The case of flash floods in Montsià county (Catalonia, Spain): From Precipitation Sources to Thunderstorm Cells

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1 - Objectives

- **Evaluate economic losses & CCS payouts (1996–2020)**
- **Diagnose meteorological & moisture drivers of 2018, 2021 and 2023**
- **Quantify heavy-rain & flood frequency (1980–2023)**
- **Detect trends in extreme rainfall & distribution metrics**

2 - Region of interest

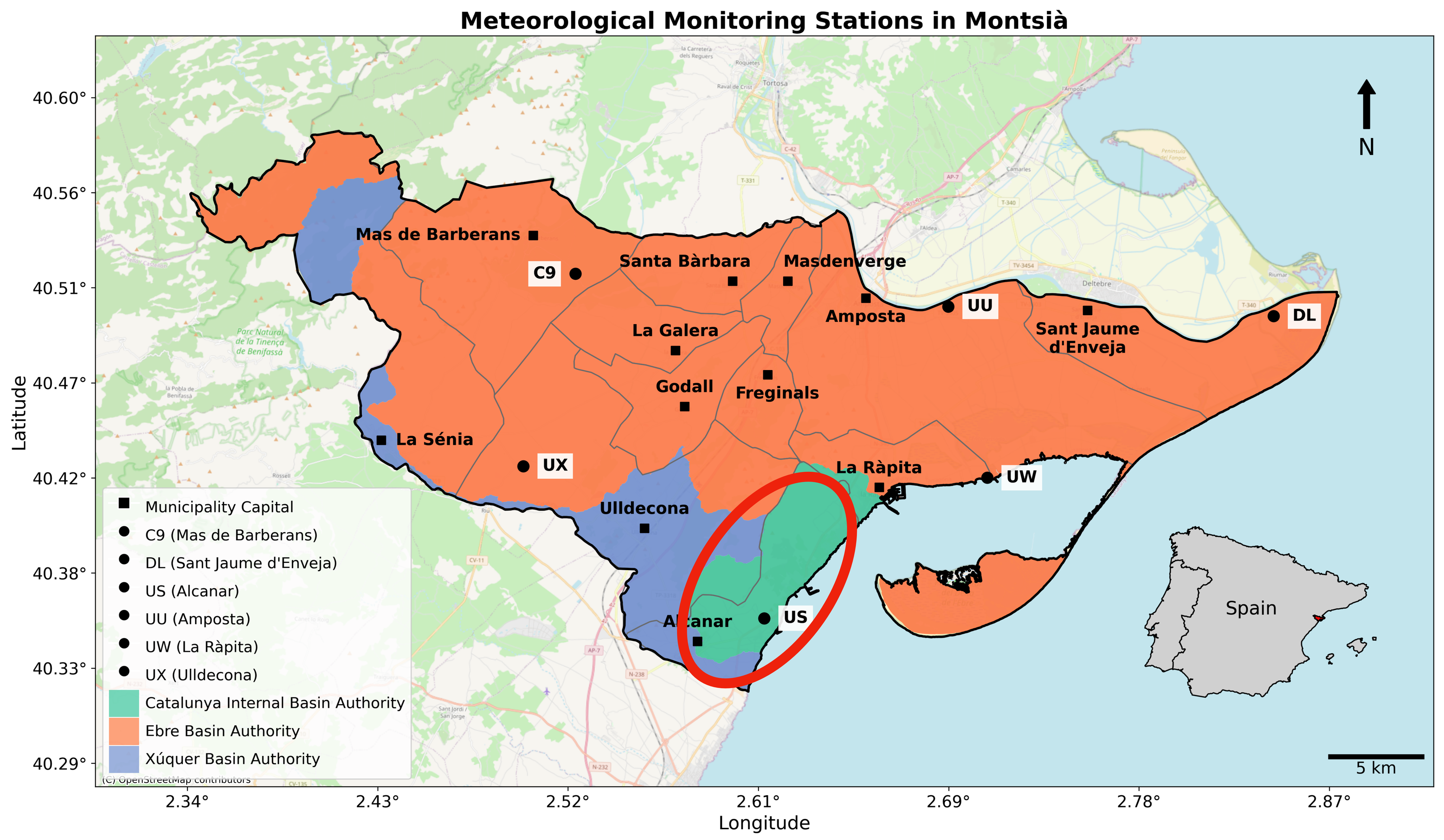

Fig.1. Division of Montsià county into three hydrographic basins, indicating the locations of XEMA meteorological stations (circles) and municipal capitals (squares).

3 - Data & Meteorological Networks

- **Ground Observations**
  XEMA AWS (1-min, 189 sites; 6 in Montsià)
  XRAD Panadella radar (C-band, 1km/6min)
  XDD lightning (CG & IC, 1km/1s)
- **Atmospheric Reanalysis & Modelling**
  ERA5 (0.25°, 1h, ECMWF)
  FLEXPART v10.4 (15M parcels) for E2P tracking
- **Impacts & Events**
  INUNGAMA flood database (1980–2023)
  CCS compensation data (1996–2023)
- **Providers**
  SMC · ECMWF · AEMET · CCS

Fig.2. Aerial view of Les Cases d'Alcanar, Alcanar municipality (Montsià). Photo: VEOy.com / Adobe Stock, ID 180952881 (standard licence)

4 - Flash-Flood Case Studies (Municipality of Alcanar)

Date	Total Precipitation (mm)	Precipitation Period (UTC)	Pmax-30min (mm)
October 2018	200	12:00-18:00	52 mm
September 2021	252	9:00-12:00	72 mm
October 2023	206	4:30-07:00	62 mm

5 - Methods

- **Flood losses & payouts (1996–2020):** analysis of 54 flood events in Montsià using CCS compensation records, with a focus on Alcanar. Case-specific impact data included for 2018, 2021, and 2023.
- **Meteorological drivers (2018, 2021, 2023):**
  Synoptic analysis using ERA5 reanalysis and radar/lightning data. FLEXPART Lagrangian model applied to trace moisture sources (E2P method) 30 days prior to each event.
- **Heavy-rain frequency (1980–2023):** return periods for daily and hourly rainfall estimated at six Montsià stations using multiple statistical distributions (GEV, GPD, etc.). Best-fit models selected via Kolmogorov-Smirnov tests, Q–Q plots, and R^2 values.
- **Trend detection (1991–2023):** trends assessed in extremes, percentiles, and distribution shape (skewness, kurtosis, SD) using linear regression and t-tests. Missing-data years excluded. Smoothed with 5–10 year moving averages.

6 - Economic Impacts

Between 1996–2023, **54 floods** hit **Montsià**, **31** in **Alcanar** alone, with most **episodes** concentrated in **autumn.** **Average** CCS compensation in Alcanar was **€79,217/event**, but payouts surged in **2018 (€1.42M), 2021 (€10.2M)**, and **2023 (€1.3M)**. These three events **triggered emergency plans**, caused major **infrastructure disruption**, and marked a sharp **post-2017** rise in **flood severity** and **costs**.

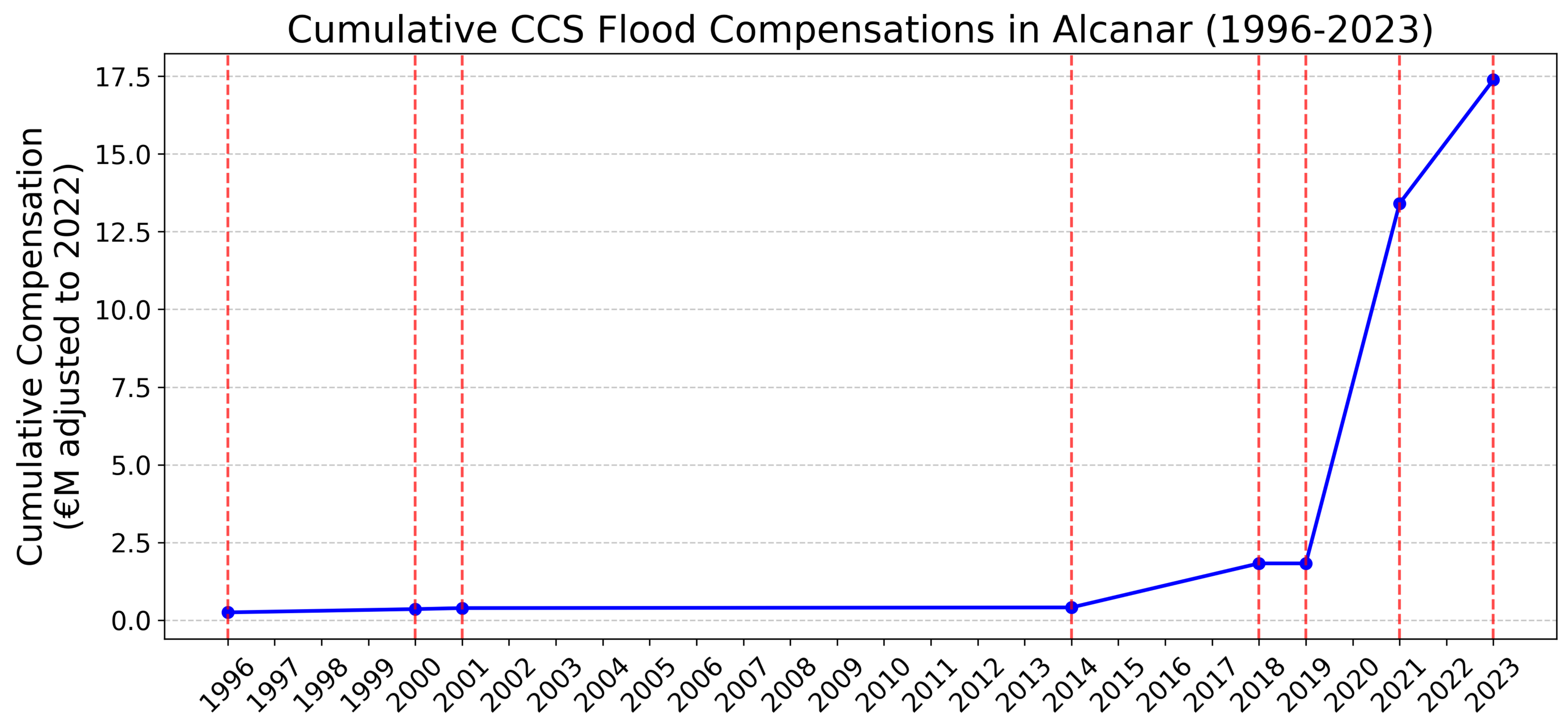

Fig.3. Evolution of cumulative flood compensations paid by the CCS in the municipality of Alcanar from 1996 to 2023 (€M, adjusted to 2022 values). The vertical red dashed lines indicate years for which CCS compensations were paid (8 episodes in total, one per year).

7 - Meteorological Summary

Intense rainfall episodes in the region are **associated** with a persistent **easterly/southeasterly low-level flow** and a **south/southwesterly flow aloft**, typically driven by a cold or **cut-off low southwest** of the **Iberian Peninsula**, aided by an **Atlantic-European anticyclone**. These patterns promote **moist onshore advection** and **high precipitable water. Radar data** show **multi-scale convective** features, with **convective trains** being predominant. Despite **moderate CAPE** and **high low-level equivalent potential temperatures**, echo tops remain below 12 km, indicating **non-deep convection**. An **upper-level jet streak** supports sustained **cell regeneration** in all cases.

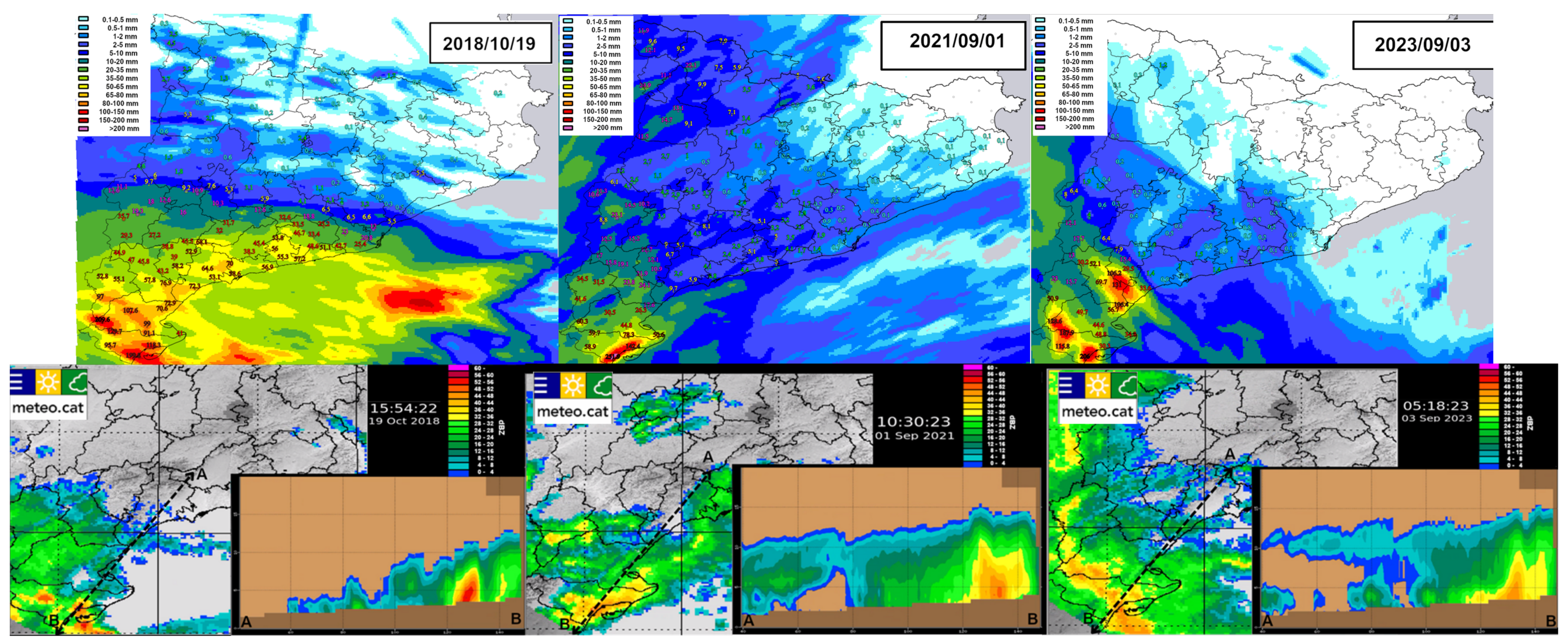

Fig.4. Heavy-rain episodes in Catalonia: 19 Oct 2018, 1 Sep 2021 and 3 Sep 2023 (left→right). Each column shows (top) 24 h gauge-radar rainfall, (bottom) peak-time 4 km CAPPI reflectivity, and (bottom-right) vertical echo along transect A–B, exposing plan-view intensity and storm depth.

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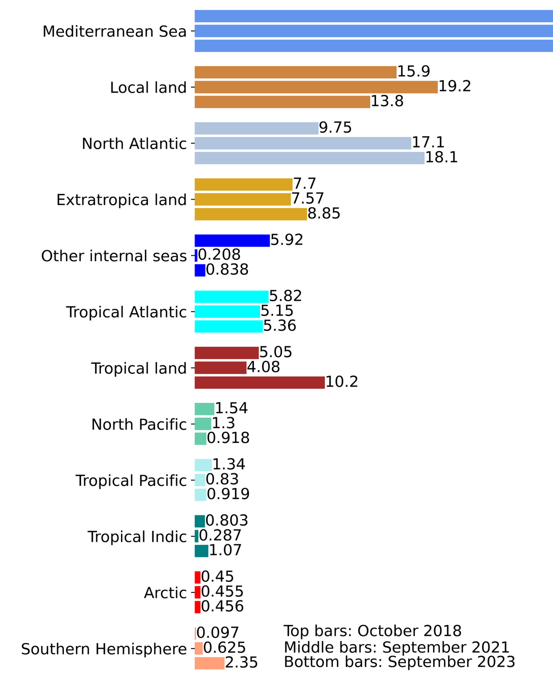
8 - Moisture Sources

The **Mediterranean Sea** and its surrounding regions typically provide over **50%** of the **atmospheric moisture** during **extreme rainfall events**. However, significant **additional contributions** from distant sources—such as the **North Atlantic, tropical Africa**, and even **North America**—are **essential** to explain the extraordinary precipitation totals. Though each remote source accounts for only **5–10%**, their cumulative input is **substantial**, underscoring the **multi-source** and **multi-scale dynamics** that drive **flash flood** events in the **Western Mediterranean.**



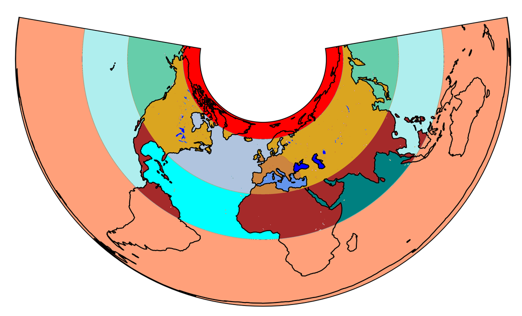


Fig.5. Precipitation fractions (%) for the October 2018 (top bars), September 2021 (middle bars), and September 2023 (bottom bars) events, categorized by source and represented in different colors in the plot on the right.

9 - Return Periods

Meteorological station data from **Montsià** reveal **concerning rainfall return levels**, with daily totals rising from **112 mm** (**2-year**) to 340 mm (100-year) and **hourly intensities** reaching up to **120 mm/h**. **Alcanar** stands out for its **particularly intense rainfall patterns**, showing **daily accumulations** from **67 mm** (**2-year**) to **285 mm** (**100-year**), and hourly peaks up to **100 mm/h** for a **50-year** return period.

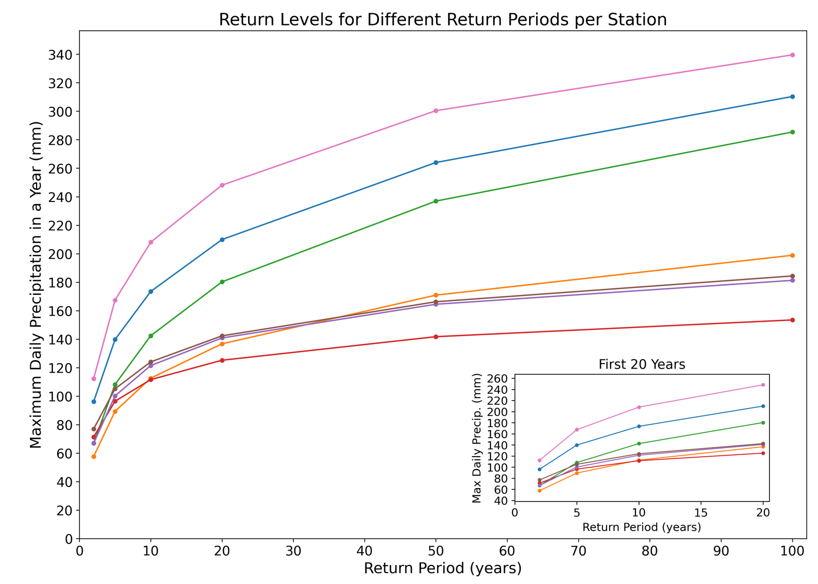


Fig.6. Maximum daily precipitation (in mm) as a function of the return period (in years) for each meteorological station and for Montsià county as a whole (code MM).

10 - Precipitation Trends

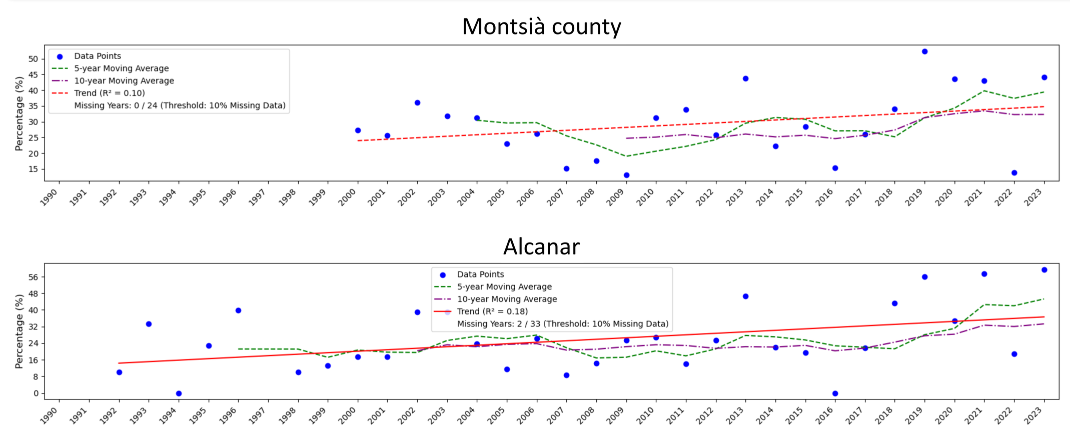


Fig.7. Percentage of annual precipitation exceeding 40 mm per day from the early 1990s to 2023. The red trend line depicts the direction and strength of the trend, with a solid line marking statistical significance at the 95% confidence level and a dashed line representing a non-significant trend.

The **updated flood database** indicates a **statistically significant rise** in **flood events** in **Alcanar**, with a similar but **non-significant trend** across **Montsià**. **Supporting evidence**—including **increased precipitation percentiles**, **threshold exceedances**, and **higher skewness and kurtosis**—points to **growing rainfall extremes** and **higher annual maxima** over the past **5–6 years**.

11 - Conclusions & Outlook

- **Economic losses** in **Montsià** (1996–2023) total **> 17 M €** in **Alcanar** alone, with the **2018, 2021 and 2023 floods** surpassing previous decades in both **rainfall** and **CCS payouts**.
- **Meteorological analysis** of **2018, 2021, and 2023** shows persistent **easterly/southeasterly low-level flow** and **southwesterly flow aloft**, linked to **cut-off lows** and **moist advection**. **Convective trains, jet streaks,** moderate **CAPE,** and high low-level **θₑ** (potential equivalent temperature) favored repeated cell **regeneration**.
- **Moisture sources** include the **Mediterranean** (main contributor) and remote regions (**North Atlantic, tropical Africa, North America**), emphasizing **multi-source input** in **extreme events**.
- **Return level analysis** (1991–2023) reveals 100-year daily maxima up to **340 mm** (**Montsià**) and **285 mm** (**Alcanar**), with hourly peaks reaching **120 mm/h** and **100 mm/h**, respectively.
- **Extreme rainfall variability** has **increased** in the past **5–6 years**, as shown by **higher precipitation percentiles, threshold exceedances**, and rising **skewness** and **kurtosis**.
- Effective **adaptation** requires **updating return period models**, integrating **remote moisture dynamics**, and improving **early warning systems** through **radar, mesoscale modelling**, and cross-agency **coordination**.