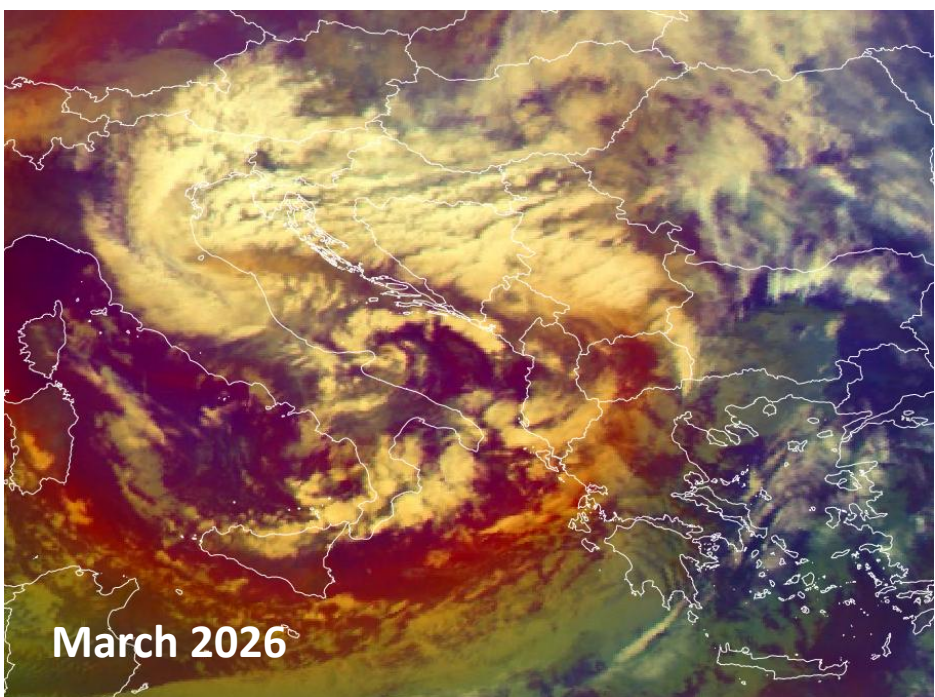
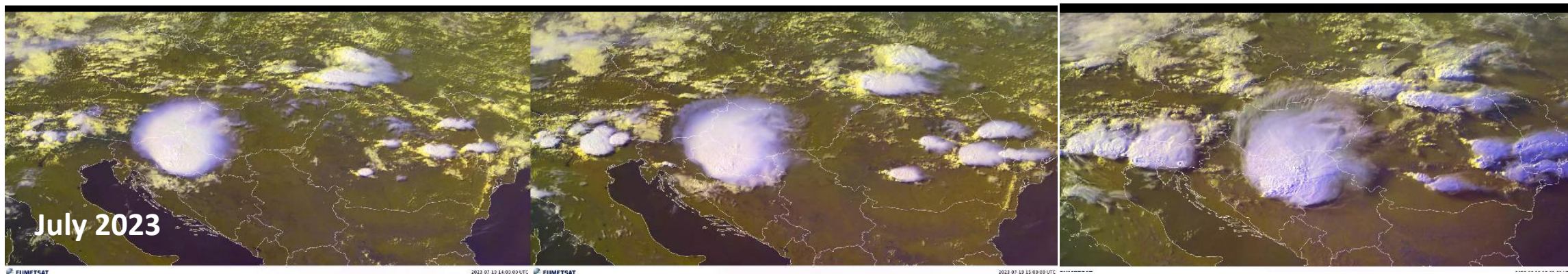




Multi-Scale Forecasting of Severe Wind Events

Insights from two contrasting cases in Zagreb

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Croatian Meteorological and Hydrological Service

Wed 9 Sep 2026, 16:45 CEST | Room Mission 2

Similar impacts, different predictability regimes

Substantial damage in Zagreb with wind as the main driver and rainfall as amplifier.



MARCH 2026

- Widespread and persistent
- Synoptic forcing + terrain
- Wind with heavy rainfall



JULY 2023

- Fast-moving MCS
- Abrupt local passage
- Extreme local gusts

Both were rare and damaging; their mechanisms and forecast horizons were fundamentally different.

We compare information horizons - not model rankings

Available tools do not form a simple chain-type of information but are available in parallel
What to expect regarding a high impact event?

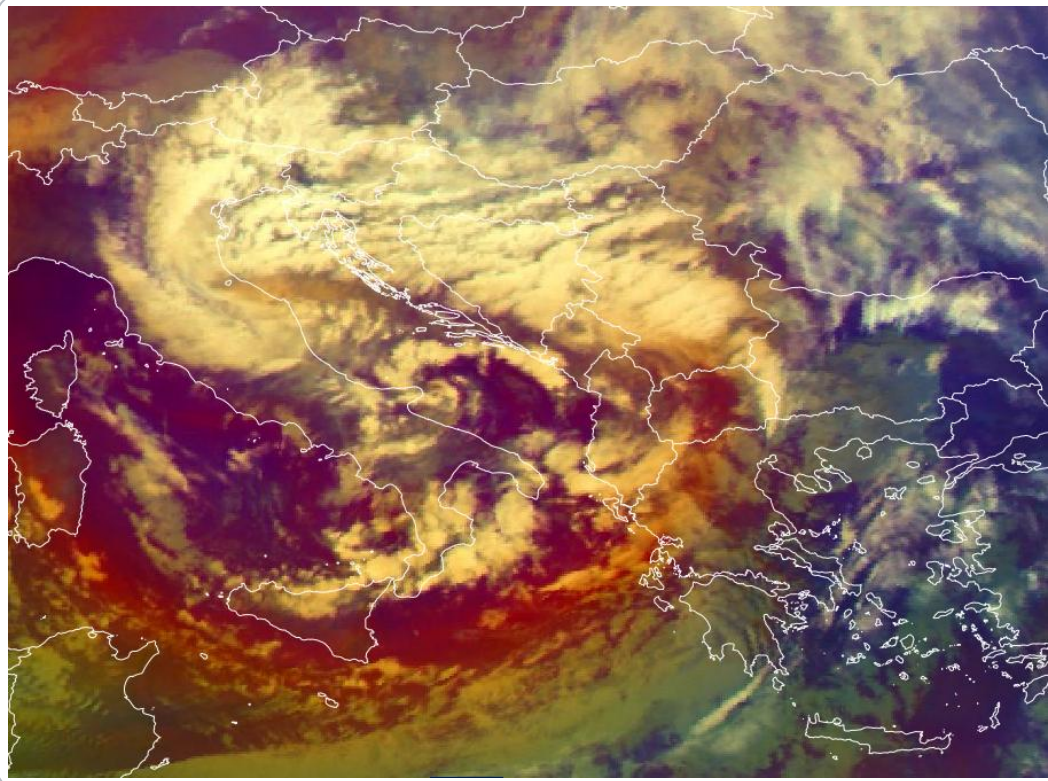


Information horizon = earliest stable, spatially relevant and actionable signal

Forecast components and configurations

Component	Primary role	Configuration used in this study
IFS	Global NWP	~9 km, hydrostatic, hourly, to + 10 days, 2 runs daily
ALADIN-HR40	Regional NWP	4 km, hydrostatic, hourly to +72 h, 4 runs daily, ALARO
ALADIN-HR20	Regional NWP	2 km, non-hydrostatic, forecasts to +72 h, 4 runs daily, ALARO
LSTM / HRAN	Deterministic post-process.	NWP ML / analogue post-processing, same as NWP
Chance of Rain	Precipitation probability	Neural network using NWP and temporal predictors
INCA	Analysis and nowcasting	1 km, radar + station; 15-min up to few hours, hourly update

March 2026: synoptic forcing met local acceleration



Cyclone Deborah:

- Developed after a cold front slowed north of the Alps and secondary cyclogenesis occurred in the Alpine lee
- Deepened over Adriatic while high pressure remained over central Europe
- Produced persistent northerly to north-easterly flow
- The satellite image shows mature synoptic system

Adriatic cyclone
pressure gradient

NNE low-level jet
momentum transfer

Medvednica lee side
local acceleration

March 2026: synoptic forcing met local acceleration

The structure relevant for Zagreb:

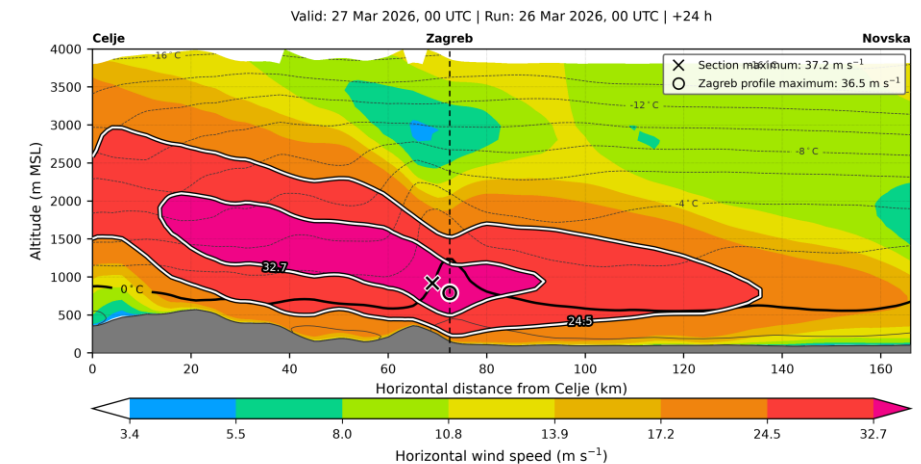
- Deep cyclone
- A low-level jet developed between the north-eastern Alps and the northern Adriatic, the core descended toward Zagreb
- Acceleration on the southern side of Medvednica hill amplified the flow further.

Multi-scale chain:

- + synoptic pressure-gradient flow,
- + concentration of momentum in the low-level jet,
- + local acceleration over and south of Medvednica



ALADIN HR40 vertical cross-section: Celje-Zagreb-Novska



Adriatic cyclone
pressure gradient

NNE low-level jet
momentum transfer

Medvednica lee side
local acceleration

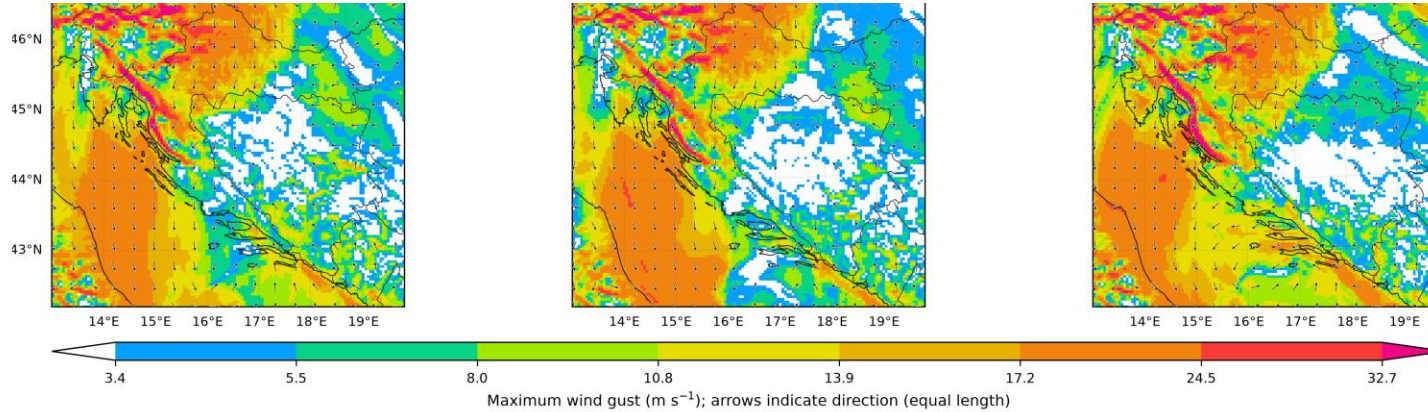
ALADIN-HR signals the March 2026 hazard 72 h ahead

Wind gusts

+ 72h

+48 h

+24 h

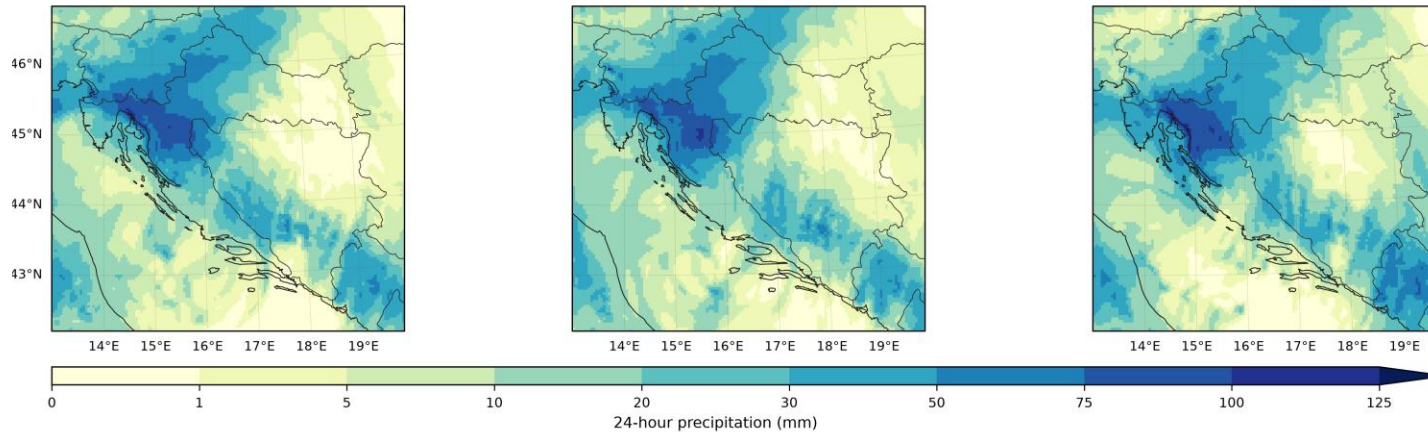


Precipitation

(d) Run: 24 Mar 2026, 00 UTC (+72 h)

(e) Run: 25 Mar 2026, 00 UTC (+48 h)

(f) Run: 26 Mar 2026, 00 UTC (+24 h)



WHAT WAS STABLE

- Hazard corridor: from Slovenia into NW Croatia
- Prolonged event with wide spatial extent
- Present in several consecutive runs

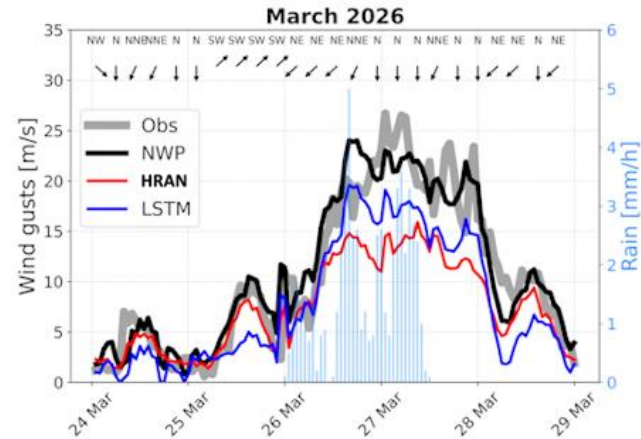
WHAT REMAINED UNCERTAIN

- Peak timing
- Local magnitude
- Weakening rate

**Forecast consistency
created useful lead time
(rather than perfection)**

Downstream tools can only refine an existing signal (up to certain degree...)

DETERMINISTIC PP FORECASTS



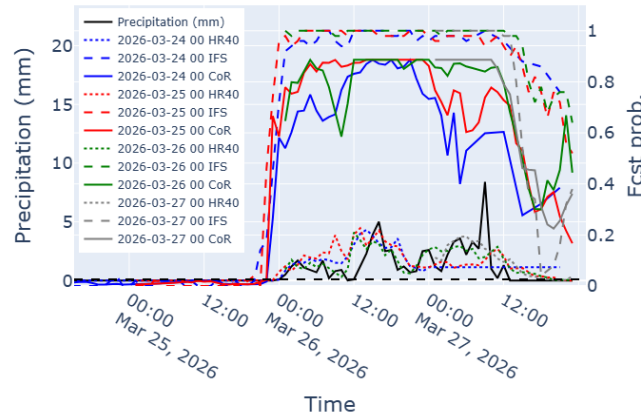
NWP signal for prolonged strong wind episode was already present.

ML/PP followed but compressed it

CoR remains high throughout the episode

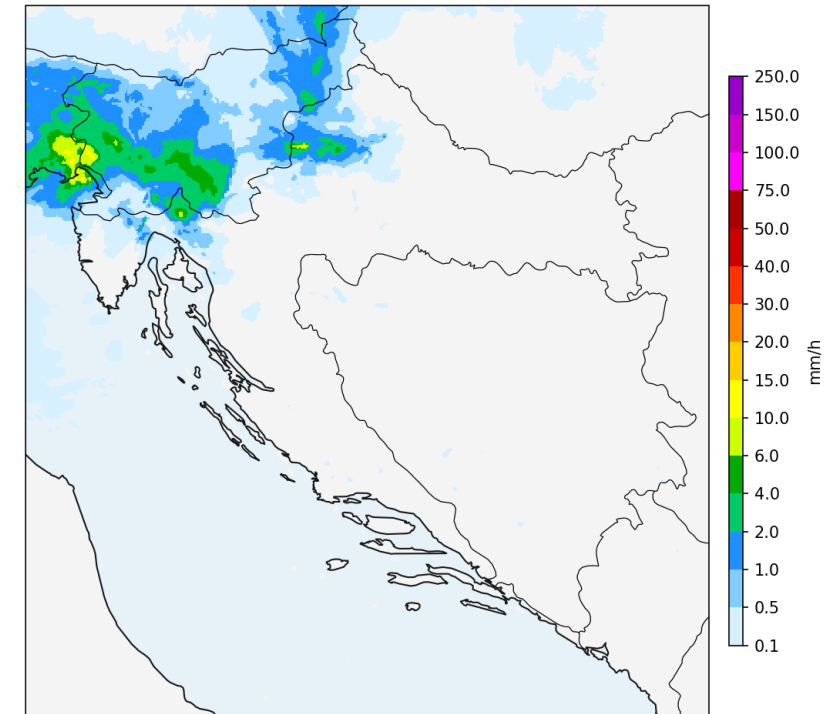
INCA refined the precipitation field, supporting monitoring and local timing

PROBABILISTIC PP FORECASTS



ANIMATED INCA PRECIPITATION ANALYSIS

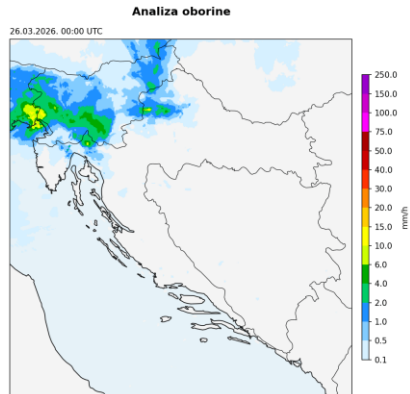
26.03.2026. 00:00 UTC



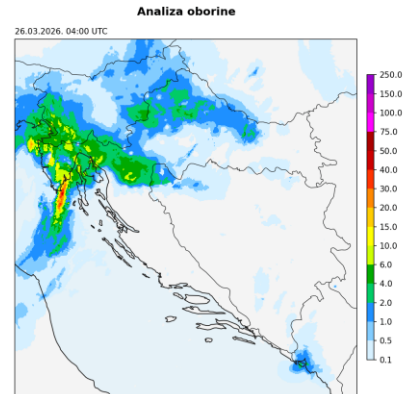
Backup: static INCA frames for March 2026

BACKUP

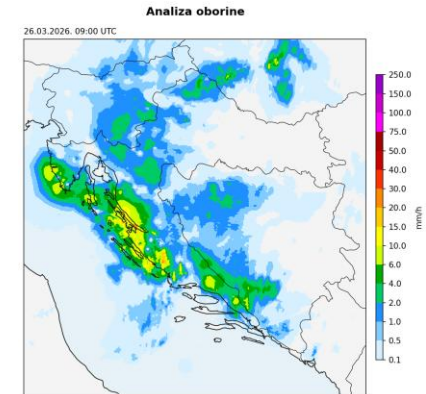
Frame 1



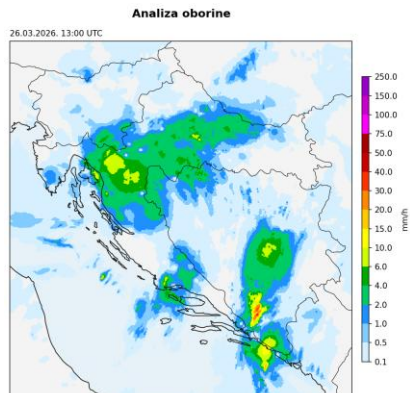
Frame 2



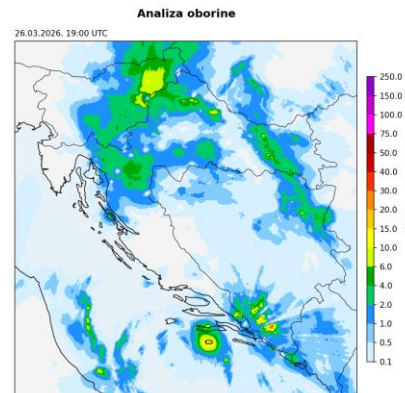
Frame 3



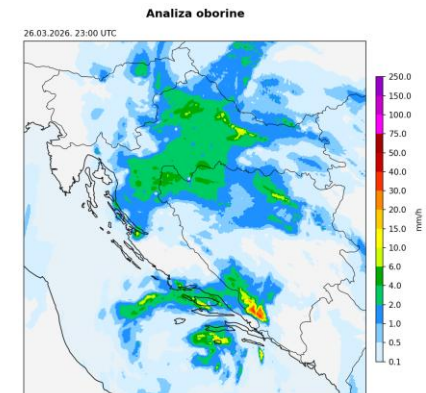
Frame 4



Frame 5

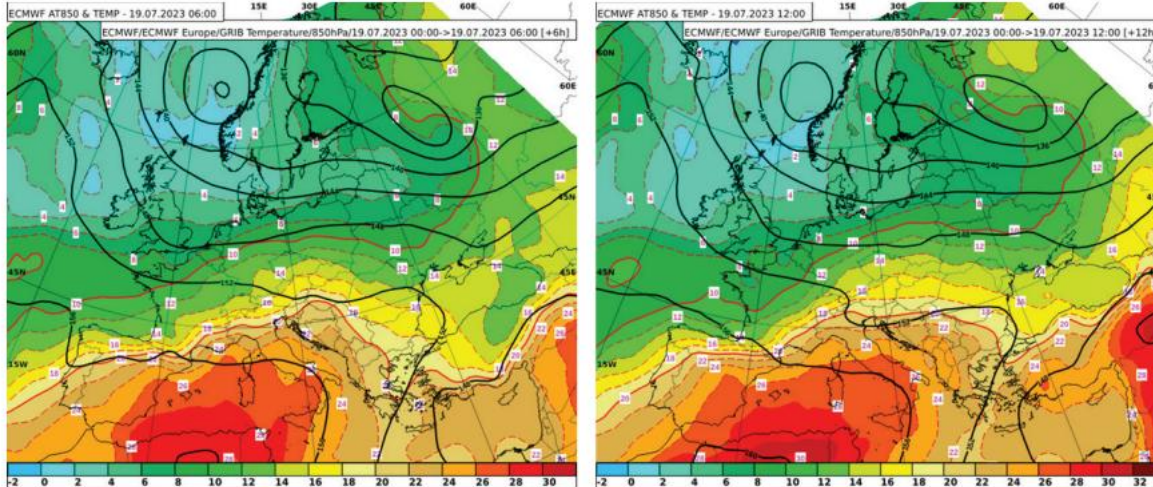


Frame 6



July 2023: predictable environment, uncertain realization

IFS 850 hPa FORECASTS: Temp & abs. topography (08 and 14 local time)



In Zagreb - hot and humid weather ($> 33^{\circ}\text{C}$)
12 UTC sounding confirms favorable local conditions

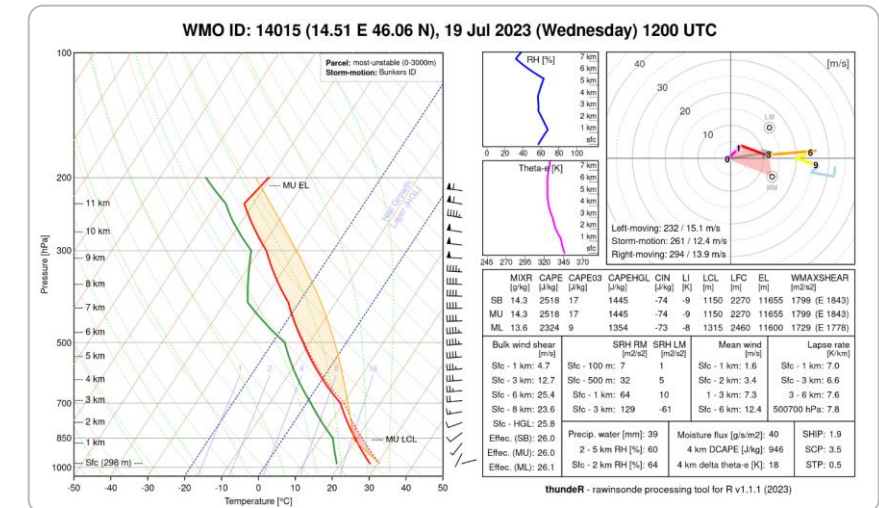
MUCAPE
2272 J kg^{-1}

0-6 km shear
26.7 m s^{-1}

DCAPE
885 J kg^{-1}

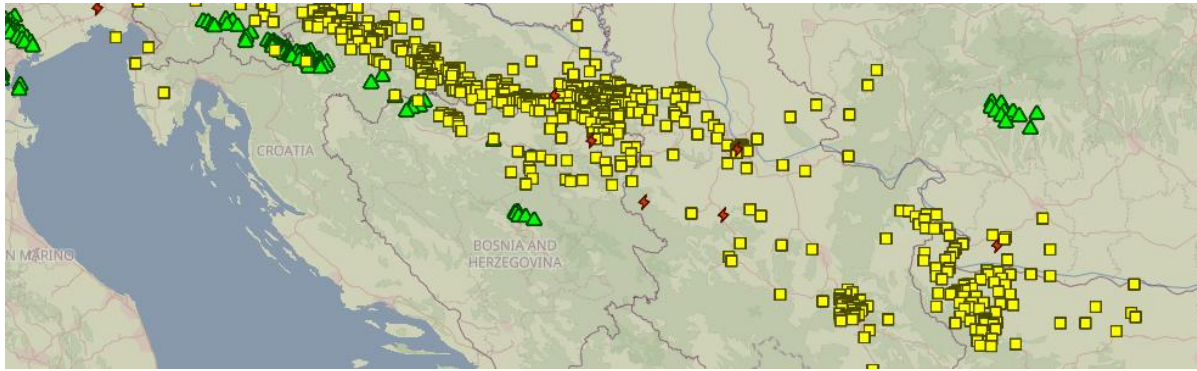
Inverted-V in lower troposphere supported evaporatively enhanced downdrafts

- Croatia is in between 2 air masses:
Very warm air associated with a southern ridge, and cooler air connected with a trough to the north
- All the ingredients for deep convection over northern Italy: moisture, instability and lift
- Ingredients were there but lacking organized structures and precipitation realization
- SW and W flow in the upper levels moved convective clouds over Slovenia towards Croatia, while the system was strengthening and forming a MCS
- MSC forming supercells due to favorable local conditions in Zagreb

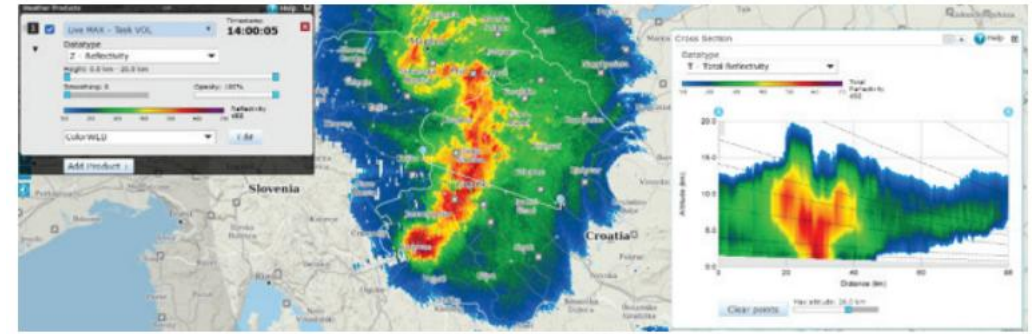


July 2023: predictable environment, uncertain realization

What did happen? System travels 650 km, entering Croatia in a 110 km long line

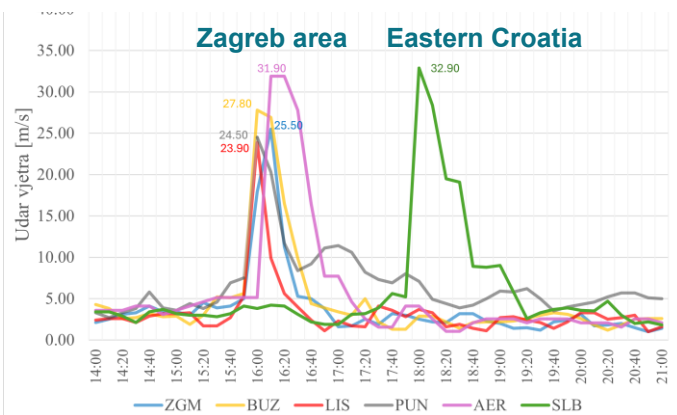


Track of the MCS on 19 July 2023, reconstructed from reports of damaging severe winds (yellow squares), hail (green triangles), and lightning (red lightning symbols) submitted to the European Severe Weather Database (ESSL ESWD).



Characteristic vertical radar-reflectivity cross-section
Local minimum at lower levels + area of substantially higher reflectivity above:
Bounded Weak Echo Region (BWER)

Wind gust observations at several stations

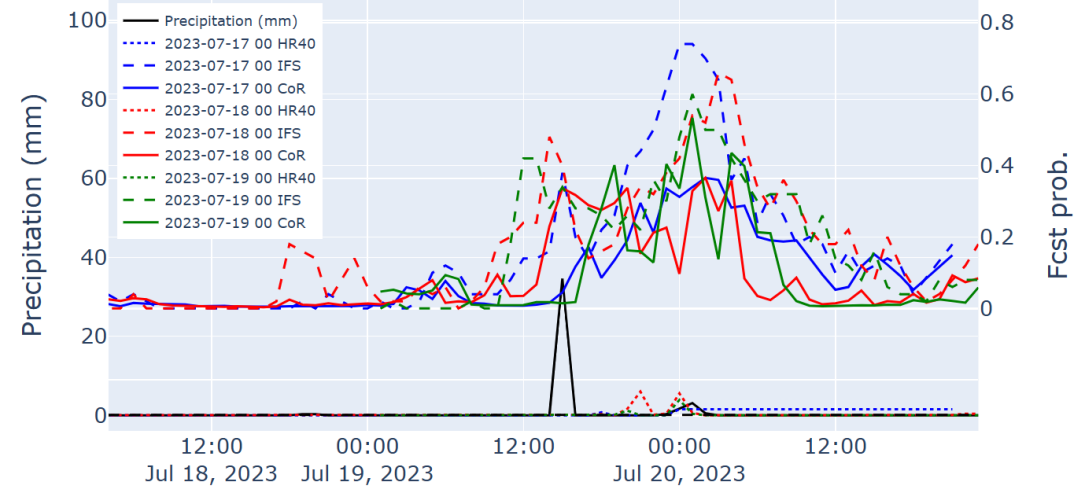
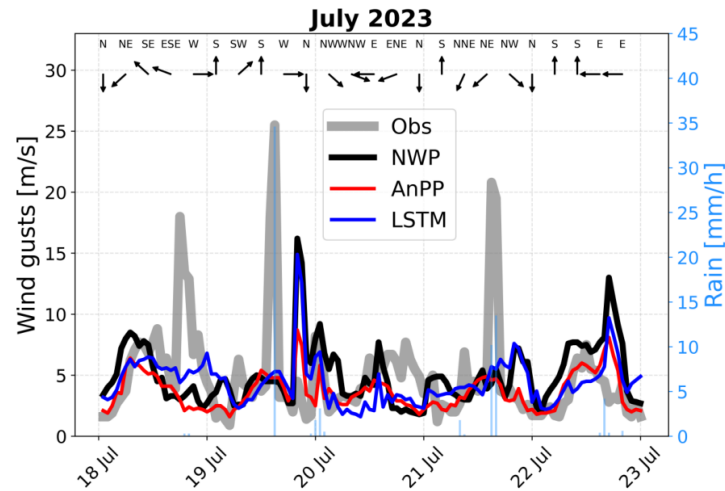


Zagreb – Maksimir station:

- the gust reached about 25.5 m/s,
- temperature fell almost 13 degs in about ten minutes,
- more than 15 mm of rain fell in five minutes

Ingredients were predictable. The realized track, timing and local gust maximum were not.

Post-processing inherited the missing convective signal



CASE-SPECIFIC RESULT

NWP - Local peak weak or displaced

LSTM followed but weakened NWP structure

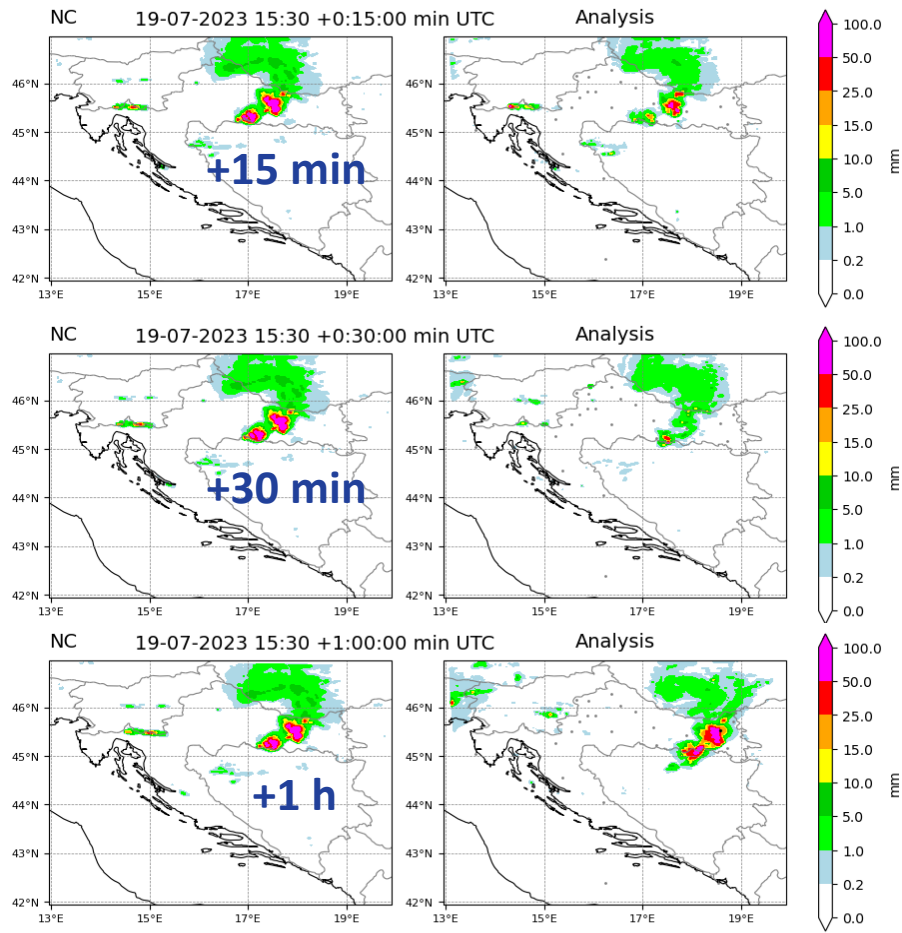
Analogue further smoothed the peak

CoR weak, inconsistent or late

Post-processing cannot reliably reconstruct storm organization absent from its predictors.

Radar and INCA became decisive after storm organization

NOWCAST FROM 15:30 UTC VERIFYING ANALYSIS

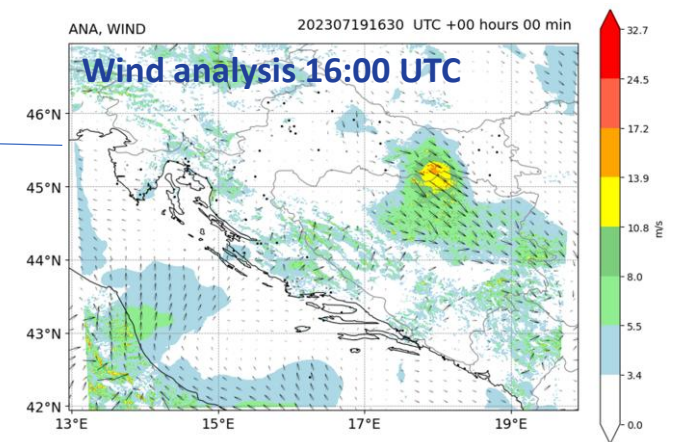
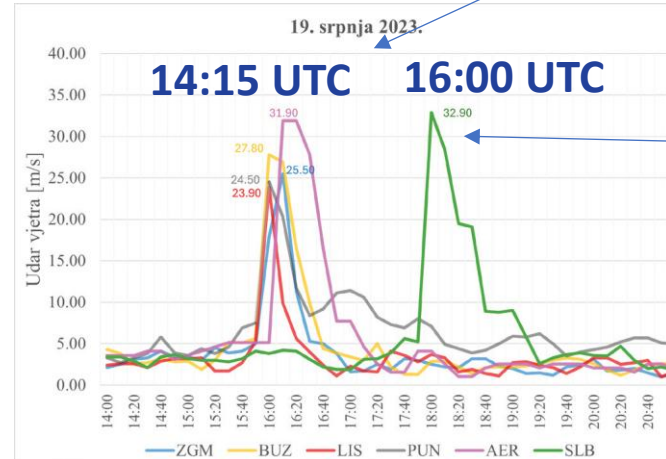
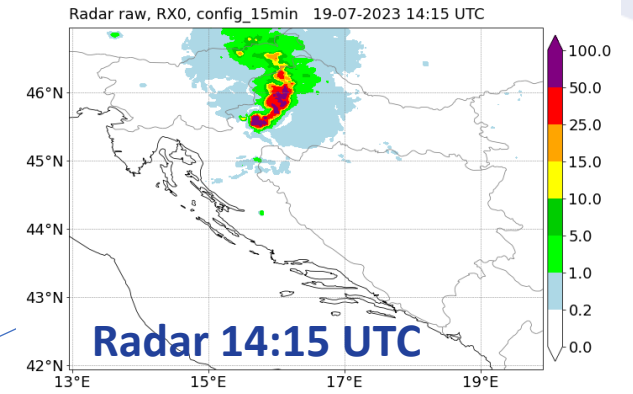


Optical-flow method captured the propagation direction

Eastward motion too slow

Errors grew with LT since no explicit growth and decay

Obs extrapolation does not solve convection, but helps monitor organized system



Useful information entered the chain at different lead times



The optimal forecast weight for each component changed with lead time and governing process.

Seamless forecasting is process-aware weighting - not equal blending.

Multi-scale means conditional weighting



1

March 2026: Coherent large-scale forcing

Consistent regional NWP leads to early anticipation.

2

July 2023: Ingredients without resolved organization

Keep risk conditional, increase monitoring and reweight rapidly toward radar and INCA.

3

ML post-processing

(Somewhat) preserves raw signals for extremes, but main use for calibration and local correction;

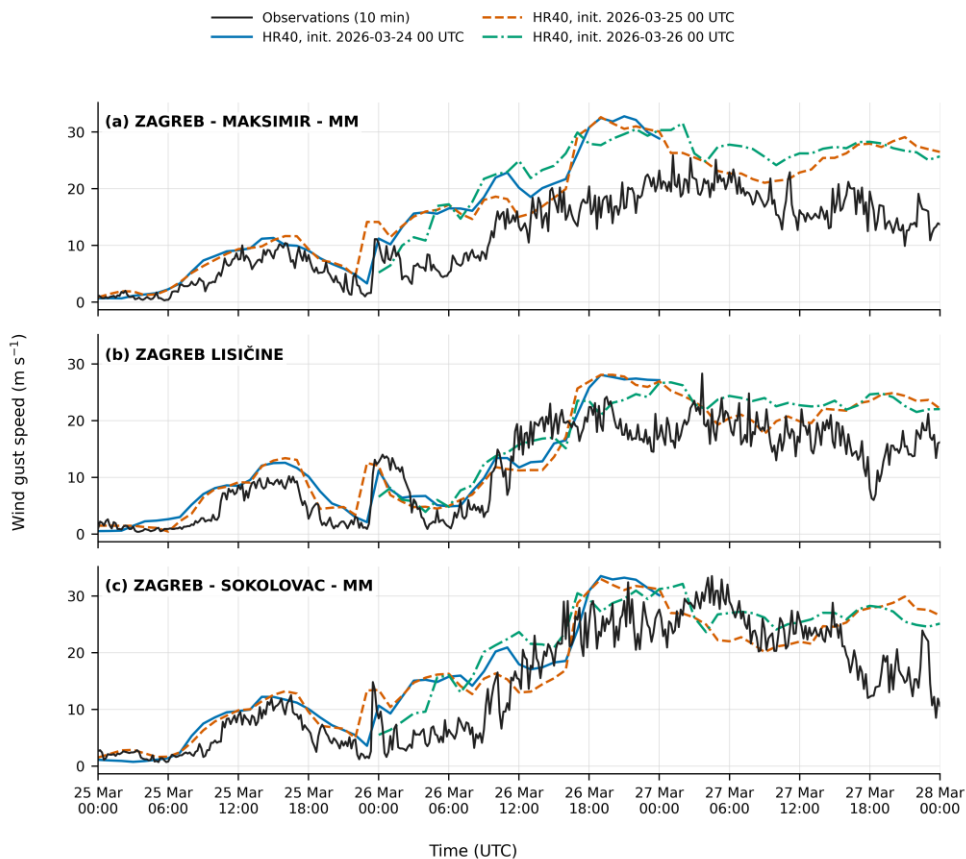
Thank you!

Seamless forecasting is process-aware weighting - not equal blending.

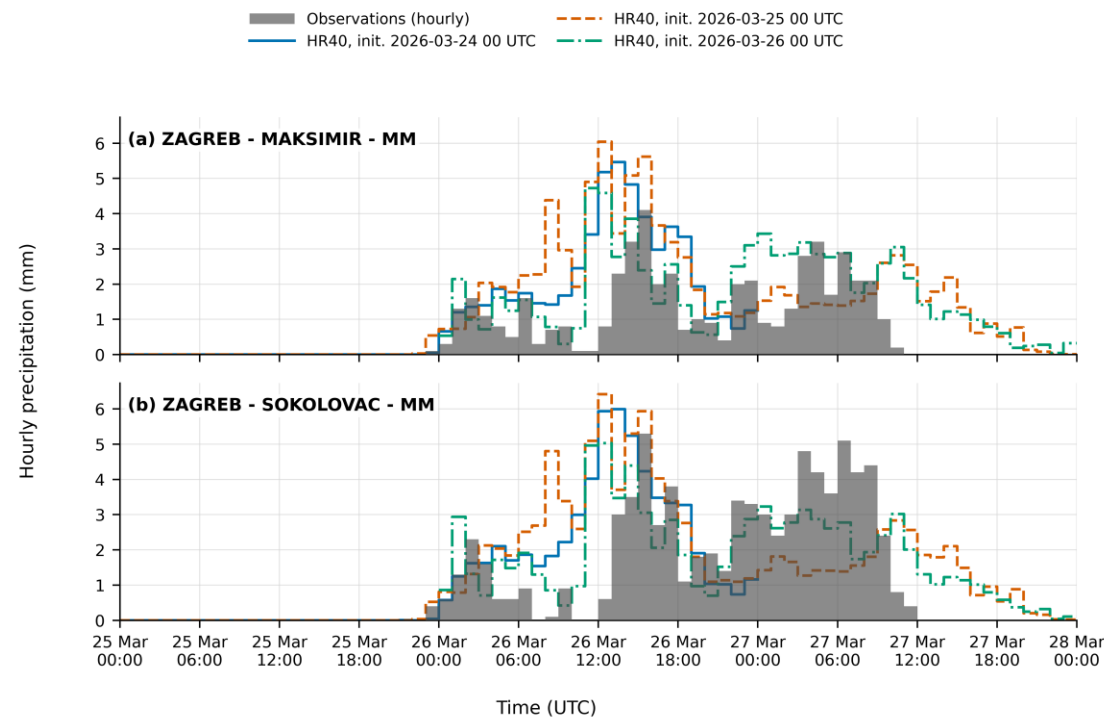
- ALADIN-HR40
 - 4 km horizontal grid spacing, hydrostatic.
 - About 480 x 432 horizontal grid points and 73 vertical levels in the supplied methodological material.
 - Forecasts to +72 h, four cycles per day.
- ALADIN-HR20- 2 km horizontal grid spacing, non-hydrostatic.
 - About 450 x 450 horizontal grid points and 87 vertical levels.
 - Forecasts to +72 h, four cycles per day.
- LSTM- Separate model for each variable; predicts the NWP error rather than the complete state.
 - Four hidden layers and forecasts to +72 h in the supplied poster.
 - Wind and gust training used 39 stations and about three years of data.
 - Median quantile loss, $q = 0.5$, helps explain attenuation of peaks.
- HRAN- Analogue post-processing
- Chance of Rain- Feed-forward neural network using ALADIN-HR20, HR40, IFS and temporal predictors.
 - Broader evaluation used 58 locations.
 - It improved reliability and Brier score relative to IFS, while IFS retained greater sharpness.
- INCA: Integrated Nowcasting through Comprehensive Analysis
 - Radar and surface observations provide the analyses.
 - The precipitation nowcast uses Farneback optical flow to estimate displacement from recent precipitation edges.
 - This version does not explicitly predict convective growth and decay.

Backup: March station forecasts

BACKUP



Wind gust



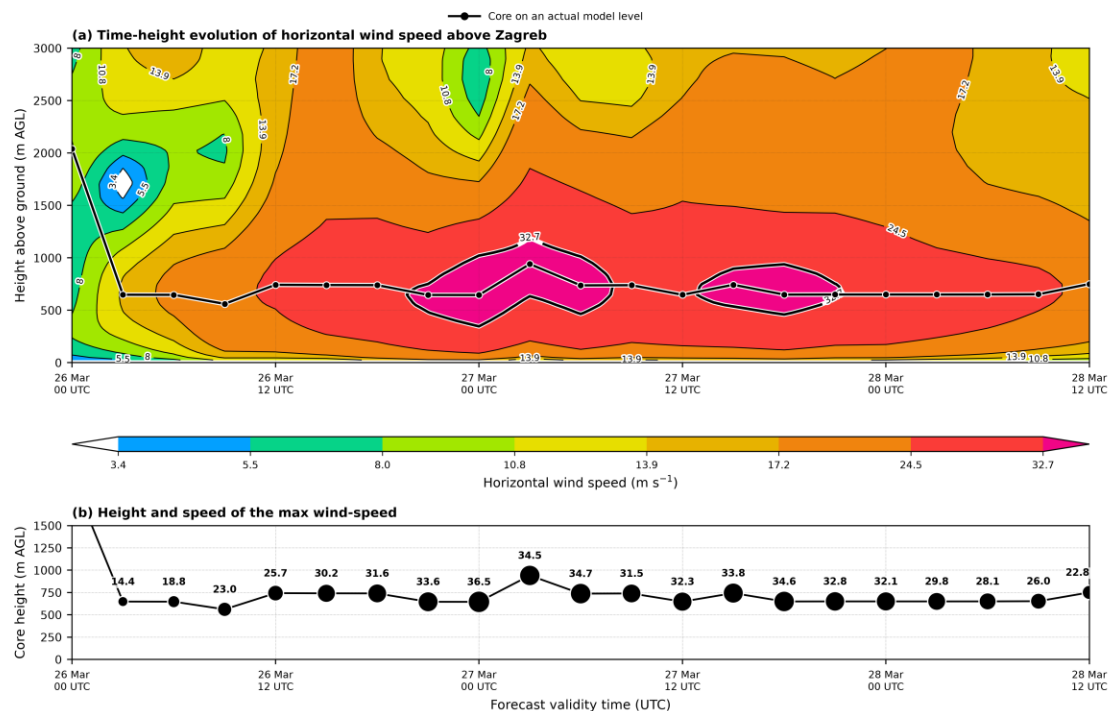
Hourly precipitation

Backup: evolution of the March low-level jet

BACKUP

ALADIN HR40: evolution of the low-level wind maximum above Zagreb

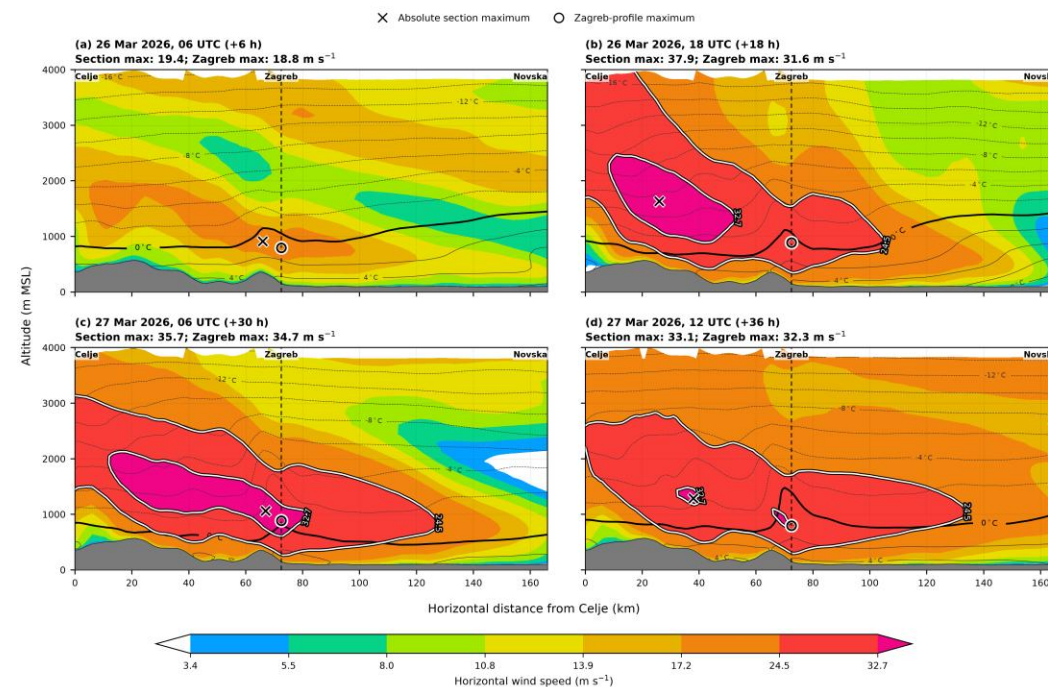
Model run: 26 Mar 2026, 00 UTC



Time-height evolution above Zagreb

ALADIN HR40 vertical cross-sections: Celje-Zagreb-Novska

Model run: 26 Mar 2026, 00 UTC



Celje - Zagreb - Novska sections