https://doi.org/10.5194/hess-2023-104
Preprint. Discussion started: 10 May 2023

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Synoptic weather patterns conducive to compound extreme rainfall-wave events in the NW Mediterranean

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Abstract. The NW Mediterranean coast is an area at high risk of impacts generated by extreme rainstorms and coastal (wave) storms, which generally result in flash floods, coastal erosion, and flooding along a highly urbanised territory. In many cases, these storms occur simultaneously, and compound events can increase the local impacts (when they occur in the same place) or accumulate the impact throughout the territory (when they occur in different locations). In both cases, multivariate and spatially compound events represent a challenge for risk management because they can overwhelm the capacity of emergency services. In this study, we analysed the prevailing atmospheric conditions during the occurrence of different types of extreme episodes to produce the first classification of synoptic weather patterns (SWPs) conducive to compound events (heavy rainfall and storm waves) in the Spanish NW Mediterranean. For this purpose, we developed a methodological framework by combining an objective synoptic classification method based on principal component analysis and k-means clustering with a Bayesian Network to characterise the nonlinear relationships between SWPs and different variables characterising storms. This method was applied to a dataset of 562 storm events recorded over 30 years, of which 112 were compound. The obtained SWPs were grouped into three main types, of which the *Cut-Off* was dominant in terms of multivariate event occurrence and was also the situation under which the most severe compound events occurred. The position and depth of the upper-level cold air pools and surface lows affect the relative weight and spatial distribution of the terrestrial (rain) and maritime (waves) components. Finally, the Bayesian Network allowed for a quantitative assessment of the obtained SWP classification by measuring the prediction skill of the target storm variables (i.e. daily precipitation or maximum wave height). Reasonably good skill results were obtained using the SWP as a predictor when accompanied by an additional variable capturing seasonality and event duration. These findings contribute to the overall understanding of compound terrestrial-maritime phenomena in the study area and may assist in the development of effective risk management strategies.

1. Introduction

The NW Mediterranean coast frequently experiences flash floods during heavy rainfall episodes (Llasat and Puigcerver, 1992; Llasat et al., 2014; Gaume et al., 2016) and coastal storms when high waves erode and flood the coastal fringe (Mendoza et al., 2011; Jiménez et al., 2012). When they occur jointly, they produce compound extreme events that significantly affect the territory by increasing the impact locally in places where both hazards concur and by distributing the impact throughout the territory because of the simultaneous occurrence in remote places (Zscheischler et al., 2020). For instance, the recent impact of the Gloria storm (January 2020) caused just in Catalonia (NW Mediterranean, Spain) four casualties; structural damage in different breakwaters along the coast; a railway bridge collapse; and impacts associated with extreme waves, rainfall, and wind action distributed throughout the territory (Amores et al., 2020, Canals and Miranda, 2020). Thus, the Consorcio de Compensación de Seguros (Spanish national reinsurance company) paid 143 million € for storm-induced damage (only for insured property) (Luján-López, 2022). A substantial challenge for adequate risk management is the intensity of the observed damages and their spatial extension because they may overwhelm protection services (e.g. during the Gloria storm, civil protection services received approximately 15,000 calls and performed 2510 services in 4 days, as reported by the Ministry of Home Affairs of the Government of Catalonia).

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Thus, compound floods as an example of compound events have attracted increasing attention during the last decade (Wahl et al., 2015; Wu et al., 2018; Bevacqua et al., 2019; Hendry et al., 2019; Camus et al., 2022**)**. However, despite the apparent high relevance of these events in the NW Mediterranean, coastal compound events have been characterised mainly as part of large-scale (continental) analyses for multivariate event types in which different hazards act simultaneously at the same location (Paprotny et al., 2018; Zscheischler et al., 2018, Bevacqua et al., 2019). A recent analysis of compound events in the NW Mediterranean found them to be relatively frequent (approximately 3.4/year) and generally dominated (at the basin scale) by the spatially compound type, in which the simultaneity of heavy rainfall and storm waves occurs in different parts of the territory, whereas some areas were dominated by multivariate events (Sanuy et al., 2021). From a risk management perspective, the magnitude of the impact and its associated risk must be attributed to the occurrence and intensity of the involved hazards and to the level of exposure and vulnerability of the affected areas (e.g. Kron, 2013).

These hazards are generated under certain weather systems; consequently, the identification of meteorological conditions conducive to extreme events of certain characteristics allows indirect estimation of their probability of occurrence (Catto and Dowdy, 2021; Camus et al., 2022) and can therefore become a relevant element in risk management. Thus, weather classification has become a fundamental tool, and various methods have been used, ranging from synoptic weather classification by manual procedures (Hess and Brezowky, 1969; Lamb, 1972) and correlation-based map typing (Yarnal, 1993; Wu et al., 2018) to approaches more subjective than those, such as principal components and clustering (e.g. Gutierrez et al., 2005; Camus et al., 2022). These weather types can be used to predict event characteristics if their links are properly characterised. In this context, Bayesian Networks (BNs) have been used to assess the dependencies of multiple nonlinearly related variables in natural hazard analysis (Beuzen et al., 2018; Plant et al., 2016; Couasnon et al., 2018) and can therefore be used to characterise the output of objective weather classification methods and their conditioning on target variables of interest (e.g. Sanuy et al., 2021).

Weather patterns dominant during rainfall and coastal storms in the NW Mediterranean have been well identified (Martín-Vide et al., 2008; Mendoza et al., 2011; Gilabert and Llasat, 2017; Gil-Guirado et al., 2021). However, synoptic weather patterns (SWPs) conducive to compound events characterised by the joint occurrence of these extreme hazards across the area have not. In this regard, a recent analysis of concurrent intense precipitation and extreme wind events over the Iberian Peninsula identified their link with cyclones and associated atmospheric rivers; however, the results suggested that the climatology of extreme weather events in the NE sectors (NW Mediterranean coast) is driven by different mechanisms (Hénin et al., 2021). Notably, the area is characterised by a complex orography that modulates precipitation and winds and a coastal storm climate characterised by the main contribution of waves to erosion and flooding due to the low relative magnitude of surges (Mendoza and Jiménez, 2009; Sanuy et al., 2020).

To investigate the meteorological conditions under which compound events are generated in the NW Mediterranean and account for their responsibility for the magnitude of contributing hazards and how they vary across the territory, we classified weather conditions during recorded storm events (univariate and compound) over 30 years (1990-2020). Principal Component Analysis (PCA) before k-means clustering using multiple atmospheric variables (e.g. Aran et al., 2011; Gil-Guirado et al., 2021; Camus et al., 2022) was applied as an objective classification approach, focusing on the mean sea level pressure (MSLP), 500 hPa geopotential height, and wind fields of individual and compound events. The types obtained were related to storm properties throughout the territory using a BN approach. This study presents the first classification of SWPs conducive to compound events on the NW Mediterranean coast, composed of episodes of heavy rainfall and storm waves.

2. Study area and data

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2.1. Study area

The study area is in the NW Mediterranean and comprises the approximately 600 km long coastline of Catalonia and the river basins flowing into it (Figure 1). The presence of many small torrential catchments in the area, combined with the orographic forcing of Mediterranean air masses, triggers convective instability and affects pressure fields (Jansà et al., 2014), leading to intense rainfall and flash floods. Studies have shown that the hydrology and morphology of a region play a significant role in the occurrence of flash floods (Llasat and Puigcerver, 1992; Llasat et al., 2014). Coastal storms in the area are dominated by NE–E extreme waves, with secondary impacts from S–SE (Mendoza et al., 2011). Wave-induced run-up during coastal storms is the main factor responsible for coastal flooding; storm surges make a lower contribution to inundation in this part of the NW Mediterranean (Mendoza and Jiménez, 2009; Sanuy et al., 2020). In recent decades, the region has experienced an overall shoreline retreat due to factors such as the reduction of sediment supply from rivers, and the presence of numerous obstacles altering the natural littoral dynamics (Jiménez and Valdemoro, 2019), such that wave action on a progressively narrowing coastline has led to a significant increase in coastal damages (Jiménez et al., 2012).

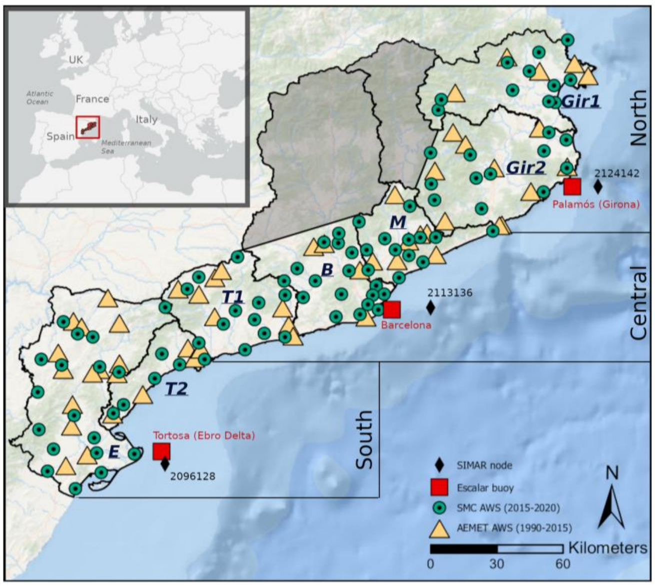

Figure 1. Study area map showing the distribution of dataset nodes in basins and coastal sectors, namely Automatic Weather Stations (AWS), wave buoys, and SIMAR data.

The terrestrial part of the study area was divided into seven sectors of natural river catchments along the coast (hereafter called basins), based on the literature (Llasat et al., 2016; Sanuy et al., 2021). This subdivision allowed for a focused analysis of direct pluvial hazards occurring in the lower part of the basins, excluding the upper part of long and regulated river catchments, such as the Ter in Girona and the Llobregat in Barcelona (Figure 1). Moreover, the marine part was divided into three large sectors covering the main wave climate areas of the coast: north, central, and south. Each wave sector characterised the corresponding waves in more than one basin (Figure 1).

2.2. Data

2.2.1 Rain

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Rainfall data for the study area were collected by Automatic Weather Stations (AWS) from two networks distributed throughout the study area, covering the coastal basins of interest (Figure 1, Table 1). The datasets included daily cumulative rainfall for 1990-2015 recorded by the Spanish State Meteorology Agency (AEMET) and 30 min data for 2015-2020 by the Meteorological Service of Catalonia (SMC), which were converted to daily cumulative precipitation before merging.

Table 1. Number of Automatic Weather Stations (AWS) per basin and dataset

Costal Sector	Basin		AEMET AWS (1990-2015)	SMC AWS (2015-2020)
North	Gir1	(Girona north)	6	11
	Gir2	(Girona south)	9	12
Central	M	(Maresme)	7	13
	B	(Barcelona)	5	16
	T1	(Tarragona north)	8	12
South	T2	(Tarragona south)	5	7
	E	(Ebro Delta)	14	18
Total			54	86

2.2.2 Waves

The wave data consisted of a reconstruction of the significant wave height (Hs) and peak period (Tp) for the Palamós, Barcelona, and Tortosa wave buoys (Figure 1) by using multilinear regression with eight atmospheric and oceanic ERA5 variables, including wind directionality (SMC, 2021). Because wave direction was excluded in the reconstruction of the observations, it was assigned for each storm event using data from the SIMAR database located near the buoys, which comprises a wave hindcast dataset up to 2006 and a wave reanalysis dataset from 2006 to the present, developed by Puertos del Estado (www.puertos.es).

2.2.3 Atmospheric variables

The synoptic classification was based on ERA5 data (Hersbach et al., 2023a and 2023b), which consisted of MSLP, 500 hPa geopotential height (Z500), and 10 m elevation wind components (U10 and V10). The data had a spatial resolution of 0.25ºx0.25º and a temporal resolution of 3 h, covering a synoptic scale from 25ºW to 30ºE longitudes and 30ºN to 65ºN latitudes.

3. Methods

3.1. General framework

The developed methodology consists of three main steps (Figure 2):

- (A) Event identification, in which rain and wave storm events are identified and typified in terms of individual or compound events based on the presence of one or both meteorological drivers.
- (B) Weather classifications associated SWPs for each event type.
- (C) BN analysis to identify dominant SWPs, compare critical SWPs, and evaluate the ability of the SWP system to estimate the target variables at the basin scale.

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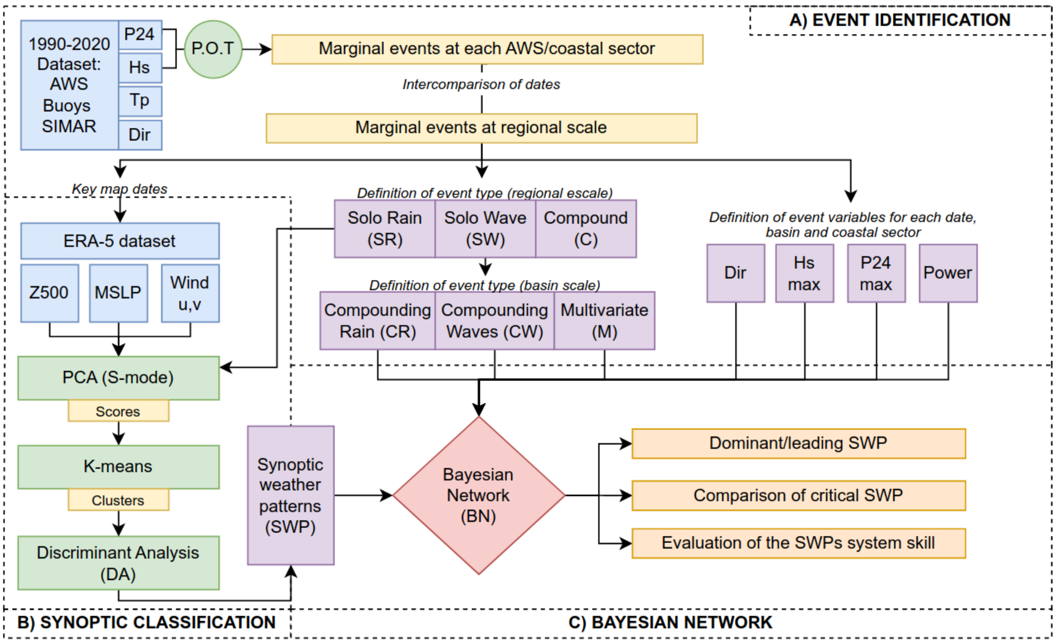

Figure 2. General methodological framework.

3.2. Event identification

In each basin, rain and coastal storm events were identified using the Peak Over Threshold method for all stations within the basin. Rainstorms were identified using a P24h threshold value of 40 mm with a 3 d interval to identify independent events. This value has been identified as the lower limit for including events that, if locally convective, can be related to flash flood potential (Barbería et al., 2014; Cortès et al., 2018). For each identified event in the basin, the maximum P24 at any station and the accumulated P24 at the same station were retained, thus obtaining a single time series of rainstorms per basin. Wave storms were identified using a dual-threshold approach (Sanuy et al., 2020) with a 0.98 quantile, 6h minimum duration, and 3 d lag for independent events to identify storms and define their duration, and the 0.995 quantile as the second threshold to retain only extreme episodes. The absolute thresholds for the 0.995/0.98 quantiles, aggregating the data of the three wave datasets, were 2.9/2.2 m, respectively. Each event was characterised by the maximum Hs and power content (approximated as the integration of H^2 Tp over the storm duration, where Tp is the wave peak period). The corresponding wave direction was obtained from the simultaneous SIMAR data by classifying the mean direction at the peak of the storm into 22.5° directional bins (i.e. NNE, NE, ENE, E, ESE, SE, SSE, S).

The final dataset of storm events comprised three types, related to their characteristics at regional scale: (i) compound events (C), defined as simultaneous rain and wave events in any of the basins; (ii) solo-rain (SR) events, characterised by the presence of a rainstorm of P24 ≥ 40 mm in at least one basin without the co-occurrence of a wave storm; and (iii) solo-wave events (SWs), characterised by no rainfall event in any basin but with a wave storm in any of the coastal sectors. At local scale, referring to Sanuy et al. (2021) and considering the different consequences of compound events from a risk management standpoint, we classified compound events at each basin as as multivariate (with both rain and wave events occurring in the same basin), compounding waves (affecting the basin only through wave events, whereas the rainstorm occurs in a different location), or compounding rain (affecting the basin only through rain events, whereas the wave storm occurs in a different sector).

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Storm (individual and compound) events were subjected to basic exploratory analysis to characterise their annual and seasonal frequencies and average magnitudes.

3.3. SWP classification

To identify the weather patterns, we used the objective methodology applied by Aran et al. (2011) and Gil-Guirado et al. (2021). The methodology comprised two steps: PCA and Cluster Analysis (CA). The PCA + CA approach was applied thrice, separately to the SR, SW, and C events identified in the previous step, using the +00 UTC maps of the date corresponding to the peak of each event (maximum rain in the case of SR and maximum wave height in the case of SW and C events).

PCA was used to reduce the data dimensions of the MSLP, Z500, and wind maps (U10 and V10). PCA was applied separately to the anomalies of the maps for each variable to ensure that only the fundamental variation modes of the data were considered in the clustering process. The number of components was determined by the scree-test (Cattell, 1966). CA was then applied to the PC score matrix to determine the main synoptic types associated with the events in the study area. The nonhierarchical k-means method was used as the clustering algorithm (McQueen, 1967), and the elbow method was used to determine the number of clusters (Thorndike, 1953 cited by Zhang et al. 2016).

All SWPs thus obtained were finally grouped into three main general synoptic patterns known to cause significant rain and winds in the NW Mediterranean (Romero et al., 1999): the Cut-Off low, Atlantic low, and Through configurations. The *Cut-Off* system is characterised by a closed upper-level low that becomes fully detached (Cut-Off) from the prevailing westerly flow and moves autonomously. It is generally observed during autumn and spring, with prolonged episodes of easterly to southerly winds over the Mediterranean Sea (Llasat et al., 2007; Ferreira, 2021). The *Through* type is characterised by the presence of an elongated region of relatively low atmospheric pressure at 500 hPa, which, unlike the cut-off lows, is not normally associated with closed circulation. This type is generally observed during late summer and autumn and is associated with prolonged episodes of northeast winds over the Mediterranean Sea (Romero et al., 1999, Gil-Guirado et al., 2021). The *Atlantic low* system is characterised by the presence of a low-pressure system in the Atlantic, an anticyclonic ridge affecting Europe (resulting in anticyclonic conditions), and cyclonic circulation over the Iberian Peninsula. This type is generally observed during autumn and early winter and is associated with prolonged episodes of southerly surface winds over the Mediterranean Sea (Romero et al., 1999; Gil-Guirado et al., 2021).

3.4. Bayesian Network

BNs are tools used to analyse complex systems by assessing the interdependence and conditional probability of variables (Pearl, 1988; Jensen, 1996). They have been effective in descriptive and predictive applications for natural hazards, where the difference is how the variables are connected and discretised (Beuzen et al., 2018). Descriptive BNs were used to characterise all nonlinear relationships between variables to explore the specific relationships between predictors and target variables. The BN variables are discrete and given as probabilities at different steps. In this case, a descriptive BN for each event type, compound (Figure 3), SR and SW (Figure S0), is used to (i) identify the leading SWPs (target) in terms of their regional likelihood of exceeding a certain rain and/or wave intensity (parent); (ii) understand the local probabilities of event intensity (target) for the obtained SWPs (parent); and (iii) evaluate the SWP system's proficiency in predicting target variables to determine its effectiveness in classifying future wave-rain events in the NW Mediterranean region. Thus, the BN allows for the comparison of critical spare days (SWPs) and the spatial characterisation of the dominant SWP.

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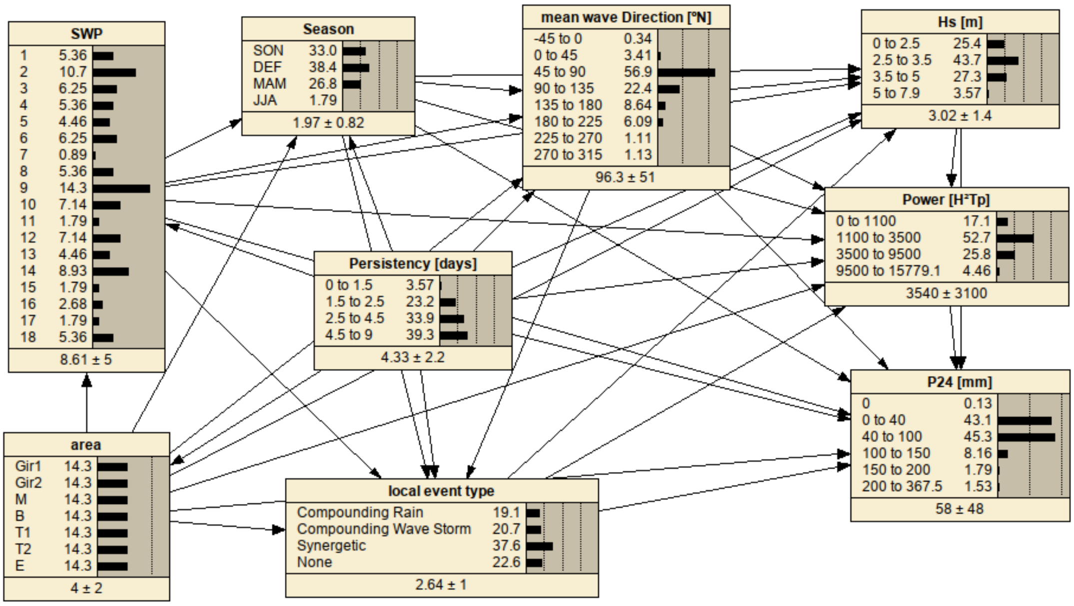

Figure 3. Bayesian Network (BN) used to analyse the SWP classification of compound event type.

The training dataset contained 3934 cases with information on the seven basins and 562 dates on which a storm event was recorded. Each case had data on event persistence (maximum duration in days of the wave and/or rainstorms), maximum daily rainfall and wave height, wave power content, mean wave direction, local event classification, SWP, and season.

The discretisation of the variables was based on expert knowledge of the threshold combinations representative of the study site. Variables P24 and Hs were discretised using local thresholds for hazard intensity. P24 = 40 mm is considered a local threshold for flash flood potential due to convective events (Barbería et al., 2014; Cortès et al., 2018); P24 = 100 mm and P24h = 200 mm are the thresholds for potentially damaging and extreme rainstorms, respectively, using the warning criteria of the Meteorological Service of Catalonia (definition of meteorologically hazardous scenarios in www.meteocat.cat, last accessed April 2023). Wave storms were classified using the local classification of Mendoza et al. (2011). It uses the storm power content (*Pow*), with class II (moderate) events having mean Pow = 3500 m^2hs and mean peak Hs = 3.5 m, and class IV (severe) storms having mean Pow = 9100 m^2hs and mean peak Hs = 5 m. Energy content class values in Mendoza et al. (2011) were translated to power content thresholds by applying a factor of 10 (i.e. assuming as representative a mean value of Tp of 10s over the whole duration of wave events).

The predictive capability of the SWP system was assessed using the BN skill measure, which was calculated as *skill = 1-msr/msd*. It compares the mean square of the residuals of the linear regression between the Bayesian mean value and data (*msr*) to the mean square of the data (*msd*). The standard deviation of the prediction may serve as a weight, with less emphasis placed on predictions that are uncertain (high standard deviation) than on confident outputs (Plant et al., 2016). Hence, an incorrect but uncertain prediction was considered more skillful than a confidently incorrect prediction. Both weighted and unweighted skills were calculated for the BN tests of interest.

4. Results

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4.1. Compound events characterisation

From 1990 to 2020, Catalonia experienced 112 compound heavy rainfall-wave storm episodes, of which 47 were classified as "severe" with P24 ≥ 100 mm and/or storm class ≥ IV. Furthermore, 376 solo-rain (SR) and 74 solo-wave (SW) events (see Methods) were recorded during the same period, of which 37 SR were severe, and none of the SW events reached storm class IV. On average, the entire territory experienced 3.7 compound events/year, 16.3 SR/year, and 6.2 SW/year, and the frequencies of severe events were 1.6, 1.23, and none, respectively. No statistically significant trend was detected for any event type during the analysis period (Figure 4).

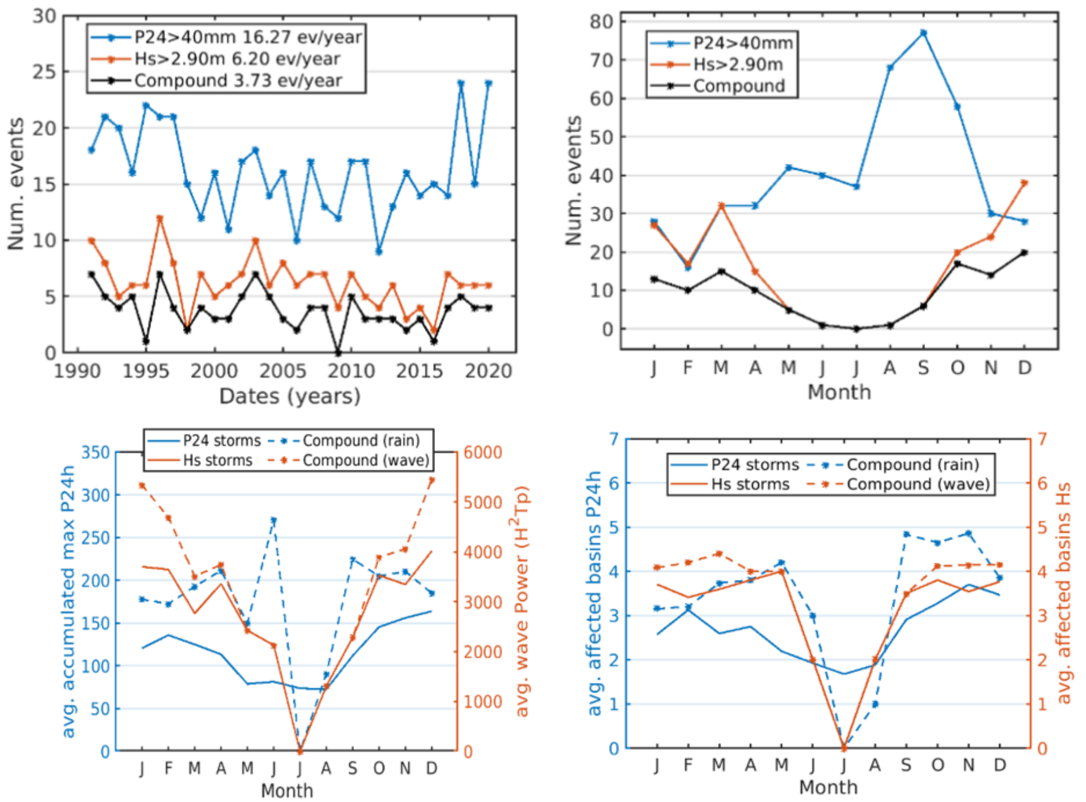

Figure 4. Annual frequency (a), monthly frequency (b), average monthly magnitudes of individual and compound events (c), and average monthly number of affected basins (d) along the Catalonian coast.

The seasonal distribution of storms contributing to compound events was substantially different. Thus, rainstorms occur throughout the year, with two peaks occurring in spring and late summer-autumn. By contrast, wave storms were absent during the summer, with the main season being from September to March (Figure 4). The combination of both temporal patterns conditions the occurrence of compound events year-round, which reflects the temporal pattern of wave storms, which—although less frequent than rainstorms—are the controlling factor. A significant property of these compound events with respect to individual storms that indicates their damaging potential is that when heavy rain and wave storms are compounded, the characteristics that determine their intensity (i.e. rainfall, wave height, and storm power) are greater and with a larger spatial extent (as indicated by the number of affected basins affected) than when they occur individually (Figure 4). Thus, during the wave storm season, the maximum event-accumulated precipitation values registered at a single station were on average 55% higher during compound events than during solo rainstorms; the maximum Hs and wave power were on average 4% and 20 % higher than during solo wave storms.

Despite the relatively small study area, approximately 600 km of coastline, the occurrence and characteristics of these events are not uniform throughout the territory, owing to the orography and coastal configuration conditioning them. Thus, the annual frequency of compound events decreased from north to south, with 2.6, 1.2, and 1.2 events per year in the northern, central, and southern coastal sectors, respectively (Figure S1). Notably, for a compound event to occur simultaneously over the entire area is "rare" (Sanuy et al., 2021) and has only occurred during some extreme storms (e.g. Gloria), which, together with the other four episodes, represent a 0.9% of the total events and 4.5% of the compound events.

This spatial variability was also reflected in the magnitude of the events, with the wave storm energy flux being equilibrated across sectors and the largest Hs wave storms occurring in the north (Figure S1). This also applies to rainstorms with the highest average P24 values in that sector.

4.2. Identifying conducive synoptic weather conditions

The weather pattern classification approach identified 18 SWPs for the 112 recorded compound events, 17 SWPs for the 376 rainstorms, and 12 SWPs for the 74 wave storms (Figures S2-S7). These weather types were linked to their seasonality and other storm variables, such as rain and wave intensity, in each basin by using BNs to model their dependence. The probabilities calculated using the BNs (Tables 2, and Tables S1-S3) consider both the temporal frequency of the types (when they were verified) and the spatial extent of the hazards (in how many basins they occurred), highlighting the dominant SWP (Figures 5 and 6) in terms of their spatiotemporal association with severity.

The *Cut-Off low* configuration prevailing during 121 recorded storms (22%) was the dominant weather system under which compound events were generated (53 %). Moreover, this importance was even more evident for the most severe events, such that approximately 75% of local events with rainfall of P24 ≥ 200 mm, and approximately 69% of extreme wave conditions (class IV storms) occurring in any coastal sector were generated under it (Table 2). Notably, this configuration was the dominant situation for the occurrence of local multivariate events (55 %). The *Through* configuration was the most frequent situation in which any type of storm was generated, with 319 events (approximately 57%), and the second in frequency in relation to compound events (28%). For severe compound events, approximately 25% of rainstorms with P24 ≥ 200 mm and approximately 31% of class IV wave storms were recorded under this configuration (Table 2). In this case, a significant number of multivariate events were generated (42% of evens). The *Atlantic low* type generated the fewest compound events (approximately 19%), accounting for a similar percentage (22%) of the total number of storms (122 events) as that of the *Cut-Off* systems. The most severe events were not conducive to any of the recorded compound events with class IV wave storms or rains with P24 > 200 mm. Moreover, the *Atlantic low* is nonsignificant regarding the generation of multivariate events (3 % of events).
The dominant SWPs conducive to the occurrence of severe compound events are shown in Figures 5 and 6, with all of them accounting for a minimum relative cumulative spatial-temporal (all basins) probability associated with severe rain (P24 ≥ 200 mm) and/or wave conditions (class IV) of 10% (Table S1). These severe compound events are often associated with highly unstable weather conditions, such as Cut-Off lows, which can lead to an intense, warm, and humid flow of air from the east along the NW Mediterranean coast, with a broad trajectory over the Mediterranean Sea. This feature was reflected in the identified seven types prevailing during these conditions (Figures 5 and 6); the most represented (71 %) were those of the Cut-Off configuration (Figure 5).

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Table 2. Probabilities of occurrence by general synoptic configuration (Cut-Off, Through, and Atlantic low) and type of event. Colour scale ranges from light to dark according to quantiles relative to the maximum value in each column. Blue colours represent probabilities of occurrence calculated over the respective number of events (without specific conditions); red scale colours represent BN probabilities conditioned to different thresholds of P24 and wave power and calculated considering their cumulative occurrence in all basins. See Tables S1-S3 for disaggregated probabilities by SWP.

				% relative to event dates				% relative to the event type				
Event type	**Synoptic configura-tion**	**n days**	**n/N (N=562)**	**1-P24 ≥ 100 mm**	**P24 > 200 mm**	**Class ≥ IV**	**2- Class ≥ II + Hs≥ 3,5 m**	**1- P24 ≥100 mm**	**P24 ≥200 mm**	**Class ≥IV**	**2- Class ≥II + Hs ≥3.5m**	**1+2+ Multi.**
Compound (C)	Atlantic low	22	3,9 %	3,6 %	0,0 %	0,0 %	5,4 %	15,5 %	0,0 %	0,0 %	9,0 %	3,2 %
	Cut-Off	**59**	**10,5 %**	**15,5 %**	**17,2 %**	**68,6 %**	**30,3 %**	**67,7 %**	**75,0 %**	**68,6 %**	**50,3 %**	**54,8 %**
	Through	31	5,5 %	3,8 %	5,7 %	31,4 %	24,5 %	16,7 %	25,0 %	31,4 %	40,7 %	42,0 %
Solo Wavestorm (SW)	Atlantic low	17	3,0 %	**	**	0,0 %	12,1 %	**	**	0,0 %	30,4 %	**
	Cut-Off	16	2,8 %	**	**	0,0 %	13,8 %	**	**	0,0 %	34,8 %	**
	Through	41	7,3 %	**	**	0,0 %	13,8 %	**	**	0,0 %	34,8 %	**
Solo Rainstorm (SR)	**Atlantic low**	**83**	**14,8 %**	**32,8 %**	**15,4 %**	**	**	**42,6 %**	**20,0 %**	**	**	**
	Cut-Off	46	8,2 %	12,7 %	15,4 %	**	**	16,4 %	20,0 %	**	**	**
	Through	**247**	**44,0 %**	**31,6 %**	**46,2 %**	**	**	**41,0 %**	**60,0 %**	**	**	**

The most frequent type, SWP2c-SPC, was characterised by inducing severe rain and wave conditions in the entire territory and was responsible for the highest probability of occurrence of class IV wave storms along the coast (40%). These events can have devastating impacts. The best examples of this behaviour from historical episodes generated by SWP2c-SPC are storm Gloria in January 2020 and the November 2001 event, which affected the entire territory and produced significant damage associated with strong winds, rain, and waves (Table 3). SWP14c-NPC exhibited a similar synoptic configuration but with key differences, such as the position of the Cut-Off and the accompanying high-pressure system to the north. These differences condition the wind fields and lead to a lower probability of class IV wave storms than the previous weather type, which tend to be localised in the southern sector in terms of power content and in the northern sector in terms of Hs. Nonetheless, SWP14c-NPC is associated with severe rainstorms and multivariate events primarily in the northernmost basins and secondarily affecting the Maresme, Barcelona, and Ebro delta areas, as described for remarkable historical events such as those in April 2010 and November 1999 (Table 3). This weather type was responsible for 33% of P24 ≥ 200 mm over the study area basins.

The remaining two severe Cut-Off types, SWP6c-SEPC and SWP10c-IPC, corresponded to detached upper-level lows originating from the Atlantic throughs, which differentiates them from the previous types. The main difference between WP6c-SEPC and SWP10c-IPC is the position of the upper- and surface-level lows, which condition the effects over the territory. SWP6c-SEPC favours energetic wave conditions, which translates into a high association with class ≥ IV storms that affect all coastal sectors (20 %), with maximum wave heights concentrated on the central coast and a high probability of multivariate local events in all basins. SWP10c-IPC favours extreme rainfalls (~17% association to P24 ≥ 200 mm) that can also be severe at the central basins. Both types can be traced to remarkable historical events (Table 3).

The remaining severe compound types corresponded to the Through configuration (Figure 6). SWP8c-NMT and SWP16c-EET were related to severe coastal storms and were characterised by upper-level throughs from Eastern Europe with a surface high-pressure system located in the North Sea. The main difference is the location and intensity of the low surface pressure in the Mediterranean zone and the depth and extension of the front. In the case of the SWP8c-NMT, the upper level reaches the NW Mediterranean, which makes it associated with P24 ≥ 200 mm rainfall events (8.3%), concentrating severe precipitation

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and wave conditions in the two northern basins. This type of event lags behind the famous St. Esteve 2008 event (Table 3). SWP16c-EET has less probability of intense rainfall, although severe conditions of both terrestrial and maritime components may also be verified to the south. Because of the depth of the upper level, it is also closely associated with snow events reaching coastal zones, such as in March 2010 (Table 3). Finally, the SWP4c-WET type, characterised by frontal systems covering western Europe and the British Islands, is associated with extreme rainfall (16.7%) and concentrates severe conditions in the northernmost basin, with accompanied moderate precipitation and wave storms throughout the territory. Historical events related to this type highlight their effects on the northern basin (Table 3).

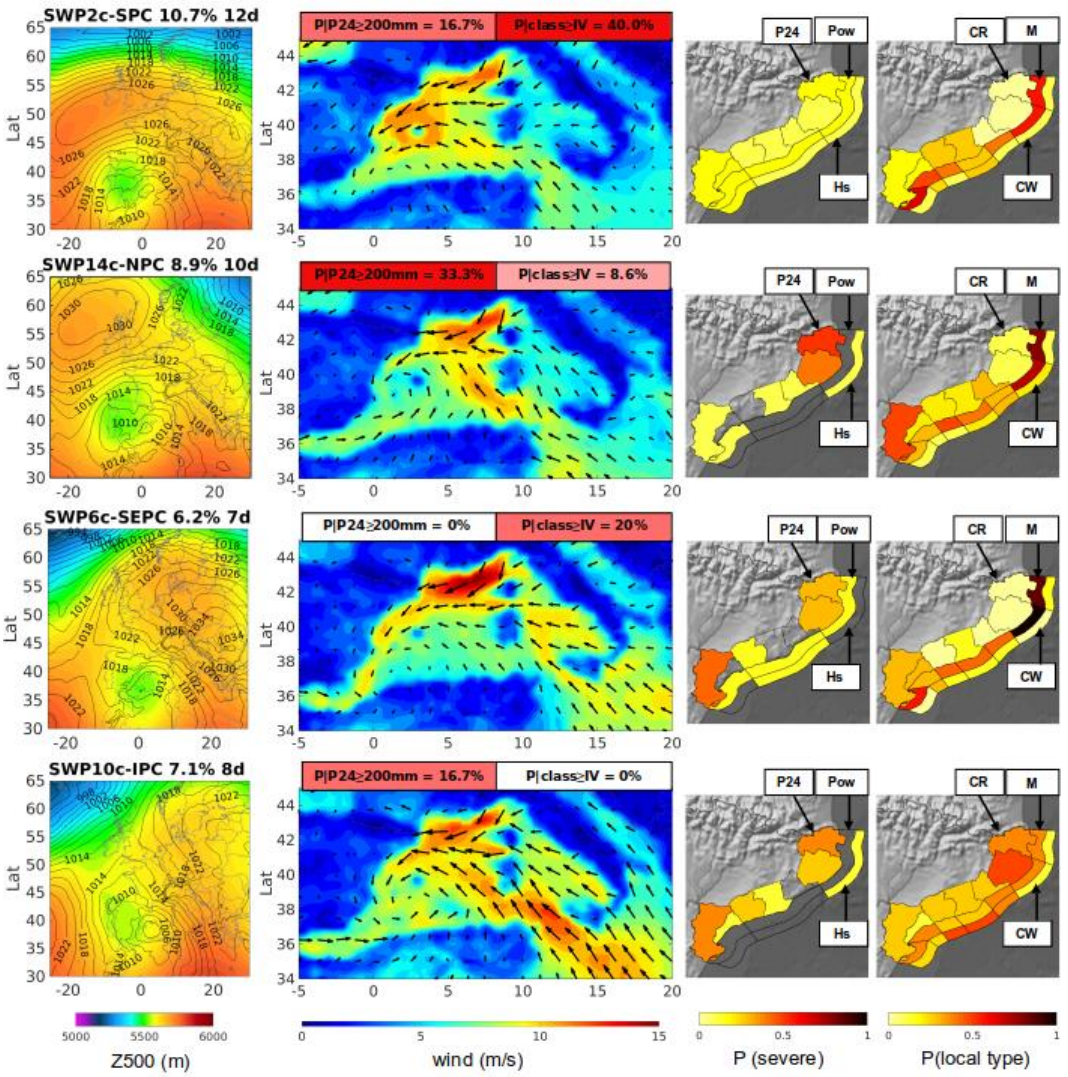

Figure 5. Dominant synoptic weather patterns (SWPs) of severe compound events: Cut-Off configuration. (a) Composites of geopotential at 500 hPa (Z500) and mean sea level pressure (MSLP, shown as contour lines). (b) Composites of the SWP wind fields, and probabilities of SWP occurrence relative to the event type and conditioned to severe conditions. The colour scale in the boxes ranges from light to dark, based on quantiles relative to the maximum value of each component (rain/waves). (c) Probability of severe rain (P24≥100 mm) and wave storm (power content, Pow ≥ class IV; wave height Hs ≥ 5m) conditions in each basin. (d) Probability of simultaneous occurrence of rain and waves (M) versus the probability of experiencing only the rain (CR) or wave (CW) components in each basin.

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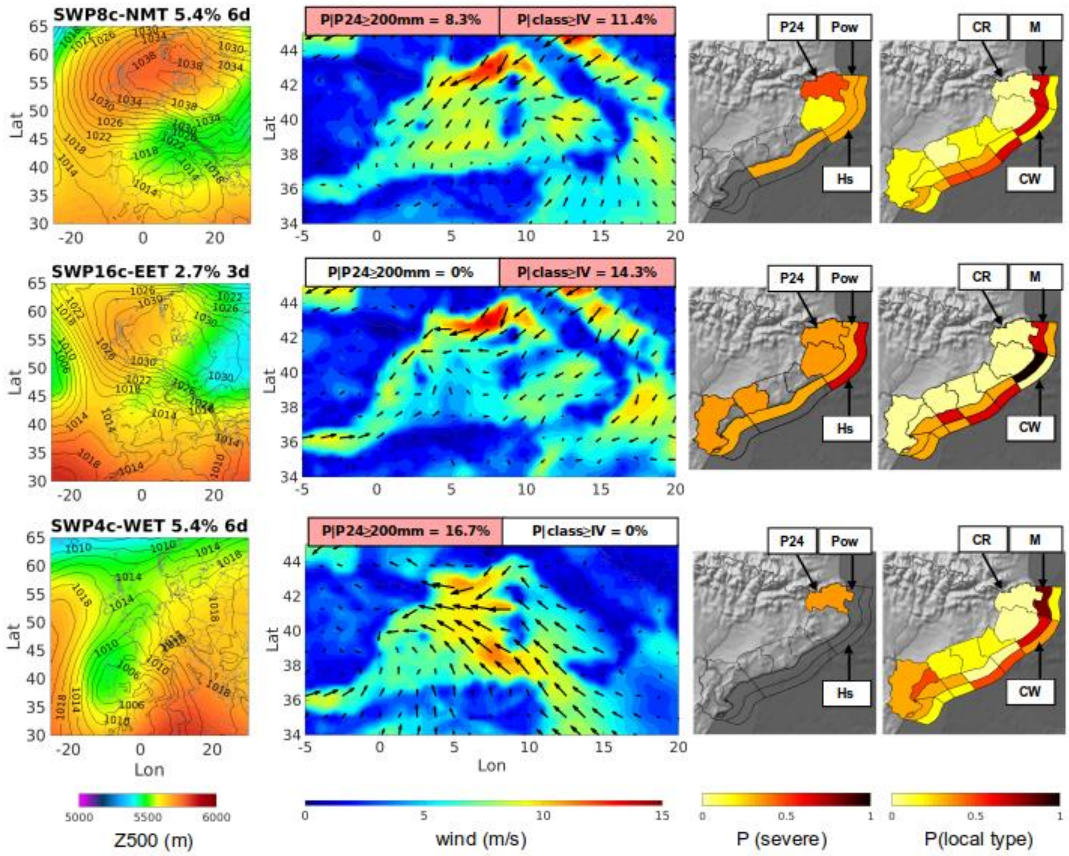

Figure 6. Dominant synoptic weather patterns (SWP) of severe compound events: Through configuration. (a) Composites of geopotential at 500 hPa (Z500) and mean sea level pressure (MSLP, shown as contour lines). (b) Composites of the SWP wind fields and probabilities of SWP occurrence relative to the event type and conditioned to severe conditions. The colour scale in the boxes ranges from light to dark, based on quantiles relative to the maximum value of each component (rain/waves). (c) Probability of severe rain (P24≥100 mm) and wave storm (power content, Pow ≥ class IV; wave height Hs ≥ 5m) conditions in each basin. (d) Probability of simultaneous occurrence of rain and waves (M) versus the probability of experiencing only the rain (CR) or wave (CW) components in each basin.

Compound severe types were compared with the SR and SW patterns visually to check possible similarities across event typologies and by using the BN distributions of the variables of interest over the territory. Notably, no severe SW events were recorded, and the obtained SWPs (Figures S4-S5, Table S2) were distinct from the compound type in their synoptic structures. In the case of SR events (Figures S6-S7, Table S3), three patterns were associated with P24 ≥ 200 mm (Figure 6), each of them featuring one of the general synoptic configurations. The most dangerous pattern was SWP9r-NWPT, which corresponded to the Through type. It was the least frequent of the three types (22%), although its association with extreme rainfall (60%) was triple that of the other two, with severe conditions covering the entire territory, except for the central basin. This pattern can be linked to historical events, such as 10 October 1994 (Table 3). The other two dominant SR types were both associated with a 20% probability of the presence of severe rain in any basin. The Atlantic low configuration SWP10r-IL was the most frequent (45%), can be associated with severe rainfall affecting the region's northern and southern ends and the central basin, and was linked to historical events such as 10 June 2000 (Table 3). The Cut-Off configuration SWP11r-SBIC delivers localised severe

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conditions over the territory and is especially dangerous because of its convective capacity, which produces flash floods over the Maresme area, as in the case of October 2016 (Table 3).

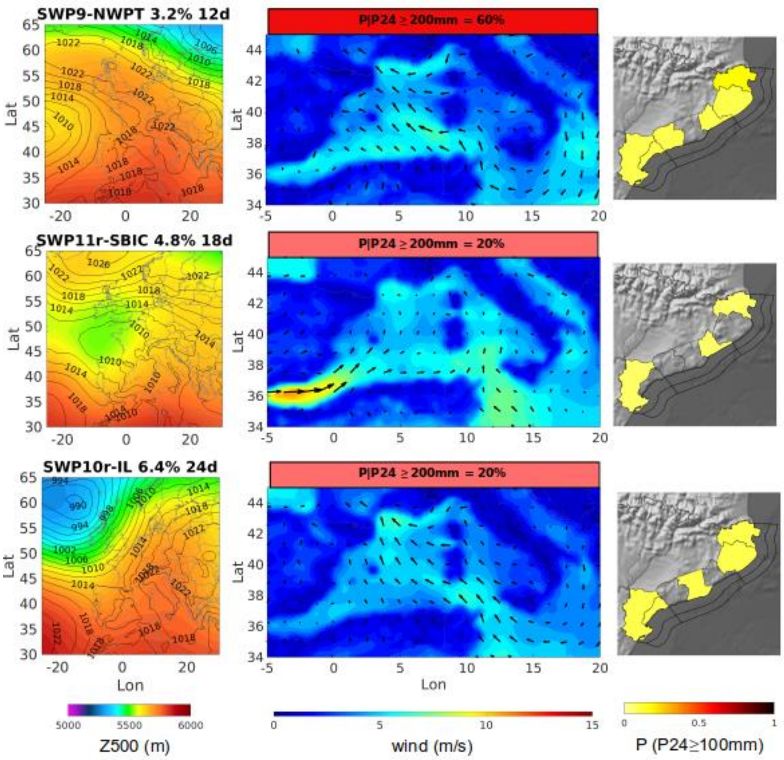

Figure 7. Dominant synoptic weather pattern (SWP) types of severe solo-rain (SR) events. (a) Composites of geopotential at 500 hPa (Z500), and mean sea level pressure (MSLP, shown as contour lines). (b) Composites of the SWP wind fields and probabilities of SWP occurrence relative to the event type and conditioned to severe conditions. The colour scale in the boxes ranges from light to dark, based on quantiles relative to the maximum value of each component (rain/waves). (c) Probability of severe rain (P24≥100 mm) conditions in each basin.

Table 3. List of main historical events associated with the identified dominant compound and solo rain SWP, with a summary of reported impacts and references.

SWP	Event type / general configuration	historical date	main impacts	references
SWP2c-SPC	Compound / Cut-Off	20/22-01-2020	Record-breaking events at all basins with accumulated precipitations exceeding 500 mm. Exceptional floodings with casualties at the Ter and Tordera rivers	Amores et al. (2020) Canals & Miranda (2020)
		11/15-11-2001	Record winds of 170 km/h in northern basins. Strong coastal erosion over the whole territory. Double peak coastal storm with rainfalls during the second peak	Genovés & Jansá, (2002) Mendoza et al. (2011)
SWP14c-NPC	Compound / Cut-Off	13-10-2010	More than 100 mm in the northern basins causing flash floods	ACA (2011)
		12-11-1999	Generalised rainfall with P24 ≥ 200 mm at the northern basins. Overflow of Manol and Muga rivers and damage to roads and margins	ACA (2011) Gázquez et al. (2004)
		31-10-1993	Precipitation of 270 mm in 4 d at the northern basins, leaving isolated villages, damaged roads, flooded housing and transport affections	ACA (2011)

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SWP6c-SEPC	Compound / Cut-Off	21/22-01-2017	Event featured by an intense wave storm affecting the north and central coasts, with rains almost reaching 200 mm at the northern basins	www.meteotecadecatalunya.cat
		3-11-2015	Intense to severe rainfalls over the whole territory, which exceeded 200 mm in the internal basins causing 4 casualties due to flash flood events. On the coast, several flash floods were registered without casualties	www.meteotecadecatalunya.cat
SWP10c-IPC	Compound / Cut-Off	29/30-11-2014	P24 of 336 mm registered at the Ebro delta area and 200 mm at the northern basin. Intense rainstorms in all other areas, with accompanying moderate coastal storm	www.meteotecadecatalunya.cat
		15/16-03-2011	Precipitations reaching more than 300 mm in 3 d at Viladrau, and exceeding 150 mm at multiple locations. Northern rivers such as Fluvià or Muga were close to overflowing (the emergency inundation plan was activated)	ACA (2011)
SWP8c-NMT	Compound/ Through	26-12-2008	Coastal storm with impacts mainly in the two northern basins with accompanying moderate rainfall with snow at low altitudes	Sanuy et al., (2021) Mendoza et al., (2011) Sánchez-Vidal et al., (2012)
SWP16c-EET	Compound/ Through	8-3-2010	Heavy snowfall affecting ⅔ of the Catalan territory, with snow reaching the coastal municipalities	www.meteotecadecatalunya.cat
		18-10-2003	Some inundations and affections to roads at the upper sections of the Ter River. Moderate storms in coastal basins	ACA (2011)
SWP4c-WET	Compound/ Through	9-04-2002	Overflow of the Manol and Muga Rivers (northern basin)	ACA (2011)
		26/27-09-1992	Overflow of the Fluvià River and landslides in some interior basins	ACA (2011)
SWP9r-NWPT	Solo Rain / Through	10-10-1994	Extensive rainfalls mainly affecting the southern basins, and secondarily, the central coastal sectors, with 66 stations registering daily precipitation over 100 mm and 11 exceeding a P24 of 200 mm	ACA (2011) Gázquez et al. (2004)
SWP11r-SBIC	Solo Rain / Cut-Off	12-10-2016	Convective autumn rainfalls exceeding 200 mm in the Maresme area, with record intensities exceeding 100 mm in 1 h, mainly due to the unusually warm temperatures of the Mediterranean Sea	www.meteotecadecatalunya.cat
SWP10r-IL	Solo Rain / Atlantic Low	10-06-2000	Convective intense rainfalls mainly affected central and southern basins, with reported damages reaching 65M€ and 5 casualties	ACA (2011) Gázquez et al. (2004)

4.3. Analysis of Bayesian Network skill

The BN model was used to evaluate the effectiveness of the identified SWPs in estimating the variables of interest, that is, P24 and Hs, at the basin scale. Skill was measured using the mean of the output probability distributions. The weighted skill also considers the output uncertainty (i.e. standard deviation). BN predictions were obtained based on different combinations of parent variables (Figure 8). When the starting information used consists only of the SWP, the BN was able to estimate P24 and Hs during compound events with a skill of 0.25 and 0.32, respectively. The SWP also showed similar accuracy in estimating Hs for solo-wave storms. However, solo-rain storms are challenging to predict, and using only the SWP type results in a skill level of 0.1.

However, adding information on one additional variable, such as event season (P24 in compound events), persistency (P24 in solo-rain events), or storm power content at the coast (Hs both in compound and solo.wave events), significantly improved the BN skill in estimating the local values, reaching skills of 0.43 and 0.34 for P24 (C and SR, respectively) and 0.67 and 0.51 for Hs (C and SW, respectively). When these variables were combined in a 3-parent estimation, using SWP + season + persistence to estimate P24 and SWP + season + power to estimate Hs, skills increased to 0.7/ 0.47 for C/SR basin P24, and 0.72/0.62 for C/SR sector Hs. The obtained weighted skills, which account for the BN output uncertainty, were closer to 1. Thus, the BN correctly captured the uncertainty in its estimations. Notably, in meteorological applications, values of skill over 0.2 are

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considered "useful," and values over 0.5 are considered "good" (Sutherland et al., 2004). This analysis suggests the potential to further improve prediction accuracy by introducing additional variables.

a)	TARGET						
		P24			Hs		
	PARENT	skill	wg. skill	RMSE (mm)	skill	wg. skill	RMSE (m)
Compound (C)	*SWP*	0,25	0,74	37,5	0,32	0,43	0,80
	SWP+season	**0,43**	**0,88**	**32,7**	0,43	0,53	0,76
	SWP+Pers	0,43	0,86	33,0	0,49	0,57	0,74
	SWP+Pow	0,41	0,84	33,6	**0,67**	**0,71**	**0,60**
	SWP+Dir	0,43	0,84	33,0	0,45	0,57	0,76
	****SWP+season+Pers***	**0,7**	**0,87**	**24,0**	0,63	0,69	0,68
	****SWP+season+Pow***	0,67	0,88	25,0	**0,72**	**0,74**	**0,61**
Solo Wave (SW)	*SWP*	**	**	**	0,32	0,35	0,62
	SWP+season	**	**	**	0,46	0,57	0,61
	SWP+Pers	**	**	**	0,44	0,52	0,63
	SWP+Pow	**	**	**	**0,51**	**0,58**	**0,59**
	SWP+Dir	**	**	**	0,46	0,54	0,62
	****SWP+Pow+season***	**	**	**	**0,62**	**0,67**	**0,59**
Solo Rain (SR)	*SWP*	0,1	0,15	27,9	**	**	**
	SWP+season	0,19	0,53	26,7	**	**	**
	SWP+Pers	**0,34**	**0,7**	**24,2**	**	**	**
	SWP+Pow	0,17	0,62	27,0	**	**	**
	SWP+Dir	0,22	0,89	26,1	**	**	**
	****SWP+Pers+season***	**0,47**	**0,78**	**21,9**	**	**	**

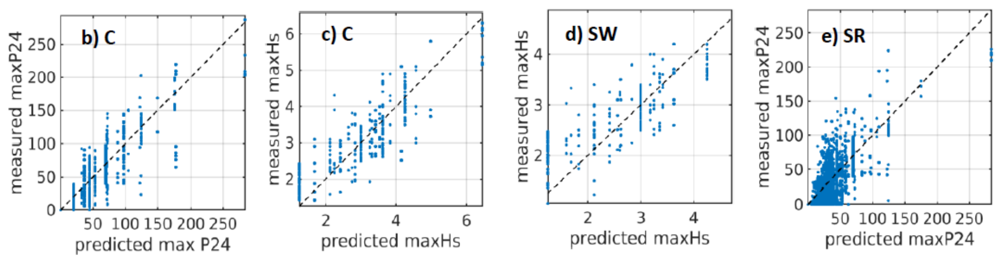

Figure 8. Skill scores of the Bayesian Network (BN) model's predicted mean values of event maximum Hs and P24, based on different combinations of parent variables by event type (a). Combinations with the highest skill scores are highlighted, mark as (*) and correspond to the scatter plots in the lower portion of the table, which show the comparison between the BN-predicted mean value and the observations (b, c, d, e).

5. Discussion

The proposed framework, which combines a classification method with a BN, successfully identified and characterised the main SWPs and associated general synoptic configurations, leading to severe compound events. In addition to the dominant cases presented in Results, other SWPs conducive to compound events with severe rainfall (P24≥100 mm) corresponded to the shallower versions of the Cut-Off as is depicted in the composites (Figure S2) and rainfall probabilities (Table S1) of SWP3c-sSEPC, SWP13c-NPC, and SWP17c-sSPC. This SWPs were characterised by shallow and less extensive upper-level lows (relative to the dominant types in Figure 5) that cause more localised impacts owing to convective precipitation. These types were associated with a few historical floods in Catalonia reported by the ACA (2011), emphasising the local convective nature associated with small cold air pools at upper levels. Although some of these events reached P24≥200 mm at really small spatial scales, the sparse coverage of stations in the available dataset for the 1990-2015 period (Figure 1, Table 1) was not appropriate for capturing the local maximum peaks, highlighting the need to broaden the coverage of precipitation measurements over the territory to adequately characterise the local impacts. Despite this, the AWS dataset was adequate for the purposes of this study, which consisted of obtaining a regional baseline of weather types conducive to compound events.

The literature on compound coastal flooding has investigated the combined effects of surges with river discharges or surges with precipitation (Couasnon et al., 2018; Paprotny et al., 2018; Hendry et al., 2019; Camus et al., 2022; Whal et al., 2015; Wu et al., 2018; Bevacqua et al., 2019). Although precipitation can be used as a proxy for the hydrometeorological flooding potential in small river catchments, as observed in NW Mediterranean conditions (Bevacqua et al., 2020), surges are known to be relatively less important than wind waves in contributing to flooding in the NW Mediterranean (Mendoza and Jiménez, 2009; Sanuy et al., 2020). Therefore, the analysis of significant Hs and wave power during coastal storms becomes fundamental to characterise the hazardous maritime component and "indicate" both coastal erosion and flooding potential.

Most of the research on compound events has focused on multivariate types at large scales because potential synergetic effects between hazards (maritime and terrestrial) may occur at sensitive locations (Whal et al., 2015; Couasnon et al., 2018; Paprotny et al., 2018; Wu et al., 2018; Bevacqua et al., 2019; Hendry et al., 2019; Camus et al., 2022). The recent impact of storm Gloria in January 2020 in the NW Mediterranean (e.g. Amores et al., 2020; Canals and Miranda, 2020), although of multivariate type when considering the whole region, highlights the overwhelming capacity of accumulation of the impact of terrestrial and maritime hazards on different parts of the territory. Under these conditions, civil protection services had to prioritise interventions according to urgency because of the simultaneity of emergency calls (approximately 15,000) and demanded interventions (approximately 2,500) in all coastal sectors, as reported by the Ministry of Home Affairs of the Government of Catalonia. Establishing the characteristics of compound events, such as their regional dominance in terms of multivariate phenomena, and their basin-by-basin probabilities of synergistic versus cumulative potential impacts, is critical to improving event preparedness, based on the limited resources available, and thus, considering compound-type events where rainfall and coastal extremes occur in different basins. The results showed that Cut-off (55%) and Through (42%) weather configurations were most responsible for multivariate events, with Cut-Offs SPW2c-SPC and SPWc14-NPC (Figure 5, Table S1) being responsible for 42% of multivariate events in all basins, and being the SWPs dominant in spatial extension of multivariate local events throughout the region.

The classification method developed by Aran et al. (2011) successfully identified synoptic conditions conducive to both compound and solo-rain/wave events in the NW Mediterranean. Camus et al. (2022) applied a similar method to classify the daily synoptic conditions of compound surges and river discharges on the North Atlantic coast using the MSLP and precipitation fields. However, in this study, we chose the Z500 level, MSLP, and surface wind as predictors of local precipitation and wave intensity because combining information on upper and surface pressures has been found to provide a good representation of convective and flash flood events in subtropical regions, such as the NW Mediterranean (Miró et al., 2018).

The role of general weather configurations in storm characteristics (Table 2) is consistent with the literature on the characterisation of severe events in the study area, such as extreme rainfall (Romero et al., 1999, Gázquez et al., 2004), convective rainfall (Barbería et al., 2014; Cortès et al., 2018), floods (Gil-Guirado et al., 2022), and coastal storms (Mendoza et al., 2011). The dominant Cut-Offs SWP2c-SPC/SWP14c-NPC and SWP6c-SEPC/SWP10c-IPC (Figure 5) were identified by Gil-Guirado et al. (2022) (denoted as PSP8 and PSP1, respectively) as configurations with the greatest number of associated terrestrial floods on the Spanish Mediterranean coast. These dominant severe compound types were also identified by Peña et al. (2011), who related the Cut-Off configuration called the C6-Mediterranean Low to the presence of strong winds, heavy showers, and sea wave erosion in the region. With respect to marine hazards, Mendoza et al. (2011) performed a preliminary analysis of the synoptic situations associated with severe events (class III–V coastal storms). They found that the most extreme storms (class V events) occurred in the presence of a Mediterranean Cyclone, which corresponded to the here identified Cut-Off (SWP2c-SPC/SWP14c-NPC) and Through types (SWP8c-NMT). The other configurations identified for less extreme

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marine events (class III to IV storms), denoted as Southern and Eastern Advections, are also identified in this work as part of the Atlantic low and Cut-off types, respectively.

BNs were used to study the nonlinear relationships among the defined systems and to identify the main SWP associated with the severe intensity of rain and wave storms and their individual or combined occurrence. The BN, combined with knowledge of event persistence and season, was successful in obtaining value-threshold probabilities at the basin scale and validated the obtained SWP system to be further used as a reference baseline to classify future dates (e.g. by analogue-classification methods) and explore changes in the probabilities of severe rain-wave conditions and their regional distribution in the NW Mediterranean. Future dates should be selected with consistent variable threshold criteria and using consistently downscaled datasets that include both the hydrometeorological and maritime components of future scenarios. Improvements could also include the inclusion of additional variables related to atmospheric convection (e.g. temperature fields) and parameters related to interannual cyclicities, such as atmospheric teleconnections, to improve the estimation of the rain component and properly identify dangerous situations with precipitation between 40 and 100 mm (only harmful if convective) and with P24≥100 mm (also including persistent situations leading to fluvial saturation). This would be a step further towards characterising the impact potential of the studied hazard drivers, which would make the methodology usable as a quick EWS before the execution of physical models from the forecasting synoptic maps.

6. Conclusions

This study presents a methodological framework to create a baseline for SWPs and induced hazard variables characterising storm events in the coastal zone, which combines an objective classification method and a Bayesian Network. The use of the BN facilitated the comparison of similar patterns, and the identification and characterization of severe SWPs. The BN showed good performance in the resolution, by means of discrete probability distributions, of the nonlinear relationships between weather types and intensities of rainfall and coastal storms at the basin scale. The analysis of BN skills showed that the combination of weather type information with other variables, such as seasonality, rain persistence, and coastal storm classification, allows a reasonably good estimation of daily rainfall and Hs.

Its application permitted the identification of SWPs conducive to the occurrence of extreme compound events arising from a combination of heavy rainfall and high waves along the NE Spanish Mediterranean coast (P24 ≥ 200 mm, storm class ≥ IV). The *Cut-Off* synoptic configuration proved to be the dominant severe compound type. The *Through* synoptic type followed in compound events and was dominant in solo-rain storms. The *Cut-Off* and *Through* types were equally responsible for solo-wave storms. Despite its capacity to generate severe events, the *Atlantic low*, is mainly related to solo-rain events and is the least hazardous synoptic configuration in terms of solo-wave storms or compound events.

BN results also allowed us to characterise the association of the obtained weather types with the local probabilities of multivariate phenomena (if present) in any basin and the distribution of accompanying compounding rainstorms and wave storms over the territory. The Cut-Off and Through synoptic configurations were the main factors responsible for the occurrence of multivariate events in the entire region. All dominant SWPs showed the potential to affect the entire region, with synergistic events that were concentrated in the northern basins, followed by the Ebro Delta. Together with the local probabilities of exceeding the severity thresholds, this information is essential from a risk management perspective, as improving event preparedness allows for improving the allocation of limited resources, helping to prevent the saturation of civil protection services during regionally extensive events. The work also represents a first step towards a quick predictive

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system based on SWPs and additional accompanying variables to detect and characterise incoming extreme events before a detailed prediction based on physical modelling.

Author contributions

MS conceptualised the research, built the BN, performed the analysis, and co-wrote the manuscript. JCP conceptualised the research, guided the SWPs classification, and characterised the obtained types. SA developed the reconstruction of wave observations. JAJ conceptualised the research, co-wrote the manuscript, managed the project, and secured funding. All authors contributed to the interpretation and discussion of the obtained results and to the writing of the final manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Acknowledgements

This study was conducted within the framework of the C3RiskMed (PID2020-113638RB-C21, AEI/10.13039/501100011033) research project, funded by the Spanish Ministry of Science and Innovation. The first author was funded by the Margarita Salas postdoc grant.

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