Modelling Climate Change

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meteomatics

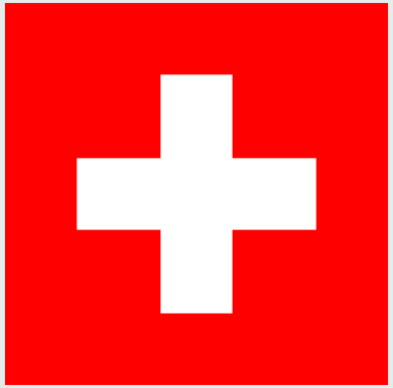
World-class meteorology & data science

We are the global leader in weather intelligence.

We provide the most accurate weather data for any location at any time, to improve our customers' business.

70

Highly-trained
staff across 3 offices

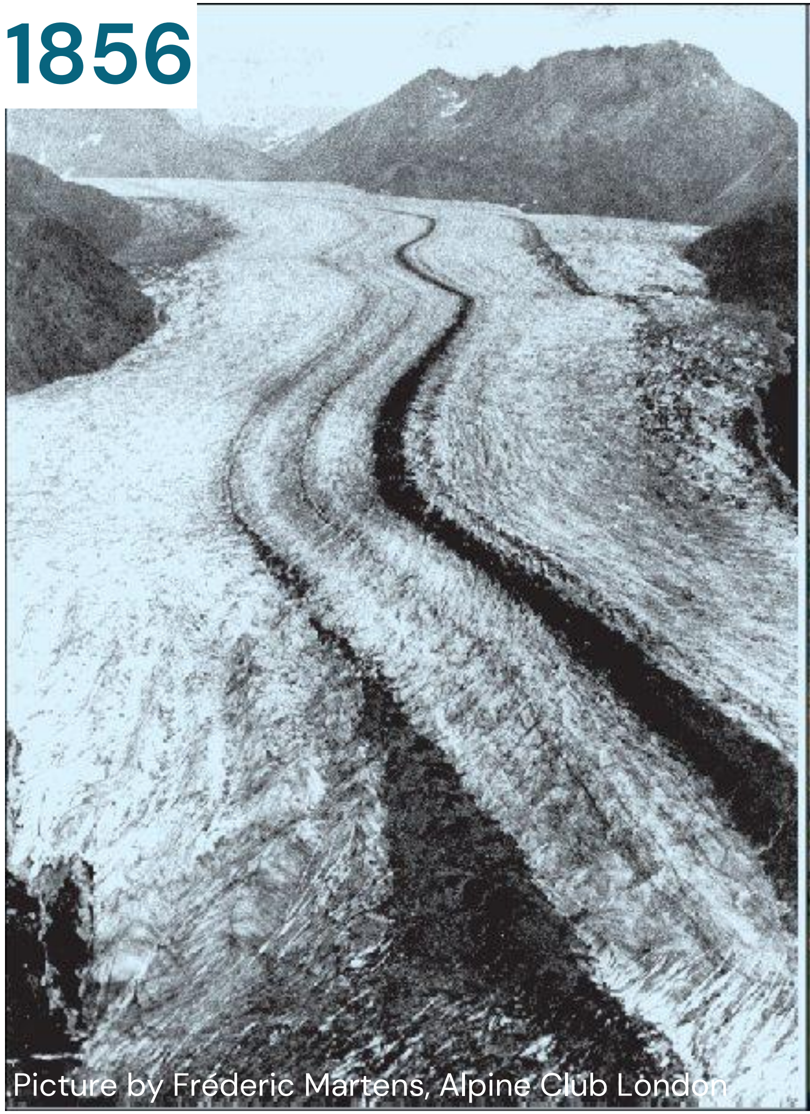


Swiss precision
engineering

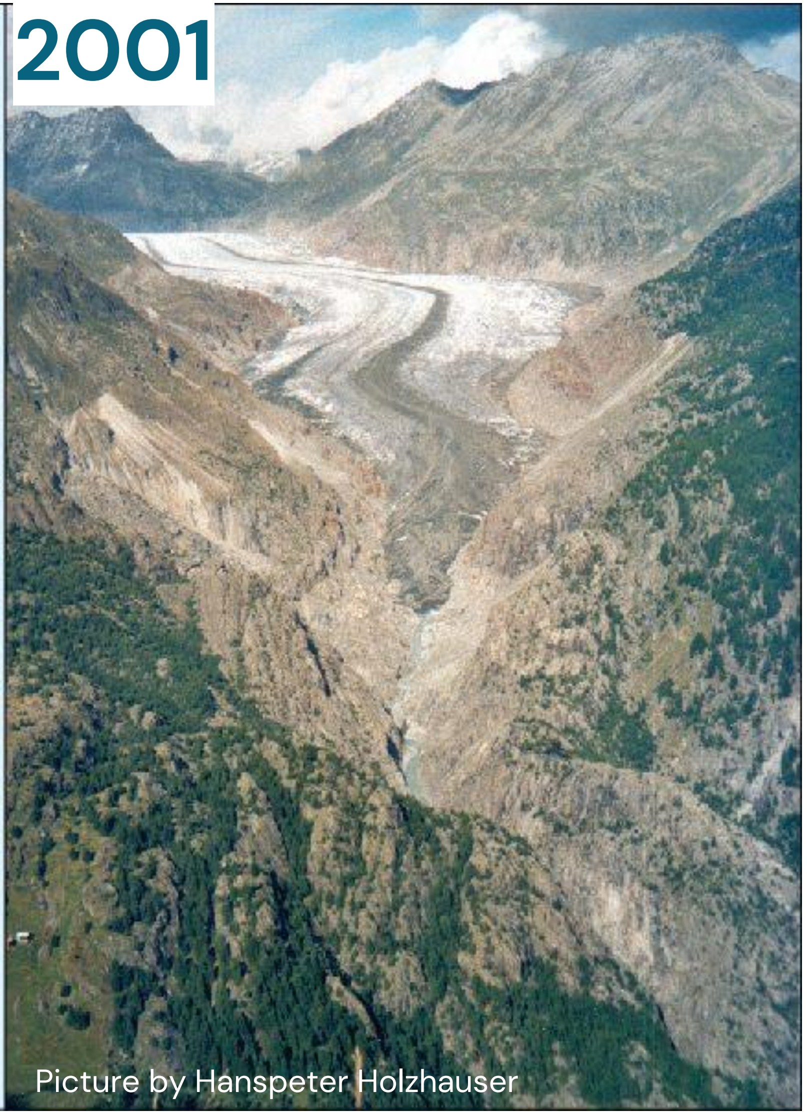
Global clients
& partners

Aletsch glacier retreat due to climate change

1856

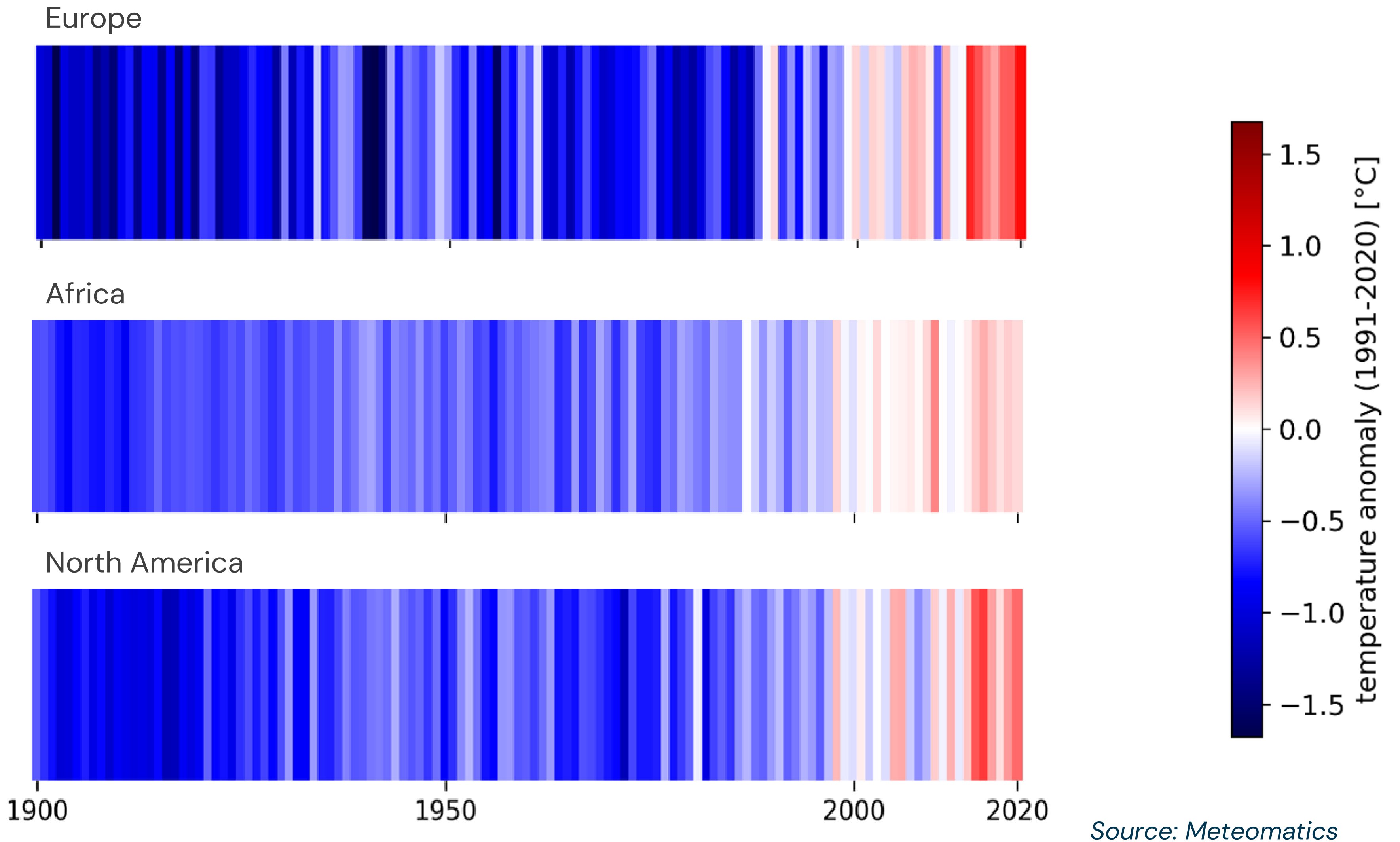

Picture by Fréderic Martens, Alpine Club London

2001


Picture by Hanspeter Holzhauser

Climate change

Global temperature rise very apparent in Meteomatics climatological data



Source: Meteomatics

Governing equations in weather forecast models

Newton's 2nd law: $\frac{d\mathbf{V}}{dt} = -\frac{1}{\rho}\nabla p - 2\boldsymbol{\Omega} \times \mathbf{V} + \mathbf{g} + \mathbf{f}_{\mathrm{r}}$

1st law of thermodynamic: $c_p \frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = \dot{q}$

Continuity equation: $\frac{1}{\rho}\frac{d\rho}{dt} + \nabla \cdot \mathbf{V} = 0$

Ideal gas law: $p = \rho R T$

Governing equations in weather forecast models – spherical coordinates

First we set out the continuous equations in (λ, θ, η) coordinates, where λ is longitude and η is the hybrid vertical coordinate introduced by Simmons and Burridge (1981); thus $\eta(p, p_s)$ is a monotonic function of the pressure p, and also depends on the surface pressure p_s in such a way that

$$\eta(0, p_s) = 0 \quad \text{and} \quad \eta(p_s, p_s) = 1$$

The momentum equations are

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + V\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta} - fV + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \lambda}(\ln p)\right\} = P_U + K_U \qquad (2.1)$$

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2 + V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} + fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \theta}(\ln p)\right\} = P_V + K_V \qquad (2.2)$$

where a is the radius of the earth, $\dot{\eta}$ is the η-coordinate vertical velocity ($\dot{\eta} = \mathrm{d}\eta/\mathrm{d}t$), ϕ is geopotential, R_{dry} is the gas constant for dry air, and T_{v} is the virtual temperature defined by

$$T_{\mathrm{v}} = T[1 + \{(R_{\mathrm{vap}}/R_{\mathrm{dry}}) - 1\}q - \sum_k q_k]$$

Source: ECMWF IFS documentation CY47R3

Governing equations in weather forecast models – spherical coordinates

where T is temperature, R_{vap} is the gas constant for water vapour, q is specific humidity and q_k denotes other thermodynamically active moist species namely cloud liquid water, ice, rain, snow. P_U and P_V represent the contributions of the parameterised physical processes, while K_U and K_V are the horizontal diffusion terms.

The thermodynamic equation is

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_{\mathrm{v}}\omega}{(1+(\delta-1)q)p} = P_T + K_T \tag{2.3}$$

where $\kappa = R_{\mathrm{dry}}/c_{p_{\mathrm{dry}}}$ (with $c_{p_{\mathrm{dry}}}$ the specific heat of dry air at constant pressure), ω is the pressure-coordinate vertical velocity ($\omega = \mathrm{d}p/\mathrm{d}t$), and $\delta = c_{p_{\mathrm{vap}}}/c_{p_{\mathrm{dry}}}$ (with $c_{p_{\mathrm{vap}}}$ the specific heat of water vapour at constant pressure).

The moisture equation is

$$\frac{\partial q}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} + \dot{\eta}\frac{\partial q}{\partial \eta} = P_q + K_q \tag{2.4}$$

In (2.2) and (2.3), P_T and P_q represent the contributions of the parameterised physical processes, while K_T and K_q are the horizontal diffusion terms.

The continuity equation is

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla\cdot\left(\mathbf{v}_{\mathrm{H}}\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0 \tag{2.5}$$

where ∇ is the horizontal gradient operator in spherical coordinates and $\mathbf{v}_{\mathrm{H}} = (u, v)$ is the horizontal wind.

Source: ECMWF IFS documentation CY47R3

Governing equations in weather forecast models – spherical coordinates

The geopotential ϕ which appears in (2.1) and (2.2) is defined by the hydrostatic equation

$$\frac{\partial \phi}{\partial \eta} = -\frac{R_{\mathrm{dry}} T_{\mathrm{v}}}{p} \frac{\partial p}{\partial \eta} \tag{2.6}$$

while the vertical velocity ω in (2.3) is given by

$$\omega = -\int_0^\eta \nabla \cdot \left(\mathbf{v}_{\mathrm{H}} \frac{\partial p}{\partial \eta} \right) \mathrm{d}\eta + \mathbf{v}_{\mathrm{H}} \cdot \nabla p \tag{2.7}$$

Expressions for the rate of change of surface pressure, and for the vertical velocity $\dot{\eta}$, are obtained by integrating (2.5), using the boundary conditions $\dot{\eta} = 0$ at $\eta = 0$ and at $\eta = 1$

$$\frac{\partial p_{\mathrm{s}}}{\partial t} = -\int_0^1 \nabla \cdot \left(\mathbf{v}_{\mathrm{H}} \frac{\partial p}{\partial \eta} \right) \mathrm{d}\eta \tag{2.8}$$

$$\dot{\eta} \frac{\partial p}{\partial \eta} = -\frac{\partial p}{\partial t} - \int_0^\eta \nabla \cdot \left(\mathbf{v}_{\mathrm{H}} \frac{\partial p}{\partial \eta} \right) \mathrm{d}\eta \tag{2.9}$$

Since we use $\ln(p_{\mathrm{s}})$ rather than p_{s} as the surface pressure variable, it is convenient to rewrite (2.8) as

$$\frac{\partial}{\partial t}(\ln p_{\mathrm{s}}) = -\frac{1}{p_{\mathrm{s}}} \int_0^1 \nabla \cdot \left(\mathbf{v}_{\mathrm{H}} \frac{\partial p}{\partial \eta} \right) \mathrm{d}\eta \tag{2.10}$$

Source: ECMWF IFS documentation CY47R3

Solving the coupled Navier-Stokes equations

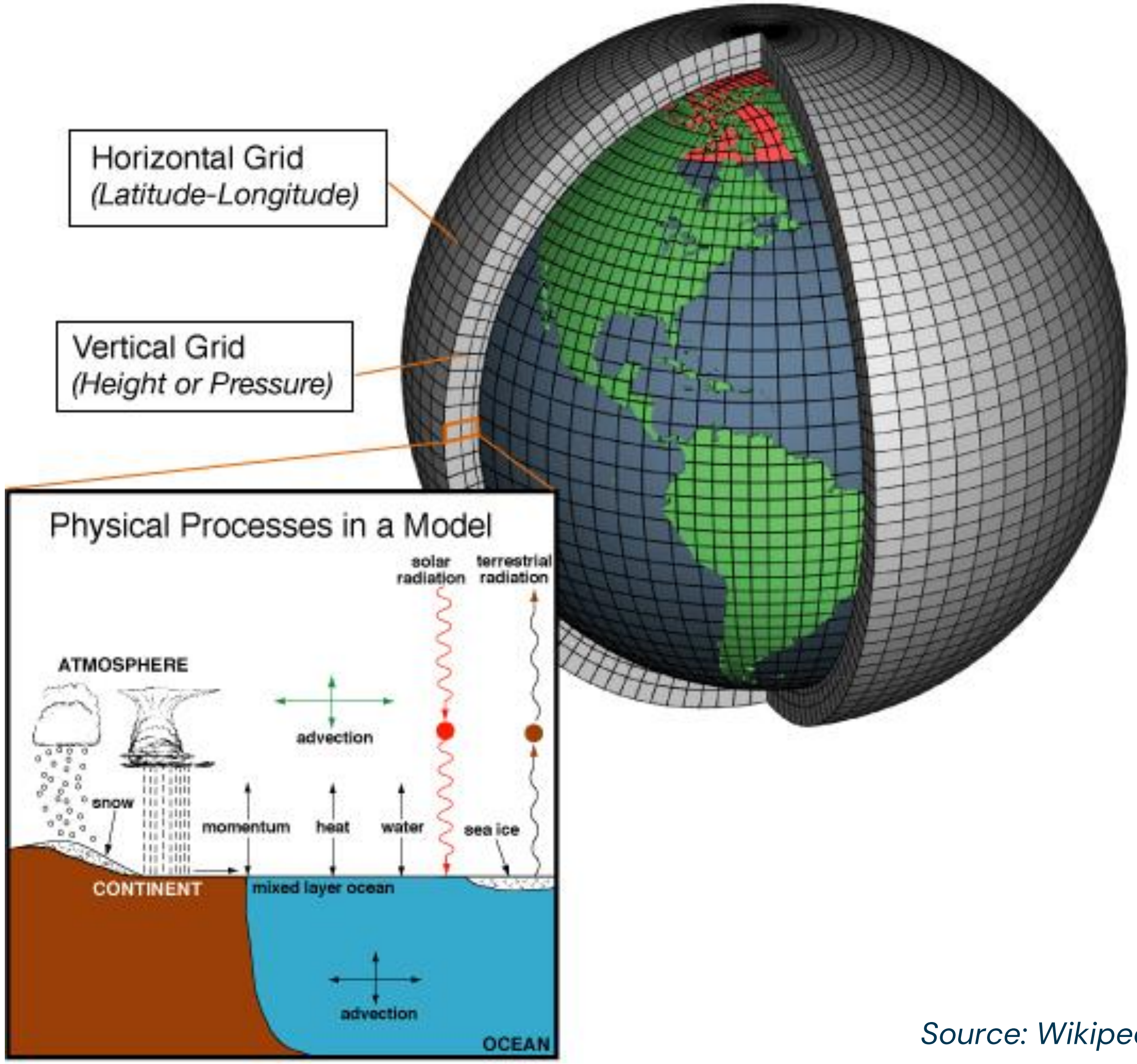
Global circulation models

- Spherical harmonics (ECMWF IFS)
- Icosahedral grids (DWD ICON)
- Finite volume cubed-sphere (NOAA GFS/FV3)
- Triangular adaptive meshes
- .....

Some challenges

- No regular grids
- Time-stepping, atmospheric waves, sound waves
- Energy balance
- Soil & ocean related processes
- Physical processes & chemistry(!)

A typical resolution is 8-20km



Source: Wikipedia

Solving the coupled Navier-Stokes equations

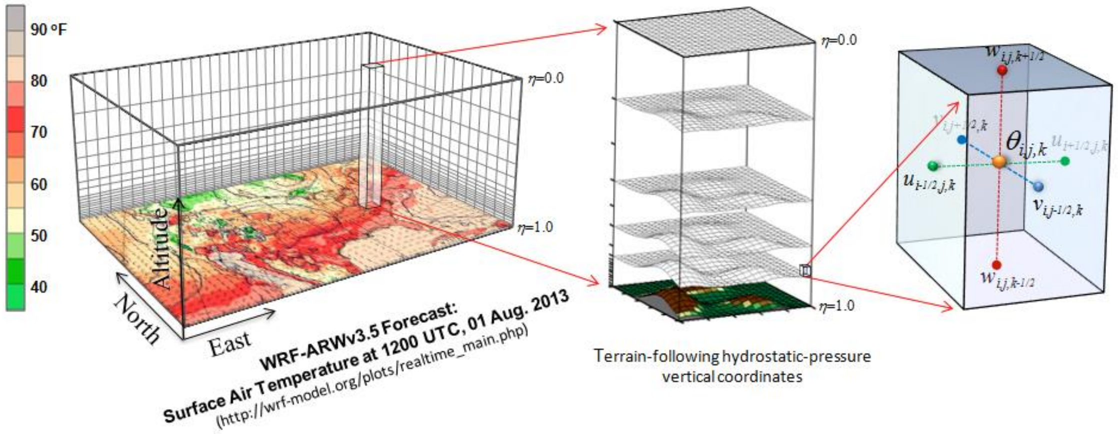
Local area models

- Finite differences (WRF)
- Icosahedral grids (DWD ICON)
- Triangular adaptive meshes
- .....

Challenges

- Boundary conditions, nesting
- Time-stepping, atmospheric waves
- Physical surface processes
- ...

A typical resolution is 1-4km

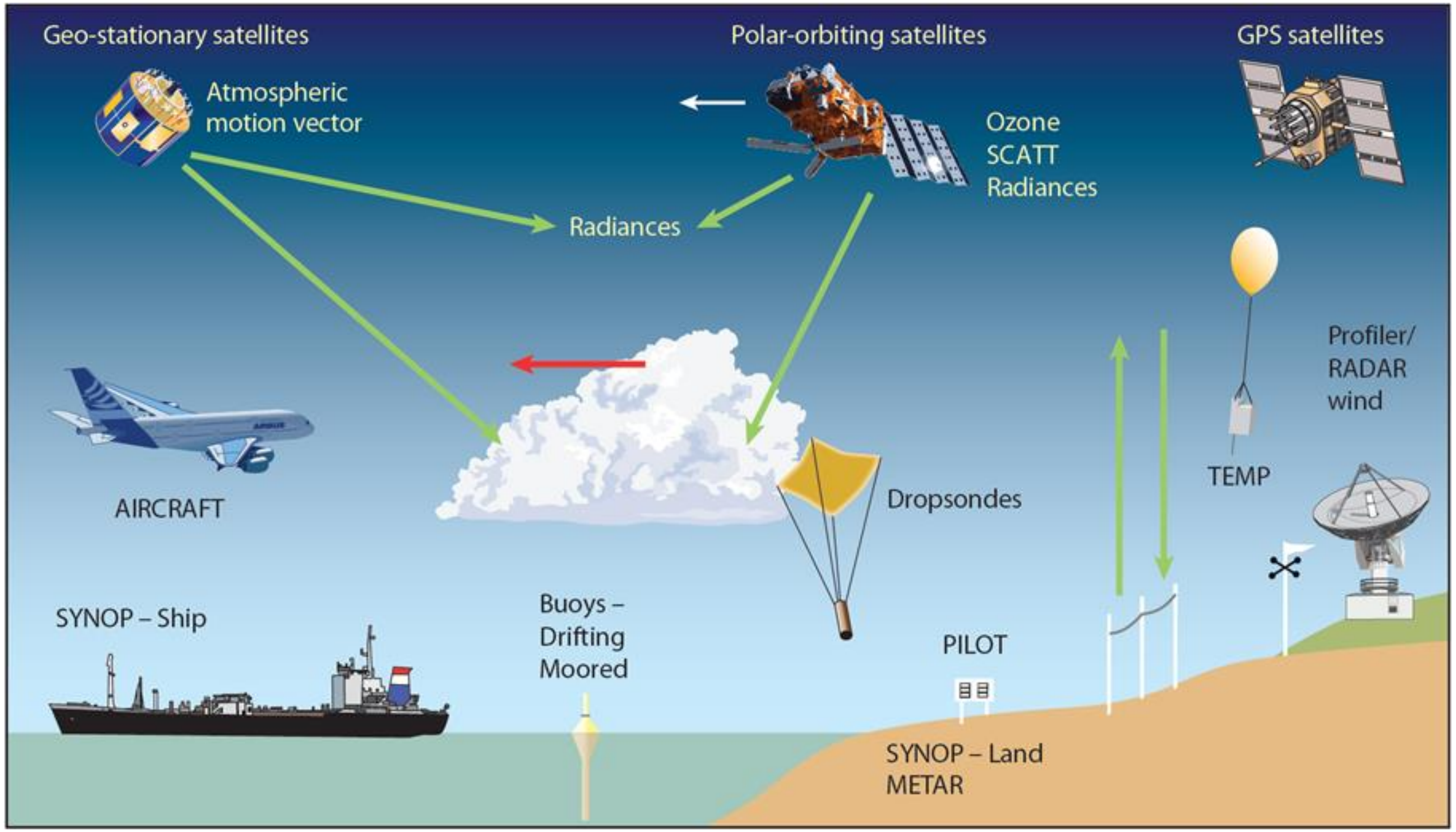


Source: Wikipedia

Weather data assimilation

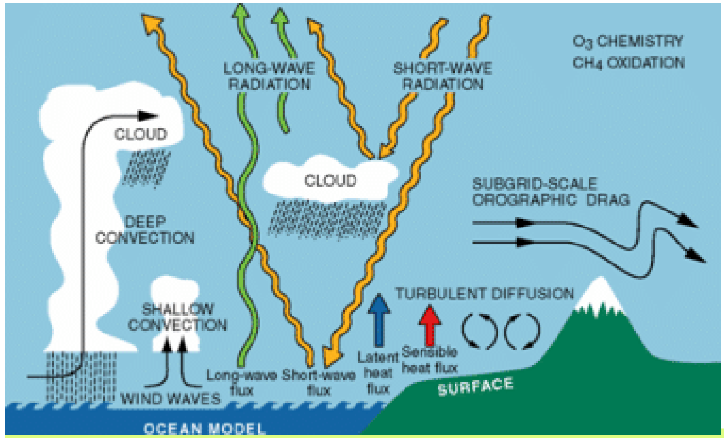
Challenge

- the current atmospheric conditions are unknown
- the initial conditions used in weather models are only approximations



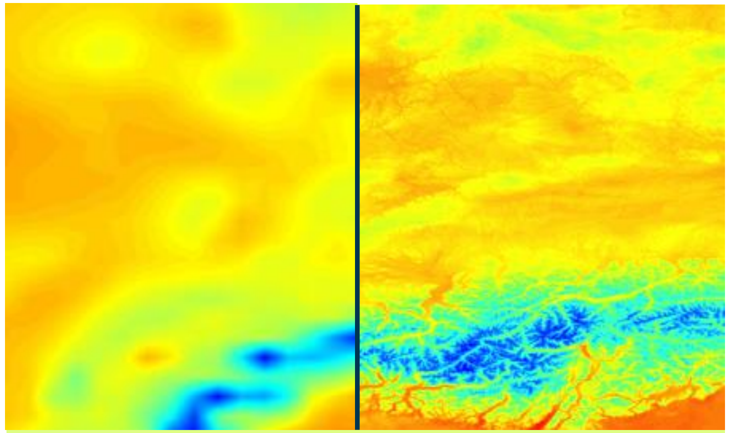
Source ECMWF

Computing power depends on...



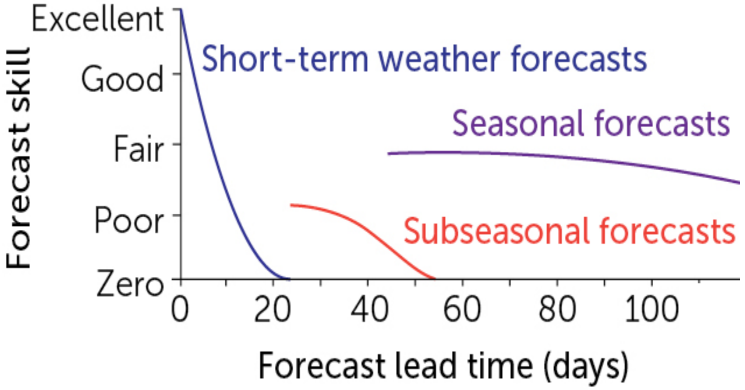
Model complexity

Higher number of parametrized physical processes increase the computing power needed



Model resolution

Higher horizontal and vertical resolution increase the computing power needed



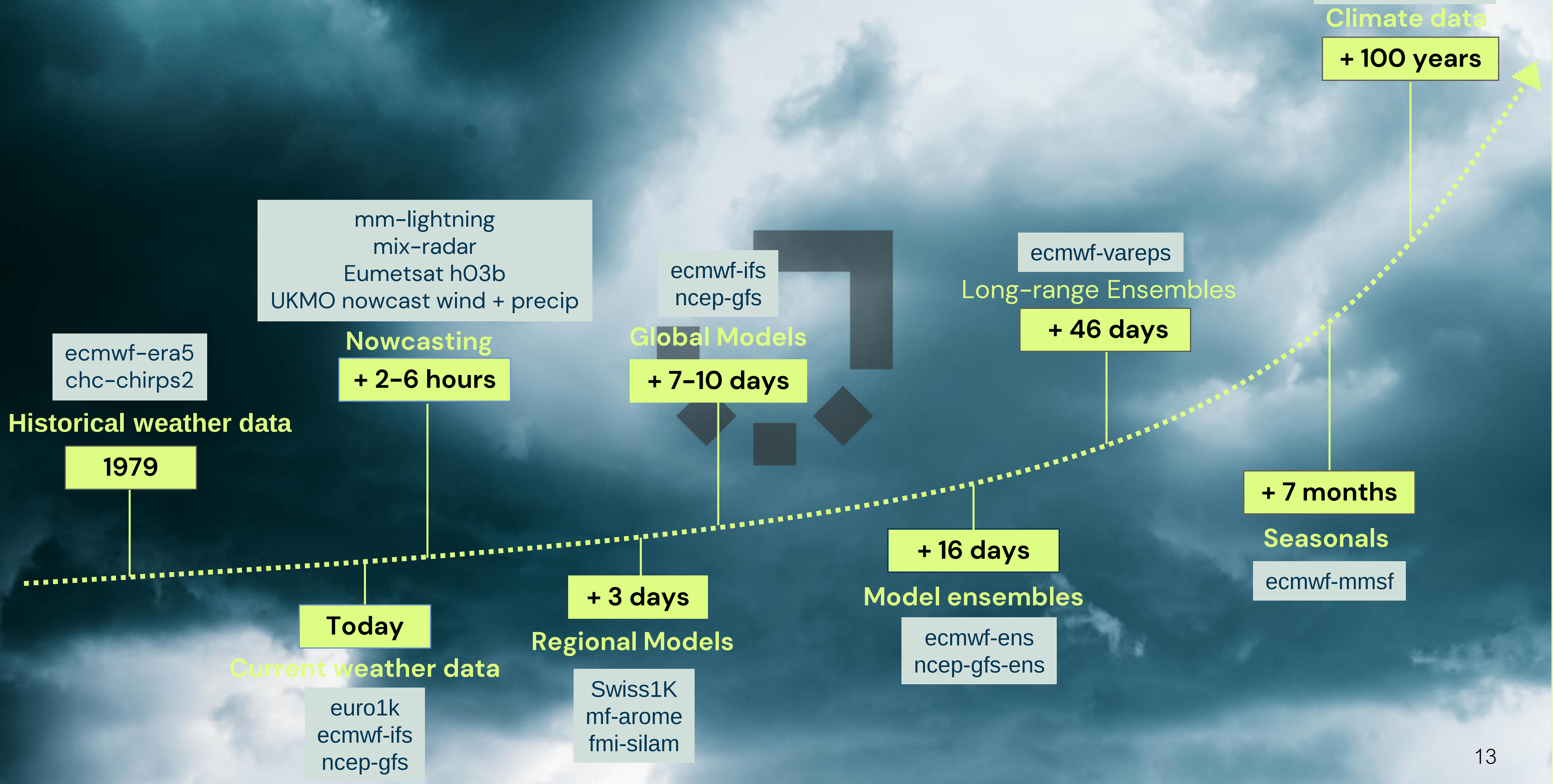
Forecast horizon

Forecast for longer time periods (more time steps) need higher computing power and loose in accuracy

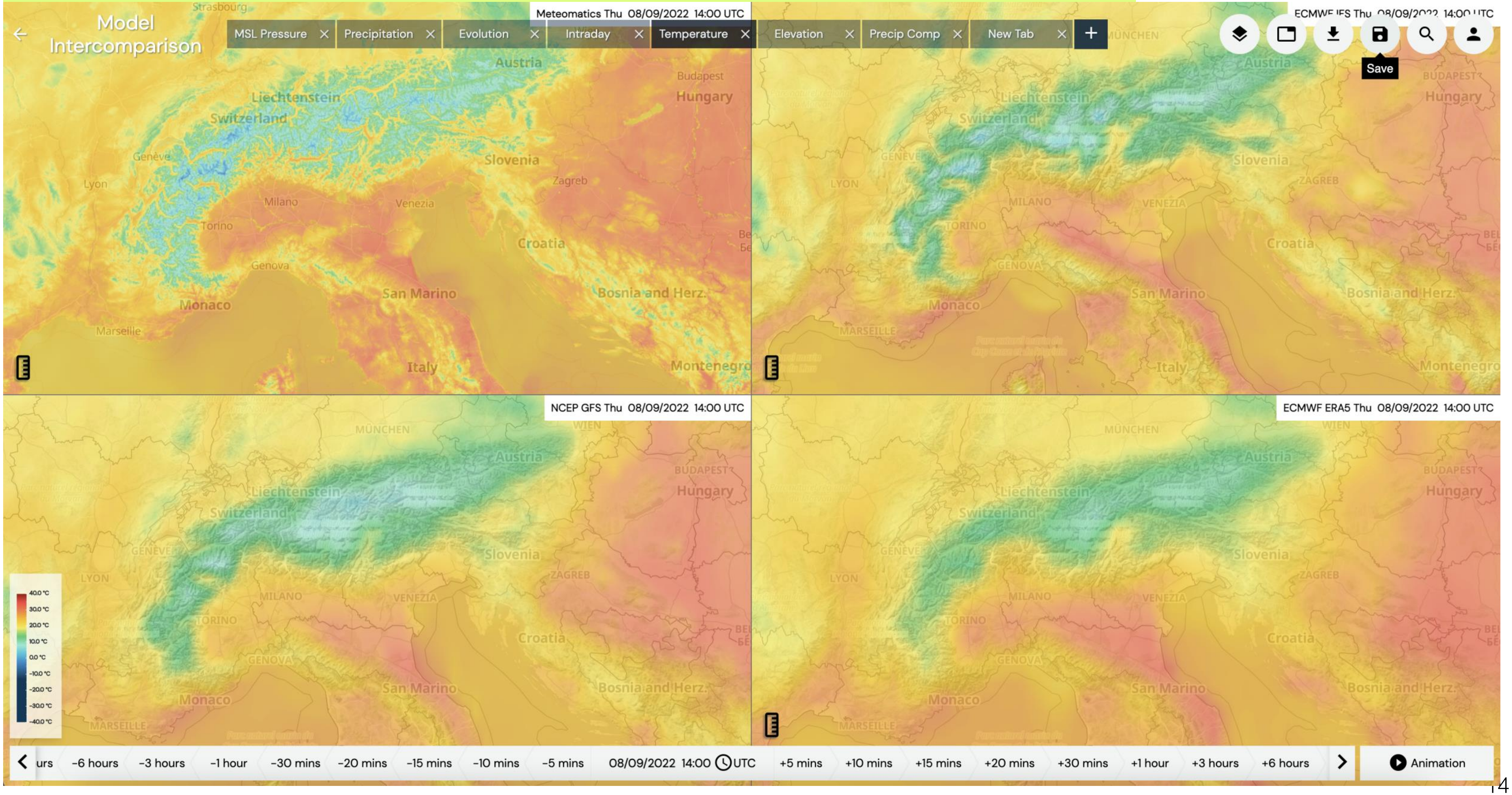
Weather models cannot forecast climatology

Models with lower complexity and resolution can forecast future climate

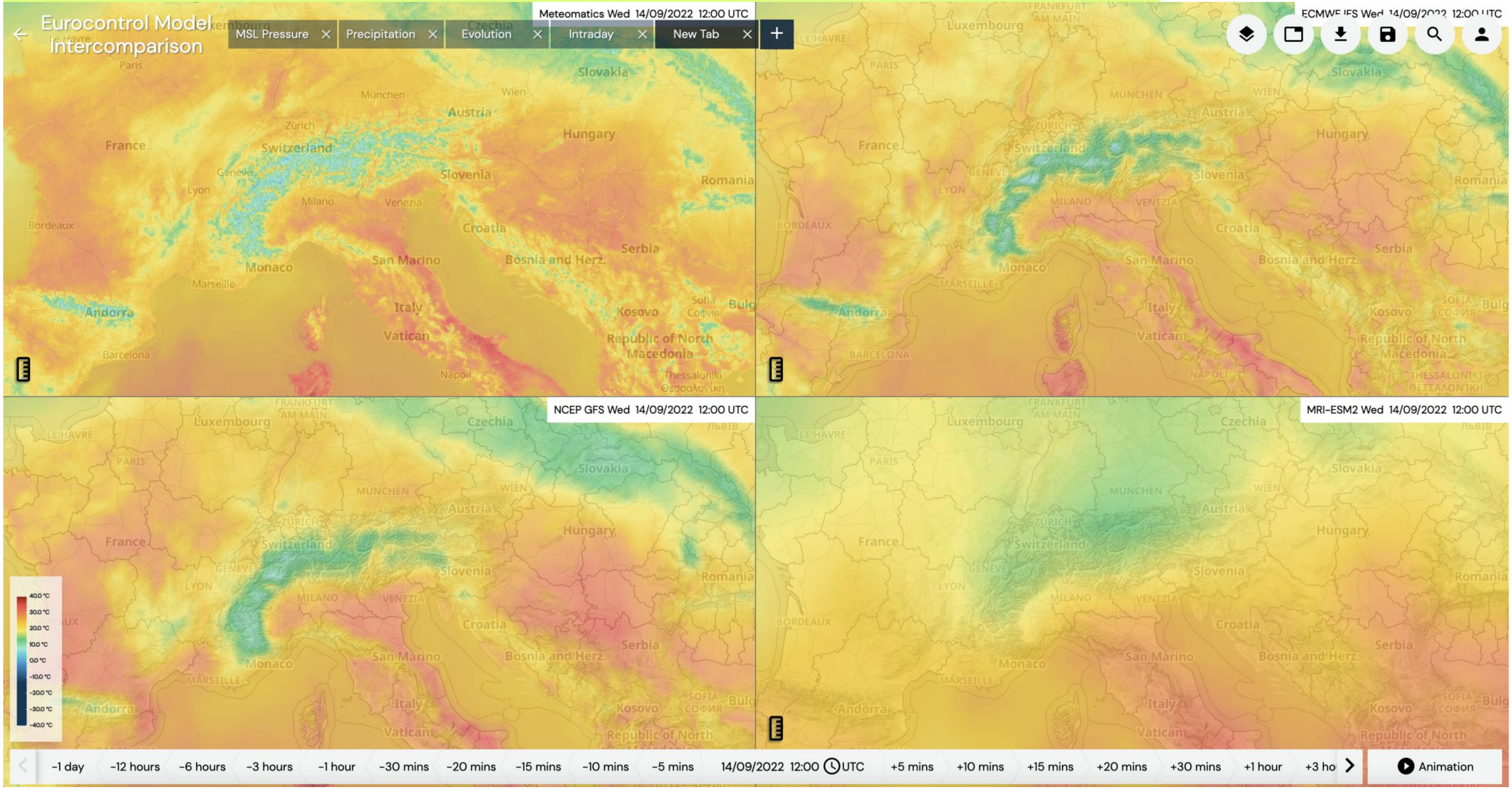
Atmospheric models



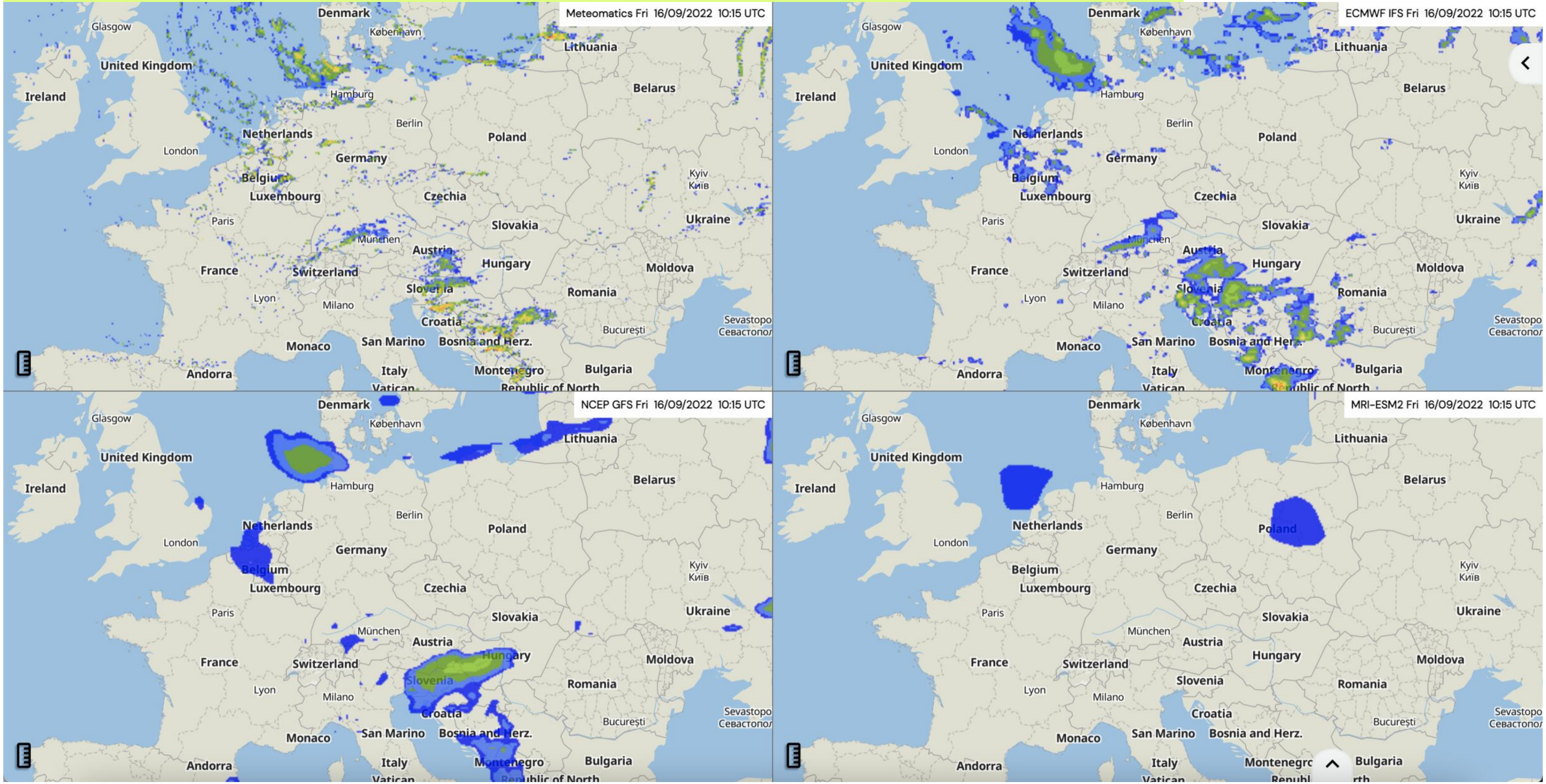
Different model resolutions



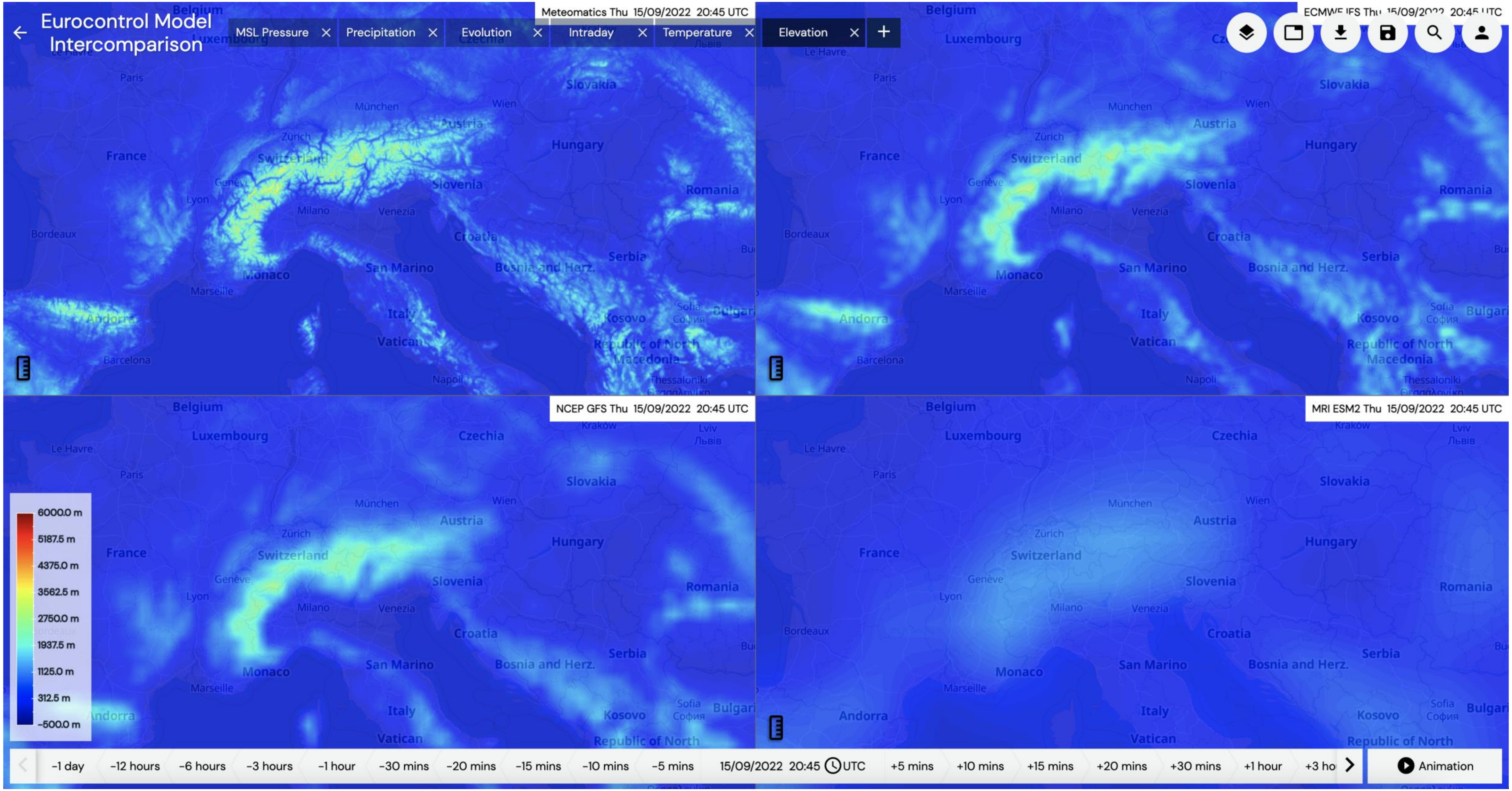
Different model resolutions



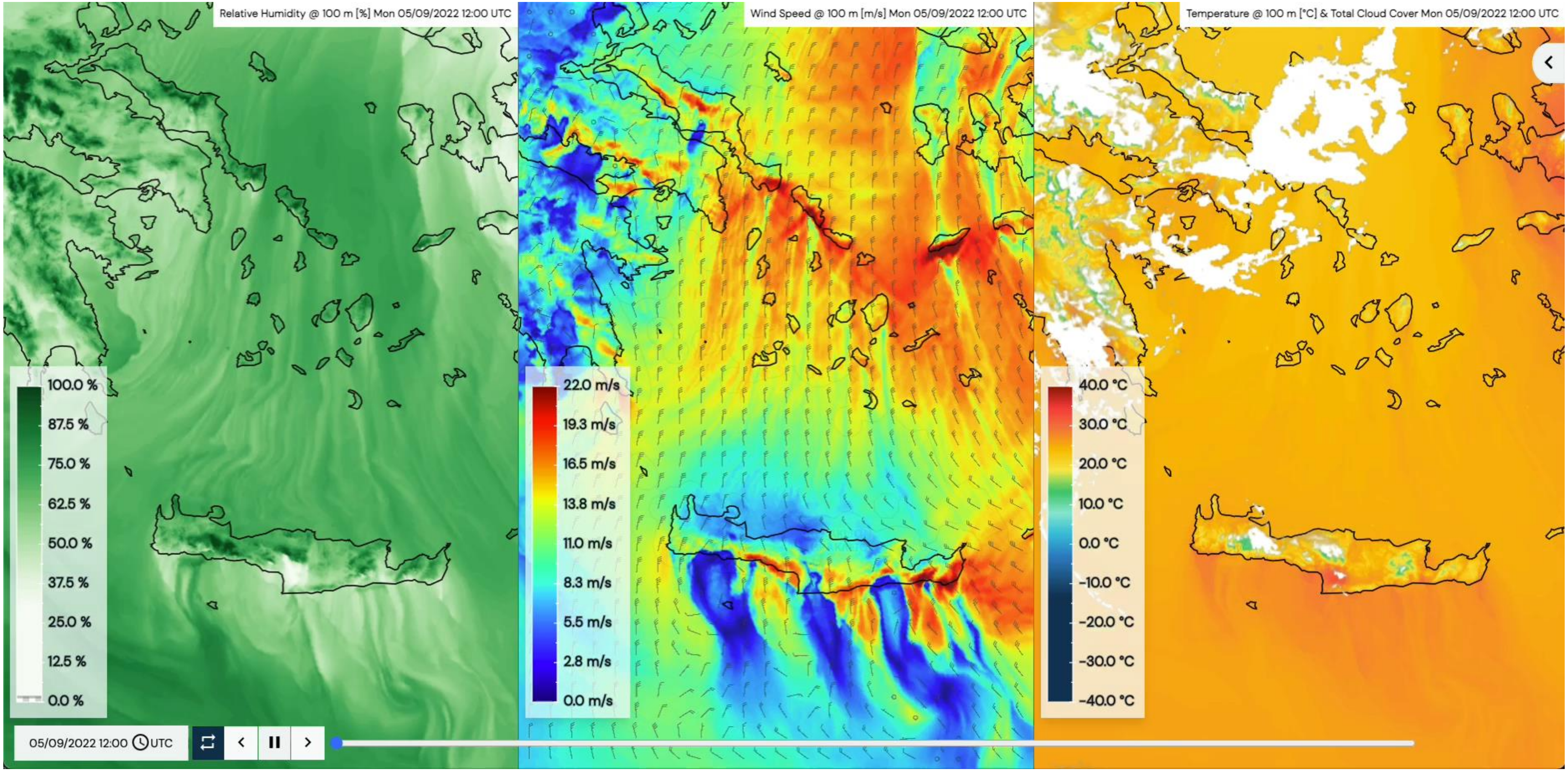
Different model resolutions



Different model resolutions



Certain phenomena can only be resolved at higher resolution



Phenomena that can't be resolved by Climate Models

Not explicitly resolved in global climate models

- Thunderstorms
- Hurricane force winds
- Hail
- Local fog
- Terrain induced effects / channelization
- Flash floods
- Contrails…

Work-around (aka "solution")

- Investigate proxy variables: atmospheric stability

What makes us trust in climate models?

Start climate model in the past and compare output with reanalysis data.

Climate models are not reanalysis data: But we try to calibrate probability densities to replicate ERA5.

Adding now CO_2 chemistry & increase supports the warming trend at global scale we already observe.

Thus, we can assume that the models give insight how the global warming trend will continue.

Weather API Structure

Global & Regional Weather Models

Satellite Data

Lightning

Radar

Maritime Data

Meteodrones

Weather Stations

Digital Terrain Model

Air Quality

MeteoCache

7+ Petabytes of historical, real-time & forecast weather data

Hosted securely at an external data centre

Up to 90-metre spatial & 5-minute temporal resolution

Weather API

API Requests

HTTPS://

-Data processing, interpolation & downscaling on the fly

-Automated data source selection (optional)

-Optimised for lightning-fast delivery

100% Uptime

Users

CSV JSON XML

Standard file formats

Clear & consistent data formatting

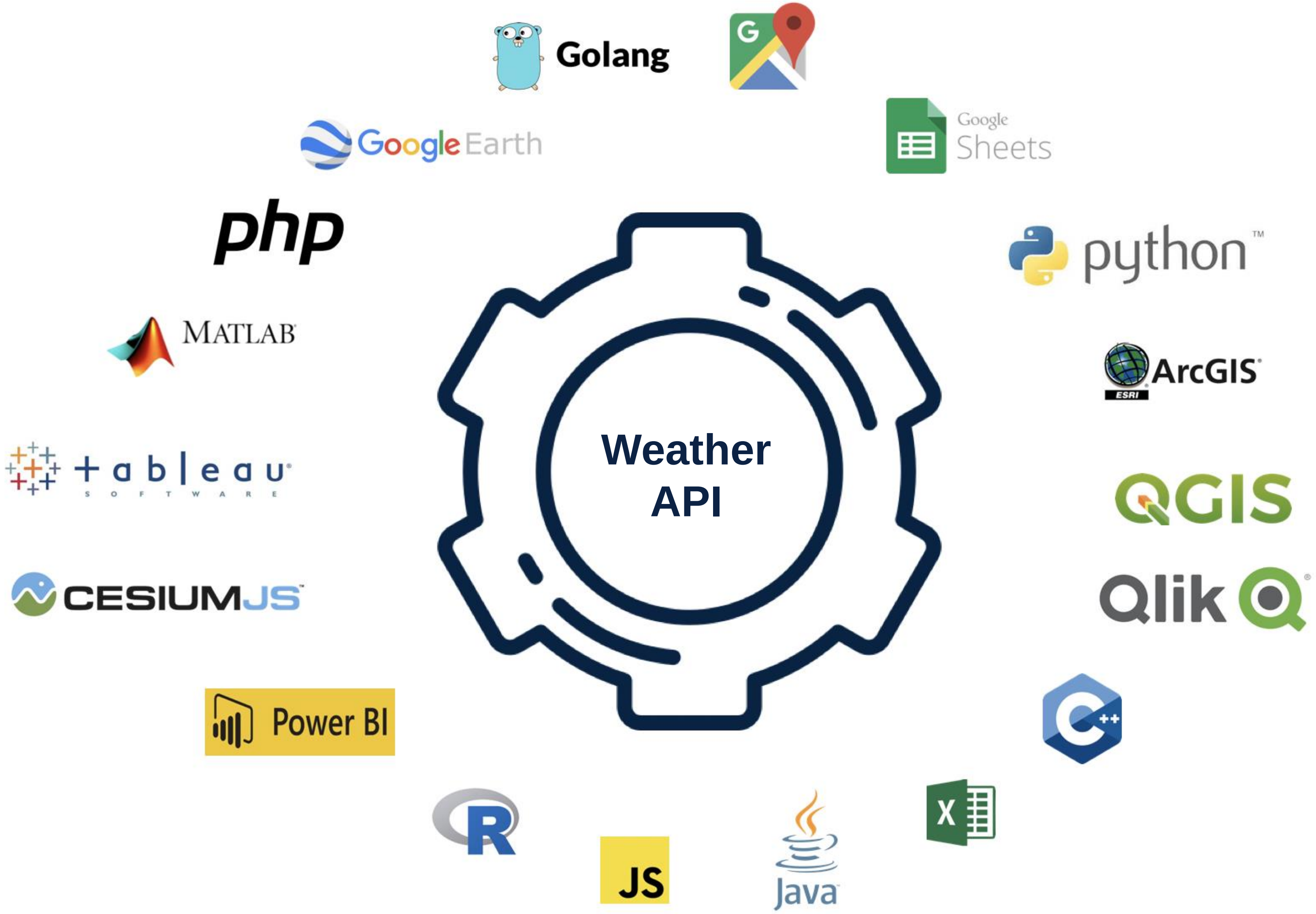
Continuous time series, gap-free data

python ArcGIS

& more…

Open source data connectors accelerate integration

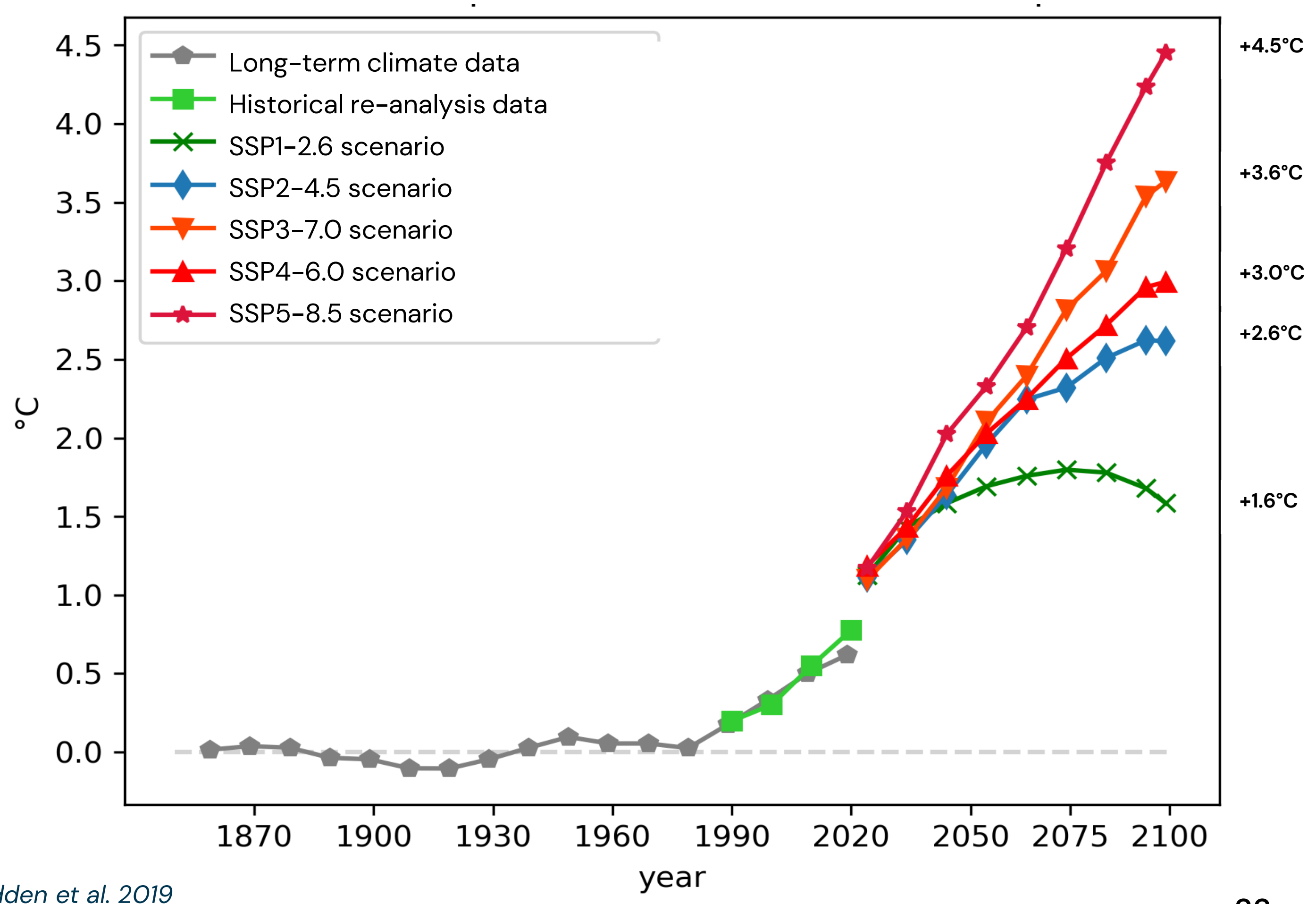
Variety of possible integrations



Climate scenarios based on widely accepted shared socioeconomic pathways (SSPs)

Climate parameters[1]

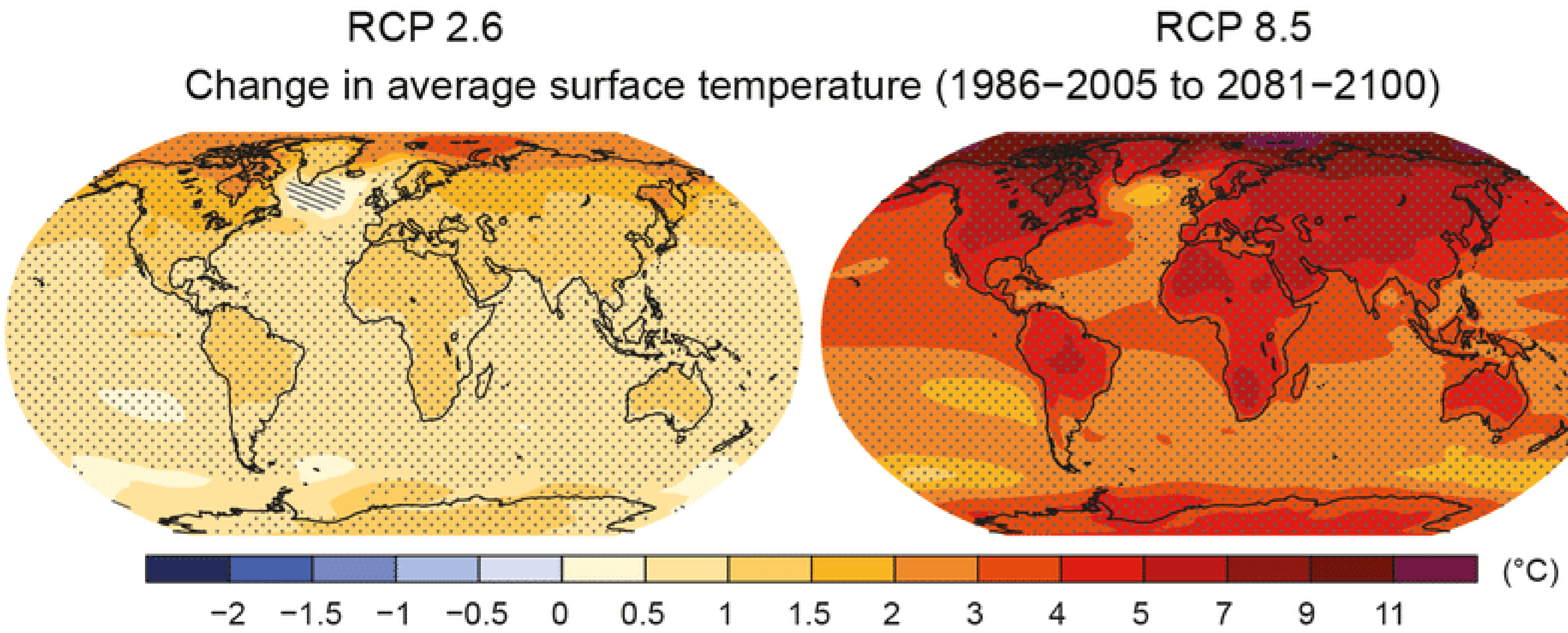
SSP1: Sustainability	• RCP • Temperature	2.6 W/m2 +1.6°C
SSP2: Middle of the Road	• RCP • Temperature	4.5 W/m2 +2.6°C
SSP3: Regional rivalry	• RCP • Temperature	7.0 W/m2 +3.6°C
SSP4: Inequality	• RCP • Temperature	6.0 W/m2 +3.0°C
SSP5: Fossil-fuelled development	• RCP • Temperature	8.5 W/m2 +4.5°C



Source: O'Neill et al. 2014, Meinshausen et al. 2017, Keywan et al. 2017, Gidden et al. 2019

(1) 2014 IPCC RCP scenarios; global temperature change by 2100 vs. pre-industrial period

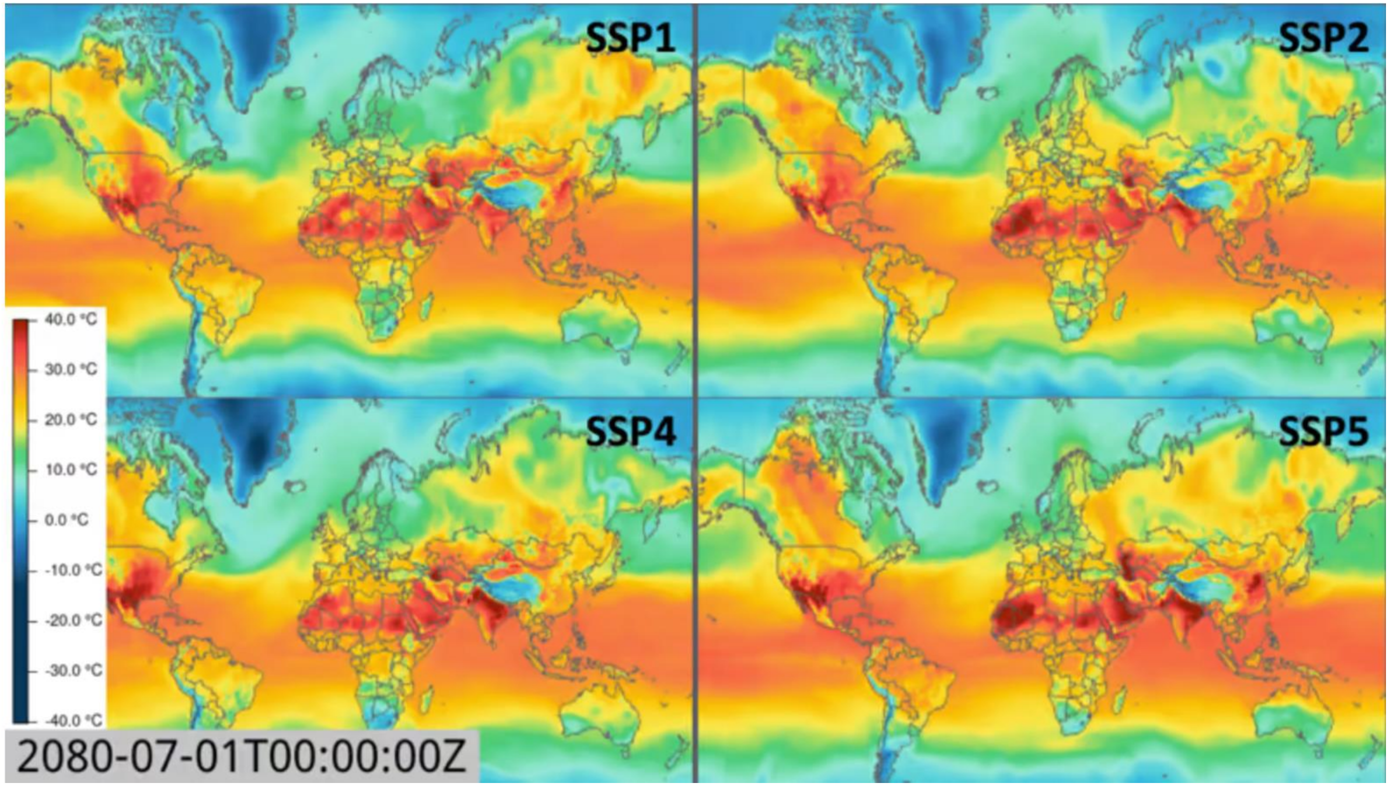
Temperature increase based on SSPs



IPCC report WG1, AR5

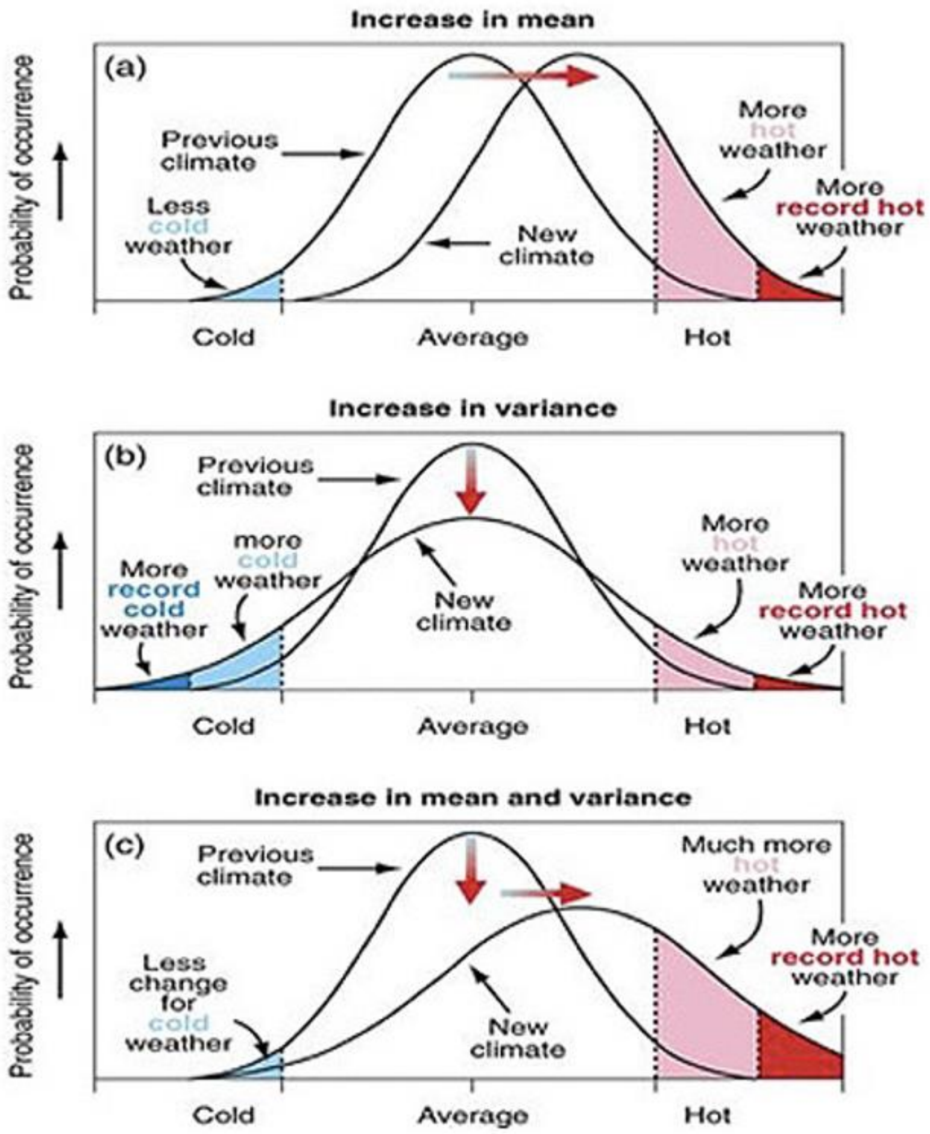
Meteomatics Climate Data

- We provide the 5 climate scenarios (SSPs) recognized by IPCC, on a global coverage,
- All scenarios are available up to 2100
- Over 120 years of data are available with one API call
- Data Source: MRI-ESM2.0 (comparability ensured through CMIP6)
- Atmospheric parameters
- Downscaled to 90m
- Around 40 derived parameters available: wind direction, wind gusts, pbl height, max/min/mean parameters with different units and timescales



Meteomatics global 2m temperature for July 1st, 2080 (MetX)

Climate change modelling of extreme events



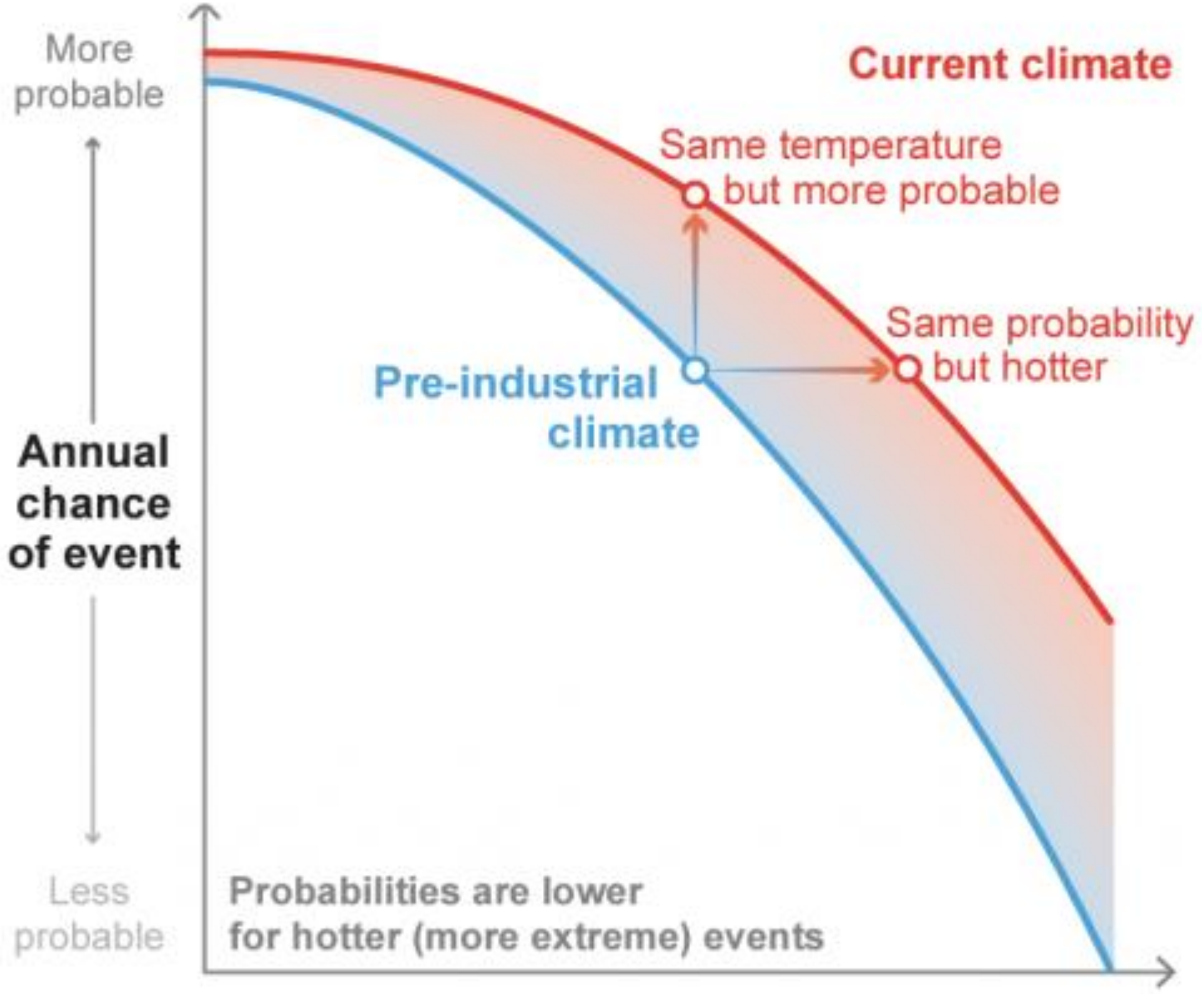
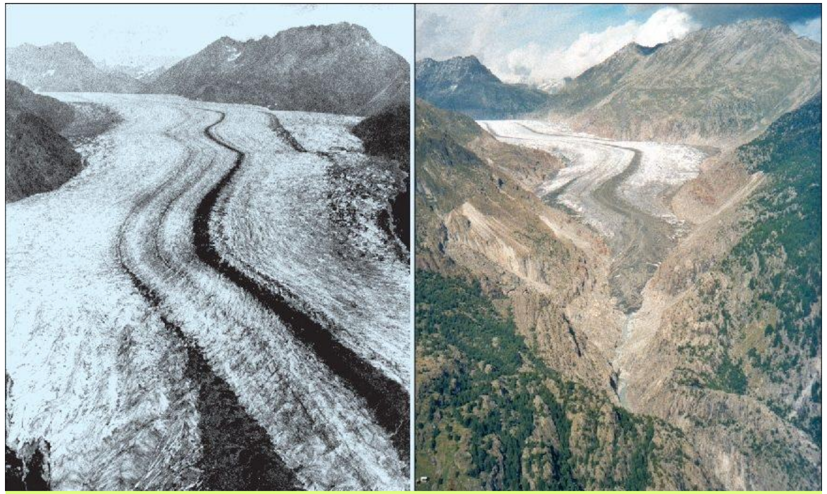


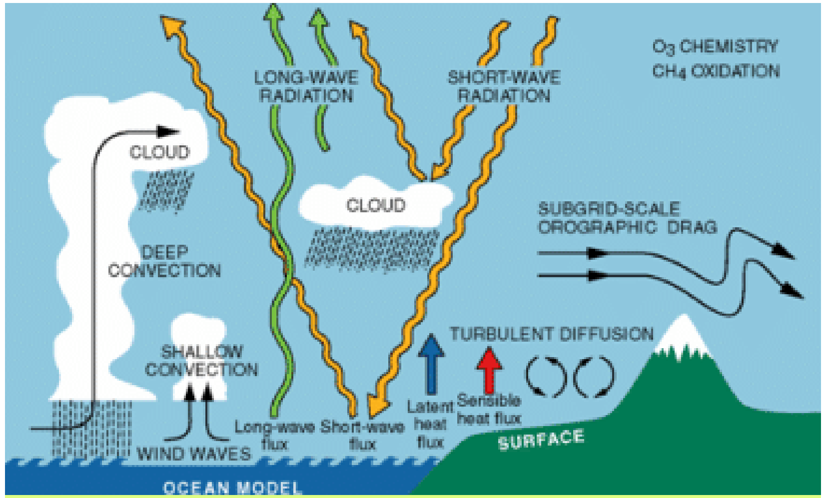
Diagramm by Riskope

IPCC, *AR6 WG1, Chapter 11,*

Conclusion



Climate change is a fact



Modelling of atmospheric processes is complex

More work is needed to improve climate models and represent climate change

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