Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology

Towards Convection-Resolving Climate Modeling

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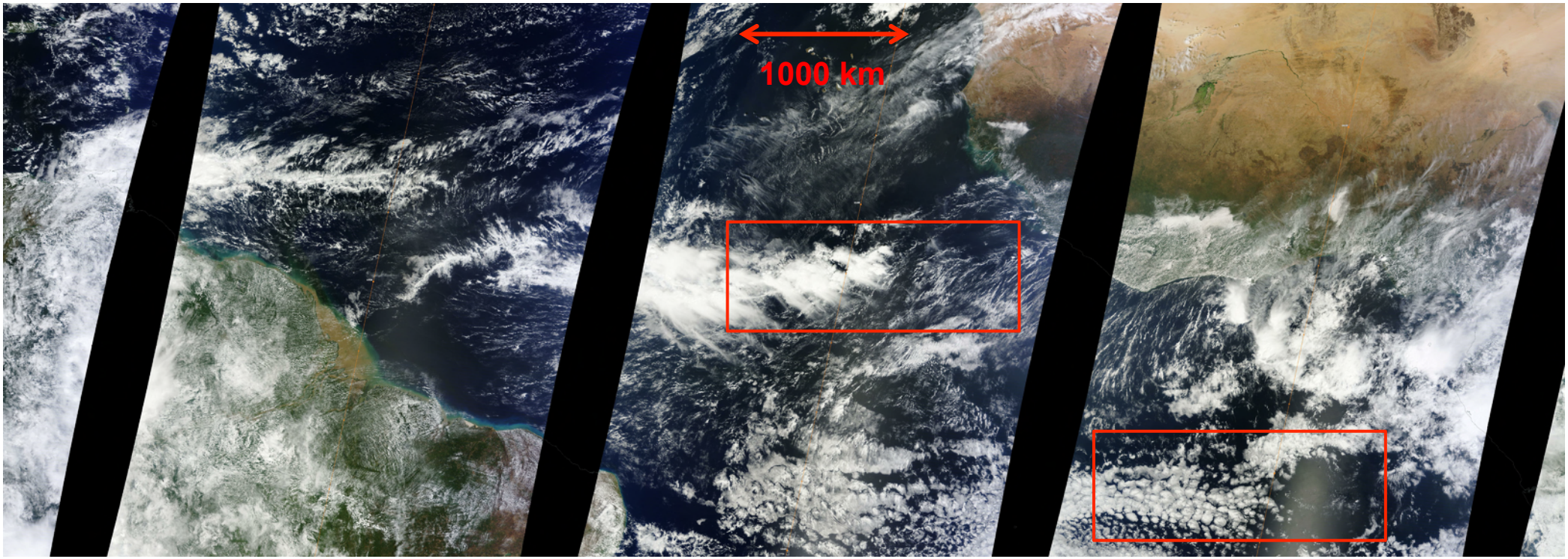
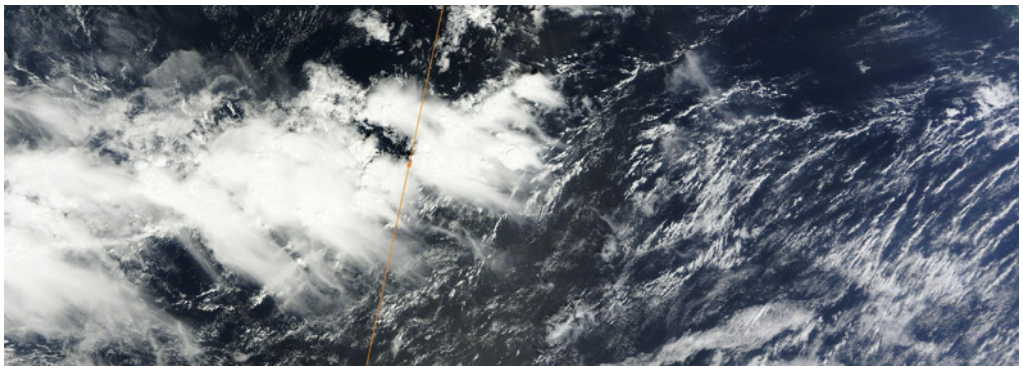
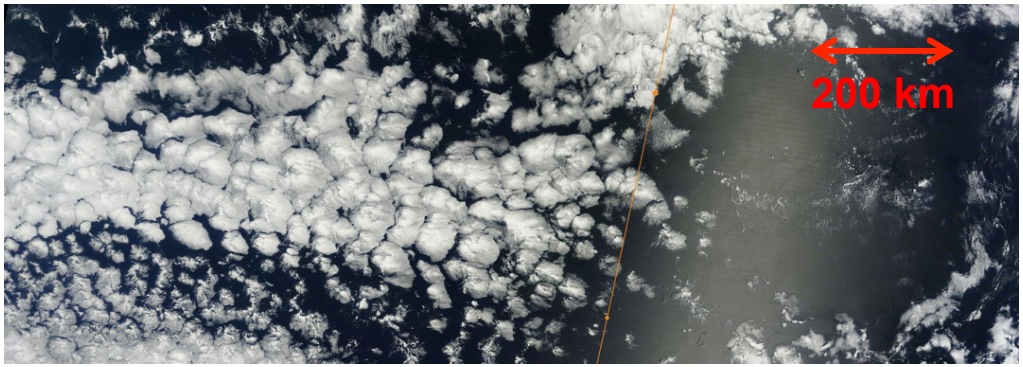
5th WGNE Workshop, June 20, 2017, Montréal, Québec, Canada

Mesoscale matters







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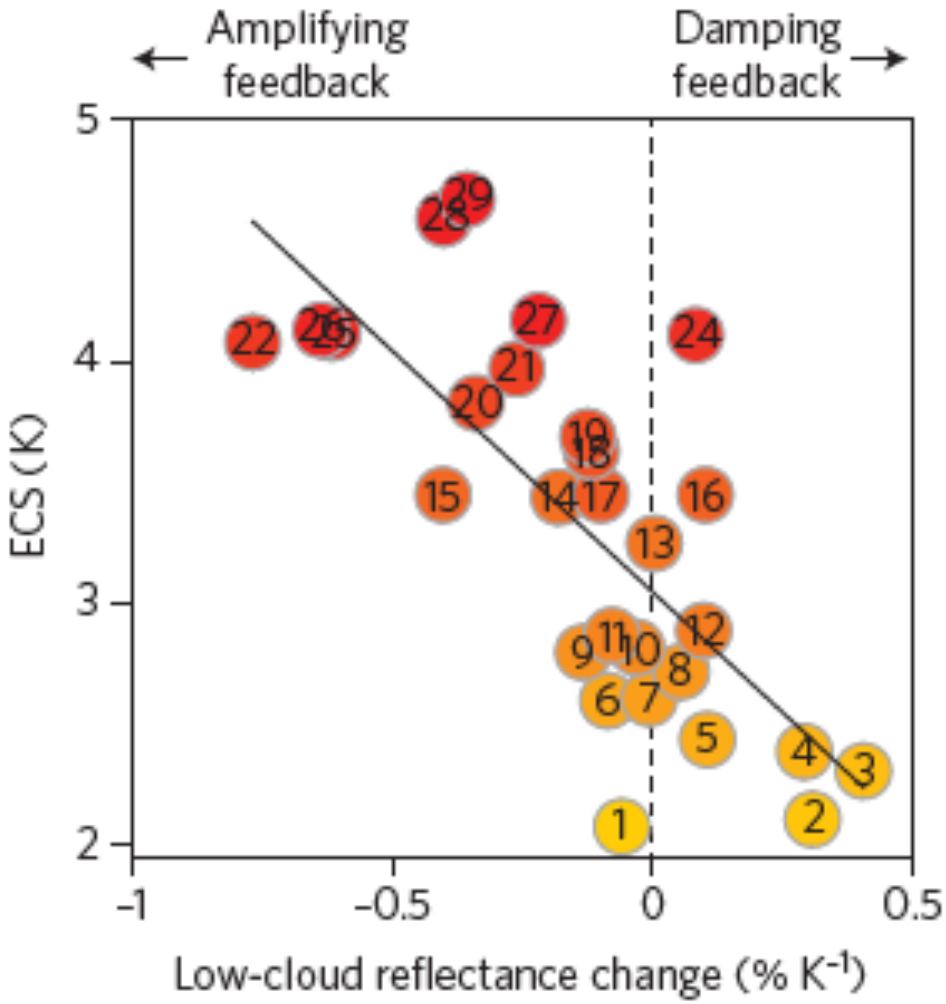
Modis (Terra), December 1, 2013

MPI for Meteorology

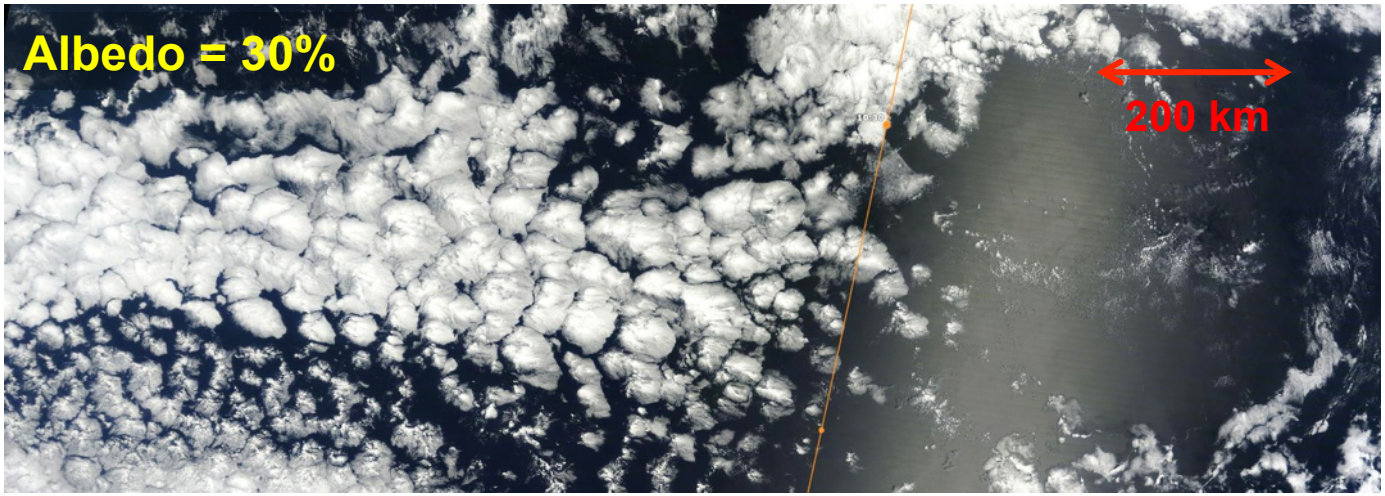
Climate sensitivity and clouds

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

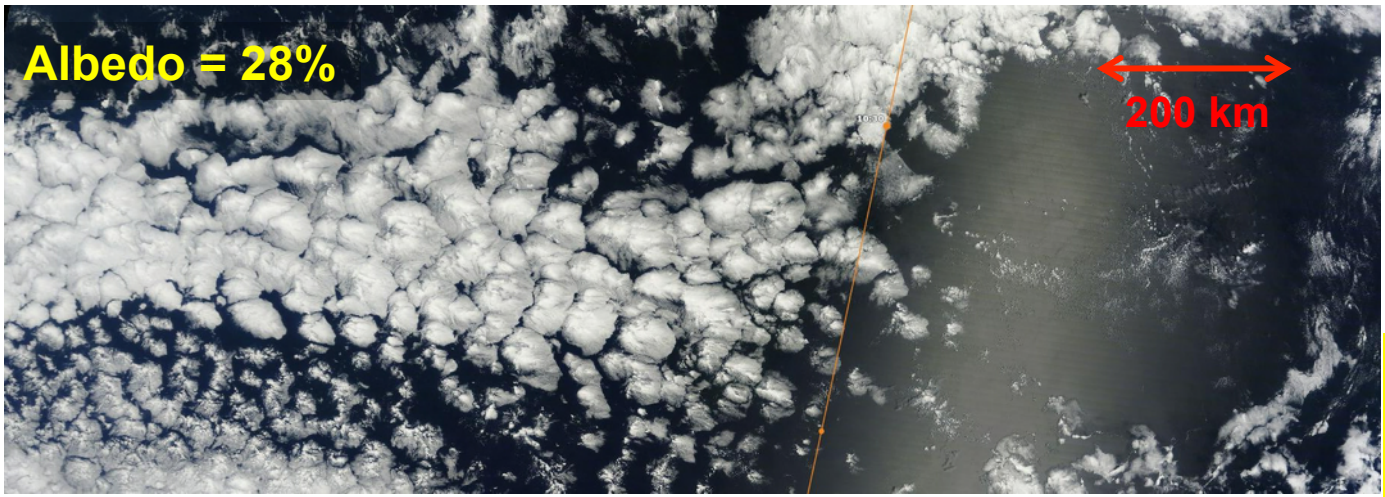


(Schneider et al. 2017, Nature CC; see also Bony et al. 2015, NGS)

What is the difference?



Global-mean albedo corresponds to **30%**
(Wild et al. 2013)



If climate change would decrease albedo to **28%**, the associated positive feedback would double the greenhouse effect!

Assessment should rely on multiple lines of evidence (IPCC) and on first principles (as far as possible)

Convection and flash-flooding

Tram Stop "Haldenbach"

Many floods in urban environments are due to short-term events!

OUTLINE

Motivation

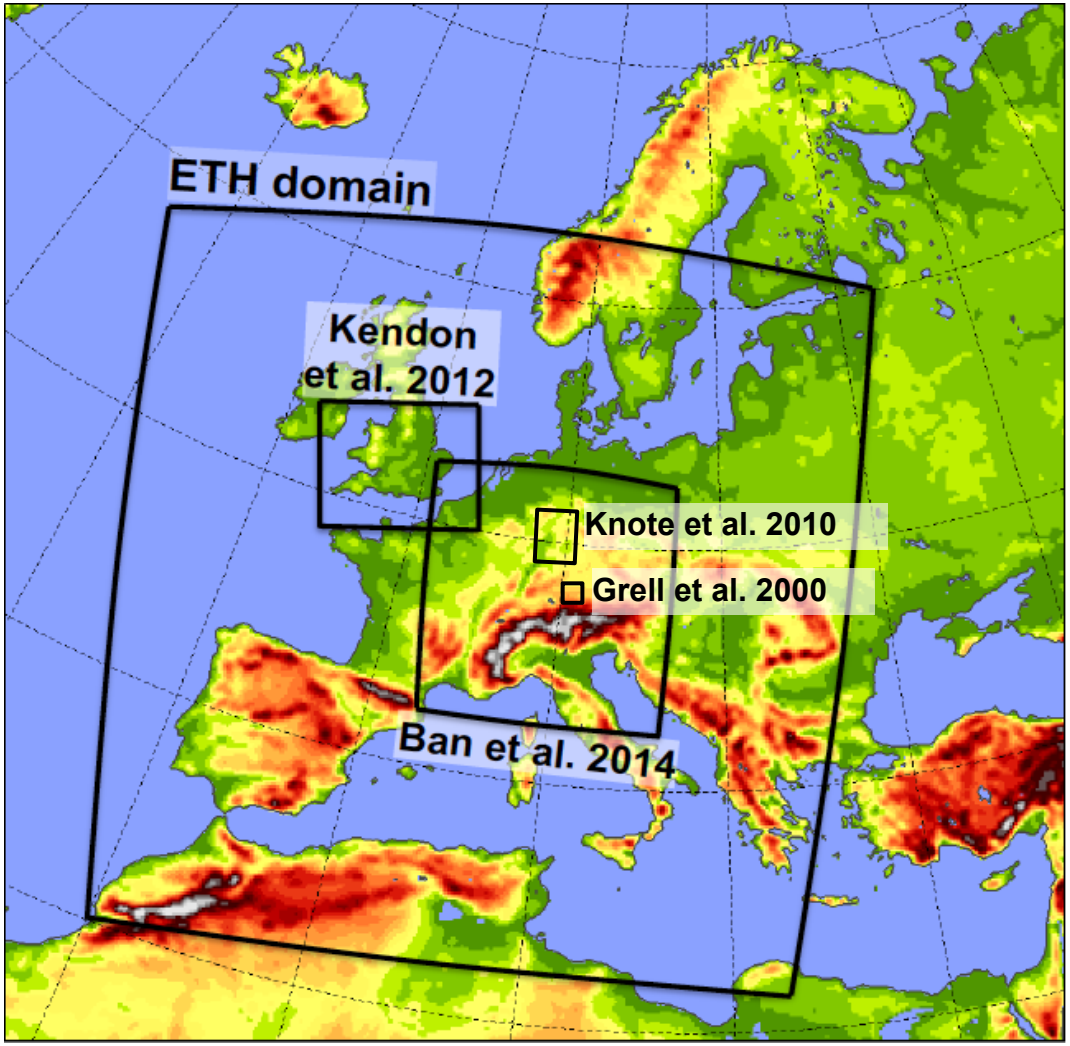
Decade-long simulations at Δ = 2 km

Precipitation scaling with climate change

Convergence?

Challenges

European climate simulations at km-scale



Grell et al. 2000:
46x46 gridpoints at 1 km
14 months

Knote et al. 2010:
ca 200 x 150 gridpoints at 1.3 km
several decades

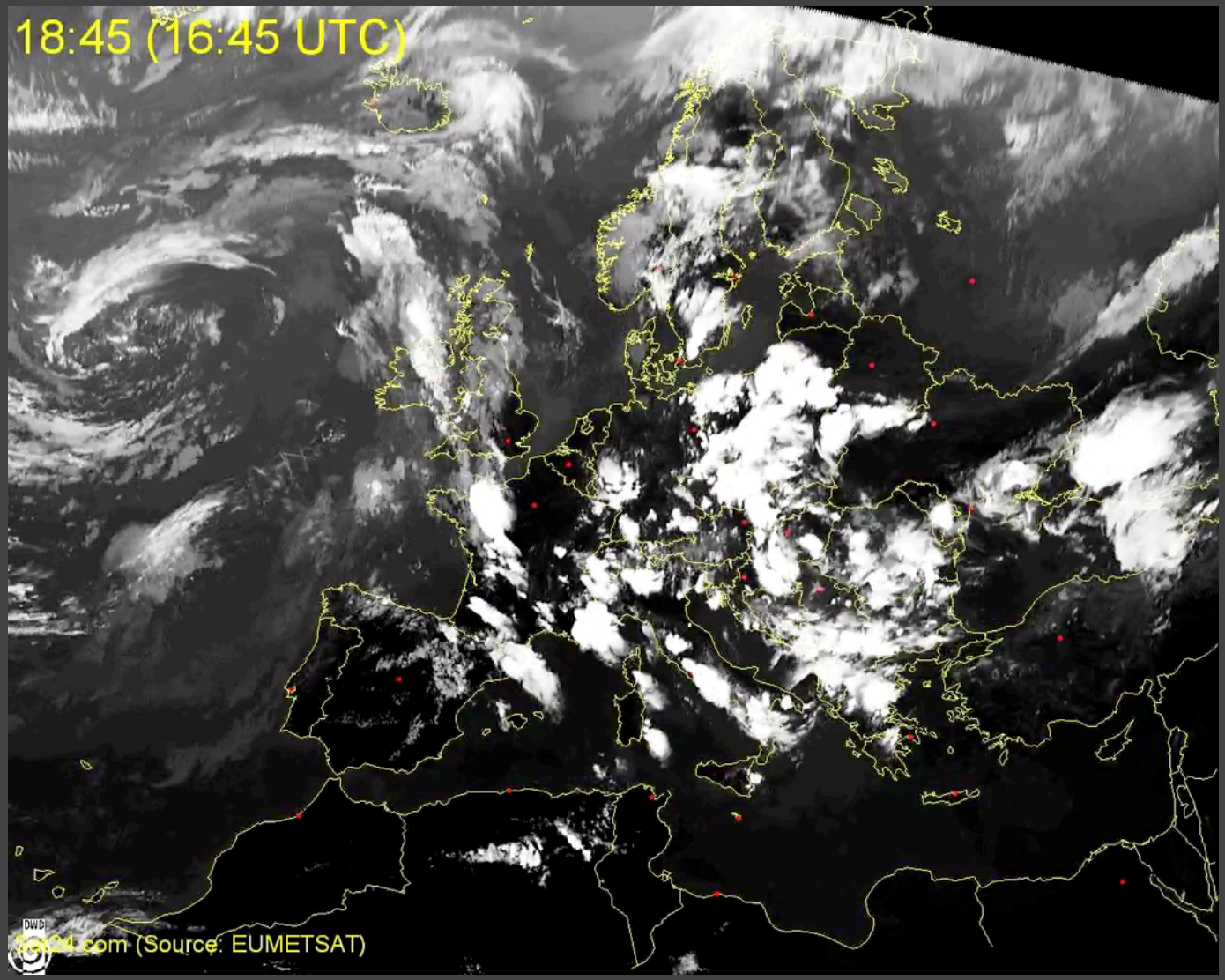
Kendon et al. 2012:
ca 400 x 300 gridpoints at 1.5 km
several decades

This presentation:

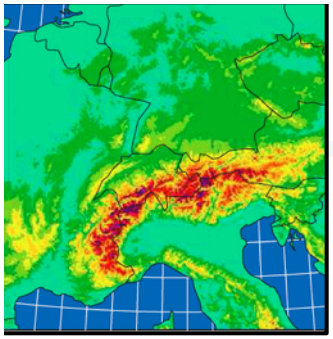
Ban et al. (2014 JGR; 2015 GRL):
500 x 500 gridpoints at 2.2 km
several decades
driven by ERA-Interim and
MPI-ESM-LR (RCP 8.5)

Leutwyler et al. (GMD 2016; 2017 JGR):
1536 x 1536 gridpoints at 2.2 km
one decade completed
driven by ERA-interim

Diurnal convection over Europe



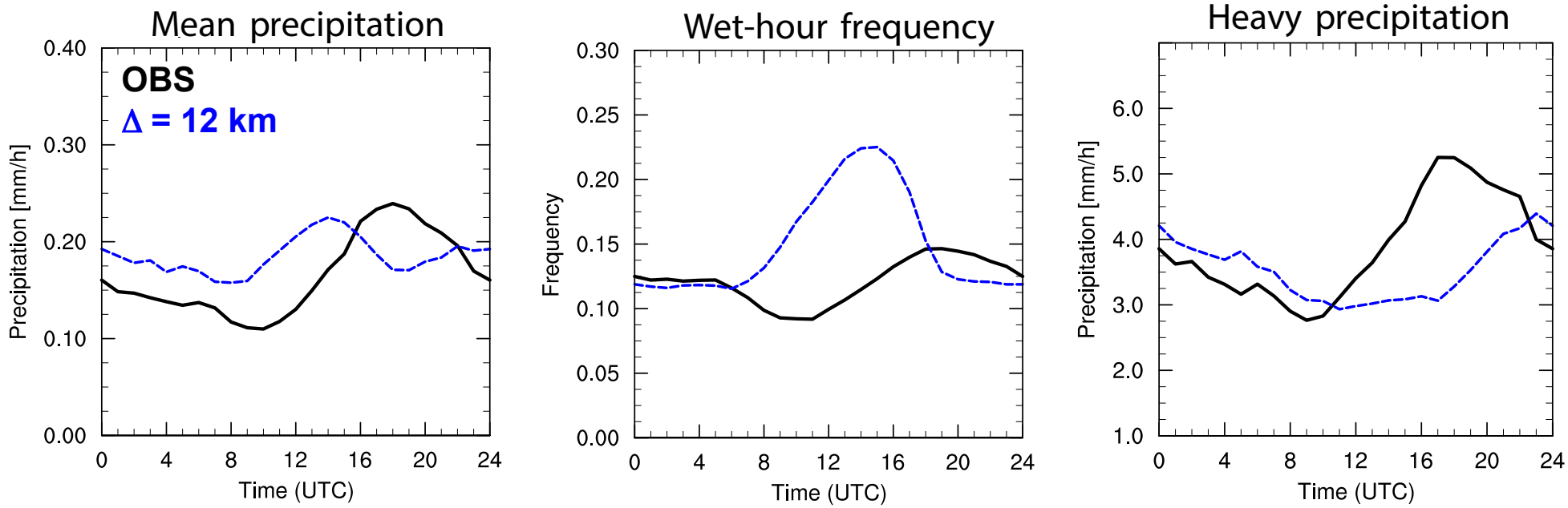
(SEVIRI 10.8µm, June 30 till July 2, 2009; Michael Keller, ETH Zürich)



Alpine domain
2.2km (500x500x60)

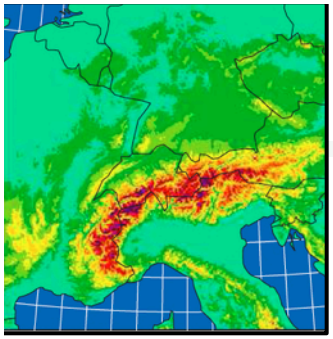
Validation of diurnal cycle

10-year long simulation driven by ERA-Interim;
Validation against 62 rain-gauge stations in Switzerland (JJA)



poor representation of diurnal cycle with Δ=12 km

(Ban et al. 2015, GRL)



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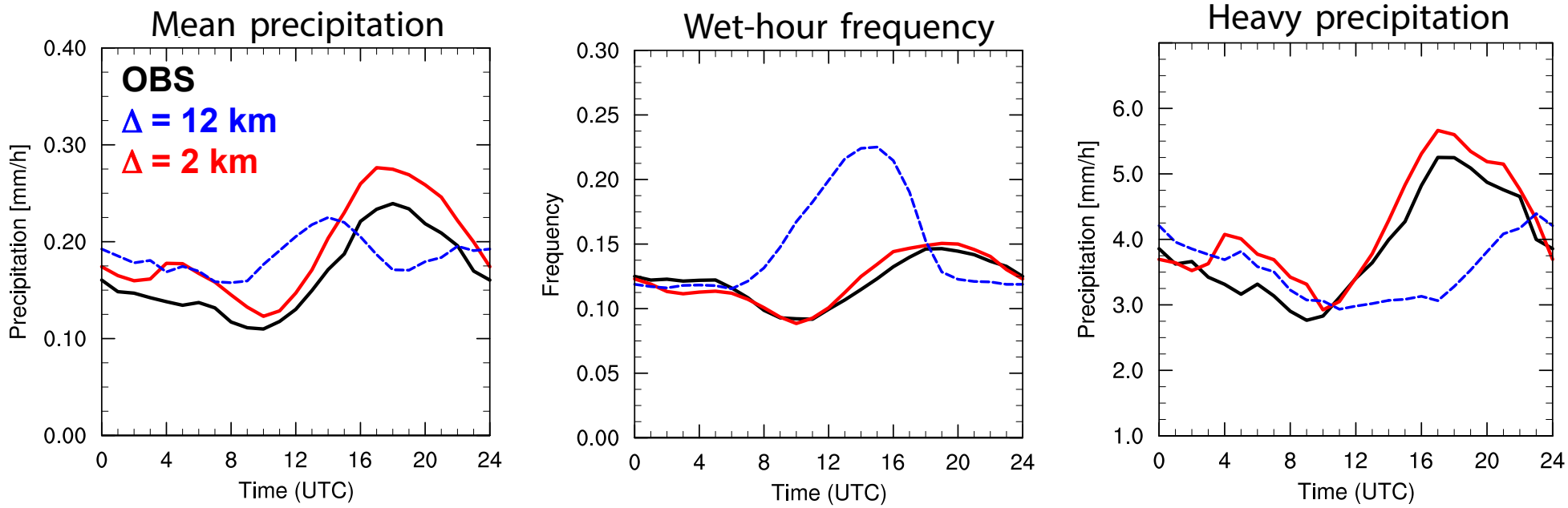
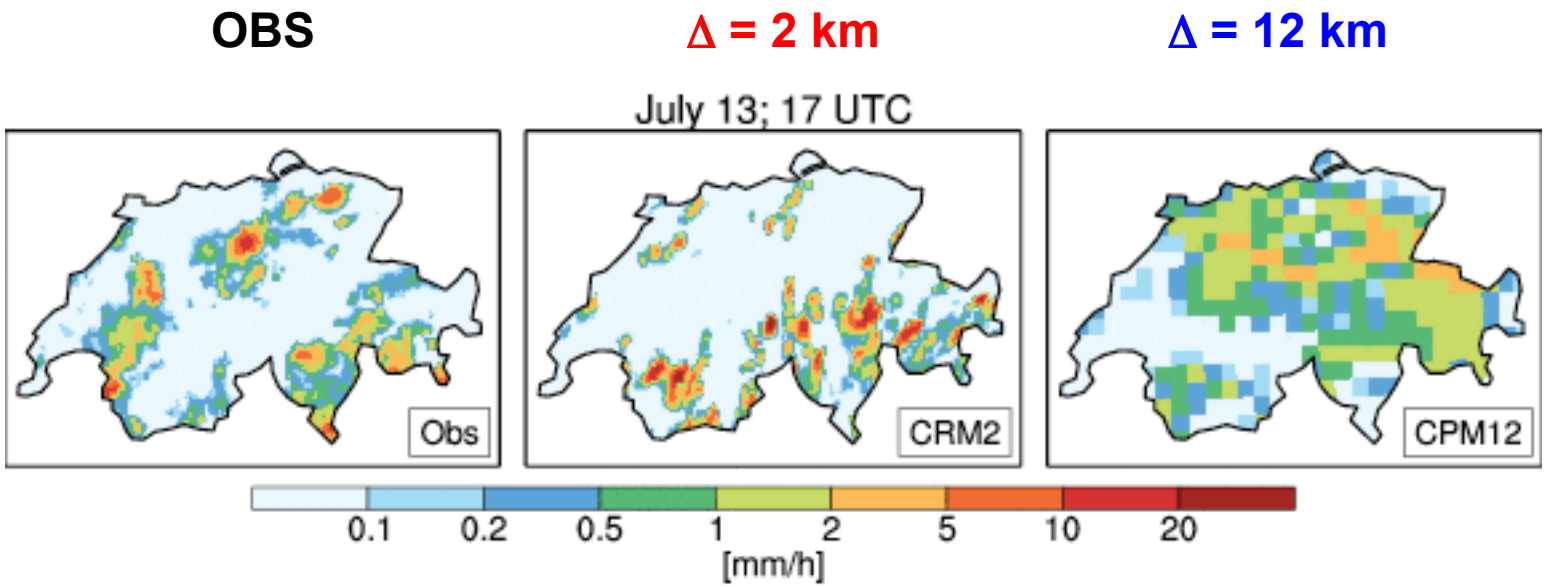


poor representation of diurnal cycle with Δ=12 km
dramatic improvement with Δ=2 km

(Ban et al. 2015, GRL)

Intercomparison of hourly sequence



Individual cells cannot be evaluated (chaotic dynamics)

Δ=2km qualitatively captures short-term small-scale events

Δ=12km largely misses heavy short-term events

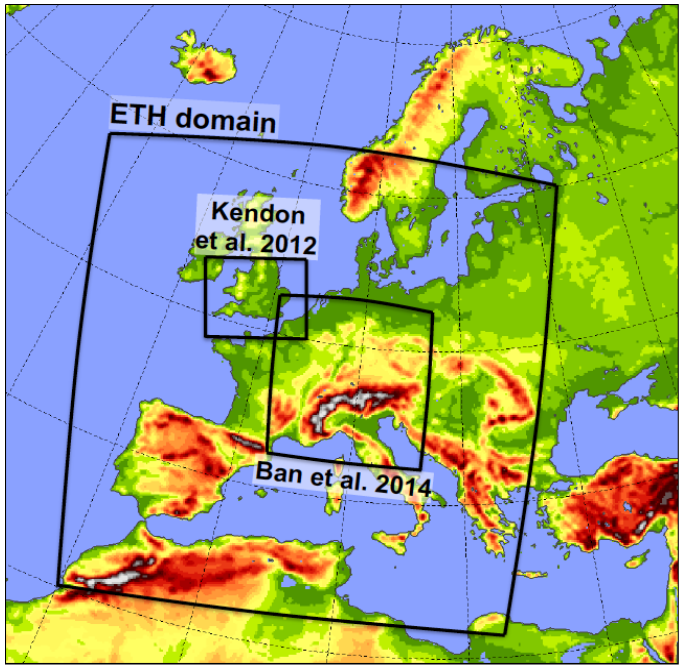
(Ban et al., 2014, OBS1h = Wüest et al. 2010)

European-scale simulations

GPU-version of COSMO model

- Large effort led by Oliver Fuhrer (MeteoSwiss)
  - runs entirely on GPUs
  - dynamical core rewritten in C++ and CUDA
  - parameterizations use OpenACC
- Also used for operational NWP (Δ=1 km)
- Runs on Piz Daint (Cray, CSCS)

Piz Daint: Linpac peak performance: 6x10^{15} Flop/s



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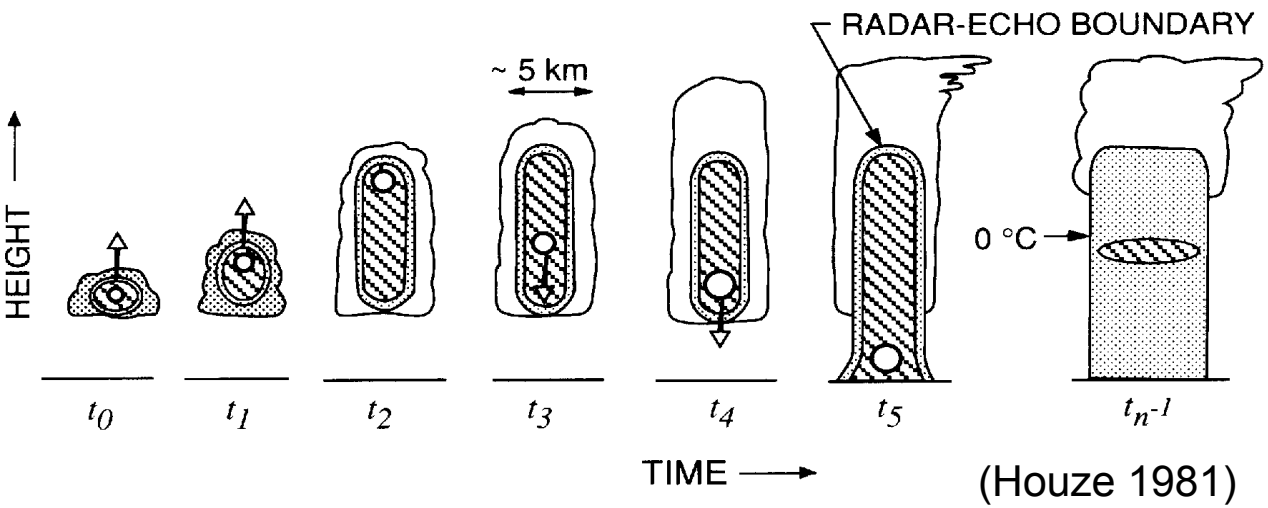
European-scale climate simulations

- Δ=2.2 km, 1536 x 1536 x 60 grid points
- Driven by intermediate Δ=12 km simulation
- Split-explicit, Δt = 20 s

Oliver Fuhrer (MeteoSwiss), Xavier Lapillone (C2SM / ETH), et al.;
Thomas Schulthess (CSCS), et al.;
PhD of David Leutwyler, Leutwyler et al. (2016, 2017)

Domain size matters

The statistics of convective cells needs to develop within computational domain!



(Houze 1981)

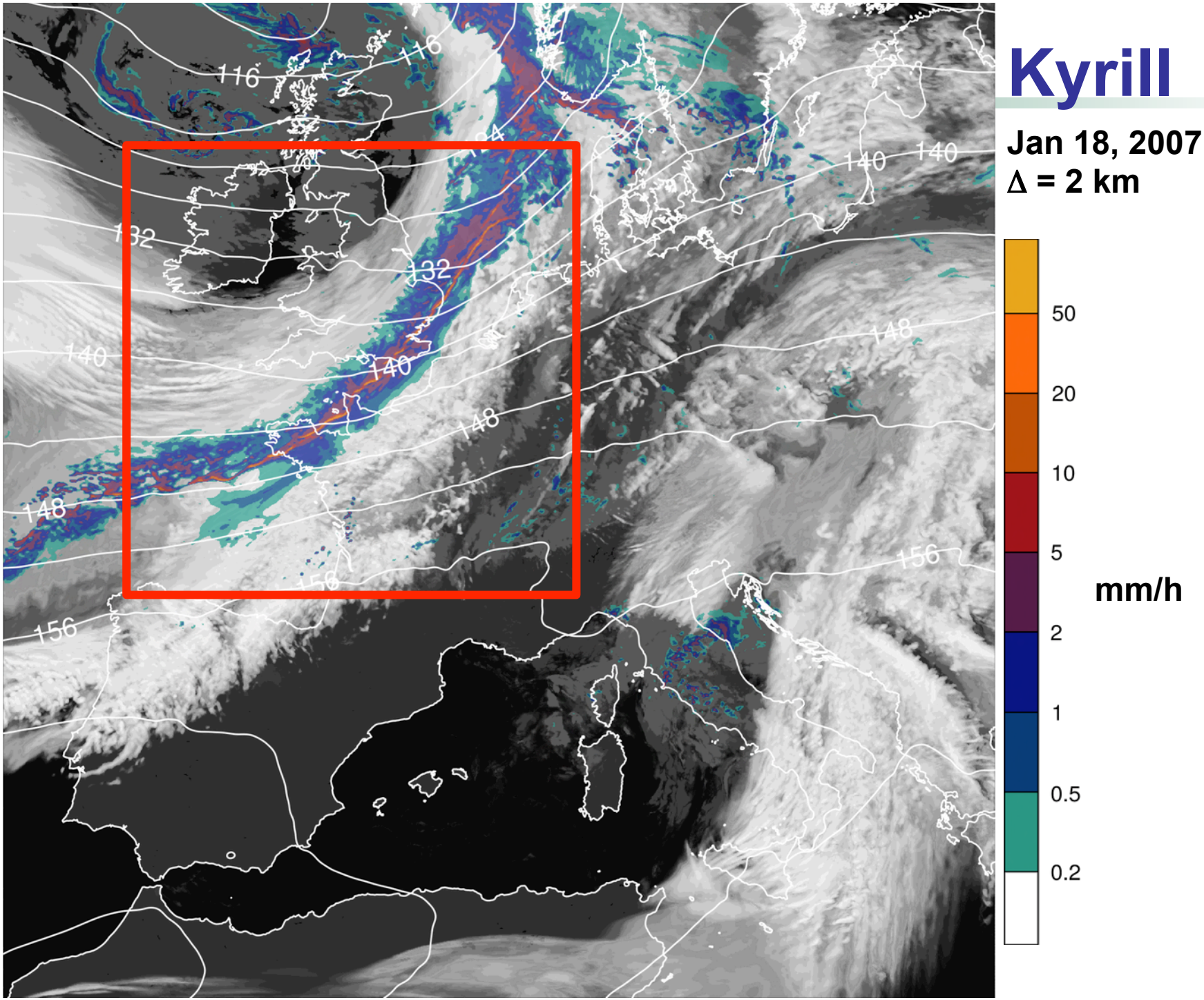
Lifecycle of a convective cell:

Lifetime:	6h
Propagation:	10 m/s
Distance:	200 km

- **A boundary zone of 100-200 km is affected by transition from parameterized to explicit convection.**
- **Very small domains damage the statistics of convection.**
- **Our simulations use wide lateral relexation zone (25-50 grid points).**

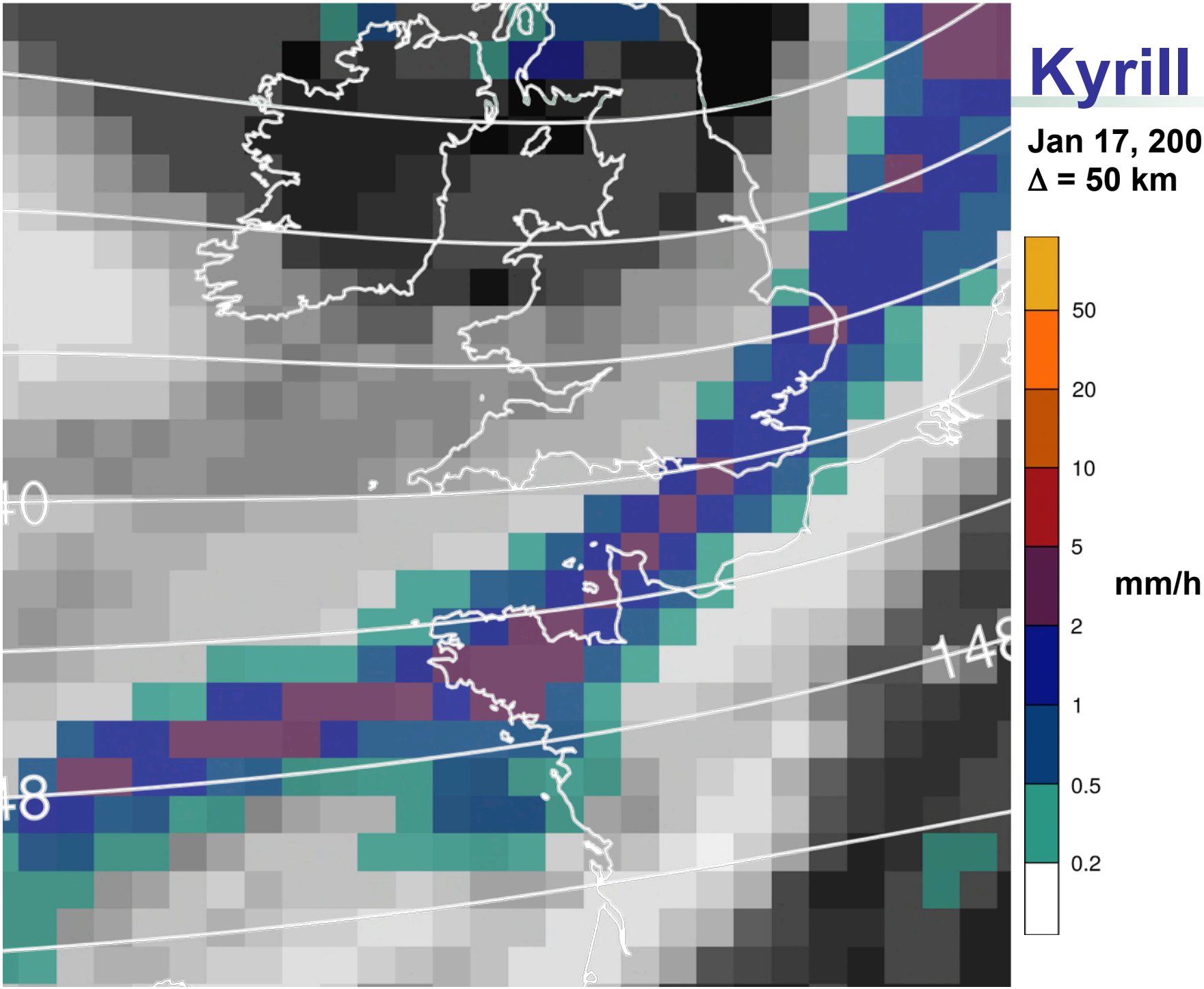
Kyrill

Jan 18, 2007, 12 UTC
Δ = 2 km



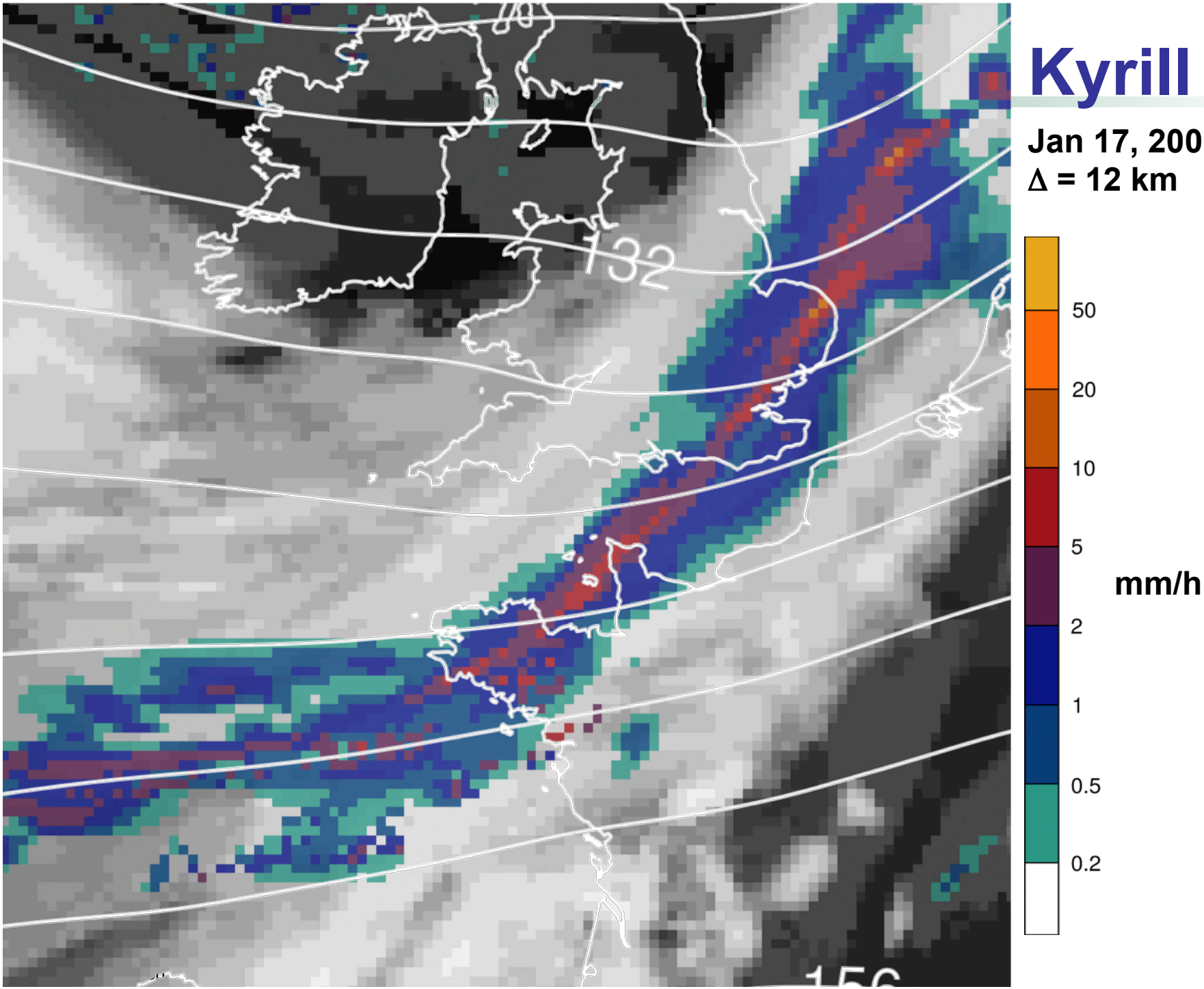
Kyrill

Jan 17, 2007, 12 UTC
Δ = 50 km



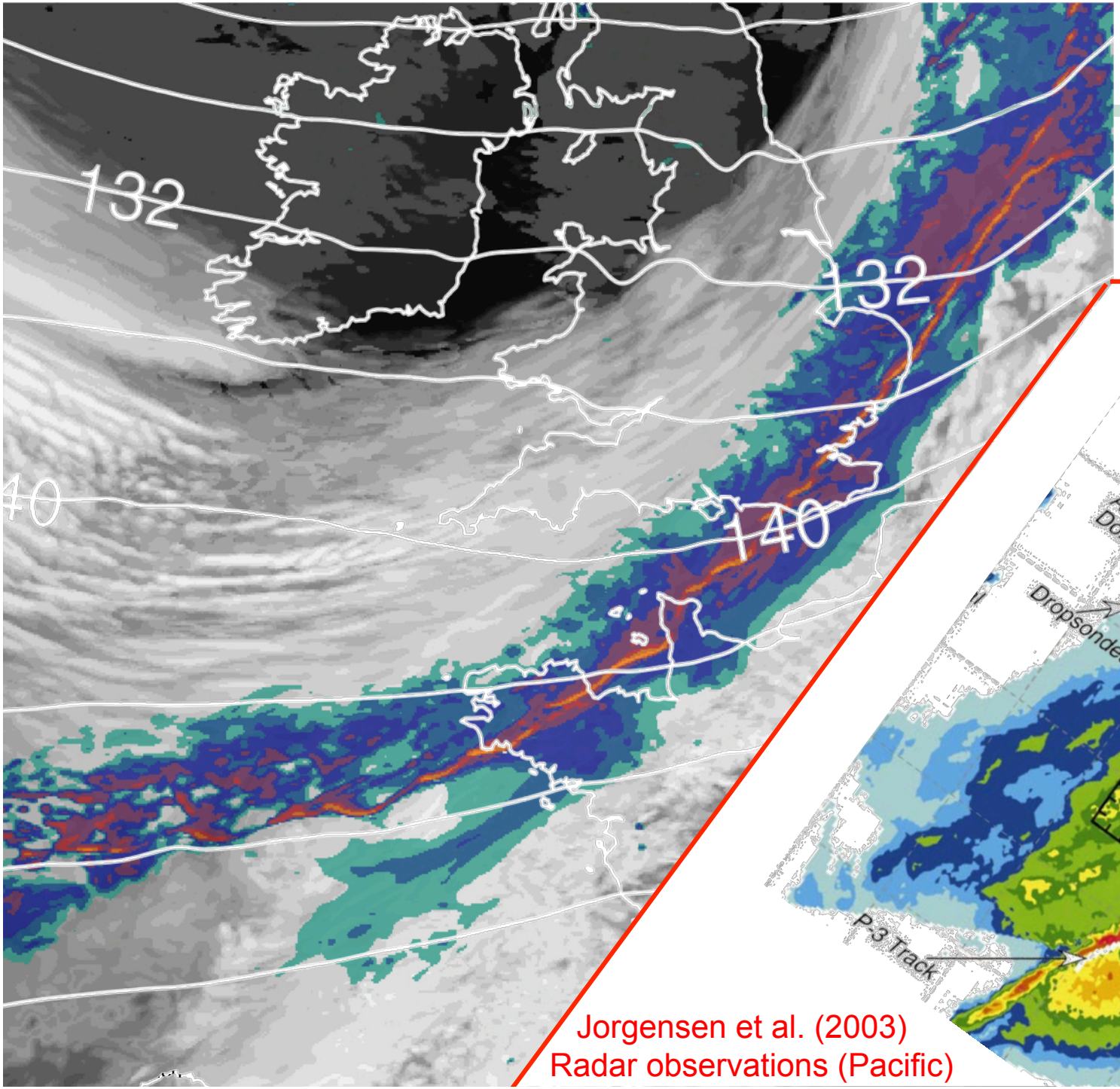
Kyrill

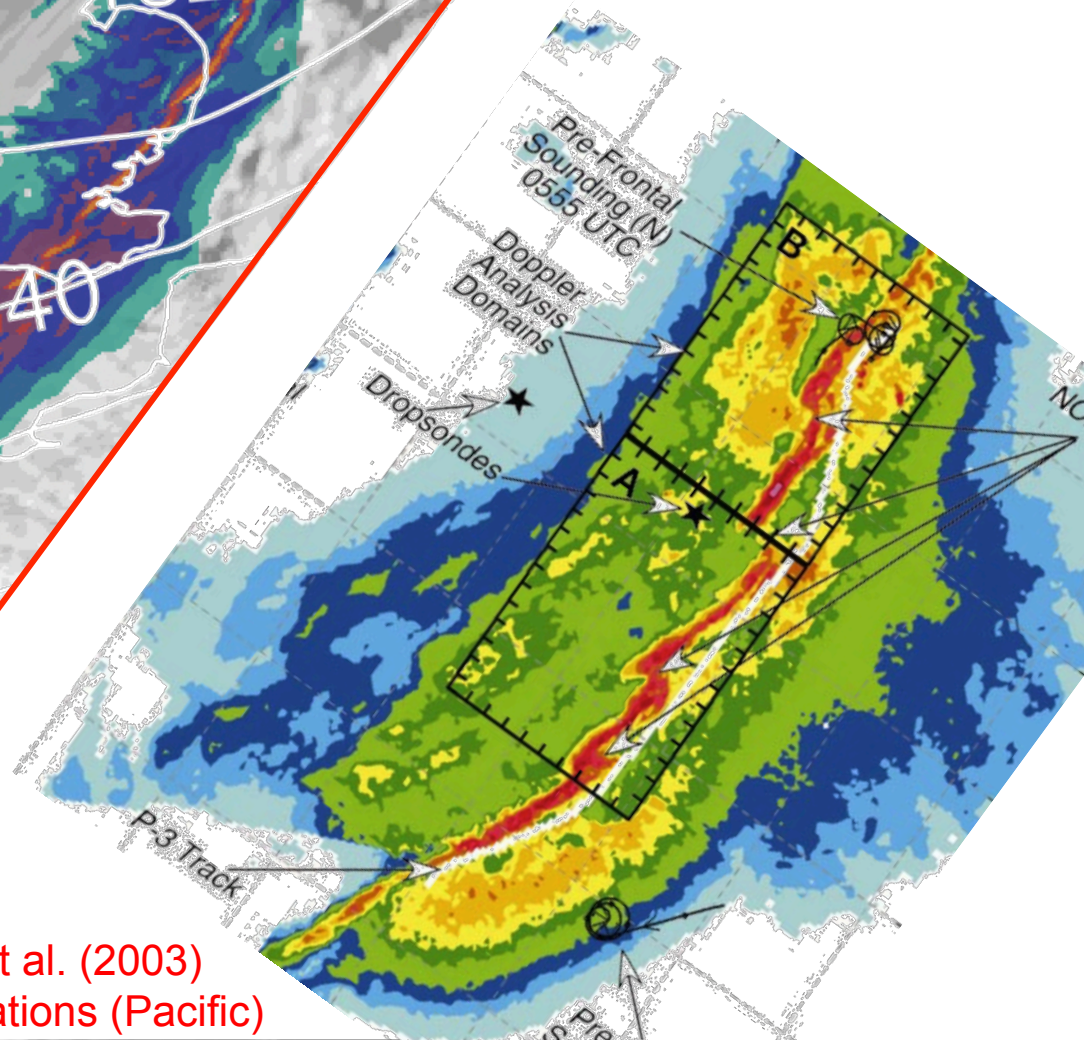
Jan 17, 2007, 12 UTC
Δ = 12 km



Kyrill

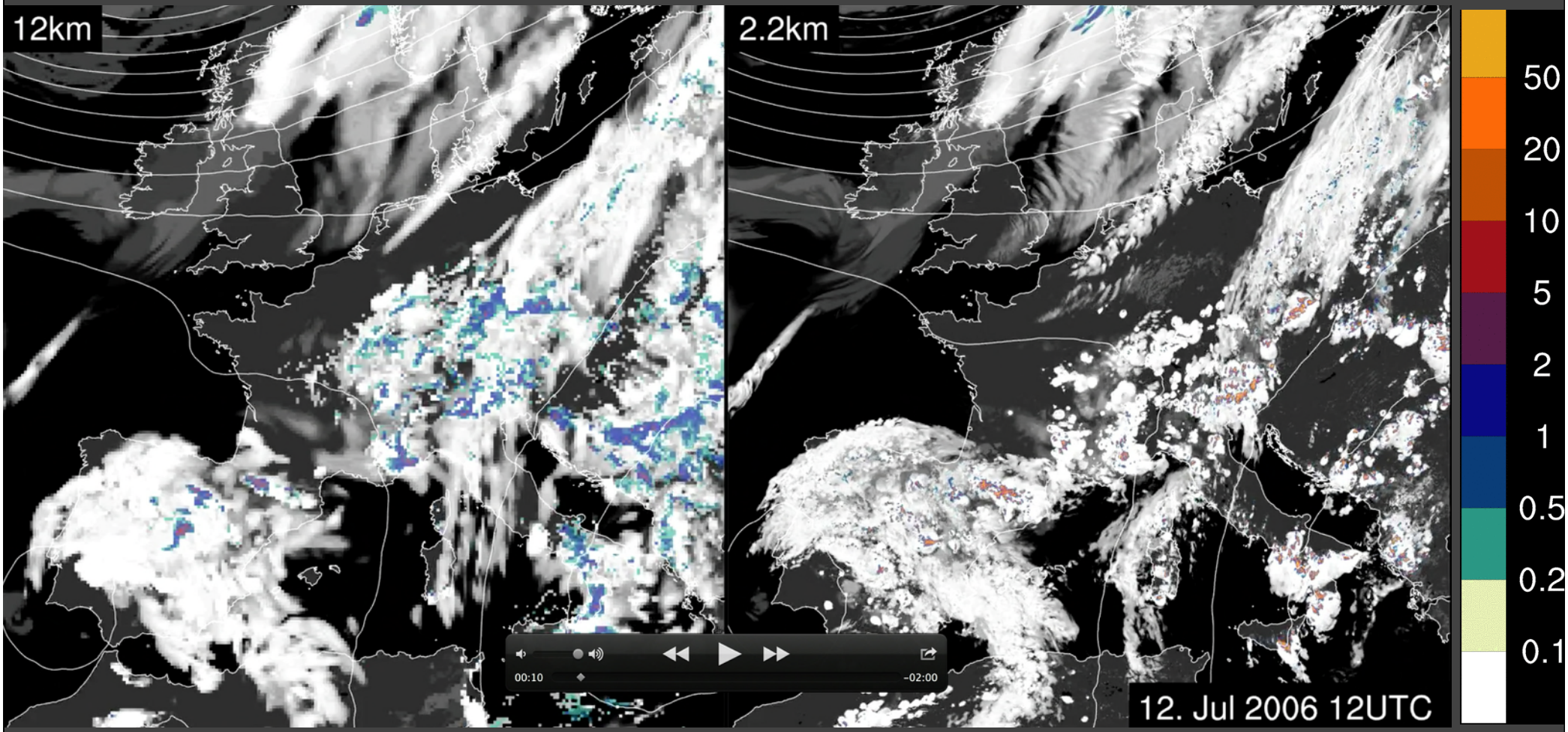
Break-up of cold-frontal rain band at Δ = 2 km





Jorgensen et al. (2003)
Radar observations (Pacific)

Summer convection
Simulations at 12 and 2 km



[mm/h]

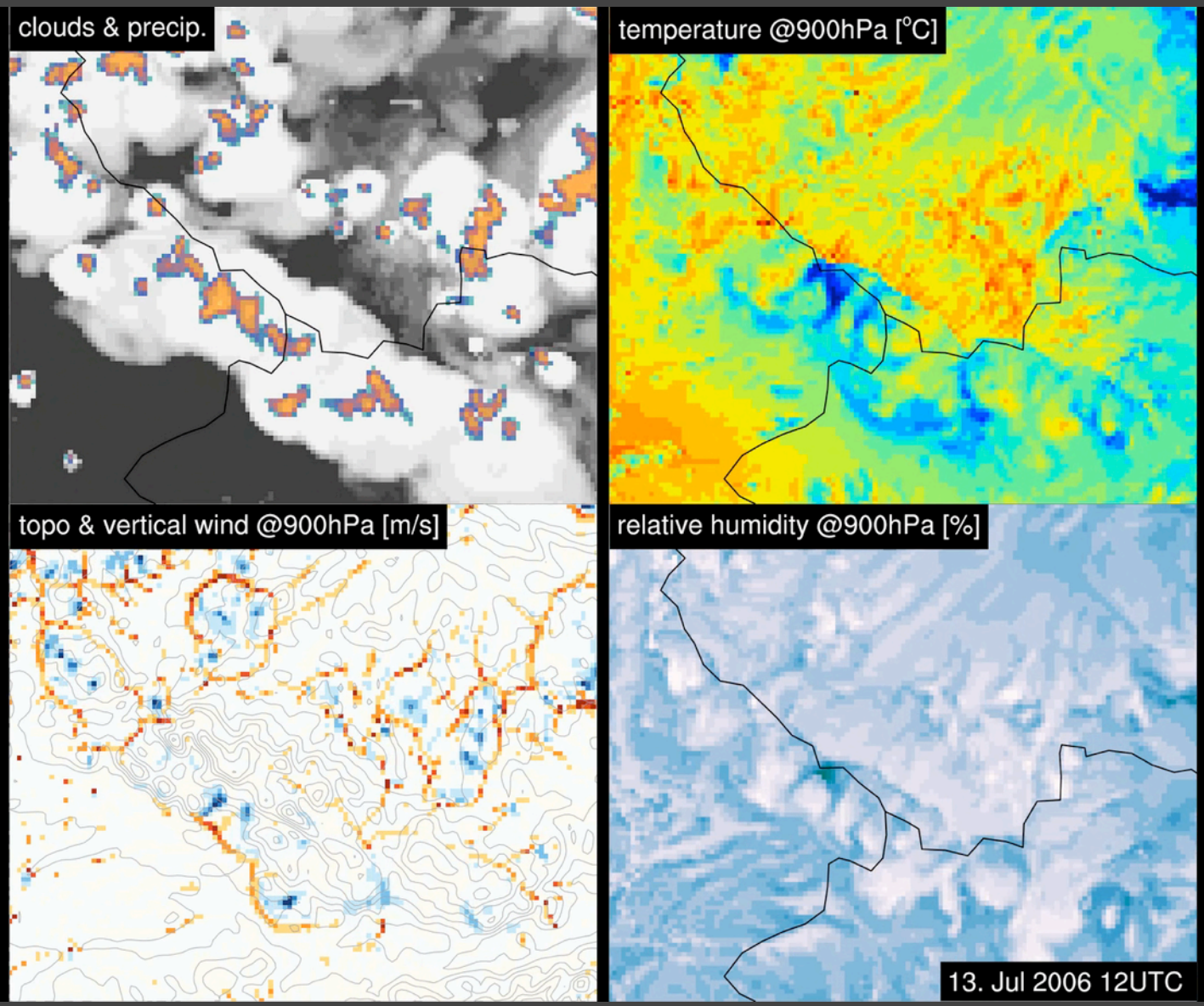
Schär, ETH Zürich

David Leutwyler, ETH Zurich, animations via crCLIM: http://www.c2sm.ethz.ch/research/crCLIM

Convection over lake Constance

April 27, 2016, Lake Constance (Kurt Abderhalden)

Simulations at 12 and 2 km



David Leutwyler, ETH Zurich, animations via crCLIM: http://www.c2sm.ethz.ch/research/crCLIM

Intercomparison of two modeling systems

UK / Swiss model intercomparison project:

- Coordinated simulations driven by ERA-Interim
- Set-up as in Leutwyler et al. (2017):
  2.2 km grid spacing, European domain
- Currently based on 5 years of simulations (1999-2003)

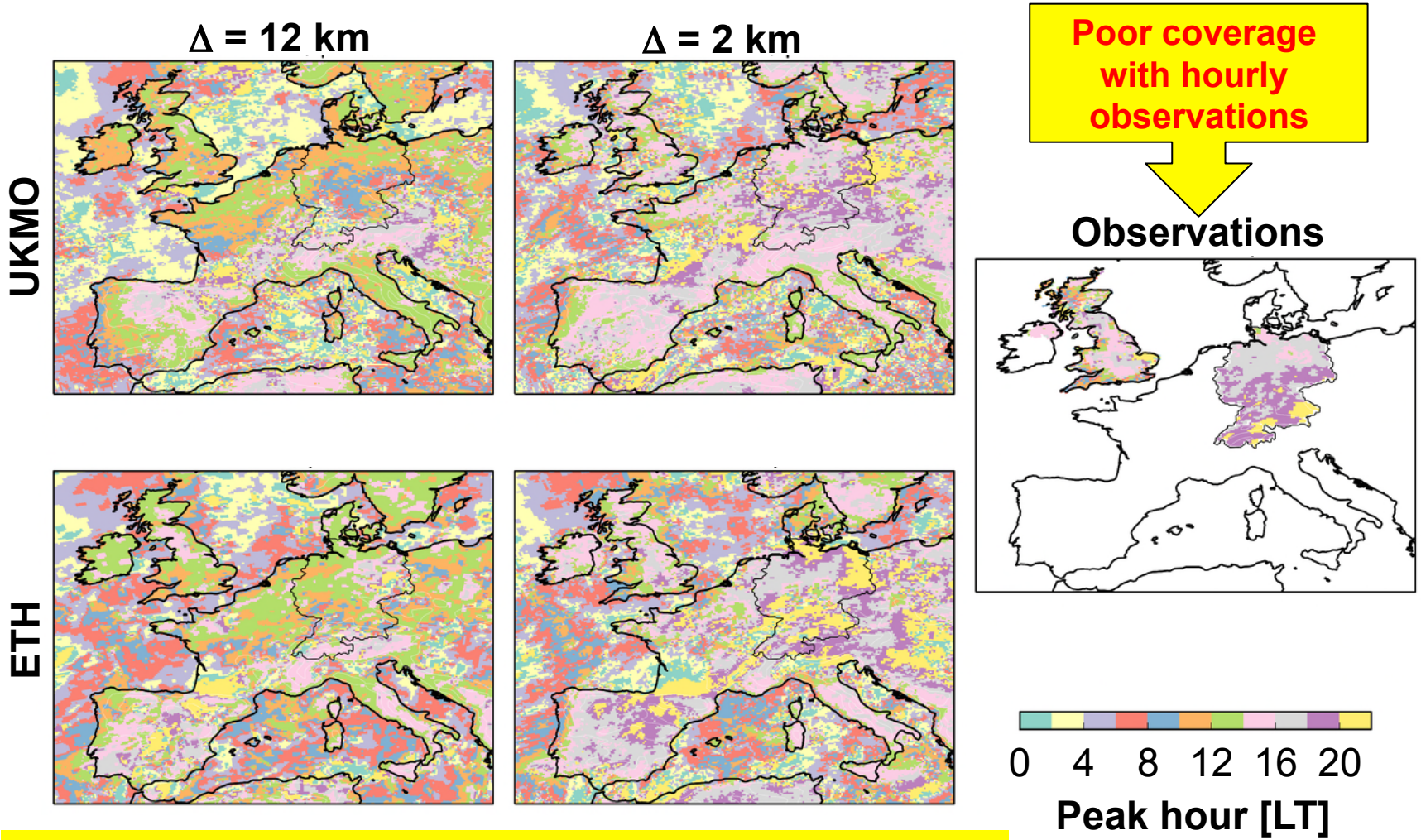
Both models have been developed and are used for NWP, but:

- Models are based on completely different dynamical cores
  - UK model: Unified Model (UM), semi-implicit semi-Lagrangian
  - Swiss model: COSMO-GPU, split-explicit
- Equipped with different parameterization packages
- Tuned / calibrated for different climates

(Ségolène Berthou et al., in prep)

Intercomparison of two modeling systems

JJA phase of diurnal cycle of precipitation (harmonic fit)



Basic biases and improvements are remarkably similar, despite using completely different models!

(Ségolène Berthou et al., in prep)

OUTLINE

Motivation

Decade-long simulations at Δ = 2 km

Precipitation scaling with climate change

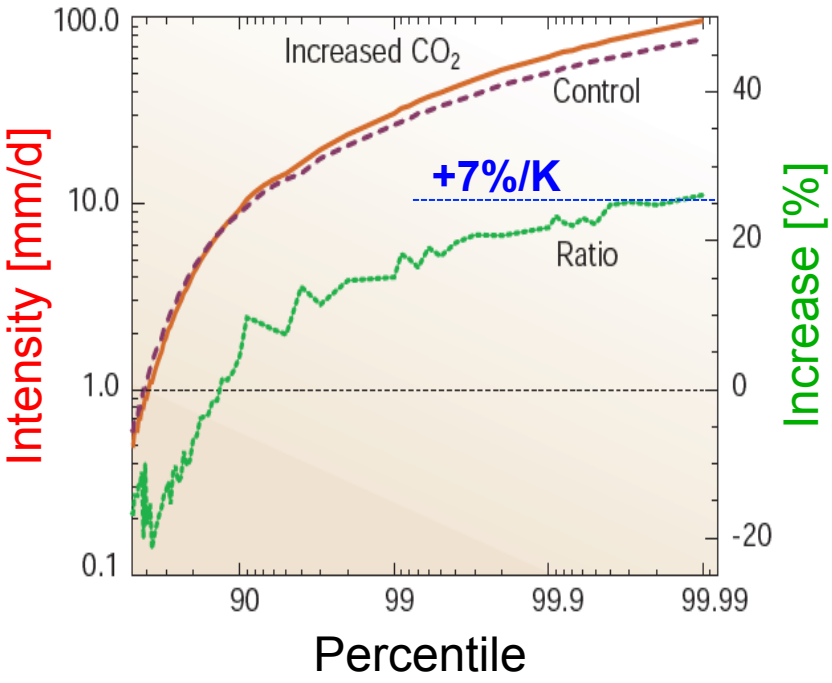
Convergence?

Challenges

Adiabatic or super-adiabatic scaling?

Allen and Ingram (2002):

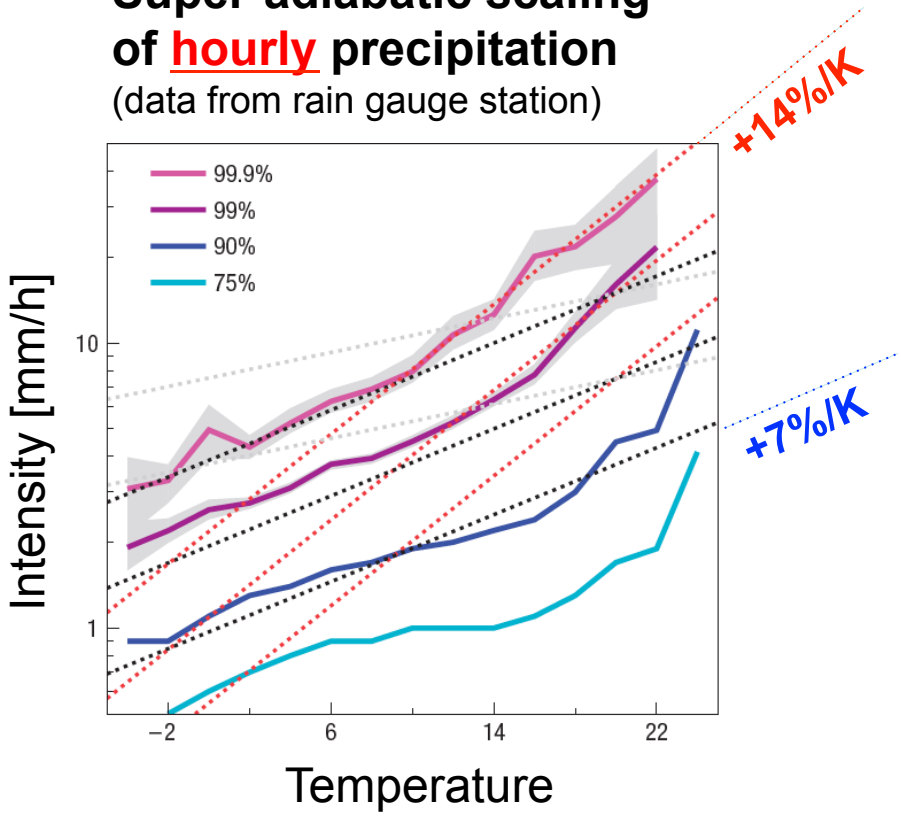
Clausius-Clapeyron scaling of daily precipitation
(data from climate change experiment)



Supported by many studies
(Frei et al. 1998; Allan and Soden 2008, O'Gorman and Schneider, 2009)

Lenderink and van Meijgaard (2008):

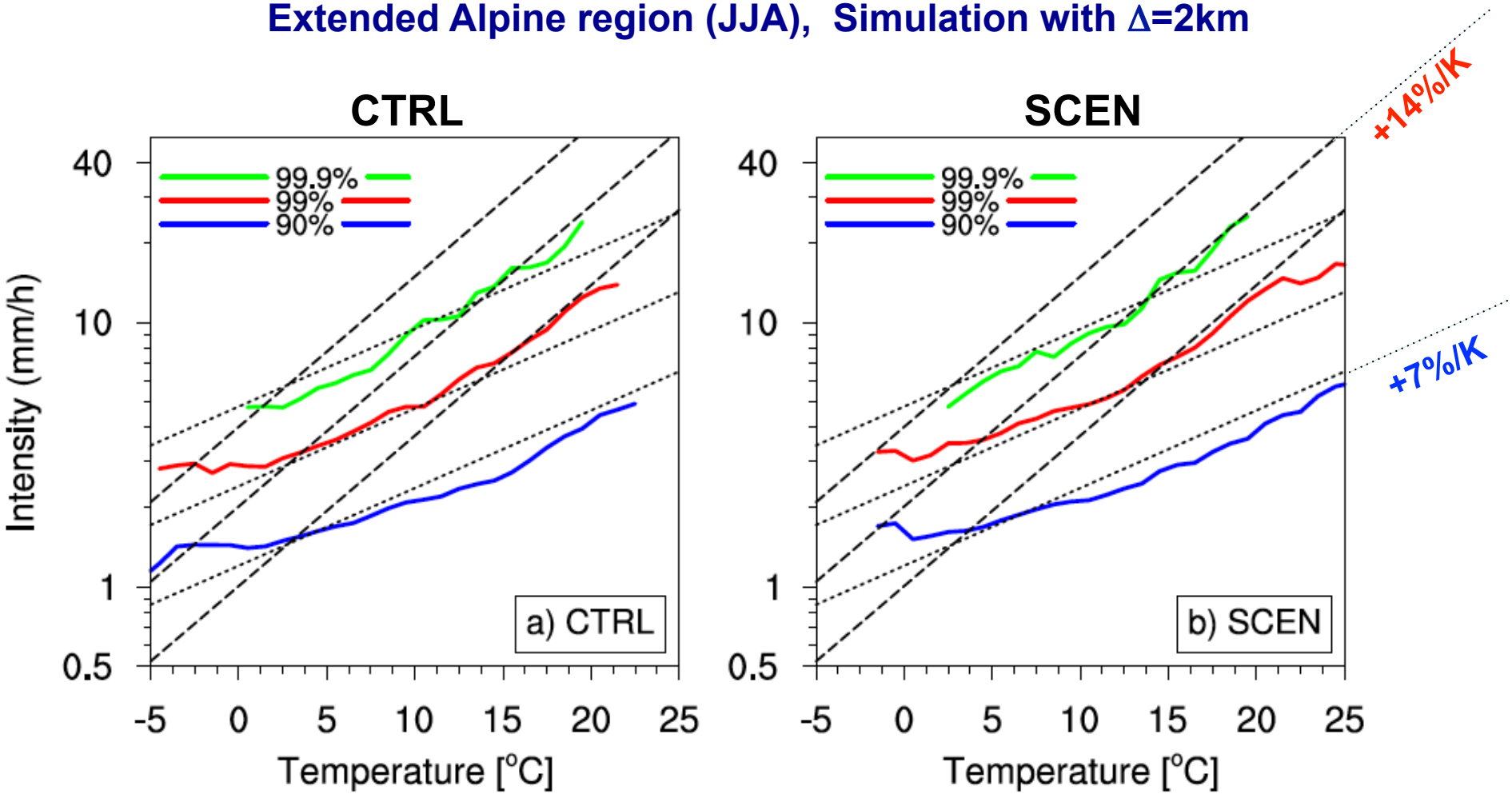
Super-adiabatic scaling of hourly precipitation
(data from rain gauge station)



Some scenario simulations support this type of scaling
(e.g. Kendon et al. 2014)

Super-adiabatic scaling, CTRL and SCEN

Extended Alpine region (JJA), Simulation with Δ=2km

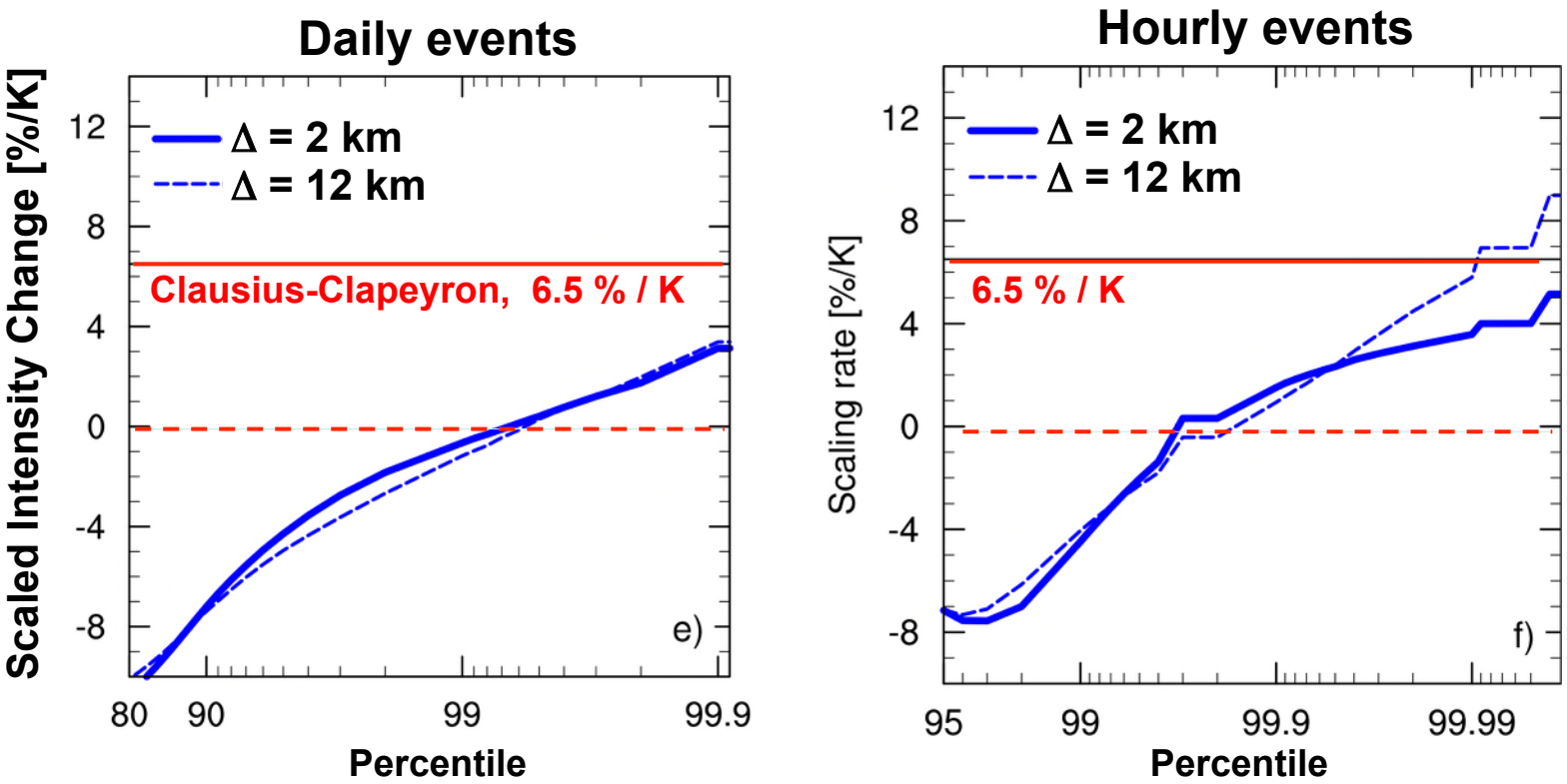


Super-adiabatic scaling evident within both CTRL and SCEN

(Ban et al., 2015)

Precipitation scaling with climate change

Extended Alpine region (JJA), RCP8.5, 2081-2090 versus 1991-2000



- SCEN-CTRL consistent with Clausius-Clapeyron scaling (6-7%/K), although super-adiabatic scaling is simulated within CTRL and SCEN
- There are some subtleties in percentile definition: beware of wet-day percentiles!
- Significant differences at large percentiles between 12 and 2km resolution

(Ban et al., 2015; Schär et al. 2016)

OUTLINE

Motivation

Decade-long simulations at Δ = 2 km

Precipitation scaling with climate change

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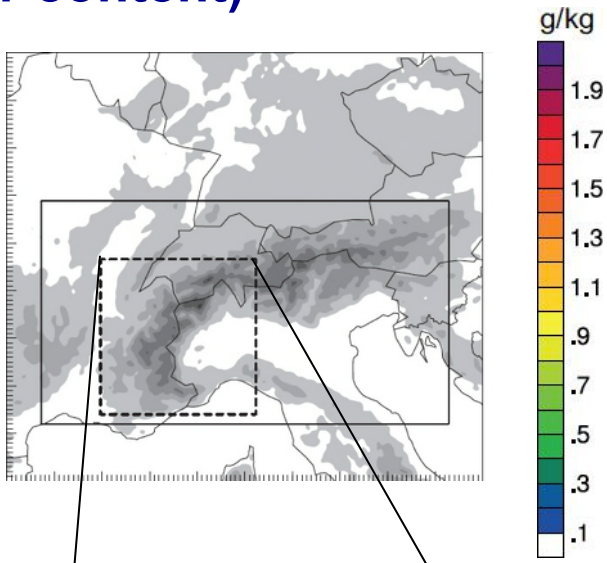
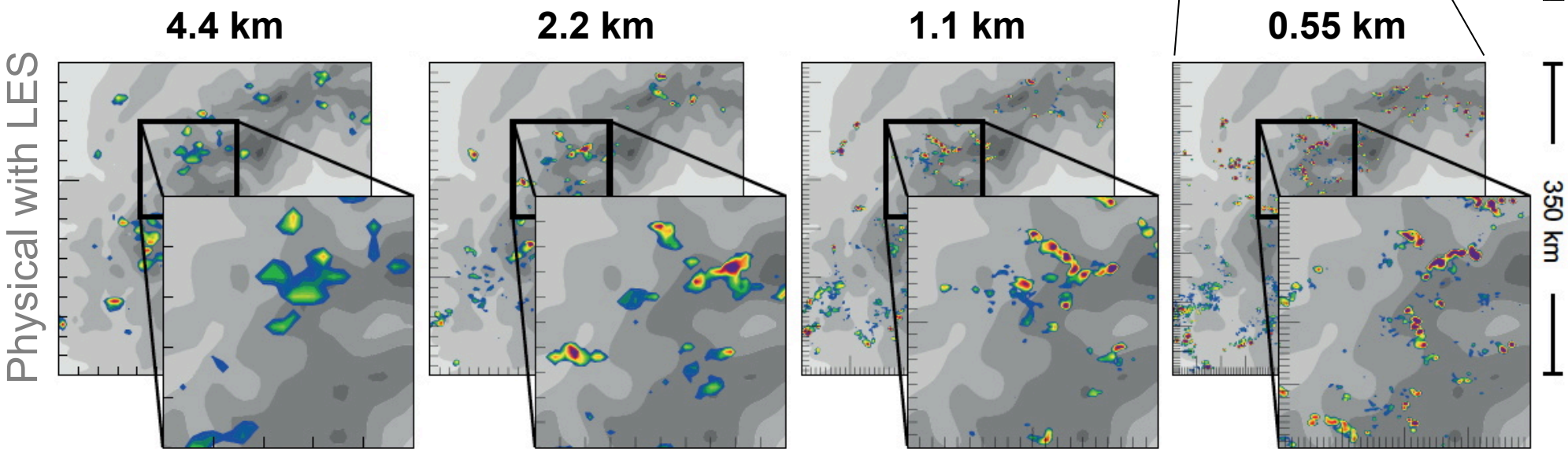
Challenges

Convergence?

Summer convection over Alps (liquid water content)

- Scales of convective cells decrease with $\Delta x \rightarrow 0$
- Structure of updrafts does not converge
- Convergence is far from obvious!

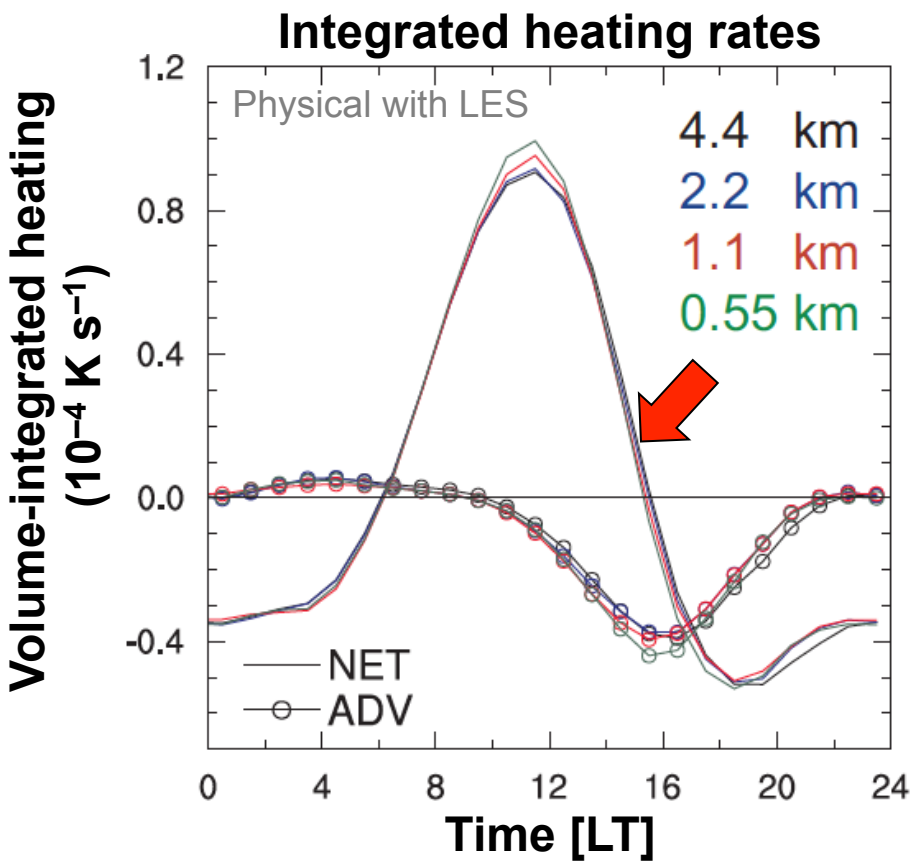




(Langhans et al., J. Atmos. Sci, 2012)

Bulk convergence

Bulk = domain and time-averaged



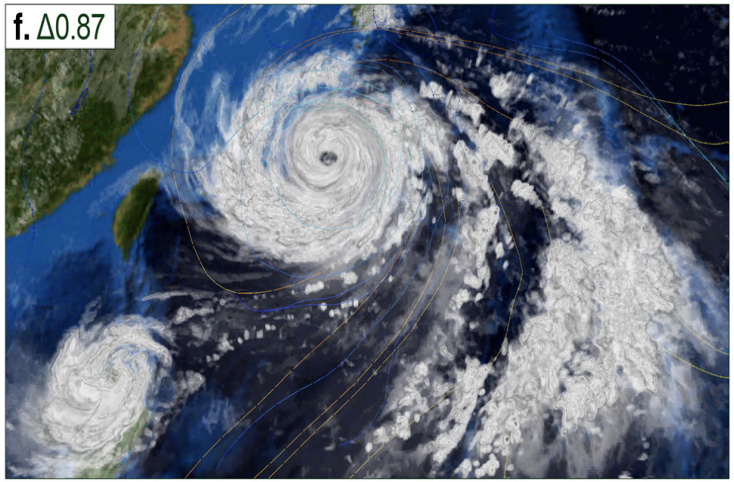
- **Simulations exhibit astounding degree of bulk convergence already at O(4 km)!**
- **Despite lack of convergence in small-scale structures.**

(Langhans et al., J. Atmos. Sci, 2012)

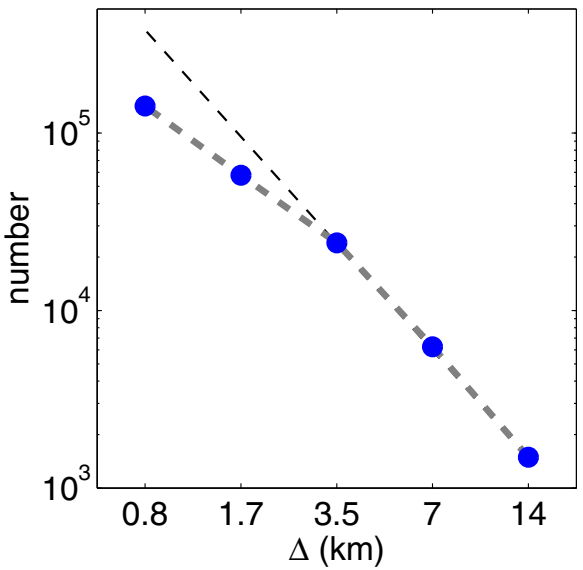
Structural convergence

Structural = Structure of deep updrafts

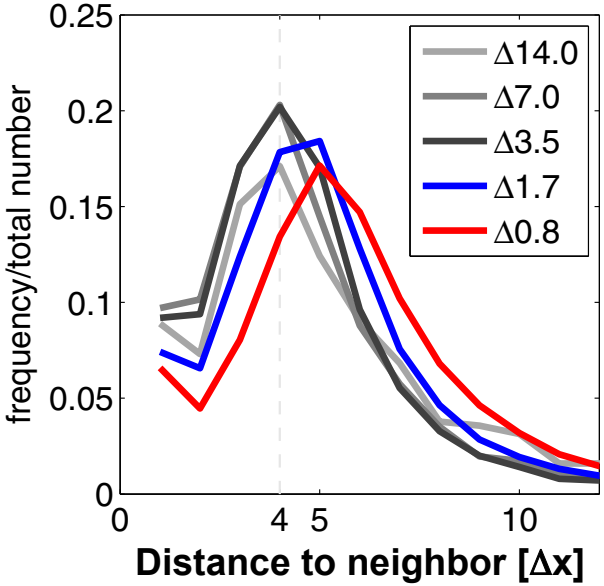
Statistics of convection from global NICAM simulations



Number of updrafts



Distance between updrafts



There is "trend of convergence" around Δ=2 km, but statistics not yet fully converged.

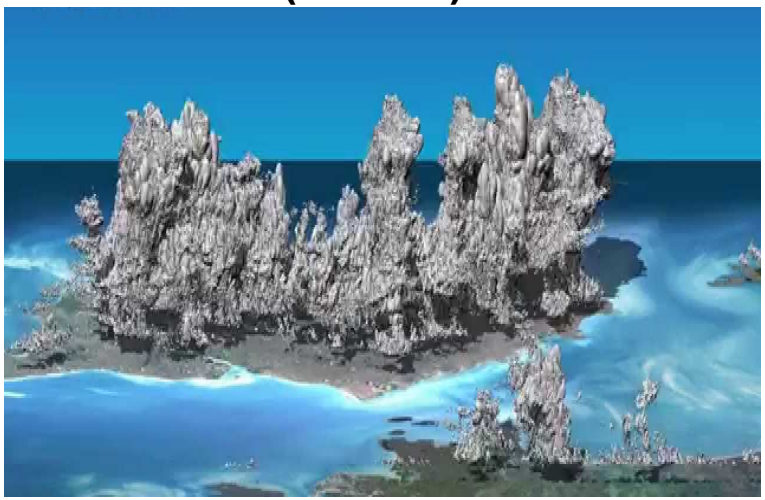
They find resolution-dependence of OLR.

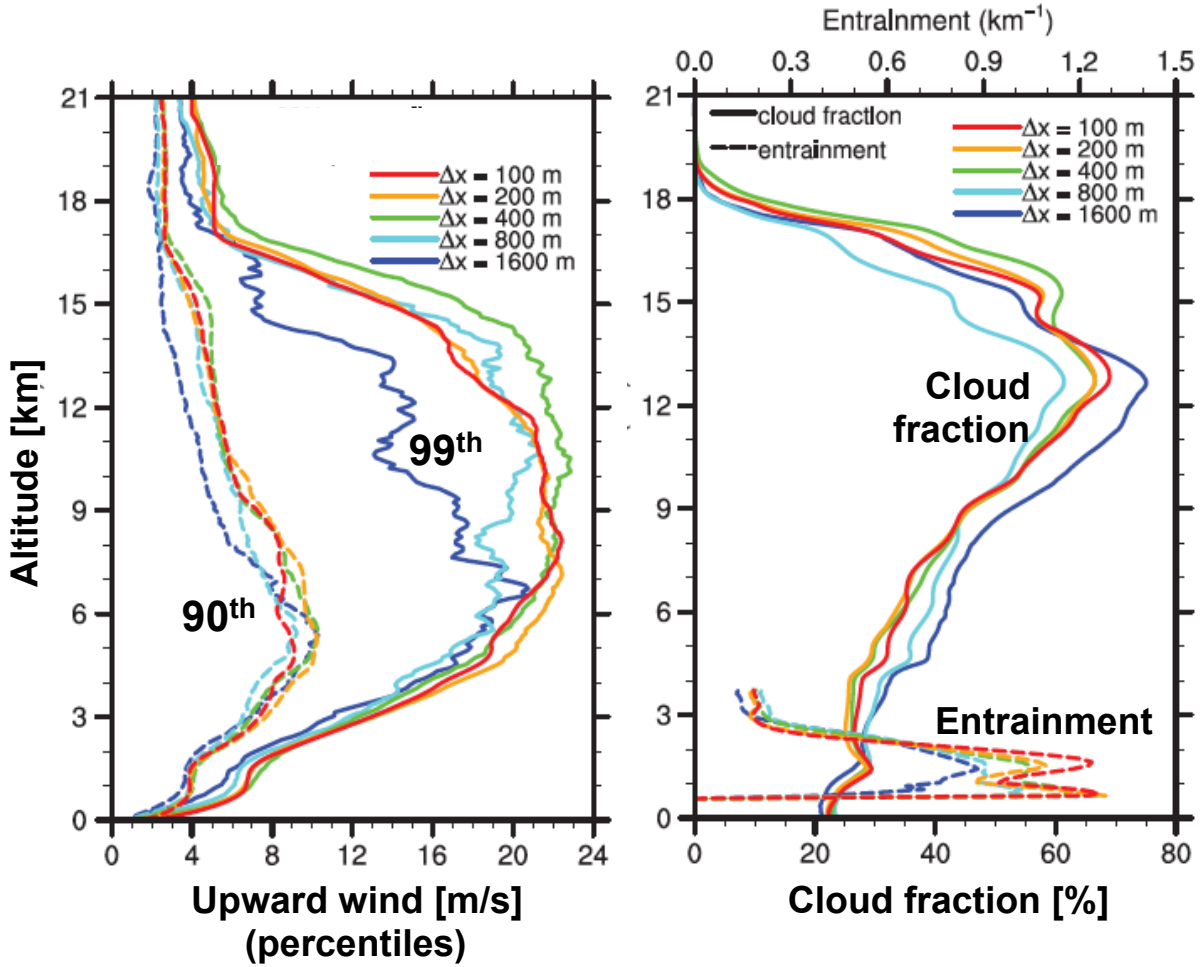
(Kajikawa et al. 2016; Miyamoto et al. 2015)

Structural convergence

Structural = Structure of deep updrafts

Convection over Tiwi Islands (Hector)





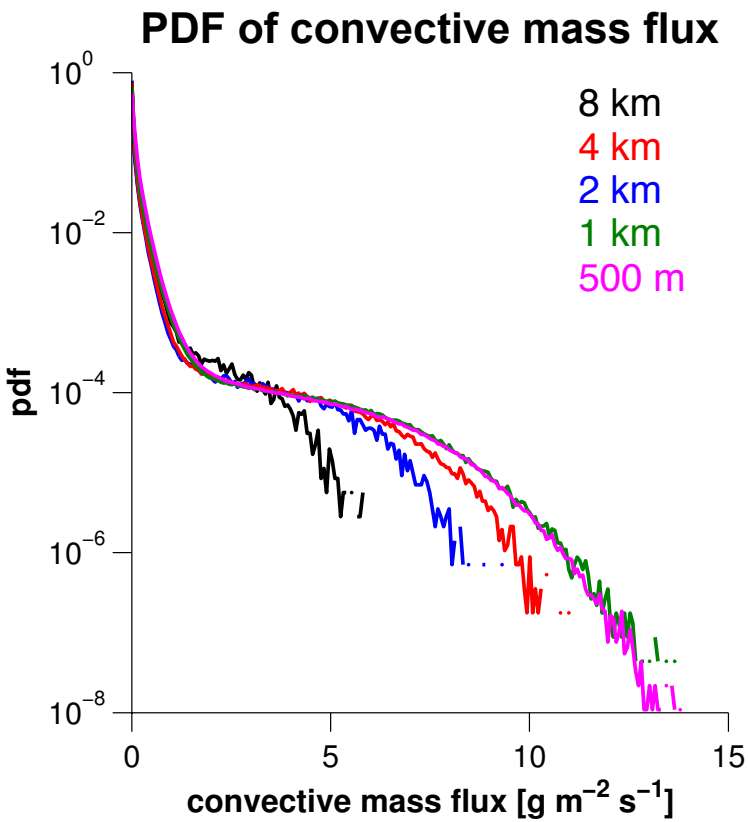
Properties of updrafts converge at O(200 m)

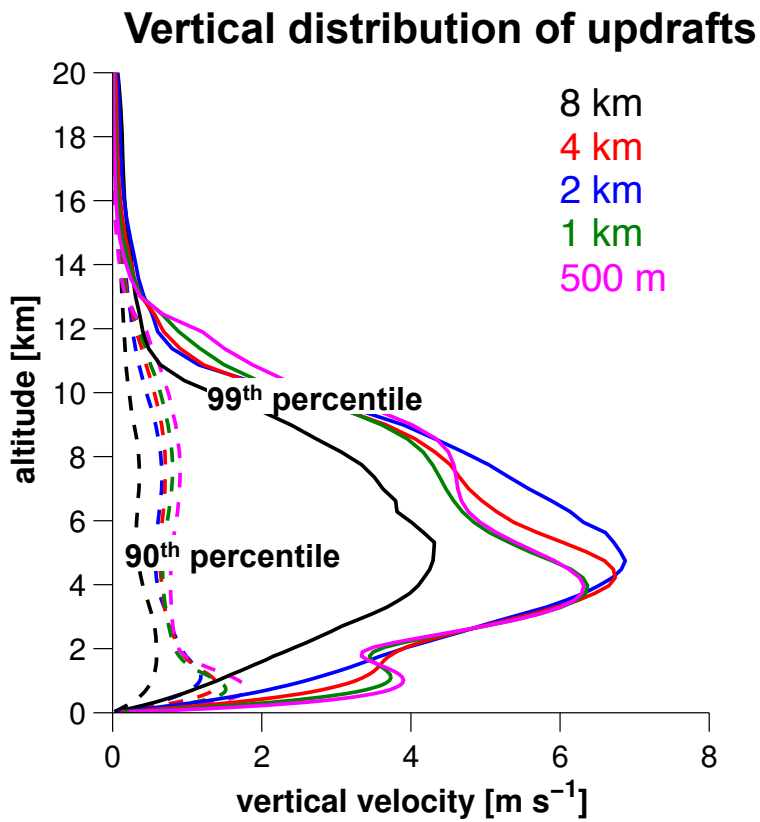
(Dauhut et al. 2015, ASL

Structural convergence

Structural = Structure of deep updrafts

Convergence in idealized simulations





Properties of deep updrafts converge near 1 km

(Davide Panosetti, PhD ETH Zurich)

OUTLINE

Motivation

Decade-long simulations at Δ = 2 km

Precipitation scaling with climate change

Convergence?

Challenges

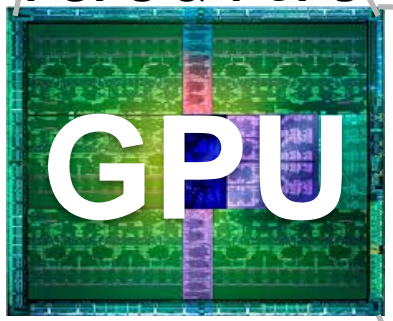
Hardware Challenge

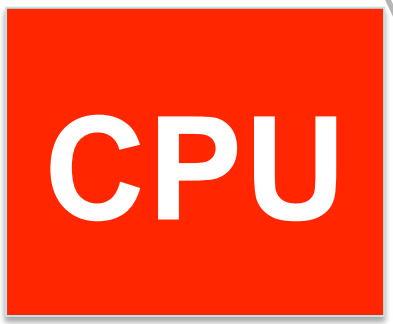
Emerging hardware architectures are highly heterogeneous

Piz Daint = 5272 Nodes

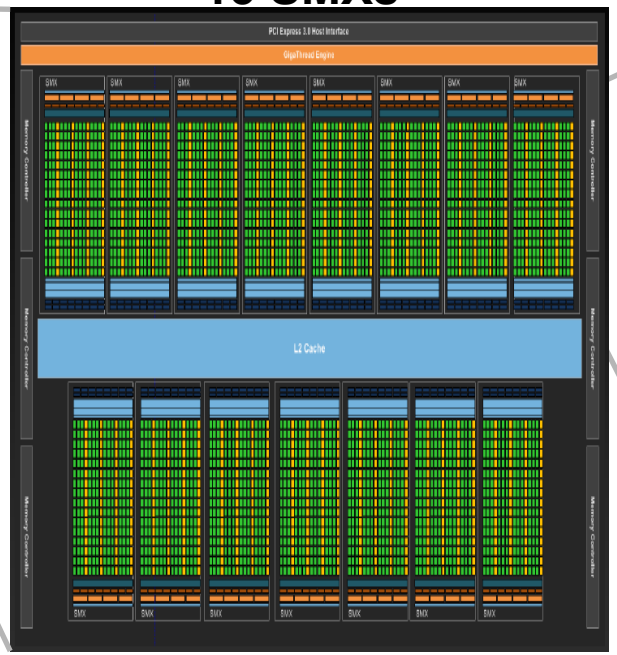
Piz Daint Cray XC30

1 Node = 1 GPU & 1 CPU

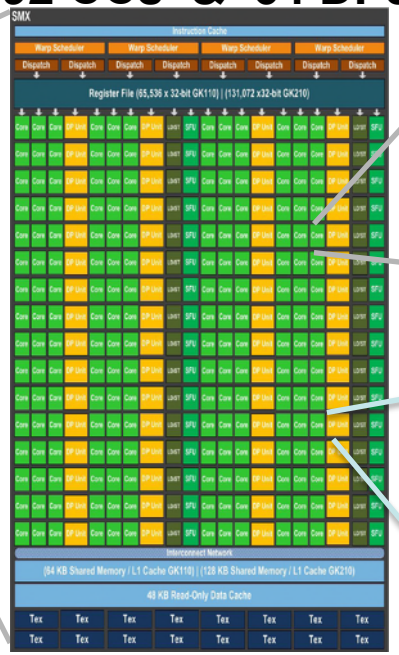




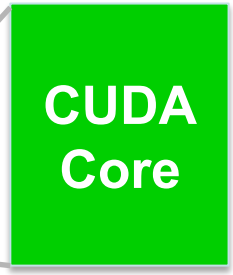
1 GPU = 15 SMXs



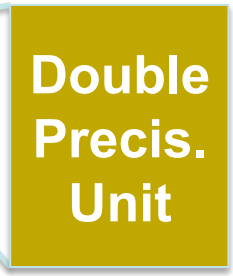
1 SMX = 192 CCs & 64 DPs



1 CC



1 DP



Schär, ETH Zürich

Emerging challenges

1) **Heterogeneous design of modern supercomputers (e.g. with GPUs):**
   Trend will likely continue, HPC will continue to exploit commodity hardware!

2) **Mass storage requirements and I/O bandwidth are becoming a key challenge**
   I/O Requirements for 10-year simulation (with a dramatically reduced output list):
   - European simulations (Leutwyler et al. 2017): 55 Terabyte
   - Global simulations at same resolution: 25 Petabyte

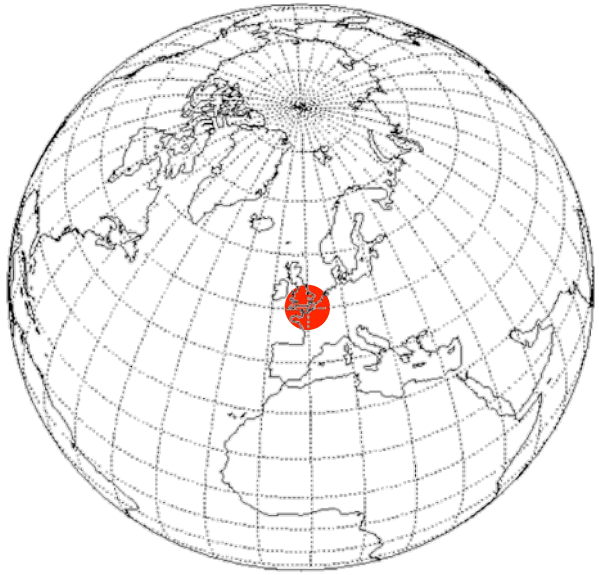
   Fundamental limitation is the I/O bandwidth!

3) **Moving data is becoming THE critical bottle neck:**
   Moving data within cores and across cores is more costly than compute operations.

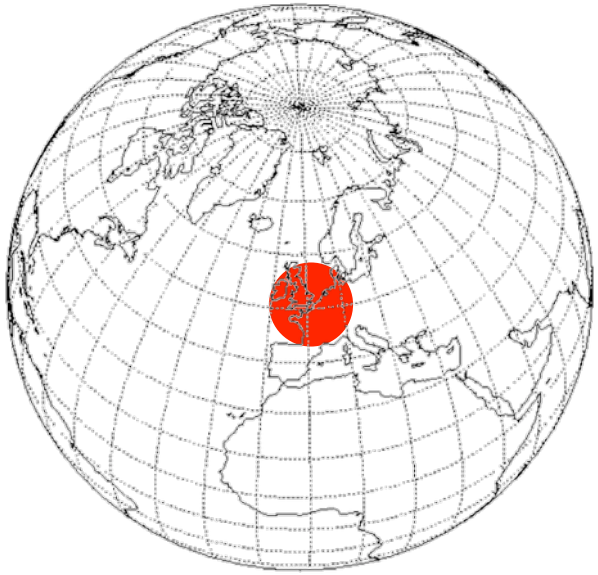
(with input from Thomas Schulthess, Thorsten Hoefler, ETH Zürich)

Propagation in models

In order to minimize communication of data,
numerical methods should reflect principles of physical propagation

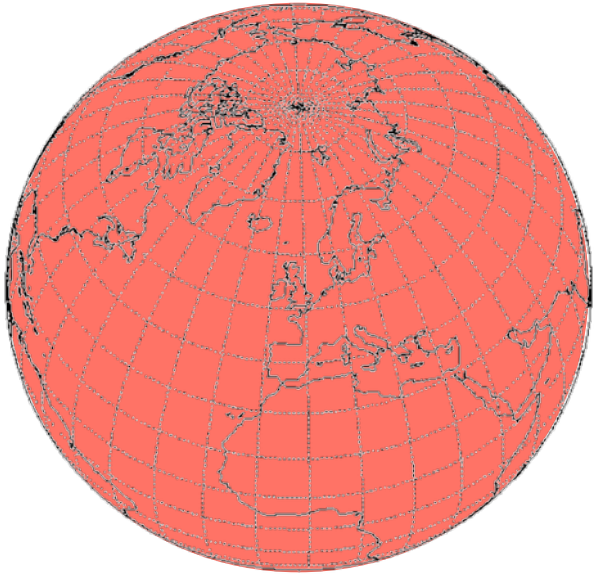


Propagation
in the real atmosphere
(ca 1200 km / hour,
critical speed: sound waves)



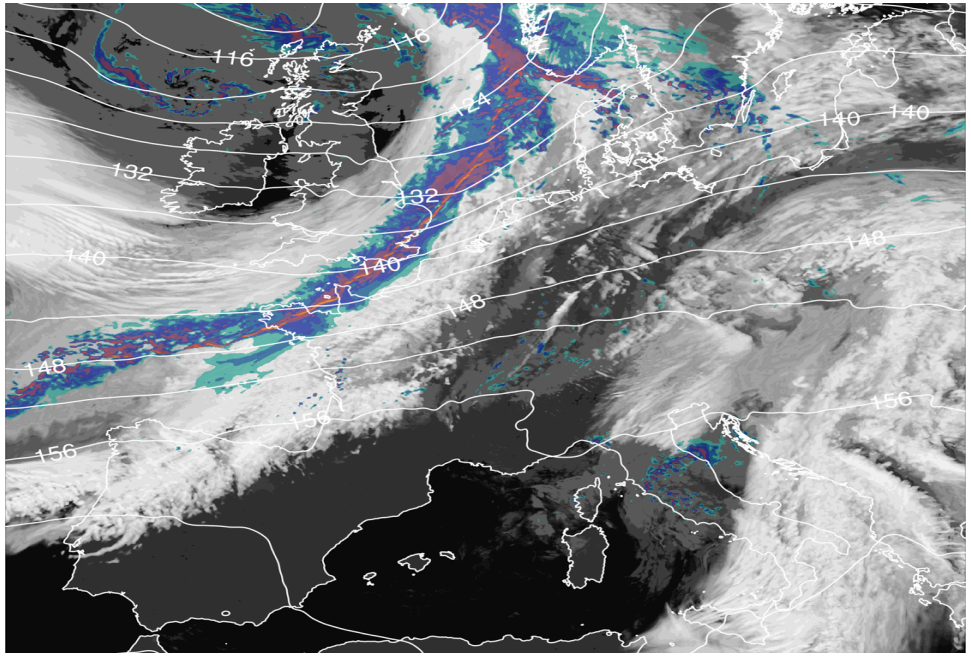
Propagation of data
in a split-explicit model
(ca 2000 km / hour)

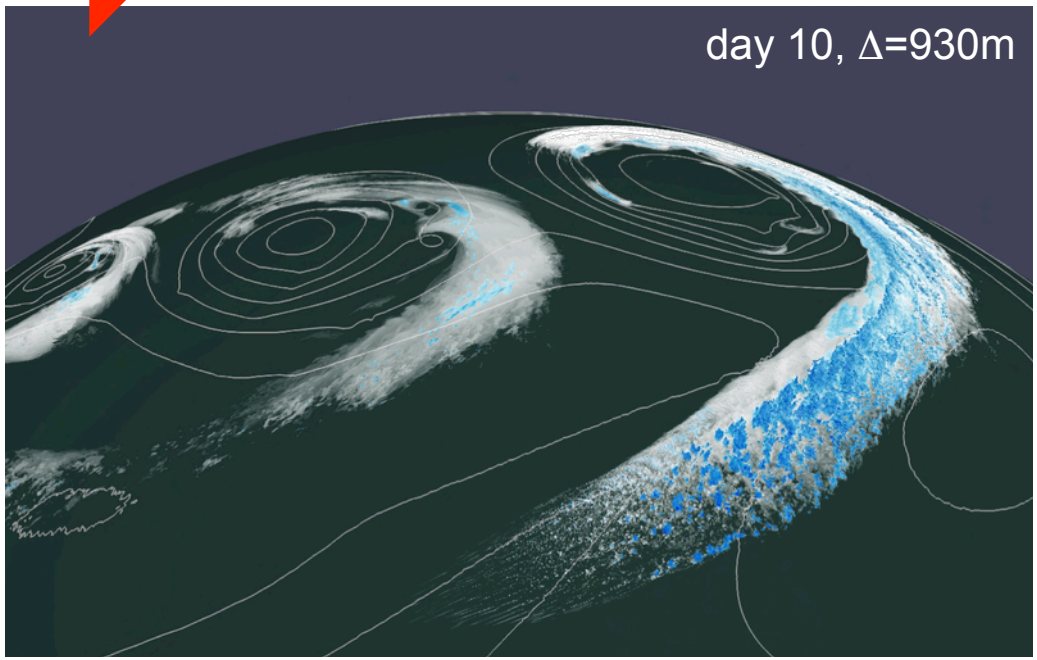
Approach in
COSMO-GPU



Propagation of data
in global spectral models
(and some implicit models)
(global communication
at each time step)

European domain → Proof of concept → Global domain





European simulations:

- Can run 1 day in 10 min (1 yr in 2.5 days)
- Requires 12x12=144 GPU nodes (P100) (2.8% of nodes of PizDaint)
- Near-perfect weak scaling => Can expand domain without increasing wall-clock time.

(Leutwyler et al. 2016)

Near-global simulations:

- Domain: 80°S…80°N (98.4% of planet)
- Resolution: up to Δ=0.01° (930 m)
- Number of grid-points: up to 3.46×10^{10}
- Dry and wet baroclinic waves (Jablonowski & Williamson 2006, Park et al. 2012)

(Fuhrer, et al. 2017 in preparation)

peak performance: 6×10^{15} Flop/s

Summary

- **Decade-long European-scale simulations**
  - Able to run 1 day in 10 minutes (1 year in 2.5 days)
  - Domain-decomposition with 12 x 12 domains, each running on a GPU/CPU node (144 nodes, 2.8% of PizDaint [after upgrade])

- **Global simulations**
  - Exploit excellent weak scaling on dedicated hardware:
    On upgraded PizDaint (4888 nodes), one can run 1.9 km near-globally:
    1 day in 17 minutes (0.23 simulation years per day).
  - **In principle, global convection-resolving AGCM simulations are feasible today!**
  - **Would require online analysis (I/O bandwidth becomes critical bottle neck).**
    See project crCLIM at ETH: http://www.c2sm.ethz.ch/research/crCLIM.html

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Animations: can be downloaded via crCLIM website at http://www.c2sm.ethz.ch/research/crCLIM