

Lagrangian analysis of near-continental dispersion

A 20-probe balloon swarm case study from Italy to Croatia

Maria Palomba ¹, Bo Yi Zhang ¹, Eleonora Zulli ¹, Shahbozbek Abdunabiev ¹, Virginia Poli ², and Daniela Tordella ¹

[1] DISAT, Politecnico di Torino, Italy

[2] ARPA Emilia-Romagna, Bologna, Italy

Project overview

The Atmospheric Boundary Layer (ABL) is a major source of uncertainty in weather and climate modeling. Centered on Lewis Fry Richardson's (1926) milestone work [1] on multi-point atmospheric diffusion, the HOUSEFLIES project – developed by the Philofluid Research Group at Politecnico di Torino (DISAT/DET) – introduces an innovative Lagrangian multi-point observation platform [2][3]. By deploying coordinated clusters of ultralight, partially biodegradable mini radiosondes, the system resolves transport, entrainment and diffusion across atmospheric scales. This setup was also recently applied to mountain meteorology during the July 2025 TEAMx field campaign in the Sterzing valley.[4][9]

Aim of the study

1. Validate HOUSEFLIES in its first **long-range deployment** (20 probes, ~800 km, 16.8 hours);
2. Characterize multi-scale **relative dispersion**;
3. Apply **DNG** (Distance-Neighbour Graph) metric at various scales;
4. Model–observation integration: physical diagnostic via analyses of **ICON** (Icosahedral Nonhydrostatic) NWP model.

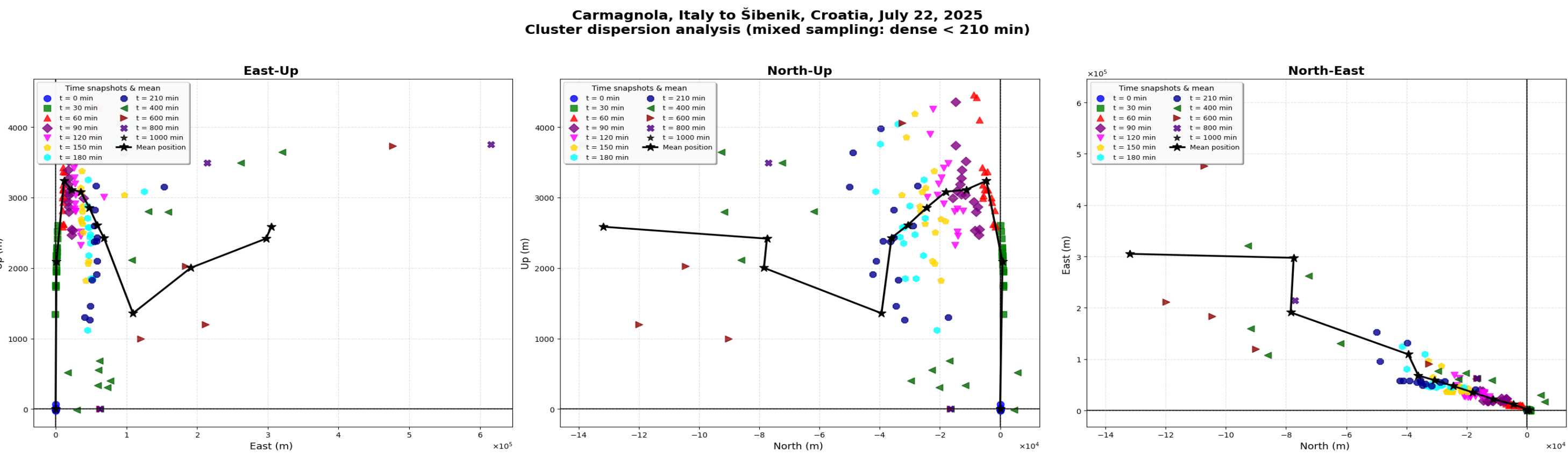


Figure 1 - ENU planar projections of relative probe positions

Projections of the probe cluster onto the East–North, East–Up, and North–Up planes of the local East–North–Up (ENU) reference frame. The evolution of the projected distributions highlights scale-dependent cluster stretching, vertical stratification and relative dispersion processes.

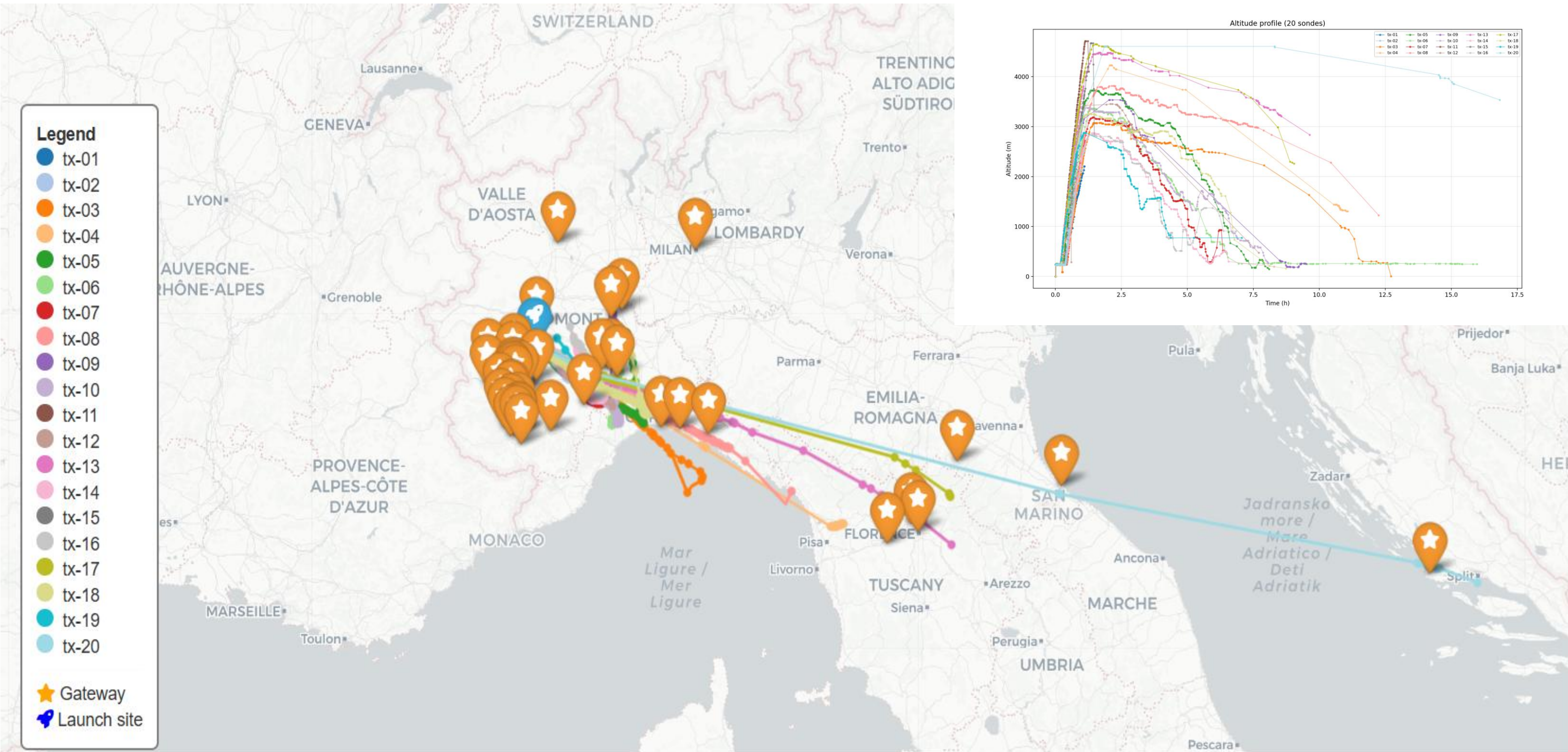


Figure 2 – Flight trajectory, deployment overview and altitude profiles of the balloon swarm

Trajectory of the 20-probe HOUSEFLIES balloon swarm from northern Italy to Croatia. The map shows launch and **TTN gateway** locations, individual probe **tracks** and the overall spatial evolution of the swarm during the ~800 km, 16.8 h long-range deployment. Furthermore, time-altitude evolution of the 20 probes illustrates the variability in flight duration and trajectory for each sensor.

Methods and results

Atmospheric dispersion analysis

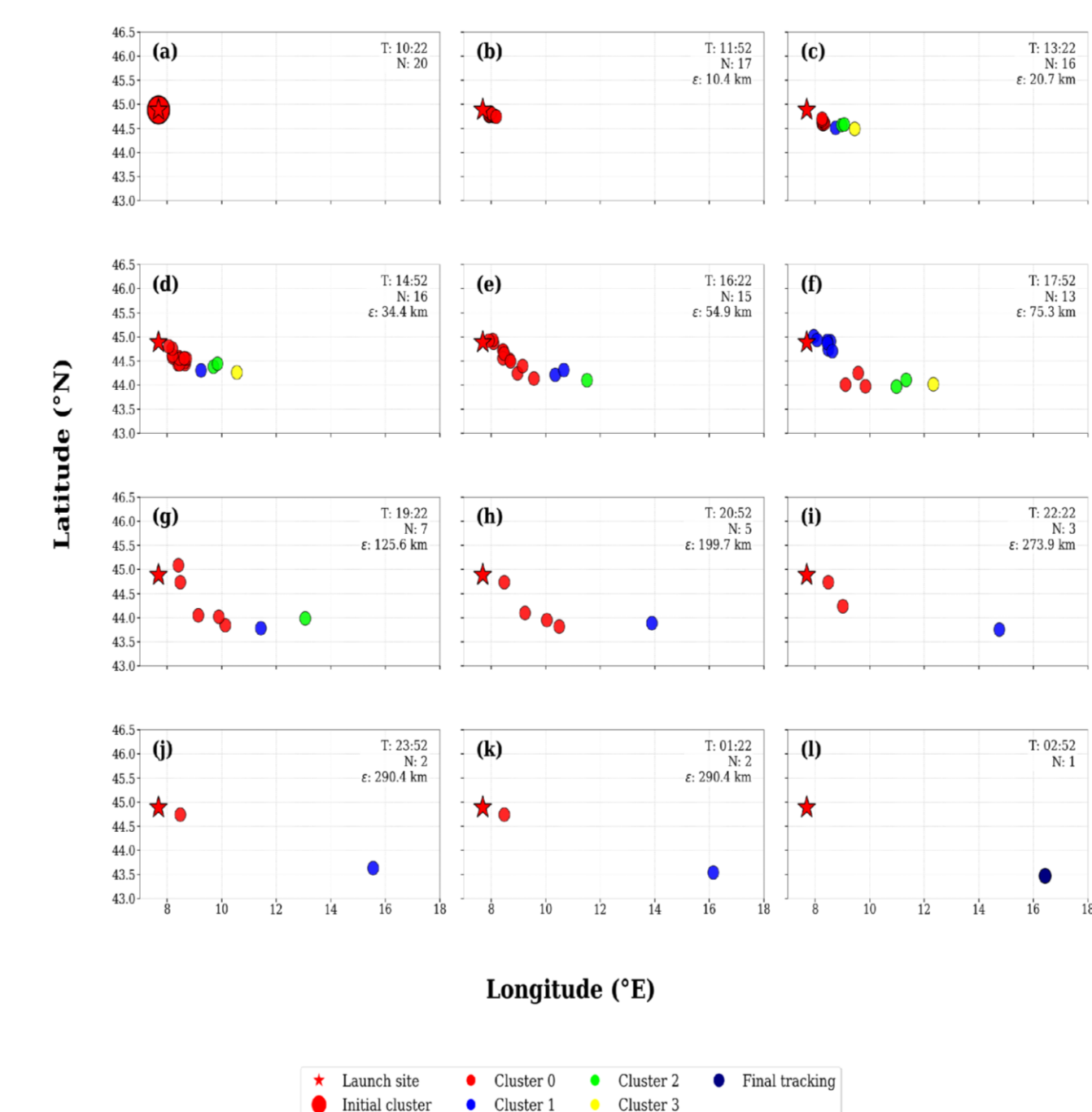


Figure 3 – Atmospheric dispersion analysis

Scale-dependent clustering metrics and probe distributions reveal intermittent mixing and non-uniform spreading. The dynamic proximity parameter ϵ , defined as the mean fraction of common distance-neighbour pairs, quantifies cluster coherence and highlights the patchy nature of atmospheric dispersion.

ICON cross-diagnostics with observations

Regimes $R1 \rightarrow R2 \rightarrow R3$

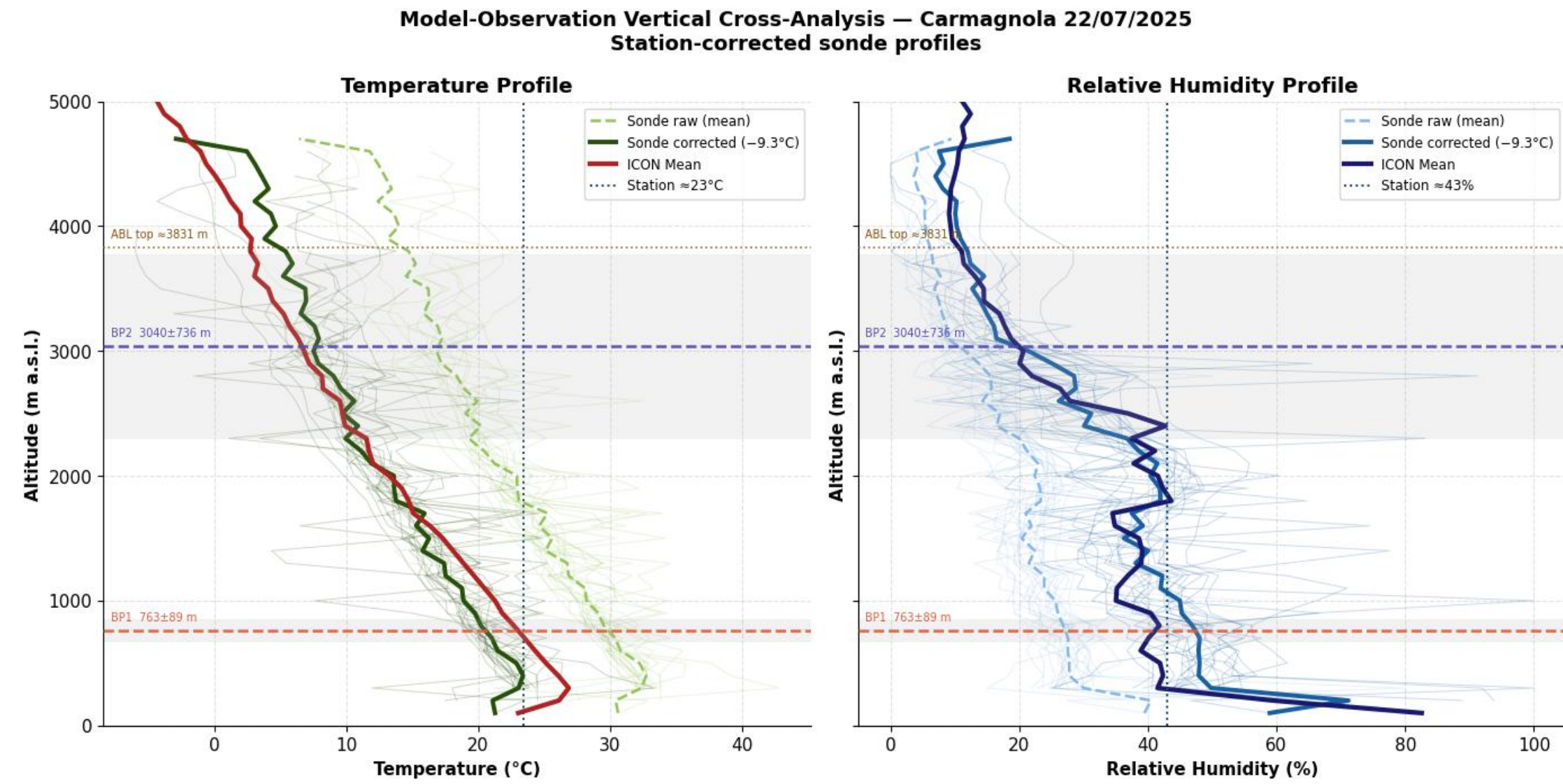


Figure 6 - Vertical cross-diagnostics of temperature and humidity profiles

Comparison between balloon swarm observations and ICON model analyses. Raw data were corrected by a constant offset of -9.33°C to mitigate sensor solar bias, calibrated against ground-based station data at launch time (10:22 UTC). Corrected profiles show improved alignment with ICON curves, which represent co-located 4D means sampled along each balloon's trajectory and vertically averaged with equal weight on a common 0–5000 m grid model.

Relative dispersion scaling - 3 regimes

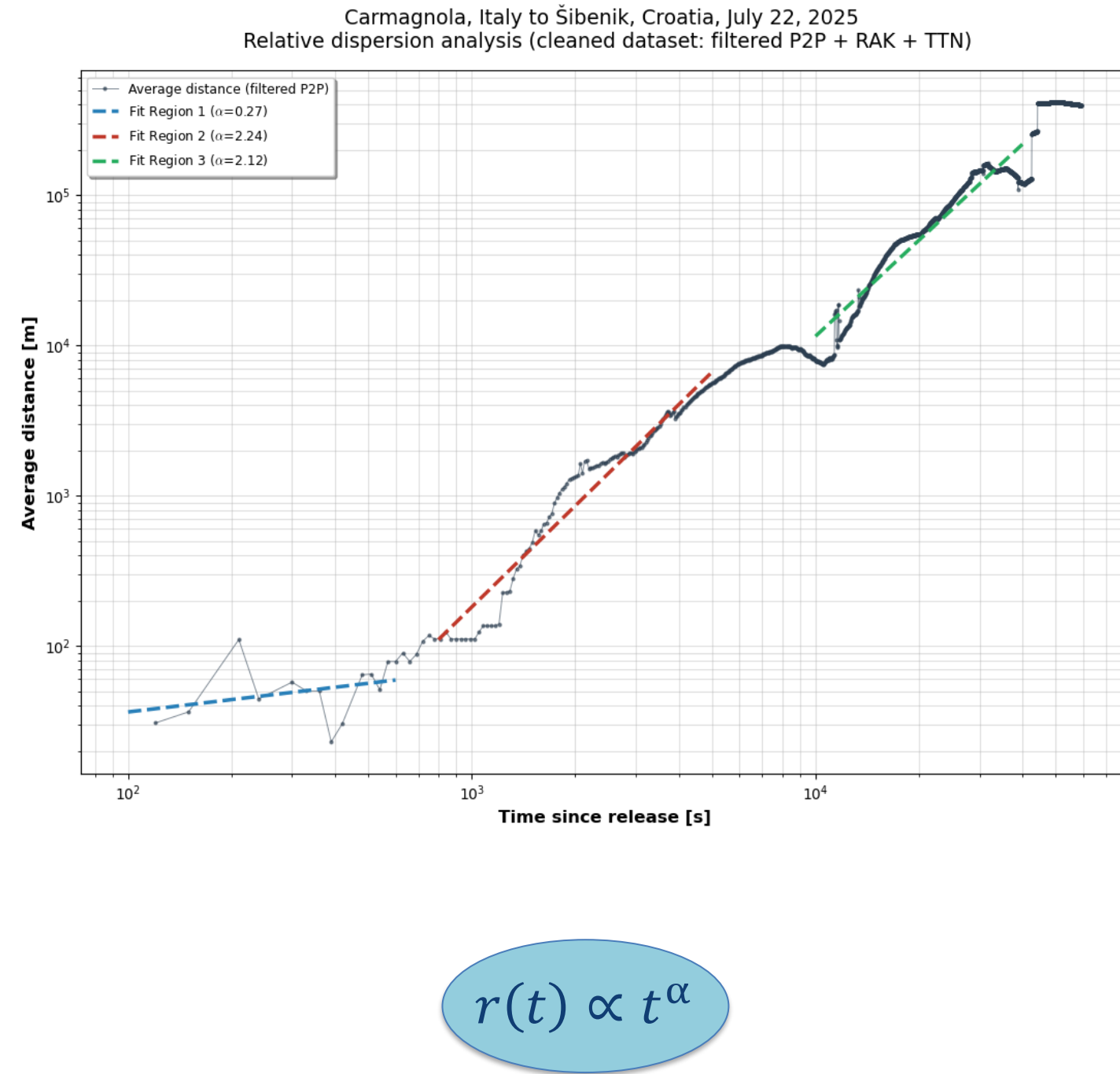


Figure 4 – Global analysis of relative dispersion scaling across three regimes

Scale-dependent relative dispersion dynamics. Orography affects dispersion up to a certain extent as shown by results reported in Zulli et al. [9] based on data collected during Sterzing Valley field campaign. For stratification dependent simulations results, refer to Zhang et al. [8].

Phase	Time (s)	α	C^*	Rate (m/s)	Regime
Region 1	100-600	0.27	$1.03 \cdot 10^1$	0.04	Sub-diffusive
Region 2	800-5000	2.24	$3.53 \cdot 10^{-5}$	1.52	Super-diffusive
Region 3	10000-40000	2.15	$2.92 \cdot 10^{-5}$	6.88	Shear-dispersion

C^* ($\text{m s}^{-\alpha}$) is the power-law prefactor in $D(t) = C^* t^\alpha$, where $D(t)$ is the typical distance of a sonde pair at time t ; its units depend on α , so values are not comparable across regions.

Table 1: Relative dispersion parameters and separation rates for the balloon swarm across different flight phases. For regimes refer to [5],[1],[6],[7]. The reported separation rate is the instantaneous derivative $\frac{dD}{dt} = C\alpha t^{\alpha-1}$ evaluated at the temporal midpoint (t_{mid}) of each window.

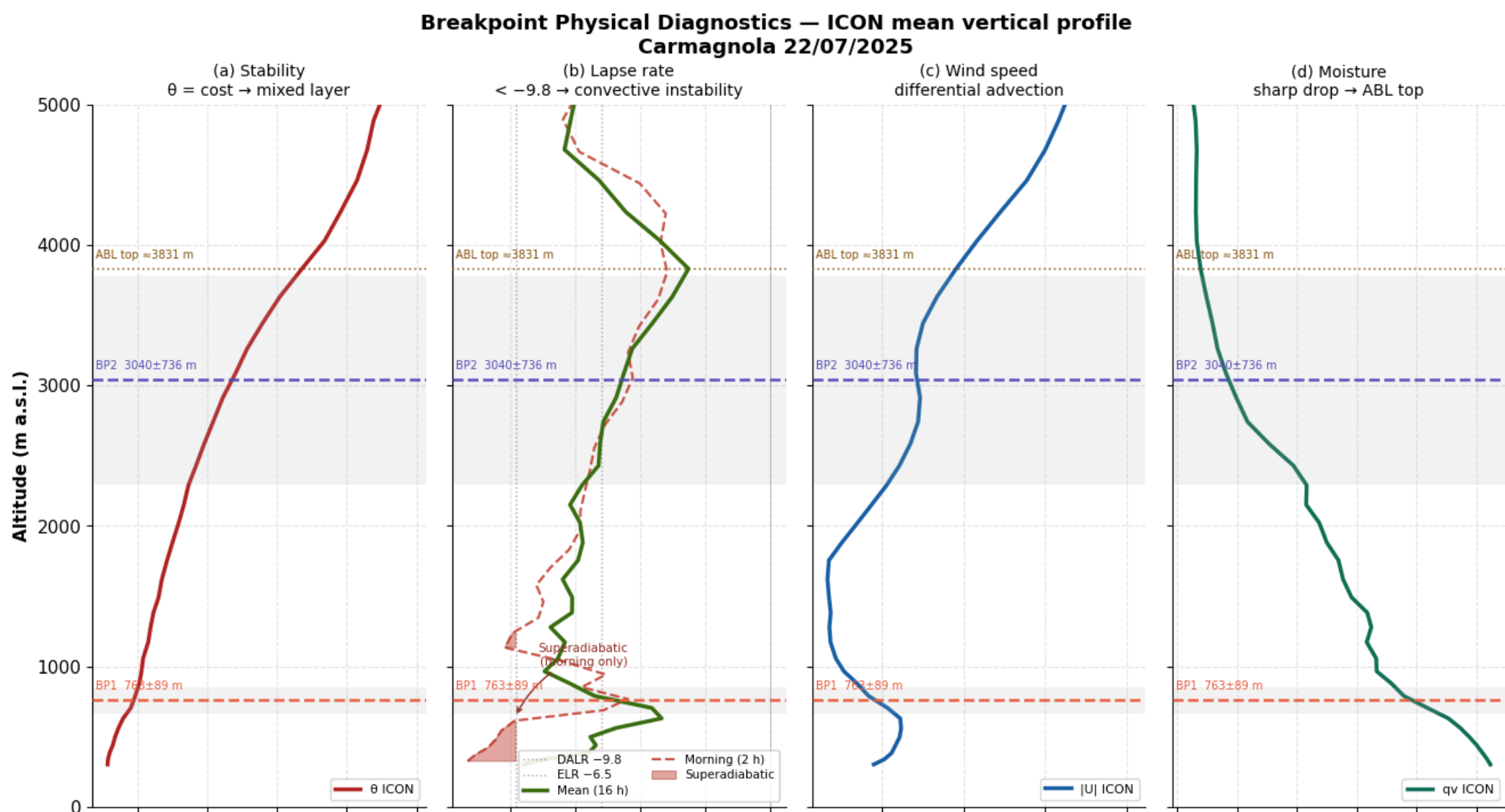


Figure 7 - Breakpoint atmospheric diagnostics and boundary layer structure

ICON model vertical profiles along the balloon swarm flight trajectory (launch from Carmagnola on July 22, 2025), showing four diagnostics: **(a) Stability**: potential temperature θ . **(b) Thermal Stratification**: lapse rate dT/dz with unstable layers (shaded red) near the surface reaching -9.8 K/km. **(c) Kinematics**: wind speed profile indicating differential advection and critical shear zones. **(d) Moisture**: specific humidity q_v with a sharp drop at the ABL top (~ 3831 m). Horizontal dashed lines mark the experimental swarm trajectory breakpoints (BP1 at ~ 763 m and BP2 at ~ 3040 m), linking swarm dispersion changes to model-predicted thermodynamic transitions. Deployment under fair weather and a deep convective ABL over the flat Po Valley minimized NWP errors, creating **favourable conditions for model-observation comparison**.

Conclusions

The experiment successfully validates a 20-probe Lagrangian system over ~800 km, identifying three physically distinct dispersion regimes that are **consistent with the thermodynamic transitions identified through ICON atmospheric diagnostics**.

Key future perspectives and ongoing work



1. ADVANCED PATCH ANALYSIS
Conduct **block-based analysis** of patches, Richardson numbers



2. INTEGRATED FORECASTING
Enhance **high-impact weather models** by merging Lagrangian swarms with fixed-station networks



3. HAZARD MONITORING
Develop scalable real-time tracking of **air quality**, industrial **plumes** and volcanic ash



4. OPERATIONAL PIPELINE
Build a flexible and fully operational **multi-scenario pipeline** to advance the physical understanding of **turbulent dispersion**

References

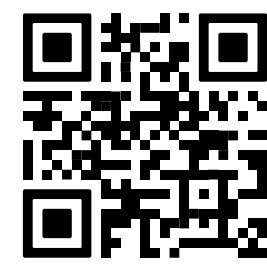
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AN OPEN INVITATION FOR DIALOGUE



OPEN QUESTION
CONTACT
maria.palomba@studenti.polito.it

What do you consider the most effective strategy for implementing **block-based analysis** and the associated **Richardson number computation**?
Ideas, insights and suggestions are welcome! Looking forward to learning from you and enjoying doubts together!



Discover the **HOUSEFLIES** Project
Philofluid Research Group — Politecnico di Torino