_2 measurements and modelling suggest that forest carbon uptake may be significantly underestimated by both the National Inventory Report and terrestrial biosphere modelling (Steinkamp et al., 2017). Recent results confirm this carbon sink with additional measurements and modelling and show that it has lasted for at least a decade (Figure 4).

New Zealand's Climate Change Commission recently recommended a transition away from relying on plantation forestry towards planting native forests for carbon sequestration. However, little is known about the sensitivity of New Zealand's unique indigenous forests to future climate change. Ongoing measurements will help to understand the sensitivity of these forests to climate change and how their carbon uptake will respond to environmental changes.

Estimating Amazonia's contribution to the global carbon budget

Tropical regions, such as Amazonia, play an important role in the global carbon budget. Amazonia hosts the Earth's largest tropical forest, but only has a few of the in situ observations needed to monitor large-scale carbon fluxes, as is the case with other tropical regions. To improve estimates of Amazonia's contribution to the global carbon budget, an aircraft measurement program was started in 2010 over four different sites in this region: Alta Floresta (ALF), Rio Branco (RBA), Santarém (SAN) and Tabatinga/Tefé (TAB/TEF). Overall, 600 CO_2 and CO aircraft vertical profiles have been collected between 2010 and 2018 (Gatti et al., 2021).

These profile observations, and the use of column budget techniques to calculate carbon flux and long-term temperature and precipitation information, help us understand the carbon sink from natural and perturbed ecosystems, as well as how forests react to climate stress. This is crucial information for reaching carbon neutrality, which will be hard to attain if the forests lose their sink capacity through land-use and land-cover changes and the impacts of climate change, as observed in most human-impacted regions of Amazonia.

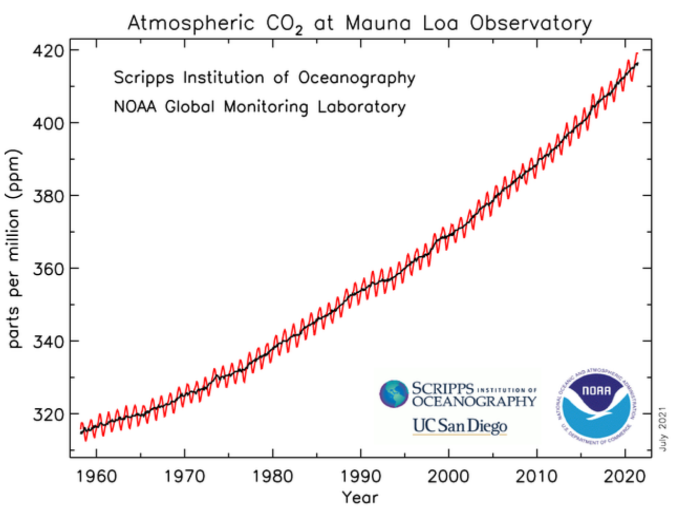

Figure 2. Monthly mean CO_2 mole fraction in ppm at Mauna Loa observatory from March 1958 to June 2022. The dashed red line represents the monthly mean values, centred on the middle of each month. The black line represents the same, however, the average seasonal cycle has been removed by a statistical treatment (Source: www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html).

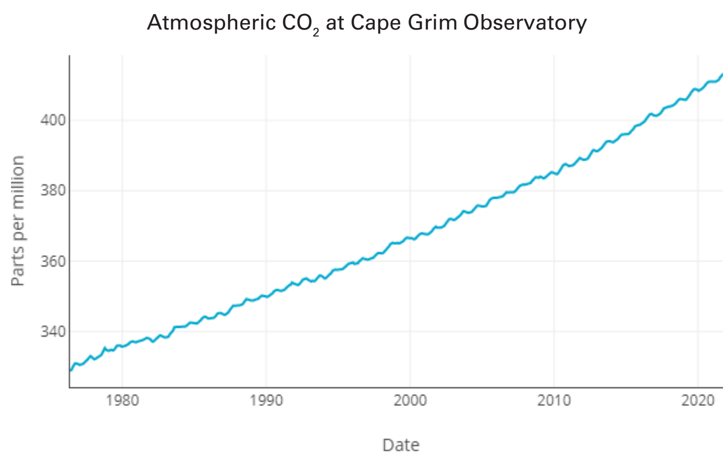

Figure 3. Monthly mean CO_2 mole fraction in ppm from May 1976 to June 2022 at Cape Grim observatory (Source: https://www.csiro.au/greenhouse-gases/).

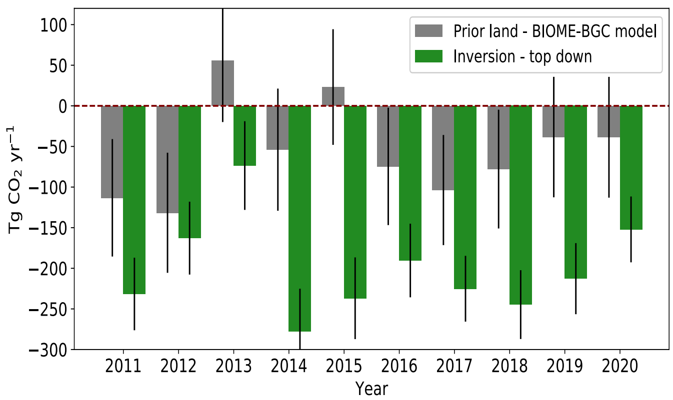

Figure 4. Annual average carbon flux from New Zealand's terrestrial biosphere estimated from the Biome-BGC model (gray) and from atmospheric CO_2 measurements and modelling (green) (updated from Steinkamp et al., 2017).

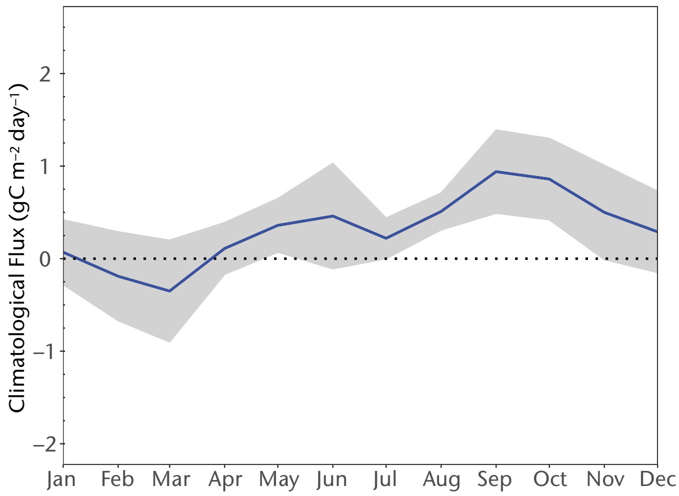

Figure 5. Average 9-year monthly means of ALF carbon flux (2010–2018). The gray band denotes the standard deviation of the monthly means and the 9-year mean climatological carbon flux at south-eastern Amazonia (Gatti et al., 2021).

Data analysis shows that the south-east region, captured by the ALF site (8.80° S, 56.75° W), has the largest CO_2 emissions to the atmosphere (Figure 5), followed by the north-east region, captured by the SAN site (2.86° S, 54.95° W). The CO_2 gradients from the annual mean vertical profiles and the estimated carbon fluxes indicate that areas that are more affected by land-use and land-cover change show higher carbon emissions to the atmosphere. The regions in the eastern Amazon have experienced very strong dry-season temperature increases, precipitation decreases and large areas of deforestation over the last 40 years, while the western regions experience relatively low levels of human disturbance and dry-season climate trends.

There is recognition that support for observation-based methods supposes substantial developments of the observational and analysis infrastructure. The WMO Integrated Global Greenhouse Gas Information System (IG³IS), one example of an observation-based information system, uses atmospheric observation and analysis tools to improve knowledge of GHG sources and sinks at national and smaller scales. A growing number of countries are initiating programs to merge observation-based emission information with activity and emission-factor based estimates. IG³IS has developed good practice documents to ensure that estimates done at various scales and in different countries, cities, and facilities can be compared with each other.

WMO is currently exploring the possibility of developing an internationally coordinated, operational Global Greenhouse Monitoring Infrastructure to observe and model GHG concentrations in the atmosphere and the relevant fluxes between atmosphere, land, and oceans. The development of this initiative is being undertaken in consultation with representatives of existing observing entities, both in situ and space-based, with relevant modelling and data assimilation activities and with the potential user community.

Global Greenhouse Gas Emissions and Budgets

Global Carbon Project

Key messages

- Total anthropogenic carbon dioxide (CO_2) emissions were estimated at 38.0 gigatons of CO_2 per year ($GtCO_2\ yr^{-1}$) in 2020, with a preliminary estimate of 39.3 $GtCO_2\ yr^{-1}$ in 2021
- Preliminary data shows that global CO_2 emissions in 2022 (January to May) are 1.2% above the levels recorded during the same period in 2019 (prior to the pandemic)
- A quarter of GHG emissions from land-use change are associated with the trade of food between countries, of which more than three quarters are due to land clearing for agriculture, including grazing.

Total anthropogenic CO_2 emissions, including those from fossil sources (coal, gas, oil) and emissions from land use, land-use change and forestry (LULUCF), were estimated at 38.0 $GtCO_2\ yr^{-1}$ in 2020 (1 Gigaton = 1 Petagram = 1 billion tons). The 2021 preliminary estimate is 39.3 $GtCO_2\ yr^{-1}$ (Friedlingstein et al., 2022; Jackson et al., 2022).

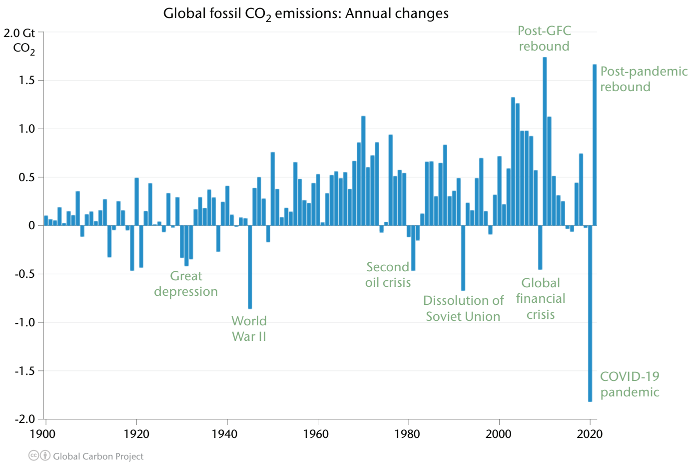

Figure 1. Annual absolute changes in global fossil CO_2 emissions (Friedlingstein et al., 2022).

Global fossil CO_2 emissions in 2021 returned to the pre-pandemic levels of 2019 after decreasing by 5.4% in 2020 due to widespread lockdowns in response to the COVID-19 pandemic. The 2020 drop in emissions was the single biggest absolute drop in historical record, owing to the large decline in economic activity (Figure 1).

Fossil CO_2 emissions rebounded by 4.8% (4.2%–5.4%) in 2021 reaching 36.4 ± 1.8 $GtCO_2\ yr^{-1}$ (Figure 1). Emissions from coal and gas in 2021, rose above 2019 levels, while emissions from oil were still below the 2019 level as road transportation and international aviation, in particular, remained below pre-pandemic levels.

Preliminary data shows that global CO_2 emissions in 2022 (January to May) are 1.2% above pre-pandemic levels during the same period in 2019 (Figure 2). In particular, electricity generation (power) and emissions from industry have increased by 1.9% and 3.8%, respectively. Domestic and international aviation have remained at 14% and 31%, respectively, well below 2019 levels (Carbon Monitor 2022; Davis et al., 2022; Liu et al., 2022).

The global increase in emissions observed in the first five months of 2022 is largely driven by the USA (+5.7%), India

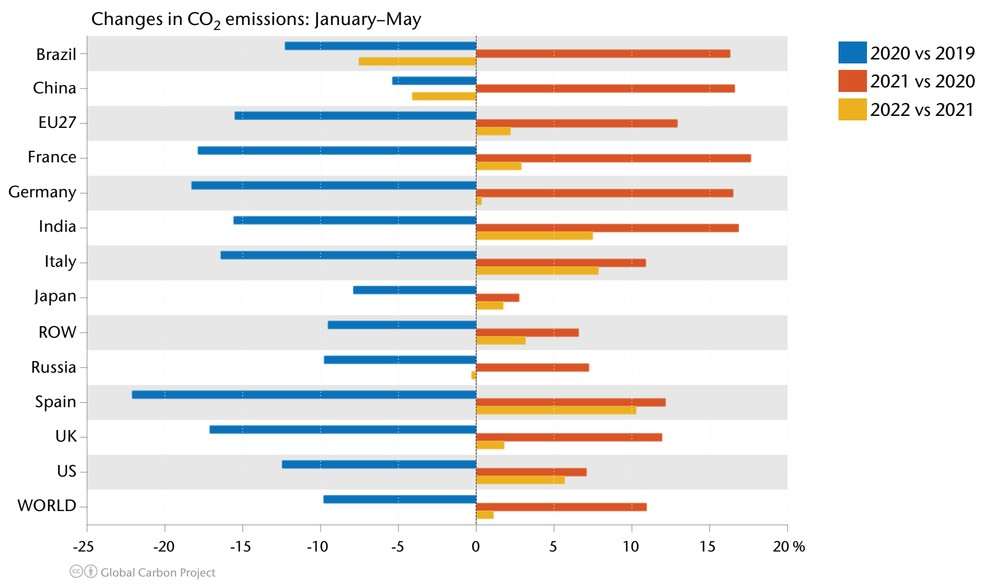

Figure 2. Changes in fossil fuel CO_2 emissions for the world and a selected group of countries for January-May in 2020, 2021 and 2022 compared with the same period in the previous year (Carbon Monitor, 2022)..

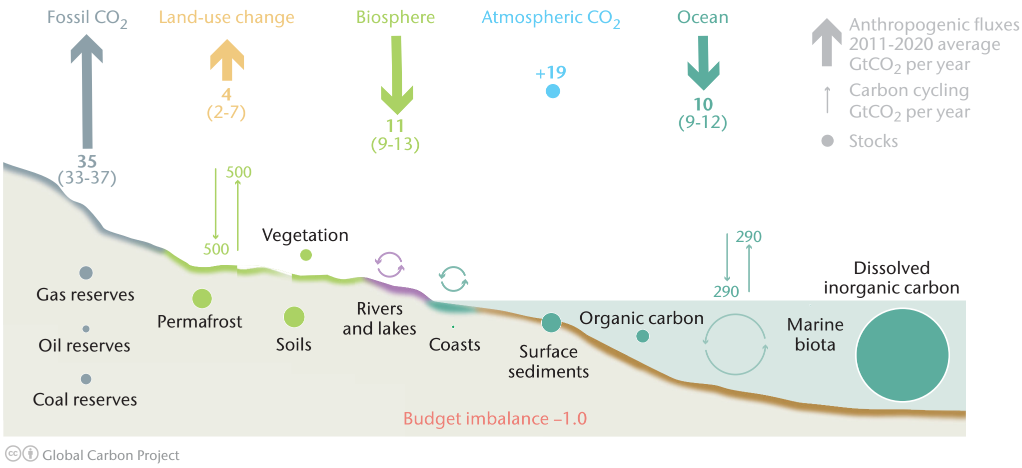

Figure 3. Human perturbation of the global carbon budget, averaged globally for the decade of 2011–2020 (Friedlingstein et al., 2022).

(+7.5%) and most of the European countries. Some other countries, such as Brazil , China, and the Russian Federation, remain at levels below 2021. Global – and some regional – trends in 2022 contrast with strong emission increases during the immediate rebound period from January to May 2021 when countries were emerging from the severe 2020 COVID-19 pandemic lockdowns. While the 2021 increase was due to direct stimulus to and fast recovery of the economy, the 2022 slow down and decline in emissions in some countries are due to readjustments in the economy after the 2020 crisis, continuous supply chain disruptions, and the scarcity of key commodities due to the war in Ukraine. The emissions decline in China was the result of extended confinement policies and strict travel restrictions on international arrivals in response to local outbreaks of COVID-19.

Despite a strong fluctuation in global emissions over the past 2.5 years, fossil CO_2 emissions significantly decreased in 23 countries, accounting for about one quarter of global emissions (9 $GtCO_2$ yr^{-1}), during the pre-pandemic decade of 2010–2019. This includes many European countries as well as Japan, Mexico, and the United States of America. The decline in these countries shows progress towards decarbonization, although a trend of increased global emissions still dominated the decade (Friedlingstein et al., 2022; Le Quéré et al., 2021).

Unlike fossil CO_2 emissions, the atmospheric CO_2 impact from LULUCF is the result of the net balance between human activities that lead to carbon release (e.g., deforestation) and other activities that lead to carbon uptake (e.g., reforestation, forest regrowth). Net emissions from LULUCF were estimated at 2.9 ± 2.6 $GtCO_2$ yr^{-1} for 2021, associated with very large uncertainties. This is lower than the average of 4.1 ± 2.6 $GtCO_2$ yr^{-1} for the 2011–2020 decade. The decadal net source was made up of near-constant gross emissions of about 14 ± 2.2 $GtCO_2$ yr^{-1} that were partly offset by carbon removals on managed lands of 9.9 ± 1.5 $GtCO_2$ yr^{-1}.

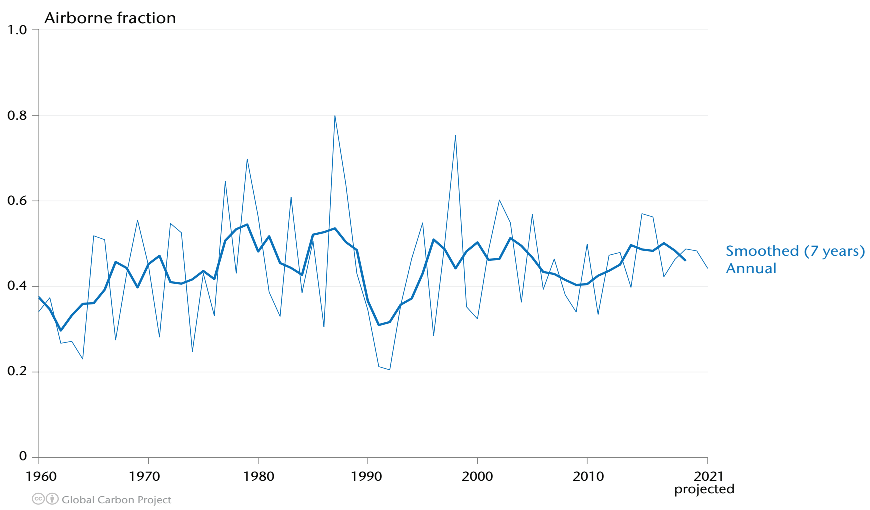

Figure 4. Fraction of anthropogenic CO_2 emissions (fossil + LULUCF) that remains in the atmosphere, 1960–2021 (Friedlingstein et al., 2022).

Although final global average figures for 2021 are not yet available, the data indicates that the anthropogenic CO_2 emissions led to a continued increase in global atmospheric CO_2 concentrations. However, natural CO_2 sinks on land and oceans continued to uptake more CO_2 in response to increasing atmospheric CO_2 with an average (2011–2020) of 10.2 ± 1.5 $GtCO_2\,yr^{-1}$ for the ocean sink and 11.2 ± 2.2 $GtCO_2\,yr^{-1}$ for the land sink (Figure 3). The increasing CO_2 sinks have led airborne fraction (the fraction of anthropogenic emissions remaining in the atmosphere) to stay, on average, relatively constant over the past six decades at 45%, albeit with large year-to-year and decadal variability (Figure 4). This implies that 55% of all anthropogenic CO_2 emissions are, on average, removed by natural land and ocean sinks, underscoring the importance and relevance of understanding their future evolution under climate and atmospheric changes.

Trading emissions in foods

International trade in goods, services and fossil fuels leads to disconnects between countries that consume goods and services, or extract fossil fuels, and those that burn the fossil fuels and report the related emissions. However, little has been known about how much global land-use (i.e. non-energy) emissions relate to foods traded internationally.

Based on a new accounting of land-use GHG emissions from agriculture and land-use change, a new analysis shows that emissions from trade in food were 5.8 gigatons of CO_2 equivalent ($GtCO_2e$) in 2017, representing 27% of GHG emissions from land-use change (Hong et al., 2022). $GtCO_2e$ include all major GHGs (e.g., carbon dioxide, methane and nitrous oxide).

More than three quarters of the traded emissions were associated with changes in land use to enable the expansion of agriculture, including grazing. The top exporters of traded food emissions were Brazil and Indonesia, largely due to the high deforestation rates of carbon-dense forests (Figure 5). Brazil exported 40% of its land-use emissions, while Indonesia about 42%.

A detailed mapping of the traded carbon emissions associated with producing food commodities can enable international cooperation to reduce land-use emissions.

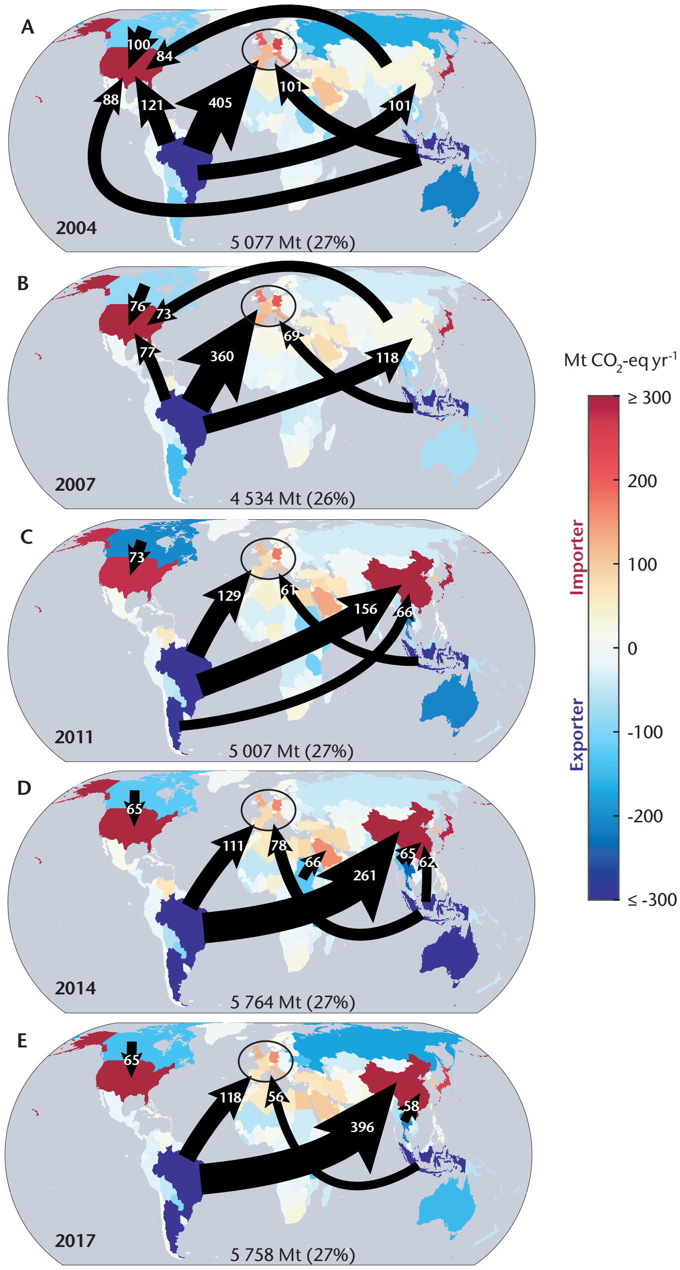

Figure 5. Global distribution of land-use emissions embodied in trade between regions in 2004 (A), 2007 (B), 2011 (C), 2014 (D), and 2017 (E) (Hong et al., 2022).

IPCC headline statements

- Total net anthropogenic GHG emissions have continued to rise during the period 2010–2019 (IPCC Working Group III, 2022)
- Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009 (IPCC Working Group III, 2022)
- Net anthropogenic GHG emissions have increased since 2010 across all major sectors globally (IPCC Working Group III, 2022).

State of the Global Climate: 2018–2022

WMO

Key messages

- The five-year average global mean temperature for 2018–2022 was 1.17 ± 0.13 °C above the 1850–1900 average, making it the fourth warmest 5-year period on record after 2016–2020, 2015–2019, and 2017–2021
- Ocean Heat Content, which is the measurement of heat stored in the ocean, was higher than any other 5-year period for 2018–2022
- Average sea-ice extent in the Arctic from 2018–2022 was below the 1981–2010 long-term average and the Antarctic reached its lowest or second lowest minimum sea-ice extent on record (according to different data sources).

The flagship annual WMO *State of the Global Climate* reports provide a summary of the state of global climate indicators, including global temperature, ocean heat and cryosphere indicators, such as sea ice and snow cover, among others. Each report includes input from National Meteorological and Hydrological Services, climate centres and experts around the world as well as from a wide range of UN partners. This chapter provides a brief summary of the key findings from the 2021 report and recent updates covering the 5-year period from 2018 to June 2022.

Global temperature

The years from 2015 to 2021 were the seven warmest on record. The 2018–2022 global mean temperature average (based on data up to May or June 2022) is estimated to be 1.17 ± 0.13 °C above the 1850–1900 average. This number is the average of six data sets[1], which individually have a range of 1.13 to 1.21 °C. It is the fourth warmest 5-year period on record according to all data sets surveyed (Figure 1), after 2016–2020, 2015–2019, and 2017–2021. Additionally, it is the warmest non-overlapping period, with the second being 2013–2017.

The recent, slightly lower, five-year average is associated with the switch from a strong El Niño present in 2015/2016 to persistent La Niña conditions that affected 2021 and the first half of 2022. El Niño gives a short-term boost to global temperatures, whereas years affected by La Niña are typically a little cooler.

The effect of the extended La Niña can be seen in the Pacific where surface temperatures were below the 1981–2010 period (Figure 2) in the eastern tropical Pacific, but warmer than average in the North Pacific and Southwest Pacific. Only a few areas of the world – parts of North America, the Southern Ocean and an area south of Greenland - were cooler than the recent average. However, most areas across the world were warmer than recent averages. Temperatures averaged over 2018–2022 were particularly high around Eurasia, large areas of Africa, Australia, and parts of South and Central America.

Ocean heat content

Most of the excess energy that accumulates in the Earth system due to increasing concentrations of GHGs is taken

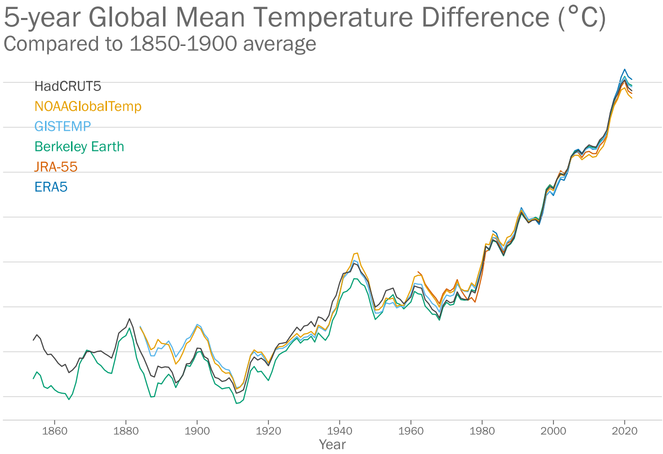

Figure 1. Five-year running average of global temperature anomalies (°C relative to 1850– 1900) from 1850–1854 to 2018–2022 (data to May or June 2022) shown as a difference from the 1850–1900 average. Six data sets are shown as indicated in the legend.

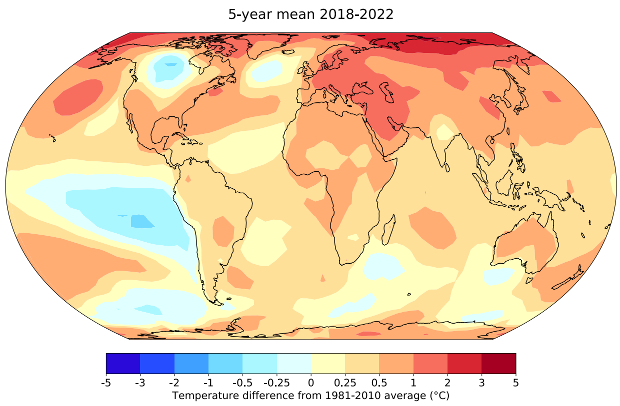

Figure 2. Five-year mean near-surface temperature difference from the 1981–2010 average for the period 2018–2022 (data to May or June 2022). Each map grid cell value is the median calculated from six data sets: HadCRUT5, GISTEMP, NOAAGlobalTemp, Berkeley Earth, JRA-55 and ERA5.

[1]The six data sets are HadCRUT5 (2022 to May), GISTEMP, NOAAGlobalTemp, Berkeley Earth, ERA5 and JRA-55 (2022 to June).

up by the ocean. This added energy warms the ocean and the consequent thermal expansion of the water leads to sea-level rise – to which melting land ice also contributes. The surface layers of the ocean have warmed more rapidly than the deeper waters, resulting in a rise in the global mean sea-surface temperature and an increase in the incidences of marine heatwaves.

Around 90% of the accumulated heat in the Earth system is stored in the ocean, which is measured through Ocean Heat Content. Measurements of the layer from the surface to a 700 metre (m) depth show that the 2018–2022 global heat content (data to May 2022) was higher than in any previous year (Figure 3). The linear rate of change in the National Centers for Environmental Information (NCEI) "Levitus" data set in the years 2018–2022 is 0.8 x 10^{22} Joule/year. This corresponds to a heat flux in the 0–700 m layer of 0.7 Watts m^{-2}.

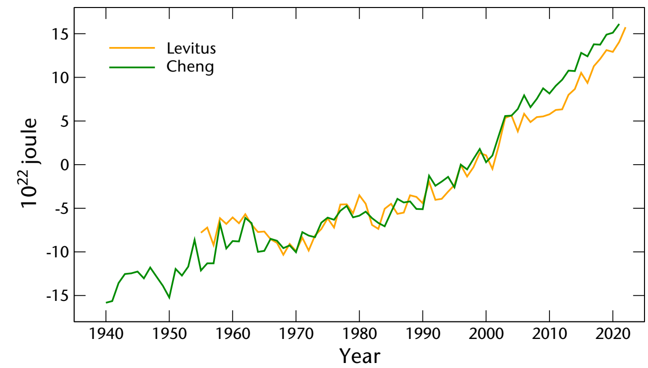

Figure 3. Global ocean heat content 0-700 m from 1940 to May 2022 (Institute of Atmospheric Physics ocean analysis).

The upper 2 000 m depth of the ocean continued to warm in 2021 and it is expected that it will continue to do so in the future – a change which is irreversible on centennial to millennial timescales (Riser et al., 2016 and Roemmich et al., 2019).

All data sets agree that ocean warming rates show a particularly strong increase in the past two decades. Ocean warming rates for the 0–2 000 m depth layer (relative to the ocean surface) reached 1.0 (0.6) ± 0.1 W m^{-2} over the period 2006–2021 (1971–2021). For comparison, the values for the upper 700 m depth amount to 0.7 (0.4) ± 0.1 W m^{-2} over the period 2006–2021 (1971–2021). Below the 2 000 m depth, the ocean also warmed, albeit at a lower rate (Purkey et al., 2010) of 0.07 ± 0.04 W m^{-2}.

Cryosphere

Human influence is very likely the main driver of the decrease in Arctic sea-ice area between 1979–1988 and 2010–2019, which recorded decreases of about 40% in September and about 10% in March (IPCC, 2021). The current Arctic sea-ice cover (both annual and late summer) is at its lowest level since at least 1850 and is projected to reach practically ice-free conditions at its summer minimum at least once before 2050.

There has been no significant trend in Antarctic sea-ice area from 1979 to 2020 due to regionally opposing trends and large internal variability (IPCC, 2021). Antarctic sea-ice extent increased slowly from the start of the satellite era to around 2015, as can be seen in Figure 4. However, it dropped rapidly between 2015 and 2017, then returned close to the long-term average between 2017 and 2021 before reaching its lowest or second lowest minimum on record, according to different data sources from February 2022.

Glaciers are also highly sensitive to changes in temperature, precipitation, sunlight, and warming ocean waters, as well as other factors. Over the period 2000–2019, global glaciers and

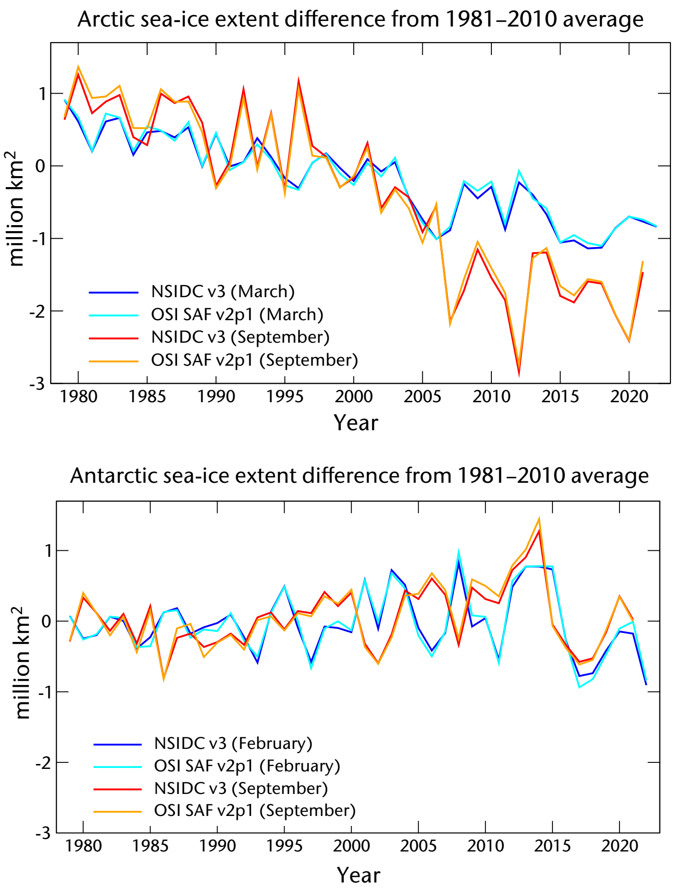

Figure 4. Sea-ice extent differences from the 1981–2010 average in the Arctic (upper) and Antarctic (bottom) for the months with maximum ice cover (Arctic: March; Antarctic: September) and minimum ice cover (Arctic: September; Antarctic: February) from 1979 to March 2022 (US National Snow and Ice Data Center (NSIDC) and EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI-SAF)).

ice caps (excluding the Greenland and Antarctic ice sheets) experienced an average mass loss of 267 ± 16 gigatons (Gt) per year. Mass loss was higher, at 298 ± 24 Gt per year, in the later part of the period 2015–2019. However, glaciers in several mid-latitude regions thinned at more than double the global average (0.52 ± 0.03 m per year) from 2015 to 2019. Examples include thinning of 1.52 m per year in New Zealand, 1.24 m per year in Alaska, 1.11 m per year in Central Europe, and 1.05 m per year in Western North America (not including Alaska).

The World Glacier Monitoring Service collates and analyses global glacier mass balance data, including a set of 42 reference glaciers with long-term observations. For the glaciological year 2020/2021, preliminary data available from 32 of these reference glaciers indicate an average global mass balance of –0.77 m water equivalent (m w.e.)[2]. This is a smaller mass loss than the average for the last decade (–0.94 m w.e. from 2011 to 2020), but is larger than the average mass loss for the period 1991–2020, –0.66 m w.e.

2021 extreme events

Although understanding broad-scale changes in the climate is important, the acute impacts of weather and climate are most often felt during extreme meteorological events such as heavy rain and snow, droughts, heatwaves, cold waves, and storms, including tropical storms and cyclones. These can lead to or exacerbate other high-impact events such as flooding, landslides, wildfires and avalanches. This section highlights extreme weather events from 2021 and is based largely on input from WMO Members.

In 2021, exceptional heat waves affected western North America with record temperatures reaching 49.6 °C in British Columbia, Canada, breaking the previous Canadian national record by 4.6 °C. The extreme heat extended into the United States as well, which recorded its hottest summer on record averaged over the continental Untied States. Extreme heat also affected Central Europe and the broader Mediterranean region where Syracuse in Sicily, Italy, reached 48.8 °C. There were also numerous major wildfires during and after these heatwaves, from Canada to Siberia, where wildfires raged for the third successive year.

Western Europe experienced some of its most severe flooding on record in mid-July 2021. The worst-affected area was western Germany and eastern Belgium, where 100 to 150 mm of rain fell over a wide area on 14/15 July and Hagen (Germany) reported 241 mm of rainfall in 22 hours. Meanwhile, other parts of the world suffered from drought. In the Greater Horn of Africa, particularly Somalia, Kenya, and part of Ethiopia, drought developed during the course of the year after three successive below-average rainy seasons.

Abnormally cold conditions affected many parts of the central United States and northern Mexico in mid-February 2021. The most severe impacts were in Texas, which generally experienced its lowest temperatures since at least 1989. Additionally, the winter of 2020/2021 was particularly cold for many parts of Northern Asia. The Russian Federation had its coldest winter since 2009/2010 and below-average temperatures affected much of Japan in late December and early January. Much of China was also unusually cold during this period, with Beijing reaching –19.6 °C on 7 January 2021, its lowest temperature since 1966.

[2]Metres water equivalent (m w.e) is the depth of water that would result if the lost ice were melted and spread across the surface area of the glacier.

Global Climate Predictions: 2022–2026

Met Office, UK/WMO/World Climate Research Programme (WMO/International Science Council/IOC-UNESCO)

Key messages

- There is an almost 50% likelihood that at least one of the years from 2022–2026 will temporarily exceed warming of 1.5 °C above pre-industrial levels (1850–1900 average)
- There is a 93% probability that at least one year between 2022 and 2026 will be warmer than the warmest year on record (2016) and that the five-year mean temperature for 2022–2026 will be higher than that for 2017–2021
- There is an increased likelihood of wetter conditions in the Sahel, northern Europe, Alaska, and northern Siberia and of drier conditions over the Amazon from May to September in the coming five years (2022–2026).

The WMO Lead Centre for Annual to Decadal Climate Prediction produces a summary of predictions for the coming five years (Hermanson et al., 2022). These predictions provide the best estimate of the near-term climate and are based on the world's leading decadal prediction systems from WMO-designated Global Producing Centres and non-designated contributing centres. These predictions include multiple realizations (120 in total) with observed initial conditions of the type used in seasonal prediction and boundary forcing of the type used to drive long-term climate projections. Note that these predictions assume that no major volcanic eruptions occur during the period in question. This chapter highlights the Centre's predictions for the 2022–2026 period.

Climate predictions for 2022–2026

Global temperature

Global mean near-surface temperatures are likely to increase from 2022–2026 and stay well above the 1991–2020 reference. Annual mean global near-surface temperature for each year in this five-year period is predicted to be between 1.1 and 1.7 °C higher than pre-industrial levels, that is the average temperature over the period 1850 to 1900.

Using the best estimate of warming since pre-industrial times, the likelihood of the annual mean global near-surface temperature temporarily exceeding 1.5 °C above pre-industrial levels for at least one of the next five years is 48% and is increasing with time. However, there is only a small probability (10%) that the five-year mean will exceed this threshold. Note that the Paris Agreement level of 1.5 °C refers to long-term warming, but individual years above 1.5 °C are expected to occur with increasing regularity as global temperatures approach this long-term threshold.

There is a 93% probability that at least one year in the next five will be warmer than the warmest year on record (2016) and that the mean temperature for 2022–2026 will be higher than that of the last five years. Confidence in forecasts of global mean temperature is high since estimates of skill from hindcasts are high.

The predicted temperature patterns for 2022–2026, relative to the 1991–2020 average, are presented in Figure 1 for two extended seasons: May to September (left) and November to March (right). For the next five May to September seasons, temperature patterns are predicted to average above the 1991–2020 average almost everywhere, with enhanced warming over land in the northern hemisphere. For the

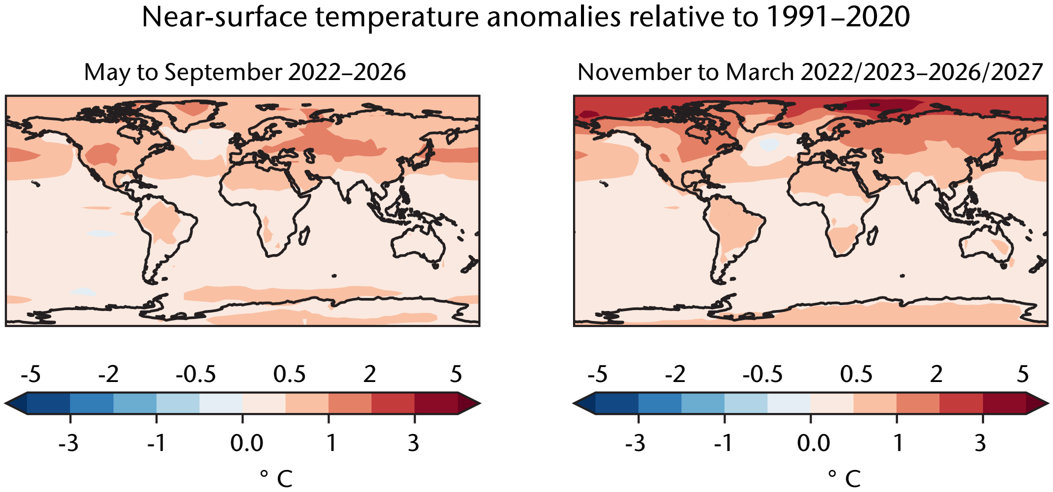

Figure 1. Predictions for the next five extended seasons of near-surface temperature anomalies (in °C) relative to 1991–2020. Ensemble mean prediction for May to September 2022–2026 (left) and ensemble mean prediction for November to March 2022/2023–2026/2027 (right).

next five November to March seasons, the predictions show warm anomalies almost everywhere, with land temperatures showing larger anomalies than those over the ocean. The Arctic (north of 60°N latitude) near-surface temperature anomaly is more than three times as large as the global mean anomaly. Skill is high in most regions giving medium to high confidence in predictions for both seasons apart from parts of the North Pacific, some areas in Asia, Australia, and the Southern Ocean.

Global precipitation

The 2022–2026 predicted precipitation patterns relative to the 1991–2020 average are presented in Figure 2 for the extended May to September (left) and November to March (right) seasons. For the next five May to September seasons, predictions show increased likelihood of wet anomalies in the Sahel, northern Europe, Alaska, and northern Siberia, and dry anomalies over the Amazon. Skill is low to medium for these regions, giving low to medium confidence. There are wet anomalies over southern and eastern Asia, but the predictions have little historical skill in predicting 5-year mean precipitation for this region.

For the November to March season over the years 2022/2023–2026/2027, precipitation predictions favour wetter than average conditions at high latitudes in the northern hemisphere. The pattern of increased precipitation in the tropics and high latitudes and reduced precipitation in the subtropics is consistent with climate warming. Skill is moderate over large parts of northern Eurasia, Greenland and the Canadian Arctic Archipelago, giving low to medium confidence in the forecast for an increased chance of precipitation in these regions.

This work is done in collaboration with the World Climate Research Programme (WCRP) as part of the development of WMO climate services. The forecasts are used by National Meteorological and Hydrological Services and research projects worldwide and will soon be used by WMO Regional Climate Centres to provide early warnings to mitigate the impacts of climate hazards.

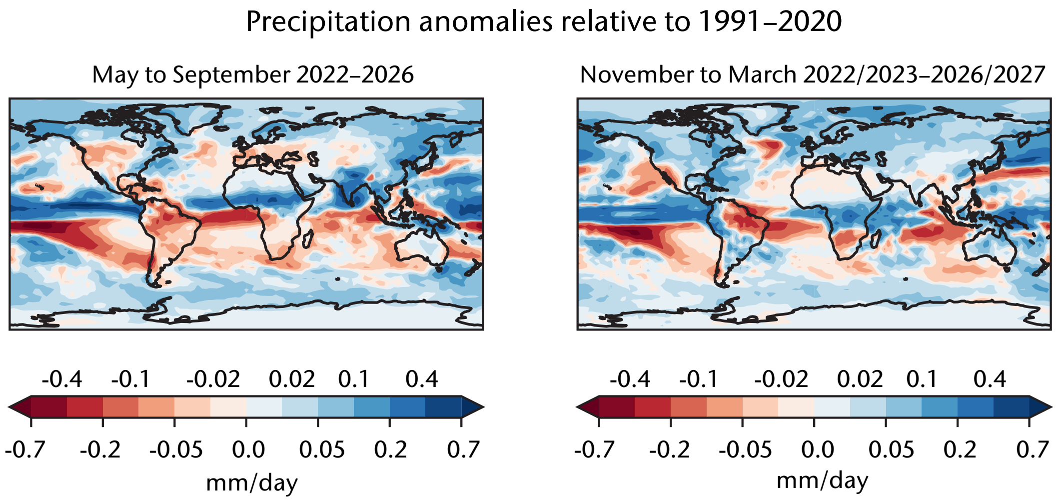

Figure 2. Predictions for the next five extended seasons of precipitation anomalies (in mm/day) relative to 1991–2020. Ensemble mean prediction for May to September 2022–2026 (left) and ensemble mean prediction for November to March 2022/2023–2026/2027 (right).

Key messages

- New national mitigation pledges for 2030 (as of 4 November 2021) show some progress toward lowering Greenhouse Gas (GHG) emissions, but their aggregate effect on global emissions is insufficient to meet the goals of the Paris Agreement. The ambition of these new pledges needs to be four times higher to get on track to limit warming to 2 °C and seven times higher to get on track to 1.5 °C
- Global warming over the course of the twenty-first century is estimated to be limited to 2.8 °C (range: 2.3–3.3 °C, 66% probability), assuming a continuation of current policies, or 2.5 °C (range 2.1–3.0 °C, 66% probability) if new or updated (conditional and unconditional) pledges are fully implemented
- If the full implementation of all net-zero pledges and announcements to date are included in the assessment, in addition to the updated unconditional and conditional Nationally Determined Contributions (NDCs), estimated warming over the twenty-first century is projected to be limited to 2.1 °C (range: 1.9–2.3 °C) and 1.9 °C (range: 1.9–2.2 °C), respectively, with a 66% probability.

The *Emissions Gap Report* provides annual science-based assessments of the gap between estimated future GHG emissions and global emissions levels aligned with achieving the goals of the Paris Agreement. The Report analyzes future global GHG emissions if countries implement their climate mitigation pledges and the global emissions levels from least cost pathways that are aligned with limiting global warming to well below 2 °C and pursuing 1.5 °C. In 2021, the spotlight was on the implication of new or updated climate mitigation pledges for 2030, the status of net-zero emissions pledges and pathways, and the estimated global warming at the end of the century under current policies, pledges and scenarios.

By 4 November 2021, the cut-off date for the addendum to the Emissions Gap Report 2021 (UNEP 2021a), 152 countries – accounting for 88% of global GHG emissions – had communicated new or updated mitigation pledges for 2030. More than 60% of the new or updated mitigation pledges result in lower 2030 emissions than previous pledges, which shows some progress. Additionally, the updated pledges are generally more transparent and include GHG targets to a greater extent than prior pledges. Since then, 18 countries have submitted new or updated mitigation pledges. Two of these (Brazil and Republic of Korea) were announced before 4 November 2021 and were included in the assessment. Australia submitted a strengthened NDC on 16 June 2022, the effects of which has not been considered in the assessment. The remaining new or updated pledges submitted in 2022 will have limited effects on global emissions projections.

The aggregate impact of new or updated mitigation pledges is limited – they are estimated to lead to a total reduction in global GHG emissions of only 4.8 gigatons of CO_2 equivalent ($GtCO_2e$) annually by 2030 (Figure 1). The aggregate reduction is about 0.7 $GtCO_2e$ greater than that reported in the Emissions Gap Report 2021 (UNEP, 2021b), which was based on pledges announced or submitted with a cut-off date of 30 September 2021.

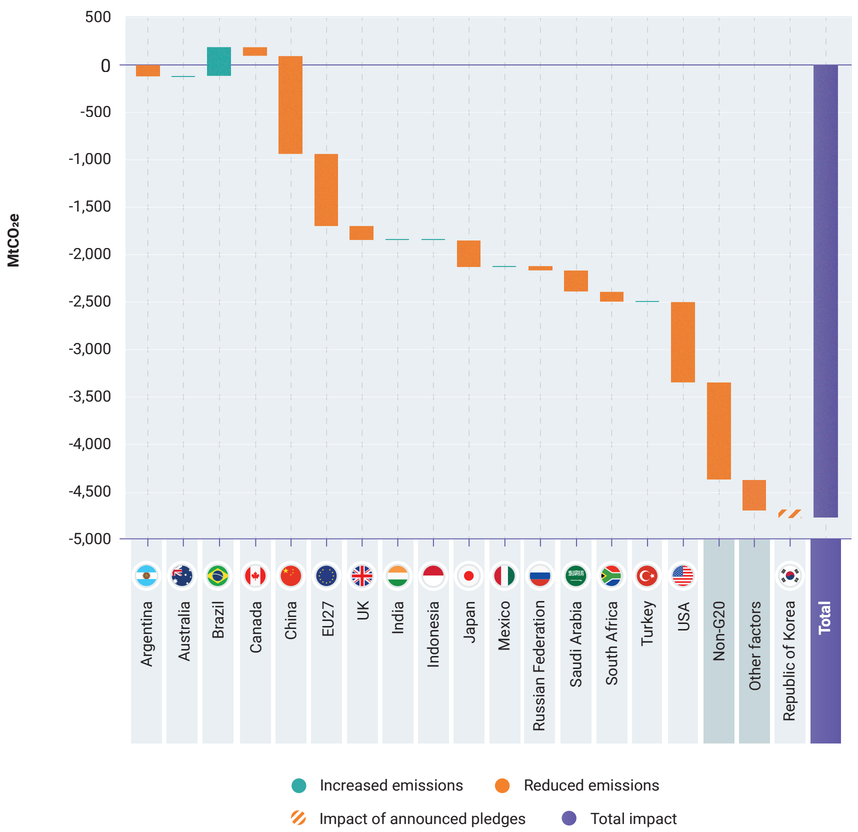

Figure 1. Impact of 2030 mitigation pledges on 2030 global emissions relative to previous pledges. Note: The figure is based on new or updated mitigation pledges as of 4 November 2021 and does not include Australia's updated NDC target (UNEP, 2021a).

The emissions gap remains large

The emissions gap in 2030 (Figure 2) highlights that while the new and updated mitigation pledges narrow the gap slightly compared to previous pledges, they are highly insufficient to bridge the gap. Overall, analysis reveals that ambition of new pledges would need to be four times higher to get on track to 2 °C and seven times higher to get on track to 1.5 °C.

Full implementation of unconditional pledges is estimated to result in a gap to a 1.5 °C pathway of 27 $GtCO_2e$ (range: 24–29 $GtCO_2e$). This is about 5 $GtCO_2e$ lower than the gap assessed in the 2020 report (UNEP, 2020), due to the updated NDCs and announced mitigation pledges. If the conditional NDCs are also fully implemented, the emissions gap is further reduced by about 3.5 $GtCO_2e$.

The emissions gap between a 2 °C pathway and the unconditional NDCs and announced mitigation pledges is about 12.5 $GtCO_2e$ (range: 9–15 $GtCO_2e$), which is about 2.5 $GtCO_2e$ lower than last year. While NDC and announced mitigation pledges reduce global emissions by about 4.5 $GtCO_2e$ compared with previous NDCs, the updated 2 °C scenario estimate for 2030 is about 2 $GtCO_2e$ lower than in previous *Emissions Gap Reports*, which means that the gap is only reduced by about 2.5 $GtCO_2e$.

A continuation of current policies is projected to result in global GHG emissions of about 55 $GtCO_2e$ (range: 52–58 $GtCO_2e$) in 2030. This is 4 $GtCO_2e$ lower than the median estimate of the 2020 *Emissions Gap Report* (UNEP, 2020) and 9 $GtCO_2e$ lower than the 2010-policies scenario, which illustrates how global emissions would evolve had there been no new climate policies since 2010. Around half of the decrease between the 2020 and 2021 *Emissions Gap Reports* reflects climate policy progress in countries, while the other half is because of the general slowdown of economies due to the COVID-19 pandemic.

Collectively, countries are falling short of meeting their new or updated pledges with the policies that are currently being implemented. This implementation gap in 2030 is 3.5 $GtCO_2e$ for unconditional NDCs and 7 $GtCO_2e$ for conditional NDCs. Notably, as a group, G20 members are not on track to achieve either their original or new 2030 pledges. Only 10 G20 members (Argentina, China, EU27, India, Japan, the Russian Federation, Saudi Arabia, South Africa, Türkiye and the United Kingdom) are on track to achieve their previous NDCs. Among them, under current policies, three members (India, the Russian Federation and Türkiye) are projected to reduce their emissions to levels at least 15% lower than those implied by their unconditional NDC target, indicating that these countries have significant room for raising their NDC ambition.

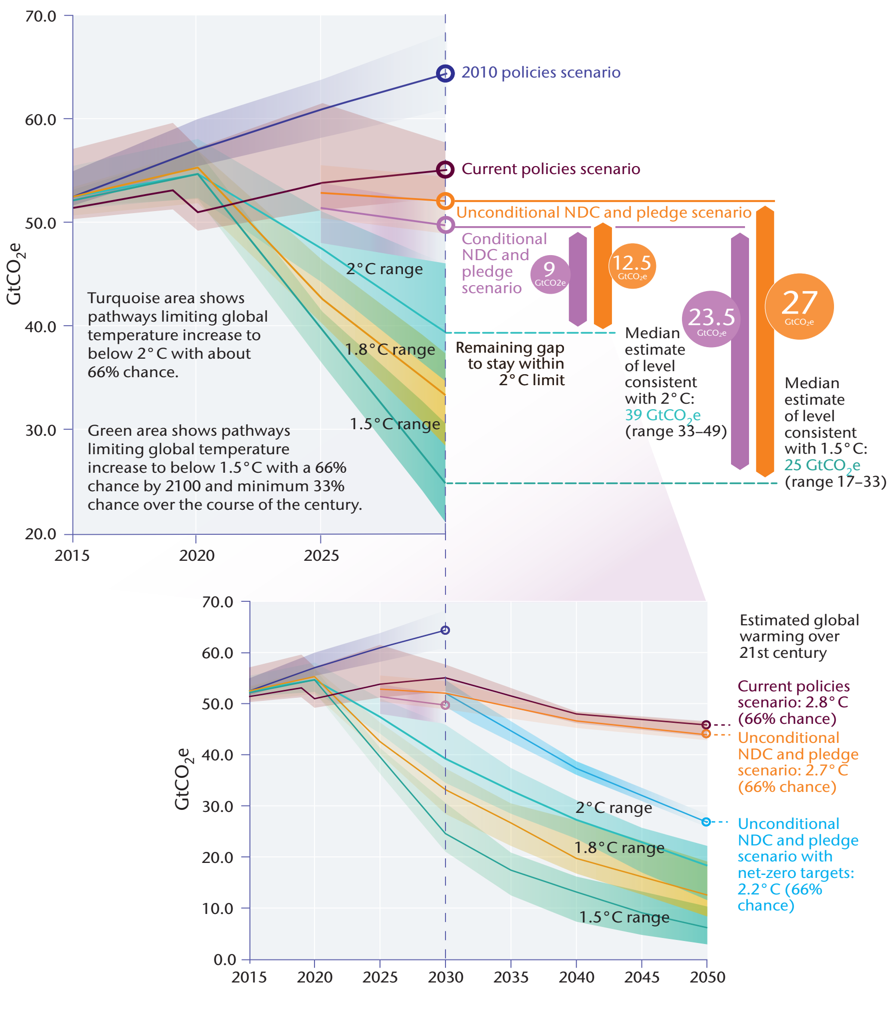

Figure 2. Global greenhouse gas emissions under different scenarios and the emissions gap in 2030 (median estimate and tenth to ninetieth percentile range) (UNEP, 2021a; 2021b).

Announcement of long-term net-zero emissions pledges – a promising development

Globally, 74 parties have pledged a net-zero emissions target that is stated in national legislation, a policy document, or a public announcement by the Government or a high-level Government official. These pledges cover 76% of current global domestic GHG emissions, 83% of gross domestic product, and 64% of the global population.

By number, the majority of these targets are for 2050, aligning with the mid-century timescale indicated by the Intergovernmental Panel on Climate Change (IPCC) as necessary, globally, for limiting warming to 1.5 °C. Existing targets show variations in scope and large ambiguities with respect to the inclusion of sectors and GHGs. The majority are furthermore unclear or undecided on the inclusion of emissions from international aviation and shipping and the use of international offsets.

Few G20 targets put emissions on a clear path towards net-zero emissions

As an indication of the consistency between nearer-term actions and net-zero targets, Figure 3 plots the emissions paths for a subgroup of G20 members implied by their current NDCs and their net-zero target. Of the nine G20 members for which an emissions path could be estimated based on their net-zero target and their NDCs, none have NDC targets that put them on an accelerated path towards their net-zero emissions targets. Five of these nine members, accounting for about one fifth of global domestic GHG emissions, have NDC targets that put the country's domestic emissions onto a linear path towards achieving their net-zero targets. In the other four cases, the NDCs lead to emissions in 2030 that are about 25%–95% higher than a linear path towards their net-zero targets would imply. Recognizing that countries face very different circumstances, these countries urgently need strengthened and more ambitious near-term climate plans for their net-zero targets to remain achievable.

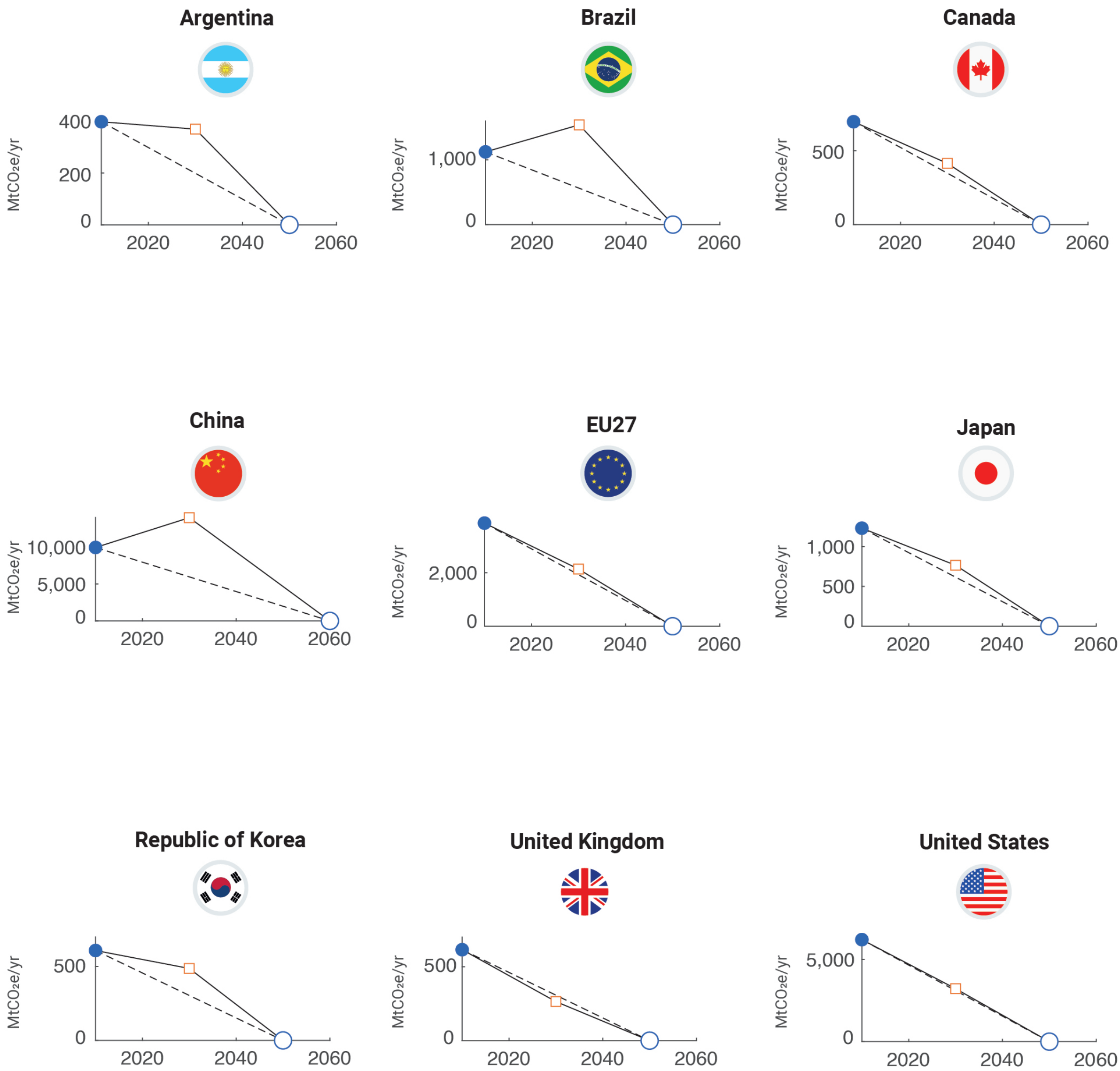

Figure 3. Overview of net-zero pathways implied by climate pledges by selected G20 members (UNEP, 2021b).

Global warming implications: we are far from the Paris Agreement goal

A continuation of current policies is projected to limit global warming to 2.8 °C with a 66% probability over the course of the twenty-first century with a range of 2.3–3.3 °C, inter alia due to uncertainties about how emissions would continue after 2030.

A continuation of the new or updated unconditional NDCs and other pledges is estimated to limit warming to 2.7 °C (range: 2.2–3.1 °C) by the end of the century with a 66% probability. If conditional pledges are also fully implemented, these estimates are lowered to 2.5 °C (range: 2.1–3.0 °C). As noted earlier, currently the implementation gap in 2030 is 3.5 $GtCO_2e$ for unconditional NDCs and 7 $GtCO_2e$ for conditional NDCs.

Only when the full implementation of all net-zero pledges and announcements to date are taken into account, in addition to the updated unconditional and conditional NDCs, do warming projections get closer to the Paris Agreement goal. Under this scenario, warming over the twenty-first century is projected to be limited to 2.1 °C (range: 1.9–2.3 °C) and 1.9 °C (range: 1.9–2.2 °C) with a 66% probability.

However, there are several caveats. Given the lack of transparency of net-zero pledges, the absence of a reporting and verification system, and the fact that few 2030 pledges put countries on a clear path to net-zero emissions, it remains uncertain if net-zero pledges will be achievable.

IPCC headline statements

- Projected global GHG emissions from NDCs announced prior to the 26th Conference of Parties (COP26) of the UN Framework Convention on Climate Change (UNFCCC) would make it likely that warming will exceed 1.5 °C and also make it harder after 2030 to limit warming to below 2 °C (IPCC Working Group III, 2022)
- Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot and in those that limit warming to 2 °C (>67%) and assume immediate action. In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*) (IPCC Working Group III, 2022)
- Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100 (*medium confidence*) (IPCC Working Group III, 2022).

Tipping Points in the Climate System

WMO/World Climate Research Programme
(WMO/International Science Council/IOC-UNESCO)

Key messages

- Major tipping points include changes in the Atlantic Meridional Overturning Circulation, the melting of polar ice sheets, the migration of large-scale weather and climate patterns, drying of the Amazon rainforest, or disruptions of major weather systems, such as the monsoon
- The combined effects of higher temperatures and humidity during hot spells in some regions could reach dangerous levels in the next few decades, which could lead to physiological tipping points, or thresholds beyond which outdoor human labor is no longer possible without technical assistance
- Further research on tipping points will be crucial to help society better understand the costs, benefits and potential limitations of climate mitigation and adaptation in the future.

"Tipping points" have become a widely-used shorthand for many aspects of non-linear changes in a complex system. What we now refer to collectively as "tipping points in the climate system" were first addressed in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as "surprises" (Stocker et al., 2001) and subsumed under the "Reasons for Concern" as "large-scale singular events" or "discontinuities in the climate system" (IPCC, 2001). These tipping points have both global and regional consequences and include changes in the Atlantic Meridional Overturning Circulation (AMOC), the melting of polar ice sheets, the migration of large-scale weather and climate patterns, and dieback of the Amazon rainforest.

Tipping points with global consequences

AMOC is an important driver of the distribution of heat, salt, and water in the climate system, both regionally and globally. Based on paleoclimate proxy data, it has been suggested that AMOC may be weaker in the current climate than at any other time in the last millennium (Caesar et al., 2021). In addition, recent models consistently indicate that the AMOC will weaken as CO_2 continues to increase (Weijer et al., 2020). Although direct measurements since 2004 show no significant trends (Worthington et al., 2021), continuous long-term weakening of the AMOC, as robustly suggested by models (Jackson et al., 2022), may increase its vulnerability to other changes, such as freshwater delivery from melting ice sheets and glaciers. As a result, the continued study, identification, and observation of early warning signals of a potential tipping point in the AMOC is crucial (Boers, 2021).

The melting of the polar ice sheets on Greenland and Antarctica have been considered tipping elements for many years (Figure 1). Their tipping would be particularly dangerous as they would have global consequences due to substantial additional sea-level rise on the timescales of centuries to millennia (Clark et al., 2016). The IPCC Fifth Assessment Report communicated that crossing a critical global warming threshold between 1 °C and 4 °C would lead to significant and irreversible melting of the Greenland Ice Sheet (Stocker et al., 2013). However, this range was reassessed and found to be at or slightly above 1.5 to 2 °C – that is, the global warming limits of the Paris Agreement (Pattyn et al., 2018). At this warming level, the West Antarctic Ice Sheet would also be at increasing risk of irreversible ice loss (Garbe et al., 2020). While the underlying physical mechanisms are well-researched and theoretically understood, determination of the critical thresholds for the individual ice basins under realistic conditions and topography is very difficult, and large uncertainties remain (Pattyn and Morlighem, 2020).

Figure 1. Crossing tipping points associated with ice-sheet instabilities in Antarctica, or with rapid discharge from ice streams in Greenland, can have serious global impacts. (Terminus of Jakobshavn Isbrae, Greenland, Photo T.F. Stocker).

Regional tipping points

Recently, regional tipping points, such as migration of large-scale weather and climate patterns, changes in extreme and compound events, and drying of the Amazon rainforest, have moved into focus. There is concern that their impacts may have serious consequences for local communities (Figure 2) and could cause further cascading impacts, including global feedbacks, such as potential effects of regional droughts on the global carbon cycle (Humphrey et al., 2018). Overall, while these tipping points may first occur regionally in several locations, over time they may add up to a global scale with cumulative and compounding impacts (e.g., Kornhuber et al., 2020).

A gradual migration of large-scale weather or climate patterns may be registered regionally as tipping into a new regime. The paleoclimate record, for example, has pointed to phases when the monsoon belt has shifted or changed in intensity in response to large-scale hemispheric climate changes during the last 30 000 years (Brovkin et al., 2021). A recent analysis suggests that future warming could lead to an intensification of the Indian monsoon and its variability, expressed possibly as shorter and heavier rains (Katzenberger et al., 2021).

In mid-latitude regions, changes in soil moisture can lead to threshold effects in evaporative regimes, and to an associated non-linear amplification of heat extremes (Seneviratne et al., 2010; Miralles et al., 2014; Vogel et al., 2018). Furthermore, the frequency of threshold-based climate extremes generally increases non-linearly with increasing global warming, with the largest relative changes for the most extreme events (Kharin et al., 2018). Changes in regional mean climate and the intensity of climate extremes tend to vary linearly as a function of global warming (Wartenburger et al., 2017). However, they can also lead to the crossing of regional ecosystem thresholds (Guiot and Cramer 2016; Warren et al., 2018; Ratnayake et al., 2019; Breshears et al., 2020) and to climate regime shifts in combination with vegetation changes and societal responses. An example of this is the dust bowl period in the United States (e.g., Cowan et al., 2020).

The marine environment is also prone to regional tipping. Marine heat waves, for example, could occur more frequently and more intensely (Frölicher et al., 2018). Ocean acidification, caused by the ocean's absorption of increasing atmospheric carbon dioxide concentrations in its role as a carbon sink, could cross thresholds with consequent coral bleaching and other marine ecosystem impacts (Hoegh-Guldberg et al., 2019). Regional tipping points of marine systems due to warming, ocean acidification, and deoxygenation can, in combination, cause global impacts (Heinze et al., 2021).

The Amazon rainforest, a unique ecosystem of global significance and value, is under pressure from deforestation and anthropogenic climate change. Although projections of its future evolution are highly uncertain, studies point to the likelihood of further drying (Baker et al., 2021). More extended dry seasons and extreme drought events, and self-reinforcing feedbacks, could further reduce the forest extent (Zemp et al., 2017) with a potential approach to a tipping point (Boulton et al., 2022) where the forest is unsustainable. Loss of the Amazon rainforest would have potentially devastating consequences on regional climate, biodiversity and social systems as well as potentially wider impacts through changes of the hydrological and carbon cycles.

Figure 2. Thresholds and tipping points may be increasingly encountered in regional weather patterns and extremes with consequences for local communities and ecosystem services (Drought and developing storm in the Ebro Delta, Spain, 2020. Photo WMO/Agusti Descarrega Sola).

Consequences of tipping points on human health and well-being

The impact of climate change on human health is receiving greater attention (Romanello et al., 2021) as the potential threats are multiple. The combined effects of higher temperatures and humidity during hot spells in some regions could reach dangerous levels in the next few decades (Pal and Eltahir, 2016), which could lead to physiological tipping points, or thresholds beyond which outdoor human labor is no longer possible without technical assistance. Already, a substantial fraction of heat-related mortality today can be attributed to anthropogenic warming (Vicedo-Cabrera et al., 2021) and this trend is increasing in extent and magnitude. Hence these events can cause tipping points and threshold behaviour in the Earth system, which includes the biosphere, the carbon cycle, and society, as socioeconomic impacts are expected to be strong and irreversible on intermediate timescales.

Taken together, tipping points in the climate system are a scientific topic of great public interest. The WCRP, for example, is addressing this issue in one of their Lighthouse Activities through an international platform to combine theoretical-mathematical approaches, observational monitoring, and comprehensive climate modelling efforts. Non-linear processes in the climate system are at the origin of tipping elements, so a concerted international effort in high-resolution coupled Earth system modelling developing and utilizing exa-scale computing infrastructure (Slingo et al., 2022; Hewitt et al., 2022) will provide an improved representation of climate feedbacks and of dynamical responses responsible for tipping elements.

Finally, a formal scientific consensus on tipping points and irreversible climate change, which is central to estimating climate risk, yet fraught with deep uncertainty, is policy-relevant. The latest IPCC report has assessed tipping points and outlines the limits of the current status of knowledge. A cross-working group IPCC Special Report on "*Climate Tipping Points and Consequences for Habitability and Resources*" would help strengthening a consensus on this topic and trigger the much needed advances in scientific understanding to more comprehensively inform adaptation and mitigation strategies.

IPCC headline statements

- Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets, and global sea level (IPCC Working Group I, 2021)
- The probability of low-likelihood, high impact outcomes increases with higher global warming levels (*high confidence*). Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice-sheet melt and forest dieback, cannot be ruled out (*high confidence)* (IPCC Working Group I, 2021)
- The rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt (*high confidence*) (IPCC Working Group II, 2022).

Key messages

- Cities – home to 55% of the global population, or 4.2 billion people – are responsible for up to 70% of human-caused emissions and are also highly vulnerable to the impacts of climate change
- Climate change in cities will lead to increased rates of heavy precipitation, accelerated sea-level rise, exacerbated acute and chronic coastal flooding, drought, higher than average annual temperatures and extreme heat events, which will exacerbate socioeconomic challenges and inequalities
- Cities have an important role in addressing climate change by implementing inclusive, urgent, and scaled-up mitigation action and increasing the adaptive capacity of billions of urban inhabitants in ways that contribute to achieving the Sustainable Development Goals (SDGs) and benefit rural communities.

There is a clear, yet rapidly closing, window of opportunity for meaningful global action on climate adaptation, mitigation, and resiliency in order to secure a livable future. Cities and settlements will play a highly significant role in how this window of opportunity is leveraged. Cities have become early responders to climate change because they are responsible for up to 70% of human-caused emissions and their neighborhoods and critical infrastructure systems are often highly vulnerable. They currently host 55% of the global population, some 4.2 billion people, and the number of urban dwellers is projected to increase to 68% by 2050 (United Nations, 2019). Therefore, now is the time to integrate adaptation and mitigation, coupled with sustainable development, into the ever-dynamic urban environment.

Climate challenges in global cities

As presented by global climate modelling scenarios, climate change in cities will manifest as directional shifts in climate envelopes and increased frequency and intensity of extreme events. These climate changes include higher average annual temperature, longer heatwaves and increased rate of heavy precipitation events as well as accelerated sea-level rise and exacerbated coastal flooding. Increases in frequency of extreme rainfall and heavy downpour events are already causing more frequent flooding of inland coastal cities.

Today, cities are facing more frequent and more intense heat waves, compared to conditions during the 1950s (Rosenzweig et al., 2021). For example, between March and May 2022, Delhi, India, experienced five heat waves with record-breaking temperatures reaching up to 49.2 °C (120.5 °F). A recent attribution study concluded that climate change made this prolonged hot weather 30 times more likely and that the same event would have been about 1 °C cooler in a pre-industrial climate. Half of Delhi's residents live in low-income, informal settlements, increasing vulnerability to extreme heat (Zachariah et al., 2022)

Globally, by the 2050s, over 1.6 billion people living in over 970 cities will be regularly exposed to 3-month average temperatures reaching at least 35 °C (95 °F) (Rosenzweig

Urban health risks: heat extremes and pronounced vulnerabilities

The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report highlights that some parts of the world already exceed the international standard for safe work activity during the hottest months of the year as the capacity of the human body to thermoregulate may be exceeded on a regular basis (IPCC, 2022). Excessive heat in workplaces represents a serious health hazard, with reductions in cognitive and physical work performance and increases in sick leave leading to lost productivity (Jay et al., 2021).

Health inequalities from heat exposure and existing vulnerabilities, including pre-existing health conditions (e.g., cardiovascular diseases), socioeconomic dimensions (e.g., precarious housing), demographic factors (e.g., age and gender), geographic aspects (e.g., water-stressed zones) and sociopolitical factors (e.g., political instability), are particularly pronounced in urban settings. As characteristics of the built environment contribute to intracity temperature variation, surface urban heat-island intensity was found to be worse for both people of colour and the poor in nearly all major USA cities, supporting previous evidence that minority and low-income populations bear the brunt of urban exacerbations of heat threats to health (Hsu, 2021).

Future IPCC scenarios indicate with very high confidence that major changes in ill health will occur through greater risk of injury, disease and death due to more intense heat waves and fires (IPCC, 2022). However, rising temperatures and more frequent and intense heat waves do not occur in isolation, but need to be understood as part of a complex system of compounding and cascading climate hazards, direct and indirect health impacts, and urban characteristics and vulnerabilities. To disentangle this complexity and identify sustained urban solutions, there is a critical need for integration of transdisciplinary and cross-sectoral approaches putting health at the core of urban strategies and actions.

et al., 2021). Figure 1 shows the extreme heat risk for current and projected future urban populations in global cities. Simultaneous heatwaves and droughts are more likely to occur on the global scale – one example of the many possible compounding risk combinations.

Low-lying coastal cities and settlements, such as Bangkok (Thailand), Houston (USA) and Venice (Italy), are highly likely to face more frequent and more extensive coastal flooding due to sea-level rise, storm surges and subsidence. Additionally, urban areas on small islands do not currently have the capacity to adequately prepare for and respond to natural disasters. In September 2019, Nassau and Freeport, two major cities in the Bahamas, suffered devastating impacts from Category 5 Hurricane *Dorian*. The storm caused US$ 3.4 billion in damages and killed 74 people (Zegarra et al., 2020). The number and severity of climate-related disasters in cities is projected to increase in the coming decades (Gencer et al., 2018).

Climate change is not an isolated challenge for cities. It is interlinked with existing critical infrastructure issues, financial constraints and systemic inequities. By continuing to address climate challenges as they occur, decision-makers put themselves in positions of responsive rather than proactive action. There is an urgent need to address pressing ecological, social, economic, and climate justice needs within cities and settlements.

Global responsibilities of cities and opportunities ahead

Cities are sites where rapid experimentation with inclusive decision-making and multi-level governance can take place. This creates enabling conditions for effective climate resilient development, which concerns both nature and people, including green spaces and their benefits for biodiversity and human health. Urban areas are at the nexus of bottom-up approaches – with, for example, community-led groups, local and Indigenous Peoples or youth movements – and top-down climate change drivers and actions. Incorporation of dynamic climate approaches into urban design is essential for cities to scale up their climate action planning. Climate resiliency should be central in every financial decision that cities and their metropolitan regions make.

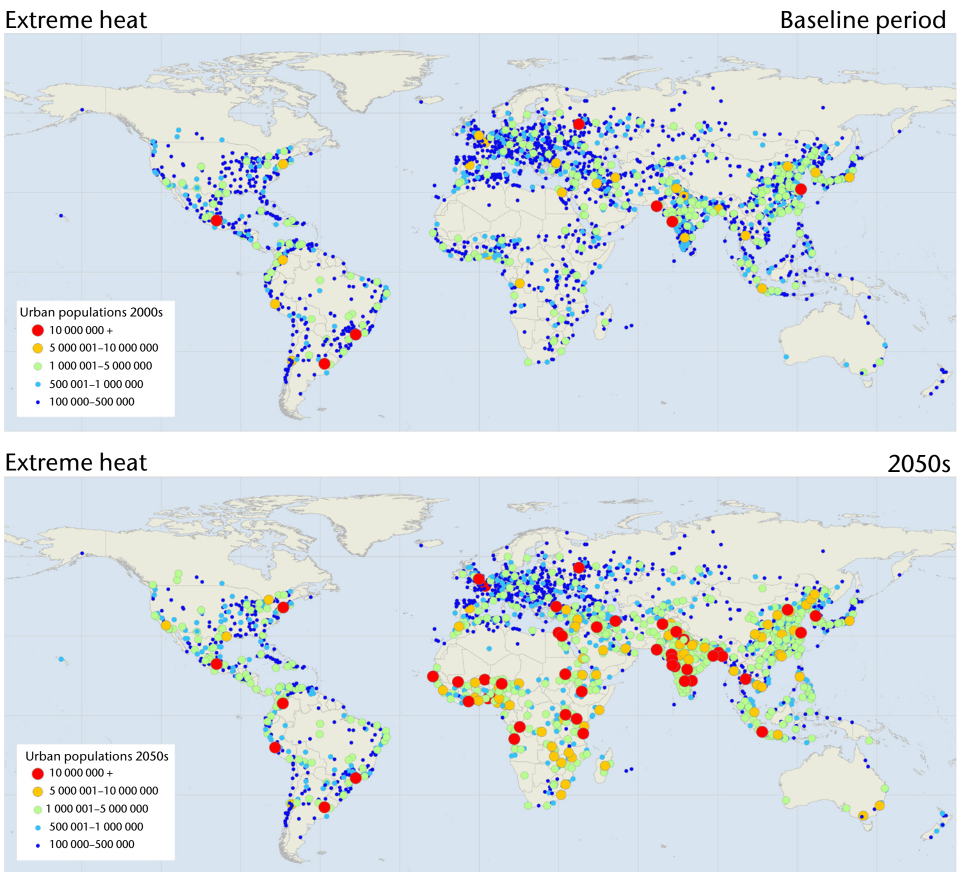

Figure 1. Cities with populations of 100 000 and greater in the 2000s (top) and estimated urban populations in the 2050s (bottom). Data source for baseline population in 2000s from Natural Earth Dataset. Data source for population in the 2050s estimated from the Global Rural-Urban Mapping Project population growth estimates applied to the baseline population data in the 2000s Natural Earth Dataset (Center for International Earth Science Information Network (CIESIN), Columbia University (Rosenzweig et al., 2021).

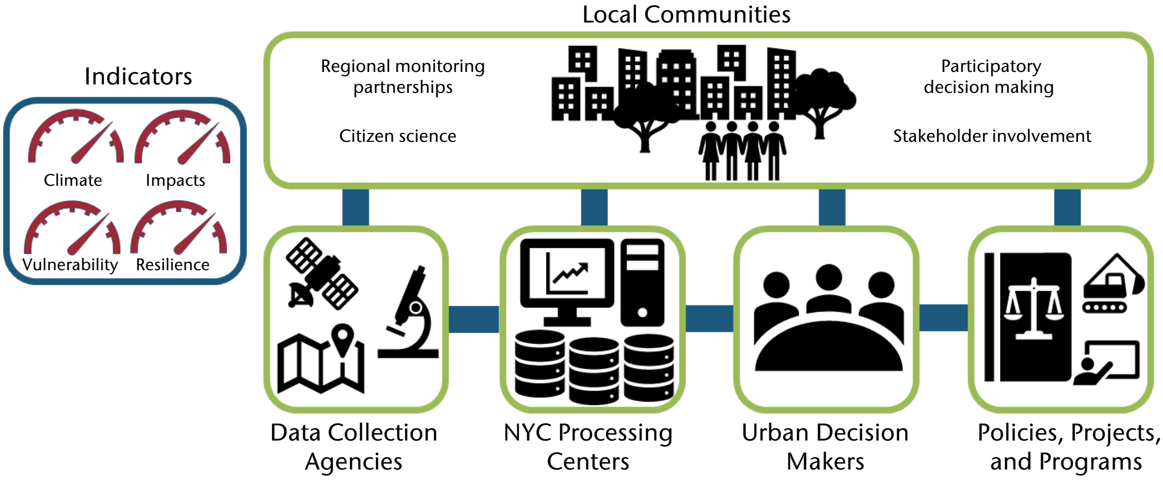

Figure 2. New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM) will track four types of indicators – from data collection agencies, processing centres, urban decision-makers, and others – as well as policies, projects and programs. The proposed NYCLIM system is co-generated by scientists, practitioners, and local communities to determine the most useful indicators for planning and preparing for climate change in New York City (Rosenzweig et al., 2019).

Effective urban climate adaptation and implementation strategies require ongoing, consistent, reliable, high-resolution, spatial and temporal monitoring of key regional climate indicators. Long-term, quality-controlled urban data is fundamental to the understanding of environmental challenges (Solecki et al., 2022). Co-generation of knowledge and research while working with stakeholders is crucial to create usable climate data at the city level. Figure 2 provides an example in New York City, which focuses on tracking resiliency indicators and monitoring over time.

There are many lessons to be learned from the coronavirus pandemic, including adapting standards for illness prevention and unified health communications. As the pandemic recedes, climate change needs to be part of the recovery. Environmentally just policies and practices in cities will lead to higher standards of living, both physically and mentally, as well as overall lowered vulnerability to both climate change and future pandemics. To further this advance, an increased focus on access to green spaces and nature-based solutions should be prioritized.

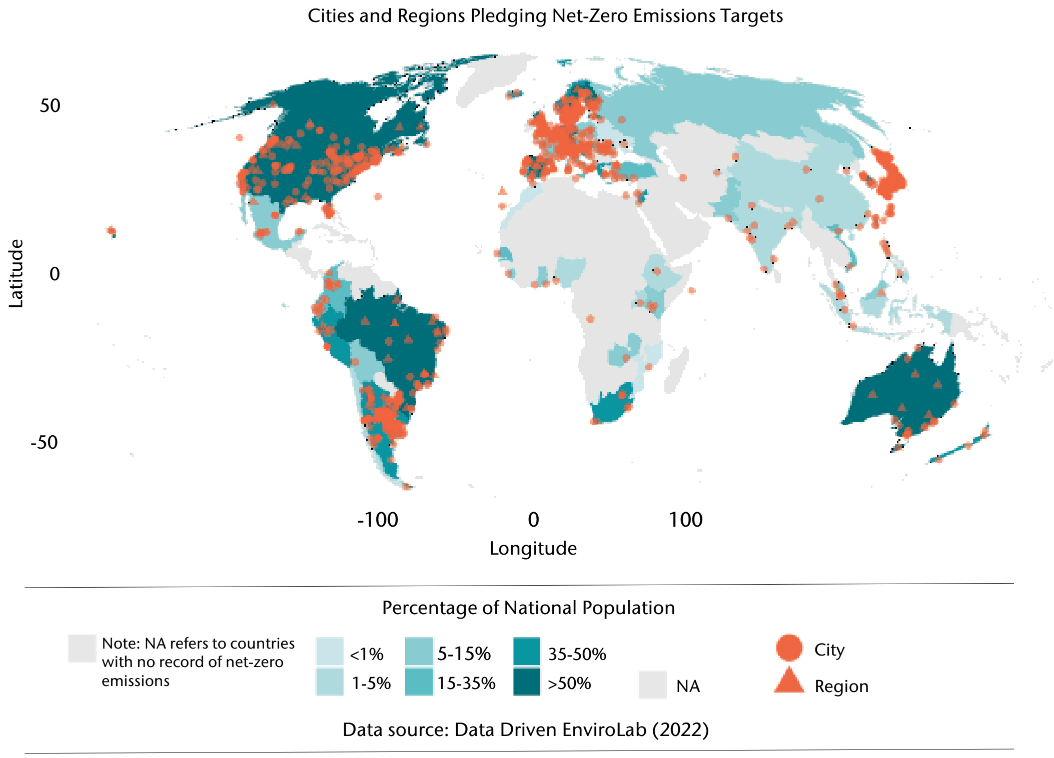

Figure 3. Over 14% of cities and regions have pledged to reach net-zero emissions (Data-Driven EnviroLab, 2022).

Cities, supported by networks such as the Urban Climate Change Research Network (UCCRN), the Global Covenant of Mayors (GCoM), C40, the International Council for Local Environmental Initiatives (ICLEI), United Cities and Local Governments (UCLG), and others, can effectively develop the managerial and governance capacity needed to fulfil climate action stock takes under the requirements of the Paris Climate Agreement and SDG 11: Sustainable Cities and Communities. Currently, 1 676 cities and 146 regions, which account for over 14% of the global population, have pledged to reach net-zero emissions (Data-Driven EnviroLab, 2022, Figure 3). This shows great promise; however, the 14% must transition from pledging their support into scaled-up political action and transformative implementation.

Climate-inclusive planning and investments in social and ecological systems, green and gray infrastructure, healthcare services, and technological advancements have significant ability to increase cities' adaptive capacity. Low-income and marginalized groups, as well as surrounding metropolitan regions, must be included throughout the climate decision-making processes.

The need for urgency is upon us. The scientific understanding of climate change has reached the highest degree of certainty ever, and awareness of urban-focused risk, including hazards, vulnerabilities and exposures, has increased. Cities have a vital role to play by implementing inclusive, urgent, and scaled-up urban climate action required to enhance resiliency, limit the degrees of warming, and keep the planet livable.

IPCC headline statements

- Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves (*very high confidence*). Urbanization also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). In coastal cities, the combination of more frequent extreme sea level events (due to sea level rise and storm surge) and extreme rainfall/riverflow events will make flooding more probable (*high confidence*) (IPCC Working Group I, 2021)
- Interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. However, the global trend of urbanization also offers a critical opportunity in the near-term, to advance climate resilient development (*high confidence*) (IPCC Working Group II, 2022)
- Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions (IPCC Working Group III, 2022).

Extreme Weather Events and Socioeconomic Impacts

WMO World Weather Research Programme

WORLD METEOROLOGICAL ORGANIZATION

Key messages

- The number of weather, climate and water-related disasters has increased by a factor of five over the past 50 years, causing, on average, US$ 202 million in losses daily
- Extreme weather events cause long-lasting socioeconomic impacts, especially in the most vulnerable communities, which are often the least equipped to respond, recover and adapt
- In 2022, human-caused climate change further contributed to significant economic and human losses associated with heavy rainfall and extreme heat events around the globe.

Extreme weather events cause significant socioeconomic impacts. WMO reports that the number of weather-related disasters has increased by a factor of five over the past 50 years, claiming, on average, the lives of 115 people and causing US$ 202 million in losses daily (WMO, 2021). As attribution science continues to improve, evidence of the link between human-induced climate change and observed extremes, such as heatwaves, heavy precipitation and tropical cyclones, has strengthened (IPCC 2021). And while extreme weather events can impact anyone, it is the world's most vulnerable populations, particularly those living in poverty and marginalized communities, that suffer the most.

Extreme weather events in 2022

Tropical Storm Ana and Tropical Cyclone Batsirai

The 2021/2022 south-west Indian Ocean tropical cyclone season was very active with 12 named storms – five of which reached intense tropical cyclone status. Tropical Storm *Ana* was the first storm of the season, bringing strong winds, heavy rain, and widespread flooding to Madagascar, Malawi, Mozambique and Zimbabwe in late January 2022. It was followed by *Batsirai*, an even stronger tropical cyclone, shown in Figure 1.

The storms caused severe humanitarian impacts across the region – one of the poorest and most vulnerable in the world. In Mozambique, for example, nearly 64% of the population lives in extreme poverty, and in Madagascar, 42% of children under the age of five suffer from chronic malnutrition (World Bank, 2021; World Food Programme, 2021). As a result of these storms, tens of thousands of people were displaced, infrastructure was destroyed, and flooded farmlands further exacerbated food insecurity (Otto et al., 2022).

Using published peer-reviewed methods, the World Weather Attribution initiative found that climate change likely increased the intensity of rainfall associated with these storms (Otto et. al., 2022). As the atmosphere becomes warmer, it holds more water, which, on average, makes wet seasons and events wetter. With further emissions and rising temperatures, heavy rainfall episodes, like those associated with *Ana* and *Batsirai*, will become more common.

Vulnerable populations, such as those impacted by *Ana* and

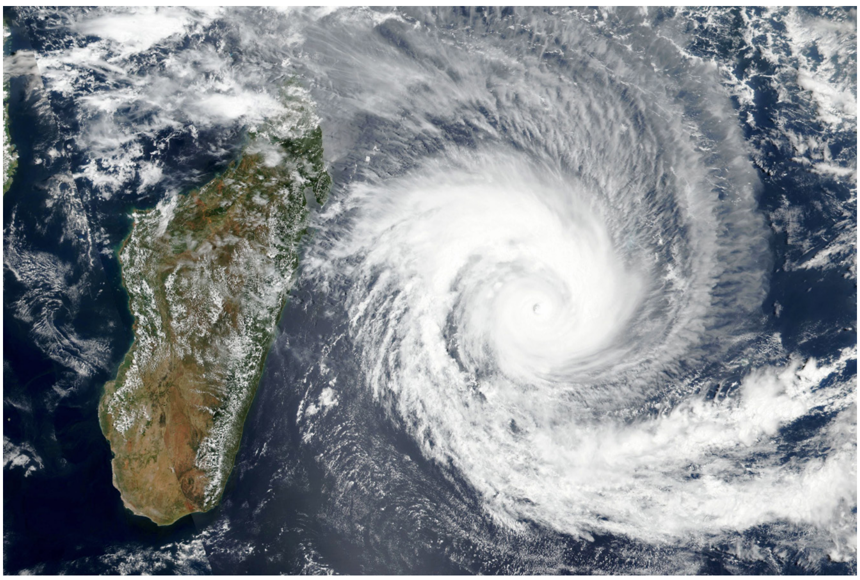

Figure 1. Tropical Cyclone Batsirai off the coast of Madagascar in the south-west Indian Ocean (https://earthobservatory.nasa.gov/images/149418/cyclone-batsirai).

Batsirai, are hit hardest by extreme weather events because they have the fewest resources to respond, recover and adapt to a changing climate. When disasters strike, they set back progress towards achieving the Sustainable Development Goals and exacerbate existing poverty and inequality. However, effective adaptation, such as the implementation of early warning systems, can reduce climate risks, minimize losses and damages and support climate resilient development (See Chapter: *Early Warning Systems: Supporting Adaptation and Disaster Risk Reduction*) (IPCC, 2022).

Flooding in eastern Australia

Throughout 2022, successive spells of heavy rainfall over eastern Australia resulted in major floods. In late February and early March 2022, an atmospheric river transported large amounts of moisture to the Australian coast, leading to a record-breaking rainfall event and some of the worst flooding in the country's history. Brisbane, the third largest city in Australia, experienced three consecutive days with rain totals greater than 200 mm – the first such occurrence since routine weather observations began. Subsequently, spells of heavy rain continued to hit the rain-soaked region from March to July 2022, leading to additional severe flooding (Figure 2).

The rapidly rising floodwaters resulting from this extreme rainfall caused widespread devastation and economic losses. Communities in Australia are generally better equipped to respond, recover and adapt compared to communities in lower-income countries, however, the floods still highlighted socioeconomic inequalities that exacerbate vulnerability. For example, in the devastated town of Lismore, marginalized Aboriginal communities were particularly hard hit as well as lower-income families who are more likely to live in flood-prone locations and to be unable to afford flood insurance (Williamson, 2022).

The varied nature of the extreme rainfall, with some areas experiencing persistent heavy rain for several days and others receiving short but very intense rain, makes defining how the event may be connected to human-caused climate change challenging. Climate science indicates an increasing risk of short-duration, but extreme, rainfall with continued human-induced warming. Additional factors, such as the underlying La Niña also increased the chances of wetter than average conditions across the region.

European heatwaves

In June and July 2022, Europe was affected by two extreme heat waves resulting from warm air in northern Africa spreading to the north and east, reaching Central Europe and the United Kingdom. Daily maxima exceeded 40 °C in parts of Iberia, which was 7–12 °C above normal for that time of year. In Portugal, a peak temperature of 47.0 °C was measured, exceeding the national July record of 46.5 °C (1995). Additionally, for the first time on record, temperatures in the UK exceeded 40 °C with a provisional record temperature of 40.3 °C recorded in Coningsby on 19 July, beating the previous record of 38.7 °C set in 2019. According to the World Weather Attribution initiative, human-caused climate change made the heatwave in the UK at least 10 times more likely (Zachariah et al., 2022). Figure 3 shows heatwaves across southwestern Europe from 1950 to July 2022.

Figure 2. Flooding in Corinda and Oxley, suburbs of Brisbane, Australia, on 1 March 2022 (Getty Images/Bradley Kanaris/Intermittent).

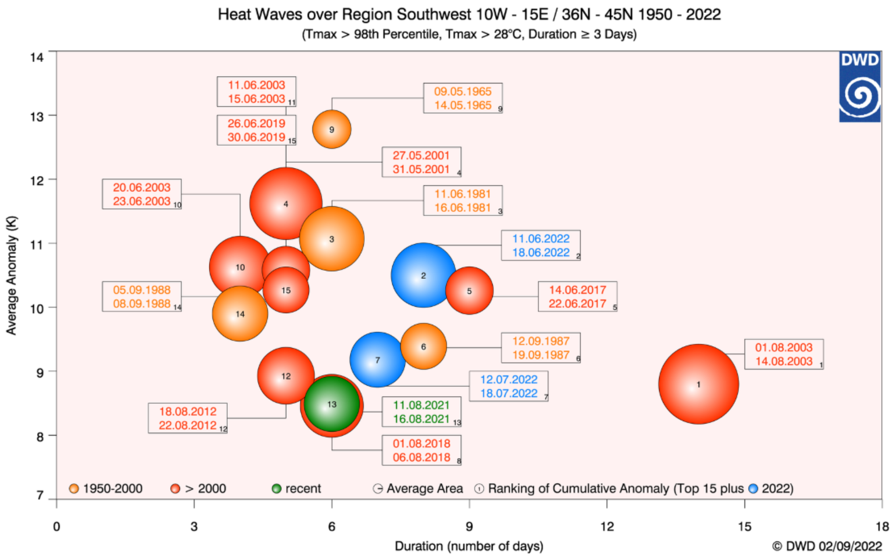

Figure 3. Heat waves in southwestern Europe (Portugal, Spain, southern France, eastern Italy) from 1950 to 21 July 2022 in dependency of their duration (x-axis) and intensity (average anomaly, y-axis). The size of the bubbles (radius) show the spatial extension of the heat waves, annotations indicate their starting and ending dates. Bubble colours highlight the year of occurrence: blue: 2022, green: most recent before 2022, red: 21st century, orange: 20th century (Deutscher Wetterdienst (DWD), https://www.dwd.de/EN/ourservices/rcccm/int/rcccm_int_hwkltr.html).

Summer heatwaves pose a significant risk to human and ecosystem health. The elderly and people with chronic health conditions are particularly vulnerable, but other factors – such as socioeconomic conditions, work conditions, urbanization, and levels of preparedness – can also increase vulnerability. In London, for example, the urban heat island made the city significantly warmer than surrounding areas and high levels of inequality exacerbated vulnerability (Zachariah et al., 2022). Across Europe, first reports indicate that the heatwaves led to several thousand deaths, although it is too early to know the full human toll of these extreme events. Additionally, a coinciding marine heatwave led to devastating consequences for marine life and an extended drought across large parts of Europe impacted freshwater and other aquatic ecosystems through low river waters, plant stress and forest fires.

IPCC headline statements

- Human-induced climate change is already affecting many weather and climate extremes in every region around the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the IPCC 5th Assessment Report (IPCC Working Group I, 2021)
- With further global warming, every region is projected to experience increasing concurrent and multiple changes in climatic impact-drivers (IPCC Working Group I, 2021)
- Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (*medium confidence*) (IPCC Working Group II, 2021).

Early Warning Systems: Supporting Adaptation and Disaster Risk Reduction

WMO/UN Office for Disaster Risk Reduction

WORLD METEOROLOGICAL ORGANIZATION

UNDRR
UN Office for Disaster Risk Reduction

Key messages

- Early warning systems save lives, reduce losses and damages, contribute to disaster risk reduction and support climate change adaptation
- Less than half of all countries in the world have reported the existence of Multi-Hazard Early Warning Systems (MHEWS), with coverage particularly low in Africa, Least Developed Countries and Small Island Developing States
- Ensuring everyone on Earth is protected by MHEWS will require collaboration across diverse actors and innovative financing solutions.

With 3.3 to 3.6 billion people living in contexts that are highly vulnerable to climate change (IPCC, 2022), it is more important than ever for the international community to take ambitious action to not only mitigate emissions, but also adapt to climate change, particularly extreme weather and compounding events, which can lead to long-lasting socioeconomic impacts.

Multi-Hazard Early Warning Systems (MHEWS) integrate hazard information with risk analysis to provide meaningful early warnings that allow governments, communities, and individuals to understand the risks related to impending events and to act to minimize impacts. These systems, shown in Figure 1, consist of four elements: disaster risk knowledge; monitoring, observations and forecasting; warning communication; and preparedness. When implemented appropriately, MHEWS save lives, reduce losses and damages contribute to disaster risk reduction and support climate change adaptation. They also provide a significant return on investment, as highlighted in the box below on the socioeconomic benefits of early warning systems.

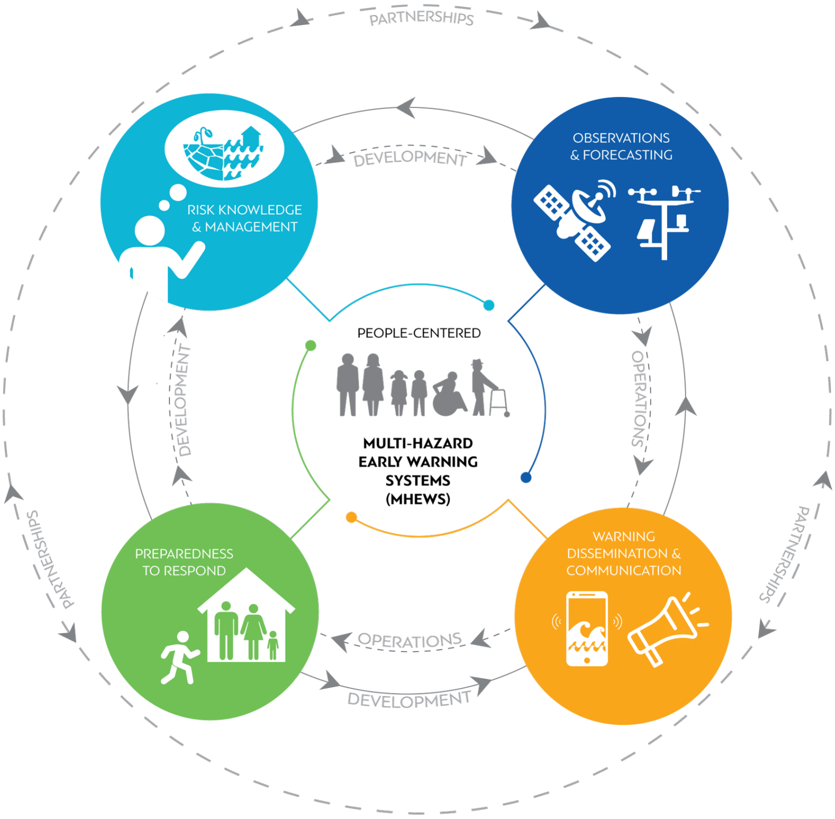

Figure 1. Elements of a multi-hazard early warning system (WMO Early Warnings for All: The UN Global Early Warning Initiative for the Implementation of Climate Adaptation, August 2022 update).

Socioeconomic benefits of early warning systems

Several studies demonstrate consistently high returns and provide a strong economic rationale for investments into MHEWS. Drawing on the findings presented by the Global Commission on Adaptation (2019), the MHEWS average cost-benefit ratio (9:1) is higher than any other adaptation measures considered in this study, ahead of making new infrastructure resilient or improving dryland agriculture crop production. This implies that every US$ 1 invested in early warning systems could result, on average, in US$ 9 in net economic benefits. However, the full socioeconomic benefits of MHEWS are likely to be underestimated as some benefits are difficult to monetize, such as potential lives saved.

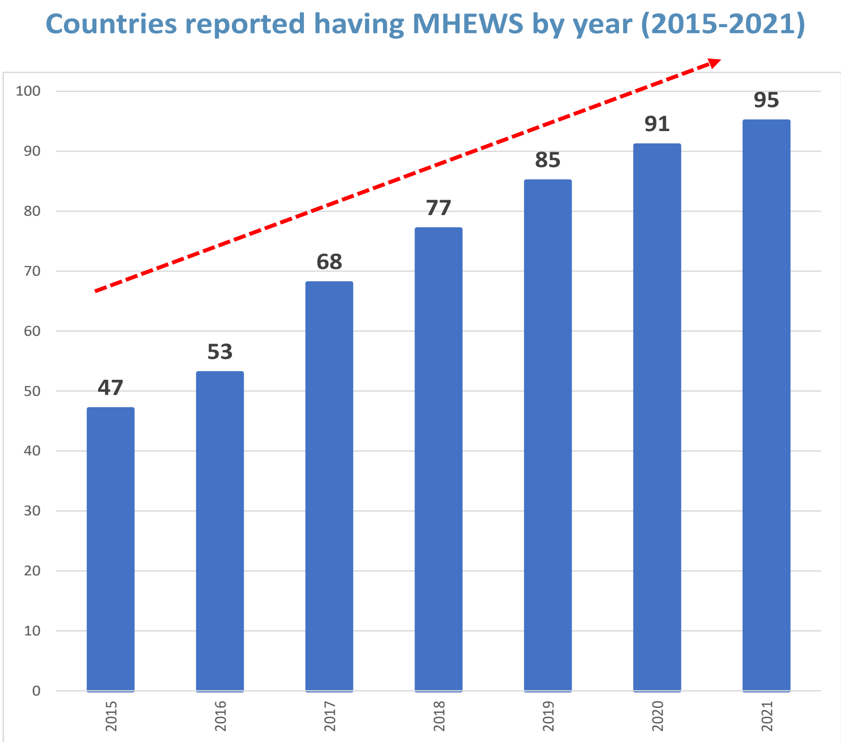

Figure 2. Number of countries reporting having MHEWS from 2015 to 2021. All data is cumulative as of April 2022 (UNDRR: Sendai Framework Monitor, 2022).

MHEWS are recognized as a critical element of disaster risk reduction (DRR) and climate change adaptation. As a result, they are reflected in both the Sendai Framework for Disaster Risk Reduction 2015–2030 and the Paris Agreement in addition to contributing towards the UN Sustainable Development Goals. One of the seven targets of the Sendai Framework is to "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" (Target G).

However, as of April 2022, less than half of all countries in the world have reported the existence of MHEWS, with coverage particularly low in Africa. Further, less than half of the Least Developed Countries (LDCs), and only one third of Small Island Developing States (SIDS) have reported the existence of MHEWS (Sendai Framework Monitor, 2022). Additionally, analysis from an accelerated data collection campaign conducted by WMO in June/July 2022 shows even fewer countries have MHEWS that are based in national legislation and regulatory frameworks, which are essential to ensure their effectiveness. And while coverage of MHEWS is increasing, there is very little progress in making these systems risk-informed and in having ready-to-act contingency measures if the early warning is issued or triggered.

To address this critical issue and support climate adaptation, United Nations Secretary-General António Guterres announced that the UN will spearhead new action to ensure every person on Earth is protected by early warning systems within five years. The WMO has been asked to lead this initiative and is developing, with key partners, an action plan that will deliver "Early Warnings for All", across the full early warning to early action value chain, at the global, regional, national, and local levels.

Effective implementation will require inputs from a wide range of actors, including National Meteorological and Hydrological Services, National Disaster Management Offices, academia, policy makers, and other UN agencies on a variety of related issues, such as technology, innovation, and finance. UNDRR and WMO, for example, are collaborating to develop a global status analysis of early warning systems based on Sendai Framework reports and WMO data.

Implementation of this action plan will also require new innovative and pre-existing financing solutions. Investing in the Systematic Observations Financing Facility (SOFF), the Global Water Information Services (GWIS) and the Climate Risk Early Warning Systems (CREWS) initiative will be crucial. Additionally, accelerated investment programs of key Multilateral Development Banks (MDBs) and innovative new financial instruments will play an important role in ensuring everyone on Earth is protected by MHEWS.

The Systematic Observations Financing Facility (SOFF): A foundational element of the UN Early Warning Systems Initiative

Early warnings can only be as good as the data underpinning them. In 2021 the Global Basic Observing Network (GBON) was established, committing all countries to generate and exchange basic weather and climate data. However, today, less than 10% of these internationally agreed data are available from LDCs and SIDS. These critical data gaps hinder the provision of high-quality climate services around the globe.

For this reason, WMO, the UN Development Programme and the UN Environment Programme established the Systematic Observations Financing Facility (SOFF) as a UN Multi-Partner Trust Fund, with the support of an initial group of funding partners. SOFF provides long-term, technical and financial support to the countries with the largest capacity gaps to close their GBON data gap, with a focus on LDCs and SIDS. This new mechanism contributes to achieving the adaptation and systematic observation goals of the Paris Agreement through improved climate and weather observations essential for effective climate services and early warnings.

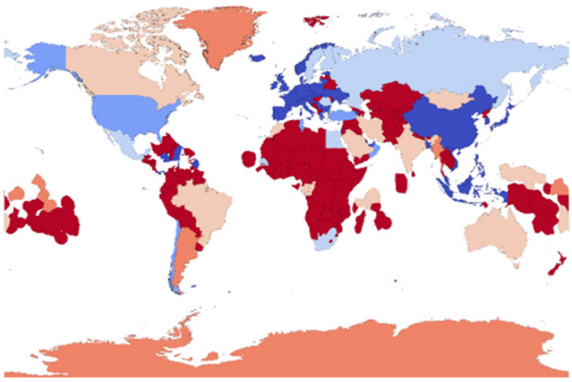

Figure 3. Areas in dark red are far from meeting the most important requirements of the GBON. Areas in light red are close to meeting the requirements. Areas in blue shades meet or exceed the requirements (WMO Secretariat, 2022).

IPCC headline statements

- Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*) (IPCC Working Group II, 2022)
- Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries (IPCC Working Group II, 2022)
- There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (*high confidence*) (IPCC Working Group II, 2022).

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