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Hydrometeorological Persistence and Compound Extremes in the Azores: Observational Evidence and Synoptic Context from ERA5 Reanalysis

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Abstract

Hydrometeorological extremes reflect rainfall intensity, persistence, and interactions among atmospheric variables. Quality-controlled daily observations from Chã de Macela (São Miguel Island, Azores; 2011–2023) were used to examine precipitation extremes, wet and dry spells, and compound events. The primary same-day definition (precipitation ≥ P95, wind speed ≥ P90, and relative humidity ≥ P90) identified eight events. Six events (75%), 92 of 233 P95 days (39.5%), and 22 of 47 P99 days (46.8%) occurred within persistent wet spells. Sensitivity tests identified four same-day events using wet-day precipitation percentiles; allowing ±1-day alignment yielded 15 and six events under full-record and wet-day precipitation thresholds, respectively. Moving-block bootstrap comparisons of ERA5 data showed that P95 days had mean sea-level pressure 5.45 hPa lower and total column water vapour 3.69 kg m^{-2} higher than non-extreme wet days. Within the P95 set, compound days had pressure 4.49 hPa lower than non-compound days (95% CI: −9.04 to −0.69), whereas the water-vapour contrast was inconclusive. Visual examination suggested three descriptive configurations: persistent, vertically coherent cyclonic systems; pronounced meridional gradients in surface pressure and geopotential height; and a developing large-scale disturbance. These results describe persistence and synoptic context but do not establish predictive compound-event signatures.

Keywords: Azores; compound hydrometeorological events; extreme precipitation; precipitation persistence; wet and dry spells; synoptic configurations; ERA5 reanalysis; North Atlantic circulation

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1. Introduction

Hydrometeorological extremes constitute one of the most significant sources of natural hazards worldwide, affecting ecosystems, infrastructure, water resources, and human activities. Extreme precipitation events have become a major focus of climate research because of their environmental, social, and economic impacts and their expected intensification under climate change [1]. In recent decades, increasing attention has been devoted not only to the magnitude of extreme events but also to their temporal organization, persistence, and interaction with other environmental variables. This shift reflects the growing recognition that severe impacts often arise from prolonged or combined atmospheric conditions rather than from isolated meteorological anomalies [2,3].

Traditionally, hydrometeorological studies have focused on the analysis of individual variables, particularly precipitation, temperature, or wind. However, recent research has demonstrated that multiple drivers frequently interact to produce impacts that exceed those associated with each variable considered separately. Such situations are commonly referred to as compound events, defined as the combination of multiple climatic or meteorological factors that jointly contribute to environmental or societal risk [4,5]. Examples include the simultaneous occurrence of intense precipitation and elevated wind speeds, prolonged wet periods followed by extreme rainfall, or combinations of elevated atmospheric moisture and persistent storm activity.

Precipitation persistence represents another critical aspect of hydrometeorological variability. While individual extreme rainfall days can generate significant impacts, the cumulative effects of consecutive wet days may be equally important, particularly in relation to flooding, slope instability, soil saturation, and water-resource management. Persistent wet periods can substantially amplify the consequences of subsequent extreme rainfall episodes by progressively reducing infiltration capacity and increasing antecedent soil moisture conditions [6,7]. Conversely, prolonged dry periods influence water availability, ecosystem functioning, and drought development, highlighting the importance of analysing both wet and dry persistence characteristics.

Islands located in the North Atlantic are strongly influenced by the passage of extratropical cyclones, frontal systems, atmospheric rivers, and other forms of large-scale circulation variability [8,9]. These processes can generate prolonged periods of enhanced moisture transport and sustained precipitation, producing hydrometeorological conditions that differ substantially from those observed in continental regions.

The Azores archipelago occupies a strategically important position in the North Atlantic and is frequently exposed to synoptic-scale systems that modulate precipitation, wind, humidity, and cloud cover. Despite the climatological significance of the region, relatively few studies have investigated the relationship between hydrometeorological persistence and compound-event occurrence using a 13-year daily observational record. Most previous investigations have focused on individual variables, seasonal climatology, or large-scale circulation patterns, while the combined role of persistence and compound hydrometeorological behaviour remains comparatively underexplored.

In this context, the present study investigates hydrometeorological variability at the Chã de Macela station (São Miguel Island, Azores) using a daily dataset for 2011–2023 that was subjected to quality-control screening. Particular emphasis is placed on the identification of extreme rainfall events, wet and dry spell persistence, and compound hydrometeorological events involving precipitation, wind, humidity, and solar radiation. By combining climatological characterization, persistence analysis, and compound-event detection, this work aims to improve understanding of the mechanisms underlying hydrometeorological severity in oceanic island environments and to contribute to the growing literature on compound hydrometeorological events.

Although the statistical characterization of extreme precipitation and compound hydrometeorological events provides valuable information on their frequency, magnitude and persistence, understanding the atmospheric mechanisms responsible for their occurrence requires a synoptic-scale perspective. In recent years, atmospheric reanalyses have become fundamental tools for investigating the large-scale circulation patterns associated with hydrometeorological extremes. Among these products, the ERA5 reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) provides a physically consistent reconstruction of the global atmosphere by combining numerical weather prediction models with a wide range of observational data [10]. ERA5 has been widely used to investigate extreme precipitation events, atmospheric rivers, cyclonic systems, and

compound weather and climate events across different regions of the world [5,10]. Recent studies have further highlighted the growing importance of compound-event research for understanding complex climate hazards and improving risk assessment under changing environmental conditions [11].

Previous studies have shown that extreme precipitation events are frequently associated with large-scale atmospheric circulation features, including persistent cyclonic systems, pronounced pressure gradients, enhanced moisture transport and anomalous geopotential-height patterns [5,9]. Relatively little attention has been given to the synoptic-scale conditions accompanying compound hydrometeorological events in oceanic island environments, particularly in the North Atlantic and the Azores. Owing to their strategic location between subtropical and mid-latitude circulation regimes, the Azores constitute a natural laboratory for investigating the interaction between large-scale atmospheric forcing, precipitation persistence and compound-event behaviour. The present study differs from previous regional assessments by examining wet spell persistence and compound-event occurrence using a daily station record subjected to quality-control screening and by linking individual events to ERA5-derived atmospheric fields.

The objective of this study is to characterize hydrometeorological persistence, identify compound hydrometeorological events, and examine the synoptic context of their occurrence in the Azores.

2. Materials and Methods

2.1. Study Area

The study was conducted using observations from the Chã de Macela hydrometeorological station, located on São Miguel Island, Azores Archipelago, in the North Atlantic Ocean. Owing to their location in the transition zone between subtropical and mid-latitude atmospheric regimes, the islands are frequently influenced by extratropical cyclones, frontal systems, and large-scale moisture transport processes.

São Miguel is the largest island of the archipelago and exhibits marked topographic variability, which strongly influences local climatic conditions. The Chã de Macela station is located in the central part of the island at 37.77° N, 25.53° W, and an elevation of 309 m above mean sea level, as shown in Figure 1.

The climate of São Miguel is typically temperate oceanic, characterized by mild temperatures throughout the year, relatively high humidity, and abundant precipitation. Seasonal variability is largely controlled by the migration of the North Atlantic storm track, resulting in wetter conditions during autumn and winter and comparatively drier conditions during summer. The island's exposure to Atlantic weather systems and its complex terrain make it an appropriate natural laboratory for investigating precipitation persistence, hydrometeorological extremes, and compound atmospheric events.

2.2. Data Sources and Quality Control

Two complementary data sources were used in this study: (i) daily observations from the Chã de Macela hydrometeorological station and (ii) ERA5 atmospheric reanalysis fields. The observational dataset was used to characterize local hydrometeorological variability, whereas ERA5 data were employed to investigate the associated large-scale atmospheric conditions.

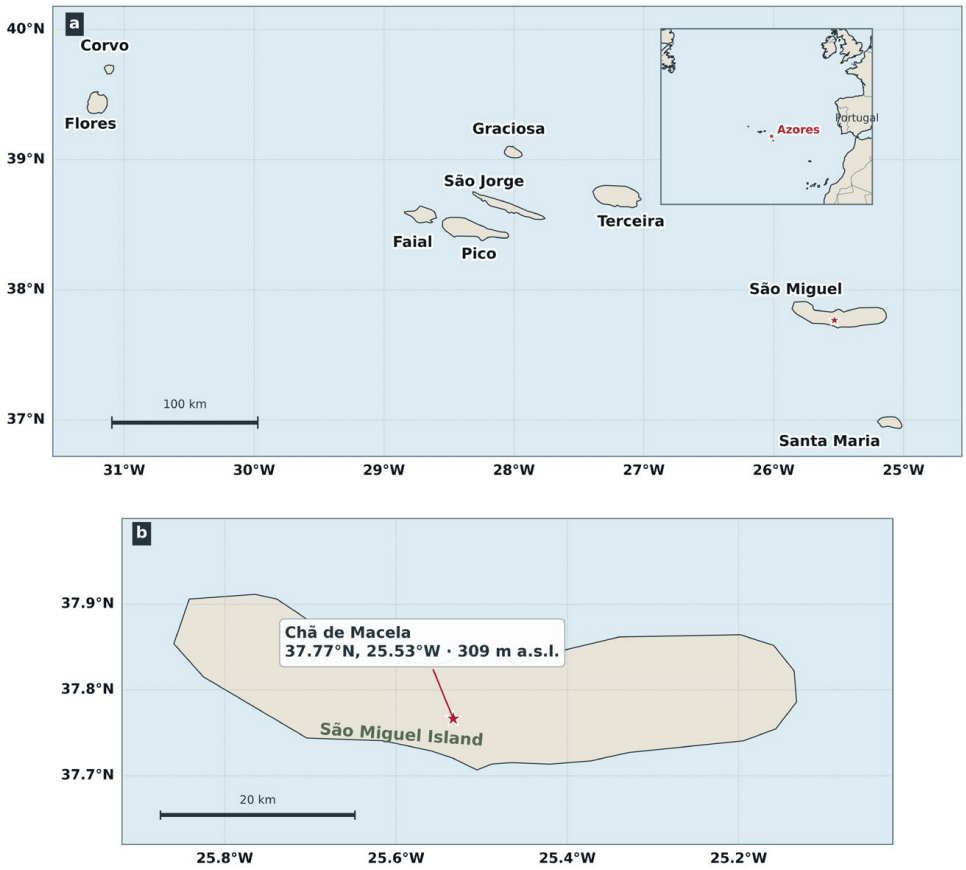


Figure 1. Location of the Chã de Macela hydrometeorological station. (**a**) Geographical distribution of the Azorean islands, with an inset showing the location of the archipelago in the North Atlantic; (**b**) location of the Chã de Macela station on São Miguel Island (37.77° N, 25.53° W; 309 m a.s.l.).

2.2.1. Station Data and Quality-Control Procedure

The analysis was based on daily observations collected at the Chã de Macela hydrometeorological station (São Miguel Island, Azores) between 1 January 2011 and 31 December 2023. The dataset included data on precipitation, solar radiation, mean air temperature, maximum air temperature, minimum air temperature, wind speed, wind direction, relative humidity, and evaporation. All variables were recorded at daily resolution.

The 2011–2023 study period comprised 4748 calendar days. The station archive contained 4718 rows representing 4717 distinct dates. Thirty-one calendar dates were absent from the archive, precipitation was missing or non-numeric on a further 57 dates, and 31 December 2017 occurred twice with contradictory observations. The duplicated date was excluded from the analysis, and missing and excluded observations were not imputed. Data completeness in Table 1 was calculated relative to the 4748 calendar days in the study period.

Quality control was applied as a screening procedure rather than as an independent instrument-level validation. The daily dataset was examined for missing and duplicated dates, non-numerical entries, internal consistency among variables, and values outside the expected ranges of the respective variables. Original observations were not modified or removed solely because they were statistically extreme. Missing dates and non-numerical precipitation records were not imputed and interrupted the corresponding wet- and dry-spell sequences.

Table 1. Completeness and quality control of hydrometeorological data at Chã de Macela (2011–2023).

Variable	Missing Values (n)	Record Completeness (%)	Minimum	Maximum	Mean
Precipitation (mm)	89	98.13	0.00	71.70	3.24
Solar radiation (W m^{-2})	89	98.13	3.50	559.50	118.93
Mean air temperature (°C)	224	95.28	0.10	29.50	15.05
Wind speed (km h^{-1})	192	96.96	0.62	254.79	5.66
Wind direction (°)	165	96.52	9.60	332.90	177.00
Relative humidity (%)	164	96.55	0.08	100.00	71.60
Evaporation (mm day^{-1})	217	95.43	0.00	15.43	2.31

Note: Completeness was calculated relative to the 4748 calendar days between 1 January 2011 and 31 December 2023. Unavailable values include absent dates, missing or non-numerical observations, and the duplicated date excluded from date-based analyses. Potentially anomalous observations were identified through quality-control screening rather than independently validated. The descriptive statistics in Table 1 include flagged observations retained as supplied. Their dates or intervals, reported values, screening rationale, and analytical treatment are documented in Table S1 of the Supplementary Materials.

The unusually high wind-speed values were retained as reported in the source file. Because the original sub-daily observations, instrument metadata, calibration information, and maintenance records were unavailable, these values were not interpreted as independently verified storm-related observations. Other flagged observations and source-structure issues were handled as described in Table S1 of the Supplementary Materials, which reports their dates or intervals, reported values, screening rationale, and treatment in the analyses.

To describe the temporal distribution of the two station variables used in the compound-event definition, annual means, sample variances, and full-record P90 exceedance frequencies were calculated for the reported daily wind-speed and relative humidity fields. The same fixed P90 thresholds (8.60 km h^{-1} for the reported daily wind-speed field and 97.0024% for relative humidity) were applied to every year. Exceedance frequencies were calculated relative to the number of valid observations in each calendar year. Missing and non-numerical observations and both records for the duplicated date of 31 December 2017 were excluded, and no values were imputed or homogenized. The resulting annual indicators are presented in Table S3 of the Supplementary Materials.

The resulting precipitation series comprised 1875 wet days, 2784 dry days, 88 days without valid precipitation data, and one excluded date. For the variables reported in Table 1, completeness ranged from 95.28% to 98.13%, with precipitation and solar radiation both reaching 98.13%.

2.2.2. ERA5 Atmospheric Reanalysis Data

To investigate the large-scale atmospheric conditions associated with extreme and compound hydrometeorological events, atmospheric reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset were used. ERA5 provides a physically consistent reconstruction of the global atmosphere through the assimilation of observational data into a numerical weather prediction framework [10].

Daily mean sea level pressure (MSLP) and total column water vapour (TCWV) were obtained from the ERA5 post-processed daily statistics on single-level products (dataset identifier: derived-era5-single-levels-daily-statistics), available through the Copernicus Climate Data Store. The downloaded variables were mean sea level pressure (CDS variable name: mean_sea_level_pressure) and total column water vapour (CDS variable name:

total_column_water_vapour). This product consists of ERA5 hourly fields aggregated to daily time steps on a regular 0.25° × 0.25° latitude–longitude grid.

Daily MSLP and TCWV values were calculated as arithmetic means of the 24 hourly ERA5 fields from 00:00 to 23:00 UTC for each calendar day. The grid point nearest to the Chã de Macela station (37.7667° N, 25.5333° W) was located at 37.75° N, 25.50° W, with its centre over land on São Miguel Island. The station-nearest grid-point series was retained throughout the statistical analysis, and no spatial averaging was applied. Given the ERA5 grid spacing and the steep coastal topography of São Miguel, these values are interpreted as regional atmospheric estimates associated with the station dates rather than as measurements of conditions at the station elevation. MSLP was converted from Pa to hPa, whereas TCWV was retained in kg m^{-2}.

MSLP and TCWV were used to examine the atmospheric conditions associated with wet days, dry days, extreme precipitation events, and compound hydrometeorological events. The precipitation-based atmospheric analysis was restricted to the 4659 records with valid precipitation, MSLP, and TCWV data. For the synoptic maps, MSLP was obtained from the ERA5 hourly data on single-level products, while geopotential at 500 hPa was obtained from the ERA5 hourly data on pressure levels and converted to geopotential height by division by standard gravity ($g_0 = 9.80665$ m s^{-2}).

For the synoptic analysis, ERA5 fields were extracted over the North Atlantic domain (45° N–30° N, 40° W–15° W) at 12:00 UTC, covering a seven-day window centred on each compound event (±3 days). This configuration allowed the evolution of large-scale circulation features, including cyclonic systems, pressure gradients, and geopotential-height patterns, to be examined.

The synoptic grouping was based on visual examination of the MSLP and Z500 evolution during the eight compound events. Its purpose was to organize the case descriptions and identify recurring features within this small event set. The grouping was not derived from an objective circulation-classification algorithm and was not applied to non-compound P95 days. It should therefore be interpreted as an exploratory typology rather than as a classification of circulation patterns characteristic of compound events.

2.3. Climatological and Extreme Event Analysis

A climatological characterization of the Chã de Macela station was performed using daily observations from 2011 to 2023 after the quality-control screening described in Section 2.2.1. Monthly climatological statistics were calculated for all variables, including precipitation, air temperature, wind speed, relative humidity, solar radiation, and evaporation. For precipitation, daily rainfall amounts were aggregated into monthly totals for each calendar month and year. Month–year combinations with less than 95% completeness of daily precipitation data were excluded from the monthly distributions. Annual precipitation statistics were calculated only for years with at least 95% completeness. Monthly mean values were calculated for the remaining variables. These analyses provided the climatological framework required to identify seasonal patterns and evaluate hydrometeorological variability at the station.

To identify extreme hydrometeorological conditions, a percentile-based approach was adopted. Quantiles were calculated separately for each variable using all available non-missing daily observations from 2011 to 2023. Missing and non-numeric observations were excluded on a variable-by-variable basis, and no values were imputed.

$$P_q = F^{-1}(q) \quad (1)$$

where F^{-1} represents the inverse cumulative distribution function and q corresponds to the selected percentile level. Quantiles were estimated by linear interpolation between

adjacent ordered observations, using the fractional position $h = (n - 1)\, q$, where n is the number of valid observations for the variable under consideration. The unrounded quantile values were used for event classification, whereas rounded values are reported in the text and tables.

Precipitation percentiles were calculated from all valid calendar-day precipitation observations remaining after quality-control screening ($n = 4659$), including days with precipitation below 1 mm day^{-1}. This reference population was selected because the analysis defined extreme precipitation relative to the frequency distribution of all observed calendar days. As a sensitivity test, P95 and P99 were also calculated conditionally from the 1875 wet days, defined by precipitation ≥ 1 mm day^{-1}, presented in Table S4, Supplementary Materials.

The P90, P95, and P99 thresholds were 9.60, 16.31, and 36.168 mm day^{-1} for precipitation; 8.60, 11.6765, and 14.4063 km h^{-1} for the reported daily wind-speed field; and 97.0024%, 99.3525%, and 100.0% for relative humidity, respectively. The event classification used the precipitation P95 and P99 thresholds and the P90 thresholds for the reported daily wind-speed field and relative humidity. Because reduced solar radiation was included in one secondary event combination, the corresponding lower-tail threshold was P10 = 30.178 W m^{-2}. Percentile-based thresholds are widely used in climatological and hydrometeorological studies to identify conditions that are unusual relative to the local distribution [2,12]. In the present study, these thresholds are specific to the Chã de Macela record and should not be interpreted as universal physical or impact-based thresholds.

The percentile analysis was subsequently applied to the daily series after quality-control screening to determine the frequency, timing, and magnitude of extreme events. Days meeting or exceeding the precipitation P95 threshold were classified as extreme rainfall events, whereas days meeting or exceeding the P99 threshold were considered very extreme rainfall events. The wind speed, relative humidity, and solar radiation thresholds were used in the multivariable event combinations described in Section 2.5.

The resulting extreme-event database provided the basis for subsequent persistence and compound-event analyses. In addition to identifying individual extreme days, the percentile thresholds were used to investigate whether the most severe events occurred as isolated episodes or as components of longer-lasting hydrometeorological regimes.

Because daily MSLP and TCWV were serially correlated, uncertainty in the between-group contrasts was estimated using a circular moving-block bootstrap applied to the joint daily record. The primary analysis used 30-day blocks and 10,000 resamples, and sensitivity analyses used block lengths of 14 and 60 days with 5000 resamples. The full-record percentile thresholds were held fixed in all bootstrap samples. Contrasts were expressed as mean differences and Cliff's delta, with percentile-based 95% confidence intervals. Non-extreme wet days, defined by precipitation ≥ 1 mm day^{-1} and <P95, were used as the reference group for the P95 and P99 comparisons. Spearman's rank correlation was used as the primary measure of association because daily precipitation was zero-inflated and strongly skewed. Confidence intervals for Spearman's ρ were estimated using the same circular moving-block bootstrap framework, with 10,000 resamples and a 30-day block length. Pearson's coefficient was retained as a descriptive measure of linear association. As a sensitivity analysis, Spearman's correlations were recalculated using only wet days. P95 days without valid wind-speed or relative-humidity observations were excluded from the comparison between compound and non-compound events.

Sensitivity analyses using block lengths of 14 and 60 days produced confidence intervals consistent with those obtained using the primary 30-day specification; the corresponding results are reported in Table S5.

2.4. Persistence Metrics

To investigate the temporal organization of hydrometeorological conditions, persistence metrics were calculated from the daily precipitation series. Persistence was evaluated through the identification of consecutive wet and dry periods, commonly referred to as wet spells and dry spells.

A wet day was defined as a day with precipitation greater than or equal to 1 mm day^{-1}, whereas a dry day was defined as a day with precipitation below 1 mm day^{-1}. Consecutive wet days were grouped into wet spells, while consecutive dry days were grouped into dry spells. This threshold has been widely used in climatological and hydrological studies to distinguish meaningful precipitation occurrences from trace rainfall amounts. Dry spells were included only as a descriptive reference for comparing the persistence of precipitation and non-precipitation regimes; the subsequent severity analysis focused exclusively on wet spells.

In the primary analysis, calendar dates with missing or non-numerical precipitation observations, including dates absent from the archive and the excluded duplicated date, were treated as breaks in the daily sequence. They were not classified as dry days and did not bridge adjacent spells. As a sensitivity test, isolated one-day gaps were assigned the common wet- or dry-day category of the valid observations immediately before and after the gap when those categories agreed; longer or discordantly flanked gaps continued to interrupt the sequence. No precipitation amount was imputed, and this conditional assignment was used only to recalculate spell membership and duration.

For each wet and dry spell, the following characteristics were calculated:

- Start date;
- End date;
- Duration (days);
- Accumulated precipitation (wet spells only);
- Maximum daily precipitation within the spell;
- Mean wind speed;
- Mean relative humidity;
- Mean solar radiation.

Several persistence indicators were subsequently derived from the identified spells. These included the total number of wet and dry spells, the mean and median spell duration, the maximum spell duration, and the accumulated precipitation associated with each wet spell.

To investigate the role of persistence in hydrometeorological severity, wet spells lasting five or more consecutive days were classified as persistent wet spells. This threshold was selected to distinguish short-lived precipitation episodes from sustained wet regimes capable of generating cumulative hydrological impacts. The occurrence of extreme precipitation events and compound hydrometeorological events within persistent wet spells was subsequently evaluated to determine whether severe conditions tend to develop as isolated events or as part of longer-lasting hydrometeorological regimes.

2.5. Identification of Compound Hydrometeorological Events

Compound hydrometeorological events were identified from the simultaneous occurrence of extreme or locally unusual conditions in multiple atmospheric variables. Following the compound-event framework proposed by [4,5], the analysis allowed for statistical and physical dependence among the variables. The combinations were used to characterize the multivariable meteorological context of the events and were not assumed to represent independent contributions to hazard or impact. The event definitions and thresholds used in the analysis are summarized in Table 2.

Table 2. Criteria used to identify persistence and compound hydrometeorological events.

Category	Definition
Wet day	Precipitation ≥ 1 mm day^{-1}
Dry day	Precipitation < 1 mm day^{-1}
Wet spell	Consecutive wet days
Dry spell	Consecutive dry days
Extreme rainfall event	Precipitation $\geq$ P95
Very extreme rainfall event	Precipitation $\geq$ P99
Persistent wet spell	Wet spell ≥ 5 consecutive days
Core compound event	Precipitation $\geq$ P95 + Wind $\geq$ P90 + Relative Humidity $\geq$ P90, with all three criteria satisfied on the same calendar day

The identification procedure used percentile thresholds calculated separately for each variable from the available non-missing daily observations after quality-control screening. Extreme precipitation events were defined using the precipitation P95 threshold, whereas the P90 thresholds were used to identify locally elevated values of the reported daily wind-speed field (W) and relative humidity (RH). These variables represent precipitation intensity, upper-decile values of the reported daily wind-speed field, and high relative humidity within the Chã de Macela observational record.

A core compound hydrometeorological event was defined as a day simultaneously satisfying the following conditions:

$$\mathrm{CE} = \begin{Bmatrix} 1, \text{ if } P \geq P_{95}, W \geq W_{90}, RH \geq RH_{90} \\ 0, \text{ otherwise} \end{Bmatrix} \quad (2)$$

The primary compound-event definition required all three criteria to be satisfied on the same calendar day. To assess sensitivity to daily aggregation, an alternative ± 1-day definition was also applied. Under this definition, a P95 precipitation day was classified as compound when the P90 wind-speed and relative-humidity thresholds were each reached at least once within the three-day window extending from the preceding day to the following day; the two exceedances were not required to occur on the same calendar day.

The station-relative wind-speed threshold was used because the purpose of the classification was to identify the co-occurrence of locally unusual meteorological conditions, rather than exceedances of an operational wind-warning threshold. The P90 criterion provides a reproducible definition of the upper decile of the reported daily wind-speed field within the Chã de Macela record and allows wind, precipitation, and relative humidity to be assessed against their respective local distributions. The resulting compound-event classification therefore identifies extreme precipitation accompanied by upper-decile values of the reported daily wind-speed field and relative humidity. It does not imply that each variable independently reached a hazardous or impact-producing magnitude.

High relative humidity and reduced solar radiation are physically associated with precipitating cloud systems and may reflect conditions produced by the same weather system as the rainfall. Their percentile thresholds were therefore used to describe meteorological co-occurrence within the station record. The relative-humidity criterion identified near-saturated conditions accompanying P95 precipitation, while the low-radiation combination was retained as a secondary indicator of cloudy conditions and was not included in the core three-variable event definition. No independent impact or additional risk was assigned to either variable.

Because wind-gust observations were not available in the station archive, the sensitivity of the compound event classification was assessed using higher thresholds for the reported

daily wind-speed field and relative humidity. The precipitation criterion was retained at P95, while the wind-speed and relative-humidity criteria were raised from P90 to P95, separately and jointly. Event classification was performed using the unrounded percentile values.

Following event identification, the temporal occurrence of compound events was compared with the persistence metrics described in Section 2.4. Each compound event was assigned to its corresponding wet spell, allowing an assessment of whether compound hydrometeorological conditions preferentially occurred during persistent wet regimes or as isolated atmospheric events.

Because quality-control screening identified relative-humidity intervals recorded on a 0–1 scale within a field otherwise expressed as percent, together with a repeated day-of-year block affecting January–September 2012, an additional sensitivity analysis evaluated the dependence of the compound-event catalogue on these source-structure issues. The analysis was repeated after (i) converting the flagged 0–1 relative-humidity values to percent and (ii) excluding these values, with January–September 2012 excluded from percentile estimation and spell statistics in both cases. As an additional temporal sensitivity test, thresholds and compound events were recalculated for 2019–2023. Results are reported in Table S6.

3. Results

The results are presented in the following subsections, covering climatological variability, precipitation extremes, wet- and dry-spell persistence, compound events, and associated atmospheric conditions.

3.1. Climatological Characterization of the Chã de Macela Station

The monthly precipitation distributions at Chã de Macela showed a marked seasonal cycle and considerable interannual variability, as illustrated in Figure 2. Precipitation was generally higher from October to March. December had the highest median monthly total (165.4 mm) and mean monthly total (158.3 mm), followed by October, March, and February. July was the driest month, with median and mean monthly totals of 33.4 and 39.5 mm, respectively. Considering years with at least 95% completeness of daily precipitation data, mean annual precipitation during 2011–2023 was 1166.9 ± 192.2 mm, with annual totals ranging from 764.0 mm in 2011 to 1435.4 mm in 2021.

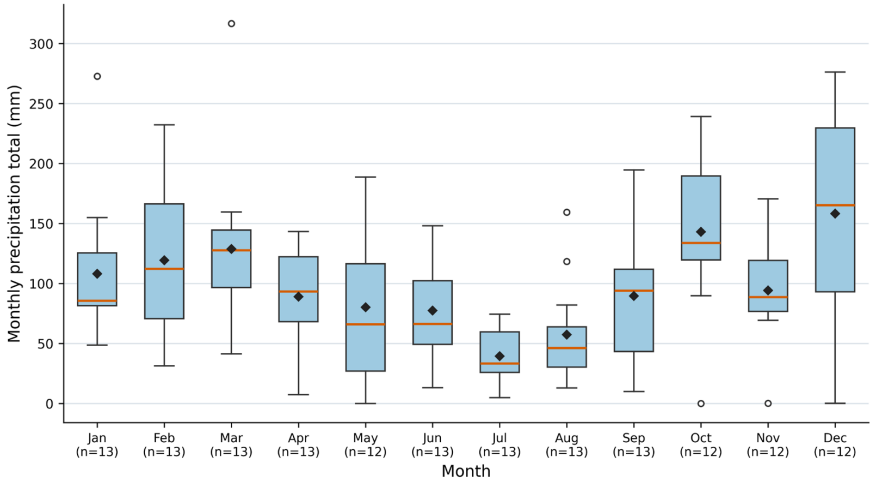


Figure 2. Distribution of monthly precipitation totals at Chã de Macela during 2011–2023. Light-blue boxes represent the interquartile range (25th–75th percentiles), orange lines indicate medians, and black diamonds indicate means. Whiskers extend to the most extreme observations within 1.5 times the interquartile range below the first quartile and above the third quartile; open circles represent observations beyond these limits. n denotes the number of valid monthly totals.

This seasonal behaviour is consistent with the enhanced influence of extratropical cyclones and frontal systems during autumn and winter, when the North Atlantic storm track is displaced southward and more frequently affects the Azores. During summer, the increased influence of subtropical anticyclonic conditions contributes to reduced precipitation totals and more stable atmospheric conditions.

3.2. Extreme Hydrometeorological Conditions

The percentile-based analysis revealed substantial variability in hydrometeorological conditions throughout the 2011–2023 observational period. For precipitation, the 95th percentile (P95) corresponded to 16.3 mm day^{-1}, while the 99th percentile (P99) reached 36.2 mm day^{-1}. Based on these thresholds, 233 days were classified as extreme rainfall events (P95), whereas 47 days met or exceeded the P99 threshold and were therefore considered very extreme precipitation events.

The highest daily precipitation recorded during the study period reached 71.7 mm, corresponding to approximately four times the P95 threshold and nearly twice the P99 threshold. Several additional events exceeded 60 mm day^{-1}, highlighting the occurrence of rare but potentially significant hydrometeorological episodes at the station.

The frequency distribution of extreme-event categories is presented in Figure 3. While extreme precipitation events (P95) occurred relatively frequently throughout the observational record, progressively stricter combinations of atmospheric conditions resulted in substantially lower numbers of events. Only 47 days met or exceeded the P99 threshold, whereas 44 and 46 events simultaneously satisfied the criteria of precipitation ≥ P95 combined with wind speed ≥ P90 and relative humidity ≥ P90, respectively. The largest number of dual-variable events was obtained for the combination of extreme precipitation and reduced solar radiation (precipitation ≥ P95 and radiation ≤ P10), with 80 occurrences.

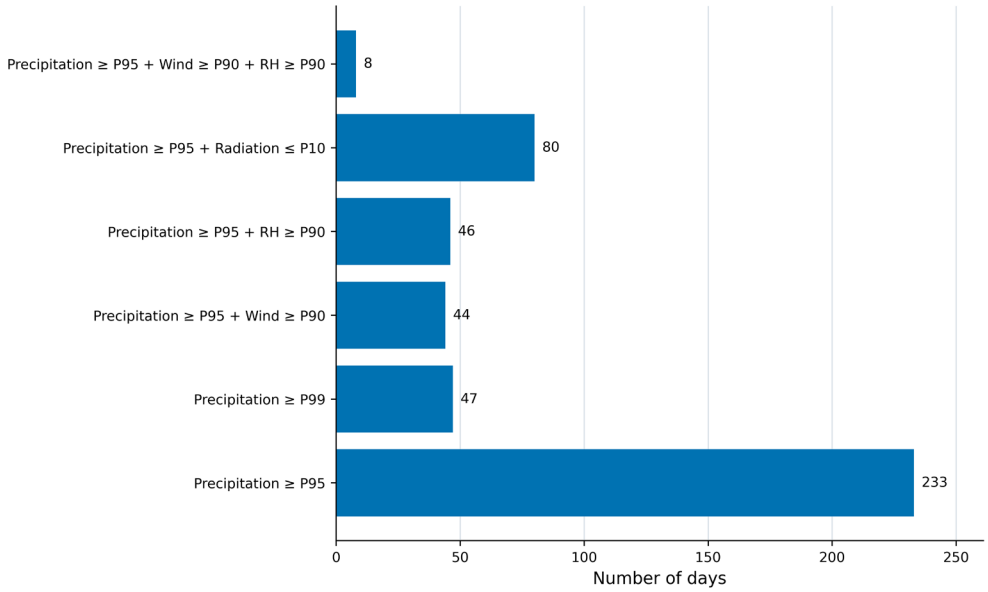


Figure 3. Frequency of extreme and compound hydrometeorological event categories at the Chã de Macela station during 2011–2023.

The precipitation–relative-humidity and precipitation–low-radiation combinations are reported as frequencies of physical co-occurrence and were not interpreted as independent impact-based hazard categories.

The most restrictive category was the core compound event definition, based on the simultaneous occurrence of precipitation ≥ P95, wind speed ≥ P90, and relative

humidity ≥ P90. Under this station-relative definition, eight days satisfied all three criteria shown in Figure 3. The smaller number relative to the individual and two-variable categories reflects the restrictiveness of the combined criteria.

3.3. Persistence of Wet and Dry Conditions

Beyond the magnitude of individual precipitation extremes, the temporal persistence of wet and dry conditions constitutes a fundamental component of hydrometeorological variability. The identification and characterization of wet and dry spells provide insight into the duration, frequency, and cumulative effects of precipitation regimes, allowing an assessment of whether hydrometeorological severity is primarily driven by isolated extreme events or by sustained periods of anomalous atmospheric conditions.

3.3.1. Distribution of Wet and Dry Spell Duration

A total of 792 wet spells and 792 dry spells were identified during the 2011–2023 study period using the precipitation threshold defined in Section 2.4. The nearly equal number of wet and dry episodes reflects the highly dynamic nature of hydrometeorological conditions at Chã de Macela, where frequent transitions occur between precipitation and non-precipitation regimes.

The duration distribution of wet and dry spells is presented in Figure 4. Most events were relatively short-lived, with both wet and dry spells typically lasting fewer than five consecutive days. Wet spells exhibited a mean duration of 2.37 days and a median duration of 2 days, whereas dry spells persisted for an average of 3.52 days, also with a median duration of 2 days. These results indicate that dry conditions tend to persist slightly longer than wet conditions, despite the generally humid character of the Azorean climate.

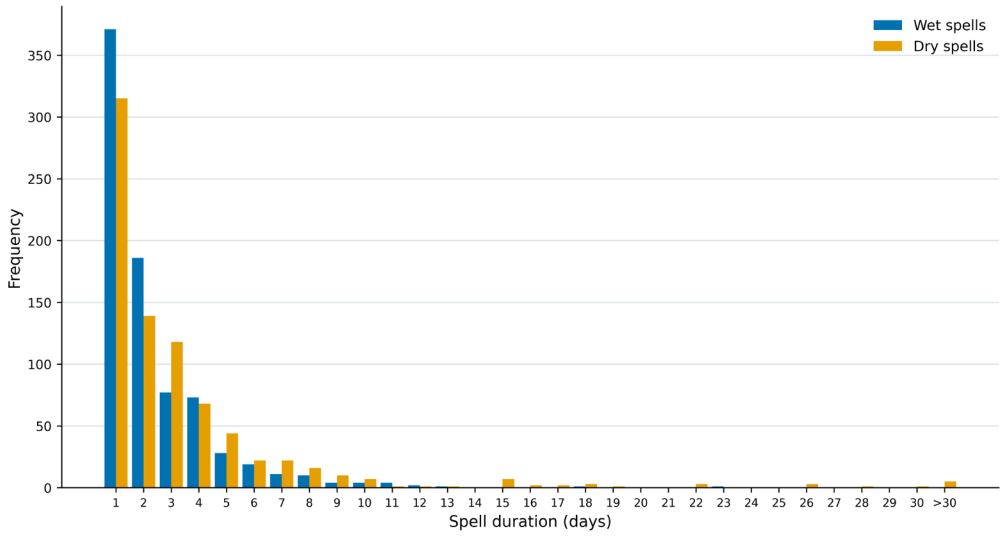


Figure 4. Frequency distribution of wet- and dry-spell durations at the Chã de Macela station during 2011–2023. Durations exceeding 30 days were grouped into a single terminal class (>30 days).

The frequency distribution reveals a pronounced positive skewness, with a large number of short-duration events and a relatively small number of highly persistent episodes. Although most wet spells lasted only one to three days, several episodes exceeded ten consecutive days, demonstrating the capacity of the regional climate system to sustain prolonged precipitation regimes. An even greater persistence was observed for dry spells, including a small number of exceptionally long events.

The maximum wet-spell duration reached 23 consecutive days. The screened series also yielded a 110-day dry sequence extending from 1 October 2011 to 18 January 2012. Because

the 2012 portion overlaps a repeated day-of-year block identified during quality-control screening, this sequence is reported as a descriptive feature of the supplied record rather than as an independently validated drought episode (Table S1, Supplementary Materials).

The sensitivity analysis, summarized in Table S2 of the Supplementary Materials, identified two isolated one-day gaps that could be conditionally bridged: 1 December 2017 between two wet days and 31 December 2017 between two dry days. Under this alternative rule, the numbers of wet and dry spells each decreased from 792 to 791. Mean wet- and dry-spell durations changed only from 2.367 to 2.372 days and from 3.515 to 3.521 days, respectively. The maximum wet-spell duration remained 23 days, the maximum dry-spell duration remained 110 days, and the number of persistent wet spells remained 85. The principal persistence metrics were therefore insensitive to the treatment of isolated missing precipitation days. The interpretation of the 110-day sequence nevertheless remains subject to the source-structure limitation documented in Table S1.

The most persistent wet spells are examined in greater detail in the following subsection.

3.3.2. Most Persistent Wet Spells

The ranking of wet spells according to accumulated precipitation provides further insight into the hydrometeorological significance of persistent rainfall regimes at the Chã de Macela station. The ten wet spells with the highest accumulated precipitation are presented in Figure 5. The most significant event occurred between 28 February and 22 March 2013, lasting 23 consecutive days and accumulating approximately 304 mm of precipitation. This episode represents the most persistent and hydrologically important wet spell identified during the 2011–2023 period. The accumulated rainfall during this event substantially exceeded that of all other wet spells, highlighting its exceptional character within the observational record.

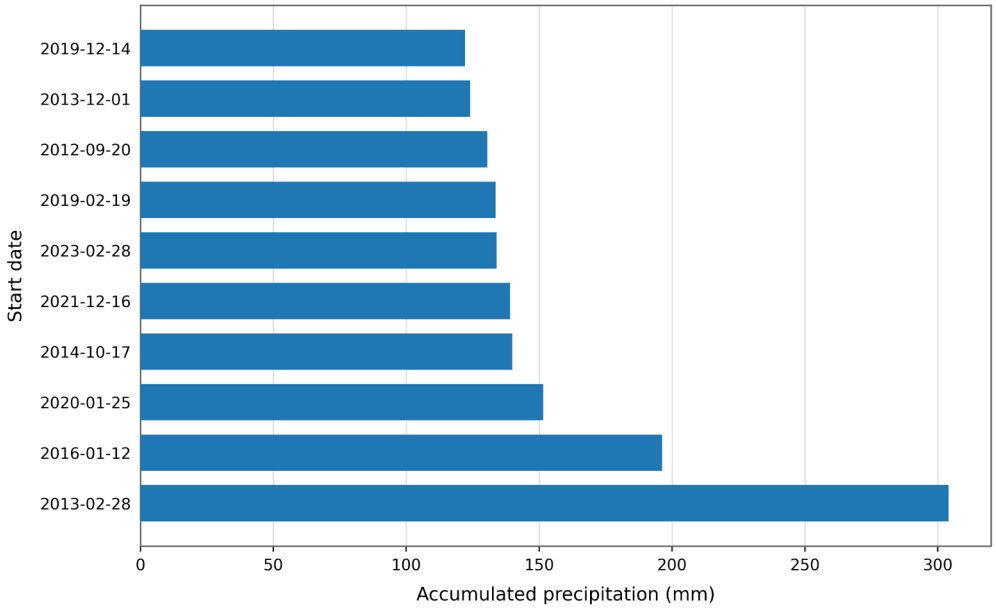


Figure 5. Ten wet spells with the highest accumulated precipitation at the Chã de Macela station during 2011–2023.

The second most important event began on 12 January 2016 and accumulated approximately 196 mm of precipitation. Other notable wet spells accumulated between 134.0 and 151.5 mm, including those beginning on 25 January 2020, 17 October 2014, 16 December 2021

and 28 February 2023. These episodes occurred in different seasons and years of the observational period.

A notable feature of Figure 5 is the presence of the wet spell beginning on 28 February 2023 among the most important rainfall episodes. This event is particularly relevant because it also contained one of the core compound hydrometeorological events identified in the study, illustrating the close relationship between persistence and hydrometeorological severity.

Several wet spells accumulated more than 120 mm of precipitation, showing that prolonged rainfall periods contributed substantially to precipitation variability at Chã de Macela. The occurrence of extreme precipitation and compound hydrometeorological events within these spells is examined in the following subsection.

3.4. Compound Hydrometeorological Events

The compound-event analysis revealed that the simultaneous occurrence of multiple hydrometeorological extremes was relatively uncommon during the 2011–2023 study period. Although 233 days met or exceeded the precipitation P95 threshold and 47 days met or exceeded the P99 threshold, only eight events satisfied the criteria established for core compound hydrometeorological events, namely the concurrent occurrence of precipitation ≥ P95, wind speed ≥ P90, and relative humidity ≥ P90.

The full-record precipitation thresholds were 16.310 mm day^{-1} for P95 and 36.168 mm day^{-1} for P99. When the reference population was restricted to wet days, the corresponding thresholds increased to 26.030 and 51.382 mm day^{-1}, respectively. These wet-day-based thresholds identified 94 P95 days and 19 P99 days, compared with 233 and 47 days under the full-record thresholds. They also reduced the number of same-day compound-event days from eight to four. Allowing the P90 wind-speed and relative-humidity thresholds to occur within ±1 day of the P95 precipitation day increased the number of qualifying compound-event days from eight to 15 under the full-record P95 threshold and from four to six under the wet-day P95 threshold (Table S4).

The annual indicators showed substantial temporal variation in both variables (Table S3). Annual mean values of the reported wind-speed field ranged from 1.51 to 22.61 km h^{-1}, and annual frequencies of exceedance of the full-record P90 threshold ranged from 0% to 45.31%. The particularly high values in 2017 were influenced by the flagged wind-speed interval documented in Table S1. For relative humidity, annual means ranged from 48.50% to 86.39%, while annual P90 exceedance frequencies ranged from 0% to 27.33%. Relative-humidity exceedance frequencies were between 15.34% and 27.33% during 2019–2023, compared with 0–5.81% during 2011–2018. Because the record contains the scale-inconsistent intervals documented in Table S1, these differences cannot be attributed exclusively to climatic variability or to changes in the observing system.

The eight compound-event days identified using the station-relative criteria are presented in Table 3. They occurred between 2019 and 2023 and combined extreme precipitation with locally elevated values of the reported daily wind-speed field and high relative humidity. These eight cases constitute the exploratory event set used in the subsequent persistence and synoptic analyses.

Reported daily wind speed among the eight compound events ranged from 8.60 to 14.80 km h^{-1} (2.39–4.11 m s^{-1}). These values correspond to the upper part of the wind-speed distribution at Chã de Macela but are modest in absolute terms. The wind criterion should therefore be interpreted as a station-relative indicator of locally elevated values in the reported daily wind-speed field, rather than as a threshold for strong or damaging winds.

Table 3. Core compound hydrometeorological events identified at the Chã de Macela station during 2011–2023.

Date	Precipitation (mm)	Wind Speed (km h^{-1})	Relative Humidity (%)
17 December 2019	18.5	10.04	97.52
27 December 2019	25.8	9.04	100.00
28 January 2020	28.7	9.10	100.00
2 June 2020	18.8	12.70	97.96
3 January 2021	32.2	10.42	97.49
30 December 2022	17.2	8.60	99.70
28 February 2023	53.8	8.70	98.50
6 June 2023	63.3	14.80	99.30

Note: Core compound events were defined by the simultaneous occurrence of precipitation ≥ P95, wind speed ≥ P90, and relative humidity ≥ P90. Event classification was based on the unrounded percentile thresholds.

Among the eight identified compound events, the event of 6 June 2023 recorded the highest daily precipitation (63.3 mm) and wind speed (14.8 km h^{-1}), together with a relative humidity of 99.3%. The event of 28 February 2023 recorded the second-highest daily precipitation (53.8 mm), with a relative humidity of 98.5%. All eight compound events occurred between December 2019 and June 2023. Given the 13-year observational record and the small number of events, this temporal concentration alone should not be interpreted as evidence of a long-term trend.

A sensitivity analysis was performed by retaining the P95 precipitation criterion and raising the thresholds for the reported daily wind-speed field and relative humidity from P90 to P95. The primary definition, based on wind speed ≥ P90 and relative humidity ≥ P90, identified eight events. Raising only the wind-speed threshold to P95 (11.68 km h^{-1}) reduced the number to two events, whereas raising only the relative-humidity threshold to P95 (99.35%) identified three events. No events satisfied both the P95 wind speed and P95 relative-humidity criteria. The number of identified events therefore depended markedly on the selected percentiles. The P90 criteria were retained as the primary station-relative definition because they identify the upper decile of the reported daily wind-speed field and of relative humidity within the Chã de Macela record. The resulting events were therefore treated as an exploratory set rather than as an operational or impact-based hazard category.

The additional quality-control sensitivity analysis showed that the compound-event catalogue was also sensitive to the documented source-structure issues (Table S6). After excluding January–September 2012, both alternative treatments of the flagged 0–1 relative-humidity intervals—conversion to percent or exclusion—identified the same four compound-event days (27 December 2019, 28 January 2020, 2 June 2020, and 6 June 2023), two of which occurred within persistent wet spells (50%). When thresholds were recalculated using 2019–2023 only, three compound-event days were identified, two within persistent wet spells (66.7%). These results indicate that the eight-event catalogue and the 75% persistence share depend on the treatment of documented inconsistencies in the station record.

The occurrence of these events across wet-spell duration classes is examined in the following section.

3.5. Wet-Spell Persistence and Hydrometeorological Severity

The analyses presented in the previous sections indicate that hydrometeorological severity at Chã de Macela is influenced not only by the intensity of individual precipitation events but also by the persistence of wet conditions. To investigate this relationship, the

occurrence of extreme rainfall events and compound hydrometeorological events was examined within the context of the wet-spell structure identified from the observational record.

A total of 85 wet spells were classified as persistent, corresponding to episodes lasting five or more consecutive days. Although these events represented only a small fraction of the 792 wet spells identified during the study period, they played a disproportionately important role in the occurrence of hydrometeorological extremes.

Of the 233 precipitation events meeting or exceeding the P95 threshold, 92 occurred within persistent wet spells, corresponding to approximately 39.5% of all extreme rainfall events. A similar pattern was observed for the most severe precipitation episodes. Of the 47 events meeting or exceeding the P99 threshold, 22 occurred during persistent wet spells, representing 46.8% of all very extreme rainfall events. Compound hydrometeorological events were also concentrated within persistent wet spells. Six of the eight core compound events identified in the study occurred within persistent wet spells, corresponding to 75% of the compound events. The distribution of extreme and compound events according to wet-spell duration classes is presented in Figure 6. Extreme rainfall events were observed across a broad range of wet-spell durations; however, the highest frequencies occurred within spells lasting between four and fourteen days. All eight compound-event days occurred within wet spells lasting between four and fourteen days, and six occurred within persistent wet spells lasting at least five days. No compound-event day occurred during an isolated one-day precipitation episode. Given the small number of cases, this distribution describes the temporal setting of the identified events and does not establish that persistence favours the occurrence of compound conditions.

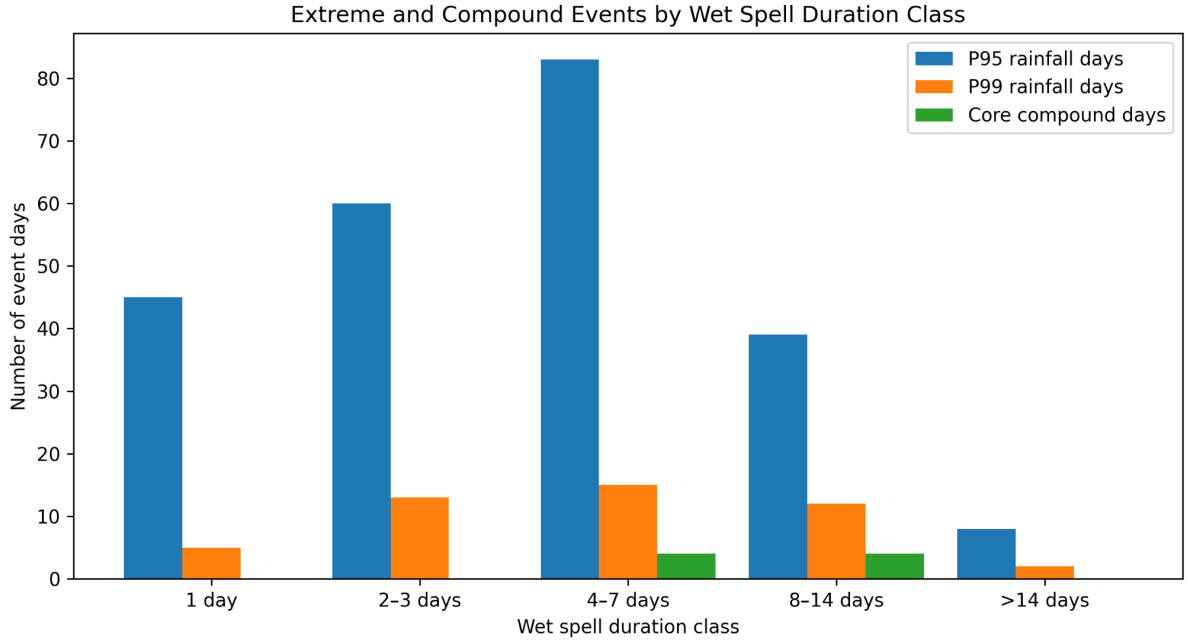


Figure 6. Distribution of P95 rainfall days, P99 rainfall days, and core compound-event days by wet-spell duration class at the Chã de Macela station during 2011–2023.

The relationship between wet-spell duration and accumulated precipitation is shown in Figure 7. The distribution also identifies wet spells containing P95 precipitation days and compound-event days, allowing precipitation accumulation and event occurrence to be examined in relation to wet-spell duration.

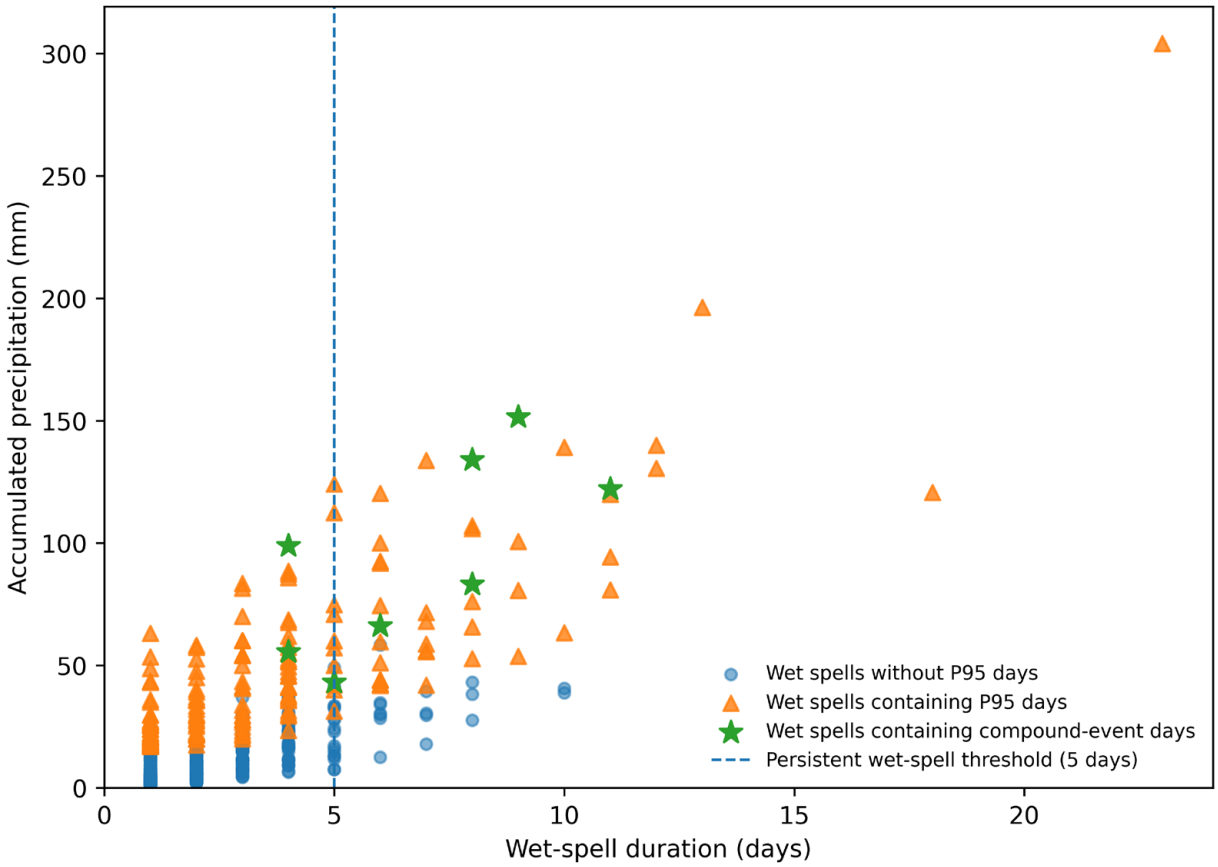


Figure 7. Relationship between wet-spell duration and accumulated precipitation at the Chã de Macela station during 2011–2023. Each point represents an individual wet spell. Wet spells containing P95 precipitation days and core compound-event days are identified separately. The vertical dashed line indicates the five-day threshold used to define persistent wet spells.

The following section examines how the precipitation regimes identified at Chã de Macela are related to MSLP and TCWV.

3.6. Relationship Between Precipitation, MSLP and TCWV

Spearman's rank correlation was used as the primary measure of association. Across all complete days ($n = 4659$), precipitation was negatively associated with MSLP ($\rho = -0.369$; 95% CI: −0.420 to −0.315) and positively associated with TCWV ($\rho = 0.173$; 95% CI: 0.125 to 0.223). The wet-day sensitivity analysis produced estimates in the same directions ($n = 1875$; MSLP: $\rho = -0.319$, 95% CI: −0.366 to −0.269; TCWV: $\rho = 0.201$, 95% CI: 0.148 to 0.253). Pearson coefficients, retained only as descriptive measures of linear association, were −0.337 for precipitation–MSLP and 0.197 for precipitation–TCWV across all complete days, and −0.286 and 0.199, respectively, when the analysis was restricted to wet days.

To compare atmospheric conditions across precipitation regimes, days were classified as dry, wet, P95, and P99 events. Mean MSLP and TCWV values are presented in Table 4. The category means showed progressively lower MSLP and higher TCWV from dry days to P99 events.

Dependence-aware contrasts in MSLP and TCWV among precipitation regimes were estimated using a circular moving-block bootstrap with 10,000 resamples and 30-day blocks. Mean differences, 95% confidence intervals, and Cliff's δ effect sizes are presented in Table 5.

Table 4. Relationship between precipitation, mean sea level pressure (MSLP), and atmospheric moisture availability (TCWV) at Chã de Macela during 2011–2023.

Metric	N	MSLP (hPa)	TCWV (kg m^{-2})
Dry days	2784	1024.03	21.73
Wet days	1875	1019.11	24.16
P95 events	233	1014.33	27.39
P99 events	47	1012.67	29.14
Correlation with precipitation (Pearson)	-	−0.337	0.197
Correlation with precipitation (Spearman)	-	−0.369	0.173

Note: Wet days were defined as days with precipitation ≥ 1 mm day^{-1}, whereas dry days had precipitation < 1 mm day^{-1}. P95 and P99 events are overlapping subsets of wet days and were classified using the unrounded percentile thresholds. N denotes the number of complete station–ERA5 records in each category. The dry- and wet-day groups together comprise 4659 records with valid precipitation, MSLP, and TCWV data.

Table 5. Dependence-aware contrasts in mean sea level pressure (MSLP) and total column water vapour (TCWV) across precipitation regimes.

Comparison	Variable	Group *n*	Reference *n*	Mean Difference	95% CI	Cliff's δ	95% CI
Wet vs. dry	MSLP (hPa)	1875	2784	−4.92	[−5.73, −4.14]	−0.381	[−0.431, −0.328]
Wet vs. dry	TCWV (kg m^{-2})	1875	2784	2.43	[1.79, 3.11]	0.176	[0.125, 0.229]
P95 vs. non-extreme wet	MSLP (hPa)	233	1642	−5.45	[−6.76, −4.14]	−0.394	[−0.468, −0.315]
P95 vs. non-extreme wet	TCWV (kg m^{-2})	233	1642	3.69	[2.59, 4.71]	0.281	[0.202, 0.355]
P99 vs. non-extreme wet	MSLP (hPa)	47	1642	−7.11	[−9.25, −4.79]	−0.545	[−0.682, −0.384]
P99 vs. non-extreme wet	TCWV (kg m^{-2})	47	1642	5.44	[3.42, 7.51]	0.436	[0.298, 0.567]

Note: Differences are expressed as the first group minus the reference group. Non-extreme wet days (n = 1642) were defined as days with precipitation ≥ 1 mm day^{-1} and below the unrounded P95 threshold. The comparison groups comprised 1875 wet days, 2784 dry days, 233 P95 days, and 47 P99 days. P99 days form a subset of the P95 group. Confidence intervals were obtained from 10,000 circular moving-block bootstrap samples using 30-day blocks.

Wet days had a mean MSLP 4.92 hPa lower and a mean TCWV 2.43 kg m^{-2} higher than dry days. Relative to non-extreme wet days, P95 events had a mean MSLP 5.45 hPa lower (95% CI: −6.76 to −4.14) and a mean TCWV 3.69 kg m^{-2} higher (95% CI: 2.59 to 4.71). The corresponding differences for P99 events were −7.11 hPa (95% CI: −9.25 to −4.79) and 5.44 kg m^{-2} (95% CI: 3.42 to 7.51), respectively. These estimates indicate that more intense precipitation days in the station record were associated with lower atmospheric pressure and greater moisture availability. They describe statistical associations and do not, by themselves, establish causation or distinguish compound from non-compound P95 events.

The distribution of MSLP across the four precipitation regimes is shown in Figure 8.

The progressive decrease in MSLP from dry days to P99 events indicates that increasing precipitation intensity was associated with progressively lower-pressure conditions. Atmospheric moisture availability also varied across the precipitation regimes, as shown by the TCWV distributions presented in Figure 9. Together, Figures 8 and 9 document the concurrent variation in MSLP and TCWV across precipitation categories at Chã de Macela.

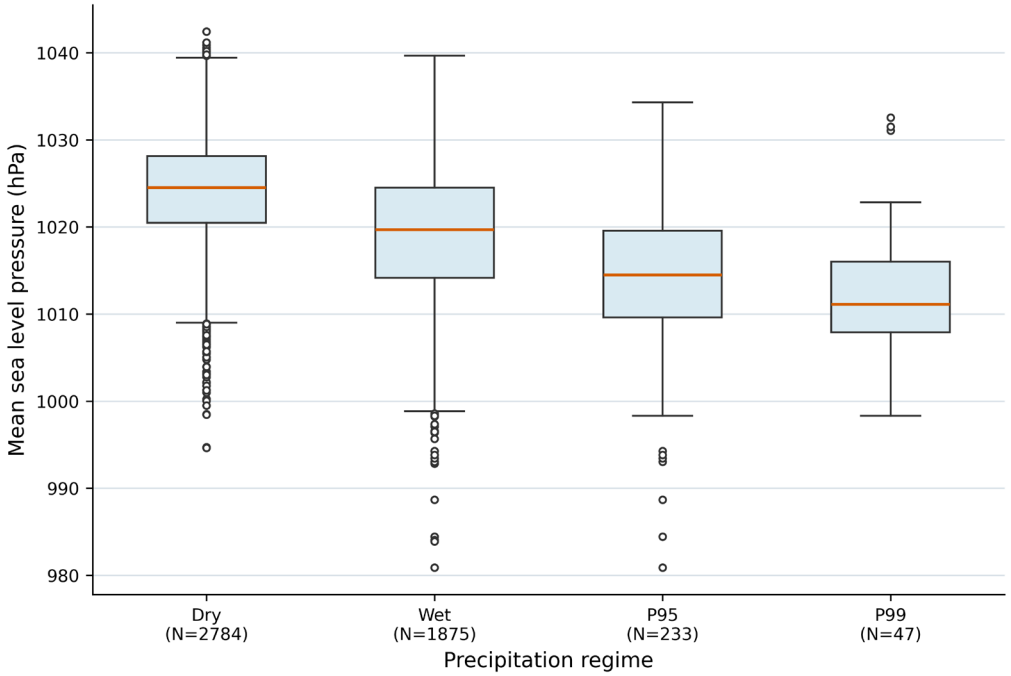


Figure 8. Distribution of mean sea level pressure (MSLP) for dry days, wet days, and extreme precipitation events (P95 and P99) at Chã de Macela during 2011–2023. Light-blue boxes represent the interquartile range (25th–75th percentiles), and orange lines indicate medians. Whiskers extend to the most extreme observations within 1.5 times the interquartile range below the first quartile and above the third quartile; open circles represent observations beyond these limits. N denotes the number of observations in each category.

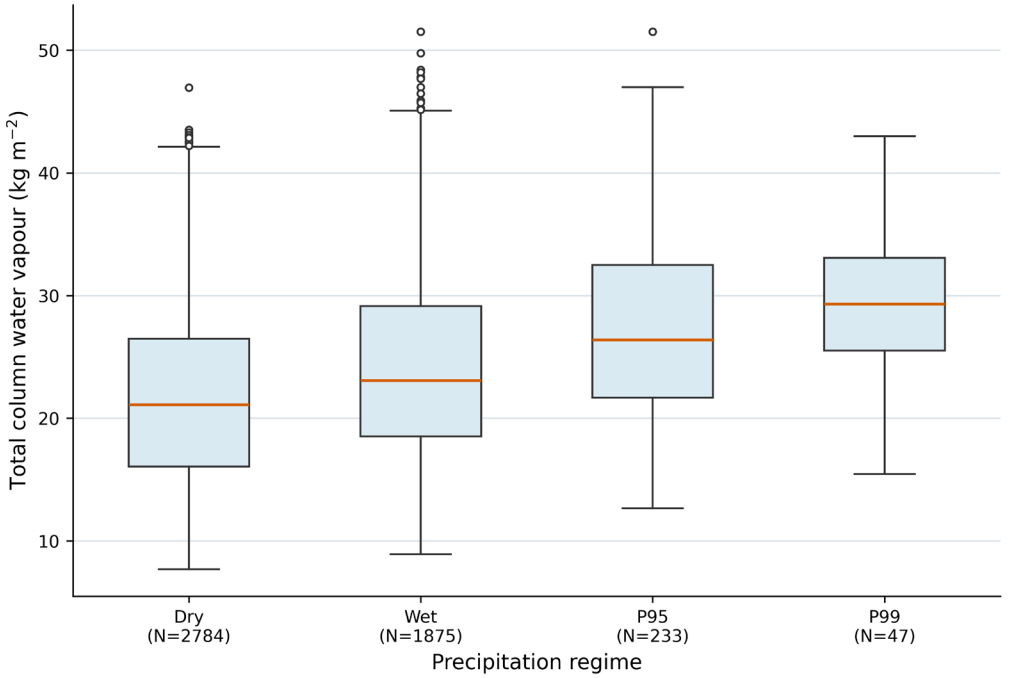


Figure 9. Distribution of total column water vapour (TCWV) for dry days, wet days, and extreme precipitation events (P95 and P99) at Chã de Macela during 2011–2023. Light-blue boxes represent the interquartile range (25th–75th percentiles), and orange lines indicate medians. Whiskers extend to the most extreme observations within 1.5 times the interquartile range below the first quartile and above the third quartile; open circles represent observations beyond these limits. N denotes the number of observations in each category.

Median TCWV increased from approximately 21 kg m^{-2} during dry days to approximately 29 kg m^{-2} during P99 events, while MSLP decreased progressively across the precipitation regimes. This pattern indicates that extreme precipitation at Chã de Macela was associated with greater atmospheric moisture availability and lower-pressure conditions; it does not, by itself, establish a distinct circulation mechanism. To examine whether compound events occurred under conditions different from those of other P95 days, MSLP and TCWV were compared between compound and non-compound P95 days presented in Table 6. Of the 233 P95 days, 227 had valid wind-speed and relative-humidity observations and could be classified: eight met the compound-event criteria, and 219 did not. The remaining six days were excluded from this comparison because wind-speed or relative-humidity observations were missing.

Table 6. Dependence-aware comparison of mean sea level pressure (MSLP) and total column water vapour (TCWV) between compound and non-compound P95 days.

Variable	Compound P95 Days, Mean ($n = 8$)	Non-Compound P95 Days, Mean ($n = 219$)	Mean Difference	95% CI	Cliff's δ	95% CI
MSLP (hPa)	1010.08	1014.58	−4.49	[−9.04, −0.69]	−0.360	[−0.628, −0.066]
TCWV (kg m^{-2})	28.52	27.32	1.20	[−1.79, 4.11]	0.167	[−0.094, 0.428]

Note: Differences are expressed as compound minus non-compound P95 days. Of the 233 P95 days, 227 had valid reported daily wind-speed and relative-humidity observations and could be classified; eight met the compound-event criteria, and 219 did not. Six P95 days were excluded because wind-speed or relative-humidity observations were missing. Confidence intervals were obtained from 10,000 circular moving-block bootstrap samples using 30-day blocks.

Compound P95 days had a mean MSLP 4.49 hPa lower than non-compound P95 days (95% CI: −9.04 to −0.69; Cliff's $\delta = -0.360$). The estimated mean TCWV difference was 1.20 kg m^{-2}, but its confidence interval included zero (95% CI: −1.79 to 4.11; Cliff's $\delta = 0.167$). Thus, the eight compound events were associated with lower MSLP, whereas the evidence for a difference in TCWV was inconclusive. Given the small number of compound events, these estimates should be interpreted as exploratory. The synoptic evolution of the compound events is presented in the following section as case-study context.

3.7. Synoptic Context of Selected Compound Events

To examine the synoptic context within the eight-event set, mean sea level pressure (MSLP) and 500-hPa geopotential height (Z500) fields were analysed for one representative event from each of the three descriptive configurations suggested by visual examination. The event of 6 June 2023, representing the persistent closed cyclonic system configuration, was selected as the first case because it recorded the highest daily precipitation and the highest reported daily wind speed among the eight events, together with near-saturated relative humidity. Its synoptic evolution is shown in Figure 10.

The compound event of 6 June 2023 was associated with the progressive development of a deep synoptic-scale depression over the central North Atlantic (Figure 10). Between 3 and 5 June, mean sea level pressure decreased steadily, while a closed low-geopotential centre became established at 500 hPa. The correspondence between low surface pressure and reduced geopotential heights indicates a vertically coherent cyclonic structure affecting the Azores.

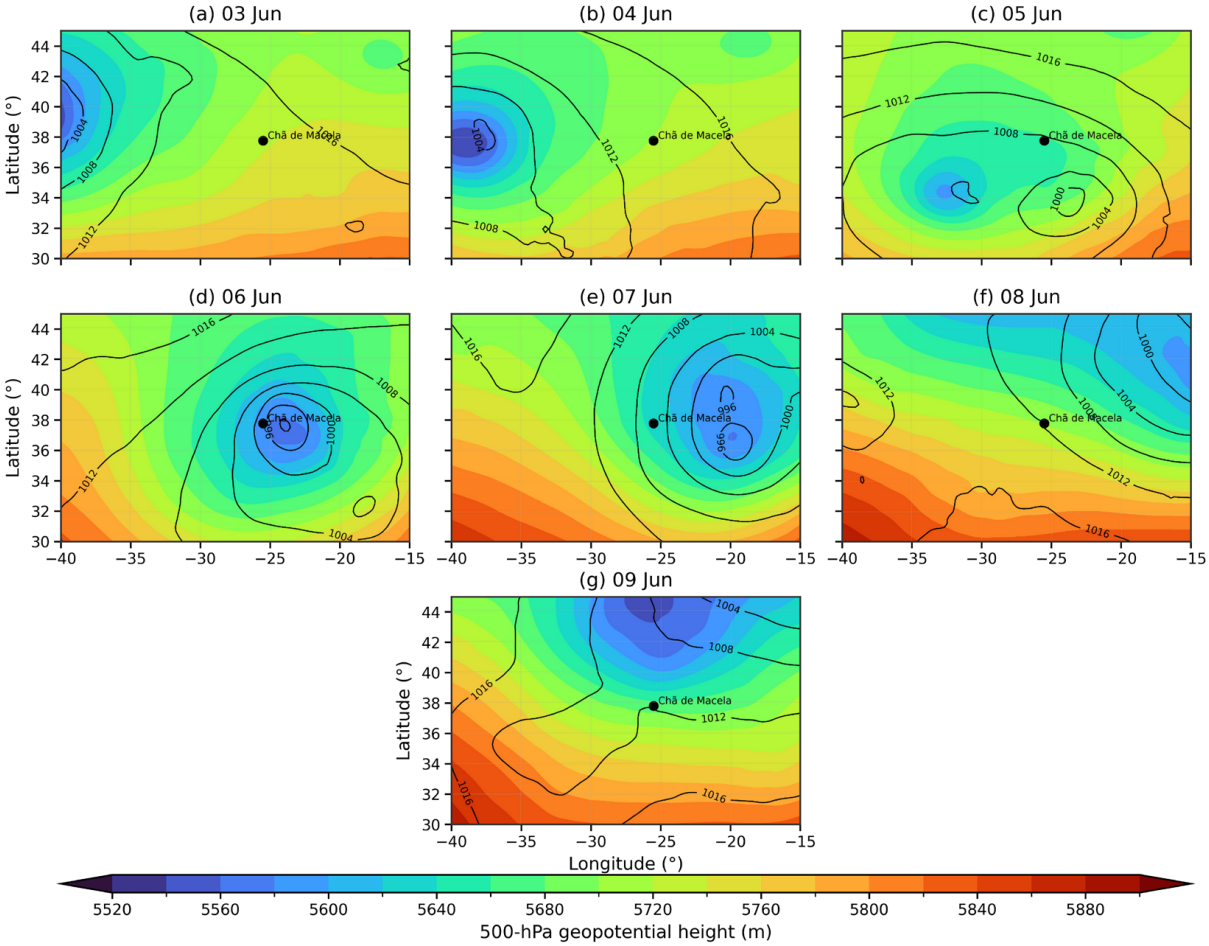


Figure 10. Evolution of mean sea level pressure (MSLP; black contours, hPa) and 500-hPa geopotential height (color shading, m), shown at 12:00 UTC on each day: (**a**) 3 June 2023; (**b**) 4 June 2023; (**c**) 5 June 2023; (**d**) 6 June 2023, the compound-event day; (**e**) 7 June 2023; (**f**) 8 June 2023; and (**g**) 9 June 2023. The black circle marks the location of Chã de Macela.

The event reached maximum intensity on 6 June, when precipitation at Chã de Macela reached 63.3 mm. At this stage, the depression attained its greatest intensity near the Azores, with minimum sea-level pressures of approximately 992–994 hPa and a well-defined closed circulation at 500 hPa. Following the event peak, the system progressively weakened and shifted eastward between 7 and 9 June, accompanied by a gradual recovery of the pressure and geopotential-height fields.

The persistence of the cyclonic circulation over several consecutive days is consistent with dominant synoptic-scale forcing during the event. Its vertical coherence and persistence support its classification as a persistent closed cyclonic system extending from the surface to the middle troposphere.

Figure 11 presents the synoptic evolution of the compound event of 28 February 2023, selected to represent the category characterized by pronounced meridional gradients.

Figure 11 shows the synoptic evolution associated with the compound hydrometeorological event of 28 February 2023. Between 25 and 28 February, a broad cyclonic circulation developed over the central North Atlantic, characterized by a deep low-pressure system located northwest of the Azores and a pronounced meridional gradient in 500-hPa geopotential height. During this period, the geopotential-height gradient progressively intensified, placing São Miguel near the transition zone between lower geopotential heights to the northwest and higher geopotential heights to the southeast. Maximum precipitation at Chã de Macela (53.8 mm) occurred on 28 February, when the station lay within the pronounced

meridional geopotential-height gradient associated with this circulation pattern. Unlike the compound event of 6 June 2023, which was characterized by a closed cyclonic centre directly affecting the Azores, the event of 28 February occurred within a pronounced geopotential-height gradient near a deep depression, rather than during the passage of a mature, closed cyclone over the archipelago. Following the event peak, the circulation gradually weakened and shifted eastward, accompanied by increasing mean sea level pressure and a progressive recovery of geopotential heights over the region.

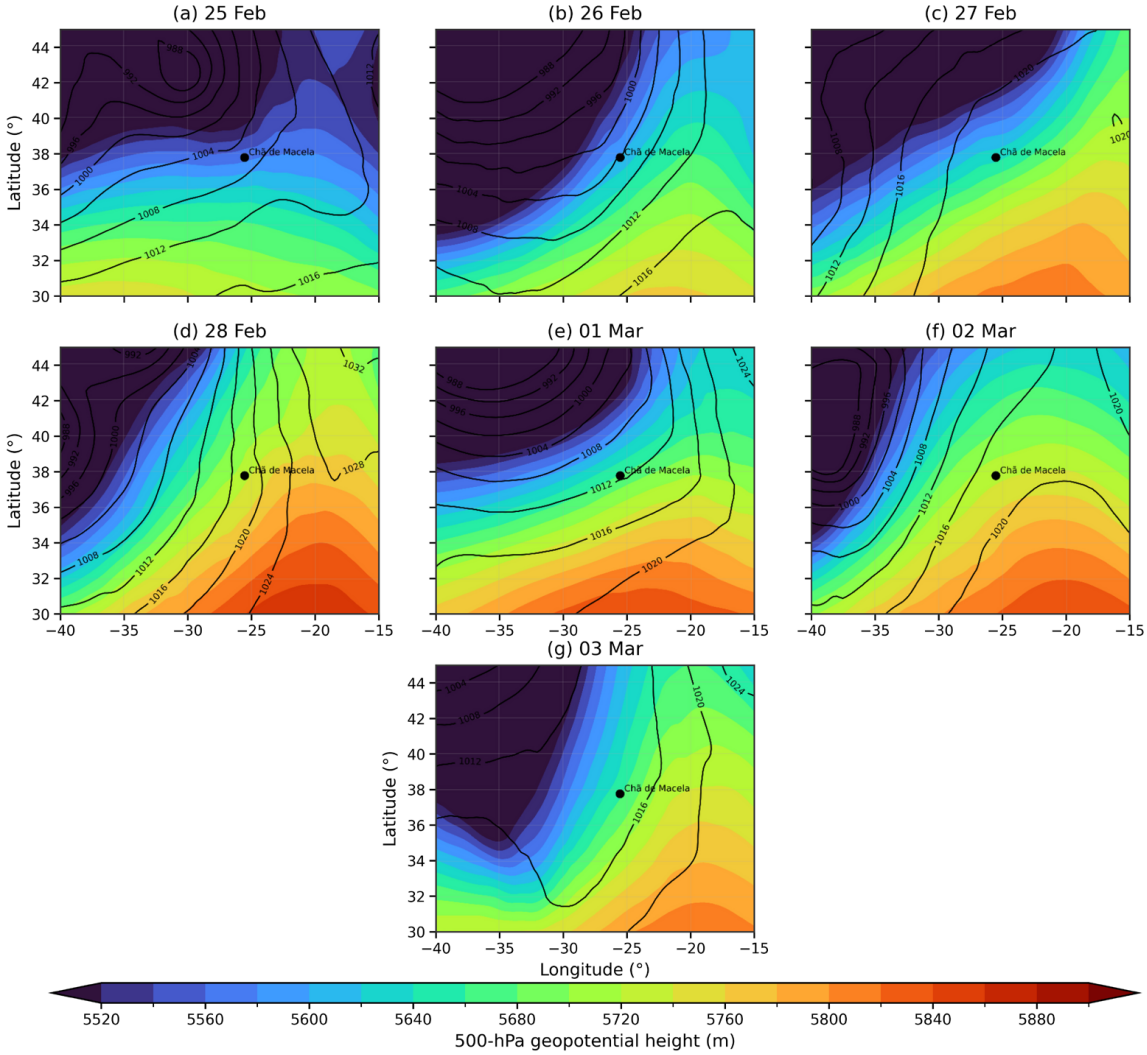


Figure 11. Evolution of mean sea level pressure (MSLP; black contours, hPa) and 500-hPa geopotential height (color shading, m), shown at 12:00 UTC on each day: (**a**) 25 February 2023; (**b**) 26 February 2023; (**c**) 27 February 2023; (**d**) 28 February 2023, the compound-event day; (**e**) 1 March 2023; (**f**) 2 March 2023; and (**g**) 3 March 2023. The black circle marks the location of Chã de Macela.

This configuration supports the classification of the event within the pronounced meridional-gradient category.

Figure 12 presents the synoptic evolution associated with the compound hydrometeorological event of 28 January 2020, selected to represent the developing or pre-conditioning disturbance category.

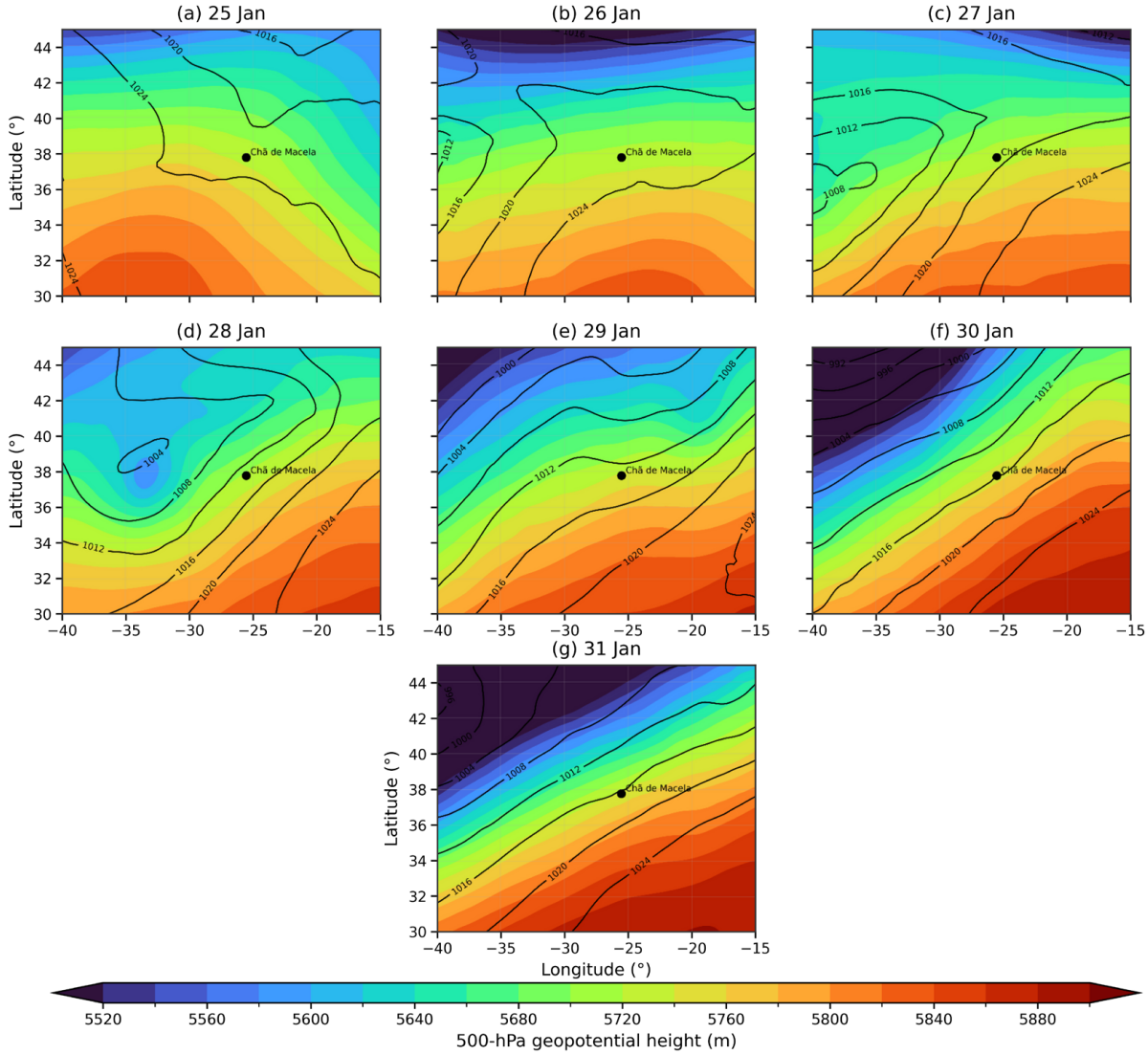


Figure 12. Evolution of mean sea level pressure (MSLP; black contours, hPa) and 500-hPa geopotential height (color shading, m), shown at 12:00 UTC on each day: (**a**) 25 January 2020; (**b**) 26 January 2020; (**c**) 27 January 2020; (**d**) 28 January 2020, the compound-event day; (**e**) 29 January 2020; (**f**) 30 January 2020; and (**g**) 31 January 2020. The black circle marks the location of Chã de Macela.

Figure 12 shows the synoptic evolution associated with the compound hydrometeorological event of 28 January 2020. In contrast to the mature closed-cyclone pattern represented by the event of 6 June 2023, this event did not coincide with the mature phase of a closed cyclonic system centred near the Azores. Between 25 and 27 January, the region was characterized by relatively high surface pressure and a broad geopotential-height gradient, with no well-defined low-pressure centre directly affecting São Miguel.

On 28 January, when maximum precipitation at Chã de Macela reached 28.7 mm, the station was located within a transition zone between lower geopotential heights to the north and higher geopotential heights to the south. Although the surface pressure field did not show a deep closed depression over the archipelago at this stage, the configuration is consistent with the development of a baroclinic disturbance. Within this case, the compound-event criteria were met during the intensification phase of the disturbance, before the circulation reached its mature stage.

After the event peak, between 29 and 31 January, the synoptic disturbance became more clearly defined, with lower geopotential heights and intensifying pressure gradients developing to the north and northwest of the Azores. This temporal sequence supports the

classification of the event as a developing or pre-conditioning disturbance, distinct from the mature, vertically coherent closed-cyclone pattern observed on 6 June 2023. This case shows that compound hydrometeorological events in São Miguel can occur at different stages of synoptic disturbance evolution and are not restricted to mature cyclonic systems.

The synoptic analyses of the remaining five compound events are provided in the Supplementary Materials (Figures S1–S5).

3.8. Exploratory Synoptic Typology of the Eight Compound Events

Visual examination of the eight cases suggested three descriptive synoptic configurations within the compound-event set. The grouping was based on the evolution of mean sea level pressure (MSLP) and 500-hPa geopotential height (Z500) and is summarized in Table 7.

Table 7. Exploratory synoptic grouping of the eight compound-event cases identified at Chã de Macela (2011–2023).

Event Date	Precipitation (mm)	Synoptic Configuration
17 December 2019	18.5	Pronounced meridional gradient
27 December 2019	25.8	Pronounced meridional gradient
28 January 2020	28.7	Developing or pre-conditioning disturbance
2 June 2020	18.8	Persistent closed cyclonic system
3 January 2021	32.2	Persistent closed cyclonic system
30 December 2022	17.2	Pronounced meridional gradient
28 February 2023	53.8	Pronounced meridional gradient
6 June 2023	63.3	Persistent closed cyclonic system

One configuration included three cases with persistent and vertically coherent cyclonic systems extending from the surface to the middle troposphere. Closed surface low-pressure centres reduced 500-hPa geopotential heights, and cyclonic circulation lasting several days were observed during the events of 2 June 2020, 3 January 2021, and 6 June 2023.

The second configuration included four cases associated with pronounced meridional gradients in geopotential height and surface pressure. The events of 17 December 2019, 27 December 2019, 30 December 2022, and 28 February 2023 occurred while São Miguel was located within transition zones between contrasting pressure and geopotential-height fields, without a mature, closed cyclone centred over the archipelago.

The remaining case, on 28 January 2020, occurred during the development and intensification of a larger-scale disturbance. The compound-event criteria were met before the associated circulation reached maximum maturity.

This grouping is an exploratory description of the circulation fields observed during the eight cases. Because the same procedure was not applied to the non-compound P95 days, the configurations cannot be interpreted as patterns unique to compound events or as estimates of their relative climatological frequency.

4. Discussion

At Chã de Macela, the temporal setting of rainfall was closely associated with event severity. Persistent wet spells (at least five consecutive days) accounted for 85 of the 792 wet spells identified, yet they contained 92 of the 233 P95 rainfall days (39.5%), 22 of the 47 P99 rainfall days (46.8%), and six of the eight compound events (75%). This concentration is important, but it should not be interpreted as evidence that persistence alone caused the compound conditions. Rainfall totals varied substantially among spells of similar duration, and the dataset does not include soil moisture, runoff or impact observations with which to test antecedent hydrological effects. Persistence is therefore interpreted here as the temporal

context in which extreme rainfall and simultaneous satisfaction of the precipitation, wind speed and relative humidity criteria were more frequent. This interpretation is consistent with studies reporting that persistent or recurrent circulation anomalies are associated with compound hydrometeorological events and hydroclimatic extremes over periods ranging from several days to weeks [13–16].

The MSLP and TCWV analyses provide complementary atmospheric context. The moving-block bootstrap estimates indicated progressively lower MSLP and higher TCWV from dry to wet days and from non-extreme wet days to P95 and P99 events, with confidence intervals that did not include zero; see Table 5. Extreme precipitation was therefore associated with lower-pressure and moister atmospheric conditions. Within the P95 set, compound days had a mean MSLP 4.49 hPa lower than non-compound days (95% CI: −9.04 to −0.69), whereas the estimated TCWV difference of 1.20 kg m^{-2} was imprecise and its confidence interval included zero (95% CI: −1.79 to 4.11). Given the small number of compound events, the MSLP contrast should be interpreted as exploratory, while the evidence for a TCWV difference remains inconclusive. These scalar comparisons do not determine why some P95 events also met the wind-speed and relative-humidity criteria, nor do they establish that the case-study synoptic configurations distinguish compound from non-compound P95 events. The sensitivity analysis further showed that the compound-event count depended on the selected station-relative thresholds. Raising either the wind-speed or relative-humidity threshold from P90 to P95 substantially reduced the number of cases, and no event met the P95 thresholds for both variables. The eight-event set should therefore be interpreted as an exploratory classification of extreme precipitation accompanied by locally elevated values of the reported daily wind-speed field and high relative humidity, rather than as a distinct impact-based hazard class. Evaluation against wind-gust or documented impact data would be required to establish its operational significance.

The ERA5 values were obtained from a single grid point and cannot resolve the coastal and topographic variability surrounding Chã de Macela. Sensitivity to alternative spatial extractions was not evaluated. The numerical MSLP and TCWV estimates are therefore interpreted as regional atmospheric context rather than as local station-scale conditions.

The compound-event count was sensitive to both the precipitation reference population and the temporal co-occurrence rule. Daily aggregation may assign precipitation and elevated wind associated with the same frontal passage to adjacent calendar days, particularly when the passage occurs near midnight. The same-day definition is therefore conservative with respect to temporal alignment. Conversely, the ±1-day window may include conditions that occurred during different stages of a weather system or arose by chance within the three-day interval. The eight same-day cases were consequently retained as the primary exploratory event set, while the alternative counts are reported as sensitivity results.

High relative humidity and reduced solar radiation during heavy-rainfall days are physically linked to moist, cloudy, and precipitating conditions and may arise from the same weather system. Their co-occurrence with P95 precipitation does not demonstrate an independent contribution to hazard. In this analysis, relative humidity describes near-saturated station conditions accompanying extreme precipitation, and the low-radiation combination provides a secondary description of cloud-related conditions. Since no impact data were included, the additional risk associated with either criterion could not be quantified.

Studies in China and at the global scale have reported that precipitation extremes respond more strongly to warming than mean or total precipitation [17,18]. Long-term change and relationships with large-scale climate indices were not examined in this 13-year, single-station study.

The concentration of all eight compound events after 2018 should not be interpreted as evidence of a temporal trend. The quality-control screening documented data com-

pleteness and flagged potentially anomalous observations, as detailed in Table S1 of the Supplementary Materials. The annual summaries presented in Table S3 show substantial temporal variation in the reported wind speed and relative humidity fields. Detailed metadata on changes in instrumentation, exposure, logging resolution, and daily aggregation were unavailable, and no suitable independent station series was identified for a relative homogeneity assessment. The available information therefore does not allow the observed variation to be attributed reliably either to climatic variability or to changes in the observing system.

The quality-control sensitivity analysis confirmed that the compound-event catalogue is sensitive to the documented structure of the station record. Both correction and exclusion of the flagged relative-humidity intervals, combined with exclusion of the repeated January–September 2012 block, reduced the catalogue from eight to four events and the proportion occurring within persistent wet spells from 75% to 50%. A 2019–2023 analysis using period-specific thresholds yielded three events, two of which occurred within persistent wet spells. The eight events are therefore retained as the primary record-relative catalogue under the original full-record definition, but neither their number nor the 75% persistence share should be interpreted as robust to alternative treatment of the documented data inconsistencies.

The observations were not homogenized, and a shorter analysis period was not selected solely from the station series, because either procedure could remove genuine climatic variability or introduce unsupported adjustments. Longer records and observations from other Azorean stations will be required to reassess their temporal distribution. The case analyses separated the eight compound events into three synoptic configurations. Three events occurred with persistent, vertically coherent cyclonic systems; four occurred within pronounced meridional gradients in surface pressure and 500-hPa geopotential height; and the event of 28 January 2020 developed while a larger disturbance was still intensifying. The gradient cases are especially informative because they show that a cyclone did not need to be centred over the archipelago for compound conditions to occur. Rather, São Miguel could be affected by conditions within a transition zone on the flank of a North Atlantic disturbance. Multiple circulation patterns have also been associated with compound rainfall–wave events in the north-western Mediterranean [19] and with severe flash-flood-producing storms in Liguria [20]. The agreement is conceptual rather than evidence of identical mechanisms: the regions, hazards and diagnostics differ. The three configurations provide a descriptive framework for the eight compound events rather than evidence of circulation patterns that distinguish compound from non-compound extreme-rainfall days. Cyclonic systems, pronounced pressure gradients, and developing disturbances may also occur during other wet or extreme-rainfall events. Because the MSLP and Z500 sequences were not classified for the non-compound P95 days, their relative frequency or enrichment could not be quantified. The maps should therefore be interpreted as case-study context showing the synoptic evolution of the selected events. A systematic comparison would require an objective circulation classification applied to the full set of extreme-rainfall days.

The coexistence of these configurations is physically consistent with the position of the Azores between subtropical and mid-latitude circulation regimes. São Miguel may be influenced by mature cyclones, by pronounced pressure and geopotential-height gradients on their flanks, or by disturbances that have not yet reached maximum development. In that setting, a single circulation index or pressure threshold is unlikely to capture the full range of atmospheric configurations associated with the compound events identified here. Compound hydrometeorological events can arise from interactions among meteorological conditions, antecedent conditions, and large-scale atmospheric processes operating over different temporal and spatial scales [21–25]. The relative influence of these factors may

vary with event severity [26], so mechanisms identified for ordinary wet days cannot be assumed to apply to the most severe precipitation events.

Wet-spell duration may serve as a screening variable when interpreted together with rainfall intensity and evolving synoptic fields; the observed 75% share does not establish predictive skill, particularly with only eight compound events. Evaluation over longer records and at additional stations is needed before persistence can be used in an operational warning framework. Future analyses should also include low-level winds, integrated water-vapour transport, moisture-flux convergence and atmospheric-river diagnostics, and should link atmospheric conditions to soil moisture, streamflow and documented impacts. Extending the analysis to other stations would broaden the spatial basis of the study and determine whether the three configurations recur across the Azores.

Previous regional studies considered projected changes in precipitation seasonality and extreme events in the Azores [27,28]. Carvalho et al. [28] worked at a broader spatial scale, using ERA5 and CMIP6 to examine historical and projected climate indices. Here, daily observations from Chã de Macela are used to identify wet-spell persistence and compound events, and each event is examined using MSLP, TCWV and Z500 fields. The difference is therefore one of both scale and inference: regional climate projections in the earlier study and event-by-event links between local observations and synoptic evolution in the present analysis.

5. Conclusions

This study investigated hydrometeorological variability at the Chã de Macela station (São Miguel Island, Azores) using daily station observations for 2011–2023 after quality-control screening, together with ERA5 atmospheric reanalysis data. Particular emphasis was placed on the identification of extreme precipitation events, wet and dry spell persistence, compound hydrometeorological events, and the synoptic context observed during their occurrence.

The results revealed a pronounced seasonal precipitation cycle characteristic of the Azorean climate, with the wettest conditions occurring during autumn and winter and the driest conditions during summer. Although most wet and dry spells were short-lived, the analysis identified several highly persistent episodes, including a 23-day wet spell that accumulated approximately 304 mm of precipitation. These findings demonstrate the importance of persistence as a fundamental component of hydrometeorological variability in the study area.

A total of 233 P95 precipitation days, 47 P99 precipitation days, and eight core compound-event days were identified. Persistent wet spells contained 92 of the 233 P95 days (39.5%), 22 of the 47 P99 days (46.8%), and six of the eight compound-event days (75%). These proportions describe the temporal distribution observed within the station record. The small number of compound events does not support conclusions about the predictive or causal role of wet-spell persistence. The compound-event count and persistence share were sensitive to alternative treatments of documented inconsistencies in the station record and should therefore be interpreted as record-dependent estimates.

The integration of station observations with ERA5 reanalysis data showed that extreme precipitation at Chã de Macela generally occurred under lower-pressure and moister atmospheric conditions. Relative to non-extreme wet days, P95 events were associated with lower MSLP and higher TCWV. Within the P95 set, the eight compound days had lower MSLP than the 219 non-compound days, whereas the TCWV contrast was inconclusive. Given the small number of compound events, these results should be interpreted as exploratory. MSLP and TCWV describe the broad atmospheric setting of the events but do not, by themselves, explain why some P95 days also satisfied the wind-speed and relative-humidity criteria.

Visual examination of the eight compound-event cases suggested three descriptive synoptic configurations: persistent and vertically coherent cyclonic systems, pronounced meridional gradients in geopotential height and surface pressure, and a developing large-scale disturbance. These configurations provide a framework for describing the selected cases. Because the same analysis was not applied to non-compound P95 days, the results do not establish that these configurations are characteristic of, or exclusive to, compound events.

Precipitation persistence and synoptic context provide complementary information for characterizing compound hydrometeorological events in São Miguel. Longer records and observations from additional stations are needed to determine whether the relationships identified at Chã de Macela also occur elsewhere in the Azores.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrometeorology1020012/s1, Table S1: Audit trail of observations and data intervals flagged during quality-control screening of the Chã de Macela daily station file (2011–2023); Table S2: Sensitivity of wet- and dry-spell metrics to the treatment of isolated missing precipitation days; Table S3: Annual statistics and full-record P90 exceedance frequencies for the reported daily wind-speed and relative-humidity fields; Table S4: Sensitivity of precipitation percentile thresholds and compound-event counts to the precipitation reference population and temporal co-occurrence rule; Table S5: Sensitivity of moving-block bootstrap confidence intervals to block length; Table S6: Sensitivity of compound-event identification to alternative treatment of documented station-record inconsistencies; Supplementary Text S1: Additional compound-event analysis; Figures S1–S5: Synoptic evolution of the five additional compound events.

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Abbreviations

The following abbreviations are used in this manuscript:

ERA5	ECMWF Reanalysis version 5
ECMWF	European Centre for Medium-Range Weather Forecasts
MSLP	Mean Sea Level Pressure
TCWV	Total Column Water Vapour
Z500	Geopotential height at 500 hPa

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