EUCP and CONSTRAIN

Towards km-Resolution Global Climate Models: Scientific ane Technical Challenges

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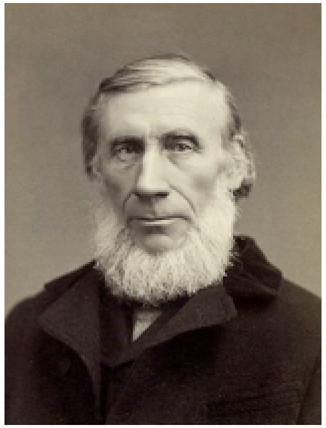
LTP/PSI Thursday Colloquia. Paul-Scherrer-Institute, May 20, 2021

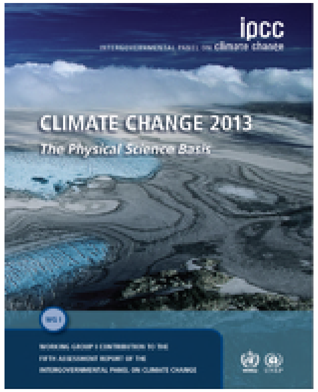
Joseph Fourier (1824) recognized role of greenhouse gas effect:
“This distinction between **luminous heat** and **dark heat** explains the increase of temperature caused by **transparent bodies**.”

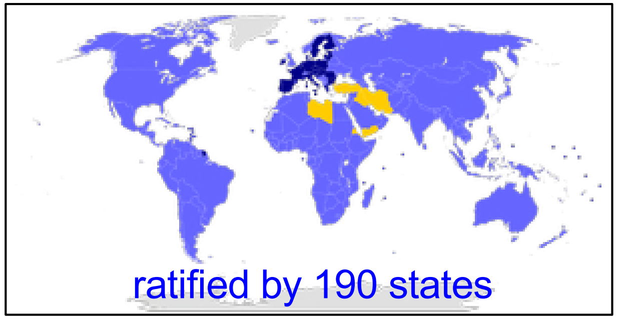
John Tyndall (1861):
Identified main GHG: **H_2O, CO_2, O_3 and CH_4**



Svante Arrhenius (1896):
Doubling of CO2 => warming of ca 5.5 K

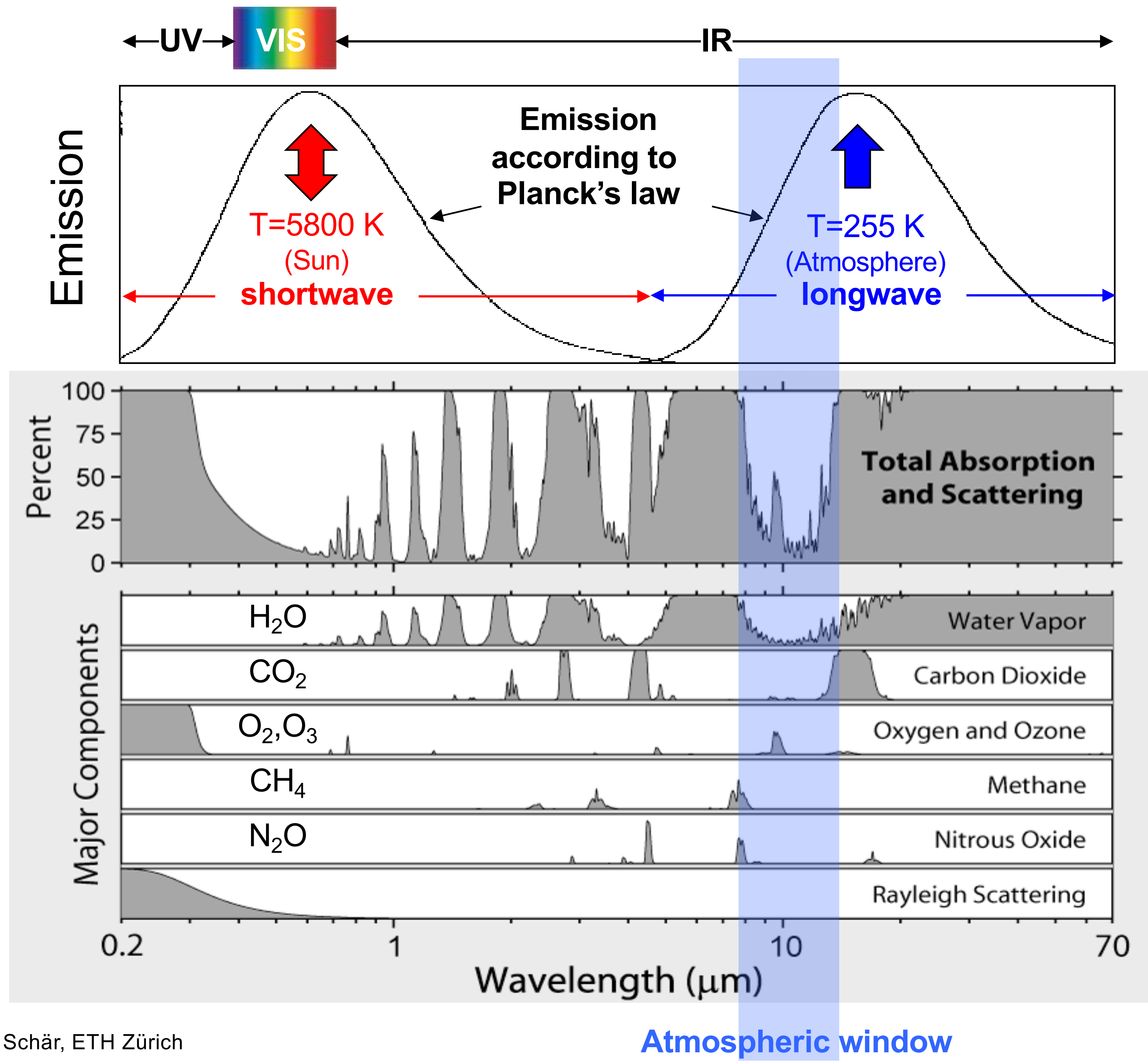
IPCC (2007, 2013):
Broad scientific consensus
(Intergovernmental Panel on Climate Change)





Paris Agreement (2015):
Broad political consensus
⇒ Substantial emission reductions by 2030
⇒ Switzerland: Vote on CO_2 law in June 2021

Greenhouse effect



Energy balance of planet determined by
- incoming/outgoing SW and
- outgoing LW radiation

The greenhouse effect is due to the absorption of long-wave radiation by trace gases.

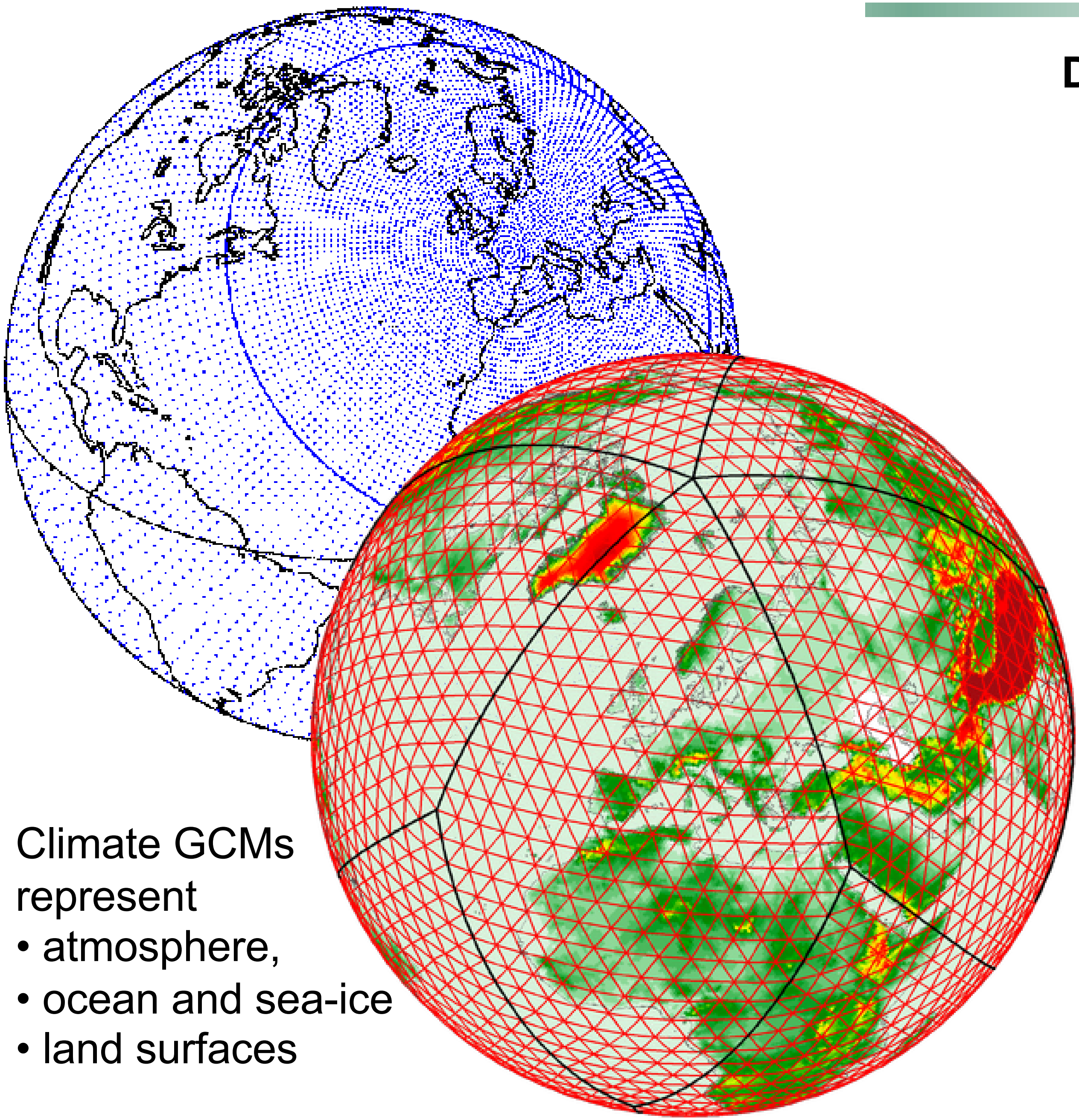
Absorption by GHGs

Changes in GHGs imply adjustments of climate system to attain a new balance, e.g. changes in
- temperature, humidity, clouds
- circulation, stratification, etc

Implies potential feedbacks

(Peixoto and Oort 1992; Wikipedia)

Global Climate Models



Climate GCMs represent
- atmosphere,
- ocean and sea-ice
- land surfaces

Dry atmospheric dynamics

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F^x$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F^y$$

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z$$

with $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla \qquad \mathbf{V} = (u,v,w)$

$$p = \rho R T$$

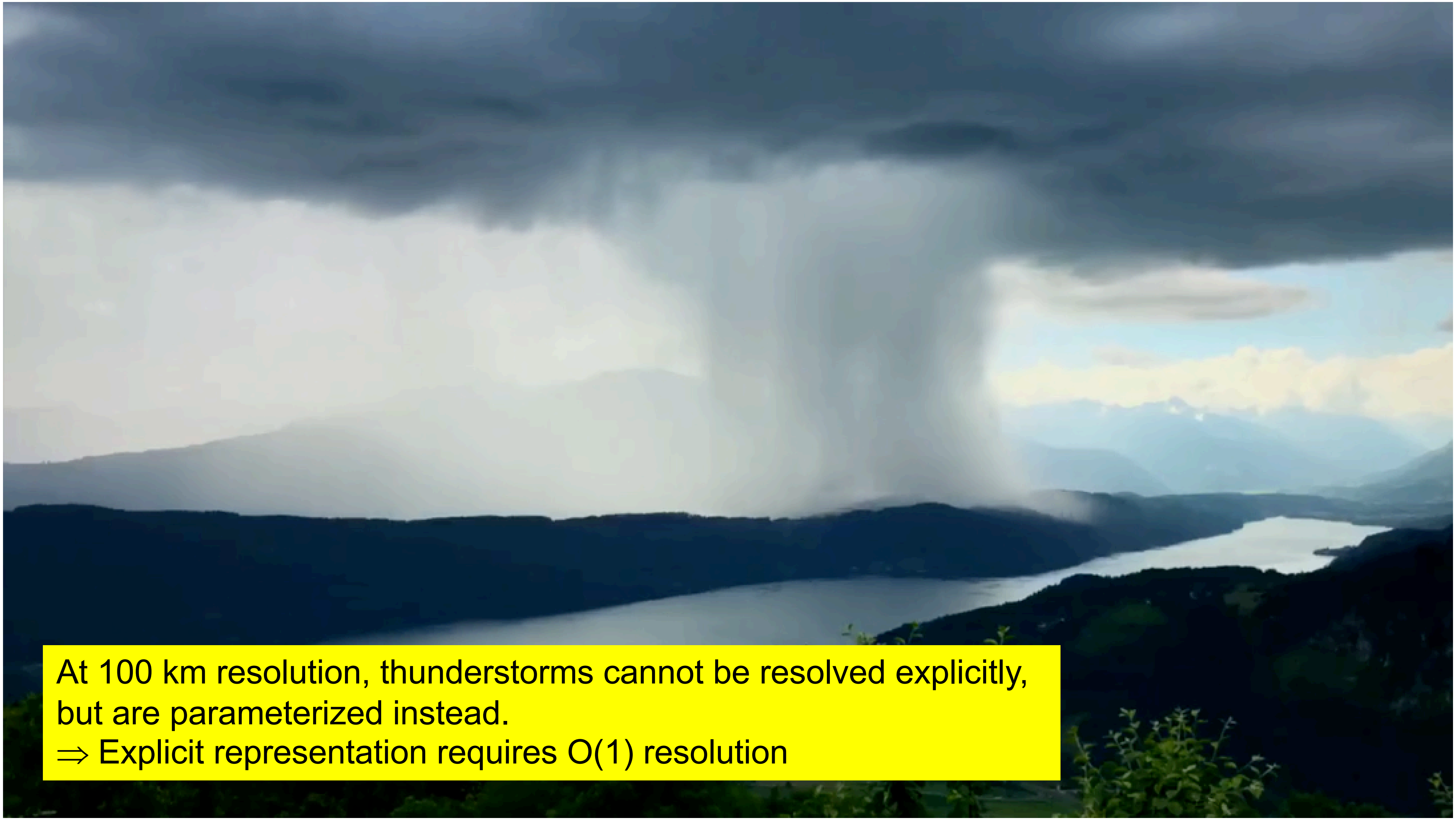
$$\frac{DT}{Dt} - \frac{1}{c_p \rho}\frac{Dp}{Dt} = H$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\left(\rho\mathbf{V}\right) = 0$$

Typical resolutions 50-200 km

Horizontal discretization: ICON (MPI-M, DWD) and Arpège (MeteoFrance)

Small scales

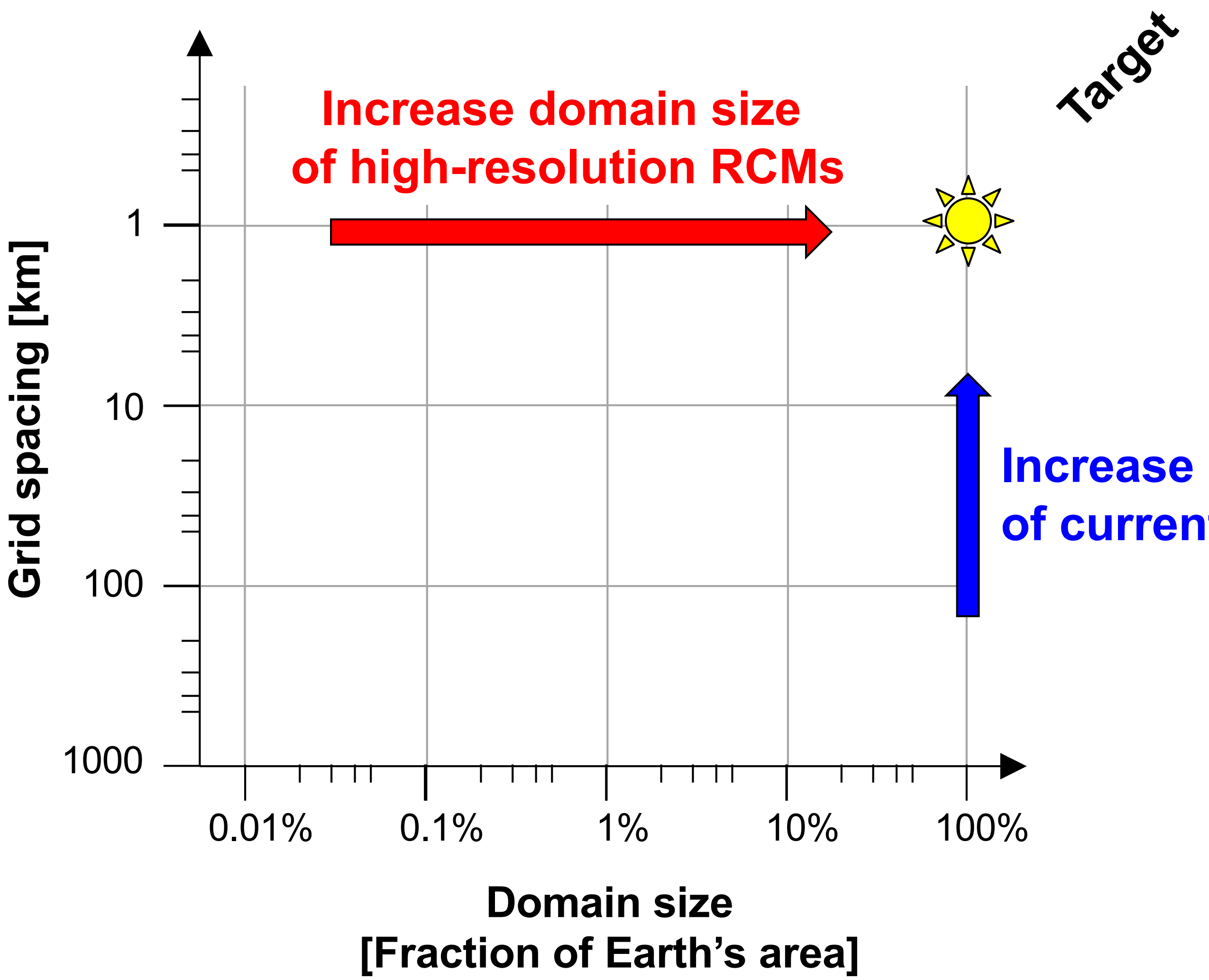


At 100 km resolution, thunderstorms cannot be resolved explicitly, but are parameterized instead.

⇒ Explicit representation requires O(1) resolution

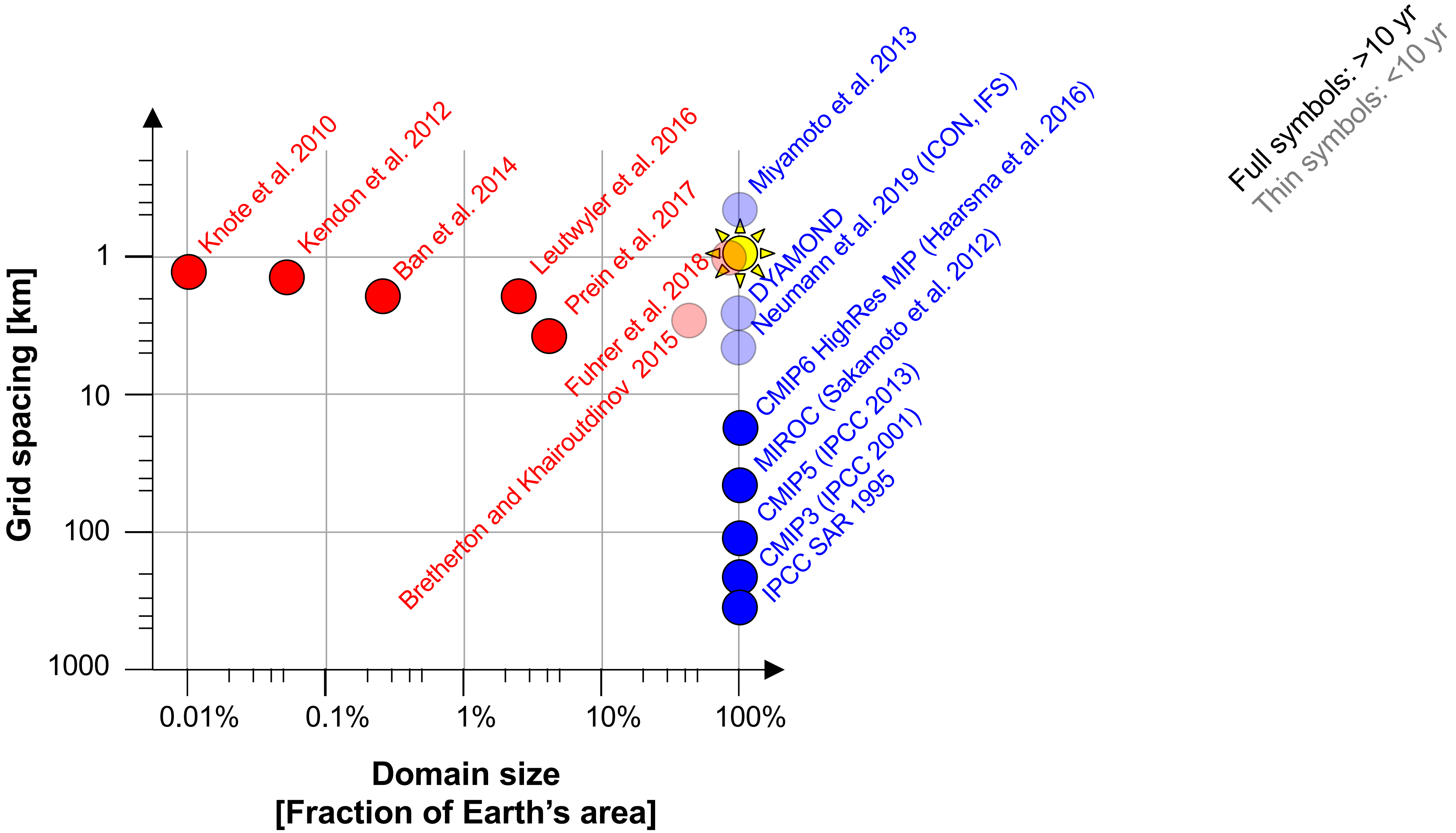
Convection over Lake Millstätter, Austria, June 10, 2018 (Peter Maier, Facebook)

Approaches to global km-scale models



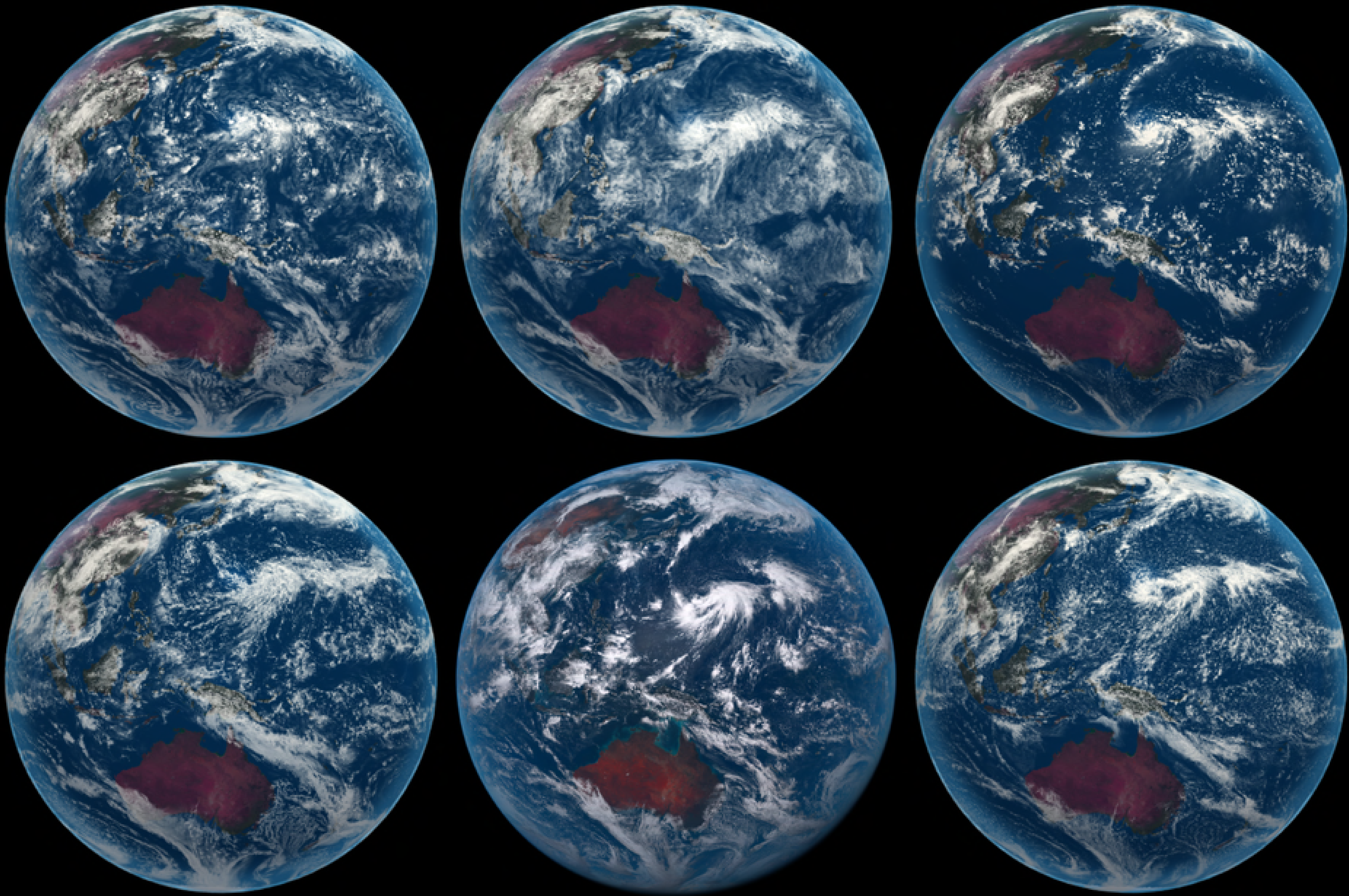
(Schär et al., BAMS, 2020)

Development of RCM and GCM simulations



(Schär et al., BAMS, 2020)

Who is who? (5 models, 1 satellite picture)



Schär, ETH Zürich

DYAMOND models (Stevens, Satoh et al. 2019)

Why is km-resolution attractive?

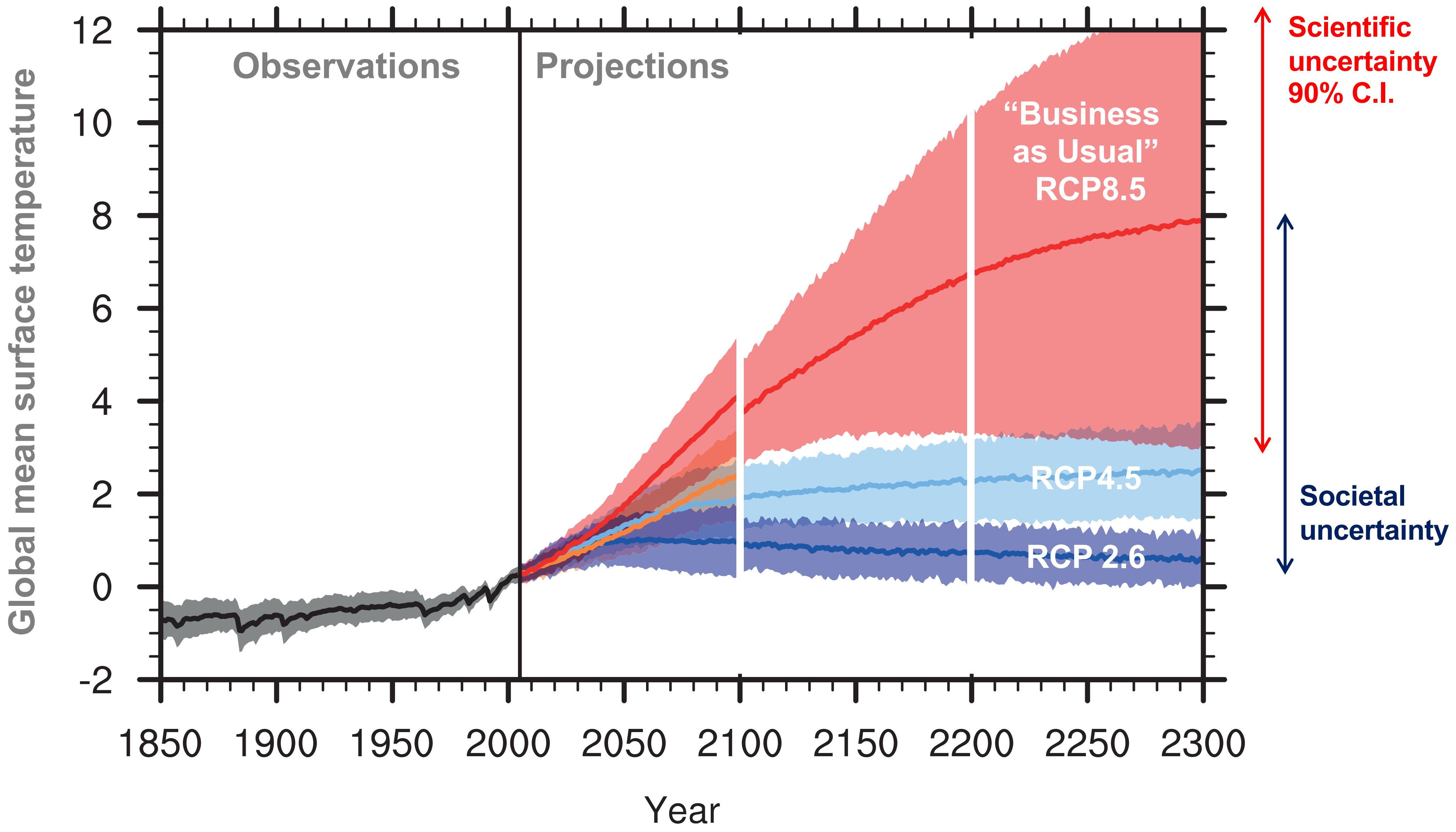
Severe weather and extreme events

Zürich, Haldenegg

Station Lausanne, 11. Juni 2018
41 mm precipitation in 10 min

Schär, ETH Zürich

Global warming (past and future)



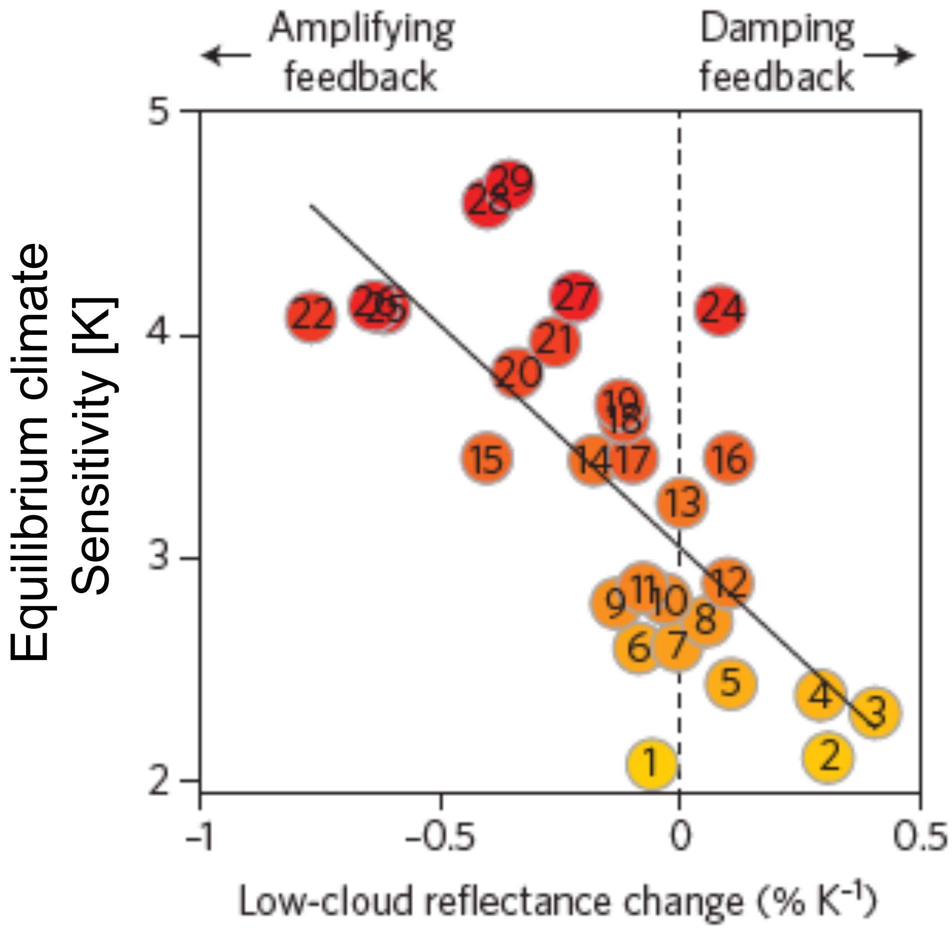
Scientific uncertainties as large as societal uncertainties!

Schär, ETH Zürich

(IPCC AR5, 2013)

Climate sensitivity and clouds

ECS = equilibrium climate sensitivity = equilibrium warming for $2xCO_2$



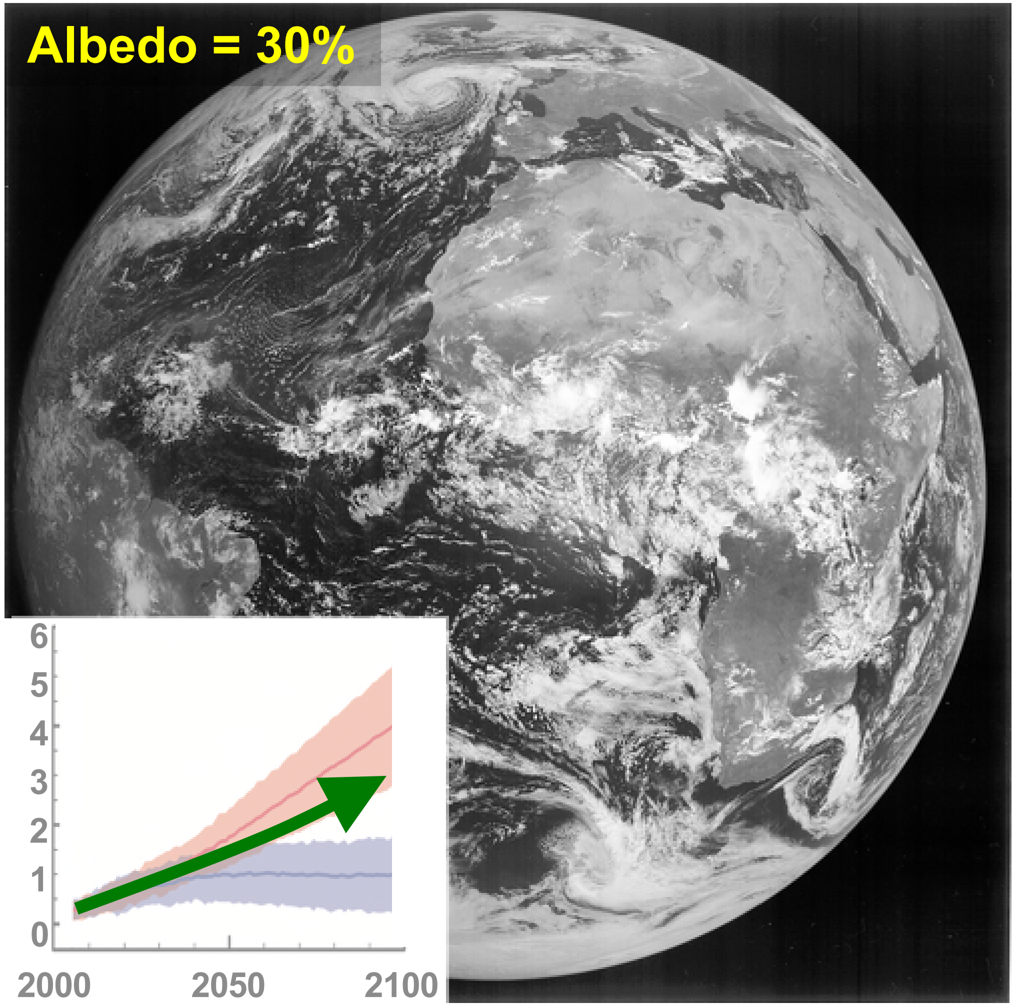
Uncertainties of global projections strongly depend upon tropical cloud cover.

In some models, cloud cover and reflection of solar radiation increases (negative feedback), in other it decreases (negative feedback).

In current GCMs, the representation of clouds is strongly affected by the parameterization of convection. High-resolution models use an explicit representation instead.

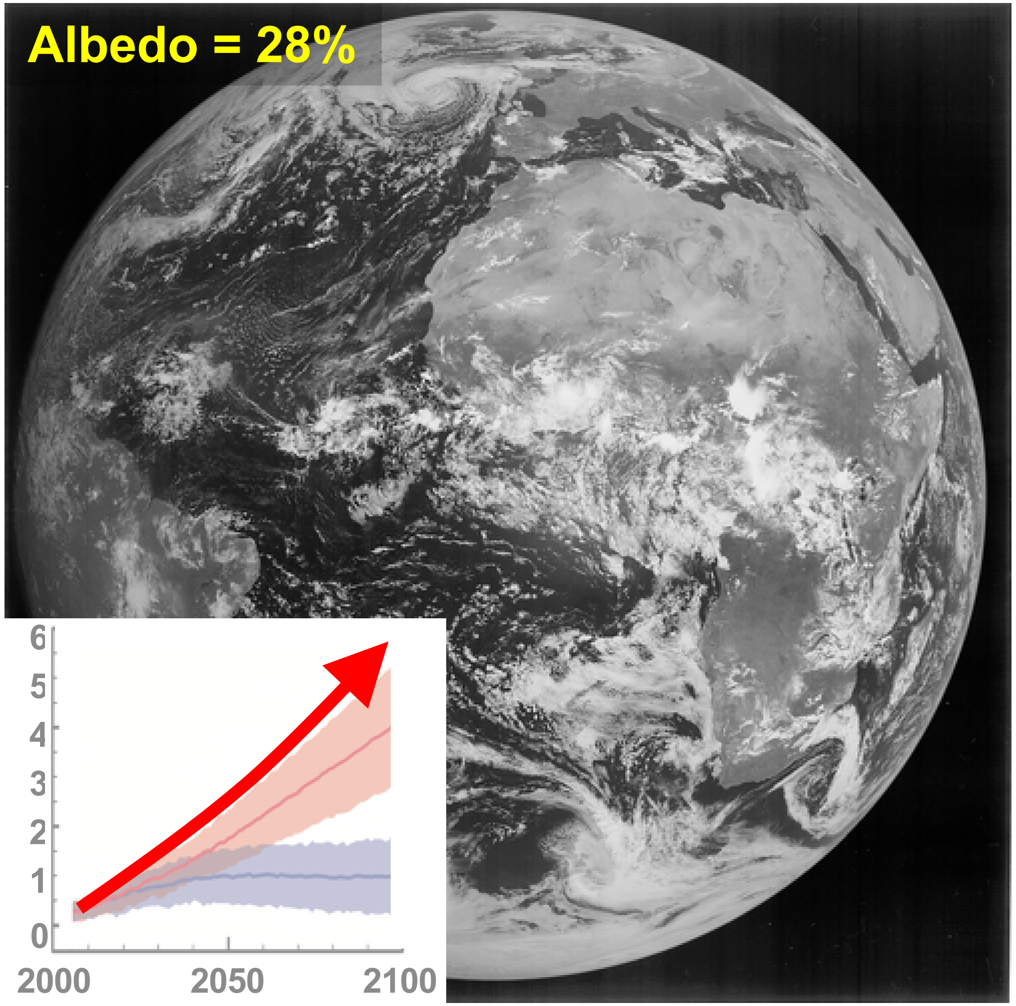
(Schneider et al. 2017, Nature CC; see also Bony et al. 2015, NGS)

What is the difference



$\Delta\alpha = 0\%$

ECS ≈ 3 ºC



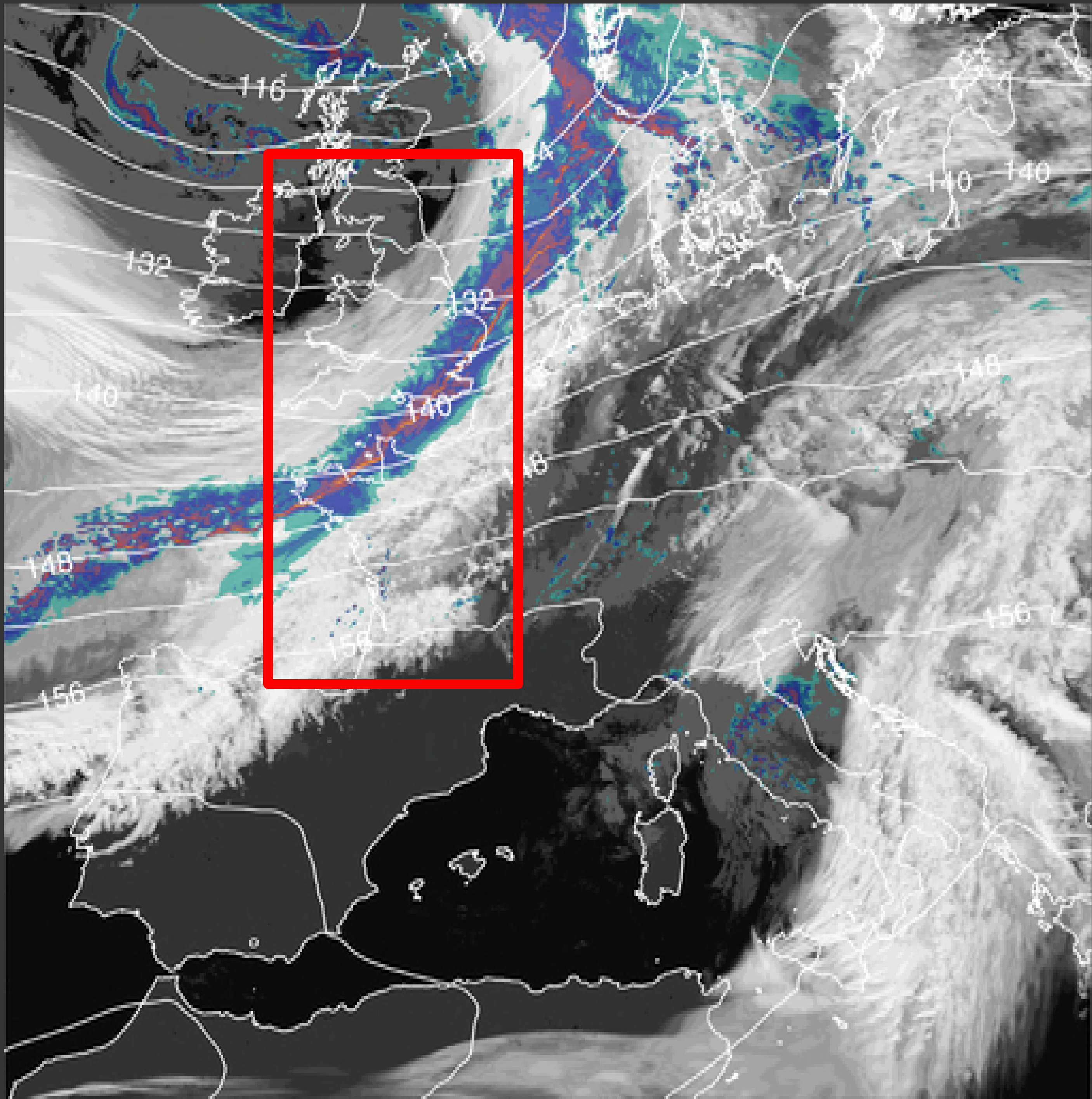
$\Delta\alpha = -2\%, \ \Delta R_{toa} \approx 7 \ \mathrm{W/m^2}$

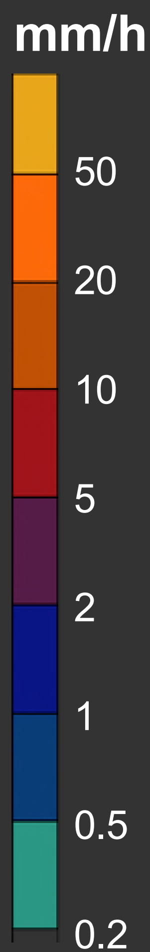
ECS ≈ 8 ºC

(Bony et al. 2006, 2015; Sherwood et al. 2014; Schneider et al. 2017)

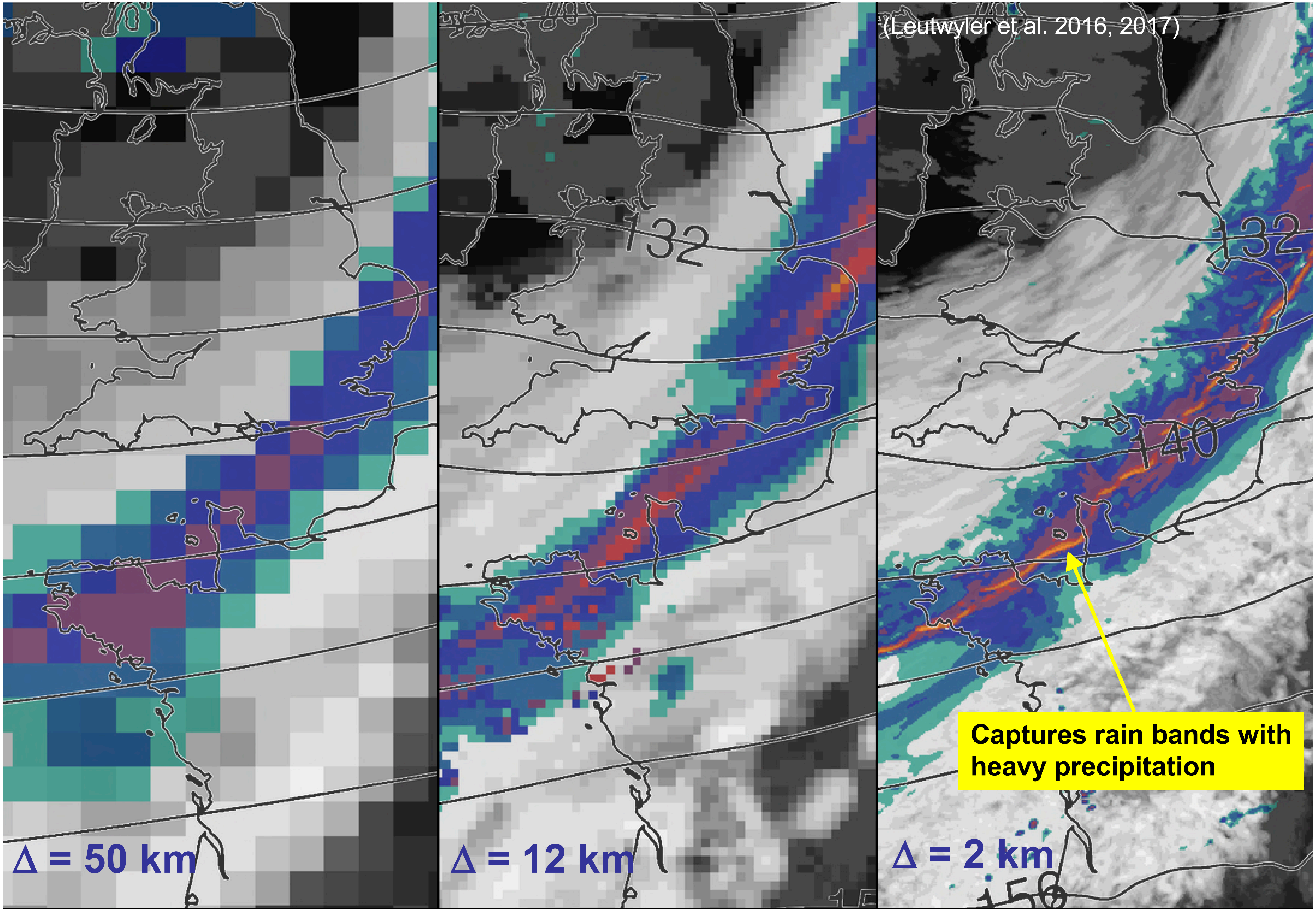
What are the prospects of km-resolution?

Limited-area simulation driven by reanalysis



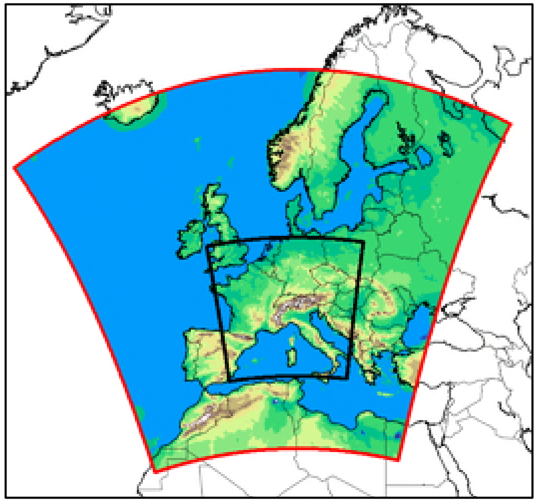


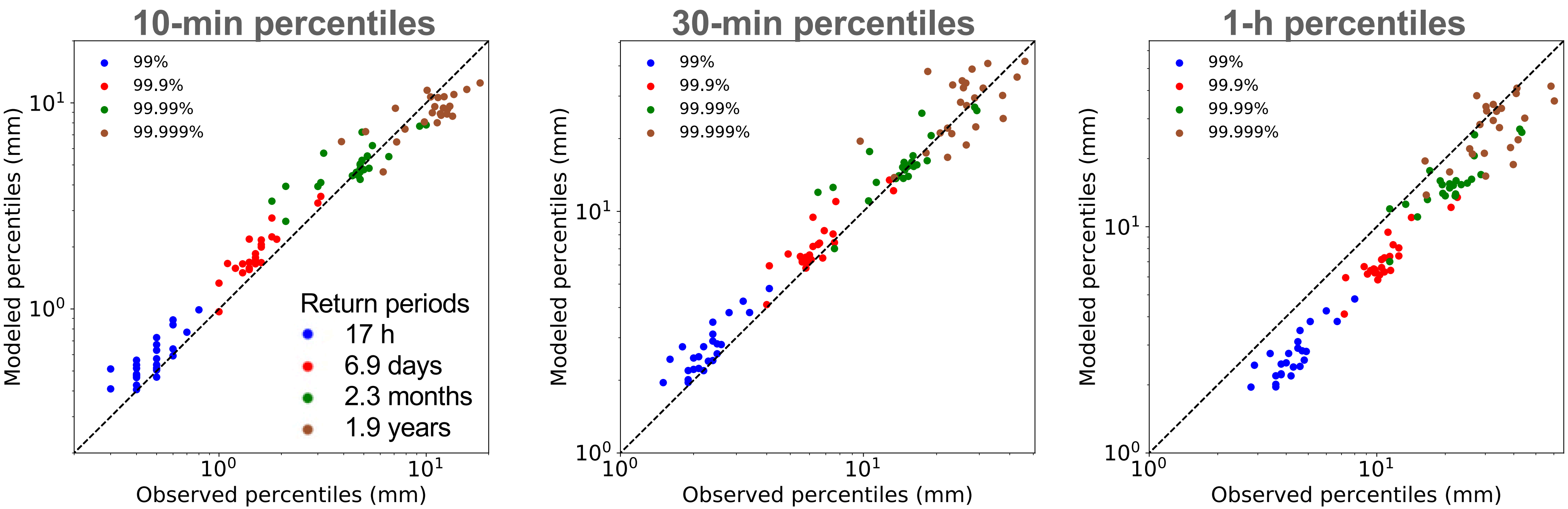
Leutwyler et al. (2016, 2017) http://www.c2sm.ethz.ch/research/crCLIM


(Leutwyler et al. 2016, 2017)
132
132
140
156
Captures rain bands with heavy precipitation
Δ = 50 km
Δ = 12 km
Δ = 2 km

Precipitation extremes: Validation

- Previous research: much improved representation of 1h-precipitation extremes (e.g. Ban et a. 2014, others)
- Satisfactory validation against rain-gauge observations in Switzerland even for 10-min accumulation.
- Results are based on 10-year simulation over Central-Europe at 2.2 km resolution, with high-resolution output (6 minutes). Validation against rain-gauge stations in Switzerland.





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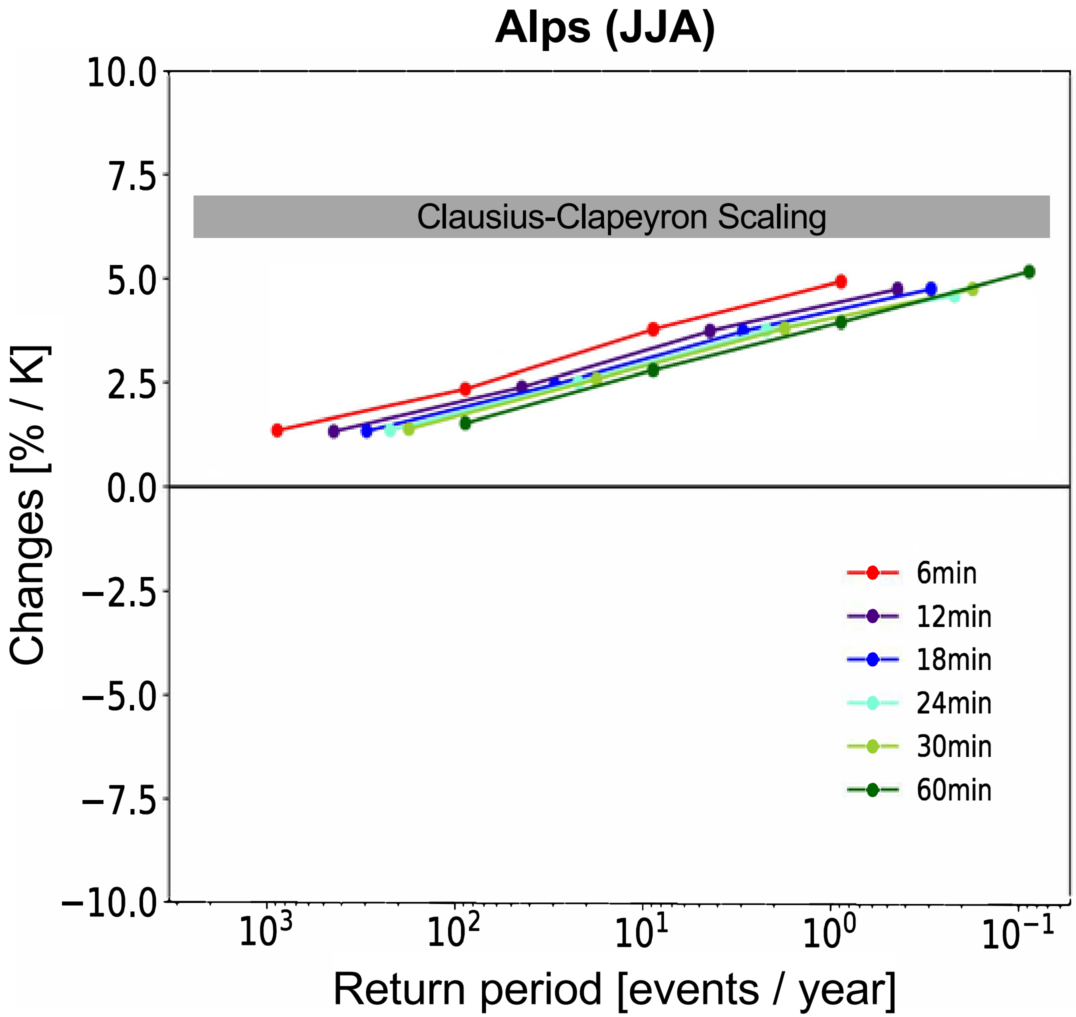
(Vergara, Ban and Schär, GRL, 2021)

Precipitation extremes: projections



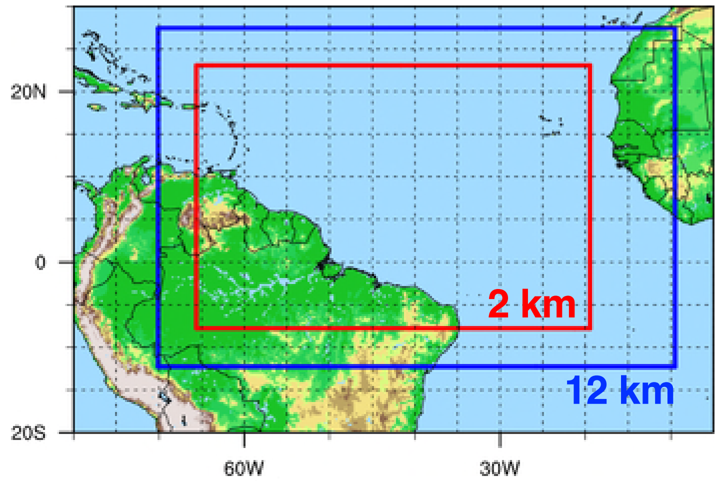
- RCP8.5 emission scenario
  - CTRL: 1996-2005
  - SCEN: 2090-2099

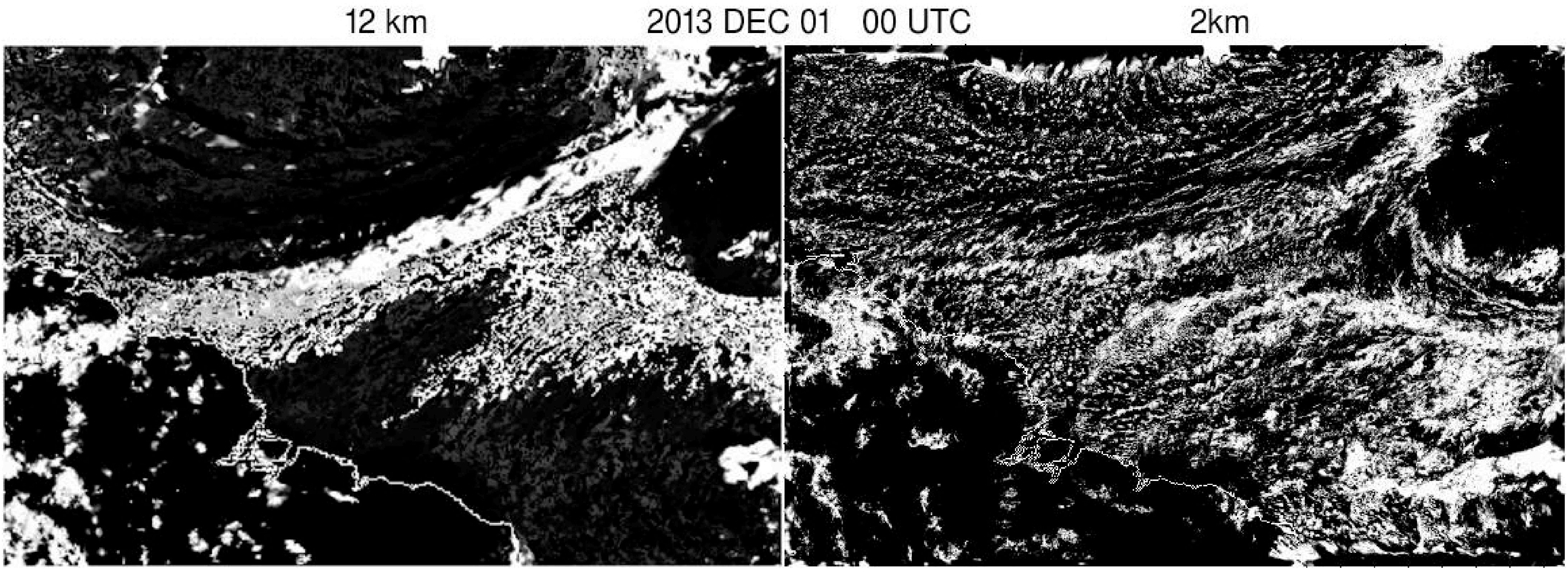
  Driven by MPI-ESM GCM
- Projections:
  - Increases of heavy events,
  - More pronounced for high-intensity events
- For very heavy events, increases appear to be limited by Clausius-Clapeyron increase of 6.5%/K
- Note: temperature scaling considers mean warming at 700 hPa (Ban et al. 2021)

(Vergara, Ban and Schär, GRL, 2021)

Extended simulations in sub-tropics

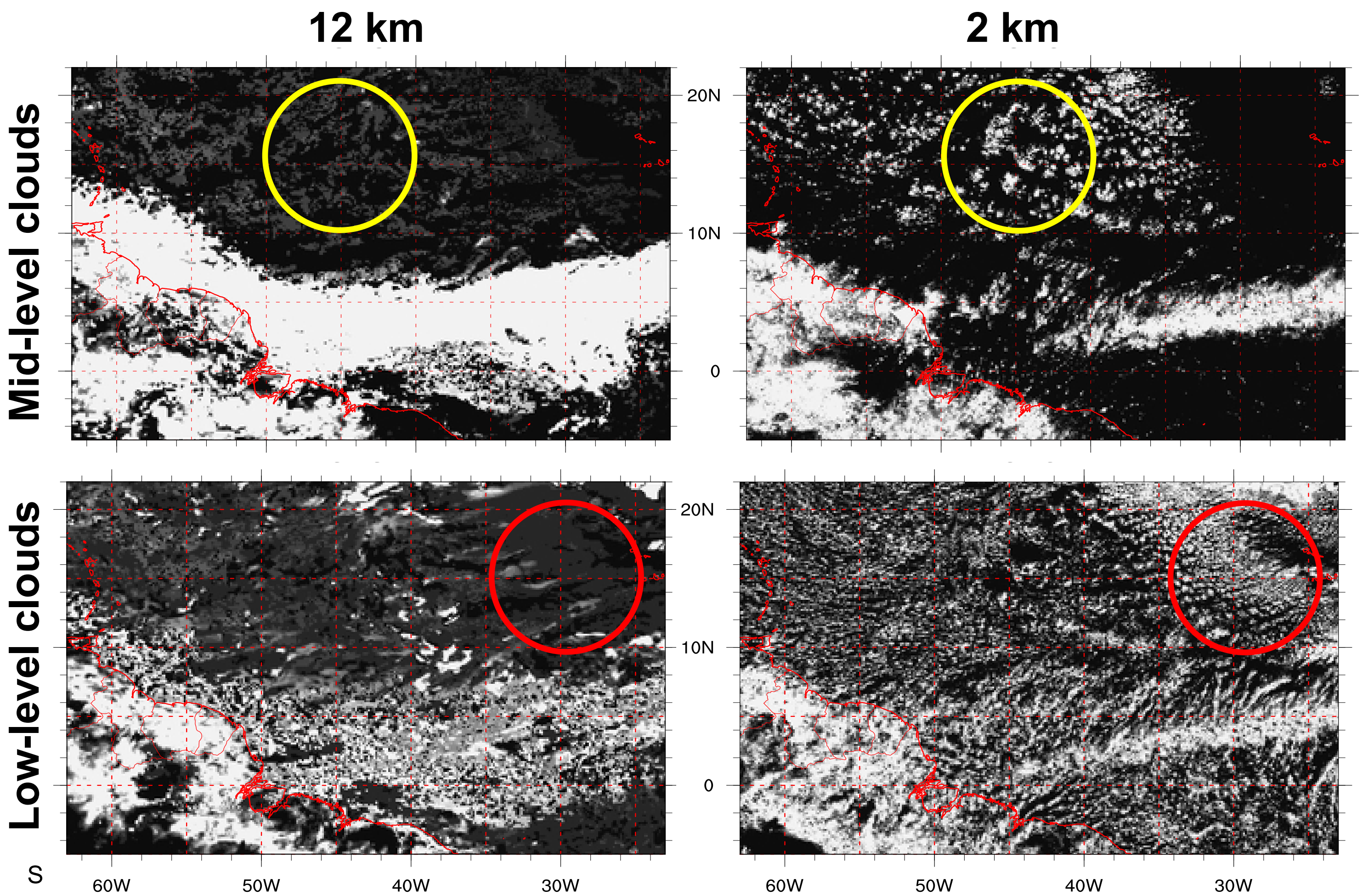
- Motivation: Role of tropical clouds for climate sensitivity
- Question: Can a 2-km model represent tropical clouds?



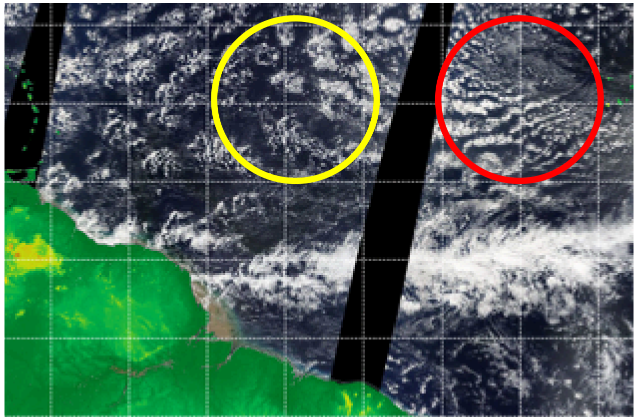


(Hentgen, Ban, Vergara and Schär, in revision)

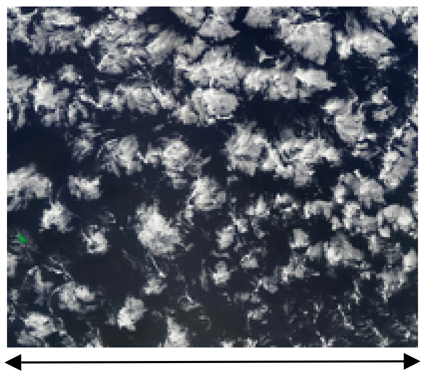
Meso-scale clouds in sub-tropics



Observation VIS (MODIS)



"flowers"



(Stevens et al. 2019)

Model credibly captures some of the meso-scale cloud structures

(Hentgen, Ban, Vergara and Schär, in revision)

Is $\Delta x = \mathrm{O}$(km) sufficient?

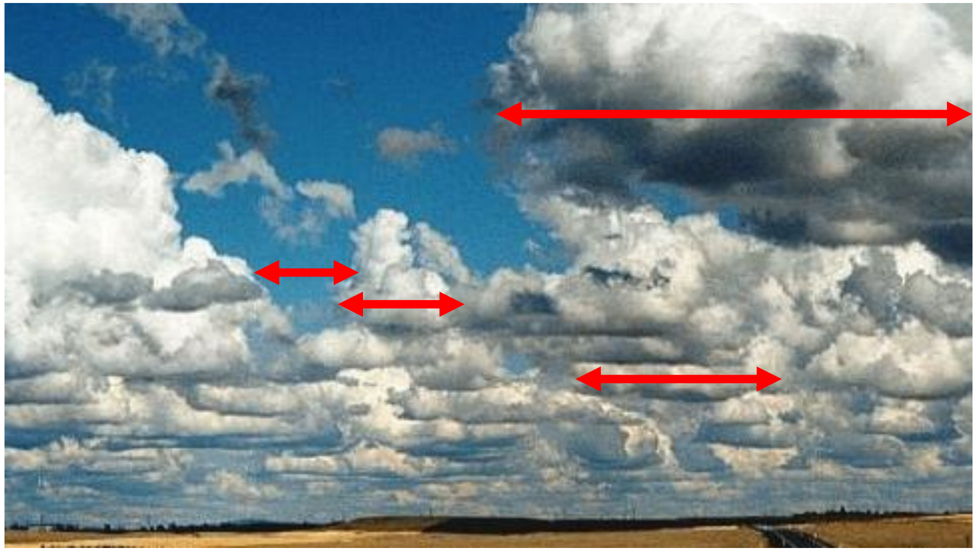
Is $\Delta x = O(\text{km})$ sufficient?

Bulk convergence

Area-averaged bulk effect:
E.g., heating and moistening of cloud layer

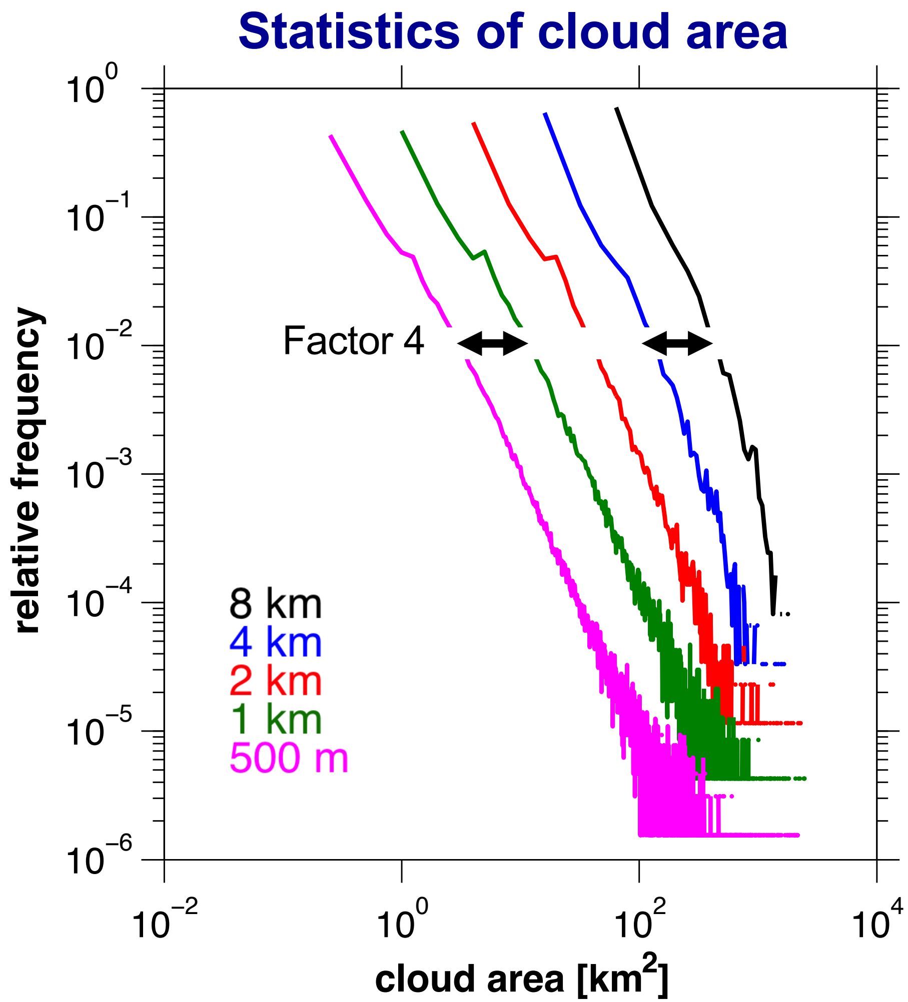
Requires budgeting analysis
(Langhans et al. 2012, Panosetti et al. 2018)

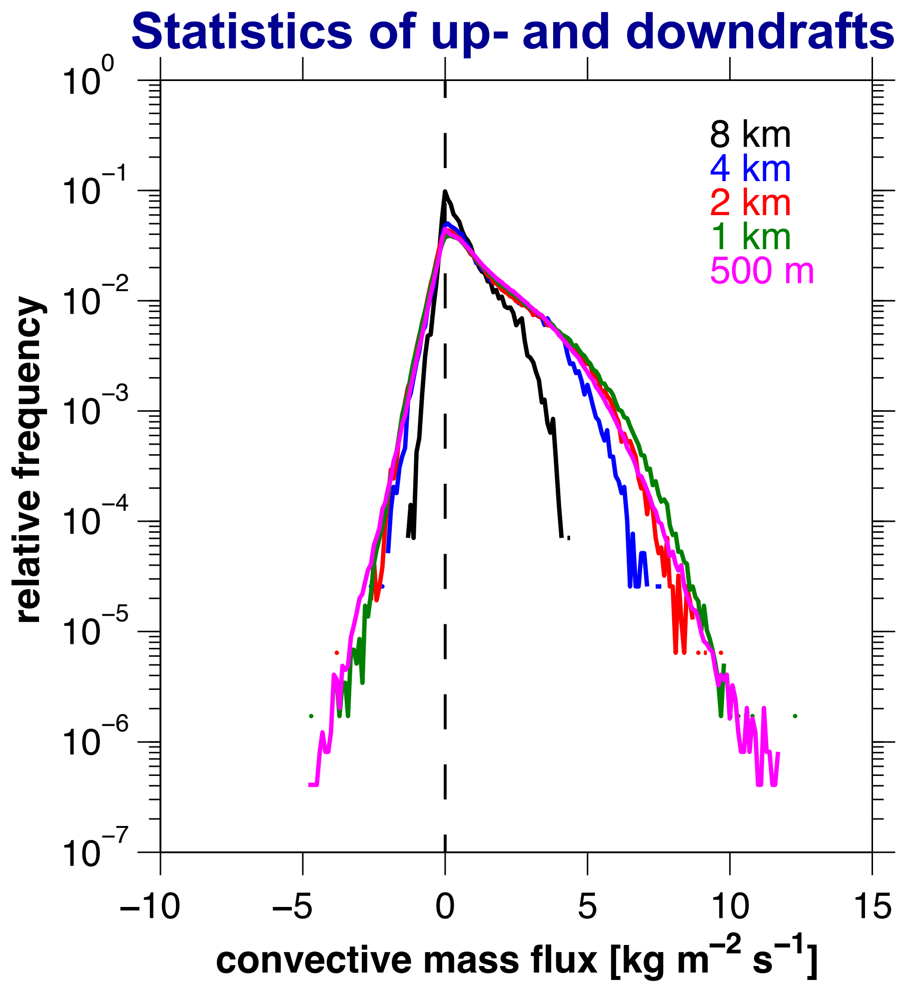
Structural convergence



Statistics of cloud ensemble:
E.g., spacing and size of convective clouds

Structural and bulk convergence





Lack of structural converge!

Bulk statistics of updrafts converges

(Panosetti et al. 2018; see also: Panosetti et al. 2019, Dauhut et al. 2015, many others)

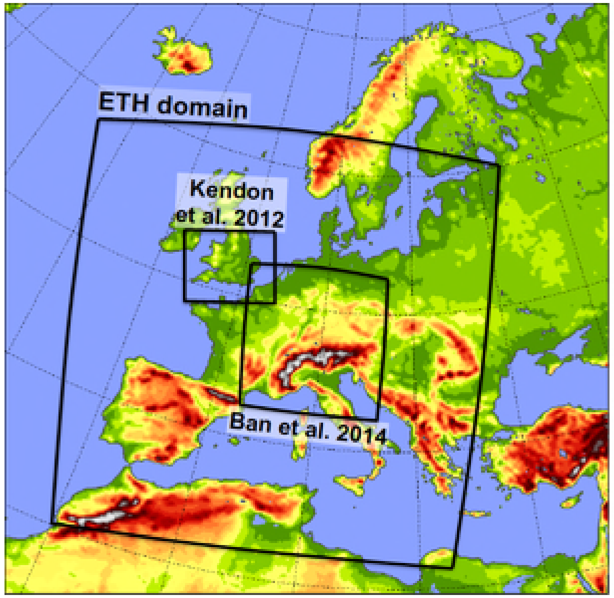
What hardware?

km-scale climate simulations

COSMO model

- Source code about 400,000 lines
- GPU-Version:
  - collaboration between MeteoSwiss, CSCS, ETH
  - refactoring led by Oliver Fuhrer (MeteoSwiss)
  - dynamical core rewritten in C++ and CUDA
  - parameterizations use Fortran and OpenACC
- Also used for weather prediction (Δ=1 km)

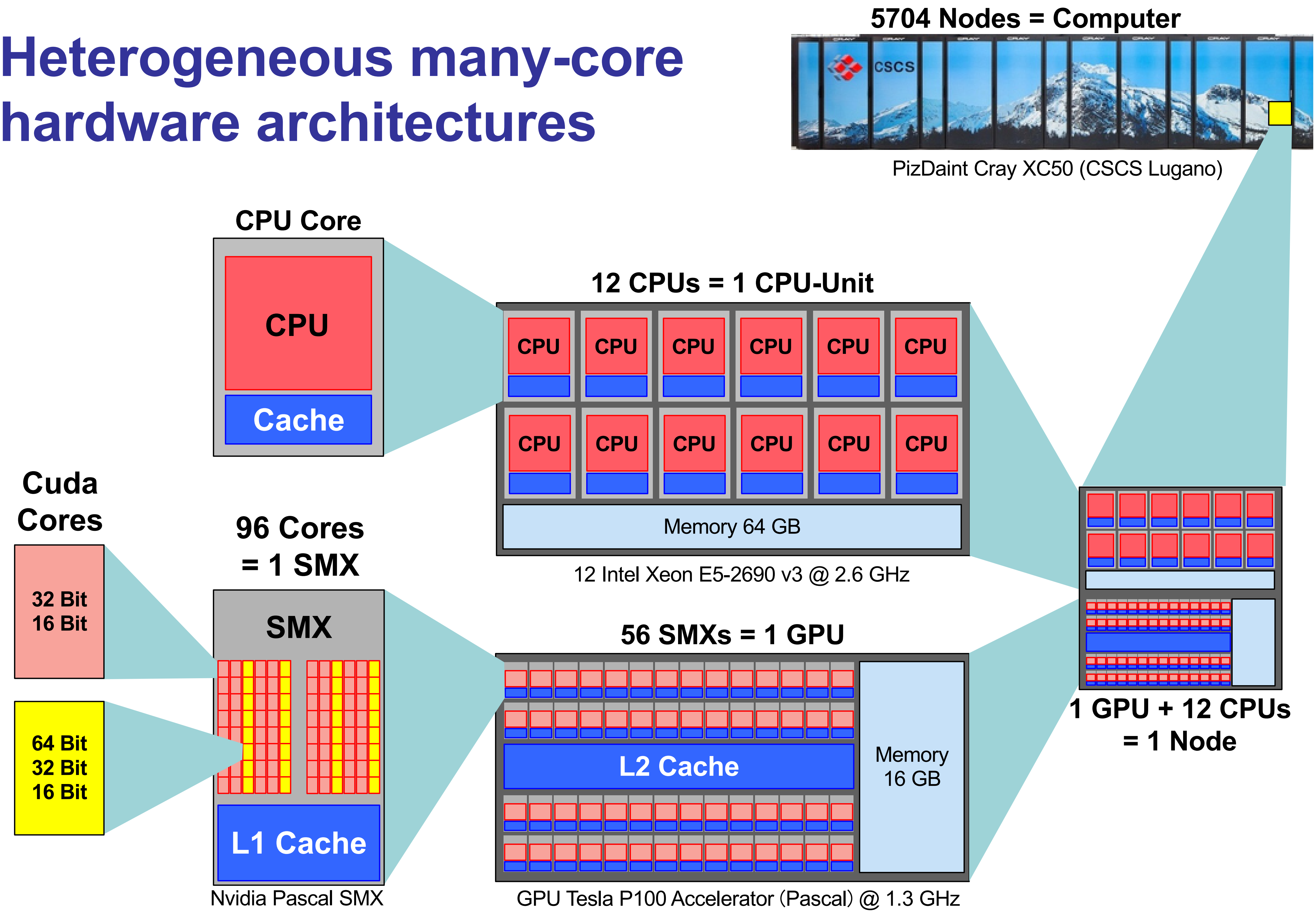
Piz Daint: Linpac peak performance: 20×10^{15} Flop/s



European-scale climate simulations

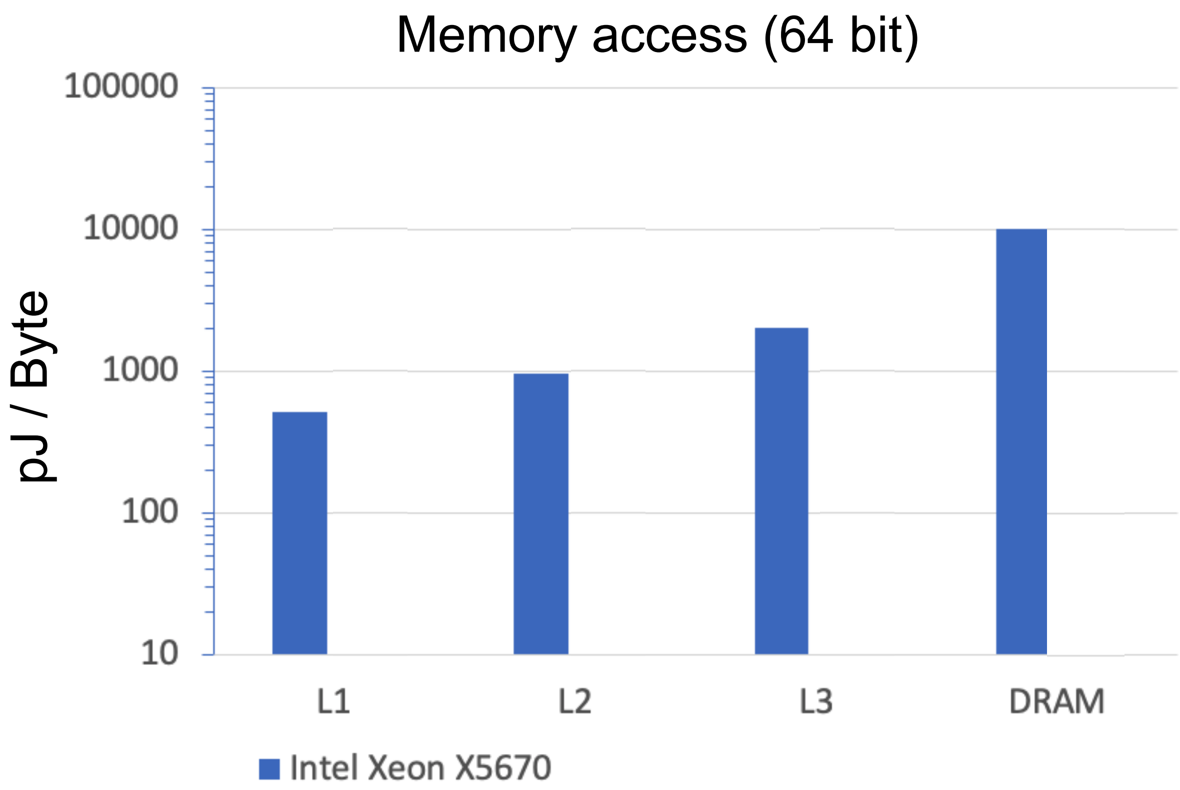
- Δ=2.2 km, 1536 x 1536 x 60 grid points
- Driven by intermediate Δ=12 km simulation
- Split-explicit time step, Δt = 20 s
- Domain-decomposition on 100 = 10 x 10 compute nodes
- Simulations over decades (take 2-3 months)

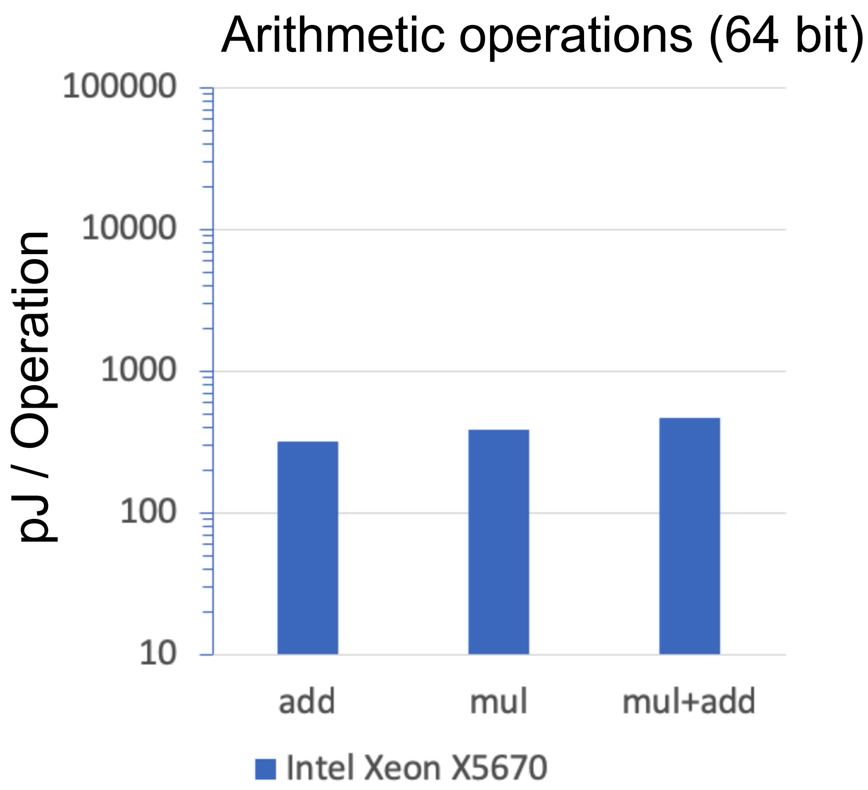
Heterogeneous many-core hardware architectures



Energy consumption of hardware operations

(in pJ = Picojoules = 10^{-12} Joules)





$$\text{Arithmetic intensity} = \frac{\text{\# of operations}}{\text{\# of memory access}}$$

Atmospheric codes dominated by memory access

=> Heterogeneous hardware architecture

=> Discussion of Flops not so relevant

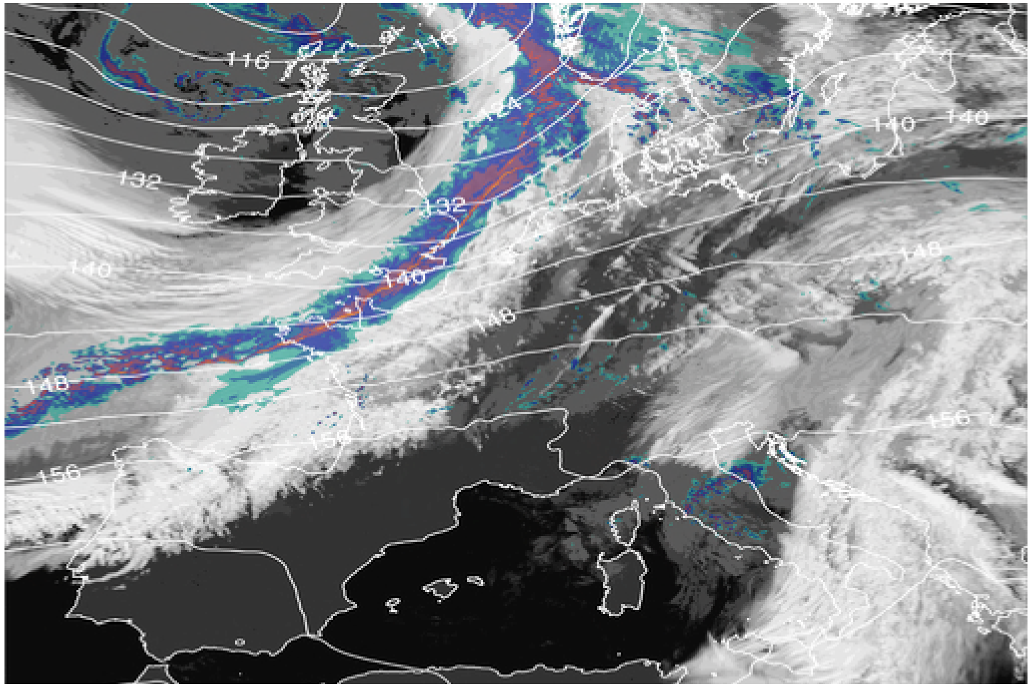
(Schär et al. 2020; Molka 2010)

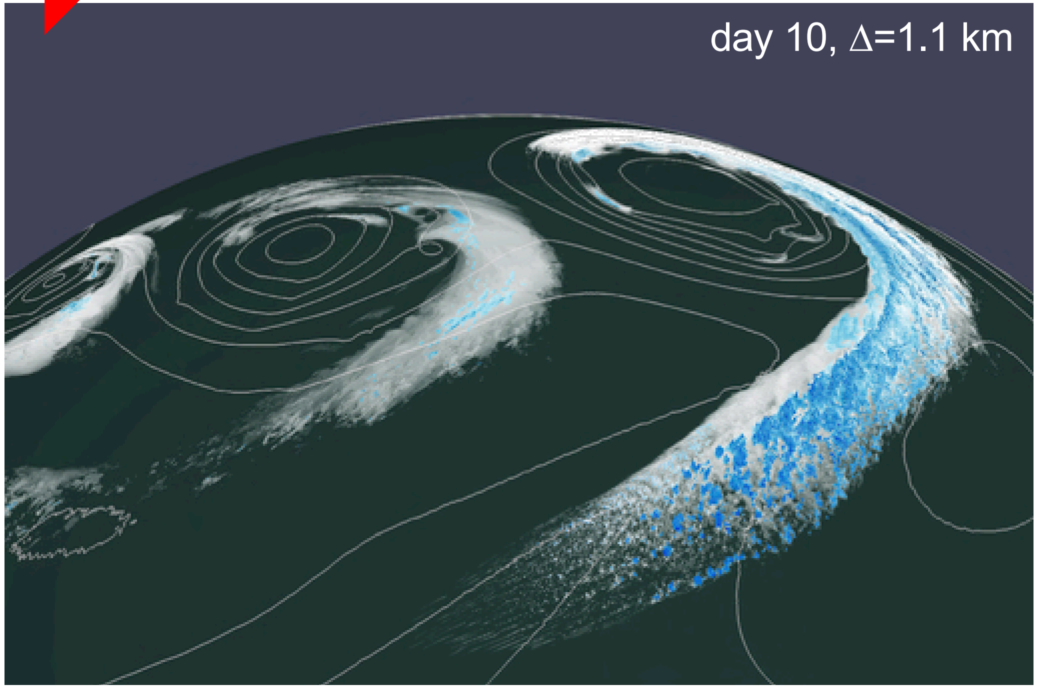
When can $\Delta x = 1\ \mathrm{km}$ be reached in global climate models?

European domain

Proof of concept

Global domain





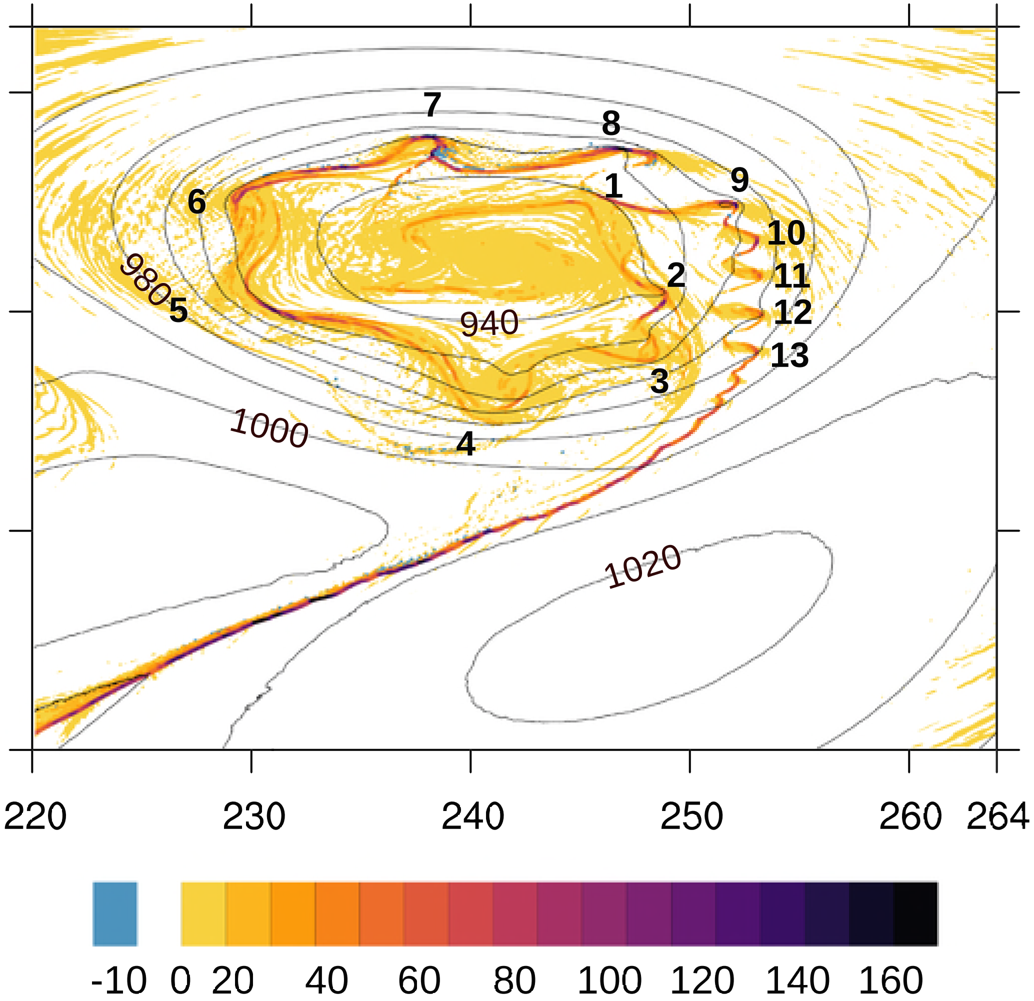
- Domain: Continental Europe: 2.2% of planet
- Horizontal resolution: 2.2 km
- Grid-points: 1536 × 1536 × 60 = 1.4×10^8
- Regional climate simulations (decades)
- Performance at 2.2 km resolution (without I/O): 0.25 SYPD: 1 day in **16 minutes** on **144 nodes**

- Domain: near global, 80º S – 80º N: 98.4% of planet
- Horizontal resolutions: 2.2 and 1.1 km at equator
- Grid-points: up to 36,000 x 16,000 x 60 = 3.5×10^{10}
- Idealized dry and wet baroclinic waves (10 days)
- Performance at 2.2 km resolution (without I/O): 0.23 SYPD: 1 day in **15 minutes** on **4,888 nodes**

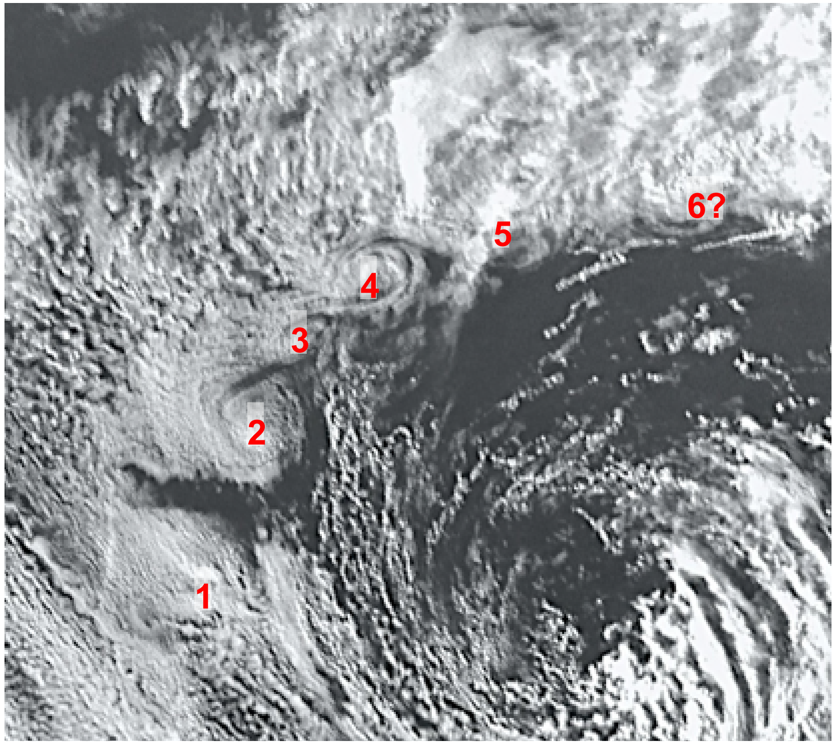
Time to solution is independent of domain size, as code exhibits near-perfect weak scaling.
But computational cost increases (more nodes needed)

(Leutwyler et al. 2017; Fuhrer et al. 2018, GMD)

Barotropic instability of cyclone core



16/02/23, 17:15 UTC, VIS



Thanks to Ralph Rickli for making us aware of this case)

Secondary instability (day 10, Δ=1 km global):
Frontal collapse enables barotropic instability

(Leutwyler and Schär, 2019, GMD)

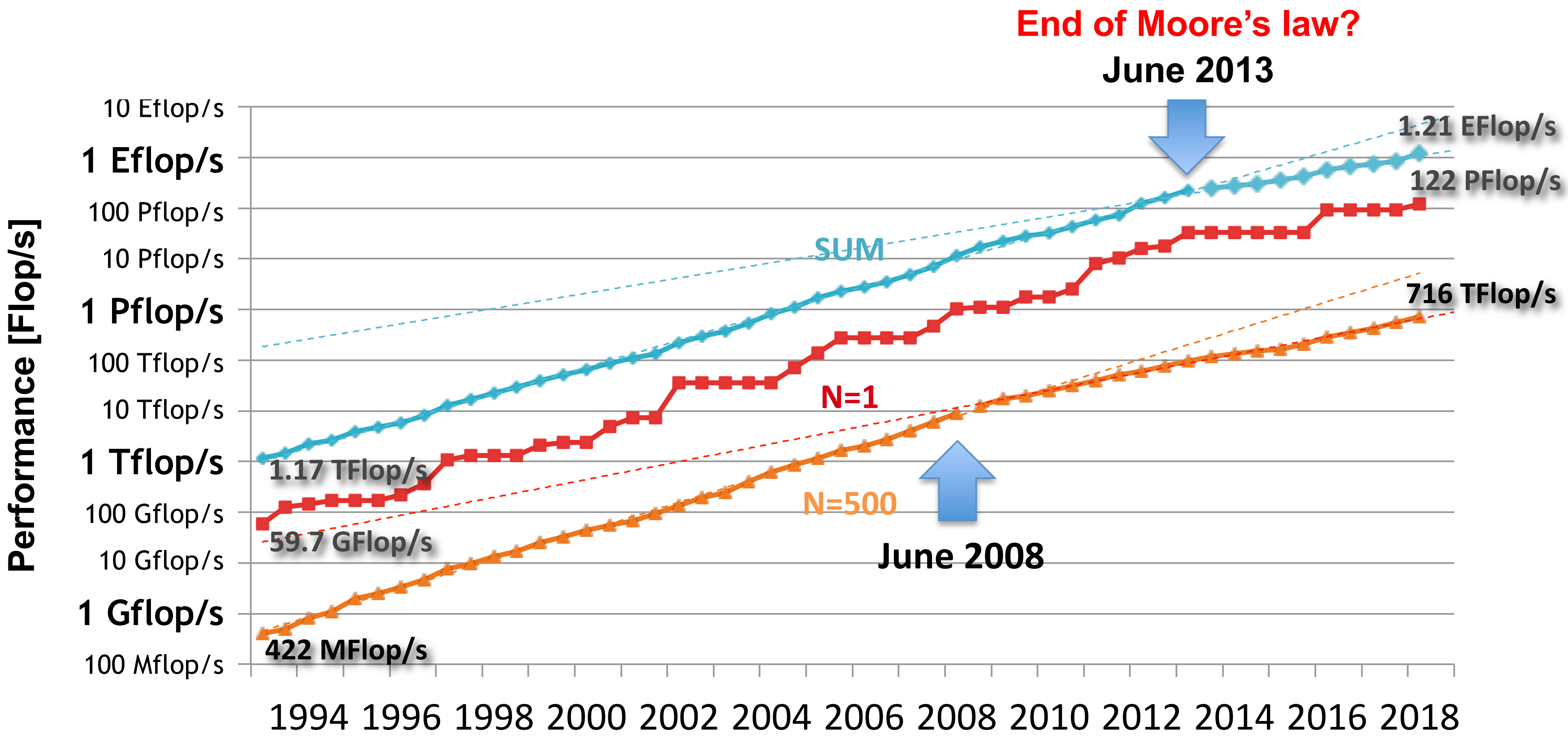
Stipulated performance target

Horizontal resolution	1 km (globally quasi-uniform)
Vertical resolution	180 levels (surface to ∼100 km)
Time resolution	0.5 min
Coupled	Land-surface/ocean/ocean-waves/sea-ice
Atmosphere	Non-hydrostatic
Precision	Single or mixed precision
Compute rate	1 SYPD (simulated years per wall-clock day)

- Target:
  - global, coupled, non-hydrostatic, 1 km resolution
  - at a speed of 1 SYPD (simulated year per day)
- Estimates using COSMO and IFS
- “We conclude that these models currently execute about 100–250 times too slow for operational throughput rates.“
- Next slide: how long do we need to wait?

(Schulthess et al. 2019)

Top500 supercomputers



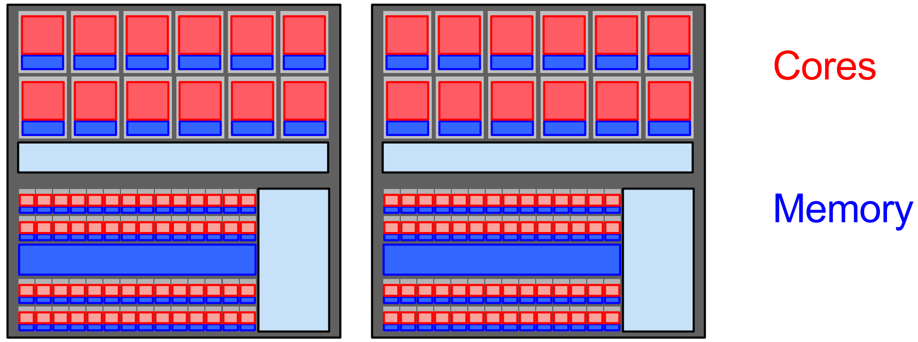
Factor 2 every 14 months
Factor 1000 every 11 years

Factor 2 every 24 months
Factor 1000 every 20 years
Factor 250 in 16 years

(www.top500.org, June 2018)

Can we be faster with better coding strategies?

How to write code for next-generation hardware



Use Fortran with compiler directives (i.e. MPI, OpenMP, OpenACC)

Rewrite (parts of) the code using the GPU's language (e.g. Cuda)

Rewrite model using domain-specific languages (e.g. GridTools)

Is this sustainable with $O(10^6)$ lines of source code?
(and frequent changes in hardware and codes)

Domain-specific languages (DSLs)

Frontend

Climate scientist (domain scientist)

Mathematical Model

Discretization, Solver

High-level implementation

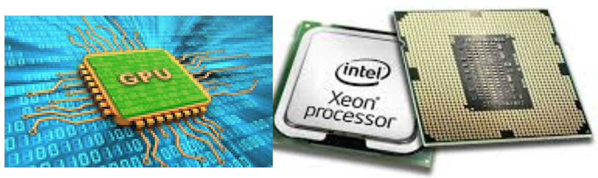
- No hardware dependent details (vectorization, threading, parallelization, directives, …)
- Exploits operators on computational mesh
- Generates an intermediate representation of the code (LLVM MLIR, clang)

Separation of concerns

Backend

Computer scientist

Domain-specific Compiler



- Provides executable for different architectures
- Takes care of hardware-dependencies
- Exploits automatic optimization

(Oliver Fuhrer)

GridTools: a DSL for weather and climate

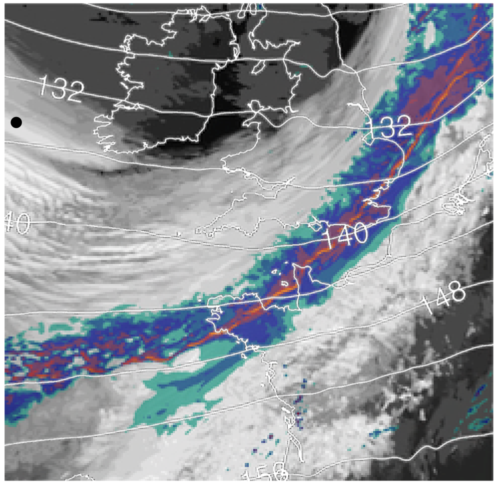
Domain-specific language for Earth system model components

- Joint development of CSCS / MeteoSwiss / ETH
- Provides stencil operations on grids (e.g. Laplacian, gradient, etc)
- Multiple interfaces (C++, Python, gtclang)
- Open-source release in March 2019

(Thomas Schulthess, Mauro Bianco, Oliver Fuhrer, et al)

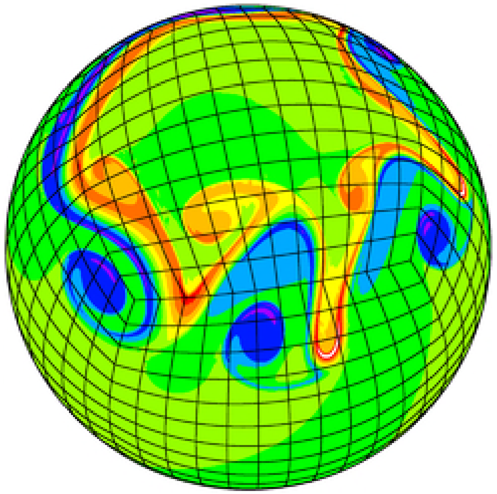
Current applications:

- Limited-area grids: Operational NWP and climate (COSMO) using FORRAN, C++ and Cuda
- Global grids: work with FV3, IFS-FVM and ICON has started, using Python / GridTools frontend
- Backends: - Python: Python (for debugging), NumPy (vectorized syntax)
  - C++: x86 CPUs, MIC Xeon Phi, NVIDIA GPU

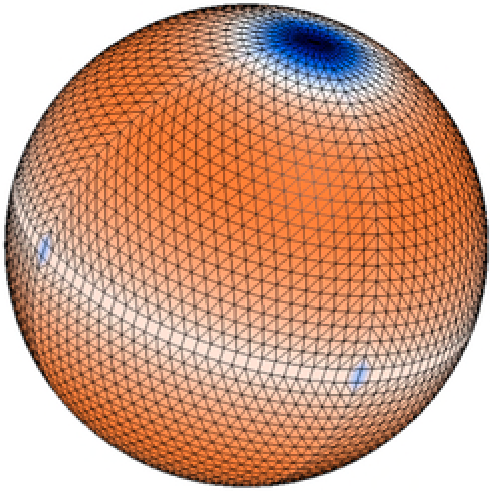


COSMO: Rotated lat/lon

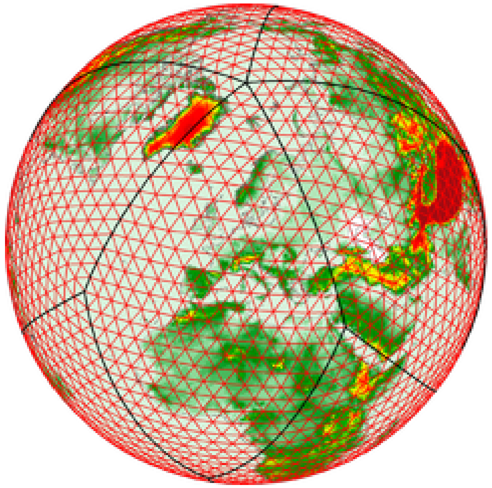
Schär, ETH Zürich



FV3: Cubed sphere

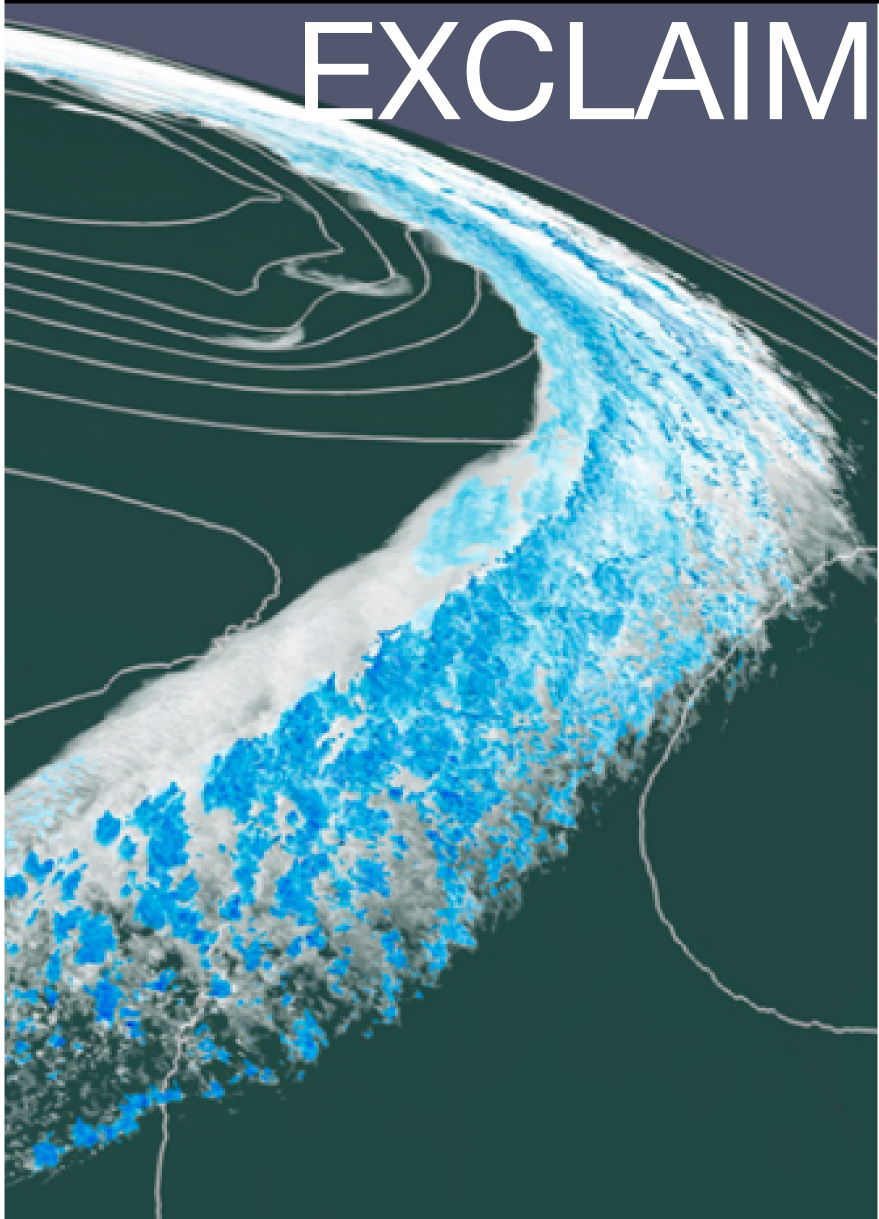


IFS-FVM: Octahedral mesh



ICON: Icosahedral mesh

The EXCLAIM Project



Extreme scale **c**omputing and data platform for c**l**oud-resolving we**a**ther and cl**i**mate **m**odeling

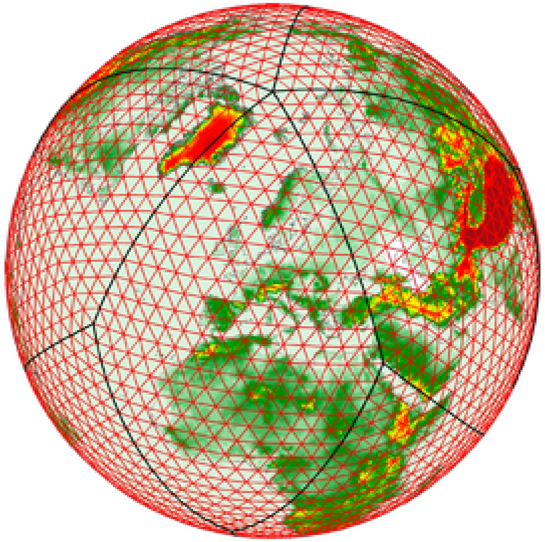
C2SM
Center for Climate Systems Modeling

The EXCLAIM project

A new project of ETH, MeteoSwiss, CSCS

Started April 1, 2021

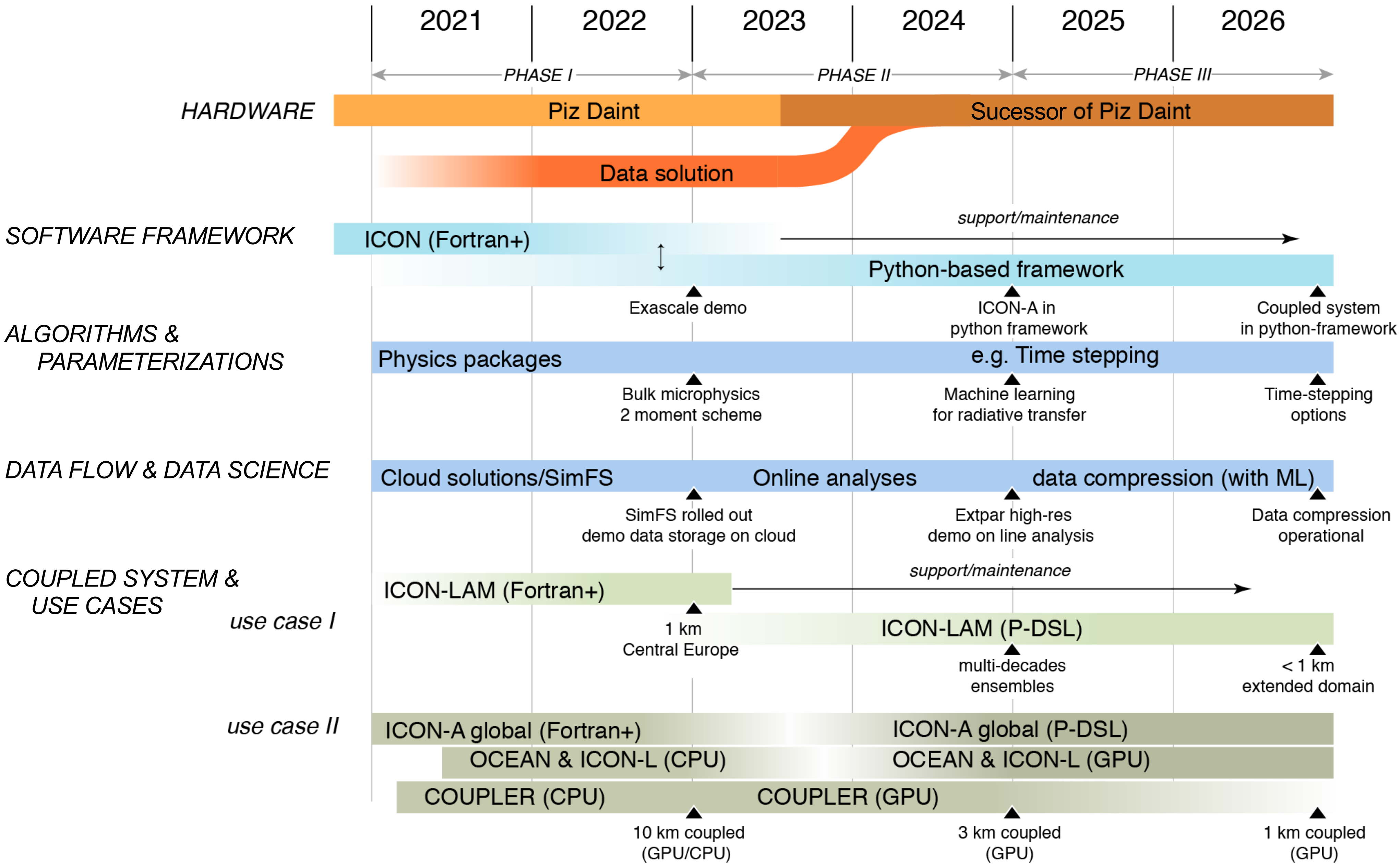
Main goal: rewrite ICON using Python-based DSLs



ICON-Model

- global and regional options
- successor of COSMO

EXCLAIM Roadmap



Schär, ETH Zürich

Summary

Around 1980, the resolution of GCMs has reached Δx=100 km
$\Rightarrow$ Appropriate representation of quasi-horizontal motions
$\Rightarrow$ Revolution in NWP

In this decade, resolution will reach Δx=1 km
$\Rightarrow$ Appropriate representation of vertical (across-θ) motions
$\Rightarrow$ Removes two critical parameterizations
$\Rightarrow$ Improves representation of hydrological cycle and extremes

Will Δx=1 km reduce the uncertainty of climate projections?
$\Rightarrow$ We do not know with certainty, but we should try!