Air Quality Monitoring & synergies with Astrophysical Research

Data, Models, and the Role of LIDAR Technology

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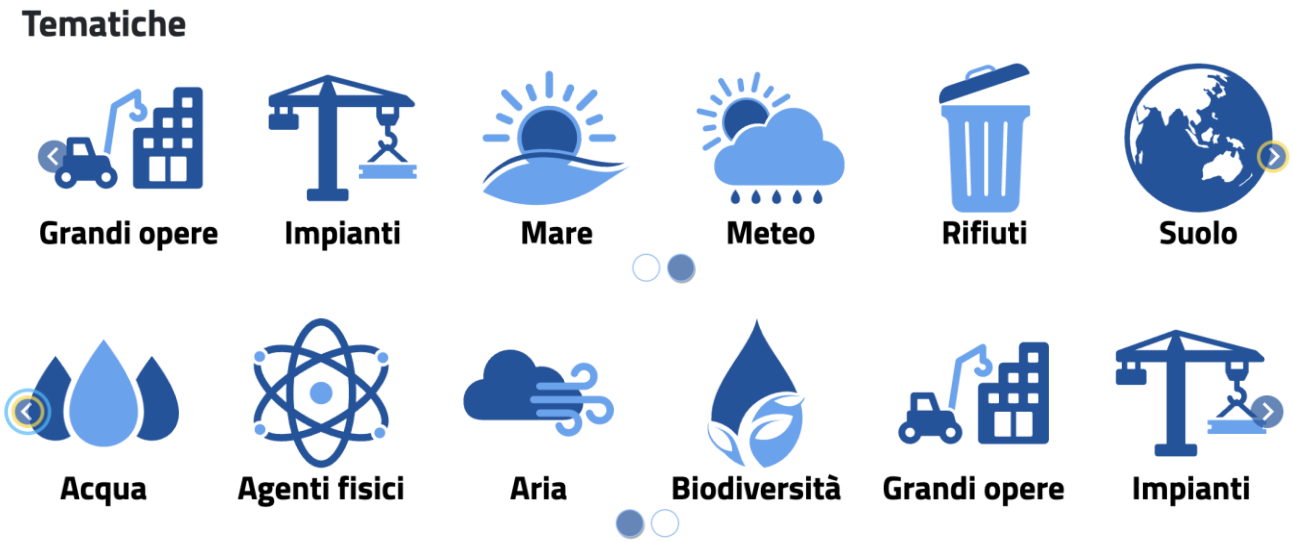
Overview

- ARPA: weather & air quality monitoring methods
- Focus on LIDAR technology
- Air quality modeling (CHIMERE & SPRAY)
- Connections with astrophysical modeling (PLUTO & jet simulations)
- Others…

What is ARPA?

Regional Environmental Protection Agency (Italian: Agenzia Regionale per la Protezione Ambientale), commonly shortened to ARPA, is the Italian environmental agency, **one for each region of Italy**.

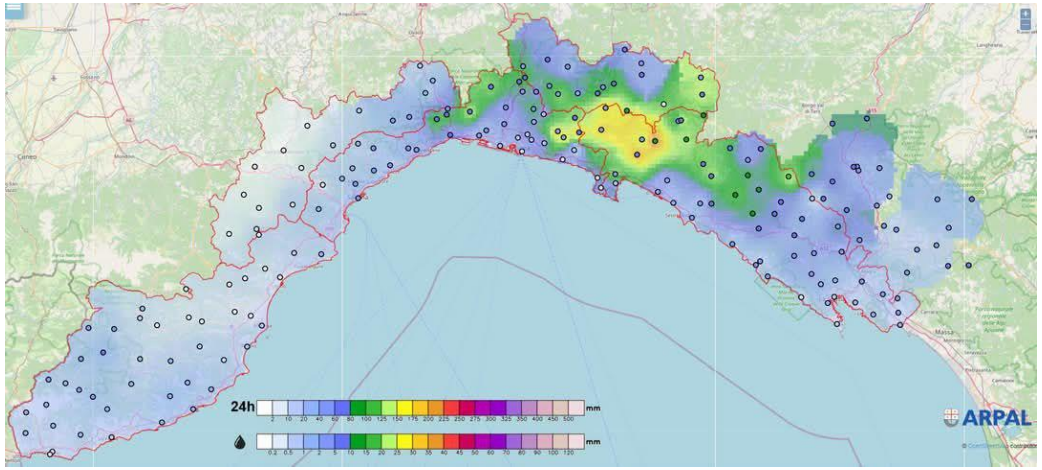


Weather measurements

Typical Configuration (WMO Standard):

- Shielded and ventilated temperature sensor, positioned at 1.5 m above ground level, at least 100 m away from major obstacles (trees, buildings, etc.).
- Wind measurements at the standard height of 10 m above ground level.
- **Key issue in site selection:** Data representativeness (considering obstacles, orography, wind, snow, etc.).
- **Need for calibration:** Instrument sensitivity, measurement error, response time, etc.

Weather Network



https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/meteo-idro-nivo/variabili_meteo

AQ Measurements

Typical Configuration (EU Standard):

- Sampling height: Typically 3–10 m above ground, avoiding direct local sources or obstacles
- Key challenges in site selection: Representativeness of the data, wind patterns, terrain features, and pollution dispersion
- Calibration and maintenance needs: Regular sensor calibration, sensitivity checks, measurement accuracy, and response time assessment.

QA Network

Urban Background: Represents general population exposure, far from direct sources

Traffic Station: Near roads, assessing vehicular pollution

Industrial Station: Near factories, measuring industrial emissions

Rural Background: Captures long-range transported pollutants

https://www.legambiente.it/wp-content/uploads/2021/11/MalAria-2025.pdf

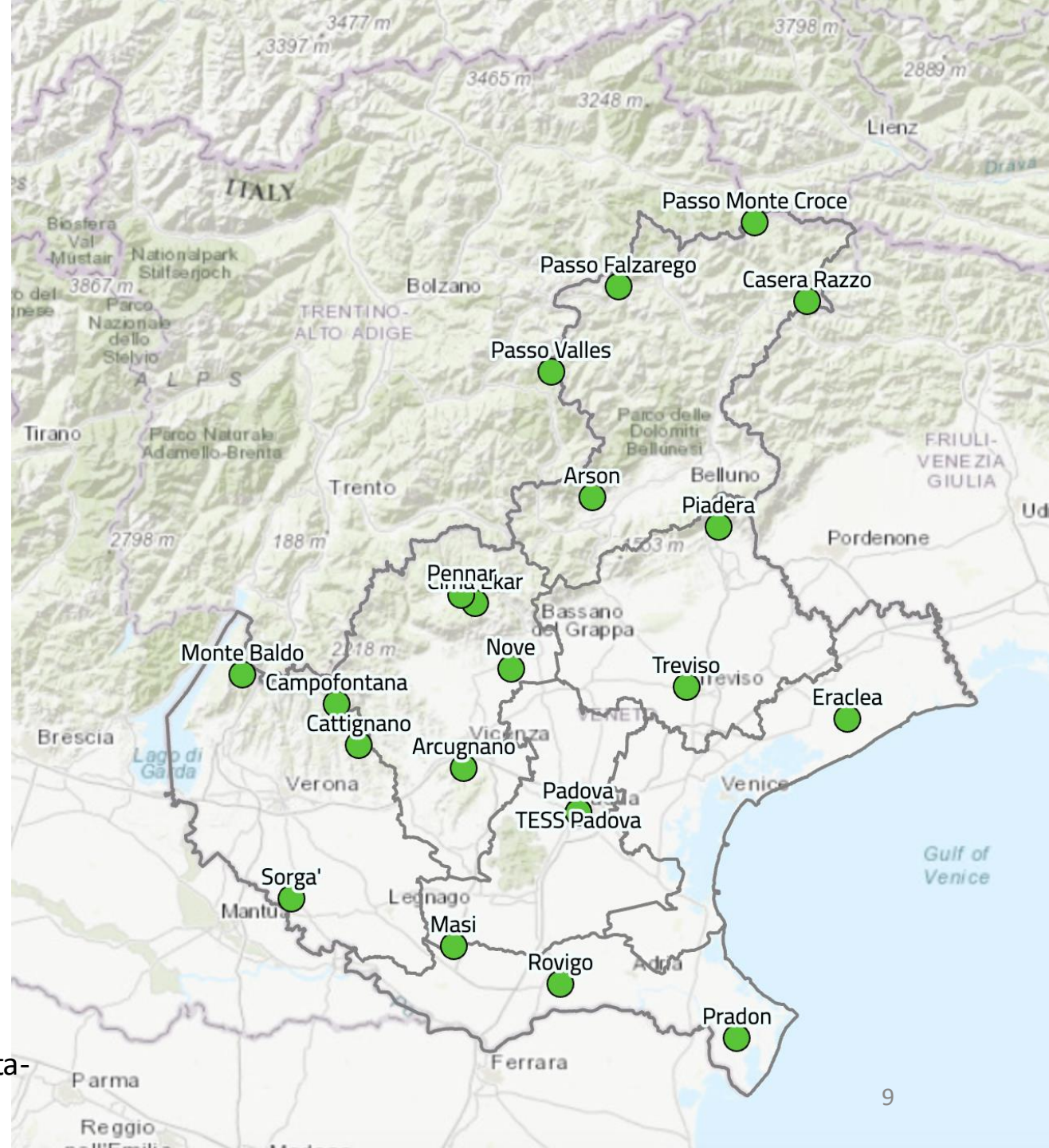
https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/aria/qualita-aria-dati-in-diretta

EU Limits

Pollutant	Limit Value [ug/m³]	Averaging Period	Objective
NO_2 (Nitrogen Dioxide)	200	1-hour (not to be exceeded more than 18 times per year)	Human health protection
	40	Annual average	Long-term exposure reduction
O_3 (Ozone)	180	1-hour (information threshold)	Public awareness
	120	8-hour (not to be exceeded more than 25 times per year, averaged over 3 years)	Human health protection
PM_{10} (Particulate Matter ≤10 um)	50	24-hour (not to be exceeded more than 35 times per year)	Human health protection
	40	Annual average	Long-term exposure reduction

Sky quality

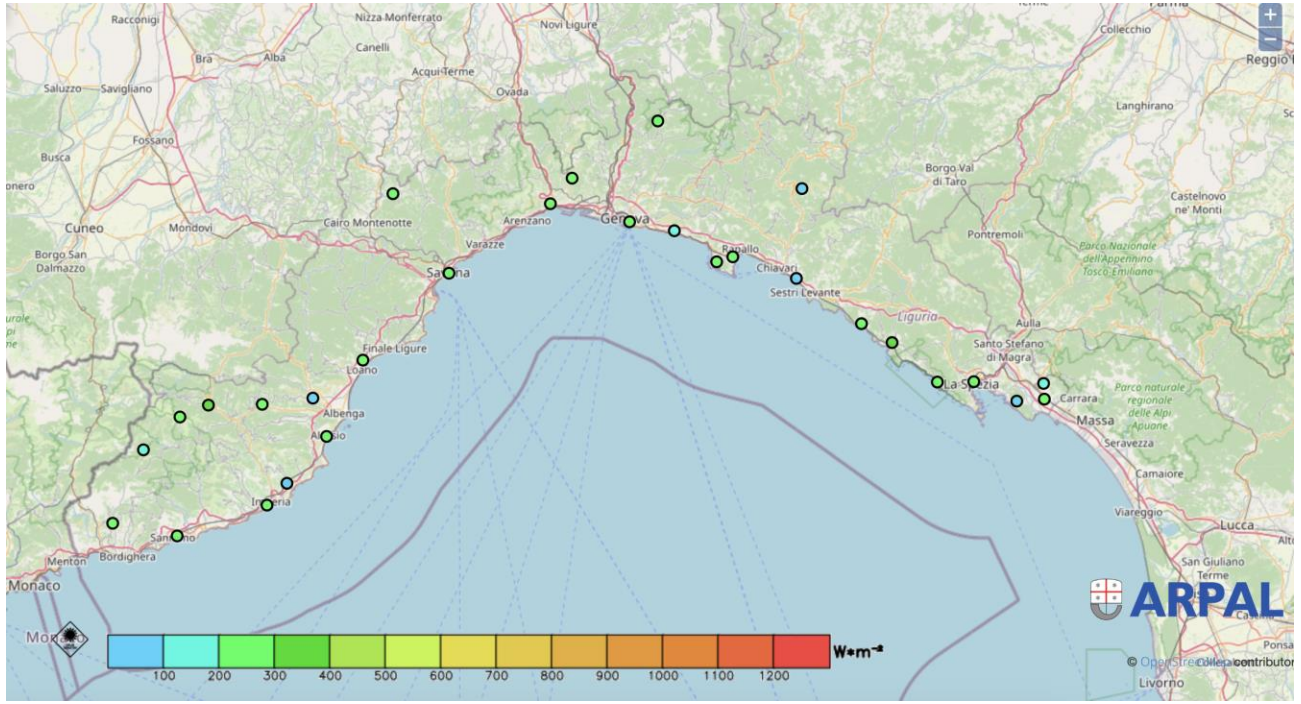
ARPA Veneto is the only, for now, with a network of sky quality meters.



https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/luminosita-del-cielo/brillanza

Solar radiation

ARPA Liguria has several Solar radiation sensors.



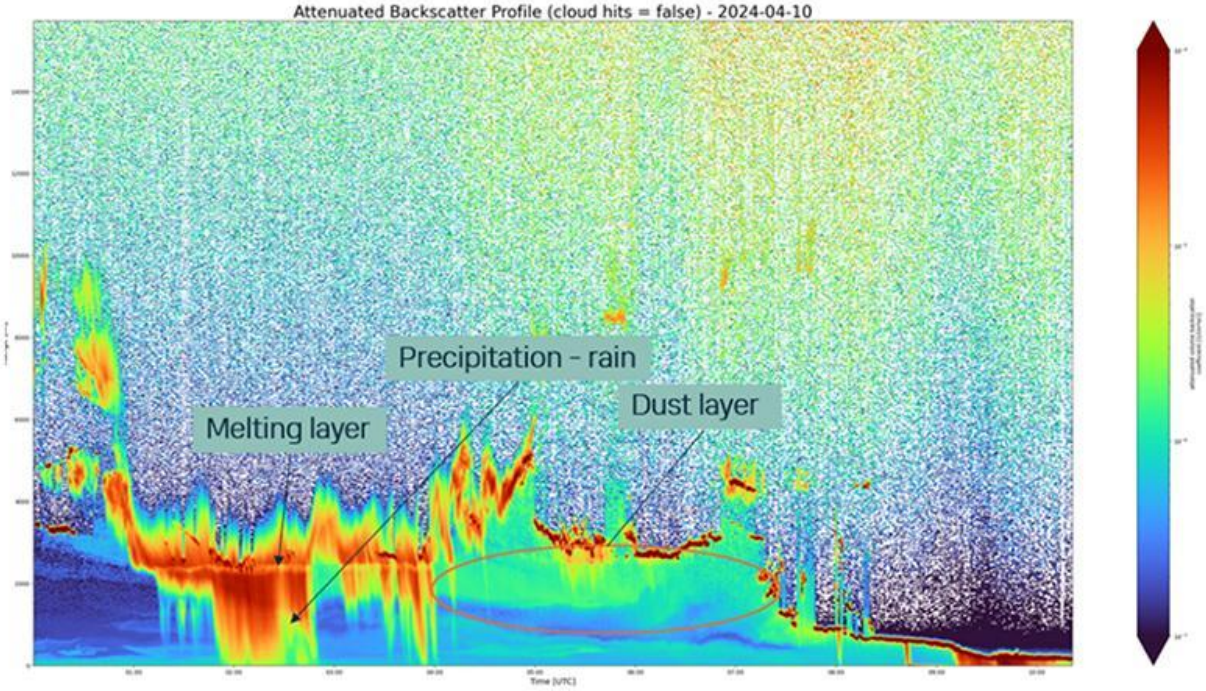
Caratteristiche tecniche del Sensore Radiometrico (Cm6b)	
Campo di misura e campo di sicurezza	Campo di misura: 0 ÷ 2000 Wm^{-2} Spettro di misura: 305 ÷ 2800 nm
Uscita elettrica	Tensione continua proporzionale al valore di irradianza misurato: 9 ÷ 15 µV/Wm^{-2}
Intervallo campionamento	1 minuto
Sensibilità	≤ 0,5 W/m^2
Linearità	≤ 1,5%
Intervalli di operatività rispetto ai parametri ambientali	Campo di temperatura: -40 ÷ +80 °C
Precisione complessiva sull'intero campo di misura	≤ 2%
Caratteristiche elettriche dell'uscita, alimentazione, consumi	Impedenza di uscita 70 ÷ 110 Ω. Lo strumento non necessita di alimentazione
Tempo di risposta	< 5 sec, per 1/e; < 55 sec. per 99%
Costanza nel tempo delle caratteristiche del sensore in condizioni operative	Deriva: ≤ 1% per anno

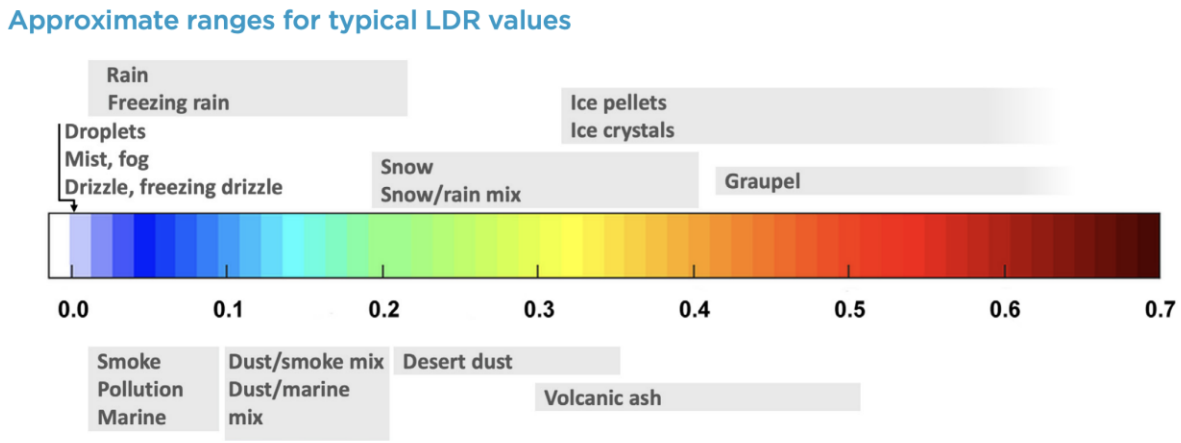
https://omirl.regione.liguria.it/#/map

LIDAR

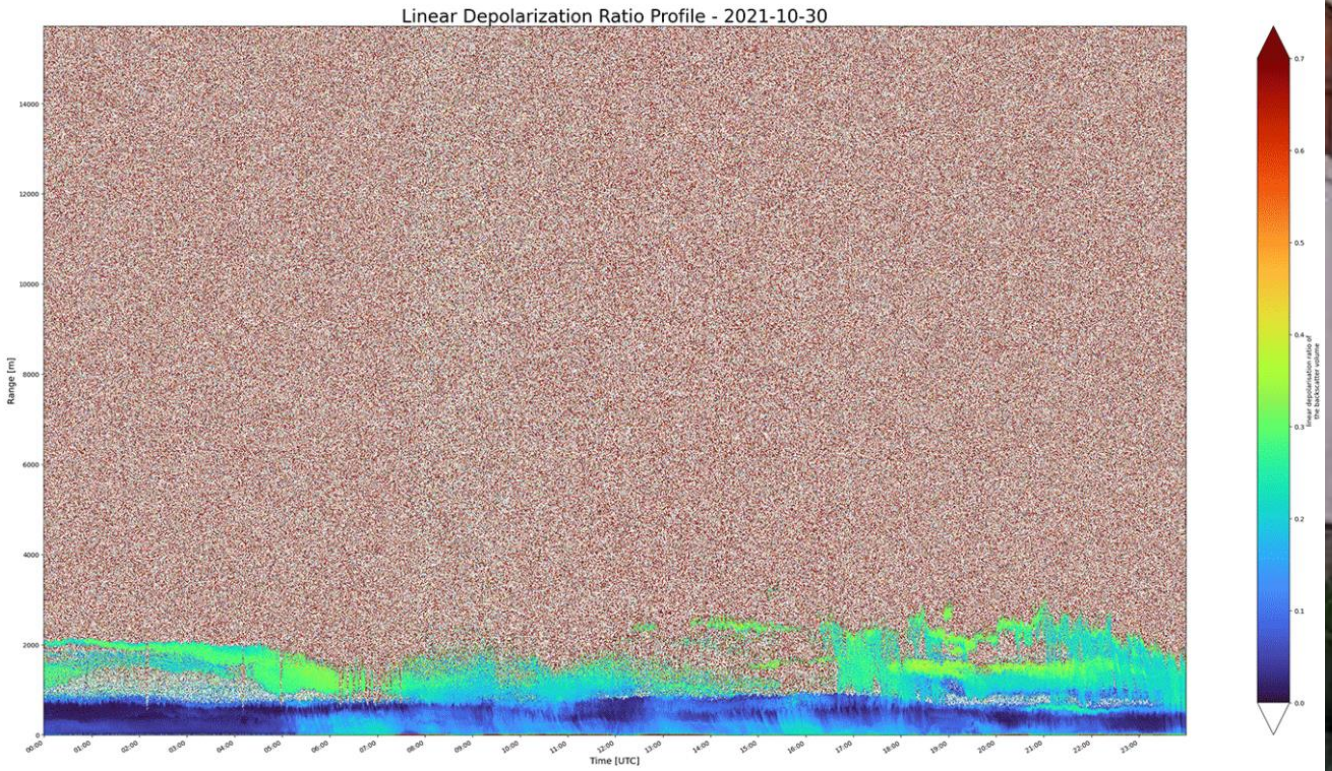
- Analysis of the backscattering of a laser signal by molecules and aerosols present in the atmosphere. High spatial (a few meters) and temporal (1 minute) resolution

- Depending on the type of LIDAR and the wavelength used, it is possible to obtain high-resolution vertical profiles of temperature, humidity, and aerosols, cloud height, wind in the lower layers, and more.





LIDAR in La Palma

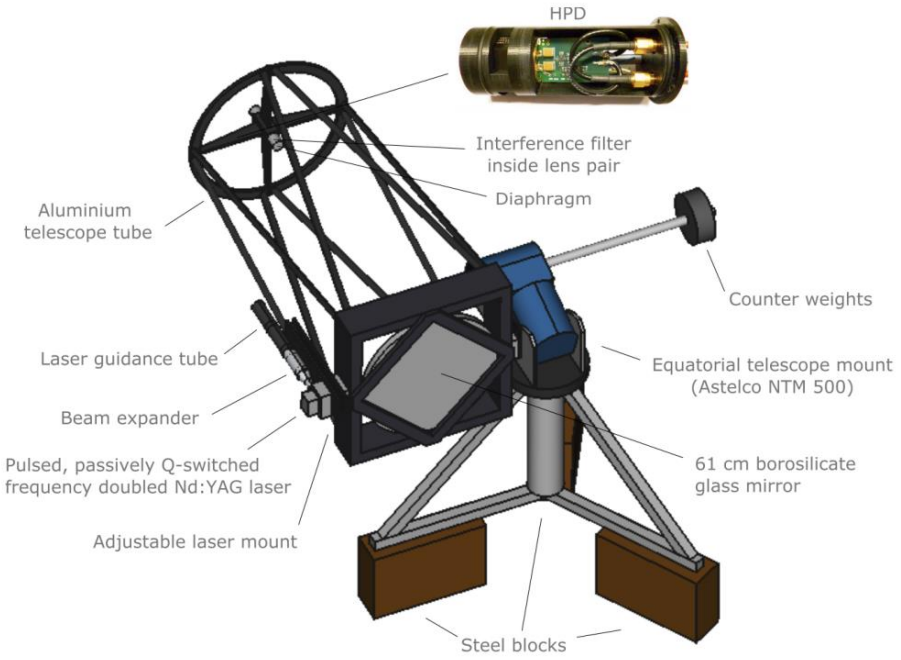


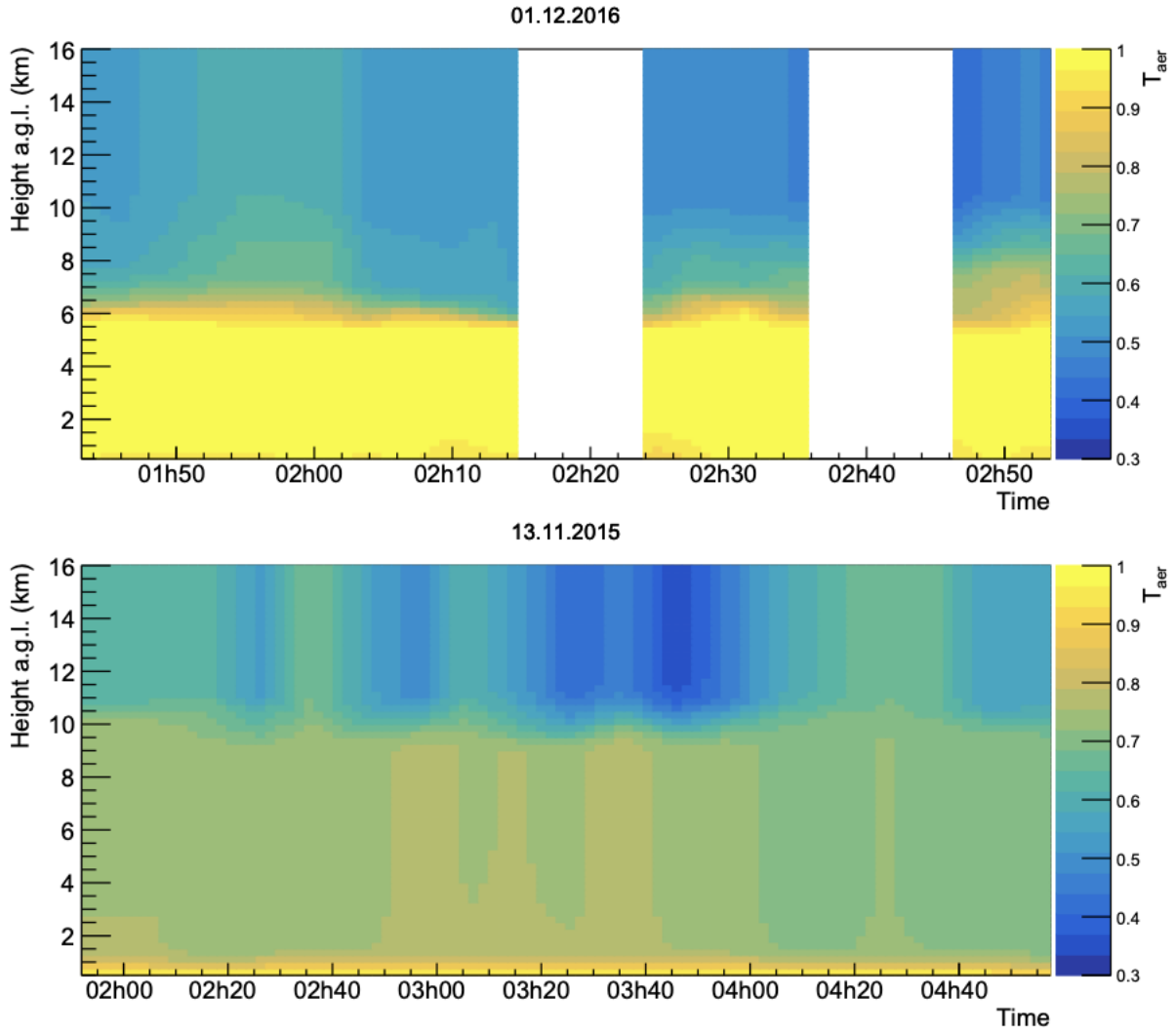
https://www.mdpi.com/2072-4292/14/22/5680#

https://www.vaisala.com/en/blog/2023-01/detecting-volcanic-ash-rain-canary-islands

LIDAR in Astronomy

Classifying the respective nocturnal aerosol conditions, the obtained aerosol extinction profiles can be better used to correct IACT science data affected by enhancements in the aerosol ground layer and by clouds.





https://www.aanda.org/articles/aa/pdf/2023/05/aa45787-22.pdf

QA Modelling

Navier-Stokes equation

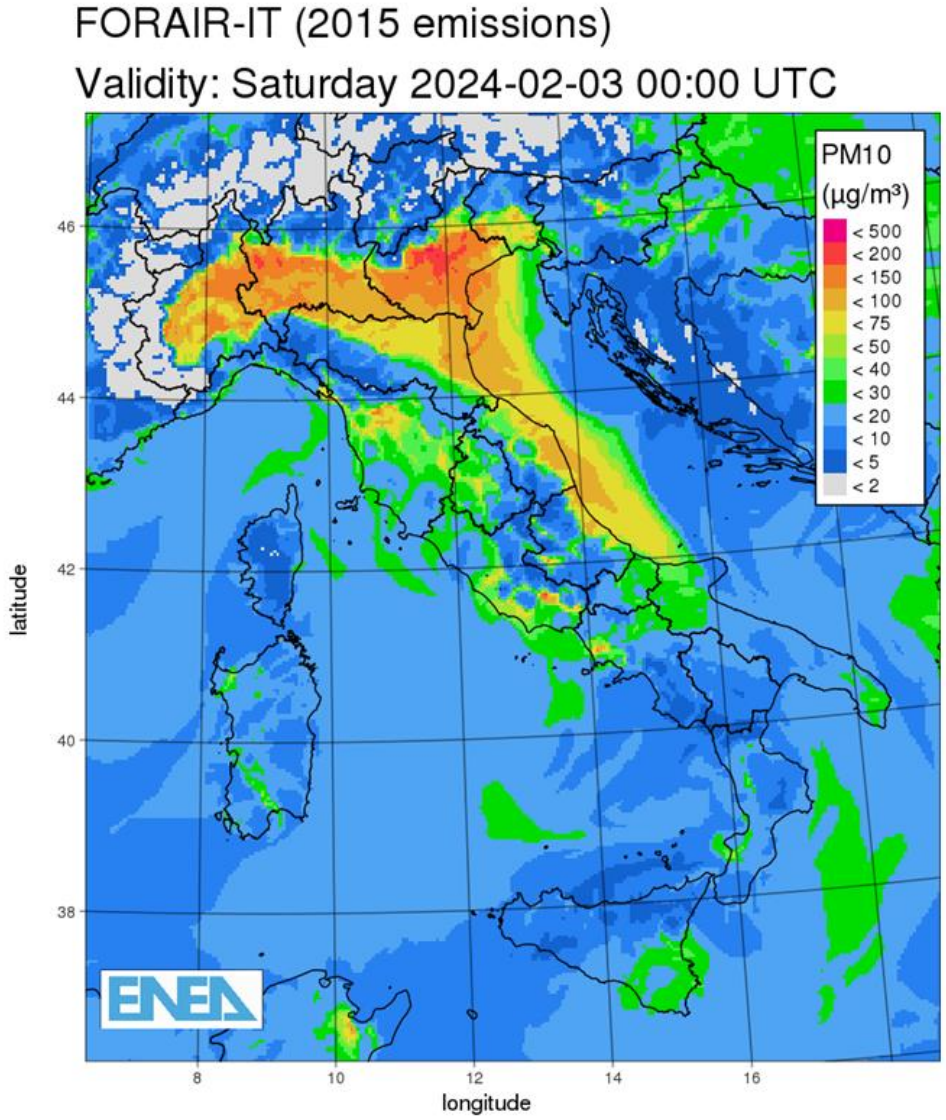
momentum balance for Newtonian fluids

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \nabla^2 u_i - g\delta_{i3} - 2\varepsilon_{ijk}\omega_j u_k$$

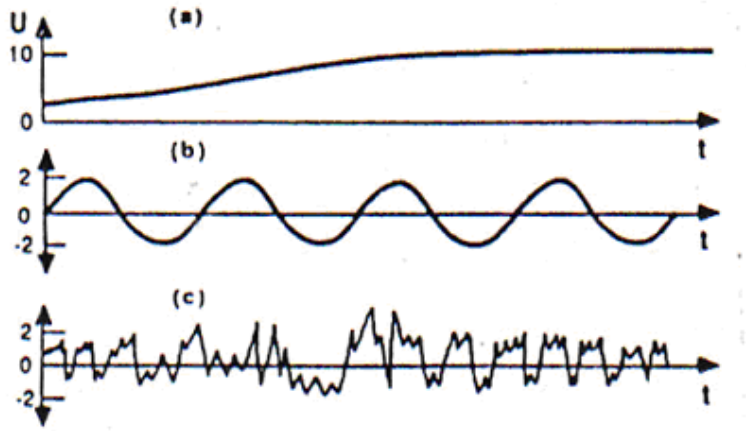
Diffusion equation

Evolution of pollution dispersion

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} = D_j \frac{\partial^2 c}{\partial x_j^2} + S_c$$



Turbolence



Description of:

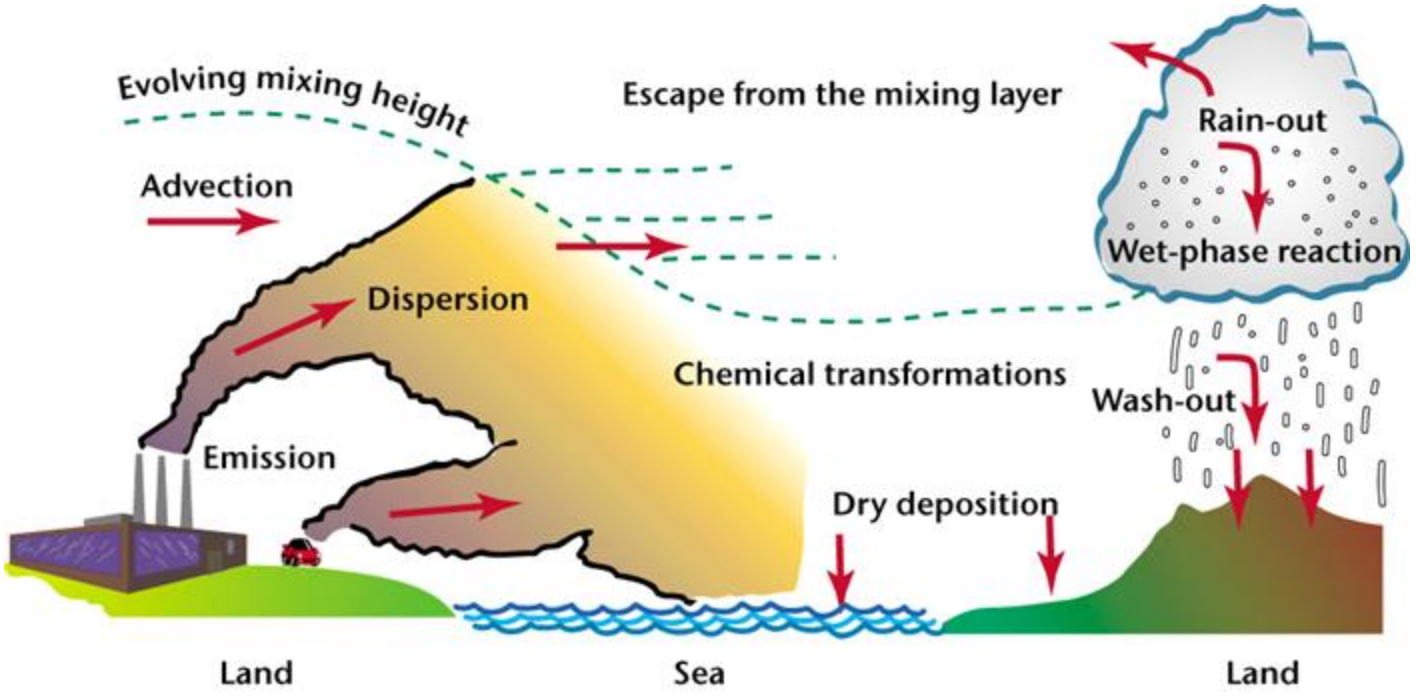
a. Average wind speed

b. waves

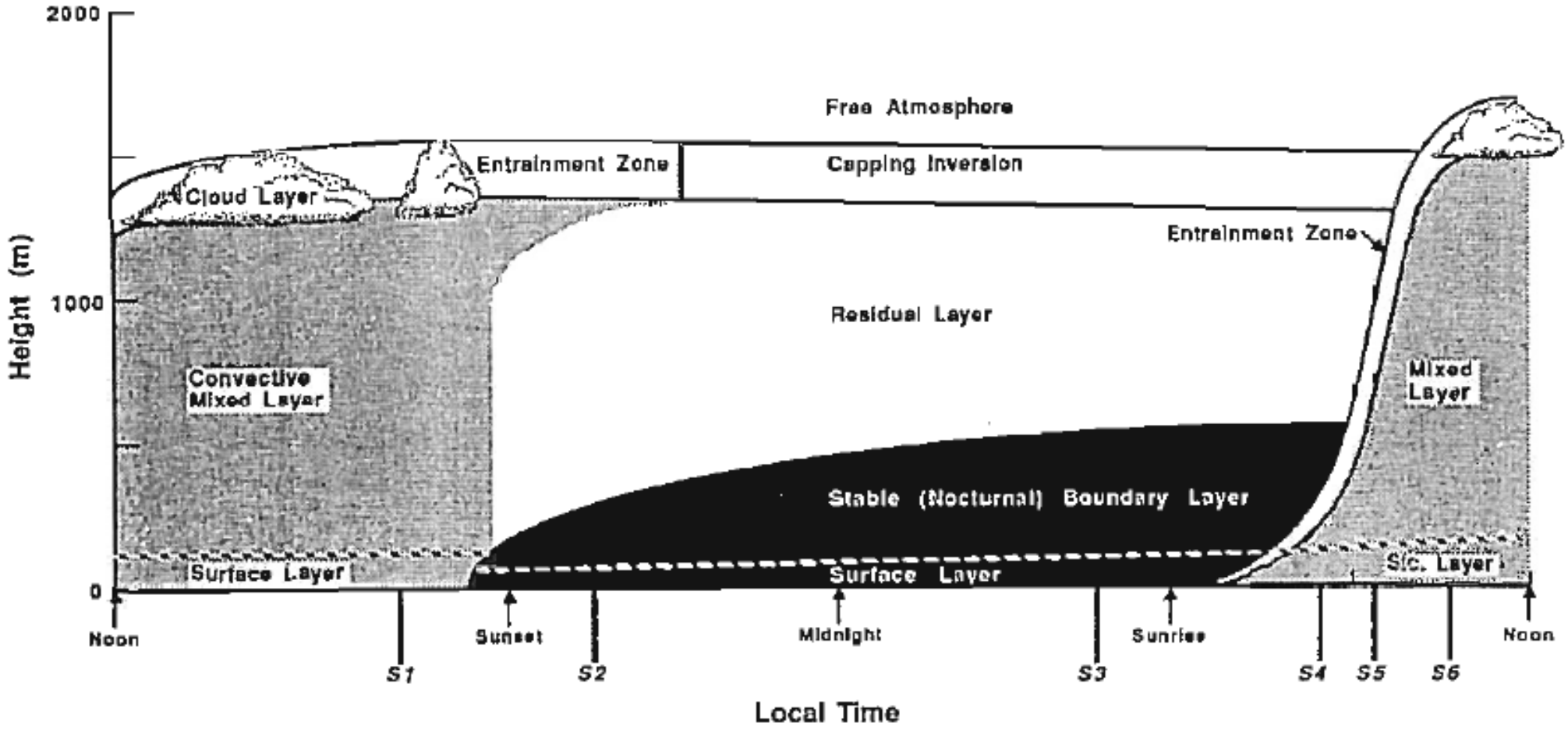
c. turbolence

Chemical and physical processes

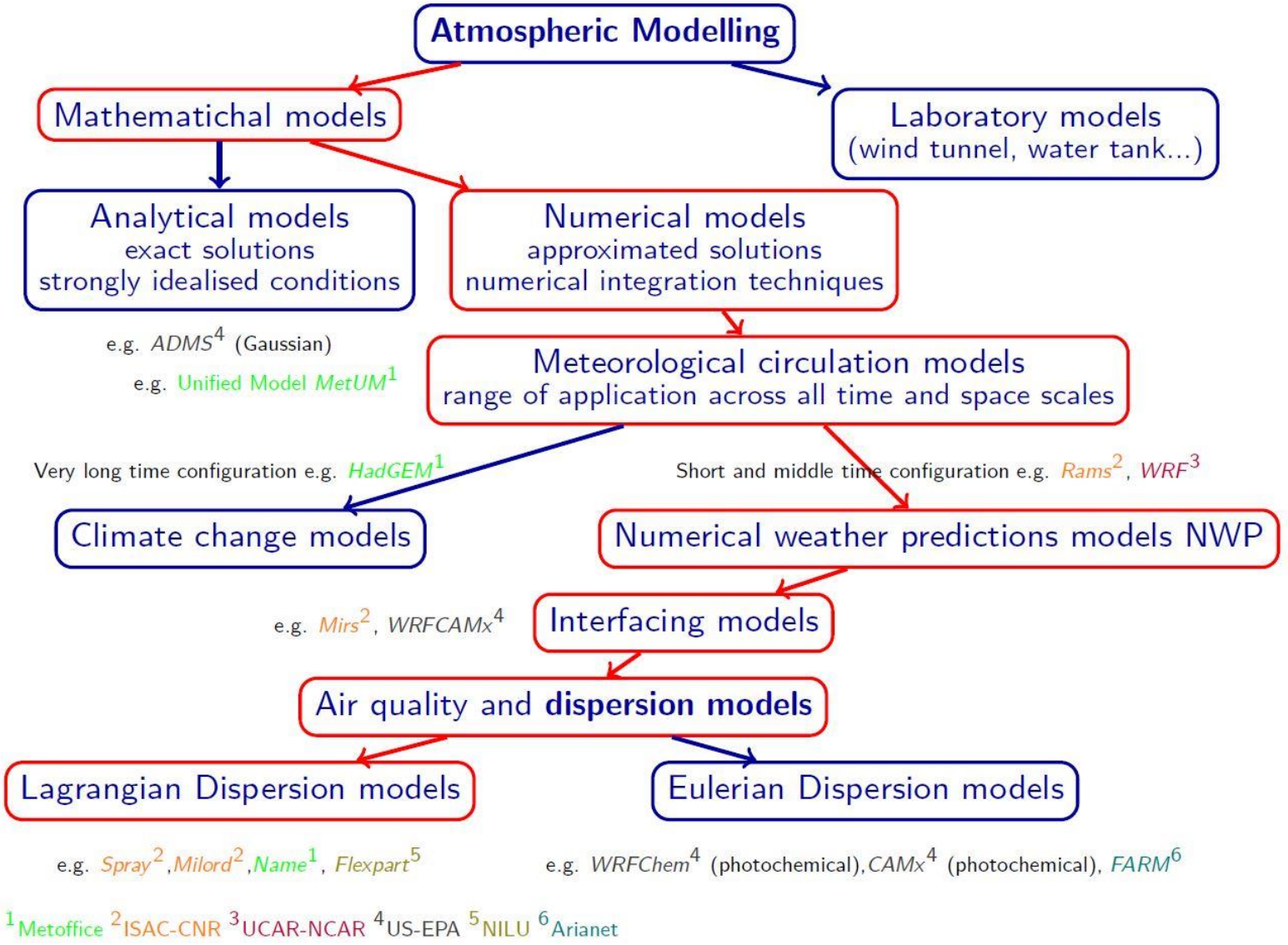
- Stability and convection
- Deacy and radiative processes
- Plume rise
- Turbolence diffusion and transport
- Rain, PBL evolution
- Atmospheric chemestry
- Dispersion of dust, sea salt, …



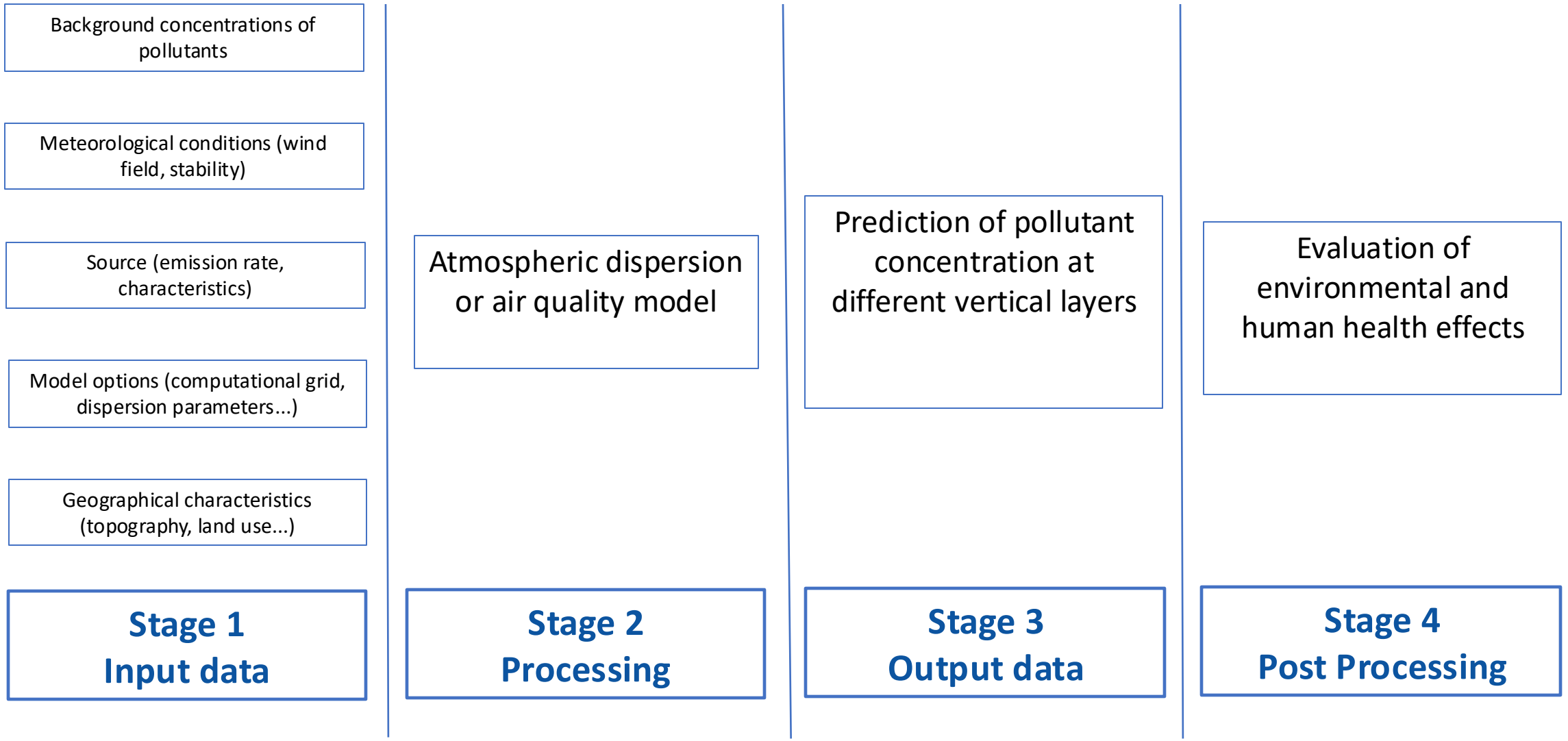
Daily variation of PBL



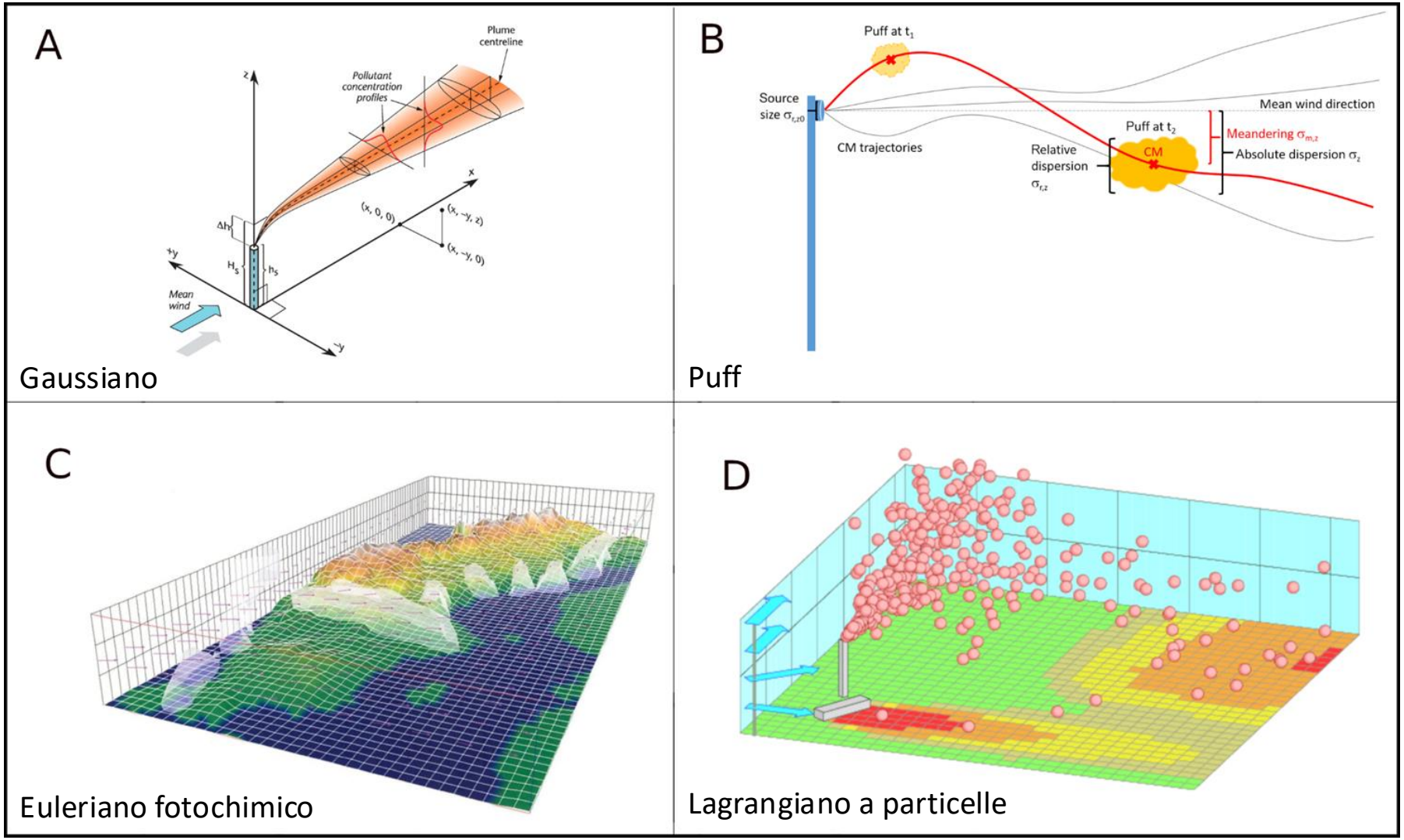
Structure of the models



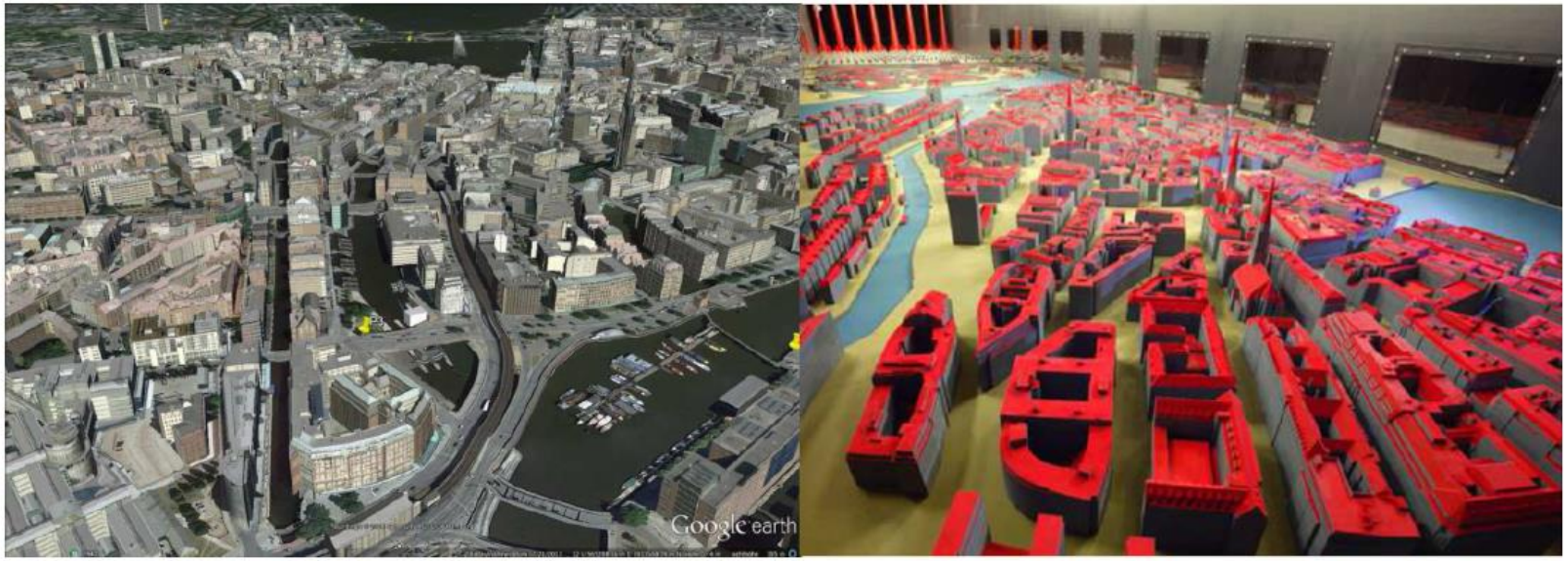
Modelling process

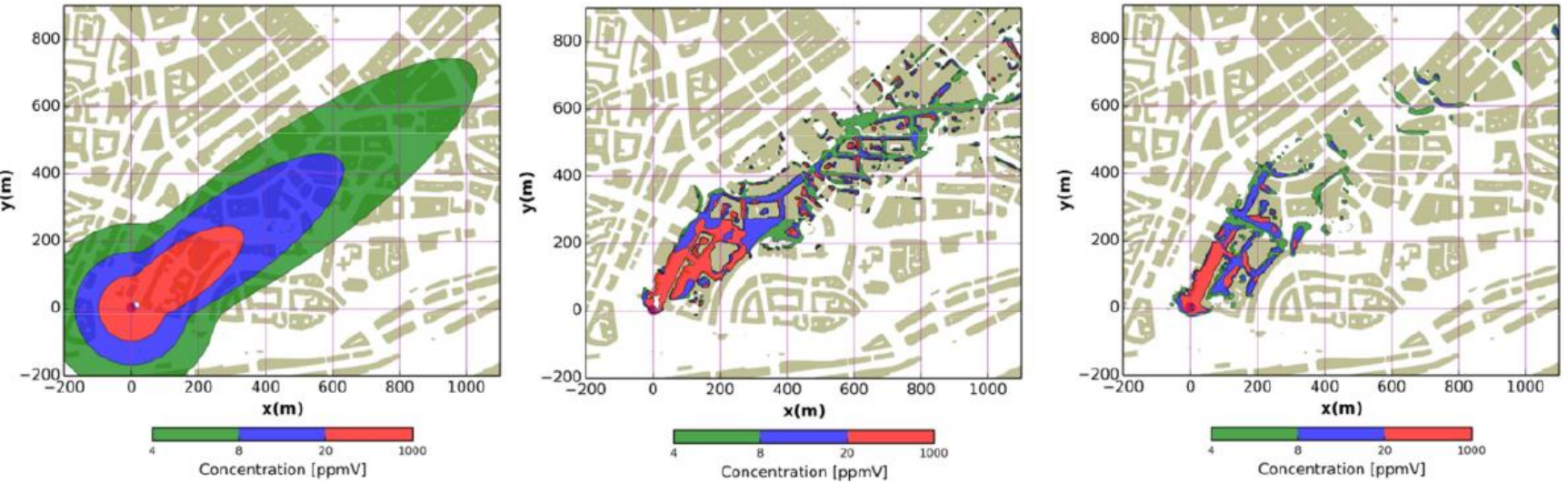


Kind of models



Which model to use?

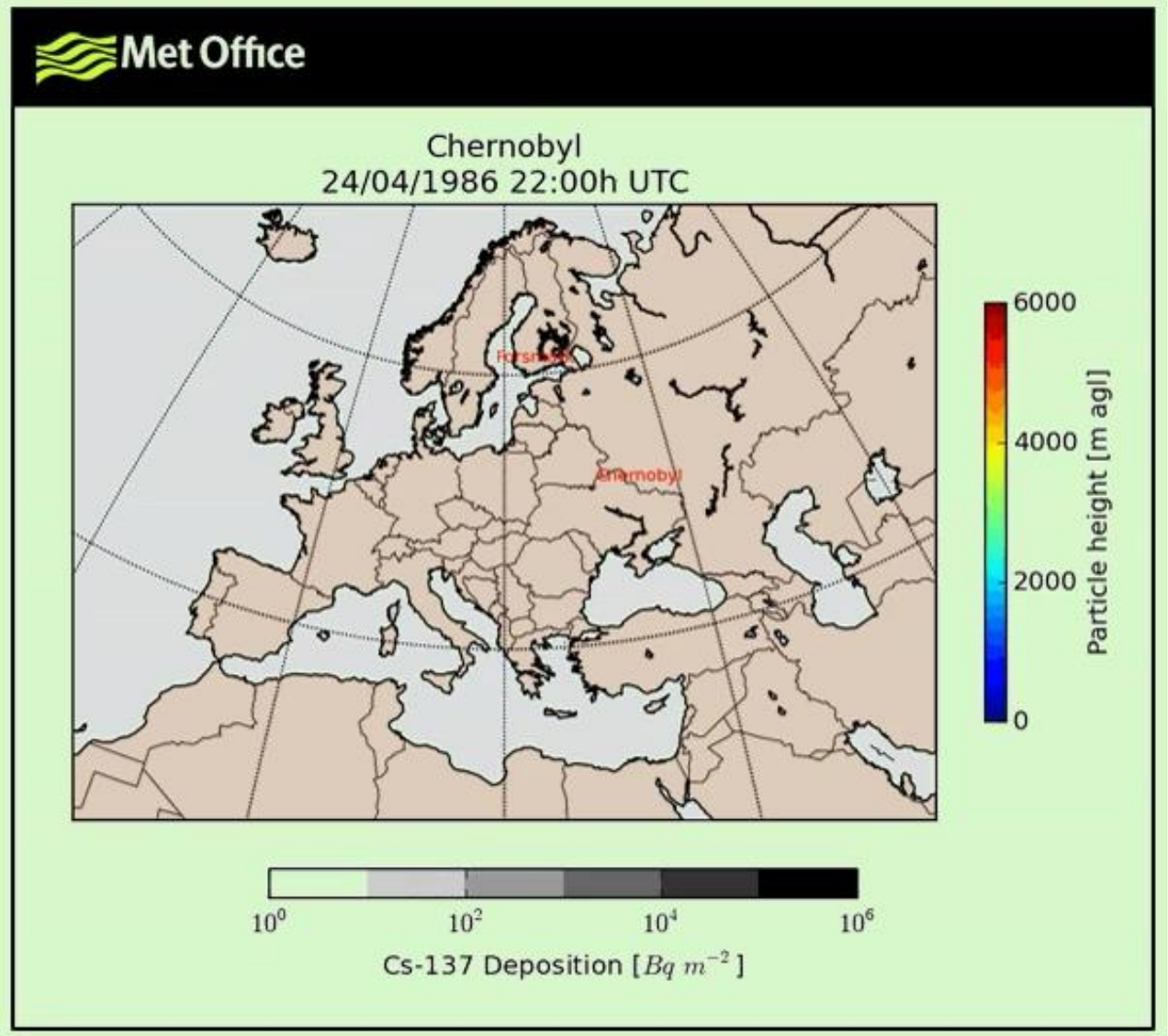




CUTE experiment

Kind of model	Time sim
Gaussian	1-5 min
Lagrangian	1-3 h
Eulerian	1-19 day

Example of application



Air Quality Modeling Setup

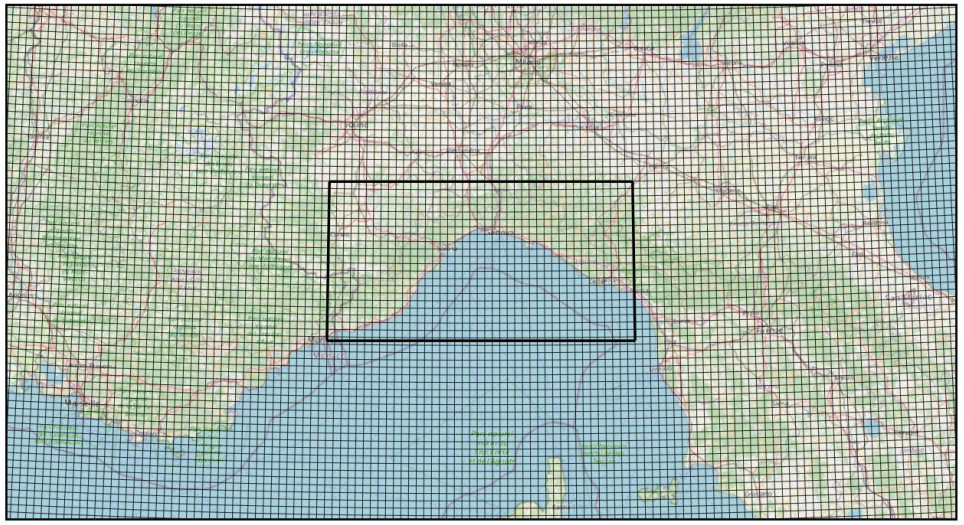
Outer Domain (Ld01)

- Horizontal resolution: 5 km, grid size: 133 x 73
- 45 (WRF) and 17 (CHIMERE) vertical levels
- Emissions: CAMS-reg v6.1
- Initial and boundary conditions for air quality: LMDz-INCA (gaseous species), GOCART (aerosols), CAMS EU
- Meteorological initial conditions: GFS

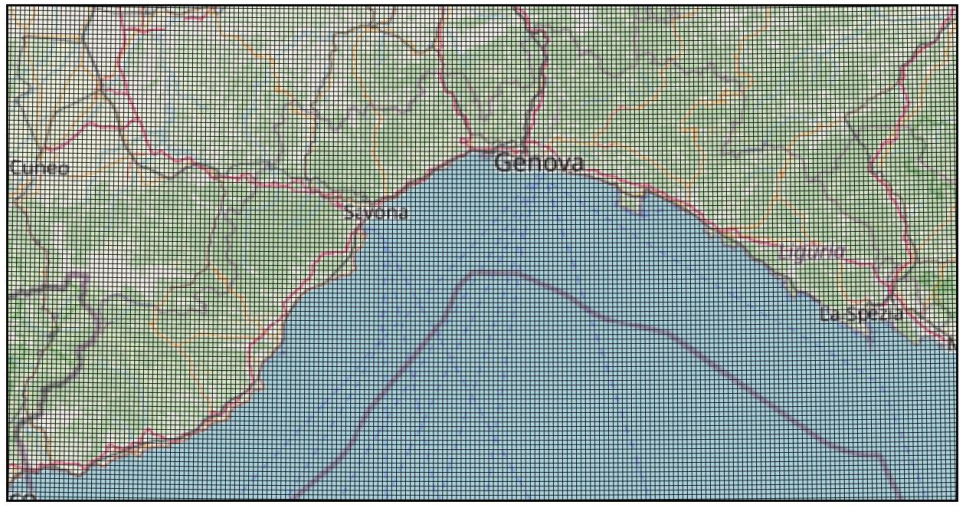
Inner Domain (Ld02)

- Horizontal resolution: 1 km, grid size: 211 x 111
- 45 (WRF) and 17 (CHIMERE) vertical levels
- Emissions: Regional inventory E2GOV
- Initial and boundary conditions for air quality: Output from Ld01
- Meteorological initial conditions: Output from Ld01

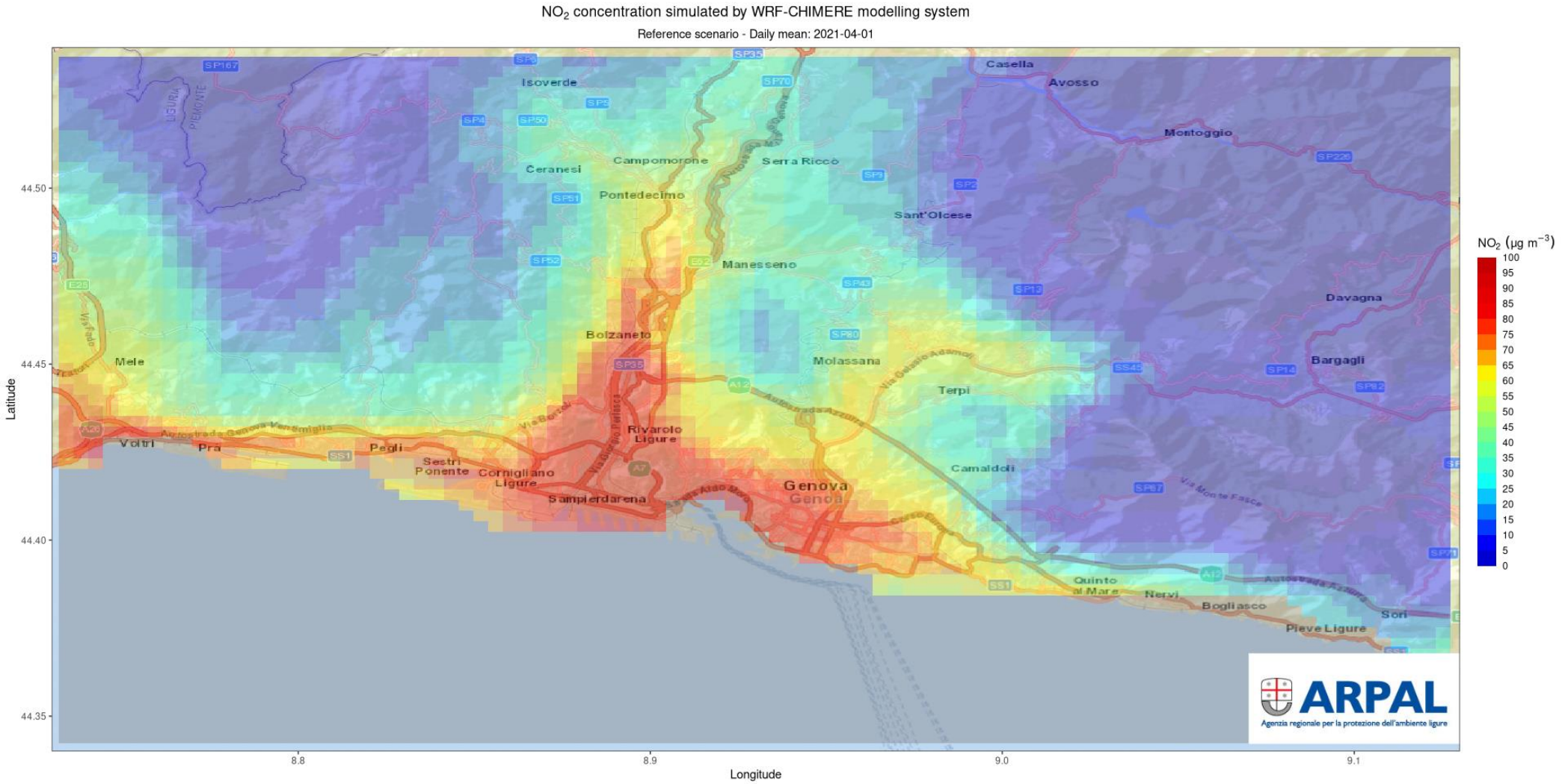
Outer Domain Ld01 (Resolution 5 km)



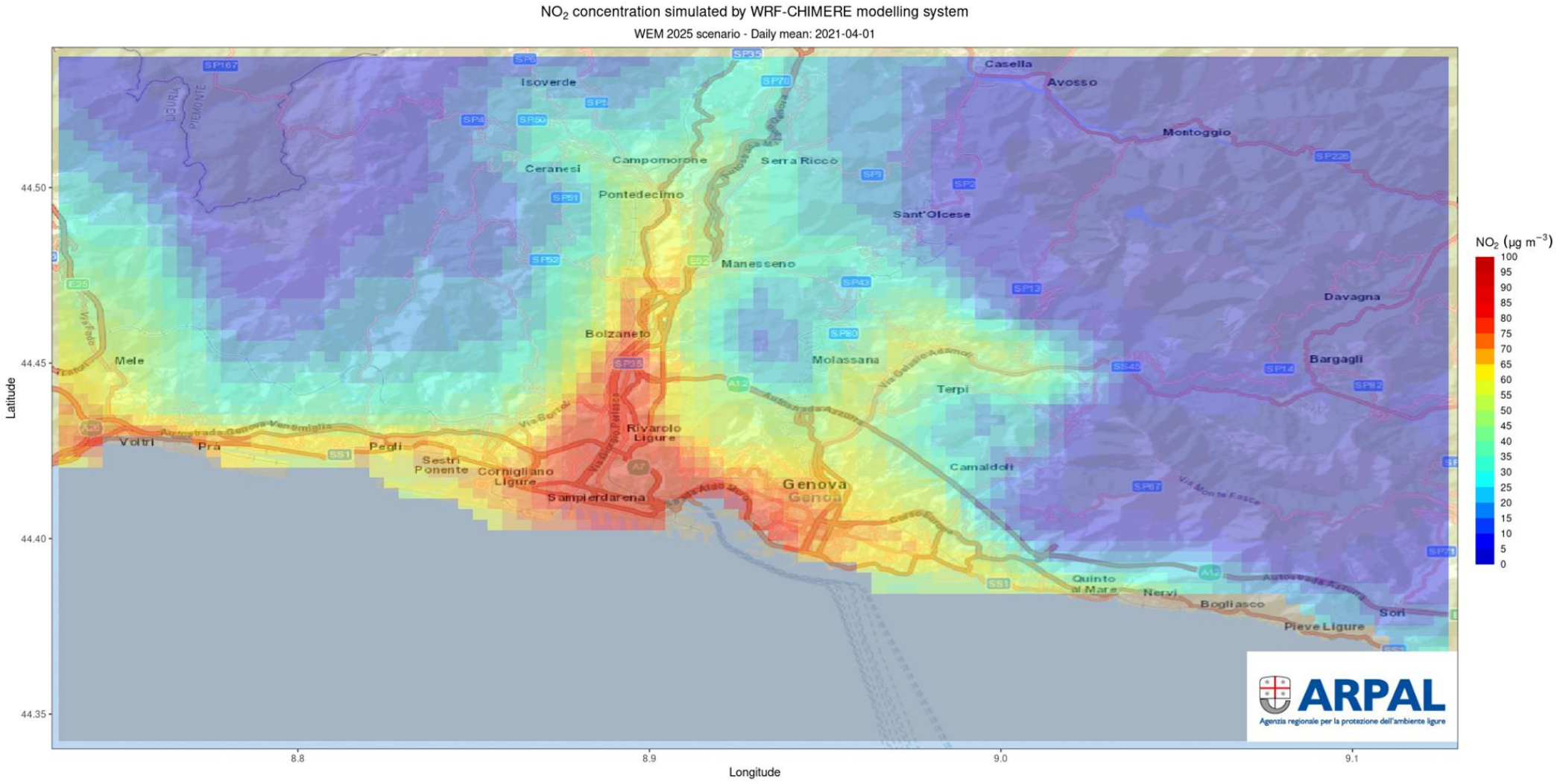
Inner Domain Ld02 (Resolution 1 km)



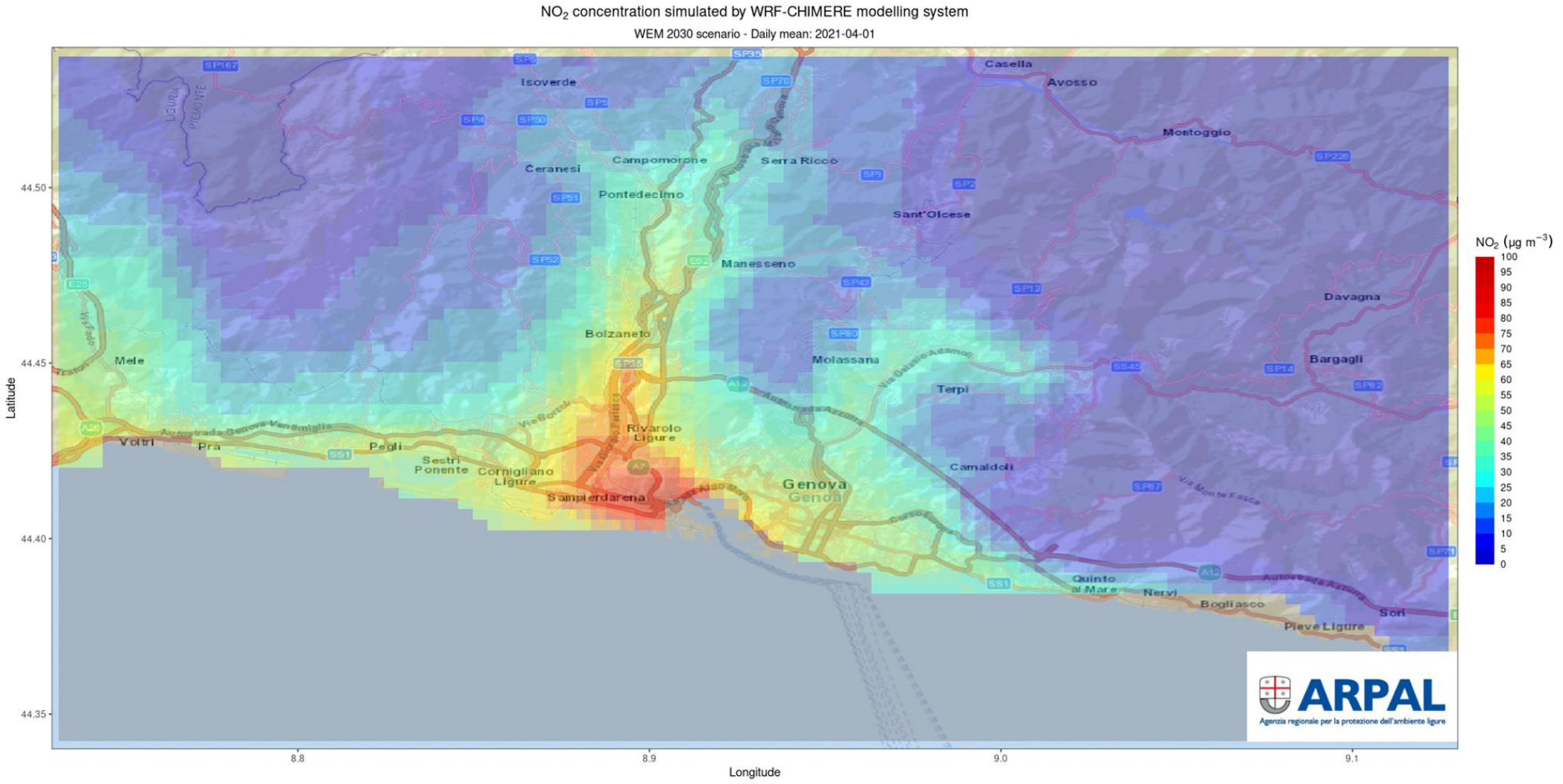
Example of application



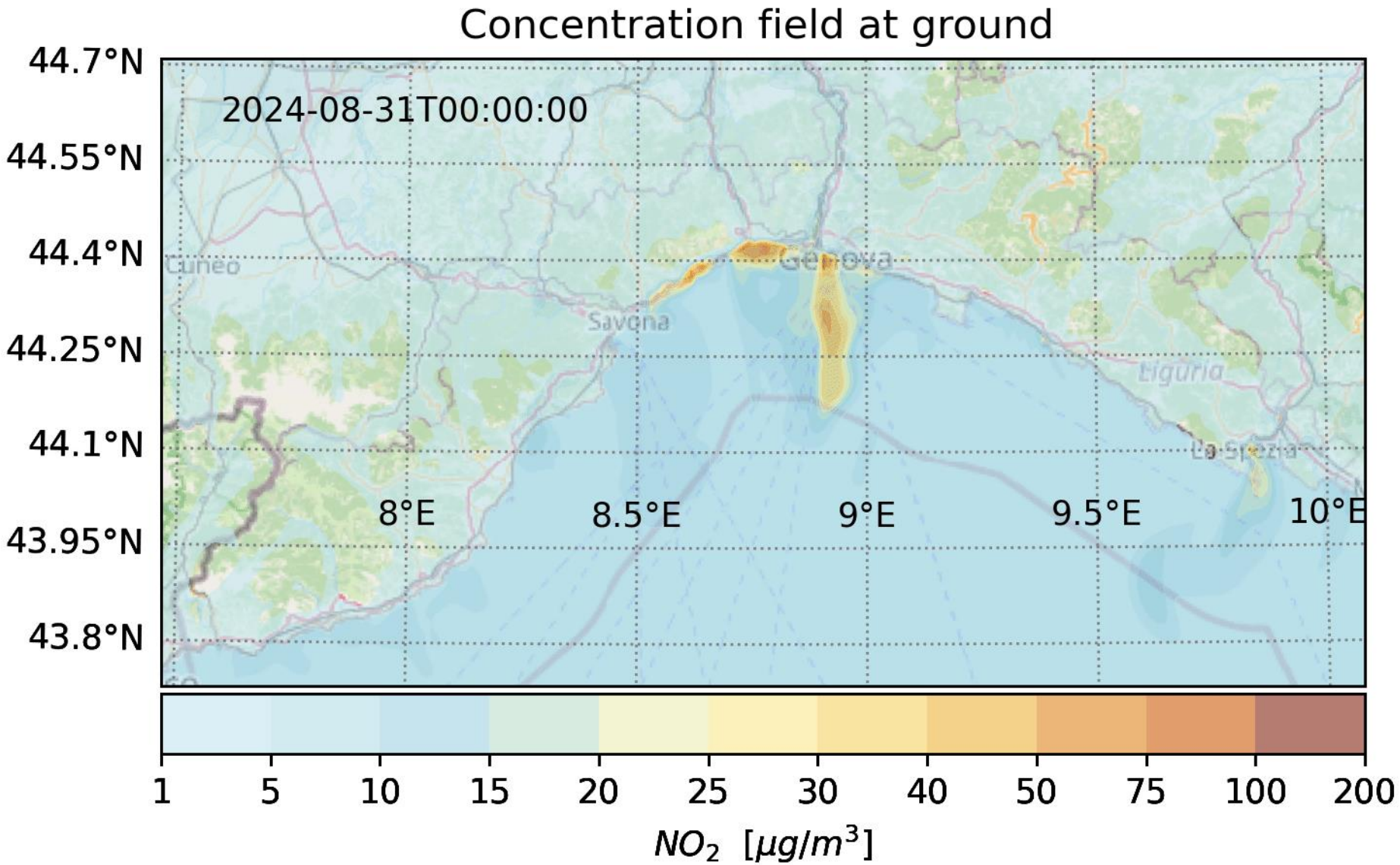
Example of application



Example of application



Example of application

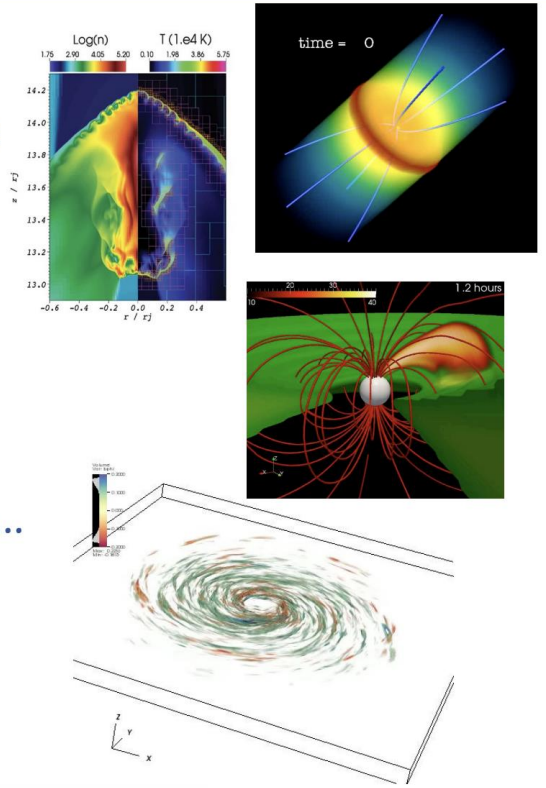


CHIMERE vs PLUTO

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

What is PLUTO ?

- PLUTO[1,2] is a finite volume (FV) Godunov-type, fluid-particle hybrid code for plasma dynamics in astrophysics;
- Target: multidimensional compressible fluid / plasma with large Mach numbers;
- Multiphysics modular support: classical fluid dynamics → special relativistic MHD;
- Non-ideal physics: viscosity, thermal conduction, resistivity, heating, etc…
- Algorithm modularity: combination of different numerical schemes;
- Publicly available at http://plutocode.ph.unito.it (v. 4.4 – CPU version)



[1]Mignone et al. ApJS (2007), 170, 228-242; [2]Mignone et al, ApJS (2012), 198, 7

ICSC Italian Research Center on High-Performance Computing, Big Data and Quantum Computing — Missione 4 • **Istruzione e Ricerca**

Mignone et al. 2024 (https://indico.ict.inaf.it/event/2752/contributions/17505/attachments/8117/16785/Mignone_gPLUTO_Elba2024.pdf=

CHIMERE vs PLUTO

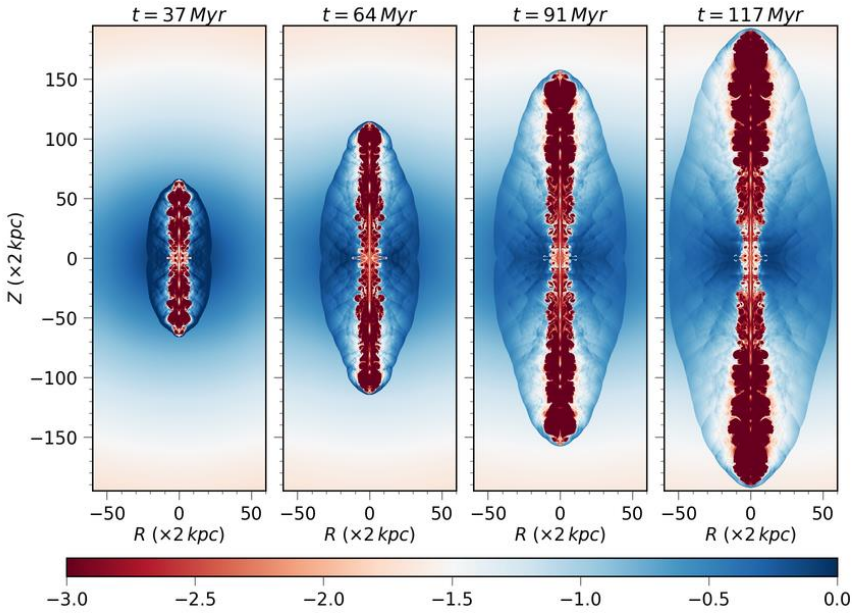
Fluid Equations, Finite Volume

- PLUTO is (primarily) an Eulerian code, solving conservation laws on a fixed / adaptive grid, e.g.:

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) && = 0 && \text{(Mass cons.)} \\
&\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} - \frac{\mathbf{B}\mathbf{B}}{4\pi} + \left(p + \frac{\mathbf{B}^2}{8\pi} \right) \right] && = 0 && \text{(Momentum cons.)} \\
&\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + p + \frac{\mathbf{B}^2}{8\pi} \right) \mathbf{u} - \frac{(\mathbf{u} \cdot \mathbf{B})}{4\pi} \mathbf{B} \right] && = 0 && \text{(Energy cons.)} \\
&\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) && = 0 && \text{(Mag. flux cons.)}
\end{aligned}
$$

- Shock-capturing relies on FV formalism, where equations are solved using the integral representation:

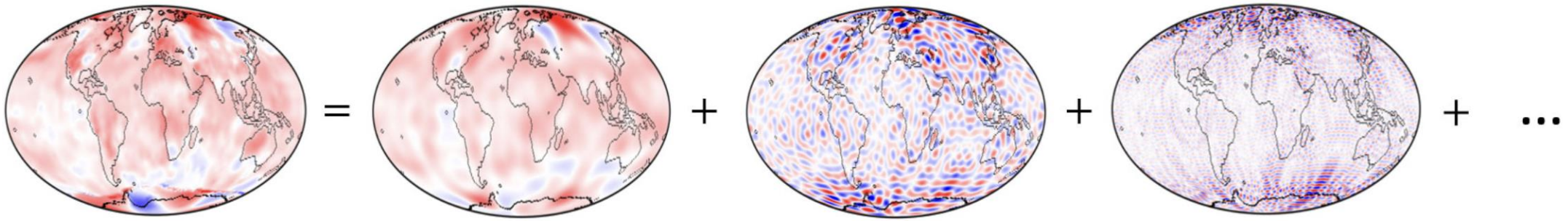
$$\frac{d \langle U \rangle}{dt} = - \oint \mathbf{F} \cdot d\mathbf{S}$$



Mignone et al. 2024
(https://indico.ict.inaf.it/event/2752/contributions/17505/attachments/8117/16785/Mignone_gPLUTO_Elba2024.pdf=

Others…Cosmology and climate change

https://arxiv.org/pdf/2205.07908



To the left is a map of Earth's global temperature. This "total" temperature can also be described as a sum of temperatures on coarse (large) scales, temperatures on finer scales, even finer scales, etc. On large scales we see the well-known climate changes. Albert Sneppen's study documents that the temperature differences become stronger on small scales (credit: Albert Sneppen).

Others…
Astronomy and Climate change

The impact of Astronomers in climate change

https://www.nature.com/collections/fhfcdebecc

https://arxiv.org/pdf/2201.08748

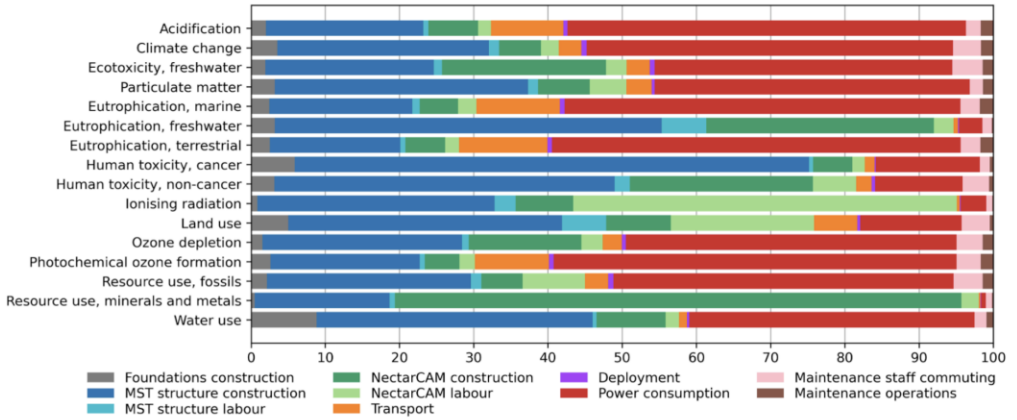
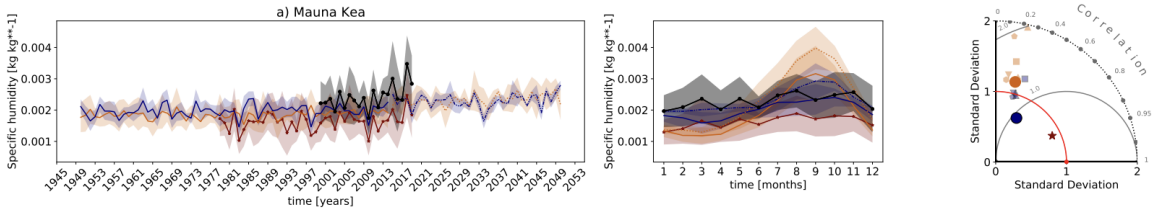


Figure 1. Contribution of activities to the life cycle impacts of one MSTN. Horizontal bars correspond to different environmental impact categories, the various activities are distinguished by different colours. All bars sum up to a total of 100%.

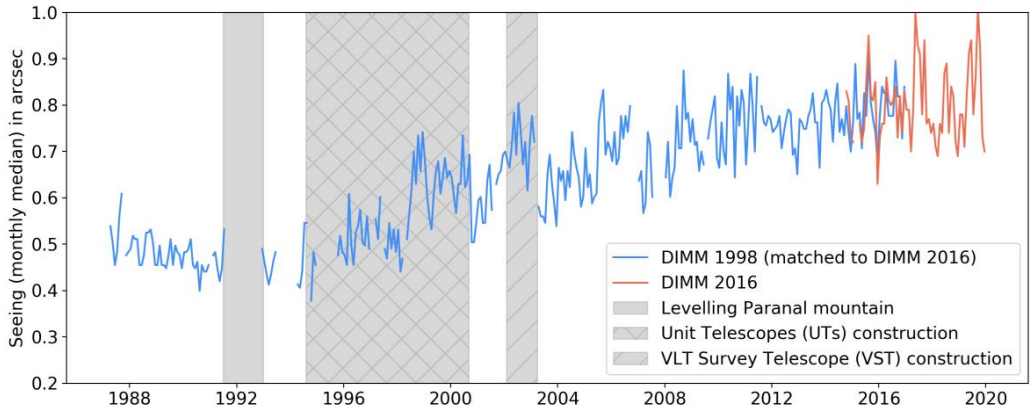
https://arxiv.org/pdf/2406.17589

https://arxiv.org/pdf/2407.16011

The impact of climate change in Astronomy



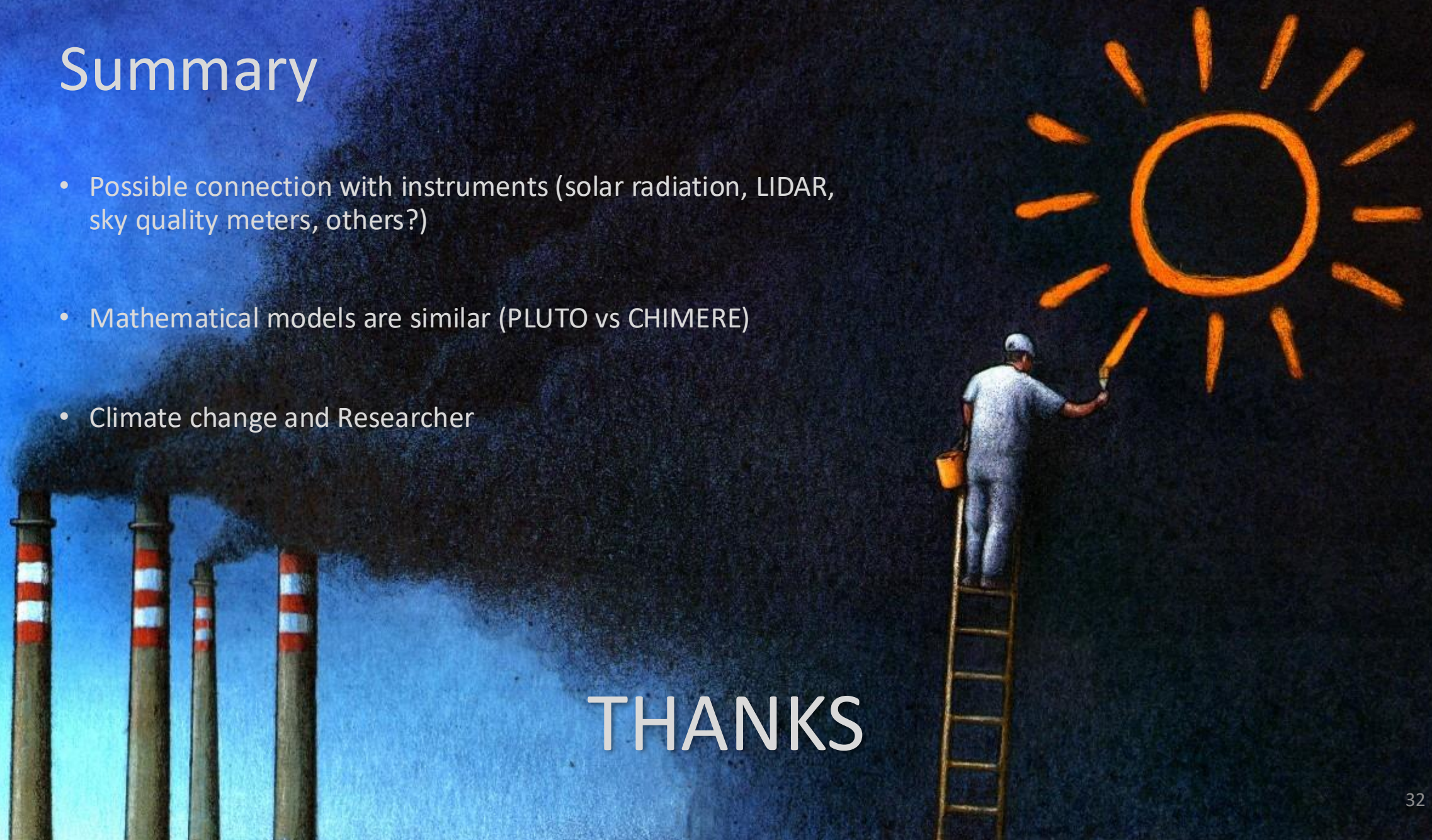
https://www.aanda.org/articles/aa/pdf/2022/09/aa42493-21.pdf



https://arxiv.org/pdf/2009.11779

Summary

- Possible connection with instruments (solar radiation, LIDAR, sky quality meters, others?)
- Mathematical models are similar (PLUTO vs CHIMERE)
- Climate change and Researcher



THANKS