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2023: Weather and Climate Extremes Hitting the Globe with Emerging Features

Wenxia ZHANG[1], Robin CLARK[2], Tianjun ZHOU[*1,3], Laurent LI[4], Chao LI[5], Juan RIVERA[6], Lixia ZHANG[1], Kexin GUI[1,3], Tingyu ZHANG[1,3], Lan LI[1,3], Rongyun PAN[1,3], Yongjun CHEN[1,3], Shijie TANG[1,3], Xin HUANG[7,8], and Shuai HU[1]

[1]*State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029, *China*

[2]*Met Office Hadley Centre, Exeter EX*1 3*PB, UK*

[3]*University of Chinese Academy of Sciences, Beijing* 100049, *China*

[4]*Laboratoire de Météorologie Dynamique, CNRS, Sorbonne Université, Ecole Normale Supérieure, Ecole Polytechnique, Paris* 75230, *France*

[5]*Max Planck Institute for Meteorology, Hamburg* 20146, *Germany*

[6]*Instituto Argentino de Nivología, Glaciología Y Ciencias Ambientales (IANIGLA), CCT CONICET, Mendoza CP* 5500, *Argentina*

[7]*Shanghai Typhoon Institute, China Meteorological Administration, Shanghai* 200030, *China*

[8]*Asia-Pacific Typhoon Collaborative Research Center, Shanghai* 201306, *China*

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ABSTRACT

Globally, 2023 was the warmest observed year on record since at least 1850 and, according to proxy evidence, possibly of the past 100 000 years. As in recent years, the record warmth has again been accompanied with yet more extreme weather and climate events throughout the world. Here, we provide an overview of those of 2023, with details and key background causes to help build upon our understanding of the roles of internal climate variability and anthropogenic climate change. We also highlight emerging features associated with some of these extreme events. Hot extremes are occurring earlier in the year, and increasingly simultaneously in differing parts of the world (e.g., the concurrent hot extremes in the Northern Hemisphere in July 2023). Intense cyclones are exacerbating precipitation extremes (e.g., the North China flooding in July and the Libya flooding in September). Droughts in some regions (e.g., California and the Horn of Africa) have transitioned into flood conditions. Climate extremes also show increasing interactions with ecosystems via wildfires (e.g., those in Hawaii in August and in Canada from spring to autumn 2023) and sandstorms (e.g., those in Mongolia in April 2023). Finally, we also consider the challenges to research that these emerging characteristics present for the strategy and practice of adaptation.

Key words: weather and climate extremes, temperature extremes, extreme precipitation, drought, wildfires

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1. Introduction

By an unusually large margin, 2023 was, globally, the warmest year on record in both the atmosphere and ocean, with a near-surface air temperature anomaly of 1.45°C ± 0.12°C compared to pre-industrial levels (1850–1900), according to six leading international datasets (WMO, 2024). New temperature records were repeatedly set in every month from June to December. Regionally, 2023 was also the warmest year for several continents (e.g., North America, South America, Africa) and countries (e.g., China) (NOAA, 2024a). Beyond the surface air temperature, the sea surface temperature (SST) and

* Corresponding author: Tianjun ZHOU
Email: zhoutj@lasg.iap.ac.cn

upper 2000 m ocean heat content also reached unprecedented values (Cheng et al., 2024). The year's record warmth resulted from a combination of the accumulated anthropogenic warming and internal climate variability, including a shift from a series of three La Niña episodes to an El Niño and a positive phase of the Atlantic Multidecadal Oscillation (Li et al., 2023b, 2024; Zheng et al., 2024).

Partly fueled by the heat, the year was also characterized by unprecedented extreme weather and climate events in many parts of the world (Figs. 1 and 2). These extreme events have long caused profound socioeconomic losses (e.g., Newman and Noy, 2023; Zhou et al., 2023; Xu, 2024; Xu et al., 2024). According to the World Meteorological Organization (WMO), during 1970–2021, extreme weather, climate and water-related events have caused at least 10 000 disasters, with reported economic losses exceeding US$4 trillion and a death toll of 2 million (WMO, 2023a).

While extreme events are nothing new, especially given the backdrop of global warming, they still warrant our attention with a need of improved understanding. This paper thus aims to provide a brief overview of global extreme events that occurred in 2023. We review the facts and our current understanding of these, and put them in context relative to the past and future, to provide a better understanding of the roles of internal climate variability and anthropogenic climate change. In particular, we highlight emerging characteristics of the various types of events that occurred. Hot extremes, for example, are occurring earlier in the year, and simultaneously in many differing regions. Rainfall extremes exacerbated by intense cyclones have also been increasing, and there have been some remarkable transitions from drought episodes to flooding, which we also cover. Interactions with ecosystems through wildfire and sandstorms are also prominent. For the rest of this paper, we devote sections to each type of extreme and then follow up with a brief summary and discussion on the research and adaptation challenges that they raise.

2. High temperature extremes

In 2023, hot extremes continued to impact multiple parts of the world with yet more records beaten. Of particular note was their earlier occurrence than usual. Hot extremes occurring at the same time in differing regions were also a feature of the year.

2.1. *High temperature extremes occurring earlier*

Large areas of the globe, in both hemispheres, were hit by hot extremes earlier than normal in 2023. Extreme high temperatures that normally occur in summer were exceeded even in spring in many regions (Figs. 3c and d). In the last week of April, for example, during spring, Southwest Europe and North Africa (principally Spain, Portugal, Morocco, and Algeria) experienced record-breaking hot extremes (Figs. 3a and b). Daily maximum temperature in Morocco exceeded 41°C locally (Philip et al., 2023). Some areas were even 20°C warmer than normal. Soil moisture deficits and unusually large surface pressure anomalies in the region jointly led to the amplification and maintenance of the hot extreme in the western Mediterranean (Lemus-Canovas et al., 2024). Conservative estimates suggest that the likelihood of such early heat events has increased by 100 times in the context of human-induced climate change (Philip et al., 2023).

Southeast Asia also suffered a record-breaking hot extreme in mid-April (Figs. 3a and b), with new records set in Thailand at 45.4°C and Laos at 42.9°C (LaCSA, 2023). The unusually hot conditions in Southeast Asia were accompanied by excessive

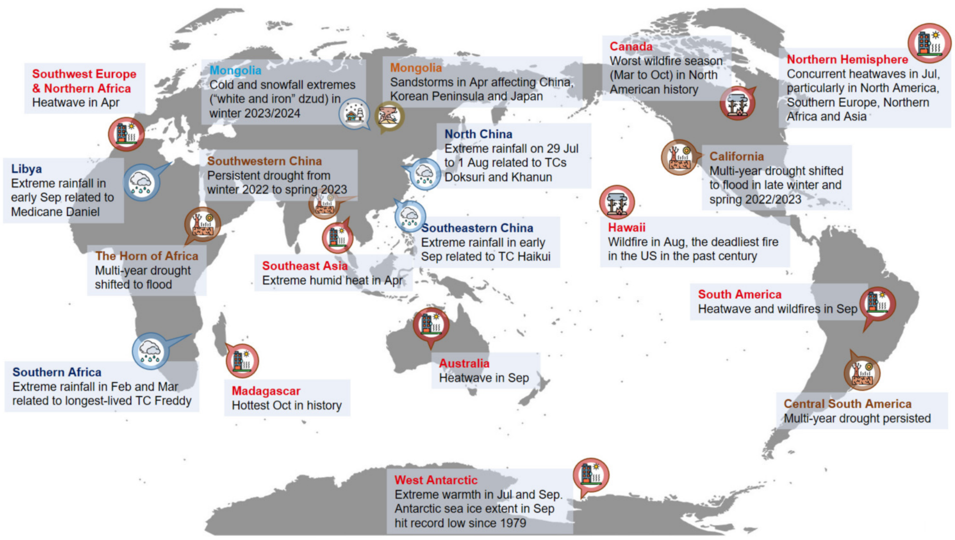

Fig. 1. An overview of major extreme weather and climate events over the globe in 2023.

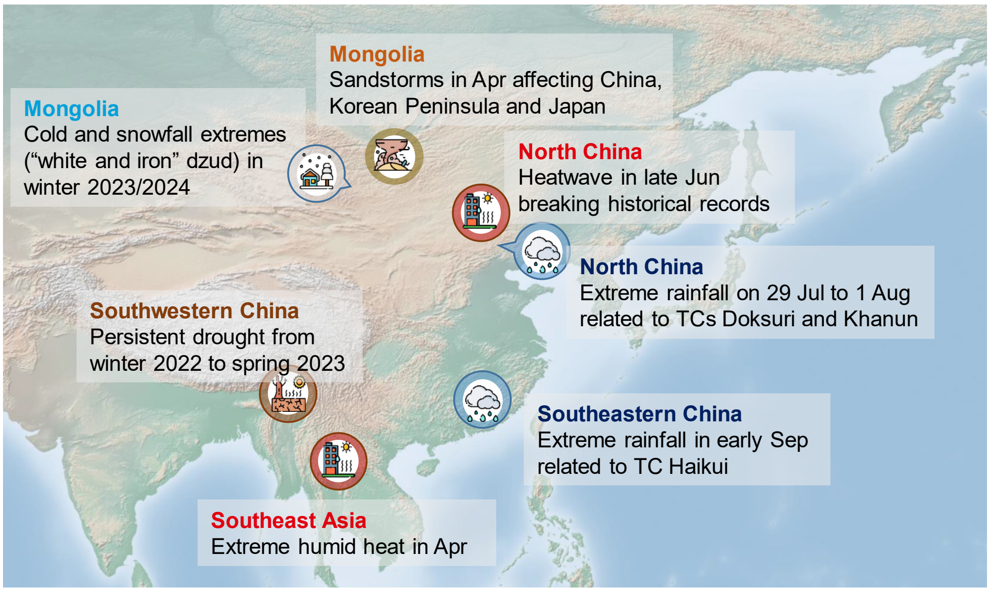

Fig. 2. An overview of major extreme weather and climate events in East Asia in 2023.

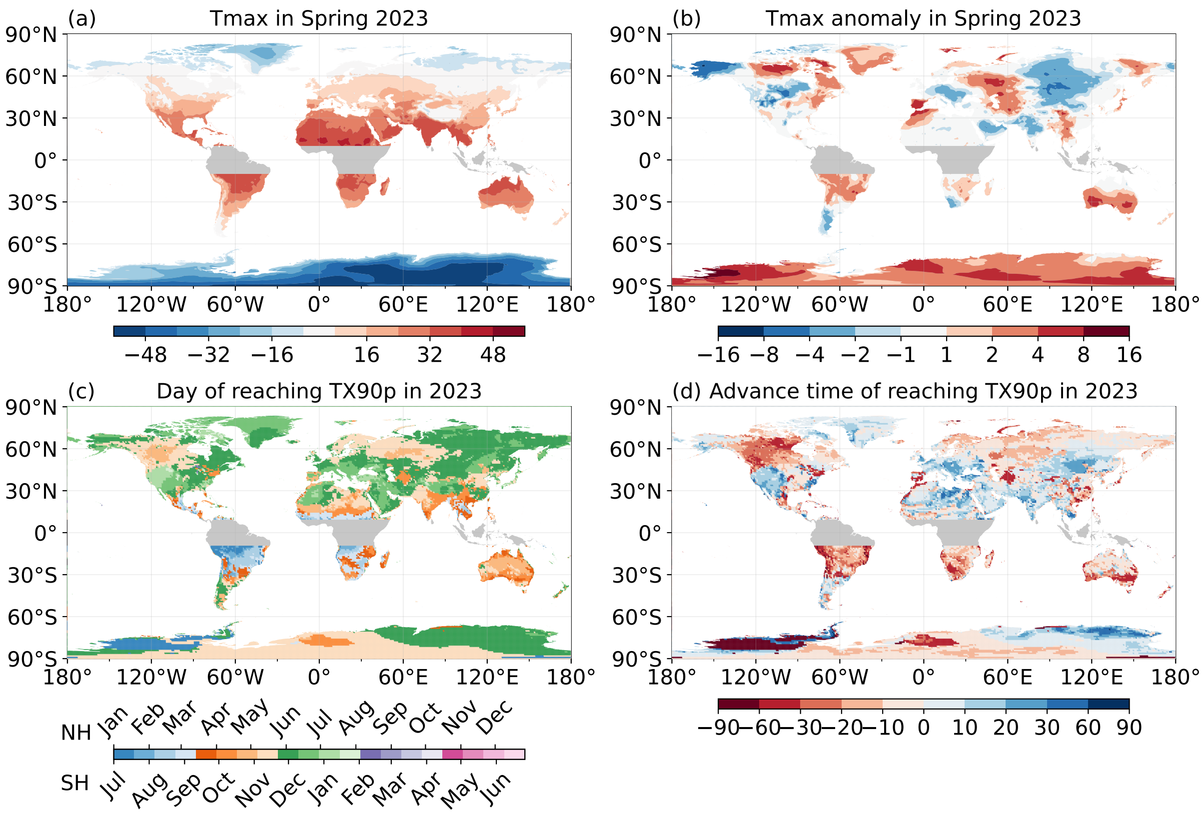

Fig. 3. (a, b) The intensity of spring high temperature in 2023: (a) daily maximum temperature (Tmax) and (b) its anomaly in spring of 2023 (April for Northern Hemisphere and September for Southern Hemisphere; units: °C). (c, d) The early occurrence of high temperature in 2023: (c) the date in 2023 when Tmax first exceeded historical TX90p (90th percentile of Tmax in the baseline 1991–2020), where the colorbar runs from January to December for the Northern Hemisphere and from July to June for the Southern Hemisphere; (d) the anomaly of the date for the first exceedance of TX90p in 2023 compared to the baseline, in which red and blue rendering indicates earlier- and later-than-normal occurrence in 2023, respectively (units: d). All anomalies are derived with respect to the baseline of 1991–2020. Note the belt of 10°S–10°N is masked given the weak seasonal cycle in the tropics. Data are from ERA5.

humidity, exacerbating its impacts on local populations in the region (Domeisen et al., 2023; Zachariah et al., 2023b). Without anthropogenic influences on climate, such extreme humid heat events would be almost impossible (Zachariah et al., 2023b).

Early spring in the Southern Hemisphere, in September 2023 also saw unusual heat in large areas of South America and Australia. Temperatures in some parts of Brazil exceeded 40°C in mid-September, while those in parts of Australia were 16°C greater than normal. In southeastern Africa, Madagascar experienced its hottest October in history (Pinto et al., 2023). Accompanying the heat, wildfires occurred in Australia and many parts of South America, including Brazil, Argentina, Paraguay and Bolivia (Paddison, 2023; The Guardian, 2023). Physically, the high temperature extreme in Australia was exacerbated by the development of an El Niño, a phenomenon typically known to cause drought in Australia (Freund et al., 2021), further exacerbating hot extremes through land–atmosphere feedbacks (Fischer et al., 2007; Miralles et al., 2012; Lemus-Canovas et al., 2024). Rapid attribution indicates that the probability of such hot extremes in both South America and Madagascar is at least 100 times greater than in a climate without human influence (Kew et al., 2023; Pinto et al., 2023).

2.2. *Simultaneous occurrence of hot extremes in the Northern Hemisphere in July 2023*

In July 2023, record-breaking hot extremes occurred in many regions of North America, southern Europe, northern Africa, and Asia (Fig. 4b). Daily maximum temperatures in both America and China exceeded 50°C, and eastern Spain recorded its hottest day in history. The extreme heat conditions in Arizona, with a record of 31 consecutive days of temperatures exceeding 43.3°C since late June in the city of Phoenix, led to significant health consequences for vulnerable populations (du Bray et al., 2023). The impacts of this event were partially exacerbated by a dry monsoon season, which threatened the urban water supply. In all of the aforementioned regions, hot extremes with the same likelihood as those observed in 2023 would have been colder in a climate without human impact (Zachariah et al., 2023a). For the record-shattering hot extreme in North China at the end of June 2023, the intensity of similar heat events increased by at least 1°C owing to anthropogenic climate change (Qian et al., 2024).

A key feature, not only of 2023's summer, but also that of 2022, was the occurrence of hot extremes simultaneously in several regions in the Northern Hemisphere — for example, over the northwest of North America, Europe, Northeast Asia, and the Yangtze River Basin in China in summer 2022 (Fig. 4a). Such behaviour is often linked to quasi-stationary Rossby waves (Teng et al., 2013; He et al., 2023). Disturbances along these circumglobal waves can be amplified through resonance at certain frequencies and wavelengths, which can further enhance heat extremes occurring remotely (Mann et al., 2018; Kornhuber et al., 2019, 2020).

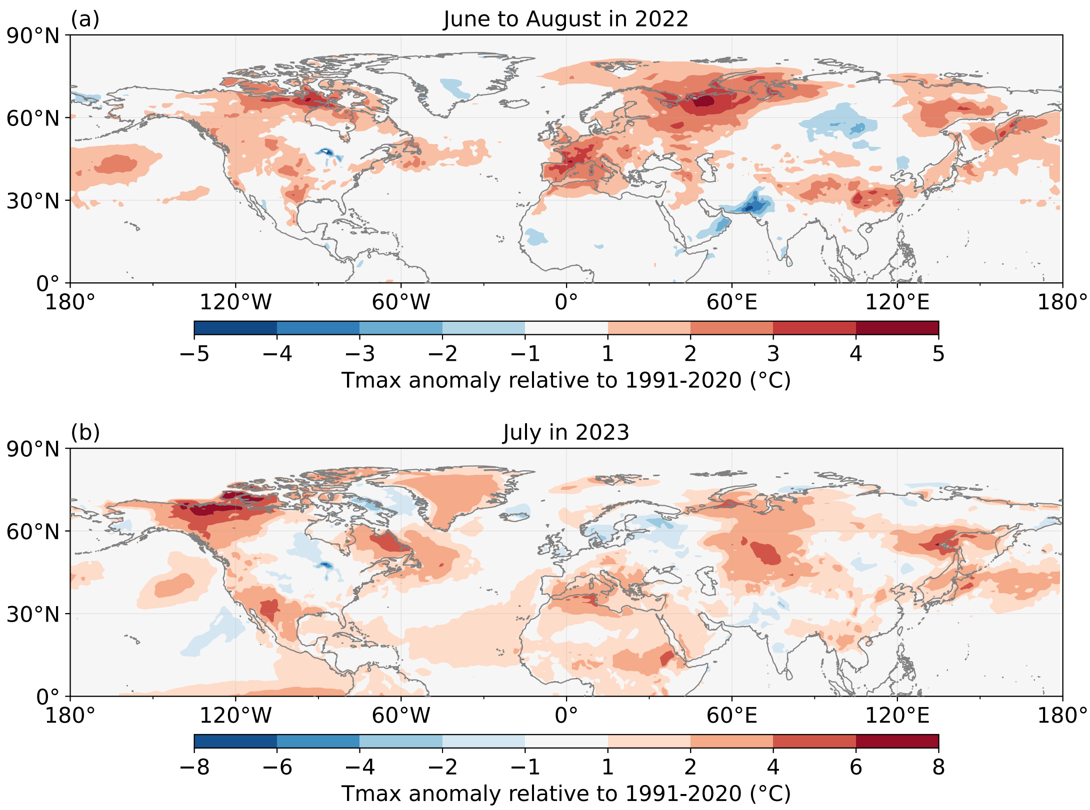

Fig. 4. The average daily maximum temperature (Tmax) anomaly for (a) June to August 2022 and (b) July 2023, relative to 1991–2020 (units: °C). Data are from ERA5.

2.3. *Highly unusual warmth in the Antarctic and record-low sea-ice extent*

Further south, the Antarctic also experienced exceptional warmth in 2023, with its third-warmest annual average temperature on record since 1850. As part of this, September set a new record, with an anomaly of 2°C (NOAA, 2024b). Accompanying the exceptional warmth, the annual Antarctic sea-ice extent also reached a record low in the satellite-era since 1979, with an average of 3.79 million square miles. Both the annual maximum (in September) and minimum (in February) were the lowest on record (NOAA, 2024a).

The record-low Antarctic sea-ice extent in 2023 appears to have been part of decadal variability, where the sea-ice extent increased slightly from 1979 to 2015 before a sharp decline immediately afterwards (Gilbert and Holmes, 2024). The variations in the Antarctic sea-ice extent, both on interannual and decadal scales, are strongly impacted by modes of large-scale natural variability such as the Southern Annular Mode and El Niño–Southern Oscillation (Gilbert and Holmes, 2024). For 2023's new record minimum, several atmospheric drivers were responsible, including a positive Antarctic Oscillation, the three-year La Niña episodes, the negative phase of the Interdecadal Pacific Oscillation, and a positive phase of the Atlantic Multidecadal Oscillation, through deepening of the Amundsen Sea low, a low-pressure system located off West Antarctica that strongly modulates the Antarctic sea-ice extent (Liu et al., 2023b). Apart from atmospheric variability, warming of the Southern Ocean subsurface also played a role in pushing the Antarctic sea ice into a new low-extent state (Zhang et al., 2022; Purich and Doddridge, 2023). In addition, the recent recovery of stratospheric ozone, through modulating surface wind, can also affect Southern Ocean heat transport and ocean heat content, and further, the Antarctic sea ice (Li et al., 2023a). It is worth noting that the influence of ozone change on the Antarctic sea-ice extent is time-varying, which depends critically on the fast and slow responses of the Southern Ocean to ozone forcing (Ferreira et al., 2015). It remains to be seen whether the recent Antarctic sea-ice minimum is a brief anomaly or the emergence of a declining trend in response to longer-term anthropogenic warming as projected by climate models (Holmes et al., 2022; Liu et al., 2023b).

2.4. *Cold and snowfall extremes over Mongolia in winter 2023/24*

Despite widespread hot extremes under global warming, harsh winters can still hit the Northern Hemispheric extratropics from time to time. This winter of 2023/24, Mongolia experienced its most severe snowfall since 1975, with temperatures dipping below −40°C and regional snowfall reaching 1 m (MNAMEM, 2024). This is the second year in a row that Mongolia has faced harsh winters, locally termed "Dzud", referring to severe winter colds and heavy snow (usually after dry summers), resulting in large-scale livestock losses (TNC, 2018). More than 90% of the country and 180 000 people were affected, along with over 4.7 million (7.3%) of its livestock having perished as of mid-March 2024, leaving herder households particularly hard hit (UNICEF, 2024).

Despite the mean climate warming, extreme cold winters have increased across large stretches of the Northern Hemispheric extratropics for the last two decades (Cohen et al., 2012). In northern Mongolia, cold-air outbreaks were 36.7% more frequent during 2000−16 than an earlier period of 1981−99 (Munkhjargal et al., 2020). Meanwhile, winter snow has increased by 40% since 1961 in Mongolia, although total precipitation has changed little (TNC, 2018). The extreme cold winters, combined with increased snow, has led to stronger dzuds since the 1990s in Mongolia (TNC, 2018). With projected increases in winter snow, the frequency of dzuds is projected to increase by 5%−20%, even under the moderate emissions scenario (RCP4.5), by 2080 (TNC, 2018).

The increased extreme winter colds in Mongolia are associated with synoptic patterns of a deepened trough over central Eurasia and strengthened northerly cold advection (Munkhjargal et al., 2020). These have been suggested to further relate to Arctic warming amplification, with an associated more meandering polar jet stream (Francis et al., 2017), and the negative phase of the Arctic Oscillation associated with Eurasian snow cover (Cohen et al., 2012).

3. Extreme precipitation

Extreme precipitation occurred in many regions in 2023, with contributions from a variety of phenomena of different time scales, including repeated La Niña episodes, monsoons and cyclones (see Table 1 for a list of the major events). Notably, a considerable proportion of these extreme precipitation events were related to cyclones. This is in line with future projections indicating that increases in extreme precipitation could be enhanced by the most intense cyclones, themselves becoming more frequent, partly owing to increases in SST and precipitable water (Liu et al., 2019; Walsh et al., 2019; Knutson et al., 2020; Guzman and Jiang, 2021; Koseki et al., 2021; Stansfield and Reed, 2023). Here, we review these extreme precipitation events with substantial contributions from cyclones.

3.1. *Long-lived Tropical Cyclone Freddy and its southern African heavy rainfall*

Formed off Northwest Australia in early February, Tropical Cyclone Freddy was a truly remarkable storm, lasting a record 35 days (WMO, 2023d) and tracking 12 000 km across the full width of the Indian Ocean to southern Africa, where it made landfall three times, wreaking havoc in the region. On 21 February, its moisture brought 200 mm of rainfall to southern Madagascar in two days, affecting over 2.2 million people. By 24 February, the rainfall had moved to Mozambique, delivering

Table 1. Major extreme precipitation events occurred in 2023.

Region	Time	Factors	Severity and impacts	Reference(s)
Australia	Early Jan 2023	Tropical Cyclone Ellie	Cumulative rainfall in a week exceeded 830 mm, breaking the water level record of the Fitzroy River. Thousands of people were left homeless.	WMO (2023d); NDMA of Australia (2023)
New Zealand	27–28 Jan 2023, 13–14 Feb 2023	Jan: Highly localised convective weather system; Feb: Tropical Cyclone Gabrielle	In many parts of Auckland on 27–28 Jan, local precipitation amount exceeded 200 mm in 6 h. In mid-Feb, daily precipitation in the North Island exceeded 500 mm locally. These two events caused 15 deaths and a total economic loss of 5.3–8.6 billion dollars.	WMO (2023d); Harrington et al. (2023); NIWA (2023)
Brazil	18–21 Feb 2023	Orographic precipitation	Local daily precipitation amount exceeded 600 mm. More than 54 losses of lives in landslides.	SP (2023)
Southern Africa (Madagascar, Mozambique and Malawi)	Feb to Mar 2023	Tropical Cyclone Freddy	The 24-h rainfall in Mozambique exceeded 200 mm during 12–15 Mar. Floods, landslides, winds and other disasters resulted in over 800 deaths and tens of thousands of people missing.	WMO (2023d); Liu et al. (2023a); OCHA (2023)
Central Africa	Early May 2023	Difficult to determine due to observational data limitation	Daily precipitation amount exceeded 182 mm at Mushubati. Severe floods and landslides caused 574 deaths. Due to limited data, it is unclear if more extreme rainfall and impacts have occurred.	WMO (2023d); Kimutai et al. (2023c)
Italy	Mid-May 2023	Low-pressure systems	Local rainfall exceeded 500 mm in 36 h, causing floods and landslides with a total economic loss of $9.7 billion.	WMO (2023d); Barnes et al. (2023); Greco and Balmer (2023)
Pakistan	Late Jun to early Jul 2023	South Asian summer monsoon	The highest daily rainfall reached 226 mm at Lahore. Cumulative precipitation in most regions was 50% greater than normal. More than 86 people died in flooding.	NDMA of Pakistan (2023); PMD (2023)
Libya	Early Sep 2023	Medicane Daniel	Local daily precipitation amount reached 414.1 mm. Floods caused the bursting of two dams, resulting in over 4300 deaths and 8500 people missing.	WMO (2023d); Zachariah et al. (2023c); (Oduoye et al. (2024)
North China	29 Jul to 1 Aug 2023	Tropical Cyclones Doksuri and Khanun	The maximum 72-h cumulative rainfall in Hebei Province reached 1003.4 mm, causing at least 56 deaths and a direct economic loss of 165.79 billion RMB.	WMO (2023d); Yang et al. (2023); Zhang et al. (2023); Fu et al. (2023)
Southeastern China	Early Sep 2023	Tropical Cyclone Haikui	The maximum hourly rainfall of 158.1 mm in Hong Kong, breaking records since 1884, caused hundreds of injuries and triggered disasters such as landslides and floods.	WMO (2023d); HKO (2023)

more than 200 mm in 72 hours. Two weeks later (11–15 March), after a prolonged period of strengthening over the sea between the African mainland and Madagascar, the cyclone made landfall again, bringing 200 mm in 24 hours in Mozambique and Malawi, causing over 800 fatalities, and displacing thousands of people (OCHA, 2023).

Several factors contributed to Freddy's persistence and intensity. Before its first landfall in Madagascar, Freddy moved along an almost straight line, barely undergoing any attenuation due to minimal frictional dissipation, favoring its development and maintenance (NASA, 2023). The zonal distribution of the Mascarene high was also conducive to the long duration of Freddy (Liu et al., 2023a). Freddy experienced seven rapid intensification stages in its lifetime due to warm SSTs and weak vertical wind shear, despite being partly counteracted by a dry atmosphere (Liu et al., 2023a).

3.2. *North China flooding related to Super Typhoons Doksuri (2023) and Khanun (2023)*

For four days in late July (29 July to 1 August), northern China experienced an extraordinary rainfall event, remarkable both for its intensity and duration. By the time the event ended, the Beijing–Tianjin–Hebei region had received a third of its usual annual rainfall. More astonishingly, Xingtai of Hebei Province recorded 1003.4 mm, almost double its usual annual 535 mm total. Resulting impacts in the Haihe River basin from mudslides and flooding led to direct economic losses exceeding 150 billion RMB (CMA, 2024a).

A combination of factors on a variety of spatiotemporal scales contributed to the rainfall. The large-scale western North Pacific subtropical high in summer 2023 was stronger than normal and partially connected with a continental high-pressure ridge. This allowed a stable atmospheric moisture channel to develop, highly efficient at funneling moisture northwards, from two super typhoons [Doksuri (2023) and Khanun (2023)] in the West Pacific. Forced lifting of the moisture by topography in the region further enhanced the rainfall (Yang et al., 2023).

Interestingly, the 2023 floods in northern China occurred just two years after a very similar event, with very similar mechanisms, affecting Zhengzhou in China's Henan Province, located to the southwest of Beijing. This too was due to moisture funneled from the western North Pacific subtropical high and typhoons (in this case, In-Fa (2021) and Cempaka (2021)) before being forced to topographically ascend (Huang et al., 2023; Wu et al., 2023a; Yin et al., 2023a). Anthropogenic warming and consequential increases in the atmosphere's water holding capacity have likely played a role in these types of extreme rainfall (Wang et al., 2022).

3.3. *Heavy rainfall in southeastern China contributed by Super Typhoon Haikui (2023)*

Further flooding occurred in China in September, courtesy of Typhoon Haikui (2023). Southeastern parts of the country were most affected, including Taiwan, Fujian, Guangdong, Guangxi, Hong Kong, and Macao, with historical September rainfall records exceeded at 17 stations. In Hong Kong, for example, an hourly rainfall of 158.1 mm was recorded, its greatest value since 1884. The cumulative rainfall reached up to 842 mm within 24 hours in the southeast of Hong Kong, which also broke the local maximum daily rainfall record (CMA, 2024a).

Typhoon Haikui (2023) formed in the Northwest Pacific on 28 August and made landfall in Taiwan on 3 September with the intensity of a severe typhoon. It then made landfall again in Fujian and Guangdong on 5 September with the intensity reduced to that of a tropical storm. After this second landfall, Haikui weakened substantially but continued to provide heavy rainfall in southeastern China for another week. Three factors contributed to the rainfall. Due to the intense moisture transport of the southwest monsoon in the South China Sea, Haikui transported more water vapor than other typhoons of similar intensity. Secondly, by virtue of being trapped by three anticyclonic systems, Haikui moved very slowly, leading to the rainfall's long duration (Chan, 2005; Emanuel, 2017; van Oldenborgh et al., 2017). Thirdly, topographic lifting also enhanced the rainfall (Gao et al., 2009).

3.4. *Libya flooding from storm Daniel*

Extreme rainfall also hit the eastern Mediterranean in September, with flooding in Greece, Turkey, Bulgaria, and Libya, brought by storm Daniel, named by Greece's national weather service. Greece received 759 mm on 5 September, followed by a record daily 414 mm in Libya five to six days later. The city of Derna, located in eastern Libya, was particularly badly impacted, with over 4300 people lost after two dams collapsed, upstream of the city (WMO, 2023d).

Despite SSTs in the eastern Mediterranean of between 25°C and 26°C in August and September in most years (Pastor et al, 2020), large-scale storms during summer and early autumn in the region are rare, partly due to climatological descent and suppressed convection forced by ascent over Asia (Rodwell and Hoskins, 1996). Small disturbances, however, can occasionally develop into tropical-like storms (Emanuel, 2005; Tous and Romero, 2013; Fita and Flaounas, 2018), informally called "medicanes", with a warm core and a central cloud-free eye if the forced descent is weaker than normal and a number of factors also occur. These include reduced vertical wind shear, ample mid-tropospheric moisture, and excessively warm SSTs (Emanuel, 2005; Tous and Romero, 2013; Romero and Emanuel, 2013). In early September 2023, all these factors occurred, allowing an initially small disturbance close to Greece to develop (NOAA, 2023a). Recent research suggests anthropogenic climate warming has intensified extreme rainfall in Libya, although the quantitative estimate has large uncertainty (Zachariah et al., 2023c).

Looking to the future, current model projections suggest that storms in the Mediterranean may become less frequent but more intense as the planet warms. Results, though, are highly uncertain and even depend on the location within the region (Tous et al, 2016; Romero and Emanuel, 2017).

4. Droughts

Persistent droughts have adversely impacted several hotspots over the globe over the past few years, and 2023 was no exception. Long-term drought continued in South America, and a new drought occurred in southwestern China. Over the western US and the Horn of Africa, however, prolonged droughts have been replaced by excessive rains and, again, consequential losses.

4.1. *Record-breaking droughts in South America*

Four years of severe drought have afflicted central South America since 2019 up to the first half of 2023, affecting Argentina, Bolivia, Chile, Paraguay, and Uruguay. Remarkably, rainfall and, consequently, soil moisture values have remained consistently below normal. For the 54 months during this period, soil moisture remained below normal for 52 months, and below the climatological 25th percentile for 23 months, based on ERA5 reanalysis (Fig. 5a). The drought was accompanied by exceptional heat (with 2023 being the warmest year on record for South America), as well as repeated heatwaves in recent years. Climate change is reported to have played a significant role in the severity and frequency of these (Rivera et al., 2023). The drought and heat exacerbated each other through land–atmosphere feedbacks. Together, they also led to widespread wildfires in Brazil, Argentina, Paraguay and Bolivia in September, resulting in large impacts on agriculture, freshwater and energy supplies, with states of emergency announced in many countries in the region (WMO, 2024). A 3% GDP reduction was recorded in Argentina in 2023 alone (Toreti et al., 2023), while soybean production in Argentina fell by 44% compared to the past five years (UN, 2023). The drought also forced the closure of Brazil's fourth-largest hydropower station, San Antonio. Waterway traffic in the La Plata Basin was also severely disrupted, affecting more than 480 000 people (CMA, 2024b).

The recent drought appears to have been part of a long-term 40-year drying trend over central South America, although confidence is low regarding whether the trend is within or beyond natural variability (Arias et al., 2023, 2024). The sustained rainfall deficit in recent years has also been related to large-scale atmospheric and oceanic conditions. Since early 2020, repeated La Niña episodes and a positive Antarctic Oscillation phase have both favored atmospheric subsidence in central and eastern South America, suppressing rainfall in the region (de Freitas et al., 2023; Geirinhas et al., 2023; European Commission et al., 2023; Toreti et al., 2023). Additionally, deforestation of the Amazon rainforest may have also contributed to the decreasing rainfall in South America (Boers et al., 2017).

With the onset of El Niño since mid-2023, drought conditions started to develop over the Amazon basin due to the subsidence linked to the downward branch of the Walker Cell (Marengo and Espinoza, 2016). However, during the exceptional drought of 2023, climate change acted as the main driver for the low rainfall and high temperatures over the basin, resulting in the lowest river levels in the past 120 years (Clarke et al., 2024).

4.2. *Persistent drought in southwestern China from winter 2022 to spring 2023*

From winter 2022 to spring 2023, southwestern China (mainly Yunnan Province) suffered from a severe and persistent drought (Fig. 5b). The intensity of the meteorological drought (i.e., precipitation deficit) was the greatest of all equivalent periods of each year since 1961, with an accumulated precipitation from January to early June of 2023 of only 138 mm in Yunnan (CMA, 2024c). Agricultural failures, water shortages and damage to local ecosystems were the result, affecting 4 million people (CMA, 2024c; DEMYP, 2024).

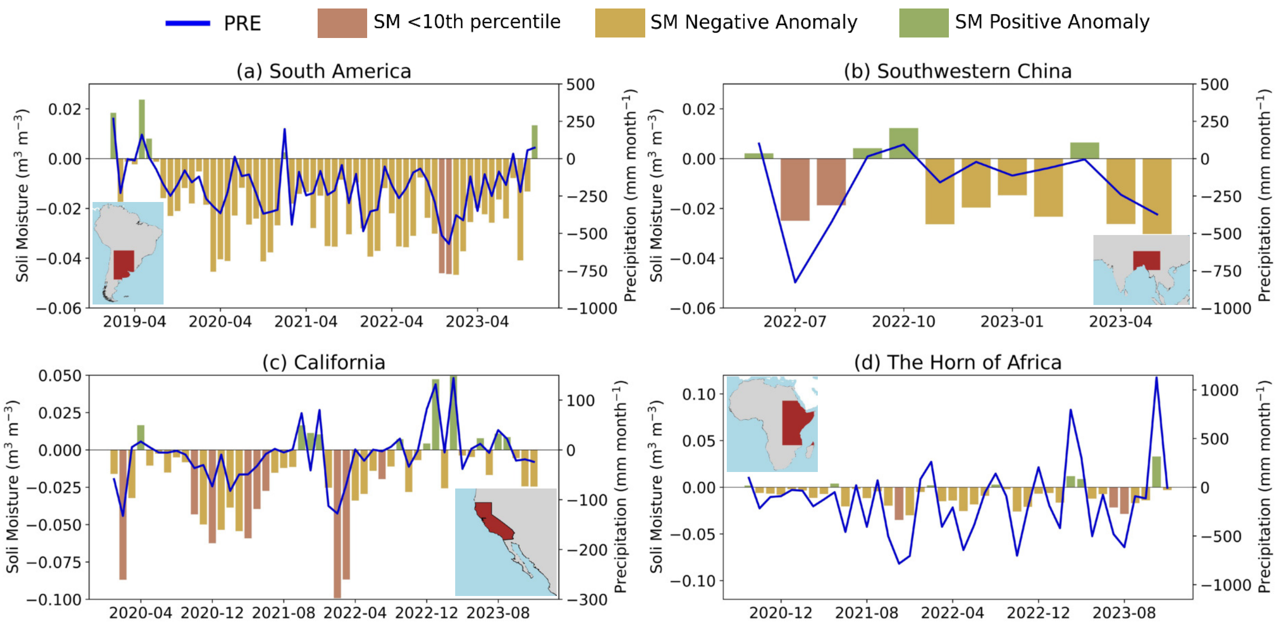

Fig. 5. The drought conditions over (a) South America, (b) southwestern China, (c) California, and (d) the Horn of Africa. Blue curves indicate monthly precipitation anomalies (right axis; units: mm month^{-1}). Bars indicate monthly soil moisture anomalies (left axis; units: m^3 m^{-3}), where brown, yellow and green shading denotes below the 10th percentile, negative anomalies, and positive anomalies, respectively. Anomalies are derived by subtracting monthly climatologies of 1991–2020. Data are from ERA5.

Droughts themselves are in fact not particularly unusual in southwestern China in winter and spring, due to the monsoon climate in the region. Over the past few decades, however, they have tended to become more frequent and severe (Ma et al., 2017; Liu et al., 2023c). This latest one appears to have arisen from a combination of factors at a variety of scales, including the shift from La Niña to El Niño, the westward extension of the western Pacific subtropical high, westerly jet anomalies, the tropical Madden–Julian Oscillation, and anomalous snow cover over the Tibetan Plateau (Liu et al., 2022, 2023c; Institute of Arid Meteorology, CMA, Lanzhou, 2023; Wang et al., 2023b).

4.3. *Drought-to-flood transition in California in late winter and spring 2022/23*

The southwestern US (principally California) has suffered from continuous drought since early 2020. For the consecutive 35 months during this drought, soil moisture has remained below the climatological 25th percentile for 23 months, and below the climatological 10th percentile for 9 months, based on ERA5 (Fig. 5c). The drought condition significantly eased from late winter 2022 onwards, with the arrival of an historic run of nine consecutive landfalling atmospheric rivers in a period of three weeks (DeFlorio et al., 2024). Excessive precipitation was 72% above normal during December 2022 and March 2023 (based on ERA5; Fig. 5c). As a result, the drought extent in the US shrank from a maximum of 46% in January 2023 to a minimum of 19% by May, the lowest since early 2020 (NOAA, 2023b). Recovery from the drought has, though, been fraught, due to significant flooding induced by the storms, particularly in California, with over 700 landslides and 1400 rescues, and some fatalities (NOAA, 2023b).

Shifts between droughts and floods are not actually that rare in California, due to its Mediterranean style climate (Wang et al., 2017; Swain et al., 2018). A similar transition also occurred in the winter and spring of 2016/17, when excessive rainfall associated with atmospheric river storms ended an earlier multiyear 2012–2016 drought in the region (Wang et al., 2017; Swain et al., 2018).

Many studies have suggested that anthropogenic climate change is increasing the risk and severity of droughts in the southwest US because of increasing temperatures (Diffenbaugh et al, 2015; Williams et al., 2015). Understanding of drought-to-flood transitions, though, is limited. As anthropogenic warming continues, climate models project increases in the frequency of both wet and dry extremes over California, accompanied by more dry-to-wet precipitation shifts (Swain et al., 2018). Such sequentially occurring extremes are likely to produce greater impacts than if occurring alone, since droughts often produce soils prone to greater runoff and flooding under heavy precipitation.

4.4. *Drought-to-flood transition over the Horn of Africa in late October 2023*

On timescales like those of California, the Horn of Africa has also suffered from prolonged drought conditions from late 2020 to early 2023, with an unprecedented sequence of five consecutive failed rainy seasons and soil moisture remaining consistently below normal (Fig. 5d). From late October 2023, however, a switch to widespread flooding occurred, with November receiving 64% more rainfall than usual (Fig. 5d; Kimutai et al., 2023a). The drought itself was the worst for 40 years in this part of Africa, with Ethiopia, Kenya and Somalia hit particularly hard (WMO, 2023c), with resulting exceptional food insecurity, pushing more than 20 million people into extreme hunger (Funk et al., 2023).

The drought is related to both anthropogenic warming in the western Pacific and the “triple-dip” La Niña sequence since 2020, via a greater zonal Pacific SST gradient and enhanced Walker Circulation, which then led to anomalous descent and moisture divergence over East Africa (Funk et al., 2023). Anthropogenic warming is estimated to have caused a 100-fold increase in the drought risk in the region compared to pre-industrial times (Kimutai et al., 2023b).

Just months after the severe drought, the Horn of Africa was hit by an exceptionally wet rainy season in October–December (OND) in 2023 (Fig. 5d). The extreme precipitation events in OND 2023 were the strongest or second-strongest on record since the 1980s, depending on event lengths (Kimutai et al., 2023a). Episodic heavy rains, despite easing the drought conditions to some extent, have led to extensive flash floods due to high water runoff from extremely dry, hardened land following the prolonged drought. The floods caused more than 300 reported deaths and displaced over a million people in Kenya and Somalia alone (Kimutai et al., 2023a).

The exceptionally heavy rainfall during OND 2023 in the Horn of Africa was enhanced by both climate change and the Indian Ocean Dipole phase (Kimutai et al., 2023a). Combining observational and modeling evidence, human-induced climate warming so far, of 1.2°C, has almost doubled the intensity of OND rainfall (Kimutai et al., 2023a).

In summary, both the droughts and extreme wet season in the Horn of Africa appear to have been exacerbated by anthropogenic climate warming, with additional modulation from internal climate variability. Gaps in understanding of the events, and particularly the transition, however, require further research.

5. Sandstorms and wildfires

5.1. *Sandstorms in Mongolia in April 2023*

Mongolia and Northwest China are arid regions, often prone to sandstorms, particularly after dry winters (Han et al., 2021). Sand dust weather events were particularly frequent in 2023, with 17, the most since 2011, of which 10 occurred in March and April (Yin et al., 2023b). The most severe sandstorm lasted five days (9–13 April), affecting large areas of northern China including Beijing, Tianjin, Xinjiang, and Inner Mongolia, and impacting an area of about 3.4 million square kilometers and more than 400 million people. On 10 April, the PM_{10} concentration in Ulanqab, Inner Mongolia, exceeded 7000 μg m^{-3}, far beyond the recommended air quality guideline 24-hour mean levels of 45 μg m^{-3} established by the World Health Organization. The sandstorm then propagated southward, passing through areas including Beijing in northern China, Nanjing in eastern China, and Fuzhou in southern China, where the PM_{10} concentration surpassed 2000, 1600 and 400 μg m^{-3}, respectively (Yin et al., 2023b). The sandstorm even affected the Korean Peninsula and Japan. Roughly 40% and 25% of the dust came from Mongolia and the Taklimakan Desert, respectively (Chen et al., 2023; Piao et al., 2023).

An unusually warm, early spring in the region appears to have been the principal cause for the abundant sand source. Temperatures were 8°C warmer than normal, reducing snow coverage and drying out the soil (Yin et al., 2023b; Filonchyk et al., 2024). Loose surface-layer sand was then transported by high winds, related to a stronger-than-normal Mongolian cyclone and convection (Yin et al., 2023b).

5.2. *Wildfire in Hawaii in August 2023*

On 8 and 9 August, the deadliest wildfire in the US for a century devastated Hawaii's second-largest island, Maui (Juliano et al., 2024). According to NOAA's National Center for Environmental Information, at least 100 people lost their lives, 2000 acres of land were burnt, 2200 structures were destroyed, and losses of $5.6 billion were incurred (Juliano et al., 2024). Fire risk at the time was greatly enhanced by persistent rainfall deficits, in part due to the developing late-2023 El Niño, but also strong winds from a dipole between high pressure northeast of Maui and a hurricane (Dora) to the south (Marris, 2023; Juliano et al., 2024).

Wildfires are not new to Hawaii. However, the area burned by wildfires in Hawaii has increased by more than fourfold over the past century (Trauernicht et al., 2015). This increase is likely to continue in coming decades as the climate warms and dries in the region. Land-cover changes and human population growth may also increase the risk (Trauernicht et al., 2015).

5.3. *Spring-to-autumn Canadian wildfires*

For Canada, 2023 was a year of historical, record-breaking wildfire activity. From March to October of 2023, at least 6700 fires broke out across Canada, burning 18.5 million hectares, an area six times greater than the 2013–22 10-year average (You et al., 2023). The fires produced 1.5 billion tons of CO_2, equivalent to the total output from all the wildfires in Canada in the past 22 years and more than double Canada's planned greenhouse gas emission reductions for the next 10 years (Wang et al., 2024).

As in Hawaii, the fires were the result of a combination of drought and extreme heat, which Canada experienced from May 2023 onwards. The disastrous 2023 wildfire season also appears to be part of a long-term trend in the country, of increasing frequency and size of large fires over the past half century. The wildfire season's length has also increased (Hanes et al., 2019).

6. Perspectives

In this paper, we have presented a summary of the world's most prominent weather and climate events in 2023. Many of the characteristics of these recent extreme events align with the projected future changes in a warmer world. These emerging features offer a foretaste of what could happen in the coming decades, although the time of emergence itself remains another important issue to be investigated. Some of the emerging features point to critical gaps in our current understanding.

For high temperature extremes, their early arrival in spring in many regions in this year is consistent with the projected earlier timing of hot extremes, which have already been observed regionally (e.g., Founda et al., 2019; Wu et al., 2023b). On the other hand, the concurrent hot extremes in different continents in the Northern Hemisphere in the summer of 2022 and 2023 are also part of the long-term increase of such events observed since the 1970s (Rogers et al., 2022). The increase in these large-scale concurrent hot extremes is driven by both warming and changing atmospheric circulations (mainly involving circumglobal teleconnections and Rossby waves) (Kornhuber et al., 2020; Rogers et al., 2022). The multiple physical links connecting atmospheric circulation patterns to concurrent surface high temperature extremes need to be better understood to improve their projections and predictions (White et al., 2022).

For precipitation extremes, this year has seen large exacerbations of rainfall amounts by intense cyclones (e.g., the Libya flooding in September and the North China flooding in July). This is in line with future projections indicating that increases in extreme precipitation could be enhanced by the most intense cyclones, partly owing to increases in SST and precipitable water (e.g., Walsh et al., 2019; Knutson et al., 2020).

Shifts between droughts and floods (such as those of 2023 in California and the Horn of Africa), as a type of sequential compounding event, can cause severer impacts than when occurring separately. Such drought-to-flood transitions have been shown to occur more frequently since the 1980s (Qing et al., 2023) and, in some regions, are projected to increase in the coming decades (Swain et al., 2018; Zhang et al., 2021). Understanding the physical reasons for the increases in these transitions, however, requires further study. This provides a new perspective for understanding the hydrological cycle.

Another feature is the increasing interactions between climate extremes and ecosystems, mainly via events such as wildfires and sandstorms. Some of these interactions are mutually exacerbating. Fire risk is projected to increase over many regions because of increased temperatures, reduced relative humidity, and rainfall deficits (Richardson et al., 2022; Senande-Rivera et al., 2022). At the same time, wildfires can affect the climate, through aerosol and greenhouse gas emissions, and damage to carbon sinks, potentially putting at risk crucial targets of carbon neutrality (UNEP, 2022; You, 2023; Wang et al., 2024).

To prepare better for climate hazards, there is a need for improved predictions, projections and early warnings. As part of this, a UN initiative, Early Warnings for All, was recently launched, aiming to provide worldwide early warning by 2027. This ambitious objective remains, however, particularly challenging for regions short of resources, regions that are often also disproportionately affected by extreme weather and climate events. According to the WMO, the death toll related to extreme weather and climate events during 1970–2021 is at 2 million globally, with 90% in developing countries (WMO, 2023a). One significant challenge in improving early-warning systems in some countries is the availability of observations. Better observations in Rwanda and the Democratic Republic of Congo, for example, where flooding caused almost 600 casualties in May 2023 (Kimutai et al., 2023c), may well have enabled better warnings.

Apart from improvements in extreme weather forecasts, impact-based forecasts are also highly valuable. By clarifying how extreme weather and climate events would translate into potential impacts, more effective warnings should be possible. This requires strengthened partnerships between scientists, forecasters, disaster managers, community leaders and decision-makers.

Fortunately, a multitude of international collaboration projects are now successfully starting to fill many of the gaps. One promising example is the Earth Virtualization Engines (EVE), with bold ambitions to empower individuals worldwide in their use of technology to improve their resilience against climate change (Stevens et al., 2024). With key technologies of high-performance computing and artificial intelligence, EVE strives to produce significantly improved multidecadal kilometer-scale global climate projections, considering user needs. This sophisticated climate information, accessible to all, is crucial to inform and inspire actions, particularly to regions short of resources. Through the generation and sharing of critical data, EVE is expected to greatly strengthen partnerships between beneficiaries and benefactors in tackling common challenges and improving resilience to extreme weather and climate.

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