Main hydrometeorological and social factors involved in the unfolding of the 22 October 2019 hazardous flash flood in Catalonia, north-eastern Spain

Universitat de les Illes Balears

A. Amengual[1], R. Romero[1], M. C. Llasat[2] , A. Hermoso[3] and M. Llasat-Botija[2]

(1) Grup de Meteorologia, Departament de Física, Universitat de les Illes Balears (UIB), Palma, Mallorca, Spain
(2) GAMA, Department of Applied Physics, Universitat de Barcelona, Barcelona, Spain
(3) Institute for Atmospheric and Climate Science, Department of Environmental Systems Science, Swiss Federal Institute of Technology, Zurich, Switzerland

arnau.amengual@uib.es

9th International Conference on Meteorology and Climatology of the Mediterranean (MetMed)
Genoa (Italy), 22-24 May 2023
MetMed

INTRODUCTION

Flash floods are the most destructive natural hazard in terms of economic and human losses in the Mediterranean region. On 22 October 2019, a heavy precipitation event (HPE) impacted the upper Francolí River basin in Catalonia, north-eastern Spain. Maximum observed rainfall amount was close to 300 mm, with a maximum 10-min rainfall accumulation close to 21.0 mm. Intense and copious rainfall triggered an extreme flash flood, resulting in death toll of six and estimated economical losses above 44 million EUR. The main hydrometeorological factors that concurred in the unfolding of this catastrophic event are examined by means of large-scale meteorological grid analyses, high-resolution mesoscale model simulations, radar-derived precipitation estimates, stream-gauge measurements, postflood field observations and hydrological modelling. The main objectives are to: (i) identify the leading physical mechanisms responsible for the onset and evolution of the convective systems, (ii) explore the main features of the HPE over the upper Francolí catchment; and, (iii) assess basin response to torrential rains.

CASE STUDY

Study area

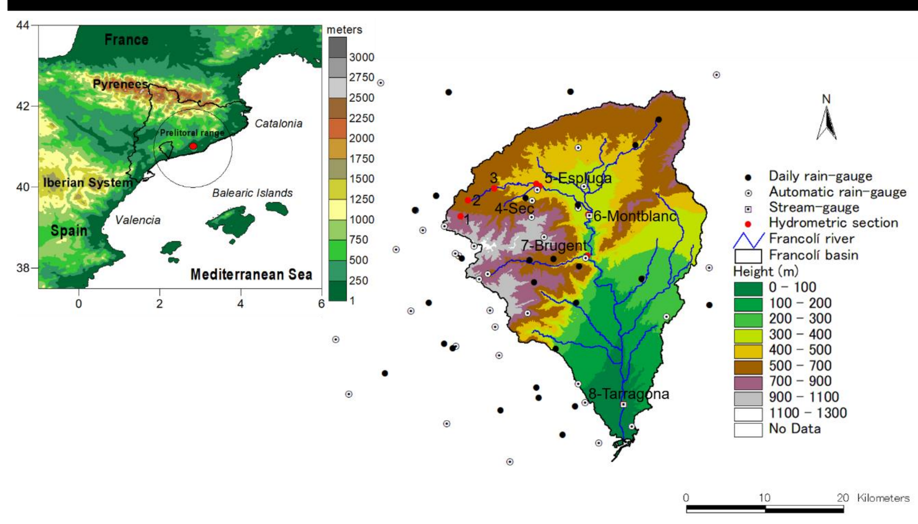

Figure 1. Top left: main geographical features of Mediterranean Spain. The location of the Barcelona weather radar from AEMET is shown as a red dot. The Francolí catchment is highlighted in thick black line. Radii of the radar circle is 100 km. Center left: main geographical features of the Francolí basin. The automatic rain-gauges are shown as white dots. Automatic stream-gauges are labelled and depicted as white squares. Daily pluviometers are illustrated as black dots. Hydrometric sections are denoted as red circles and labelled in downstream direction

The Francolí river basin spans over an area of 858 km^2, with a river length up to 60 km at its mouth in Tarragona city (Fig.1). The north-western part of the catchment is shaped by the Catalonian prelitoral mountainous ranges, with a maximum height close to 1200 m and bed slopes up to 2.0%.

The Francolí river is monitored by the Catalan Water Agency (ACA) at two cities: Montblanc (339.9 km^2) and Tarragona (809.1 km^2). Raw streamflow is recorded by the automatic stream-gauge stations with a temporal resolution of 5 and 15 min, respectively (Fig. 1). Automatic raw precipitation is recorded at 251 stations by several agencies: The Catalan Meteorological Service (SMC), the Spanish Agency of Meteorology (AEMET) and the Meteoprades amateur association. Daily rainfall amounts are recorded in 212 additional rain gauges by AEMET. The region is also monitored by the AEMET Doppler C-band weather radar deployed very close to Barcelona city (Fig. 1).

Synoptic situation

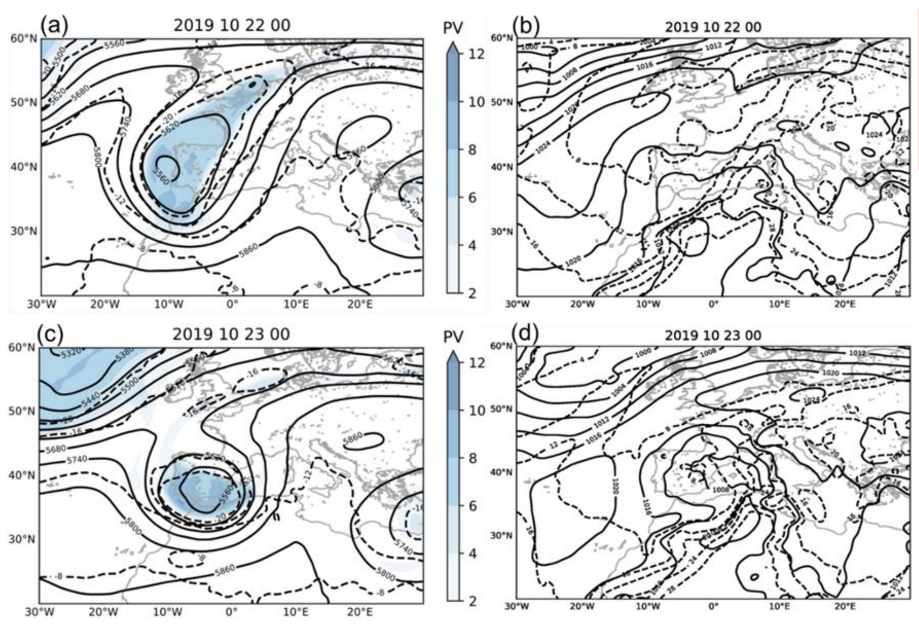

Figure 2. ECMWF analysis for geopotential height (solid lines, in gpm), temperature (dashed, in ° C) at 500 hPa, and 250-hPa potential vorticity (PVU, shaded in blue) on: (a) 22 and, (b) 23 October 2019 00 UTC. ECMWF analysis for mean sea level pressure (solid lines, hPa) and temperature at 850 hPa (dashed, in ° C) on: (c) 22 and, (d) 23 October 2019 00 UTC.

During the hours preceding the unfolding of the convective episode, an intense Potential Vorticity (PV) streamer progressed towards the Atlantic coast of the Iberian Peninsula at upper levels (Fig. 2a). In correspondence, a deep trough with cold air can be identified at mid-tropospheric levels. During the following hours, the PV streamer tilted eastwards while breaking from the main circulation and forming a closed center over the southern half of the Iberian Peninsula on 23 October 00 UTC (Fig. 2c), while the mid-tropospheric disturbance adopted the structure of a cut-off cyclone with a cold core.

The low-level thermal structure was characterized by the advance of cold air over the Iberian Peninsula, along with the upper-level PV streamer, together with the genesis of a marked temperature gradient towards the western Mediterranean (Figs. 2b and d). The circulation associated with the surface cyclone over the Balearic Islands contributed to the strengthening of the thermal front and the advection of warm and moist Mediterranean air towards Catalonia. The evolution of this baroclinic structure was instrumental to promote upward vertical motion and the destabilization of the low-level parcels. Once formed the convective systems, such circulation pattern guaranteed a continuous feeding with Mediterranean warm and moist air.

RESULTS

Leading meteorological mechanisms

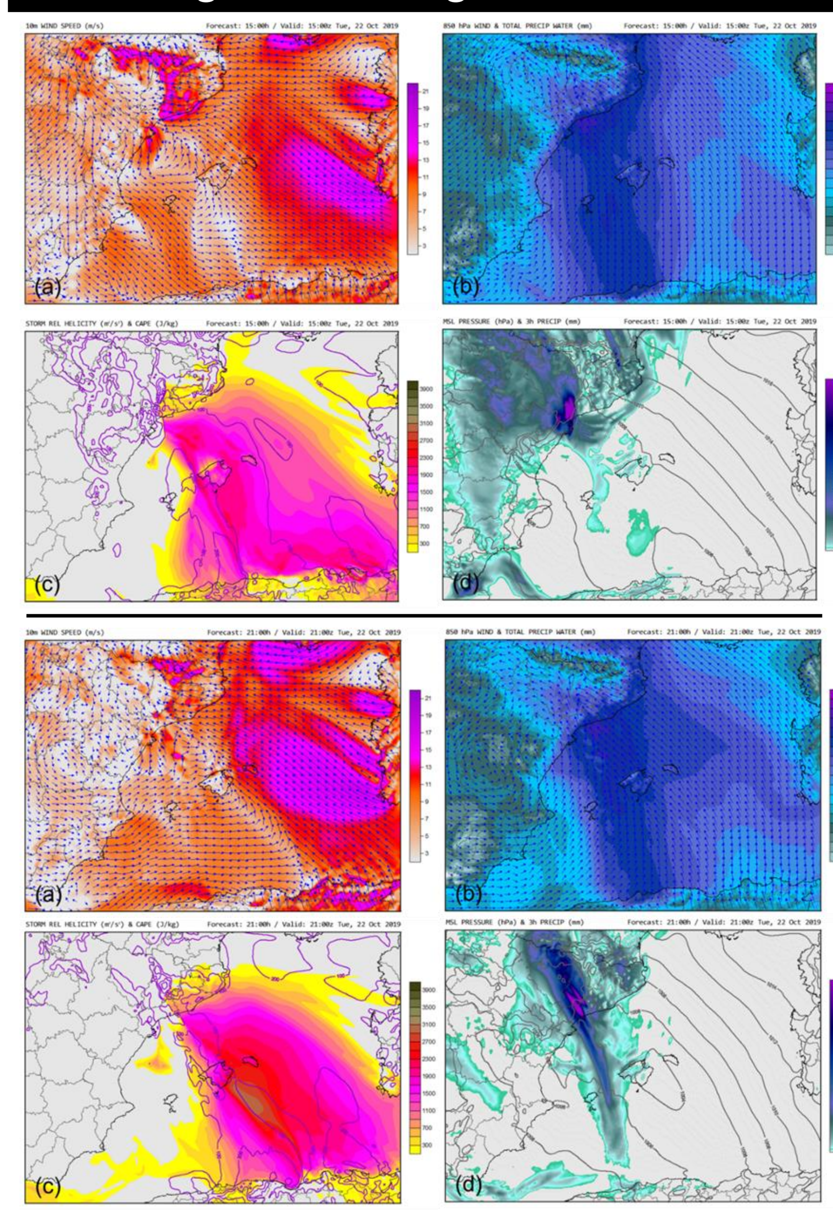

Figure 3. Top: TRAM control simulation at 15 UTC on 22 October 2019, showing: (a) surface wind field (m/s, according to scale); (b) 850 hPa wind vectors and precipitable water in the tropospheric column (mm, according to scale); (c) storm relative helicity (m2/s2, contours) and CAPE (J/kg, according to scale); and (d) sea level pressure (hPa, contours) and accumulated precipitation in previous 3 hours (mm, according to scale). Bottom: As in top, but at 21 UTC on 22 October 2019.

The specific roles of the mesoscale processes and local orography are investigated by forcing the new TRAM model with large-scale meteorological grid analyses (Romero et al., 2019). Surface wind fields confirm the impinging of a south-easterly flow towards the Catalonian precoastal orography (Figs. 3a top and bottom). Such direction is optimal for the mechanical uplift of surface parcels by the mountain slopes of Tarragona, since its ridges are aligned parallel to the coastline. The impinging surface airflow was the leading portion of a maritime low-level jet (LLJ) pattern that initiated towards the south-western coasts of Sardinia. This LLJ tended to reinforce and shifted northwards during the second half of 22 October, in association with the evolution of the synoptic-scale system and persisted during the entire HPE.

The maritime flow against the coast maintained coherence through the low troposphere (Fig. 3). This airflow brought plenty of moisture of Mediterranean origin towards the Catalonian coast. This atmospheric circulation persisted during several hours, favoring a continuous feeding of the precipitation systems and its quasi-stationary character, resulting in the so-called convective train effect (Doswell et al., 1996). Two basic ingredients for the development and maintenance of deep moist convection were the: (i) low-level water vapor flux convergence; and, (ii) upward vertical motion.

The ingestion of air parcels possessing convective o latent instability became a crucial additional ingredient (Romero et al., 2000). The model-simulated CAPE (Figs. 3c top and bottom) confirms the existence of high values of CAPE. These unstable vertical profiles were persistently advected towards the coastlands of Catalonia. Finally, the topographically complex terrain and the arrangement of the precoastal mountain ridges in Tarragona were the critical element for the disproportionate rain totals and intensities over the upper Francolí catchment.

Precipitation analysis and flood response

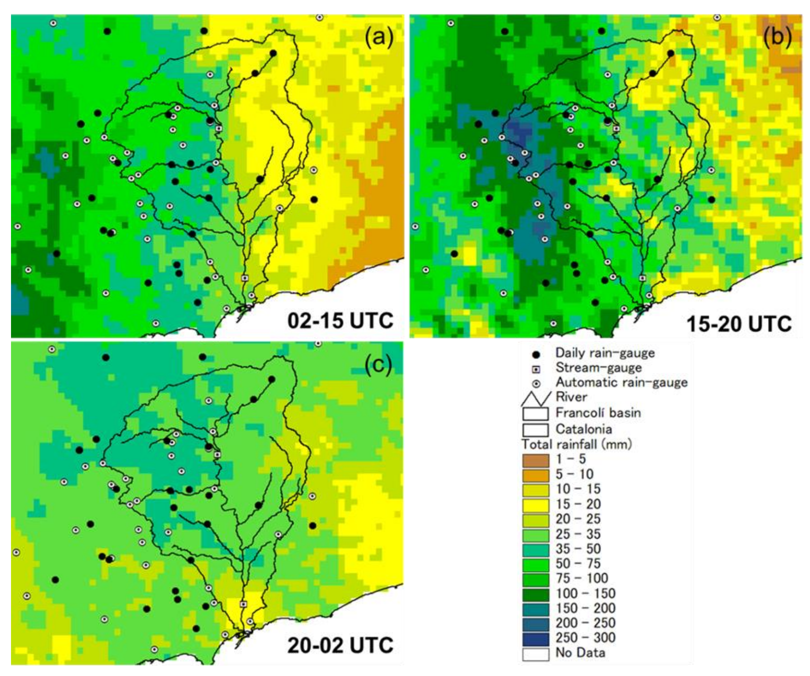

Figure 4. Spatial distribution of the accumulated radar-derived precipitation from: (a) 02 UTC to 15 UTC on 22 October; (b) 15 UTC to 20 UTC on 22 October and; (c) 20 UTC on 22 October to 02 UTC on 23 October. The Francolí river catchment is highlighted with a thin black line. White squares stand for the automatic stream-gauges. White dots show the position of the automatic rain-gauges. Daily pluviometric stations are denoted by black dots.

The 48-h radar-derived rainfall field confirms that the lifting associated with local topographic forcing had a paramount role in enhancing maximum rainfall amounts over the northwestern headwaters of the Francolí catchment. Values above 150 mm were exclusively circumscribed across this area, with cumulative precipitation well above 300 mm in the highest mountainous reliefs. From 16 to 20 UTC, the intense downpours adopted the form of quasi-stationary heavy rainfall, overwhelming the basin. The persistent convective systems produced extreme bursts of rain: maximum observed 10-min rainfall rate and 4-h accumulation were 124.8 mmh^{-1} and 193.4 mm, respectively.

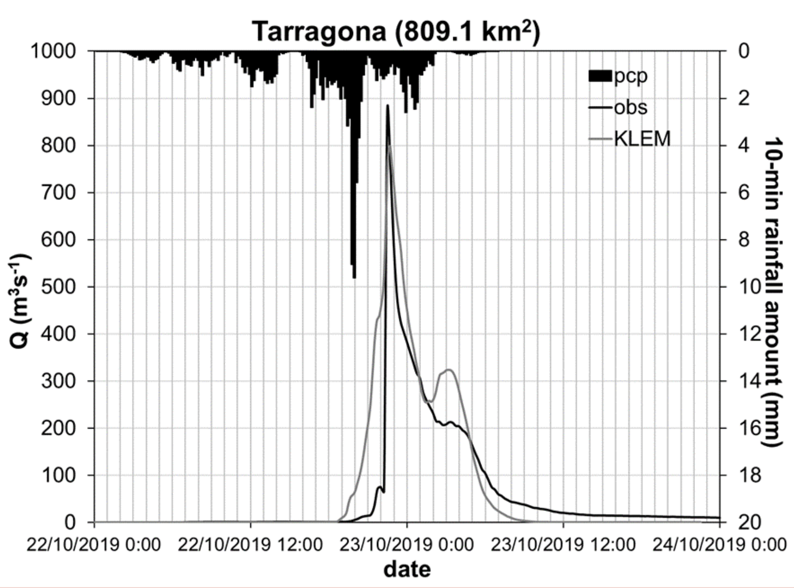

Figure 5. Observed and KLEM radar-driven discharge simulation for the 22 October flash flood at Tarragona flow-gauge. Also shown are the 10-min catchment-area average rainfall amounts enclosed by this hydrometric section.

The KLEM hydrological model captures adequately the overall basin response, with a high goodness-of-fit in peak magnitude and timing. However, the observed water balance is moderately overestimated at the expense of a slight underestimation in peak discharge (Table 1; Figure 5)

Basin	Gauge	Flow volume			Flow peak			NSE
		Observed (mm)	KLEM (mm)	Error (%)	Observed (m^3s^{-1})	KLEM (m^3s^{-1})	Error (%)	
Francolí	Tarragona	12.4	15.1	21.5	871.0	798.8	-10.9	0.7

Table 1. Observed and radar-driven simulated flow volume and peak discharge at the Tarragona hydrometric section. Model performance also shown in terms of the different skill scores. Negative values in relative errors denote model underestimation.

Catchment dynamics

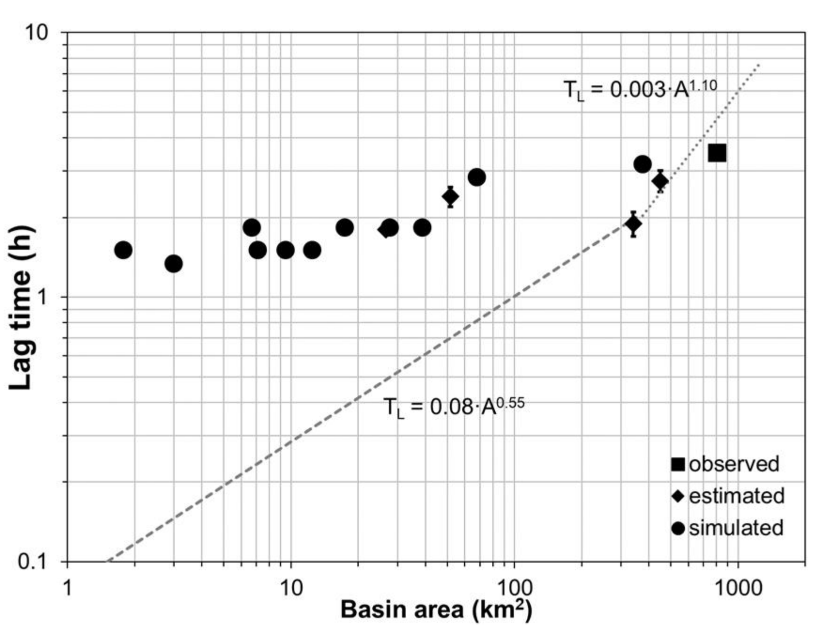

Figure 6. Lag time versus drainage area for the Francolí basin before the 22 October 2019 flash flood. Uncertainties in the estimated lag times are shown as vertical bars. Also shown the power-law relationships after Marchi et al. (2010).

Postflood field observations and hydrological modelling confirm that the Francolí basin exhibited paroxysmal dynamic processes typical of extreme flash flooding. Catchment average hillslope and channel flow velocities were of 0.25 ms^{-1} and 4.5 ms^{-1}, respectively. The high speeds of the superficial flows are associated to the steep slopes and channels of the upper Francolí river basin. Catchment dynamics across the different drainage scales are quantified through lag time (Fig. 6).

Lag times were less than 2 h for basin areas up to 50 km^2, of 2.5–3 h for drainage extents between 50 km^2 and 350 km^2, and of 3–3.5 h for catchment extensions between 375–810 km^2. Lag times exhibit a relative constant value of roughly 1.5 h for basin areas less than 15 km^2. Response times are also relatively steady –about 1.8 h– for drainage extents between 15–40 km^2. Response times for drainage sizes larger than 350 km^2 were strongly influenced by the hydraulics of the flow. The strikingly extreme channel velocities –up to 10 ms^{-1}– resulted in a sharp transition with drainage size.

CONCLUSIONS AND FUTURE RESEARCH

- Low-level convergence was fostered by: (a) the impinging of a maritime LLJ towards the Catalonian precoastal orography and subsequent mechanical uplifting of surface parcels by the mountain slopes, and; (b) a north-westerly flow channeled along the Ebro valley which opposed the maritime flow
- The atmospheric circulation promoted the so-called convective train effect. Basic ingredients were the: (a) low-level water vapor flux convergence; (b) upward vertical motion, and; (c) ingestion of air parcels possessing convective o latent instability.
- The lifting associated with local topographic forcing had a paramount role in enhancing extreme rainfall over the Francolí river catchment
- Post-flood field observations and hydrological modelling points out to a marked non-linearity in basin response due to large initial soil retention capabilities. Pronounced heterogeneities in catchment dynamics arise due to the impact on the flood bore of several bridges along the river
- Catchment response times reveal an abrupt transition across drainage scales: Basin extents larger than 350 km^2 are in the lower limit of the envelope curve derived by Marchi et al. (2010), while lag times for drainage areas smaller than 350 km^2 are well above the inferior envelope bound.
- For drainage sizes smaller than 350 km^2, this behavior can be ascribed to the relatively delayed basin response to precipitation at small scales due to extreme soil moisture deficit and runoff threshold exceedance. Response times for drainage sizes larger than 350 km^2 were strongly influenced by the hydraulics of the flow.
- Nevertheless, people responsible for risk management have to cope with unusual short lead times when facing these sudden and fast natural hazards over Mediterranean Spain. Future research will compare these hydrological response times with the timing of the social response.

REFERENCES

• Doswell III, C. A., Brooks H., and Maddox, R., 1996:. Flash flood forecasting: An ingredient-based methodology. Wea. Forecasting, 11, 560–581.
•Marchi, L., Borga, M., Preciso, E., and Gaume, E., 2010: Characterisation of selected extreme flash floods in Europe and implications for flood risk management. J. Hydrol., 394(1-2), 118-133.
•Romero, R., C. A. Doswell III, and C. Ramis, 2000: Mesoscale numerical study of two cases of long-lived quasi-stationary convective systems over eastern Spain. Mon. Wea. Rev., 128, 3731-3751.
•Romero, R., M. Vich, and C. Ramis, 2019: A pragmatic approach for the numerical prediction of meteo-tsunamis in Ciutadella harbour (Balearic Islands). Ocean Modelling, DOI 10.1016/j.ocemod.2019.101441.

AKNOWLEDGEMENTS

This work was sponsored by: Ministerio de Ciencia e Innovación - Agencia Estatal de Investigación/TRAMPAS (PID2020-113036RB-I00/AEI/10.13039/501100011033). The authors are grateful to AEMET (Spain) and particularly its members Ramón Pascual and Gabriela Cuevas for providing technical documentation and different kinds of meteorological observations regarding this flash flood event.
The authors are also grateful to Eduard Marion from Meteoprades for providing rainfall observations. The ACA and SMC agencies are also acknowledged for providing the data needed to perform this work.