Chapter 1
Introduction to Weather and Climate Models

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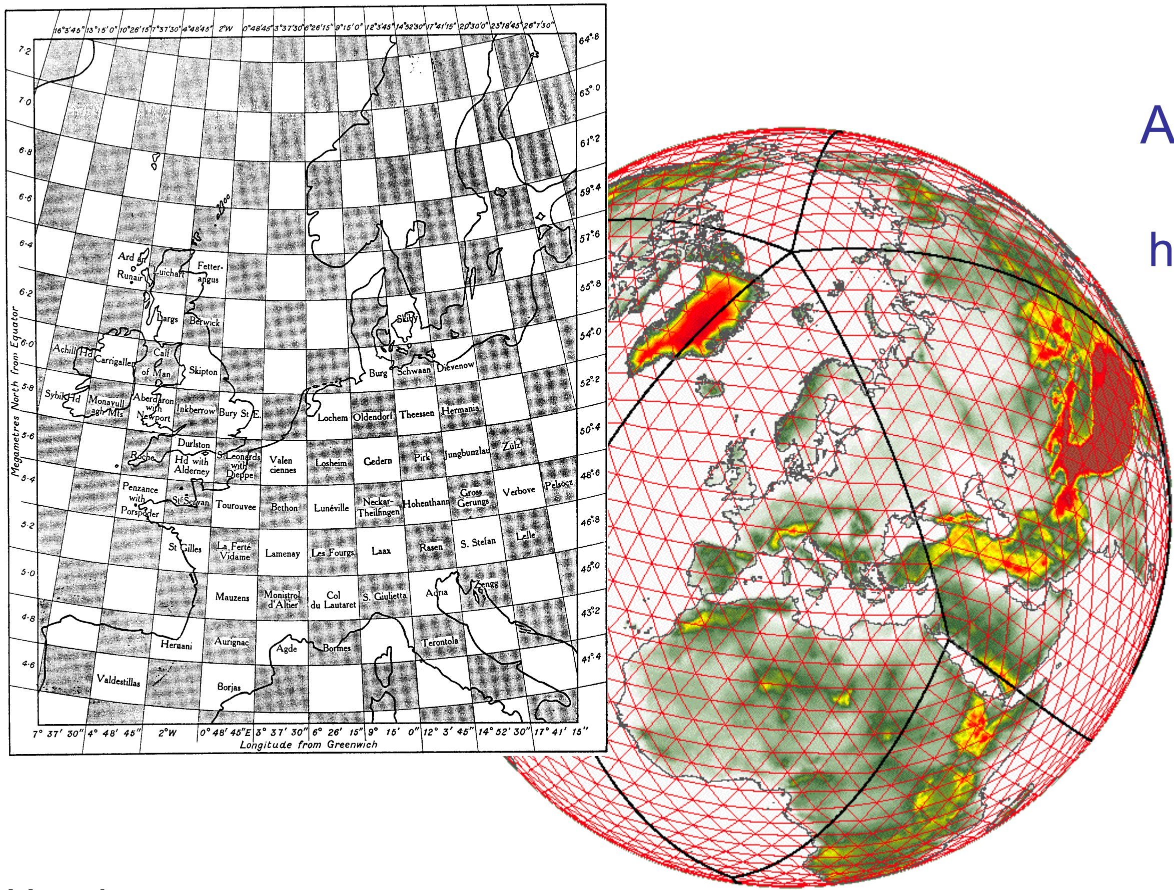


Handouts
Numerical Modelling of Weather and Climate
Christoph Schär and Ulrike Lohmann
http://www.iac.ethz.ch/edu/courses/master/modules/numerical_modelling_of_weather_and_climate

Outline

Historical perspective

Atmospheric scales

Governing equations

Parameterizations

Initial conditions

Climate models

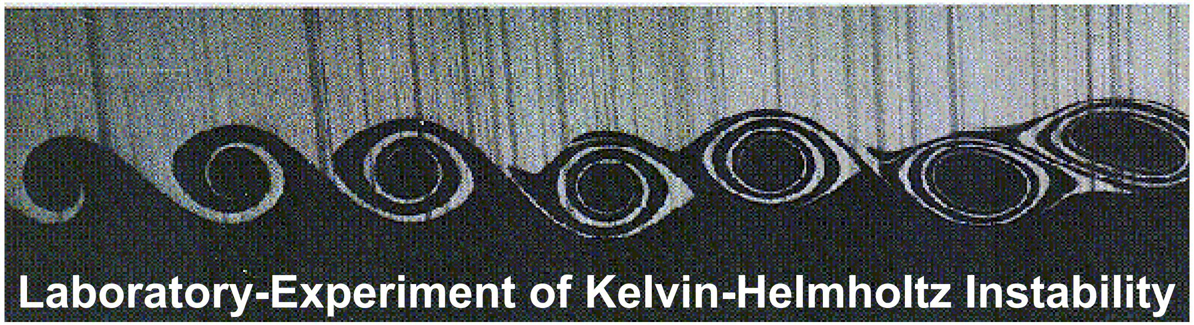
Computational aspects

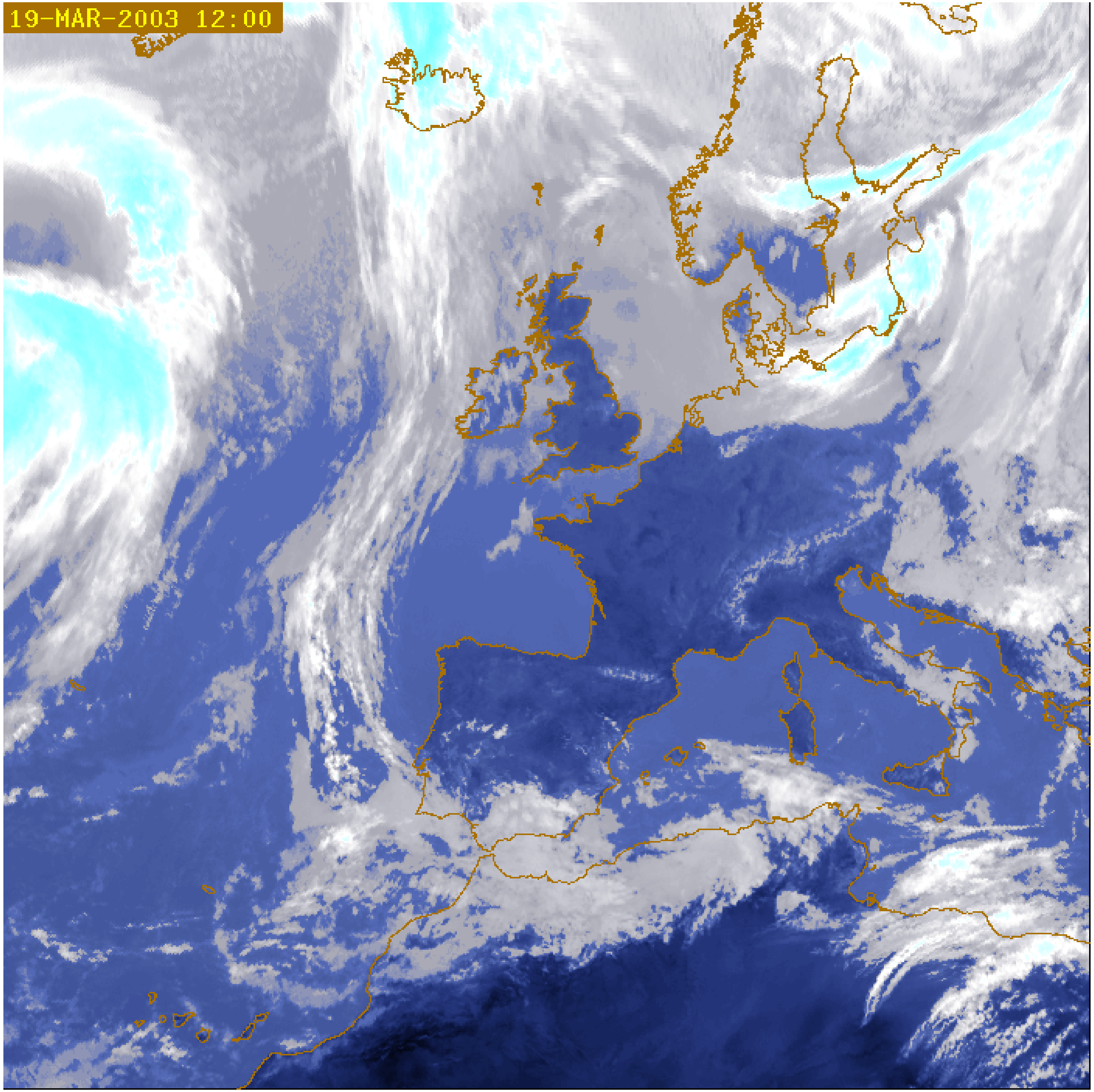
Picture: Thomas Schumann

Sometimes the atmosphere exhibits physical principles in a textbook fashion, ….

Richardson-Number Criteria:

$$Ri = \left(\frac{-g}{\rho} \frac{\partial \rho}{\partial z} \right)^{1/2} \left| \frac{\partial \mathbf{v}}{\partial z} \right|^{-1} \leq \frac{1}{4}$$





…. more generally, however, the atmosphere looks very complicated, and a direct link to simple physical principles is not evident.

IR Satellite Picture
MeteoSwiss, Zürich

Vilhelm Bjerknes (1862-1951)

In 1904, Bjerknes proposed that „weather forecasting should be considered as an *initial value problem* of mathematical physics.“

His proposal was motivated by his new circulation theorem, that overcame obvious limitations of Kelvin's earlier theorem.

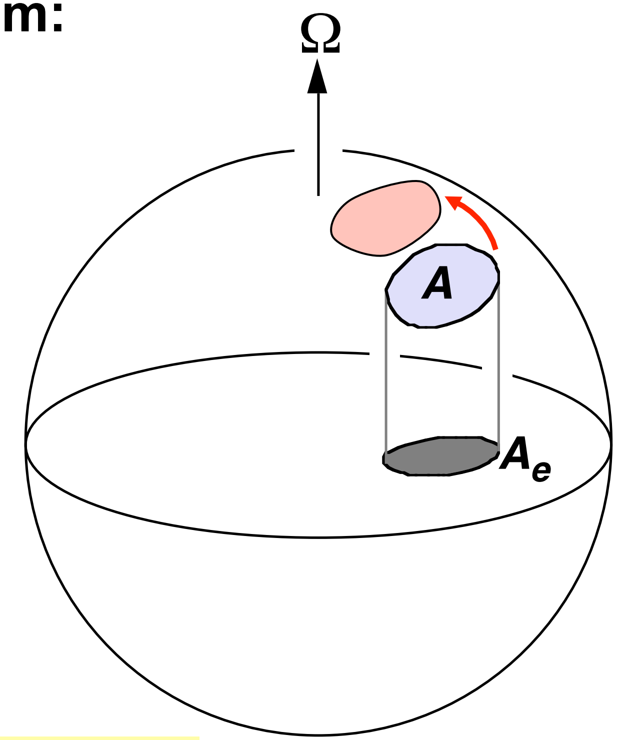
Circulation Theorem:

Circulation:

$$C = \oint \mathbf{v} \cdot \mathbf{ds}$$

Kelvin 's Theorem:

$$\frac{dC}{dt} = 0$$



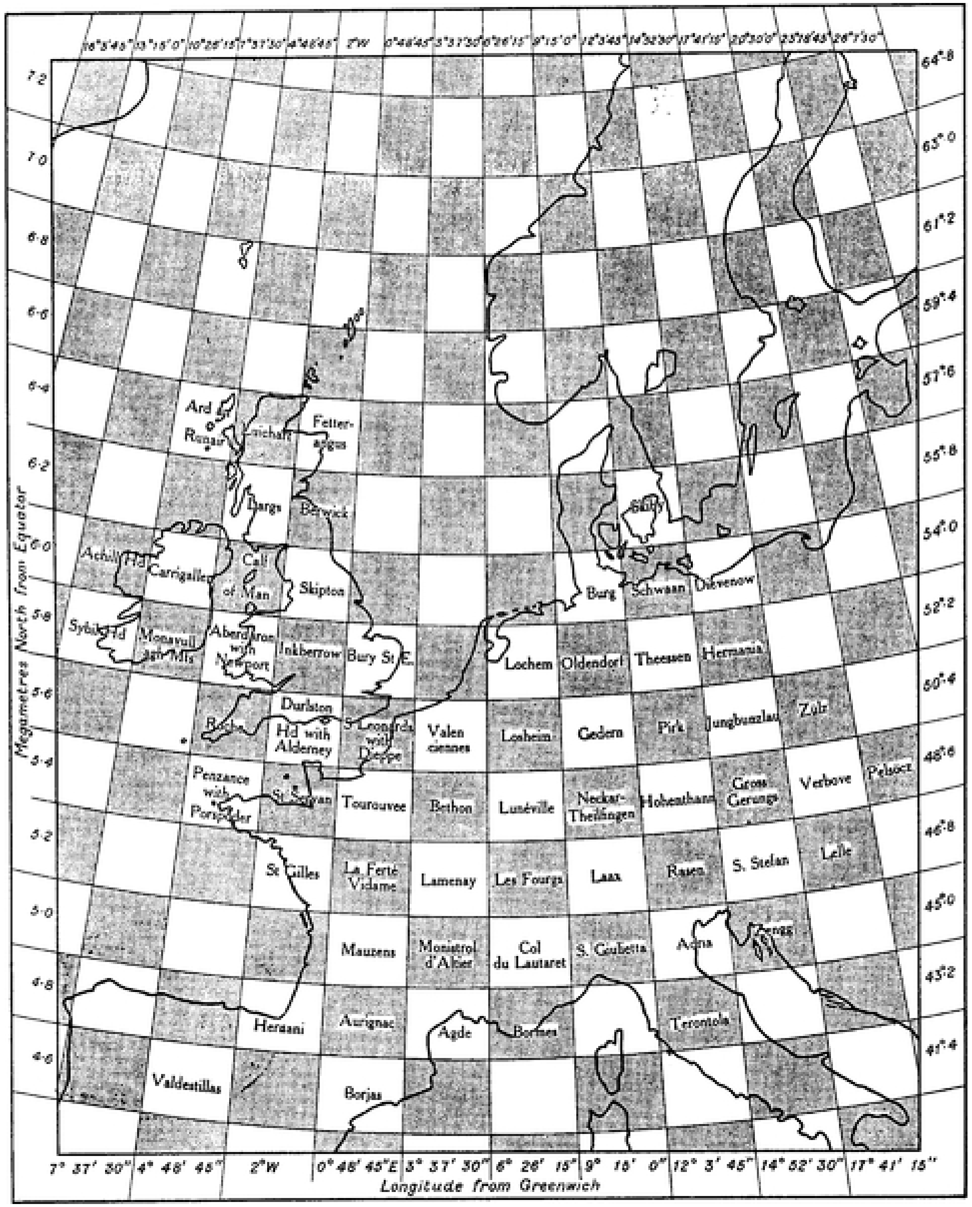
Bjerknes ' Theorem:

$$\frac{dC}{dt} = \underbrace{-2\Omega\frac{dA_e}{dt}}_{\text{Earth's rotation}} \underbrace{-\oint \rho^{-1} dp}_{\text{baroclinic effects}}$$

Lewis F. Richardson (1881-1953)

In 1922, Richardson provided the first formulation of the atmospheric equations on a computational grid.

“If the coordinate chequer were 200 km square in plan, ... 64,000 computers would be needed to race the weather. In any case, the organisation indicated is a central forecast-factory.”



Extracts from Richardson's Book

«Individual computers are *specialising on the separate equations*. Let us hope for their sake that they are moved on from time to time to new operations.»	***Parallelization***
«It took me the best part of six weeks to draw up the *computing forms*»	***Distributed Memory***
«The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values *so their neighbouring computers can read them*.»	***Communication***
«From the floor ..... a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre. ..... One of his duties is to *maintain an uniform speed* of progress. ..... He turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.»	***Synchronization***
«In a neighbouring building there is a research department. ..... Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe it freely.»	***"Cooling"***

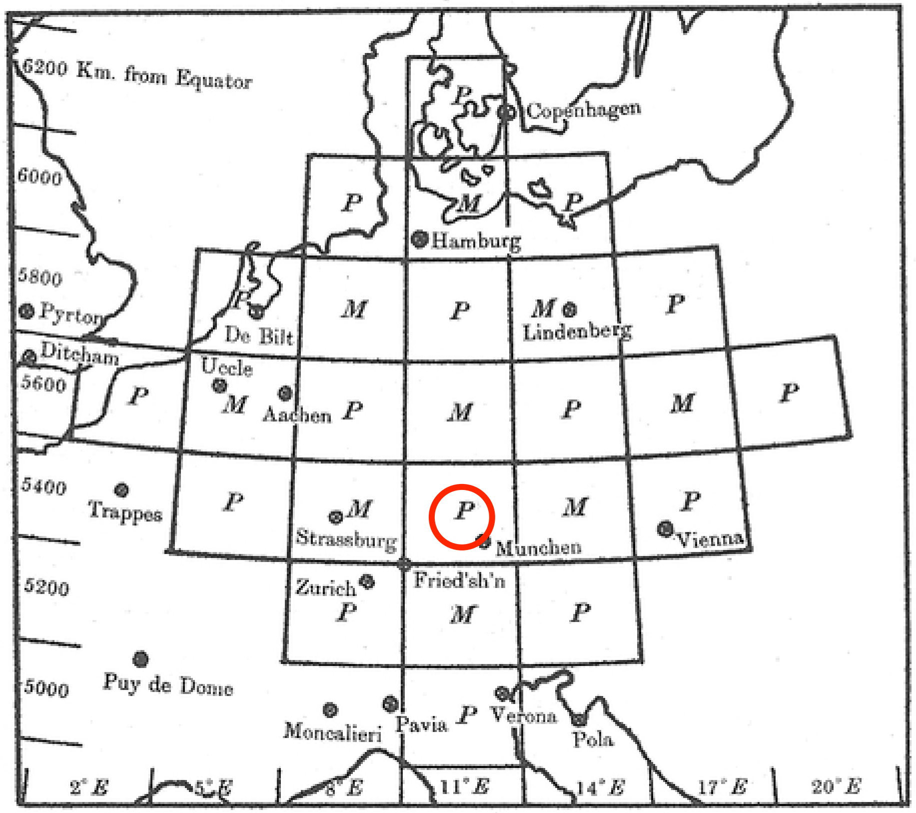
Richardson's forecast (proof of concept)

Richardson conducted one 6-hour forecast for a single grid-point to the North of Munich.

He conducted only one single time step, so the main result was the pressure tendency at this point.

The forecast was published 14 years after the event:

- Initialized: May 20, 1910, 4 UTC
- Executed: during 6 weeks in 1916
- Published: 1922 (in his book)



Richardson used a staggered grid (P = pressure, M = momentum). Red circle shows targeted grid point. Locations with radio- or pilot-balloon ascents are also indicated.

Divergence of horizontal momentum-per-area. Increase of pressure

COMPUTING FORM P XIII.

The equation is typified by: $-\frac{\partial R_{s}}{\partial t} = \frac{\partial M_{Es}}{\partial e} + \frac{\partial M_{Ns}}{\partial n} - M_{Ns}\frac{\tan\phi}{a} + m_{Hs} - m_{Hs}^{*} + \frac{2}{a}M_{Hs}$. (See Ch. 4/2 #5.)

* In the equation for the lowest stratum the corresponding term $-m_{H}$ does not appear

Longitude *11° East* $\delta e = 441 \times 10^5$ — Latitude *5400 km North* $\delta n = 400 \times 10^5$ — Instant *1910 May 20ᵈ 7ʰ G.M.T.* $a^{-1}.\tan\phi = 1{\cdot}78 \times 10^{-9}$ — Interval, δt *6 hours* $a = 6{\cdot}36 \times 10^8$

REF.:—				previous 3 columns	previous column	Form P XVI	Form P XVI	equation above	previous column	previous column	previous column
h	$\frac{\partial M_E}{\partial e}$	$\frac{\partial M_N}{\partial n}$	$-\frac{M_N \tan\phi}{a}$	$\mathrm{div}'_{EN} M$	$-g\delta t\, \mathrm{div}'_{EN} M$	m_H	$\frac{2M_H}{a}$	$-\frac{\partial R}{\partial t}$	$+\frac{\partial R}{\partial t}\delta t$	$g\frac{\partial R}{\partial t}\delta t$	$\frac{\partial p}{\partial t}\delta t$
	$10^{-6}\times$	$10^{-6}\times$	$10^{-6}\times$	$10^{-6}\times$	$100\times$	$10^{-6}\times$	$10^{-6}\times$	$10^{-6}\times$		$100\times$	$100\times$
h_0						0					0
	−61	−245	−6	−312	656			−229	49·5	483	
h_2						−83					483
	367	−257	2	112	−236		0·06	−136	29·4	287	
h_4						165					770
	93	−303	−16	−226	478		[illegible]	[illegible]	[illegible]	262	
h_6						[illegible]					1032
	32	−55	−12	−35	74		[illegible]	[illegible]	[illegible]	[illegible]	
h_8						[illegible]					1265
	−256	38	−8	−226	479		[illegible]	[illegible]	[illegible]	186.	
h_e						[illegible]					1451
	NOTE: $\mathrm{div}'_{EN} M$ is a contraction for $\frac{\delta M_E}{\delta e} + \frac{\delta M_N}{\delta n} - M_N\frac{\tan\phi}{a}$				SUM = 1451 $= \frac{\partial p_G}{\partial t}\delta t$						check by $\Sigma - g\delta t\, \mathrm{div}'_{EN} M$

Lea[illegible] the subsequent columns to be filled up after [illegible] vertical velocity has been computed on [illegible] P XVI

$$\frac{\partial p_s}{\partial t} = 145.1 \text{ hPa/6h}$$

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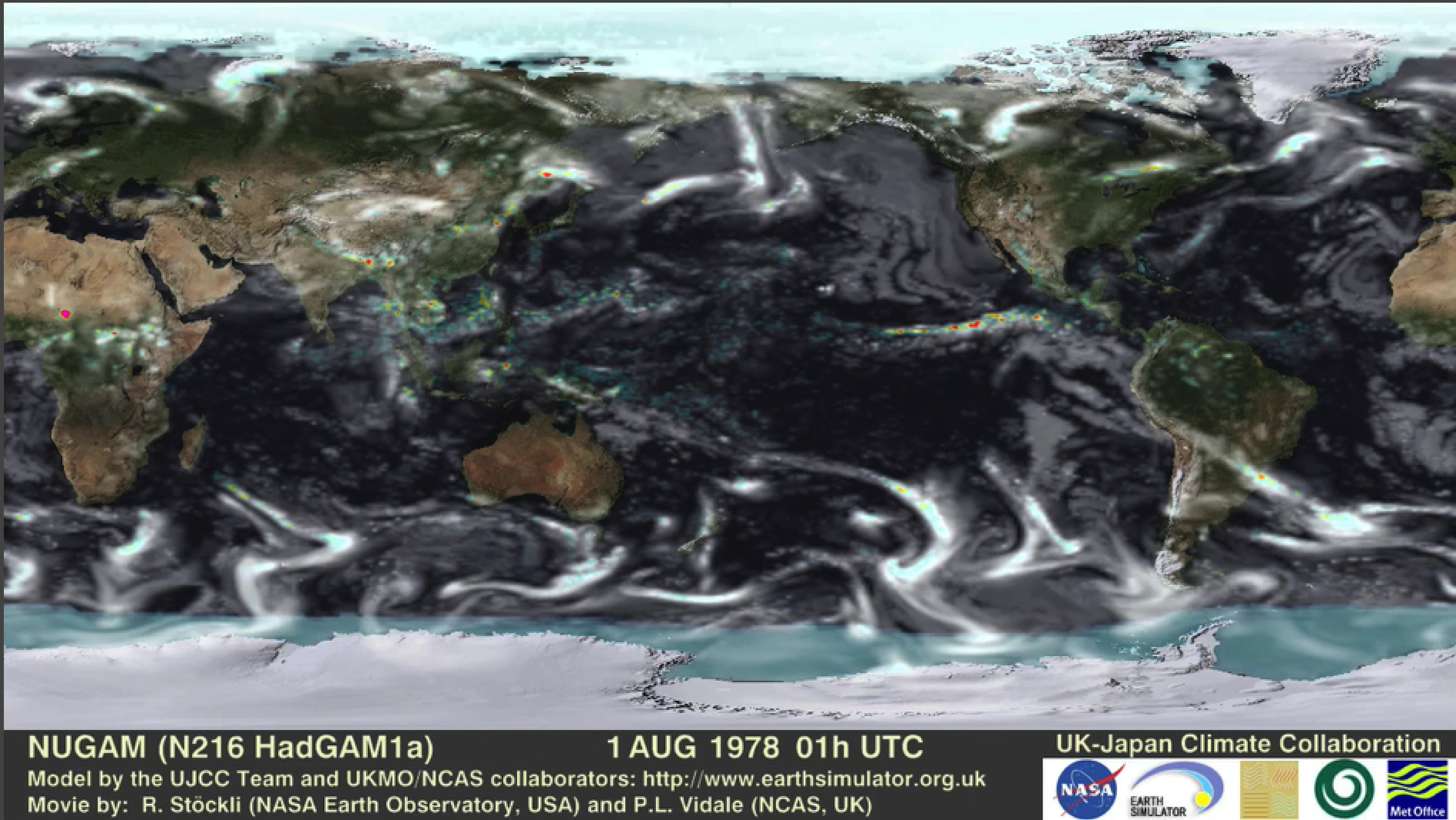
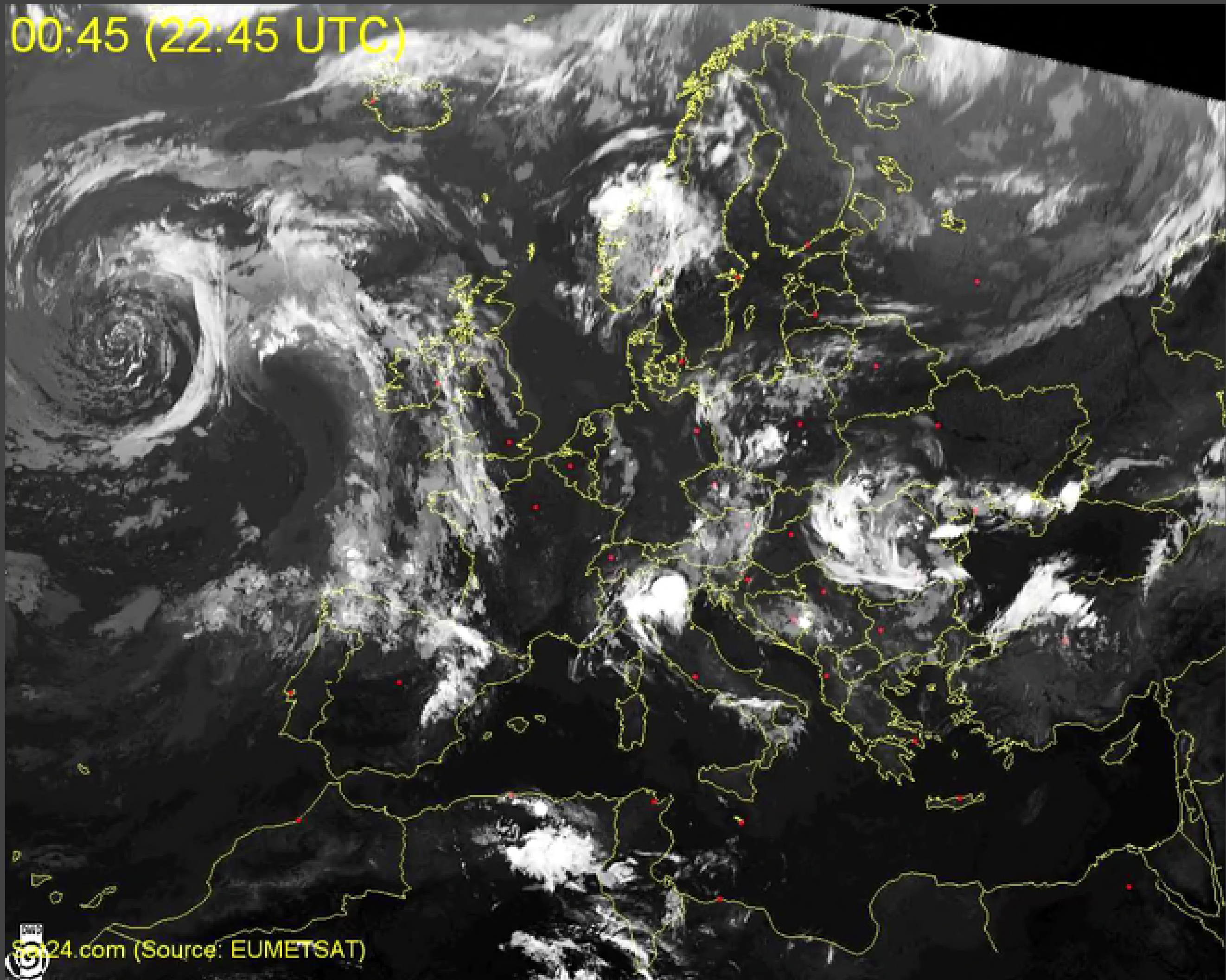
Global



10,000 km

(High-resolution global model)

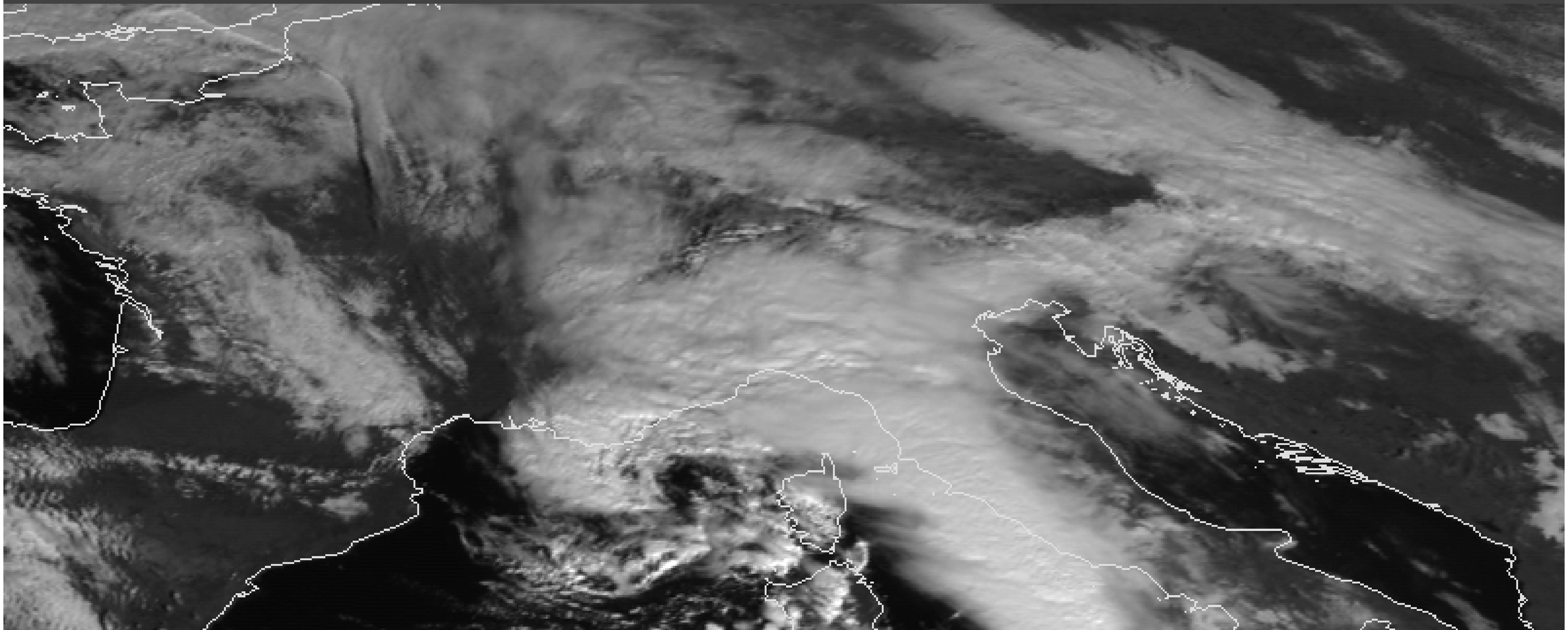
Continental



1000 km

(SEVIRI 10.8µm, June 30 – July 2, 2009; Michael Keller, ETH Zürich)

Regional / Mesoscale

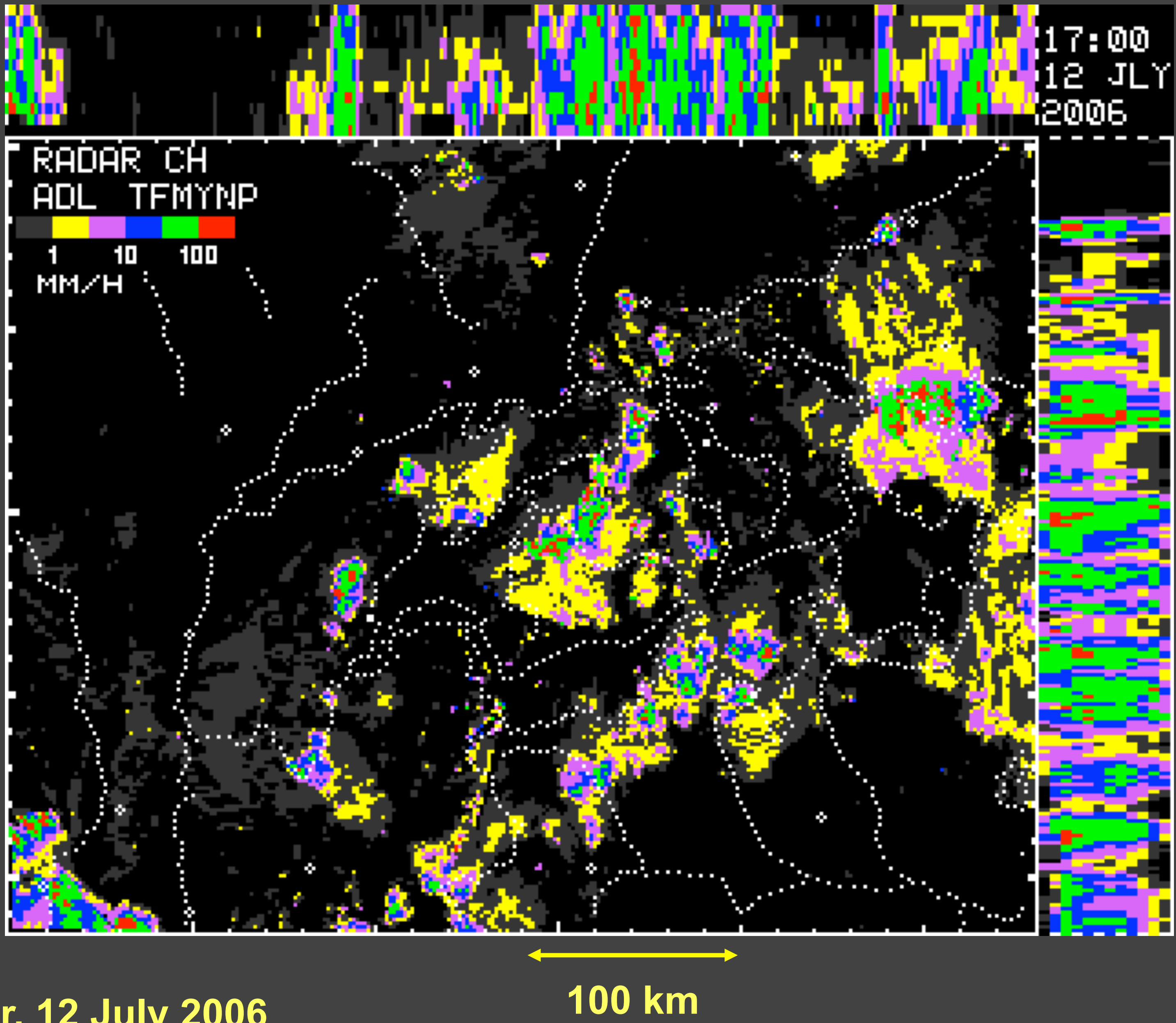


500 km

21. October 1999

(MAP, Meteosat Rapid Scan, VIS

Regional / Mesoscale



Weather radar, 12 July 2006

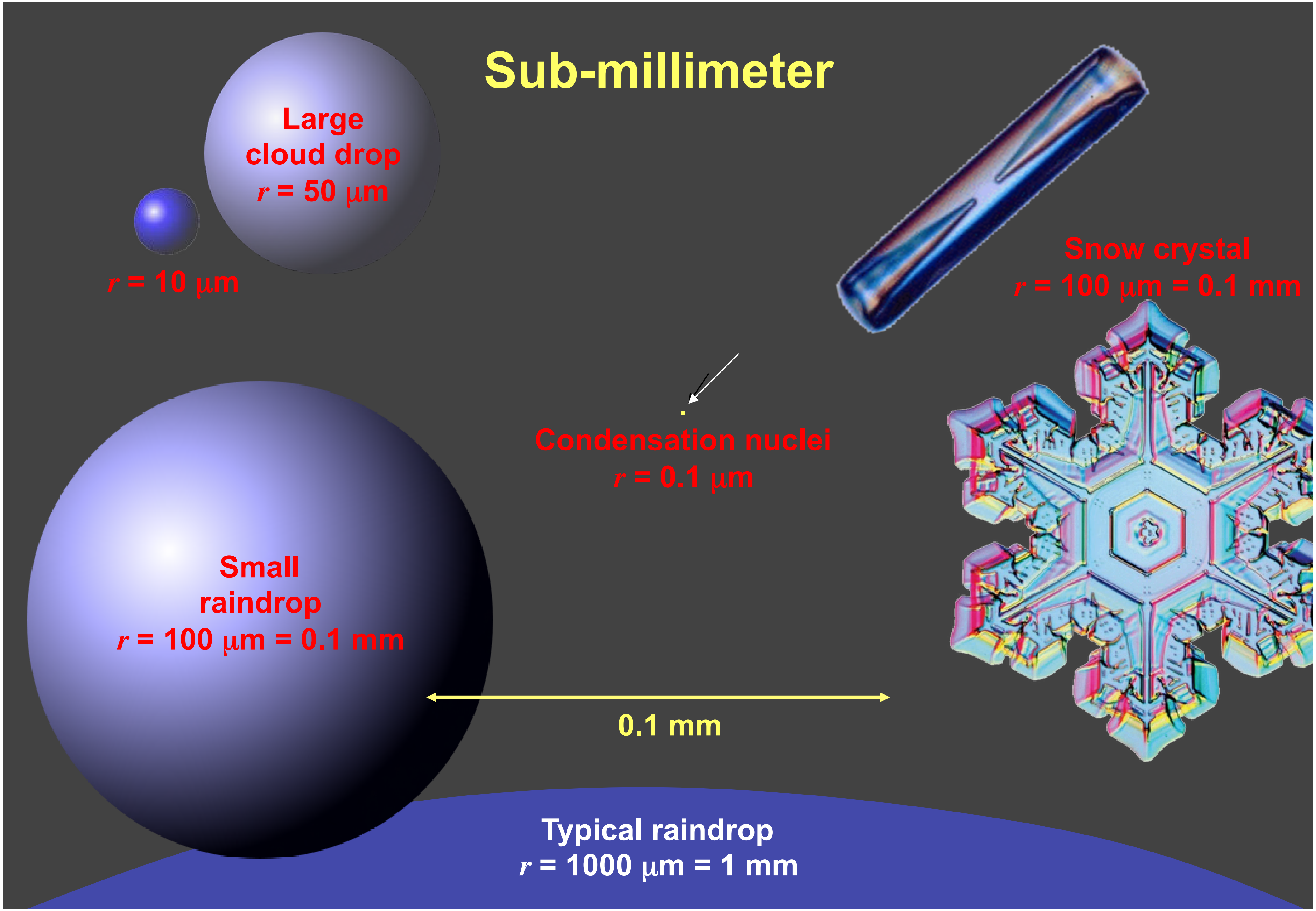
(MeteoSwiss)

Local






Meter to kilometer

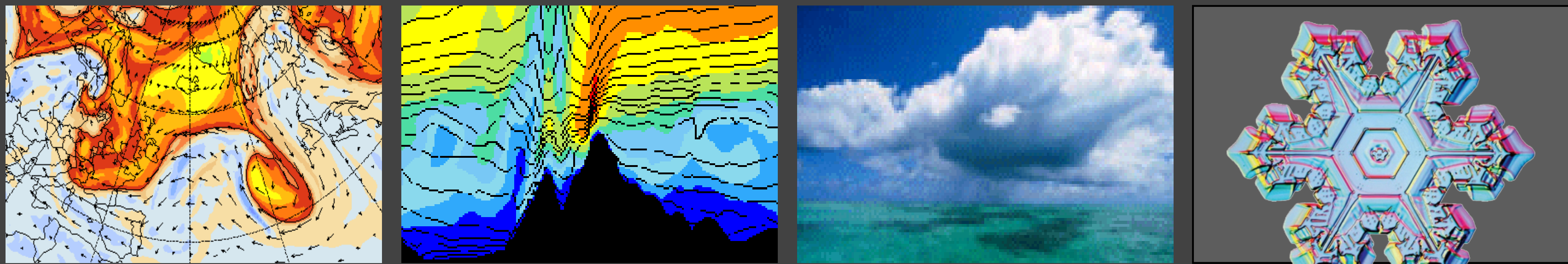

Sub-millimeter
Large cloud drop r = 50 μm
r = 10 μm
Snow crystal r = 100 μm = 0.1 mm
Condensation nuclei r = 0.1 μm
Small raindrop r = 100 μm = 0.1 mm
0.1 mm
Typical raindrop r = 1000 μm = 1 mm

Lewis F. Richardson (1881-1953)

**Big whirls have little whirls,
little whirls have lesser whirls.**

"down-scale"

10^6 m = 1 Mm



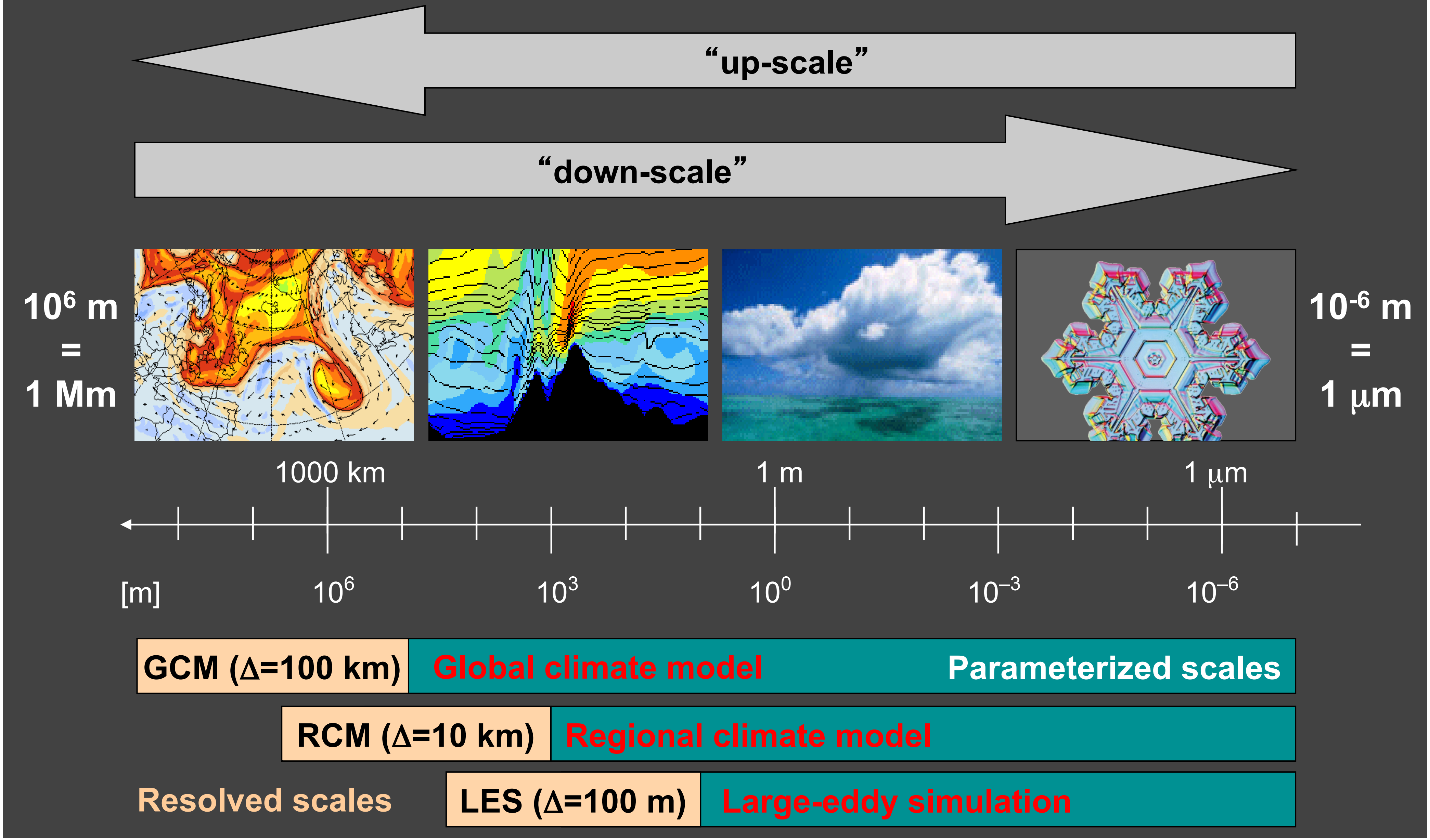
10^{-6} m = 1 μm

"up-scale"

Edward N. Lorenz (1917-2008)

**Does the flap of a butterfly's wings in Brazil
set off a tornado in Texas?**

Multi-scale interactions in the climate system



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Ingredients to Deterministic Weather Forecasting

1. Governing set of equations
   - Equations describing the motion and thermodynamics of the atmosphere (“***dynamics”***).
   - Equations describing the interaction of the atmospheric flow with a wide range of physical processes (***parameterizations, “physics”***). This includes: radiation, boundary layer processes, turbulence, cloud microphysics, soil hydrology, etc.

2. Discretized form of equations on a computer (***model***)

3. Initial conditions to start integration
   - Sufficient measurements to initialize model (***observing system***)
   - Preparation of the observations on a computational grid (***data assimilation***)

"Euler Equations" in Cartesian Coordinates

Momentum equations

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_x \qquad \frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F_y$$

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

with $\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$

Equation of state

$$p = \rho R T$$

Thermodynamic equation

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

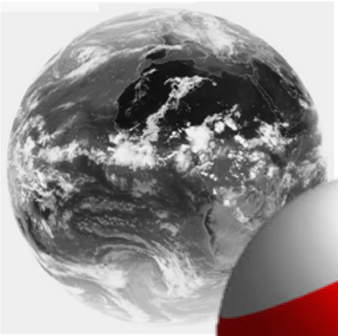
Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} + \frac{\partial (v\rho)}{\partial y} + \frac{\partial (w\rho)}{\partial z} = 0$$

Why not the full "Navier-Stokes Equations"?

Reynolds-number in atmospheric flows is far too large!

Anisotropy of Atmosphere



Diameter: 12,700 km
Depth of troposphere: 10 km (90% of atmosphere's mass)

Scaled to a Billiard ball:
Diameter: about 5 cm
Depth of troposphere: 0.04 mm

=> Implies $\Delta z \ll \Delta x, \Delta y$

Critical velocities

~300 m/s	sound propagation
~100 m/s	horizontal wind velocity
~20 m/s	vertical gravity-wave (buoyancy-wave) propagation

Numerics: Courant-Friedrichs-Levy (CFL) stability criterion

$$\left|\frac{U \ \Delta t}{\Delta z}\right| \leq 1$$

where U denotes largest velocity in system

would require $\Delta t \leq 0.1$ s

Approach for large-scale models: Hydrostatic Approximation

Vertical momentum equation:

$$\cancel{\frac{dw}{dt}} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + \cancel{F_z}$$

Balance between pressure-force and gravity, neglect vertical acceleration

Implications:

- Suppresses vertical sound propagation
- w must be diagnosed from continuity equation (diagnostic variable)
- much easier to maintain time-step criterion
- BUT: only valid for Δx > ~10 km

Discretization on the Sphere

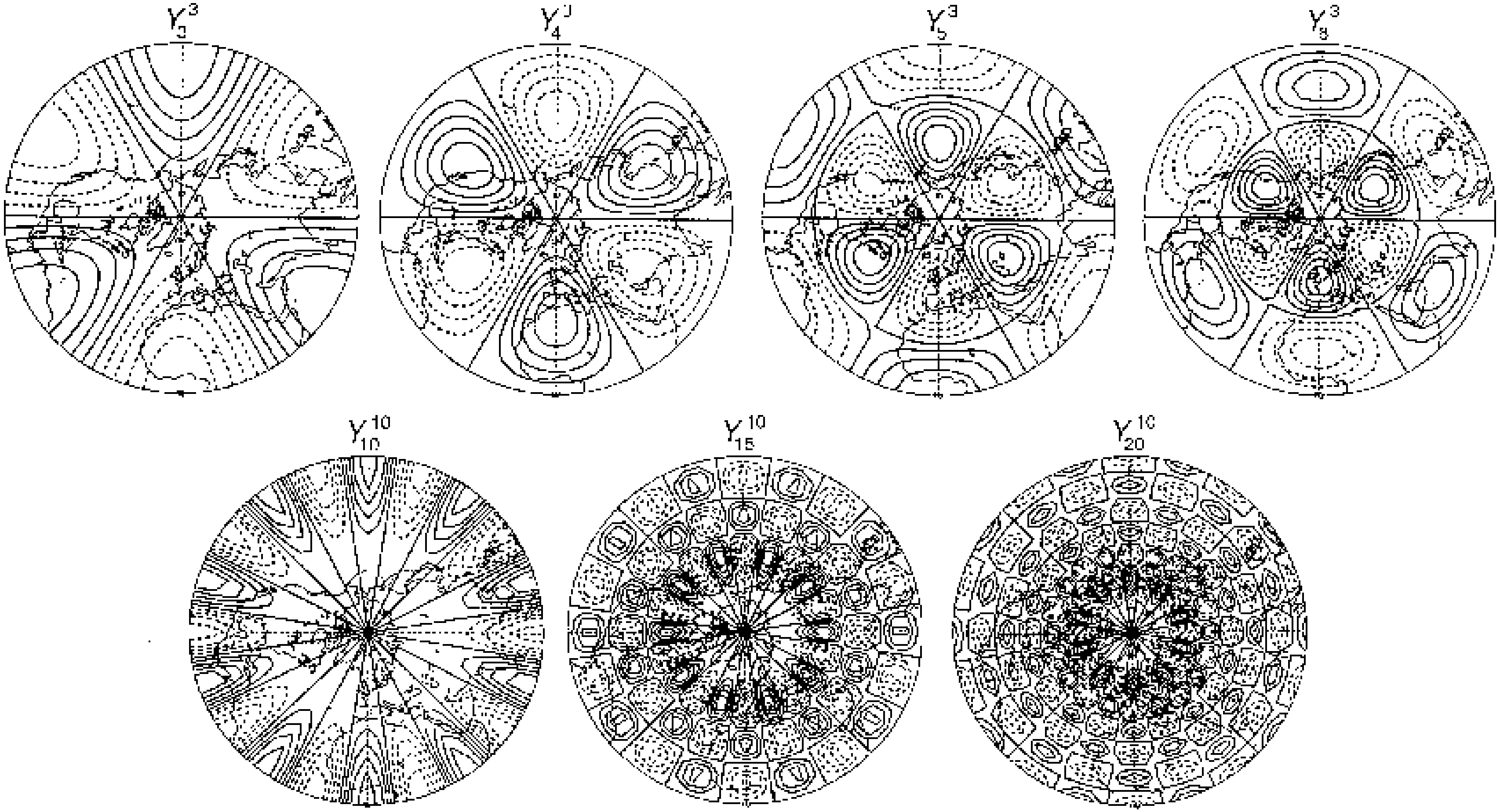
The simplest model grid on the sphere is a regular latitude / longitude grid.

It has some difficult side effects (e.g. pole problem).

Global Spectral Models

Represent a two-dimensional field ϕ on the sphere as an expansion using spherical harmonics $Y_n^m(\lambda,\varphi)$:

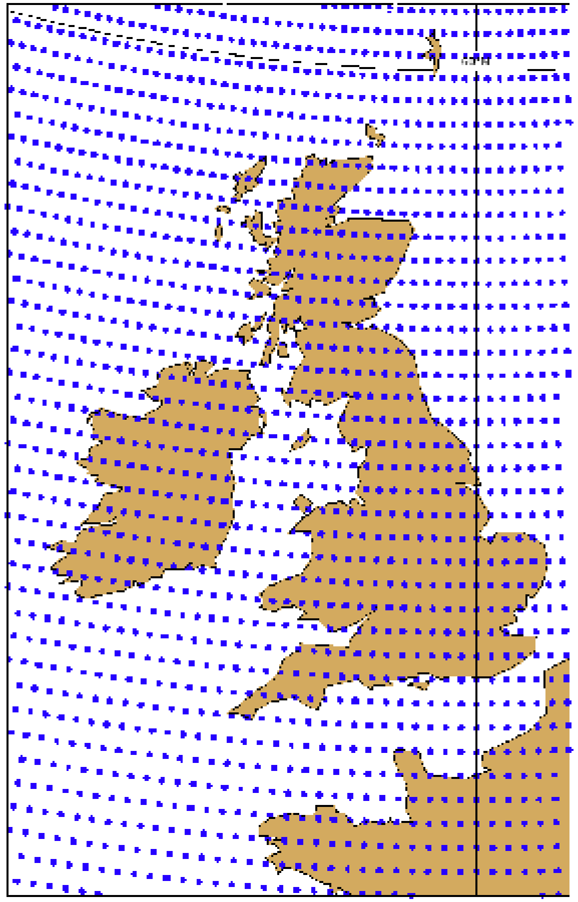
$$\phi(\lambda,\varphi,t) = \sum_{m=-M}^{M} \sum_{n=|m|}^{N(m)} \psi_n^m(t)\; Y_n^m(\lambda,\varphi)$$



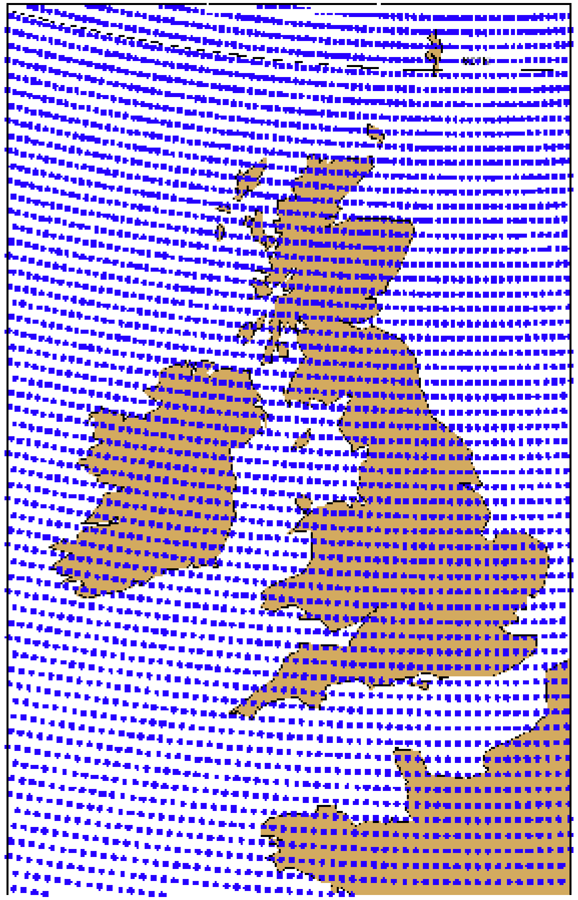
Example: ECMWF Model

Resolution Upgrades February 2006 and January 2010

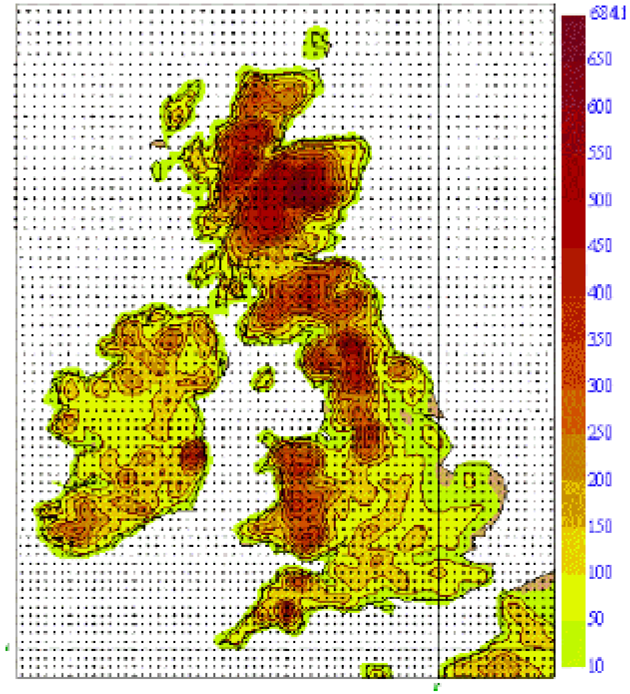
T_L511 / N256 ~ 40 km
(until Feb. 2006)
348,528 grid points



T_L799 / N400 ~ 25 km
(since Feb. 2006)
843,490 grid points



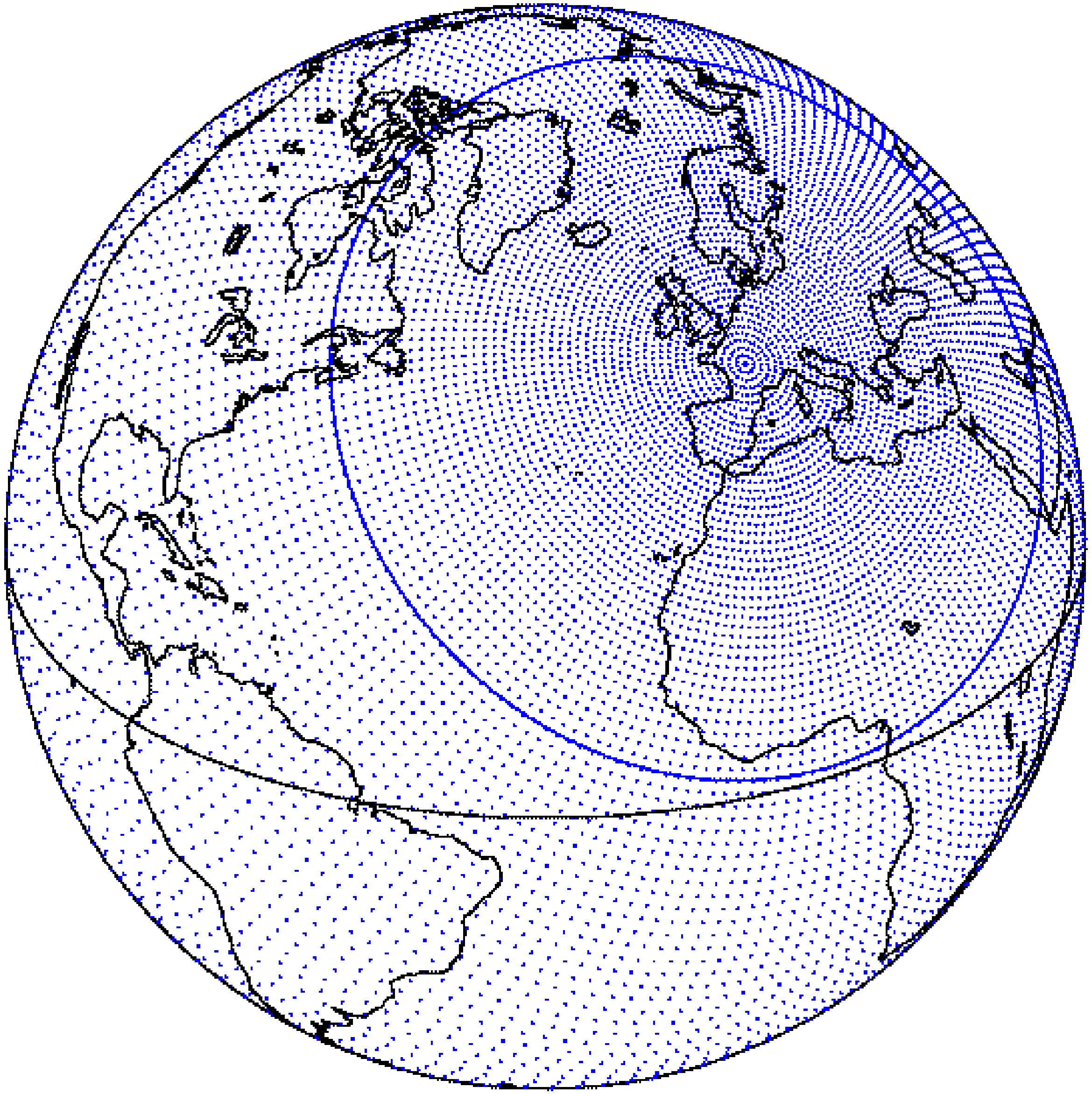
T_L1279 / N640 ~ 16 km
(since Jan. 2010)
2,140,704 grid points



(European Centre for Medium-Range Weather Forecasts, ECMWF)

Global Models with variable Resolution

Action de
Recherche
Petite
Echelle
Grande
Echelle



ARPEGE (Meteo France)

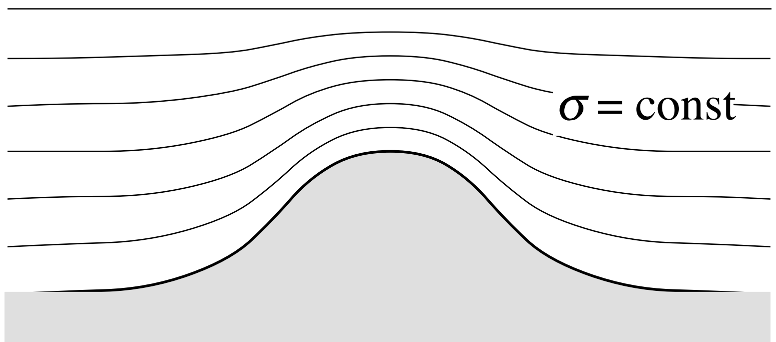
Representation on the globe with the spectral approach, but using
- grid stretching
- pole rotation

to enhance resolution over the region of interest

For example:
spectral resolution: T_L358
stretching factor: C2.4
Resulting grid:
Δ = 23 km (France)
Δ = 133 km (antipodes)

(CAS 2003, Annecy)

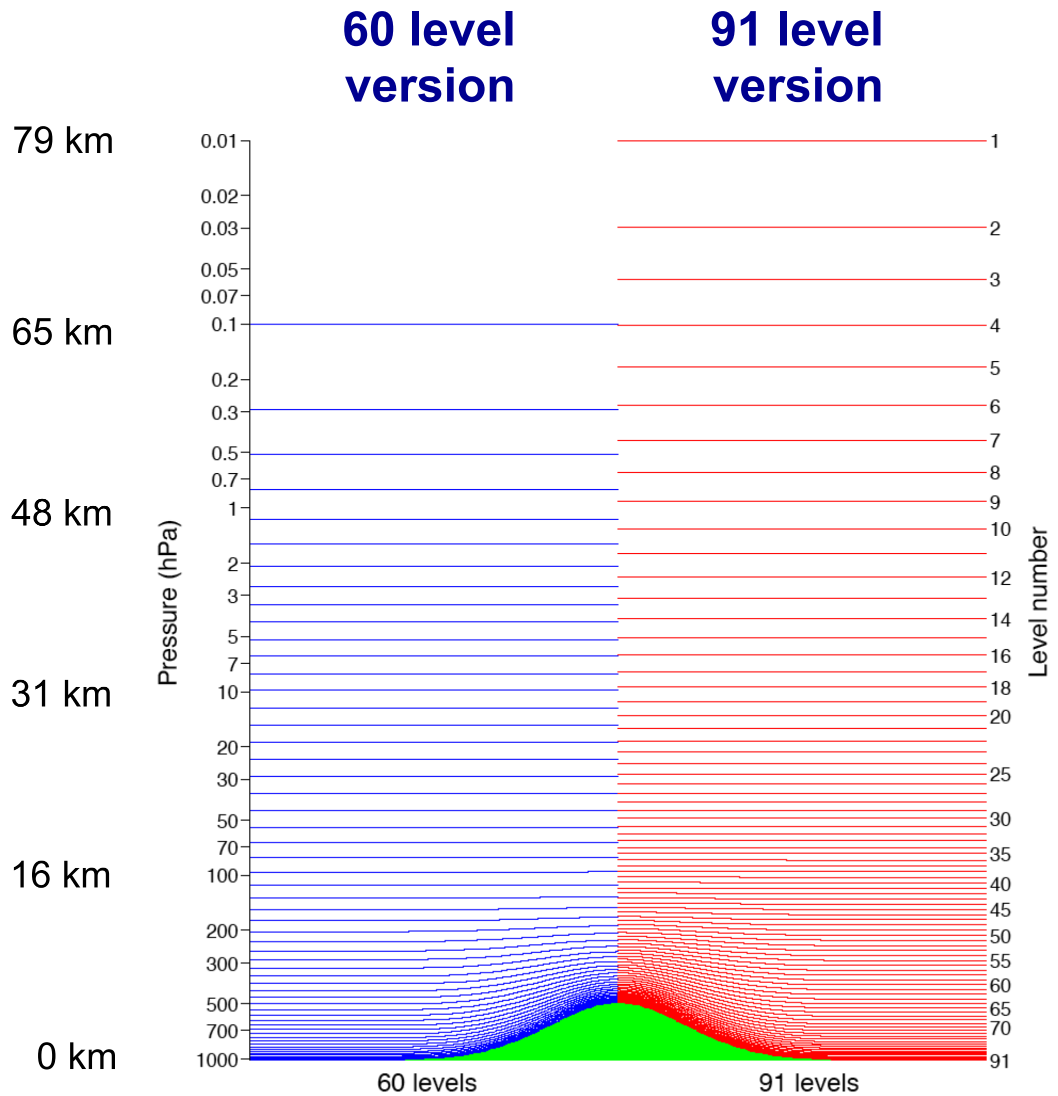
Vertical Discretization: Terrain-Following Coordinates



Typical vertical resolution in climate and numerical weather prediction models: 20-150 levels

Hydrostatic models use a pressure-based coordinate system

Current resolution at ECMWF since June 2013: 137 levels with top at 0.01 hPa (ca 79 km)



(Bauer et al. 2013, ECMWF TM 704)

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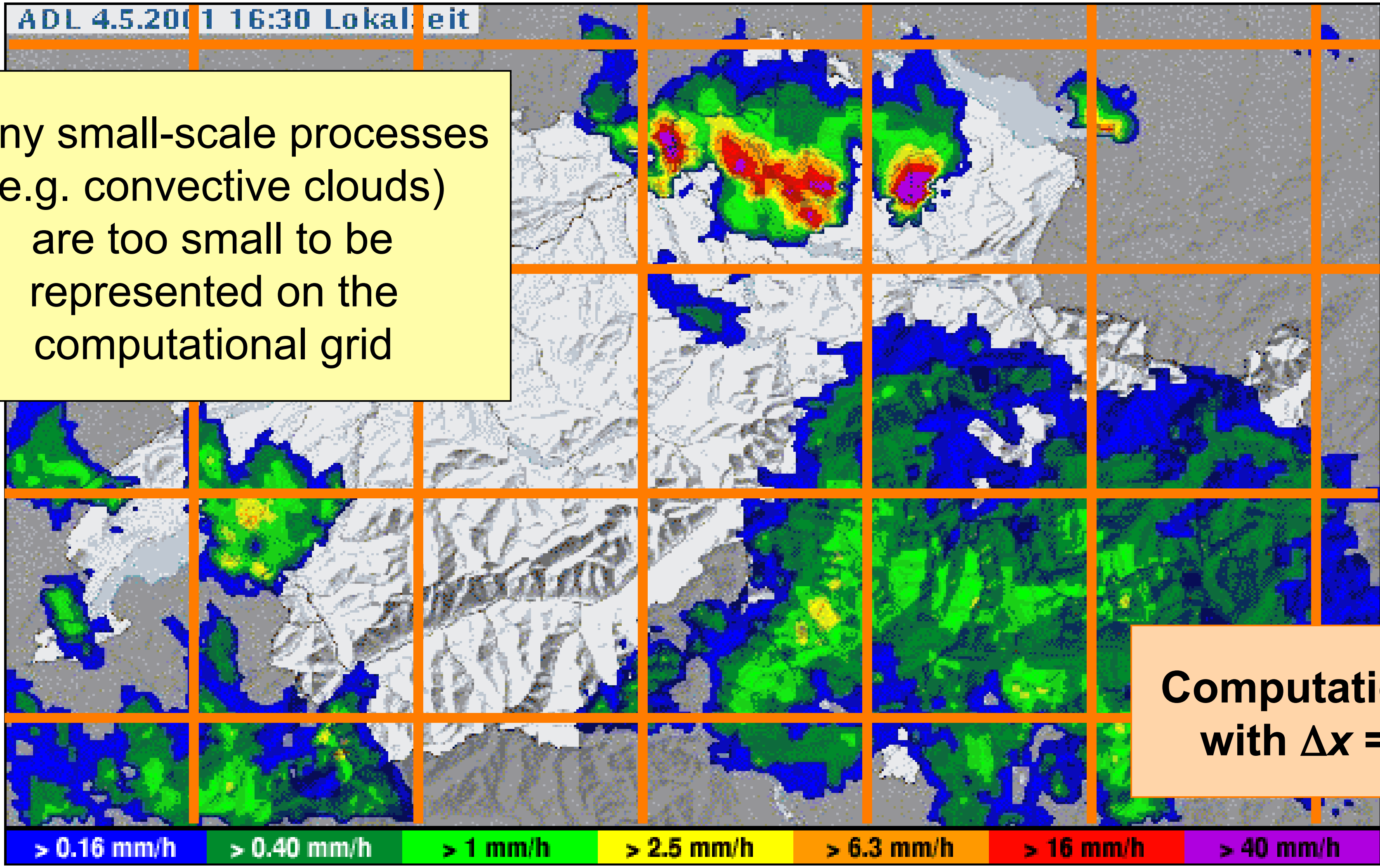
The Parameterization Problem



Many small-scale processes (e.g. convective clouds) are too small to be represented on the computational grid

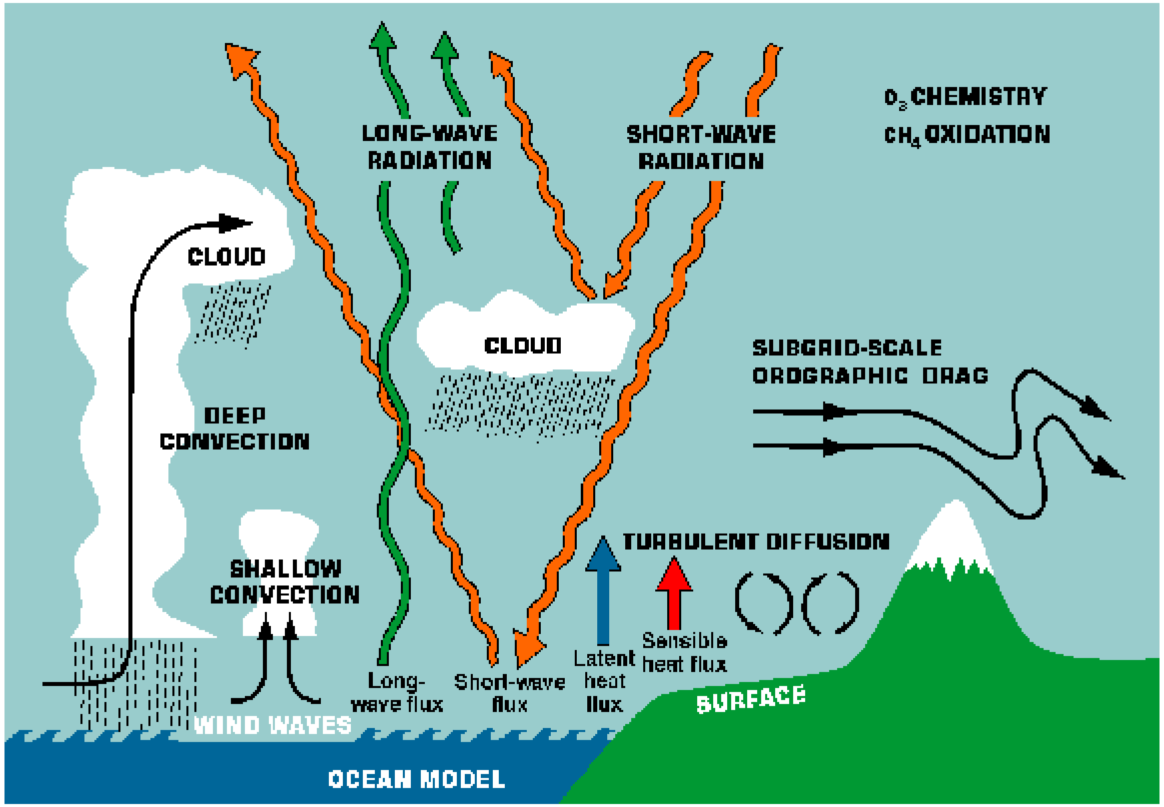
Computational grid with Δx = 50 km

Parameterized Processes

Typical atmospheric models have

$$10 \text{ km} \leq \Delta x \leq 200 \text{ km}$$

Processes that are not explicitly represented at these resolutions are **"parameterized"** instead, using physical understanding of the underlying processes, or semi-empirical relations.



Parameterized processes contribute substantially to uncertainties in weather forecasting and climate models.

(ECMWF)

Parameterized Processes

Momentum equations

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

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} + \frac{\partial (v\rho)}{\partial y} + \frac{\partial (w\rho)}{\partial z} = 0$$

Parameterized terms	$(F_x, F_y)/\rho$	non-conservative forces
	H/c_p	diabatic heating rate

Additional equations $\frac{Dq_{vap}}{Dt} = S_{vap}$ $\frac{Dq_{cld}}{Dt} = S_{cld}$ Equations for specific water vapour and cloud water content

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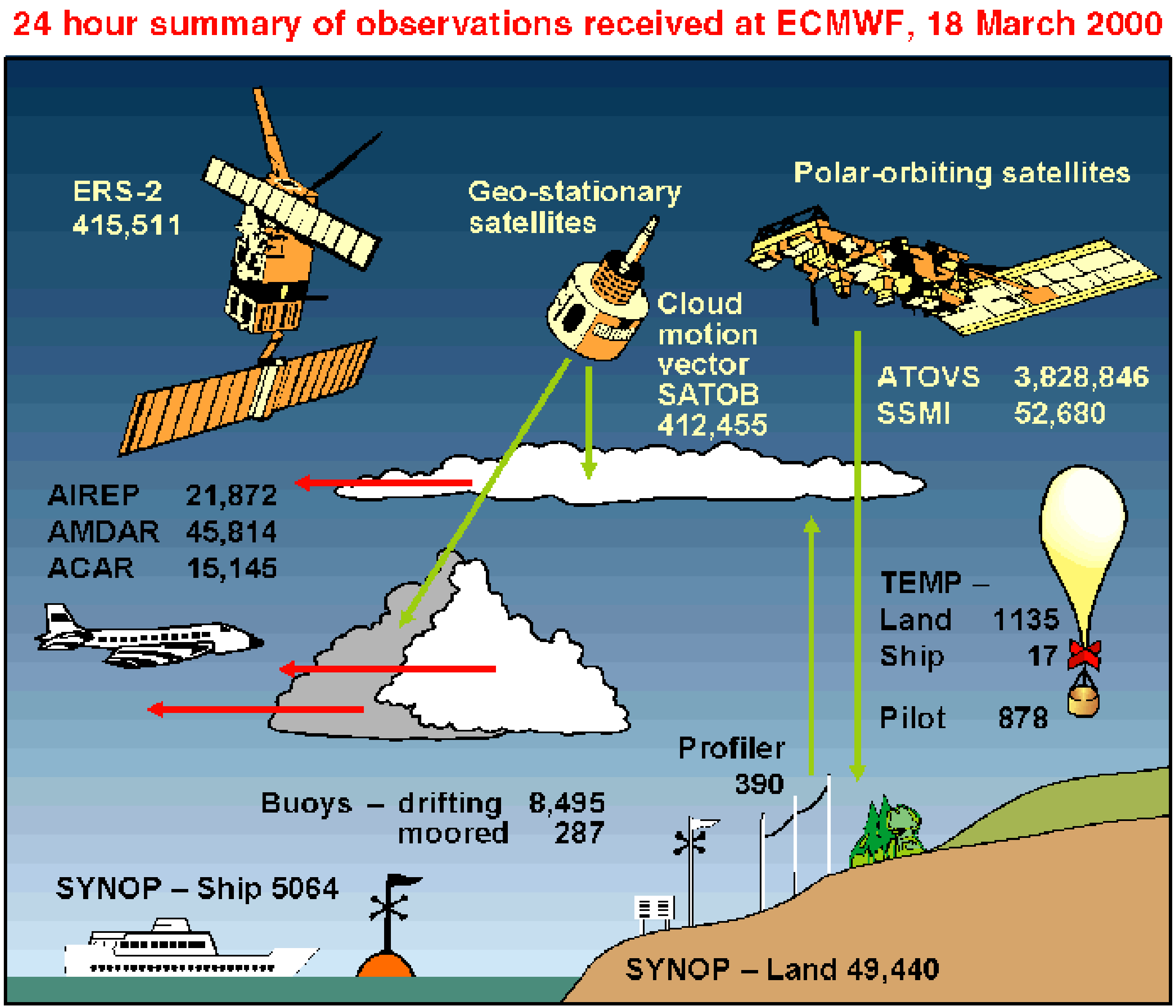
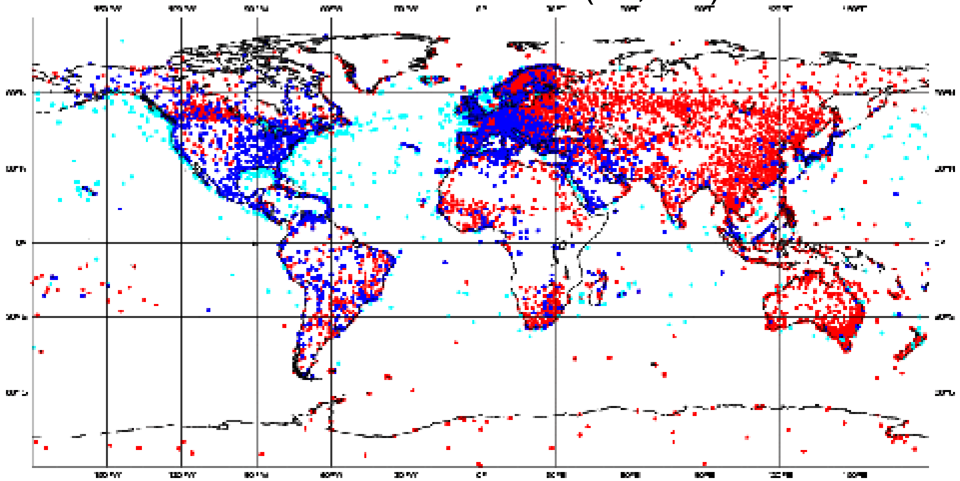
Initial conditions are obtained from observations



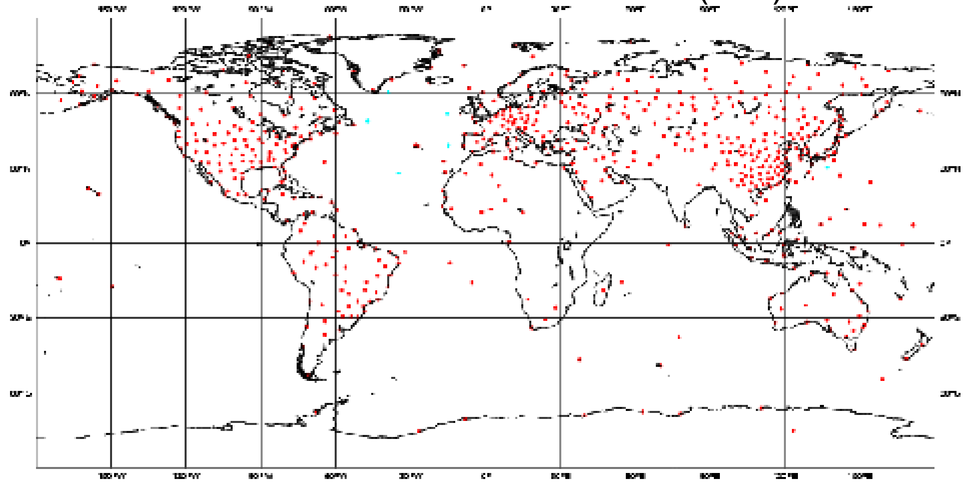
(ECMWF 2001)

Global observing system

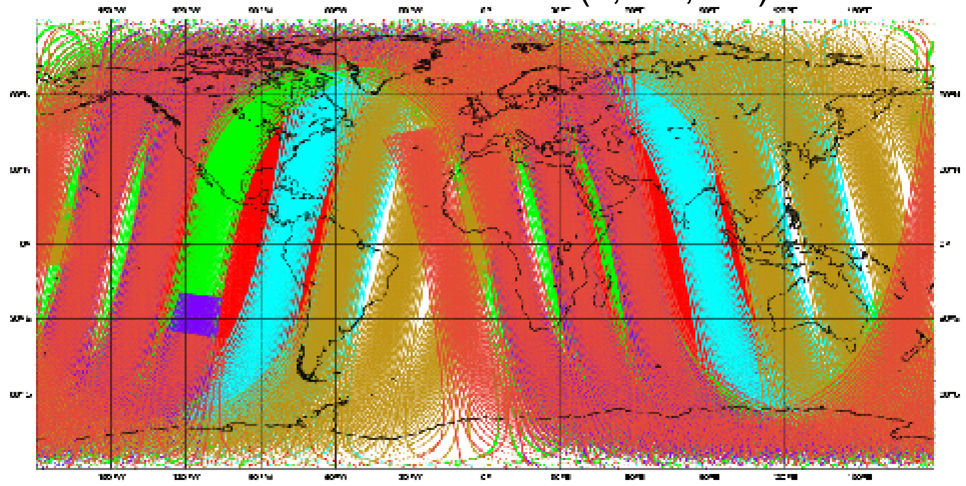
Surface observations (33,904)



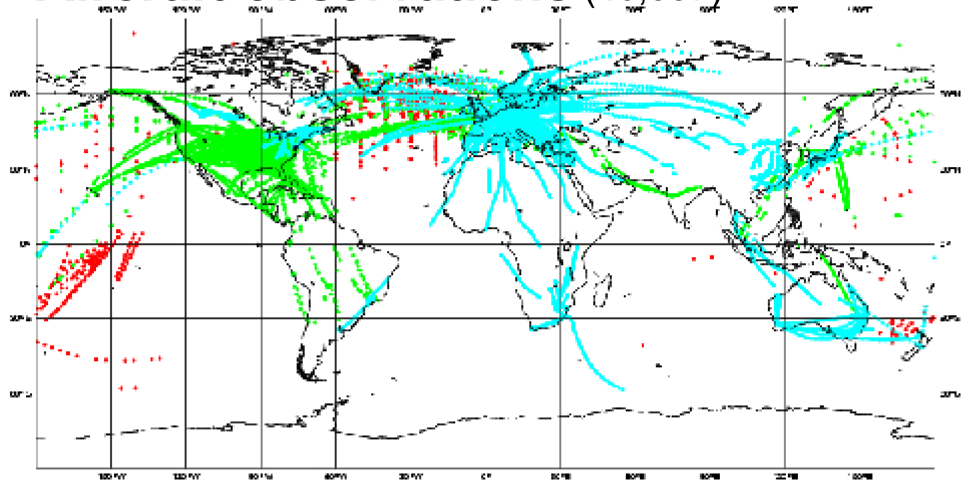
Radiosonde observations (641)



MW / IR satellite data (1,343,053)

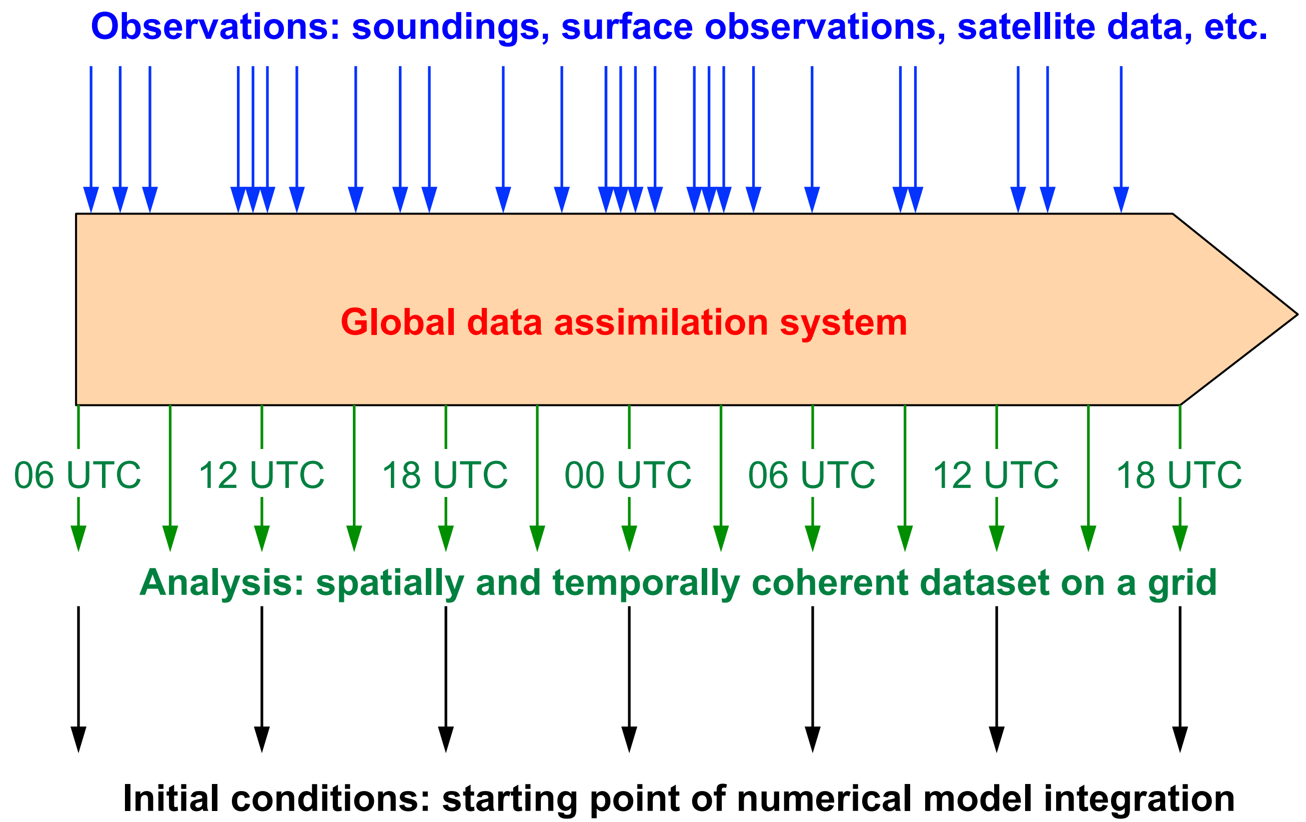


Aircraft observations (46,037)



Data received at ECMWF on May 3, 2010, 9–15 UTC (in brackets: number of obs)

Global Data Assimilation



Global data assimilation systems ingest a wide range of data from various instruments and observation times. They run a general circulation model (GCM) in hindcast mode. The resulting analysis is a spatially and temporally coherent description of the actual state of the atmosphere. In data sparse regions, where few observations are available, these systems in essence provide a mixture between a short-range (e.g. 6 h) forecast and the available observations.

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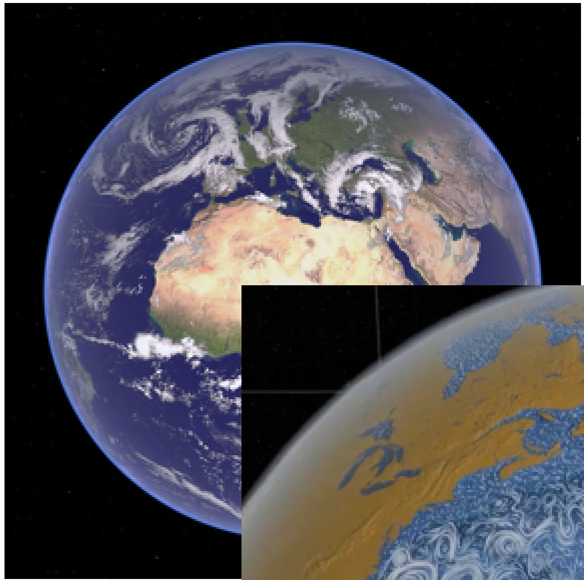
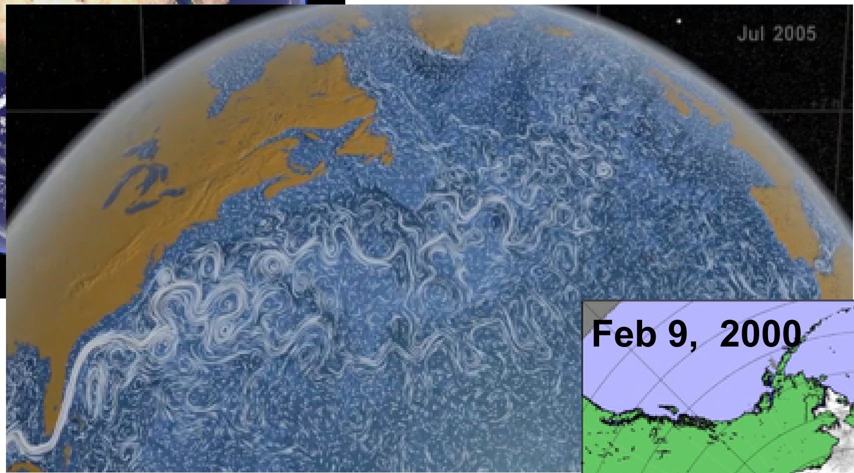
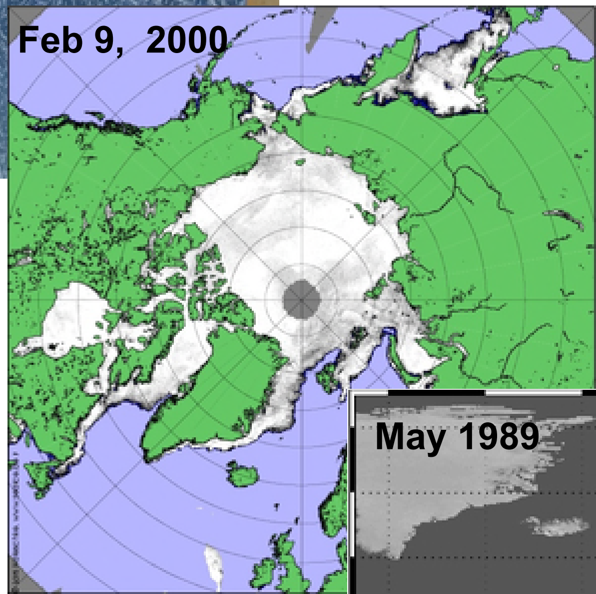
The Coupled Climate System



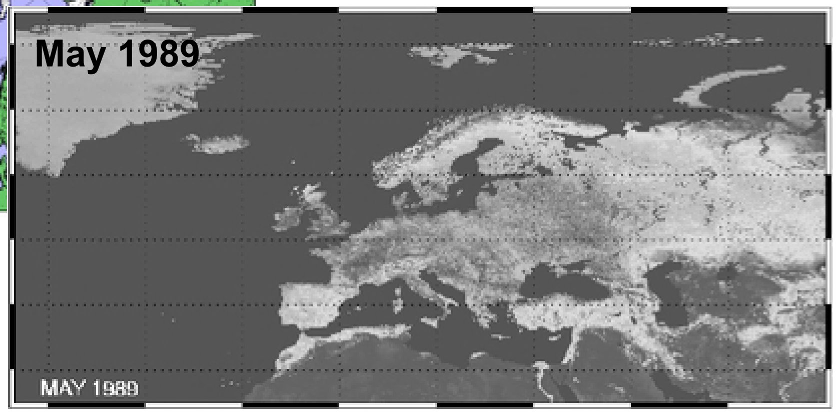
Atmosphere



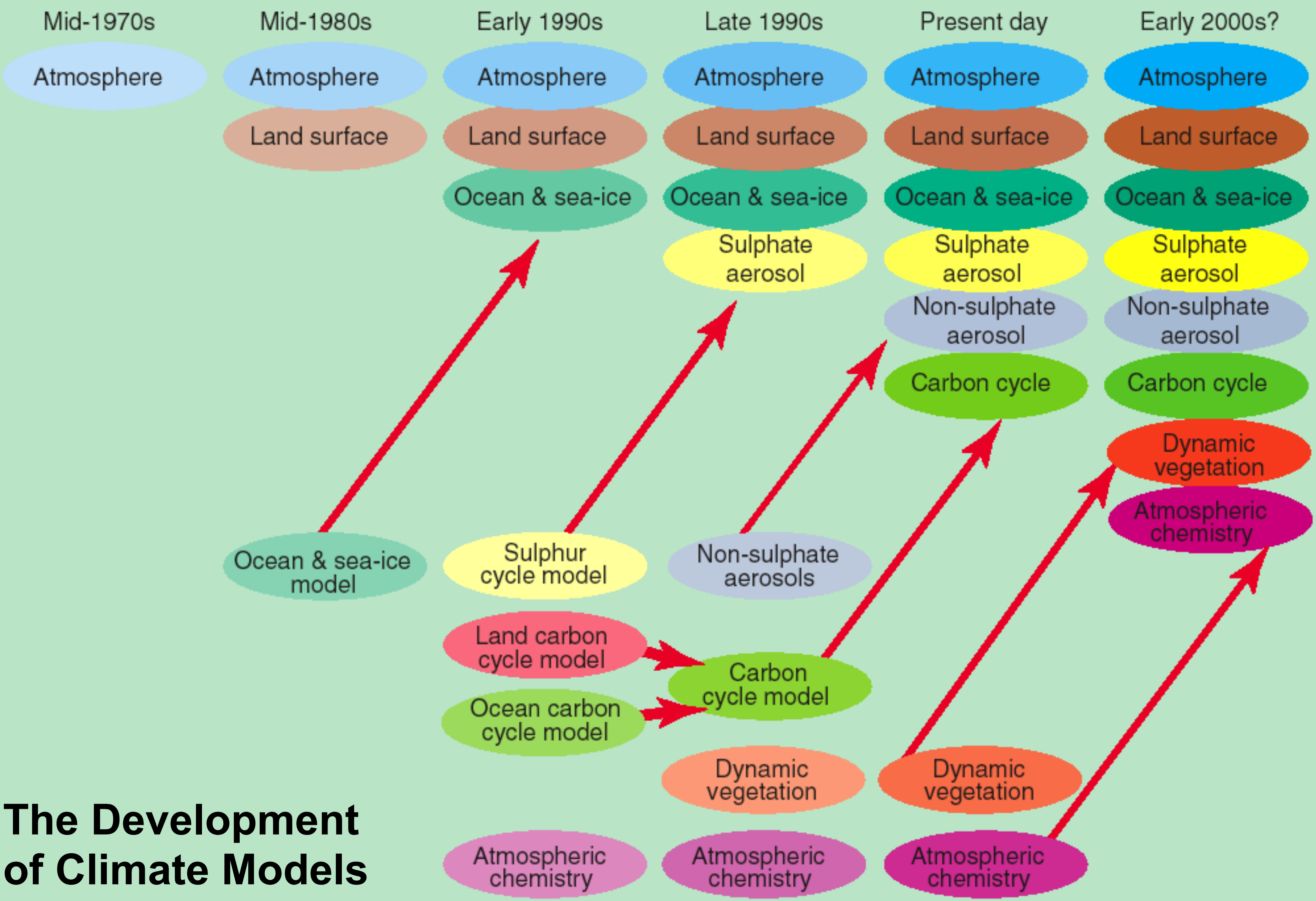
Ocean



Sea Ice

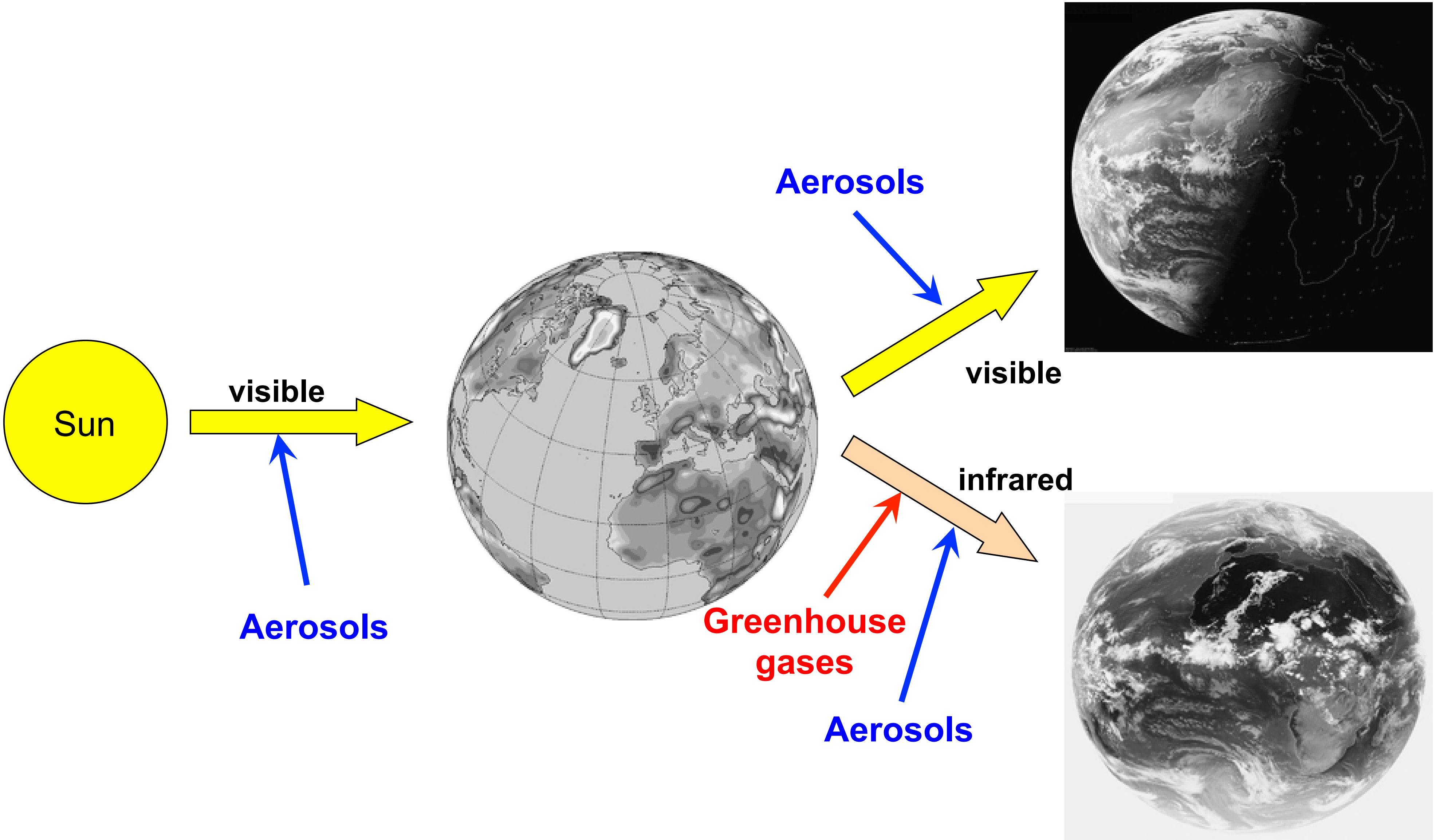


Land Surfaces



The Development of Climate Models

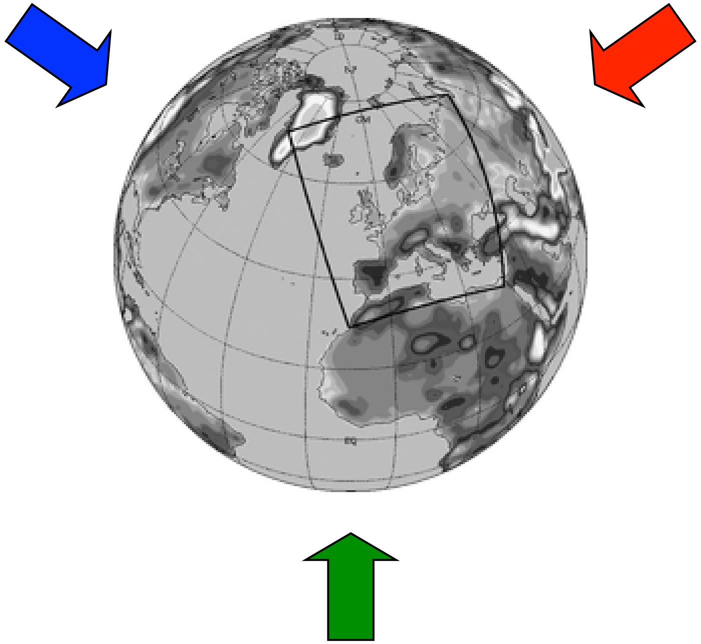
The Global Energy Balance
Energy Input = Energy Output



Sources of climate variations

External forcing
• Solar variability •
• Volcanic forcing •
• Orbital changes •

Anthropogenic forcing
• Emissions of greenhouse gases •
• Emissions of aerosol •
• Emissions of reactive gases (e.g. CFCs) •
• Land-surface changes •



Internal variability
• internal oscillation within the climate system •

Internal variability

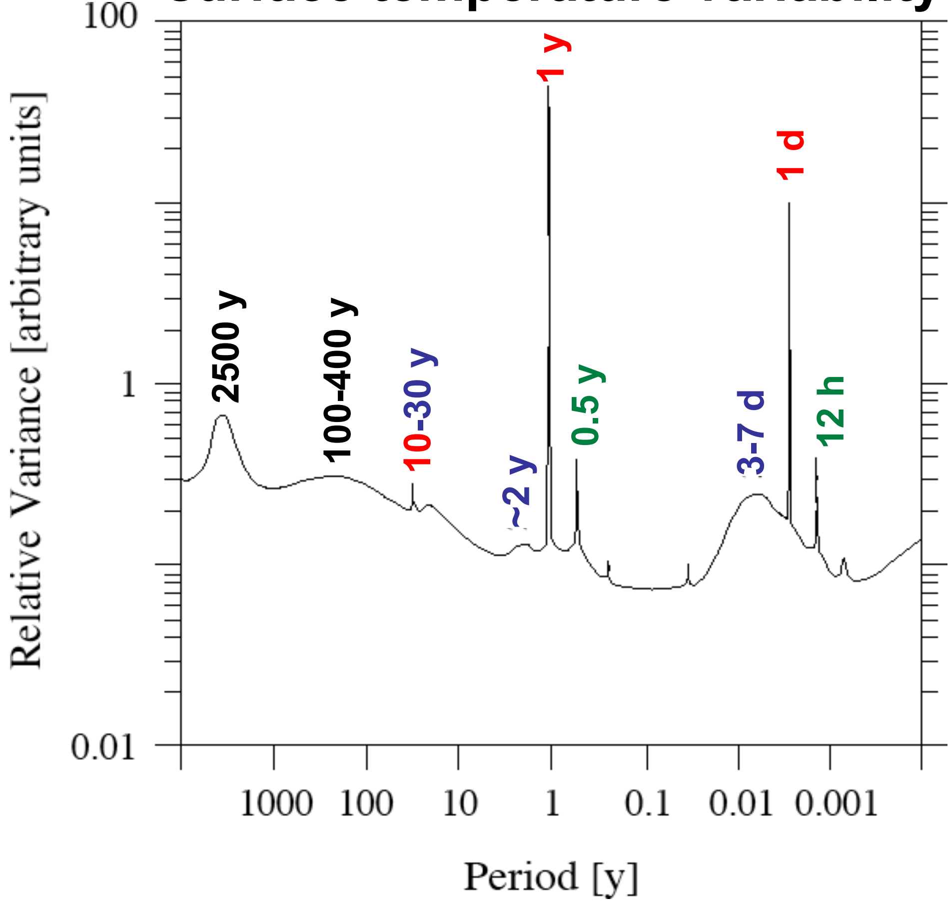
Observed climate records include

- **response to forcings (natural and anthropogenic)**
- **internal variations (e.g. due to atmospheric variability)**

Some of the observed variations are due to:

- **external forcings**
- **harmonics of external forcings**
- **internal variations**

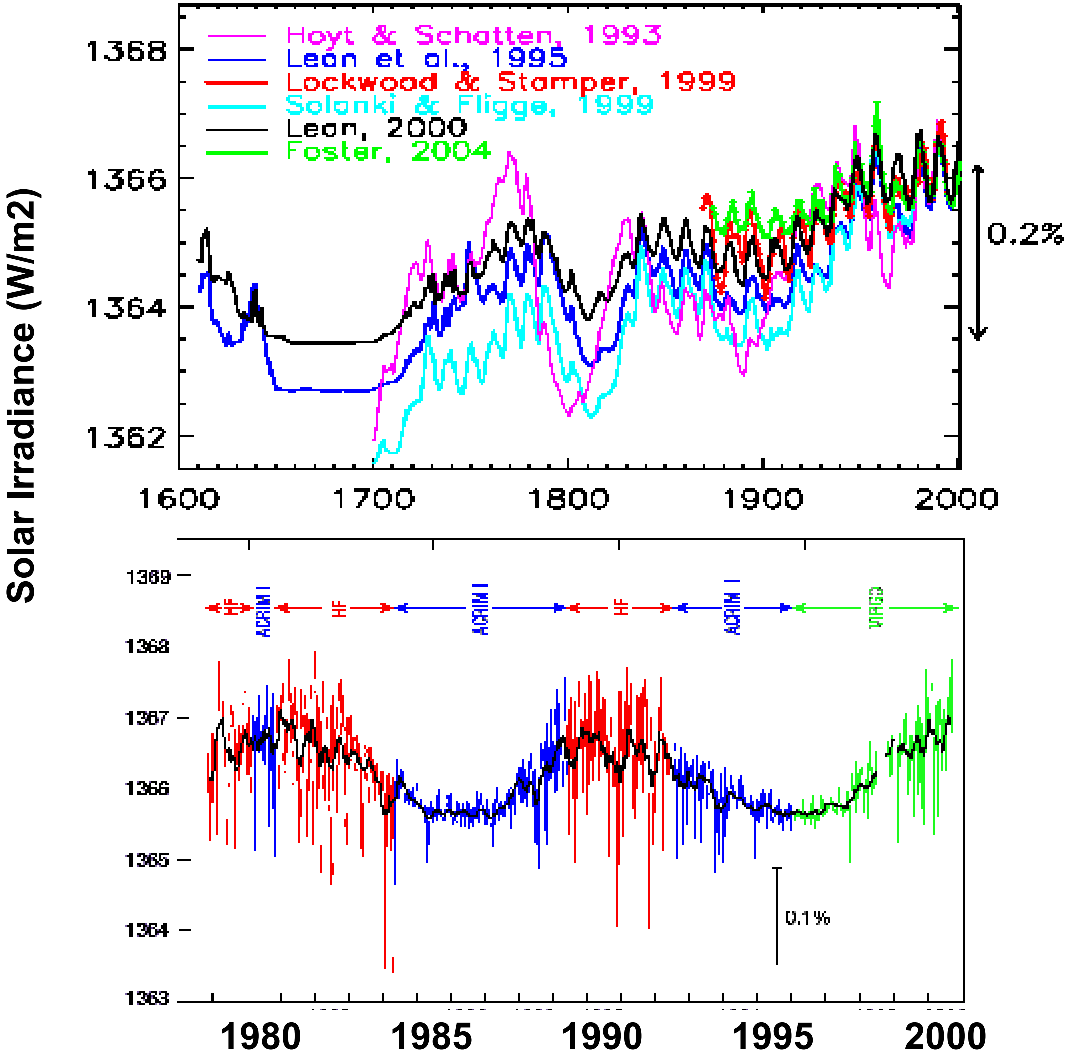
Spectrum of surface temperature variability



(Peixoto and Oort)

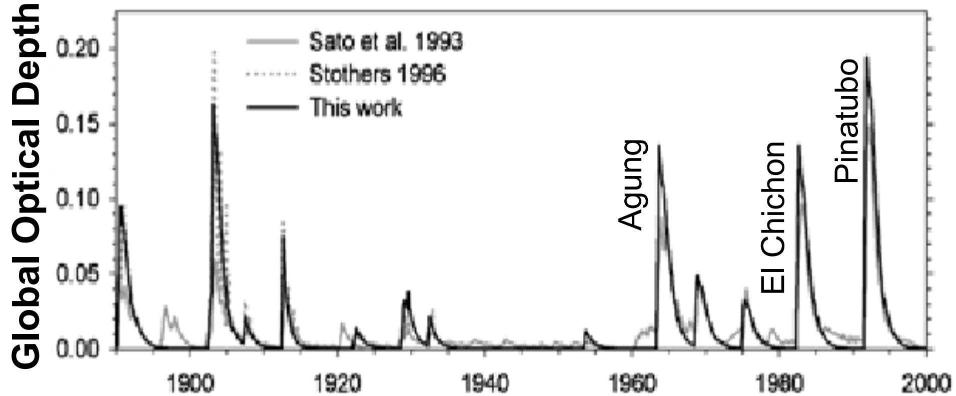
Natural Climate Forcings

Solar Forcing



(Fröhlich and Lean 2004)

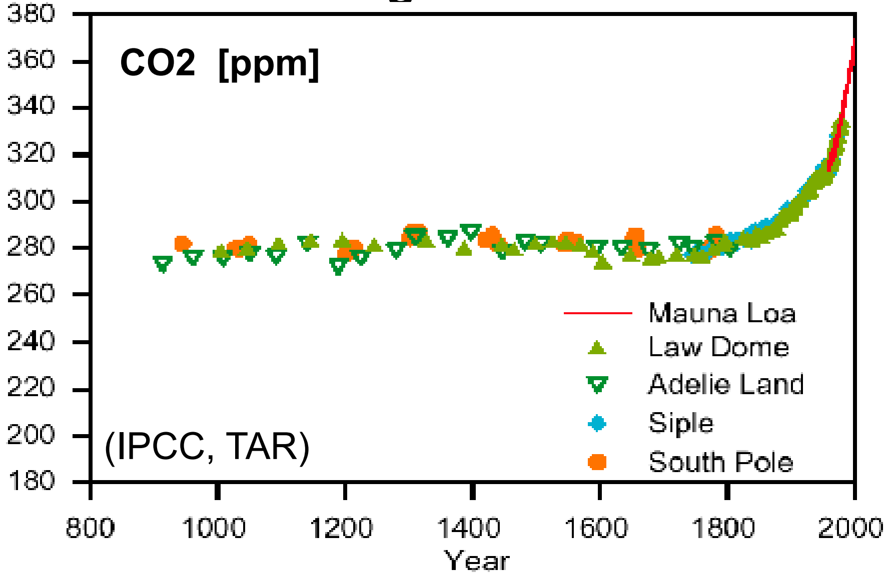
Volcanic Forcing

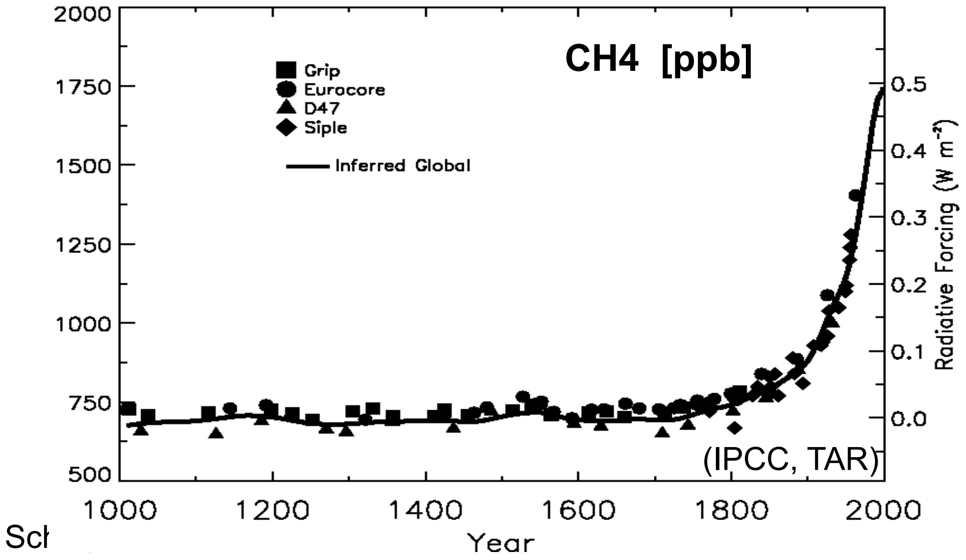


(Ammann et al. 2003)

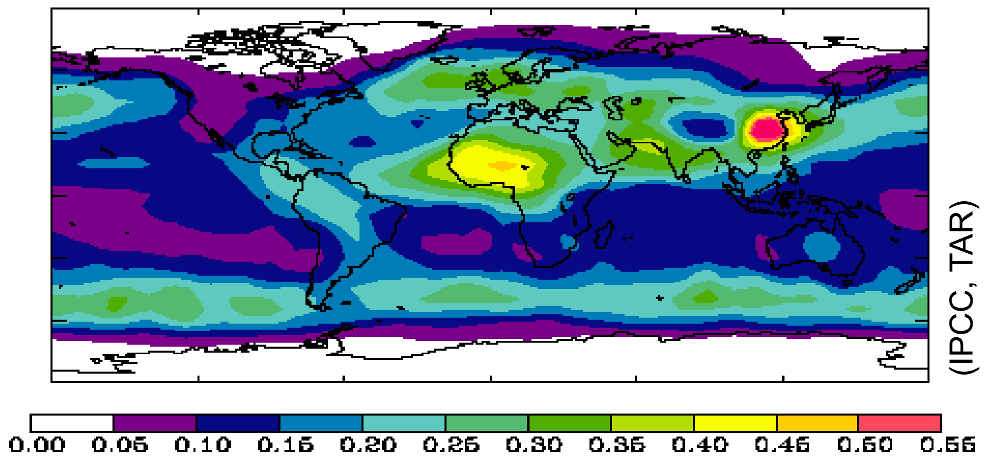
Anthropogenic Climate Forcing

Greenhouse gases

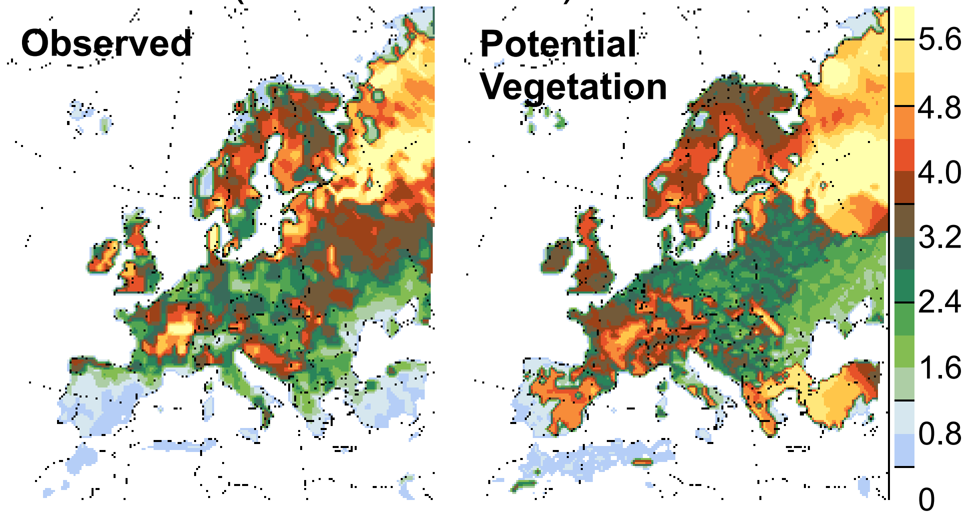




Aerosols (optical depth, year 2000)

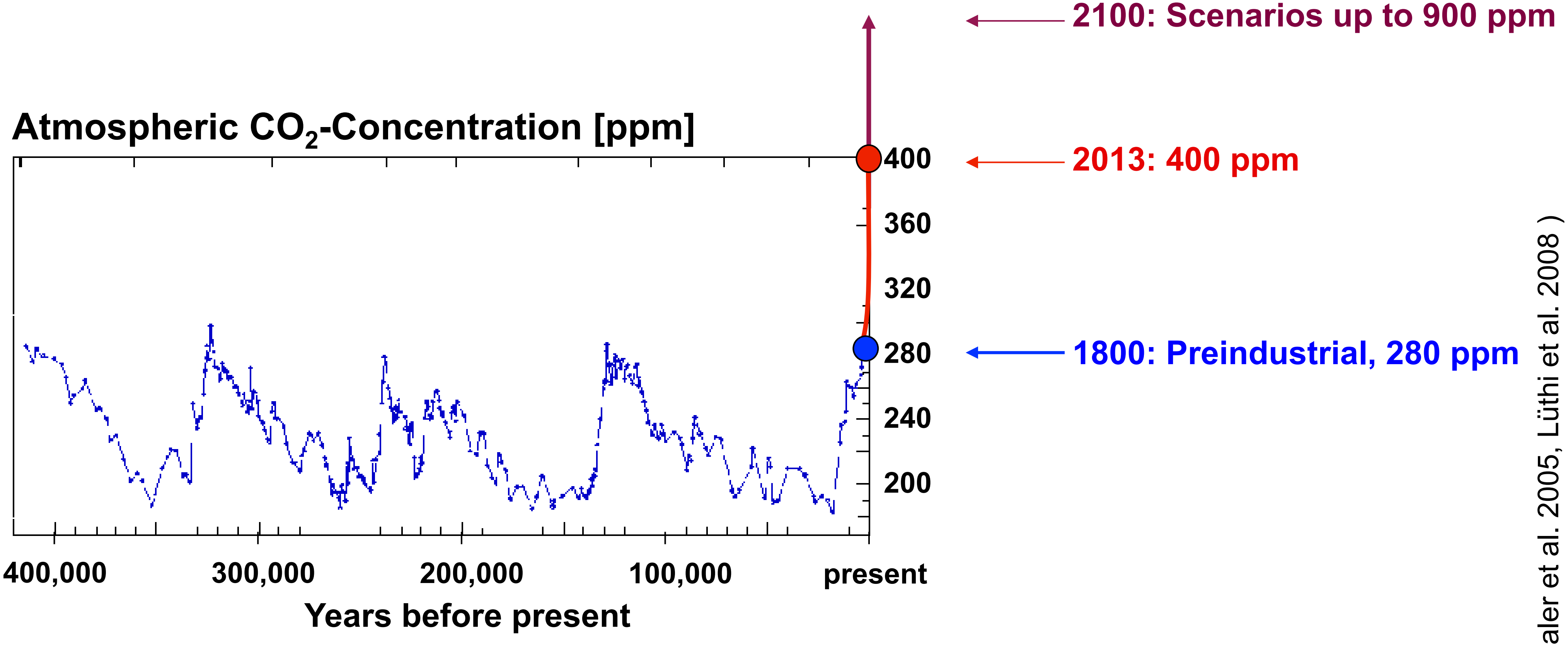


Land use (leaf area index)



(Heck et al. 2001)

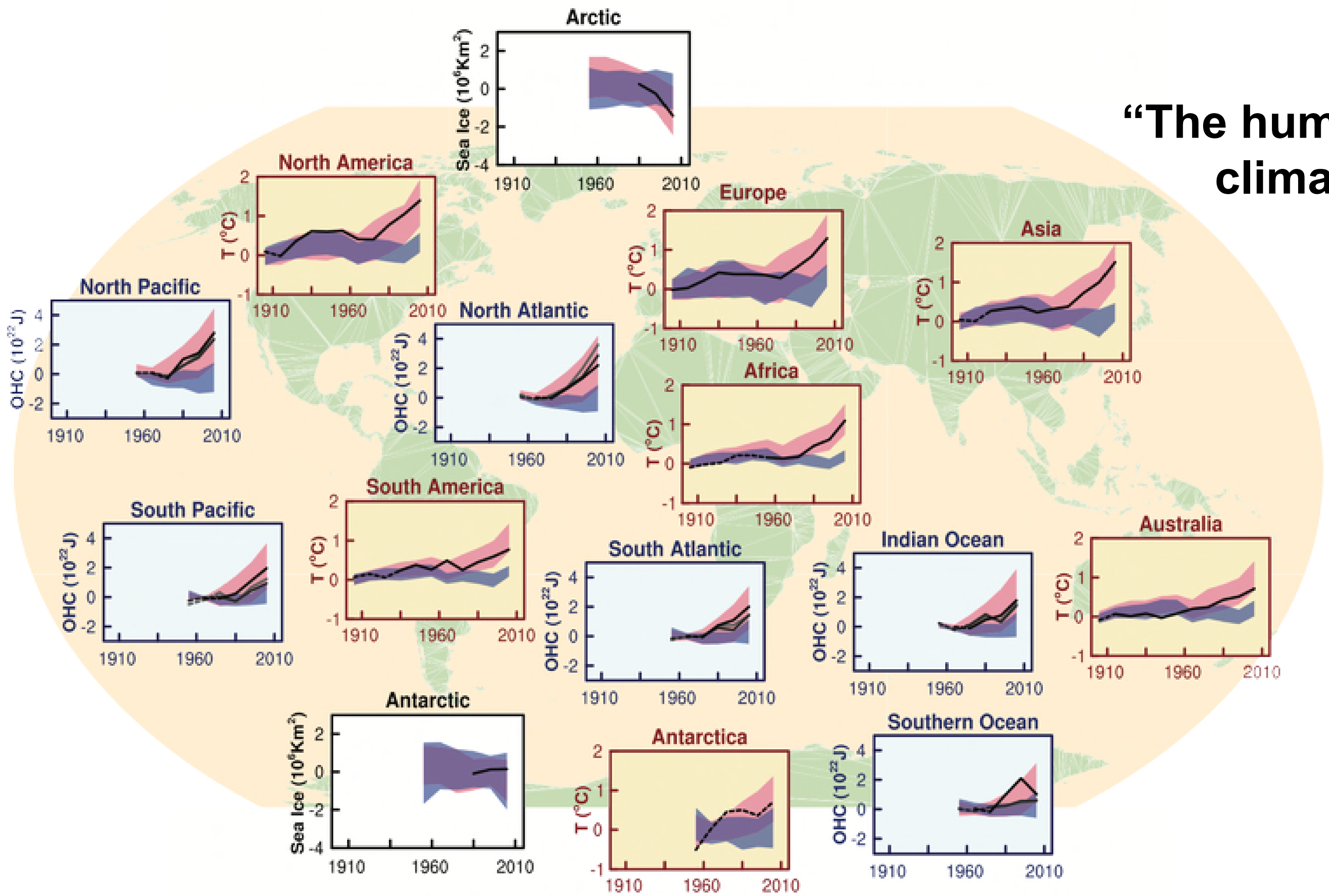
Carbon Dioxide (CO_2)



Current CO_2 concentrations are higher than ever in the last 800,000 years

(Petit et al. 1999, Siegenthaler et al. 2005, Lüthi et al. 2008)

Models with and without anthropogenic effects



"The human influence on the climate system is clear."
IPCC AR5 (2013)

Models using only natural forcings
Models using both natural and anthropogenic forcings
— Observations (temperature and ocean heat content)

Schär, ETH Zürich

Outline

Historical perspective

Atmospheric scales

Governing equations

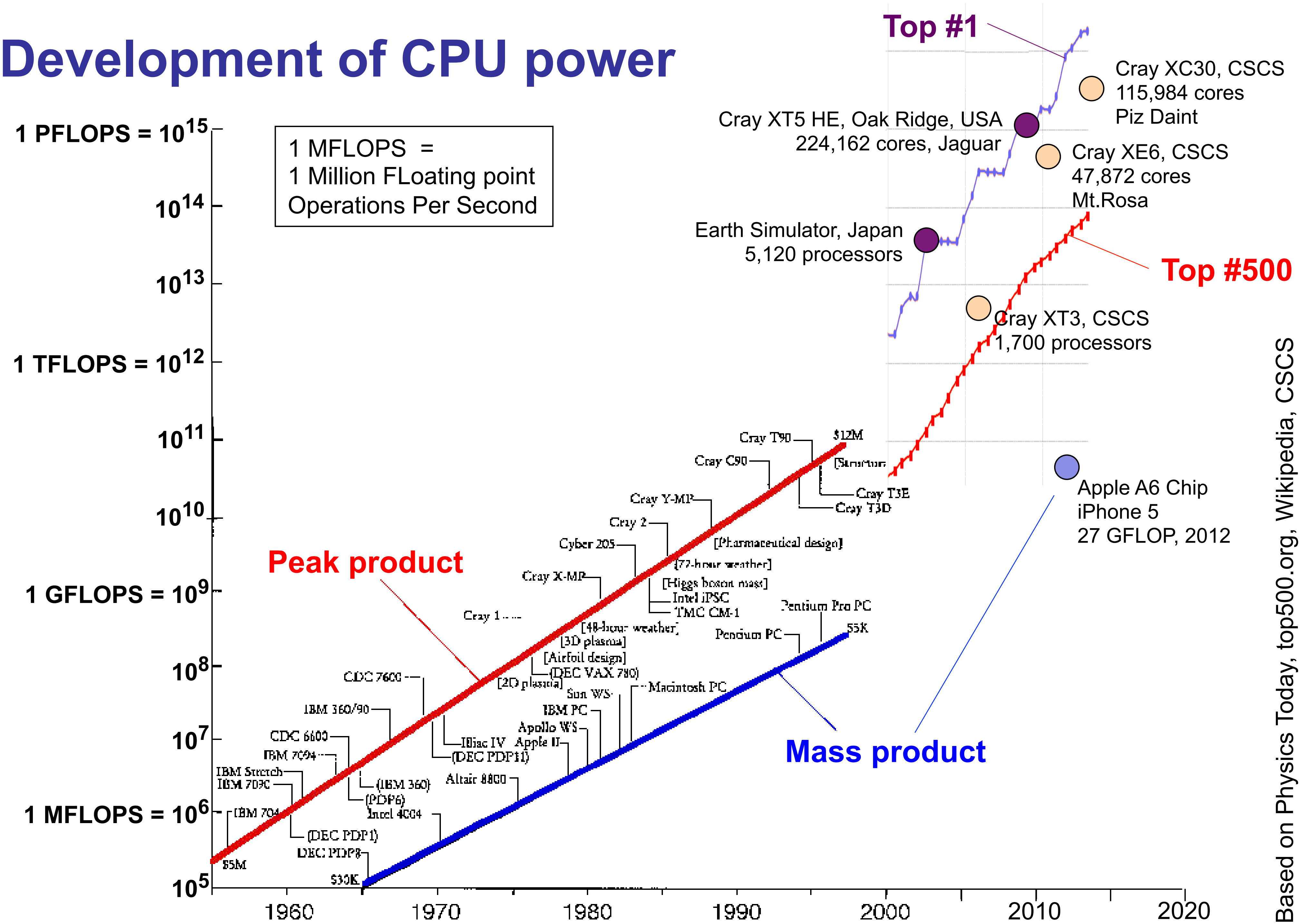
Parameterizations

Initial conditions

Climate models

Computational aspects

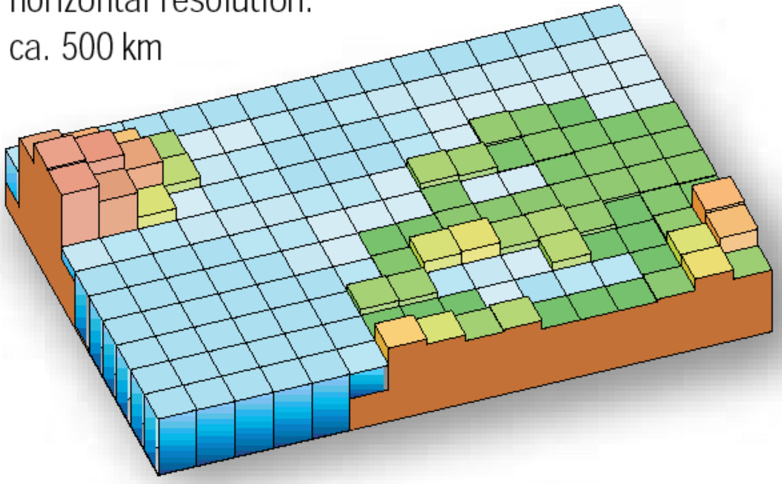
Development of CPU power



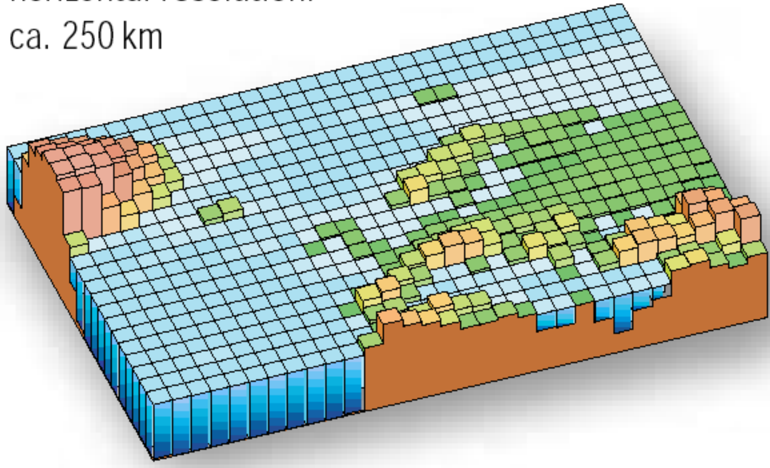
Sc

Horizontal Resolution

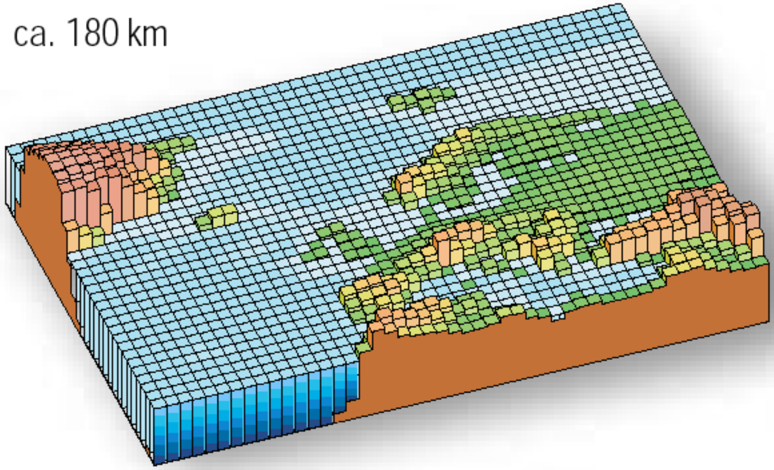
Model T21
horizontal resolution:
ca. 500 km



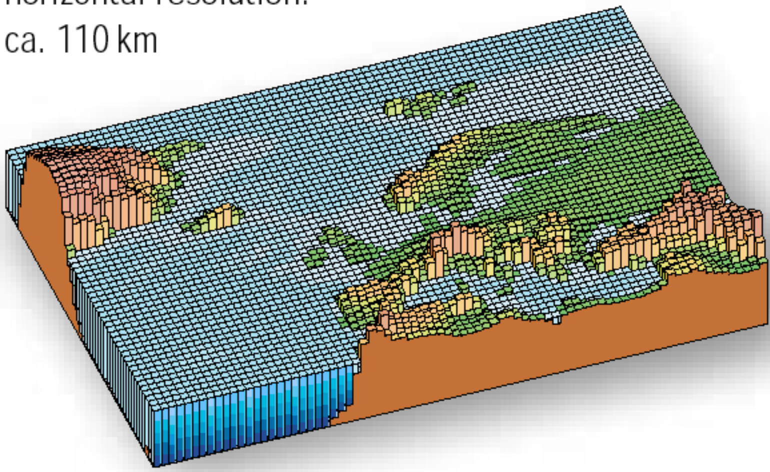
Model T42
horizontal resolution:
ca. 250 km



Model T63
horizontal resolution:
ca. 180 km

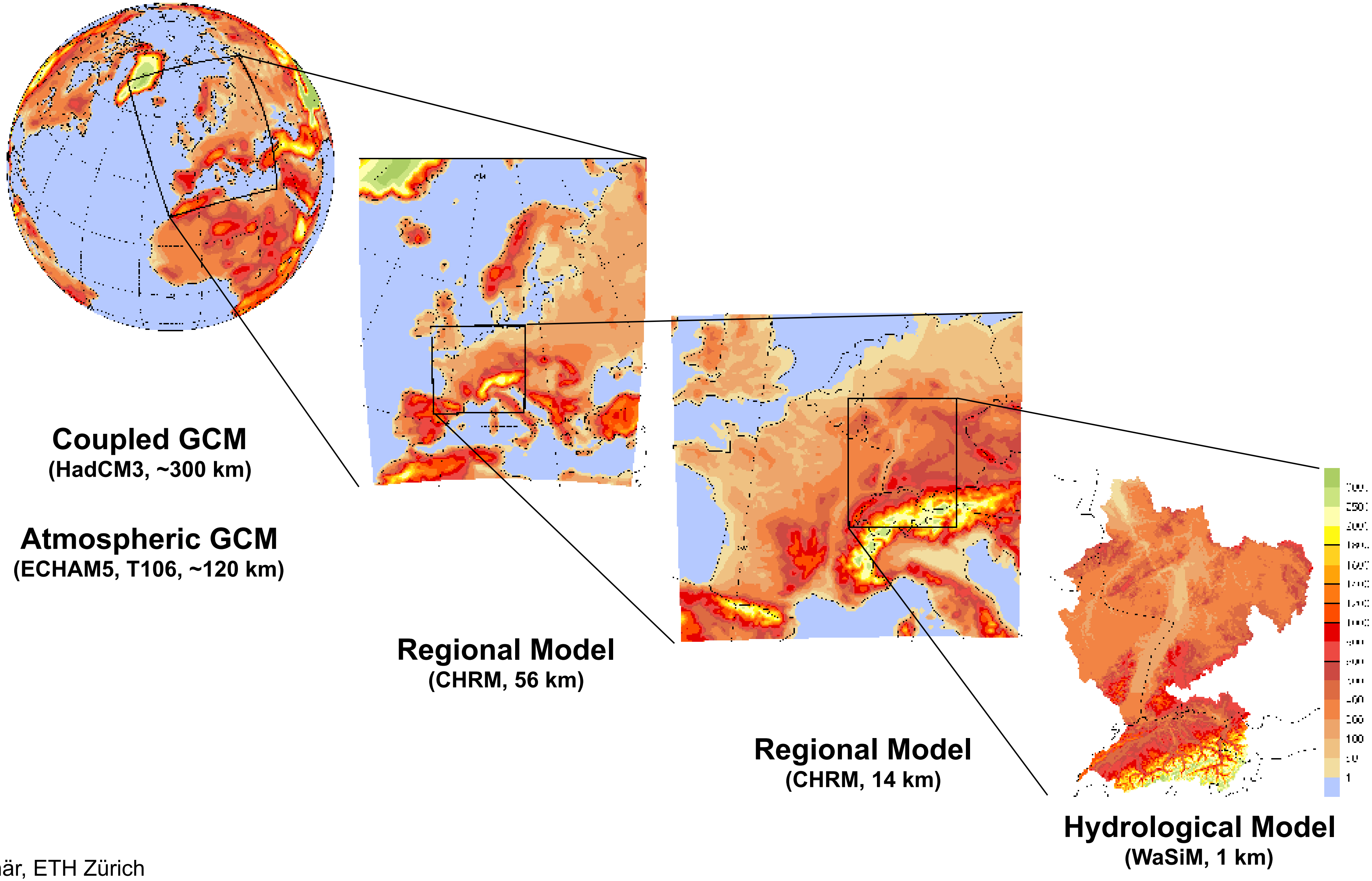


Model T106
horizontal resolution:
ca. 110 km



(MPI Hamburg)

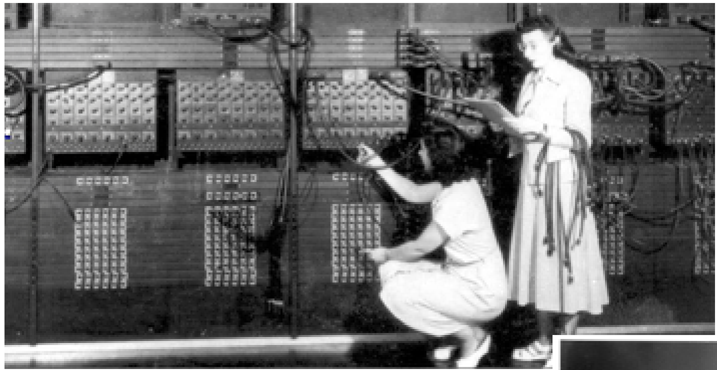
Model Chain for Climate Change Impact Study



Schär, ETH Zürich

Computational power matters

1946: Eniac



A few hundreds operations per second:

- plus / minus: 0.2 ms
- multiplcation: 2.8 ms
- square root: 300 ms

Speed around 10^3 floating point operations per second (1 kFlop/s)

John von Neumann, 1903-1957
(studied chemistry at ETH)

Today: Cray XC30 at CSCS (Lugano)

Linpack benchmark: 6×10^{15} Floating point operations per second (6 PFlop/s).

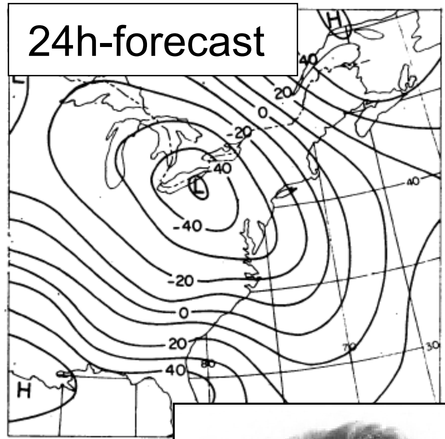
Currently fastest computer (Tianhe-2 "MilkyWay-2"), located in Guangzhou, China, is about 5 times faster.

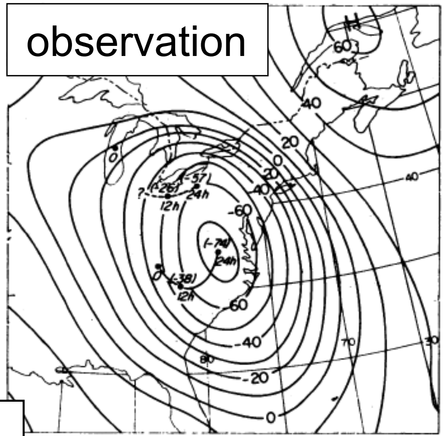
An Apple iPhone 5 has about 25 GFlop/s = 25×10^9 Flop/s

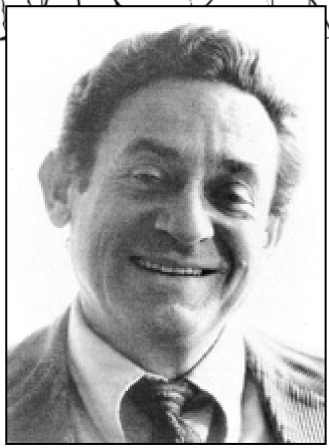
"I think there is a world market for maybe five computers."
Thomas Watson, 1943
Chairman of IBM

Model complexity matters

1954: first numerical weather forecast



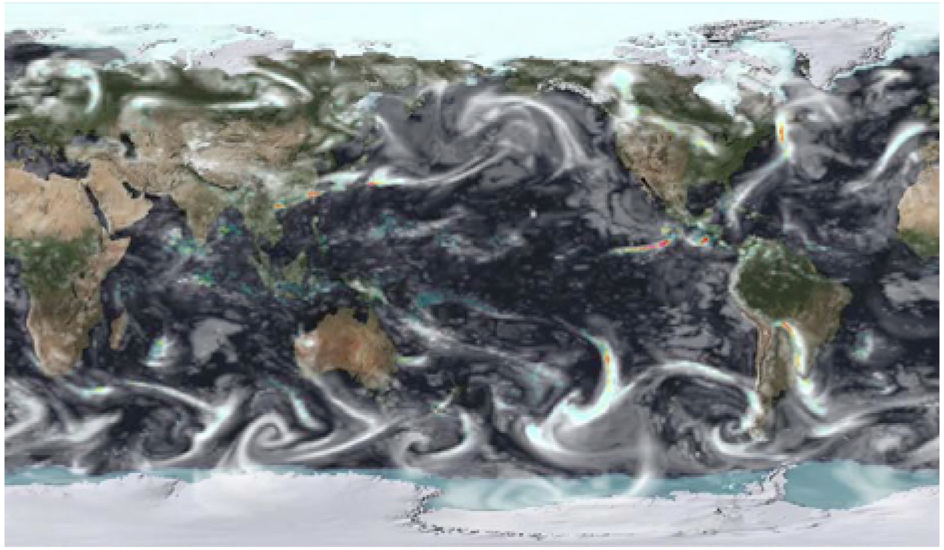




Paper has a single author
About 1000 lines of code
768 grid points

Jule G. Charney, 1917-1981

Today: high-resolution climate



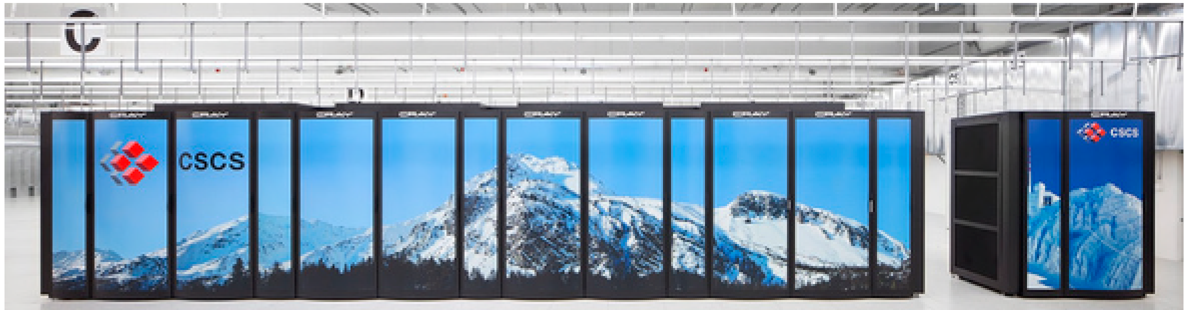
(Vidale et al., UK-Japanese collaboration)

Code of a few hundred authors,
about 1 million lines of source code,
about 120 million grid points

European-scale cloud-resolving simulations

- Enabled by GPU-capable COSMO prototype, has rewritten dynamical core, able to run on heterogeneous many-core architectures.

  Collaborative effort between MeteoSwiss (Oliver Fuhrer), ETH / C2SM and CSCS



Piz Daint: Linpac peak performance: 6×10^{15} Flop/s

- Use for climate simulations in PhD of David Leutwyler:
  Δ=2.2 km, 1500 x 1500 x 60 grid points, >10 years of integration

- Code runs since January 2014 on PizDaint (Cray hybrid XC30) at CSCS (Lugano)
  Implementation uses 144 nodes, each with 1 CPU and 1 GPU (Kepler K20X)
  Able to run 1 day in 18 minutes wall-clock time (1 year in about 5 days)

- Current test case: Storm Kyrill
  initialized January 16, 2007
  7-day simulations

(PhD David Leutwyler)

Summary

The simulation of weather and climate has come a long way towards realizing the visions of V. Bjerknes (1904) and L.F. Richardson (1922).

Some key issues:

- Small-scale processes are important for large scale features:
  => High spatial resolution desirable (computational challenge)

- Representation of sub-gridscale processes:
  => Improved parameterizations and understanding needed
  => Some parameterizations may be replaced by explicit treatment (convection)

- Nonlinearities imply intrinsic predictability limitations:
  => Probabilistic methods

- Weather versus climate
  => Weather models can be validated against observations
  => Only limited observations on decadal climate variations available