Towards
Convection-Resolving
Climate Modeling

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http://www.iac.ethz.ch/people/schaer
Mesoscale matters

Modis (Terra), December 1, 2013
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)
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!

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Motivation

Decade-long simulations at $\Delta = 2$ 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

18:45 (16:45 UTC)

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

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

Alpine domain
2.2km (500x500x60)

Mean precipitation

OBS
$\Delta = 12$ km

Wet-hour frequency

Heavy precipitation

poor representation of diurnal cycle with $\Delta = 12$ km

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(Ban et al. 2015, GRL)
Validation of diurnal cycle

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Alpine domain
2.2km (500x500x60)

Mean precipitation

OBS
Δ = 12 km
Δ = 2 km

Wet-hour frequency

Heavy precipitation

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

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(Ban et al. 2015, GRL)
Intercomparison of hourly sequence

Individual cells cannot be evaluated (chaotic dynamics)

$\Delta = 2$ km qualitatively captures short-term small-scale events

$\Delta = 12$ km 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 ($\Delta=1$ km)
- Runs on Piz Daint (Cray, CSCS)

![Image of Piz Daint: Linpac peak performance: \(6 \times 10^{15}\) Flop/s]

### European-scale climate simulations

- $\Delta=2.2$ km, 1536 x 1536 x 60 grid points
- Driven by intermediate $\Delta=12$ km simulation
- Split-explicit, $\Delta t = 20$ s

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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!

- 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 relaxation zone (25-50 grid points).

Lifecycle of a convective cell:
- Lifetime: 6h
- Propagation: 10 m/s
- Distance: 200 km

(Houze 1981)
Kyrill
Break-up of cold-frontal rain band at $\Delta = 2$ km

Jorgensen et al. (2003)
Radar observations (Pacific)
Summer convection
Simulations at 12 and 2 km

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

Convection resolving:

- Switch off convection parameterization
- More closely based on first principles

Rotunno et al. 1988
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 $\Delta = 2$ 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 evident within both CTRL and SCEN

Extended Alpine region (JJA), Simulation with $\Delta=2$km

(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

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Challenges
Scales of convective cells decrease with $\Delta x \to 0$
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 $\Delta=2$ 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

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Structural = Structure of deep updrafts

Convergence in idealized simulations

PDF of convective mass flux

Vertical distribution of updrafts

Properties of deep updrafts converge near 1 km

(Davide Panosetti, PhD ETH Zurich)
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Challenges
Hardware Challenge

Emerging hardware architectures are highly heterogeneous.

1 Node = 1 GPU & 1 CPU

1 GPU = 15 SMXs

1 SMX = 192 CCs & 64 DPs

1 CC

CUDA Core

1 DP

Double Precis. Unit

Piz Daint = 5272 Nodes

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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)

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

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Approach in **COSMO-GPU**

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**European simulations:**
- Can run 1 day in 10 min (1 yr in 2.5 days)
- Requires $12 \times 12 = 144$ GPU nodes (P100) (2.8% of nodes of PizDaint)
- Near-perfect weak scaling $\Rightarrow$ Can expand domain without increasing wall-clock time.

**Near-global simulations:**
- Domain: $80^\circ$S…$80^\circ$N (98.4% of planet)
- Resolution: up to $\Delta = 0.01^\circ$ (930 m)
- Number of grid-points: up to $3.46 \times 10^{10}$
- Dry and wet baroclinic waves
  (Jablonowski & Williamson 2006, Park et al. 2012)

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(Fuhrer, et al. 2017 in preparation)
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
References (1/2)


References (2/2)


Sørland, S.L., C. Schär, D. Lüthi1 and E. Kjellström, 2017: Regional climate models reduce biases of global models and project smaller European summer warming, submitted


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