Km-scale climate simulations

Daniel Klocke

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climate models evolution

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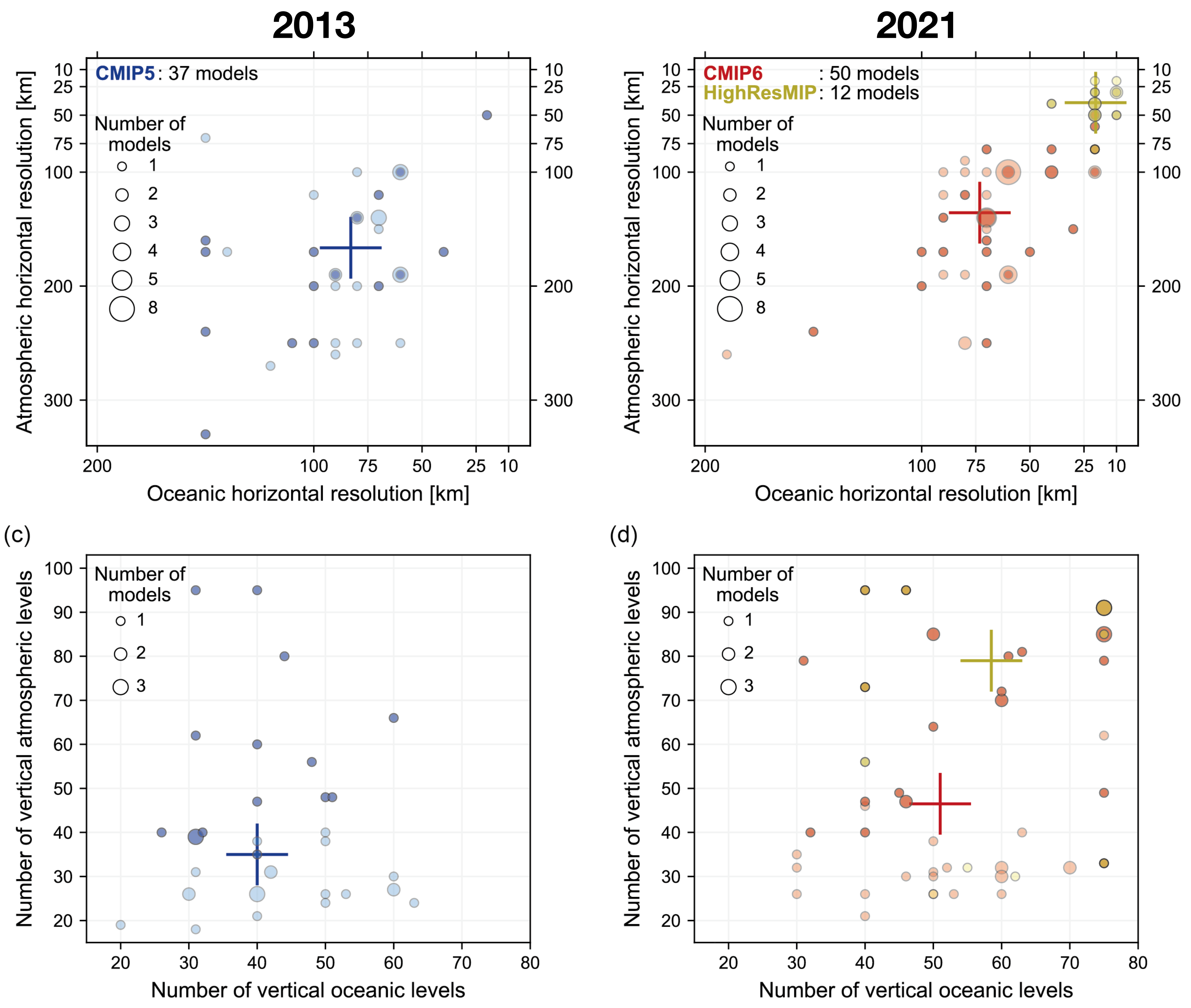
Horizontal resolution

Vertical resolution



- CMIP models refine resolution slowly: complexity, scenarios, ensemble size, simulation length are prioritised

IPCC2021

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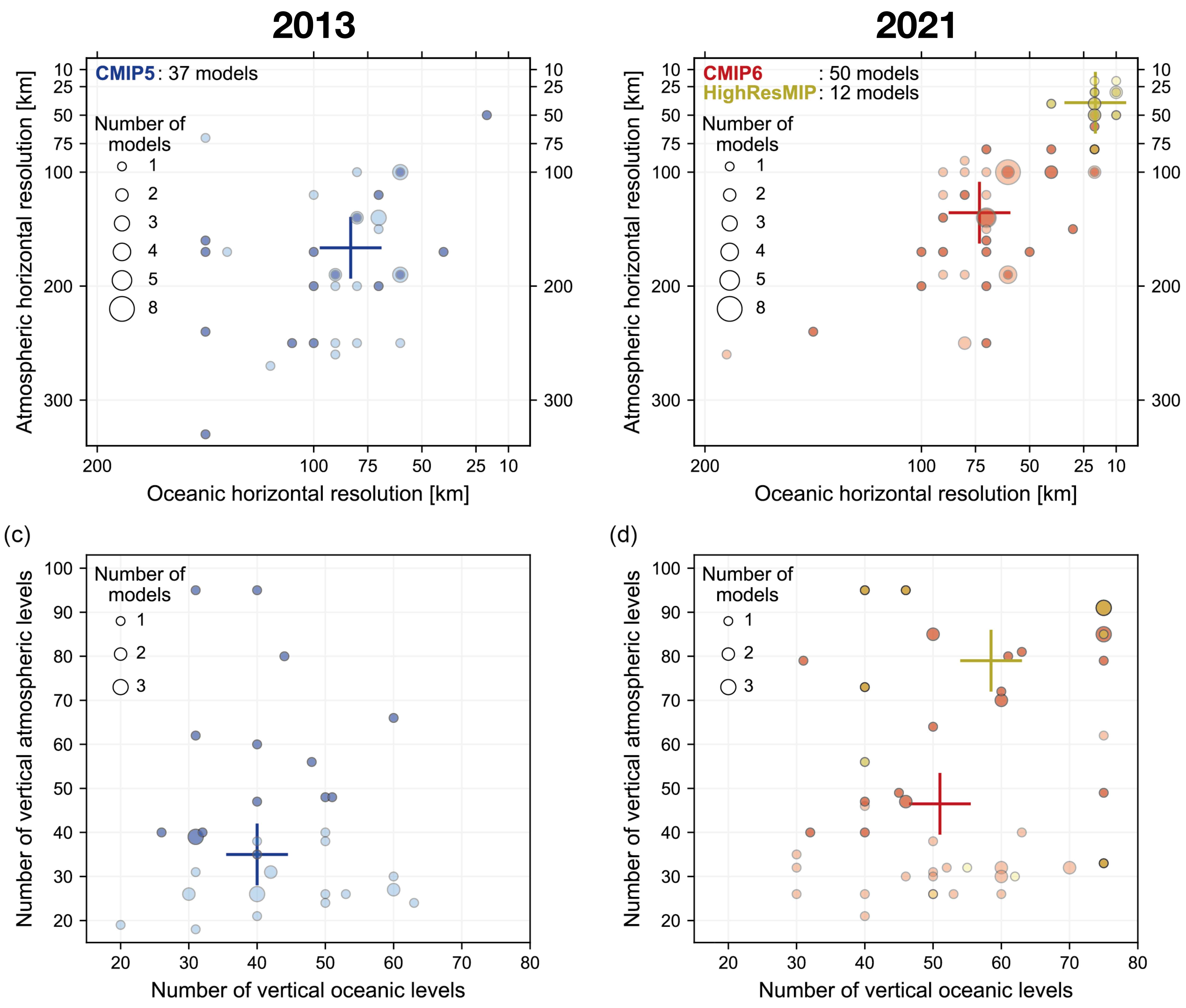
climate models evolution

Horizontal resolution

Vertical resolution



Meanwhile, fastes computer:
1993: 1 Tflop (FAR in 1990)
1995: 5 Tflop (SAR)
2001: 100 Tflop (TAR)
2007: 3 Pflop (AR4)
2013: 120 Pflop (AR5)
Now 1 Eflop (AR6)

- CMIP models refine resolution slowly: complexity, scenarios, ensemble size, simulation length are prioritised

IPCC2021

Why storm resolving models?

- For free: more realistic lower-boundary conditions orography and land-cover, bathymetry for through-flow, most of the variance in orography and simple things like resolving water sheds and precipitation intensity

lower boundary conditions

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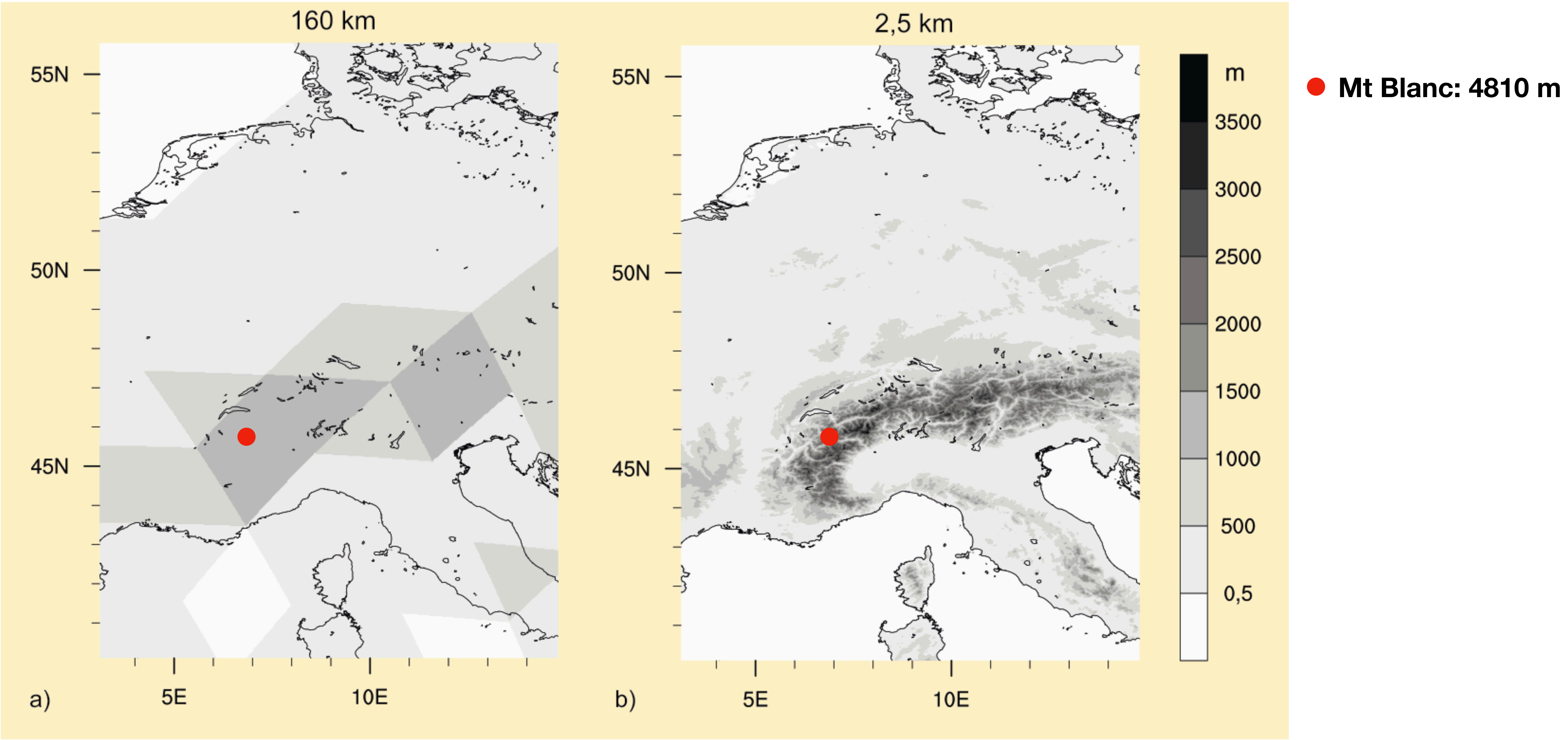

‚tradtional' climate model : 1394 m

Storm-resolving climate model : 4018 m

Hohenegger and Klocke, 2020

Why storm resolving models?

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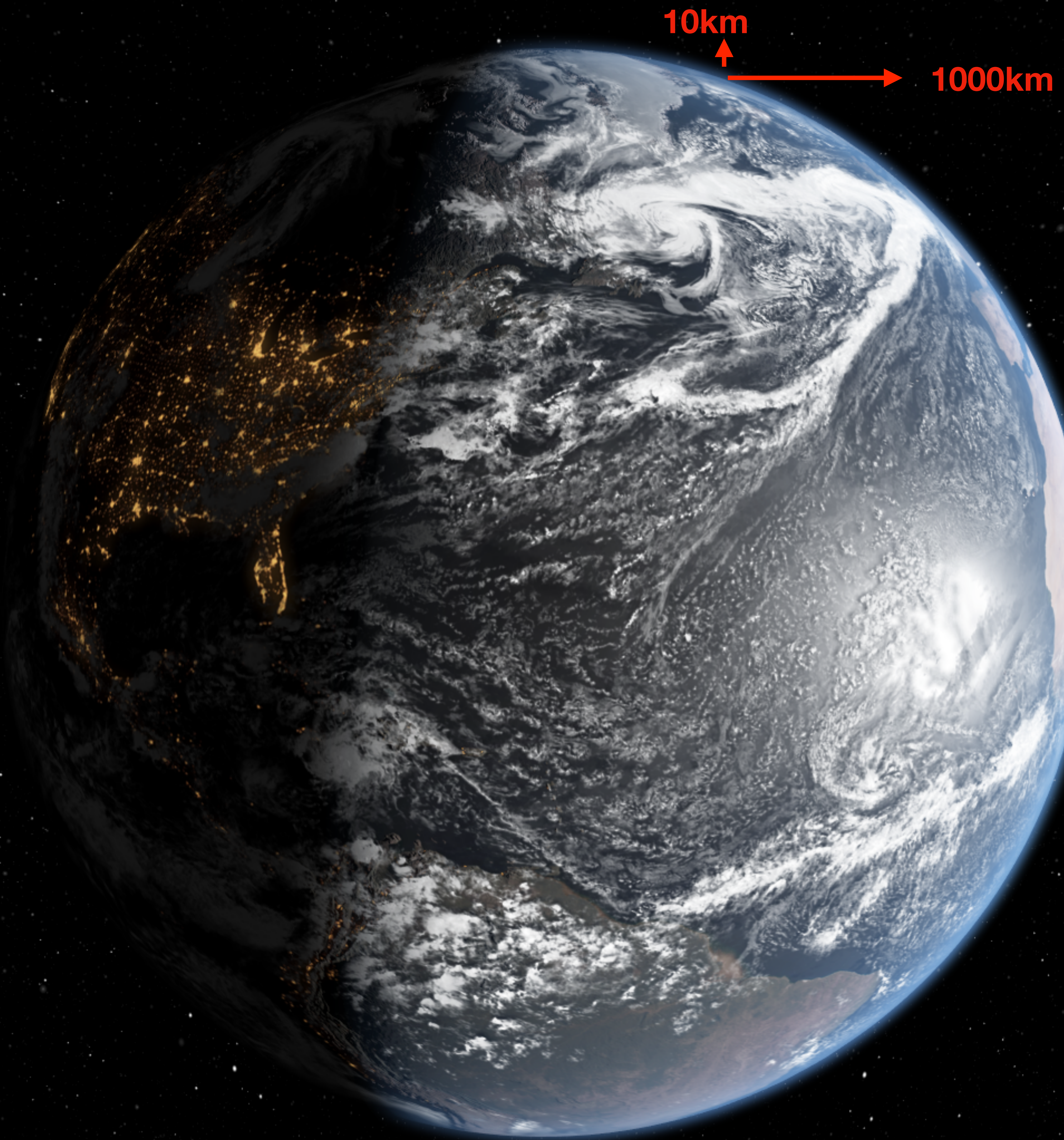
- More physics (through less ‘physics’): resolve the dominant mode of energy transport in the tropics (vertical), eddies in the ocean, ice-leads using laws of physics



The challenge: about 2^28 more computations to go from resolving the horizontal to also resolve the vertical energy transport

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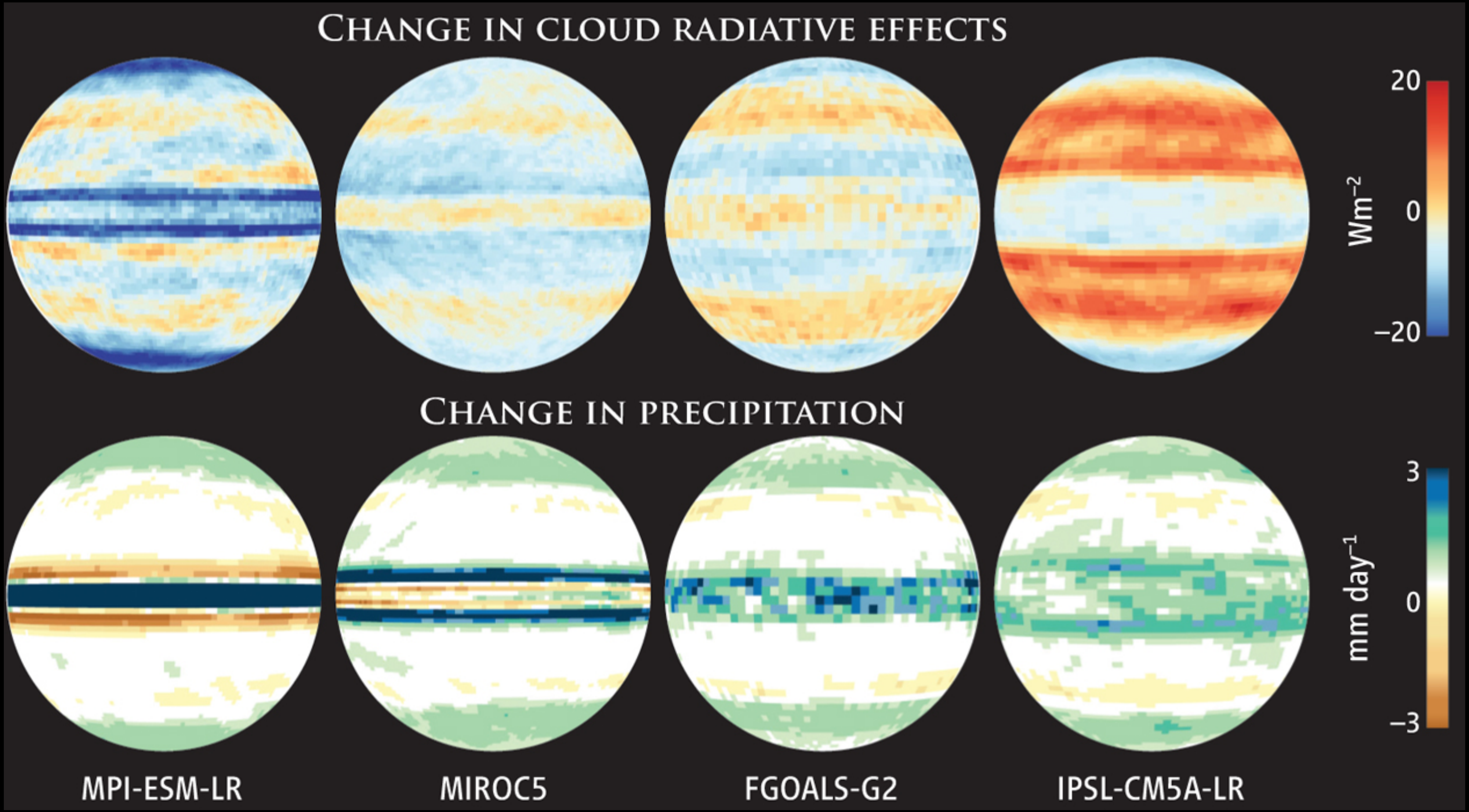
- Scale interactions from small-scales to large scale circulation, process level air-sea interactions, better representation of extremes (of course, many issues remain, some new issues come up; **it remains a model!**)

- Less equations, less lines of code, less assumptions and essentially simpler models

- Convergent behaviour across scales

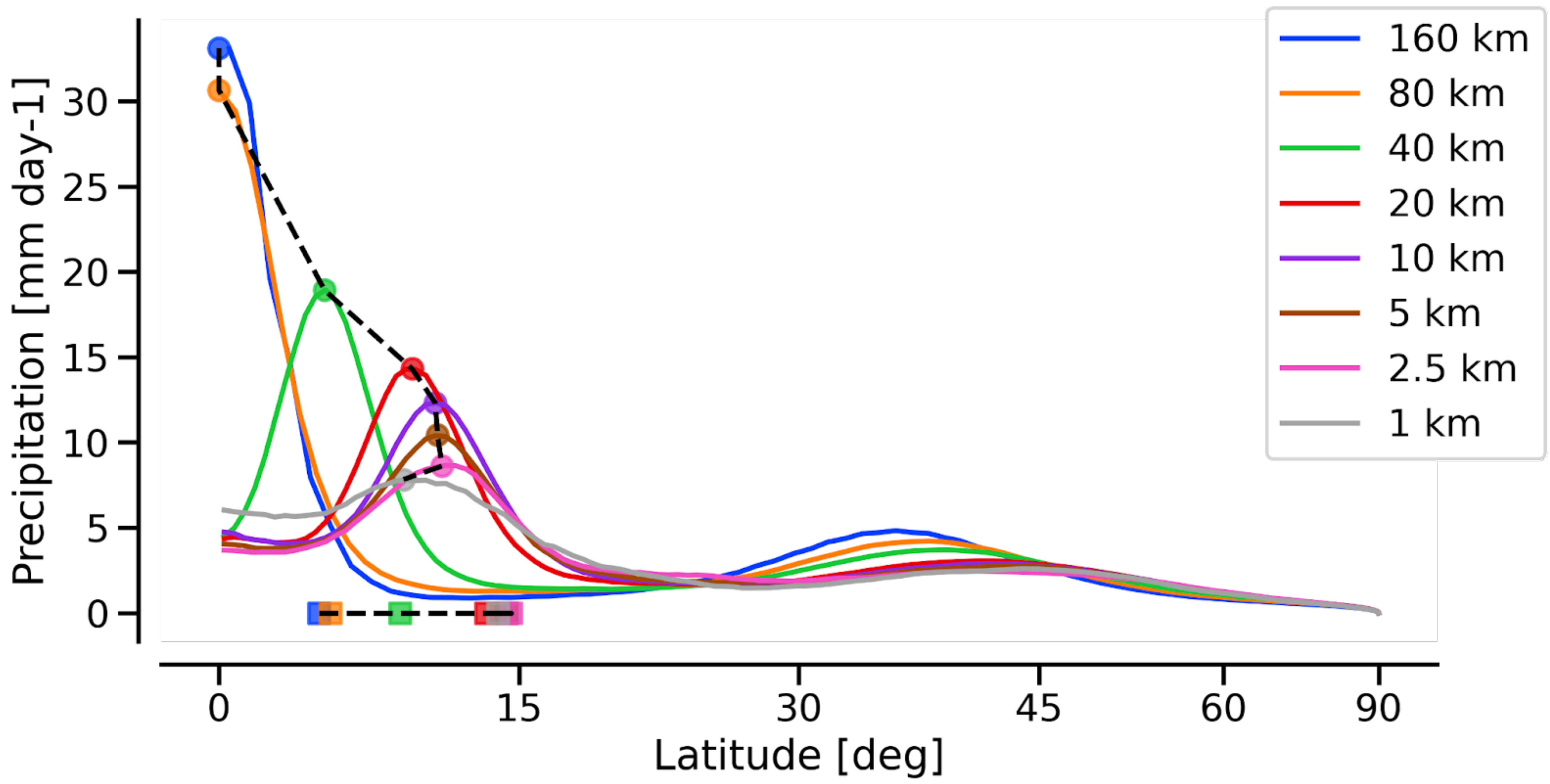
Why storm resolving models?

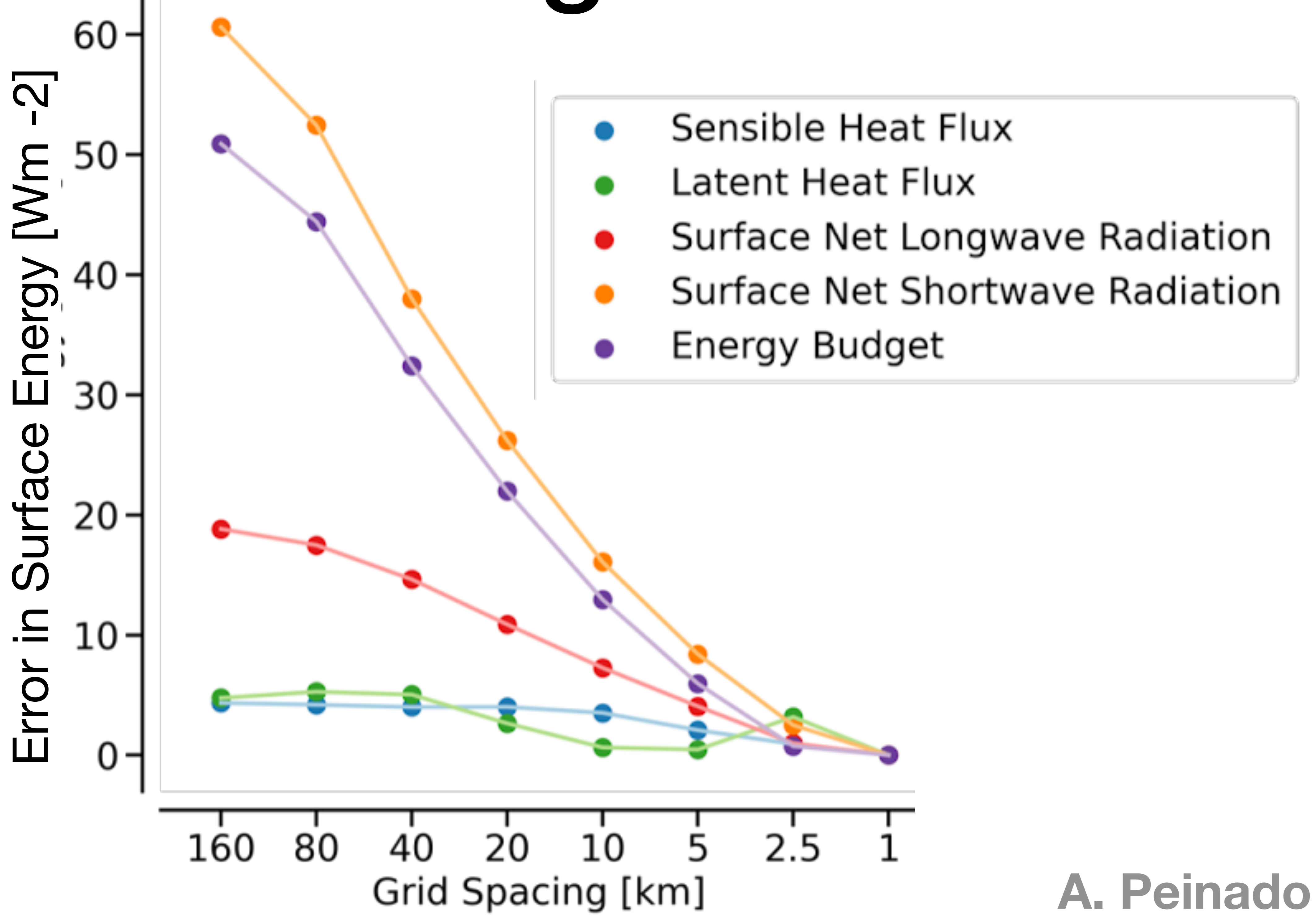
- Information at scales relevant for impact on peoples life (eg. catchment scales) and on scales we observe the Earth
- Maintains our science as a frontier application for new technologies (exa-scale computing, ai, virtualization - climate modelling today is no super computing application anymore)
- A small code base has less bugs and allows to be agile and adapt to new technologies
- Fascinating visualisations, a quality we should not underestimate
- Out-of-sample look at climate



Stevens and Bony, 2013

Convergences of an aqua planet configuration





A. Peinado

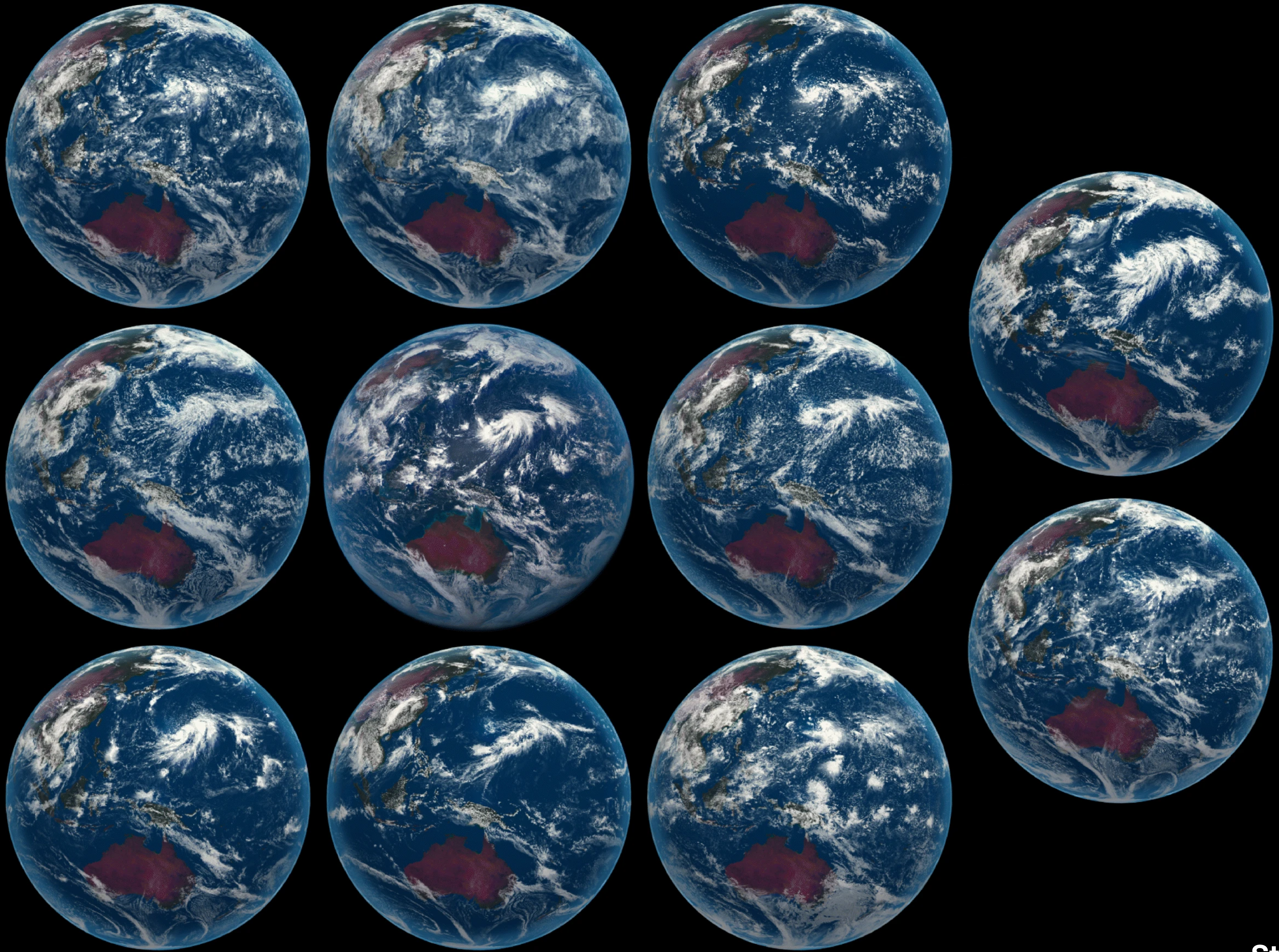
Converged for many characteristics of the general circulation

First step towards a new generation of climate models

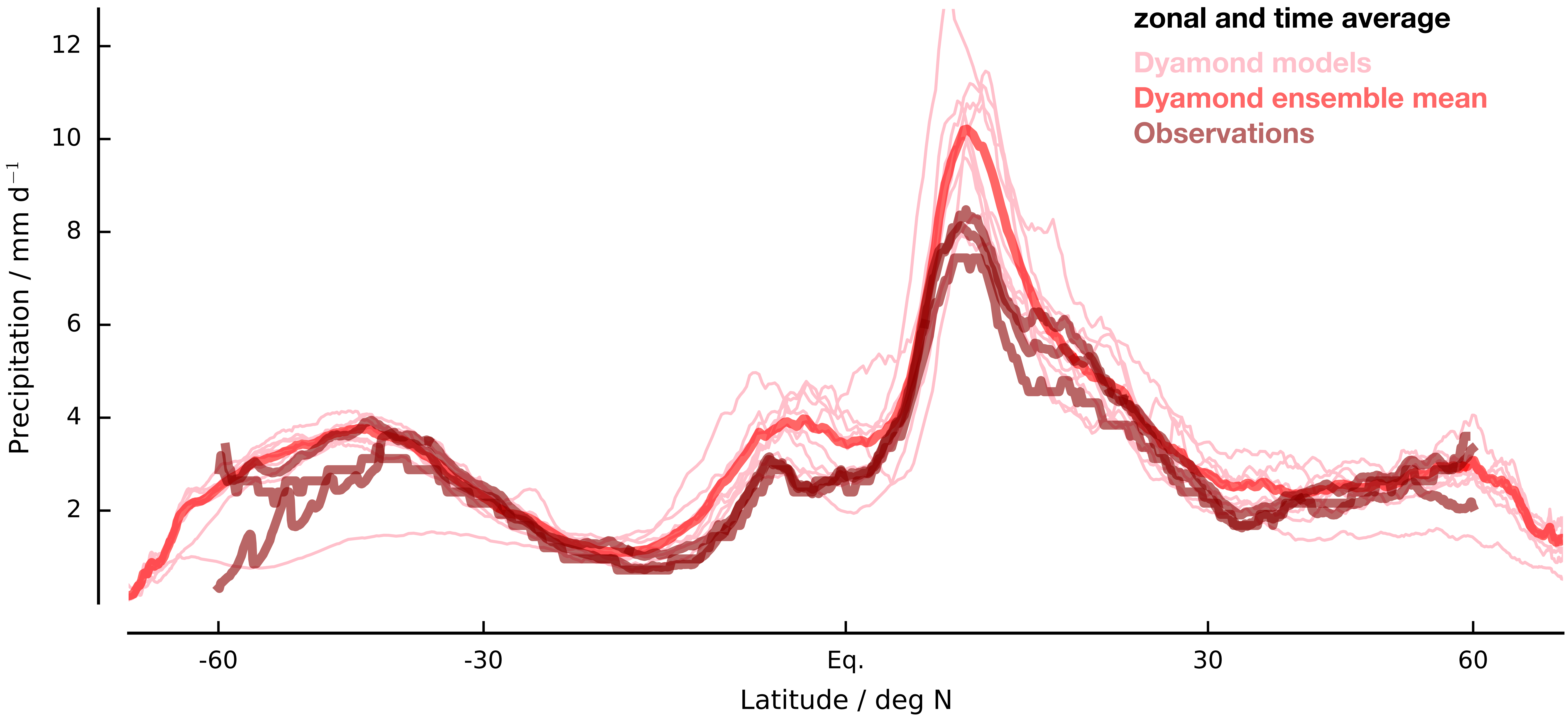
DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains

- First inter-comparison of global storm resolving models (<5km grid spacing)
- Never two models did the same experiment before
- Some of the participating models were never applied to these scales
- Start on 1.8.2016, no parametrization for convection, simulate 40 days and 40 nights
- DKRZ and ESiWACE provided support and space for data storage (2 Pb)

Stevens, Satoh et al. 2019



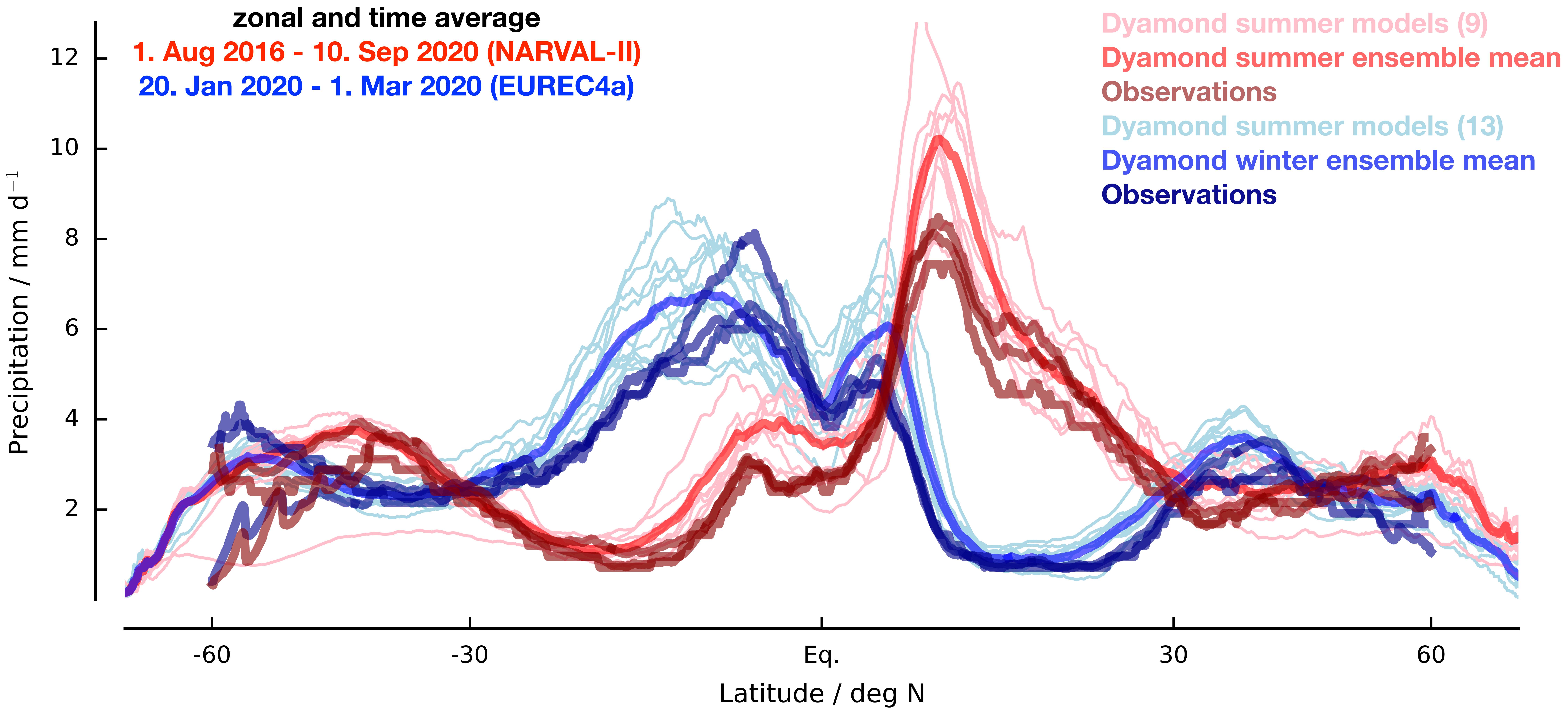
Stevens et al., 2019



Miyakawa and Klocke in preparation

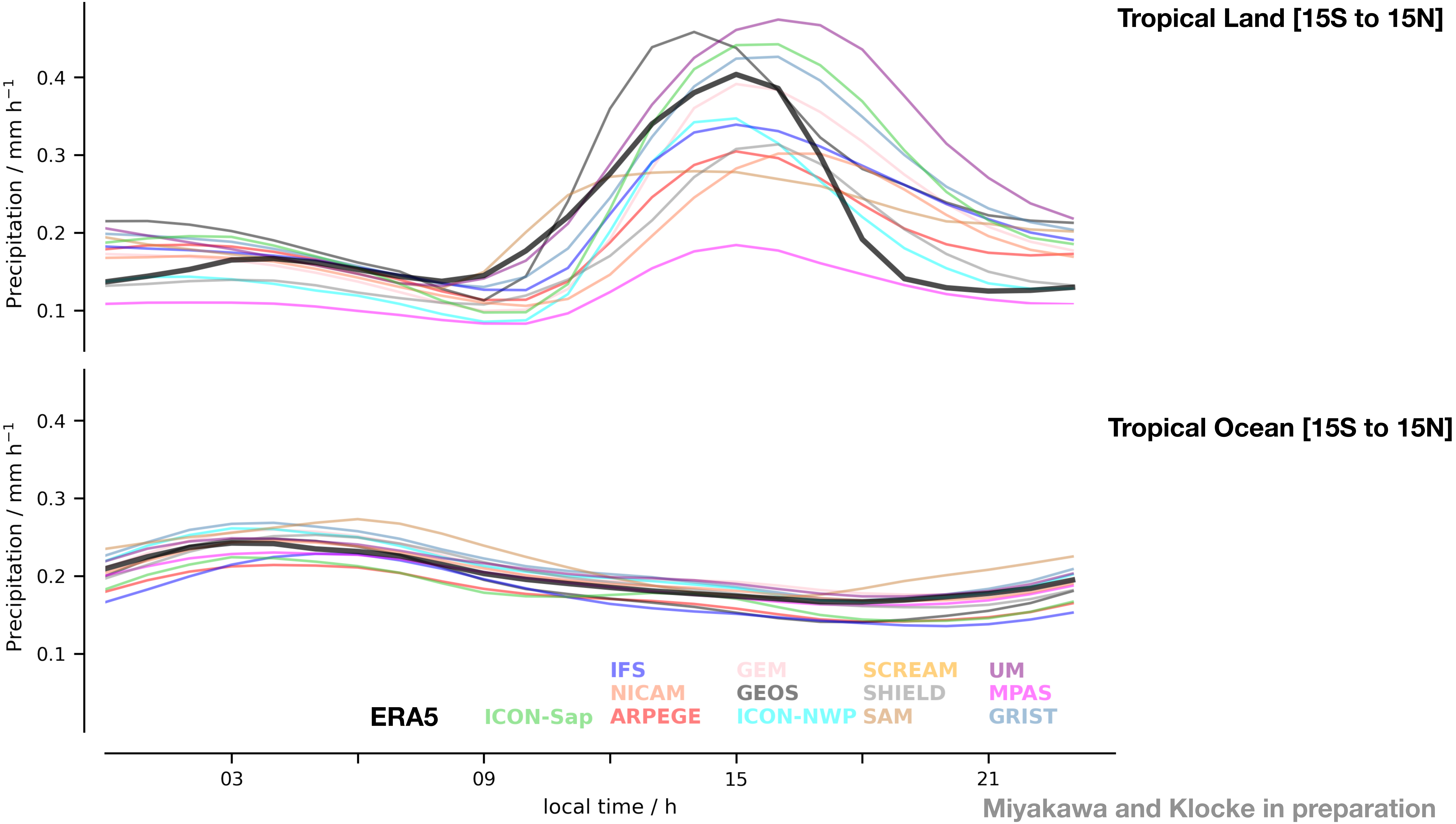

ARPEGE
GEM
GEOS-3
GRIST
ICON-NWP-2
ICON-SAP-5-A
ICON-SAP-5-C
IFS-4
IFS-9
MPAS
NICAM
SAM2
SCREAM
SHIELD
UM
visualisation by Florian Ziemen @DKRZ

Summer 2016/Winter 2020

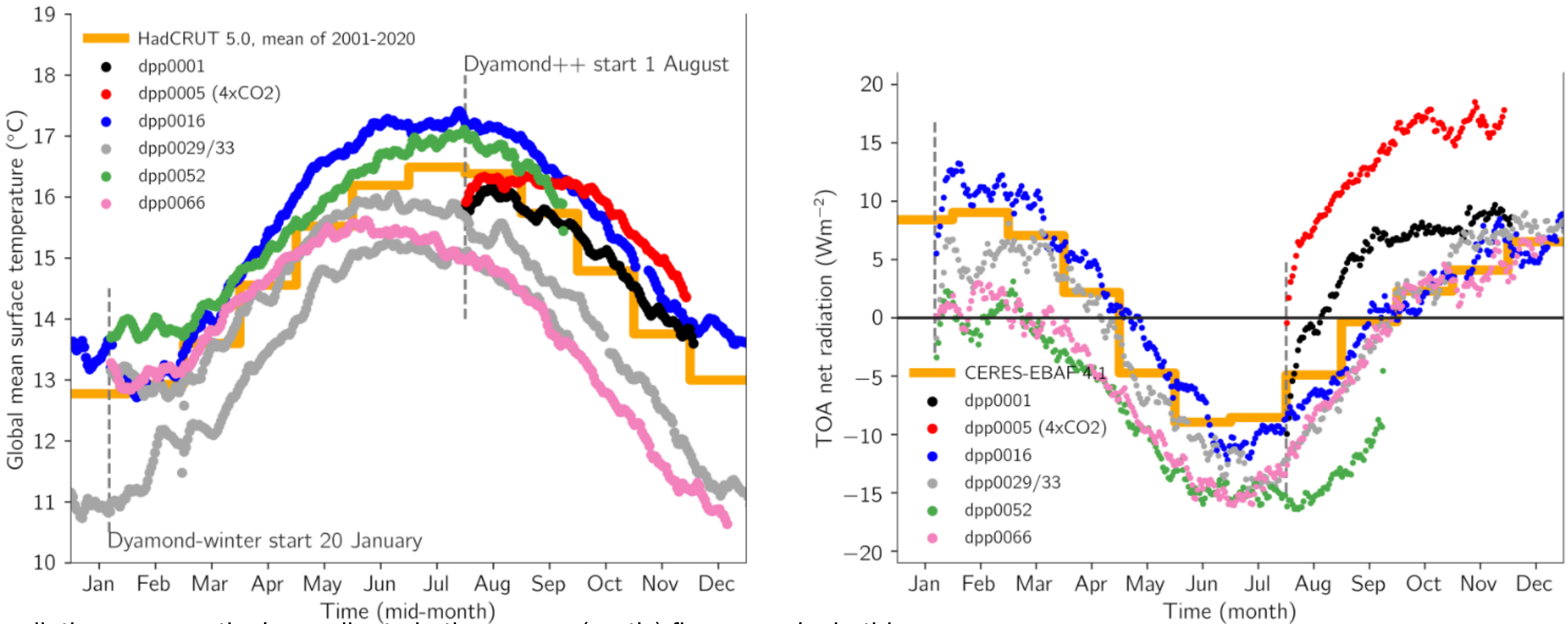


Winter also including 5 coupled atmosphere-ocean models

Miyakawa and Klocke in preparation


Tropical Land [15S to 15N]
Tropical Ocean [15S to 15N]
Precipitation / mm h^{-1}
0.1
0.2
0.3
0.4
03
09
15
21
local time / h
ERA5
ICON-Sap
IFS
NICAM
ARPEGE
GEM
GEOS
ICON-NWP
SCREAM
SHIELD
SAM
UM
MPAS
GRIST
Miyakawa and Klocke in preparation

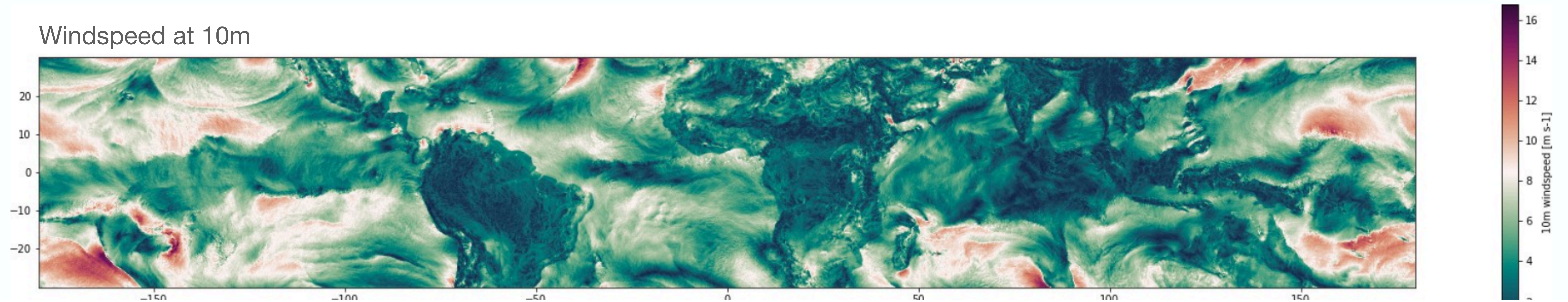
Coupled climate simulations



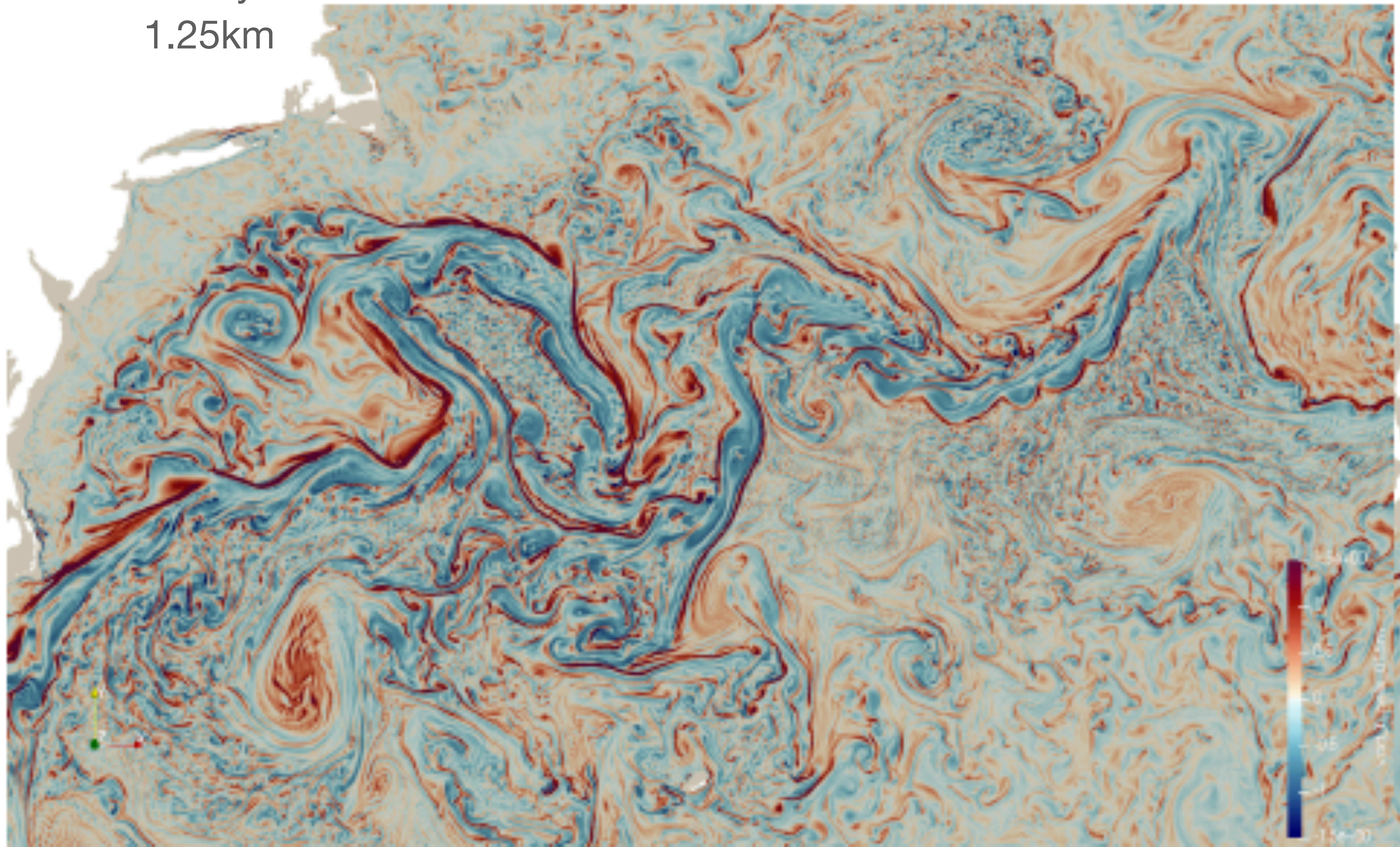
New radiation, new vertical coordinate in the ocean, (partly) fix energy leak, thin layers in the ocean, new ocean states, new treatment of run-off, discovered bugs, which were already in the ‘traditional’ climate model (only show their full effect at high resolution), new land initialisation, etc.…

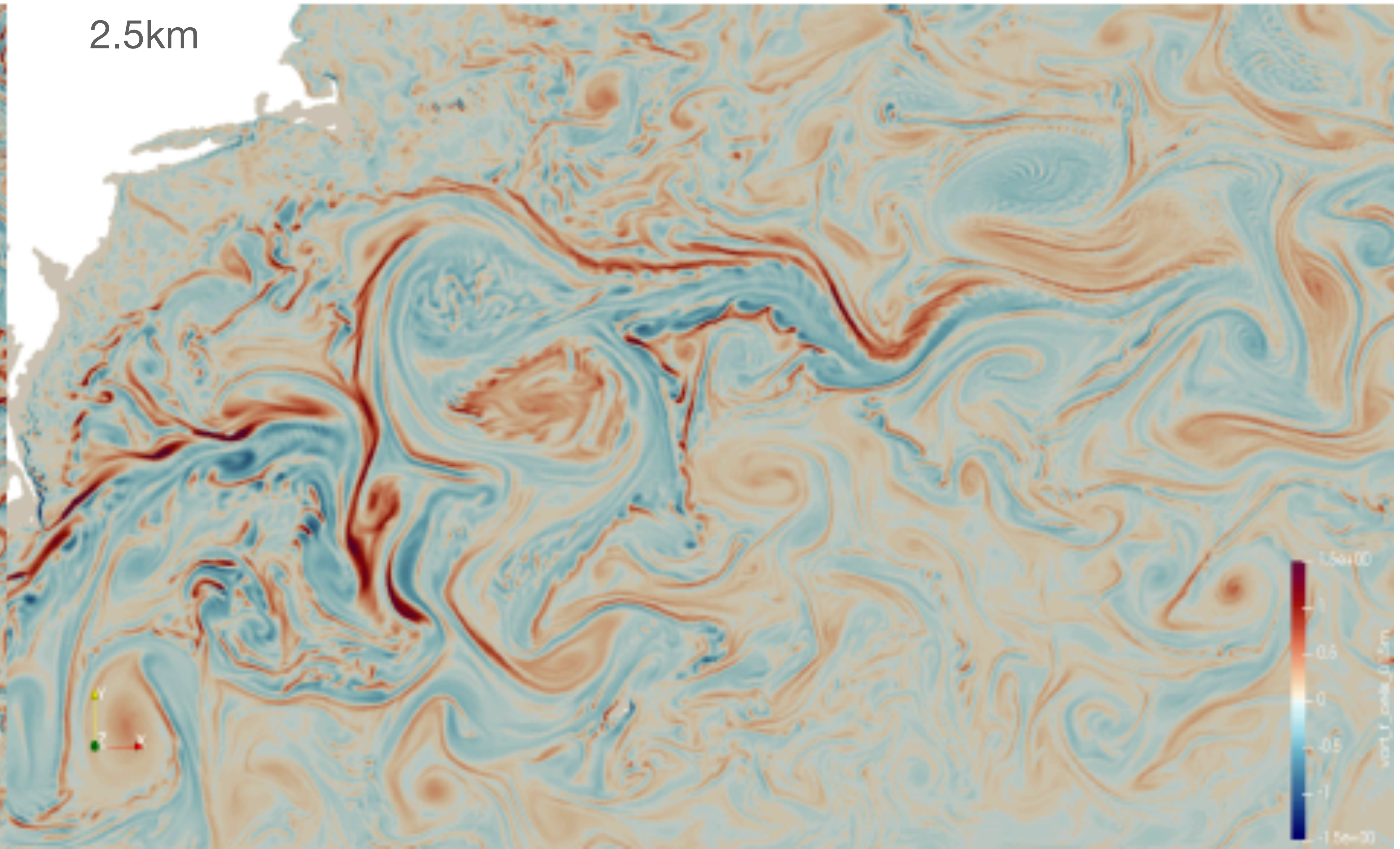
Mauritsen et al., 2022

Coupled 1.25 km simulations (just in the machine)



Local Rossby number





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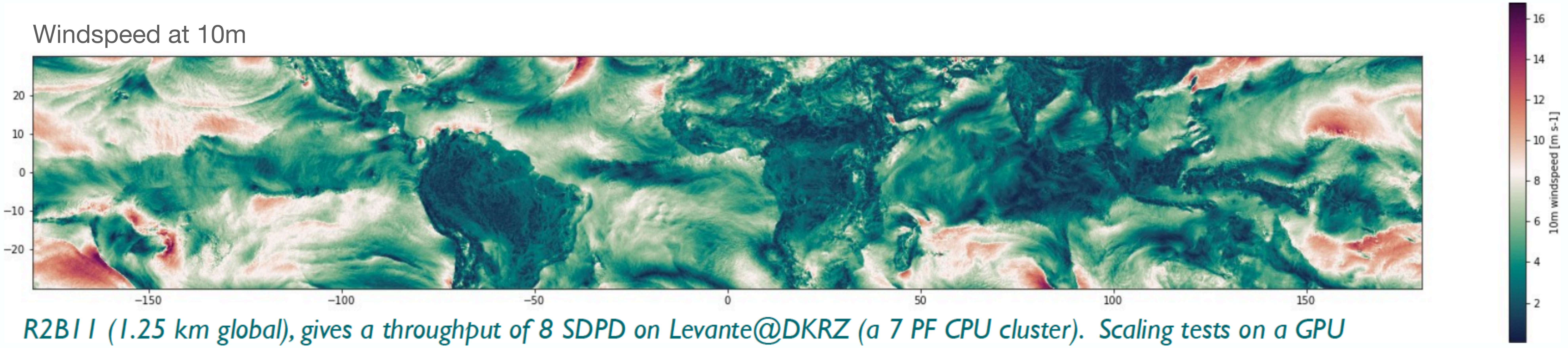
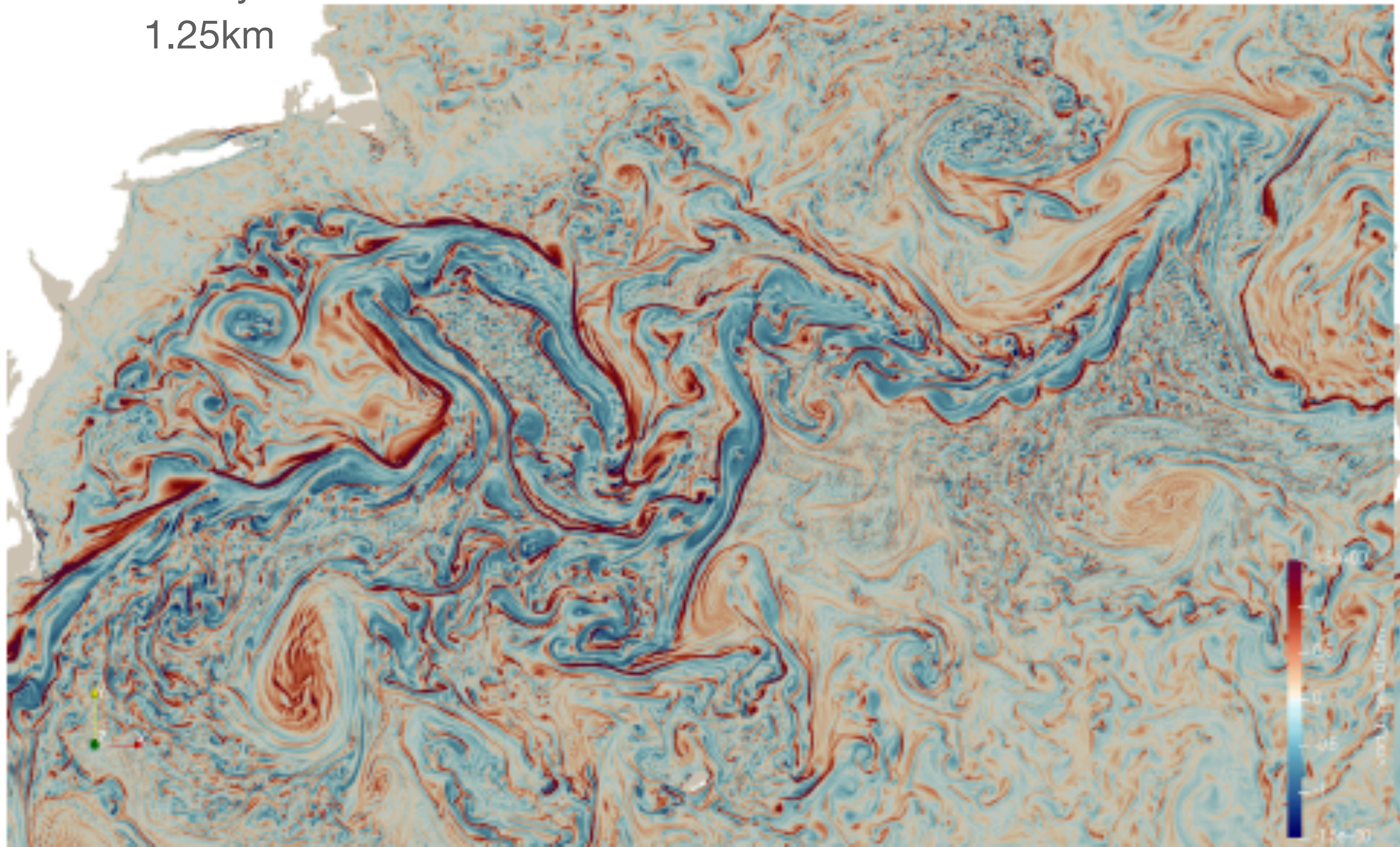
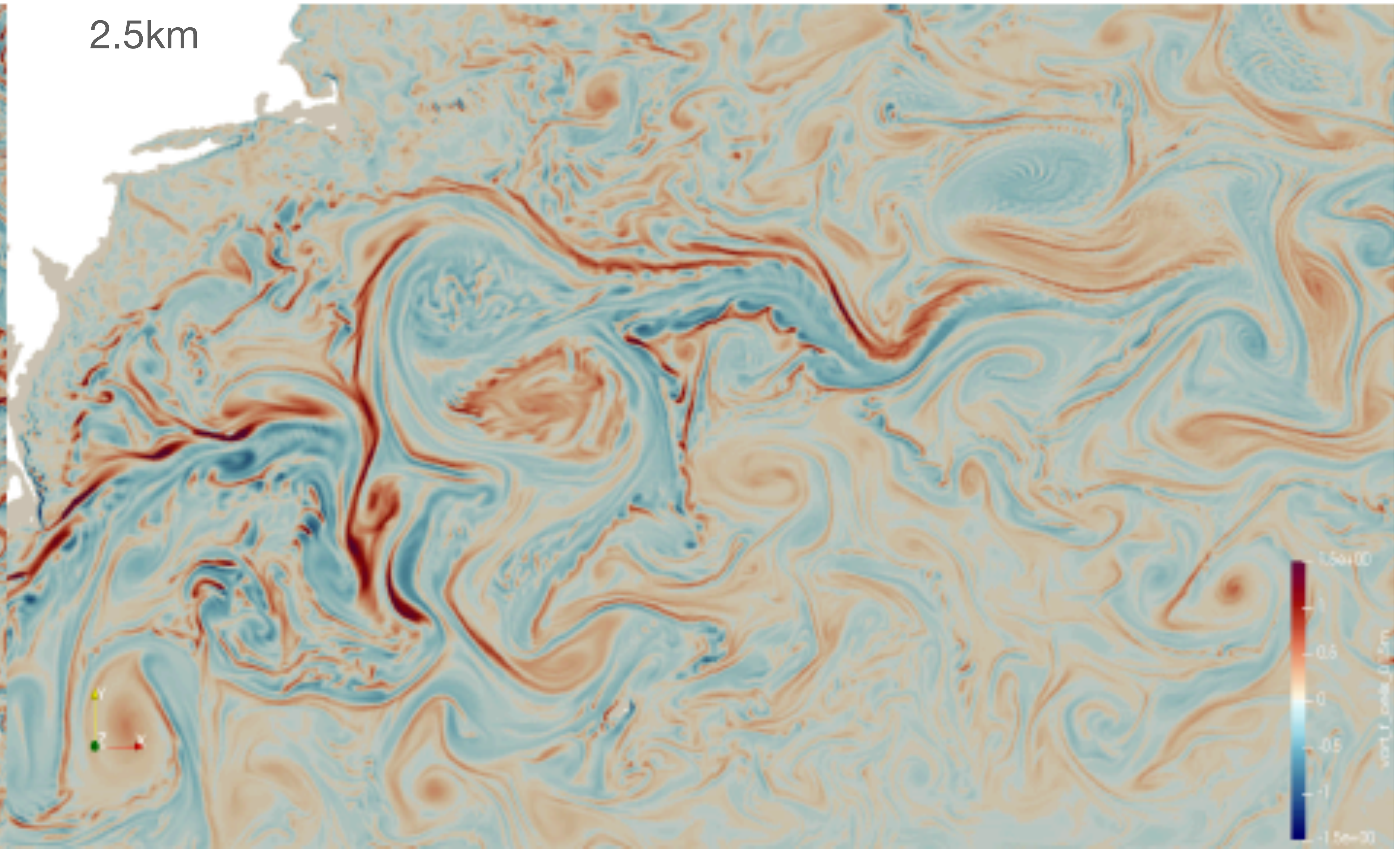


R2B11 (1.25 km global), gives a throughput of 8 SDPD on Levante@DKRZ (a 7 PF CPU cluster). Scaling tests on a GPU machine give half the performance per GPU PF with tenfold less power. Scaling to Frontier would imply 2 SYPD. Presently we probably can only scale to 0.1 or 0.2 Frontier; i.e., 30 year 10 member ensembles in six months

Kamikaze

Local Rossby number





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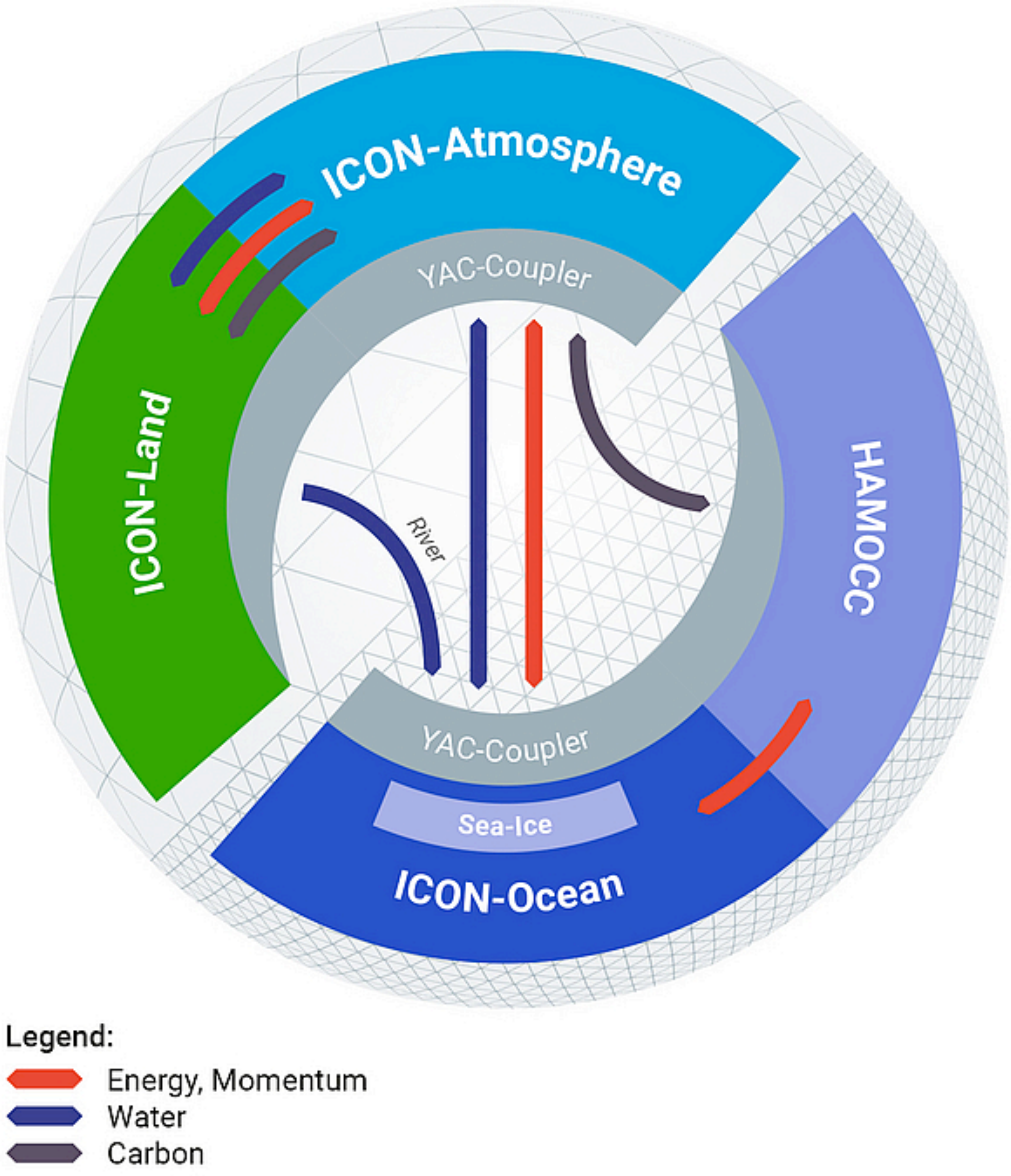

B. Stevens six weeks ago:

Where are we, where are we headed?

- 2005 — 3.5 km (Aquaplanet), for 10 days; Tomita, Miura, Iga, Nasuno, and Satoh
- 2007 — 3.5 km Atmosphere only for 7 days; Miura, Satoh, Tomita, Noda, Nasuno, Iga
- 2011 — 3.5 km 20 days (NASA-GEOS5); Putman and Suarez
- 2013 — 0.9 km 3 days NICAM, Miyamoto, Kajikawa, Yoshida, Yamaura, Yashiro, Tomita
- 2014 — 3.0 km 20 days (NCAR-MPAS); Skamarock, Park, Klemp and Snyder
- 2017 — 3.5/10 km coupled NICOCO, Miyakawa et al.,
- 2019 — DYAMOND (2.5-5.0 km) ARPEGE-NH, FV3, GEOS, ICON, IFS, MPAS, NICAM, SAM
- 2020 — 1.4 km 120 days, IFS (Hydrostatic), Wedi et al
- 2022 — 5.0 km 180 days, 10 member ensembles, Kluft et al.
- 2022 — 1.2 km 7 days, ICON, Klocke et al.
- 2022 — NextGEMS Cycle 2 (multi-annual 3-5 km-scale coupled), Hohenegger et al., Rackow et al.
- 2022 — 0.2 km, (tens of hours) NICAM.

About a factor of 2^{12} (4096) in computation complexity — we're keeping pace with Moore's Law

- 2024 — 1.2 km, 30 years, coupled ICON in less than 3 weeks on JUPITER

… adaptation to climate change, and assessing its high-end risks will require us to get the most out of these tools as soon as possible.

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< 2022 — 1.2 km coupled (days) ICON (Redler, Wieners et al.)

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Summary

- Global coupled storm and ocean-eddy resolving climate simulations are possible and increasingly feasible. Even on todays super computers. Complete seasonal cycles were simulated with this new class of models, now targeting decades

- They are a new and exciting tool and are advancing the frontiers of climate science

- The application of these models to climate studies offers the possibility of new discoveries, but challenges need to be overcome: bugs, energy balance, sensitivities to SSTs micro-physical processes.

- A lot will be learned along the way….

Impressions from global 2.5 km coupled climate simulation (visualisation by Niklas Röber @NVIDIA)