Title: Storm Gloria (2020): coexisting types of compound flooding in the West Mediterranean Region. (Previous title: Storm Gloria (2020): joint probability of multiple flood hazards and compound events in a paradigmatic Mediterranean event)

Authors: Montserrat Llasat-Botija, Raül Marcos-Matamoros, Maria Aguilera-Vidal, José Antonio Jimenez, María Carmen Llasat

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First, we would like to thank the editor and reviewers for their time in reviewing the article. Their comments and suggestions have been very valuable and constructive in helping us improve the submitted version. We would also like to thank the editor for the thorough review conducted during the "preprint posting" phase.

Below, we reply to the editor's comments. This is followed by a point-by-point reply to the comments from the two reviewers (which were already submitted during the interactive discussion). The original editor and reviewers' comments are reproduced in black, followed by our responses in blue. Text added to the manuscript appears in green italics.

Sincerely Yours

Montserrat Llasat-Botija in behalf of all co-authors

Answers to Editor

Editor comment 1: Based on your comments and referee decision, I invite you to submit a minor revision of your manuscript. Please ensure that all modifications outlined in your responses to both reviewers are fully integrated into the revised text like you proposed in your comments that I believe answers to all questions raised.

Thank you very much for reviewing the referees' reports and our responses, and for accepting the article for publication with minor revisions. We have carefully reviewed the manuscript to ensure that all changes and corrections proposed in the reviewers' answers have been included in the revised text.

Specifically, make sure to implement the following:

Editor comment 2: Apply the new proposed title.

Thank you for highlighting the key changes. Regarding the first one, the title has been changed in the manuscript.

Editor comment 3: Implement the proposed restructuring of Section 5, update the conclusions, and revise the figures as detailed in your response to Referee #1.

The revised manuscript includes the restructured version of Section 5, the updated conclusions, and the revised figures, as indicated in the response to Referee #1. We have also implemented the other changes and suggestions made by Referee #1, which, as we mentioned earlier, have been very helpful to us.

Editor comment 4: Consistently use "significant wave height" (Hs) and ensure the distinction between the SIMAR and CoExMed datasets is clearly stated in the methodology and tables, as requested by Referee #2.

We have verified that the use of the term "significant wave height" in the text is clear and appropriate, and that the sources (SIMAR and CoExMed) are correctly cited so that the reader can properly understand the origin of the data and clearly distinguish between them, especially in methodology section and in the tables. The other changes proposed by Referee #2 have been implemented. We appreciate their comments, which have improved the manuscript and the title and have helped make text clearer.

Editor comment 5: Clarify Acronyms

We have revised and clarified the acronyms

During the process of reviewing and applying the proposed changes, we have made additional corrections to improve the text. You can see those corrections in the manuscript with tracked changes.

Thank you very much for your helpful assistance throughout the process.

Answers to Referees

In this next part, we include a copy of the answers sent to the referees' comments during the public discussion. We have done a little modification in the new text of Conclusions.

Answers to Referee #1 comments

Comment 1: This work addresses an important topic related to the hazards associated with storm Gloria. Although the approach followed by the authors is outside my area of expertise, I have tried to provide a few suggestions to improve the flow and clarity of the manuscript. You are free to accept or reject my suggestions.

Response 1: *The authors would like to thank you very much for taking the time to review this manuscript and the constructive comments made. The original comments are reproduced in black, followed by our responses in blue. Added or modified text to the manuscript is indicated in italic green.*

Comment 2: Lines 11-14: "The coastal strip.... Insurance Compensation (CCS) payouts", these sentence are useless in the abstract. Consider to delete them.

Response 2: *Following your recommendation this text has been deleted from the abstract.*

Comment 3: Lines 18-24: "Multivariate....." this sentence is too long and difficult to follow.

Response 3: *The sentence has been modified and shortened to make it easier to read. New sentence is:*

"The probability of multivariate and spatially compound events was quantified using a two-sided conditional framework and copula models, while the temporally compounding case was assessed empirically from a sequence of heavy-rainfall episodes."

Comment 4: Lines 24-26: "Overall, the largest compensation values tend to occur where hazard levels are highest, although exposure, vulnerability, and insurance coverage modulate the final impacts". This statement is not clear for a reader. How, your analysis is suitable for the hazard levels, mostly considering the return period that you obtained. This is important for a reader.

Response 4: *Thank you very much for your comment, which has highlighted the existing confusion, as it seems this sentence is related to the previous one, when in fact they refer to different results. The previous sentence shows how the return periods of compound events are longer than those of individual hazards. In contrast, this sentence attempts to highlight the relationship between the spatial distribution of damage and the levels of hazard, exposure, and vulnerability.*

We have amended the sentence to make it clearer, and we have removed the term 'insurance coverage'. This refers to insured assets, and the more insured assets there are, the greater the exposure; it is therefore included within the concept of 'exposure'. The new sentence is:

"Overall, if the spatial distribution of damages is considered throughout the region, the largest values tend to occur where hazard levels are highest, although exposure (including insurance coverage) and vulnerability modulate the final impacts."

Comment 5: Line 35: substitute "affected" with "impacted".

Response 5: *Correction made. Now the sentence is:*

" Between 19 and 25 January 2020, Storm Gloria severely impacted eastern Spain."

Comment 6: Line 99: check the term "realisations", consider to change in "simulations"

Response 6: *Thank you for your comment. We agree that the term "realization" was misused. Our intention was not to describe individual realizations, but rather to present a characterization of each type of compound event, including its probabilistic analysis through the estimation of the return period of the compound event, together with the associated observed impacts. We have modified the paragraph and the new one is:*

"The remainder of this paper is organised as follows. Section 2 describes the study area and the datasets used. Section 3 outlines the methodology. Section 4 presents the temporal evolution of the storm and its associated hazards. Section 5 illustrates the different types of compound flood events identified during Storm Gloria. Section 6 analyses the interactions among the different hazards and their socio-economic consequences. Section 7 discusses the main findings and their implications, and Section 8 presents the conclusions."

Comment 7: Line 106: substitute "scope" with "area".

Response 7: *Change done*

Comment 8: Line 168 and Figure 2: I suggest to improve the synoptic description of the event, maybe using the MSLP from ERA5 with wind vectors at different time steps.

Response 8: *Thank you very much for your comment. Following your suggestion we have enhanced the description of the synoptic situation. We have replaced Figure 2 corresponding to January 20th with a set of figures constructed from ERA5 data for sea level pressure and 500 hPa geopotential (a, c, e) and mean wind speed (b, d, f) for January 20, 21 and 22, 2020*

This is the new text:

Figure 2 shows the atmospheric configuration at the surface and at 500 hPa (a, c, e) and the mean wind velocity (b, d, f), respectively, on the central days of the episode. On January 17, 2020, AEMET (the Spanish State Meteorological Agency) identified a small upper-level vortex in the North Atlantic as "Gloria." This vortex moved rapidly north of the Iberian Peninsula, where it developed into a small surface low-pressure system (AEMET, 2020). On the afternoon of January 18, it moved into the Mediterranean, strengthening and becoming centered over the southern Balearic Islands, east of the Spanish mainland coast on January 19. On the 20th, Storm Gloria was absorbed by a larger low-pressure system located in north Africa (Fig. 2a). That didn't stop the entire episode, up to the 25th, from being known as Gloria Storm. The powerful anticyclone centered over the British Isles, with a pressure near 1050 hPa, and the low-pressure system resulted in a northward-directed pressure gradient of more than 40 hPa in less than 1500 km, which explains the strong easterly winds (gusts above 100 km/h) that produced the rough seas and the continuous influx of moist Mediterranean air in low levels (Fig. 2d). In addition to the strong winds and associated waves, precipitation was persistent and intense in eastern Spain. Snow fell at very low elevations (down to 300 meters in some areas). Due to the arrival of a very cold air mass in the preceding days, located over the Iberian Peninsula, snowfall continued at very low elevations (even down to 300 meters).

The cold upper-level disturbance enhanced instability and ascent, while the low-level flow encountered coastal mountain ranges, especially from Valencia to Catalonia, that triggered intense orographic precipitation. As seen in Figure 2, the strong anticyclone and the Mediterranean low formed a Rex Block system (a stagnant atmospheric pattern where a high-pressure system sits directly north of a low-pressure system). This type of weather is characterized by its ability to remain unchanged for days or even weeks. Figure 2b shows the strong easterly winds that advected very warm and humid air over the coast.

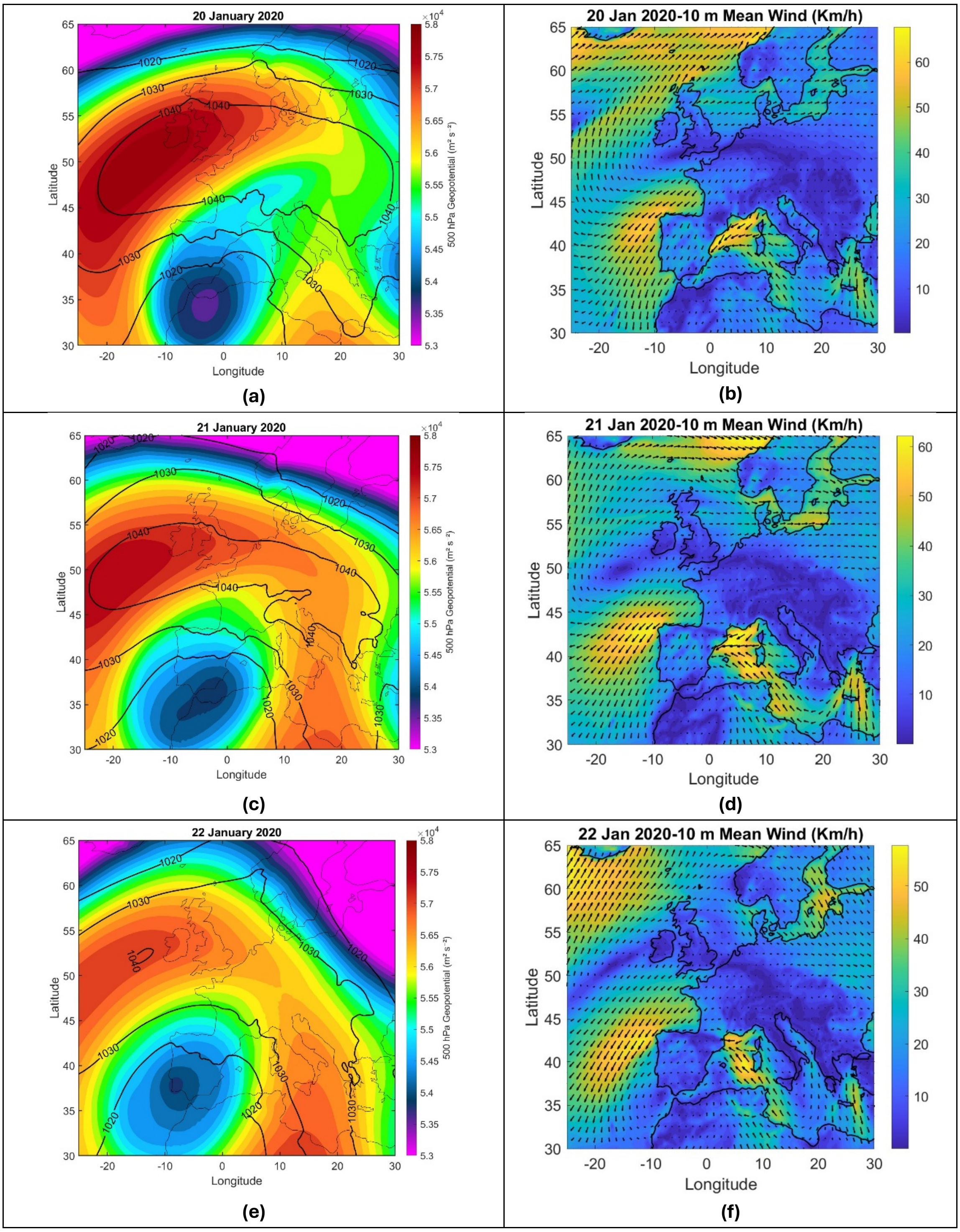

Figure 2: Sea level pressure and 500 hPa geopotential (a, c, e) and mean wind speed (b, d, f) for January 20, 21 and 22, 2020.

Comment 9: Line 185: this last sentence derives from a literature source or is it an outcome of your analysis?

Response 9: *It is an outcome of our analysis: we reviewed the atmospheric configuration throughout the days of the event to confirm that they were part of the same event. The new sentence is:*

"This definition was further supported by the synoptic reanalysis, which confirmed that the rainfall observed on 25 January was associated with the same meteorological system and should therefore be considered part of the event."

Comment 10: Lines 315: From this point I suggest to reorganize the structure of the subsections. Avoid the subdivision in Type, Description and Probabilistic Analysis for the subsections.

Response 10: We agree that this section could be organized in different ways. However, the rationale behind our current structure is closely linked to one of the main objectives of the paper: to demonstrate that a single meteorological situation may give rise to different types of compound events simultaneously, rather than to a single type of compounding. We use Storm Gloria as a representative example to illustrate this coexistence by presenting a catalogue of different compound event types that occurred during the same storm.

To improve the clarity of the presentation, we have reorganized each subsection into three parts. The first part describes the event and its associated impacts; the second part analyses its likelihood from the perspective of compound events, including the probabilistic characterization of the compound event itself rather than focusing solely on the individual hydrometeorological or marine drivers; the third part analyses the implications. We believe that this revised organization better highlights both the diversity of compound event types and their probabilistic significance while preserving the central message of the manuscript.

This is the new text:

5 Analysis of the Selected Compound Events

Storm Gloria generated multiple types of compound flood events that developed simultaneously across the Spanish Mediterranean coast. To illustrate the diversity of mechanisms involved, three representative examples are analysed, corresponding to multivariate, spatially compound and temporarily compound events (Table 4). Together, these case studies demonstrate how different combinations of hazard drivers produced distinct impact pathways and management challenges during a single atmospheric episode. In addition, the event generated cascading impacts, such as the collapse of the Tordera bridges, and was influenced by preconditioning factors, including antecedent beach erosion, which further amplified storm impacts.

Table 4: Main characteristics of the selected types of compound events

Type	*Description*	*Data*	*Return period*
Multivariate	*Simultaneous heavy precipitation in the Tordera River basin + High waves in the river mouth*	*Weather stations in the Tordera River basin and waves (SIMAR and CoExMed) nodes in front of the mouth of the Tordera River.*	*85 years*
Spatially compounding	*High waves off the Jávea coast (Alicante) concurrent with heavy rainfall and flooding in the Júcar river basin (Valencia)*	*Weather stations in the Júcar River basin and waves (SIMAR and CoExMed) node in front of Jávea.*	*72 years*
Temporally compounding	*Three consecutive flood events between 11 September 2019 and 25 January 2020 in Los Alcázares (Murcia).*	*Weather stations in the Segura River basin and surrounding municipalities.*	*22 years*

5.1 Multivariate event: flooding of the Tordera delta

5.1.1 Event description

The flooding of the Tordera delta (Barcelona) provides a representative example of a multivariate compound flood, in which fluvial and coastal processes interact simultaneously at the same location (Fig. 4). During Storm Gloria, intense rainfall over the Tordera River basin generated exceptionally high river discharge, while energetic wave conditions at the river mouth impeded drainage to the sea. The resulting backwater effect increased water levels within the lower river reach and enhanced flooding across the delta plain. At the same time, wave overtopping contributed to inundation of the seaward part of the delta, further increasing flood extent.

The severity of the event was enhanced by the geomorphological evolution of the delta. The Tordera coastline has undergone persistent shoreline retreat as a consequence of reduced sediment supply, resulting in progressive erosion of the beach system (Jiménez et al., 2018). This loss of the natural coastal buffer has increased the exposure of low-lying areas to marine flooding during severe storms. Consequently, the Tordera delta has been identified as one of the principal hotspots of compound flooding along the Catalan coast (Sanuy et al., 2021).

Exposure within the delta is also particularly high owing to the presence of transport infrastructure, agricultural land and numerous campsites located immediately behind the beach. Although campsite occupancy peaks during summer, when the probability of severe storms is comparatively low (Sanuy and Jiménez, 2021; Aguilera-Vidal et al., 2025), their location whithin low-lying flood-prone areas makes them particularly vulnerable to compound flooding.

One of the most significant consequences of the event was the collapse of the railway bridge crossing the Tordera River after one of its piers was undermined by the flood flow. The subsequent failure of the adjacent road bridge produced major disruption to regional transport (González, 2020), illustrating how a compound flood can trigger cascading failures in interconnected infrastructure systems.

5.1.2 Probabilistic characterization

The probability of occurrence of this compound event was evaluated using P24h recorded at meteorological stations within the Tordera river basin and Hs from the offshore CoExMed node located seaward of the river mouth (Fig. 6), representing the fluvial and marine drivers, respectively.

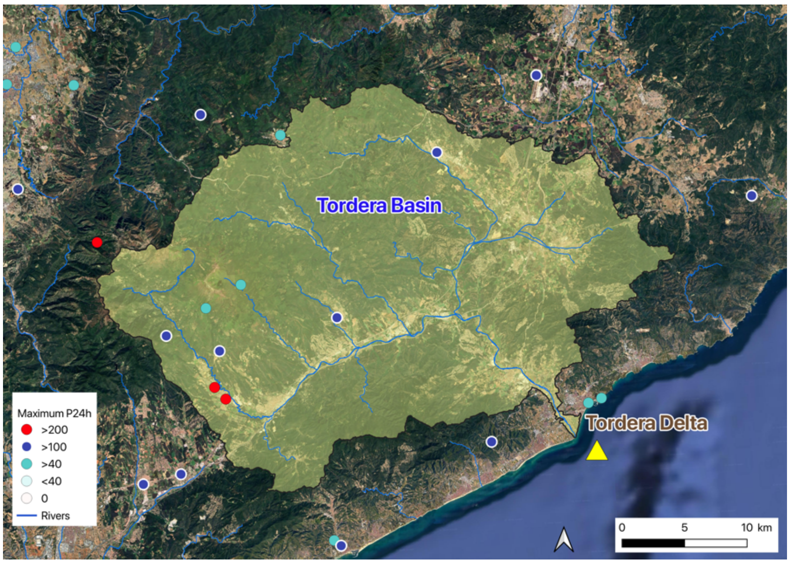

Figure 6: AEMET AWS (operative automatic weather stations) in the Tordera River basin and surrounding areas, and CoExMed wave node off the river mouth (yellow triangle). The stations are coloured according to the maximum recorded P24h value following the criteria described in 3.1 (Map data © 2025 Google).

During Storm Gloria, the maximum precipitation recorded within the basin reached 225 mm, while offshore Hs attained 4.5 m, equivalent to approximately 5.9 m in the SIMAR reanalysis. Considered independently, these values correspond to return periods of approximately 24 years for precipitation and 60 years for wave height. Assuming statistical independence between both drivers, their simultaneous occurrence would therefore correspond to an estimated return period of approximately 1,440 years.

Copula modelling, however, revealed a positive dependence between rainfall and wave extremes. Rainfall-conditioned events were best represented by a survival BB7 copula (Kendall's $\tau = 0.20$), whereas wave-conditioned events followed a Tawn Type I copula with a similar degree of dependence. Accounting for this dependence substantially increased the likelihood of joint occurrence, reducing the estimated return period from 1,440 years to approximately 85 years (Fig. 7). This result demonstrates the importance of explicitly considering dependence between flood-generating processes, as assuming independence would considerably overestimate the rarity of the event.

5.1.3 Implications

Beyond its statistical rarity, the Tordera case illustrates the distinctive characteristics of multivariate compound flooding. The interaction between fluvial discharge and coastal processes generated impacts considerably greater than those expected from either driver acting in isolation. Moreover, the concentration of critical infrastructure, tourism facilities, and agricultural land within the delta transformed a hydrometeorological event into a complex societal disruption.

The collapse of the road and railway bridges demonstrates how multivariate compound events may initiate cascading failures that propagate well beyond the directly flooded area. Recovery was further complicated by the involvement of multiple administrative authorities responsible for transport infrastructure, coastal management, and flood protection. Six years after the storm, adaptation measures combining nature-based solutions, shoreline restoration, land-use planning, and structural interventions are still being implemented within the Tordera delta, illustrating the long-term challenges associated with recovering from compound flood disasters.

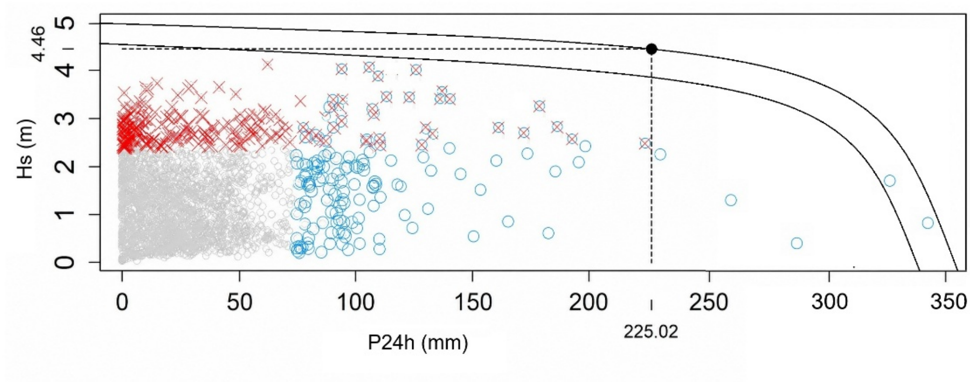

Figure 7: Estimated joint return period of the Gloria storm at the Tordera River mouth. Red crosses denote events with Hs exceeding the local storm threshold, blue circles denote events with P24 exceeding the local precipitation threshold, and grey symbols represent non-extreme conditions. The overlap of red crosses and blue circles denotes compound extreme events. Curves indicate joint return periods of 50 years (inner curve) and 85 years (outer curve), the latter corresponding to Storm Gloria (black filled circle).

5.2 Spatially compounding event: heavy rainfall in the Júcar basin and severe wave conditions along the Jávea coast

5.2.1 Event description

This case illustrates a spatially compound flood event, in which the principal flood-generating hazards occurred simultaneously but at geographically distinct locations (Fig. 4). During Storm Gloria, intense rainfall affected the Júcar River basin, generating widespread pluvial and fluvial flooding, while exceptional wave conditions developed along the Gulf of Jávea, producing severe coastal flooding and erosion. Although these hazards were hydrologically independent, their concurrent occurrence substantially increased the complexity of emergency response and recovery.

The example presented here is representative of a much broader regional pattern. Throughout the storm, heavy rainfall and energetic wave conditions affected multiple sectors of the Valencian Community simultaneously. The region covers approximately 23,300 km^2, includes more than 470 km of densely urbanised coastline, and is crossed by numerous torrential rivers and ephemeral streams. Consequently, emergency management authorities were required to respond simultaneously to inland flooding, coastal inundation, infrastructure damage, and transport disruption occurring at different locations but within the same administrative jurisdiction.

Along the Jávea coastline, significant wave heights reached between 7 and 10 m, producing widespread damage to beaches, promenades, ports, and seafront properties. At the same time, heavy rainfall within the Júcar basin caused extensive pluvial and fluvial flooding, resulting in road closures, transport disruption, and temporary airport operational restrictions. Unlike the multivariate event described for the Tordera delta, the principal challenge here did not arise from the interaction of hazards at the same location but from their simultaneous occurrence across a large geographical area, which substantially complicated emergency coordination and resource allocation.

5.2.2 Probabilistic characterization

The probability of occurrence of this spatially compound event was estimated using P24h recorded within the Júcar river basin together with Hs from the CoExMed node located in the Gulf of Jávea (Fig. 8), representing the fluvial and marine drivers, respectively.

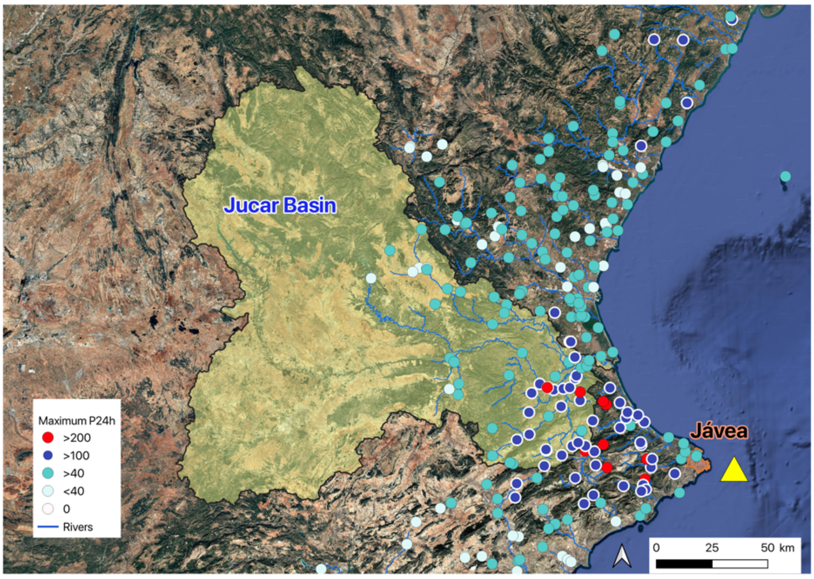

Figure 8: Location of the AEMET AWS (automatic weather stations) inside the Júcar River basin and surrounding area, and the node CoExMed located in the Gulf of Jávea (yellow triangle). The stations are coloured according to the maximum recorded P24h value following the criteria described in 3.1 (Map data © 2025 Google).

During Storm Gloria, maximum daily precipitation within the basin reached 274 mm, whereas Hs attained 7 m (equivalent to approximately 10 m in the SIMAR reanalysis). Considered independently, these values correspond to return periods of approximately 1.5 years for precipitation and 100 years for wave height. Assuming statistical independence, the simultaneous occurrence of both extremes would therefore correspond to a return period of approximately 150 years.

Copula analysis identified a positive dependence between rainfall and wave extremes. Rainfall-conditioned events were best represented by a survival Tawn Type II copula (Kendall's $\tau = 0.12$), whereas wave-conditioned events followed a Tawn Type I copula with a similar dependence structure. Accounting for this dependence reduced the estimated joint return period from approximately 150 years to 72 years (Fig. 9).

Although the dependence between both drivers is weaker than in the multivariate Tordera case, it still substantially increases the probability of joint occurrence. This result illustrates that even relatively modest statistical dependence can significantly influence estimates of the likelihood of spatially compound flood events.

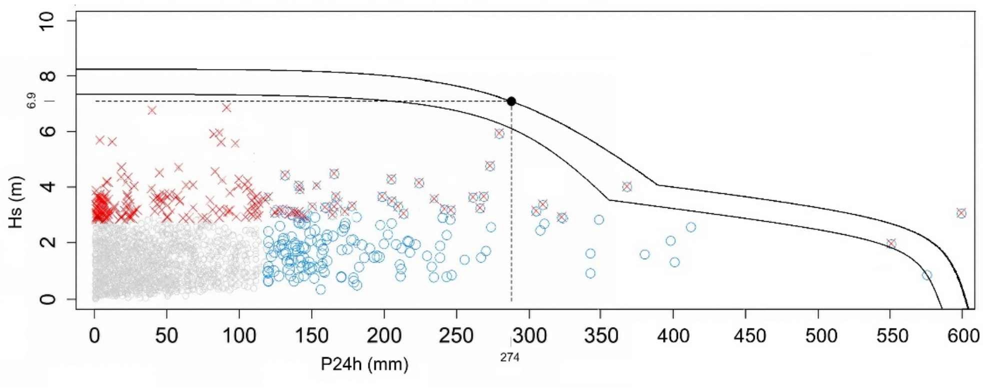

Figure 9: Estimated joint return period of the Gloria storm at the Júcar river basin and the Jávea coast. Red crosses denote events with Hs exceeding the storm threshold at Jávea, blue circles denote events with P24 exceeding the precipitation threshold at the Júcar river basin, and grey symbols represent non-extreme conditions. The overlap of red crosses and blue circles denotes compound extreme events. Curves indicate joint return periods of 50 years (inner curve) and 72 years (outer curve), the latter corresponding to Storm Gloria (black filled circle).

5.2.3 Implications

Unlike multivariate compound floods, whose impacts arise from the physical interaction of coincident hazard drivers, spatially compound events primarily increase the complexity of emergency management. Simultaneous flooding at multiple locations forces emergency services to distribute personnel, equipment, and logistical resources across large geographical areas, reducing operational flexibility and increasing the potential for resource shortages.

Storm Gloria clearly illustrates these challenges. During the peak of the event, inland flooding, coastal inundation, infrastructure damage, and transport disruption occurred simultaneously throughout the Valencian Community, requiring coordinated response by a single regional authority across widely separated locations. This type of event therefore places exceptional demands on emergency planning, interagency coordination, and resource allocation.

More broadly, the case demonstrates that the severity of spatially compound events depends not only on the magnitude of individual hazards but also on their geographical footprint. As recently shown for the Spanish Mediterranean coast by Aguilera-Vidal et al. (2026), certain atmospheric circulation patterns promote strong spatial connectivity between rainfall and coastal storms, increasing the probability that multiple flood emergencies will occur simultaneously over large regions. Consequently, incorporating spatial connectivity into hazard assessments is essential for realistic emergency planning and regional flood-risk management.

5.3 Temporally compounding event: successive flood episodes in Los Alcázares

5.3.1 Event description

The flooding of Los Alcázares (Murcia) illustrates a temporally compound flood event, in which the impacts of Storm Gloria were amplified by the occurrence of previous damaging floods before recovery had been completed. Unlike the multivariate and spatially compound examples presented above, the defining characteristic of this event is therefore not the magnitude of any individual storm but the clustering of damaging events before recovery from previous floods had been completed.

Los Alcázares is located on the western shore of the Mar Menor, within the lower Segura River basin (Fig. 10). The municipality is intersected by several ephemeral channels, including the Rambla del Albujón and the Rambla de la Maraña, which produce a diffuse flood response as runoff reaches the urban area through multiple drainage pathways. Extensive urban development within flood-prone areas, together with the modification of natural drainage channels and the presence of transport and utility infrastructure across flow paths, has substantially increased both exposure and flood vulnerability (Tragsatec and MITECO, 2020).

Figure 10: Map of the municipality of Los Alcázares and neighbouring municipalities in Murcia mentioned in the text, showing rivers and the location of AEMET AWS (automatic weather stations). The stations are coloured according to the maximum recorded P24h value during the Storm Gloria 2020 following the criteria described in 3.1 (Map data © 2025 Google).

The first event in the sequence occurred between 11 and 15 September 2019, when exceptionally intense rainfall generated widespread flooding throughout the Segura basin. Maximum P24h reached 321 mm in San Javier and 257 mm in Molina de Segura (Northwest of San Javier, 35 km from the sea) causing extensive damage to buildings, public infrastructure, and municipal services in Los Alcázares

(Fig. 11). The severity of the event led the municipality to be officially declared an "area seriously affected by a civil protection emergency". For this episode alone, the CCS paid more than EUR2022 24 million in Los Alcázares, accounting for 74% of the total compensation disbursed in the municipality between 1996 and 2020)

Approximately three months later, on 2-3 December 2019, a second heavy-rainfall episode affected the basin. Although less intense than the September event, with a maximum P24h of 145 mm (while San Javier registered 115 mm in 24 hours), it caused renewed flooding while recovery operations from the previous disaster were still underway. Roads were inundated, around one hundred residents were evacuated, and infrastructure that had only partially been repaired suffered additional damage.

Storm Gloria constituted the third event in the sequence. On 20-21 January 2020, maximum P24h again reached approximately 145 mm within the Segura basin. Although the direct physical damage was less severe than that produced by the September flood, the social consequences were substantially greater because the municipality had not yet recovered from the previous two events. The repeated occurrence of flooding generated widespread public dissatisfaction and culminated in a large demonstration in Los Alcázares on 26 January 2020 demanding more effective mitigation measures.

Taken together, these three events exemplify the concept of a temporally compounding. The severity of the January 2020 disaster resulted not only from the meteorological conditions associated with Storm Gloria but also the persistence of physical damage, accumulated economic losses, and declining social resilience following the preceding floods.

(a) *(b)*

Figure 11: Floods in Los Alcázares: (a) September 2019, during the DANA event (source: Confederación Hidrográfica del Segura); and (b) January 2020 (source: Government of the Region of Murcia)

5.3.3 Probabilistic characterization

The probability of this temporally compound event was estimated using daily precipitation records from the Segura River basin, which were considered representative of the regional hydrometeorological forcing responsible for the repeated flooding of Los Alcázares (Fig. 10).

Consequently, the estimated return period refers to the recurrence of a sequence of basin-scale rainfall extremes rather than to flood losses in the municipality itself.

During Storm Gloria, maximum P24h reached 145 mm within the basin. This event occurred under exceptionally wet antecedent conditions, with accumulated precipitation of 115 mm during the preceding month and 257 mm over the previous three months, indicating that Gloria formed part of an unusually persistent period of heavy rainfall.

The defining characteristic of this case is therefore not the magnitude of an individual storm but the temporal clustering of successive extremes (e.g. Haigh et al. 2016). Within less than five months, the basin experienced three major rainfall episodes, one exceeding 300 mm and two exceeding 140 mm in 24 hours. A comparable sequence occurred only twice during the available 43-year observational record, corresponding to an empirical return period of approximately 22 years. Although this estimate provides a useful indication of the rarity of the event sequence, it should be interpreted with caution because of the limited length of the observational record and the uncertainty associated with estimating the recurrence of clustered extreme events from empirical observations alone.

5.3.3 Implications

The Los Alcázares case demonstrates that the impacts of compound events depend not only on hazard magnitude but also on recovery dynamics. Although the January 2020 flood was considerably less severe than the September 2019 event from a hydrometeorological perspective, its occurrence before complete recovery had been achieved substantially amplified its societal consequences.

This amplification operated through several mechanisms. Physically, previously damaged infrastructure remained more vulnerable to subsequent flooding. Economically, repeated losses imposed an increasing burden on households, businesses, and public administrations. Socially, the succession of disasters progressively reduced community resilience and increased public dissatisfaction regarding flood management and recovery measures. Consequently, the disaster was defined not by the intensity of the final event alone but by the cumulative effects of the entire event sequence.

The case also highlights an aspect that is frequently overlooked in conventional flood-risk assessments. Return periods are generally calculated for individual events, implicitly assuming that each event occurs under independent antecedent conditions. However, when recovery times exceed the interval between successive extremes, disaster severity becomes strongly conditioned by event sequencing rather than by the magnitude of any single event. Recovery time should therefore be regarded as an integral component of compound flood risk assessment, particularly in regions where climate change is expected to increase the frequency of extreme precipitation events and reduce the time available for recovery.

Taken together, the three case studies illustrate that compound flood events differ not only in their physical mechanisms but also in the scales at which they operate and in the management challenges they generate. Multivariate events amplify hazard intensity through the interaction of coincident drivers, spatially compound events increase the complexity of emergency response by simultaneously affecting multiple locations, and temporally compound events amplify impacts through incomplete recovery between successive disasters. Storm Gloria demonstrates that all three mechanisms may coexist within a single atmospheric episode, producing a level of societal disruption that cannot be understood from any individual event type alone.

Comment 11: Line 393: the Figure 6 reports only the points of raingauges and buoy, no results are mapped, the same for the Figure 7.

Response 11: *Thank you for your comment. Initially, the maps only showed the station's location. In response, we have modified the figures to show the rainfall intensity (maximum P24h) observed at each site during the event, as you can see in the answer to the previous comment.*

Comment 12: Line 605: The conclusion is very long, I suggest to summarize the outcomes of the study.

Response 12: *OK, thanks. We have modified the conclusion as follows:*

Storm Gloria represents one of the most remarkable recent examples of compound flooding affecting the Spanish Mediterranean coast. Between 19 and 25 January precipitation was widespread, exceeding 500 mm at numerous stations (maximum of 527.5 mm). The event reached its peak between 19 and 21 January, when several stations recorded daily precipitation totals exceeding 250 mm, wind gusts above 110 km h-1 and maximum significant wave height above 8 m.

By combining meteorological observations, probabilistic analyses, documented impacts, and economic-loss data, this study provides an integrated assessment of how a single atmospheric episode generated multiple types of compound flood events and the consequences that followed. The results demonstrate that Storm Gloria simultaneously produced multivariate, spatially compound, and temporally compound flood events, each characterised by different physical mechanisms and distinct implications for emergency management. Multivariate events amplified impacts through the interaction of coincident fluvial and coastal processes at the same location, spatially compound events increased the geographical footprint of the emergency by simultaneously affecting different sectors of the coast, and temporally compound events intensified impacts because recovery from previous floods had not been completed. Together, these examples show that different compound-event types may coexist within a single storm and jointly contribute to the overall severity of the disaster.

The probabilistic analyses further demonstrate the importance of explicitly accounting for dependence between hazard drivers. For both the multivariate and spatially compound examples, considering statistical dependence substantially reduced the estimated joint return periods compared with the assumption of independence, confirming that conventional univariate approaches may considerably underestimate the likelihood of compound extremes.

The comparison between meteorological severity and economic compensation also highlights that hazard intensity alone is insufficient to explain disaster losses. Although the largest compensation payments generally occurred in areas experiencing the highest hazard levels, important regional differences emphasise the controlling influence of exposure and vulnerability. Moreover, while flooding accounted for most insured losses at the regional scale, coastal flooding became nearly as important as wind-related damage when only coastal municipalities were considered, underscoring the need to explicitly include marine processes in coastal flood-risk assessments.

Beyond direct economic losses, Storm Gloria generated numerous cascading impacts that persisted well beyond the meteorological event itself. Damage to transport infrastructure, beaches, ports, and *coastal ecosystems required recovery periods extending over several years, while reconstruction efforts were further complicated by the onset of the COVID-19 pandemic shortly afterwards. At the same time, the event also generated beneficial geomorphological responses, including sediment redistribution within the Tordera delta and recharge of aquifers and reservoirs. These contrasting effects illustrate the dual role of extreme storms as both destructive events and natural agents of coastal morphodynamic adjustment, emphasising the need to evaluate both adverse and beneficial consequences when assessing coastal resilience.*

From a management perspective, Storm Gloria exposed important limitations in current approaches to coastal flood risk. While emergency response was initially coordinated at municipal level, the large geographical footprint of the storm rapidly exceeded local response capacity and required increasing regional and national coordination. The event also placed considerable pressure on institutional mechanisms, including the Insurance Compensation Consortium, whose operational capacity had already been affected by previous flood events during late 2019. These observations highlight that compound events should be viewed not only as physical phenomena but also as governance challenges requiring coordination across administrative boundaries and throughout the entire disaster-management cycle, from preparedness to long-term recovery.

Beyond the specific case of Storm Gloria, this study demonstrates the value of integrating hazard characterisation, probabilistic dependence analysis, and observed impacts within a common framework for the analysis of compound events. Such an approach provides a more realistic representation of coastal flood risk than analysing individual hazards independently and offers a practical basis for improving early-warning systems, emergency planning, and long-term adaptation strategies. The framework presented here provides a practical basis for incorporating compound-event thinking into coastal flood-risk assessment and adaptation planning, an increasingly important requirement for climate-resilient management of Mediterranean and other vulnerable coastal regions

Although this episode has been shown to be a paradigmatic case of different types of compound events, it was not a typical Mediterranean flood event. Such events usually occur in autumn and are mainly characterised by flash flooding. The magnitude and uniqueness of the event can be considered aligned with the consequences of climate change. This underscores the need to be prepared for unprecedented situations, as proposed by Kreibich et al. (2022).

Answers to Referee #2 comments

Comment 1: I have only some minor remarks on the manuscript. Otherwise, the manuscript is written in good English and contains interesting and important results.

Response 1:

The authors would like to thank you very much for taking the time to review this manuscript and the constructive comments made. The original comments are reproduced in black, followed by our responses in blue. Added or modified text to the manuscript is indicated in italic green.

Please find detailed responses next.

Comment 1: I think the title of the manuscript is a bit misleading. The main topic of the manuscript is not the values of joint probabilities, which are discussed quite briefly, but the description of the Gloria storm and its impacts in different coastal regions. I suggest the authors to shorten the title to " Storm Gloria (2020): multiple flood hazards ..." (rest of the title as it is).

Response 1: *Thank you very much for your comment that has helped us to see a little mistake: it was a paradigmatic case of compound floods in the Mediterranean but not a paradigmatic Mediterranean flood case.*

New title: "Storm Gloria 2020: coexisting types of compound flooding in the West Mediterranean Region"

Comment 2: In many places, the authors refer to "wave height", "highest recorded wave height" , "maximum wave height" etc. I suppose they mean always the observed significant wave height, not measurements of individual waves. This should be clarified at least. I suggest to correct these terms when necessary, as in Table 2 and elsewhere.

Response 2: *We thank the reviewer for this helpful observation. We agree that the terminology needed to be clarified, as the values used in the manuscript refer to significant wave height rather than to individual wave measurements. We have therefore revised the manuscript and added the term "significant" where necessary, including in Table 2 and elsewhere. In addition, we have added the "CoExMed" subscript to distinguish these data from those obtained from the SIMAR dataset. Both concepts are now explained in the Methodology section:*

"Wave conditions were characterized using two complementary datasets. The first consisted of hourly significant wave heigh (Hs) time series from the SIMAR wave reanalysis produced by Puertos del Estado (http://www.puertos.es/es-es/oceanografia), extracted at 50 nodes distributed along the Spanish Mediterranean coast. For the spatial analysis, each SIMAR node was associated with its nearest coastal municipalities. To estimate the probability of multivariate and spatially compound events, Hs time series from the CoExMed wave reanalysis (Toomey et al., 2022) were used at two offshore locations near Tordera (Barcelona) and Jávea (Alicante). Unlike SIMAR, CoExMed provides a long-term wave hindcast (1950-2021) generated using a consistent modelling framework (i.e. same wave model, computational grid, and atmospheric forcing throughout the entire period), making it more suitable for statistical analysis of extremes. However, it should be noted that CoExMed systematically underestimates storm wave heights relative to SIMAR"

Comment 3: I suggest to add explanation of TCA (atypical cyclonic storms) to Table and Figure captions so that the reader does not have to search for it. Alternatively TCA could be mentioned already in the abstract.

Response 3: *Change done. The term TCA is only used by the Insurance Compensation Consortium when referring to the group of phenomena of meteorological origin different from floods (usually strong winds and tornadoes). We have added an explanation in the manuscript to clarify the concept, and we have made a revision of the use of this term throughout the manuscript according to your comments.*