

A Brief Introduction to Numerical Weather Prediction Models

Ciudad de México

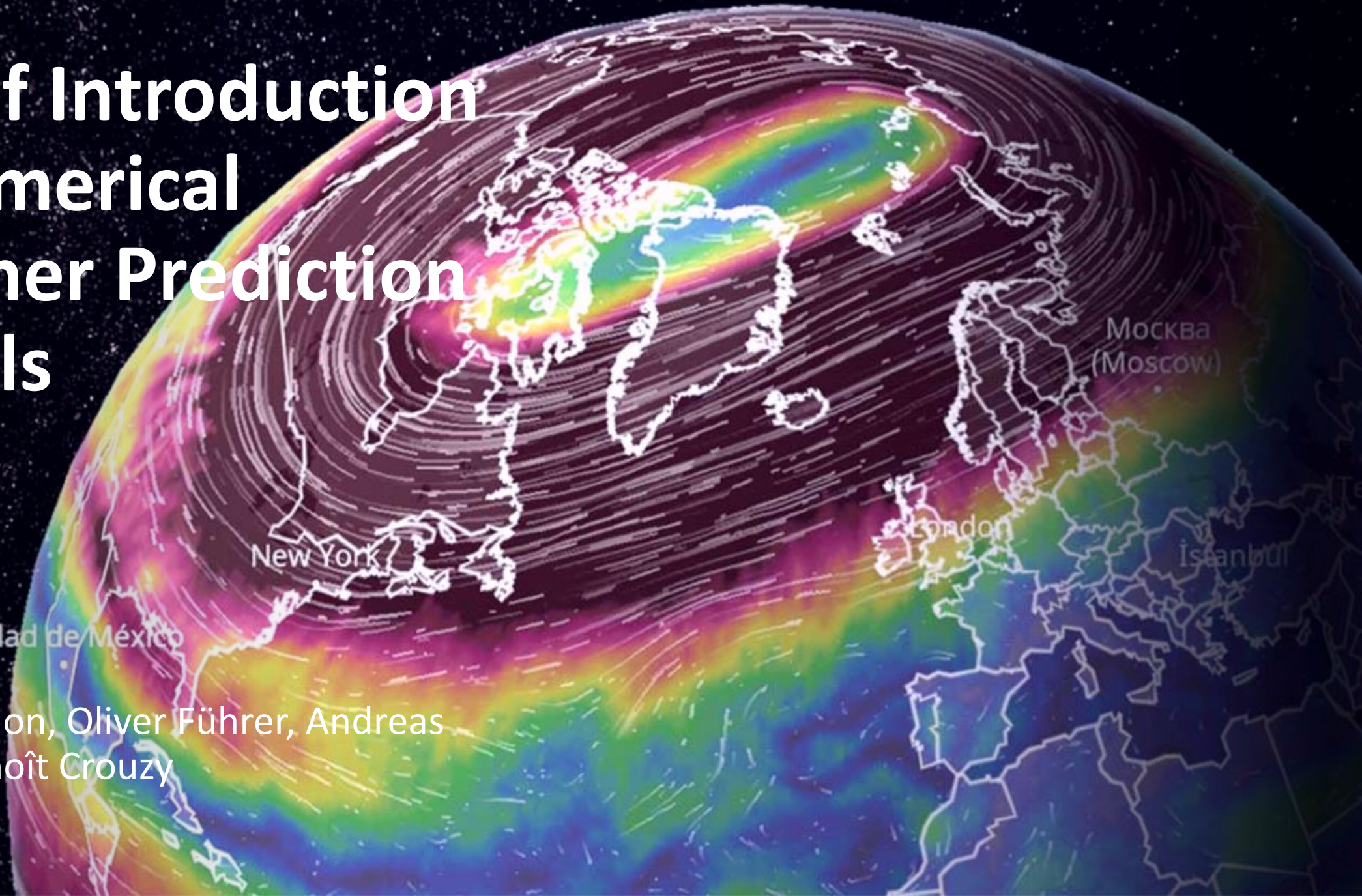
New York

London

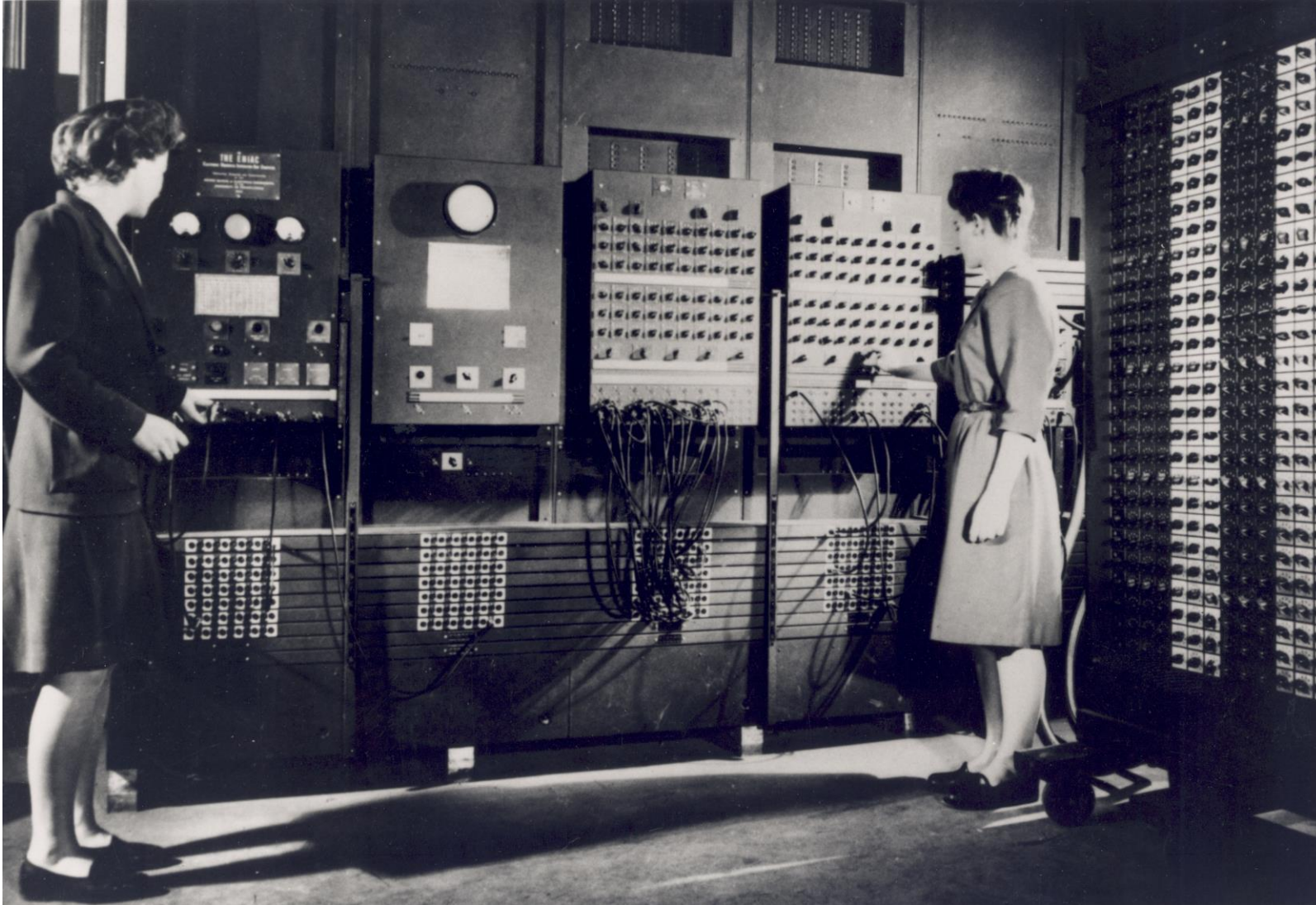
Москва
(Moscow)

İstanbul

Fiona Tummon, Oliver Führer, Andreas
Pauling, Benoît Crouzy



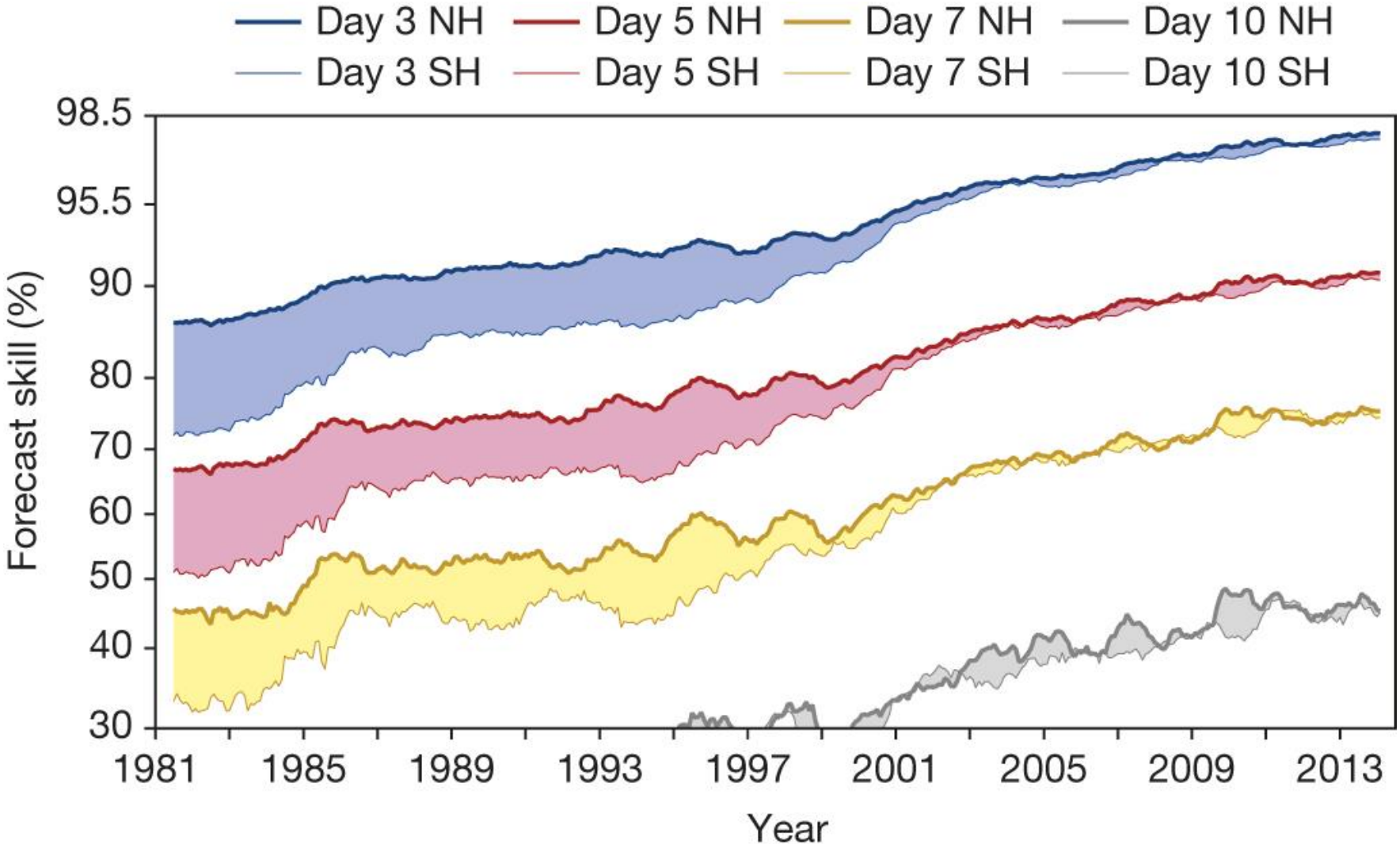
It all started quite a long time ago...



ENIAC was used for the first computer-based weather forecasts

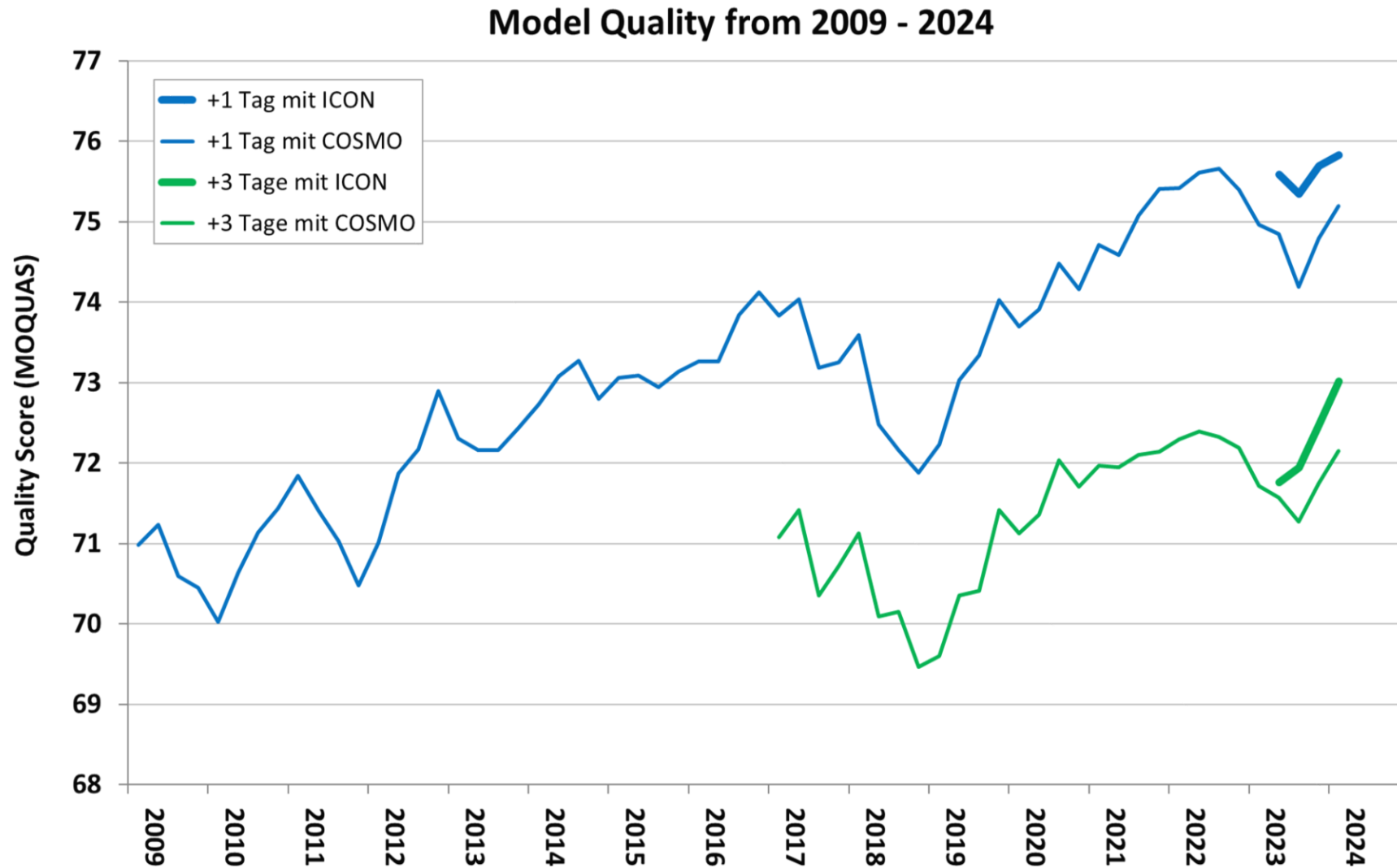
First time that computation time < the forecast period itself!

Forecast skill has improved dramatically



Bauer et al., 2015, doi: 10.1038/nature14956

MeteoSwiss forecast skill

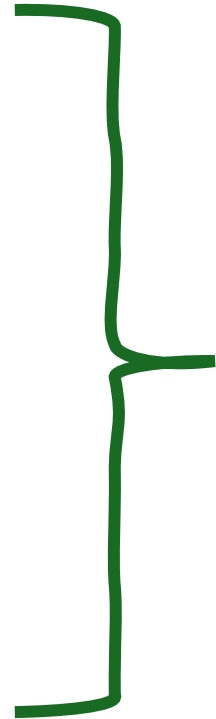




Building a model

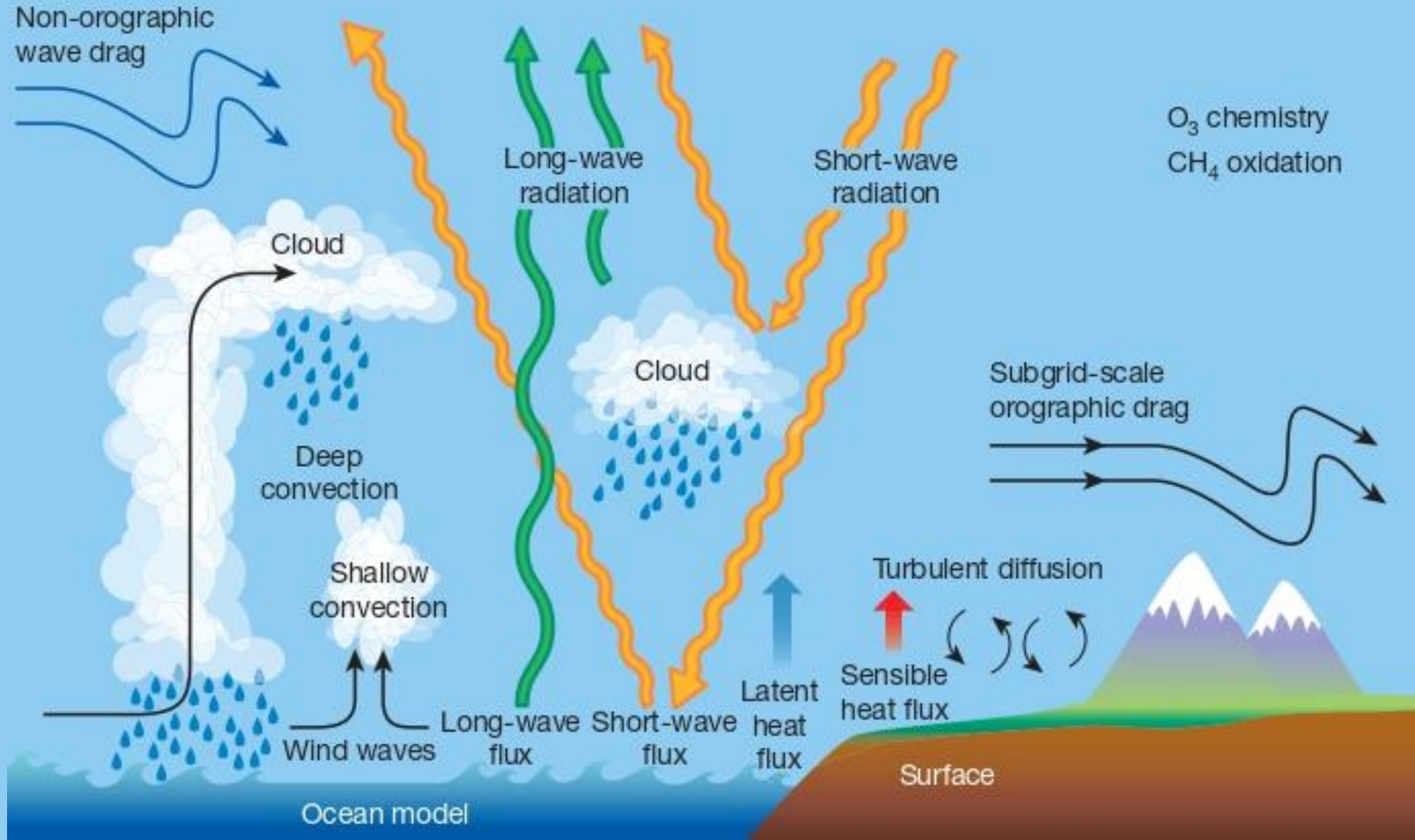
These models are built on dynamical cores:

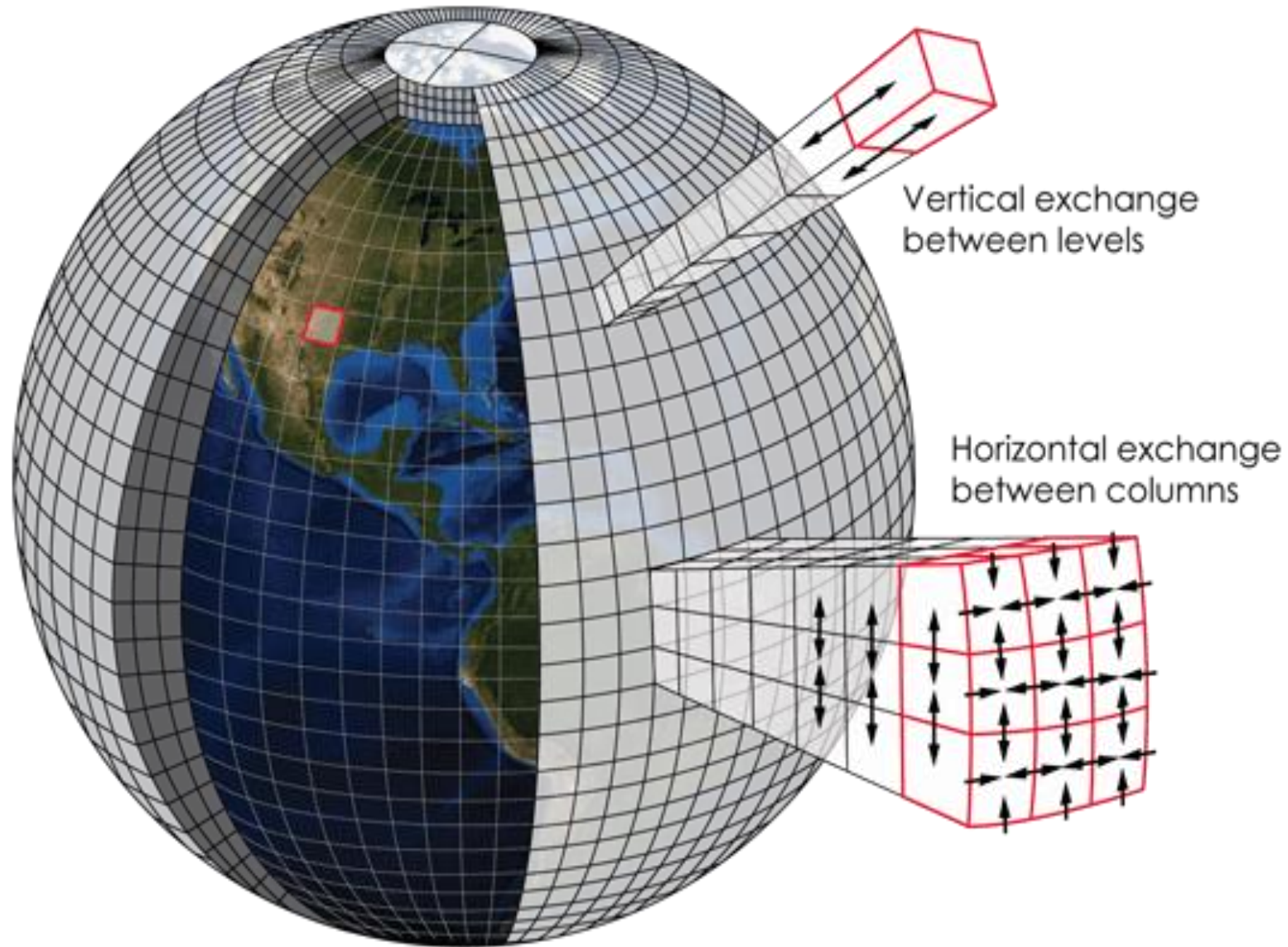
- Equations of motion
- Equations of state
- Thermodynamic equation
- Mass balance equation
- Water balance equation
- ...
- ...



**How air moves +
exchanges of heat
and moisture**

Atmospheric processes





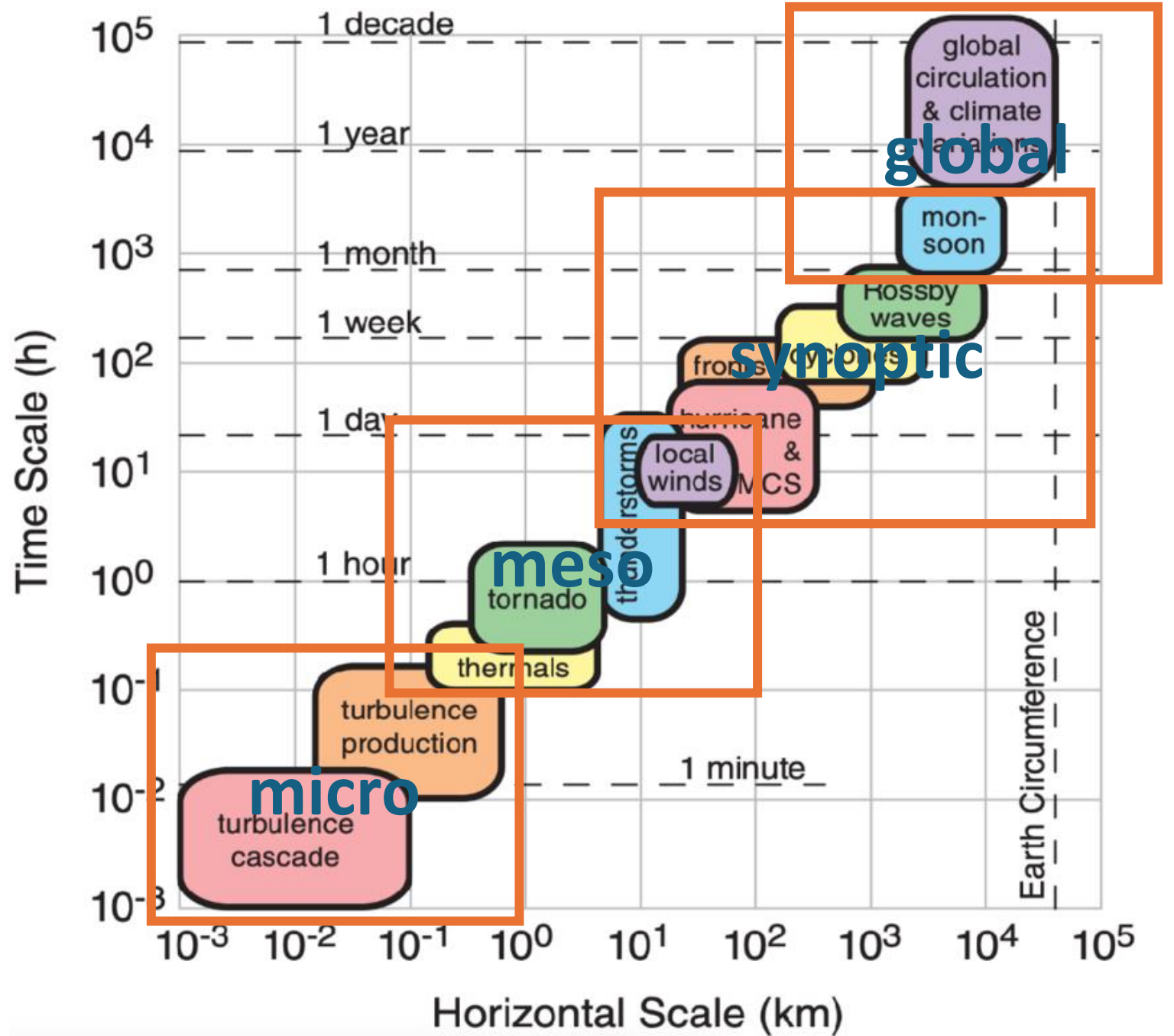
Variables at the surface:

- Temperature
- Humidity
- Pressure
- Moisture fluxes
- Heat fluxes
- Radiation fluxes

Variables in the atmospheric column:

- Wind vectors
- Humidity
- Clouds
- Temperature
- Height
- Precipitation
- Aerosols

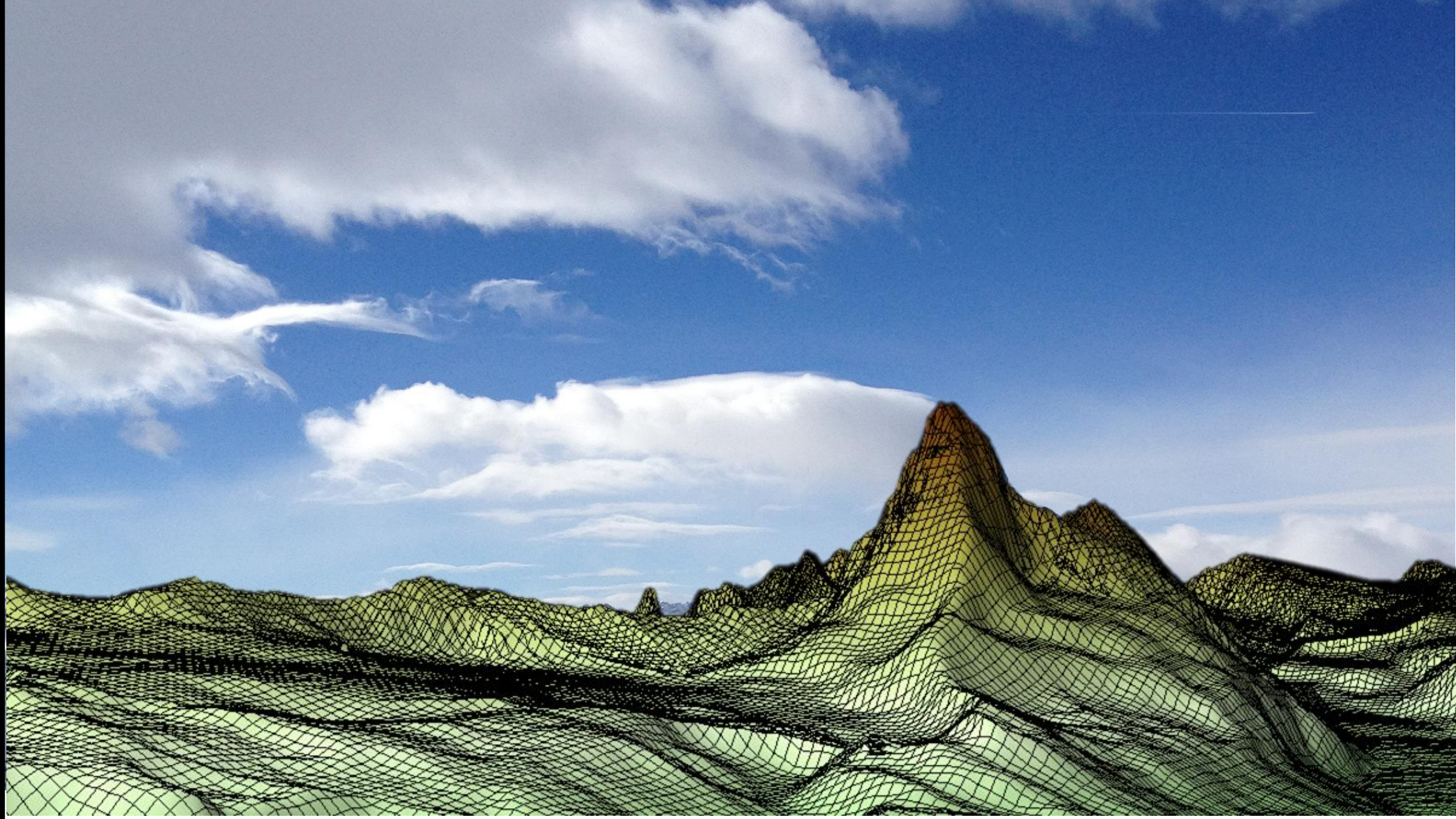
A question of scales

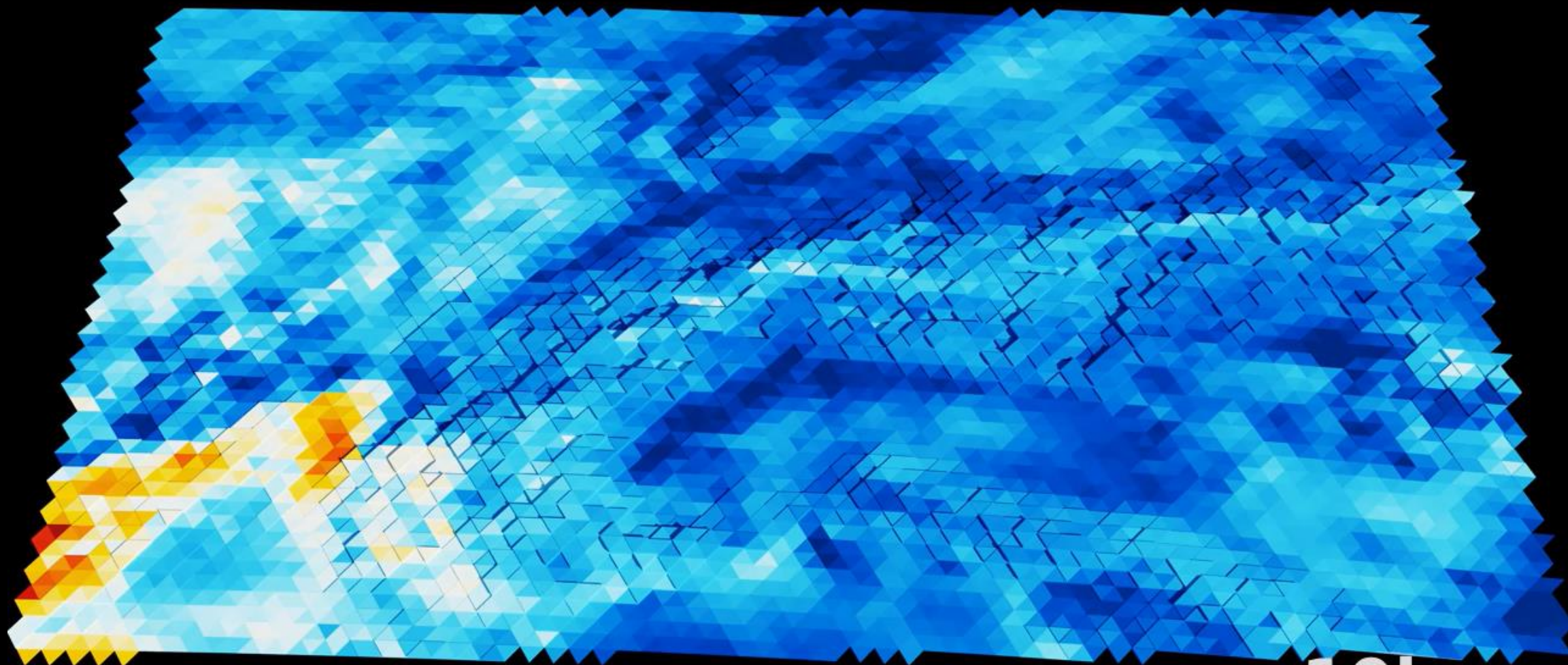


Model Resolution



Model Resolution

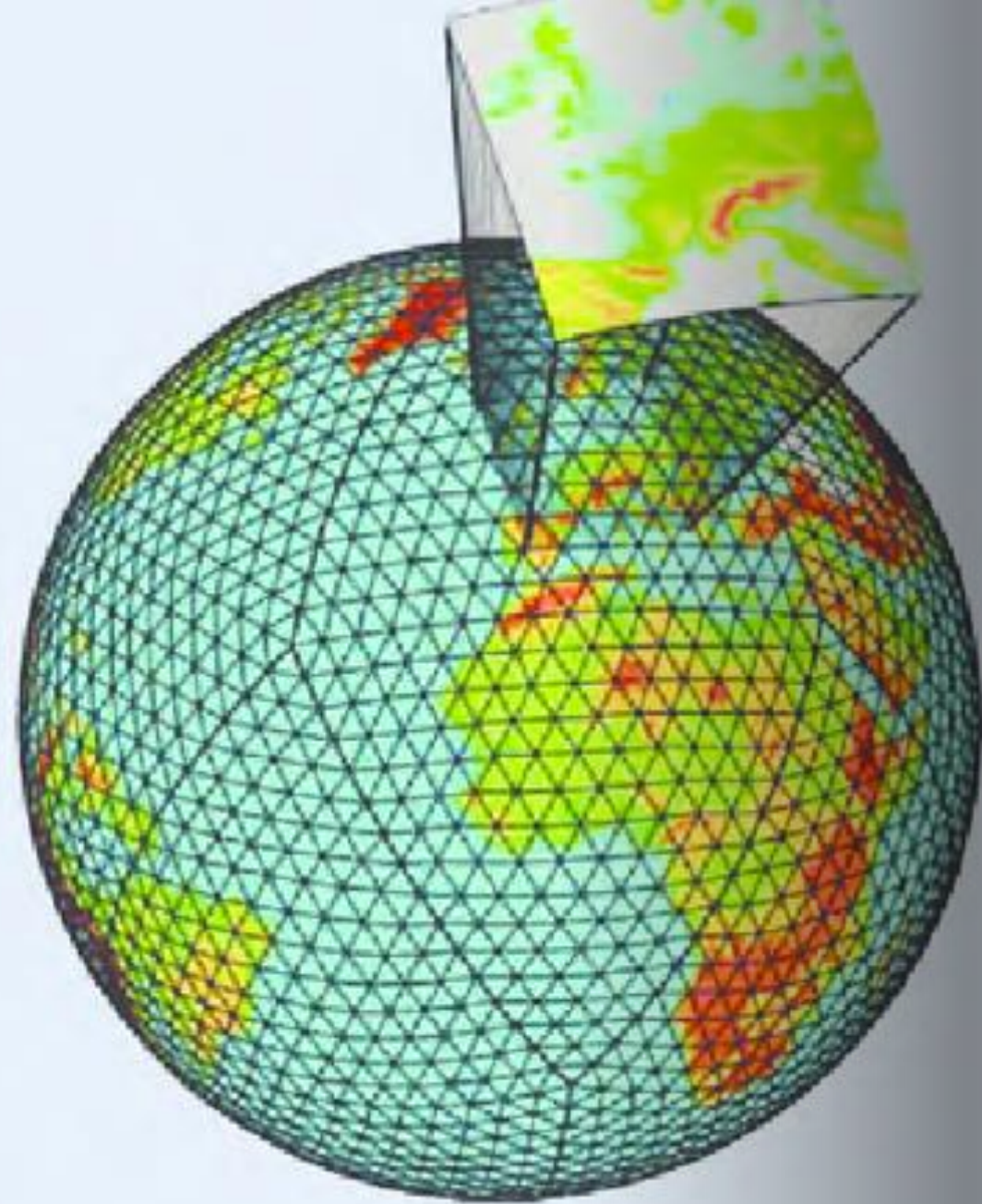
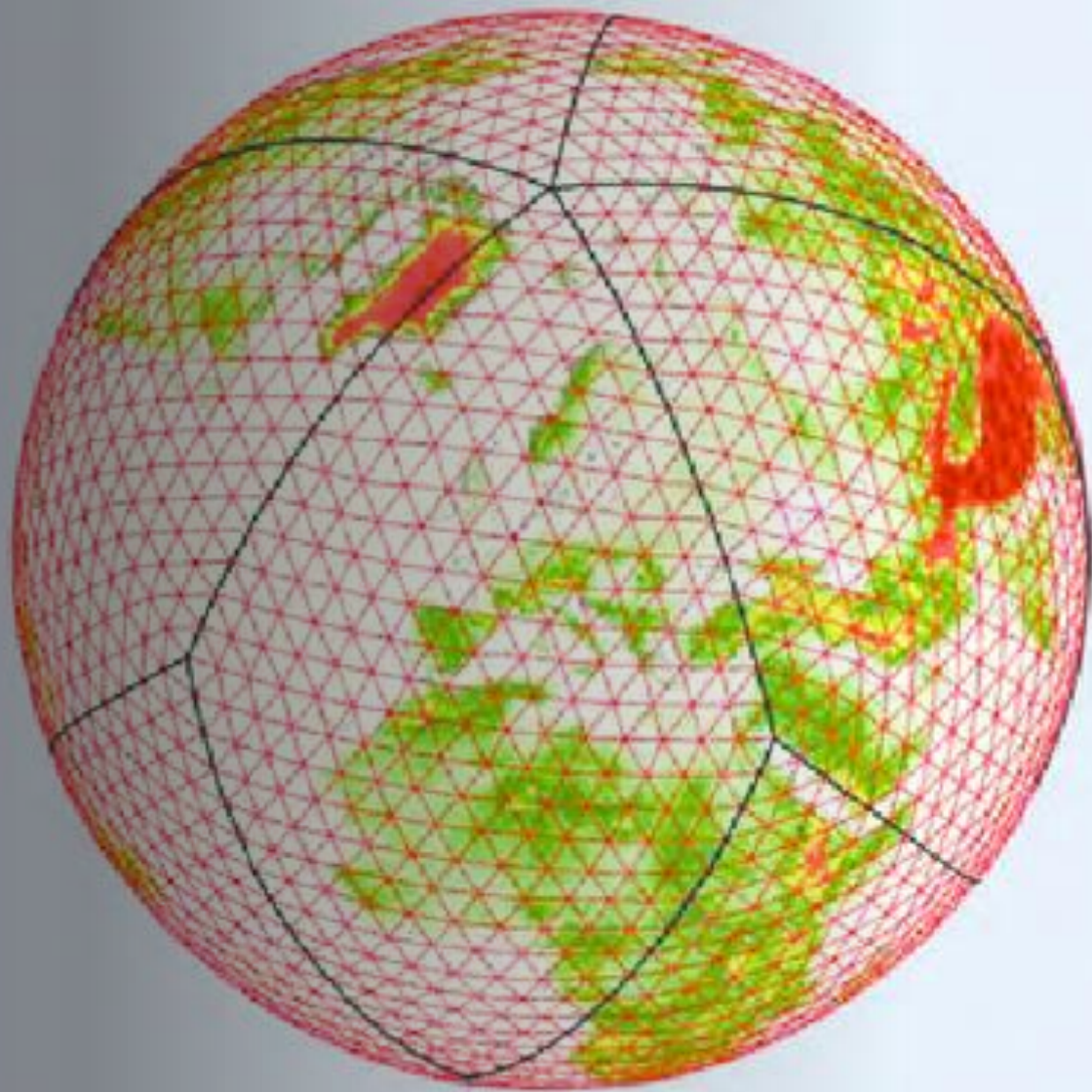




10km

23.08.2023 10am - 6pm

Model grids



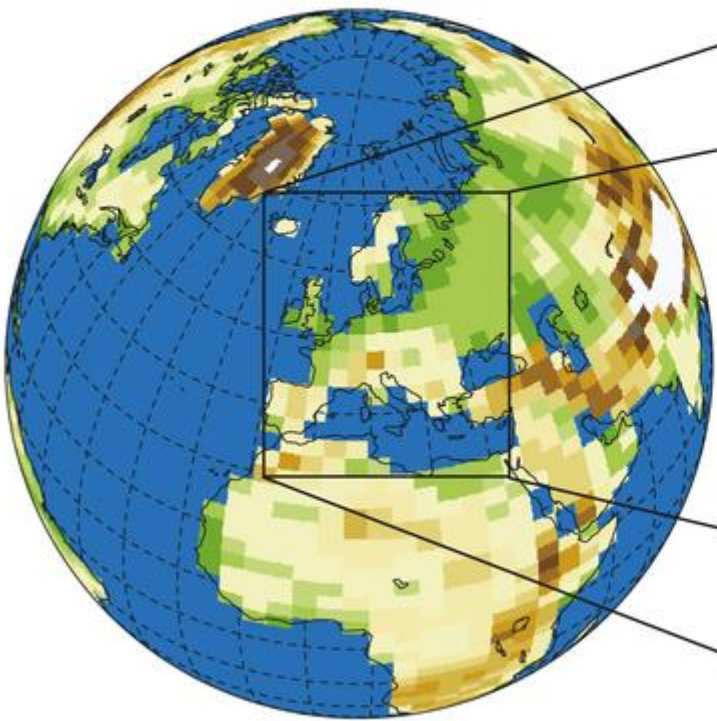
ICOsahedral Nonhydrostatic model

- Developed by DWD and Max-Planck-Institut of Meteorology
- Belongs to newest-generation NWP models
- Use of triangular mesh
- Suited for global and local modelling
- More stable in steep orography than COSMO
- Large developer community

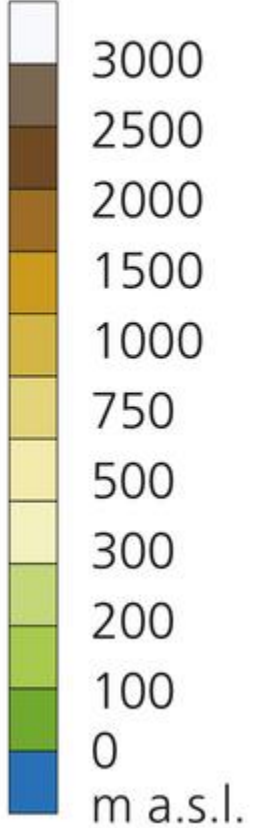
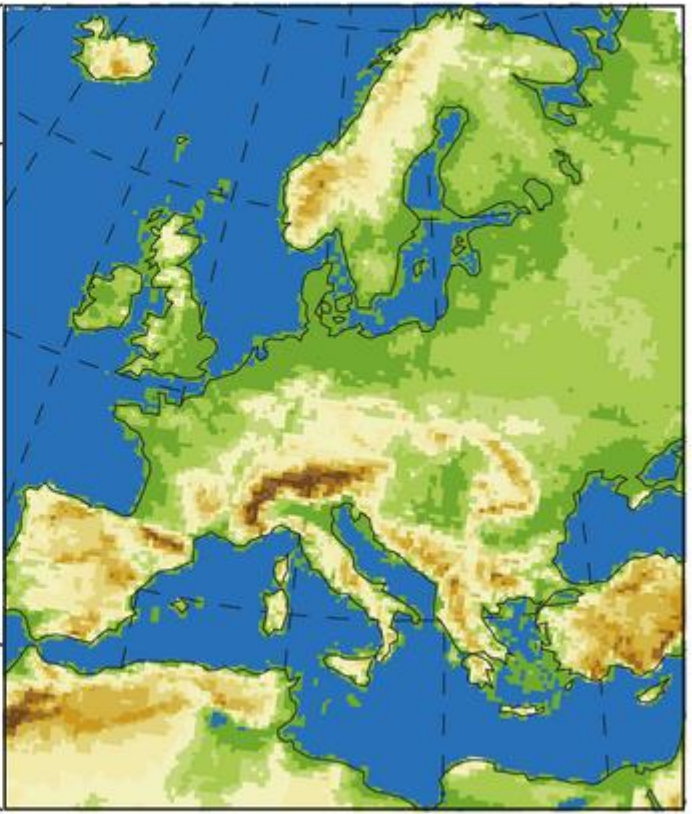


Regional downscaling

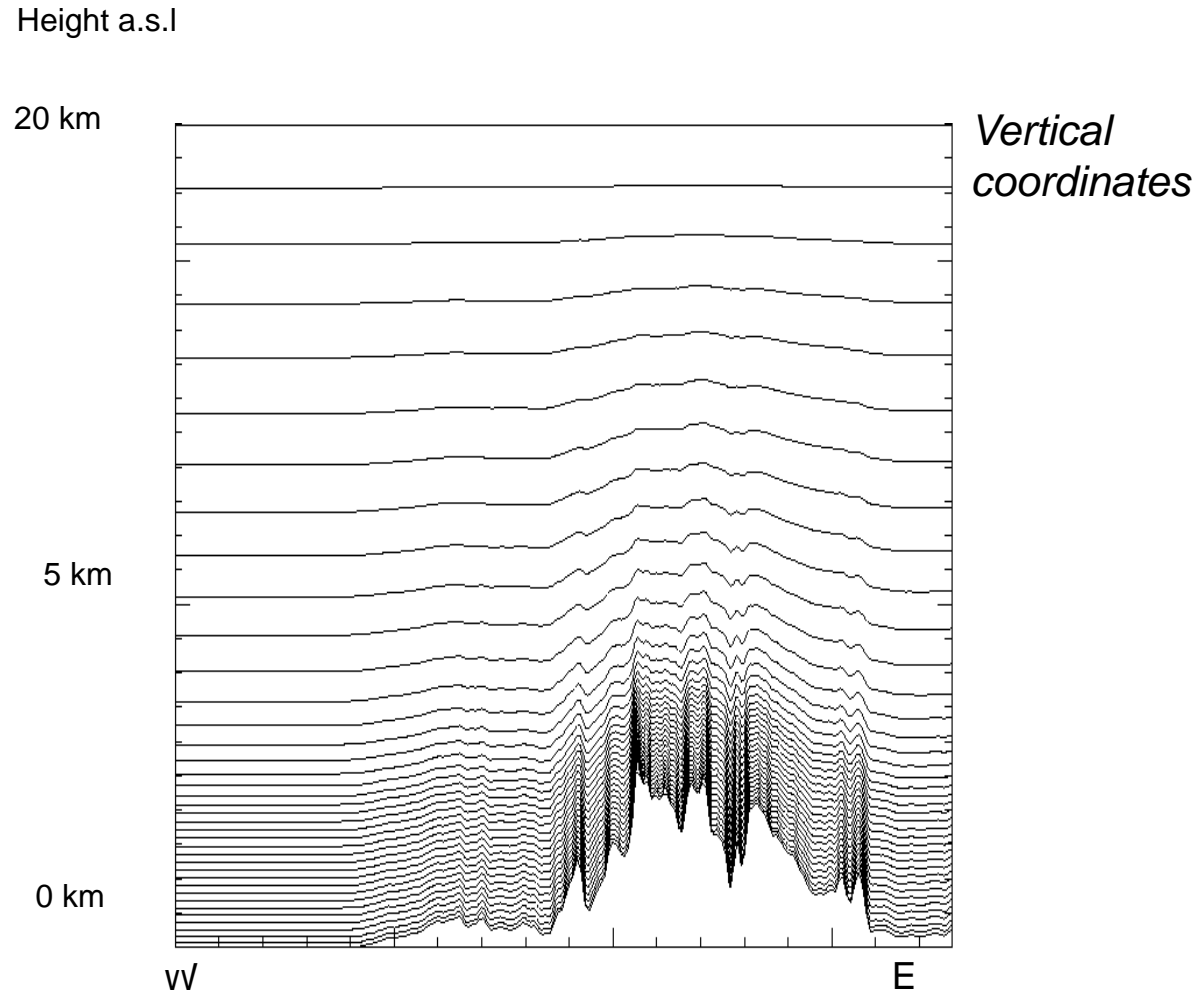
Global Climate Model



Regional Climate Model
(EURO-CORDEX)



Vertical resolution



Global Models

Geopotential heights of constant-pressure surfaces

Regional Models

Normalized pressure coordinates (sigma coordinates)

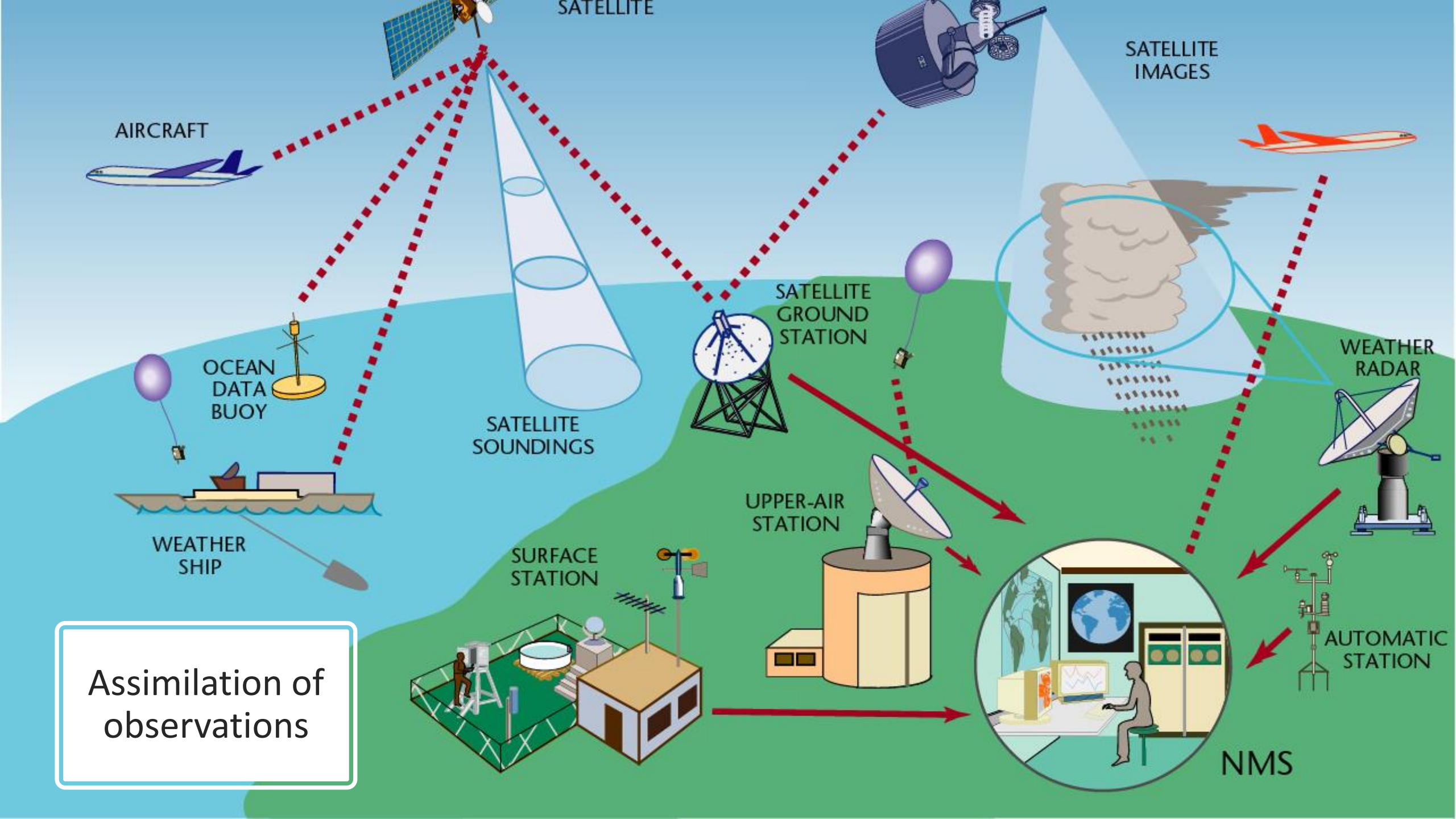


Parameterisation

- Phenomena whose **spatial scales** are **smaller** than the model grid scale can not be explicitly described.
- Other phenomena are **too complex** to be represented using basic physical principles (e.g. turbulence or cloud microphysics).
- These types of phenomena are accounted for in an *approximate* way by relating them to variables on the scale the model does resolve, this is called **parameterization**.



Step 1: Initialisation



Assimilation of observations

Data assimilation

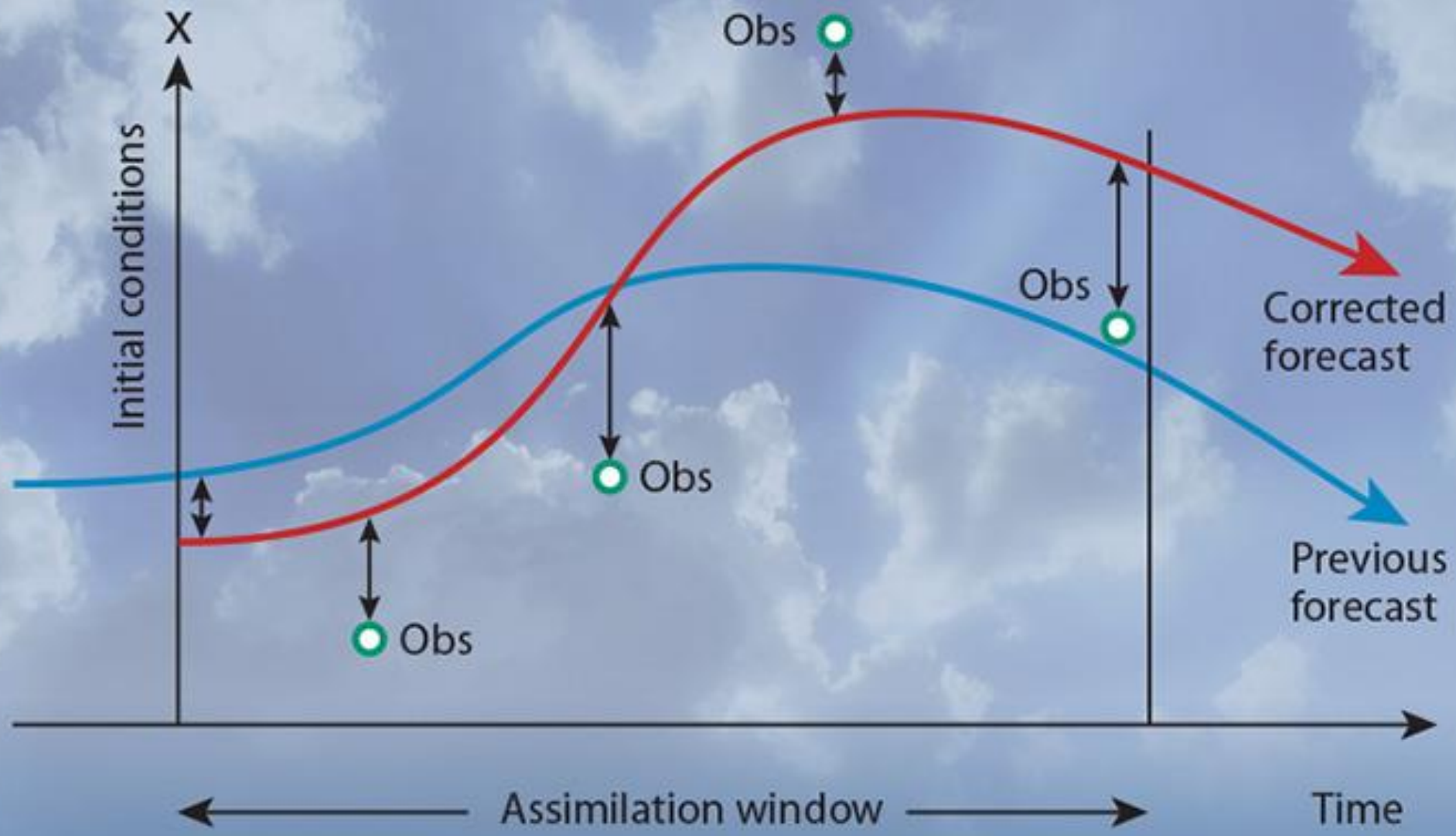
The process of combining different sources of information about an observed system, weighted by their respective uncertainty, to get the best possible estimate of a system's true state

Kalman filters (KF, EnKF, ETKF, LETKF,...)

Variational methods (3D-Var, 4D-Var,...)

Particle filters

Hybrid methods (EnVar,...)

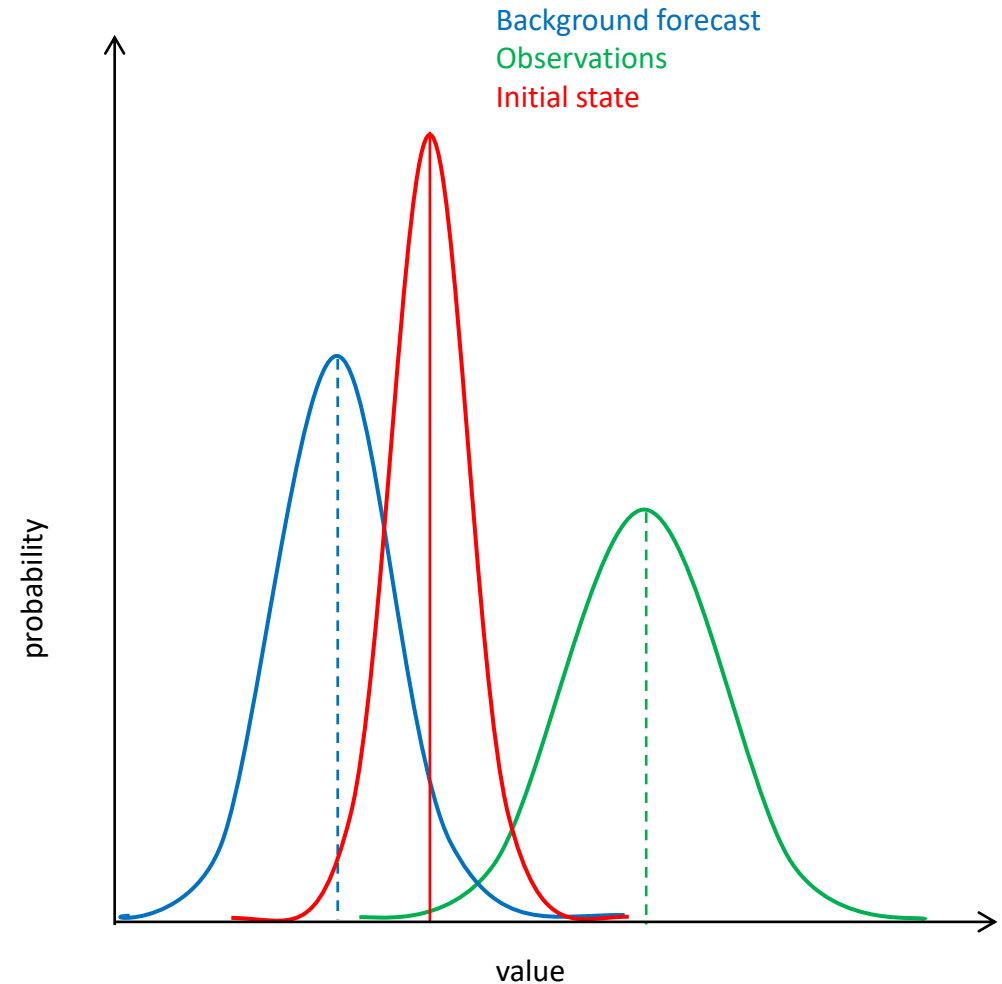


Ensemble data assimilation

$$\underbrace{\bar{x}_k^a}_{\text{Initial state mean}} = \underbrace{\bar{x}_k^b}_{\text{Background forecast mean}} + \underbrace{K_k \cdot [y_k^o - H\bar{x}_k^b]}_{\text{Correction term: weighted difference between model and observations}}$$

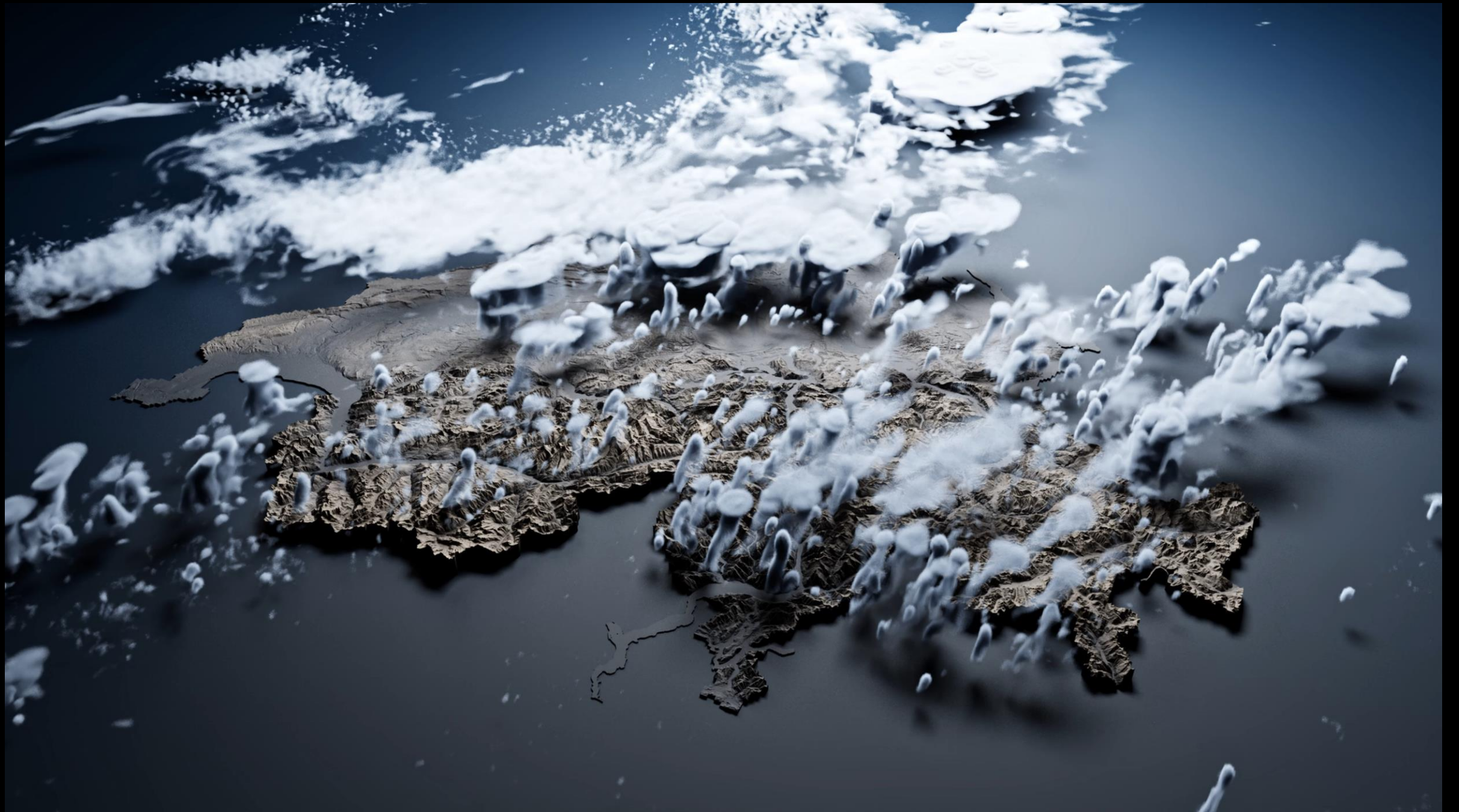
k : time step
 y_k^o : observations
 H : observation operator

$K_k = P^b H^T [H P^b H^T + R]^{-1}$: Kalman gain matrix
 P^b : forecast error covariance matrix
 R : observation error covariance matrix

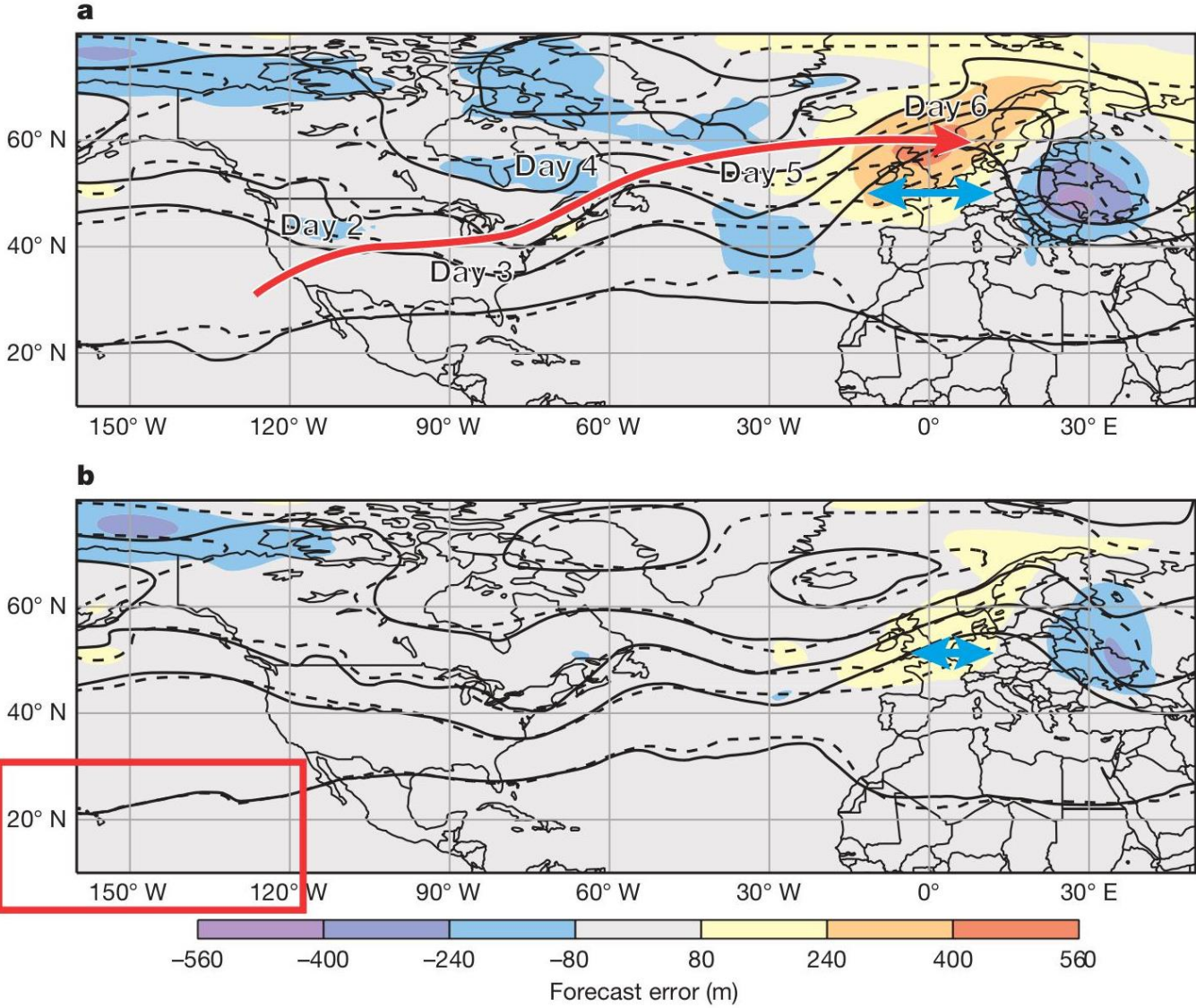




Step 2: Simulation



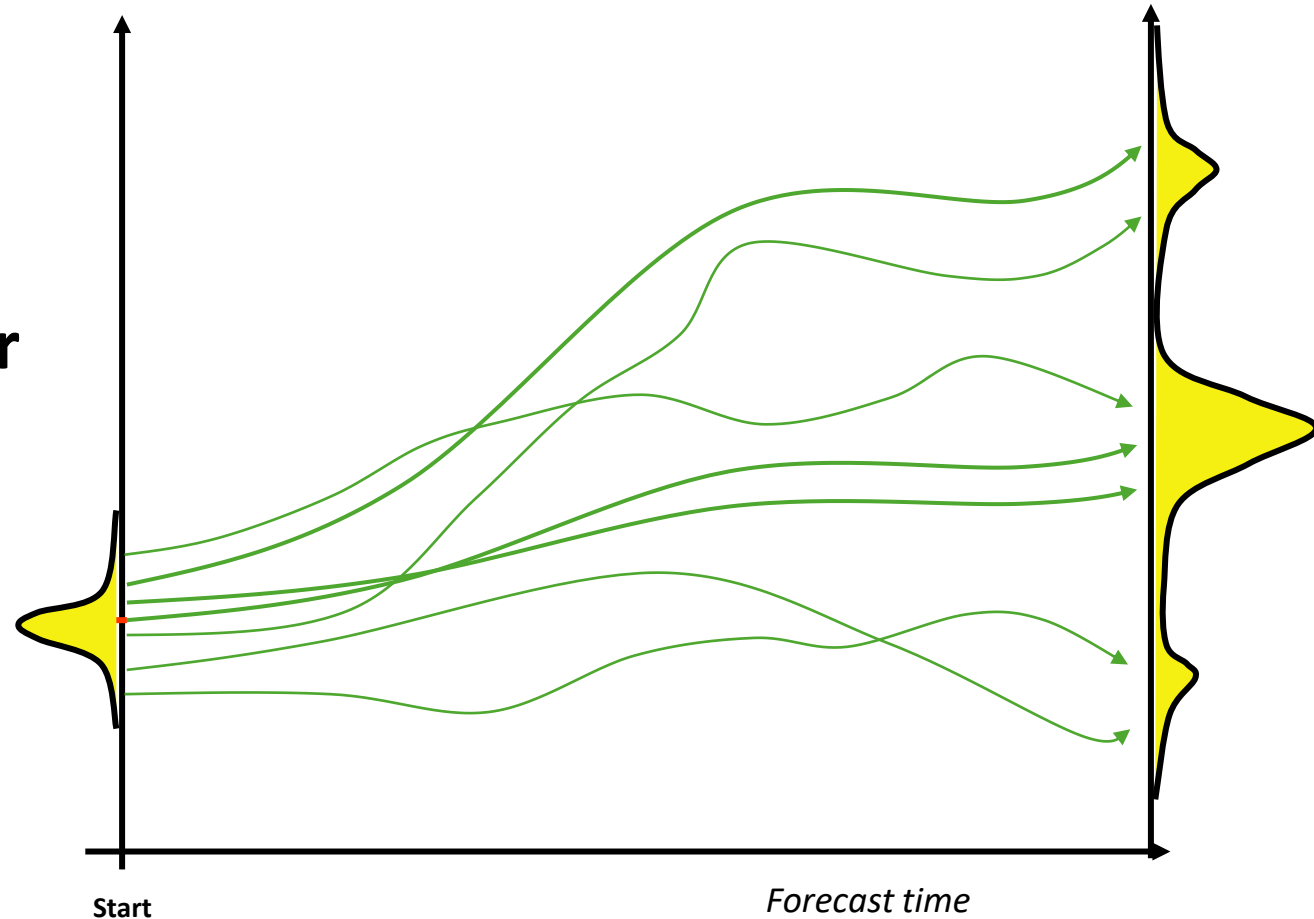
Error propagation



Bauer et al., 2015, doi: 10.1038/nature14956

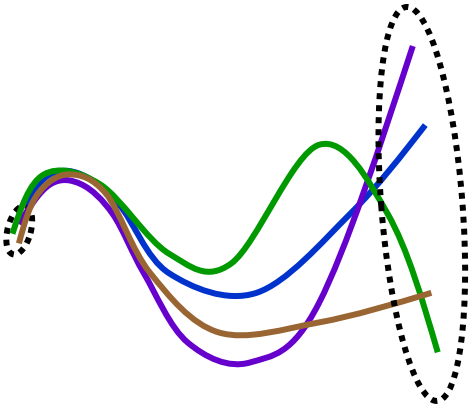
Ensemble forecasts

- Even when predictability is limited, **probabilistic information** can be computed
- Provides information about the **error of the forecast**
- Compute an **ensemble of forecasts**, each starting from slightly different initial conditions

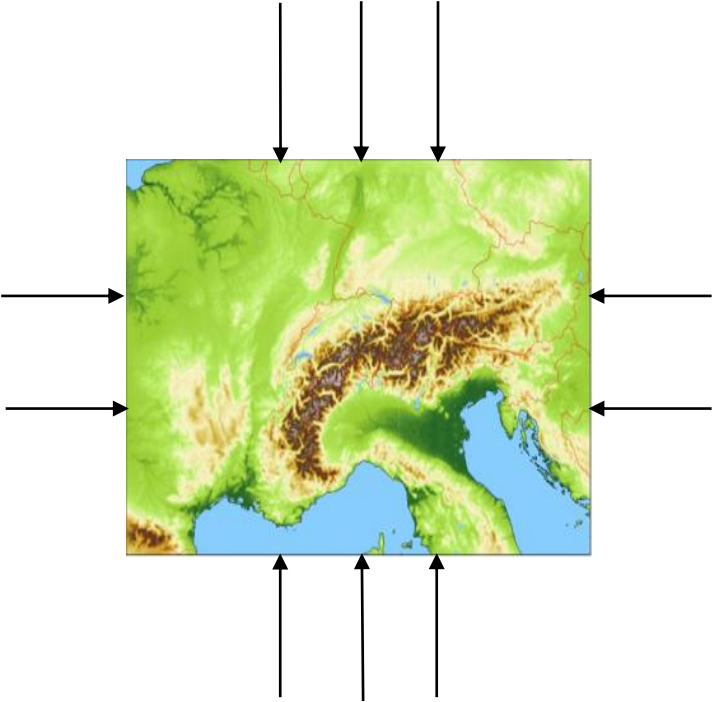


Uncertainty in ensembles

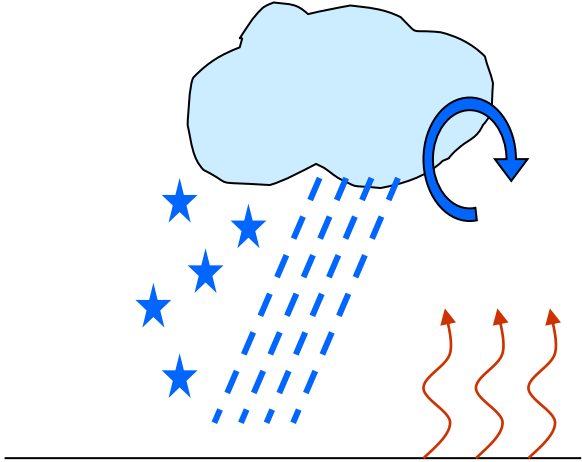
initial conditions



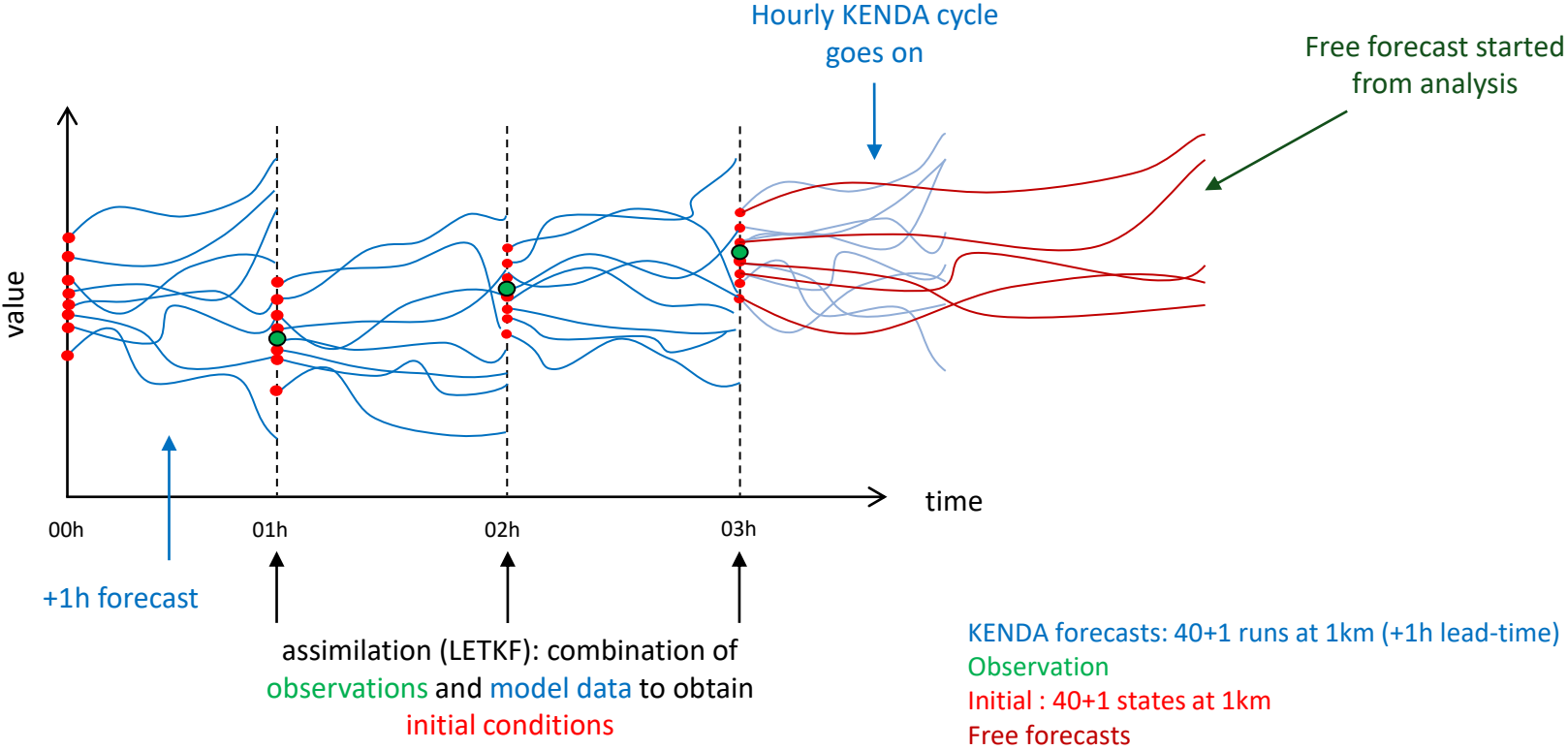
boundary conditions



model physics



Kendall update cycle



ECMWF ensemble forecast

ECMWF Ensemble forecasts

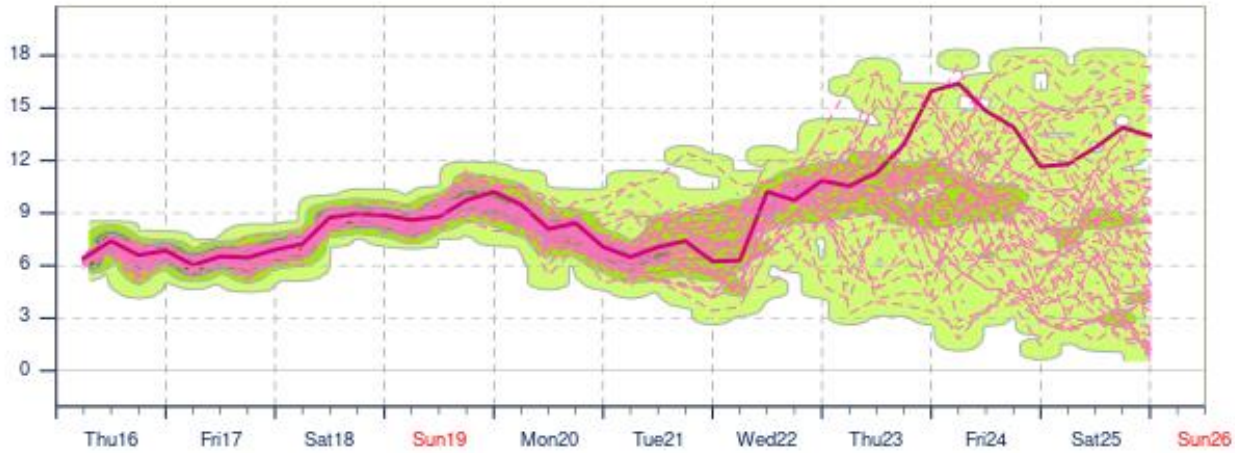
Genève - Geneva - Switzerland 46.22°N 6.17°E (ENS land point) 375 m

Control Forecast and ENS Distribution

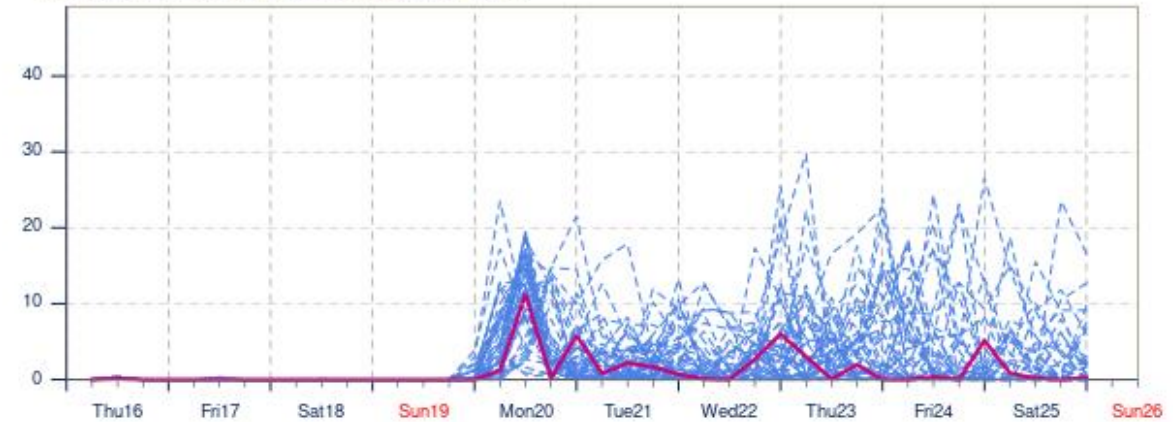
Thursday 16 October 2025 00 UTC



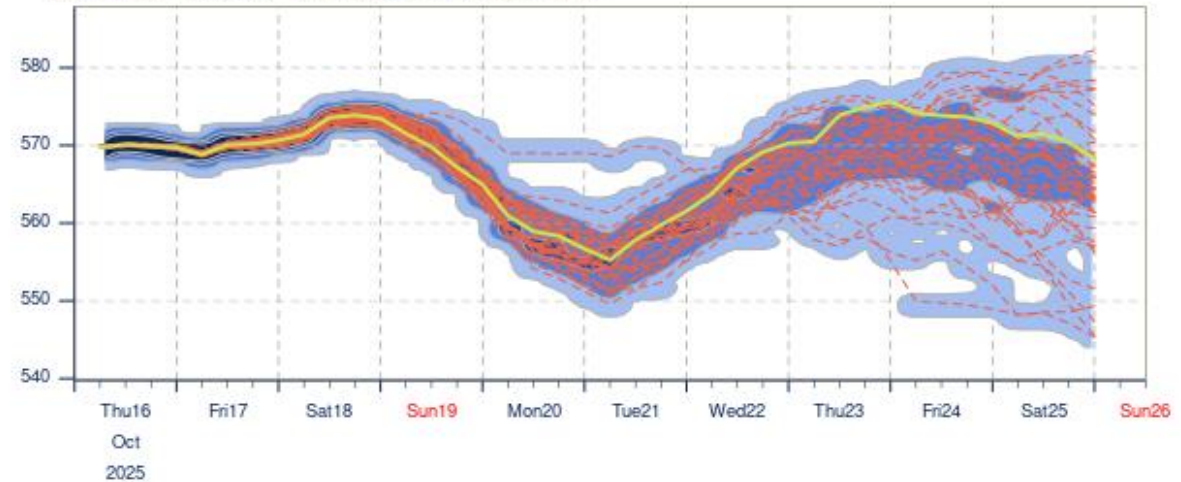
Temperature at 850 hPa - Probability for 1°C intervals



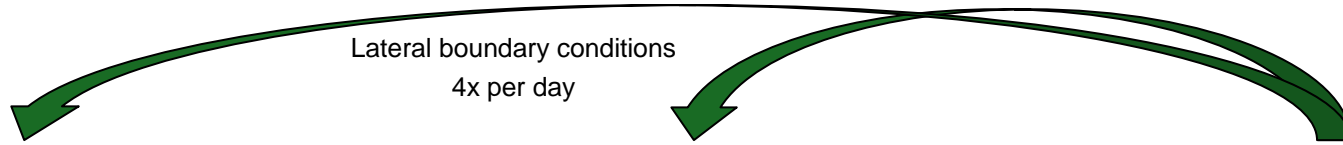
Ensemble members of Total Precipitation (mm/6h)



Geopotential at 500 hPa -- Probability for 2.5dam intervals



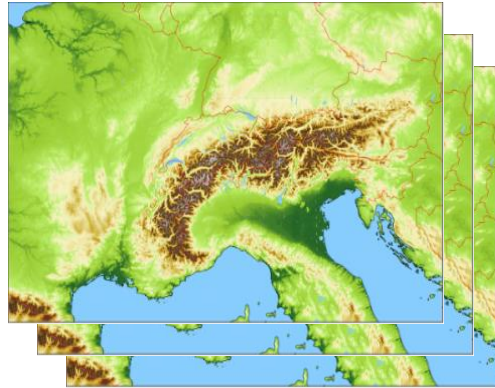
Ensembles at MeteoSwiss



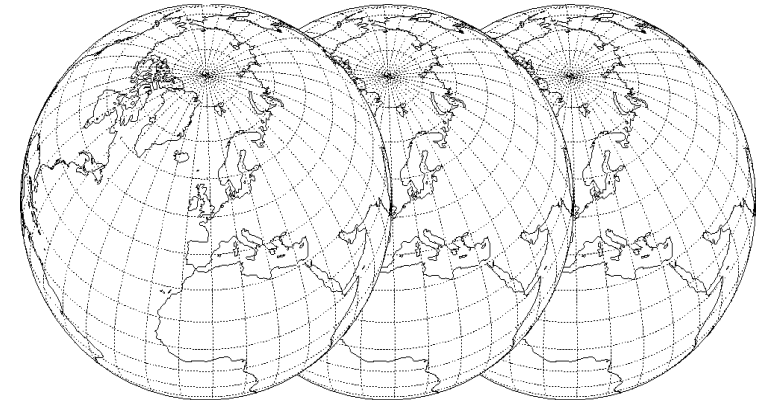
ICON-CH1-EPS: 33-hour forecasts, 8x per day
1.1km grid size (convection permitting)
11 ensemble members

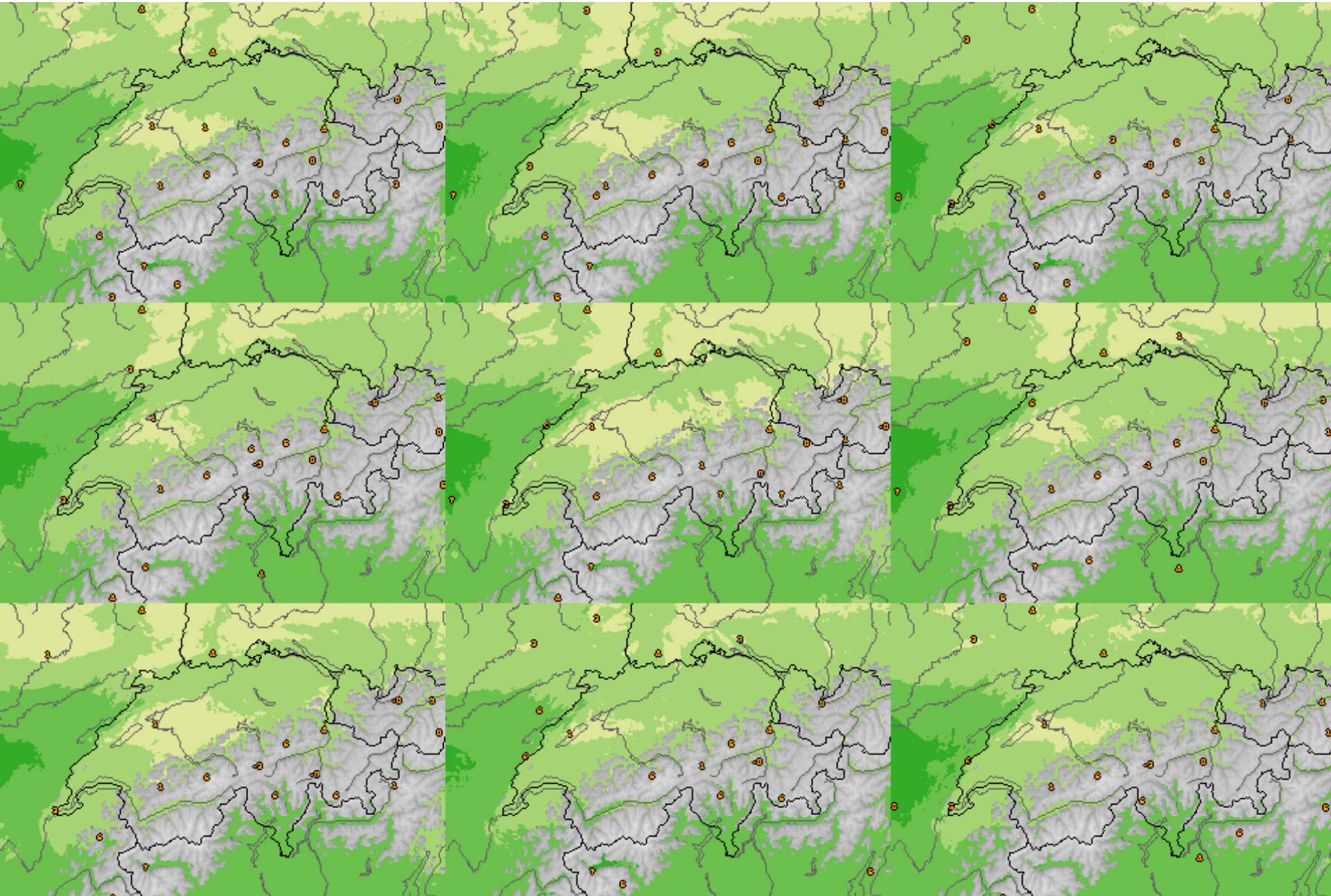


ICON-CH2-EPS: 5- day forecasts, 4x per day
2.2km grid size (convection permitting)
21 ensemble members



ECMWF IFS ENS 15 days, 2x per day, 18km /
0.2°
51 ensemble members





Temperature, 850 hPa

ICON-CH1-EPS

Valid for: 17.10.2025 06 UTC

Run: 17.10.2025 06 UTC

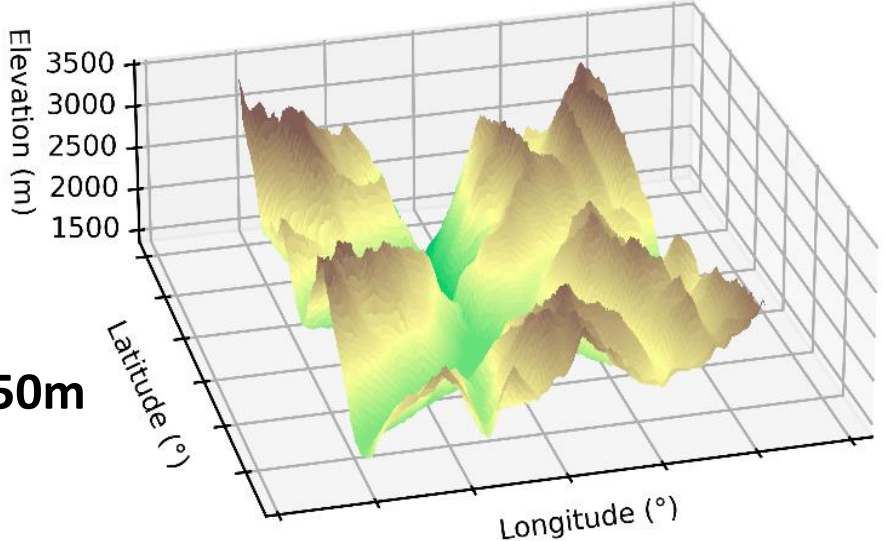
© Meteoswiss (2025)

A 3D wireframe sphere is centered in the frame, set against a dark, starry space background. Inside the sphere, a textured globe of the Earth is visible, showing continents and oceans. The wireframe is composed of a grid of light blue lines. The text "Step 3: Post-processing" is overlaid in the center of the sphere in a white, sans-serif font.

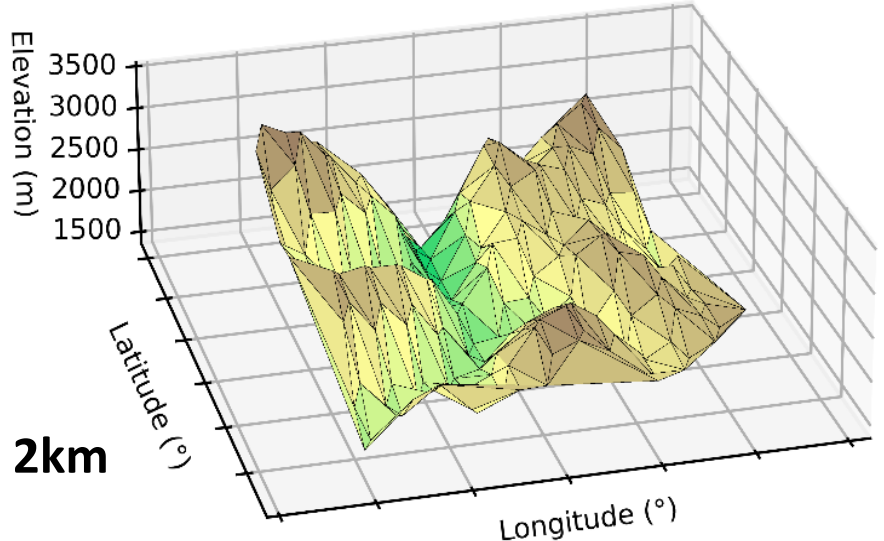
Step 3: Post-processing

Correction of systematic biases

DEM @ 50m



COSMO @ 2km



Swisscom 4G 14:10 92%

Favorit 6634 Brione (Verzasca)

Brione (Verzasca)
Do. 13:30
2.7°C

Wochenprognose

Donnerstag 27. Feb.	☀️	-4° 4°	1 mm
Freitag 28. Feb.	☀️	-1° 9°	0 mm
Samstag 29. Feb.	☀️	4° 8°	1 mm
Sonntag 01. März	☀️	1° 9°	<1 mm
Montag 02. März	☁️	1° 5°	31 mm
Dienstag 03. März	☀️	2° 12°	1 mm

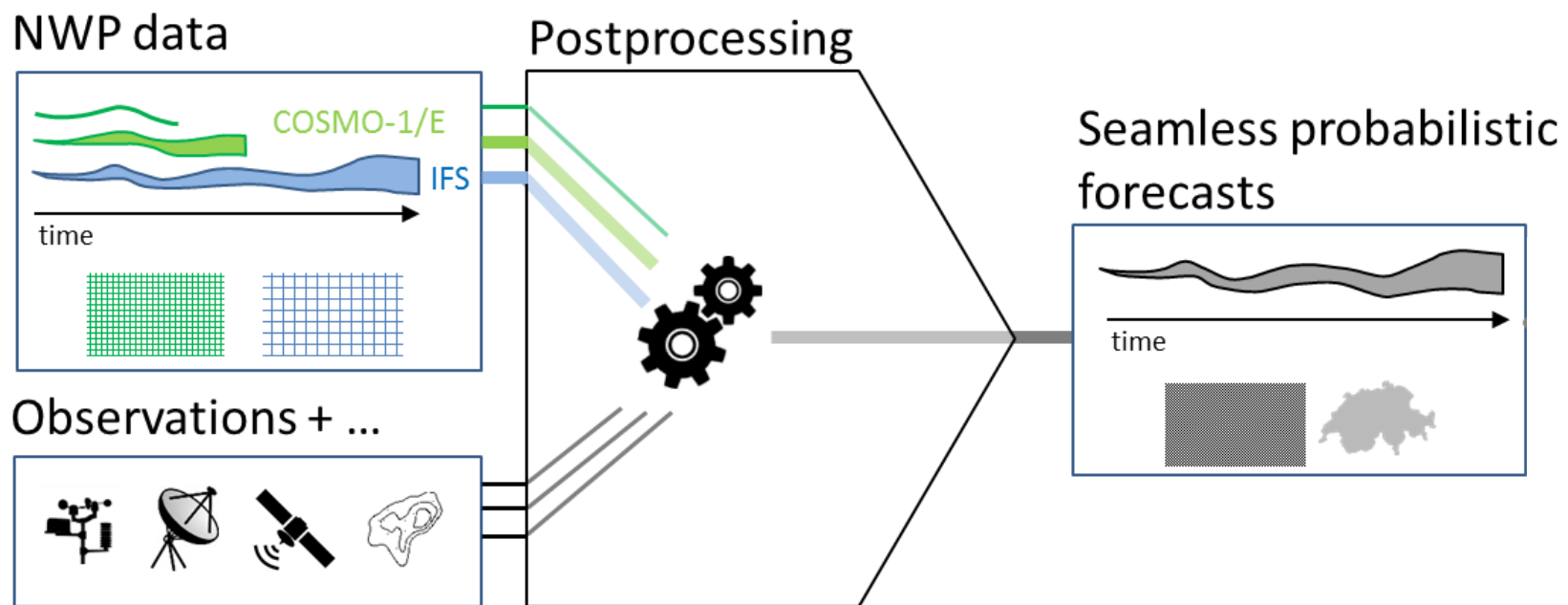
Sa. 29. Feb.

Swisscom 4G 14:08 92%

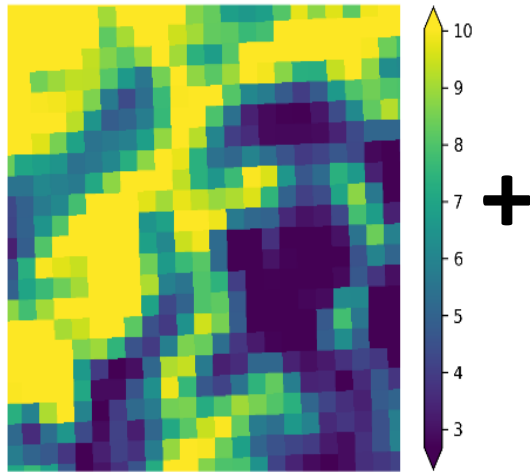
Messwerte – Do. 27. Feb., 13:50
Temperatur [°C]

Piotta	-1.4°
Acquarossa / Comprovasco	4.6°
Matro	-9.9°
Biasca	6.8°
Cevio	4.1°
Cimetta	-4.3°
Locarno / Monti	6.6°
Magadino / Cadenazzo	7.6°

Post-processing

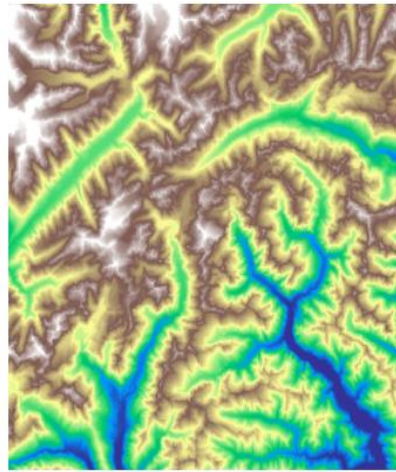


COSMO @ 2km



5 years of weather forecast simulations with 2km spatial resolution

DEM @ 50m



Digital elevation model and various derived indices describing geometry

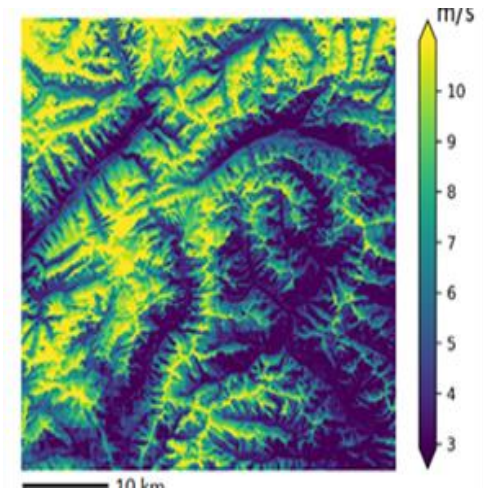
Observations



As many wind observations as possible in the Alpine area

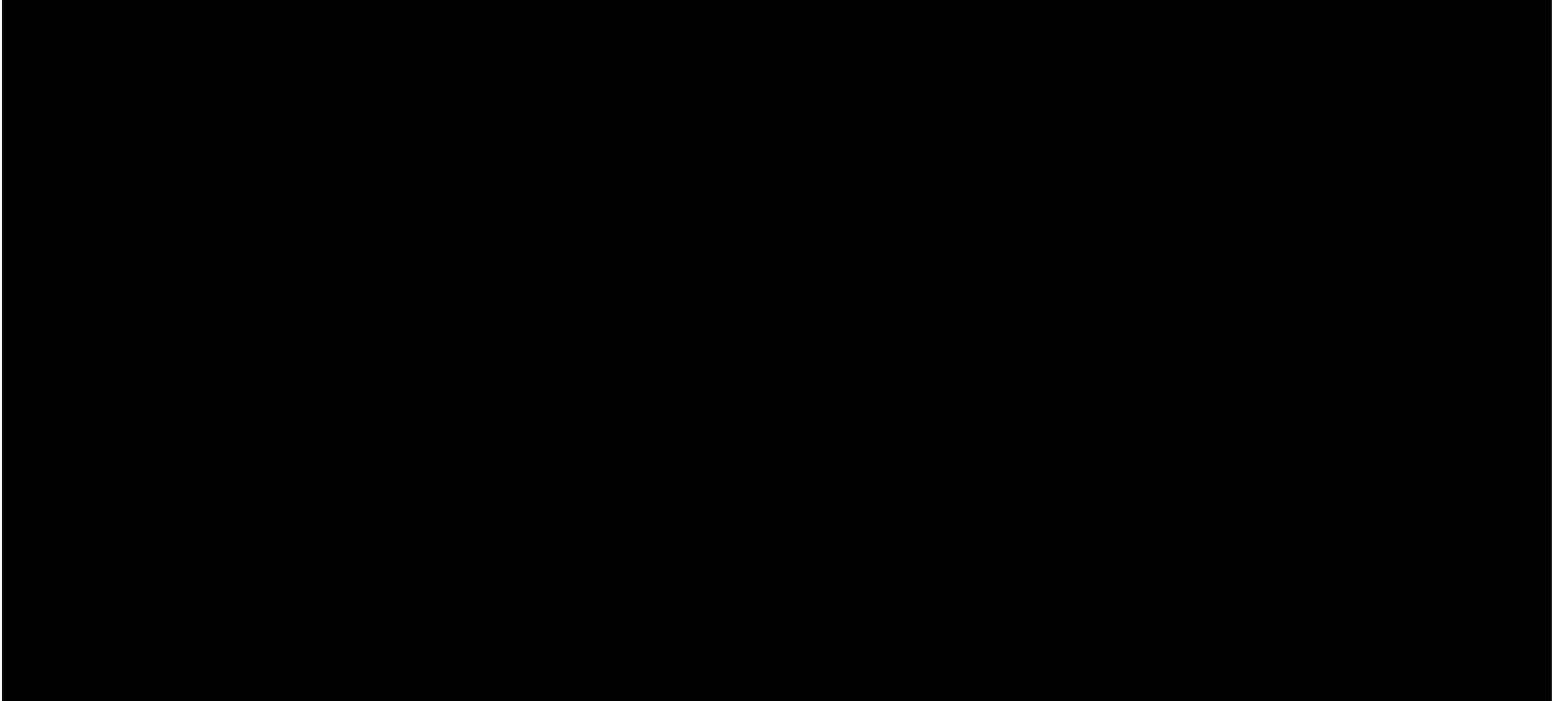
Neural Network

Forecast



Calibrated, probabilistic forecasts of wind speed, direction and gusts

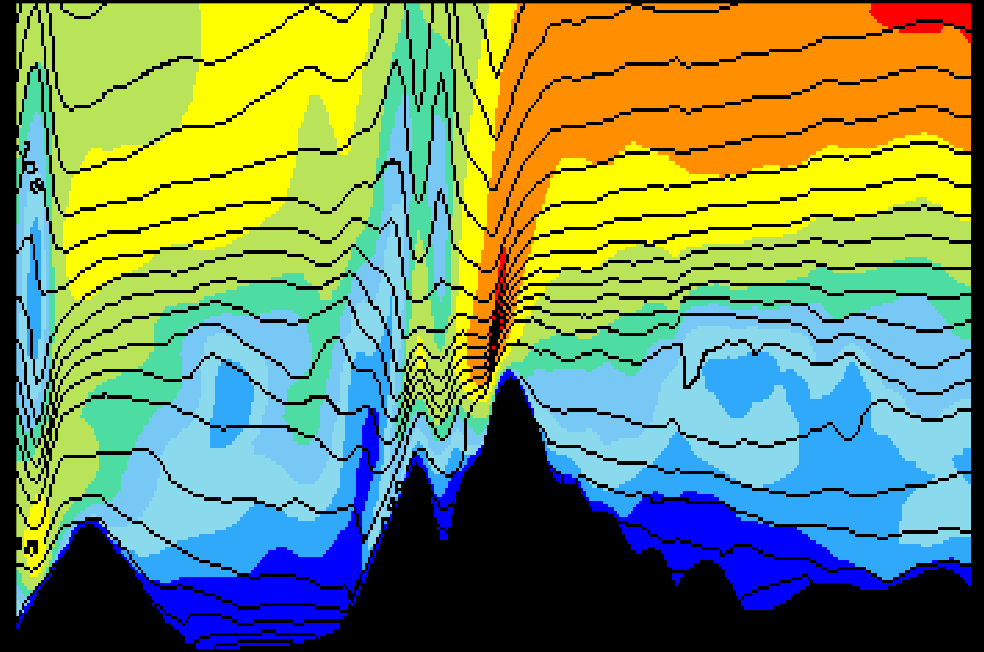
The Turing test for weather models



Summary

What do we need for numerical weather prediction ?

- Atmospheric model = Dynamic + Parametrization
- Equations discretized on a finite grid
- Knowledge of the initial state of the atmosphere
- Data assimilation to bring the model as close as possible to “reality”





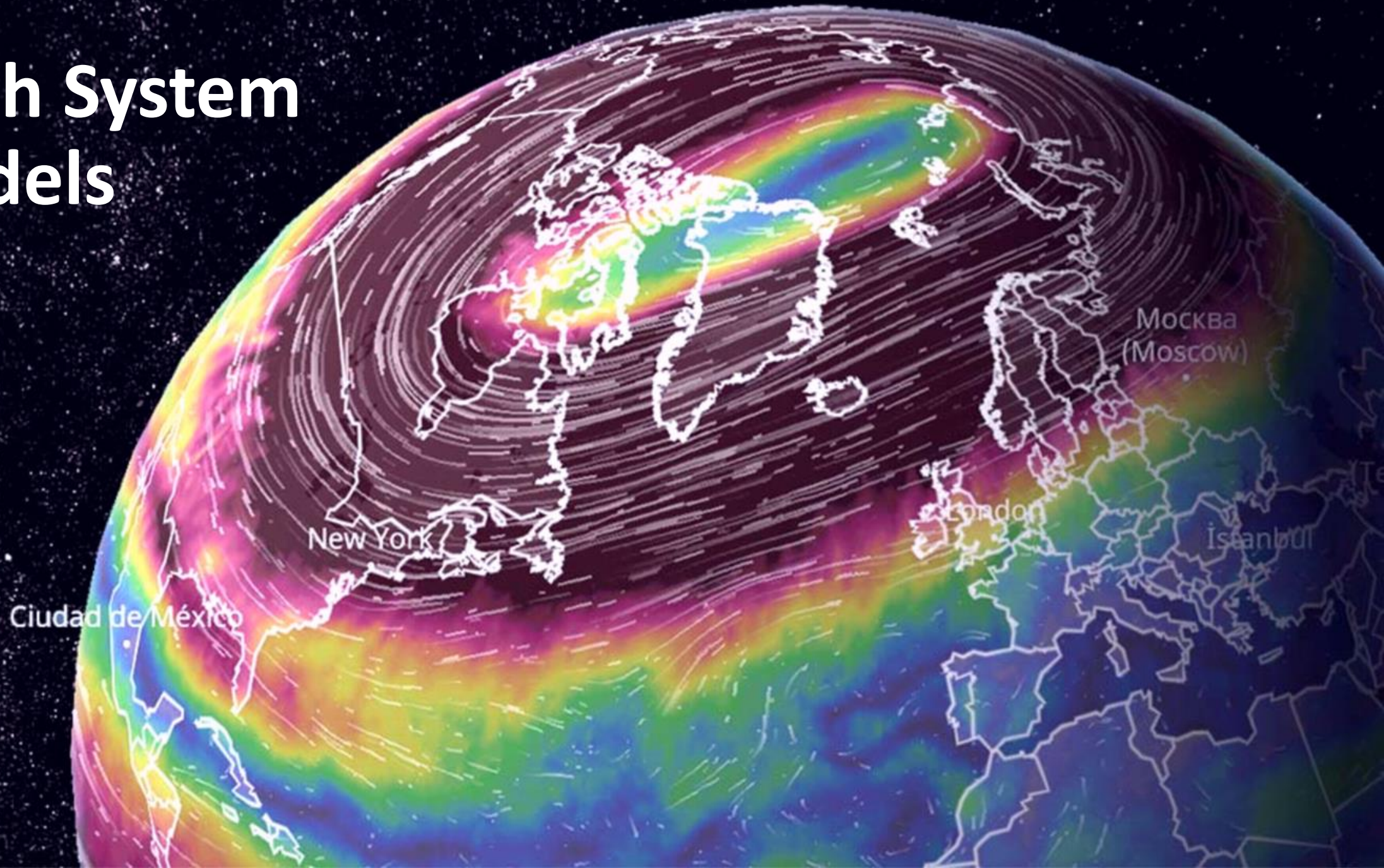
Exercise

Go to:

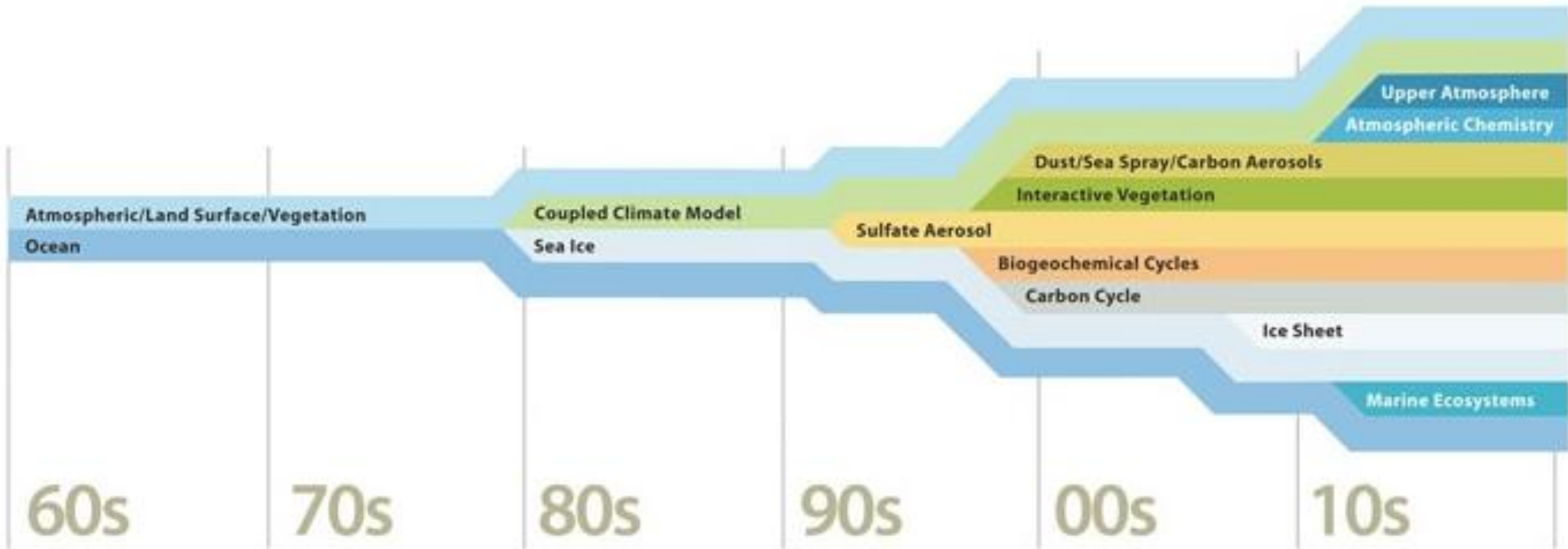
www.ready.noaa.gov/HYSPLIT_traj.php

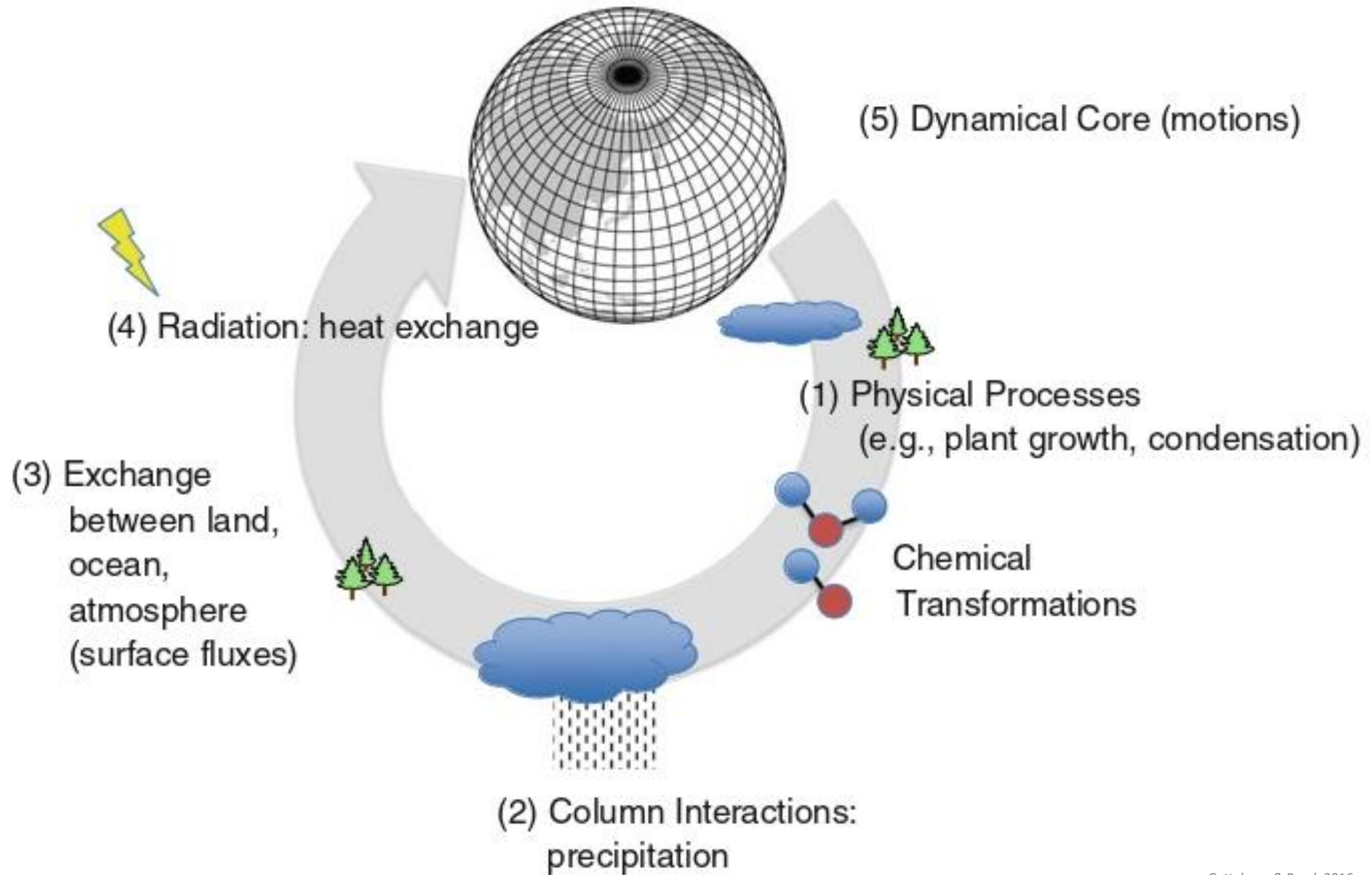
- > Choose “compute archive trajectories”
- > From the drop-down menu choose the option “GFS”
- > Explore the trajectories from different locations (e.g., Jungfrauoch, your home town, the top of Everest, the South Pole)

Earth System Models

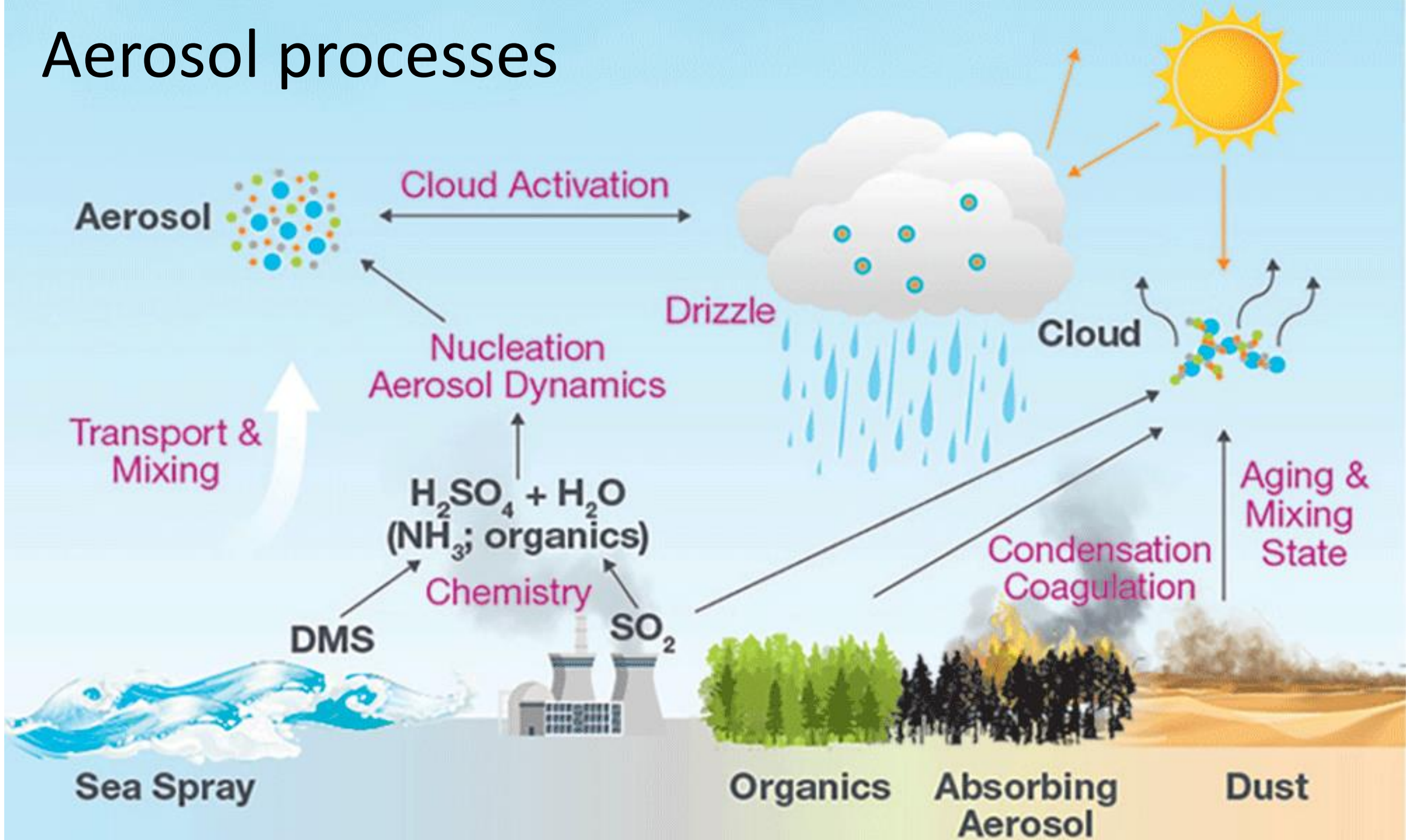


The evolution of climate models

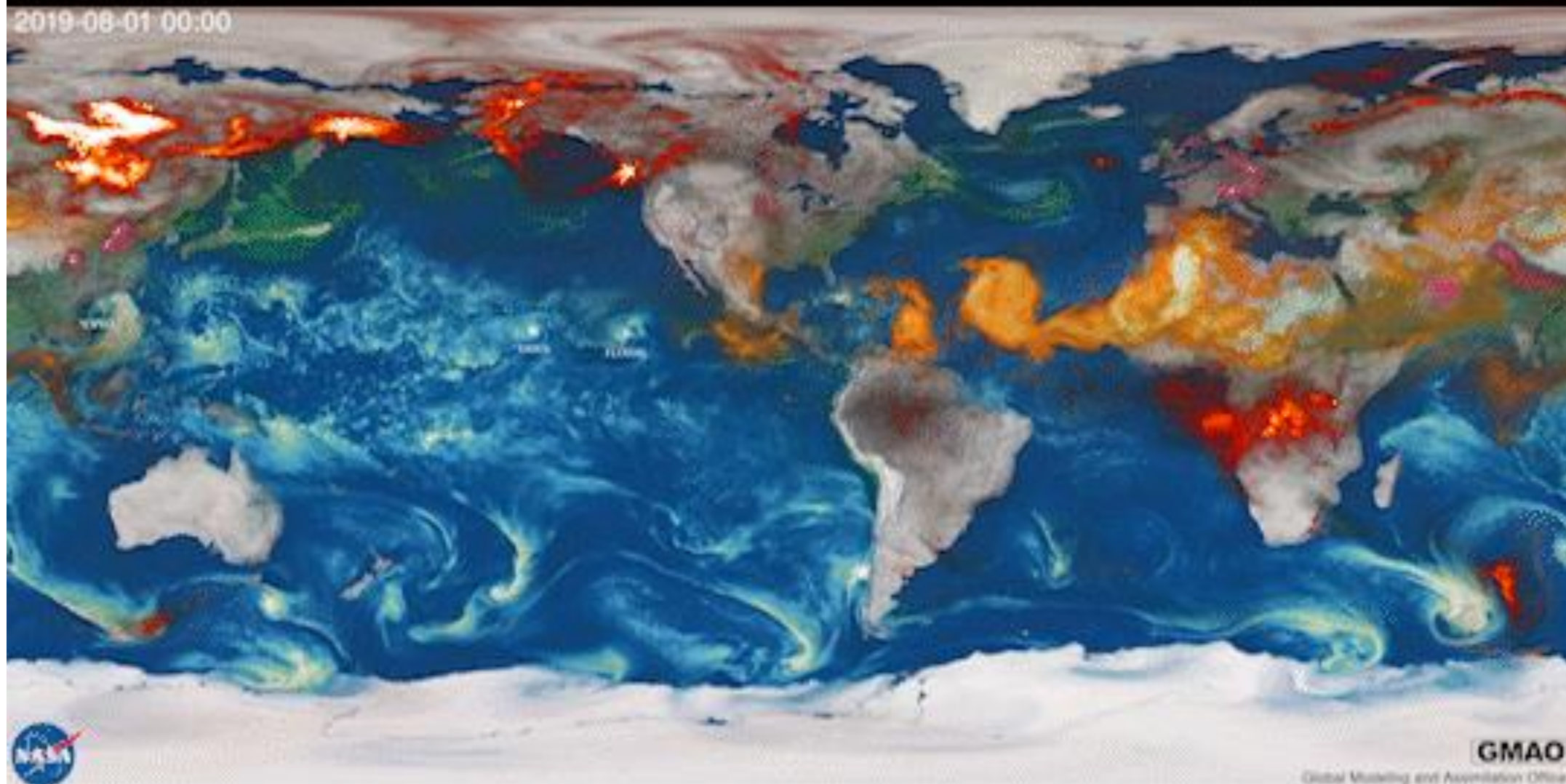




Aerosol processes



2019-08-01 00:00



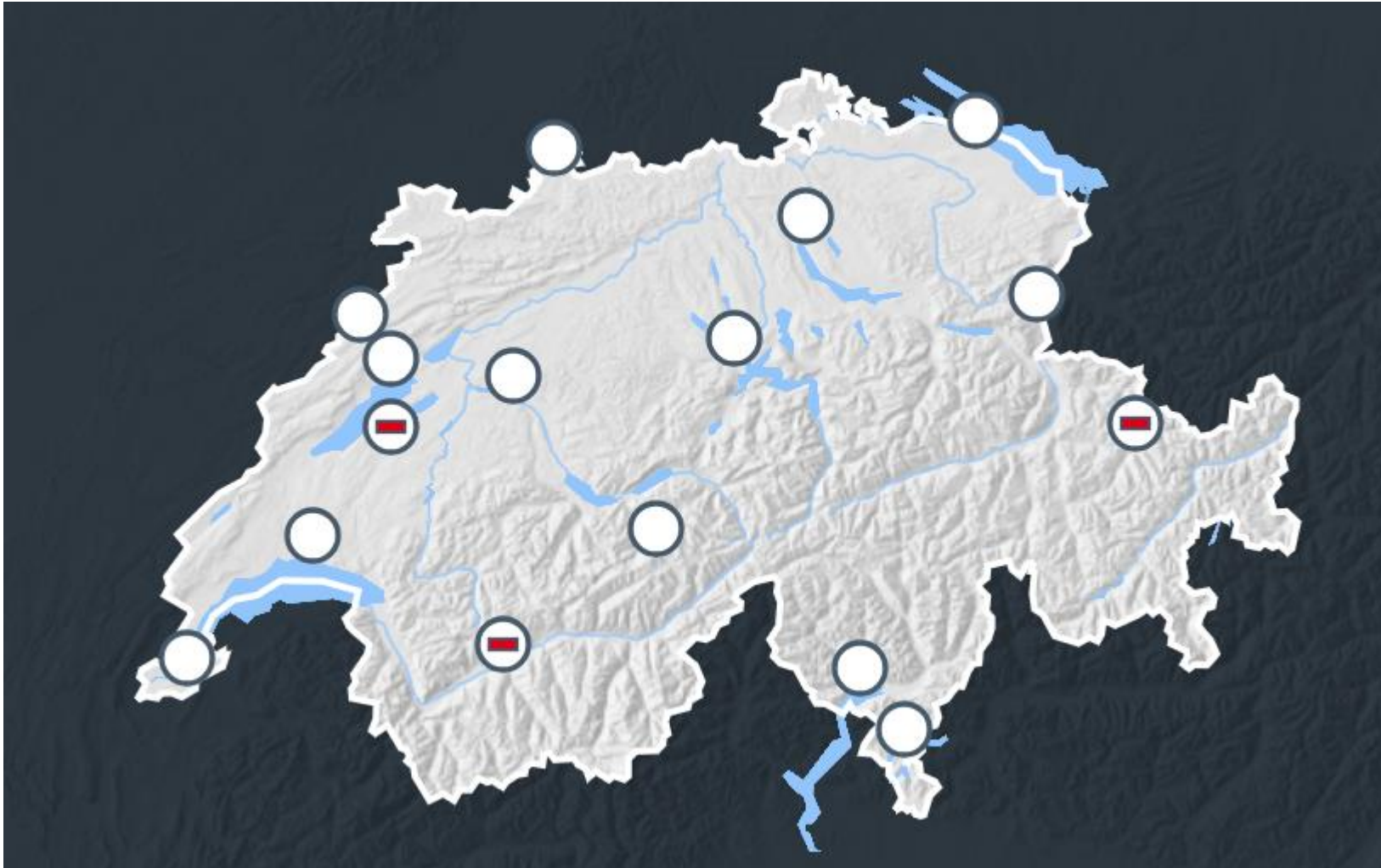
GMAO

Global Modeling and Assimilation Office

Aerosol Optical Depth at 550 nm

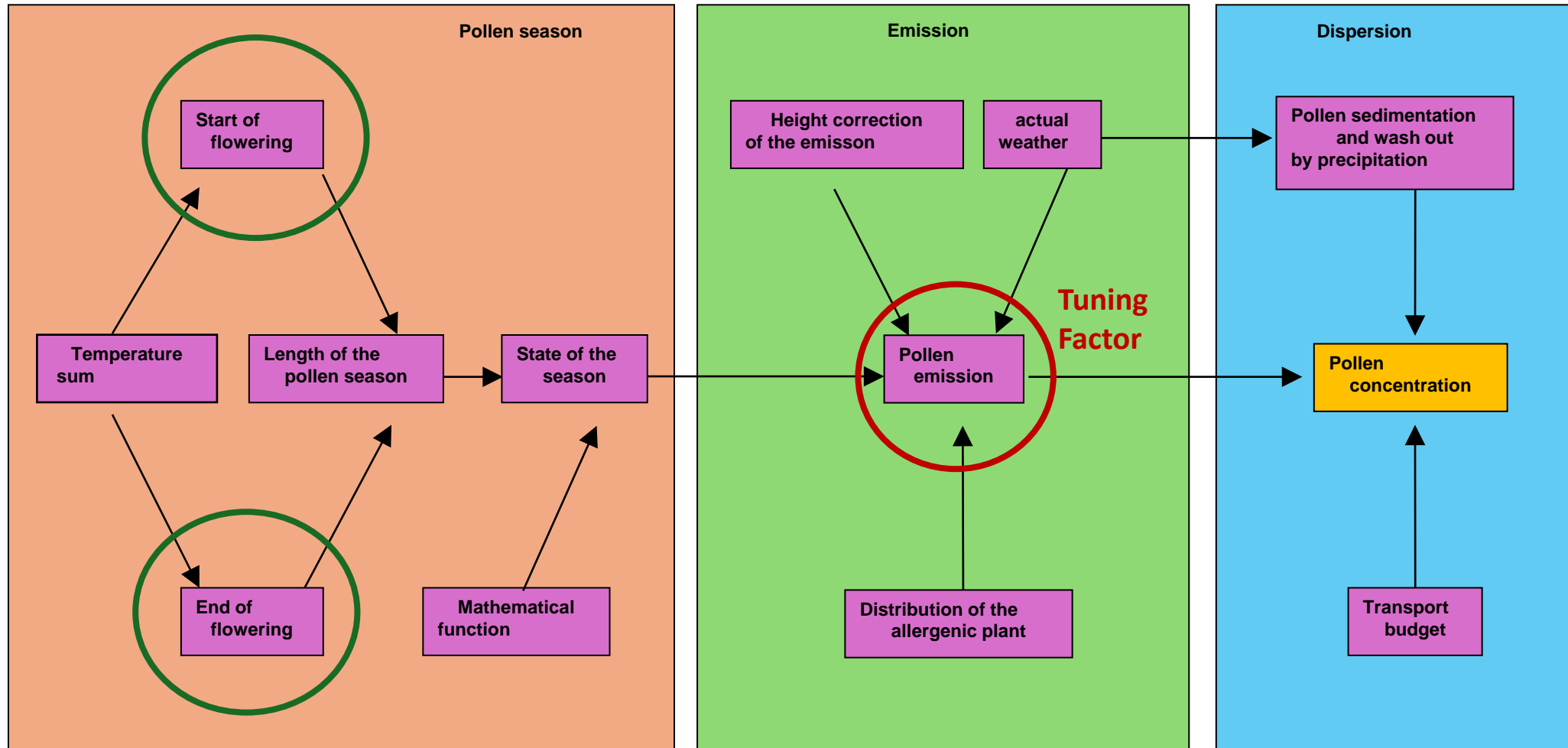


Pollen monitoring and forecasting



16 automatic
monitoring
sites across
Switzerland

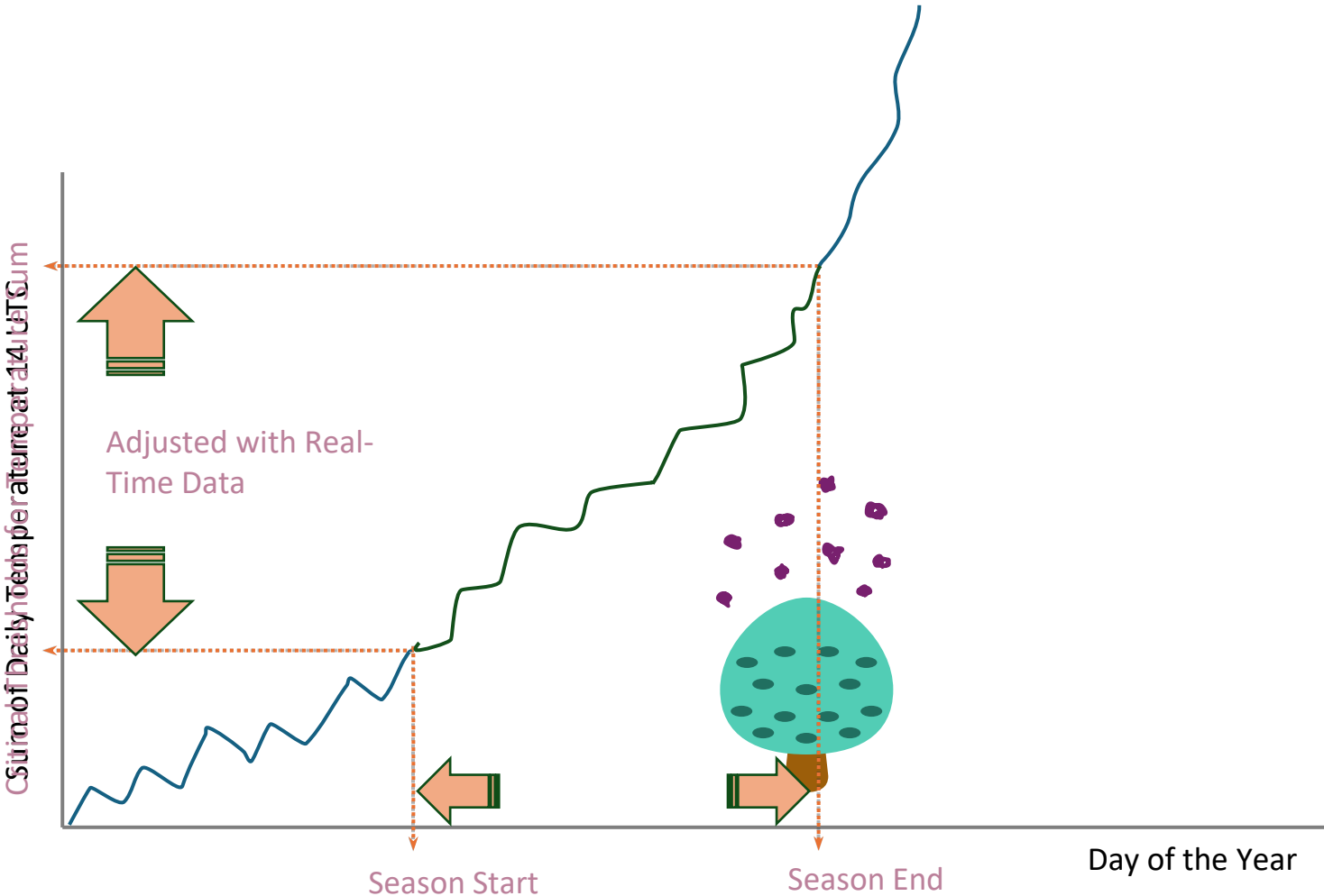
The MeteoSwiss pollen module



Phenology:
Adapting start/end
of flowering

Intensity: Adapting
the strength of pollen
emission

Pollen season: Temperature sum



Integration of real-time pollen measurements

- Model tuning: bias correction (Observation - Model)
- Applied every hour in the KENDA cycle:

$(\text{obs}/\text{mod}_{\text{past 120h}})^{1/24}$ to the tuning factor at each station +
interpolate onto grid



Masting
Years



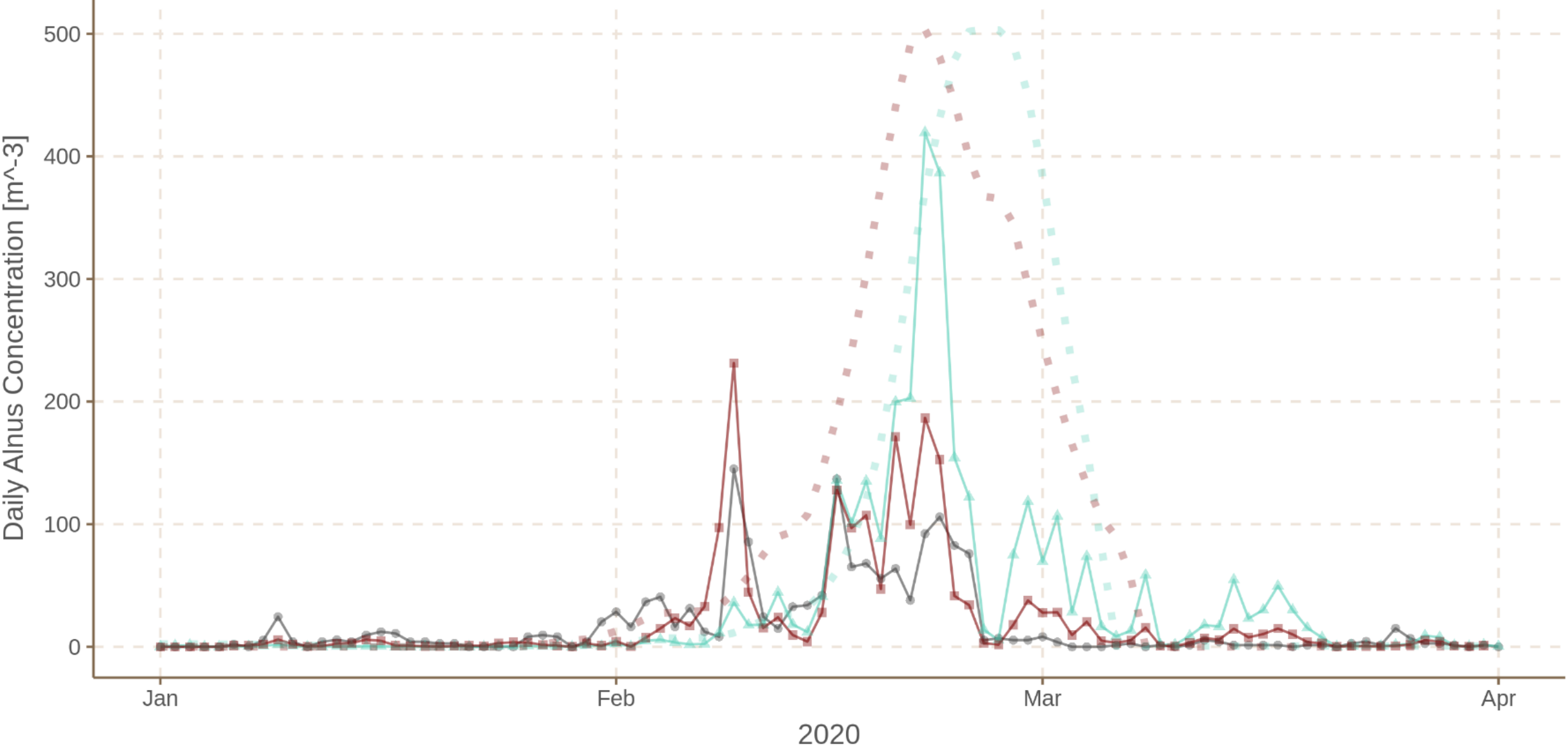
Plant
Distribution



Weather
Related Bias
Correction

Source:
<https://github.com/twitter/twemoj>

Daily Alnus Concentrations in Zürich - 2020 Season



—●— Measurements —▲— Operational - C1E —■— Tuning V3



Exercise

- Go to: <https://mscm.dkrz.de/>
- Click on “Enter” then “Standard version”
- Play around with the different components of the model and note the impacts on the global mean temperature