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2023: Weather and climate extremes hitting the globe with emerging features

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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). We finally 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

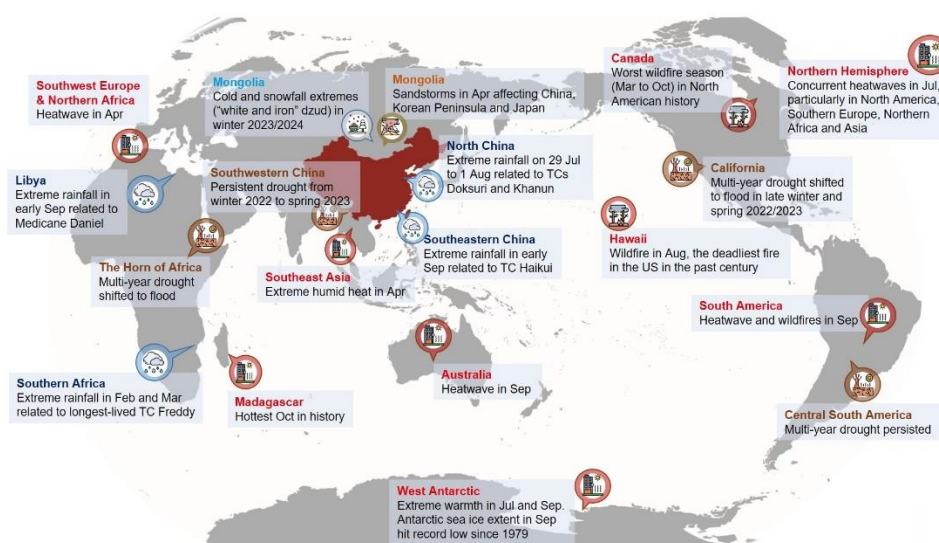
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33 1. Introduction

34 By an unusually large margin, 2023 was, globally, the warmest year on record in both the atmosphere
 35 and ocean with a near-surface air temperature anomaly of $1.45 \pm 0.12^\circ\text{C}$ compared to pre-industrial levels
 36 (1850-1900), according to six leading international datasets (WMO, 2024). New temperature records
 37 were repeatedly set in every month from June to December. Regionally, 2023 was also the warmest year
 38 for several continents (e.g., North America, South America, Africa) and countries (e.g., China) (NOAA,
 39 2024a). Beyond the surface air temperature, the sea surface temperature (SST) and upper 2000 m ocean
 40 heat content also reached unprecedented values (Cheng et al., 2024). The year's record warmth resulted
 41 from a combination of the accumulated anthropogenic warming and internal climate variability,
 42 including a shift from a series of three La Niña episodes to an El Niño and a positive phase of the Atlantic
 43 Multidecadal Oscillation (Li et al. 2023, 2024; Zheng et al. 2023).

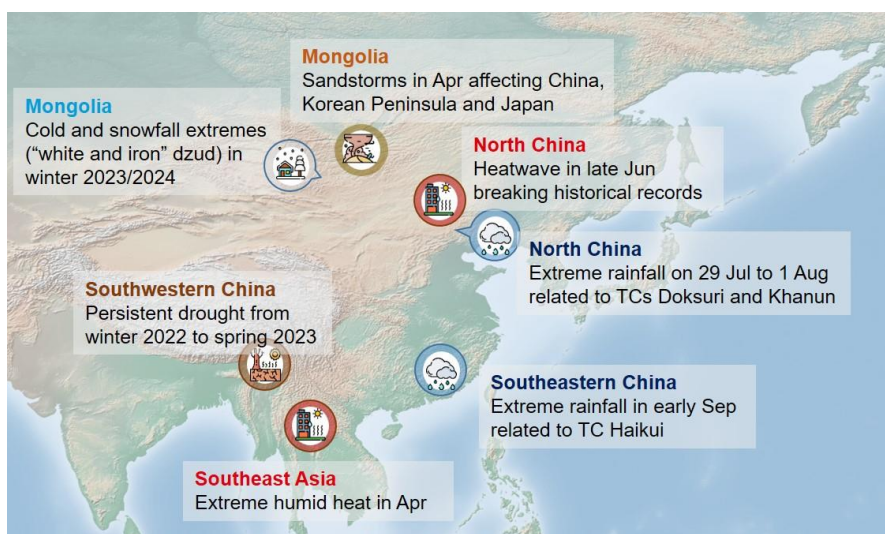
44 Partly fueled by the heat, the year was also characterized by unprecedented extreme weather and
 45 climate events in many parts of the world (Figs. 1-2). These extreme events have long caused profound
 46 socioeconomic losses (e.g., Newman et al., 2023; Zhou et al., 2023; Xu, 2024; Xu et al., 2024). According
 47 to the World Meteorological Organization (WMO), during 1970-2021, extreme weather, climate and
 48 water-related events have caused at least 10000 disasters, with reported economic losses exceeding US\$4
 49 trillion and a death toll of 2 million (WMO, 2023a).

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



62

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



64

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

66

67 2. High temperature extremes

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

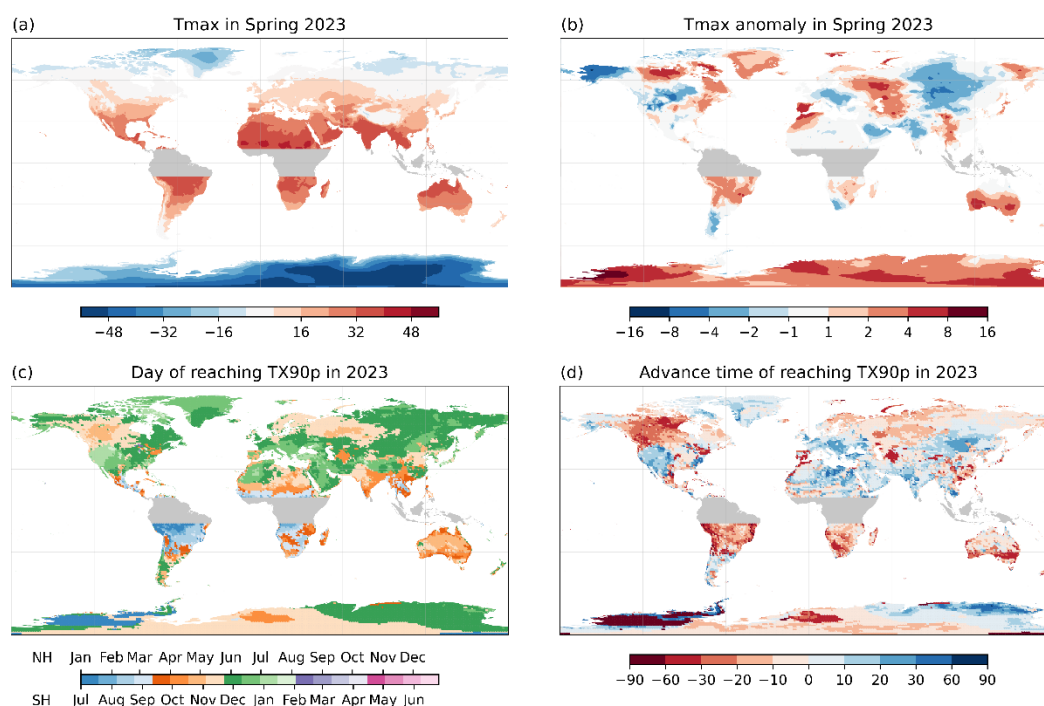
71 2.1 High temperature extremes occurring earlier

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

82 Southeast Asia also suffered a record-breaking hot extreme in mid-April (Figs. 3a and b) with new
83 records set in Thailand with 45.4°C and Laos with 42.9°C (TMD, 2023; LaCSA, 2023). The unusually
84 hot conditions in Southeast Asia were accompanied by excessive humidity, exacerbating its impacts on
85 local populations in the region (Zachariah et al., 2023b, Domeisen et al., 2023). Without anthropogenic
86 influences on climate, such extreme humid heat events would be almost impossible (Zachariah et al.,
87 2023b).

88 Early spring in the Southern Hemisphere, in September 2023 also saw unusual heat in large areas
89 of South America and Australia. Temperatures in some parts of Brazil exceeded 40°C in mid-September
90 (INMET, 2023), while those in parts of Australia were 16°C greater than normal (BOM, 2023). In
91 southeastern Africa, Madagascar experienced its hottest October in history (Pinto et al., 2023).

92 Accompanied with the heat, wildfires occurred in Australia and many parts of South America, including
 93 Brazil, Argentina, Paraguay and Bolivia (The Guardian, 2023; CNN, 2023). Physically, the high
 94 temperature extreme in Australia was exacerbated by the development of an El Niño, a phenomenon
 95 typically known to cause drought in Australia (Freund et al., 2021), further exacerbating hot extremes
 96 through land-atmosphere feedbacks (Fischer et al., 2007; Miralles et al., 2012; Lemus-Canovas et al.,
 97 2024). Rapid attribution indicates that the probability of such hot extremes in both South America and
 98 Madagascar is at least 100 times greater than in a climate without human influence (Kew et al., 2023;
 99 Pinto et al., 2023).



100

101 **Fig. 3.** (a-b) The intensity of spring high temperature in 2023. (a) Daily maximum temperature (Tmax)
 102 and (b) its anomaly in spring of 2023 (April for Northern Hemisphere and September for Southern
 103 Hemisphere; unit: °C). (c-d) The early occurrence of high temperature in 2023. (c) The date in 2023
 104 when Tmax first exceeded historical TX90p (90th percentile of Tmax in the baseline 1991-2020). Note
 105 the colorbar runs from January to December for Northern Hemisphere and from July to June for Southern
 106 Hemisphere. (d) The anomaly of the date for the first exceedance of TX90p in 2023 compared to baseline.
 107 Red and blue indicate occurring earlier and later in 2023 than normal, respectively (unit: days). All
 108 anomalies are derived with respect to the baseline of 1991-2020. Note the belt of 10°S-10°N is masked
 109 given the weak seasonal cycle in the tropics. Data are from ERA5.

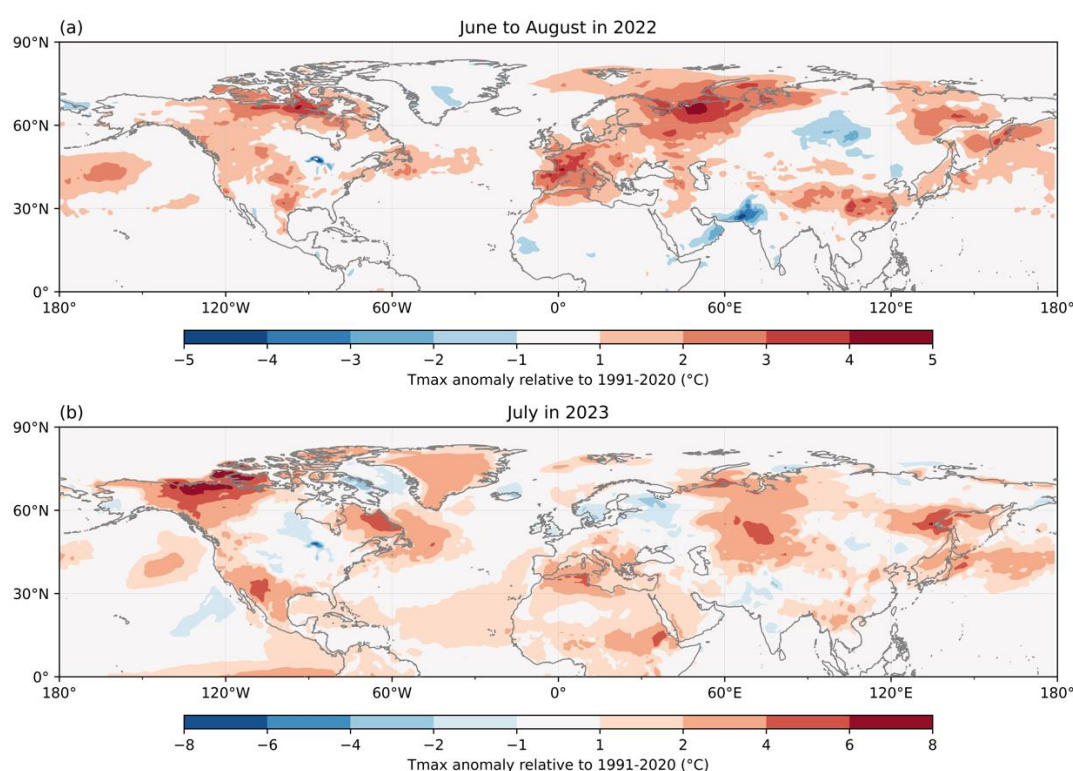
110

111 **2.2 Simultaneous occurrence of hot extremes in the Northern Hemisphere in July 2023**

112 In July 2023, record breaking hot extremes occurred in many regions of North America, Southern
 113 Europe, Northern Africa, and Asia (Fig. 4b). Daily maximum temperatures in both America and China
 114 exceeded 50°C, and eastern Spain recorded its hottest day in history. The extreme heat conditions in
 115 Arizona, with a record of 31 consecutive days of temperatures exceeding 43.3°C since late June in the
 116 city of Phoenix, led to significant health consequences for vulnerable populations (du Bray et al., 2023).

117 The impacts of this event were partially exacerbated by a dry monsoon season, which threatened the
 118 urban water supply. In all of the aforementioned regions, hot extremes with the same likelihood as those
 119 observed in 2023 would have been colder in a climate without human impact (Zachariah et al., 2023a).
 120 For the record-shattering hot extreme in North China at the end of June 2023, the intensity of similar heat
 121 events increased by at least 1°C due to anthropogenic climate change (Qian et al., 2023).

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



129

130 **Fig. 4.** The average daily maximum temperature (Tmax) anomaly for June to August 2022 (a) and July
 131 2023 (b), relative to 1991-2020 (unit: °C). Data are from ERA5.

132

133 **2.3 Highly unusual warmth in the Antarctic and record-low sea ice extent**

134 Further south, the Antarctic also experienced exceptional warmth in 2023, with its 3rd warmest
 135 annual average temperature on record since 1850. As part of this, September set the new record with an
 136 anomaly of 2°C (NOAA, 2024b). Accompanied by the exceptional warmth, the annual Antarctic sea ice
 137 extent also reached a record low in the satellite-era since 1979, with an average 3.79 million square miles.
 138 Both the annual maximum (in September) and minimum (in February) were the lowest on record (NOAA,
 139 2024a).

140 The record-low Antarctic sea ice extent in 2023 appears to have been part of decadal variability,

141 where the sea ice extent increased slightly from 1979 to 2015 before a sharp decline immediately
142 afterwards (Gilbert and Holmes, 2024). The variations in the Antarctic sea ice extent, both on interannual
143 and decadal scales, are strongly impacted by modes of large-scale natural variability such as the Southern
144 Annular Mode and El Niño-Southern Oscillation (Gilbert and Holmes, 2024). For 2023's new record
145 minimum, several atmospheric drivers were responsible, including a positive Antarctic Oscillation, the
146 3-year La Niña episodes, the negative phase of the Interdecadal Pacific Oscillation and a positive phase
147 of the Atlantic Multidecadal Oscillation, through deepening of the Amundsen Sea Low, a low-pressure
148 system located off West Antarctica which strongly modulates Antarctic sea ice extent (Liu et al., 2023).
149 Apart from atmospheric variability, the Southern Ocean subsurface warming also played a role in pushing
150 Antarctic sea ice into a new low-extent state (Zhang et al., 2022; Purich and Doddridge, 2023). In addition,
151 the recent recovery of stratospheric ozone, through modulating surface wind, can also affect the Southern
152 Ocean heat transport and ocean heat content, and further, Antarctic sea ice (Li et al., 2023). It is worth
153 noting that the influence of ozone change on the Antarctic sea ice extent is time-varying, which depends
154 critically on the fast and slow responses of the Southern Ocean to ozone forcing (Ferreira et al., 2015).
155 It remains to be seen whether the recent Antarctic sea ice minimum is a brief anomaly or the emergence
156 of a declining trend in response to longer-term anthropogenic warming as projected by climate models
157 (Holmes et al., 2022; Liu et al., 2023).

158 **2.4 Cold and snowfall extremes over Mongolia in winter 2023/2024**

159 Despite widespread hot extremes under global warming, harsh winters can still hit northern
160 hemispheric extra-tropics from time to time. This winter of 2023/2024, Mongolia has experienced its
161 most severe snowfall since 1975, with temperatures dipping below -40°C and regional snowfall reaching
162 1 m (MNAMEM, 2024). This is the second year in a row that Mongolia faced harsh winters, locally
163 termed "Dzud", referring to severe winter colds and heavy snow (usually after dry summers), resulting
164 in large-scale livestock losses (TNC, 2018). More than 90% of the country and 180,000 people were
165 affected, along with over 4.7 million (7.3%) of livestock perished as of mid-March 2024, leaving herder
166 households particularly hard hit (UNICEF, 2024).

167 Despite the mean climate warming, extreme cold winters have increased across large stretches of
168 the northern hemispheric extra-tropics for the last two decades (Cohen et al., 2012). In northern Mongolia,
169 cold air outbreaks were 36.7% more frequent during 2000-2016 than an earlier period of 1981-1999
170 (Munkhjargal et al., 2020). Meanwhile, winter snow has increased by 40% since 1961 in Mongolia,
171 although total precipitation has changed little (TNC, 2018). The extreme cold winters, combined with
172 increased snow, has led to stronger dzuds since the 1990s in Mongolia (TNC, 2018). With projected
173 increases in winter snow, the frequency of dzuds is projected to increase by 5-20% even under the
174 moderate emission scenario (RCP4.5) by 2080 (TNC, 2018).

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

180

181 **3. Extreme precipitation**

182 Extreme precipitation occurred in many regions in 2023 with contributions from a variety of

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

190 ***3.1 Long-lived Tropical cyclone Freddy and its Southern African heavy rainfall***

191 Formed off northwest Australia in early February, Tropical cyclone Freddy was a truly remarkable
192 storm, lasting a record 35 days (WMO, 2023d) and tracking 12,000km across the full width of the Indian
193 Ocean to southern Africa where it made landfall three times, wreaking havoc in the region. On February
194 21st, its moisture gave 200mm of rainfall in southern Madagascar in 2 days, affecting over 2.2 million
195 people (Météo-France, 2023). By the 24th, the rainfall had moved to Mozambique, giving more than 200
196 mm in 72 hours. Two weeks later (March 11th to 15th) after a prolonged period of strengthening above
197 the sea between the African mainland and Madagascar, the cyclone, made landfall again, giving 200 mm
198 in 24 hours in Mozambique and Malawi, causing over 800 fatalities and displacing thousands of people
199 (OCHA, 2023).

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

206 ***3.2 North China flooding related to Super Typhoons Doksuri and Khanun***

207 For 4 days in late July (July 29th to August 1st), northern China experienced an extraordinary
208 rainfall event, remarkable both for its intensity and duration. By the time the event ended, the Beijing-
209 Tianjin-Hebei region had received a third of its usual annual rainfall. More astonishingly, Xingtai of
210 Hebei Province recorded 1003.4mm, almost double its usual annual 535mm total. Resulting impacts in
211 the Haihe River basin from mudslides and flooding led to direct economic losses exceeding 150 billion
212 RMB (CMA, 2024a).

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

219 Interestingly, the 2023 floods in northern China occurred just two years after a very similar event,
220 with very similar mechanisms, affected Zhengzhou in China's Henan Province, located to the southwest
221 of Beijing. This, too, was due to moisture funneled from the Western North Pacific subtropical high and
222 typhoons (in this case, In-Fa and Cempaka) before being forced to topographically ascend (Yin et al.,
223 2023; Wu et al., 2023; Huang et al., 2023). Anthropogenic warming and consequential increases in the
224 atmosphere's water holding capacity is likely to have played a role on these types of extreme rainfall

225 (Wang et al., 2022).

226 **3.3 Heavy rainfall in southeastern China contributed by Super Typhoon Haikui**

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

233 Typhoon Haikui formed in the northwest Pacific on August 28th and made landfall in Taiwan on
234 September 3rd with the intensity of a severe typhoon. It then made landfall again in Fujian and
235 Guangdong on September 5th with the intensity reduced to that of a tropical storm. After this 2nd landfall,
236 Haikui weakened substantially but continued to provide heavy rainfall in southeastern China for another
237 week. Three factors contributed to the rainfall. Due to the intense moisture transport of the southwest
238 monsoon in the South China Sea, Haikui transported more water vapor than other typhoons of similar
239 intensity (Zhang, 2023). Secondly, by virtue of being trapped by three anticyclonic systems, Haikui
240 moved very slowly, leading to the rainfall's long duration (Chan, 2005; Emanuel, 2017; van Oldenborgh
241 et al., 2017). Thirdly, topographic lifting also enhanced the rainfall (Gao et al., 2009).

242 **3.4 Libya flooding from storm Daniel**

243 Extreme rainfall also hit the eastern Mediterranean in September, with flooding in Greece, Turkey,
244 Bulgaria, and Libya brought by storm Daniel, named by Greece's national weather service. Greece
245 received 759 mm on September 5th, followed by a record daily 414 mm in Libya 5-6 days later. The city
246 of Derna, located in eastern Libya, was particularly badly impacted, with over 4300 people lost after two
247 dams collapsed, upstream of the city (WMO, 2023d).

248 Despite SSTs in the eastern Mediterranean of between 25°C and 26°C in August and September in
249 most years (Pastor et al, 2020), large-scale storms during summer and early autumn in the region are rare,
250 partly due to climatological descent and suppressed convection forced by ascent over Asia (Rodwell and
251 Hoskins, 1996). Small disturbances, however, can occasionally develop into tropical-like storms
252 (Emanuel, 2005; Tous and Romero, 2013; Fita and Flaounas, 2018), informally called "medicanes", with
253 a warm core and a central cloud-free eye if the forced descent is weaker than normal and a number of
254 factors also occur. These include reduced vertical wind shear, ample mid-tropospheric moisture, and
255 excessively warm SSTs (Emanuel, 2005; Tous and Romero, 2013; Romero and Emanuel, 2013). In early
256 September 2023, all these factors occurred allowing an initially small disturbance close to Greece to
257 develop (NOAA, 2023a). Recent research suggests anthropogenic climate warming has intensified
258 extreme rainfall in Libya, although the quantitative estimate has large uncertainty (Zachariah et al.,
259 2023c).

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

263

264 **4. Droughts**

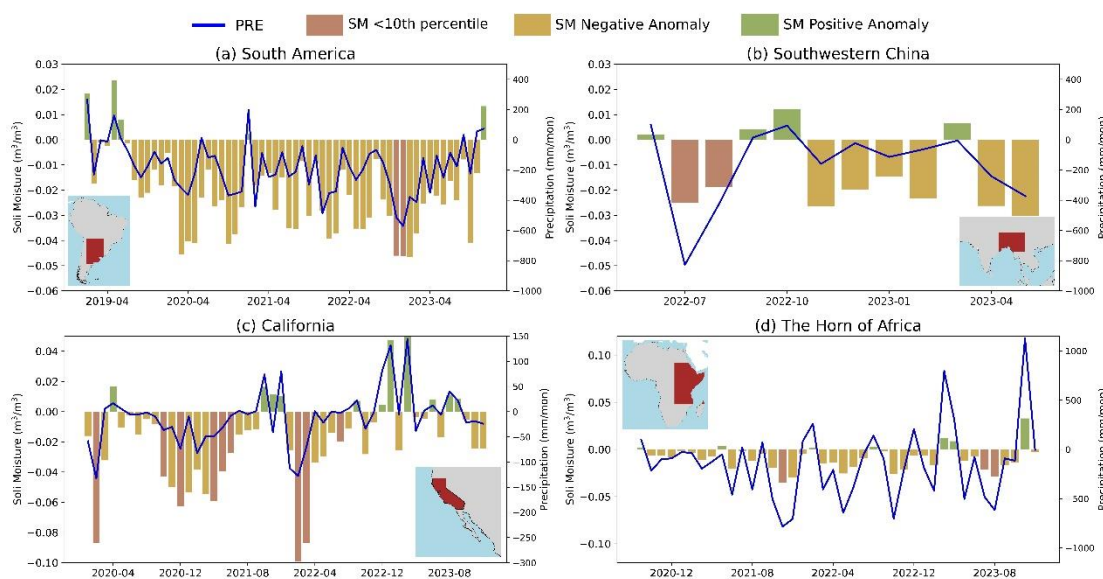
265 Persistent droughts have adversely impacted several hotspots over the globe over the past few years,
266 and 2023 was no exception. Long-term drought continued in South America, and a new drought occurred
267 in southwestern China. Over the western US and the Horn of Africa, however, prolonged droughts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

269 ***4.1 Record breaking droughts in South America***

270 Four years of severe drought have afflicted central South America since 2019 up to the first half of
271 2023, affecting Argentina, Bolivia, Chile, Paraguay, and Uruguay. Remarkably, rainfall and,
272 consequently, soil moisture values have consistently remained below normal. For the 54 months during
273 this period, soil moisture remained below normal for 52 months, and below the climatological 25th
274 percentile for 23 months, based on the ERA5 reanalysis (Fig. 5a). The drought was accompanied by
275 exceptional heat (with 2023 being the warmest year on record for South America), as well as repeated
276 heatwaves in recent years. Climate change is reported to have played a significant role in the severity
277 and frequency of these (Rivera et al., 2023). The drought and heat exacerbated each other through land-
278 atmosphere feedbacks. Together, they also led to widespread wildfires in Brazil, Argentina, Paraguay,
279 and Bolivia in September, resulting in large impacts on agriculture, freshwater and energy supplies, with
280 states of emergency in many countries in the region (WMO, 2024). A 3% GDP reduction was recorded
281 in Argentina in 2023 alone (Toreti et al., 2023), while soybean production in Argentina fell by 44%
282 compared to the past five years (UN, 2023). The drought also forced the closure of Brazil's fourth largest
283 hydropower station, San Antonio. Waterway traffic in the La Plata Basin was also severely disrupted,
284 affecting more than 480,000 people (CMA, 2024b).

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

293 With the onset of El Niño since mid-2023, drought conditions started to develop over the Amazon
294 basin due to the subsidence linked to the downward branch of the Walker Cell (Marengo and Espinoza,
295 2016). However, during the exceptional drought of 2023, climate change acted as the main driver for the
296 low rainfall and high temperatures over the basin, resulting in the lowest river levels in the past 120 years
297 (Clarke et al., 2024).



298

299 **Fig. 5.** The drought conditions over South America (a), southwestern China (b), California (c), and the
 300 Horn of Africa (d). Blue curves indicate monthly precipitation anomalies (right axis; unit: mm/month).
 301 Bars indicate monthly soil moisture anomalies (left axis; unit: m^3/m^3), where brown, yellow and green
 302 shadings denote below the 10th percentile, negative anomalies, and positive anomalies, respectively.
 303 Anomalies are derived by subtracting monthly climatologies of 1991-2020. Data are from ERA5.

304

305 **4.2 Persistent drought in southwestern China from winter 2022 to spring 2023**

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

312 Droughts, themselves, in southwestern China are not actually very unusual in winter and spring due
 313 to the monsoon climate in the region. For the past decades, however, they have tended to become more
 314 frequent and severe (Ma et al. 2017; Liu et al., 2023). This latest one appears to have arisen from a
 315 combination of factors at a variety of scales, including the La Nina to El Nino shift, the westward
 316 extension of the western Pacific subtropical high, westerly jet anomalies, the tropical Madden-Julian
 317 oscillation and anomalous snow cover over the Tibetan Plateau (IAM, 2023; Wang et al., 2023b; Liu et
 318 al., 2023; Liu et al., 2022).

319 **4.3 Drought to flood transition in California in late winter and spring 2022/2023**

320 The southwestern US (principally California) has suffered from continuous drought since early 2020.
 321 For the consecutive 35 months during this drought, soil moisture remained below the climatological 25th
 322 percentile for 23 months, and below the climatological 10th percentile for 9 months, based on ERA5
 323 (Fig. 5c). The drought condition significantly eased from late winter 2022 onwards, with the arrival of a
 324 historic run of nine consecutive landfalling atmospheric rivers in three weeks' time (DeFlorio et al., 2024).
 325 Excessive precipitation was 72% above normal during December 2022 and March 2023 (based on ERA5;

326 Fig. 5c). As a result, drought extent in the US shrank from a maximum of 46% in January 2023 to a
327 minimum of 19% by May, the lowest since early 2020 (NOAA, 2023b). Recovery from the drought
328 though, has been fraught due to significant flooding induced by the storms, particularly in California
329 with over 700 landslides and 1400 rescues, and some fatalities (NOAA, 2023b).

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

334 Many studies suggest that anthropogenic climate change is increasing the risk and severity of
335 droughts in the southwest US due to increasing temperatures (Diffenbaugh et al., 2015; Williams et al.,
336 2015). Understanding of drought-to-flood transitions, though, is limited. As anthropogenic warming
337 continues, climate models project increases in the frequency of both wet and dry extremes over California,
338 accompanied by more dry-to-wet precipitation shifts (Swain et al., 2018). Such sequentially occurring
339 extremes are likely to produce greater impacts than if occurring alone, since droughts often produce soils
340 prone to greater runoff and flooding under heavy precipitation.

341 ***4.4 Drought to flood transition over the Horn of Africa in late October 2023***

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

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

354 Just months after the severe drought, the Horn of Africa was hit by an exceptionally wet rainy season
355 in October-December (OND) in 2023 (Fig. 5d). The extreme precipitation events in OND 2023 were the
356 strongest or second strongest on record since the 1980s depending on event lengths (Kimutai et al.,
357 2023a). Episodic heavy rains, despite easing the drought conditions to some extent, have led to extensive
358 flash floods due to high water runoff from extremely dry, hardened land following the prolonged drought.
359 The floods caused more than 300 reported deaths and displaced over a million people in Kenya and
360 Somalia alone (Kimutai et al., 2023a).

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

365 In summary, both the droughts and extreme wet season in the Horn of Africa appear to have been
366 exacerbated by anthropogenic climate warming, with additional modulation from internal climate

367 variability. Gaps in understanding of the events, and particularly the transition, however, require further
368 research.

369

370 **5. Sandstorms and wildfires**

371 ***5.1 Sandstorms in Mongolia in April 2023***

372 Mongolia and northwest China are arid regions, often prone to sandstorms, particularly after dry
373 winters (Han et al., 2021). Sand dust weather events were particularly frequent in 2023, with 17, the most
374 since 2011, of which 10 occurred in March and April (Yin et al., 2023). The most severe sandstorm lasted
375 5 days (April 9th to 13th) affecting large areas of northern China including Beijing, Tianjin, Xinjiang,
376 and Inner Mongolia, impacting an area of about 3.4 million square kilometers and more than 400 million
377 people. On April 10th, the PM10 concentration in Ulanqab, Inner Mongolia exceeded $7,000\mu\text{g}/\text{m}^3$, far
378 beyond the recommended air quality guideline 24-hour mean levels of $45\mu\text{g}/\text{m}^3$ established by the World
379 Health Organization. The sandstorm then propagated southward, passing through areas including Beijing
380 in northern China, Nanjing in eastern China, and Fuzhou in southern China, where the PM10
381 concentration surpassed $2000\mu\text{g}/\text{m}^3$, $1600\mu\text{g}/\text{m}^3$ and $400\mu\text{g}/\text{m}^3$, respectively (Yin et al., 2023). The
382 sandstorm even affected the Korean Peninsula and Japan. Roughly 40% and 25% of the dust came from
383 Mongolia and the Taklimakan Desert respectively (Chen et al., 2023; Piao et al., 2023).

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

388 ***5.2 Wildfire in Hawaii in August 2023***

389 On August 8th and 9th, the deadliest wildfire in the US for a century, devastated Hawaii's second
390 largest island, Maui (Juliano et al., 2024). According to NOAA's National Center for Environmental
391 Information, at least 100 people lost their lives, 2000 acres of land were burnt, 2200 structures were
392 destroyed, and losses of \$5.6 billion were incurred (Juliano et al., 2024). Fire risk at the time was greatly
393 enhanced by persistent rainfall deficits, in part due to the developing late-2023 El Nino but also strong
394 winds from a dipole between high pressure northeast of Maui, and a hurricane (Dora) to the south (Marris,
395 2023; Juliano et al., 2024).

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

400 ***5.3 Spring-to-autumn Canadian wildfires***

401 For Canada, 2023 was a year of historical, record-breaking wildfire activity. From March to October
402 of 2023, at least 6700 fires broke out across Canada, burning 18.5 million hectares, an area six times
403 greater than the 2013 to 2022 10-year average (You et al., 2023). The fires produced 1.5 billion tons of
404 CO_2 , equivalent to the total output from all the wildfires in Canada in the past 22 years and more than
405 double Canada's planned greenhouse gas emission reductions for the next 10 years (Wang et al., 2023c).

406 As in Hawaii, the fires were the result of a combination of drought and extreme heat, which Canda

407 experienced from May 2023 onwards. The disastrous 2023 wildfire season also appears to be part of a
408 long-term trend in the country, of increasing frequency and size of large fires over the past half century.
409 The wildfire season's length has also increased (Hanes et al., 2019).

410

411 **6. Perspectives**

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

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

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

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

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

444 To prepare better for climate hazards, there is a need for improved predictions, projections and early
445 warnings. As part of this, a UN initiative, Early Warnings for All, was recently launched, aiming to
446 provide world-wide early warning by 2027. This ambitious objective remains, however, particularly
447 challenging for regions short of resources, regions which are often also disproportionately affected by

448 extreme weather and climate events. According to the WMO, the death toll related to extreme weather
449 and climate events during 1970-2021 is at 2 million globally, with 90% in developing countries (WMO,
450 2023a). One significant challenge in improving early warning systems in some countries is the
451 availability of observations. Better observations in Rwanda and the Democratic Republic of Congo, for
452 example, where flooding caused almost 600 casualties in May 2023 (Kimutai et al., 2023c), may well
453 have enabled better warnings.

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

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

467

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Table 1. Major extreme precipitation events occurred in 2023

Region	Time	Factors	Severity and impacts	References
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 homeless.	WMO, 2023d NDMA of Australia, 2023
New Zealand	Jan 27-28, 2023 Feb 13-14, 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 hrs. 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	Feb 18-21, 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-hours rainfall in Mozambique exceeded 200 mm in Mar 12-15 period. Floods, landslides, winds and other disasters resulted in over 800 deaths and tens of thousands of people missing.	WMO, 2023d Liu et al., 2023 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 hours, 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	WMO, 2023d Zachariah et al., 2023c

			8500 people missing.	Oduoye et al. 2024
North China	Jul 29 to Aug 1, 2023	Tropical Cyclones Doksuri and Khanun	The maximum 72-hour 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