Links between precipitation, circulation weather types and orography in central Italy

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Abstract
Recent analyses of satellite and surface observations reported a negative annual rainfall trend in central Italy. The complex orography of the Apennines and the strong influence of climate change in the Mediterranean basin complicates the explanation of such trends and their spatial variability. This work aims at describing the link between circulation weather types, orography and precipitation patterns observed in central Italy, as a first step towards the understanding of such climate trends. Using ERA5 reanalysis data from 1951 to 2019, four weather types are identified as most responsible for the spatial variability of rainfall in central Italy. They are associated with cyclonic circulations characterized by high water vapour transport coming from west, south-west, south-east and north-east. The analysis of wind speed and precipitation climatology for the period 1951–2019, as derived from both surface observations and reanalysis, confirms a strong influence of moist south-westerly fluxes over all the domain, while the effect of north-easterly fluxes remains confined to the Apennines and the Adriatic coast. ERA5 overestimates annual rainfall in most parts of the region, except on the north-central Apennines where the underestimation reaches average values of 300 mm. The analysis of circulation weather types and their associated precipitation variability demonstrates that this deficit can be ascribed to a wrong representation of the orographic precipitation component as seen by ERA5 in correspondence of cyclonic north-easterly and westerly flows impinging towards the north-central Apennines. Indeed the precipitation associated with north-easterly and westerly fluxes shows the strongest modulation by orography. This interaction and its possible modification by climate change effects should be considered in future studies investigating recent climate trends in central Italy.

KEYWORDS
Apennines mountains, circulation classification, climatology, ERA5, Italy, orographic effect, rainfall
INTRODUCTION

The seasonal and spatial variability of rainfall is directly linked to the global atmospheric circulation and to other local climate factors such as orography, latitude, oceanic and continental influences (Trigo and DaCamara, 2000). Understanding such variability and its relation with those factors is crucial for assessing recent climate trends (Casado et al., 2010; Cortesi et al., 2013), especially in the central Mediterranean region, where significant negative trends of rainfall are developed in certain locations (Kalimeris and Kolios, 2019).

Central Italy, where this study is conducted, is one of those locations characterized by a significant annual rainfall deficit. Recent analyses of satellite products provided by the NASA’s Tropical Rainfall Measurement Mission (TRMM) over the last two decades Caloiero et al. (2020); Kalimeris and Kolios (2019) reported a negative annual trend reaching magnitudes of $-50$ mm/10 years in central Italy, without any clear annual trends for the entire Italian territory.

Similar results are observed also by surface observations. Caporali et al. (2021) recently reviewed different studies on precipitation trends in Italy published between 1999 and 2018. Most of the 20 studies examined for central Italy agree on the negative trend of total annual precipitation both on short term (<65 years) and centennial analysis (>100 years). This is confirmed by a recent work of Pavan et al. (2019) for north-central Italy, where an extremely negative trend in annual precipitation was found from 1961 to 2015 in several areas of central Italy. This trend ranges between $-2.5$ mm/year over the coastal areas to $-8.5$ mm/year over the northeastern Apennines mountains, where this trend is significant over the 95% level (see fig. 7b from Pavan et al., 2019).

These studies at national scale are in agreement with regional studies on precipitation climatologies and trends, as evaluated over almost all Italian regions involved in this study (see map in Figure 1): Toscana (Bartolini et al., 2014; 2018); Umbria (Vergni and Todisco, 2011); Emilia Romagna (Antolini et al., 2016); Abruzzo (Scorzini and Leopardi, 2019; Curci et al., 2021); Marche (Appiotti et al., 2014; Gentilucci et al., 2019); Lazio (Tiber river basin, Romano and Preziosi, 2013). These studies confirmed the overall negative annual rainfall trend over central Italy, which becomes particularly significant over certain Apennines zones. In Abruzzo, this was also accompanied by pronounced warming over the Apennines cluster (Scorzini and Leopardi, 2019).

These trends have been usually correlated either with large-scale circulation patterns such as North Atlantic Oscillation (NAO; López-Moreno et al., 2011) or with changes in Circulation Weather Types (CWT) frequencies (Trigo and DaCamara, 2000). López- Moreno et al. (2011) found a significant negative correlation between DJFM (December-January-February-March) precipitation and the DJFM NAO (North Atlantic Oscillation) index by analysing data coming from many GCMs for the main Mediterranean mountains, including the Apennines, from 1950 to 2005. In particular, positive NAO phases contribute to strength zonal flows and increase moist and warm advection to northeast Europe while decreasing such effect over south and eastern Europe. However, Scorzini and Leopardi (2019) and Montaldo and Sarigu (2017) found such a negative correlation only on the western part of the Abruzzo and the Sardinia region.
while lower negative values were found moving towards the eastern coast. They ascribed this phenomenon to the blocking effect exerted by the Apennines on the westerly moisture fluxes, which made the eastern part less influenced by the sign of the NAO index. Such findings are in agreement with previous work by Millán et al. (2005) which stated that any correlation of precipitation amounts with large-scale circulation indexes should properly consider stations locations and response to different precipitation types (e.g., frontal, convective and orographic). In Tuscany, Bartolini et al. (2014) linked the spatial variability of rainfall trends to the different influence that Mediterranean weather circulation have on locations characterized by different regimes: total rainfall in northern Tuscany is mostly due to cyclogenesis and intrusions of Atlantic frontal systems, while in central-southern Tuscany there is a considerable fraction of rainfall amount due to frontal systems and upper-level lows coming from northern and eastern Europe. In this view, the observed decrease in the western Mediterranean Basin of cyclogenesis and Atlantic fronts inclinations caused by an increase of anticyclonic conditions (Dünkeloh and Jacobett, 2003), caused a more negative trend in northern Tuscany rather than on south-central part. Again local variations of precipitation trends can be explained only when linked to both topography and atmospheric circulation.

Therefore the complex orography of central Italy, together with its central position on the Mediterranean basin where precipitation occurs as a result of different meteorological processes (Millán et al., 2005; Vallorani et al., 2018; Miró et al., 2020), complicates the relation between precipitation variability and changes in large-scale atmospheric circulation.

A further difficulty arises from global warming which can be the driver of dynamical and thermodynamical changes of physical processes leading to precipitation. In particular, the orographic component of precipitation, which is evident from high-resolution climatologies of Italy (Crespi et al., 2018; Pavan et al., 2019), will be affected by non-trivial feedbacks in climate change scenarios (Teixeira et al., 2016) and the way it will respond to climate change depends on many different factors (Siler and Roe, 2014). As an example, the drying ratio (DR) is expected to decrease with increasing surface temperature (Kirshbaum and Smith, 2008). This effect could be even enhanced by the observed amplification of warming with elevation which is connected to different types of climate feedbacks (Pepin et al., 2015). Other than enhancing precipitation, mountains can also suppress it by, for example, blocking moist impinging flow or inducing vertical mixing with dry air aloft (Kirshbaum et al., 2018). All these phenomena are strictly connected to air stability and surface temperature.

Given this complex scenario, this work aims at describing the connection between the spatial variability of rainfall, the orography and the CWT in central Italy. To the authors knowledge, this type of analysis has never been performed before in this part of Italy and for daily rainfall variability. Recent work by Iannuccilli et al. (2021) explored the connection between extreme precipitation events and CWTs, while Vallorani et al. (2018) compared different methods for evaluating CWTs over Italy. An innovative aspect of this study in the CWT calculation is not in the methodology, which is retained equal to Vallorani et al. (2018) and Iannuccilli et al. (2021), but on the input data. In this study we use ERA5 reanalysis data (Hersbach et al., 2020) from 1951 to 2019, instead of the NCEP reanalysis two datasets from 1979 to 2015 used in previous studies. The higher resolution of ERA5 (0.25° vs. 2.5° of NCEP reanalysis) and its improved performances (Hersbach et al., 2020), can give further insights on CWTs and their physical properties over Italy.

As a foundation of this study, an annual precipitation climatology is derived from both ERA5 reanalysis and local observations coming from the national SCIA dataset (Desiato et al., 2007). Such product and its connection with CWTs could represent an important reference for central Italy, where climatology is usually calculated from each region independently.

The comparison between ERA5 reanalysis and local observations can give useful insights on which type of atmospheric processes are best modelled by reanalysis and which needs further improvements. Moreover, Copernicus users in central Italy can take advantage of this work by deducing some advice regarding the suitability of the use of ERA5 precipitation data for local applications.

Therefore this study represents a first step towards an understanding of the role of climate change and orography on the recent climate trends observed in central Italy, as described above.

Since orography is one of the key factors investigated in this study, a detailed description of the study domain is provided in Section 2. In Section 3, we give an overview of the data involved in this study and the methodology used to process them. Section 4 is entirely dedicated to the CWT calculation methodology and to the description of each obtained weather type (WT). Results are organized in two sections: Section 5.1 where we describe the precipitation climatology of central Italy; Section 5.2 where we analyse the contribution of each CWT to the total precipitation variability. Finally Section 6 conclude this article by outlining the link between CWT, orography and precipitation variability and recommending new areas for future research.
2 | STUDY AREA

This study focuses on central Italy, in the middle of the Mediterranean region (Figure 1). This area represents the beginning of the peninsular Italy and border with two seas: the Tyrhenian Sea on the west coast and the Adriatic Sea on the east coast, the first with a maximum depth almost twice as the latter. The Apennines mountains cross this area from north to south, with an approximate inclination of 140° with respect to north, making the orography very complex also in the proximity of the sea.

The selected area cross different Italian regions (from north to south: Emilia-Romagna, Tuscany, Marche, Umbria, Lazio, Abruzzo, Molise), but do not reflect administrative boundaries. The choice of the domain has been made with regards to the Apennines orientation, extension and their interaction with incoming flux of water vapour (and the resulting precipitation climatology). For this reason, the study domain (large boxed region in Figure 1a) does not include both the northernmost part of this mountains (Ligurian and Tuscan-Emilian Apennines), characterized by very different precipitation climatologies (Desiat et al., 2015; Pavan et al., 2019), and the southern part of the Apennines. Instead, the selected portion of Apennines mountains, which area is bounded by the dashed black line in Figure 1, extends from 44.25°N to 41.5°N (see reference line D_N–D_S in Figure 1) with a length of approximately 390 km (2.75°) that corresponds to the height of our study domain. The domain width is about 300 km (2°), extending from the Tyrrenian to the Adriatic. The total study area extension is about 110,000 km², where only the 30% is occupied by sea. This region is also important for its water resources: it is crossed from south to north by the Tiber river, the third-longest river in Italy; it contains the lakes Trasimeno and Bolsena, respectively the fourth and the fifth for surface area in Italy.

The cross-barrier line C_T–C_A (where T stands for Tyrrenian and A for Adriatic) divides the Apennines in two parts which share similar mountains’ height: the north-central Apennines (NC-AP), extending from the ‘Appennino Tosco-Romagnolo’ to the beginning of the Sibillini mountains, with maximum heights about 1700 m (Mount Catria); the south-central Apennines (SC-AP), extending from the Sibillini mountains to the end of Abruzzi Apennines, with maximum heights reaching about 2,900 m (Corno Grande). This subdivision has been made in order to highlight the different shape and altitude ranges of the orography on the two subdomains. These topographic characteristics, together with stability and speed of the approaching air, represents the main factors affecting terrain-forced flows (Whiteman, 2000). Therefore, for facilitating results description and interpretation, the domain is subdivided into four main zones: NC-AP, SC-AP, TYR and ADR. The last two zones represent the Tyrrenian and Adriatic coastal areas, respectively. Coastal areas are here considered the land between the Apennines and the correspondent seas.

By looking at high-resolution orography obtained from the Digital Elevation Model (DEM; Danielson and Gesch, 2011) in Figure 2, we can recognize three main differences between the north and south domain: (a) the distribution of orography across all the domain; (b) the altitude ranges and (c) the aspect ratio of the Apennines mountains, which can be identified by the region where the meridional average height exceed the 500 m, that is the area between the leftmost and rightmost vertical lines in Figure 2. First of all, the NC-AP are located further away from the coast with respect to the SC-AP. Fluxes coming from the Tyrrenian side into the north domain has to travel up to 150 km, before reaching the north central Apennines. During this time they encounter hills and isolated mountains (usually called Sub-Apennines), with

![Figure 2](https://wileyonlinelibrary.com)
an average height between 300 and 400 m; a sharp elevation gradient is present on the first few km, while reaching a stable profile up to the Apennines. On the other hand, fluxes going to the south domain encounter a smoother elevation gradient on the very beginning, which increases almost linearly up to the south-central Apennines, which are much closer to the coast. On the Adriatic side this difference is smaller, but still appreciable.

The second relevant difference between north and south domains is on the Apennines altitude range: fluxes impinging towards the NC-AP encounters much lower height than those impinging towards the SC-AP. A representative mountain height, usually defined as \( H_m \) in literature (Kirshbaum et al., 2018), could be defined by looking at the maximum 90th percentile of meridional height average (grey shading in Figure 2): \( H_m = 1,000 \) m for NC-AP and \( H_m = 1,800 \) m for the SC-AP. It is worth recalling that no real unique mountain height number exists for the entire north and south central Apennines. The numbers provided above only represents reasonable values for the entire selected domains, to enable the comparison of this work with other mountain meteorology studies on different altitude ranges and for further modelling of atmospheric processes (e.g., calculation of the adimensional mountain number). The calculation of the representative height is even more complex in the southern domain, due to the high variability of elevations on the Apennines region. This variability is especially pronounced in correspondence of two large plains in the Abruzzo region: the Fucino plain, at about 140 km from the reference line \( C_T-B_T \), and the Sulmona plain, at about 175 km from the reference line \( C_T-B_T \) (in correspondence of the Apennines reference line \( D_N-D_S \) in Figure 1). These two plains plays a fundamental role in the precipitation climatology of that region, as it is pointed out later in Section 5.1.

The last relevant feature is about the variability of the aspect ratio, \( r \), that is the ratio between the along and cross-barrier dimension. This parameter, together with the adimensional mountain number, is a relevant parameter for determining the response of impinging flow to mesoscale terrain in the absence of thermal forcing (Kirshbaum et al., 2018). The cross-barrier dimension of north and south central Apennines—the difference between the km corresponding to the rightmost and leftmost vertical lines in Figure 2—is 50 km for the NC-AP and 90 km for the SC-AP. The along-barrier dimension is equal to 195 km, that is the half-width of the entire domain. Therefore the aspect ratio for the NC-AP is \( r_{SC} \approx 3.9 \), while for the SC-AP is \( r_{SC} \approx 2.2 \).

Finally we can compare the orography seen by the DEM, as described above, with the one seen by the ERA5 reanalysis (red lines on Figure 2). The number of grid points of ERA5 reanalysis along the cross-barrier direction is 10. This low resolution is a limit for the detection of orographic variability with scales smaller than 60 km. On the Adriatic side of the north domain the average height is well represented, while the rightmost part of the NC-AP is underestimated. The same underestimation is found on the first part of the Tyrrenian side, which is compensated by an overestimation between 100 and 150 km from the reference point \( C_T \). In this zone ERA5 is not capable of representing small valleys like the Chiana Valleys and Tiber valleys, which are sources of variability for the precipitation climatology (see Section 5.1). On the Adriatic side of the south domain ERA5 average height profile is slightly larger than the DEM profile, while on the remaining parts it always underestimate terrain heights. This underestimation is especially marked on the SC-AP and the two large plains of Sulmona and Fucino are not detected by the model. These differences on the terrain profile are very likely to affect the precipitation climatology seen by ERA5 in contrast with the observations.

3 | DATA AND METHODOLOGY

3.1 | Surface observations

Daily precipitation time series from 1951 to 2019 have been provided by the Italian Institute for Environmental Protection and Research (ISPRRA) through the national system for climate data collection, processing and dissemination (SCIA; Desiato et al., 2007). SCIA is accessible through a public web access (www.scia.isprambiente.it) and collects daily and monthly data of temperature and precipitation coming from several meteorological, agrometeorological and hydrological networks belonging to different regional and national authorities. Due to the heterogeneity of data sources, it is not possible to give a unique reference for the instrumental properties of raingauges. Moreover this heterogeneity is present also in time, since some data could have been taken manually (especially before 1980), while other coming from automatic raingauges measurement (especially after 1980). As a general indication, we can consider 0.2 mm as a reasonable value for the raingauge resolution for most of the considered instruments.

SCIA database is used yearly for the calculation of climate indices on Italy (Desiato et al., 2011; Fioravanti et al., 2020), but it has been used also for research purposes such as regional climate assessment (e.g., Toreti et al., 2009; Toreti et al., 2010; Fioravanti et al., 2019; Baronetti et al., 2020) or high-resolution model verification (e.g., Bucchignani et al., 2020). The data are already subjected to different quality control levels (Desiato et al., 2007; Fioravanti et al., 2019), with automatic
procedures following the ones suggested by Durre et al. (2010) and applied to the Global Historical Climatological Network (GHCN) daily dataset. The initial number of raingauges located nearby our study domain was 2,588. However many of them had very high percentages of missing data or small temporal coverage over the selected period (1951–2019). Therefore, we select first those stations which contained at least 40 years of data, where a single year was considered to be valid only if containing less than 10% of missing data (about 36 missing days). By applying this first simple criterion the number of stations was reduced from 2,588 to 696. The location of these final selected stations is shown on the map of Figure 1. The spatial distribution is quite homogeneous across all the domain, except for the Lazio region (on the Tyrrhenian side), where the station density is coarser. However this dataset still represents the most complete observational database covering central Italy. Some efforts have been made to produce high-resolution gridded observational dataset of precipitation for north-central Italy (ArCIS, Pavan et al., 2019), but such dataset does not include the south-central Apennines and the confining regions, which are a relevant part for the climatology of central Italy. Moreover European gridded observational dataset, such as E-OBS (Cornes et al., 2018), still relies on very few synoptic stations on central Italy (see fig. 1a in Cornes et al., 2018), thus increasing the uncertainty of the employed interpolation methods and limiting the possibility of describing the small scale variability of precipitation which is typical of complex terrain.

After defining the number of selected stations and their spatial distribution, further quality control procedures, following national guides (Fioravanti et al., 2016) and again the work of Durre et al. (2010), have been repeated to clean data from any other suspect values. First we apply a percentile based climatological outlier check to all time series, by comparing each daily value with the 95th percentile of daily rainfall relative to that day. The percentile calculation required a minimum of 20 nonzero values for the period of record in the 29-days window as suggested in Durre et al. (2010). Values were flagged as suspect if they exceed more than 9 times the calculated percentile. Than a spatial corroborations check (Durre et al., 2010; Fioravanti et al., 2016) was applied to verify the spatial consistency of a station with its neighbours. Neighbouring stations were identified by a search radius of 30 km around the target station and a minimum number of 2 neighbours was setted to perform the test. Only five stations over 696 did not satisfy this requirement. These isolated stations, located on Tyrrhenian Sea islands and nearby the study domain limits, were retained for their strategic role. Suspect and wrong values coming out from the previous tests were considered as missing and no gap-filling method were applied to not introduce any artificial values. Since precipitation trend analysis is out of the scope of this paper, an automatic procedure for time series homogeneization has not been included in the data post-processing. However, annual precipitation climatologies have been evaluated at different reference periods (1951–1980, 1961–1990, 1971–2000 and so on) and compared visually to find any suspect dishomogeneities. This comparison, together with the comparison of other climatologies of Italy (e.g., Crespi et al., 2018; Desiato et al., 2015; Pavan et al., 2019), confirmed us the absence of differences that could be imputed to time-series dishomogeneities.

The final temporal evolution of data availability on a daily scale is shown in Figure 3. The number of working stations per day (equivalent to the number of reliable rainfall observations per day) is above 500 until 1990. After that the number starts to decrease due to the passage from a unified network maintained by the National Hydrographical Service to separated networks maintained by regional authorities. Instead, the large drop from 300 stations to 150 in 2015 is probably due to missing or incomplete updates of the SCIA dataset. Despite this large variability in time, the final number of stations is representative of the entire study domain and it still represents the largest unified collection of rainfall observations spreading across all regions of central Italy.

3.2 | ERA5 reanalysis

This study uses the fifth generation of ECMWF’s global atmospheric reanalysis, ERA5 (Hersbach et al., 2020), as
a reference dataset for the analysis of CWT over central Italy (see Section 4) and for comparison with observed precipitation data. The high resolution system of ERA5 (HRES) provides data at hourly resolution and 31 km of spatial resolution. Figure 1 shows ERA5 orography and its resolution over the study domain and over Europe. The relevant differences between the model and the DEM orography have already been discussed on Section 2.

Although the coarse spatial resolution, ERA5 provides many significant improvements with respect to its predecessor ERA-Interim (see section 4 of Hersbach et al., 2020). This is the main reason why we choose ERA5 instead of the higher resolution regional reanalysis UERRA (C3S, 2021), which is forced by ERA-Interim. This is confirmed also by Pelosi et al. (2020), since they found that ERA5-Land outperformed systematically UERRA MESCAN-SURFEX system in reconstructing precipitation and other surface variables in a region of south-central Italy, mainly because the first benefits of the latest ERA5 global reanalysis.

ERA5 is based on the ECMWF Integrated Forecasting System (IFS) version CY41R2. A detailed description of all physical processes and their parametrizations can be found in the documentation of the correspondent model version (ECMWF, 2016).

Surface and pressure variables have been extracted from the Copernicus Climate Data Store (Hersbach et al., 2018) for the period from 1951 to 2019. The ERA5 preliminary back-extension dataset (Bell et al., 2020) has been used to cover the period from 1951 to 1978. Mean Sea Level Pressure (MSLP), Geopotential Height at 500 hPa (Z500) and at 1000 hPa (Z1000) have been downloaded at 00 UTC for all Europe (North: 75°, West: −15°, South: 30°, East: 42.5°). Daily mean of wind speed (WS) and direction (WD) at 850 hPa have been computed from hourly wind components for all Europe (North: 75°, West: −15°, South: 30°, East: 42.5°). Daily means of total column of water vapour (TCWV) and vertical integral of eastward (IVTe) and northward (IVTn) water vapour fluxes have been computed from hourly values over a smaller domain covering Italy (North: 50°, West: 5°, South: 35°, East: 25°). All these variables were used to assess and analyse the feature of each CWT over Italy (see Section 4). All computation have been performed by using the python programming language and in particular the xarray package (Hoyer and Hamman, 2017).

Daily accumulation of precipitation was derived from hourly total precipitation, corresponding to the sum of large-scale and convective precipitation. This parameter represents the daily accumulated liquid and frozen water that reaches the Earth’s surface and its units are depth in metres in water equivalent. It is worth recalling here that ERA5 total precipitation, as well as all other model parameters, is representative of a grid-box average and this has to be taken into account when comparing with local observations. This is the reason why we always interpolate local observations of rainfall to the ERA5 grid through geostatistical methods (Kriging), before direct comparison with model parameters. This approach is usually called point-to-area verification method in the quantitative precipitation forecast field (Tustison et al., 2001).

4 | CIRCULATION WEATHER TYPES

Daily CWT are classified by using mean sea level pressure (MSLP) as classification variable and obliquely rotated principal components in T-mode (PCT), also called principal component analysis in T-mode (TPCA), as classification method. PCT, as the name suggests, is a principal component analysis (PCA) based method and the key references can be found in Huth (1993, 2000). The software used to perform this classification is the widely used cost733class-1.4 (Philipp et al., 2016).

In a recent comparison of CWT classifications over a small domain centred on Italy, Vallorani et al. (2018) found that PCT was the most appropriate method for stratifying precipitation in every season when computed on a low number of circulation types. Same performance were obtained by performing PCT analysis on both mean sea level pressure and 500 hPa geopotential height. This result differs considerably from previous studies over Europe (Huth et al., 2016), and the difference was attributed to different factors: domain size, orographic complexity of the Italian territory and heterogeneity of the climate of Mediterranean regions. Those factors seem to favour the PCT method, which resulted to be the most efficient for taking into account the various physical processes that generate precipitation in the Mediterranean area (Vallorani et al., 2018). This is the main reason why PCT has been adopted also for this work, as well as in other recent works (Iannuccilli et al., 2021).

The spatial domain chosen for the CWT classification is the same of Vallorani et al. (2018) (35°N–50°N, 5°E–20°E). The temporal extent is from 1951 to 2019. The input variable is 00 UTC MSLP at 31 km resolution as provided by ERA5 reanalysis (see Section 3.2). The detailed procedure and setting for the PCT computation can be found in Huth (2000). The classification is full-year therefore one method (PCT) is defined for the whole year without any seasonal subsetting. This approach is similar to that used by Trigo and DaCamara (2000) in Portugal, and by Iannuccilli et al. (2021) in a more recent work in Italy. Huth et al. (2016) shows an improvement of the classification performances by including the seasonality effect over the central
Mediterranean region. However, they also state that ‘such results should be treated with caution, since a part of the improvement, if there is any, may be attributable to a lower number of types, not to the different definition of classifications’. Given the absence of clear advantages of using seasonal classification methods in Italy, this work, as a first step, focuses only on a yearly basis. A more in depth analysis of the seasonality effect in the Italian region is left for future work.

The final number of selected types is 9 and together they provide about the 75% of explained variance, which is similar to the values obtained in the previous work of Dünkeloh and Jacobieit (2003). This number was considered to be a good compromise between data reduction, explained variance and comparability with previous reference studies (an equivalent number was used in Vallorani et al., 2018).

The main properties of the 9 WTs (or CWTs), as obtained from the above mentioned method, are summarized in Table 1. Each WT is indicated by a number (e.g., 1) or an abbreviation (e.g., NEc). This abbreviation is introduced mainly for two reasons: facilitate the reader in remembering the main WT features; allowing a comparison with threshold-based classification methods like the Jenkinson–Collison Types (JCT, Jenkinson and Collison, 1977; Jones et al., 1993), which are widely used for the Iberian peninsula (Trigo and DaCamara, 2000; Cortesi et al., 2013).

CWTs are organized in three main synoptic circulation regimes occurring over Italy: cyclonic, indicated by small letter c; anti-cyclonic, indicated by small letter a; zonal, which in turn can be more or less cyclonic. The degree of cyclonicity of each pattern is established based on the time average of mean sea level pressure (MSLP), 500–1,000 hPa geopotential thickness (Z) and 850 hPa wind direction and speed (WD,WS) as shown in the synoptic composite maps in Figure 4. The correspondent spatial average of these parameters over the study domain is reported in Table 1.

Besides these main parameters, Table 1 reports other important variables for CWT description: the frequency of each CWT in percentage of days; the total column of water vapour (TCWV) for describing the air mass properties; the Vertical Integral of Eastward Water Vapour fluxes (IVTe, positive for fluxes from west to east) and Northward Water Vapour fluxes (IVTn, positive for fluxes from south to north), which have been confirmed to be important large scale forcing indicators for northern Italy (Grazzini et al., 2020); the mean daily precipitation (Pmean) and the mean annual precipitation (Ptot) for defining the contribution of each CWT to precipitation climatology. At this step, all quantities are derived only from ERA5 reanalysis. In Section 5, these values will be compared with those derived from observations.

To further complete our description, Figure 5 shows the seasonal frequency of each CWT.

The total number of cyclonic types is 4. They occur for almost 50% of days for the analysed period, providing for the 75% of annual rainfall. Generally, they are uniformly distributed among winter (DJF), spring (MAM) and

| Table 1 Weather type classification properties |

| WT | Days (%) | MSLP hPa | Z dam | TCWV kg m⁻² | WD | WS m s⁻¹ | IVTe kg m⁻¹ s⁻¹ | IVTn kg m⁻¹ s⁻¹ | Pmean mm d⁻¹ | Ptot mm y⁻¹ (%) |
|----|----------|----------|-------|-------------|----|----------|----------------|----------------|-------------|----------------|
| Cyclonic | | | | | | | | | | |
| 1 (NEc) | 15.8 | 1,011.6 | 549.0 | 16.9 | N | 2.9 | 17 | -43 | 3.1 | 177 (19.3) |
| 2 (SWc) | 12.1 | 1,014.1 | 552.3 | 19.3 | SSW | 6.8 | 82 | 121 | 5.4 | 238 (25.9) |
| 5 (C) | 11.6 | 1,009.2 | 552.6 | 17.8 | WSW | 5.4 | 106 | 29 | 3.9 | 167 (18.1) |
| 7 (SEc) | 10.0 | 1,019.4 | 548.3 | 16.1 | ESE | 3.0 | -21 | 23 | 3.0 | 110 (12.0) |
| Anti-cyclonic | | | | | | | | | | |
| 3 (Ea) | 8.3 | 1,019.3 | 547.6 | 14.6 | ENE | 0.3 | 14 | 0 | 1.8 | 54 (5.9) |
| 4 (NEa) | 19.2 | 1,018.6 | 554.3 | 17.5 | NNE | 2.5 | 15 | -40 | 1.0 | 71 (7.8) |
| 6 (A) | 7.8 | 1,017.9 | 566.5 | 22.9 | WSW | 1.7 | 60 | 1 | 0.4 | 10 (1.0) |
| Zonal | | | | | | | | | | |
| 8 (Wc) | 9.2 | 1,018.0 | 552.4 | 16.1 | WSW | 6.5 | 108 | 34 | 1.7 | 58 (6.3) |
| 9 (Wc) | 6.0 | 1,014.8 | 550.5 | 16.1 | W | 4.7 | 91 | 2 | 1.5 | 34 (3.7) |

Note: Each quantity is derived from ERA5 reanalysis daily fields and is averaged over the study domain shown in Figure 1a (large boxed region A₁B₁C₁D₁). From left to right: Weather type number and related abbreviation; frequency of each CWT in percentage of days; mean sea level pressure (MSLP); Total column of water vapour (TCWV); wind direction (WD) from which the wind is blowing (16 sectors wind rose); wind speed (WS); vertical integral of eastward water vapour fluxes (IVTe); vertical integral of northward water vapour fluxes (IVTn); mean daily precipitation (Pmean); mean annual precipitation (Ptot).
autumn (SON), with a lower frequency during summer (WT$_1$ representing the only exception). The wettest type is WT$_2$ (SWc), which is characterized by strong south-westerly winds transporting warm and moist air towards the Tyrrenian coast (see Figure 6b,f). Strong winds and moisture transport are found also for the pure cyclonic type WT$_5$ (C), while, on average, north-easterly winds WT$_1$ (NEc, bora winds) and south-easterly winds WT$_7$ (SEc, scirocco winds) are lighter and transport relatively drier and colder air (see differences in TCWV and Z in Table 1).

Anti-cyclonic types occurs for almost 35% of days, providing about the 15% of annual rainfall. Their frequency is usually larger in summer, with the only exception of WT$_3$ (Ea) which is characterized by very cold and stable air mass typical of winter and autumn seasons. The most frequent CWT is WT$_4$ (NEa) which is the anticyclonic counterpart of NEc. They share the same moisture transport and wind speeds, but with different synoptic circulations: in the case of NEc, a large moisture transport is active on the southern Adriatic (see Figure 6a,e) which is absent in case of NEa (not shown). This difference is at the basis of the formation of cyclonic or anti-cyclonic bora winds (Davolio et al., 2017). The driest CWT is the pure anticyclonic type WT$_6$ (A) which is typical of summer months. The remaining percentages of rainfall and frequency pertained to the two zonal types WT$_8$ and WT$_9$.

5 | RESULTS

5.1 | Precipitation climatology

The analysis of CWT of Section 4 revealed the difficulty of defining a single dominant flow pattern in producing
precipitation over central Italy. Among the cyclonic types, south-westerly and westerly flows (Types 2 and 5) produce about 45% of annual rainfall. However, north-easterly and south-easterly flows (Types 1 and 7) contribute to annual rainfall with a considerable percentage (about 30%). This makes the link between fluxes, orography and spatial distribution of rainfall more complicated than in other complex territory were precipitation is produced mainly by westerlies (e.g., Oregon and South California, see Hughes et al., 2009; Smith et al., 2005).

One simple way of verifying this complexity is by analysing the statistics of wind speed and direction relative to wet days, as previously done in Smith et al. (2005). Wet days are evaluated from raingauges data as days with daily precipitation larger than 0.2 mm. Wind speed and direction are taken from ERA5 reanalysis at 850 hPa (≈1,500 m), which is thought to be representative of the entire Apennines mountains height range (see Section 2). Wind and precipitation data have been extracted at four different locations representative of the Tyrrhenian coast (TYR), the north-central Apennines (NC-AP), the south-central Apennines (SC-AP) and the Adriatic coast (ADR). The resulting wind statistics are shown in Figure 7a–c for TYR, NC-AP and ADR zones, respectively. The wind rose for the SC-AP have been omitted because of its similarity with the NC-AP. Therefore we can think at Figure 7b as representative of the entire Apennines.

Flow dominance in producing precipitation is much clearer on Figure 7a rather than others: the most populated wind sector is from south-east to west, without significant contributions on precipitation from north-easterly winds. The majority of precipitation events in the Tyrrhenian coast can be associated with moderate (5–10 m/s) and strong (10–15 m/s) south-westerly winds. On the Apennines mountains (Figure 7b) significant precipitation is associated with both south-westerly and north-easterly winds. As expected, winds have stronger intensities over this zone. On the Adriatic coast (Figure 7c) precipitation events are more homogeneously distributed across wind sectors, with westerly and south-westerly winds still being the predominant flows associated with rainfall.

From this first picture, it is clear that Apennines are an effective barrier protecting the Tyrrhenian coast from NE fluxes and the Adriatic coast from SW fluxes. However this efficiency seems to be more pronounced in contrasting NE fluxes, since on the Adriatic coast there is still a large fraction of precipitation associated with SW fluxes. Another important common aspect to all zones is the presence of significant precipitation associated with WSW winds. This constant contribution is probably due to the pure cyclonic type WT5, where precipitation is more homogeneously distributed across the entire study domain.

Figure 8 shows annual precipitation climatologies from 1951 to 2019 derived from observations (Figure 8a) and reanalysis (Figure 8b), together with their difference (Figure 8c). The comparison between ERA5 and local observations can give us useful insights in determining the zones where precipitation climatology is more sensitive to either unresolved physical processes or unresolved dynamical circulations by the ERA5 model. It is important to point out that the differences between ERA5 and the observations have been considered physically significant only where they exceed the observation interpolation error (this range is indicated by darker red and blue
The climatology derived from raingauge observations reveals a clear modulation of precipitation by orography. The values obtained in Figure 8a are in agreement with those found in literature both on a national scale (Crespi et al., 2018; Desiato et al., 2015; Pavan et al., 2019) or a regional scale (Antolini et al., 2016; Gentilucci et al., 2019; Curci et al., 2021). Annual precipitation ranges from 1,000 to 1,500 mm over all the Apennines mountains, except for the eastern part of SC-AP in the Abruzzo region. This exception, as anticipated in Section 2, is due to the two large plains of Sulmona and Pucino where annual precipitation can reach values between 600 and 800 mm (see fig. 4 of Curci et al., 2021). Outside the Apennines region annual rainfall ranges from 600 to 1,000 with lower values close to the Adriatic coast and inner parts of Tuscany and Umbria, while higher peaks on the Tyrrhenian coast close to localized mountain systems (Sub-Apennines).

The difference between ERA5 and the observations is higher over the Apennines zone and the Tyrrhenian coast (see Figure 8c). Differences over the sea surface are not reliable since the low number of available observations. On the Tyrrhenian coast there is a general overestimation of annual rainfall, while on the Apennines we found
different signs: over the northern Apennines ERA5 significantly underestimate annual rainfall, while on the southern part it overestimate rainfall over the above mentioned high plains areas of Abruzzo and other mountainous areas on the eastern side. This opposite behaviour is a clear index of the presence of different physical mechanisms producing precipitation between NC-AP and SC-AP, which is linked to the interaction of the same type of fluxes with different mountain systems (differing both in shape and heights). Another significant difference between ERA5 and observations can be found in the quite dry inner region between Tuscany and Umbria, where ERA5 overestimates annual rainfall.

5.2 | Precipitation variability

To assess the variability of precipitation across each CWT and across the study domain, Figures 9 and 10 shows the spatial pattern of mean daily precipitation intensity for each CWT, as evaluated respectively from ERA5 and OBS. Raingauge observations are classified for each CWT and the 1951–2019 average of daily rainfall is calculated for each time-series. The obtained values are interpolated by kriging on the ERA5 grid for direct comparison. The same procedure is applied also to the percentage of total precipitation (not shown). Figures 11 and 12 shows the difference between ERA5 values and OBS values across the study domain, for mean daily rainfall and total precipitation percentage, respectively.

Opposite patterns of mean daily rainfall are evident for Type 1 (see Figures 9a and 10a) and Type 2 (see Figures 9b and 10b). The Apennines mountains cause a rain-shadow effect which prevents NEc fluxes from bringing rainfall towards the Tyrrhenian coast and SWc fluxes from reaching the Adriatic coast. This blocking effect is very strong when south-westerly fluxes impinge on the high mountains of SC-AP, especially on the southern part of Lazio region where mountains are very close to the coastal zone. In such circumstances, this area is...
characterized by strong mean daily rainfall, while on the opposite part on the Adriatic coast very low intensities are registered.

A localized orographic precipitation enhancement is also present in ERA5 daily rainfall when NEc fluxes encounter the highest mountains of SC-AP in the Abruzzo region. Three highest peaks can be easily seen from Figure 9a. Those peaks coincides geographically with the three major mountain chains of Abruzzo (from north to south: Monti della Laga, Gran Sasso e Majella).

A marked orographic precipitation enhancement is present also for the Cyclonic Type 5 (Figures 9d and 10d), where rainfall intensities larger than 3 mm·day$^{-1}$ are present almost everywhere in the study domain. This is more evident in the observations rather than in ERA5, especially for the NC-AP region, where ERA5 clearly underestimate mean rainfall intensity (see Figure 11d).

The major differences on rainfall quantities between ERA5 and OBS are then found on Types 1, 2, and 5 as seen in Figures 11a,b,d and 12a,bd. Especially the difference in total percentage of precipitation in Figure 12a,b shows a complete opposite behaviour between Types 1 and 2, with the south-eastern Adriatic coast (lower right rectangle in Figure 12) being in contrast with the other zones. We should recall here that Types 1, 2 and 5 are the three wettest cyclonic patterns which together accounts for the 64% of annual rainfall and their overall frequency is about 40%. Therefore a large difference in their associated rainfall intensity and percentage, will definitely affect precipitation climatology. On the other hand, ERA5 and OBS largely agree on rainfall patterns associated to anti-cyclonic and zonal types. The only exception can be found for zonal Type 8, since ERA5 overestimates rainfall intensity on the Tyrrhenian coast (see Figures 11g and 12g).

All the above findings are better summarized by Figure 13, where grid points and observations are grouped into zones and the spatial variability of total precipitation and mean daily rainfall is represented by boxplots.
Five main differences are clearly highlighted by Figure 13:

1. Fluxes of Type 1 and 2 show a strong signal of orographic modulation. The ascending and descending order of median values of each regional boxplot is common to both ERA5 and OBS.
2. ERA5 largely overestimates rainfall intensity and total precipitation over the Tyrrhenian coast for fluxes of Type 2.
3. ERA5 underestimates rainfall intensity and total precipitation over the Apennines and the Adriatic coast for fluxes of Type 1.
4. ERA5 is not able to capture the orographic precipitation enhancement which happen on NC-AP region for fluxes of Type 5.
5. OBS shows larger variability of rainfall parameters across the study domain than ERA5, especially in correspondence of mountainous areas (see the interquartile range of boxplots in Figure 13).

Finally in Figure 14 we summarize the contribution of each CWT to the rainfall differences between ERA5 and OBS over each selected zone. Dark blue colours indicate where ERA5 significantly overestimates OBS while dark red colours, ERA5 significantly underestimates OBS and white colours reveal where ERA5 and OBS are in agreement.

Again Figure 14a,b underline the opposition of the first two CWTs. In general ERA5 underestimate the mean daily rainfall and the total percentage of rainfall brought by WT1, while overestimating them for WT2. This is true for all selected zones. Concordant signs are usually found between Pmean and Ptot tables, with the only exception of the Adriatic coast where a positive difference of Pmean does not always correspond to a positive difference in Ptot and viceversa. This exception is due to the ERA5 underestimation of total amount of rainfall brought by NEC fluxes on the Adriatic coast (see Figure 12a). As a consequence the relative percentage of NEC rainfall seen by ERA5 is higher than observations.
**FIGURE 12** Difference of total rainfall percentage between ERA5 and raingauge observations for each CWT. Blue lines indicate the subdivision into cyclonic, anticyclonic and zonal types as shown in Figure 4 [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 13** Boxplot of total percentage of rainfall (a and b) and mean daily rainfall (c and d) for four different zones: TYR (Tyrrhenian coast); NC-AP (north-central Apennines); SC-AP (south-central Apennines); ADR (Adriatic coast). Values are calculated from observations (OBS) on the left column (a and c) and from ERA5 reanalysis (ERA5) on the right column (b and d)
even if the mean daily intensity is lower. The opposite is true for SWc fluxes.

The cyclonic type WT5 is characterized by different anomalies for Pmean over the Tyrrhenian coast (negative on the northern part and positive on the southern part) and over the SC-AP (negative on the western side and positive on the eastern side), as can be appreciated in Figure 11d. These contrasting signs cause the resulting average anomaly to be very small over those zones, masking out significant local differences.

The combined negative anomalies of WT1 and WT5 over the NC-AP cause the only total negative anomaly which we obtain when we compare ERA5 and OBS. All other total anomalies are positive thanks mainly to the positive contribution of WT7 and WT8. The only anticyclonic type which shows significant differences is WT4, where total rainfall is overestimated by ERA5 on the southern Apennines and Adriatic coast. Total differences on total percentages (last column of bottom table in Figure 14) differ from being all zeros (as it should be expected) because of the propagation of rounding errors.

### CONCLUSIONS

Recent climate studies have found a negative trend of annual rainfall over central Italy, with large significant values over the Apennines. Such trends could be ascribed to the modification of the frequency and the internal properties of the main CWT bringing rainfall in central Italy. However, the considerable role of orography and air-sea interaction in this region, further complicates the connection between CWT and precipitation regimes. The description of this link is the scope of this work and represents a first step towards the understanding of recent climate trends.

Four CWTs are identified as mostly responsible for the spatial variability of rainfall in central Italy. They are all characterized by cyclonic circulations with moisture fluxes and winds which direction depends on the relative position of the low pressure centre. When the low is positioned over northern Italy (pure cyclonic Type 5), moderate westerly winds develop and precipitation is distributed homogeneously over the territory, with a strong orographic enhancement over the entire Apennines. When the low is located over the Ligurian Sea (Type 2), strong south-westerly winds cause strong precipitation intensities concentrated over the Tyrrhenian coast and the inner part of central Italy. Orographic enhancement is evident on the western side of the Apennines, especially in the Lazio region where high mountains are located in proximities of the sea. The Adriatic coast, especially in the southern part where Apennines reaches high altitudes, receive a low amount of rainfall due to the blocking exerted by mountains. The opposite rainshadow effect is observed for north-easterly fluxes which develop when the low is located on the Adriatic sea (Type 1). The Tyrrhenian coast receives very low amount of rainfall compared to the eastern side of the Apennines and the Adriatic coast. Finally when the low is located over southern Italy (Type 7), moderate south easterly fluxes develop over the Adriatic bringing more rainfall over the southern Apennines and the southern Adriatic coast.

The combination of these fluxes, together with their relative frequency of occurrence, contributes to the precipitation climatology observed in Figure 8. The comparison with ERA5 climatology highlights an overestimation of annual rainfall amount on the Tyrrhenian coast and the south-central Apennines, while a strong underestimation is founded on the north-central Apennines. The examination of each CWT revealed that this rainfall deficit is due to a wrong representation of the orographic component of precipitation due to the Types 1 (NEc) and 5 (C). This deficiency is counterbalanced in the reanalysis by an overestimation of total precipitation amount and intensities due to Type 2 fluxes (SWc). The important contribution of NEc fluxes to the precipitation over the Apennines is also confirmed by the windrose shown in Figure 7. On the other hand the precipitation over the Tyrrhenian coast is dependent almost only on south-westerly fluxes. The precipitation regime on the Adriatic coast is still largely influenced by westerlies. The uniform dependence of precipitation regime on westerlies and its
non-uniform dependence on easterlies demonstrates that, on average, blocking exerted by Apennines mountains is more efficient for easterlies cyclonic types (Types 1 and 7), rather than westerlies cyclonic types (Types 2 and 5). This blocking is usually accompanied by an orographic precipitation enhancement on the western side of the Apennines in correspondence of SWc fluxes, and on the eastern side in correspondence of NEc and SEc fluxes. Flow over regime seems to be predominant for the pure cyclonic type and the entire Apennines receive higher rainfall amounts than other zones.

The difficulties of ERA5 in correctly representing precipitation regime for cyclonic types points out the needs of further modelling improvement for representing physical processes bringing precipitation over midlatitudes complex terrain. Moreover, ERA5 rainfall data should be used with caution when assessing the spatial variability of rainfall climatology or trends in central Italy.

The use of high resolution modelling or regional reanalysis can be employed in future work for a better understanding of the effects of global warming on the connection between rainfall, orography and CWT. Perturbation experiments on the climatological internal properties of the most critical CWTs (Table 1) could give useful insights on the physical processes underlying recent climate trends.

Moreover further work is needed to update the observational dataset, by increasing the raingauge density and including different type of observations.

**AUTHOR CONTRIBUTIONS**

Lorenzo Silvestri: Conceptualization; data curation; investigation; methodology; software; visualization; writing – original draft. Miriam Saraceni: Conceptualization; investigation; methodology; validation; writing – review and editing. Paolina Bongioannini Cerlini: Conceptualization; investigation; methodology; supervision; validation; writing – review and editing.

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