*Padova, 30 October 2019*
*Workshop: The Vaia storm: taking stock and looking ahead*

# Meteorological aspects of the Vaia storm: forcing mechanisms, predictability and atmospheric rivers

SILVIO DAVOLIO
*CNR-ISAC (Bologna)*

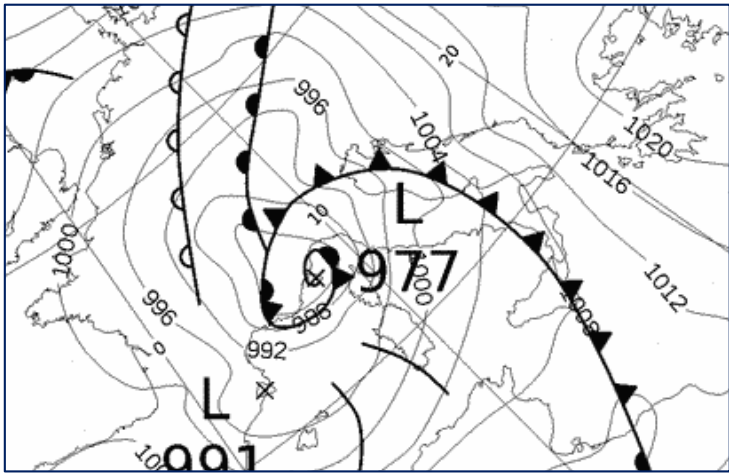
Lorenzo Giovannini[2], Francesco Marra[3], Mattia Zaramella[4], Dino Zardi[2], Marco Borga[4]

Stefano Della Fera[5], Mario Marcello Miglietta[1], Sante Laviola[1], Vincenzo Levizzani[1]

[1] *CNR - ISAC, Bologna and Padova, Italy*
[2] *Atmospheric Physics Group, Department of Civil, Environmental and Mechanical Engineering (DICAM), University of Trento, Trento, Italy*
[3] *Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel*
[4] *Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro (PD), Italy*
[5] *Department of Physics and Astronomy, University of Bologna, Italy*

# MAIN ASPECTS - MOTIVATIONS:

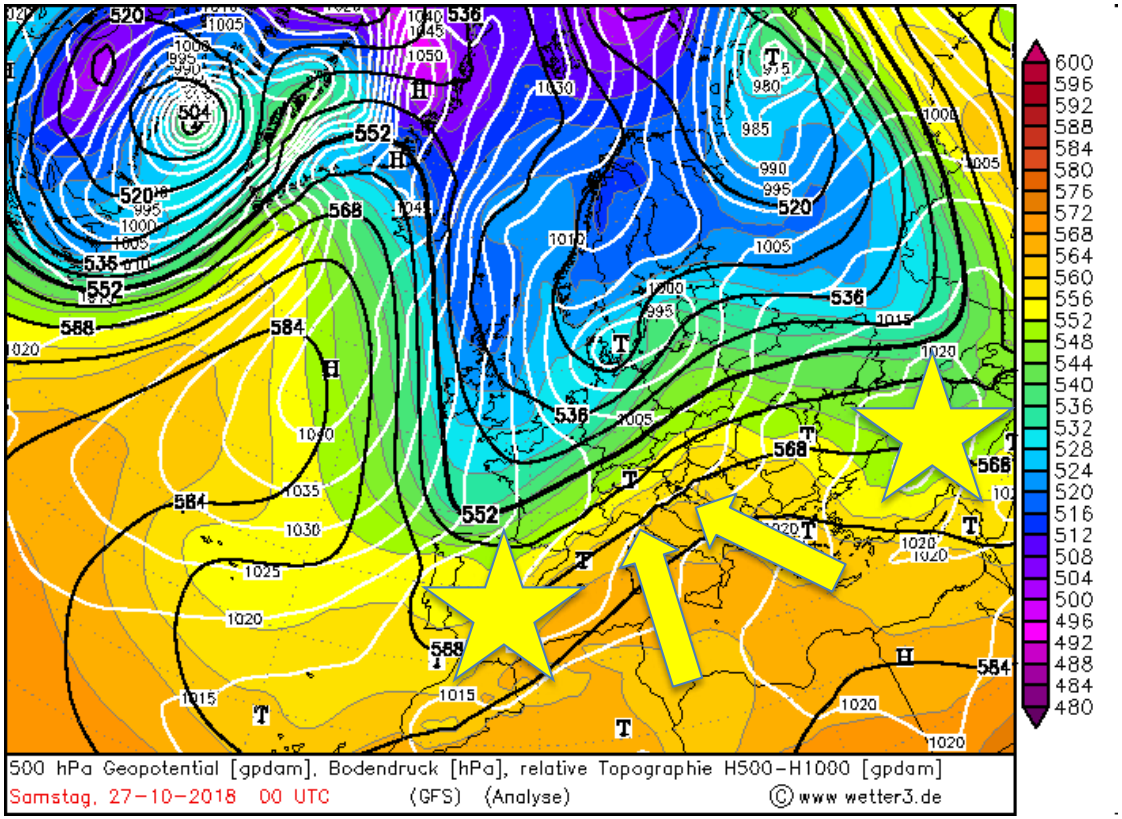
1) PRECIPITATION AND FLOODS
2) EXPLOSIVE CYCLOGENESIS
3) WIND STORMS
4) STORM SURGE
5) ATMOSPHERIC RIVER

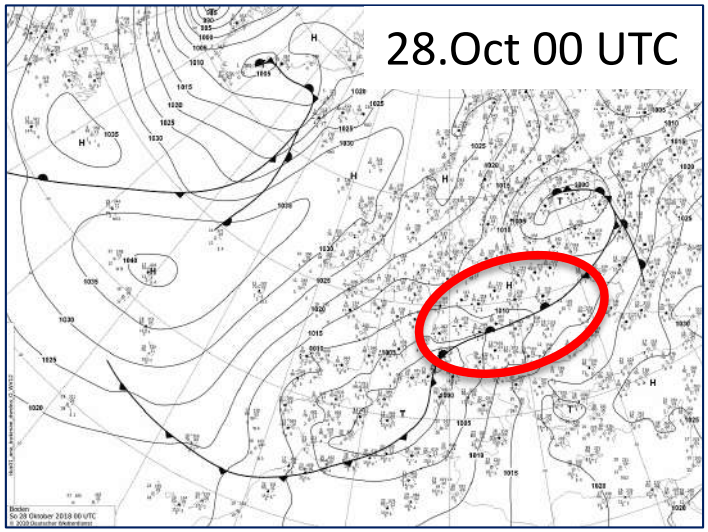



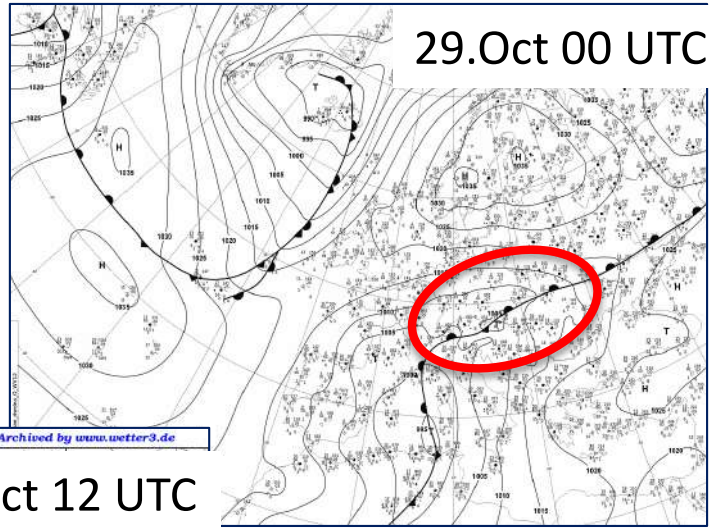

# AIM

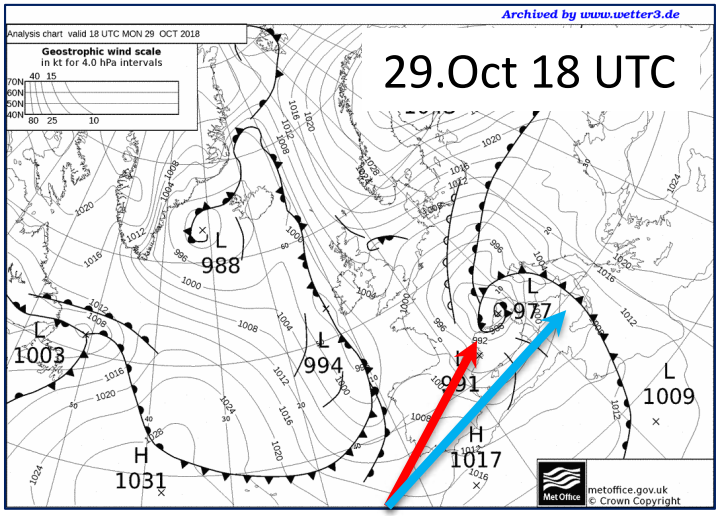
- Identify and describe the **main mesoscale features** and **mechanisms** responsible for the **extreme precipitation** and **windstorm** event that affected Italy on 27-30 October 2018.
- Combining **ground observations, satellite and radar data**, and numerical simulations performed by two convection permitting models: **WRF** and **MOLOCH**.
- Investigating the **predictability** of the event.
- **Identify** the possible presence of an ***Atmospheric River***
- Quantify its **role in feeding extreme precipitation** with respect to evaporation from the Mediterranean Sea (atmospheric water budget and numerical experiments)

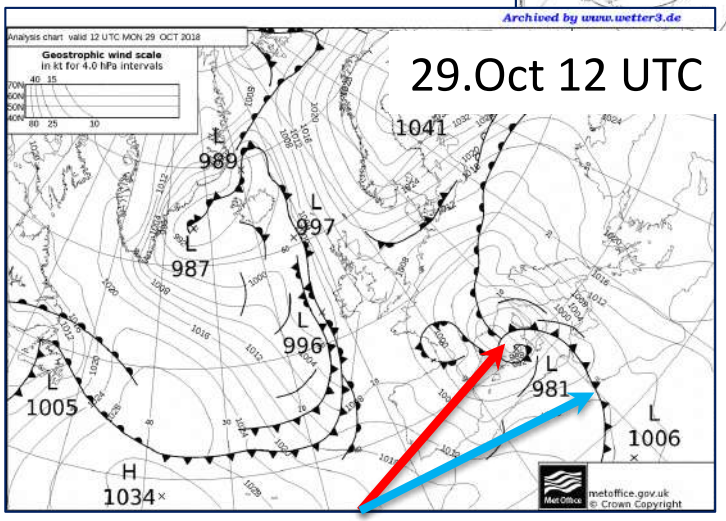
# Synoptic Evolution 27-30 October 2018



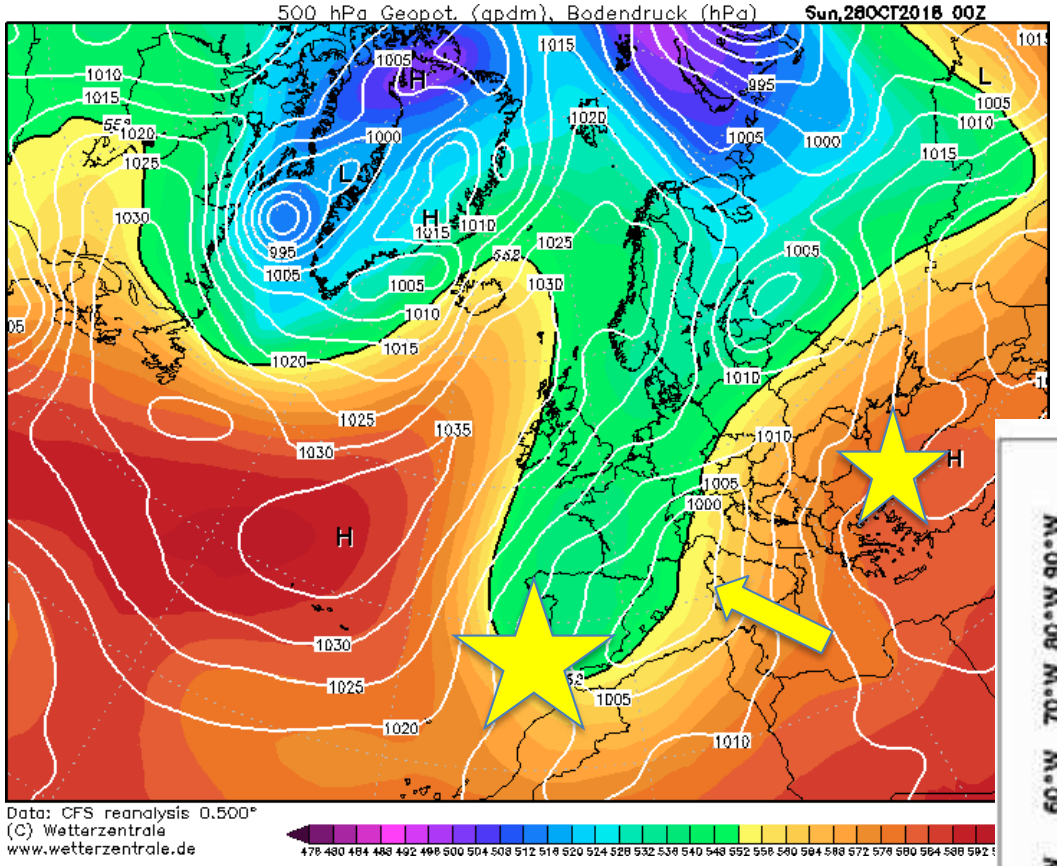



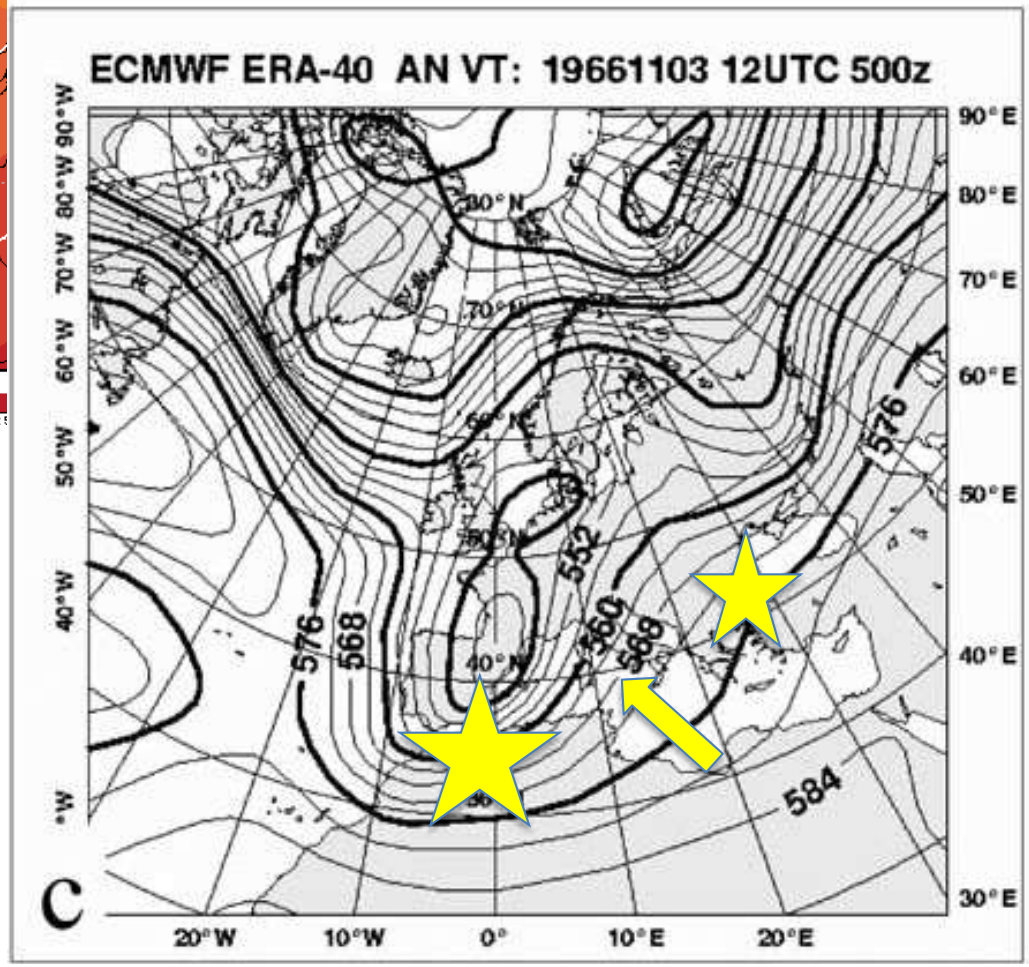



# Typical ingredients for heavy precipitation over the Alps

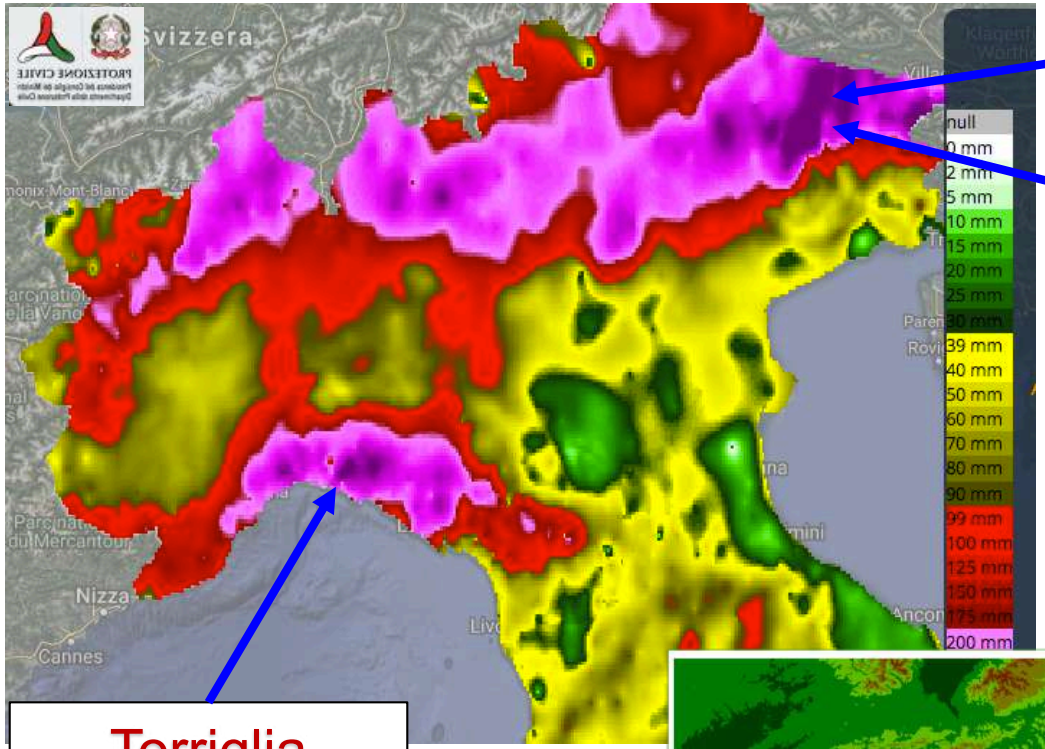



**3-4 November 1966**
**Florence and NE Italy flood**




Despite quantitative predictions of extreme precipitations is still challenging, it was found that the **large-scale flow conducive to major rain events has better predictive skill** than average conditions.

*Grazzini, 2007*



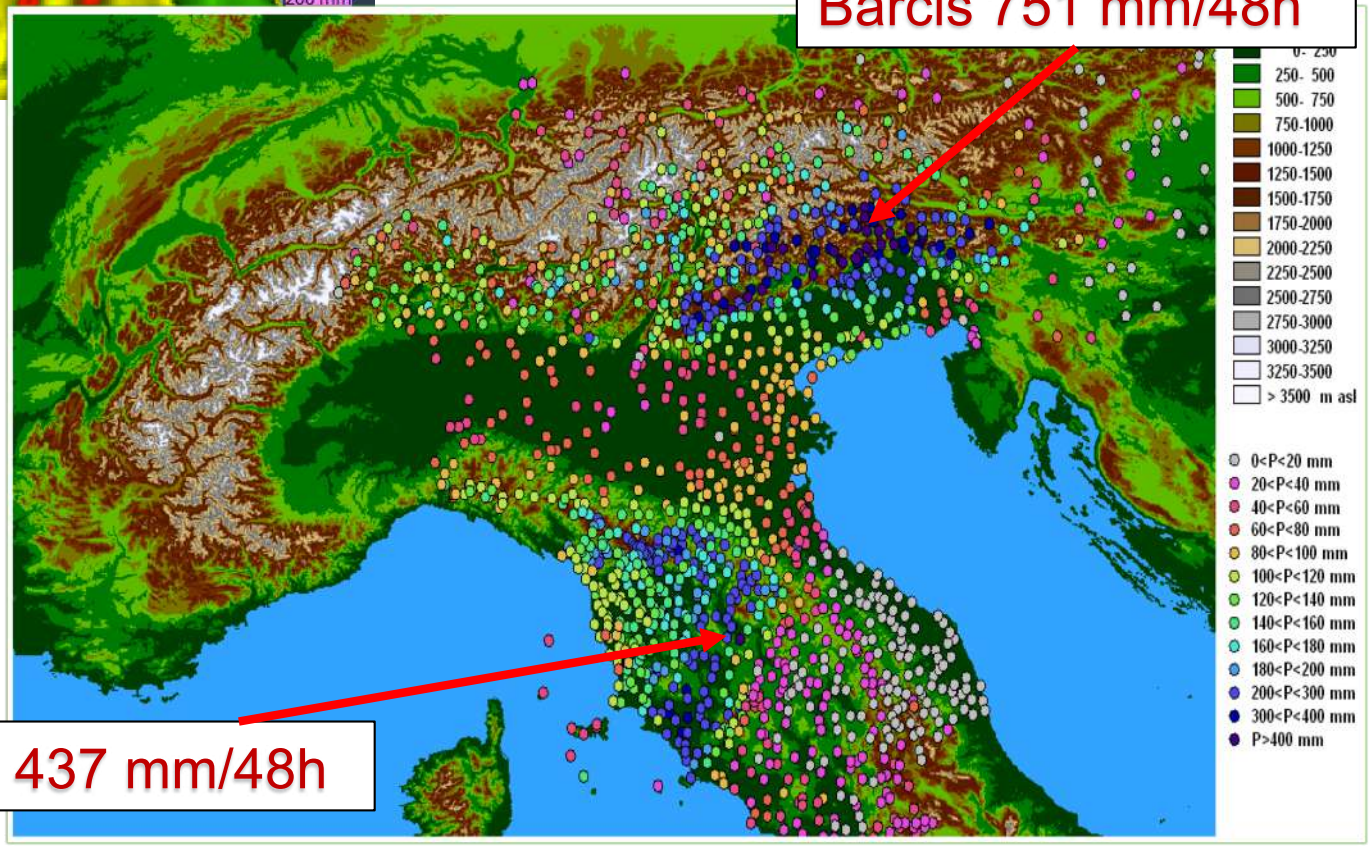

Malga Chiampiuz 817 mm/72h

Sappada 595 mm/72h

**2018 vs 1966**

Barcis 751 mm/48h

Torriglia
623 mm/72h




**27-29 Ottobre 2018**

Veneto > 400 mm/72h

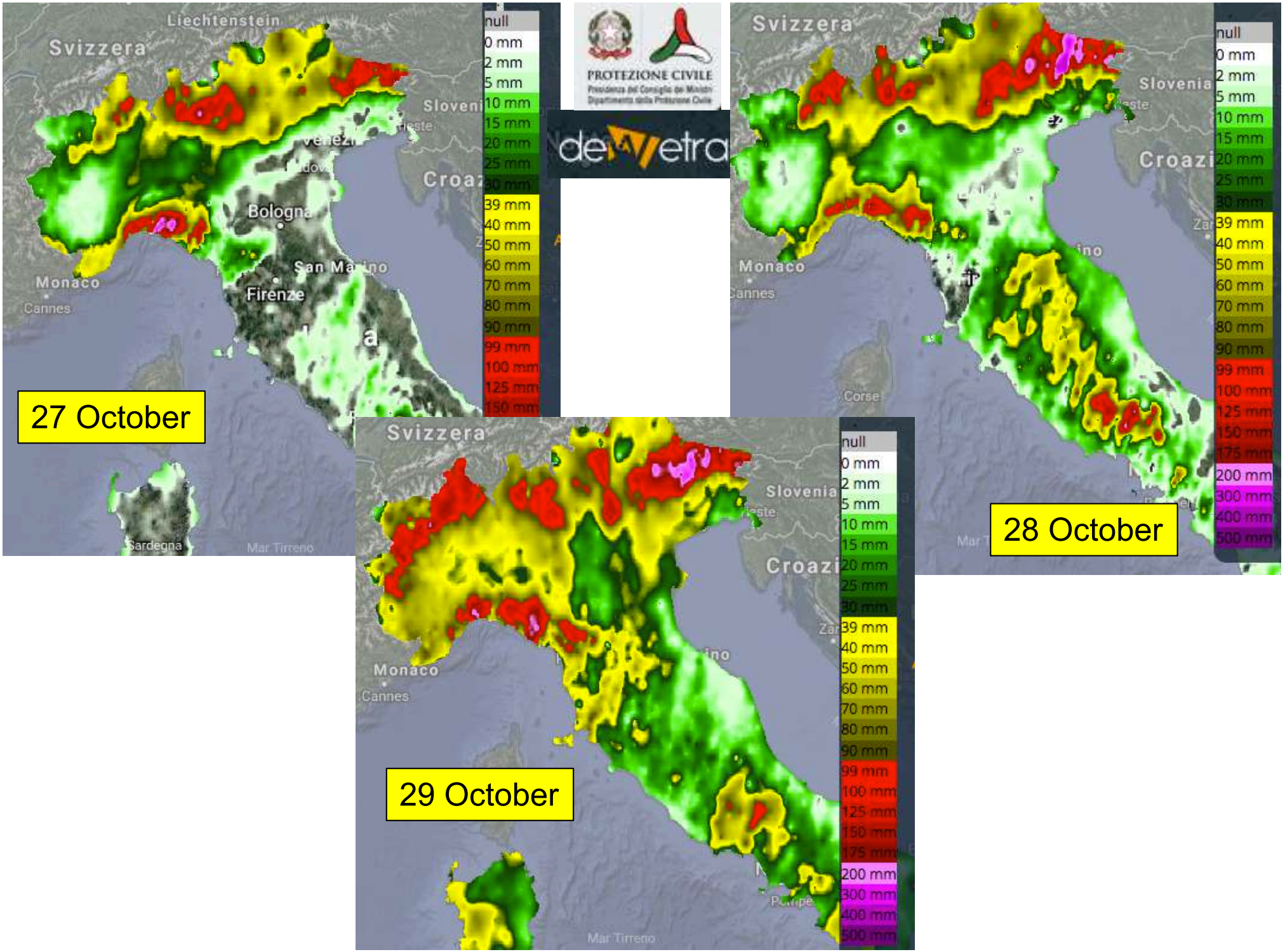
Trentino AA > 300 mm/72h

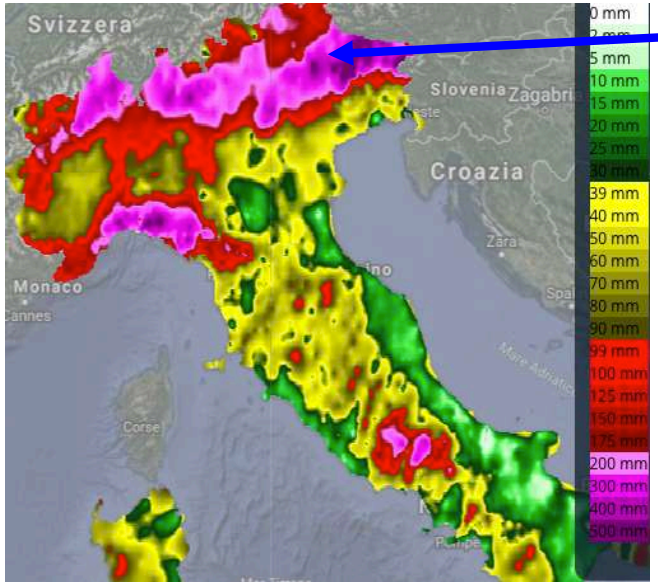
Lombardia > 500 mm/72h

Piemonte > 400mm/72h

Lazio > 400 mm/72h

Badia Agnano 437 mm/48h


PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile
27 October
28 October
29 October
Svizzera
Liechtenstein
Slovenia
Croazia
Monaco
Cannes
Bologna
San Marino
Firenze
Sardegna
Mar Tirreno
Corse
null
0 mm
2 mm
5 mm
10 mm
15 mm
20 mm
25 mm
30 mm
39 mm
40 mm
50 mm
60 mm
70 mm
80 mm
90 mm
99 mm
100 mm
125 mm
150 mm
175 mm
200 mm
300 mm
400 mm
500 mm

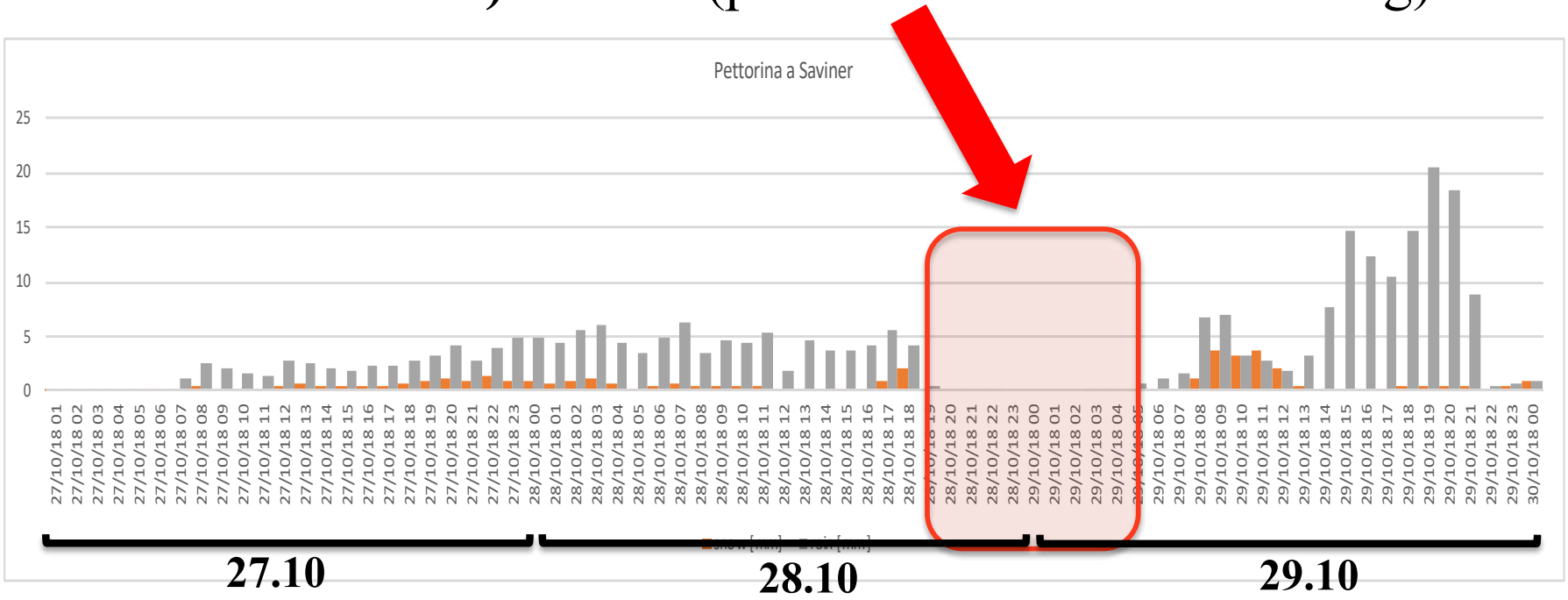



Malga Chiampiuz 817 mm/72h

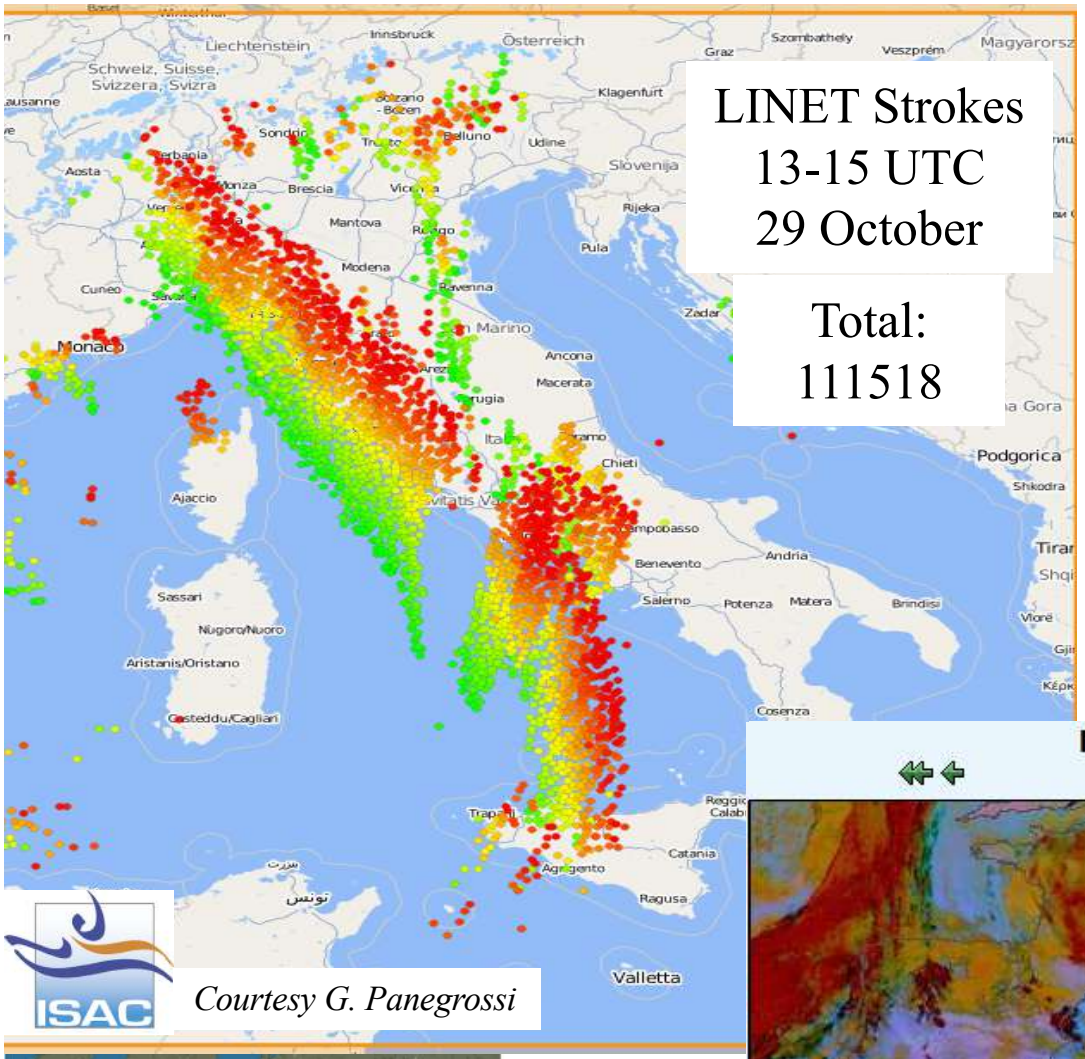
PROTEZIONE CIVILE

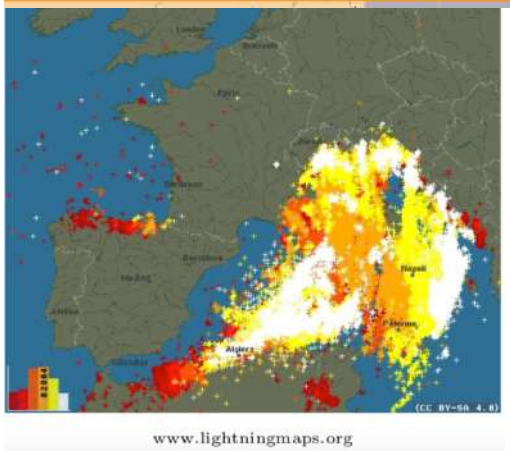
**Two phases** of the event:

1) Orographic/**stratiform** precipitation associated with the **warm front**, moderate intensity but persistent (27-28 October).
2) Orographic/**convective** precipitation shorter duration but higher intensity, associated with the passage of the **cold front** (29 October).
3) **Hiatus** (prevented extensive flooding)

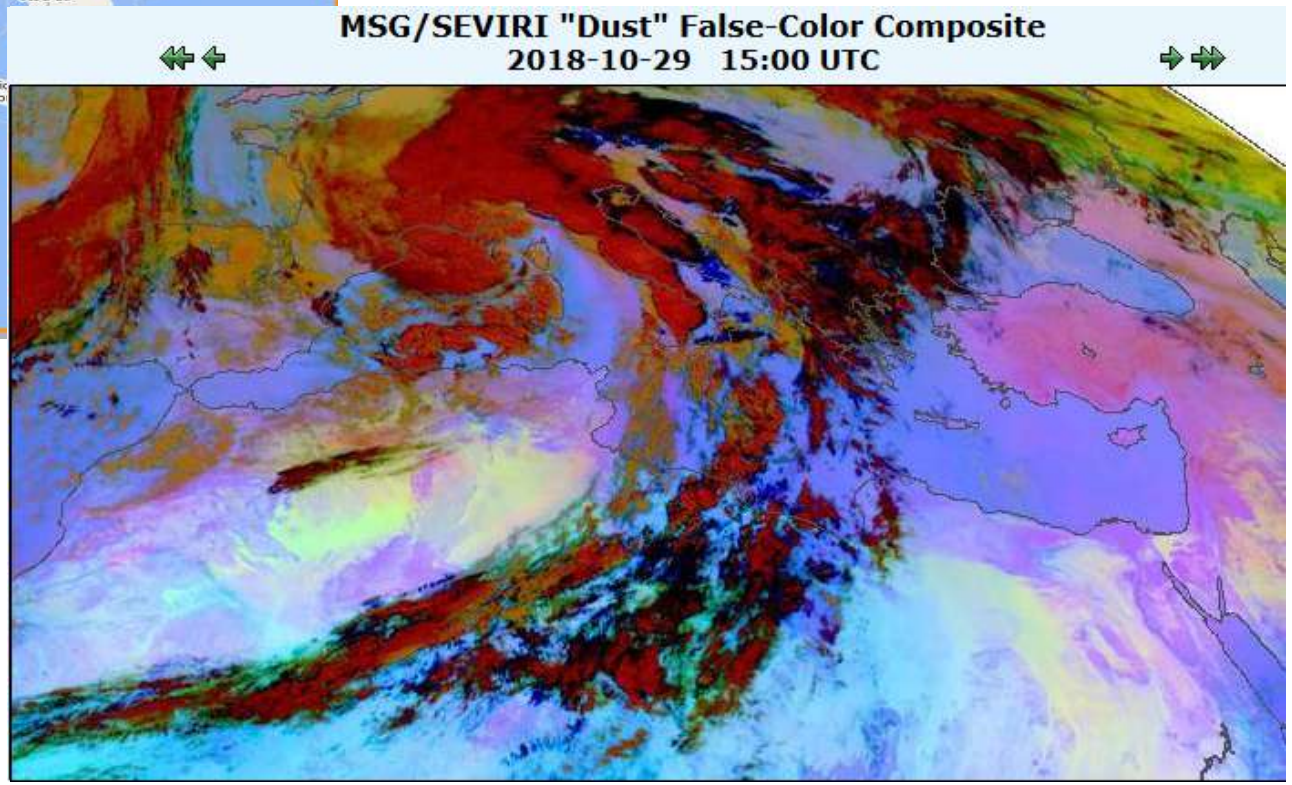


# LIGHTNING ACTIVITY

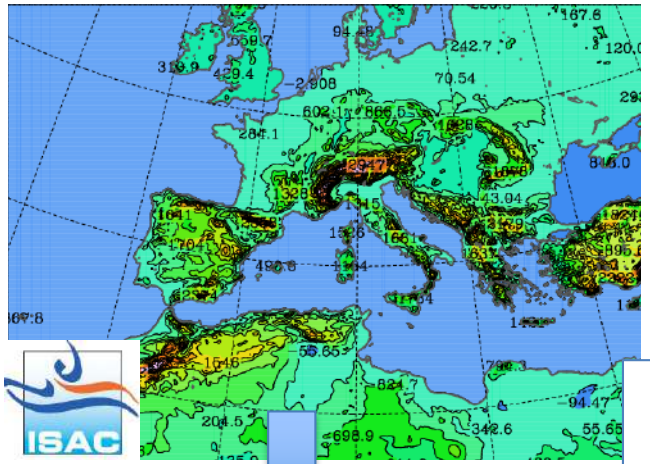



## DESERT DUST TRANSPORT



**BOLAM** – 8 km – 578x418x50

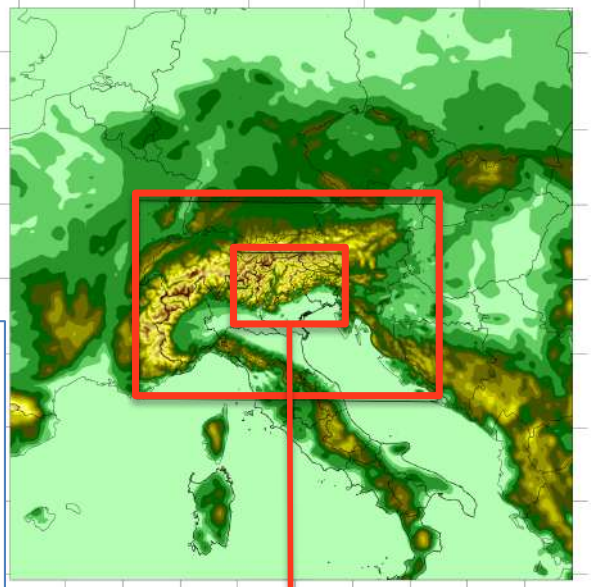


IFS/GFS analyses

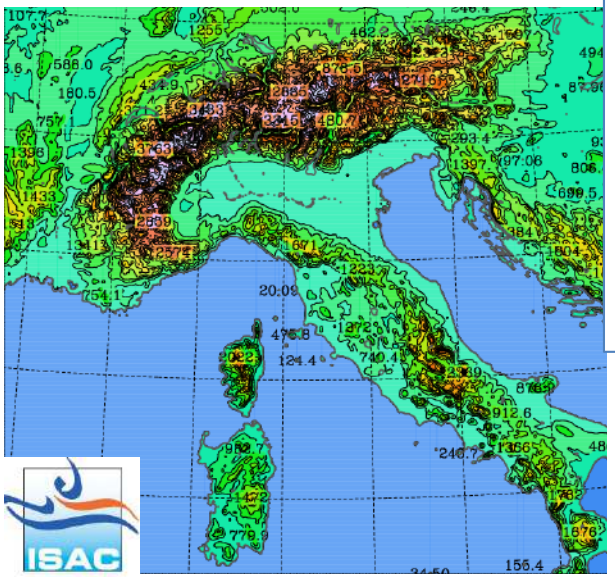
**WRF**

Domain 1: 9 km - 193x193x32

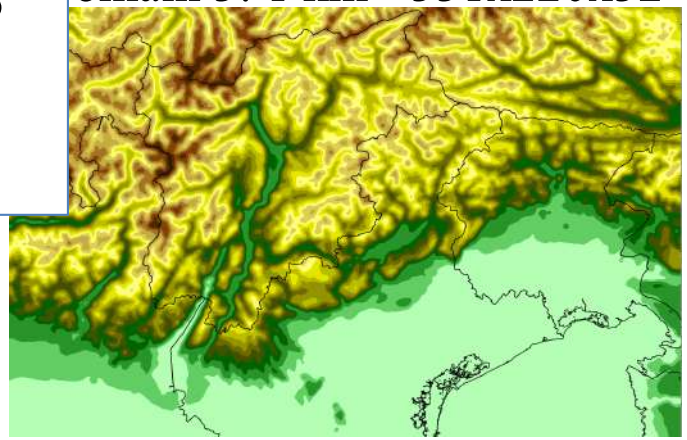
Domain 2: 3 km - 301x199x32



**MOLOCH** – 2.2 km – 514x482



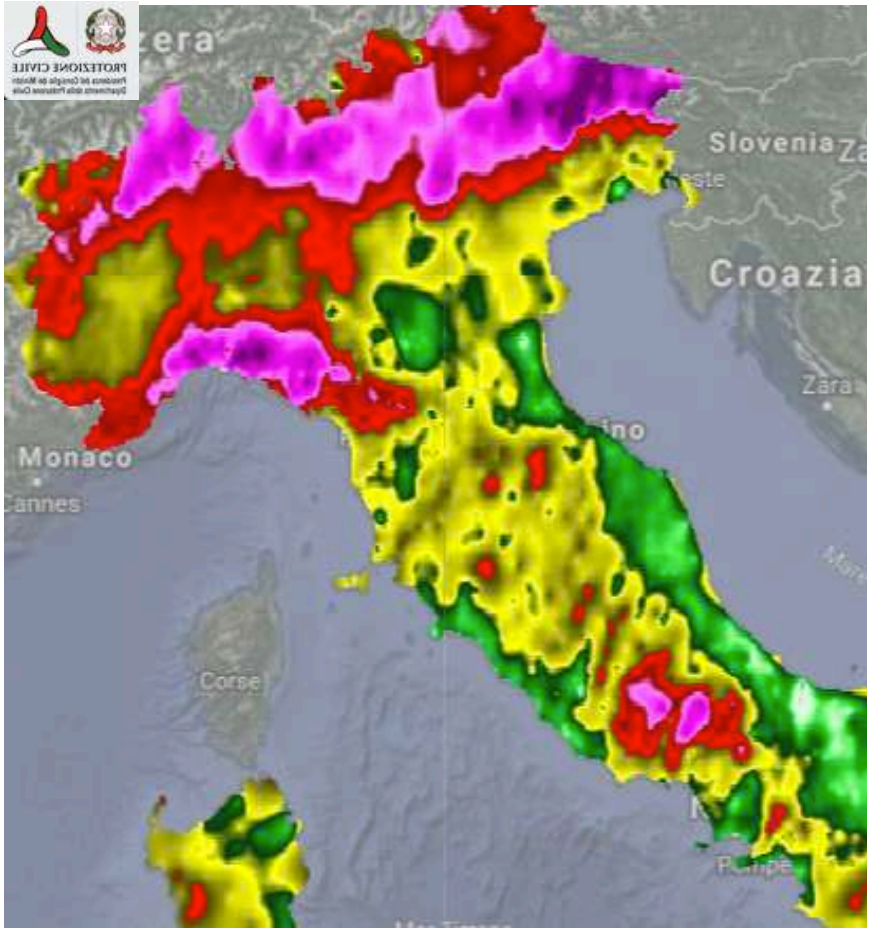
Domain 3: 1 km - 331x220x32

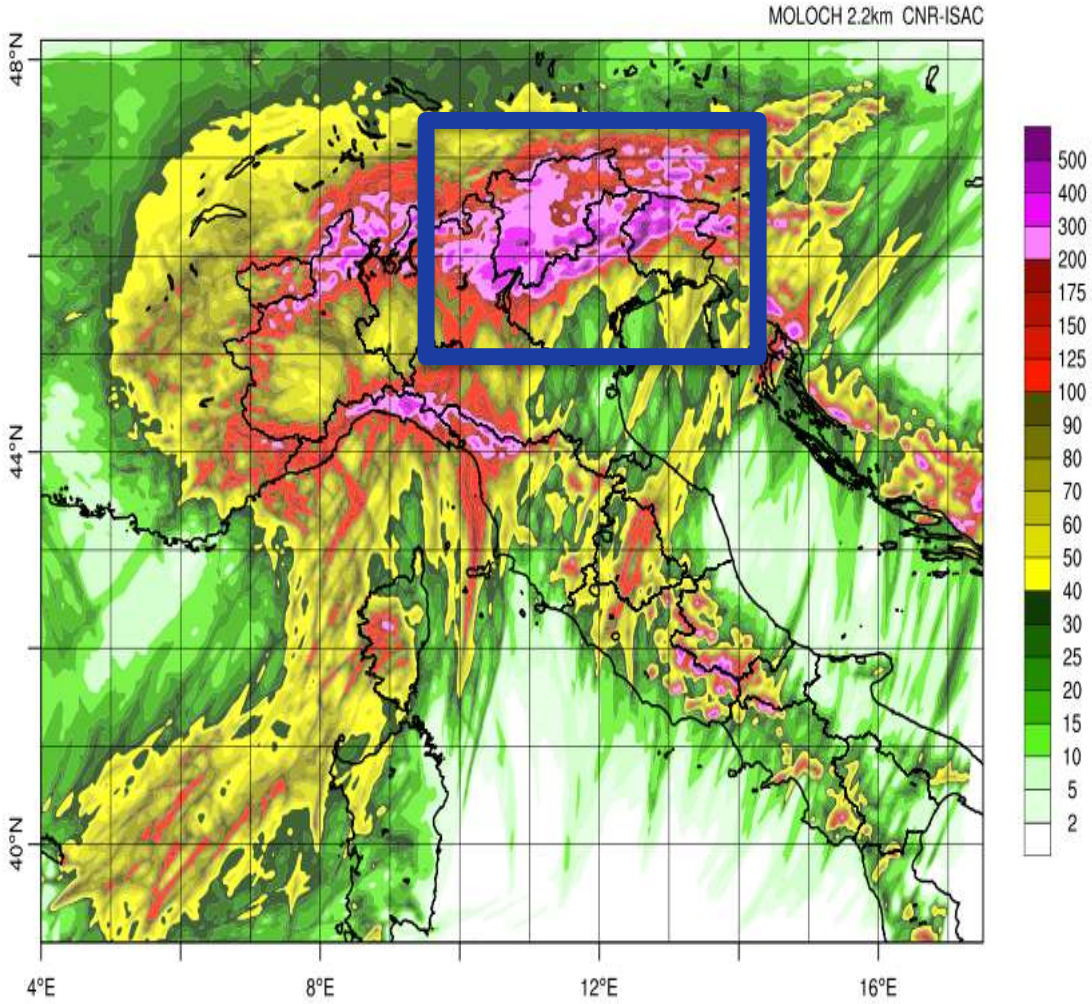


**DIFFERENT INITIAL/BOUNDARY CONDITIONS & DIFFERENT LAMS** *"ensemble approach"*

# MODEL SETUP

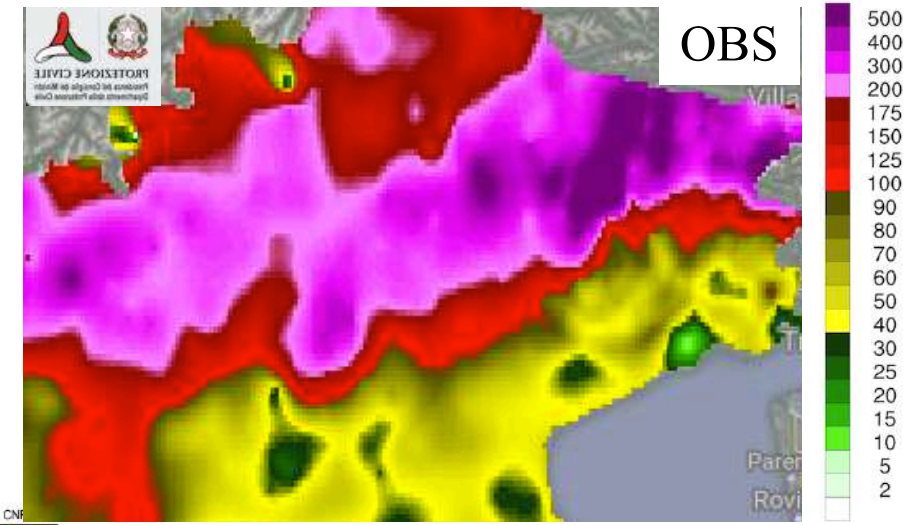
# 72h precipitation - overview



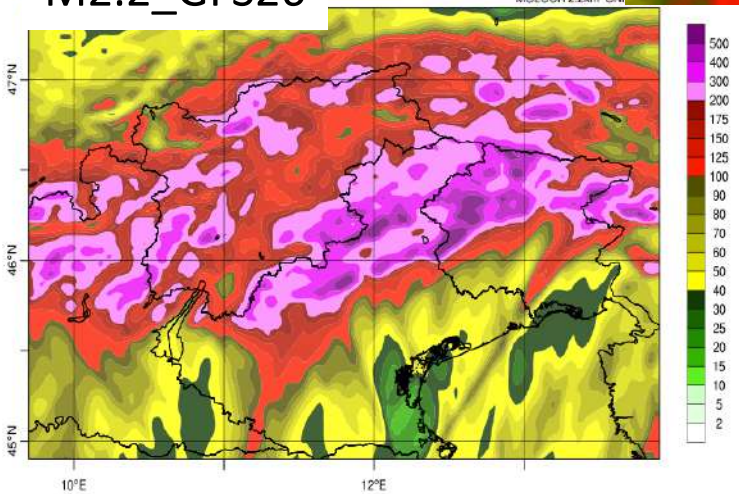




MOLOCH M2.2_IFS26 (forecast +96h)

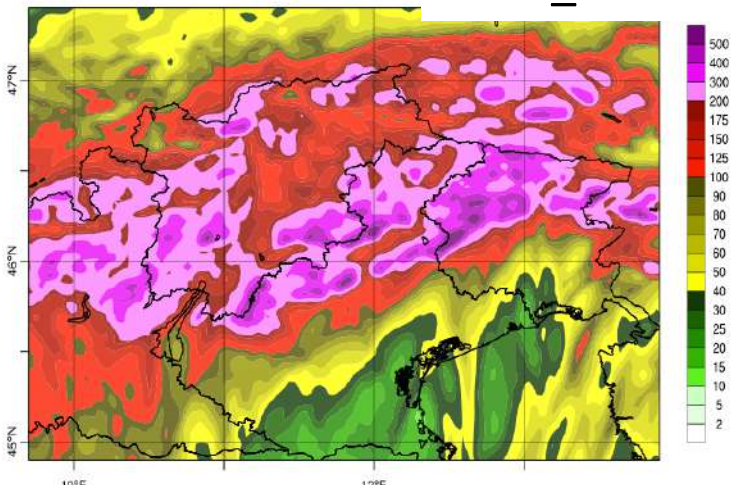
→ Focus on NE Alps in the following analysis




M2.2_GFS26

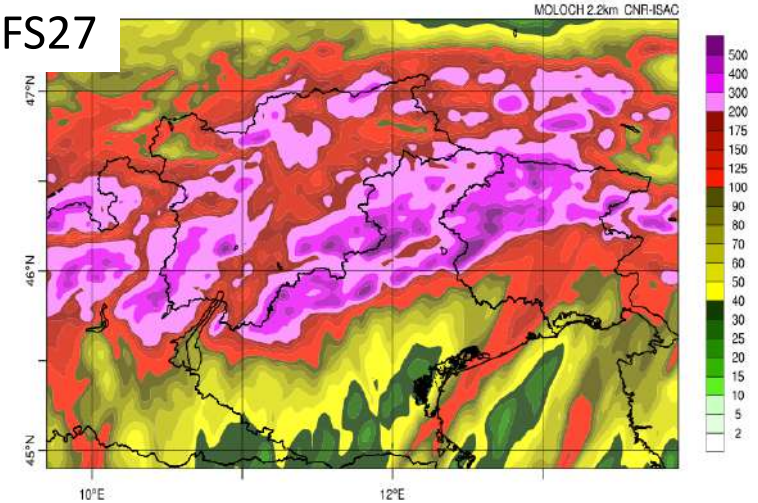



M2.2_IFS26

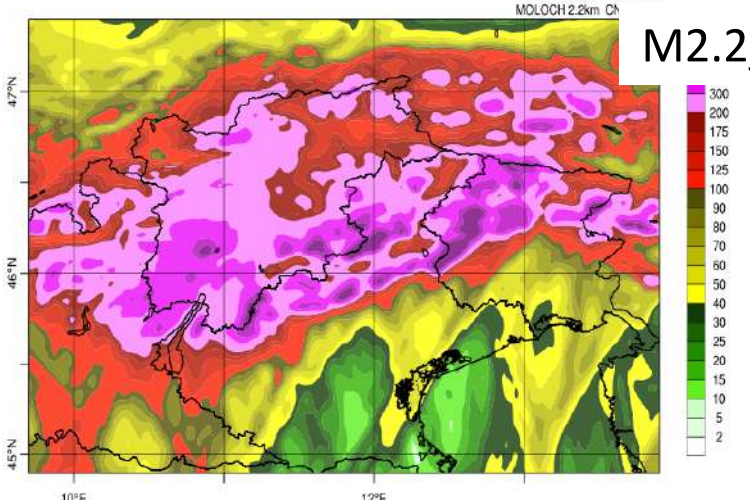


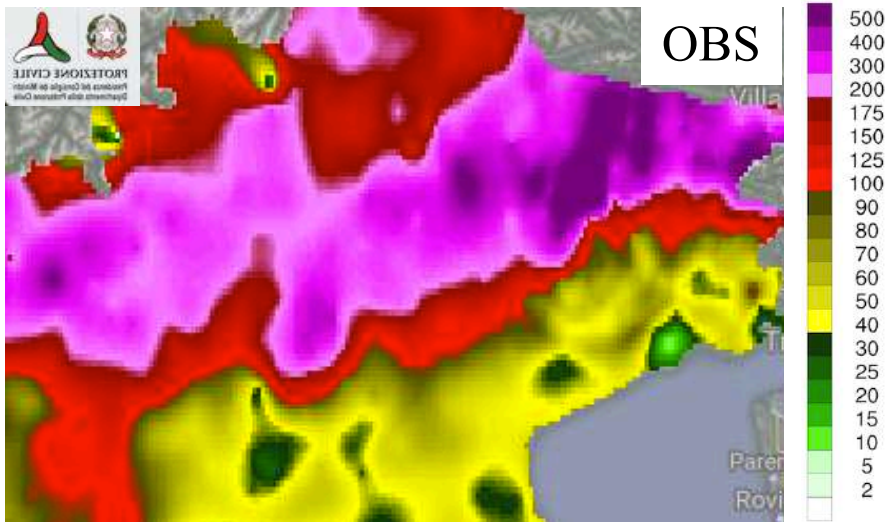

**MOLOCH**
**72h precipitation**

M2.2_GFS27




M2.2_IFS27

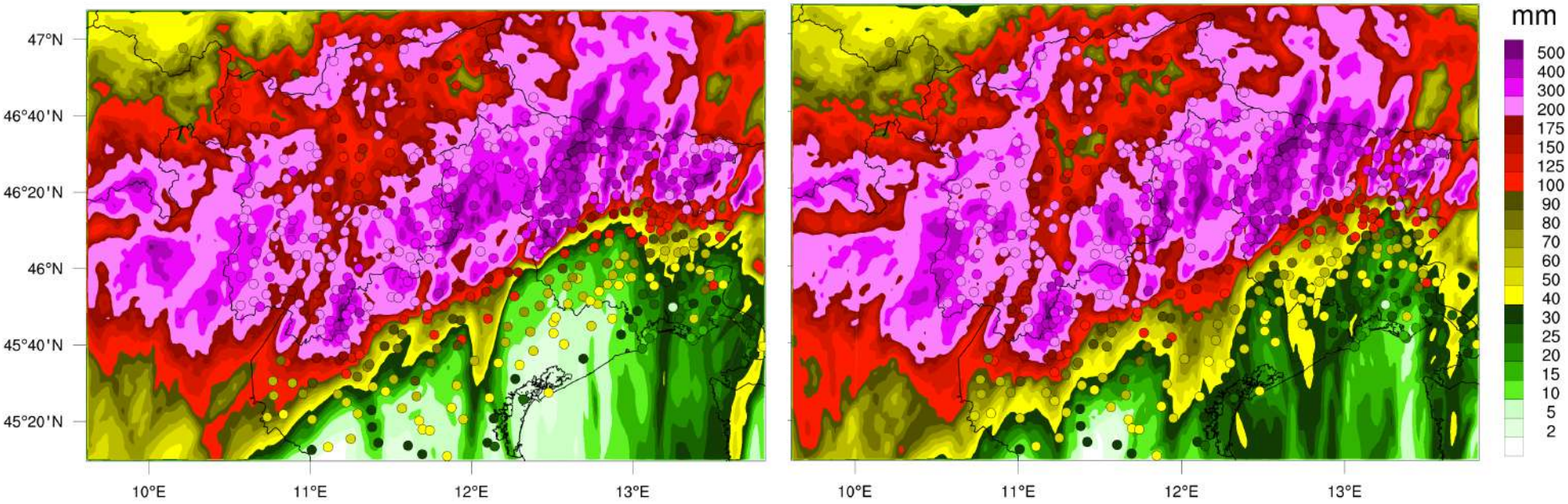





# WRF - 72h precipitation

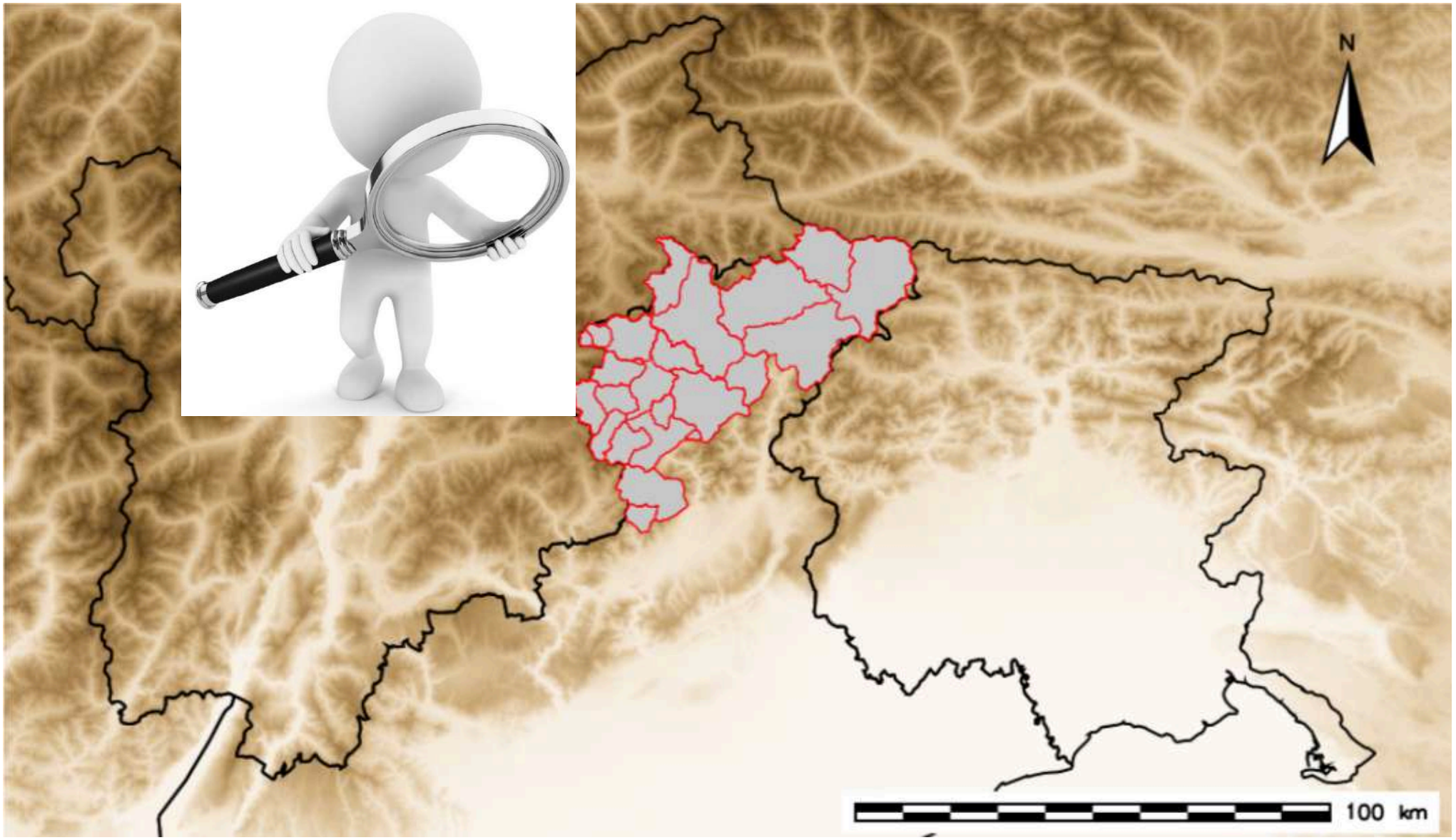
W1_GFS26

W1_IFS26

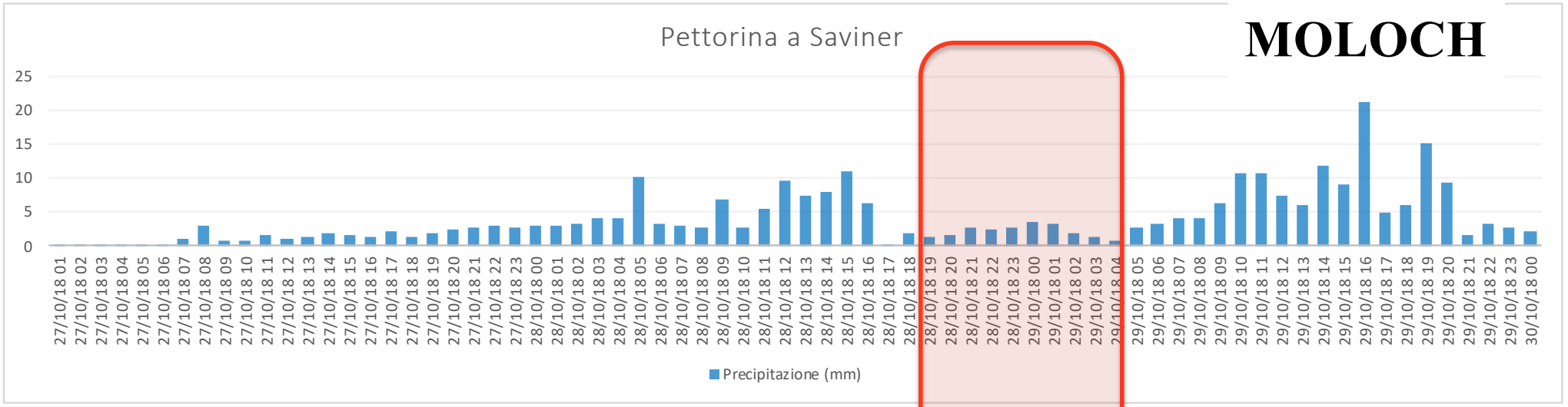


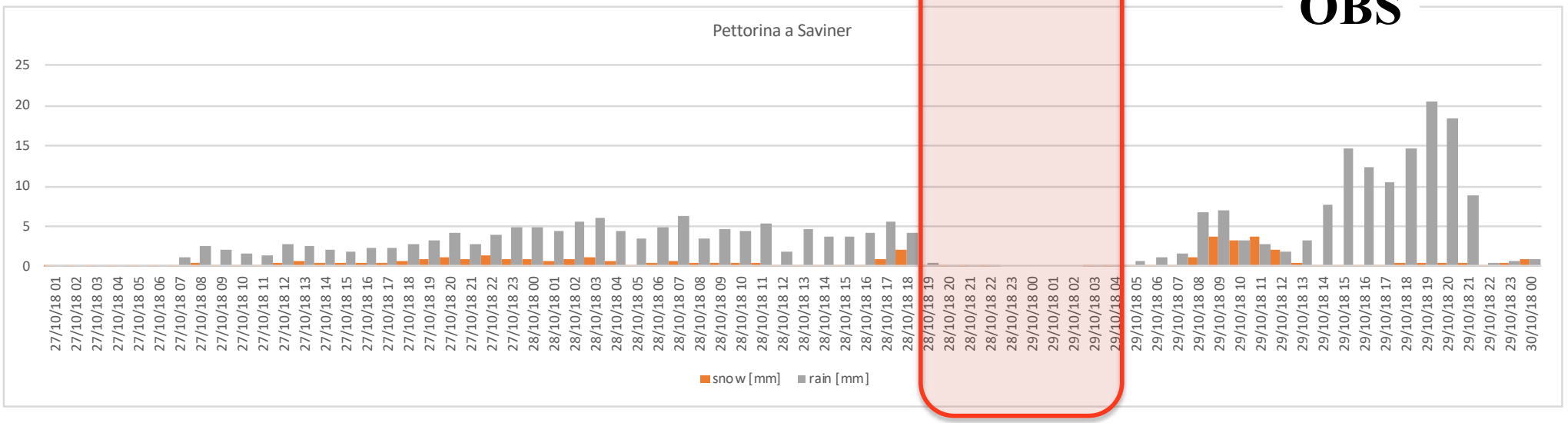

- Weak sensitivity to initial and boundary conditions
- Strong large scale and orographic forcing → relatively high predictability

# Towards smaller scales of interest for hydrological applications



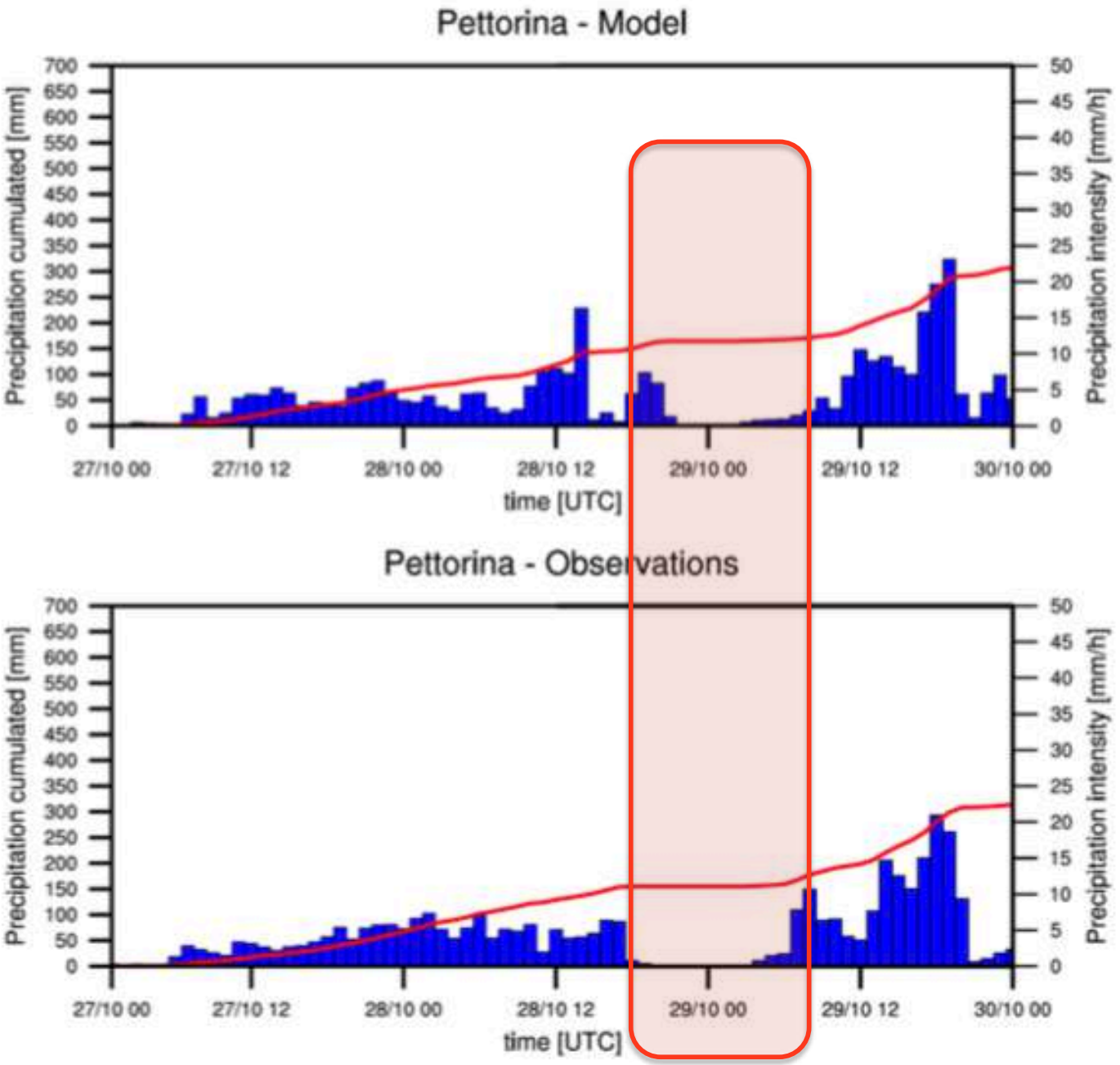

… *work in progress* - Verification at local scale: analysis over basins




- Good timing and simulation of two phases;
- Some rain during the observed hiatus

**WRF**

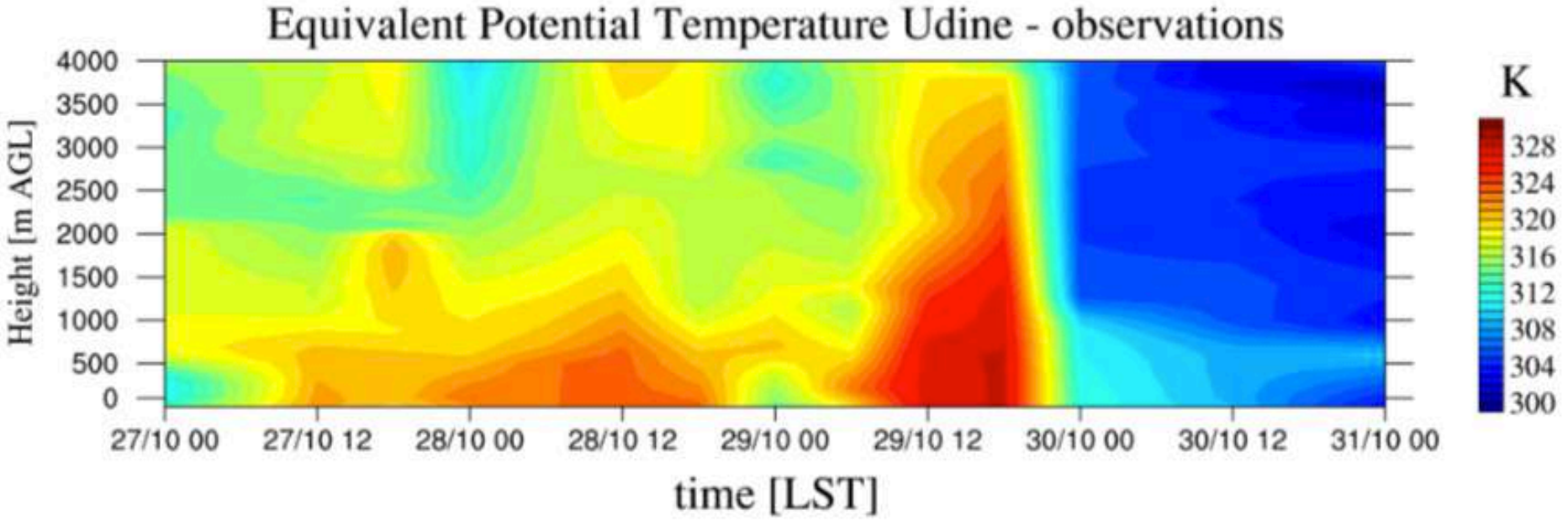


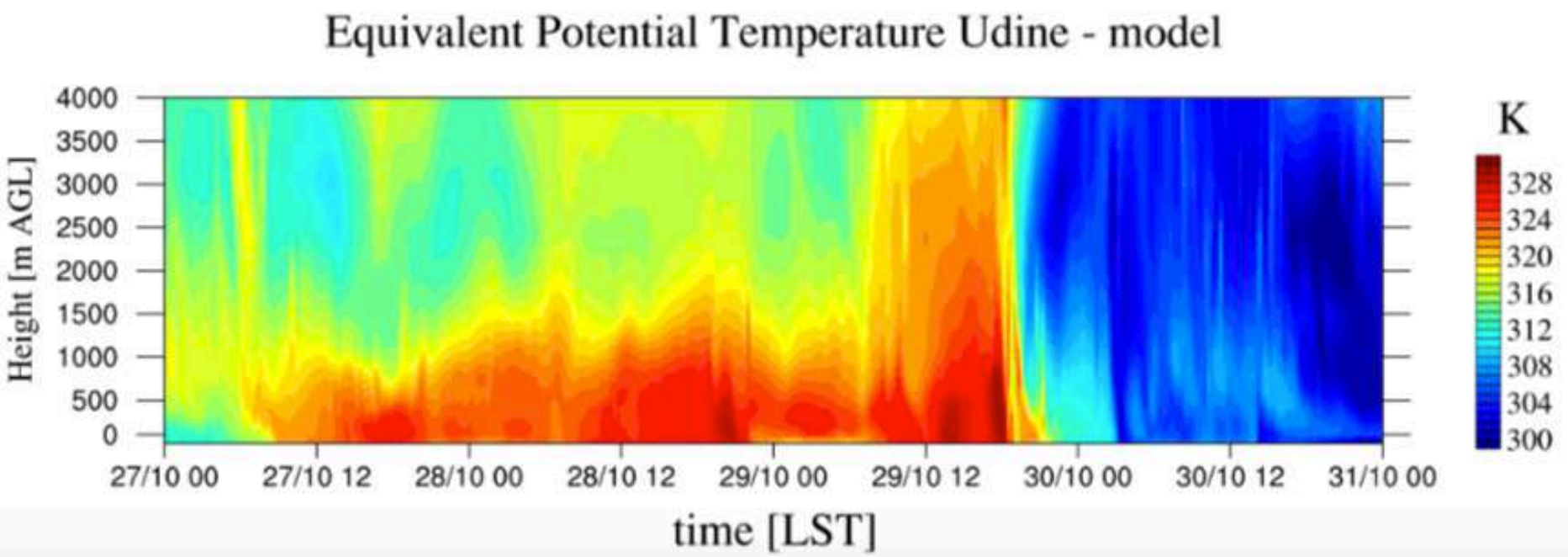

- Accurate hiatus and simulation of two phases;
- Slight time-shift

Area-averaged precipitation (mm) during the event

| **BASIN** | **AREA [km$^2$]** | **Observed areal precipitation** | **MOLOCH** | **WRF** |
|---|---|---|---|---|
| Cordevole | 27.25 | 240 | 250 | 230 |
| Pettorina | 53.31 | 310 | 290 | 290 |
| Liera | 37.7 | 370 | 360 | 400 |
| Tegnas | 49.48 | 490 | 400 | 500 |
| La Stua | 27.61 | 470 | 520 | 290 |

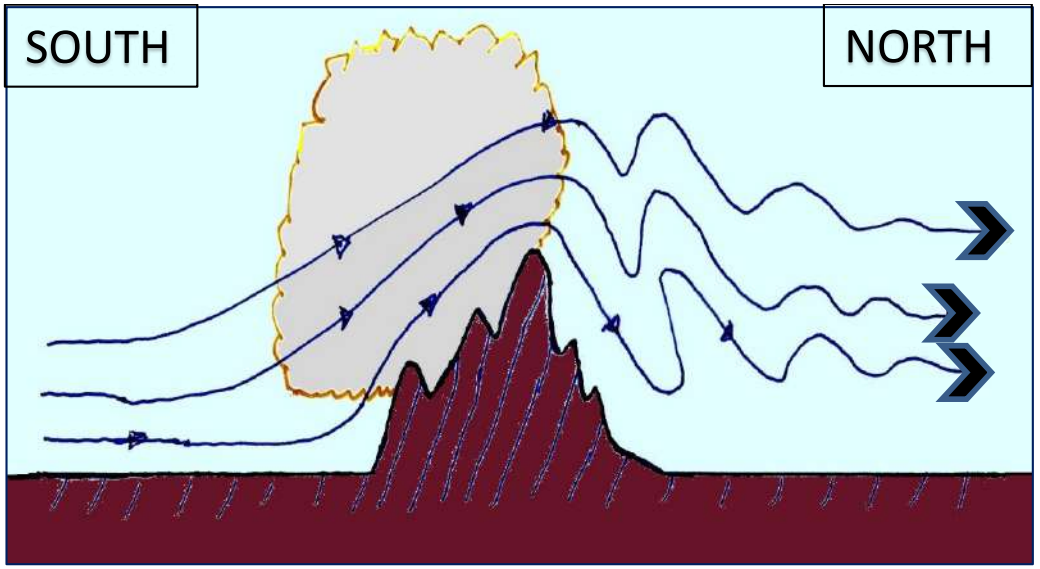
# MODEL SIMULATION VALIDATION: UDINE RADIOSOUNDINGS

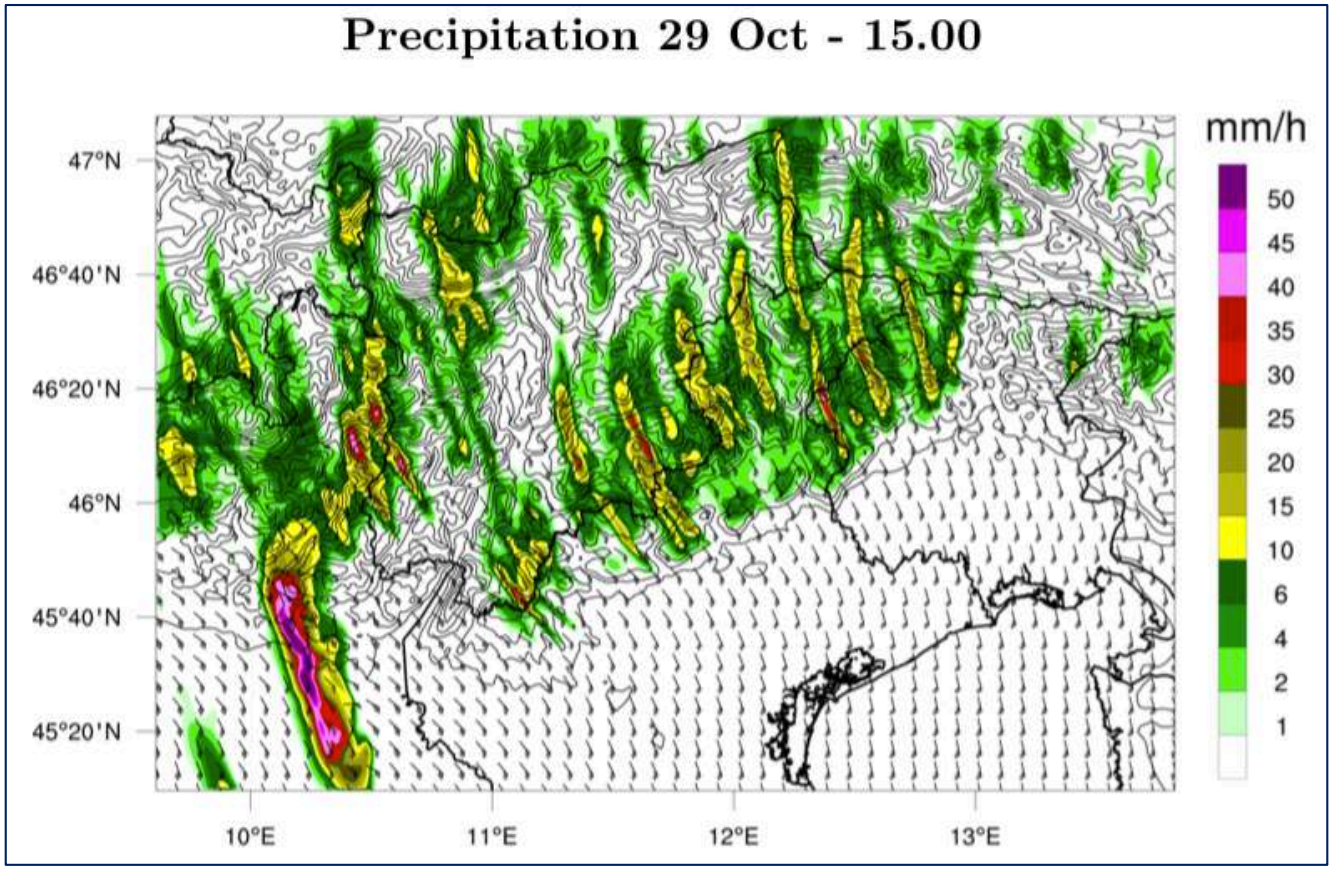


# Orographic precipitation over Alps/Prealps

Nearly neutral flow:
max uplift windward side

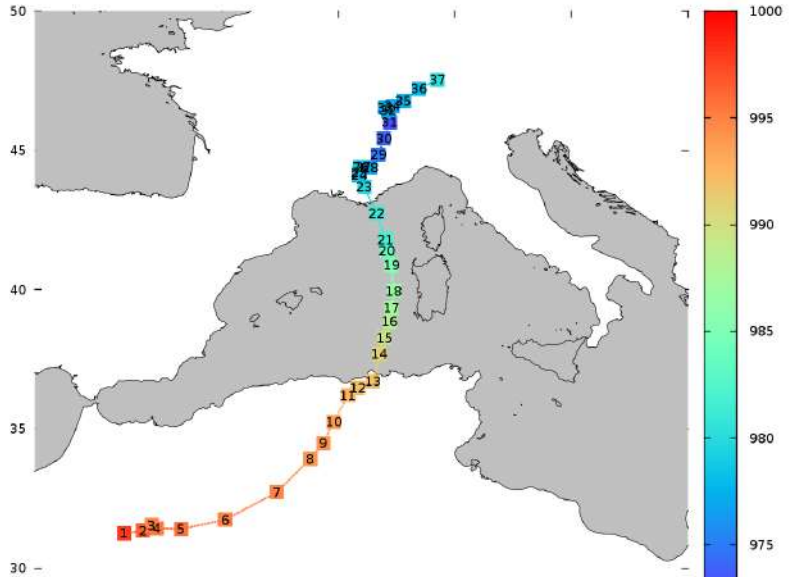



Increasing instability produces orographic convective bands

# WIND STORM & STORM SURGE

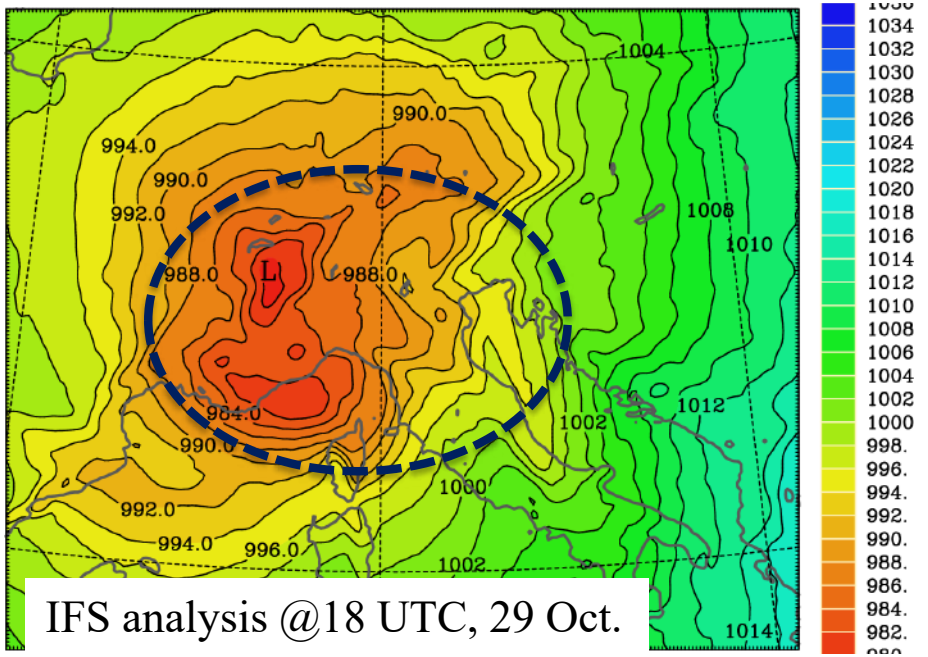
- **Large scale conditions** favourable for intense **Sirocco** over the Adriatic ("flow over")
- **Explosive Mediterranean cyclogenesis → sharp W-E pressure gradient**




BOLAM simulation
Cyclone trajectory
from 00 UTC 28 Oct to 00 UTC 30 Oct.

## Explosive Mediterranean cyclogenesis

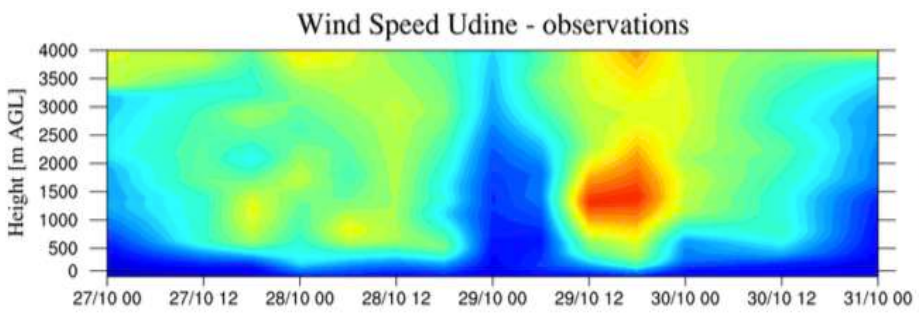
993 hPa → **977 hPa**
16 hPa in 18h
Explosive cyclogenesis @ midlatitudes

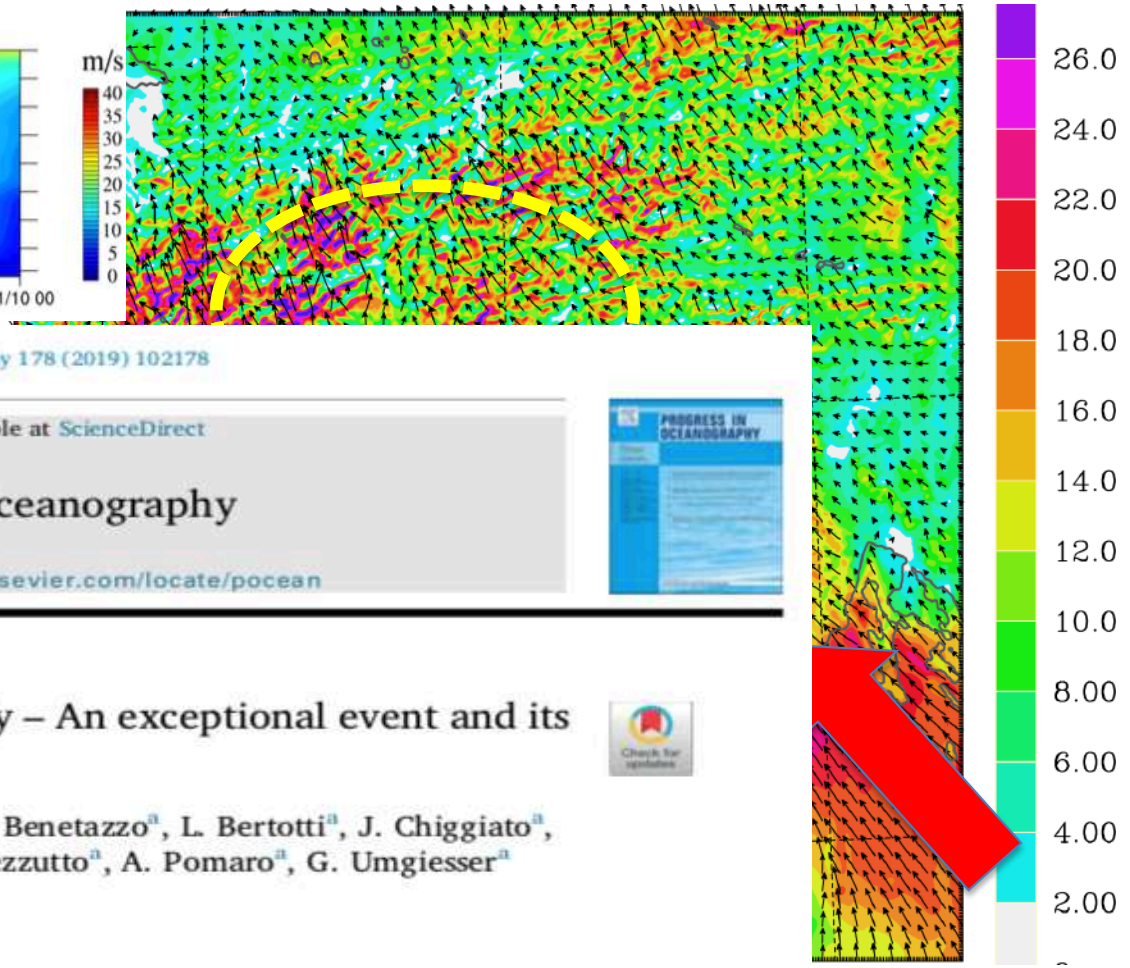



IFS analysis @18 UTC, 29 Oct.

# WIND STORM (& STORM SURGE)

- **Large scale conditions** favourable for intense **Sirocco** over the Adriatic ("flow over")
- **Explosive Mediterranean cyclogenesis → sharp W-E pressure gradient**
- Intensification of **low level wind** associated with **cold front**
- **Squeezing of Sirocco against Dinaric Alps**, due to **cold airflow** over the **Apennines**
- Local scale **turbulence, rotors, channelling**




Progress in Oceanography 178 (2019) 102178

Contents lists available at ScienceDirect

Progress in Oceanography

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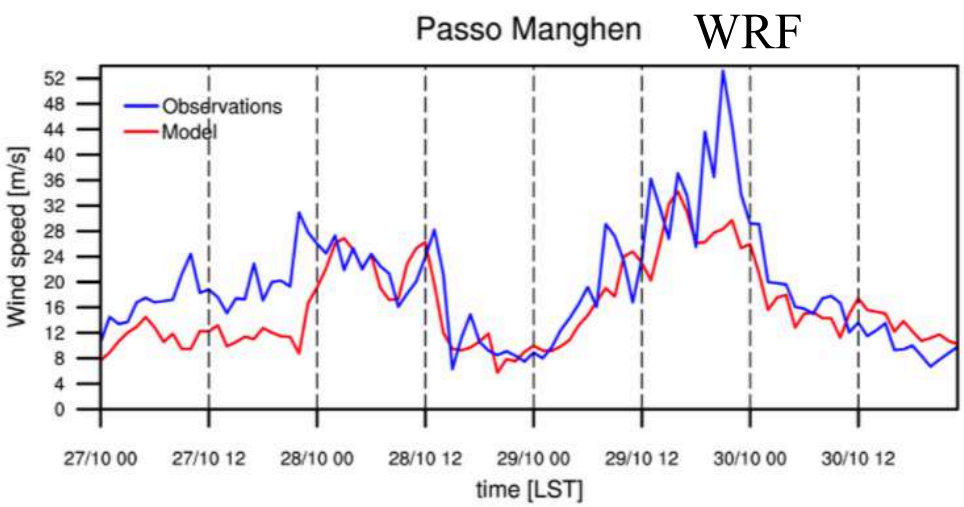
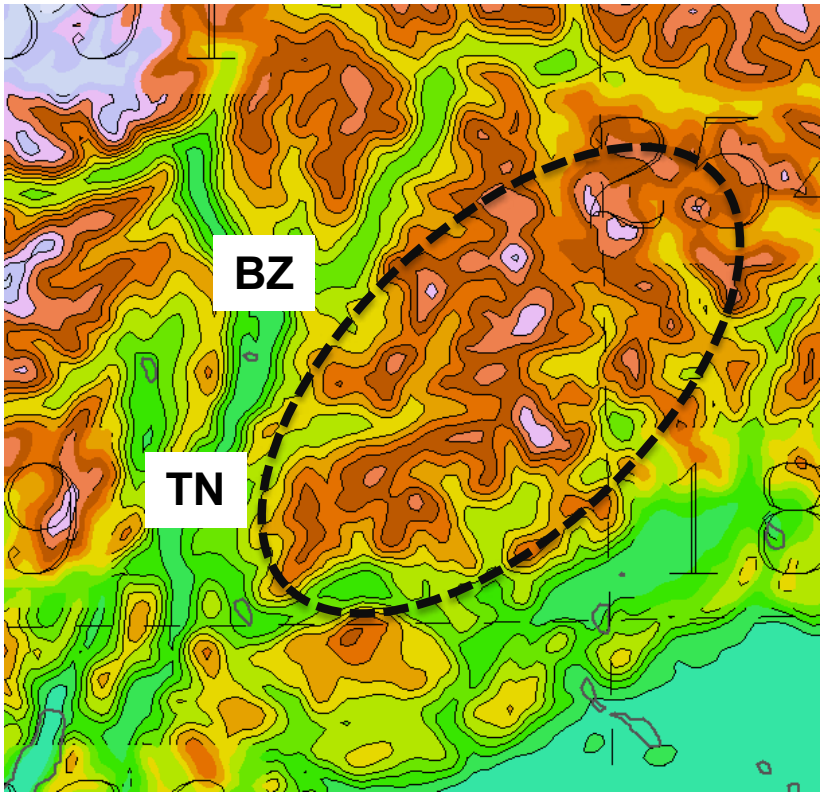
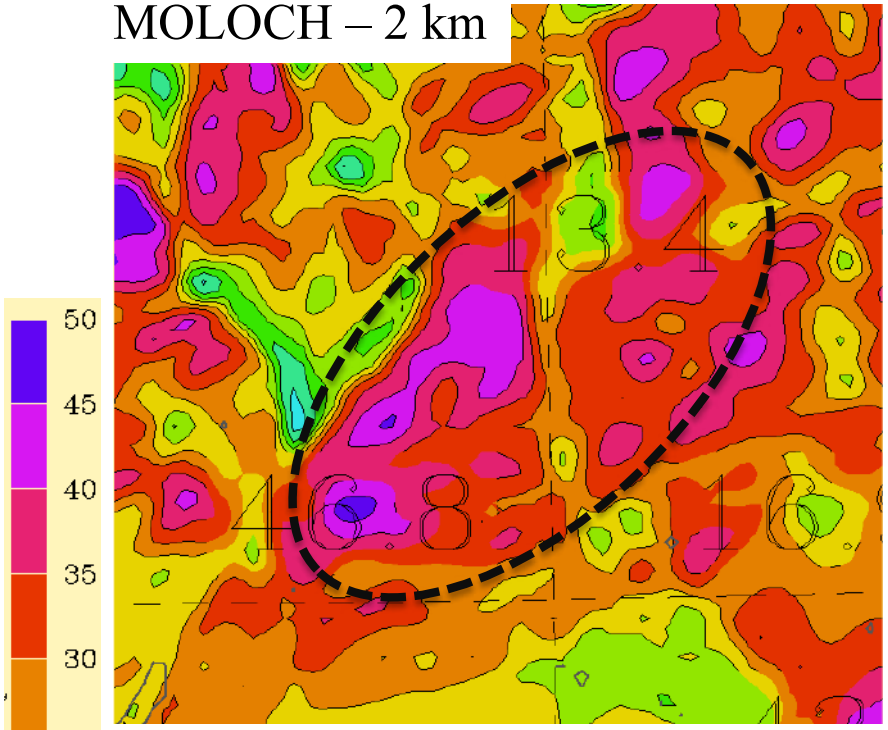
## The October 29, 2018 storm in Northern Italy – An exceptional event and its modeling

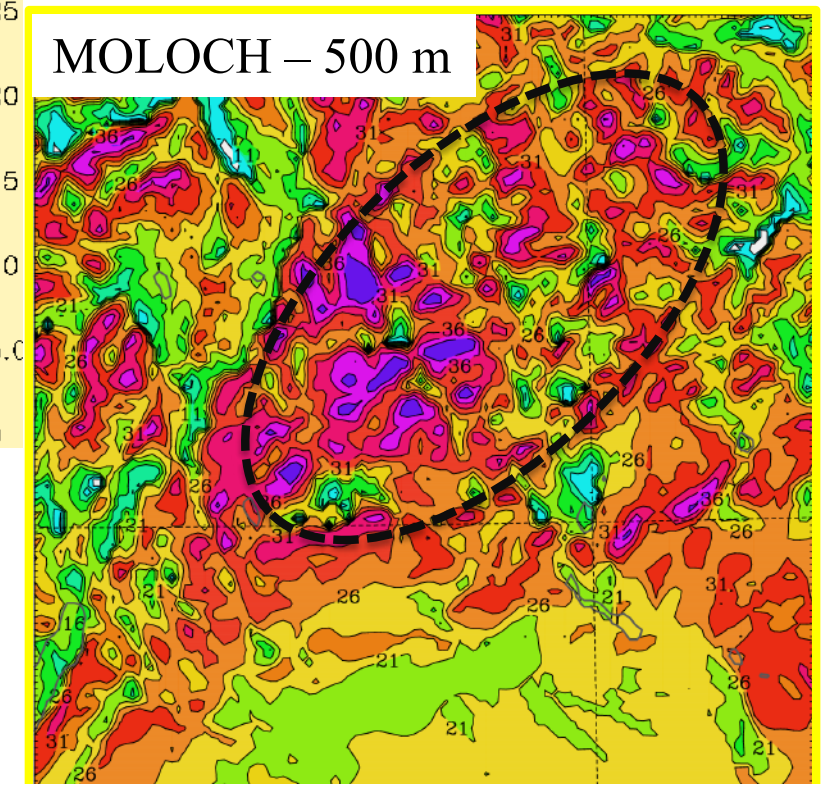
L. Cavaleri[a,*], M. Bajo[a], F. Barbariol[a], M. Bastianini[a], A. Benetazzo[a], L. Bertotti[a], J. Chiggiato[a], S. Davolio[b], C. Ferrarin[a], L. Magnusson[c], A. Papa[d], P. Pezzutto[a], A. Pomaro[a], G. Umgiesser[a]

[a] CNR-ISMAR, Venice, Italy
[b] ISAC, Bologna, Italy
[c] ECMWF, Reading, UK
[d] CPSM, Venice, Italy


Passo Manghen
WRF
Observations
Model
Wind speed [m/s]
52
48
44
40
36
32
28
24
20
16
12
8
4
0
27/10 00
27/10 12
28/10 00
28/10 12
29/10 00
29/10 12
30/10 00
30/10 12
time [LST]


BZ
TN


MOLOCH – 2 km
50
45
40
35
30
25
20
15
10
5.0
0

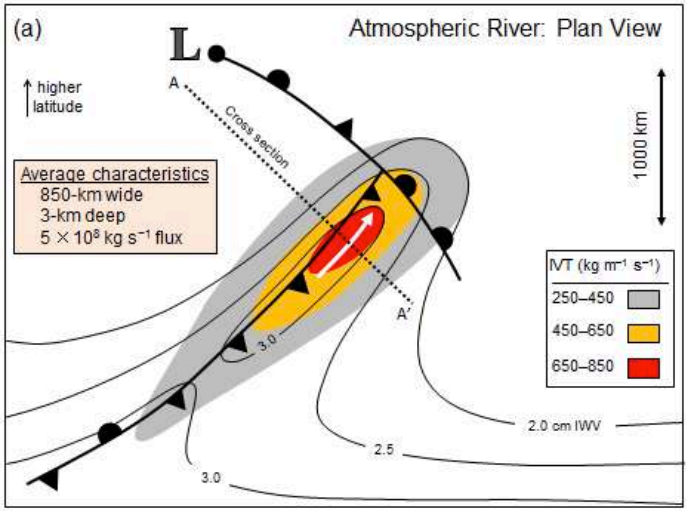

MOLOCH – 500 m

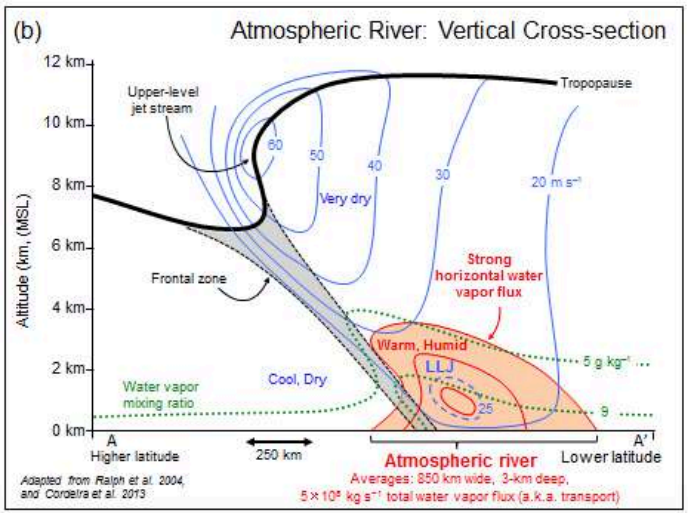
(*AMS Glossary of meteorology*)

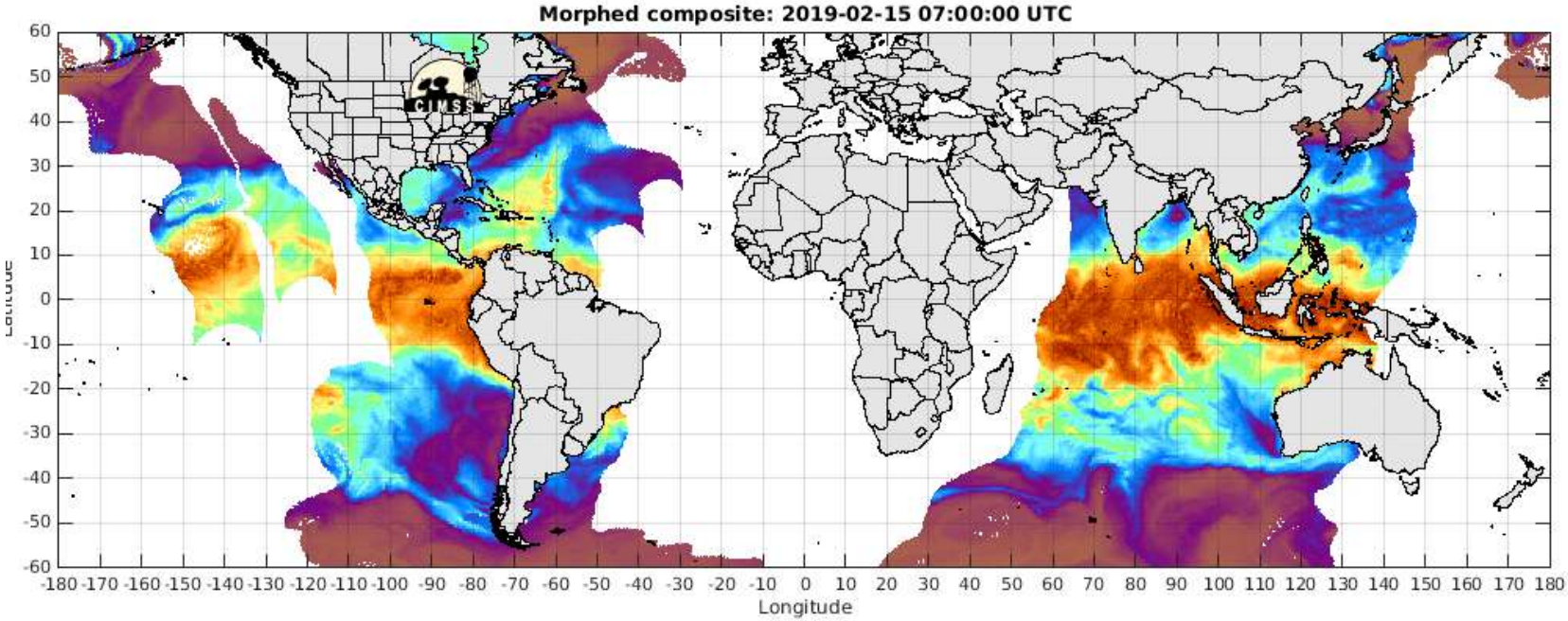
**"Atmospheric River** (AR) is a **long, narrow, and transient corridor** of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone"

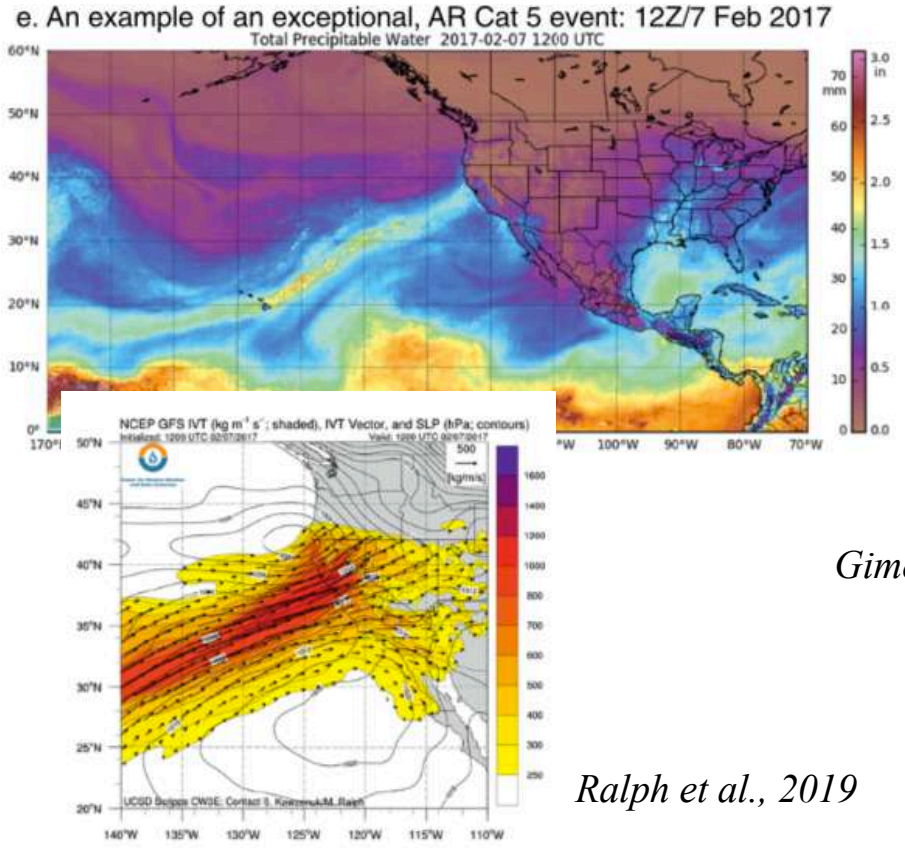
- "Horizontal water vapor transport in the midlatitudes occurs primarily in atmospheric rivers and is **focused in the lower troposphere**".

- "Atmospheric rivers are the largest "rivers" of fresh water on Earth, transporting on average more than double the flow of the Amazon River".



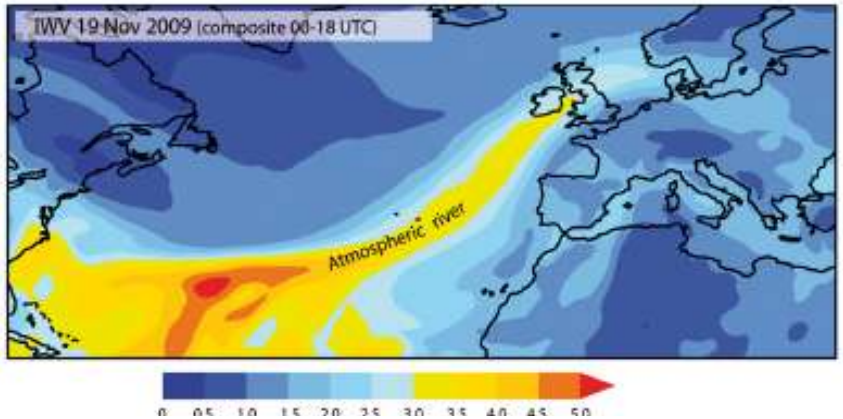


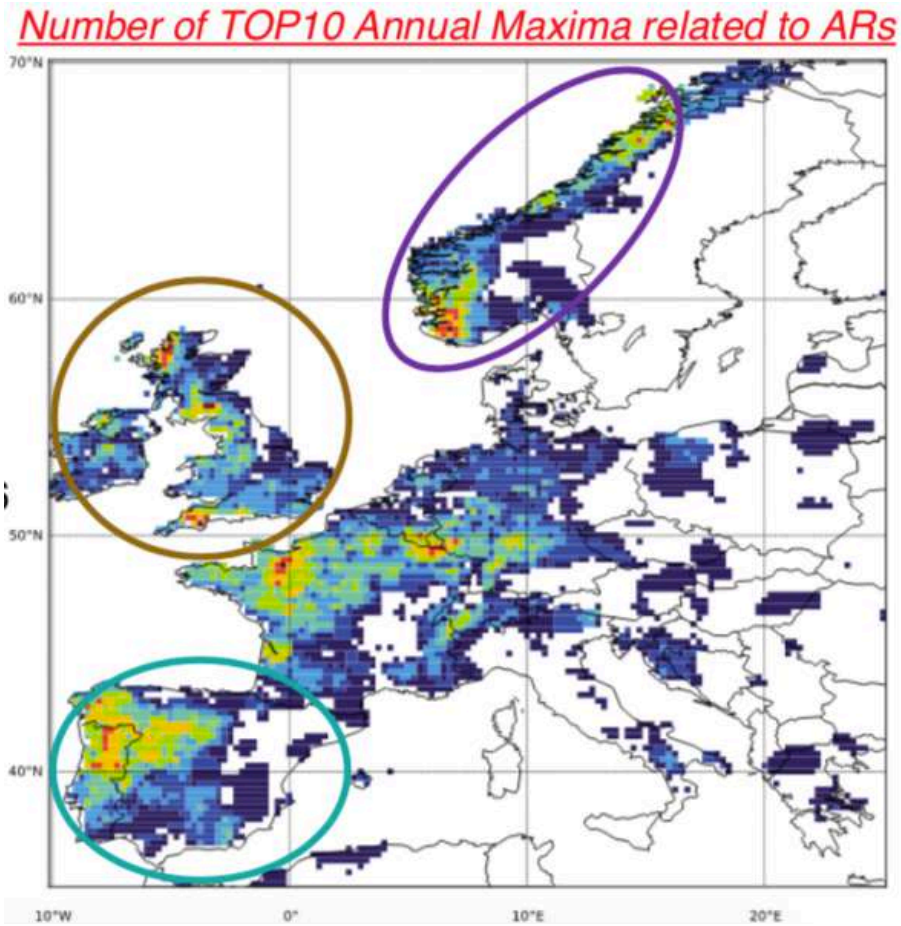

*Ralph et al., 2019*

"Atmospheric rivers **frequently lead to heavy precipitation** where they are forced upward—for example, by mountains or by ascent in the warm conveyor belt".

*Gimeno et al., 2014*



# ATMOSPHERIC RIVERS OVER EUROPE




**ARs over the Atlantic Ocean**

*Knippertz and Wernli, 2010*

**Iberica Peninsula**

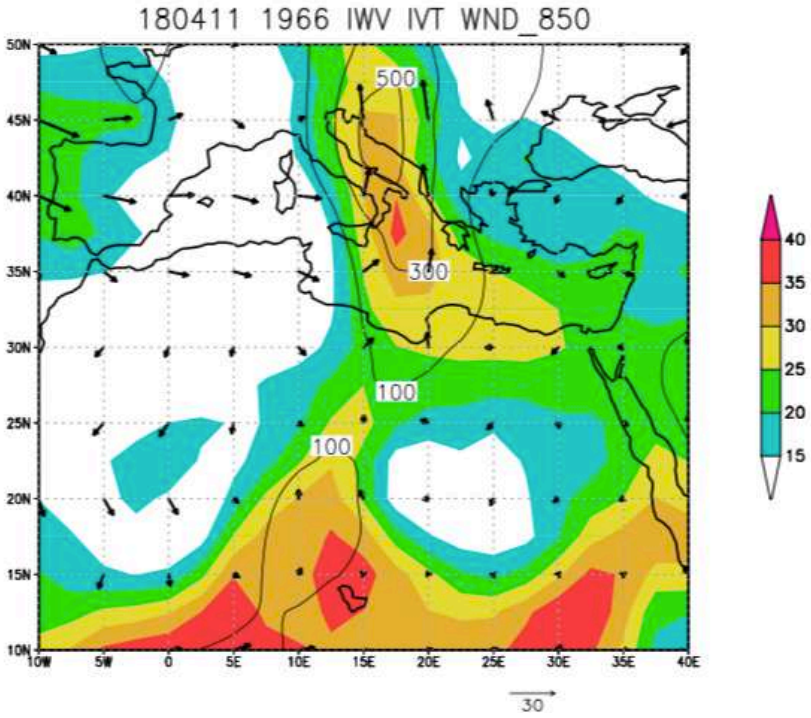
*Liberato et al., 2012; Ramos et al., 2015*

**UK e France**

*Lavers et al., 2011; Lavers and Villarini, 2013; Browning, 2018*

**Scandinavian Peninsula**

*Sodemann and Sthol, 2013; Benedict et al., 2019*




*Krichak et al., 2016*

Studying the 1966 flood the presence of an atmospheric river **over the Mediterranean** is confirmed, as only suggested in previous studies (e.g. Malguzzi et a., 2006; Buzzi et al., 2014)

# ATMOSPHERIC RIVER DETECTION

THRESHOLDS:

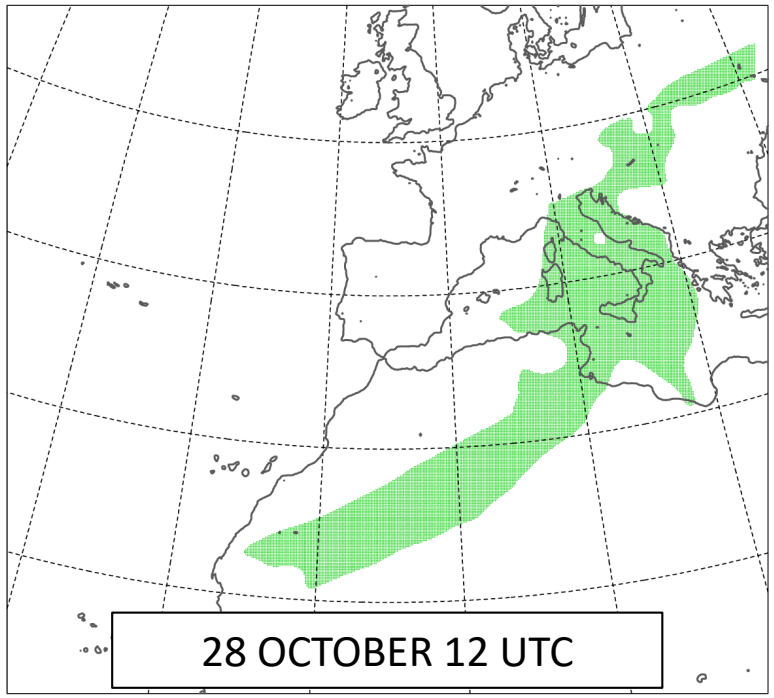
1) IWV > 2 cm
2) IVT > 250 kg $m^{-1}$ $s^{-1}$

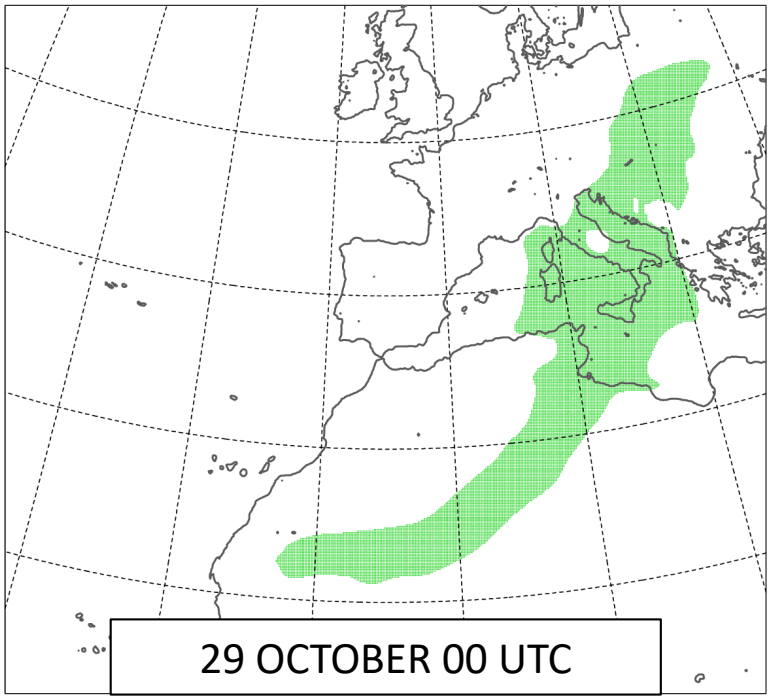
$$IWV = \frac{1}{g}\int_{1000hPa}^{300hPa} q \cdot dp$$

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000hPa}^{300hPa} q \cdot u \cdot dp\right)^2 + \left(\frac{1}{g}\int_{1000hPa}^{300hPa} q \cdot v \cdot dp\right)^2}$$

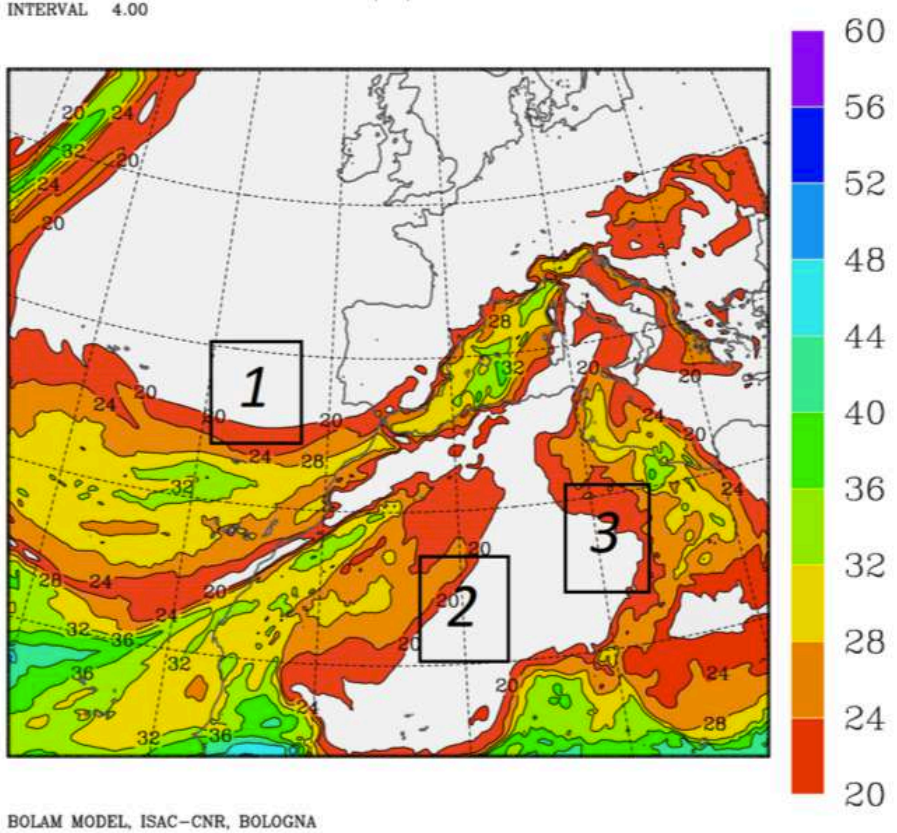
3) Length > 2000 km
4) Width < 1000 km

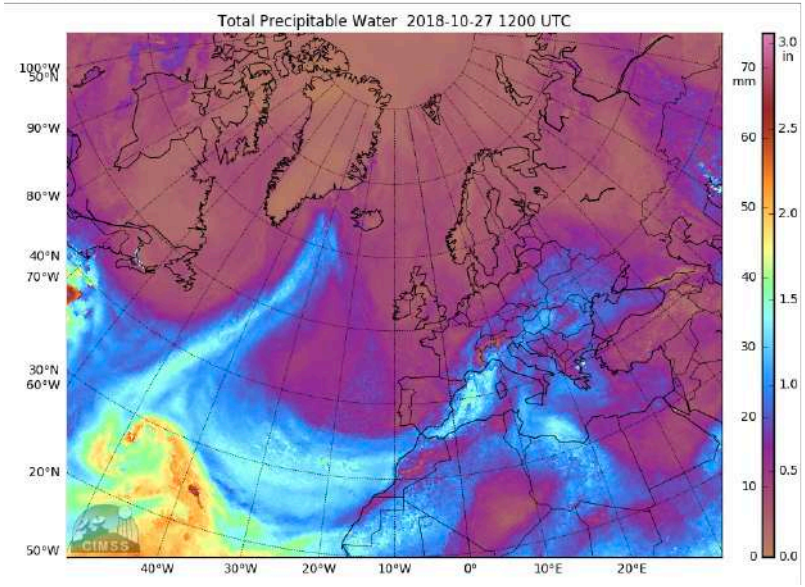
Ratio Length/Width greater than 2

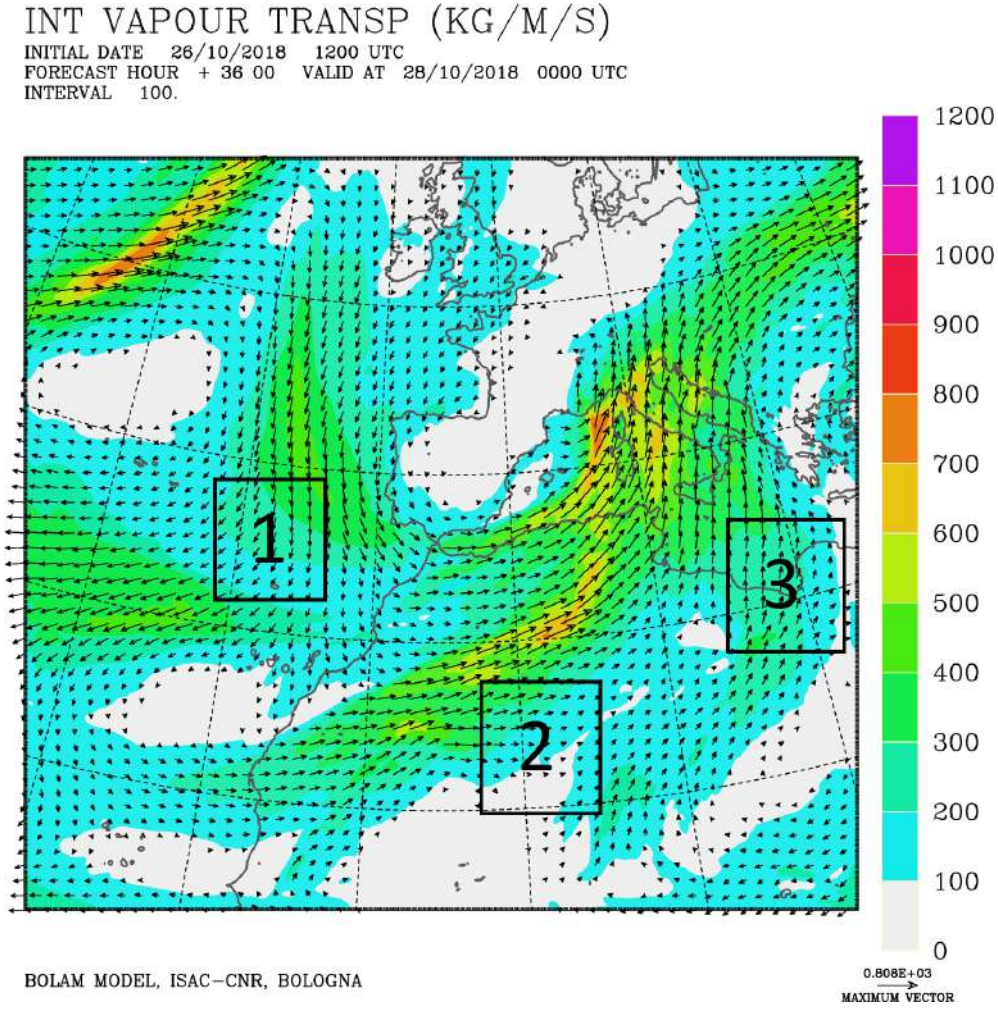


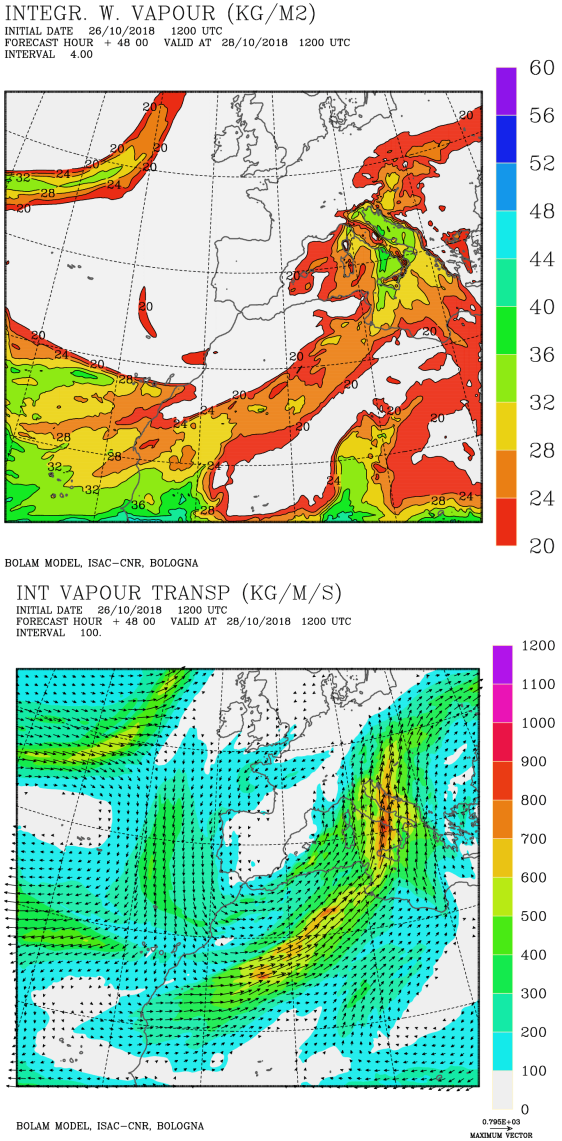
# Initial phase: 27 October, 12 UTC



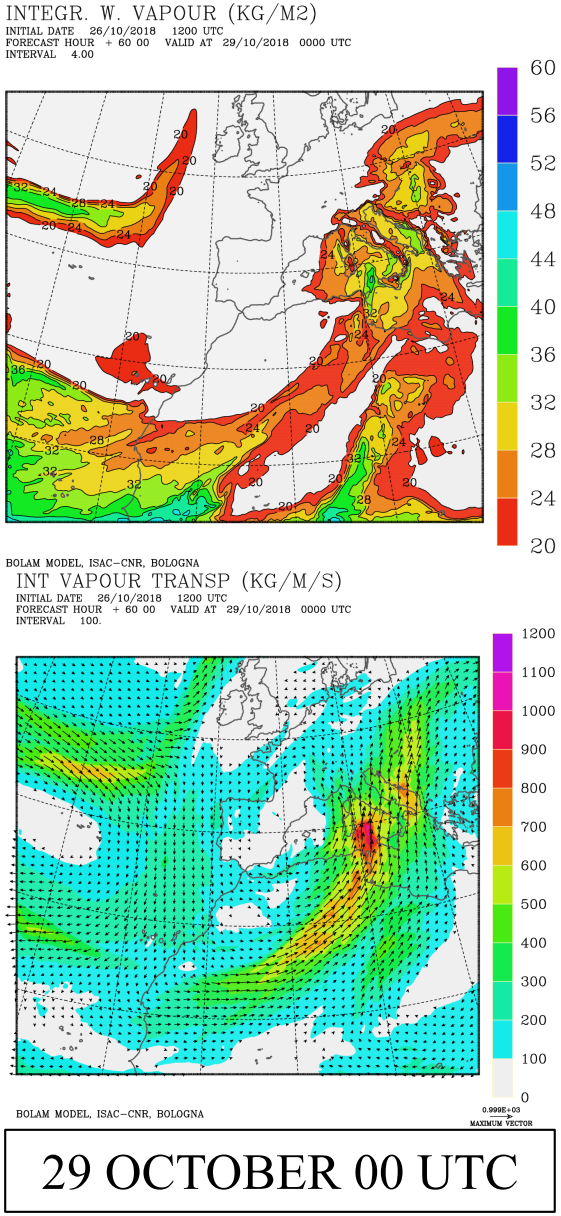



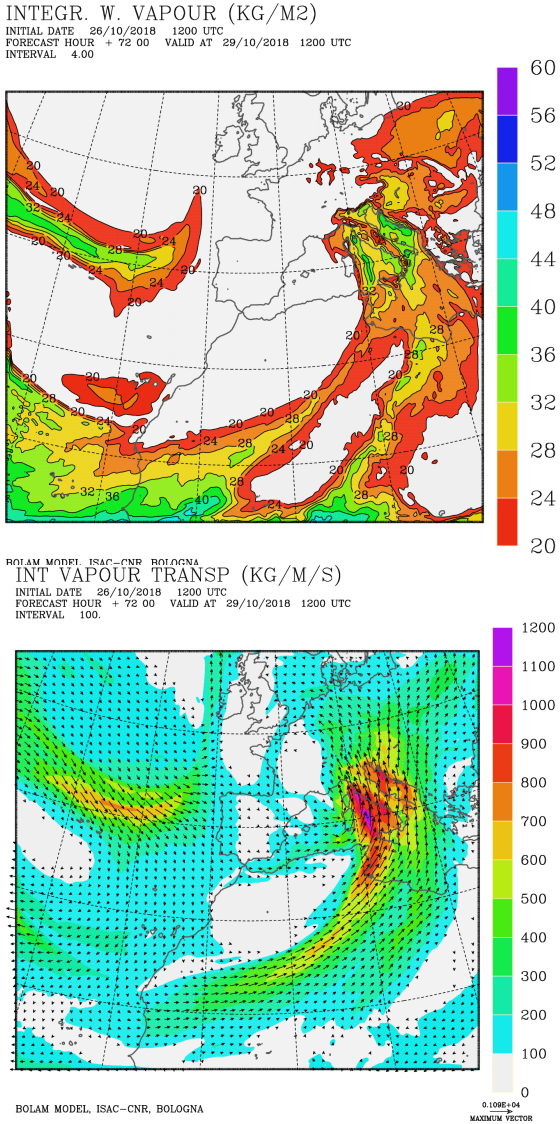
# ATMOSPHERIC RIVER EVOLUTION




28 OCTOBER 12 UTC




29 OCTOBER 00 UTC



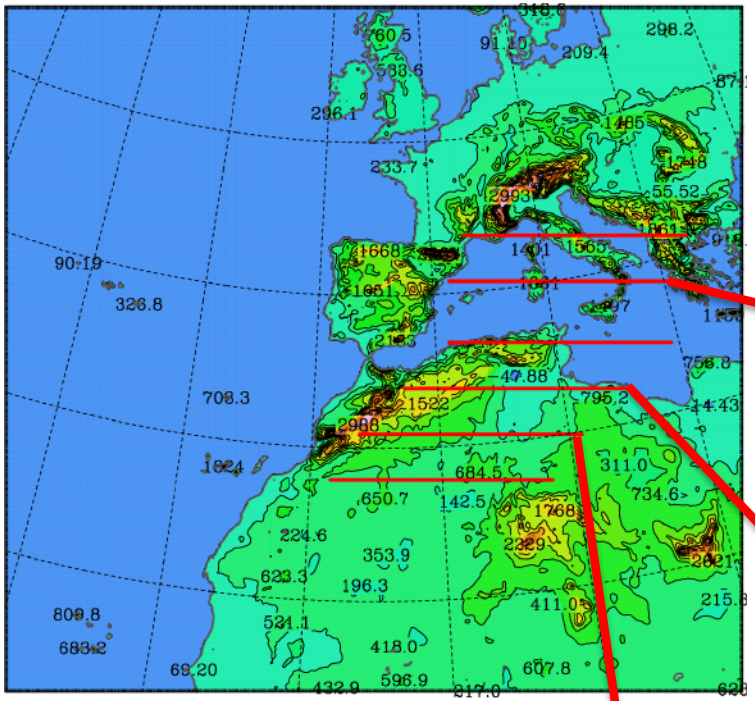

29 OCTOBER 12 UTC

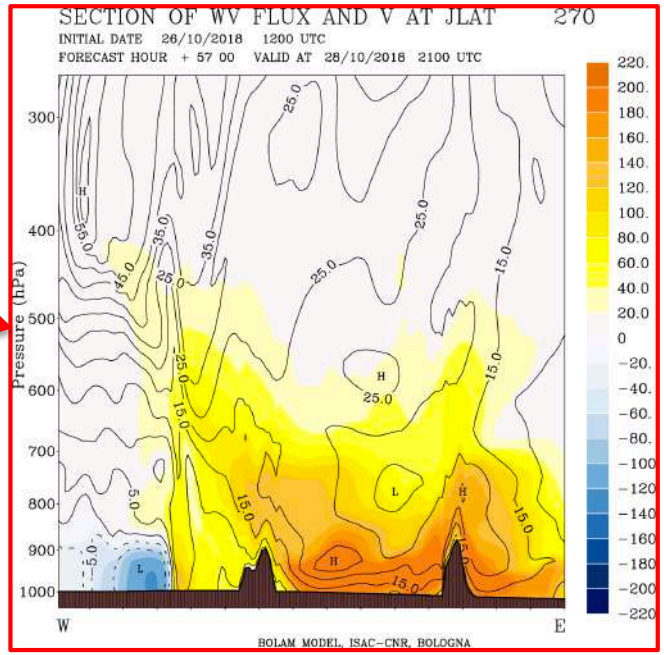
Integrated value across a vertical section 50-km wide: ~ $5 \times 10^7$ kg/s (flow)

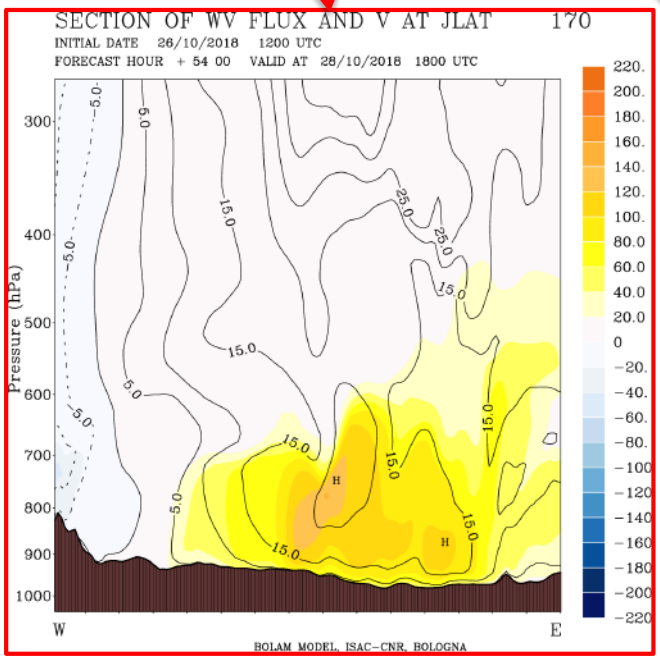
Typical flow of a Po river flood: ~ $1.3 \times 10^7$ kg/s

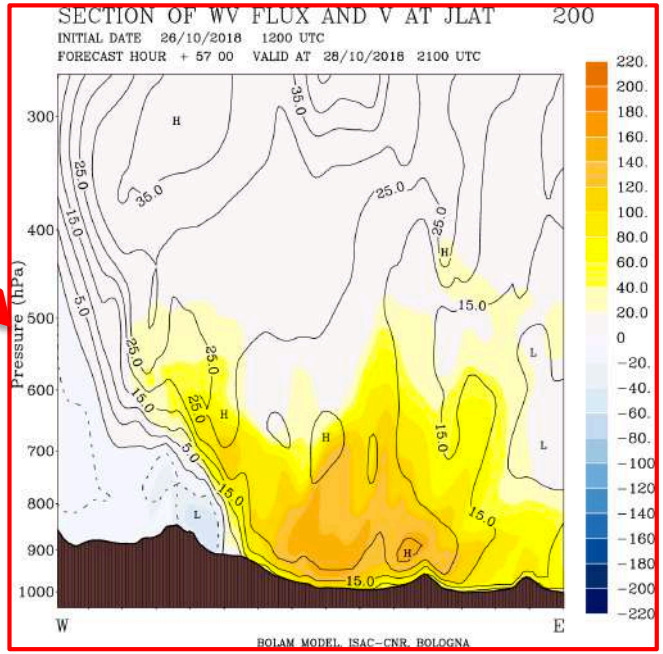
# AR CHARACTERISTICS: VERTICAL CROSS SECTIONS OF WV FLUX

Water Vapour Flux ($g\ m^{-2}s^{-1}$)

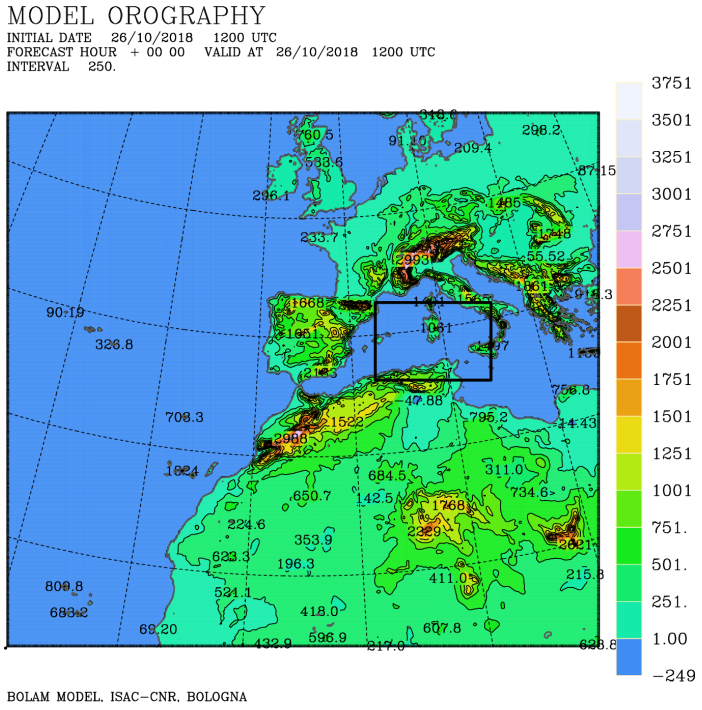


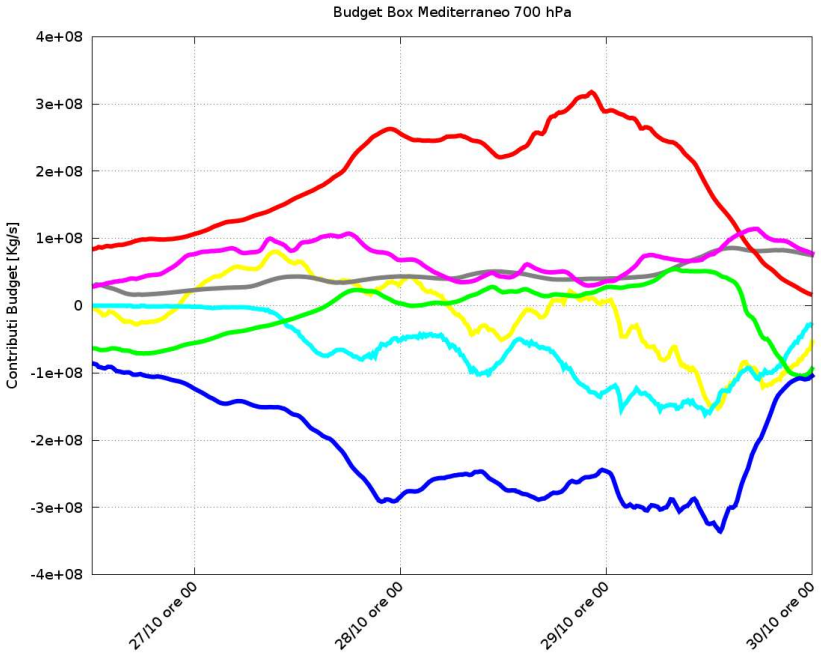


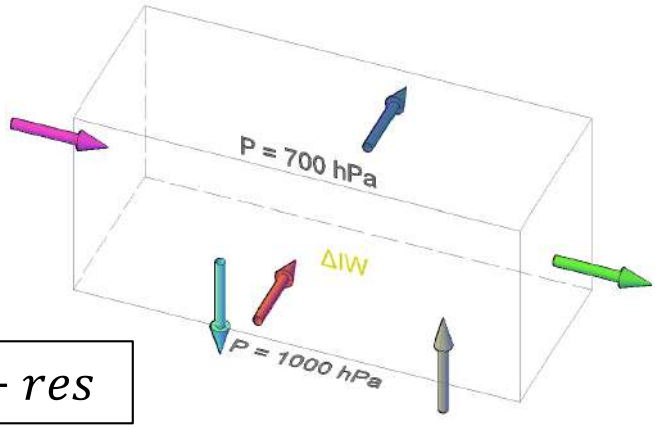



# ATMOSPHERIC WATER BALANCE



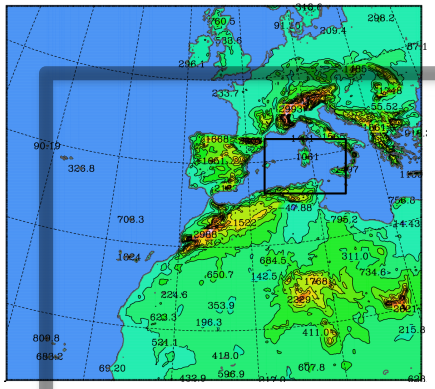

$$\Delta IW = E - P + F + res$$

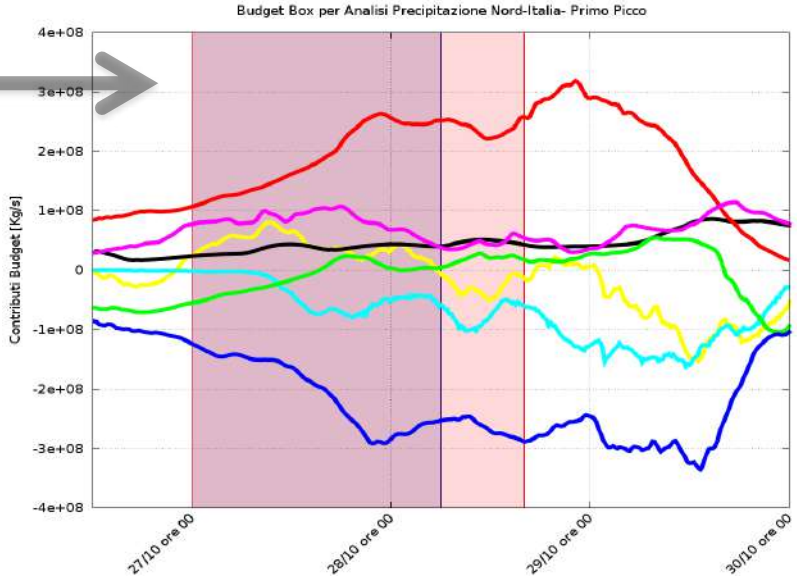
- $\Delta IW$: tendency of integrated water in the box
- $P$: precipitation
- $E$: evaporation from the sea
- $F$ fluxes across lateral sections
- $res$: residual term (negligible)

Accumulo IWV
Precipitazione
Evaporazione
Flusso Sud

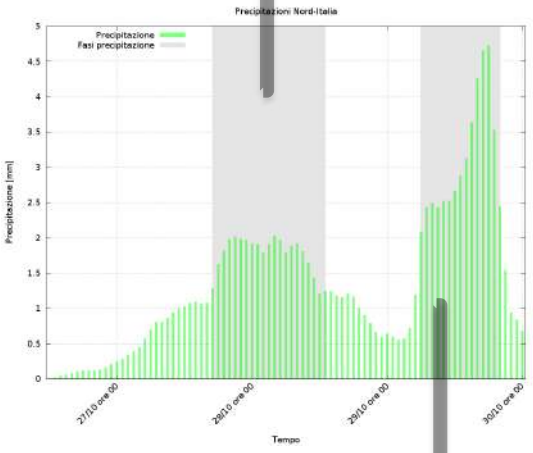
Flusso Est
Flusso Nord
Flusso Ovest

# PRECIPITATION OVER NORTHERN ITALY

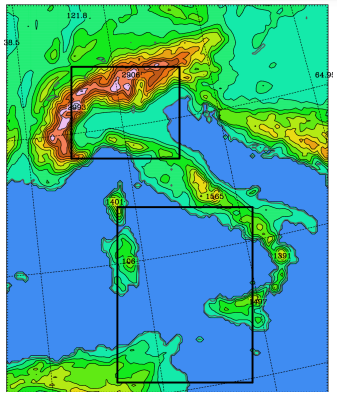


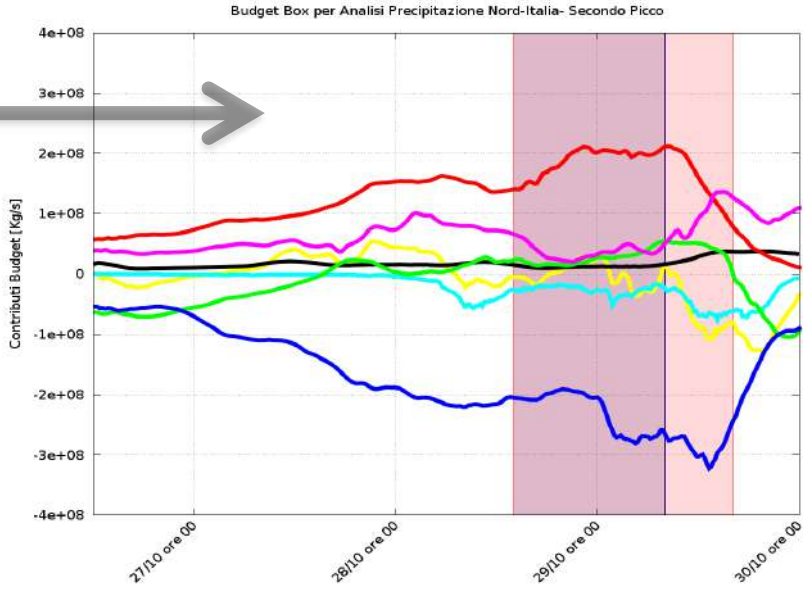



| Budget Term | Contribution |
|---|---|
| South | 55% |
| West | 24% |
| Evaporation | 21% |



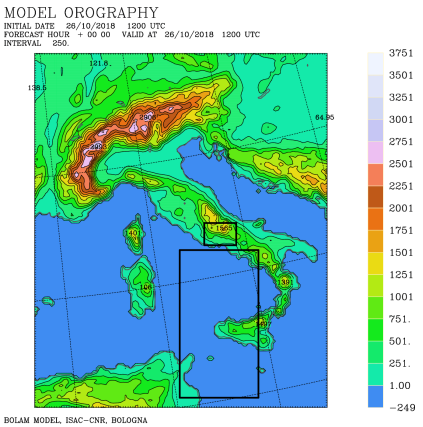

Accumulo IWV — Precipitazione — Evaporazione — Flusso Sud — Flusso Est — Flusso Nord — Flusso Ovest

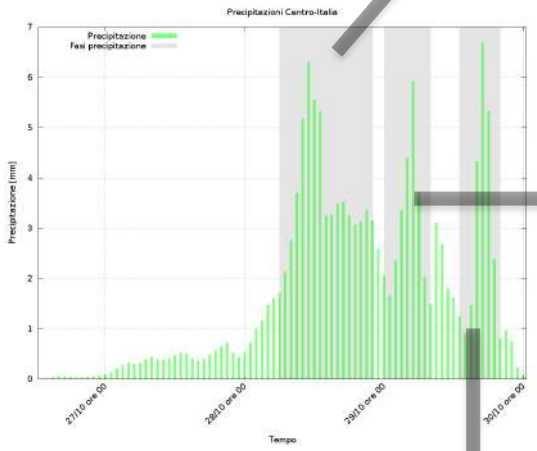


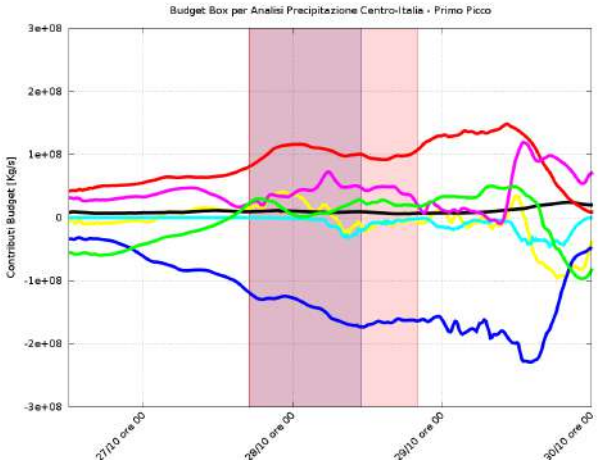



| Budget Term | Contribution |
|---|---|
| South | 66% |
| West | 13% |
| East | 9% |
| Evaporation | 12% |

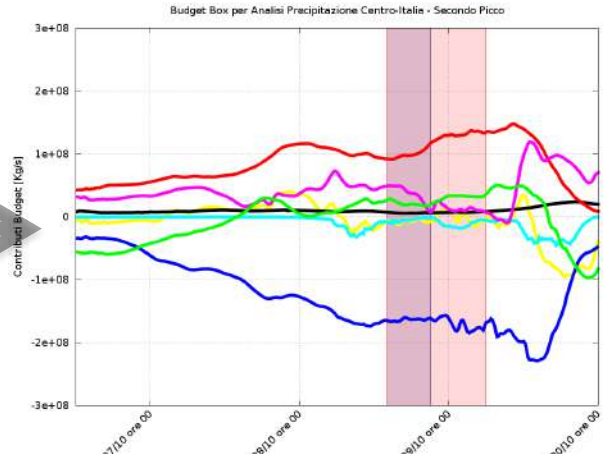
# PRECIPITATION OVER CENTRAL ITALY



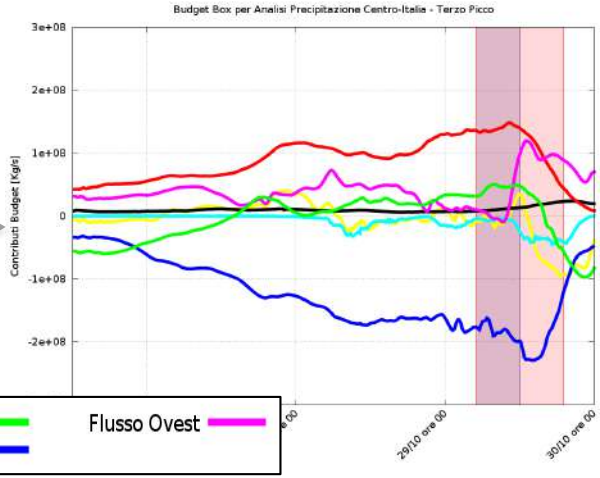




| Budget Term | Contribution |
|---|---|
| South | 57% |
| West | 24% |
| East | 8% |
| Evaporation | 11% |




| Budget Term | Contribution |
|---|---|
| South | 57% |
| West | 19% |
| East | 12% |
| Evaporation | 12% |

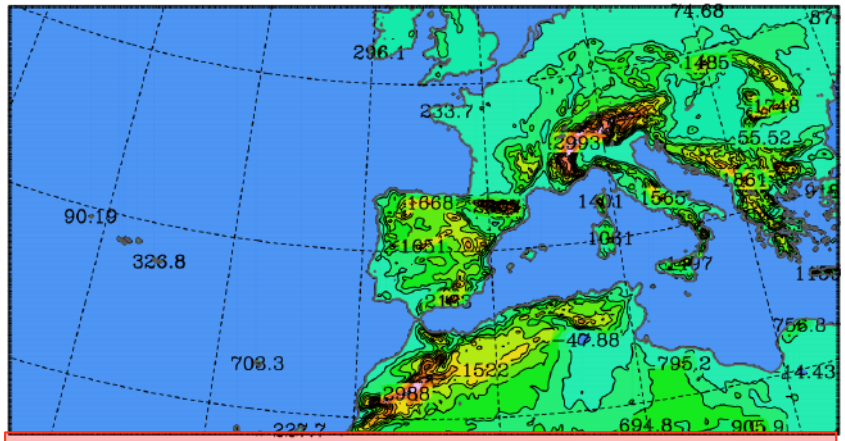



| Budget Term | Contribution |
|---|---|
| South | 47% |
| West | 19% |
| East | 15% |
| Evaporation | 19% |

Accumulo IWV
Precipitazione
Evaporazione
Flusso Sud
Flusso Est
Flusso Nord
Flusso Ovest

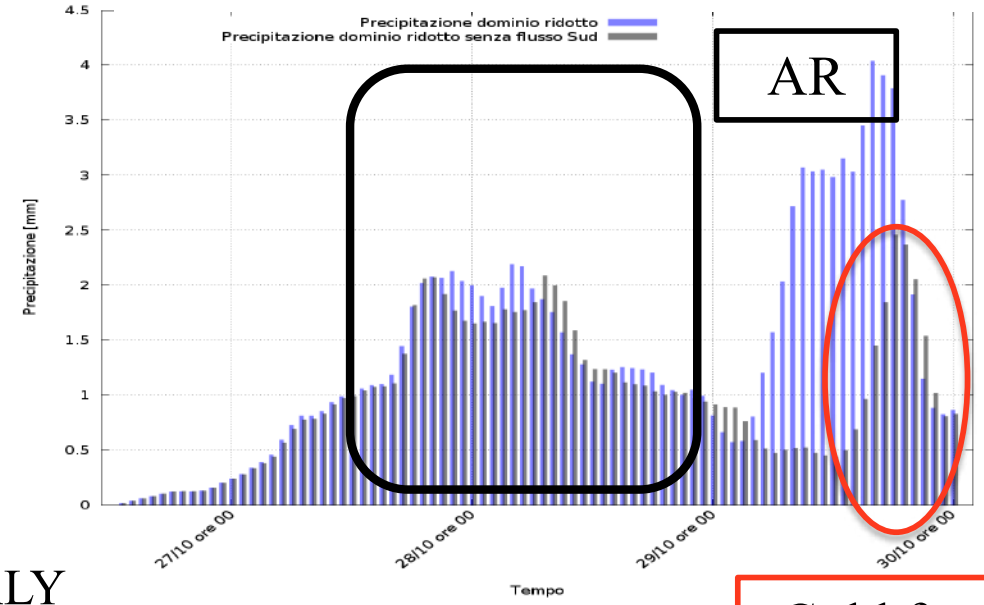
# SENSITIVITY NUMERICAL EXPERIMENTS

→ Role of moisture conveyed by the Atmospheric River



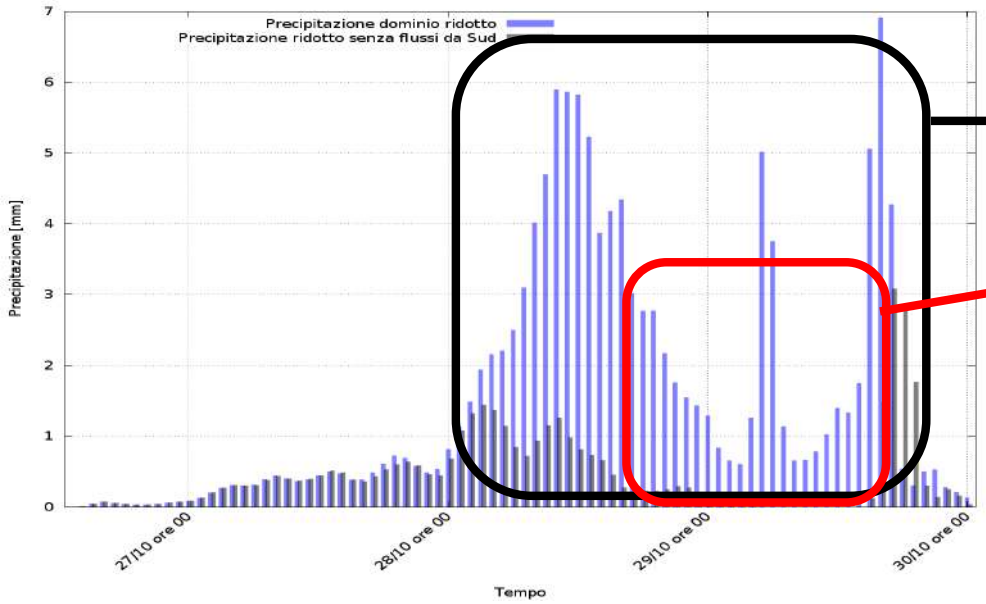

Reduction (75% less) of moisture entering from the S boundary

PRECIPITATION over N-ITALY




Cold front
Convection

PRECIPITATION over CENTRAL ITALY

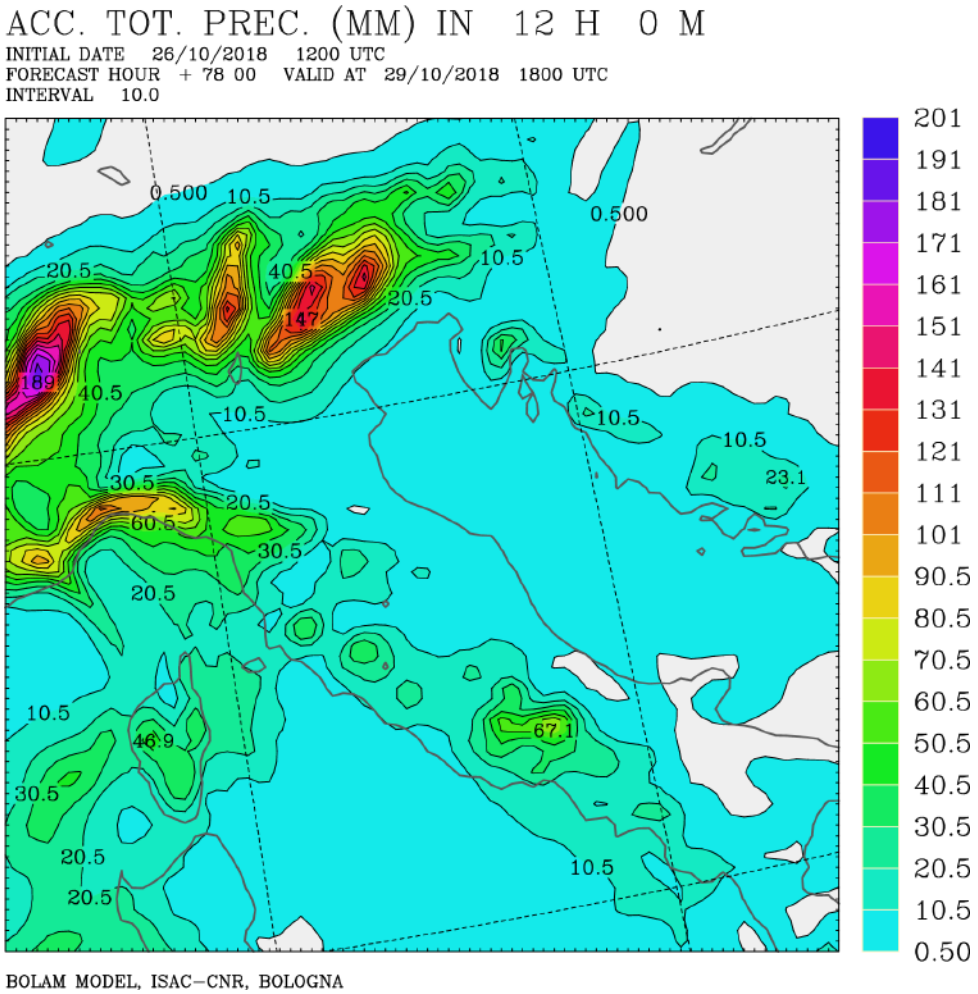



AR

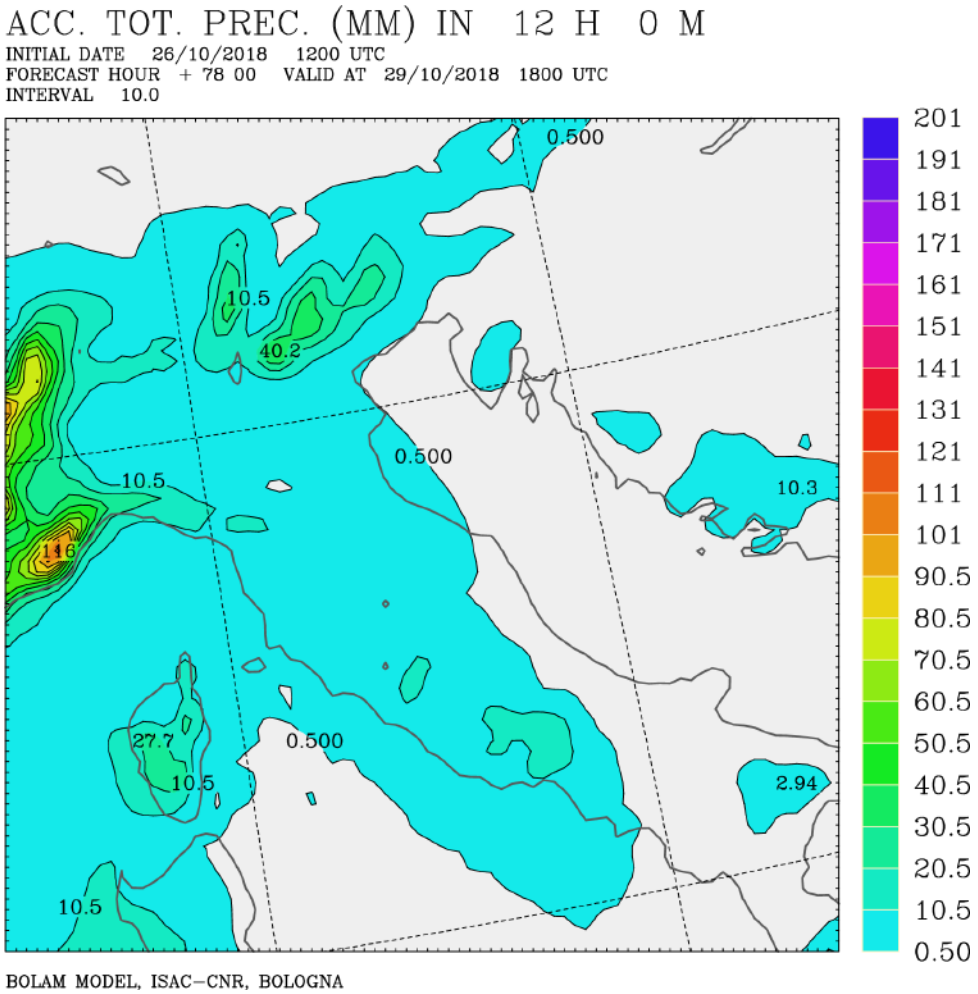
no rain!

# MOST INTENSE RAINFALL PHASE ON 29 OCTOBER

## CONTROL SIMULATION

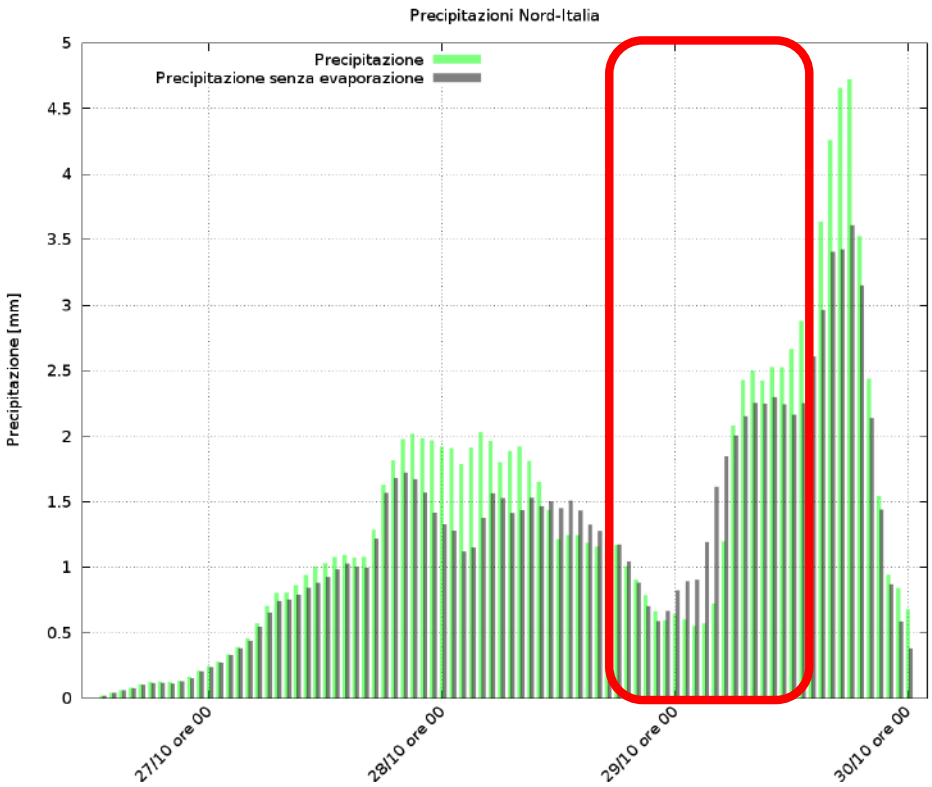



## SENSITIVITY EXPERIMENT
## *NO ATMOSPHERIC RIVER*

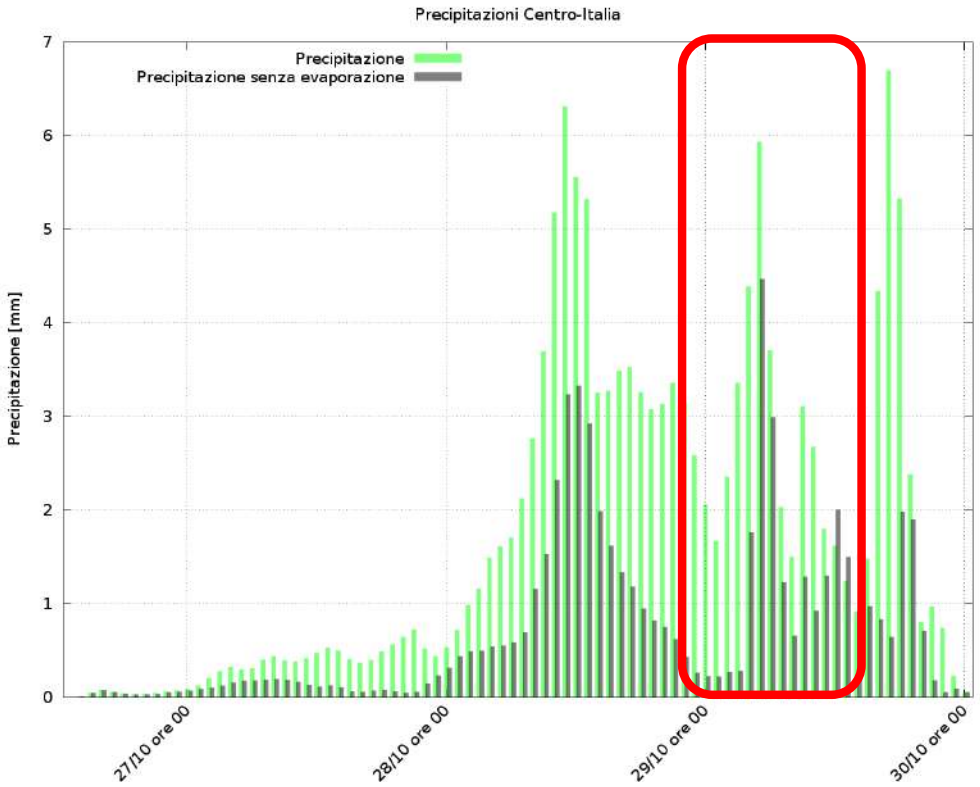


# SENSITIVITY NUMERICAL EXPERIMENTS

→ Role of evaporation from the sea




RAINFALL OVER N-ITALY




RAINFALL OVER CENTRAL ITALY

- Evaporation impact becomes smaller when the AR effects are stronger
- Non-linear and indirect impact of evaporation on rainfall, due to modified regime of flow interaction with orography

# CONCLUSIONS

- This analysis identifies rainfall characteristics and shows that **predictability** was quite high, being the event associated with a **strong large scale forcing**. MOLOCH and WRF captured reasonably well the extreme event in several aspects: **rain, wind, cyclone.**

- These studies show the mechanisms at different scales responsible for heavy precipitation, from pre-alpine rain band to remote moisture transport.

- An Atmospheric river has been «formally» identified over the Mediterranean, transporting moisture for more than 3000 km across Africa from the sub-tropical Atlantic Ocean.

- Moisture transport seems more important than local evaporation, being the first phase of precipitation over the Alps associated with transport from the Atlantic, the second phase with the Atmospheric river. Over central Italy, the Atmospheric river is the main mechanism feeding the precipitation.

- Given the wide and high impact, this kind of **severe weather** studies require a **multi-disciplinary collaborations**: Meteorology, Climate/Climatology, Oceanography, Forestry, Geology, Hydrology