Earth System Modelling

Peter Dueben

Head of the Earth System Modelling Section

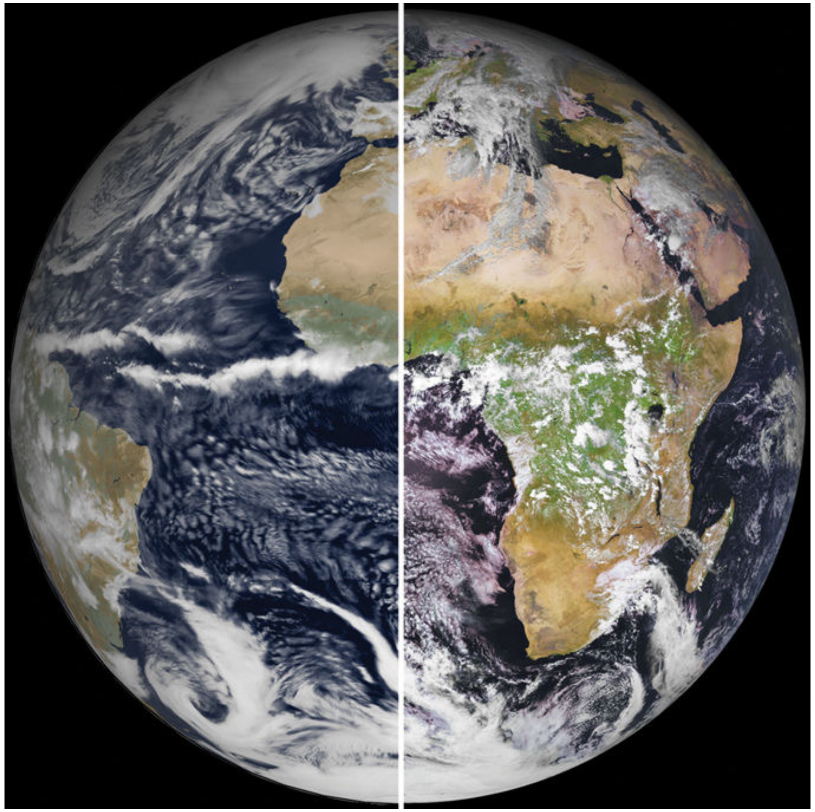
ECMWF | EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

The strength of a common goal

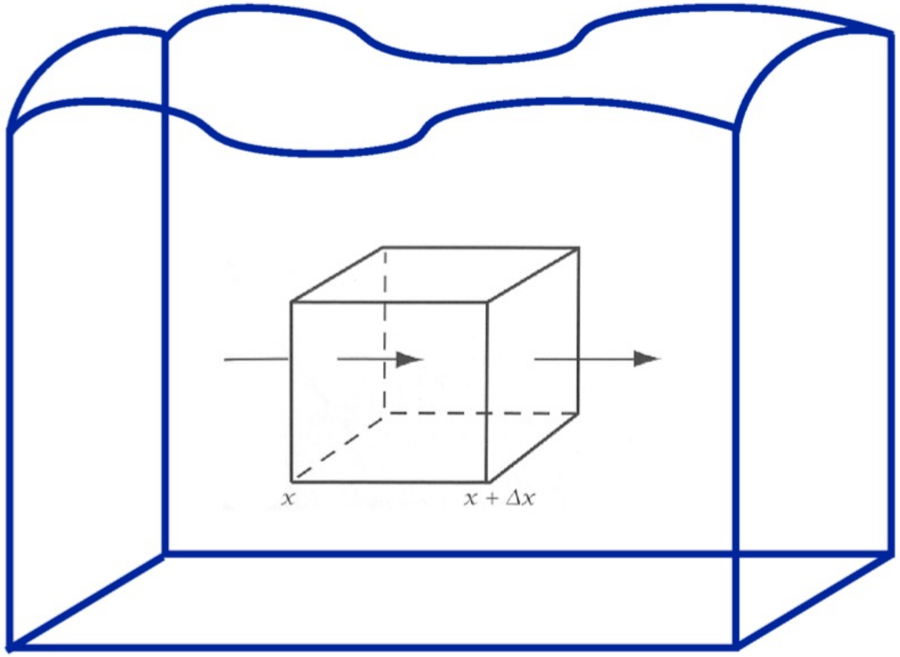
The ESIWACE and MAELSTROM projects have received funding from the European Union under grant agreement No 823988 and 955513.

Earth System Modelling and Computational Geometry of Earth System Analysis

1. What is the Earth system and why is it difficult to model the Earth system?
2. Why do we model the Earth system?
3. How do we model the Earth system?
4. How good are our models?
5. How do we represent uncertainties?
6. What geometry is important?
7. How do we use high performance computing?
8. What information is used? How does information link to geometry?
9. What is a good model?
10. What will machine learning do with Earth system modelling?



How to derive the equations?



Let's consider a volume of a fluid with a specific density ρ(x,y,z,t) and velocity **u**(x,y,z,t)

Resume:
We obtain the continuity equation of mass by evaluating mass conservations

world → continuous math description

The total mass inside the volume is given by

$$M = \int_V \rho \, dV.$$

The change of mass in the volume is given by:

$$\frac{dM}{dt} = \frac{d}{dt}\int_V \rho \, dV = \int_V \frac{d\rho}{dt} \, dV. \tag{1}$$

We can also evaluate the change of mass by looking at fluxes through the boundaries:

$$\frac{dM}{dt} = -\int_S \rho \mathbf{v} \, d\mathbf{S} = -\int_V \nabla \cdot (\rho \mathbf{v}) \, dV. \tag{2}$$

(1) and (2) together form the mass continuity equation

$$\int_V \frac{d\rho}{dt} \, dV + \int_V \nabla \cdot (\rho \mathbf{v}) \, dV = 0.$$

If we shrink the volume to an infinitesimal small area ($\lim_{\Delta x \to 0}$, $\lim_{\Delta y \to 0}$, $\lim_{\Delta z \to 0}$) we end up with the differential form of the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0.$$

We know the equations, so what’s the problem?

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\,\mathbf{v} = -\frac{\nabla p}{\rho} + \nu \nabla^2 \mathbf{v} + \frac{\mathbf{F}}{\rho} - 2\Omega \times \mathbf{v}$$

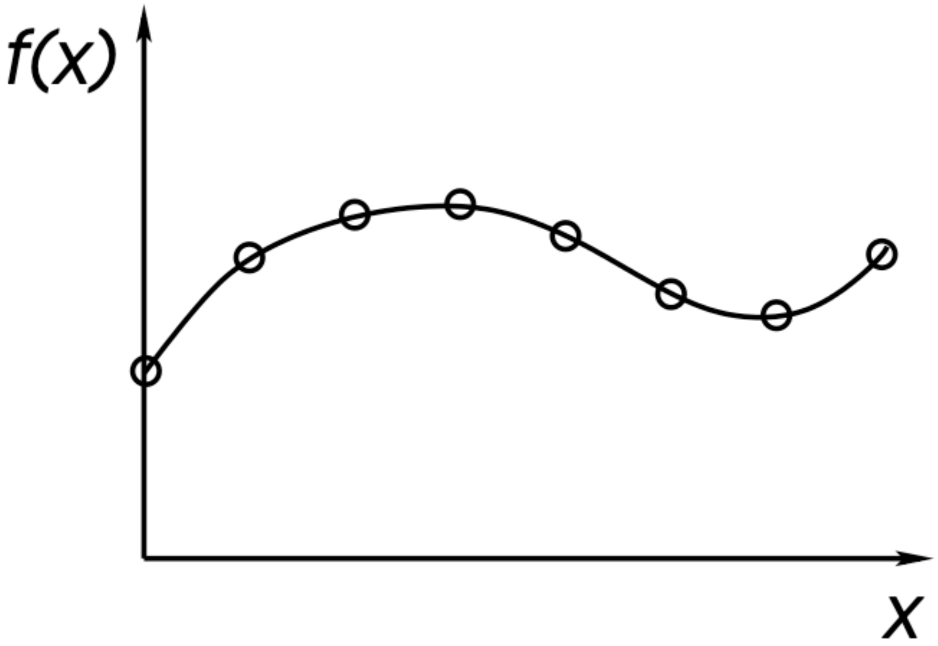
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

The equations are non-linear and we cannot solve them…

How do we still make weather predictions?

world → continuous math description → discretised equations

Finite difference method



$$\frac{\partial f(x_0,t)}{\partial x} \approx \frac{f(x_0+\Delta x,t)-f(x_0-\Delta x,t)}{2\Delta x},$$

$$\frac{\partial f(x_0,t)}{\partial x} \approx \frac{f(x_0+\Delta x,t)-f(x_0,t)}{\Delta x},$$

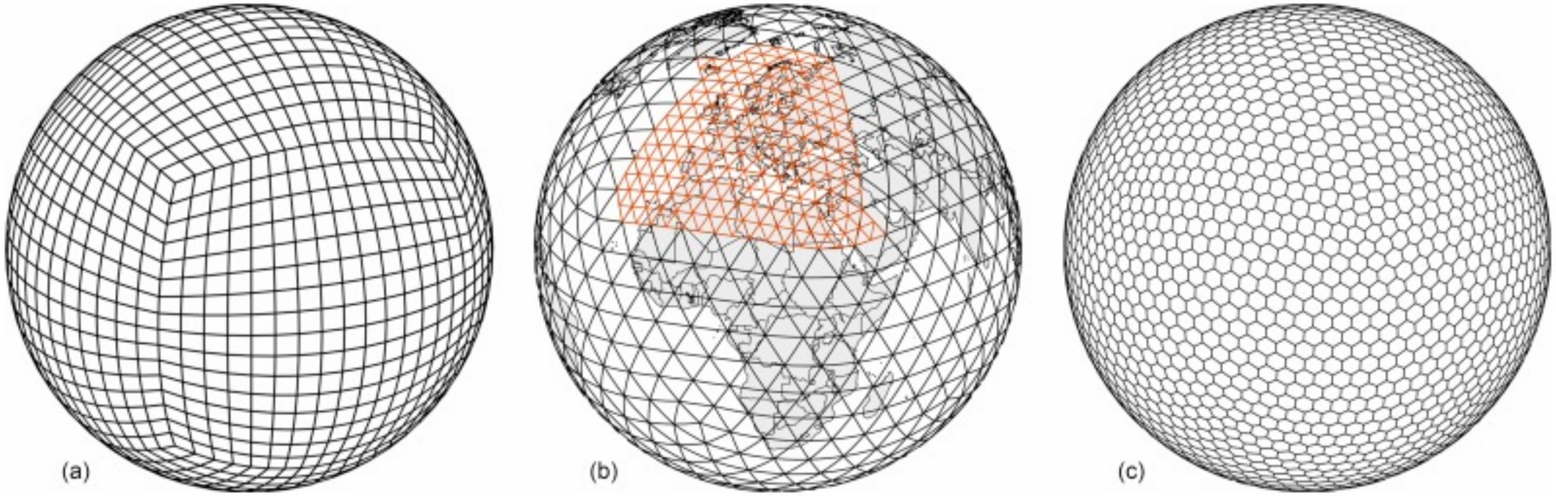
$$\frac{\partial f(x,t_0)}{\partial t} \approx \frac{f(x,t_0)-f(x,t_0-\Delta t)}{\Delta t}.$$

We discretise our function f(x) at specific grid points f(0), f(Δx), f(2Δx)…

Derivatives are described by differential quotients
→ There are plenty of different discretisation schemes

We need to discretise in both space and time

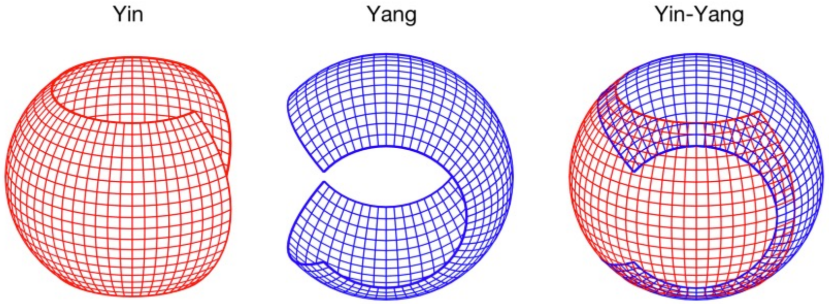
Popular grids



Cubed sphere

Icosahedral (triangular)

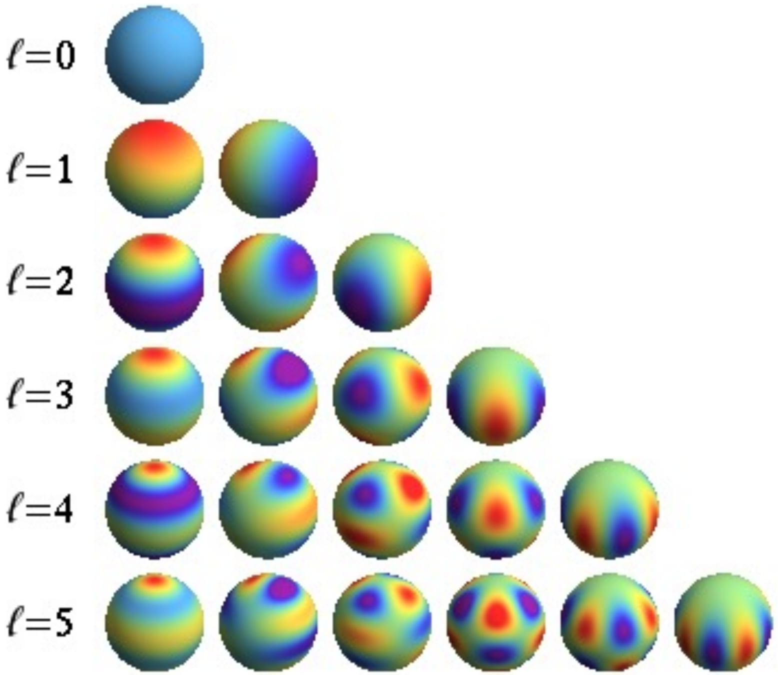
Icosahedral (hexagonal)

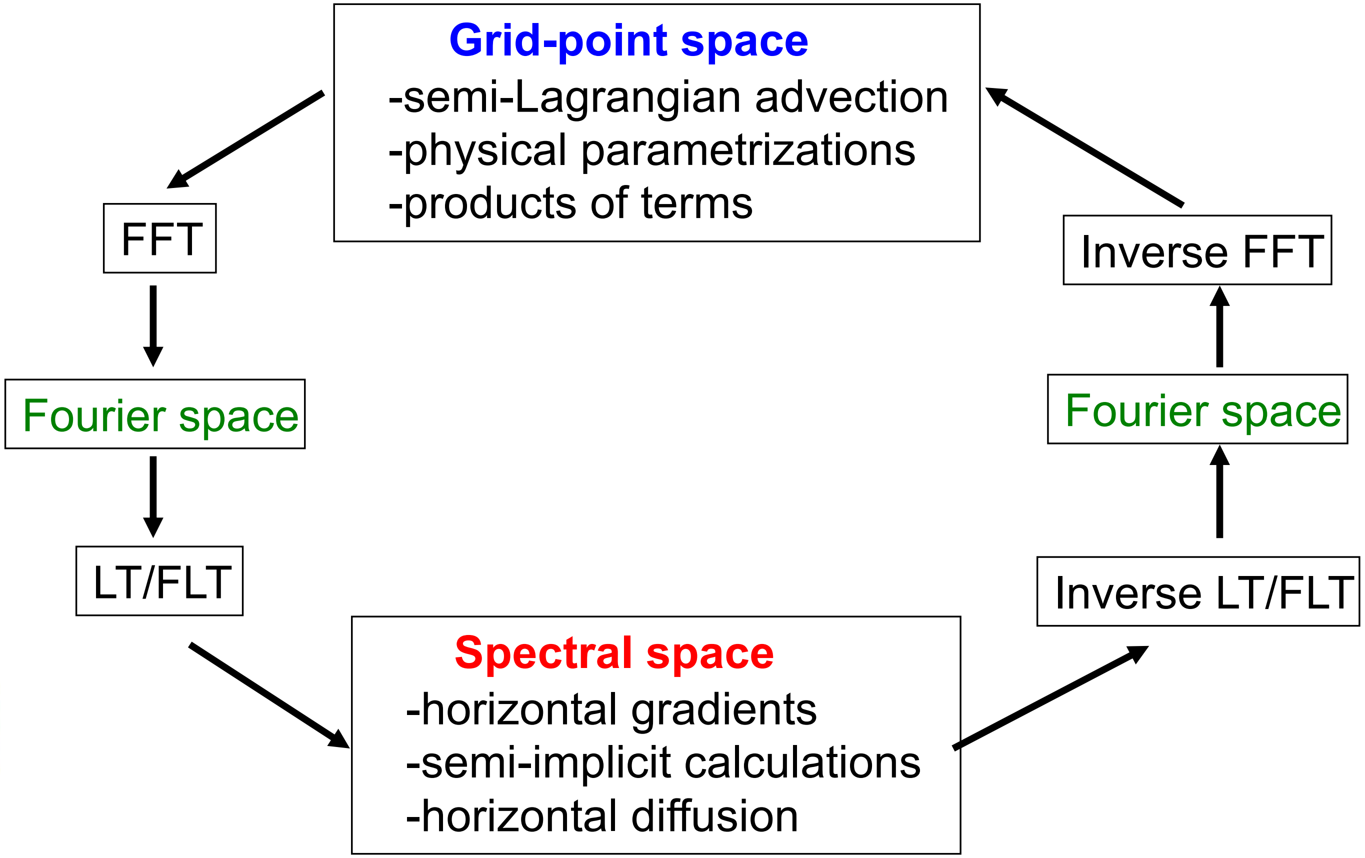


See also Annual Seminar 2020, ECMWF
https://www.ecmwf.int/en/learning/workshops/annual-seminar-2020

Slide from Nils Wedi

Spectral discretisation in the Integrated Forecast System (IFS)





Grid-point space

-semi-Lagrangian advection
-physical parametrizations
-products of terms

FFT

Fourier space

LT/FLT

Spectral space

-horizontal gradients
-semi-implicit calculations
-horizontal diffusion

Inverse LT/FLT

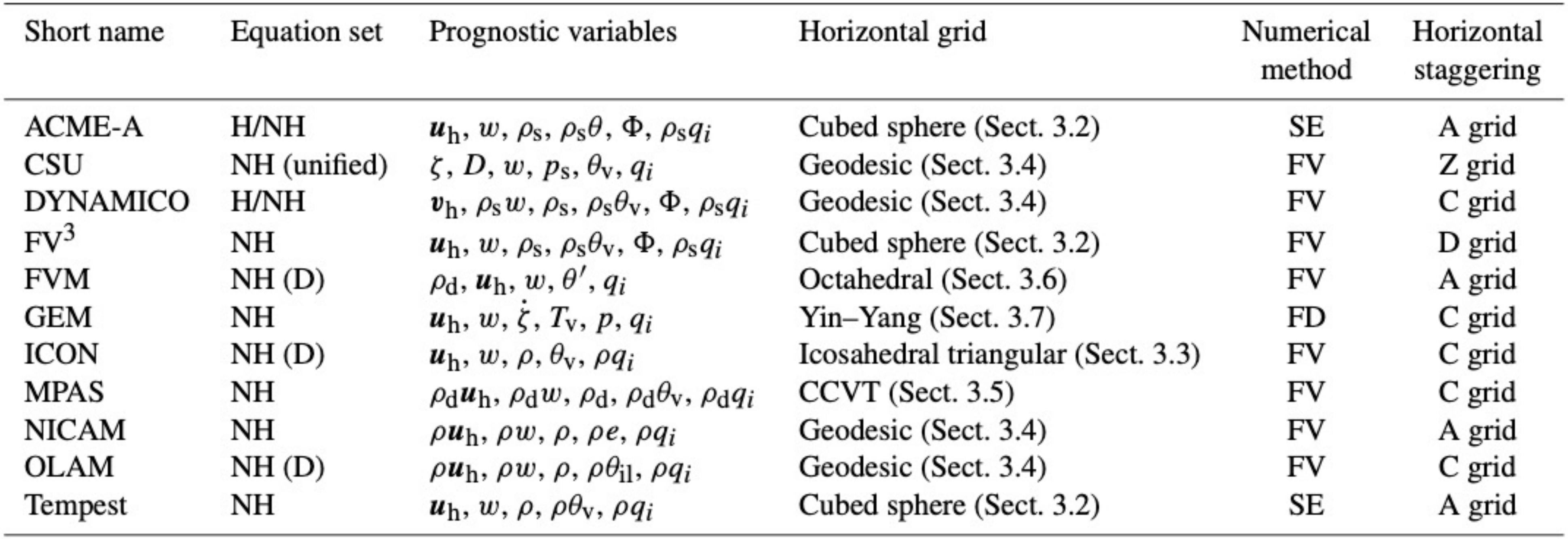
Fourier space

Inverse FFT

FFT: Fast Fourier Transform, LT/FLT: Legendre Transform

The equations of motion can also be evaluated for spherical harmonics.

There are plenty of options to discretise… and they are used



Short name	Equation set	Prognostic variables	Horizontal grid	Numerical method	Horizontal staggering
ACME-A	H/NH	$\boldsymbol{u}_\mathrm{h}$, w, ρ_s, $\rho_\mathrm{s}\theta$, Φ, $\rho_\mathrm{s} q_i$	Cubed sphere (Sect. 3.2)	SE	A grid
CSU	NH (unified)	ζ, D, w, p_s, θ_v, q_i	Geodesic (Sect. 3.4)	FV	Z grid
DYNAMICO	H/NH	$\boldsymbol{v}_\mathrm{h}$, $\rho_\mathrm{s} w$, ρ_s, $\rho_\mathrm{s}\theta_\mathrm{v}$, Φ, $\rho_\mathrm{s} q_i$	Geodesic (Sect. 3.4)	FV	C grid
FV^3	NH	$\boldsymbol{u}_\mathrm{h}$, w, ρ_s, $\rho_\mathrm{s}\theta_\mathrm{v}$, Φ, $\rho_\mathrm{s} q_i$	Cubed sphere (Sect. 3.2)	FV	D grid
FVM	NH (D)	ρ_d, $\boldsymbol{u}_\mathrm{h}$, w, θ', q_i	Octahedral (Sect. 3.6)	FV	A grid
GEM	NH	$\boldsymbol{u}_\mathrm{h}$, w, $\dot{\zeta}$, T_v, p, q_i	Yin–Yang (Sect. 3.7)	FD	C grid
ICON	NH (D)	$\boldsymbol{u}_\mathrm{h}$, w, ρ, θ_v, ρq_i	Icosahedral triangular (Sect. 3.3)	FV	C grid
MPAS	NH	$\rho_\mathrm{d}\boldsymbol{u}_\mathrm{h}$, $\rho_\mathrm{d} w$, ρ_d, $\rho_\mathrm{d}\theta_\mathrm{v}$, $\rho_\mathrm{d} q_i$	CCVT (Sect. 3.5)	FV	C grid
NICAM	NH	$\rho\boldsymbol{u}_\mathrm{h}$, ρw, ρ, ρe, ρq_i	Geodesic (Sect. 3.4)	FV	A grid
OLAM	NH (D)	$\rho\boldsymbol{u}_\mathrm{h}$, ρw, ρ, $\rho\theta_\mathrm{il}$, ρq_i	Geodesic (Sect. 3.4)	FV	C grid
Tempest	NH	$\boldsymbol{u}_\mathrm{h}$, w, ρ, $\rho\theta_\mathrm{v}$, ρq_i	Cubed sphere (Sect. 3.2)	SE	A grid

DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models, Ullrich et al 2016

IFS dynamical core options at ECMWF

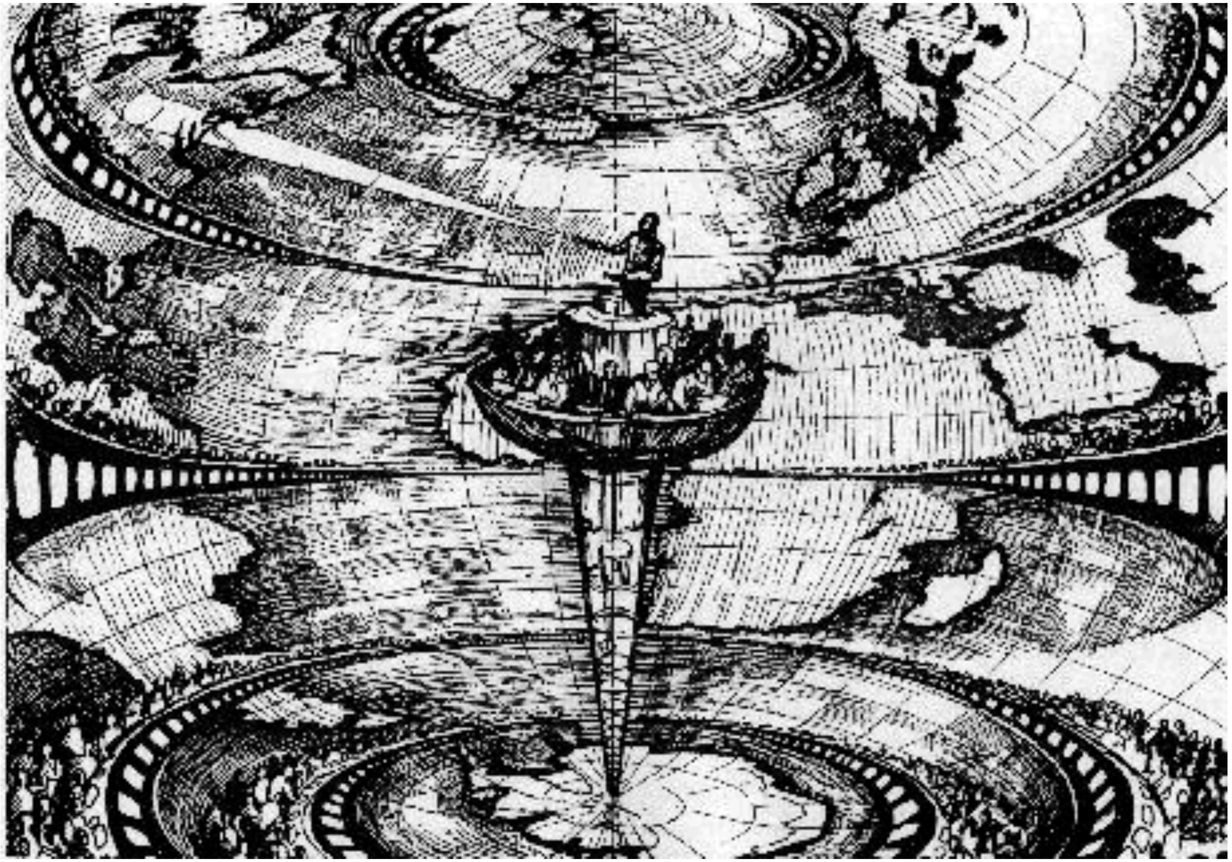
Christian Kuehnlein

| currently operational |

Model aspect	IFS-FVM	IFS-ST	IFS-ST (NH option)
Equation system	fully compressible	hydrostatic primitive	fully compressible
Prognostic variables	$\rho_\mathrm{d}, u, v, w, \theta', \varphi', r_\mathrm{v}, r_\mathrm{l}, r_\mathrm{r}, r_\mathrm{i}, r_\mathrm{s}$	$\ln p_\mathrm{s}, u, v, T_\mathrm{v}, q_\mathrm{v}, q_\mathrm{l}, q_\mathrm{r}, q_\mathrm{i}, q_\mathrm{s}$	$\ln \pi_\mathrm{s}, u, v, d_4, T_\mathrm{v}, \hat{q}, q_\mathrm{v}, q_\mathrm{l}, q_\mathrm{r}, q_\mathrm{i}, q_\mathrm{s}$
Horizontal coordinates	λ, ϕ (lon–lat)	λ, ϕ (lon–lat)	λ, ϕ (lon–lat)
Vertical coordinate	generalized height	hybrid sigma–pressure	hybrid sigma–pressure
Horizontal discretization	unstructured finite volume (FV)	spectral transform (ST)	spectral transform (ST)
Vertical discretization	structured FD–FV	structured FE	structured FD or FE
Horizontal staggering	co-located	co-located	co-located
Vertical staggering	co-located	co-located	co-located, Lorenz
Horizontal grid	octahedral Gaussian or arbitrary	octahedral Gaussian	octahedral Gaussian
Time stepping scheme	2-TL SI	2-TL constant-coefficient SI	2-TL constant-coefficient SI with ICI
Advection	conservative FV Eulerian	non-conservative SL	non-conservative SL

Slide from Nils Wedi

Richardson’s forecast factory, 1922



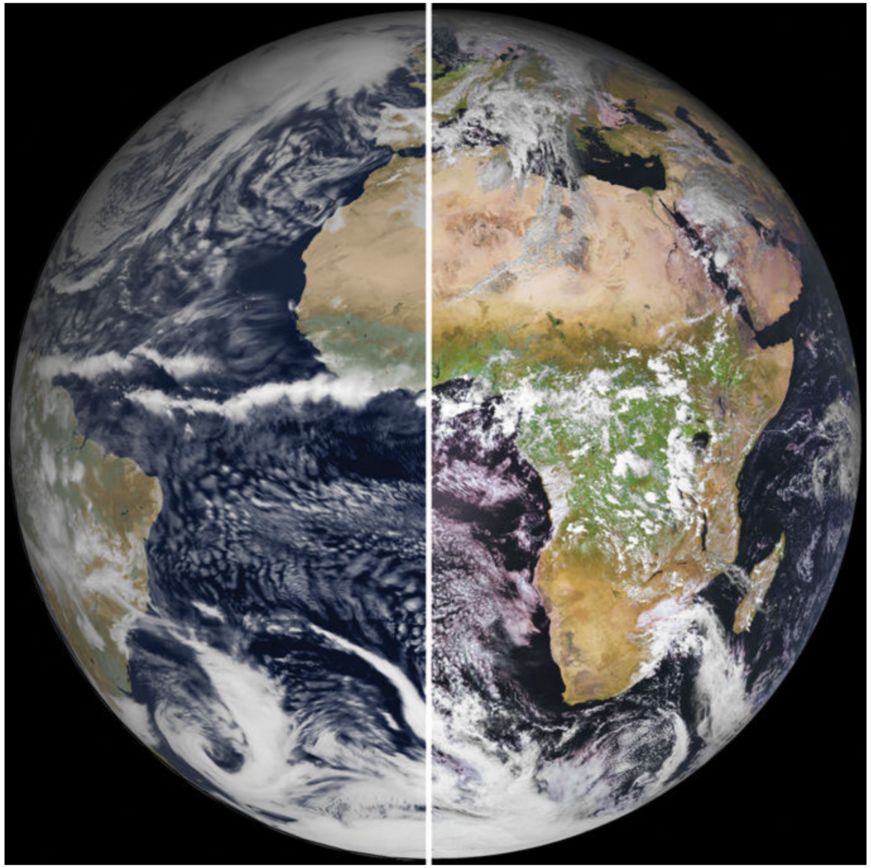
Sketch by A. Lannerback (© Dagens Nyheter, Stockholm)
Found at http://mathsci.ucd.ie

So let’s just discretise the equations and all problems are solved…?

Slide from Nils Wedi

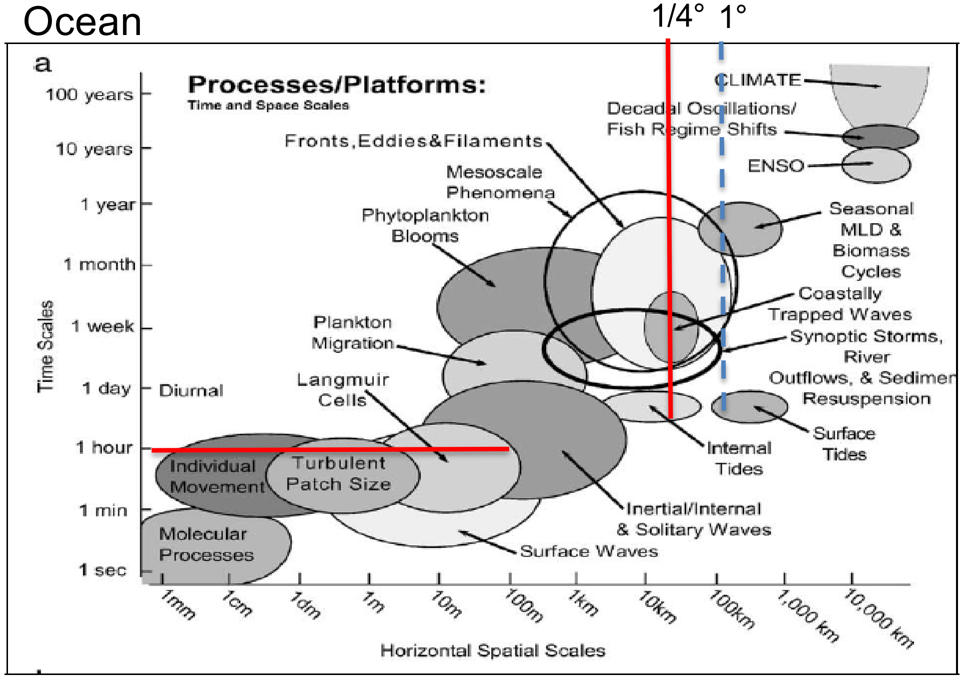
Why is it difficult to predict the weather?

- The Earth is huge, resolution is limited and we cannot represent all important processes within model simulations
- We do not know the exact initial conditions
- The Earth System shows “chaotic” dynamics which makes it difficult to predict the future based on equations
- All Earth System components (atmosphere, ocean, land surface, cloud physics,…) are connected in a non-trivial way
- Some of the processes involved are not well understood



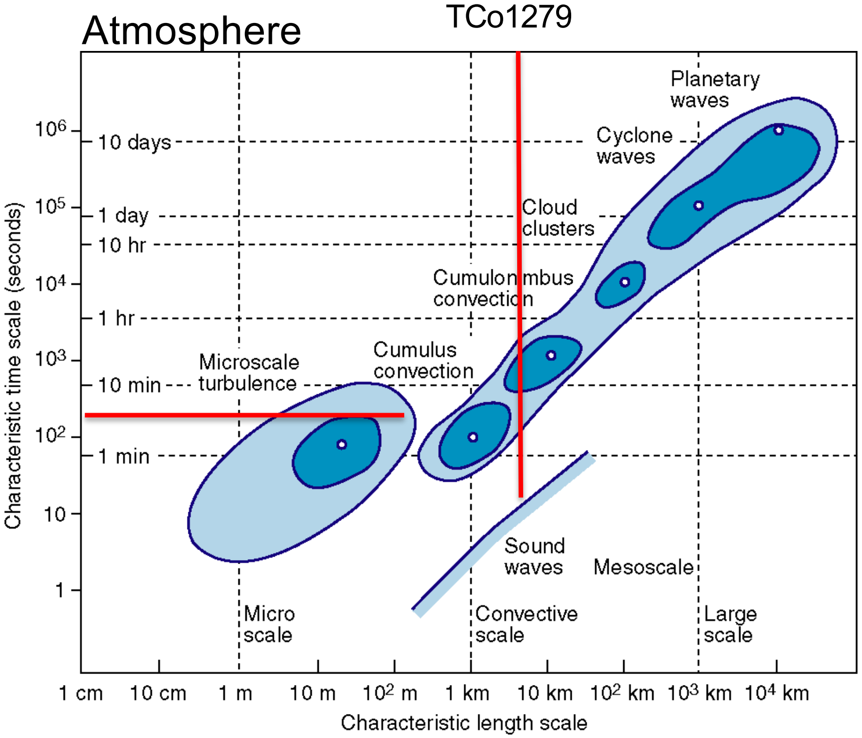
The Earth system as a multi-scale problem

Ocean



From Dickey (2003)

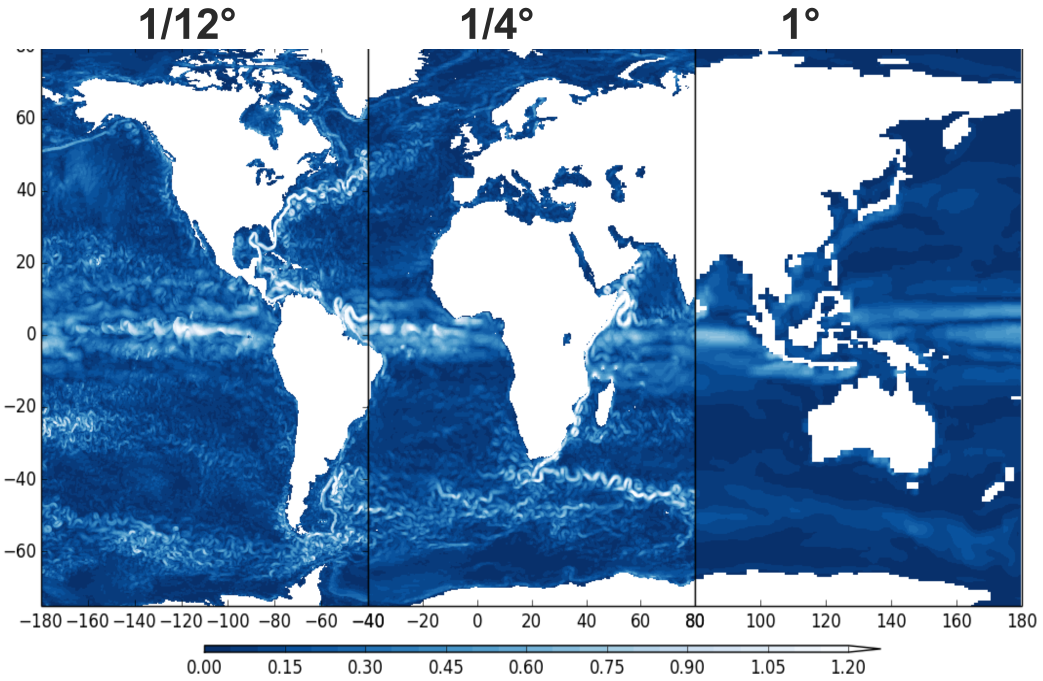
Atmosphere



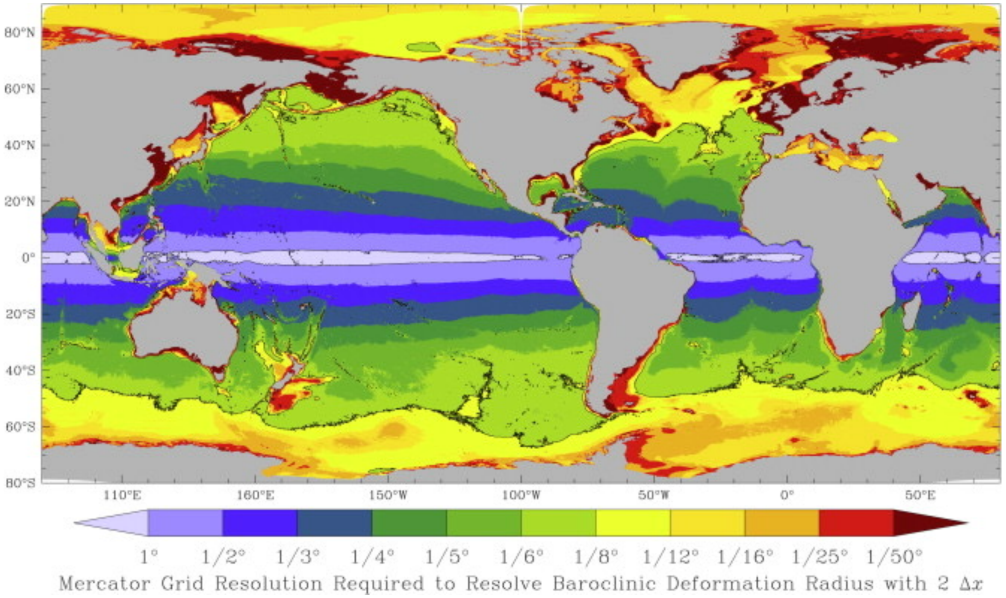
Range of fast and slow waves …

Slide from Nils Wedi

Ocean model - resolution



Hewitt et al. (2017)



Hallberg (2013)

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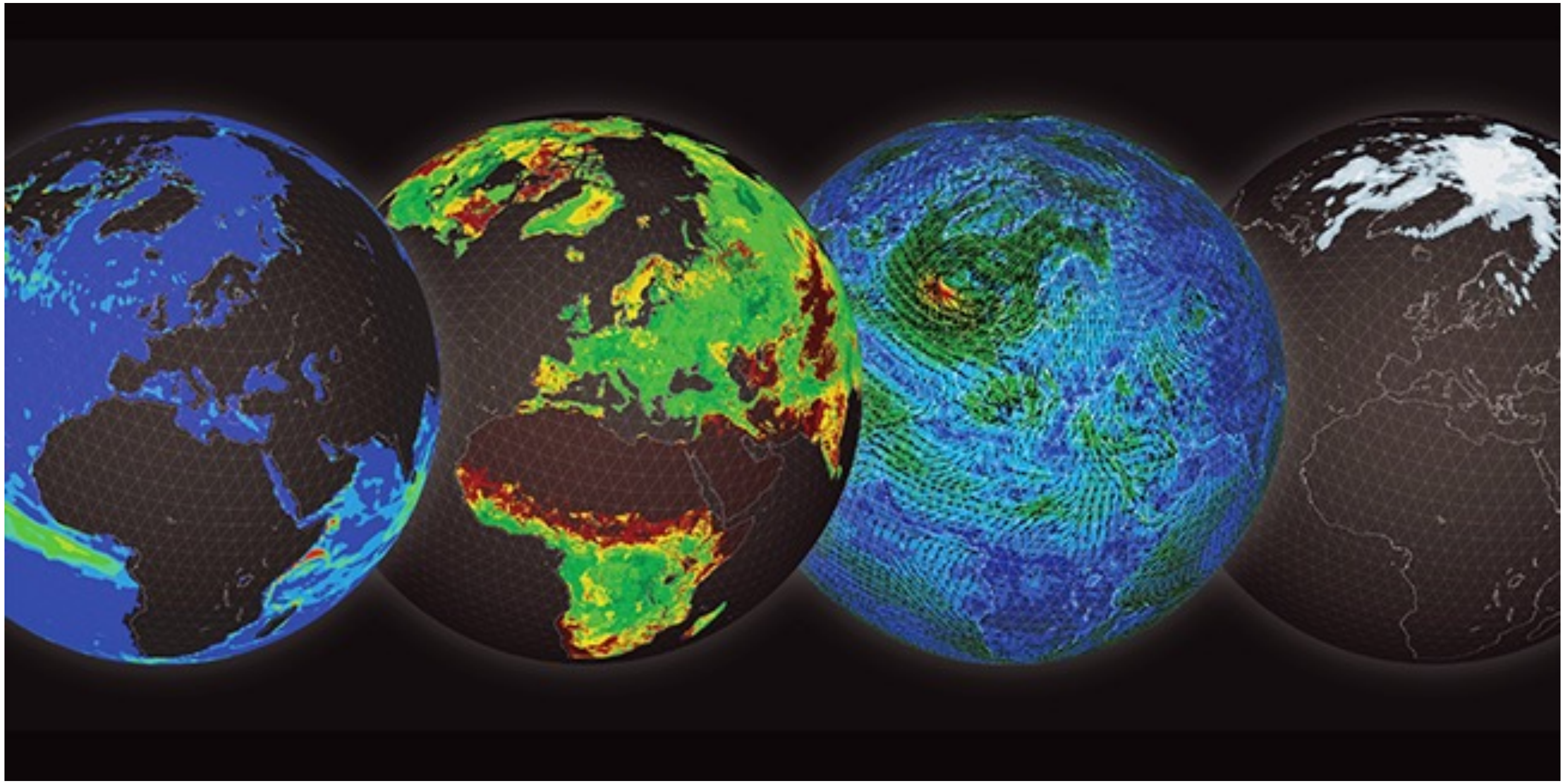
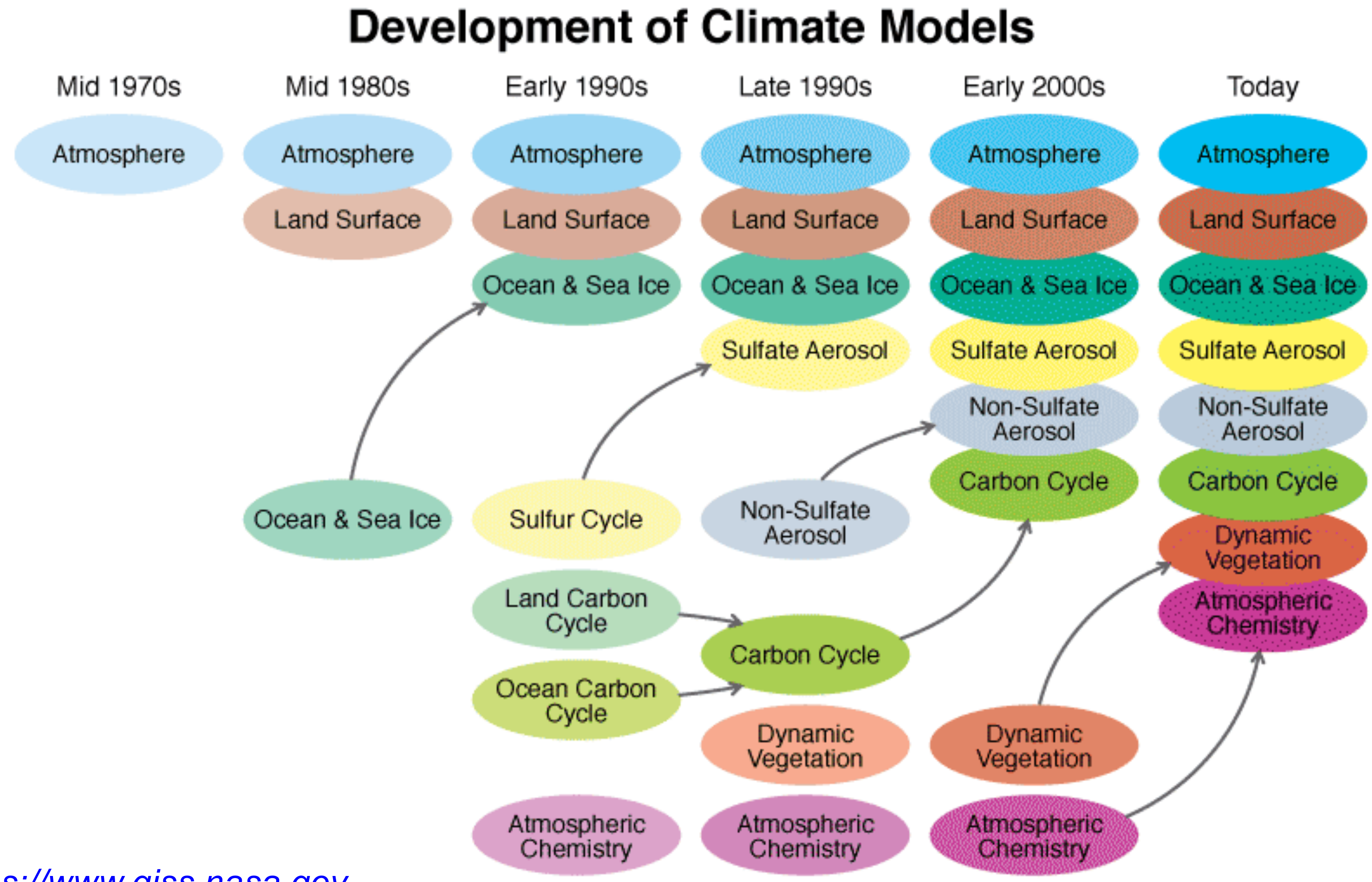
Ocean – Land – Atmosphere – Sea ice



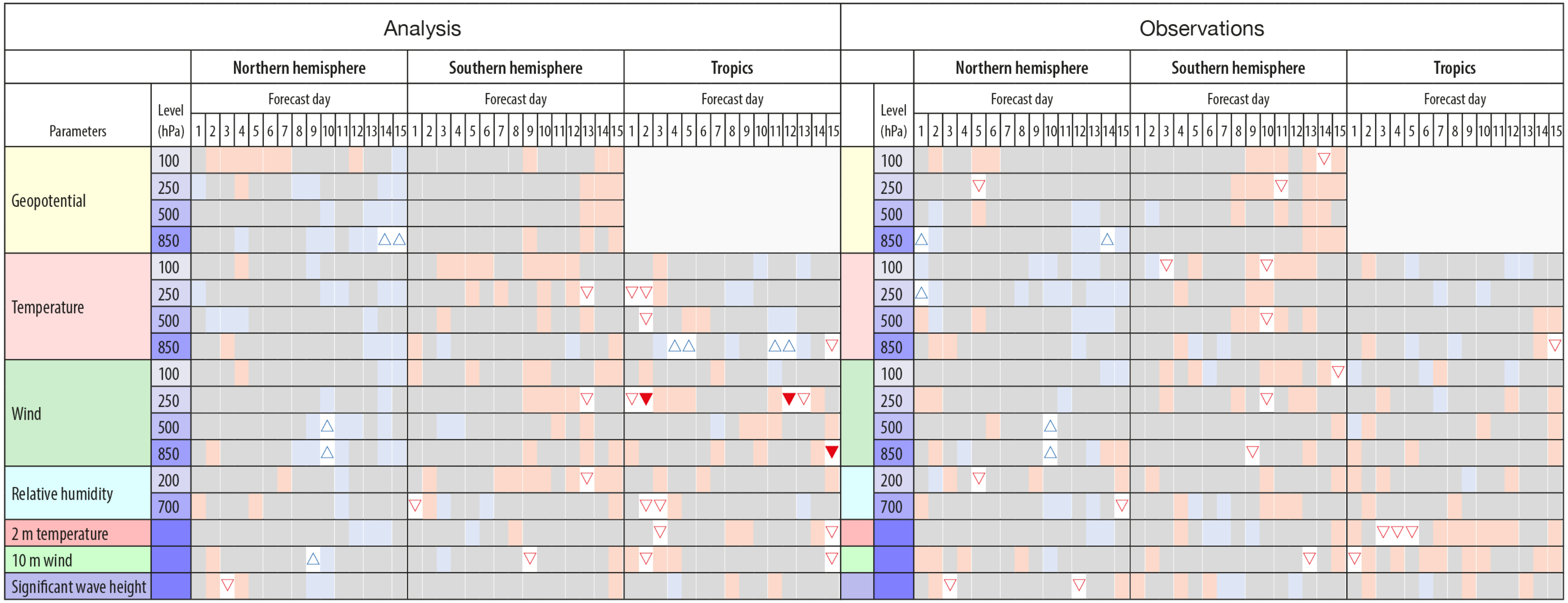
Slide from Nils Wedi

Earth System model complexity



Source: *https://www.giss.nasa.gov*

The Earth system as a coupled system



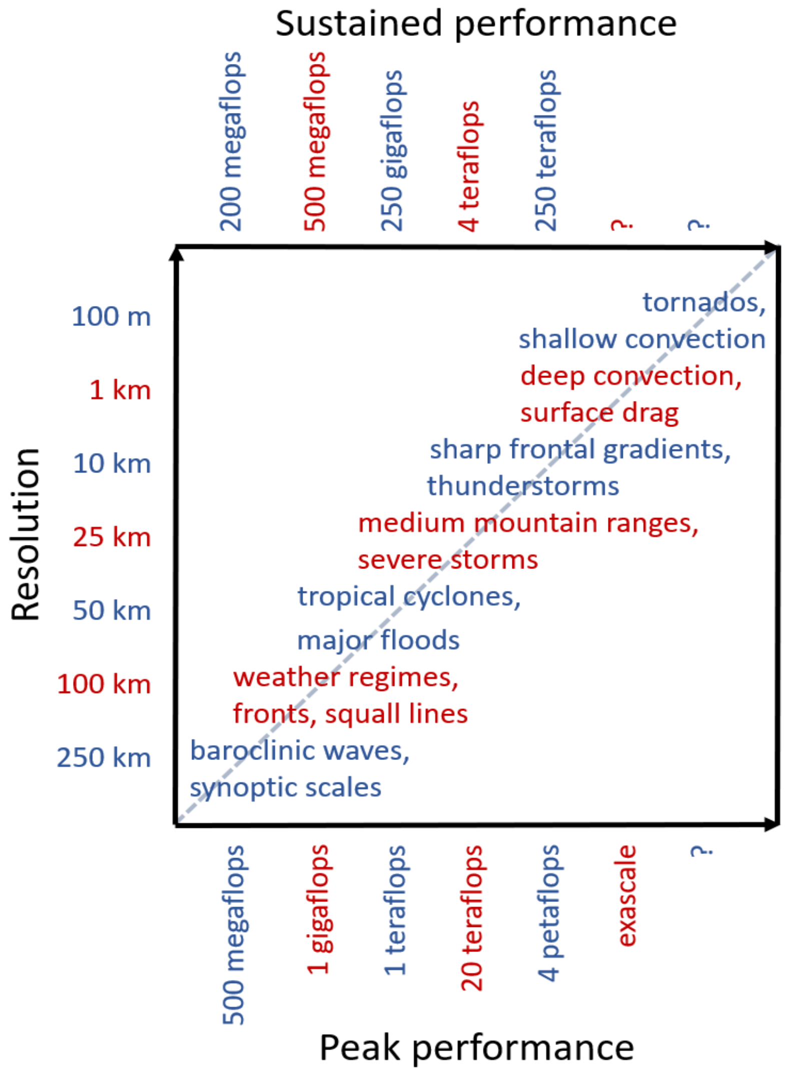
Symbol legend: for a given forecast step...

- ▲ SP better than DP statistically significant with 99.7% confidence
- △ SP better than DP statistically significant with 95% confidence
- 🟦 SP better than DP statistically significant with 68% confidence
- ⬜ no significant difference between DP and SP
- 🟧 SP worse than DP statistically significant with 68% confidence
- ▽ SP worse than DP statistically significant with 95% confidence
- ▼ SP worse than DP statistically significant with 99.7% confidence

Dueben et al. ECMWF Newsletter 2018

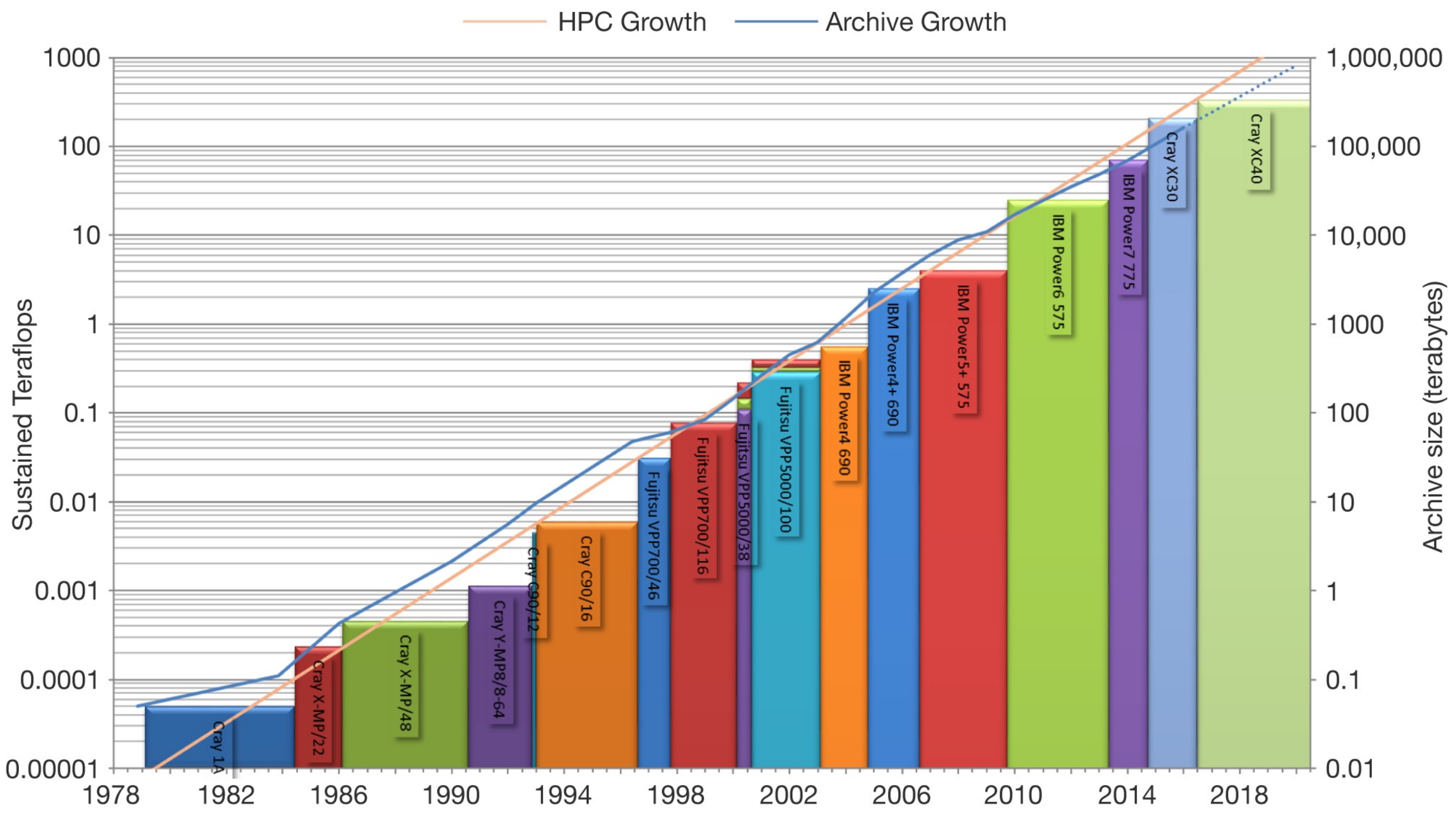
Beyond the grid…

- Not all processes can be discretised on a given grid
- Sub-grid-scale processes need to be parametrised including very important processes of the Earth system such as clouds, boundary layer turbulence, gravity wave drag, ocean eddies, land/snow/ice processes…



Adjusted from Neumann et al. Phil. Trans. A 2019

HPC and HPDA for weather and climate modelling



Bauer et al. ECMWF SAC paper 2019

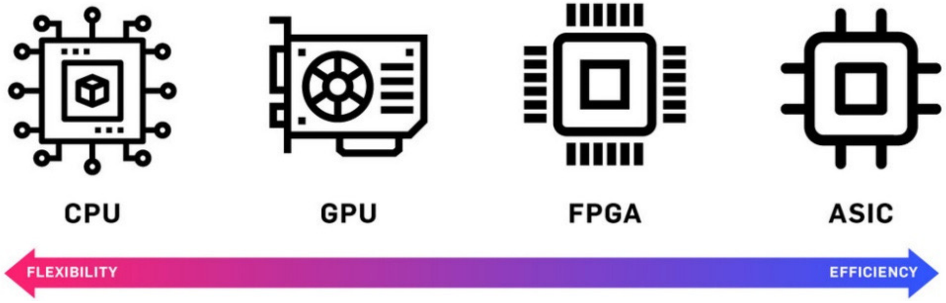
Current challenges in high performance computing?

- Individual processors will not be faster
  → Parallelisation / power consumption / hardware faults

- Hardware will be more heterogeneous
  → CPUs / GPUs / FPGAs / ASICs

- Machine learning has strong impact on hardware development
  → High floprate at low precision

- I/O is becoming a nightmare and the optimisation of data movement will be the key



Source: venturebeat.com

Energy-aware computing

- All 51 ENS members consume about 300KWh, approximately the same as a single (~5km) global 10-day forecast
- The energy consumption of *one ENS member* is equivalent to leaving the Kettle on for 2 hours !

http://ukbusinessblog.co.uk

Time-to-Solution vs.
Energy-to-Solution

Slide from Nils Wedi

Destination Earth at the horizon...

comment

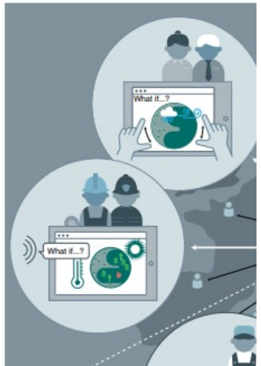
A digital twin of Earth for the green transition

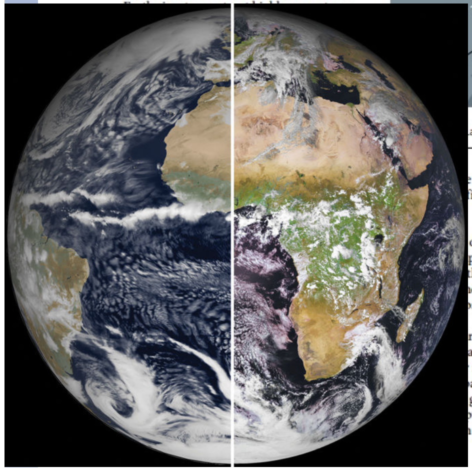
For its green transition, the EU plans to fund the development of digital twins of Earth. For these twins to be more than big data atlases, they must create a qualitatively new Earth system simulation and observation capability using a methodological framework responsible for exceptional advances in numerical weather prediction.

Peter Bauer, Bjorn Stevens and Wilco Hazeleger

The European Union (EU) intends to become climate neutral by 2050, and the set of policies designed to bring about this green transition — the European Green Deal — was announced in December 2019 (ref. [1]). Accompanied by €1 trillion of planned investment, Green Deal policies aim to help the world's second-largest economy sustainably produce energy, develop carbon-neutral fuels and advance circular products in energy-intensive industrial sectors with zero waste and zero pollution.

A key element of the Green Deal is its dependence on the 'digital transformation' — an openly accessible and interoperable European dataspace as a central hub for informed decision making. The EU identified two landmark actions to support the necessary information systems: GreenData4All[2] and Destination Earth[3]. Whereas GreenData4All will develop the European approach to discover, manage and exploit geospatial information, Destination





ayerace / Freepik

coordinated development
fic disciplines.

of Earth is an information
poses users to a digital
the state and temporal
e Earth system constrained
servations and the laws of

re familiar with a plethora of
ased monitoring tools that
impact on the environment,
ased simulation models
grasp the causes of change
tions for future adaptation
actions. The ongoing step

PERSPECTIVE
https://doi.org/10.1038/s43588-021-00023-0

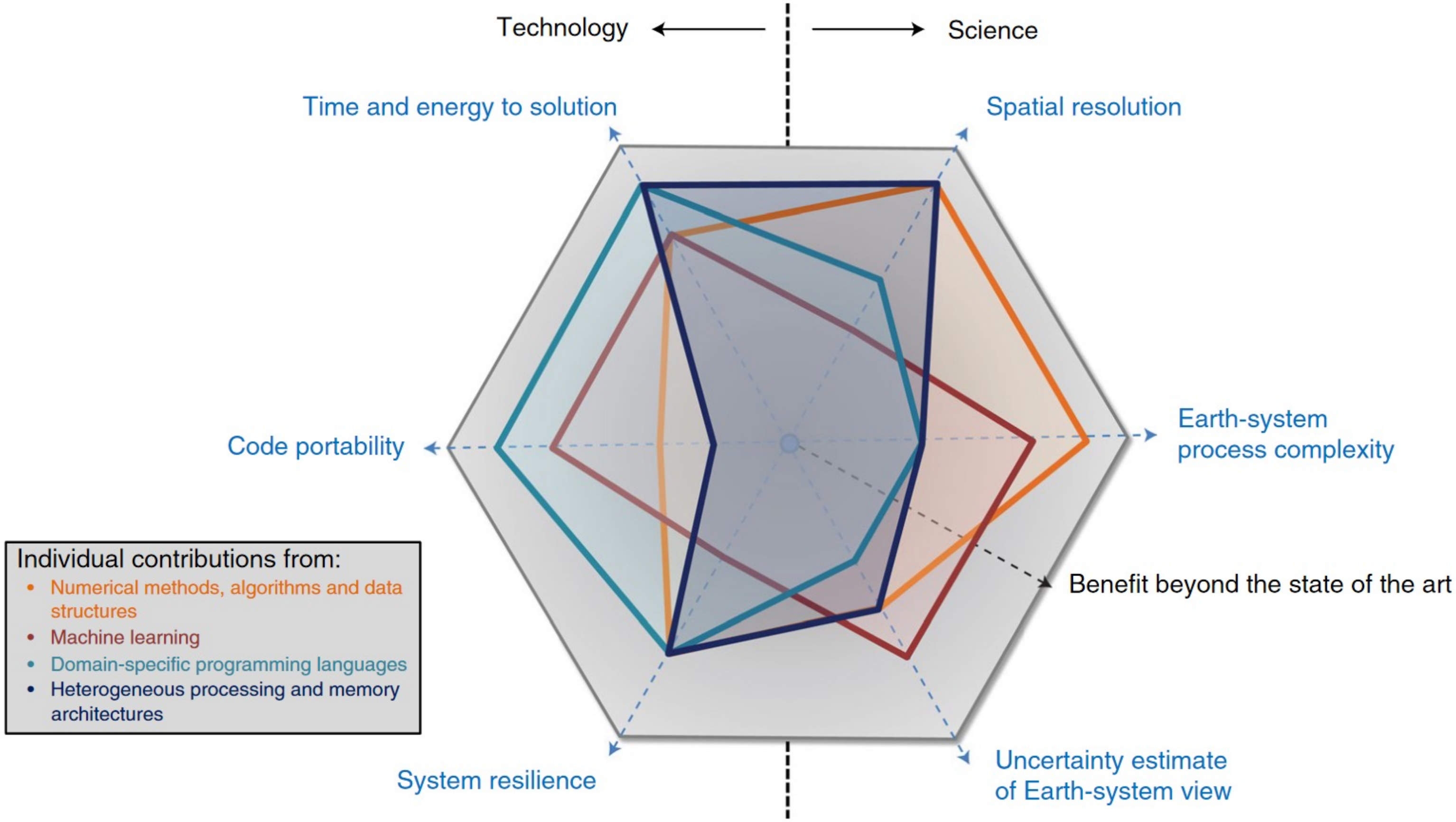
nature computational science

Check for updates

The digital revolution of Earth-system science

Peter Bauer[1], Peter D. Dueben[1], Torsten Hoefler[2], Tiago Quintino[3], Thomas C. Schulthess[4] and Nils P. Wedi[1]

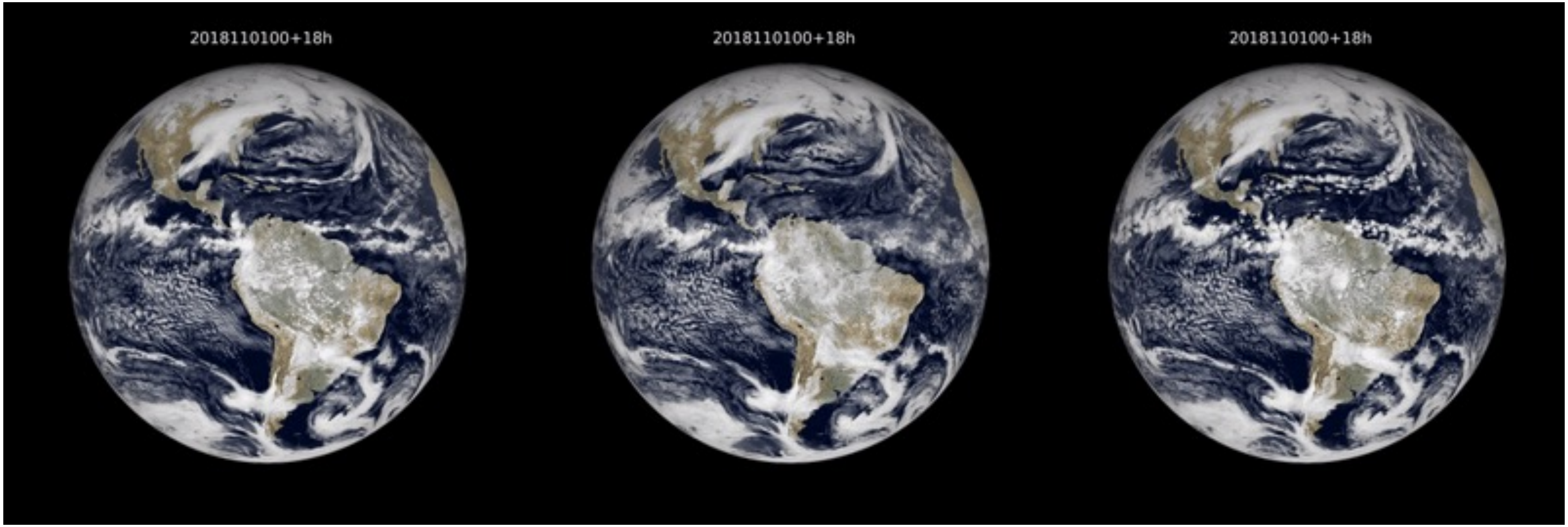
Computational science is crucial for delivering reliable weather and climate predictions. However, despite decades of high-performance computing experience, there is serious concern about the sustainability of this application in the post-Moore/Dennard era. Here, we discuss the present limitations in the field and propose the design of a novel infrastructure that is scalable and more adaptable to future, yet unknown computing architectures.



Individual contributions from:

- Numerical methods, algorithms and data structures
- Machine learning
- Domain-specific programming languages
- Heterogeneous processing and memory architectures

State-of-the-art: Global storm-resolving models

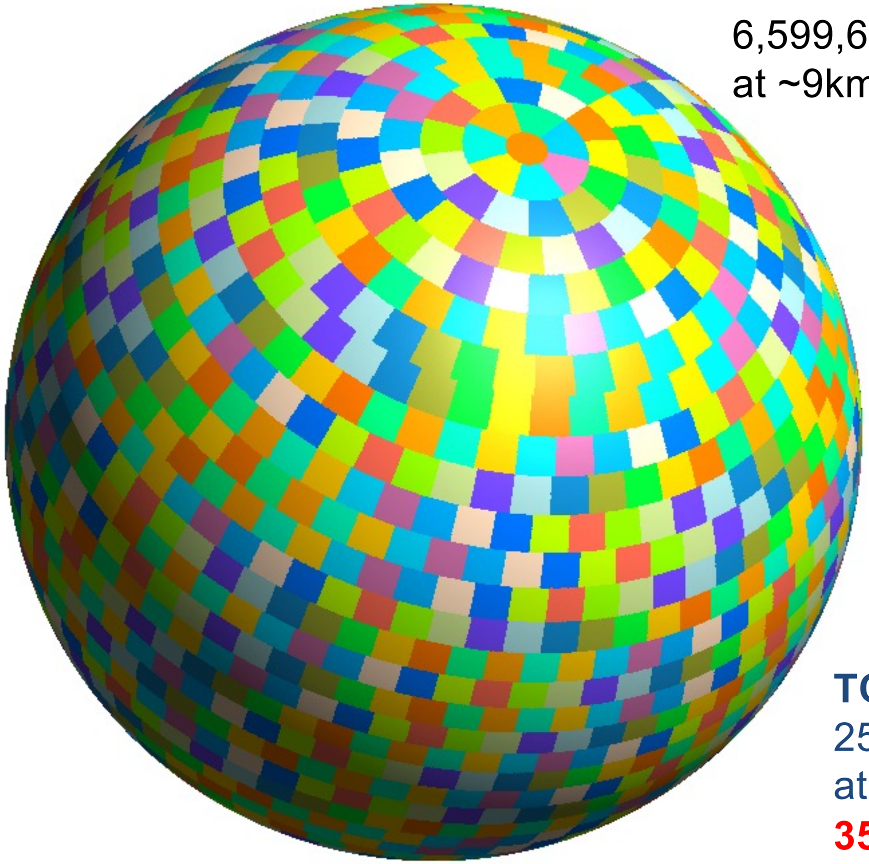


1.4 km **9 km** **9 km w/o deep**

Global weather forecast simulations have O(1,000,000,000) degrees-of-freedom, can represent many details of the Earth System, and show a breath-taking level of complexity.

Simulations can act as a virtual laboratory to understand the Earth system.

Spectral transform based model at global average 1.4 km grid spacing



6,599,680 points x 137 levels x 10 vars
at ~9km ~ **9 Billion points or ~100TB/day**

TCo7999 L137
256,800,000 points x 137 levels x 10 variables
at ~1,4km
352 billion points x 960 pp steps ==
~100TB/simulated month
Summit SIMULATION

ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

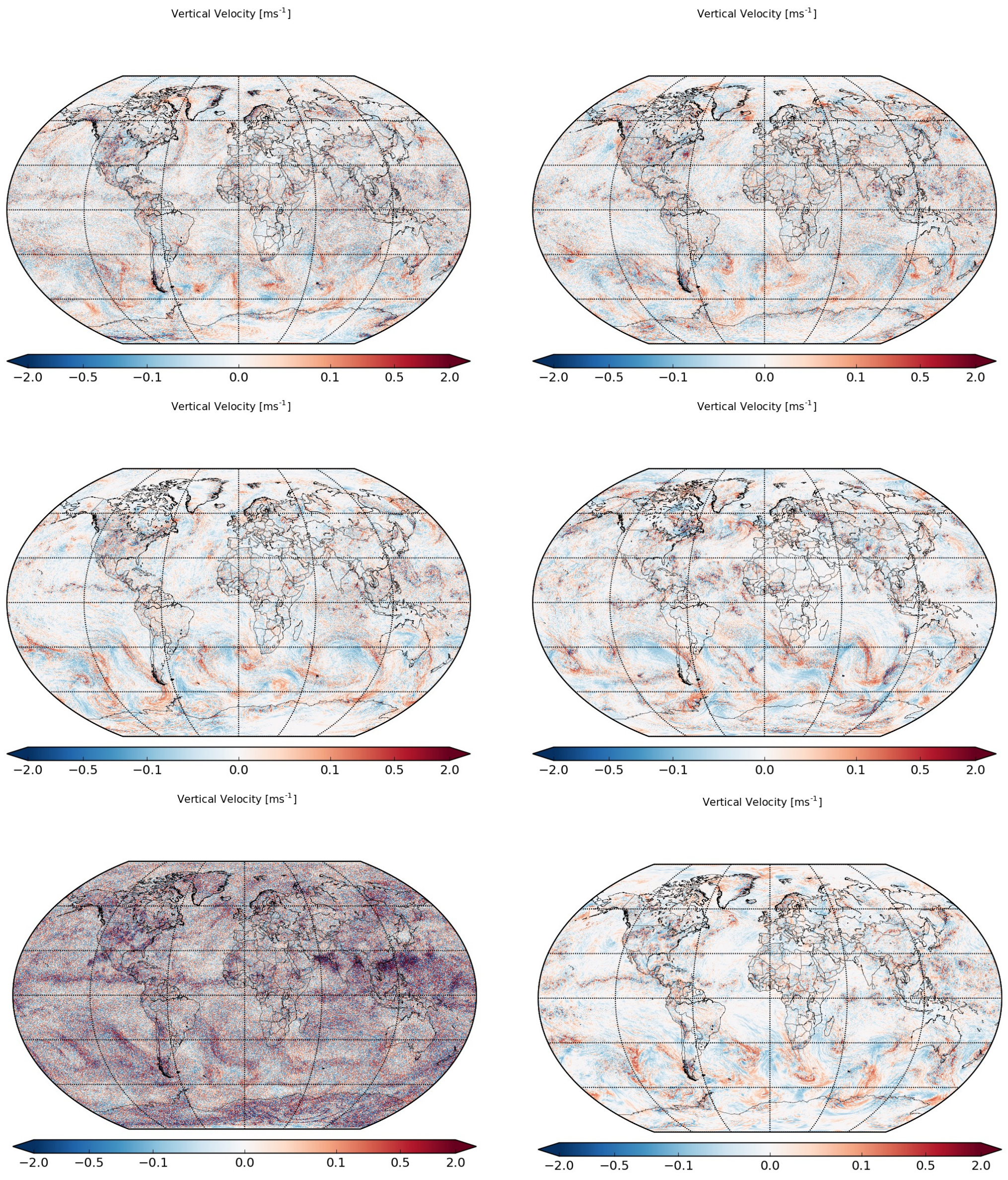
Slide from Nils Wedi

Global storm resolving models

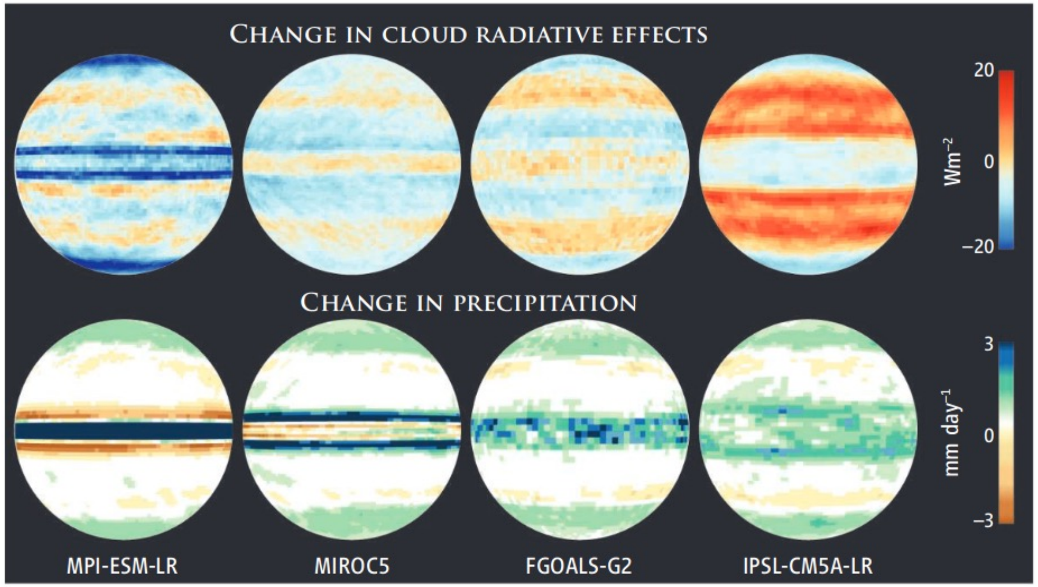
Big steps toward operational use of global storm resolving simulations

- Month-long integration of a number of models at < 5 km grid-spacing as part of DYAMOND
- Season-long integrations of the IFS model at 1.45 km grid-spacing on Summit as part of INCITE
- Year-long coupled ICON integration with 5 km grid-spacing
- 1024-member ensemble data assimilation with 3.5-km grid-spacing with NICAM
- NextGems and DestinE coming
- …

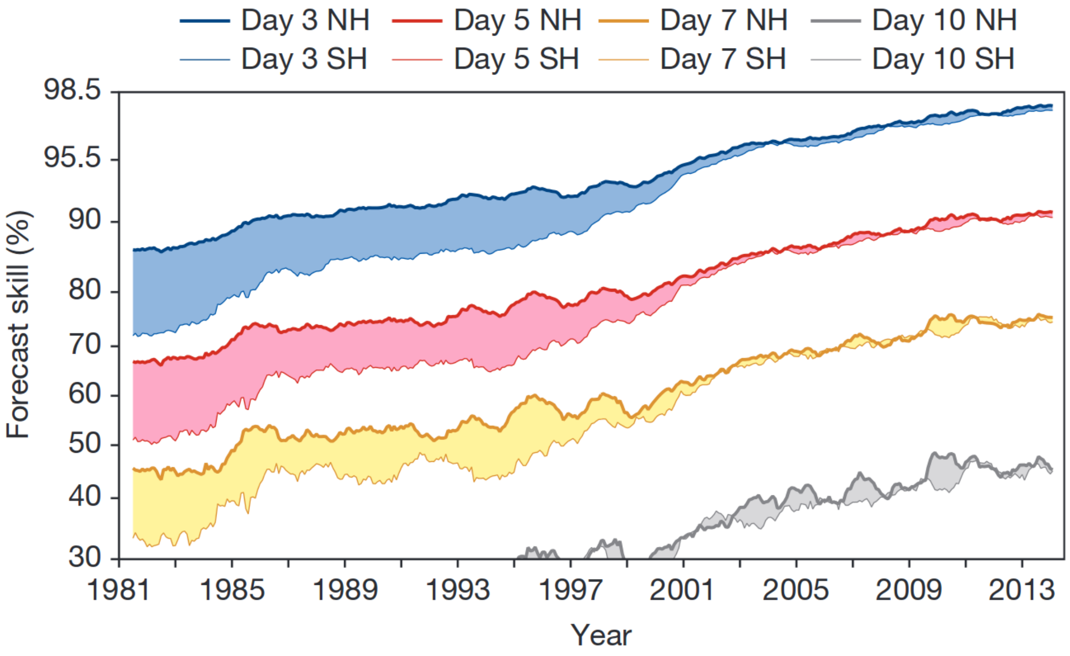
But rather a digital family than digital twins?
Figures by Roland Schrödner and Thibaut Dauhut



Are our current models up for the challenge?

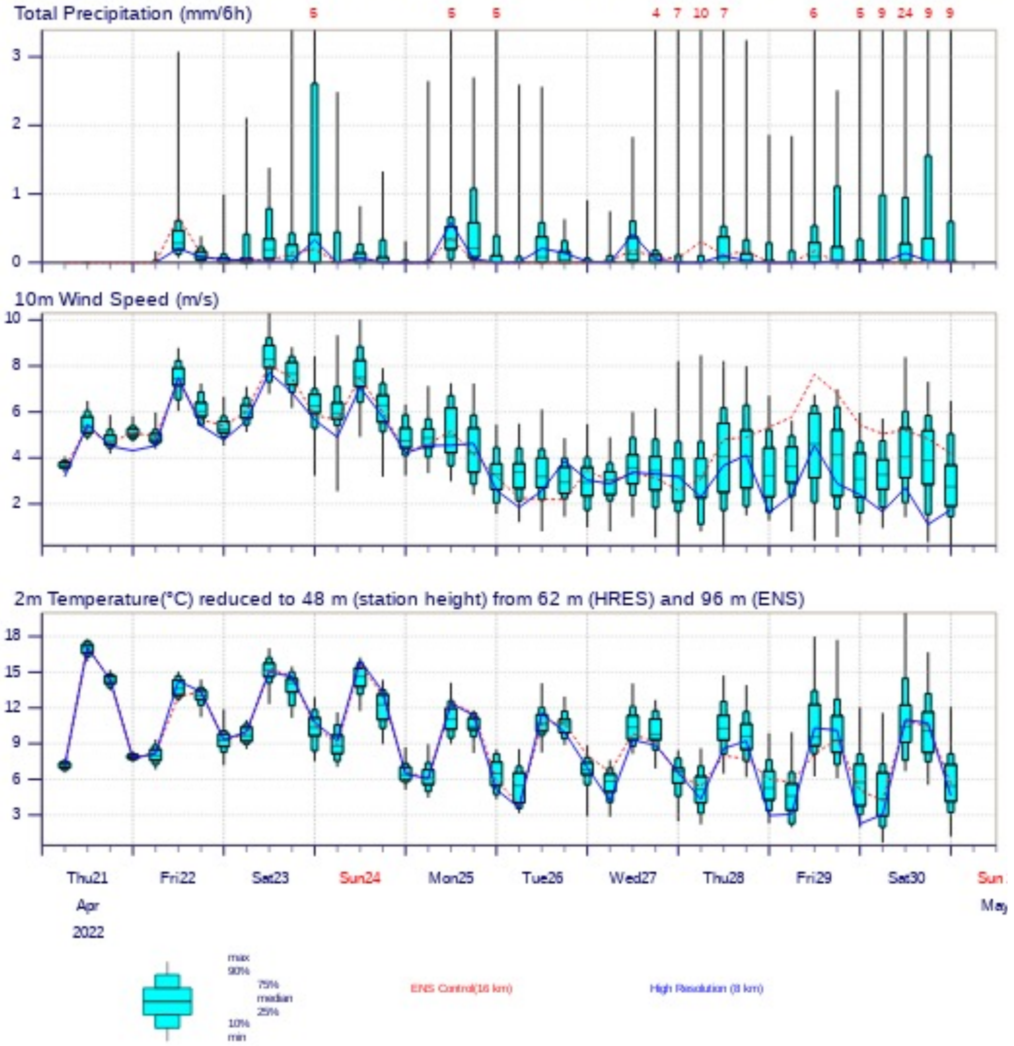


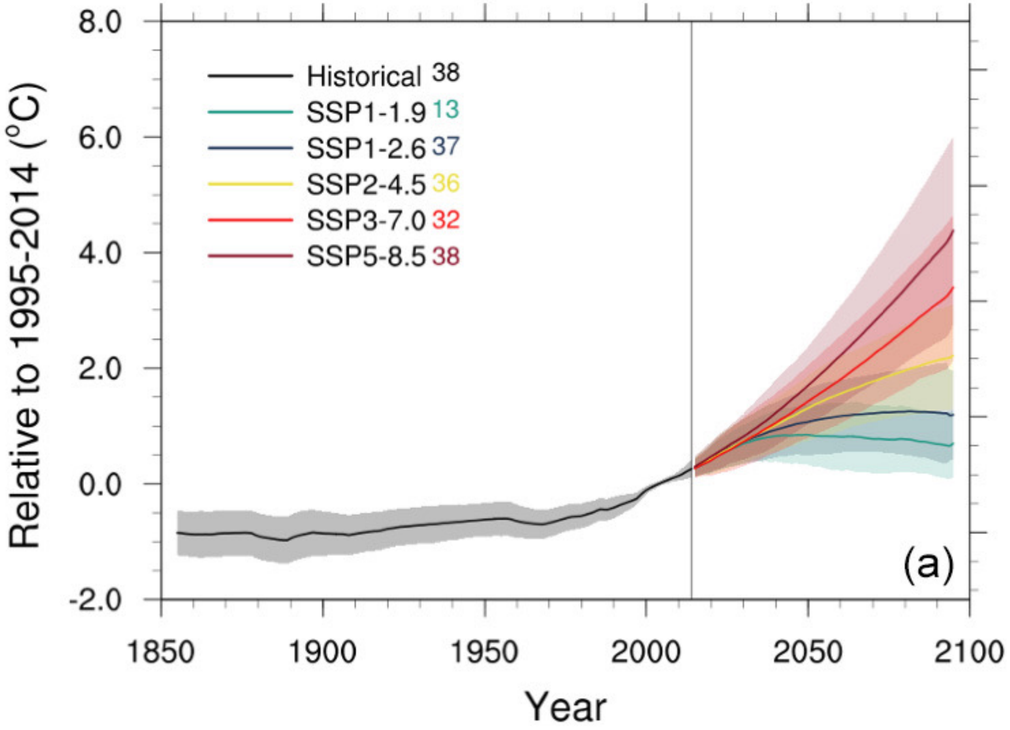
Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.



Stevens and Bony, Science, 2013.

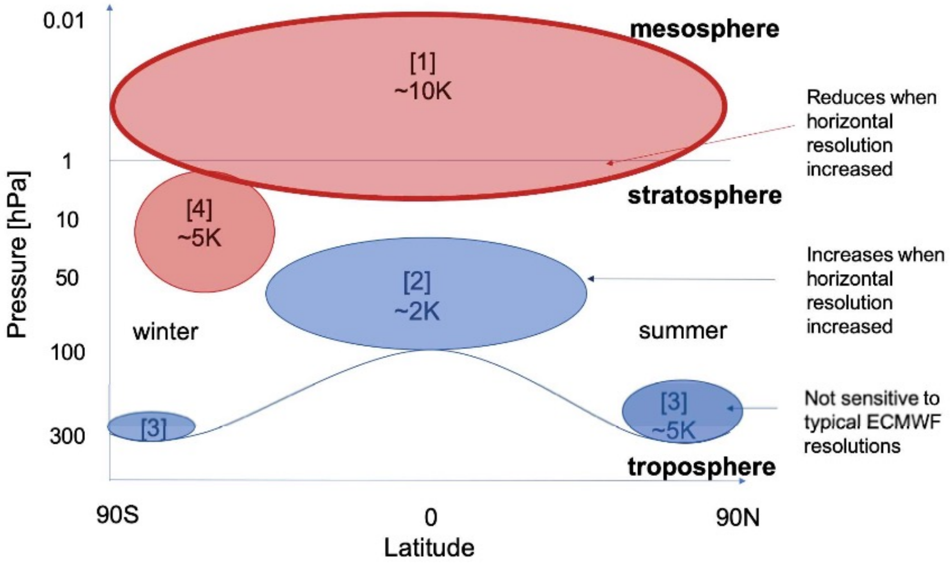
A story of uncertainties





Tebaldi et al. Earth System Dynamics 2021

Addressing stratospheric biases in IFS



Polichtchouk et al, 2021

Technical Memo

ECMWF
European Centre for Medium-Range Weather Forecasts

877

Stratospheric modelling and assimilation

I. Polichtchouk, P. Bechtold, M. Bonavita,
R. Forbes, S. Healy, R. Hogan, P. Laloyaux,
M. Rennie, T. Stockdale, N. Wedi,
N. Byrne (U. Reading), M. Diamantakis,
S. English, J. Flemming, S. Gisinger (DLR),
L. Isaksen & F. Vána

(Research & Copernicus departments)

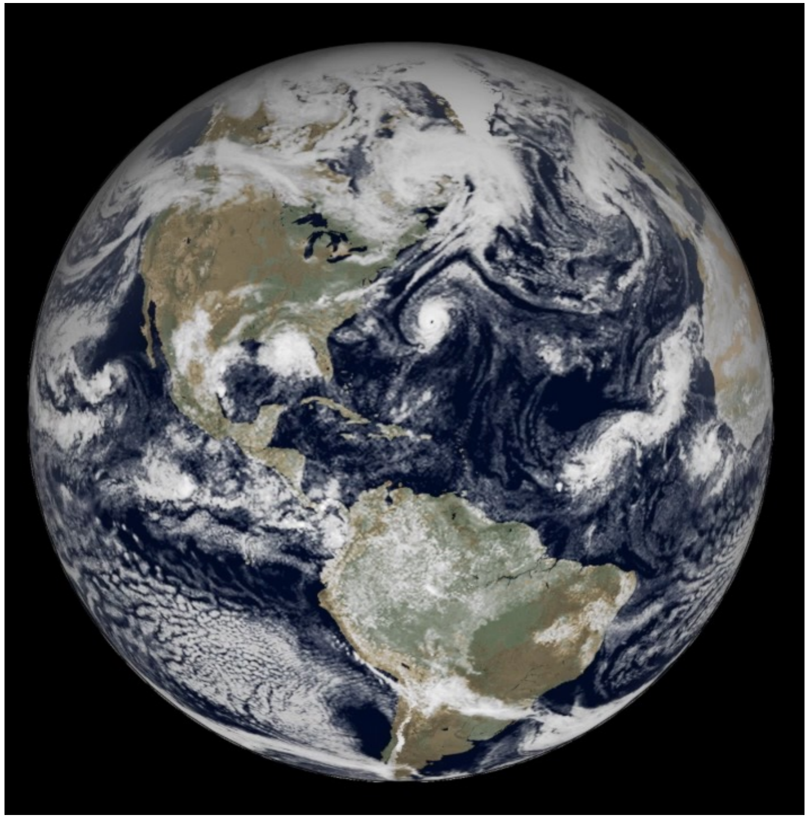
January 2021

numerics, convection and radiation, opportunities with new observations, assimilation methodology, identifying impact on the troposphere, …

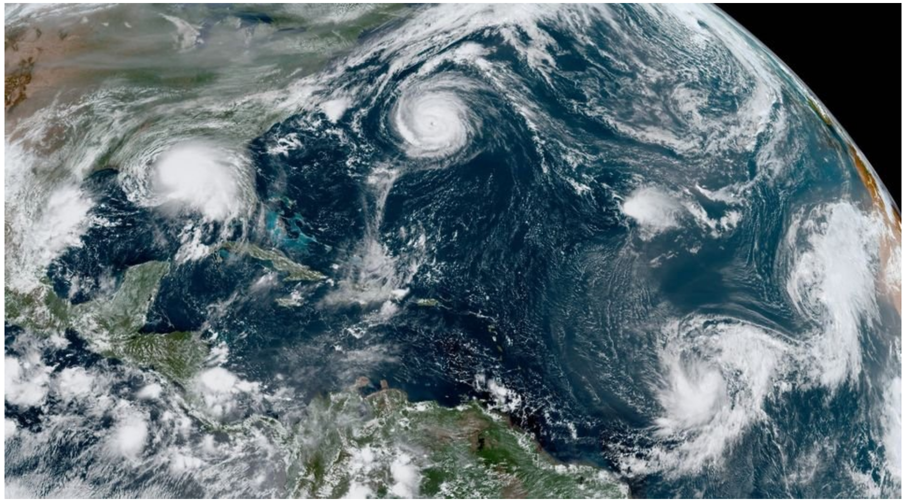
Slide from Nils Wedi

ECMWF Ensemble Forecasting

Simon Lang



TCo1279L137 51 Ensemble members 20200913 00 UTC + 41 h



NOAA

Relevant developments:

Ensemble size: How suboptimal is less than infinity?

Leutbecher, QJR, 2019

Exploring a representation of model uncertainty in the IFS due to the transport scheme

Lock et al (Annual Seminar 2020)

Revision of the SPP model uncertainty scheme in the IFS

Lang et al, QJR 2021

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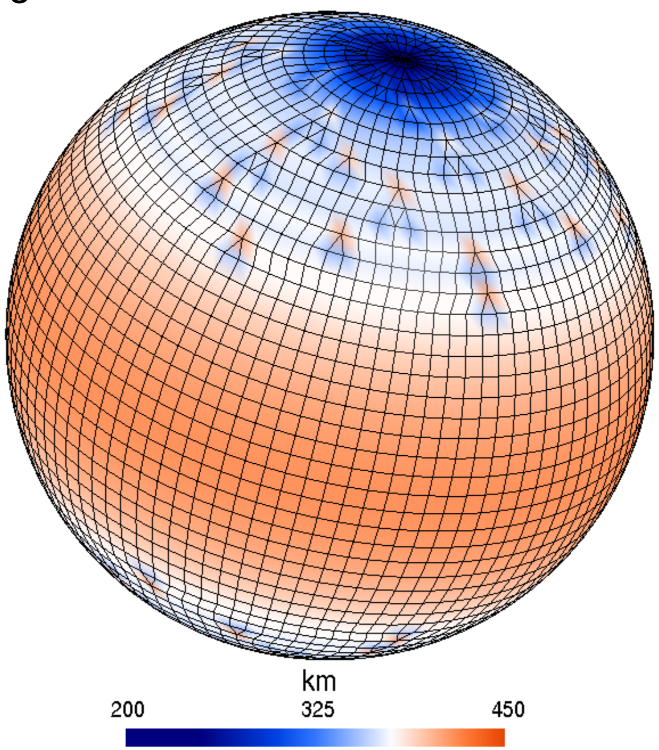
Slide from Nils Wedi

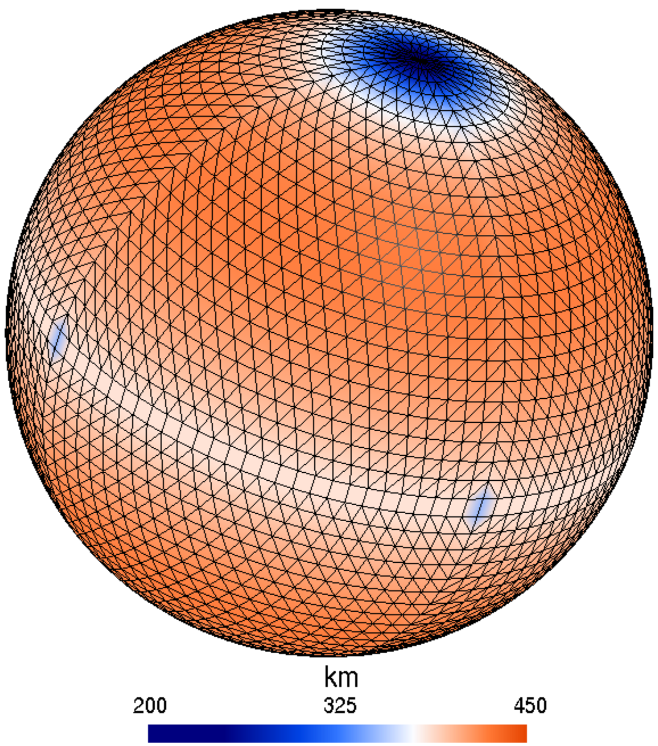
A cubic octahedral grid

What is a uniform grid ?

A further ~20% reduction in gridpoints
=> ~50% less points compared to full grid



N24 reduced Gaussian grid



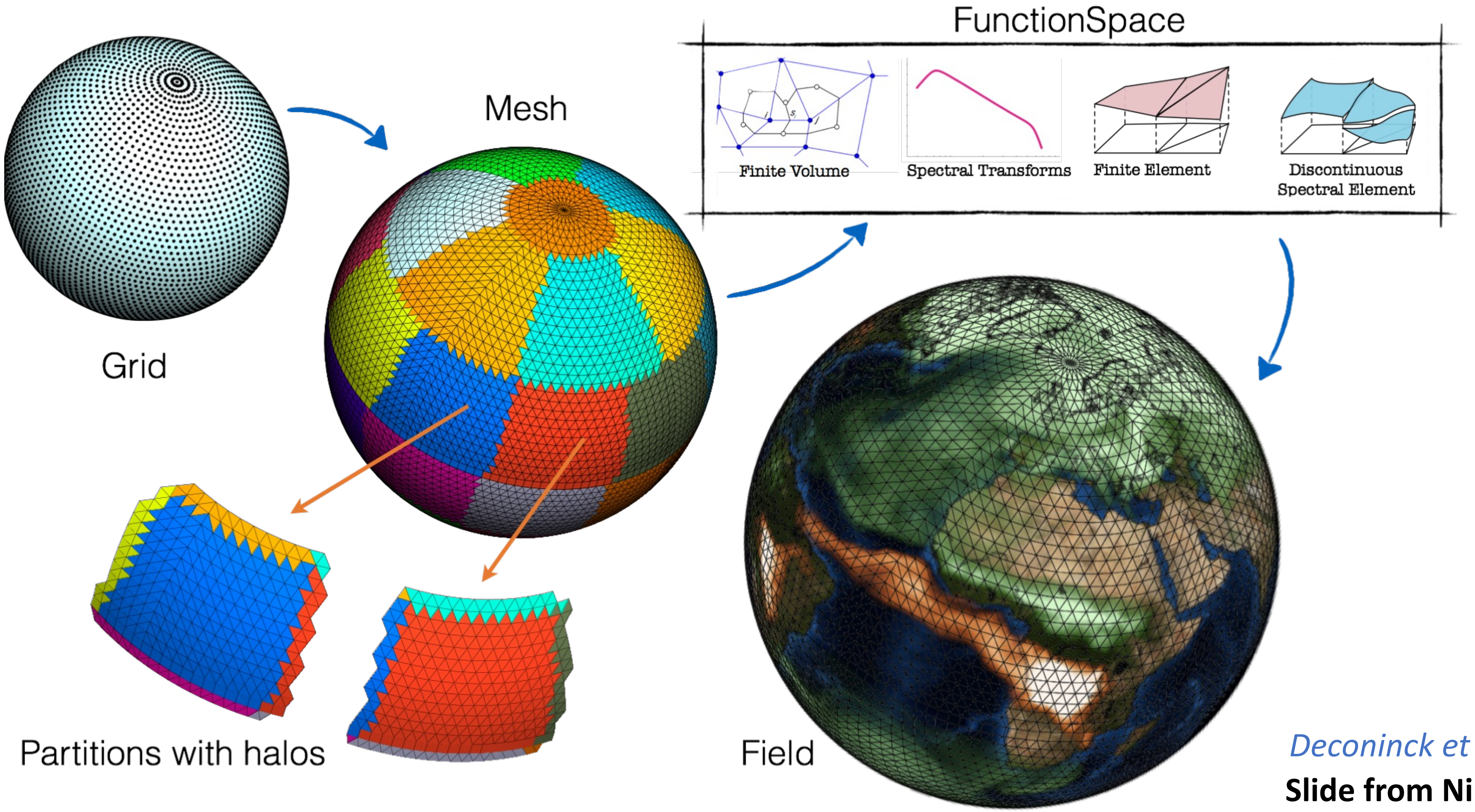
N24 octahedral Gaussian grid

(Wedi et al, 2014, 2015)

Slide from Nils Wedi

Atlas: a library for NWP and climate modelling

Funded by the
European Union



Grid

Mesh

Partitions with halos

FunctionSpace

Finite Volume

Spectral Transforms

Finite Element

Discontinuous
Spectral Element

Field

Deconinck et al. 2017

Slide from Nils Wedi

Adaptation to future HPC architectures via ESCAPE Weather and Climate Dwarfs

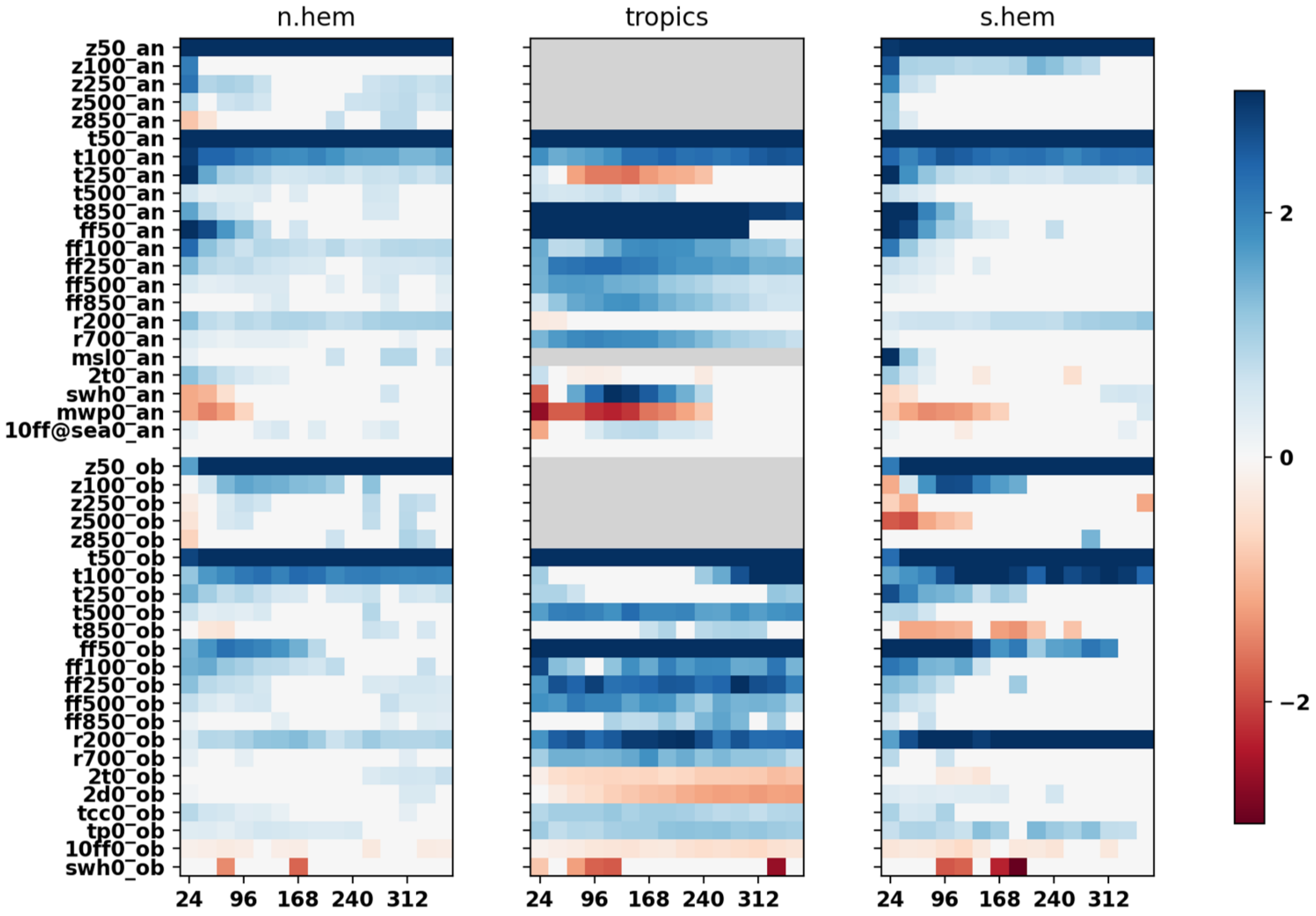
Dwarf	prototype implemented	docu-mented	based on Atlas	MPI	Open MP	Open ACC	DSL	Optalysys
D - spectral transform - SH	☑	☑	☑	☑	☑	☑		
D - spectral transform - biFFT	☑	☑		☑	☑	☑		☑
D - advection - MPDATA	☑	☑	☑	☑	☑	☑	☑	
D - advection - semi-Lagrangian	☑	☑	☑	☑	☑			
D - elliptic solver - GCR	☑	☑	☑	☑	☑		●	
P - cloud microphysics - CloudSC	☑	☑		☑	☑	☑		
P - radiation scheme - ACRANEB2	☑	🚧	🚧	☑	☑	☑		
I - LAITRI (3d interpol. algorithm)	☑	☑			☑	☑		
planned next:								
D - advection - discontinousGalerkin	●	●	●	●	●	●	●	
D - elliptic solver - multigridPrecon	●	●	●	●	●			

☑: first version running
🚧: in progress
●: planned
empty cells: not part of ESCAPE

Slide from Nils Wedi

Reduced numerical precision with single precision as first step

47R2, TCO639L137SP vs. 47R1, TCO639L91DP



Summary

- Equations → Discrete Models → Supercomputing
- Numerical models can act as a virtual laboratory for weather and climate
- Numerical models are not perfect and need to be evaluated critically with quantified uncertainties