Genesis, precursors and forecasting of extreme precipitation

Federico Grazzini
Centro Funzionale, Arpae Emilia-Romagna

arpae emilia-romagna

UniBo, Department of Physics, Science of Climate, 15/12/2025

Outline

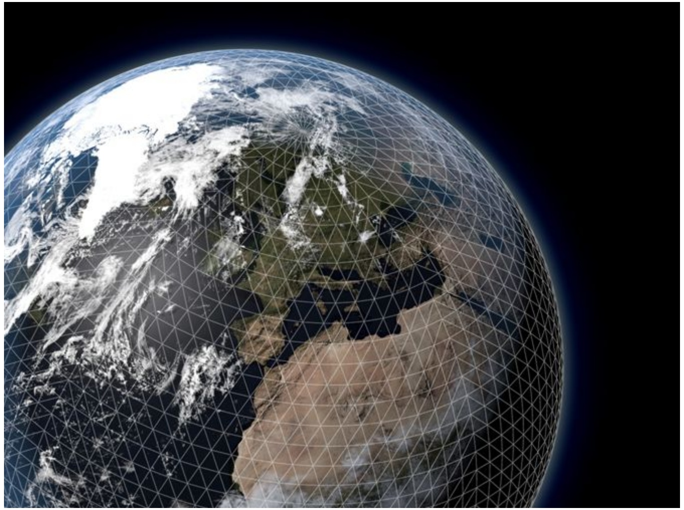
In this seminar, we will examine the processes and weather conditions conducive to intense precipitation, also in the context of climate change induced by global warming.

We will also speak about operational forecasting procedures, including the experimental use of machine learning techniques to improve the anticipation of these events

Operational weather forecasting

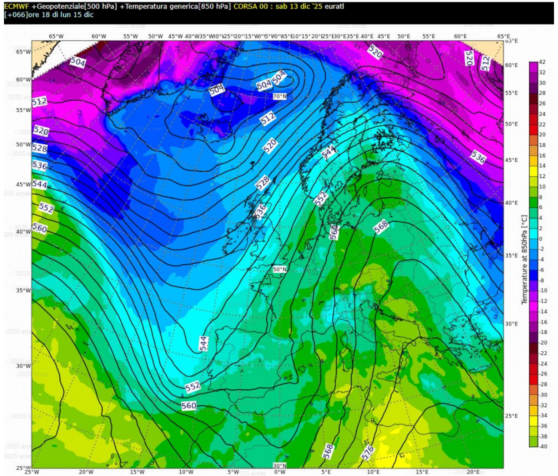
…with the arrival of the first electronic computers capable of processing these equations, albeit in a simplified manner, that numerical weather prediction was born. Since the early 1970s, some large research centres have begun to produce daily numerical forecasts.

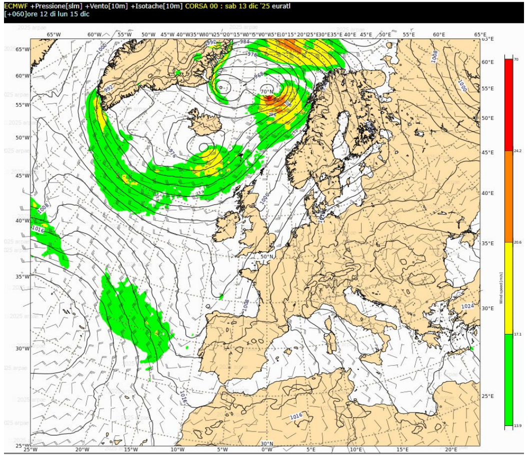
Since then, the global physical-mathematical models that arrive in the operations rooms of national meteorological services (and feed into mobile phone apps) have improved enormously thanks to the studies of four generations of meteorologists, physicists, mathematicians and software engineers that such a level of accuracy has been achieved.

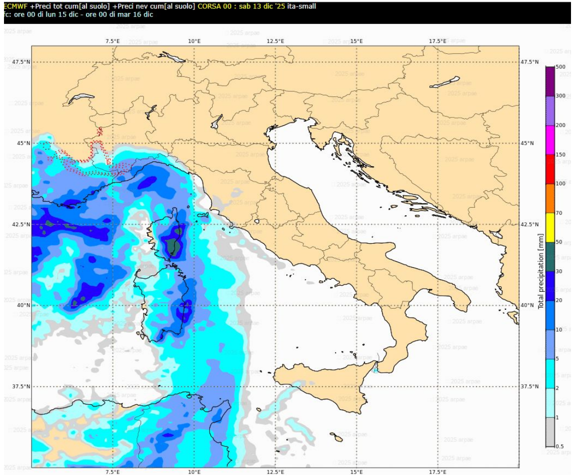


Che tempo fa secondo l'intelligenza artificiale, Internazionale, Luglio 2024
https://www.internazionale.it/notizie/federico-grazzini/2024/07/10/rivoluzione-previsioni-tempo

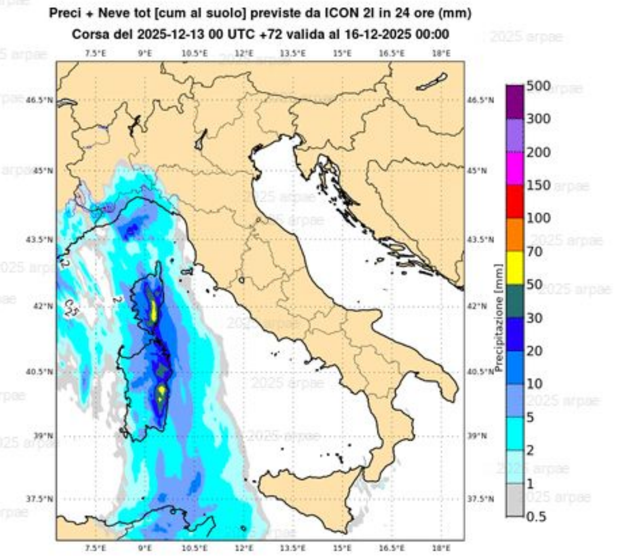
The daily work of operational meteorologist is to interpret model outputs

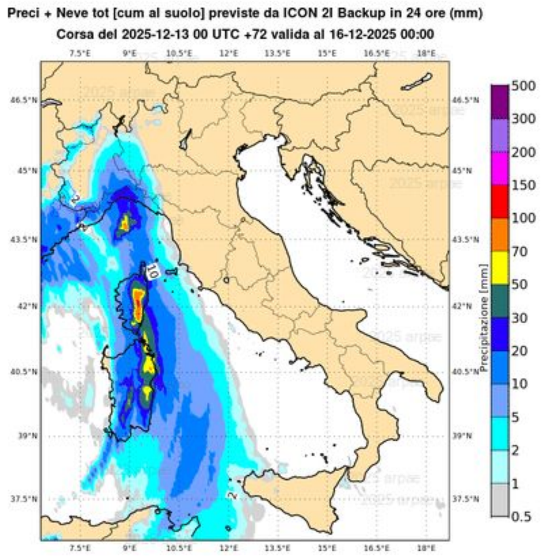


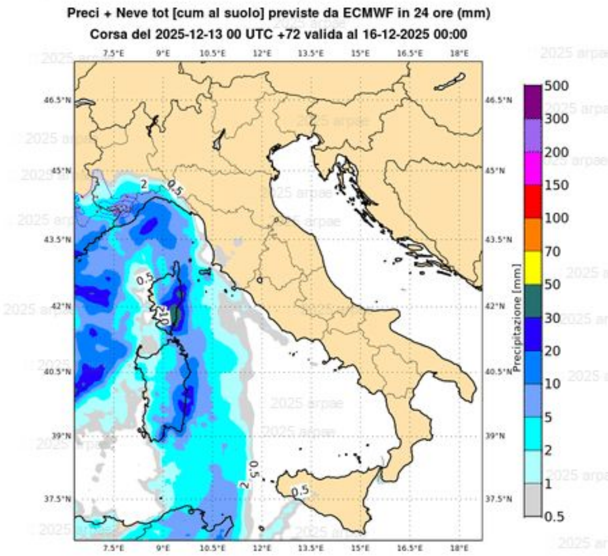




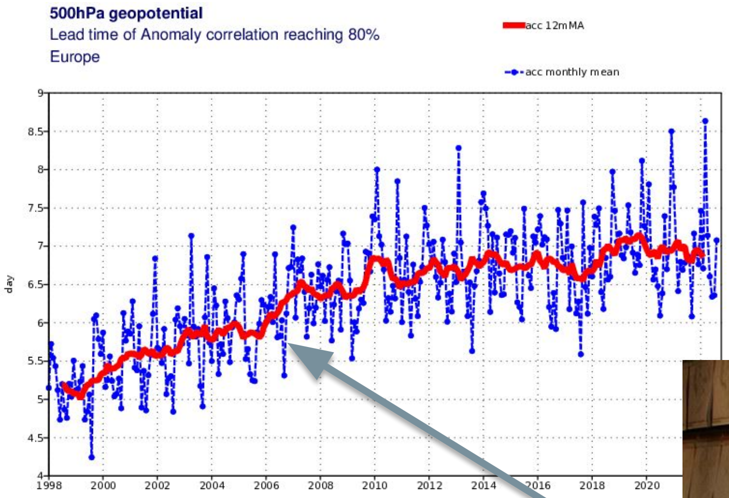
Operational weather forecasting





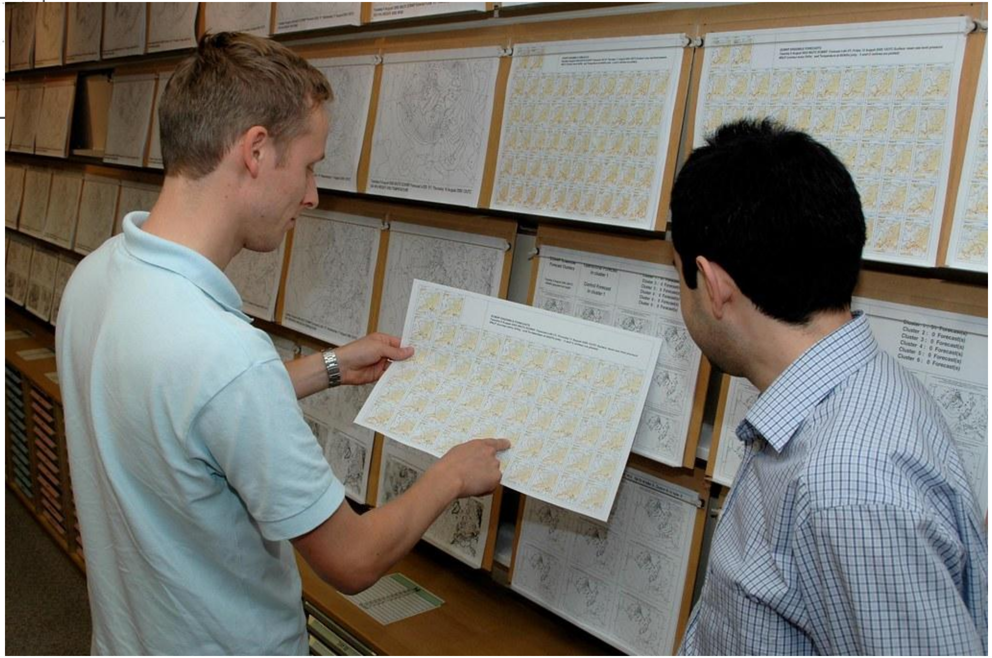


Shifting interest to severe weather



Forecast accuracy is improving steadily, 1 day /10 years.

Is this improvement visible on all weather types ?
What about for extreme events ?



In the early 2000 we were asked by management to show improvements for specific weather events

Let's focus on precipitation (extremes)

w_c : updraft velocity
$q_{s,c}$: saturation specific humidity

Efficiency ε (micropysics)

Condensation rate in the cloud

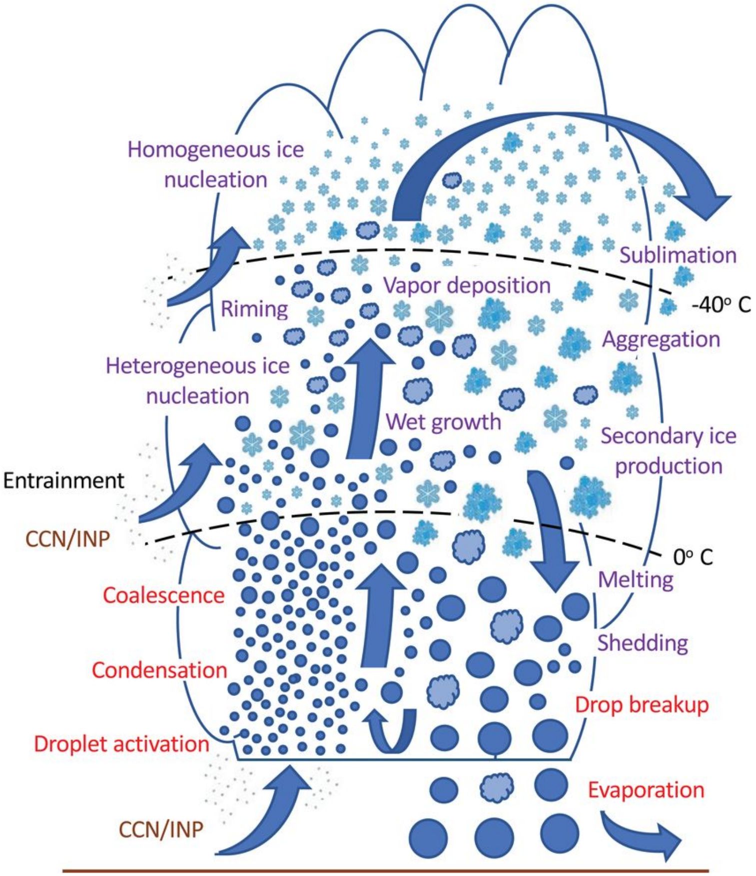
Precipitation rate $$P \approx -\varepsilon \int_{z_b}^{z_t} w_c \frac{\partial q_{s,c}}{\partial z} \rho \, dz.$$

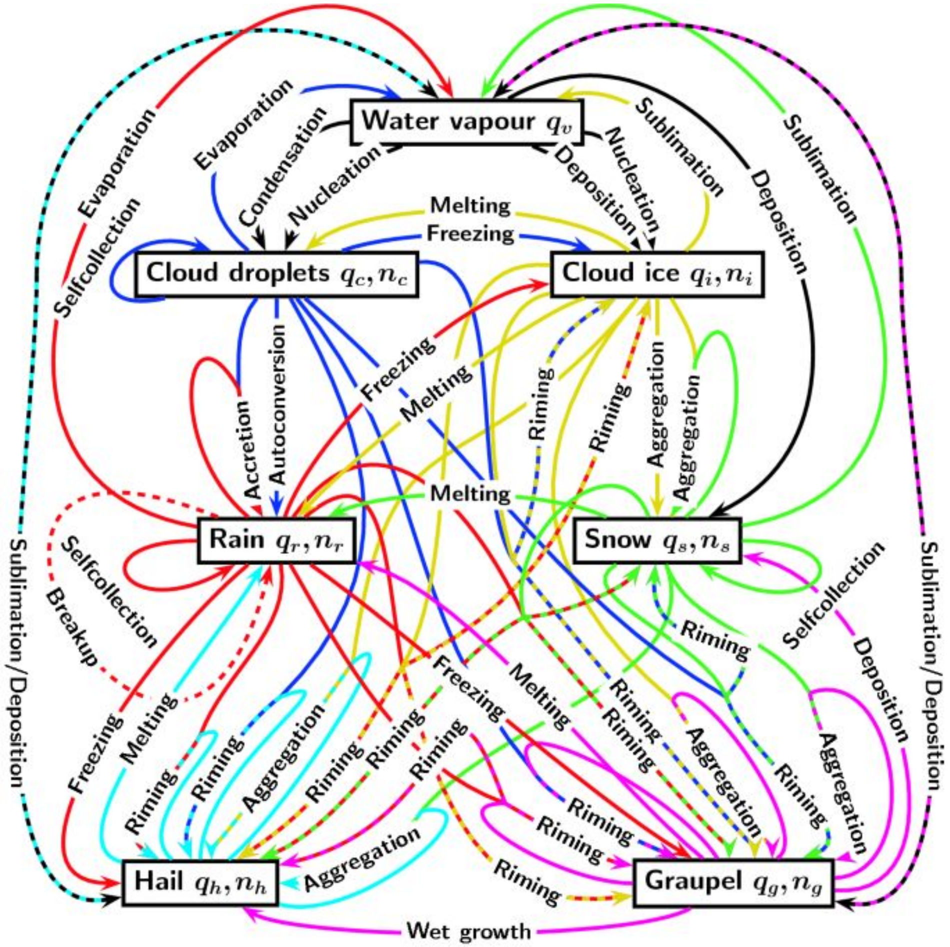
dynamic and thermodynamic contribution

3 components: microphysics, dynamic and thermodynamic

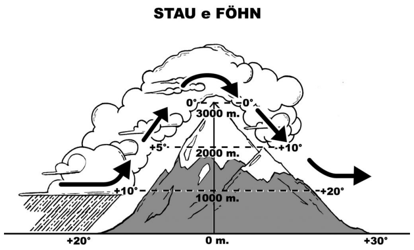
From Jessica Loriaux et al. 2017

ε Microphysics (one of the most difficult parameterization in nwp models)

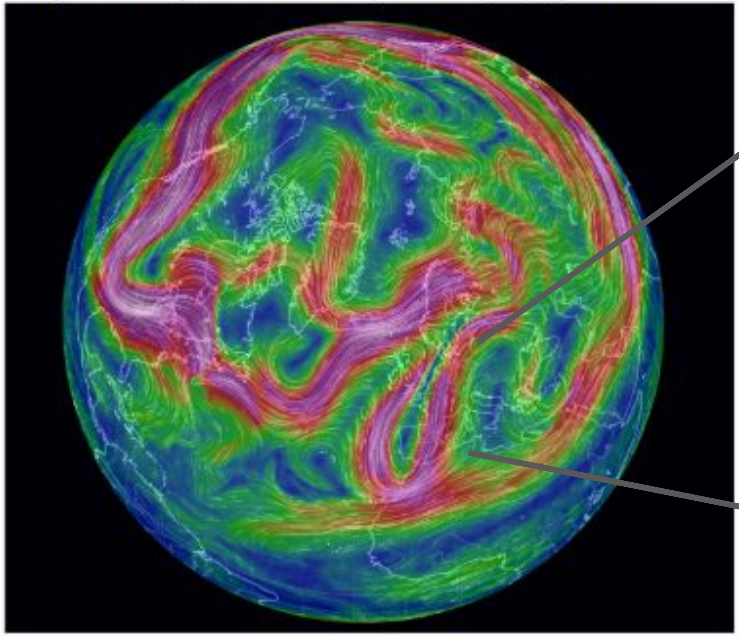




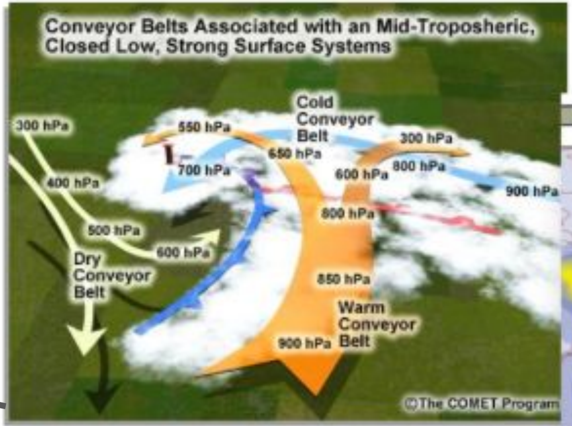
ω Dynamics (dynamically induced ascending motions)

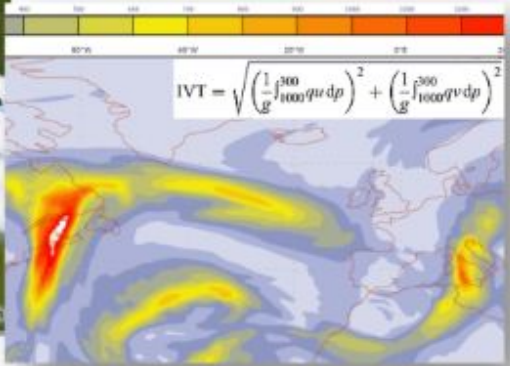


Large-scale dynamics: Rossby waves propagation

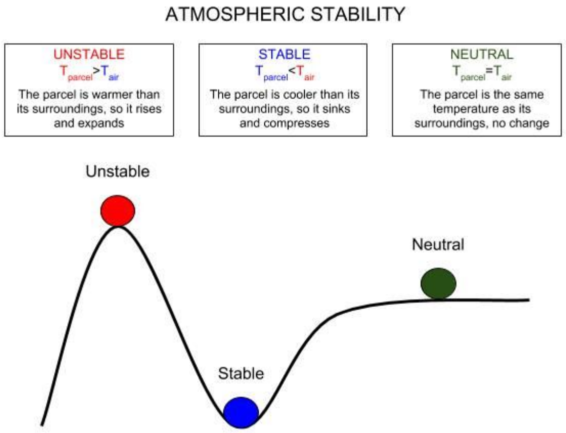


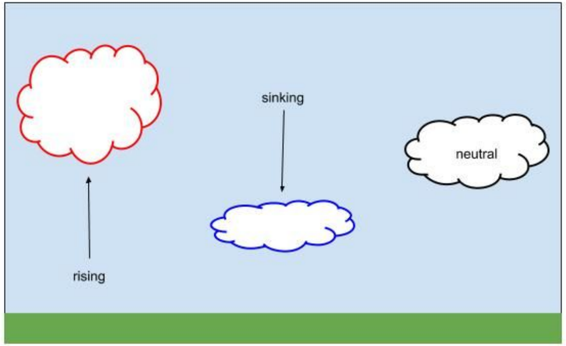
Synoptic/mesoscale processes: fronts , warm conveyor belts and water vapour transport (IVT)

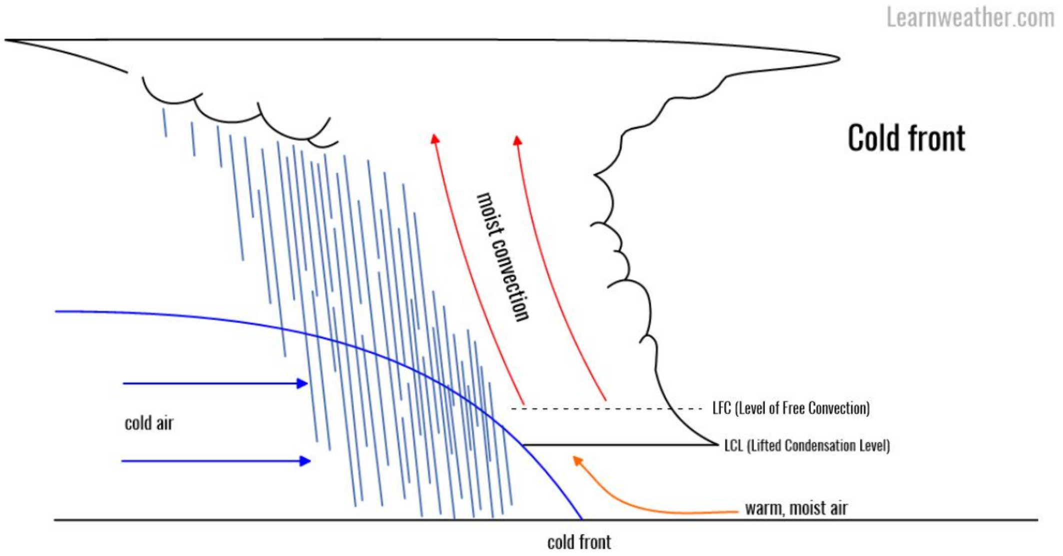


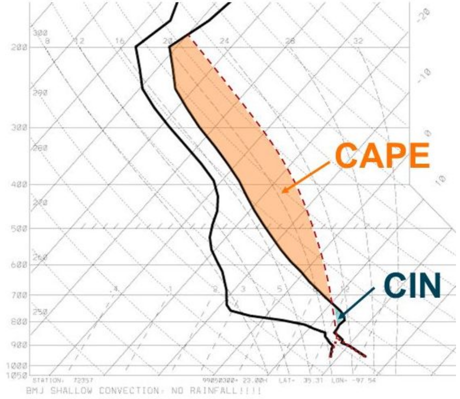


T, q_s Thermodynamics



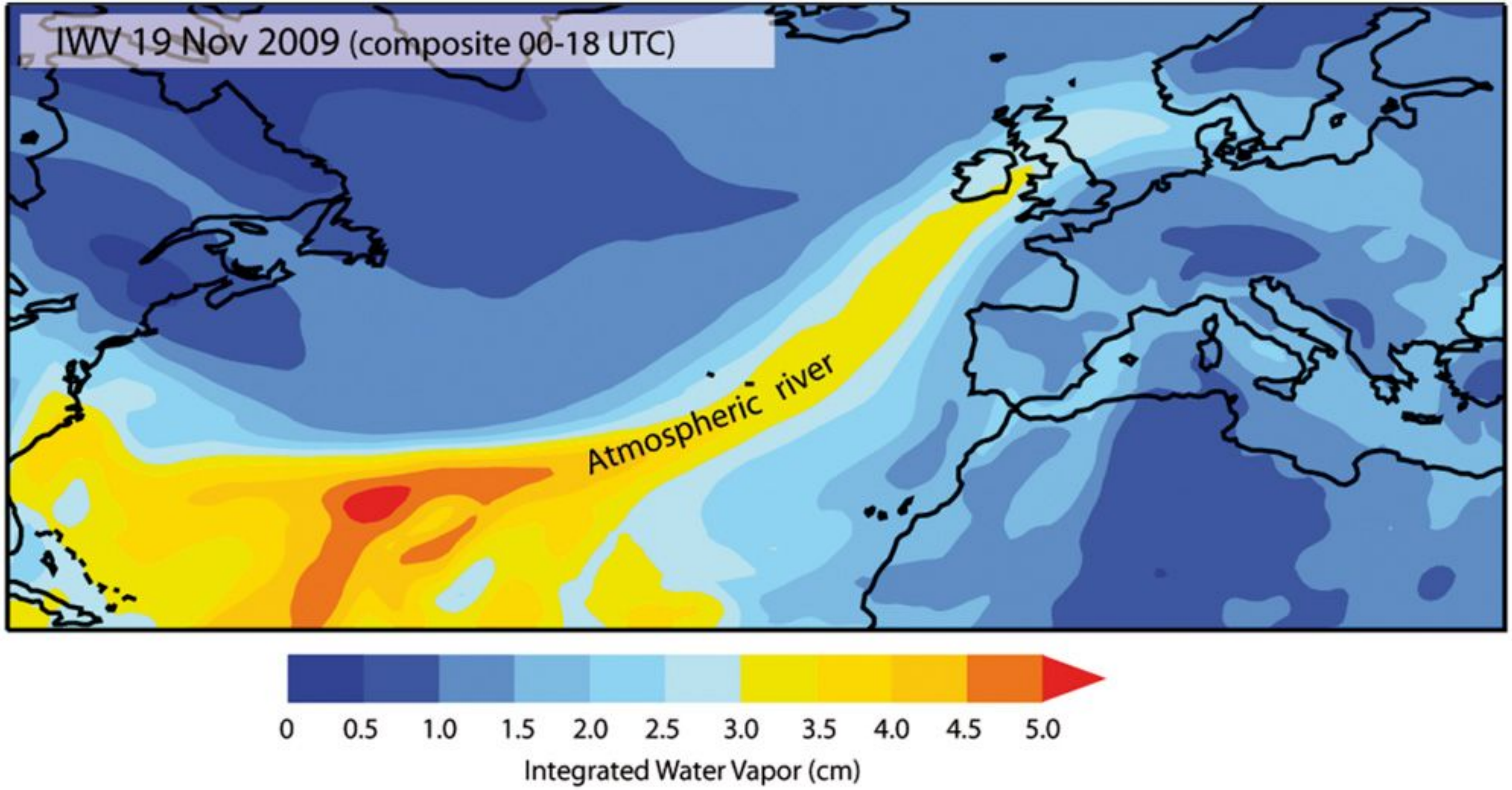






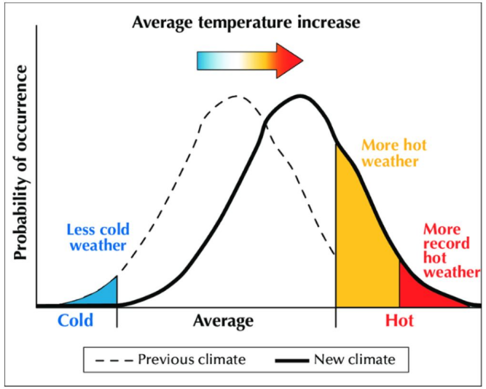
$$w_{\max} = \sqrt{2 \times CAPE} \sim 2 - 50 m/s$$

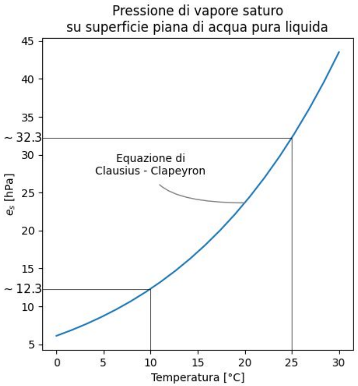
Dynamics associated with **synoptic waves** cause water vapour to be channelled into long atmospheric rivers that can sustain condensation processes and precipitation for many hours or days



Global warming dramatically alter these components

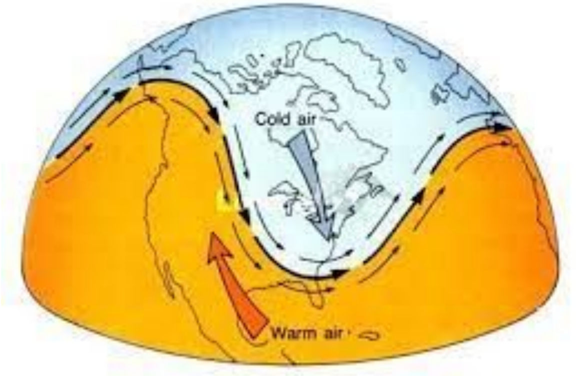
Changes in temperature and vertical profile induces significant changes in the thermodynamics



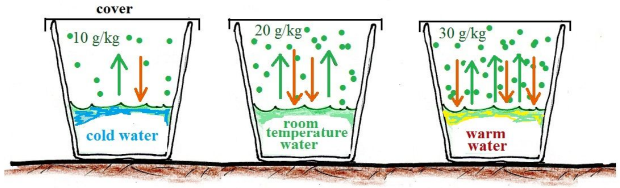


exponential increase of q_s 7% / °C

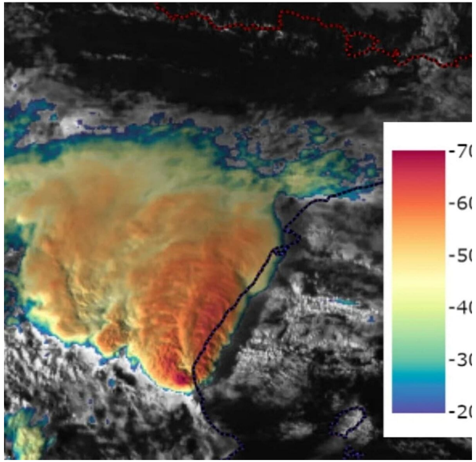
Changes in frequency and persistence of synoptic waves

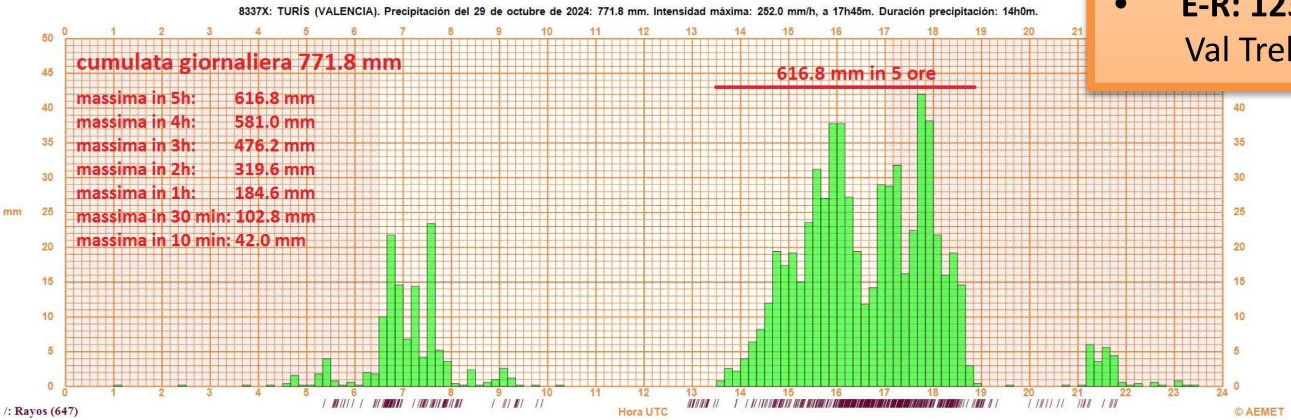


https://www.youtube.com/watch?v=MzW5Isbv2A0&t=62



The Mediterranean is an hotspot for extreme precipitation events



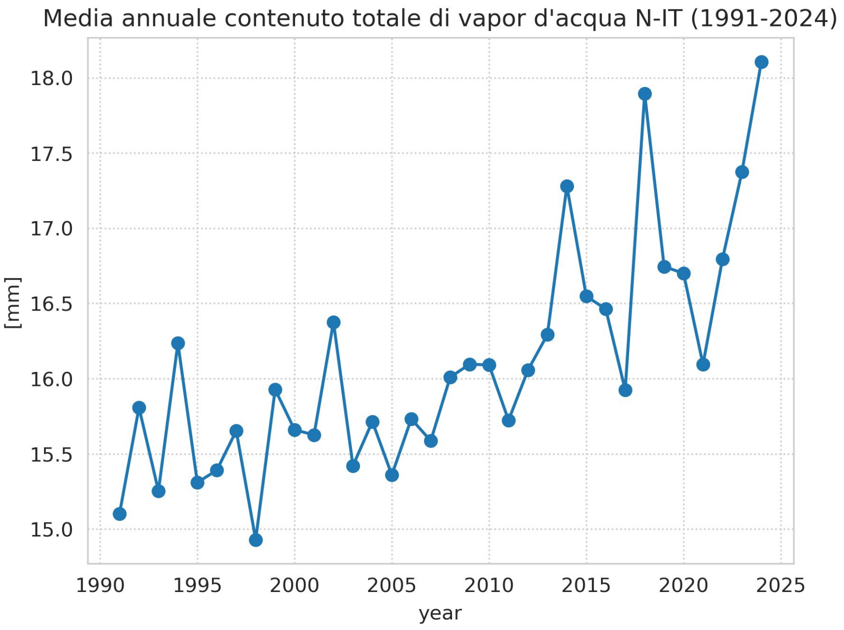


Intensity records:

- **World : 472 mm/1h**, Gansu (China), Luglio 1991 *fonte WMO N.1045*
- **Med : 185 mm/1h**, Turis (Valencia), Spain Otc. 2024
- **Italy : 181 mm/1h**, Vicomorasso (Ge), Nov 2011
- **E-R: 123mm/1h**, Rimini, Giugno 2013
  Val Trebbia Settembre 2015

EPE atmospheric ingredients are increasing

Calvo-Sancho et al. 2025, preprint on Valencia flood attribution



Anthropogenic Climate Change differences with pre-industrial conditions for deep-moist convection

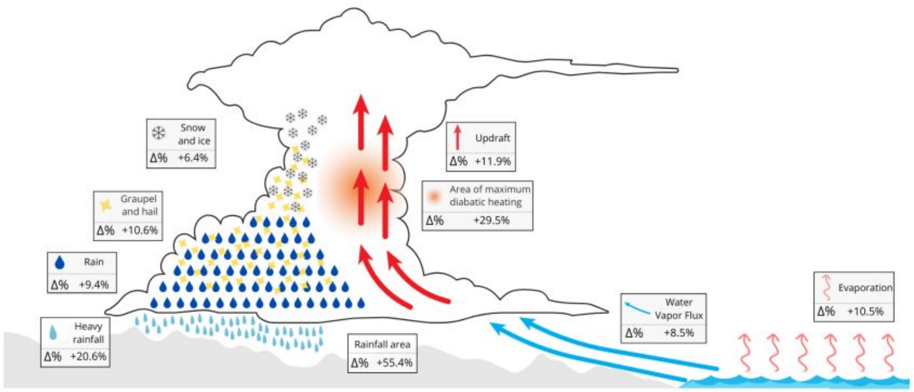


Figure 5: Extreme heavy rainfall events intensify with human-induced climate change. Heavy rainfalls events intensify due to enhanced moisture content, which increases the latent heat release, and causes stronger positive vertical motions. These changes promote higher microphysics processes activity, promoting stronger heavy rainfall (6 h) and increases in the total rainfall area.

Nonlinearities produces strong increase in LHR.
Precip intensity >> CC scaling

Different response to water vapour increase

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Increasing hourly heavy rainfall in Austria reflected in flood changes

Klaus Haslinger, Korbinian Breinl, Lovrenc Pavlin, Georg Pistotnik, Miriam Bertola, Marc Olefs, Marion Greilinger, Wolfgang Schöner & Günter Blöschl

Nature **639**, 667–672 (2025) | Cite this article

Abstract

Climate change is expected to increase heavy rainfall with concomitant increases in flooding[1]. Causes of increased heavy rainfall include the higher water-holding capacity of a warmer atmosphere and changes in atmospheric circulation patterns[2], which may translate into future heavy rainfall increases in most of Europe[3]. However, gathering evidence on the time evolution of past changes has been hampered by data limitations and measurement uncertainties, in particular for short rainfall durations, such as 1 h. Here we show an 8% increase in daily and 15% increase in hourly heavy rainfall over the last four decades by analysing a new dataset comprising 883 stations in Austria from 1900 to 2023. These increases are fully consistent between two independent networks and occurred after a retarding phase between 1960 and 1980. Hourly heavy rainfall changes are aligned with temperature increases with the sensitivity of a 7% increase per 1 °C of warming, in line with Clausius–Clapeyron scaling. Daily heavy rainfall changes, however, are aligned with atmospheric circulation indices with little correlation to air temperature, which suggests a bigger role of atmospheric circulation modes than previously thought. The daily heavy rainfall changes are remarkably consistent with observed flood increases of about 8% in large catchments. The hourly heavy rainfall changes are similarly consistent with flood changes in small catchments, although the flood increase is stronger (25% over the last four decades). Climate adaptation measures in flood management may therefore be more pressing for rivers draining smaller catchment areas than for large rivers.

Large basins > 500 km2

Small basins < 50 km2

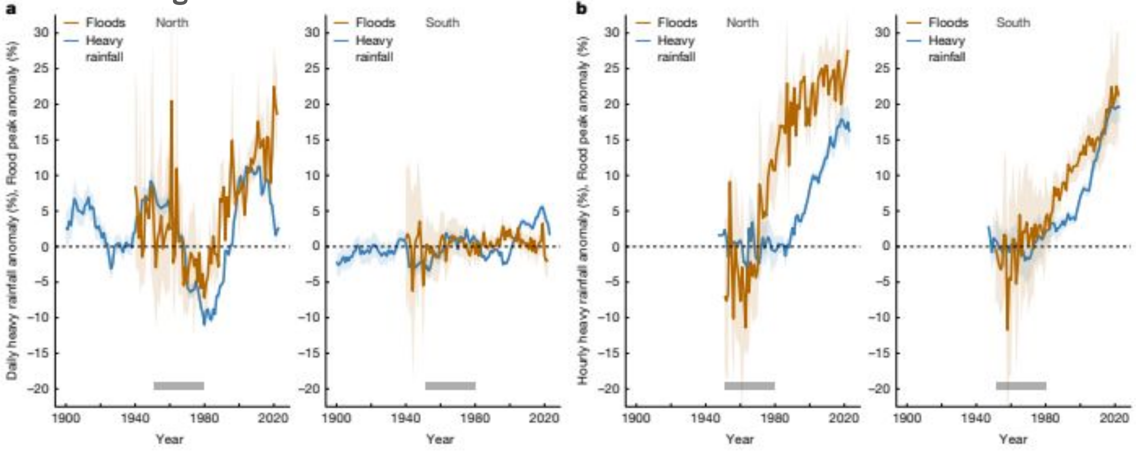
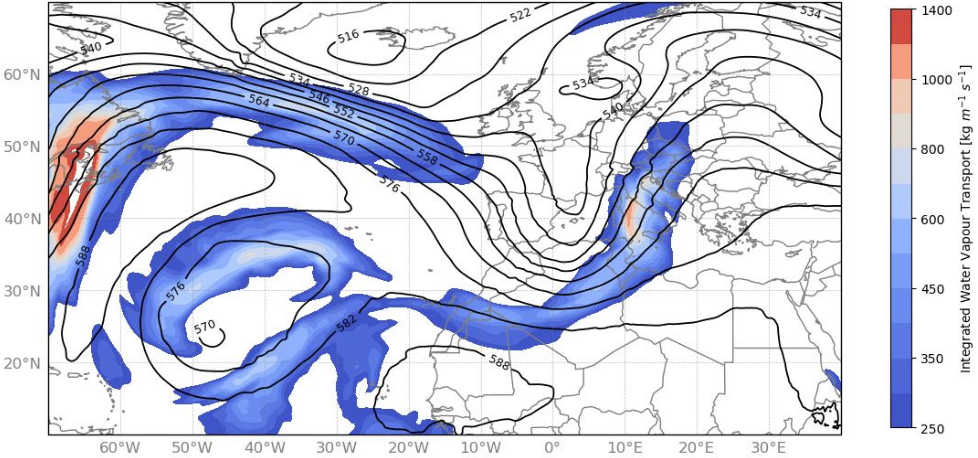


Fig. 3 | Effect of heavy rainfall evolution on flood peaks. a, Daily heavy rainfall anomalies and flood peak discharge anomalies for large catchments (greater than 500 km^2), north (left) and south (right) of the Alpine ridge. **b**, Hourly heavy rainfall anomalies and flood peak discharge anomalies for small catchments (less than 50 km^2), north (left) and south (right) of the Alpine ridge. Heavy rainfall values are 99th percentiles, as in Fig. 1, and flood peaks are the mean annual floods of the warm season. The grey bars at the bottom of the panels indicate the reference period. Solid lines indicate the mean over all stations, the shaded bands the 95% confidence interval of the mean, estimated by bootstrapping ($n = 1{,}000$). A remarkable similarity can be seen between the daily heavy rainfall and floods in large catchments and between the hourly heavy rainfall and floods in small catchments, which is related to the travel times of water within the catchments.

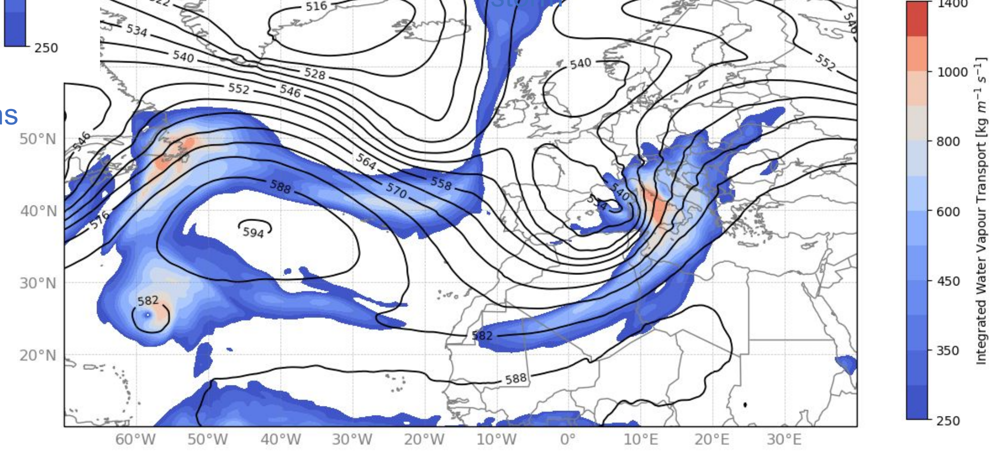
Recognizing synoptic forcing



4 November 1966 - Flood in Florence, Venice and N-east regions

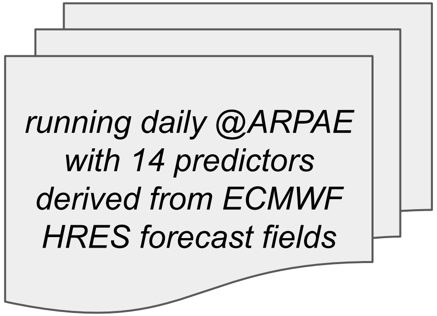
Esempio dei due eventi più significativi sul N-IT in termini di volume di pioggia scaricato in 24h (1961-2023)

29 ottobre 2018 - Vaia storm



*Sioni, F., Davolio, S., Grazzini, F. and Giovannini, L. (2023) **Revisiting the atmospheric dynamics of the two century floods over north-eastern Italy**. Atmospheric Research , 286, 106662.*
URL: https://linkinghub.elsevier.com/retrieve/pii/S0169809523000595

MaLCoX (Machine Learning model predicting Condition for eXtreme precipitation)



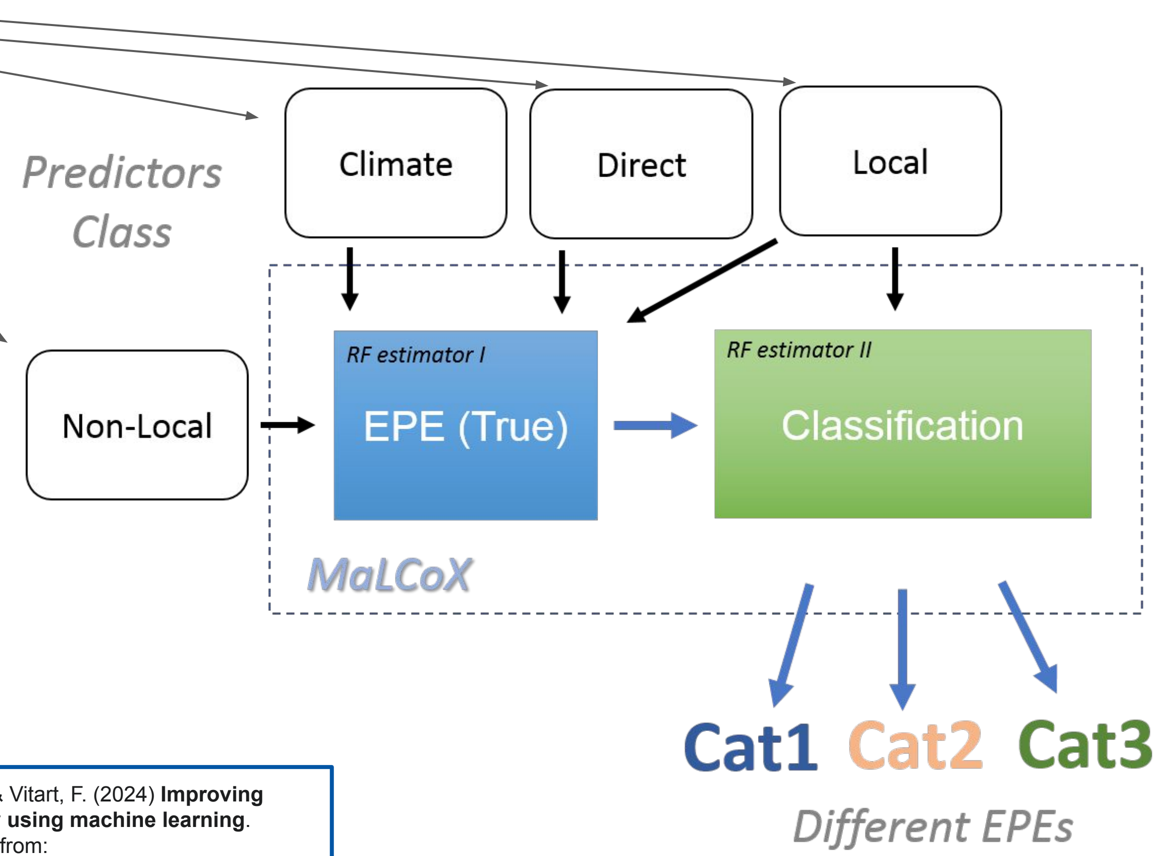


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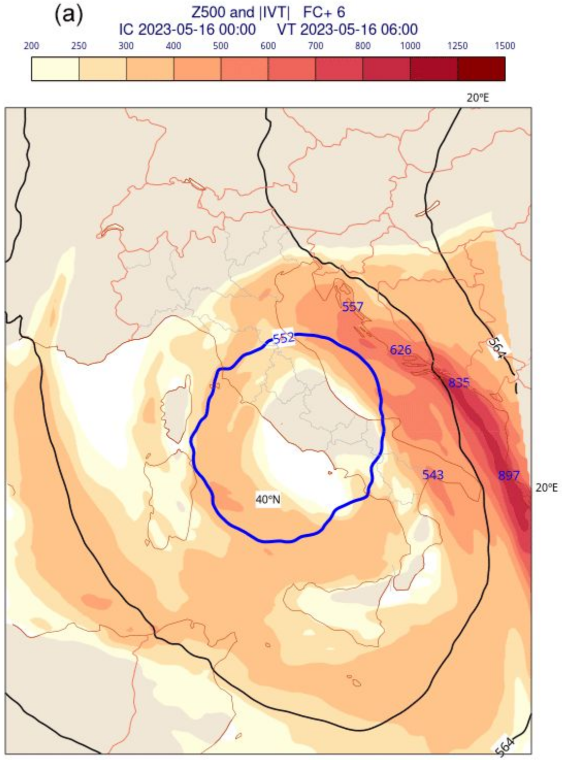
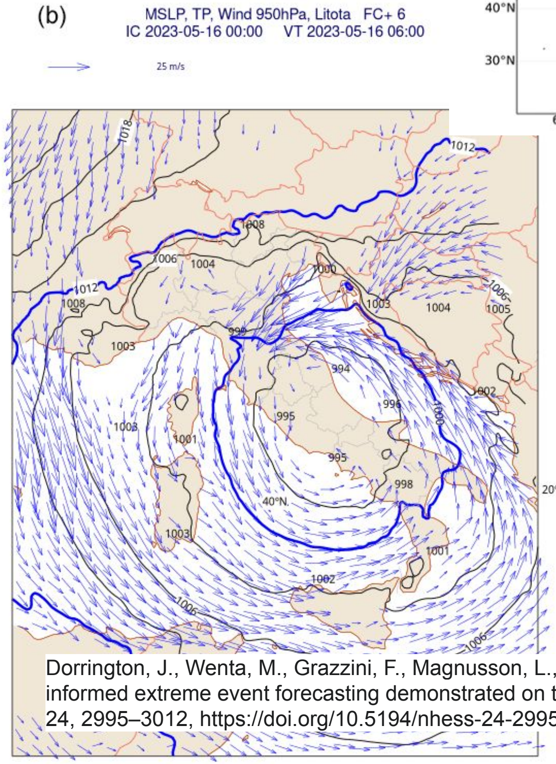
TABLE 1 Table showing the list of predictors.

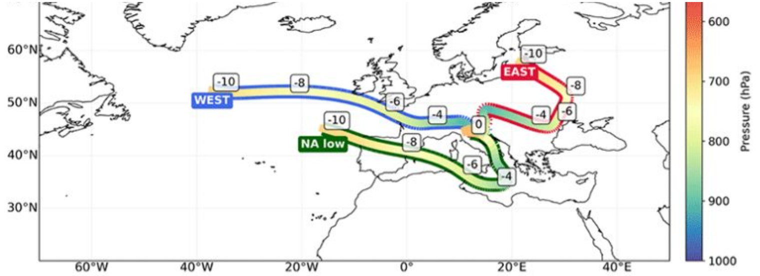
Variable	Description	Units	RF model	Class
fcst_IVTmag	IVT-normalised anomaly index lead times from 0 to −2 days		EPE (y/n)	Non-Local
fcst_Z500	Geopot-normalised anomaly index at 500 hPa lead times from 0 to −2 days		EPE (y/n)	Non-Local
fcst_V850	850 hPa meridional wind normalised anomaly index at 850 hPa lead times from 0 to −2 days		EPE (y/n)	Non-Local
IVTe	Daily mean of zonal component of integrated water vapour transport	$kg \cdot s^{-1} \cdot m^{-1}$	EPE (y/n)	Local
IVTn	Daily mean of meridional component of integrated water vapour transport	$kg \cdot s^{-1} \cdot m^{-1}$	EPE (y/n)	Local
TCWV	Daily mean of total column water vapour	$kg \cdot m^{-2}$	EPE (y/n)	Local
MSLP	Daily mean of mean sea level pressure	hPa	EPE(y/n)	Local
V_{olf}	Daily volume of rain over the target domain	m^3	EPE (y/n)	Direct
Juld	Day of the year (Julian day)		EPE (y/n)	Climate
Θ_{e850}	Daily mean of equivalent potential temperature at 850 hPa	K	Classification	Local
$\Delta\Theta_{e500-850}$	Daily minimum of delta Θ_e (500–850) hPa	K	Classification	Local
Θ_{pv2}	Daily mean of Θ on dynamical tropopause (PV = 2)	K	Classification	Local
i_{audmax}	Daily maximum of convective adjustment time-scale	hr	Classification	Local
$CAPE_{dmax}$	Daily maximum of CAPE	$J \cdot kg^{-1}$	Classification	Local

Grazzini, F., Dorrington, J., Grams, C.M., Craig, G.C., Magnusson, L. & Vitart, F. (2024) **Improving forecasts of precipitation extremes over northern and central Italy using machine learning**. *Quarterly Journal of the Royal Meteorological Society*, 1–15. Available from: https://doi.org/10.1002/qj.4755

Precursors and pathways

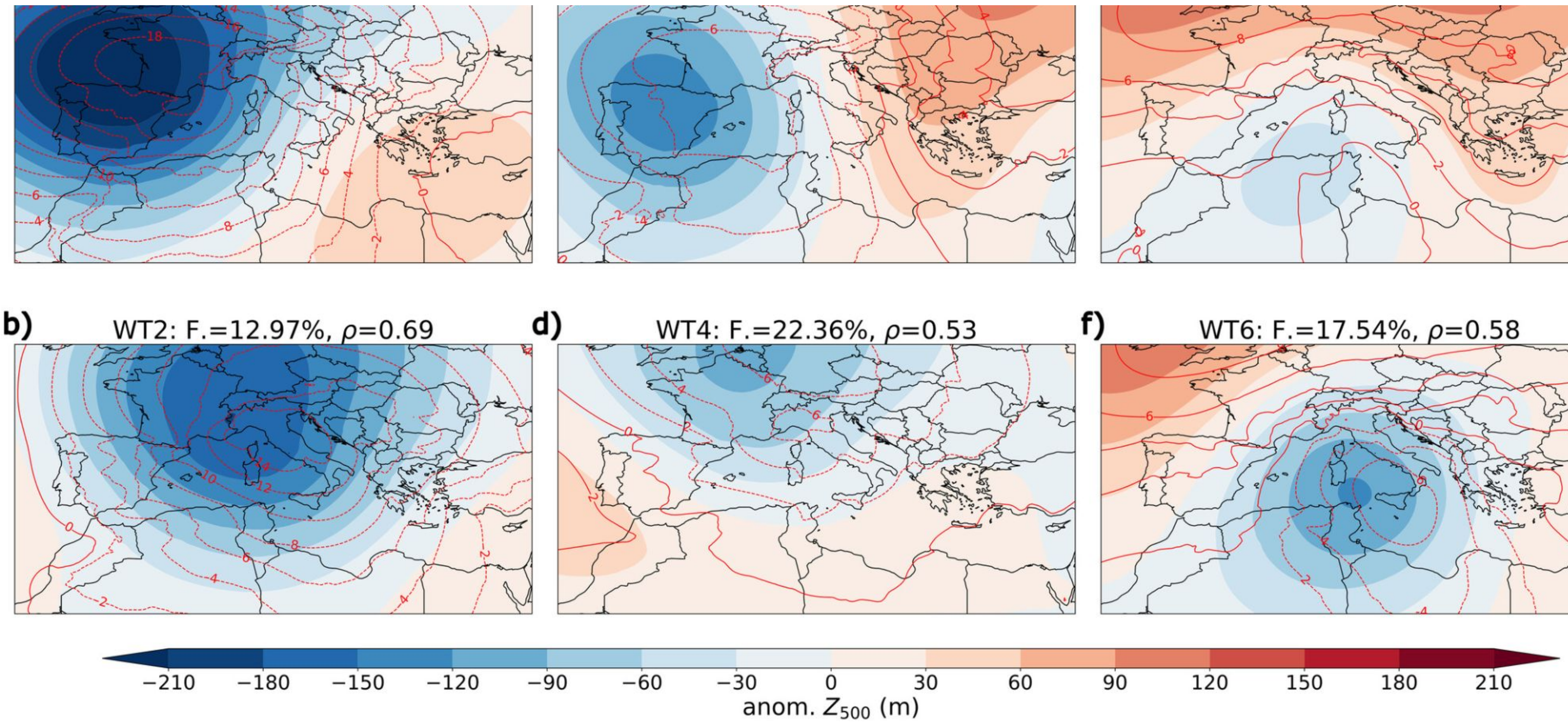






Dorrington, J., Wenta, M., Grazzini, F., Magnusson, L., Vitart, F., and Grams, C. M.: Precursors and pathways: dynamically informed extreme event forecasting demonstrated on the historic Emilia-Romagna 2023 flood, Nat. Hazards Earth Syst. Sci., 24, 2995–3012, https://doi.org/10.5194/nhess-24-2995-2024, 2024.

High risk circulation pattern for Italy



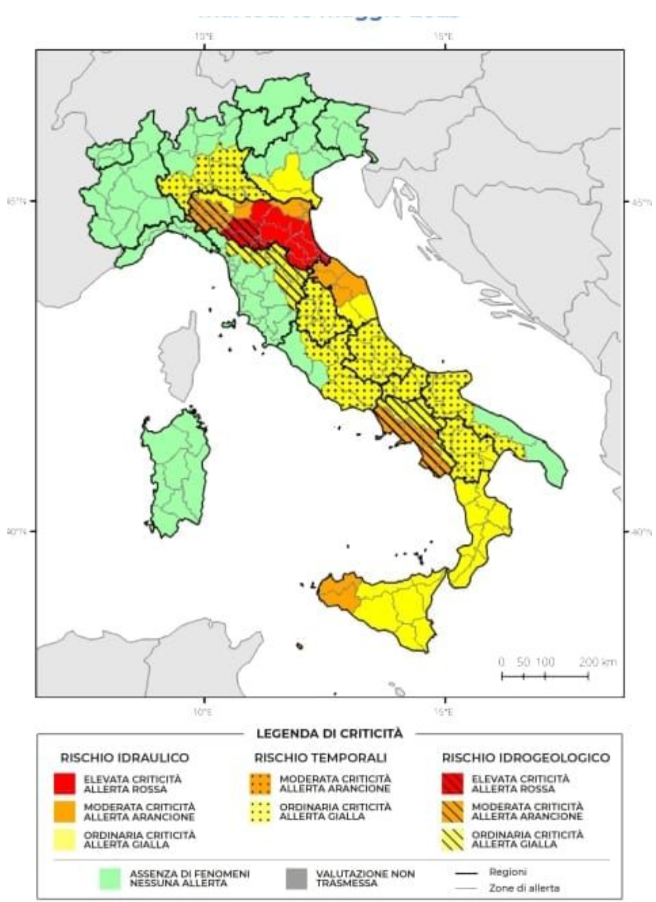
Iacomino, C., S. Pascale, G. Zappa, et al. 2025. " A Classification of High-Risk Atmospheric Circulation Patterns for Italian Precipitation Extremes." *International Journal of Climatology* 45, no. 15. https://doi.org/10.1002/joc.70118.

Italy's National Weather-Hydrogeological Warning System

Italy's National Weather-Hydrogeological Warning System is designed to prevent and manage risks from extreme weather events such as floods, landslides, and storms.

It operates through a collaborative framework involving:

- The Department of Civil Protection (DPC) at the national level, which coordinates efforts and evaluates risks with nationwide impacts.
- A network of **Functional Centers** (CF), comprising the Central Functional Center (CFC) and Regional (distributed) Functional Centers (CFD).
- The system uses a color-coded alert scale (Green, Yellow, Orange, Red) to standardize warnings and ensure timely communication to local authorities and the public.
- The network counts 21 “Centri Funzionali”: 1 central in Rome at the National Civil Protection Department, 20 in the national territory, one for each Region.
- The Emilia-Romagna Region entrust the management of the **“Centro Funzionale” to Arpae – Struttura Idro-Meteo-Clima.** Activities started on November 2005



Risk Assessment as the Basis for the Alert System

Centro Funzionale

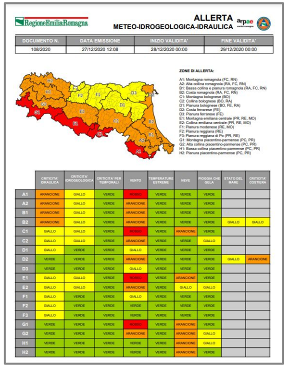
- ➔ ARPAE provides daily assessments of meteorological, hydraulic and hydrogeological hazards.
- ➔ *Evaluations are supported by the expertise of the Geological, Seismic, and Soil Service of the Emilia-Romagna Region.*

arpae emilia-romagna

Servizio Geologico Sismico e dei Suoli

- ➔ The Regional Agency for Territorial Safety and Civil Protection combines ARPAE's hazard assessments with an analysis of the region's territorial vulnerabilities.

Based on integrated risk assessments for all phenomena across all alert areas (defined by hydrological, meteorological, orographic, and administrative criteria), daily bulletins ('green' condition for all areas) or alerts ('yellow,' 'orange,' or 'red' for at least one area and phenomenon) are issued.



RegioneEmiliaRomagna

ALLERTA METEO-IDROGEOLOGICA-IDRAULICA

DOCUMENTO N.	DATA EMISSIONE	INIZIO VALIDITA'	FINE VALIDITA'
108/2020	27/12/2020 12:08	28/12/2020 00:00	29/12/2020 00:00

ZONE DI ALLERTA:

A1: Montagna romagnola (FC, RN)
A2: Alta collina romagnola (RA, FC, RN)
B1: Bassa collina e pianura romagnola (RA, FC, RN)
B2: Costa romagnola (RA, FC, RN)
C1: Montagna bolognese (BO)
C2: Collina bolognese (BO, RA)
D1: Pianura bolognese (BO, FE, RA)
D2: Costa ferrarese (FE)
D3: Pianura ferrarese (FE)
E1: Montagna emiliana centrale (PR, RE, MO)
E2: Collina emiliana centrale (PR, RE, MO)
F1: Pianura modenese (RE, MO)
F2: Pianura reggiana (RE)
F3: Pianura reggiana di Po (PR, RE)
G1: Montagna piacentino-parmense (PC, PR)
G2: Alta collina piacentino-parmense (PC, PR)
H1: Bassa collina piacentino-parmense (PC, PR)
H2: Pianura piacentino-parmense (PC, PR)

	CRITICITA' IDRAULICA	CRITICITA' IDROGEOLOGICA	CRITICITA' PER TEMPORALI	VENTO	TEMPERATURE ESTREME	NEVE	PIOGGIA CHE GELA	STATO DEL MARE	CRITICITA' COSTIERA
A1	ARANCIONE	GIALLO	VERDE	ROSSO	VERDE	VERDE	VERDE		
A2	ARANCIONE	GIALLO	VERDE	ARANCIONE	VERDE	VERDE	VERDE		
B1	ARANCIONE	GIALLO	VERDE	ARANCIONE	VERDE	VERDE	VERDE		
B2	ARANCIONE	GIALLO	VERDE	ARANCIONE	VERDE	VERDE	VERDE	GIALLO	GIALLO
C1	GIALLO	GIALLO	VERDE	ROSSO	VERDE	ARANCIONE	VERDE		
C2	GIALLO	GIALLO	VERDE	ARANCIONE	VERDE	VERDE	GIALLO		
D1	GIALLO	VERDE	VERDE	GIALLO	VERDE	VERDE	VERDE		
D2	VERDE	VERDE	VERDE	ARANCIONE	VERDE	VERDE	VERDE	GIALLO	ARANCIONE
D3	VERDE	VERDE	VERDE	GIALLO	VERDE	VERDE	VERDE		
E1	GIALLO	GIALLO	VERDE	ROSSO	VERDE	ARANCIONE	VERDE		
E2	GIALLO	GIALLO	VERDE	ARANCIONE	VERDE	GIALLO	GIALLO		
F1	GIALLO	VERDE	VERDE	GIALLO	VERDE	VERDE	VERDE		
F2	GIALLO	VERDE	VERDE	VERDE	VERDE	VERDE	VERDE		
F3	GIALLO	VERDE	VERDE	VERDE	VERDE	VERDE	VERDE		
G1	VERDE	VERDE	VERDE	ROSSO	VERDE	ARANCIONE	VERDE		
G2	VERDE	VERDE	VERDE	ARANCIONE	VERDE	ARANCIONE	GIALLO		
H1	VERDE	VERDE	VERDE	VERDE	VERDE	ARANCIONE	GIALLO		
H2	VERDE	VERDE	VERDE	VERDE	VERDE	ARANCIONE	VERDE		

Alerts are disseminated to citizens and administrators through an official weather portal

The Lamone river overflows its banks near Bagnacavallo, in the region of Emilia-Romagna, Italy, Thursday, Sept. 19, 2024. (AP)