



OPEN A cul-de-sac effect makes Emilia-Romagna more prone to floods in a changing climate

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The disastrous flood of May 2023 in Emilia-Romagna, Italy, displaced thousands of residents and had severe impacts on the economy, with extensive damage to infrastructure—roads, buildings, bridges—and losses in agriculture and livestock. The flood was caused by two consecutive precipitation events, during which no hourly rainfall extremes were recorded, but for which accumulated rainfall over several days produced nonetheless extreme flooding, with a return period of over 500 years. The persistent, long-lasting precipitation was fueled by an uninterrupted vertically integrated water flux from the Adriatic Sea over the Po Valley, driven by a cyclonic circulation over Italy that remained stationary for several days. A “cul-de-sac” effect, due to mountains that blocked moisture fluxes from the Adriatic Sea, amplified rainfall and was a root cause of the disaster. In this study, we analyze the dynamics of this case study in the context of the large-scale atmospheric circulation, focusing on the role of the stationary cyclonic structure over Italy, a feature that also characterized a similar event over the same area in 2024. Furthermore, by examining the frequency of stationary cyclones in the Mediterranean region over recent decades, we are able to suggest that the persistent, dangerous configuration observed during the 2023 and 2024 events should be of concern to other Mediterranean areas that share similar conditions. A preliminary analysis also suggests that this class of events may become more frequent in a changing climate with important implications for the early warning systems.

One of the most common causes of floods is extreme precipitation. Several studies have argued that climate change is expected to increase the frequency of heavy rainfall events, which could in turn lead to more frequent and intense flooding. In fact, heavy precipitation events are generally expected to increase more than mean precipitation under a warmer climate, which is consistent with the higher capacity of warmer air to hold moisture^{1–3}. This is also reflected in a larger portion of the Earth projected to experience increases in heavy precipitation under global warming, compared to mean precipitation². However, flood risk is influenced by multiple factors, including soil moisture, land use, and runoff sensitivity to sea level, making it difficult to link changes in extreme precipitation to flood occurrence⁴.

The identification of moisture sources has been the focus of numerous studies^{5–9}, contributing to a deeper understanding of the functioning of the hydrological cycle in different regions of the planet and providing insights into the role of synoptic-scale systems, such as atmospheric rivers and low-level jets. In this work we focus on a class of events in which the transport of moisture plays a crucial role in shaping precipitation patterns and, therefore, extreme flooding events. We do so by examining the case of the 2023 Emilia-Romagna flood in Italy. In that instance there was no hourly extreme rainfall, but prolonged and continuous rainfall over several days. It caused one of Italy's most devastating floods in recent history, leading to over 36,000 displacements, 15 fatalities, and estimated damages of EUR 8.8 billion to infrastructure, water bodies, and ecosystems¹⁰.

In recent years, concern about extreme precipitation events and their role in extreme flooding has grown across Europe, and particularly in the Mediterranean region. As oceans and landmasses warm, the relationship between evaporation, moisture transport, and precipitation is expected to evolve¹¹. Enhanced moisture convergence, combined with the greater moisture-holding capacity of a warmer atmosphere, can support heavy rainfall³. That, in turn can be further enhanced by horizontal moisture fluxes, which tend to scale with the Clausius–Clapeyron relationship^{1,12}. In our case study we identify a set of conditions, involving both moisture advection by stationary cyclones and local orography, that appear to increase the severity of flooding. A preliminary analysis of such conditions across the Mediterranean region suggests the existence of a class of locations vulnerable to this type of event. We believe that a better understanding of the drivers behind these events can lead to improved prediction and preparedness¹³.

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Results and discussion

Process description

The flood of May 2023 was characterized by significant rainfall. Some locations experienced return periods exceeding 500 years¹⁴. Yet, the flood was not strictly by a short-lived heavy rainfall event. It therefore cannot be directly attributed solely to the larger moisture-holding capacity of an increasingly warmer atmosphere. Interestingly, and despite the low probabilities involved in such an event, a very similar flooding extreme happened again in the same area just a year later, in September 2024. This second flooding event was slightly less intense, but it exhibited comparable driving circulation patterns. We use historical data to investigate the primary meteorological mechanisms underlying such events and to assess potential links to climate change.

The 2023 flood event was characterized by two prolonged precipitation episodes: the first on 1–3 May, and the second on 15–17 May. Notably, another event—less intense but still exceeding 30 mm/day—occurred on 10 May. Panel a) of Fig. 1 shows a time series of precipitation over a 60 × 60 km domain centered on Forlì—one of the most affected towns in Emilia-Romagna. The red line is based on the ERA5 reanalysis. The blue line is based on ARPAE—*Archivio Climatologico per l'Italia centro-Settentrionale*, a high-resolution observational dataset (see Methods section). Despite the well-known limitations of ERA5 in representing local precipitation patterns in certain terrain conditions, the present case study was accurately captured by ERA5 in terms of both timing and magnitude when compared to the higher-resolution ARPAE dataset. Vertically integrated water vapor content is shown in magenta, while the vertically integrated horizontal water vapor convergence is in black. Both are derived from ERA5. The water vapor content (magenta solid line panel a, Fig. 1) exceeds the regional daily median (central magenta dashed line panel a, Fig. 1), yet precipitation is primarily associated with the vertically integrated horizontal water vapor convergence (black line, panel a, Fig. 1). Indeed, horizontal moisture convergence over the region, illustrated in the hourly time series centered on the events in Fig. 1, panels b and c), preceded the onset of precipitation by several hours.

Both precipitation events in May were associated with a cyclonic circulation, centered between central Italy and Corsica, which remained stationary for an extended period due to blocking subtropical anticyclones. To illustrate the temporal evolution of key meteorological fields we focus on the event of 1–3 May, but that of 15–17 May was similar¹⁴. The cyclone drew moist air from the Adriatic Sea and began impacting eastern Emilia-Romagna on 1 May, as evidenced by the vertically integrated water vapor convergence (Fig. 2, upper left panel). As seen in the timeseries analysis, the spatial patterns of water vapor convergence (left panels) over Emilia-Romagna also precede those of precipitation (right panels). The magnitude of this convergence was driven by sustained southeastward horizontal water vapor transport, visualized by black arrows in Fig. 2 (left panels), advecting moisture into the region.

Crucially, this process was enhanced by the orographic barrier of the Apennines¹⁴. In fact the Po Valley and its adjacent areas represent a semi-closed geographical basin that is open only to south-easterly winds, specifically those generated by stationary cyclones centered in the Gulf of Genoa or, more generally, on the lee (southern) side of the Alps. This particular configuration is also the reason why the term *cul-de-sac* was introduced. Indeed, no hourly precipitation extremes were recorded during the 36-hour event, while persistent moist air advection was maintained by the quasi-stationary cyclone over central Italy. Rainfall was moderate to intense—ranging between 3 and 20 mm/h—but not extreme, and Convective Available Potential Energy (CAPE) was relatively low (not shown), indicating only weak instability and limited convective potential. However, the presence of an orographic barrier promoted moist air uplift and intensified rainfall via adiabatic cooling. This was sufficient to support sustained precipitation over the region¹⁴.

In summary, we can conclude that the extraordinary accumulation of rainfall associated to the Emilia-Romagna flood can be attributed to the combination of two main conditions: cyclone persistence which leads to sustained vertically integrated moisture flux and orographic features that enhance moisture convergence.

Historical tendency in cyclone density persistence

Based on the synoptic analysis and moisture transport mechanisms described above, it is clear that the events that occurred in May 2023 and May 2024 (not shown) share these key features: the stationary position of a cyclone near central Italy and an associated, prolonged vertically integrated moisture flux toward regions with enhancing orographic features conducive to flow convergence. These conditions, found in Emilia-Romagna, have led to extreme rainfall totals, even in the absence of deep convection or hourly precipitation extremes. The next logical question is to ask whether such conditions are becoming more frequent due to a changing climate and where else in the Mediterranean might we find them.

To explore this, we examined long-term changes in Mediterranean cyclone density persistence by analyzing cyclone track data provided by Flaounas et al.¹⁵, a data set in which the importance of cyclone tracking methods for representing cyclone genesis and trajectories is evaluated. The results by Flaounas et al.¹⁵, confirm that cyclones predominantly occur over maritime areas, particularly near the Gulf of Genoa, the Italian Peninsula, and the Adriatic and Ionian Seas. Genoa cyclones, after having persisted near their genesis area, tend to slowly move eastward and southeastward toward Greece and the Balkans, where they typically undergo gradual filling. Other regions with high cyclone density include northwestern Africa, areas near the Atlas Mountains, the Turkish coasts, and the eastern side of the Black Sea. We introduce here an objective metric—the Cyclone Density Persistence (CDP) index—to assess which areas of the Mediterranean are most prone to stationary cyclones:

$$CDP = ACD \times CP.$$

where ACD is annual cyclone density and CP is cyclone persistence. ACD is measured in [number of cyclones] and CP in [days/cyclone], then CDP is measured in [days]. This index was computed over 3° × 3° grid cells and

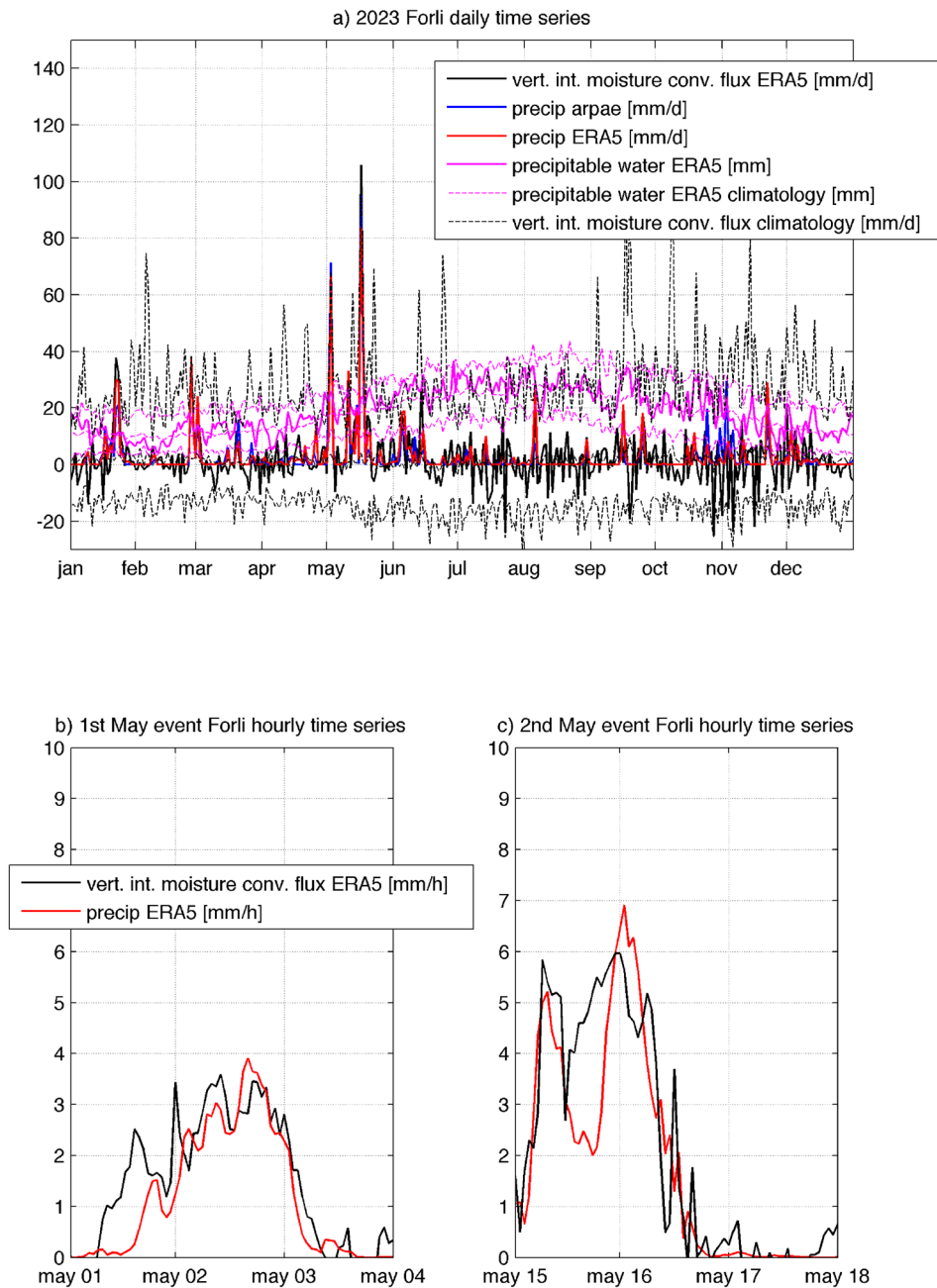


Fig. 1. Time series of quantities averaged in a box of 60 × 60 km centered over Forlì town. Panel (a) shows daily time series during the 2023 year for ERA5 vertically integrated moisture convergence (black), ARPAE precipitation (blue, 5 km resolution), ERA5 precipitation (red, 25 km resolution), ERA5 precipitable water (magenta). Dashed lines represent minimum, mean and maximum climatological values. Panels (b) and (c) show hourly time series of vertically integrated moisture convergence (black) and ERA5 precipitation (red) during the first and the second phases of the flood event of May 2023.

averaged over the 1979–2020 period (see Methods). Figure 3a reveals that the Italian Peninsula, along with the Tyrrhenian and Ionian Seas, exhibits the highest levels of cyclone activity (highlighted with blue rectangles). Lower activity is observed in the southern Mediterranean. Furthermore, an analysis of the temporal evolution of the CDP index (Fig. 3b) reveals higher values of the index in the 2000–2020 period relative to 1979–1999, especially over the Tyrrhenian, Ionian, and Balearic Seas (blue rectangles).

This spatial pattern suggests that there are some regions partially enclosed by orographic features that are likely to become more prone to experiencing prolonged water vapor advection associated with stationary or slow-moving cyclones. Such terrain is likely to confine moisture advection associated with the cyclone's circulation, enhancing convergence that can persist over multiple days. Emilia-Romagna emerges as a hotspot for this mechanism, alongside other coastal areas of Albania as shown in Fig. 4, where the composite of vertically

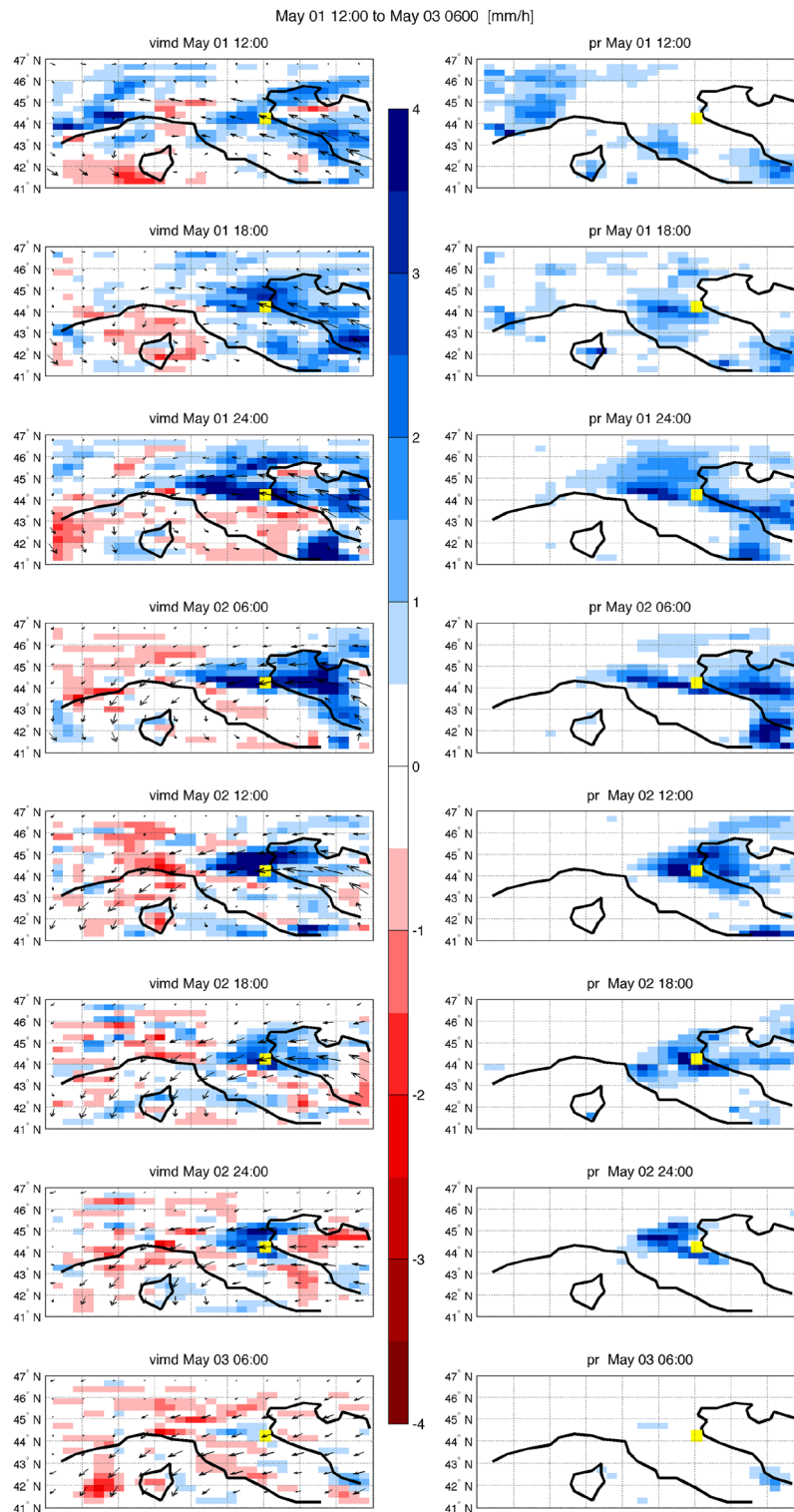


Fig. 2. Time evolution (from May 01, 12:00 to May 03, 00:00) of the vertically integrated moisture convergence flux (color patterns in left panels) together with vertically integrated water transport direction (black arrows in left panels) and precipitation (right panels) also from ERA5. The yellow square indicates Forlì location. Units are [mm/h].

integrated moisture convergence flux—associated to persistent (more than two days) cyclones over central Italy—is shown in terms of differences between 2000 and 2020 and 1979–1999 (Fig. 4, panel a) together with the orographic features (Fig. 4, panel b). These regions are particularly vulnerable to moisture convergence associated with slow-moving Mediterranean cyclones over central Italy and slow-moving cyclones over this domain are

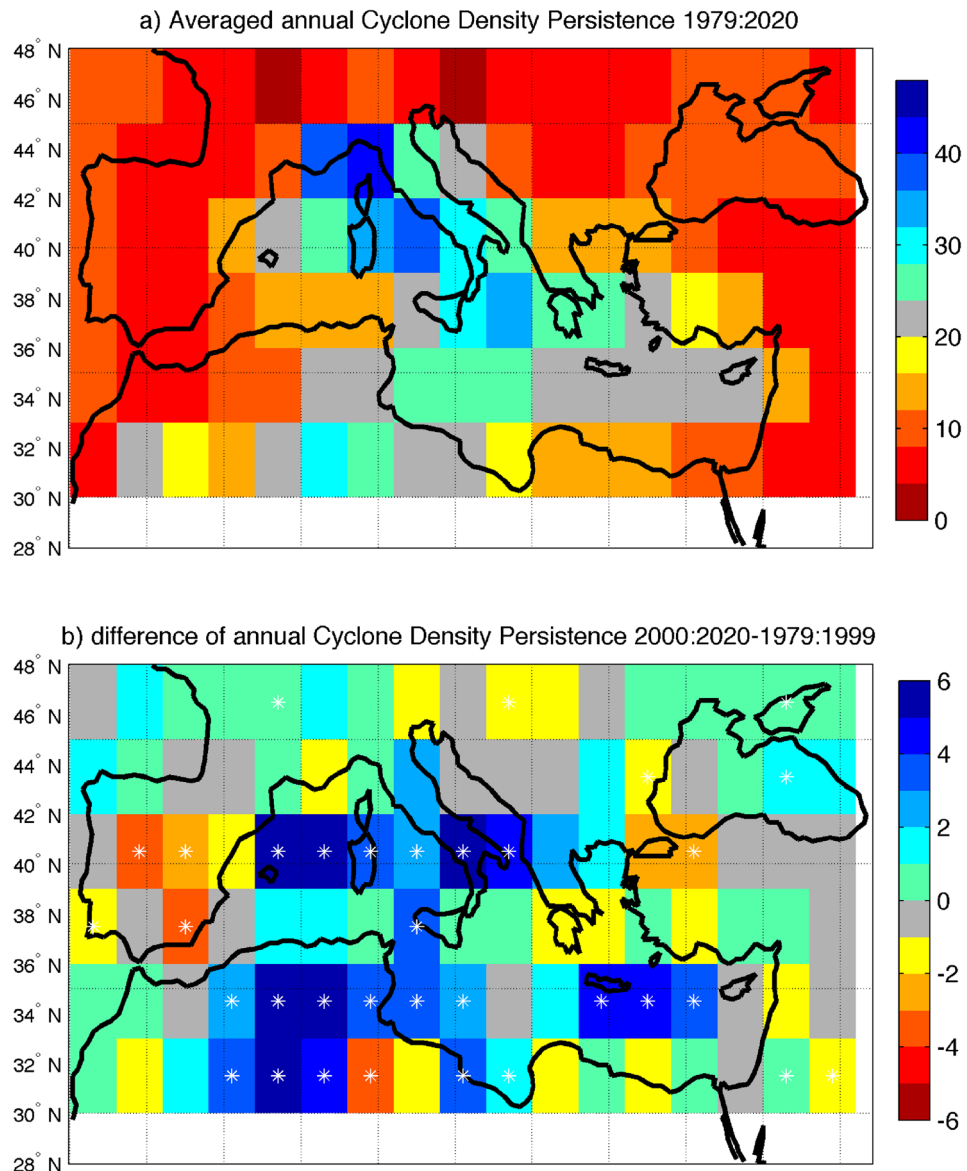


Fig. 3. Cyclone Density Persistence index (CDP, as defined in the Main text and in Data and Methods) resulting from extra-tropical storm tracks over the Mediterranean basin. Tracks by Flaounas et al.¹⁵. Panel (a) (top) shows the 1979–2020 annual climatology of CDP index values on a $3^\circ \times 3^\circ$ grid boxes over the Mediterranean basin. Panel (b) (bottom) shows the difference between CDP mean values for the 2000–2020 period and CDP values for the 1979–1999 period. Positive value: increase, negative values: decrease. Units are [days]. White stars indicate statistically significant differences (see methods).

increasing in the last decades (blue patterns in Fig. 3, panel b) and red stars compared to black stars in Fig. 4). Similar conditions can be expected for Occitanie and Provence (France), Valencia and Catalonia (Spain) when considering cyclones hovering over the western Mediterranean basin (Fig. 3). The analysis of CDP and of its change over time suggests that the observed warming of the Mediterranean may be increasing the likelihood of prolonged precipitation events and the risk of flooding wherever orography and moisture convergence interact to produce flood-risk conditions.

Conclusion and outlook

This is a preliminary study, and more work is needed to characterize other critical conditions, such as soil conditions or the state of hydraulic infrastructure, which can contribute to the formation of extreme flooding events. However, even at this early stage, the analysis highlights the potential for cyclone density persistence metrics such as the CDP index to serve as predictive tools in the development of Early Warning Systems for flooding, particularly for areas enclosed by orographic features that are likely to be associated with smaller catchments that can easily be overwhelmed by persistent precipitation. Indicators such as these could improve

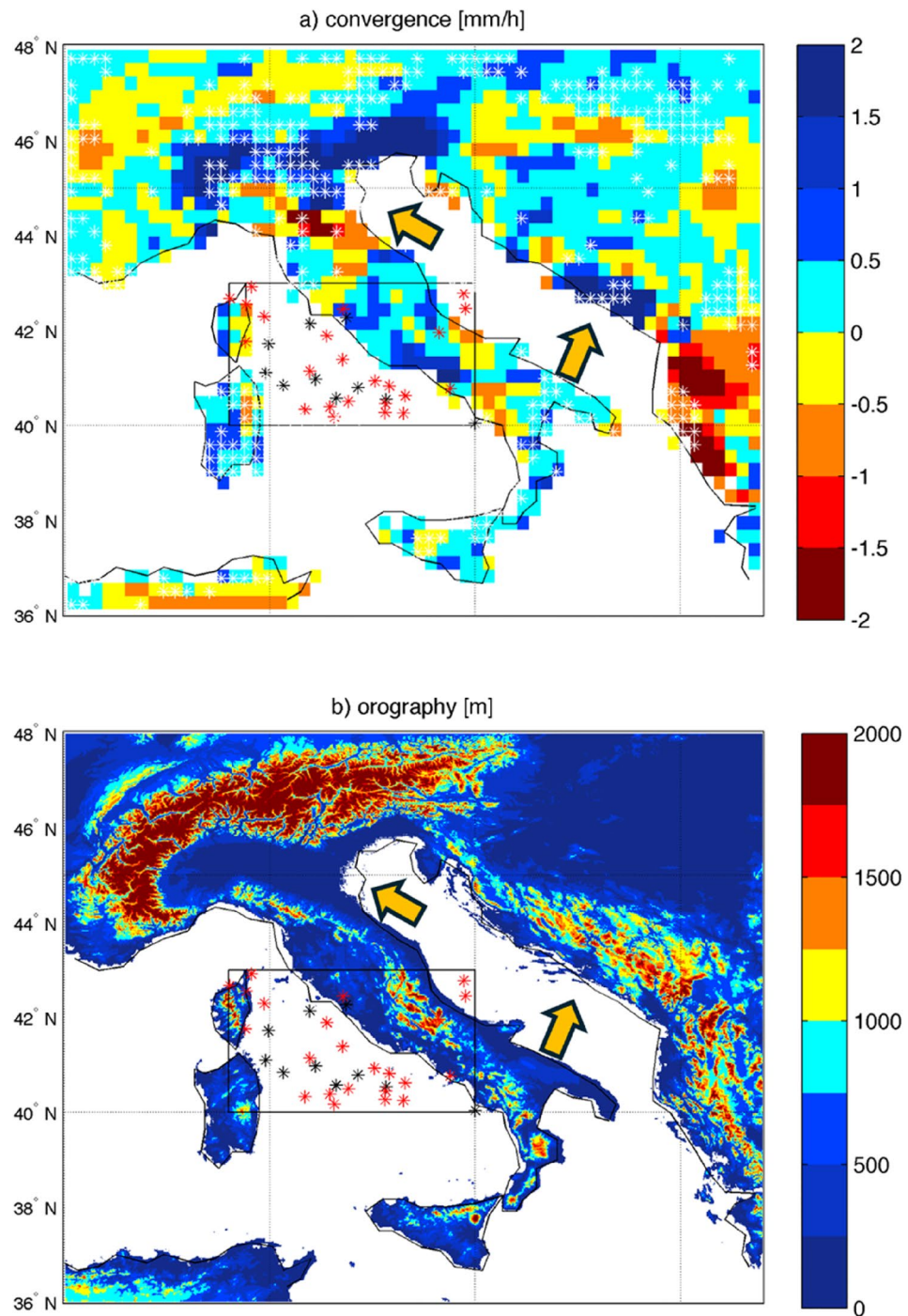


Fig. 4. Focus on areas prone to stationary cyclones over central Italy. Black box indicates the domain used to select stationary cyclones (black stars during 1979–1999, red stars during 2000–2020) lasting more than two days, to create time composites of associated vertically integrated moisture convergence flux difference between the two periods (panel a). Panel b) shows the orography¹⁹ of the region. Orange arrows point towards areas more prone to water convergence due to the vertically integrated water fluxes, induced by stationary cyclones, and confined by the cul-de-sac orographic features. White stars indicate statistically significant differences (see methods).

our ability to detect vulnerability and the effectiveness of forecasts across time scales—from short—and medium-range to seasonal outlooks—to help communities manage the risks of extreme events.

Further work is required to assess whether the observed increase in cyclone density persistence over the past four decades persists under various future warming scenarios, and how such changes might affect flood risk across the Mediterranean.

Methods

Rainfall data

Rainfall data for the year 2023 are sourced from two datasets at daily resolution:

- ARPAE (Archivio Climatologico per l'Italia centro-Settentrionale): A high-resolution observational dataset with a horizontal resolution of 5 km, available from 1961 to the present¹⁶.
- ERA5 Reanalysis: Provided by the ECMWF with a horizontal resolution of 25 km¹⁷, through the Copernicus Climate Change Service (C3S)¹⁸.

Additional ERA5 fields

To conduct a detailed analysis of the May 2023 flood events, we utilized hourly ERA5 reanalysis data for 2023. The following variables were extracted:

- Total precipitation.
- Vertically integrated horizontal water convergence.
- Vertically integrated water vapor content.
- Vertically integrated zonal and meridional water vapor transport.

Daily ERA5 data for the period 1994–2024 were also used to compute climatological averages of vertically integrated water content and horizontal water convergence (represented by dashed lines in Fig. 1).

Mediterranean cyclone Tracks, Density, and persistence

To analyze historical changes in cyclone frequency and stationarity across the Mediterranean basin, we employed cyclone track data from Flaounas et al.¹⁵.

From these tracks, we computed:

- Annual Cyclone Density (ACD): The total number of unique cyclone occurrences per year within each $3^\circ \times 3^\circ$ grid cell (each cyclone is counted only once per cell).
- Cyclone Persistence (CP): The cumulative number of days cyclones remained within a given grid cell across the year.
- Cyclone Density Persistence (CDP): Defined as the product of ACD and CP, this index quantifies both the frequency and duration of cyclone activity. CDP is expressed in units of [days].

Statistical significance

The statistical significance of the differences shown in Figs. 3 and 4 is verified at the 85% level with a bootstrap method.

Data Availability

All data:

- ARPAE precipitation data: <https://www.arpae.it/it/temi-ambientali/meteo/dati-e-osservazioni/dati-giornalieri>.
- ERA5 data: <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>.
- Mediterranean Cyclone tracks: <https://wcd.copernicus.org/articles/4/639/2023/wcd-4-639-2023-supplement.zip>.
- ETOPO orography: NOAA National Centers for Environmental Information. 2022: ETOPO 2022 15 Arc-Second Global Relief Model. NOAA National Centers for Environmental Information. DOI: <https://doi.org/10.25921/fd45-gt74>.

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Author contributions

E.S. designed and wrote the paper; A.B. collected and pre-processed data; L.C. and L.S. supported the analysis relative to the Mediterranean cyclone density persistence; P.M. contributed to the data collection and to the design of the paper; S.T. and G.B. contributed to the writing of the paper.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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