Warming in the Western Mediterranean Fuels Wetter European Storms and Heightens Extreme Flood Potential

Rapid Mediterranean warming brings extreme floods risks for Europe

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Abstract

The Mediterranean Sea is warming rapidly, with profound implications for regional hydroclimate extremes. The Gulf of Genoa, a critical source region for European storm systems, has exhibited a 1.17°C increase in sea surface temperature (SST) between 2010 and 2020. This study links accelerated SST warming to enhanced atmospheric moisture availability, suggesting a substantial increase in storm precipitable water and precipitation intensity. Intermittent marine heatwaves might further elevate storm total precipitable water (TPW), increasing the likelihood of extreme rainfall events. Projections indicate that, under current warming trajectories, storms originating from the Gulf of Genoa may contain up to twice the moisture content by 2040, substantially amplifying heavy rains across Europe. Such extreme rainfall events are a significant threat to European cities, potentially resulting in catastrophic flooding. These findings emphasize the emerging role of oceanic warming in modulating mid-latitude storm dynamics, provide a potential explanatory framework for recent catastrophic floods, and underscore the urgent need for revised hydrological models, expanded flood management strategies, and adaptive risk governance in a rapidly changing climate.

Introduction

In the last years, numerous heavy rains occurred all over the world. Both frequency and intensity of heavy precipitation events have increased since the 1950s (1) . Western Europe is among the fastest warming regions and experienced over 40 floods in 2024 (2). Unusual precipitation events caused more than 200 deaths in Valencia in 2024 and huge material damage. Losses increase fast and it's crucial to understand the progression to minimize future risks.

In Central Europe, some of the most devastating floods have been caused by moist air masses originating from the warming Mediterranean Sea. This region, particularly susceptible to rapid temperature increases, has lately experienced pronounced warming (3) (4). Moreover, the seasonal SST cycle has intensified over recent decades, producing stronger summer heatwaves (5). A small but critical region within the Mediterranean—the Gulf of Genoa—is a major hotspot for extreme weather generation. "Genoa lows" develop when cold continental air from the north collides with warm, moisture-laden air over the Mediterranean, a process amplified by the complex topography of the Alps and Apennines. These systems frequently produce intense precipitation, powerful winds, and significant flooding, thus playing a key role in driving extreme weather events across Central and Eastern Europe (6). Historical examples include the catastrophic 2002 European floods (7) triggered by two successive Genoa lows, as well as the August 2005 flood (8). Other Mediterranean-origin extreme events include the Cevenol rains (9) and recent medicanes, all capable of generating large-scale flood disasters (10). This work introduces a storyline of an extreme cyclone formed in the Mediterranean in the near global warming future. Given that the most intense storms are often the most destructive, this study focuses on the changes in the upper tail of the rainfall distribution—i.e., the most extreme events—with an emphasis on flood risk mitigation.

Global warming is causing escalating floods in many countries. The IPCC 2021 report suggested an increase of heavy rains around 7% per degree K) (1), based on the Clausius–Clapeyron relationship. However, numerous studies suggest that the actual intensification of extreme precipitation events exceeds this theoretical rate. While the atmosphere's water-holding capacity indeed rises by 7% per degree of warming, the impacts on storm systems are more pronounced. Zhang et al. highlighted that current climate models underestimate both the frequency and intensity of such extreme events (11). This suggests that some storm-intensifying mechanisms may still be absent from current climate models. Studies on tropical storms have shown precipitation increases between 13% and 17% per degree of warming (12). Notably, Hurricane Helene produced 50% more rainfall in some regions due to climate change effects (13). A long-term study by Zeder and Fischer analyzed precipitation data from nearly 1,000 European weather stations from 1900 to 2013, revealing that extreme precipitation events intensified by up to 13% in some regions, including the Swiss Prealps and Ticino (14) . Other investigations report that extreme rainfall in Northern Europe has increased by nearly 20% per degree of warming. In Norway, Konstali et al. documented a 19% rise in precipitation since 1900 (15). These findings indicate that with approximately 1 K of global warming already realized, extreme rainfall is escalating more rapidly than previously predicted, transforming formerly rare floods into increasingly common disasters. Understanding whether this trend will persist, and to what extent future precipitation and flooding risks will evolve, is essential for informed adaptation and resilience planning in European societies.

It is widely accepted that the intensification of extreme precipitation is primarily driven by increased atmospheric moisture near the surface, about 7% per 1 K of warming, according to the Clausius–Clapeyron principle (1). Warmer air retains more water vapor; however, the increase is not spatially uniform. Evaporation predominantly occurs over warm oceans, and several researchers argue that rising sea surface temperatures (SSTs) play a dominant role in the intensification of heavy rainfall associated with cyclones and hurricanes. James Hansen and others posit that elevated SSTs are a primary driver of stronger storms and more severe floods (16). Pastor and others have emphasized that specific marine zones, when anomalously warm, can act as storm intensifiers (17). Observational studies confirm that high SSTs correlate with enhanced storm intensity. For instance, a marine heatwave in 2023 over the Northwest European shelf, featuring SSTs 2.9 K above the climatological mean, resulted in a 23% increase in rainfall over the British Isles, equating to an approximate 8% increase per degree of SST anomaly (18).

Variations in precipitation intensity from intense extratropical cyclones (ECs) over the ocean can often be attributed to local differences in surface air temperature, which closely track SSTs. For the most powerful cyclones, precipitation rates rise by about 7% per degree of SST (19). Other reports, however, suggest simultaneous increases in storm size and precipitation, with rates approaching 20% per degree Celsius (20), (21). These studies collectively underscore the link between localized sea warming and amplified heavy rainfall.

This research examines recent SST trends in the Gulf of Genoa, estimates changes in total precipitable water (TPW) during summer marine heatwaves, and projects future risks of extreme rainfall under different warming scenarios.

Methods

Sea Surface Temperatures

This study investigates the potential intensification of extreme rainfall in Central Europe driven by marine heatwaves in the Gulf of Genoa. Increasing sea surface temperatures (SSTs) might influence total precipitable water (TPW) and ultimately enhance cyclone-related rainfall. Marine temperatures increase in the Gulf of Genoa was tracked in SST data from the Copernicus Marine Service (CMEMS) (22).

Sea-surface temperatures OSTIA dataset including daily worldwide measurements for years 2007-2024, was analyzed as follows: temperatures means and standard deviation were calculated for June, July and August (JJA) for the Mediterranean (5W, 36E, 30N, 46N), the Western Mediterranean (5W, 16E, 35N, 46N) and the Gulf of Genoa (7.9W, 9.8W, 43.78N, 44.4N). JJA period was chosen based on the IPCC report (1) to provide comparable results.

To robustly quantify sea warming, mean SSTs were calculated for two distinct periods: the first spanning the summers (June-July-August, JJA) from 2007 to 2013, and the second from 2016 to 2024. The period 2007 to 2013 is centered in 2010, so this mean is a multiyear-year solid based estimate of SST in 2010, minimizing yearly meteorological variability. The second mean, centered in year 2020, is a multiyear-based estimate of SST in 2020. The difference between the two values gives the the level of warming in the recent 10 years period and indicates the current speed of warming. All analyses were conducted using Python (23), and packages numpy (24), pandas (25), sciPy (26), copernicusmarine (27), and xarray (28). Results were plotted by OpenAI Data Analyst for figures 2 and 3 (29).

Cyclone TPW model

A cyclone TPW model has been generated by ChatGPT (30) and refined. The model integrates fundamental thermodynamic equations and empirical scaling relationships, and estimates structural dimensions and water content of cyclones based on air surface temperatures. The approach consists of two primary computational components: cyclone size estimation and water mass calculation.

Cyclone Size Estimation

Cyclone base area and height are calculated as a function of the surface air temperature. The model assumes that both the base area and height scale with absolute humidity, derived from the saturation vapor pressure at a given air temperature, assumed equal to SST. This approach uses the Clausius-Clapeyron relation to capture the exponential increase in atmospheric moisture with temperature.

Parameters:

- Base Area at 293.15 K: 100,000 km²

- Height at 293.15 K: 12 km

- Absolute Humidity at 293.15 K: 0.0148 kg/kg

Equations Used:

$$e_s = 6.112 \times \exp\left(\frac{17.67 \times T}{T + 243.5}\right) \quad (1)$$

$$q = \frac{0.622 \times e_s}{1013 - e_s} \quad (2)$$

$$A_{base} = 100{,}000 \times \left(\frac{q}{q_{20C}}\right) \quad (3)$$

$$H = 12 \times \sqrt{\left(\frac{q}{q_{20C}}\right)} \quad (4)$$

Total Water Mass Calculation:

To estimate the total water content of the cyclone, the model integrates moisture content across vertical layers within the structure, assuming a lapse rate and pressure gradient.

Parameters:

- Lapse Rate: 6.5 K per km
- Surface Pressure (P_0): 1013 hPa
- Scale Height (Hs): 8500 m
- Relative Humidity: 80% (assumed constant for saturation)
- Water Density: 1000 kg/m³

Vertical Integration Steps:

Cyclone's height is discretized into 500 m layers. The temperature profile is:

T_layer = T_surface - lapse_rate × altitude

Pressure was determined as P, (z = altitude).

$P = P_0 \times \exp(-z / Hs)$

Absolute humidity q for each layer is calculated as:

q_layer = 0.8 × (0.622 × e_s) / (P - e_s)

Air density at each altitude ρ as:

$\rho\_air = \rho\_air_0 \times (P / P_0) \times ((T(°C) + 273.15) / (T\_surface(°C) + 273.15))$

The sum the mass of water content across all layers gives the total water mass.

Air temperature was considered as equal to SST, It's rarely higher as the air warms the surface and increases evaporation till equilibration (Faranda D, Meteofrance, personal communication). This model merged recent information on storm size increase and precise TPW calculations based on absolute humidity at different air temperatures.

A simpler version of the model with constant size shows an increase of ca 6,9% per degree consistent with Clausius-Clapeyron relationship. The models ware used to calculate TPW at different temperatures and the increase ratio.

Results

Western Mediterranean SST Trends

This study calculated the summer (June–July–August, JJA) sea surface temperature (SST) trends in the Western Mediterranean and the Gulf of Genoa to evaluate their impact on storm-associated moisture.

Figure 1 illustrates the geographical domains used in the analysis, including the Western Mediterranean basin and a zoomed-in view of the Gulf of Genoa region. Monthly, seasonal, and robust mean SST values were computed, showing a clear and significant warming trend between the 2010 and 2020 periods (table 1). The Gulf of Genoa displayed particularly rapid warming.

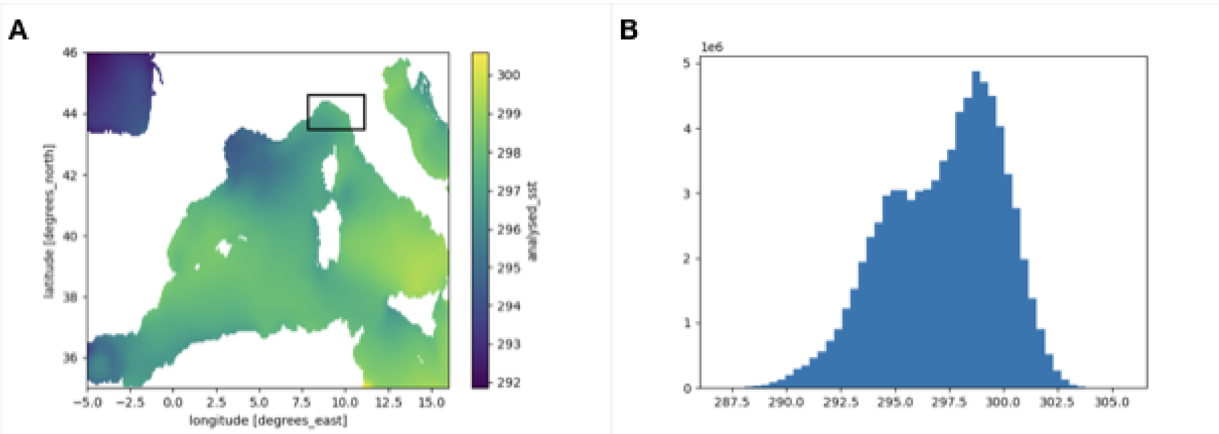

Fig. 1: a) Geographical map of Analyzed Western mediterranean region displaying the mean temperatures in the summer (JJA) in the period 2007-2024. The black rectangle indicates the Gulf of Genoa. b) Histogram of daily temperatures values (K) for JJA 2007-2024 in the Western Mediterranean. Mean (centered in 2015): 297.229K (24.08°C), standard deviation assuming normal distribution: 2.65.

Mediterranean temperatures increased strongly between the 2010 and 2020 periods. The Western Mediterranean experienced an SST increase of approximately 0.76 K during the summer. Initial calculations for August SSTs yielded a warming rate of 0.0831 K/year across the full Mediterranean basin. Further refined analysis, focusing on the Western Mediterranean and extending over all three summer months (JJA), gave a slightly lower but consistent rate of 0.076 K/year. Such temperature change was made possible by the basin's semi-enclosed geography and the broader warming trend observed across Western Europe. Historical estimates suggest a long-term warming rate of about 0.04 K/year across the Mediterranean between 1981 and 2020 (4). However, SST warming tends to be seasonally amplified in summer, with Liu et al. estimating a 1.8 K increase over 40 years, which would lead to a cumulated summer increase of ~0.065 K/year (5). The anomalous warming recorded in 2023 and the suspected recent warming acceleration also contribute to our slightly higher value.

Gulf of Genoa: A Regional Hotspot

The Gulf of Genoa, a region crucial for the formation of intense Mediterranean cyclones, was analyzed independently. This enclosed sub-basin displayed an even stronger summer SST increase: +1.17 K between the two decades under study. The findings are supported by Liu et al. (5), whose figure shows the Gulf of Genoa as a zone of maximal seasonal SST amplification. They show that the region could undergo a localized climatic shift within a relatively short timespan. The elevated SSTs in this confined region have significant implications for storm dynamics, moisture availability, and potentially the frequency and intensity of future flood events.

Table 1: Multiyear summer sea surface temperature (SST) trends in the Gulf of Genoa and the Western Mediterranean sea.

This table presents robust estimates of summer (June–August) SSTs based on daily measurements averaged over two multi-year periods: SST 2010 are the mean of indicated months from 2007 to 2013 and SST 2020 are the mean of indicated months from 2016 to 2024. The third column (increase) reports the difference in mean SSTs between the two periods, quantifying the warming trend. The fourth column provides the p-value from a Mann–Whitney U test assessing the statistical significance of the SST increase. Results confirm a highly significant warming of the Western Mediterranean, and show a particularly rapid and extreme SST rise in the Gulf of Genoa.

Sea region	**Month**	**SST 2010 (2007-2013)**	**SST 2020 (2016-2024)**	**Increase 2010 to 2020**	**Mann_Whitney (643 vs 828 daily means)**
Gulf of Genoa	**June**	294.47 K ***21.32°C***	295.48 K ***22.33°C***	+1,01	p < 0,0001****
	July	297.37 K ***24.22°C***	298.59 K ***25.44°C***	+1.22	p < 0,0001****
	August	298.04 K ***24.89°C***	299.32 K ***26.17°C***	+1.27	p < 0,0001****
	JJA	296.65 K ***23.50°C***	297.82 K ***24.67°C***	**+1.17**	p < 0,0001****
Western Mediterranean	**June**	294.39 K ***21.24°C***	295.16 K ***22.01°C***	+0.77	p < 0,0001 ****
	July	297.44 K ***24.29°C***	298.20 K ***25.05°C***	+0.76	p < 0,0001****
	August	298.49 K ***25.34°C***	299.24 K ***26.09°C***	+0.75	p < 0,0001****

Sea region	Month	SST 2010 (2007-2013)	SST 2020 (2016-2024)	Increase 2010 to 2020	Mann_Whitney (643 vs 828 daily means)
	JJA	296.80 K ***23.65°C***	297.56 K ***24.41°C***	**+0.76**	p < 0,0001****

Fig 2a and 2b illustrate the seasonal SST variation, with temperatures generally increasing through June and peaking in July or August. Additionally, Fig 2c and 2d show monthly mean temperatures progression over years. A fitted trend calculated based on daily means suggests an even more pronounced warming in recent years. However, the IPCC typically considers decadal means as the most reliable indicators of long-term climate trends, so this work is based on multiyear means for JJA.

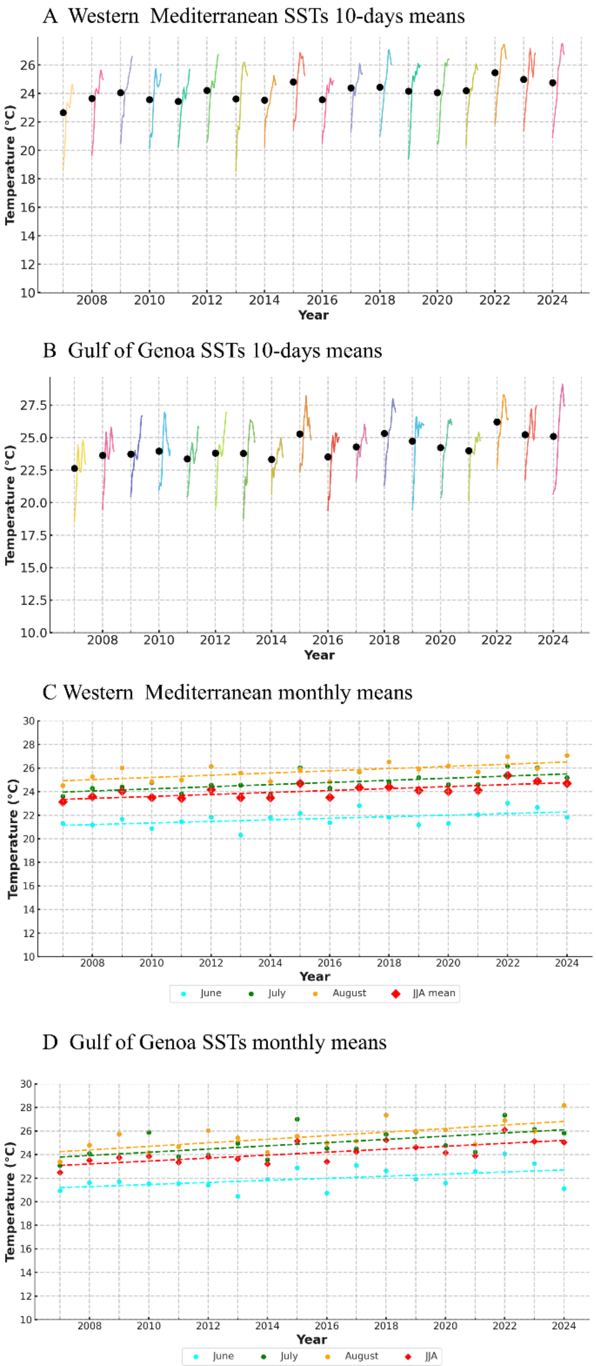

Fig 2: Smoothed SST over June, July and August for a) the Western Mediterranean and b) the Gulf of Genoa. Different colors indicate consecutive years. Colored lines are 10-days sliding means with 5-days overlap. The black dot is the JJA mean of each year. Temperatures increase during June and July and reach a peak end of July or in August.

Temperature monthly means of c) the Western Mediterranean SST and d) of the Gulf of Genoa SST in the months of June (blue), July (green), August (yellow) and the 3 months (JJA, red). Summer SSTs increase rapidly from 2007 to 2024. Increase is stronger in the Gulf of Genoa and might be stronger in the last 10 years. Increase trends (K/y or °C/y) shown with dashed lines for the period 2007-2024 are:

a) Western Mediterranean: June: +0.07, July: +0.09, August: +0.09, JJA: +0.08
b) b) Gulf of Genoa: June: +0.09, July: +0.14, August: +0.15, JJA: +0.13

for the period 2016-2024:

a) Western Mediterranean: June: +0.08, July: +0.17, August +0.18, JJA: +0.14
b) Gulf of Genoa: June: +0.09, July: +0.20, August: 0.22, JJA: +0.17.

Strong precipitation increase

The Gulf of Genoa plays a critical role in the formation of intense cyclonic systems that can cause widespread flooding in Central Europe. As this region undergoes rapid warming, the potential for more intense and moisture-laden storms increases a lot. Recent anomalous floods in Central Europe emphasize the need to investigate the upper bounds of flood risk. While existing infrastructure is adapted to average storms, extreme ones, with a return period of 100 years or more under 20th-century climatic conditions, cause important damage. This study aims to estimate how much such exceptional events could intensify by mid-century.

To do this, we first projected the potential upper-bound SSTs in the Gulf of Genoa under a constant-rate warming scenario. These SSTs correspond to marine heatwaves that could plausibly occur by 2040 if current warming trends continue. Using this projected SST data, we calculated the likely increase in total precipitable water (TPW) available to cyclones forming over the Gulf. The model assumes that TPW accumulates during storm development over the sea surface and that precipitation efficiency in a given region remains constant, and total moisture increase is 13-15% per degree. Other storm-enhancing meteorological variables, such as atmospheric instability, were treated as event probabilities, while sea surface temperatures defines the potential magnitude of future extreme cyclones.

Table 2 presents modeled SST projections under two probabilistic thresholds (10% and 1%) for extreme heatwave occurrence. By 2040, the Western Mediterranean is expected to reach a summer mean SST of 299.2 K (26 °C), with heatwaves potentially reaching 305.4 K (32.2 °C). For the Gulf of Genoa, projected average summer SST may rise to 301.6 K (28.4 °C), with extreme marine heatwaves peaking at 306.9 K (33.7 °C).

These SST levels imply a substantial increase in atmospheric moisture content, which in turn amplifies the TPW in cyclone systems forming over the region. Given that rainfall in such systems is closely tied to TPW, this would significantly raise the likelihood of catastrophic precipitation events over Central Europe. The implications are severe—not only for marine ecosystems under thermal stress but also for continental flood risk, which may exceed current protective standards by a high margin.

Table 2: Projected marine heatwave thresholds in the Western Mediterranean and Gulf of Genoa under continued warming trends.
This table contains expected future mean summer sea surface temperatures (SSTs) in the Western Mediterranean and the Gulf of Genoa, extrapolated under the assumption of constant local warming based on

recent trends (Expected Mean). Using these projected means and the current observed standard deviation, normal temperature distributions were modeled to estimate future extremes. The second column (orange; Temp P10) reports the SST threshold that will be exceeded in fewer than 10% of summer days (i.e. the 90th percentile). The third column (yellow; P1) identifies the SST threshold likely to be exceeded in fewer than 1% of summer days (i.e. the 99th percentile). The second half of the table replicates these calculations based on the higher warming rate observed in the Gulf of Genoa.

	Western Mediterranean			Gulf of Genoa		
Year	**Expected Mean K (°C)**	**Temp P10 K (°C)**	**Temp P1 K (°C)**	**Expected Mean K (°C)**	**Temp P10 K (°C)**	**Temp P1 K (°C)**
2025	**297.99 (24.84)**	301.45 (28.3)	304.25 (31.1)	**299.02 (25.87)**	301.95 (28.8)	304.25 (31.1)
2030	**298.37 (25.22)**	301.85 (28.7)	304.55 (31.4)	**299.87 (26.72)**	302.75 (29.6)	305.15 (32.0)
2035	**298.75 (25.6)**	302.15 (29.0)	304.95 (31.8)	**300.72 (27.57)**	303.65 (30.5)	305.95 (32.8)
2040	**299.13 (25.98)**	302.55 (29.4)	305.35 (32.2)	**301.57 (28.42)**	304.45 (31.3)	306.85 (33.7)
2045	**299.51 (26.36)**	302.95 (29.8)	305.75 (32.6)	**302.42 (29.27)**	305.35 (32.2)	307.65 (34.5)
2050	**299.89 (26.74)**	303.35 (30.2)	306.15 (33.0)	**303.27 (30.12)**	306.15 (33.0)	308.55 (35.4)

To estimate how warming sea surface temperatures (SSTs) may enhance storm moisture content, we modeled the increase in total precipitable water (TPW), with air temperature is equal to SST and that the relative humidity reaches 80% of absolute humidity. The model included a small area and height increase observed in recent storms in changing climate and TPW increased by 13 to 15% per degree.

Applying this model to observed warming in the Gulf of Genoa, where SSTs rose by 1.17°C between 2010 and 2020, we estimate that cyclones forming in that region now carry 16.35% more TPW compared to 2010. This change sheds light with some recent unusual events. Moreover, at constant Mediterranean warming, they might increase similarly within the following ten years period, potentially amplifying extreme precipitation in Central Europe.

Projected TPW Increase for 2025 and 2040 Events

Table 3 and Figure 3 summarize the modeled TPW increases for cyclones forming over the Gulf of Genoa under different SST scenarios. Values are presented as percentages relative to the TPW of a typical storm formed at the 2010 mean SST.

The temperatures of the Gulf of Genoa are the most relevant for storm formation. As consequence, in the year 2025, a moderate P10 heatwave (orange) could lead to double (197%) precipitations of a typical 2010 cyclones, and a rare P1 (yellow) heatwave could increase them by 262%. Under current local warming, cyclones formed in 2040 would contain 333% (P10, orange) or 447% (P1, yellow) of the water content of typical 2010 events.

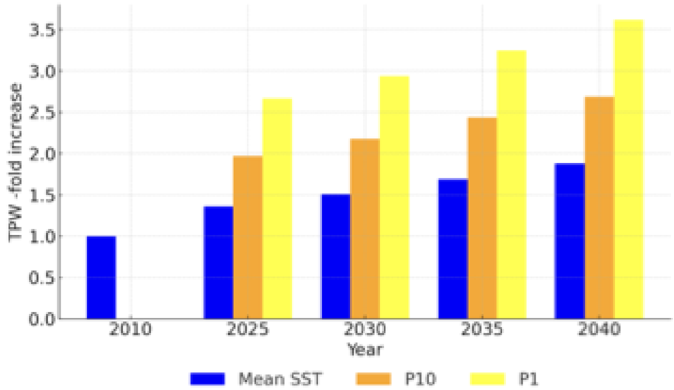

Fig 3: Increase in total precipitable water content of storms relative to baseline summer mean sea surface temperature (SST). This figure shows the total precipitable water (TPW increase in %) of storm systems formed at increasing SST. TPW values are shown for the calculated 90 percentile (P10, orange) and 99 percentiles (P1, yellow) tresholds at different timepoints compared to a baseline mean SST corresponding to the summer of 2010. TWP was calculated by the cyclone model assuming 13-15% increase per °K (see methods, table 3).

Table 3: Increase in total precipitable water content of storms relative to baseline summer mean sea surface temperature (SST), increasing at 13-15% per degree. Temp Mean column indicates the increasing summer SST mean projected from the 2010-2020 trend, Temp P10 is the temperature reached with 10% probability, P10 TPW % increase column shows the increase in moisture at that temperature, Temp P1 is the temperature reached with 1% probability, P1 TPW % increase column shows the ensuing increase in moisture. The change is calculated compared to a baseline mean SST corresponding to the summer of 2010. TWP was calculated by our cyclone model yielding 13-15% increase per °K (see methods). The results, based on a strong positive correlation between higher SSTs and air moisture content, yield a large intensification potential of storms in a warming Mediterranean climate.

	Western Mediterranean					Gulf of Genoa				
Year	**Temp Mean K (°C)**	**Temp P10 K (°C)**	**P10 TPW % Increase**	**Temp P1 K (°C)**	**P1 TPW % Increase**	**Mean K (°C)**	**Temp P10 K (°C)**	**P10 TPW % Increase**	**T P1 K (°C)**	**P1 TPW % Increase**
2025	**297.99 (24.84)**	301.5 (28.3)	181%	304.25 (31.1)	258%	**299.02 (25.87)**	28.8	197%	304.25 (31.1)	262%
2030	**298.37 (25.22)**	301.9 (28.7)	191%	304.55 (31.4)	268%	**299.87 (26.72)**	302.75 (29.6)	218%	305.15 (32.0)	294%
2035	**298.75 (25.6)**	302.15 (29.0)	198%	304.95 (31.8)	281%	**300.72 (27.57)**	303.65 (30.5)	244%	305.95 (32.8)	325%
2040	**299.13 (25.98)**	302.55 (29.4)	208%	305.35 (32.2)	296%	**301.57 (28.42)**	304.45 (31.3)	269%	306.85 (33.7)	362%
2045	**299.51 (26.36)**	302.95 (29.8)	219%	305.75 (32.6)	310%	**302.42 (29.27)**	305.35 (32.2)	301%	307.65 (34.5)	400%
2050	**299.89 (26.74)**	303.35 (30.2)	230%	306.15 (33.0)	326%	**303.27 (30.12)**	306.15 (33.0)	333%	308.55 (35.4)	447%

Table 4: Projected increase in cyclone moisture during marine heatwaves: comparison between 2007, 2025, and 2040. This table compares the total precipitable water (TPW) content of cyclones forming over the Gulf of Genoa during summers with increasing sea surface temperatures (SSTs), reflecting observed conditions in 2007 and linear trend-based projections for 2025 and 2040. The "Mean" column reports average summer SSTs for each respective year. « Temp P1 » indicates the temperature of a P1 (p 0.01) marine heatwave. « Cyclone P1 TPW » indicates the modeled TPW content of a cyclone (see Methods), while « Cyclone % Increase » shows the percentage increase in TPW relative to 2007 levels. For comparison, the final column presents the expected TPW increase of an air mass, assuming a 6.9% rise in moisture content per degree Kelvin of SST warming, as derived from the Clausius-Clapeyron relationship. The results underscore the potential for significantly more moisture-laden cyclones under future marine heatwave conditions.

Extreme storm in the year:	Mean K (°C)	Temp (P1) K (°C)	Cyclone P1 TWP	Cyclone % increase	Air mass % increase
2007	295.96 K (22.81°C)	301.15 K (28.0°C)	4.78 e12	100%	100%
2025	299.02 K (25.87°C)	304.25 K (31.1°C)	7.1 e12	149%	122.98%
2040	301.57 K (28.42°C)	306.85 K (33.7°C)	9.83 e12	206%	146.28%

Implications for Central Europe Flood Risk

Approximately two cyclones per month form over the Gulf of Genoa, often tracking across northern Italy, skirting the Alps, and moving into Central Europe—including Slovakia, Austria, Germany, and Switzerland. In Alpine regions, orographic lifting of warm, humid air produces high efficiency rainfall, amplifying flood potential. While most storms are moderate, this frequency implies that extreme storm impacts could strike Switzerland roughly once per decade, and other parts of Central Europe even more frequently.

Such extreme marine heatwave could give birth to storms carrying 360% TPW of a 'mean' Vb cyclone cyclone, formed at the mean 2010 temperature, and 206% of an extreme storm formed at 2007 temperature (table 4). As comparison with historical disasters, the 2005 flood in Switzerland, which caused ~300 mm of rainfall and inundated Lucerne (8), could cause double precipitations if a comparable event occurred in 2040 (fig 3). Simulations suggest that the rainfall potential of future events may far exceed anything currently anticipated in design standards.

The signs of warming and intensification are already visible in recent decades, including the 2002 (7) and 2005 events, but if trends persist, flood magnitudes could increase substantially before 2050.

Floods and consequences

An alternative and widely used approach to modeling future heavy rainfall events is based on the Clausius–Clapeyron relationship, which predicts an approximate 7% increase in atmospheric moisture per 1 °C of warming. Applying this principle to the air masses flowing from the Mediterranean into Central Europe, and considering observed regional warming trends, we estimate that total precipitable water (TPW) over Europe could increase by up to 50% by 2040. This alone could amplify the intensity of heavy rainfall events significantly. However, further intensification might occur due to atmospheric circulation changes.

Atmospheric blocking patterns—persistent high-pressure systems that trap cyclonic activity—can prolong rainfall events by slowing storm movement, thereby exacerbating flood potential.

Extreme convection, often triggered by surface and upper-air instability, might produce short-lived but highly intense cloudbursts, a key mechanism behind urban flash flooding and rapid river rise. In parallel, Atlantic cyclones could intensify similarly to Mediterranean ones. Additionally, "medicanes"—Mediterranean tropical-like cyclones might form more often over warmer sea in the next decades. These systems could later exhibit longer lifespans, stronger winds, and a northward shift in activity range.

Taken together, these multiple mechanisms of intensification suggest that flood risk in Europe may increase far beyond current projections. Notably, these compounding effects are not fully captured in most IPCC or national-level assessments, such as the CH2018 Swiss climate report (31). Therefore, the assumption that extreme rainfall events could double in intensity by 2040 is not only plausible—it is conservative in light of emerging evidence.

The implications for disaster management are profound. This level of intensification presents a credible risk threshold that must be integrated into national and regional evacuation, land-use planning, and infrastructure adaptation strategies. A tragic illustration of insufficient preparedness occurred in Libya in 2023, when Cyclone Daniel, a Mediterranean tropical cyclone, caused a catastrophic dam failure in Derna, killing over 13,000 people and displacing tens of thousands more.

In parallel, sea-level rise and saltwater intrusion threaten the stability of coastal infrastructure, drinking water, and ecosystems, adding yet another layer of vulnerability. Both hydro-meteorological extremes and gradual changes demand urgent and sustained investments in early warning systems, resilient urban design, and international coordination. Preparedness can save lives, but the window for action is narrowing. Integrating projected increases in flood extremes into policy frameworks is now essential.

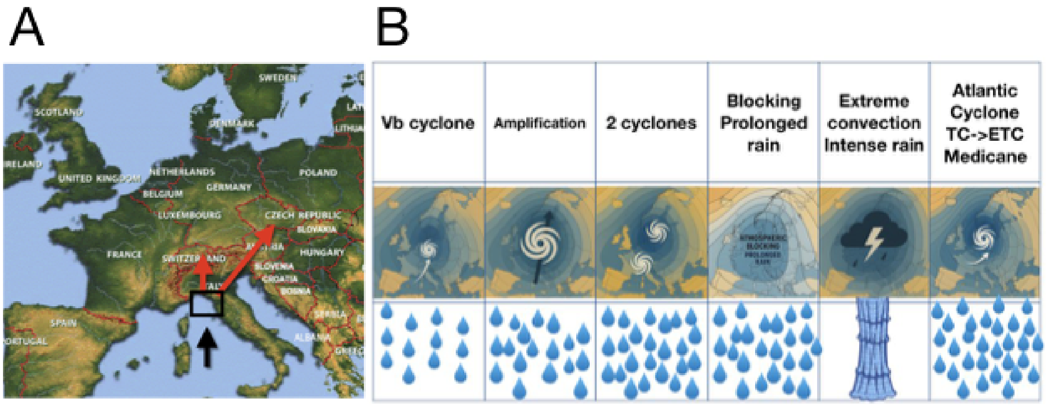

Fig 4: a) Europe map: Black arrow points to the Gulf of Genoa, the red arrows indicate frequent trajectories of cyclones formed in the Gulf of Genoa. b) Amplification risk factors: situations which might lead to increased precipitations under global warming. 20ieth century Vb cyclone; Amplification of a cyclone by global warming; 2 cyclones ; Blocking leading to prolonged rain; Extreme convection; Amplified Atlantic cyclone, tropical hurricane transition to extratropical, or a mediterranean hurricane called Medicane.

While most cities are resilient to occasional heavy rainfalls, a doubling of such precipitations causes floods. Water flows along the hills, merges in rivers, increases their flow several times and causes overflows. Further increase might lead to much more damaging floods.

This study provides rough estimates of future deluges tied to Gulf of Genoa warming and indicates that much heavier, potentially catastrophic rainfall could occur in Central Europe during the first half of the 21st century.

Discussion

Gulf of Genoa warming

The Western Mediterranean experienced rapid warming between 2010 and 2020, with the Gulf of Genoa, a key region for storm formation in Europe, warming even more rapidly, by 1.17 K over ten years. When focusing exclusively on recent years or the month of August, the warming trend appears even steeper. Minor discrepancies in reported values compared to other studies may arise due to variations in geographic coordinates and filtering criteria. Nevertheless, this study reports a significant warming trend in the Mediterranean, and particularly in the Gulf of Genoa.

Although regional warming was anticipated by IPCC climate projections, observational data now suggest an even faster rate. The IPCC Atlas, under SSP5–8.5, predicts an 8 K increase in August SSTs in the Mediterranean at 3°C global warming and a yearly warming of 0.048 K in June, and 0.02 K for July and August during the 2010–2020 period. This observational analysis finds stronger warming both regionally and for the full Mediterranean basin.

To remain conservative, this study uses multi-year trimestrial means to estimate warming rates. However, recent trends and August monthly means suggest an even more rapid acceleration. These real-world observations offer critical insights into ecosystem vulnerability and European weather extremes. Notably, observed ocean temperatures have outpaced climate model projections in recent years, consistent with reports of accelerated global warming. Hansen (32) documents this acceleration, and the World Meteorological Organization confirmed that Earth reached 1.55 °C of global warming in 2024 (33). Higher regional warming is part of the global trend, and real sea surface temperature measurements are a better, up-to-date estimation which includes all the latest climate system changes.

These shifts have serious consequences: summer marine heatwaves stress marine ecosystems, while elevated SSTs can fuel intensified storms over Europe. Warm, moisture-laden air from the Mediterranean flows north and, when lifted by the Alps, produces high precipitation efficiency, often resulting in extreme rainfall.

Though not the dominant weather pattern in Switzerland or Central Europe, Mediterranean-fed cyclones have historically caused some of the region's worst floods—including the 1868 flood (34) and the Lucerne flood of 2005 (8). With stronger warming, such events could intensify and potentially inundate entire cities. Several degree SST increases are possible in secluded parts of Mediterranean under continued local warming. These risks must be factored into disaster preparedness and adaptation strategies for exposed countries.

Where does the rain come from?

This study builds on the principle that storm total precipitable water (TPW) is primarily transported from its formation zone over the sea, based on Volosciuk model (35), which estimates that over 95% of TPW originates from the Mediterranean, with only 3–5% added over land. Trenberth and Hansen also underlined the importance of SSTs for strong storm formation. Khodayar et al. (36) showed that all HPEs within the northwestern Mediterranean form in periods and/or areas characterized by high IWV values, with the most intense events being those experiencing a more sudden increase.

Duffourg analyzed a single storm and concluded that precipitation over France originated at 40% from the Mediterranean, and at 40% from further South. The Mediterranean Sea is the main moisture source when anticyclonic conditions prevail during the last 3 or 4 days before the HPE (37). However, warm air masses forming cyclones might originate thousands of kilometers away. It complexifies the picture, and raises the possibilities of cyclones generated at higher SSTs, albeit less dependent on Mediterranean warming.

Both ERA5 and JRA-55 reanalyses show that TWP increased significantly by around 6 % /K over Europe for both ERA5 and JRA-55. On global scale, the increase per degree is slightly higher than 7% over the oceans, highest over the tropical oceans, and lower over the land. Climate models overestimate air humidity over arid regions, and yield a correct global mean, so they might underestimate the variability (38) and localized extremes. Combination of their result with Switzerland latest years' warming values of ca 2.8 K (Meteoswiss) suggests that local TPW increased by 16.8%, a mean consistent with calculated values.

Extreme events forecasts

The Swiss Climate Scenarios (31) and the IPCC under the high ca 4.5°C warming hypothesis (1) projects an increase of 20% (10-30%) of extreme precipitations by 2100. Unhappily IPCC flood estimates have already been exceeded in Europe (39) . Some of the discrepancy lies in the communication, extreme precipitations forecasts are often expressed as yearly events whereas decennial or centennal episodes cause the disasters. Moreover, models' results are sometimes yearly averages or trends which don't inform on single extreme meteorological events.

Besides, several parameters contribute to the difference. In the real world air moisture is distributed differently than modeled, there is more vapor over equatorial oceans, and less over arid lands and Europe, which experiences unpredicted drying. A recent study indicates that 82% of strongest precipitations is caused by large storms and their proportion is underestimated in the models, so extreme rains are underestimated (40). Warming also weakens the poleward temperature gradient, leading to a slower, wavier jet-stream which causes increased atmospheric blocking and longer duration of rains and heatwaves (41). Such changes can result in more persistent weather patterns, contributing to extreme events like prolonged heatwaves and cold spells.

Currently convective precipitation increase faster than the CC equation predicts (42). Higher moisture and updraft velocities, but also slower storm movement, might lead to future increase in precipitation extremes across Europe. Quasi-stationary intense rainstorms would generalize over Europe (43) (44) (45). Atmospheric unstable conditions have increased significantly over most land areas. Instability might grow further, which would lead to more convective storms (46). Some of the recent floods were caused by strong convection, large thunderstorms leading to very intense rains, made possible by high air moisture. This mechanism might trigger stronger rains per hour, which leads to pipes and rivers overflowing. Damaging weather events are often associated with extreme convective precipitation (47). Large thunderstorms also bring hail and other weather events. In our region, one such storm caused a city flood in 10 to 30 minutes of rain in Lausanne in 2018, another formed a rare tornado and a damaging downdraft (Chaux-de-Fonds 2023), and something unidentified broke 50 trees in Geneva in August 2020. Numerous new weather events hit the Earth.

Different analysis of climate model results focused on individual model outputs and identified a series of extreme events, exceeding known disasters by large margins, which will increasingly strike from 2020 (48) (49)**.** These calculations unravel risks of disasters much larger than we've ever seen, and some might be consistent with the Mediterranean extreme events scenarii developed in this study.

Heavy Mediterranean precipitations regularly impact Cevennes hills in France. They increase and reached 700 mm in 2024. Recent climate simulations also suggest that their range might increase. Future amplification is also found in Müller et al. (50) for all-year Mediterranean HPEs, in Purr et al. (51) for convective cells over Germany. Events with a 100-years return period, the rang of the largest historical events, could occur every 5 years. Precipitations increase varies between models, one of them suggests 500% higher precipitations at 4°C warming (52), so recent climate models analyses suggest extreme rain events similar to this study.

Floods

Two of the most devastating floods in recent Central European history were linked to Mediterranean Vb cyclones: the August 2002 and August 2005 events. In 2002, a Vb cyclone formed over the Gulf of Genoa, tracking northeastward and bringing torrential rainfall to the Austrian Alps, Germany, and the Czech Republic. The Czech capital, Prague, experienced catastrophic flooding (Fig. 5a–b). Over 200,000 people were evacuated, and widespread infrastructure damage took months to repair. The event delivered 354 mm of rainfall, caused €15 billion in economic losses, destroyed more than 180 bridges in Germany (53), and damaged over 10,000 homes (54).

The 2005 flood impacted Romania, Switzerland, Austria, and Germany, resulting in 42 fatalities. In the Alps, rainfall approached 300 mm, damaging thousands of homes (55). Heavy rains in the mountains often cause destructive landslides. In Switzerland, it was considered the most destructive flood in modern history, causing €3 billion insured damage (8). Like the 2002 event, it was driven by a Vb cyclone. Similarly, the historic 1868 flood (34), Switzerland's most severe, was triggered by back-to-back cyclones combined with warm Mediterranean air. Far from being isolated events, they might be part of an ongoing, fast-increasing change, bringing the danger of even larger floods in the next years. Rains changes resulting from sea warming should be refined as fast as possible.

Fig 5: a), b) 2002 Floods in Prague, Czech Republic. c) 2005 Flood in Lucern, Switzerland, d) 2005 Mudflow after 2005 heavy rain in the Swiss mountains.

The study is based on a linear warming hypothesis for the Mediterranean. While actual trends may vary due to atmospheric dynamics, accelerated global warming may drive even faster changes. James Hansen (32) suggests that the rate of global warming increased in 2010, now reaching about 0.27 °C per decade. StefanRahmstorf (in press) reports a further acceleration since 2015, with rates rising to 0.4 °C per decade.

This analysis is grounded in observational SST trends and already captures the effects of recent climate acceleration, as described by Hansen and Rahmstorf. The higher values observed in this study may reflect these intensified global and regional trends.

Outlook

Emitted carbon dioxide remains in the atmosphere for a century. So the greenhouse effect will continue until a global shift to renewable energy is completed. Although this transition is happening, the most optimistic pathways in the UNEP Emissions Gap Report 2024 (56) (summarized in Table 5) project global temperatures will continue to rise, reaching 1.5–1.6°C by mid-century before stabilizing or slightly declining under deep decarbonization (e.g., UNEP 1.5°C, IPCC AR6 C1a (1)). Smaller reductions lead to warming of 1.8°C (UNEP 1.8°C), while insufficient action could result in a 2°C increase or more (UNEP <2°C, IPCC C3a). In any scenario, warming continues for at least two decades, ushering in a period of heightened meteorological extremes. Current national pledges (NDCs) (57) might lead to a 2.8°C trajectory. High-emission scenarios like SSP3-7.0 (58) or RCP 8.5 (59) lead to stronger warming by 2100.

Table 5. Climate change scenarios: Global temperature projections and underlying scenarios for 2040, 2050 and 2100.

		Global warming by :		
Scenarios	**Scenarios storylines, main events**	**2040**	**2050**	**2100**
UNEP 1.5°C	Strong emission reductions reach 7.5% per year, major deployment of renewable energy, and some carbon dioxide removal. Earth temperature rises for ~20 years, then stabilizes and slowly falls.	+1.55°C	+1.55°C	+1.2°C
UNEP 1.8°C	Moderate to high emissions reductions. Temperature rises for ~30 years, then plateaus and slowly declines.	+1.65°C	+1.7°C	+1.6°C
UNEP below 2°C	Moderate emission reductions	+1.75°C	+2°C	+1.6°C
NDCs nationally determined contributions	Emission reductions currently committed by countries governments at the COP conferences		+2°C	+2.8°C
SSP3-7.0	This scenario pictures sustained strong CO2 emissions, and estimates temperature rise to 1.5 (up to 1.8°C) in 2040 (1). Sustained high CO_2 emissions with delayed or absent mitigation; projected warming from 1.5°C to 1.8°C by 2040.	+1.8°C	+2.1°C	+3°C
RCP 8.5	The RCP 8.5 scenario, the strongest scenario of 'business as usual' didn't include energy transition, but sustained carbon emissions and strong warming.	+2.1°C	+2.5°C	+4.5°C
Hansen 2023	Constant carbon emissions and rapid temperature increase.	+2°C	+2.5°C	3-4.5°C

		Global warming by :		
Scenarios	**Scenarios storylines, main events**	**2040**	**2050**	**2100**
F Shakhova (feedbacks based on Shakhova)	In addition to constant carbon emission and rapid temperature increase, climate feedbacks turn on and add to global warming. Permafrost emits methane (60), (61).	>2°C	2.5°C	+6°C
Feedbacks McPherson (feedbacks based on McPherson)	Loss of Amazonia and other ecosystems, then permafrost feedback, ocean heat (62).	3°C	4,5°C	5-10°C
WMO May 29th, 2025	World Meteorological Organization State of the Climate suggests the World might cross 1.5°C in the years 2025-2029.	2°C	>2°C	?

Large efforts in climate change mitigation have been undertaken, in several cities and companies solar panels have been ordered, will be installed and lower carbon emissions in the next years. These initiatives made the unconstrained emissions RCP 8.5 scenario less likely, however some scientists claim that global warming progresses now as fast as this scenario estimated.

Scientific observations by Hansen (32), Rahmstorf (in press) and WMO (33) now indicate a possible acceleration in global warming. Hansen's 2023 projections estimated 2°C warming by 2040, a threshold quickly surpassed. Notably, in 2023, Earth's cloud cover declined, hinting at a possible cloud–warming feedback (63). Further feedbacks — permafrost melt (60), ecosystem collapse (62), ocean stratification, or cloud changes (63) — could drive non-linear warming, especially beyond 1.5°C. Early 2025 ScholarGPT estimated the likelihood of permafrost melt feedback to approximatly 30% (64). This implies that all Earth warming values over 2°C are highly uncertain.

On May 28th, 2025, the World Meteorological Organization issued an update on current warming. Based on recent observations, near-surface temperature for each year between 2025 and 2029 is predicted to be between 1.2°C and 1.9°C higher than the average over the years 1850-1900. The average of the next five years will probably exceed 1.5°C (33).

Scenarios listed in table 5 mostly reflect the effects of emission reductions. Strong and rapid carbon emissions could keep Earth in the safe range, or allow the Planet to get back into the safe range in the 21st century. Middle scenarios seem to lead to slow global warming throughout the century. RCP 8.5 scenario elaborated on unconstrained carbon emissions which led to warming in the 2°C range in 2040. These forecasts stem from CMIP6 model ensembles, assuming moderate Earth climate sensitivity. Shakova and McPherson alternative hypotheses include positive feedbacks. The climate system might have positive amplifying feedbacks which might lead to a very high, uncertain and unstable warming levels. Observational scenarii, including Hansen's analysis of Earth's energy imbalance, suggest stronger responses compared to the IPCC calculations, possibly breaching 2°C by 2040.

As every 0.1°C of warming heightens the frequency and severity of extreme events, these changes carry major implications. According to the IPCC, 2°C of warming could double the frequency of floods and make rare heatwaves ten times more likely. Such hazards also threaten food systems and social organization (1).

Studies of de Vries, Fischer and Knutti (48) (49) focus on extreme events exceeding known events by large margins. They describe the occurence of huge disasters such as the 2021 flood in Germany and Belgium, which washed away part of a village in an unusual landslide, causing over hundred casualties. Fischer estimates from the current climate models that catastrophes of that scale will increasingly strike from 2020 and that around 2°C warming we'll have a 20% probability of huge calamities each year. They established that a 1000-year event is now a 40-year event, and that records will be shattered by several degrees, in individual huge events.

Centennal flood occurrences extracted from de Vries et al (48) by Scholar GPT suggest 9 centennal flood events in the years 2020-2029 (+1.6-1.82°C) and 6 in the years 2030-2039 (+1.9-2.1°C). The described change would lead to 15 centennal floods in the century, which would mean a 15-fold increase, and their strongest disaster exceeds by 39% the centennal flood precipitations.

This work estimates that higher SSTs of a rapidly warming Mediterranean Sea might overload cyclones with water, lead to a 13% increase per degree, and cause approximately double rain of extreme, rare, events such as 2002 and 2005 in the year 2040. It would lead to extreme floods in central Europe, events of similar scale to the ones described by de Vries et al (48), but not included in current climate models, so they should be added to future risks estimations.

Artificial Intelligence ScholarGPT suggested in June 2025 that Mediterranean warming by one degree would lead to a 5-15% increase of related heavy rains in Central Europe.

Kevin Trenberth (personnal communication) estimates from recent events that extreme rains increase up to 30% per degree global warming. According to him precipitations might increase by 7% per degree from increased moisture, 7% from increased intensity, 7% from increased size, and another 7% from increased duration. These risks scenarios are summarized in table 6.

Warming level	**Risk analysis**	**IPCC: IPCC report 2021 CMIP6 (1)**	**EE: (44) Extreme Events from CMIP6 Models**	**MC: Mediterranean cyclones (this study)**	**KT: Kevin Trenberth expert opinion**
2°C		Floods 4 times more frequent	39% increase in precipitations and stronger occurence of heavy rains, 6-9 centennal floods per 10 years	2040 (estimated 2°C) 100% increase TWP in large Mediterranean cyclones	30% per °C, 60% at 2°C
	Frequency	High	Medium	low	low
	Severity	Medium	High	very high	very high
	Risk	Medium	High	high	high

	Low		Medium		High		Very high	Risk level

Table 6: Extreme events risks: this table describes extreme event risks based on the IPCC report, de Vries, et al 2023 paper on extreme events and continuous Mediterranean warming projections of this study. Low risk describes no casualties and limited material damage, medium risk includes isolated casualties and limited material damage, high risk includes several casualties, important material damage and infrastructure damage, and very high risk level stands for mass casualties and city-scale destruction.

At 3°C warming, detailed flood projections are scarce, but outcomes could be extreme. The weather events might be huge such as a 60°C, or unexpected heatwave, widespread tornadoes, or a whole-city flood. Such extreme events, might lead to millions of deaths unless they're predicted and prepared. Moisture would keep increasing in the atmosphere at 7% per degree warming, but Earth climate might change a lot. CMIP6 Climate models suggest a drier central Europe, yet will probably change with the use of recent convection permitting models (52) (44). Besides, warming over 2°C might trigger climate feedbacks. Such level of warming includes widespread risks for our civilisation and entire populations, and higher warming would be a planetary disaster.

This study is based on observations of the real ongoing warming of the Mediterranean, describes current rapid changes and extrapolates future Mediterranean cyclones. It suggests rapidly evolving risks, especially for cyclone-driven precipitation, summarized in table 6. Minor floods can be mitigated through urban adaptation. However, severe floods, reaching building upper floors, causing landslides, or destroying entire villages, require evacuation planning and large-scale engineering solutions. The IPCC (1) anticipates more frequent European floods. De Vries (48) predicts multiple centennial floods in the coming decades. This study proposes even larger cyclonic floods, underscoring the urgency of updating risk frameworks.

Table 7: Risks of extreme events together with their time of occurence according to several climate and emission reductions (see table 5). The thin line yellow-orange-red line for each scenario shows the temperature progression estimated for the pathway, colors indicate temperatures, and the gray shades indicate the risks associated with this temperature. Risk color code, as table 6: IPCC (1), EE: extreme events (48), MC: Mediterranean Cyclones in this study, KT: Kevin Trenberth expert opinion.

Table 7 shows risks of extreme events rise according to different carbon emission scenarios. The table includes global warming pathways calculated with medium sensitivity CMIP6 climate models ensembles by the IPCC, and recent observations compiled by the WMO (33) and projections by James Hansen (32). If warming is maintained below 1.6°C, risks are low or moderate, and the high and very high risk events might be avoided. If warming reached 1.8°C, Earth would face many years, around half a century of high flood risks, with important evacuation requirements and large destruction costs. If global warming nears 3°C, we're exposed to catastrophic risks, the Planet might face floods in very large areas, or raging rivers making evacuations and sheltering difficult, leading to widespread devastation and casualties.

It appears now that global warming moves forward faster than suggested by the CMIP6 models. It might be due to a higher climate sensitivity or to the onset of positive feedbacks which would lead to non-linear increases of global warming. Their extent and pace are difficult to calculate, so they weren't included in the last IPCC report (1). In the year 2023, drought and fire strained vegetation absorbed less carbon, low-level clouds reduced on the planet, and there are concerns about crossing climate tipping points which would further destabilize

Earth climate (63). Recent data — from WMO (33) and Hansen (32)— indicate that warming may exceed expectations. This acceleration could be driven by high Earth system sensitivity or emerging feedback loops, so warming might accelerate. Given this, climate risks, particularly from floods, are not distant threats. They may materialize in the coming years.

It clearly demonstrates that we're exposed to much larger climate risks and these catastrophic events might occur sooner, even in the next years. Several European programs have started studying tipping points risks (TIPMIP, TipESM, ClimTip (65)). Future warming might be faster than predicted, and it's really difficult to make further projections. New weather events could also appear in the next years. Anyway, it seems unlikely that Earth temperatures would go down if the greenhouse gases increase, they'll rather climb. The rapid pace of global warming brings high and catastrophic flood risks much closer. We're already at risk of previously unknown calamities, which would rapidly to lead to the destruction of current global economics. On the other hand, only high level of organization can ensure evacuations and food supply for the populations in the beginning era of disasters. Risks are enormous. Of course, many well described solutions exist and need to be immediately applied. They'll allow the World to move upwards in the scenarios and risks table and reduce climate-related risks.

Conclusion

Flood risks across Central Europe are intensifying under ongoing climate change. This study demonstrates that global warming drives pronounced regional and mesoscale changes, with significant implications for extreme weather events. Focusing on the Western Mediterranean, particularly the Gulf of Genoa, a key source region for Central European storm systems, this work identifies rapid summer sea surface temperature (SST) increases. Modeling results indicate that continued warming of this region substantially might enhance storm total precipitable water (TPW), projecting a potential doubling of precipitation relative to the catastrophic 2005 flood events by mid-century. These findings suggest that storms could deliver unprecedented rainfall volumes, dramatically escalating flood risks across Central Europe. Moreover, recent shifts in atmospheric circulation patterns may further compound these hazards. The results underscore the urgent need for improved flood risk modeling and adaptation strategies to mitigate the escalating threat of extreme hydro-meteorological events.

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