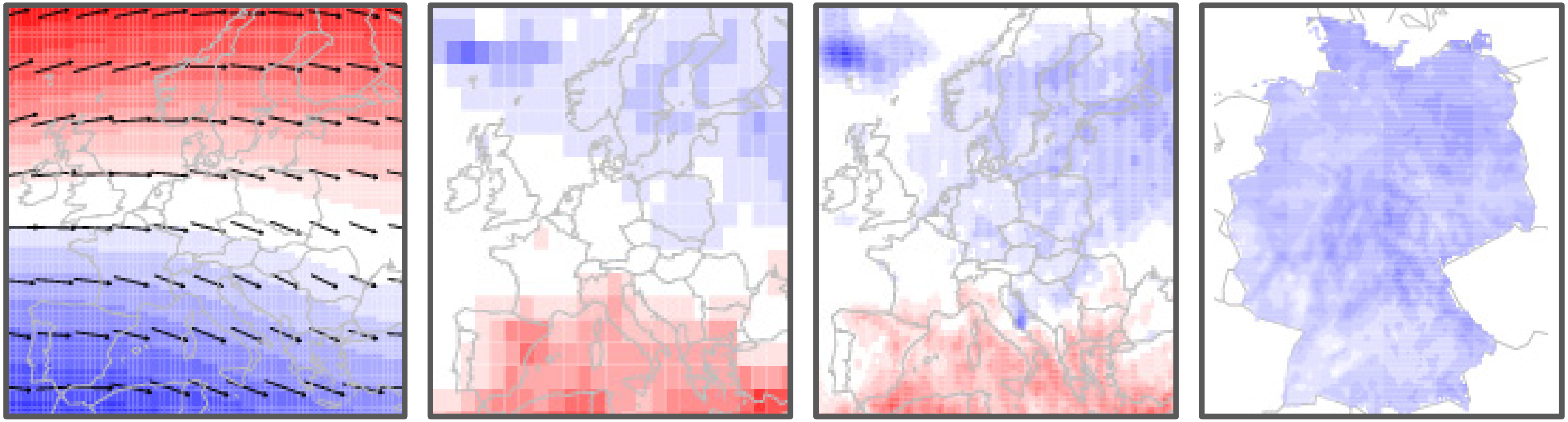
Karlsruhe Institute of Technology

MICMoR Summer School
July 16,2012

Regional climate simulations using WRF

Sven Wagner

Institute for Meteorology and Climate Research (IMK-IFU)



Curriculum Vitae:

- Education:

  - Environmental Engineering, University Stuttgart (Dipl.-Ing.)
  - Water Resources Engineering and Management (M.Sc.)
  - Exchange Student at University of Waterloo, Canada

- PhD thesis:

  “Water balance in a poorly gauged basin in West Africa using atmospheric modeling and remote sensing information”

- Research topics:

  - Impact of climate change on terrestrial hydrology: high resolution regional climate simulations and distributed hydrological simulations
  - Joint and coupled atmospheric-hydrological modelling
  - Hydro-meteorological decision support for sustainable water managem.

Outline

- Short-term versus long-term simulations
- Main steps to perform long-term WRF simulations
- Postprocessing of RCM simulations
- WRF Physics

- Examples:
  - Regional climate simulations for Central Europe
  - Impact study “Flood hazards in a changing climate” using RCM simulations

- Summary

Main differences to short-term WRF simulations

- **LONG SIMULATION TIME**
- **HUGE DATASETS (Input and Output)**

→ a good simulation strategy is required for

- Preprocessing: mainly preparation of global forcing data
- Simulations themselves
- Postprocessing: analysis and plotting simulation results

Usually:

- Preprocessing and Simulations are performed stepwise (e.g. yearly) and deleted afterwards, i.e. …

WRF regional climate simulations

Karlsruhe Institute of Technology

Preprocessing and simulations are performed stepwise (e.g. yearly) and deleted afterwards, i.e.

- Before Simulation start:

  List of output variables and output time step (hourly, daily, …) has to be defined before, all other results will be deleted!!!!

  → Variable list of subsequent climate impact studies has to be known before

- WRF output is usually post-processed immediately after simulation and then deleted (due to limited storage capacities)

- **Regional climate simulations can usually not be repeated within a project due to long simulation times and required CPU capacities !!**

WRF regional climate simulations: Preprocessing using WPS

- Geogrid:
  according to short-term WRF simulations

- Ungrib:
  - preparation of global forcing data (e.g. ECHAM5)
  - using Vtable: requires some modifications according to GRIBlevel, …
  - long-term simulations require additional **SST update**
  → SST data in wrflowinp after real.exe

- Metgrid:
  according to short-term WRF simulations

WRF regional climate simulations: real.exe & wrf.exe

Recommended modifications of **namelist.input**-file for long-term simulations:

- activation of sst_update and usemonalb
- restart = .true. : allows splitting of long-term simulation in e.g. monthly time slices
- use_adaptive_time_step = .true. : allows faster and stable simulations
- Use auxillary outputfiles (auxhist1_outname, auxhist1_interval) for saving output variables in different outputfiles: e.g.

  - one file for 2D-fields with higher temporal resolution and

  - one outputfile for 3D-fields

WRF regional climate simulations: further options

- tmn_update=1 - updates deep-soil temperature for multi-year future-climate runs
- sst_skin=1 - adds diurnal cycle to sea-surface temperature
- bucket_mm and bucket_J - a more accurate way to accumulate water and energy for long-run budgets (see later)
- output_diagnostics=1 (in 3.3.1) – ability to output max/min/mean/std of surface fields in a specified period

from *Physics_Dudhia.ppt.pdf*

WRF regional climate simulations: Postprocessing

- **Validation and Analysis of regional climate simulation results always require some statistical analysis**,

  e.g. the calculation of

  - 30-year daily mean temperature or

  - 30-year monthly precipitation sums or

  - climate indices (consecutive dry days, very heavy precipitation days,...)

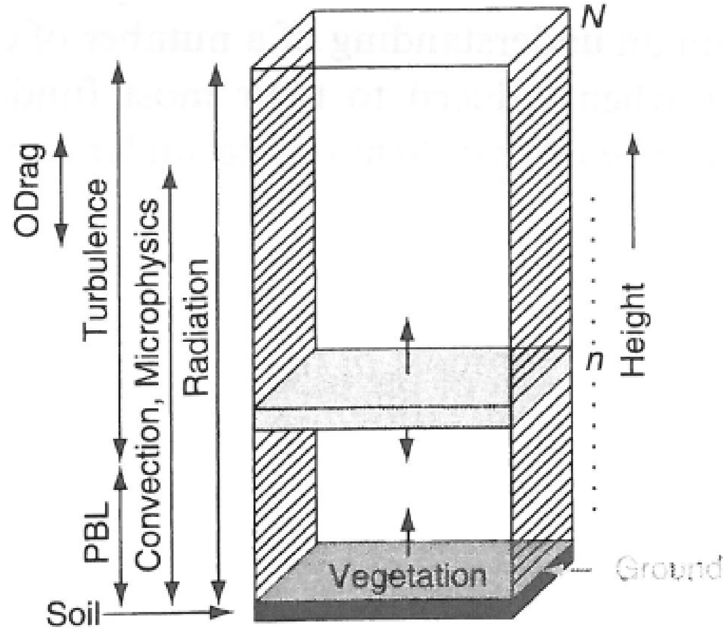
  - never validate the raw output data

- A good tool for statistical analysis of climate simulation results is the Climate Data Operators (CDO)

- All analysis and plotting programs, which are able to read netcdf-format can be used, e.g. NCL, Panoply, Matlab, R, …

WRF Physics

- Radiation
- Land Surface
- Planetary Boundary Layer
- Cumulus Parameterization
- Microphysics



- Literature:

  Stensrud (2007): PARAMETERIZATION SCHEMES: Keys to Understanding Numerical Weather Prediction Models; Cambridge University Press

- Links:

  http://www.mmm.ucar.edu/wrf/users/

  http://www.mmm.ucar.edu/wrf/users/tutorial/tutorial_presentation_winter.html

WRF USERS PAGE

Home | Model System | User Support | Download | Doc / Pub | Links | Users Forum | WRF Forecast

Search

wrf-model.org

Public Domain Notice

Contact WRF Support

WRF MODEL USERS PAGE

Welcome to the users home page for the Weather Research and Forecasting (WRF) modeling system. The WRF system is in the public domain and is freely available for community use. It is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. WRF is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers, including:

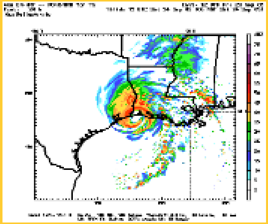
- Idealized simulations (e.g. LES, convection, baroclinic waves)
- Regional and global applications
- Parameterization research
- Data assimilation research
- Forecast research
- Real-time NWP
- Hurricane research
- Coupled-model applications
- Teaching

The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting a subset of the overall WRF code (Version 3) that includes:

- WRF Software Framework (WSF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nests, grid and observation nudging
- WRF Pre-Processing System (WPS)
- WRF-DA data assimilation system
- Numerous physics packages contributed by WRF partners and the research community

Other components of the WRF system will be supported for community use in the future, depending on interest and available resources.

WRF Forecast



WRF Real-time forecast (old site)

Announcements

wrfhelp email is currently down. It should be fixed early next week (6/29/2012).

'Known Problems' posts for V3.4 WPS (posted 5/22/12)

WRF Version 3.4 Release (4/6/2012)

'Known Problems' posts for V3.4 (posted 5/4/12)

The 13th WRF Users' Workshop: June 25-29, 2012.

The new user tutorial: July 16-27, 2012. Regisration is open.

Information on next WRF release (updated 10/17/2011)

WRF Version 3.3.1 Release (9/22/2011)

'Known Problems' posts for V3.3 (posted 5/27/11)

Program, extended abstracts, and presentations from the 12th WRF Users' Workshop, June 20 - 24, 2011.

Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

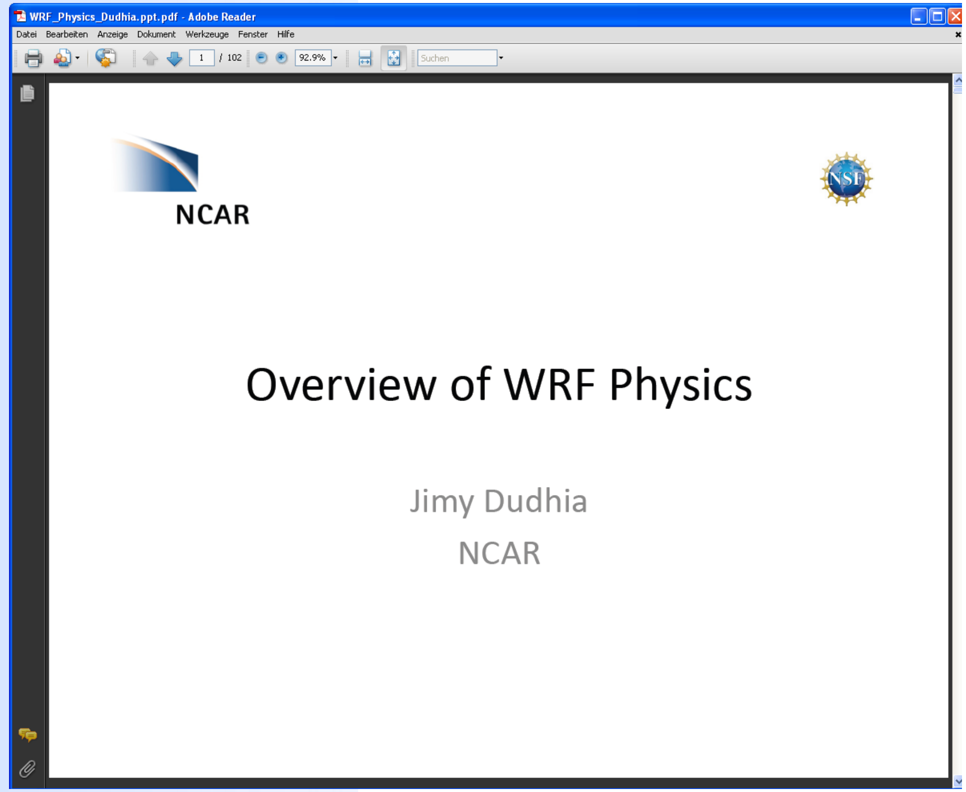
WRF USERS PAGE

Home | Model System | User Support | Download | Doc / Pub | Links | Users Forum | WRF Forecast

WRF TUTORIAL PRESENTATIONS

POWER POINT SLIDES PRESENTED AT THE JANUARY 2012 BASIC WRF TUTORIAL

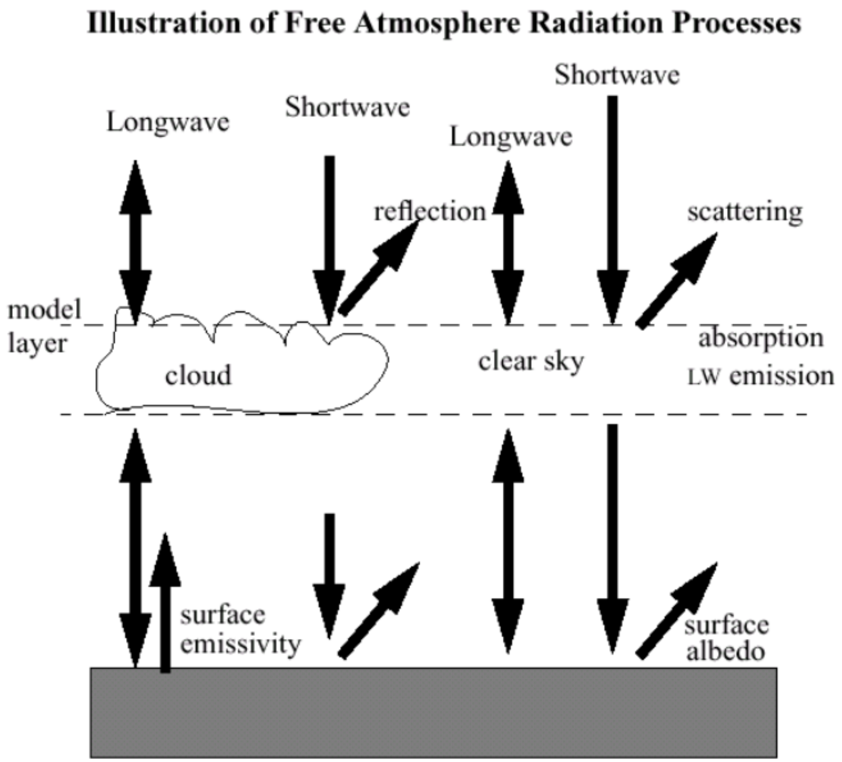
- WRF Modeling System Overview
- Compile WRF & WPS
- WPS
  - General
  - Setup and Run
  - Advanced
- Model
  - ARW Dynamics and Numerics
  - NMM Dynamics and Numerics
  - Physics
  - ARW nudging
  - WRF Nesting
  - WRF - Setup and Run
  - WRF Nesting - Setup and Run
  - Additional Namelist Options
- Initialization
  - Idealized Data
  - Real Data
- Graphics
  - NCL
  - Other Graphics
  - UPP
- WRF Utilities
- WRF Software
  - Registry and Examples
  - Architecture
- Objective Analysis (OBSGRID)
- New in WRF Versions 3.4
- Good Design Practices



WRF Physics: Radiation

It provides

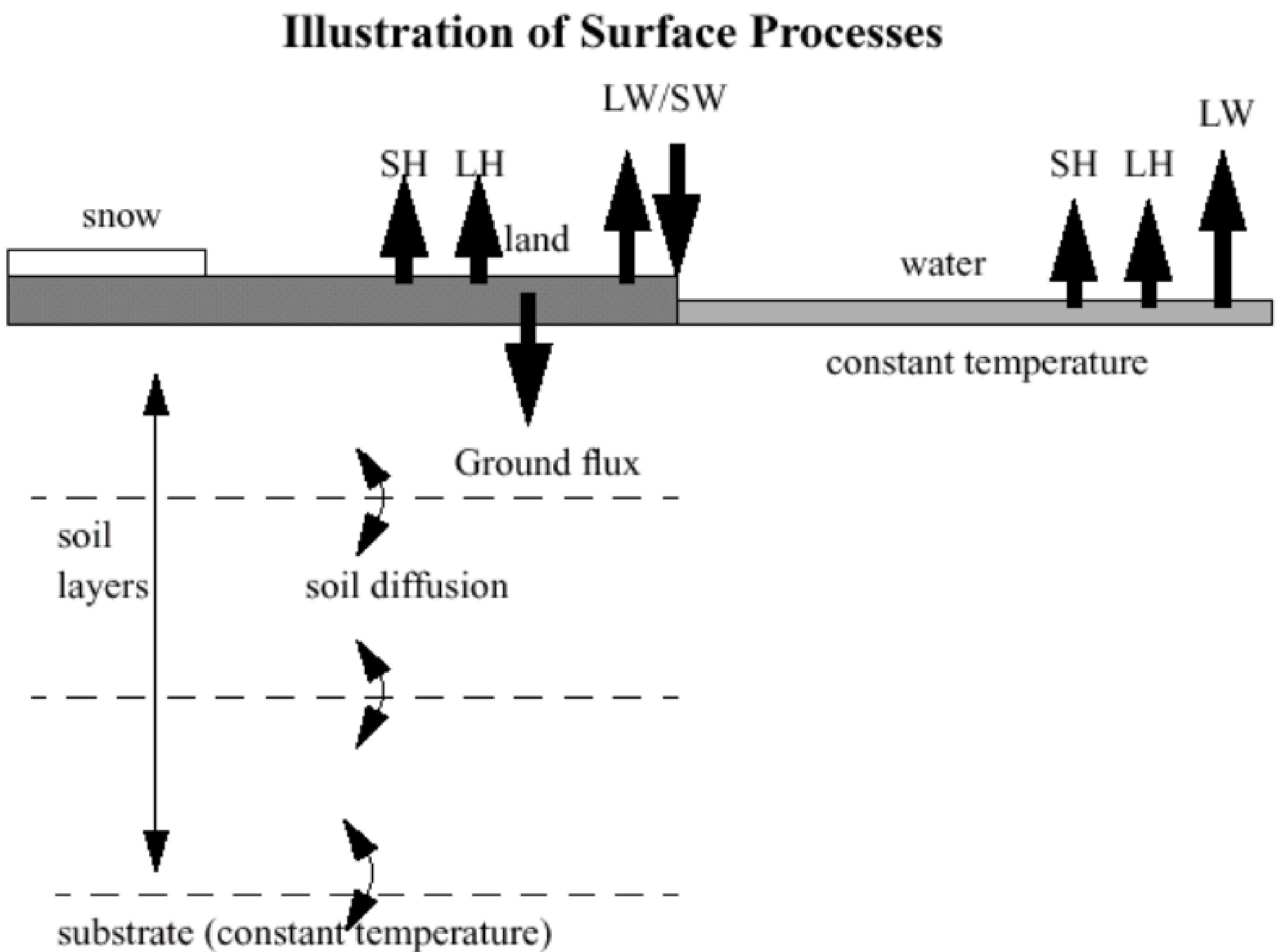
- Atmospheric temperature tendency profiles
- Surface radiation fluxes



- Compute clear-sky & cloud upward/downward radiation fluxes

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Land Surface

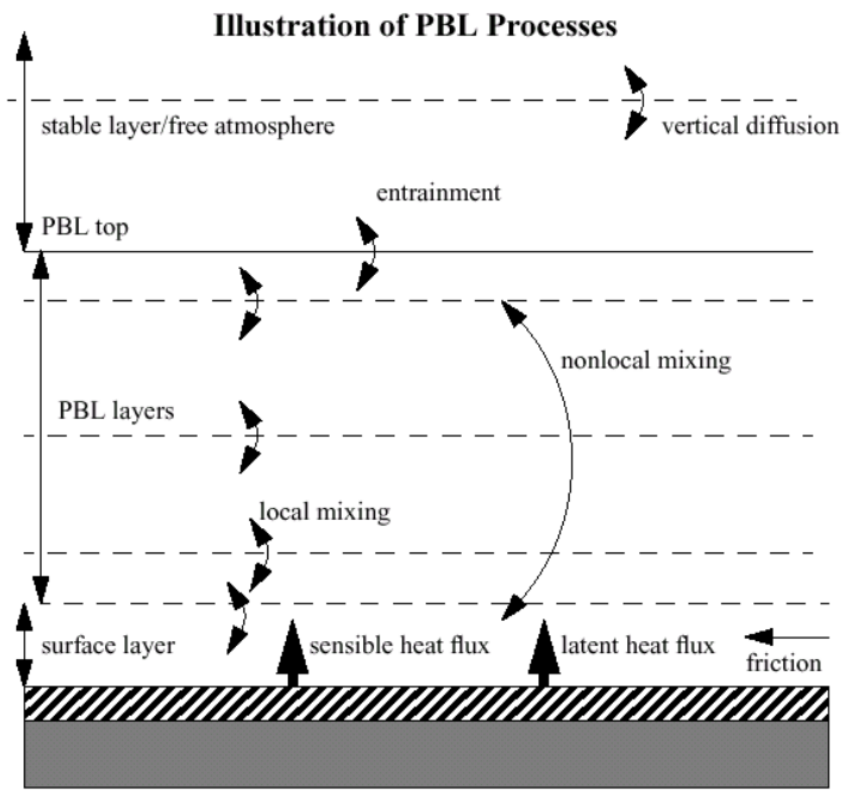


from *Physics_Dudhia.ppt.pdf*

WRF Physics: Planetary Boundary Layer (PBL)

It provides

- Boundary layer fluxes (heat, moisture, momentum)
- Vertical diffusion in whole column



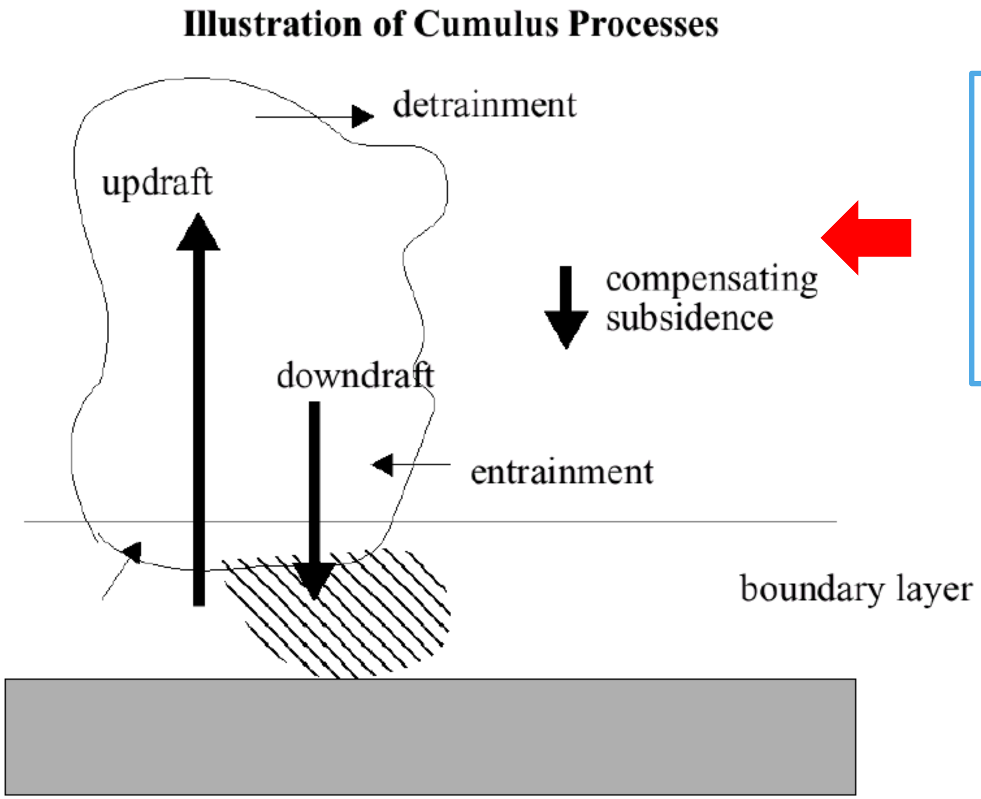
- Distribute surface fluxes with PBL eddy fluxes
- Allow PBL growth by entrainment

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Cumulus Parameterization

It provides

- Atmospheric heat & moisture/cloud tendency profiles
- Surface sub-grid-scale (convective) rainfall



2 main classes of schemes:

- ➢ mass-flux type (most schemes)
- ➢ adjustment type (Betts-Miller-Janjic)

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Cumulus Parameterization

Convection in lower atmosphere without precipitation

cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes
3	Grell-Devenyi	ARW	Qc Qi	no	no
4	Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)
5	Grell-3	ARW	Qc Qi	no	yes
6	Tiedtke	ARW	Qc Qi	yes	yes
7	Zhang-McFarlane	ARW	Qc Qi	yes	no
14	New SAS	ARW	Qc Qi	yes	yes
99	Old Kain-Fritsch	ARW	Qc Qr Qi Qs	no	no

with Qc: cloud water
Qr: rain water
Qi: cloud ice
Qs: snow mixing ratio

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Cumulus Parameterization Recommendations:

Recommendations about use

- For dx ≥ 10 km: probably need cumulus scheme
- For dx ≤ 3 km: probably do not need scheme
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- For dx=3-10 km, scale separation is a question
  - Few schemes are specifically designed with this range of scales in mind
  - G3 has an option to spread subsidence in neighboring columns
- Issues with 2-way nesting when physics differs across nest boundaries (seen in precip field on parent domain)
  - best to use same physics in both domains or 1-way nesting

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization

It provides

- Atmospheric heat & moisture tendencies
- Microphysical rates
- Surface resolved-scale rainfall

Microphysical processes:

- Cloud particle formation, growth, and dissipation (very small scales)
  → important role how moist convection develops and evolves

- Compared to microphysic parameterisation, convective parameterisation represents only cumulative effects of clouds

from *Stensrud Book*

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization

- Cloud microphysical processes represent an important uncertainty in climate modeling

For example

- increase in aerosols
  → increase clouds droplet concentration
  → decrease on droplet size (assuming a fixed water content)
  → increase in cloud albedo & less precipitation efficiency

from *Stensrud Book*

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization

2 challenges in microphysic parameterisation:

1. Number of phase changes:

   vapor ⟷ liquid (condensation; evaporation)

   solid ⟷ liquid (melting; freezing)

   vapor ⟷ solid (deposition; sublimation)

2. Number of different interactions between cloud and precipitation particles

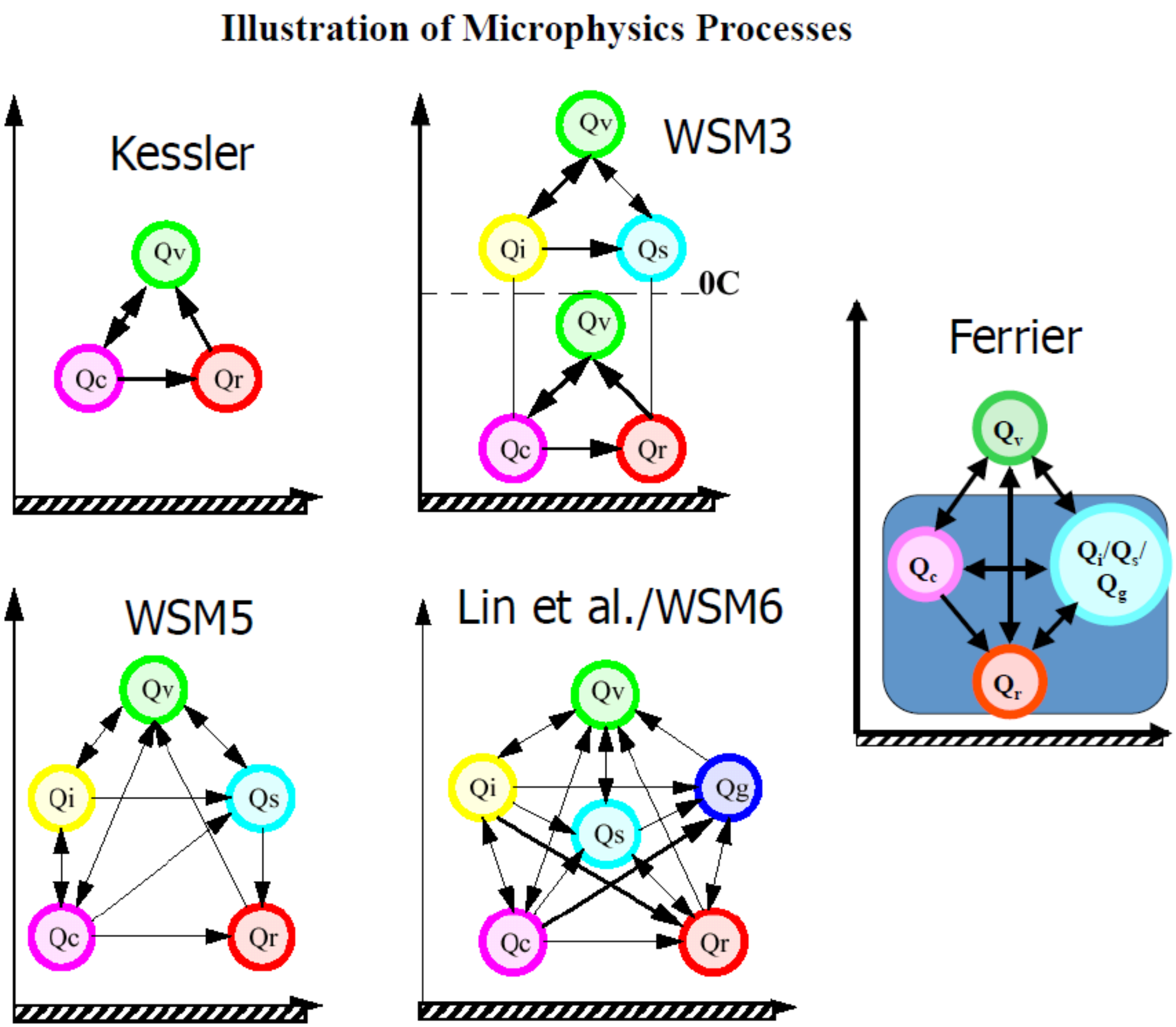
- Particle types (hydrometeors):

- vapor	- cloud water	- rain
	- cloud ice	- snow
		- graupel

from *Stensrud Book*

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization



from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization

- **Bulk** versus **Bin** microphysic parameterisation concepts:

  - Bulk approaches:
    - specified functional form for particle size distributions (inv. exp-func.)
    - predict particle mixing ratios
  - Single moment schemes: predict particle mixing ratios [kg/kg]
  - Double moment schemes: predict particle mixing ratios [kg/kg] and number concentration of hydrometeors [#/kg]

  → less tuning of parameters related to number concentration

  → perform better over a large range of environmental conditions

  - Bin approach: divides particle distribution into a number of finite size categories

from *Stensrud Book*

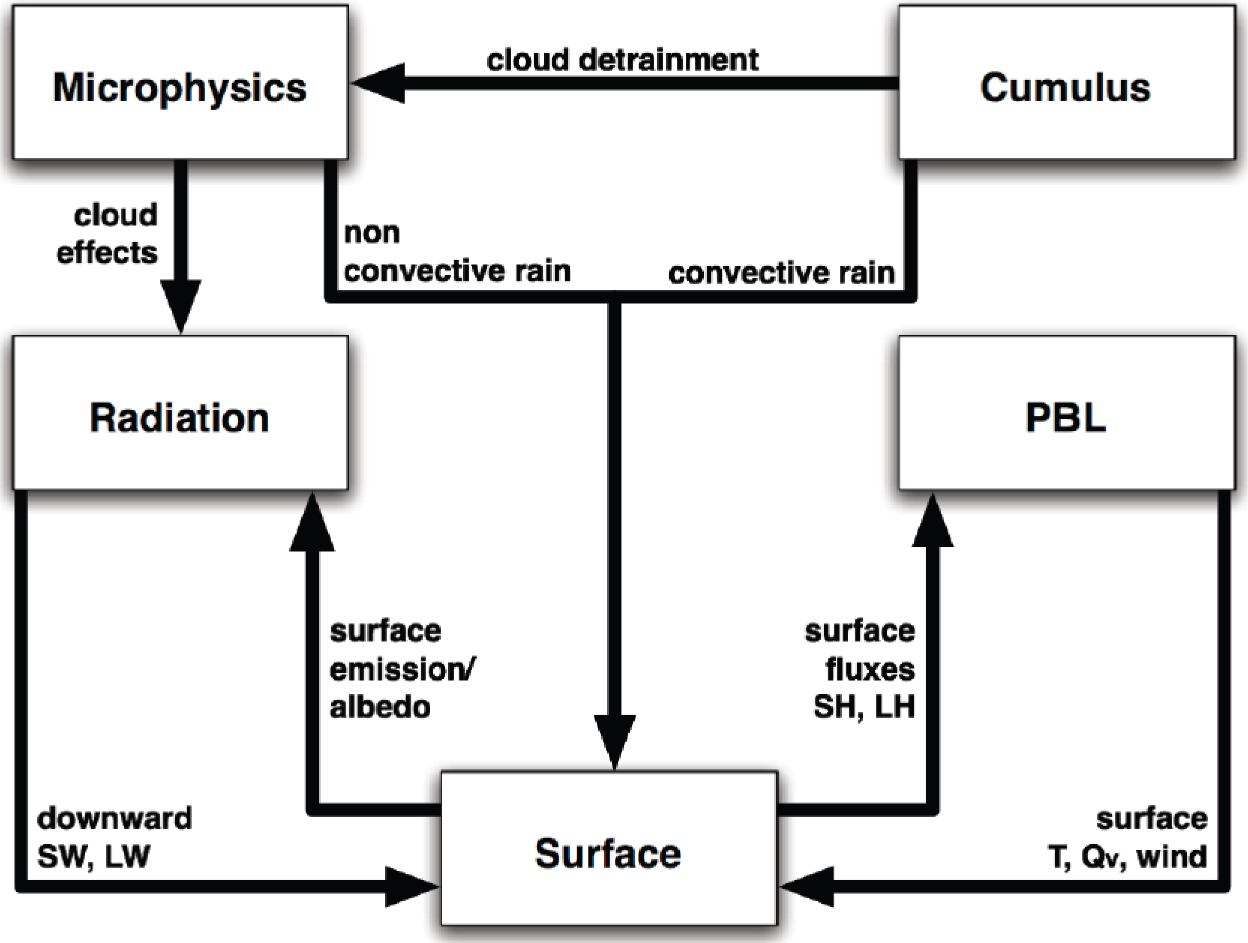
from *Physics_Dudhia.ppt.pdf*

WRF Physics: Microphysics Parameterization

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW (Chem)	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW NMM	Qc Qr Qi Qs Qg	
7	Goddard	ARW	Qc Qr Qi Qs Qg	
8	Thompson	ARW NMM	Qc Qr Qi Qs Qg	Ni Nr
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
13	SBU-YLin	ARW	Qc Qr Qi Qs	
14	WDM5	ARW	Qc Qr Qi Qs	Nn** Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn** Nc Nr

from *Physics_Dudhia.ppt.pdf*

WRF Physics: Direct Interactions of Parameterizations



from *Physics_Dudhia.ppt.pdf*

End of Theory

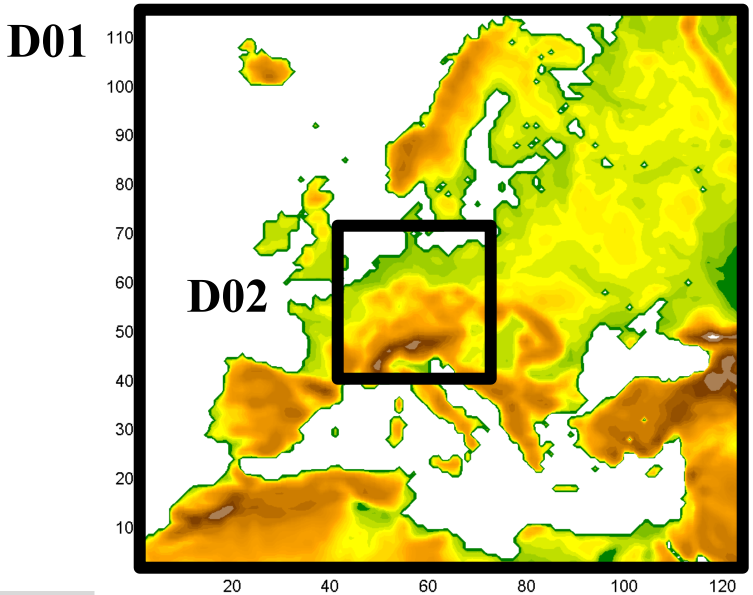
Let’s go to real cases

RCM with WRF – Weather Research and Forecasting Model

- First time long term WRF simulations for Central Europe (started 2009)
- WRF contains numerous physic options for several categories: microphysic, PBL, cumulus parameterizations, land surface models, radiation, …

➢ 1. step: Reanalysis simulations with ERA40 to find optimal setup for long-term WRF simulations for target region (Central Europe)

- Domain setup:
  - D01 (42 km):
    125 X 117 gridpoints, 41 levels
  - D02 (7km):
    176 X 176 gridpoints, 41 levels



Reanalysis–WRF simulations for Central Europe

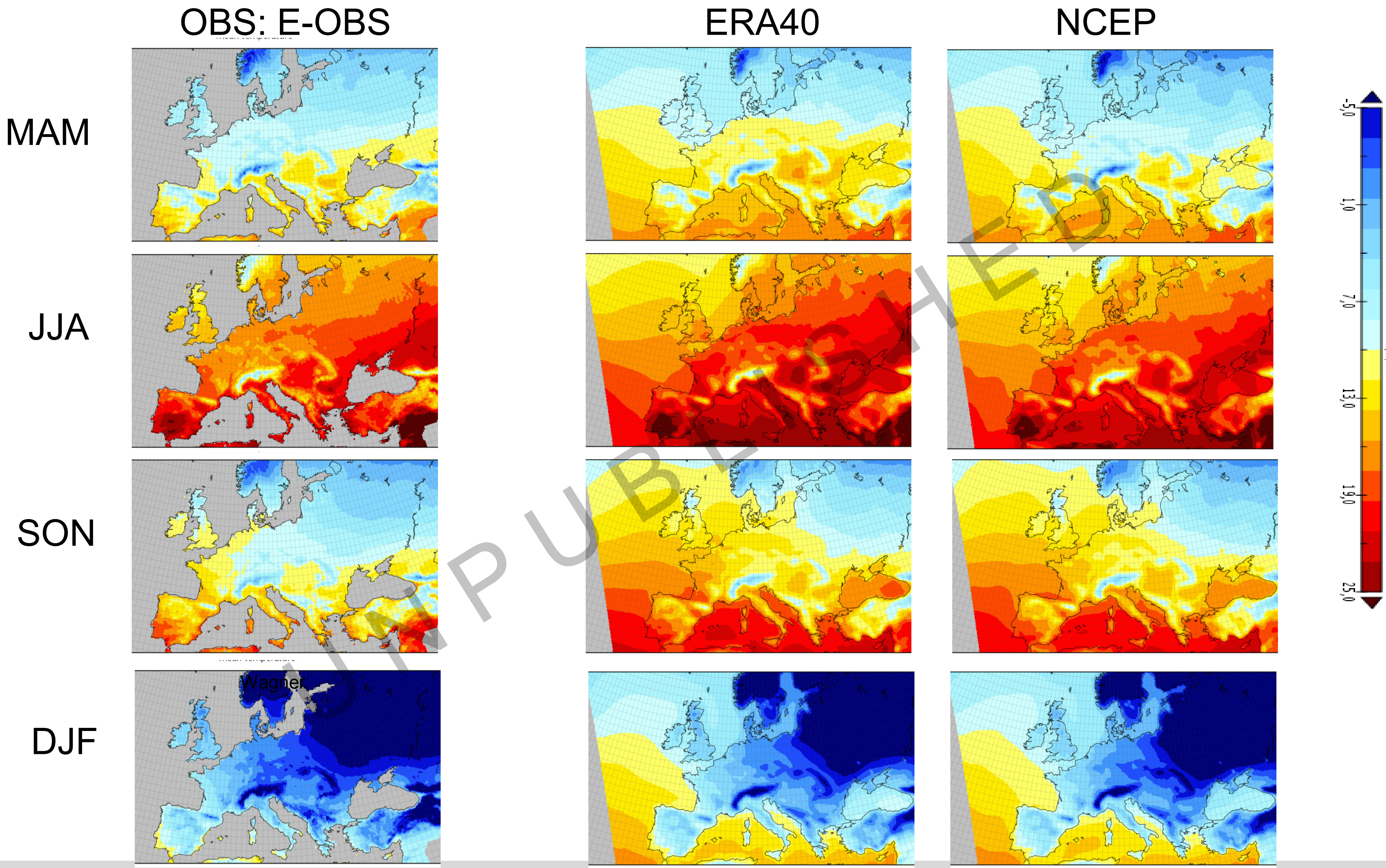
First step:

- WRF simulations using different setups with varying
  - reanalysis driving data (NCEP, ERA40)
  - physics (microphysic, PBL, cumulus parameterization, land surface models, radiation)

- WRF physics schemes in the next slides: **WRF Reference setup**

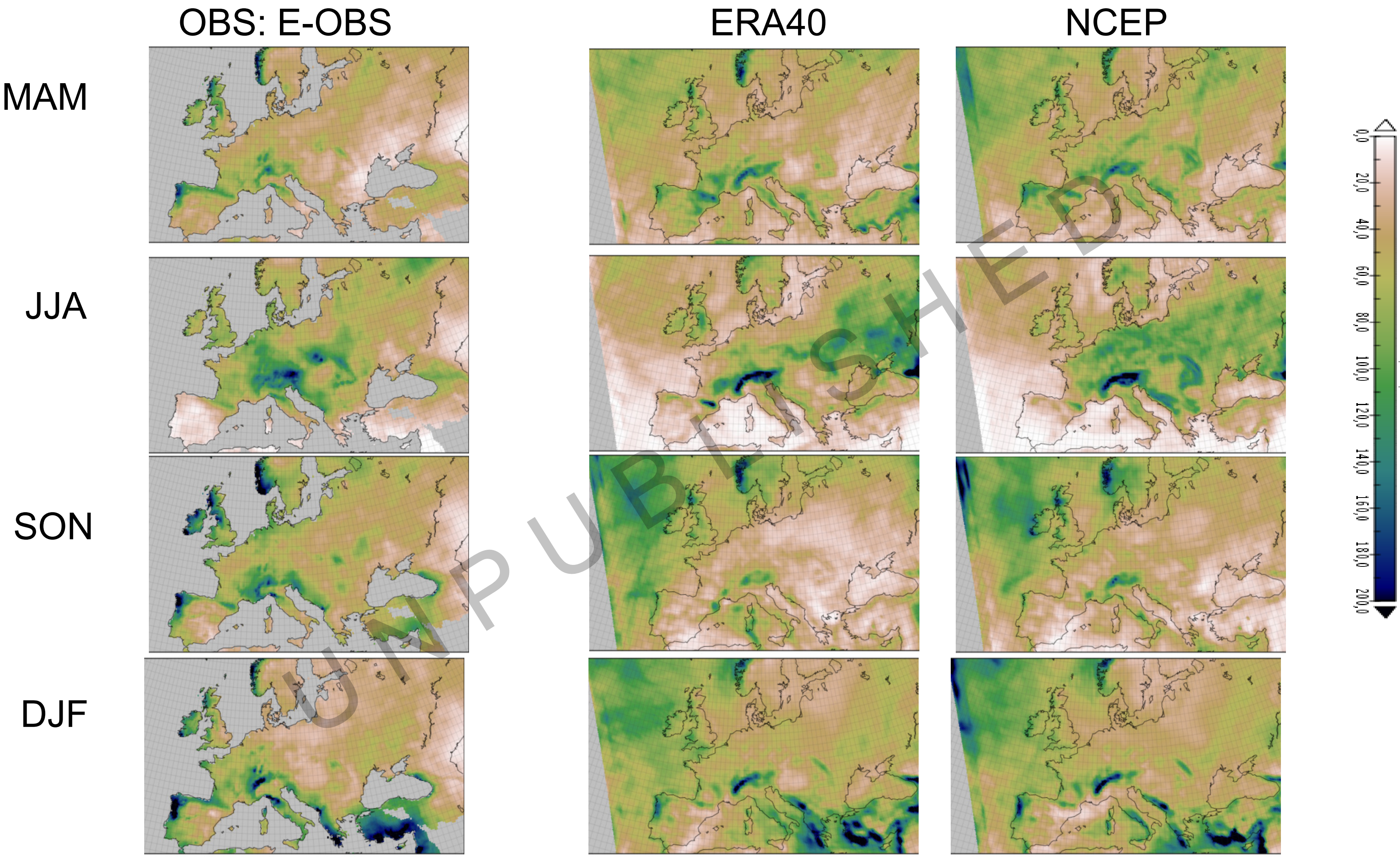
  - **Radiation: RRTM** (LW); **Dudhia** & Goddard (SW)
  - **Land Surface: NoahLSM**, RUC
  - **PBL: Yonsei University (YSU)**, MYJ (Mellor-Yamada-Janjic)
  - **Cumulus: Kain-Fritsch**, Grell-Devenyi
  - **Microphysics: WSM5**, Eta(Ferrier), Thompson

WRF results: using Reanalysis ERA40 vs NCEP



WRF results: using Reanalysis ERA40 vs NCEP

Karlsruhe Institute of Technology

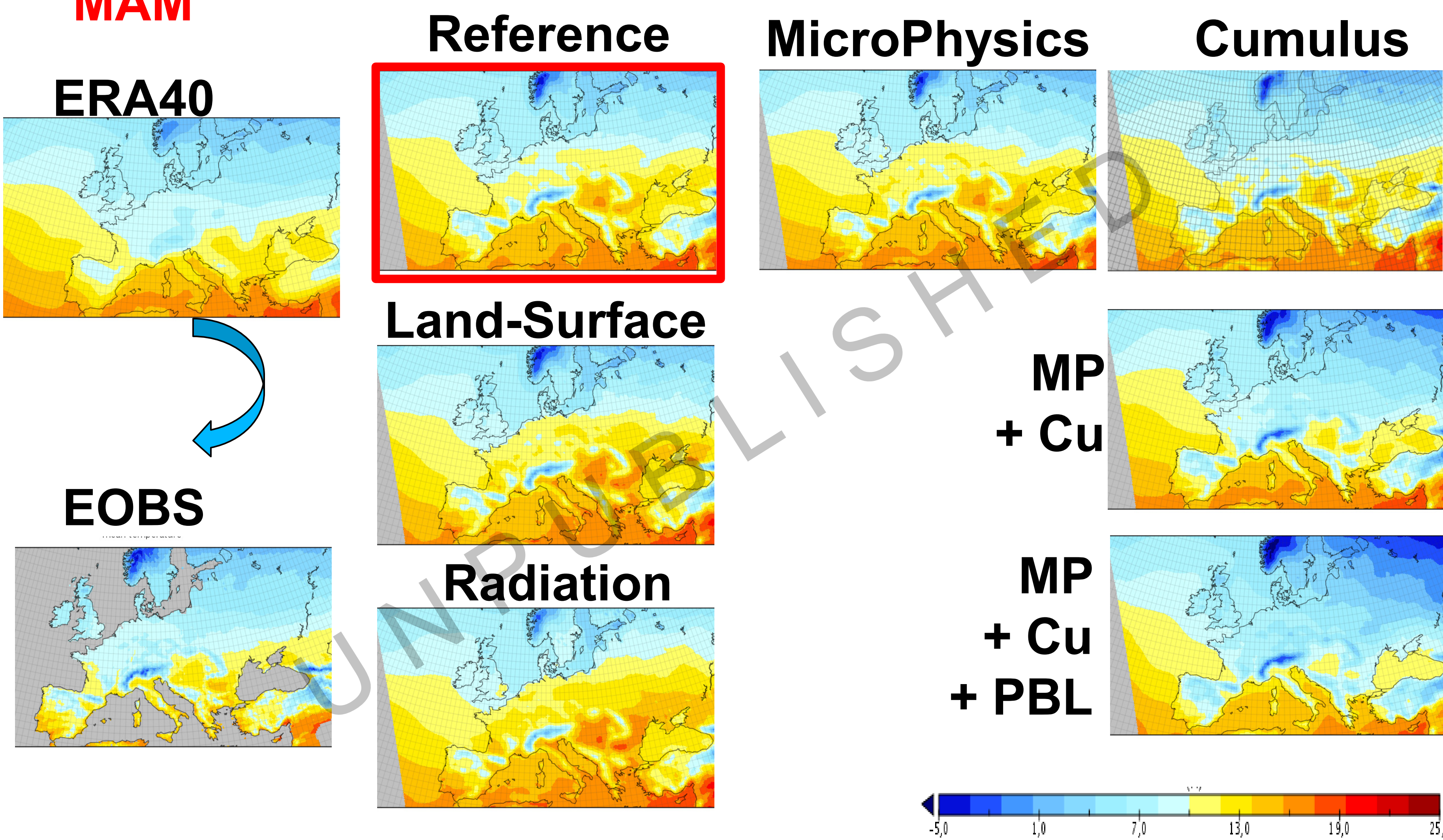


Wagner

WRF Physics: ERA40 vs. WRFOUT 1968: T2 [°C]

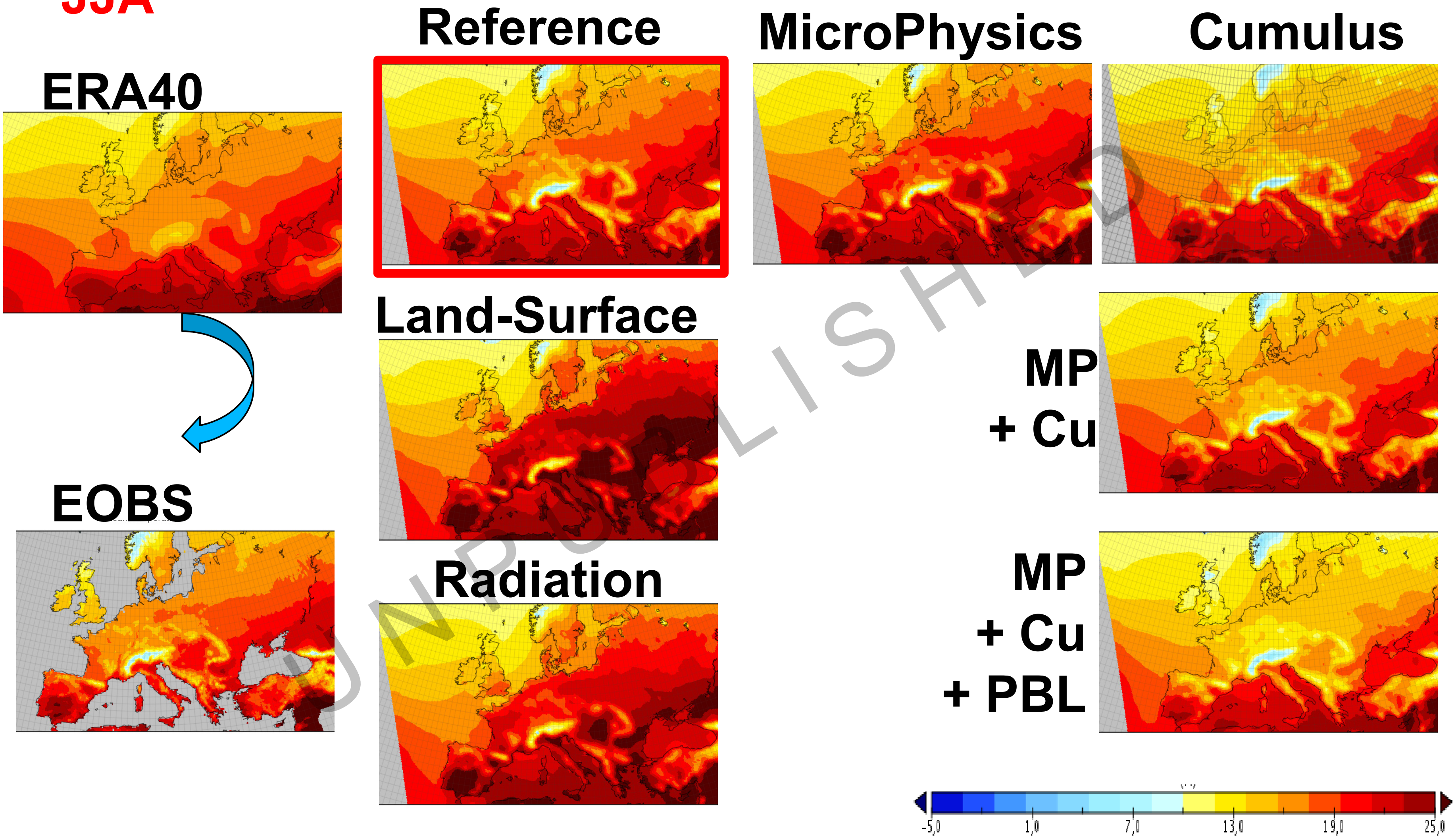
Karlsruhe Institute of Technology

MAM



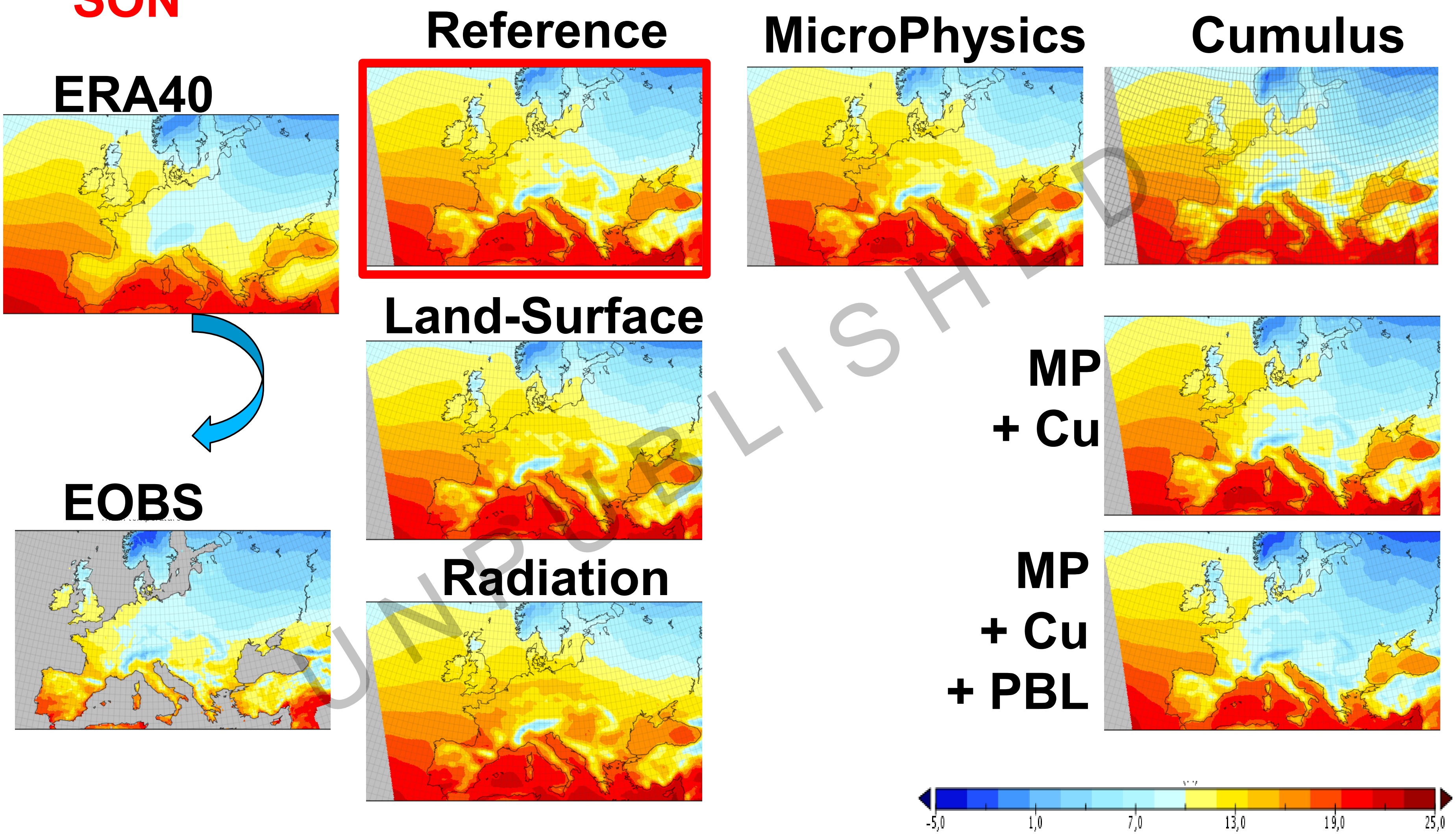
WRF Physics: ERA40 vs. WRFOUT 1968: T2 [°C]

JJA



WRF Physics: ERA40 vs. WRFOUT 1968: T2 [°C]

SON

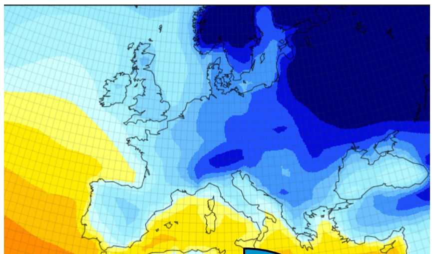


WRF Physics: ERA40 vs. WRFOUT 1968: T2 [°C]

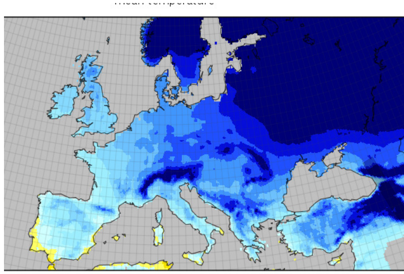
Karlsruhe Institute of Technology

DJF

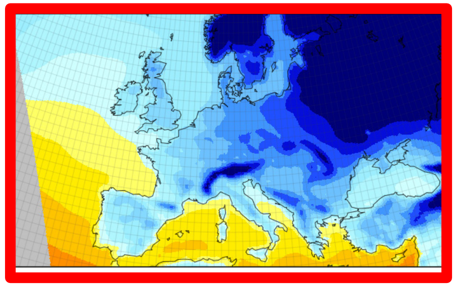
ERA40



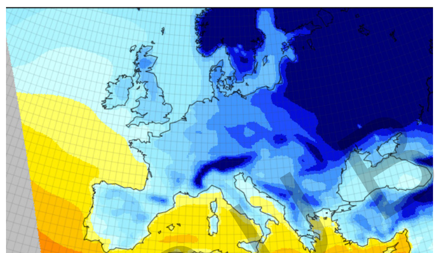
EOBS



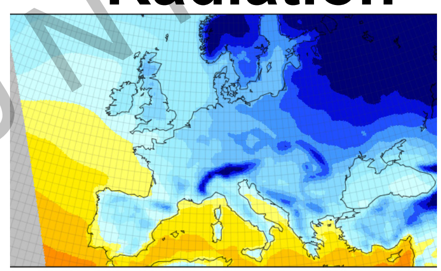
Reference



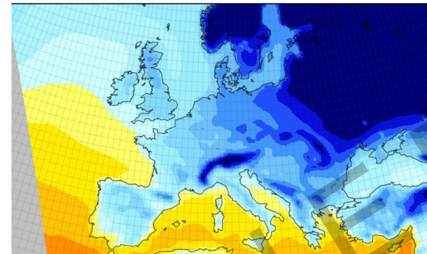
Land-Surface



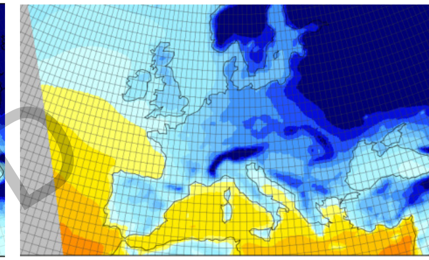
Radiation



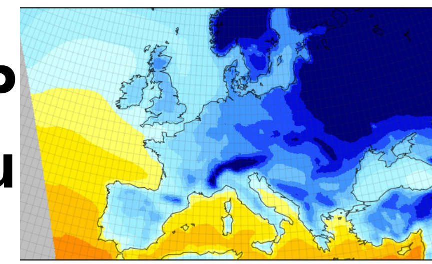
MicroPhysics



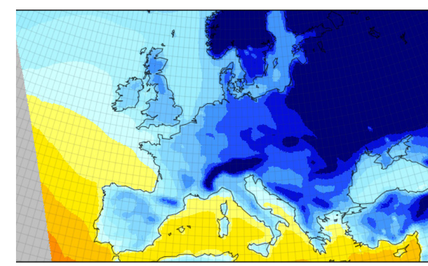
Cumulus

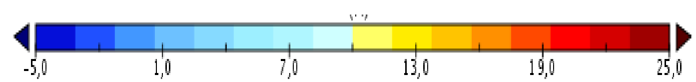


MP + Cu

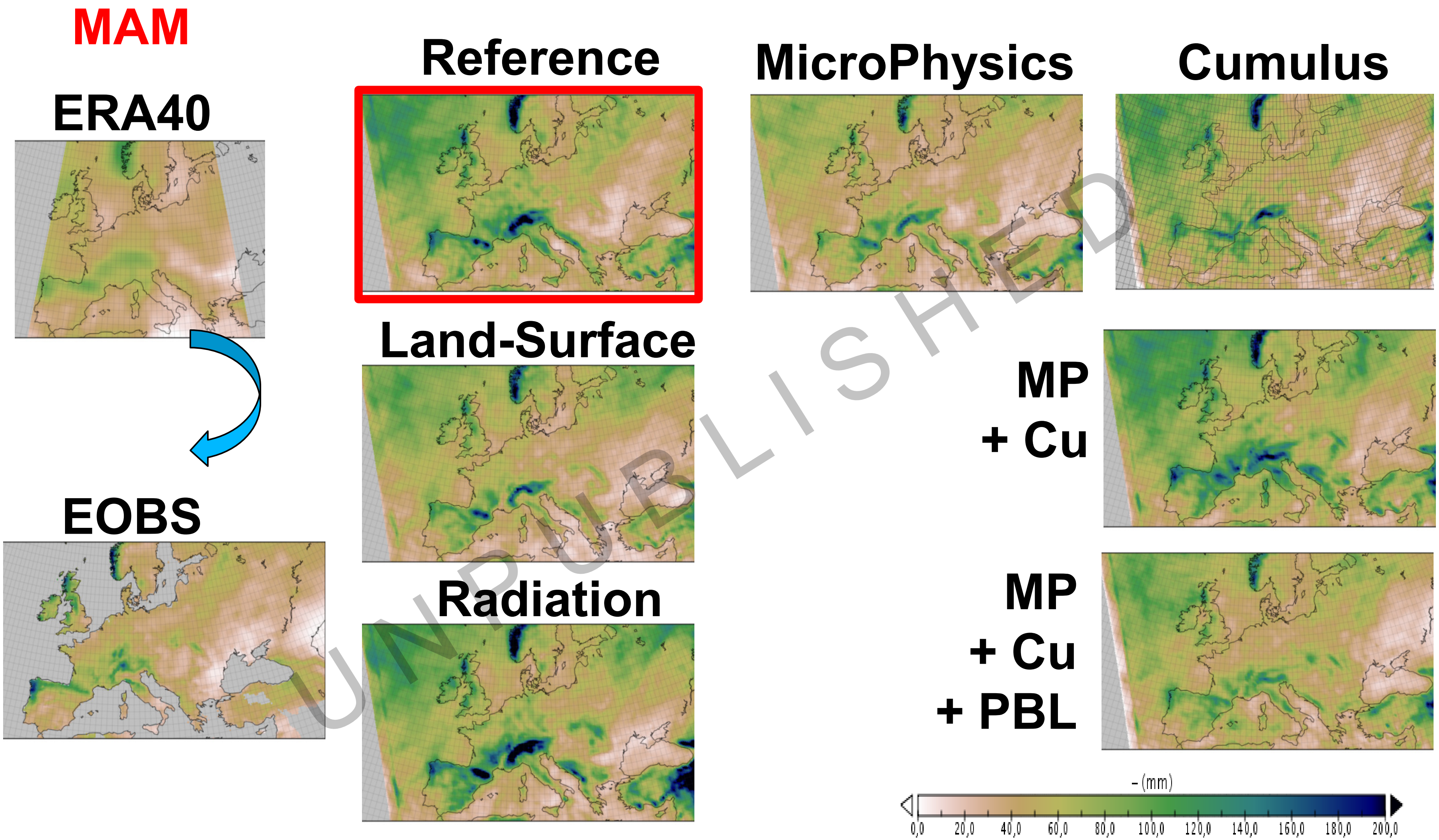


MP + Cu + PBL

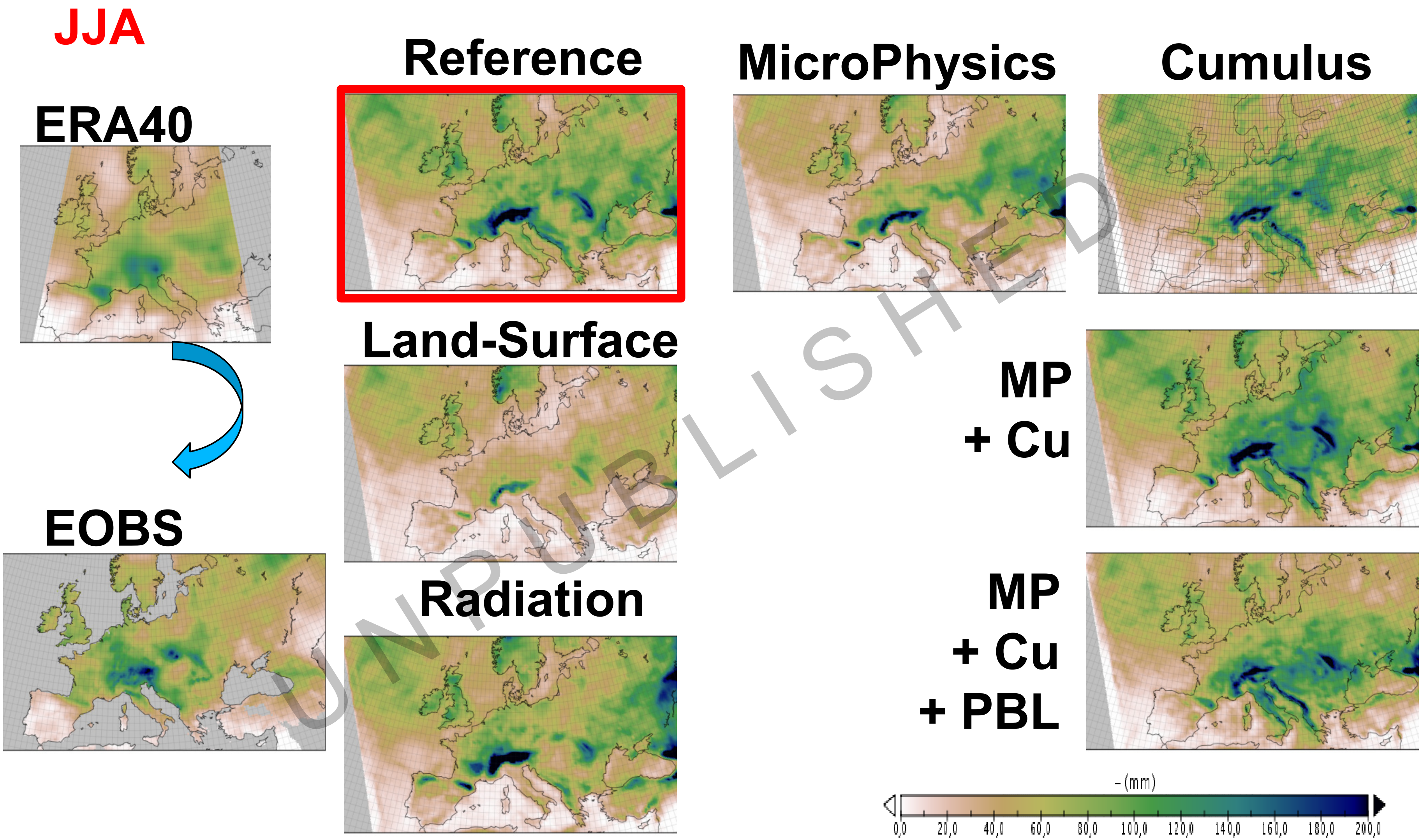




WRF Physics: ERA40 vs. WRFOUT 1968: RAIN



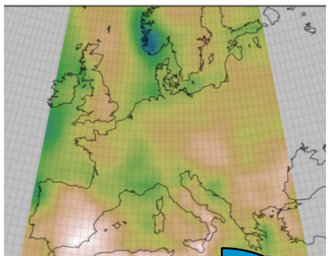
WRF Physics: ERA40 vs. WRFOUT 1968: RAIN



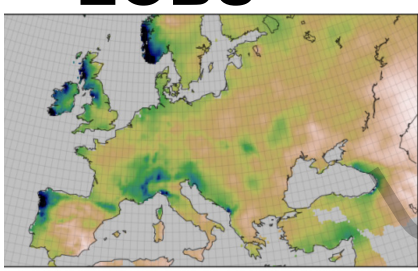
WRF Physics: ERA40 vs. WRFOUT 1968: RAIN

SON

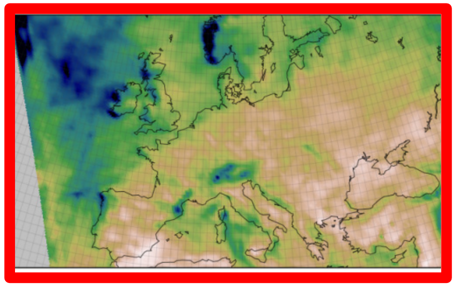
ERA40



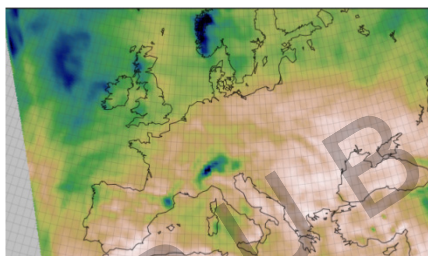
EOBS



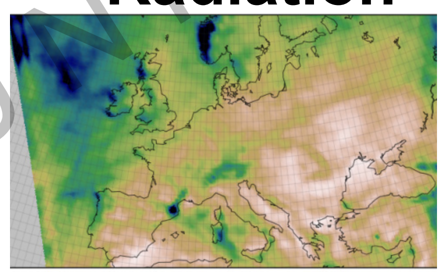
Reference



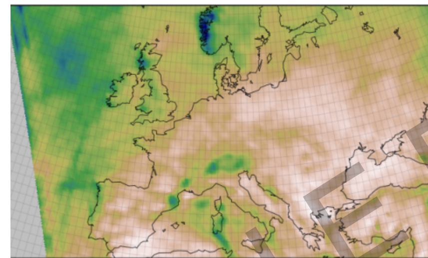
Land-Surface



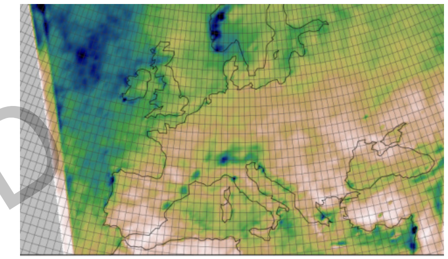
Radiation



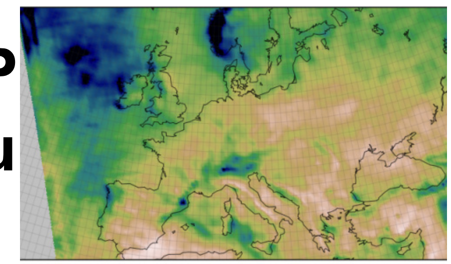
MicroPhysics



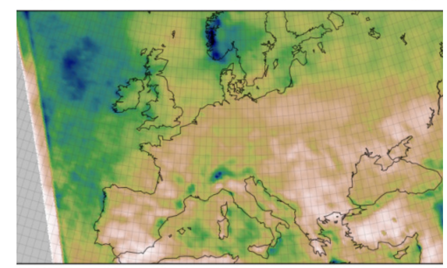
Cumulus

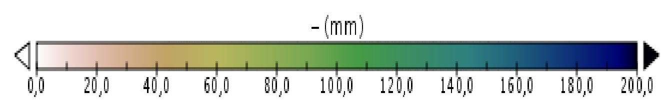


MP + Cu



MP + Cu + PBL



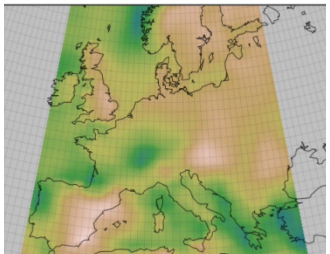


WRF Physics: ERA40 vs. WRFOUT 1968: RAIN

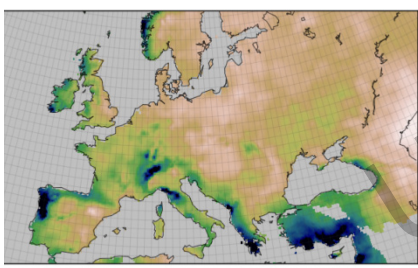
Karlsruhe Institute of Technology

DJF

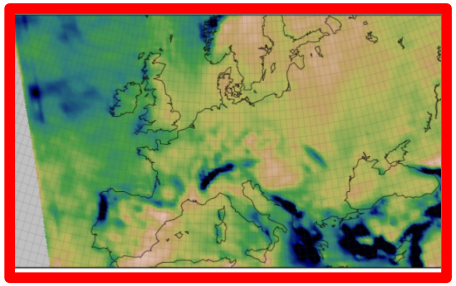
ERA40



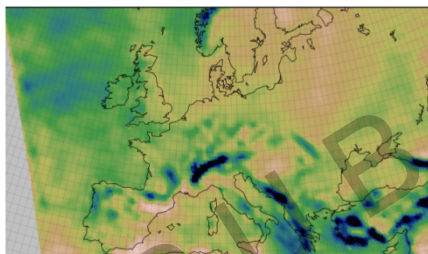
EOBS



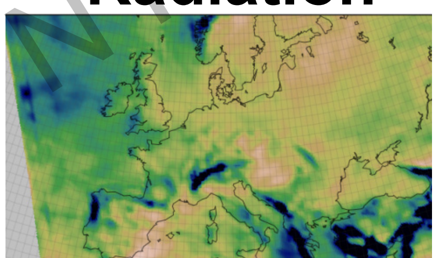
Reference



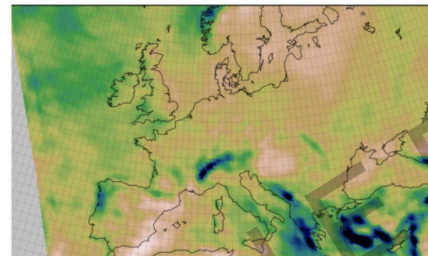
Land-Surface



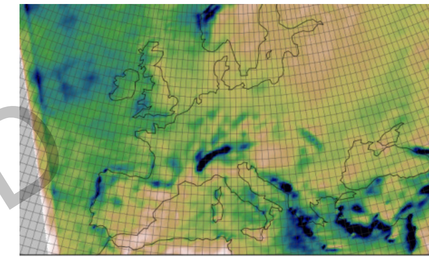
Radiation



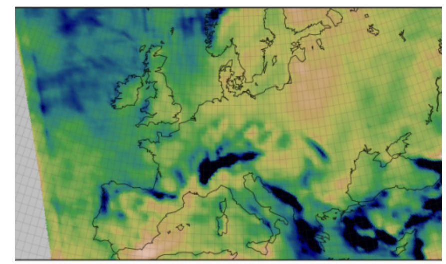
MicroPhysics



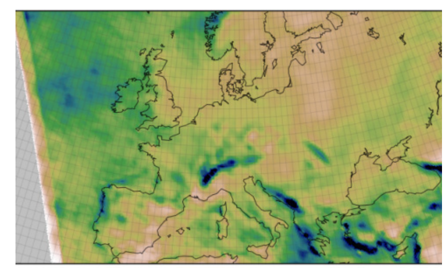
Cumulus

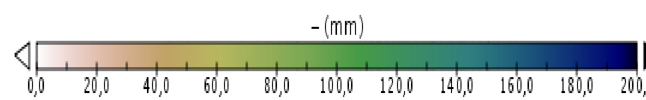


MP + Cu



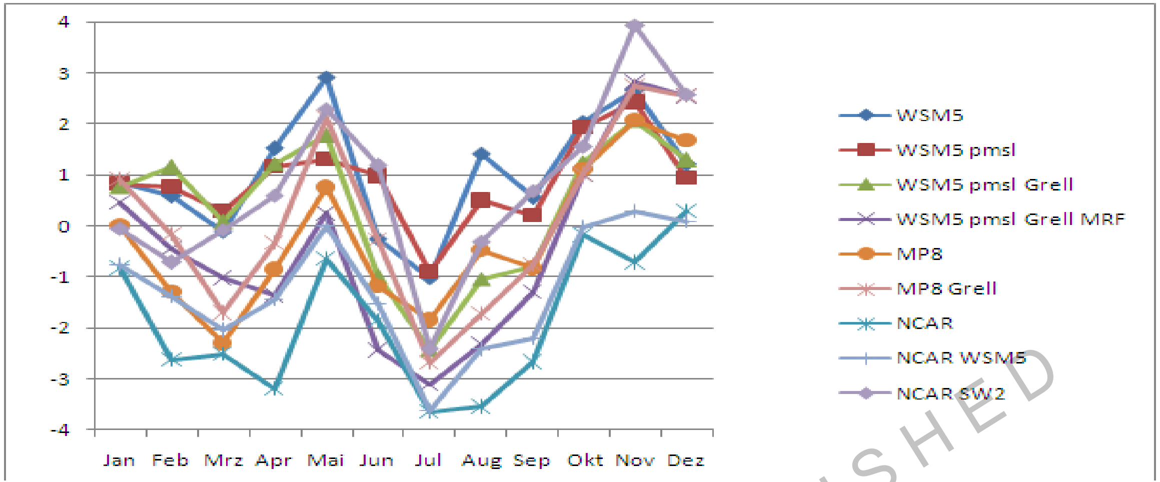
MP + Cu + PBL



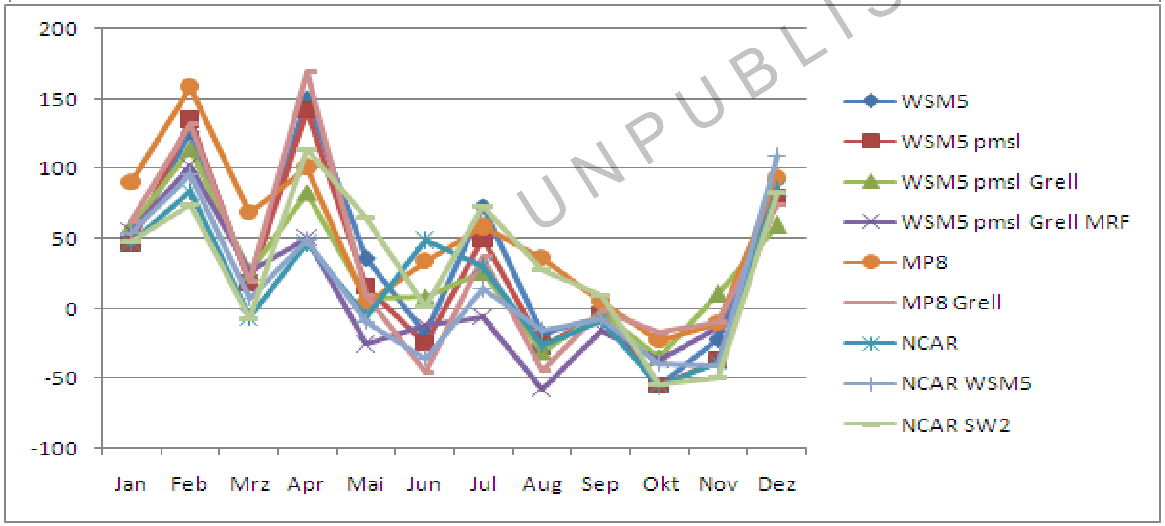


WRF Physics: D1 1968: Germany areal average

Temperature bias [°] (EOBS)



Precipitation bias [%] (EOBS)

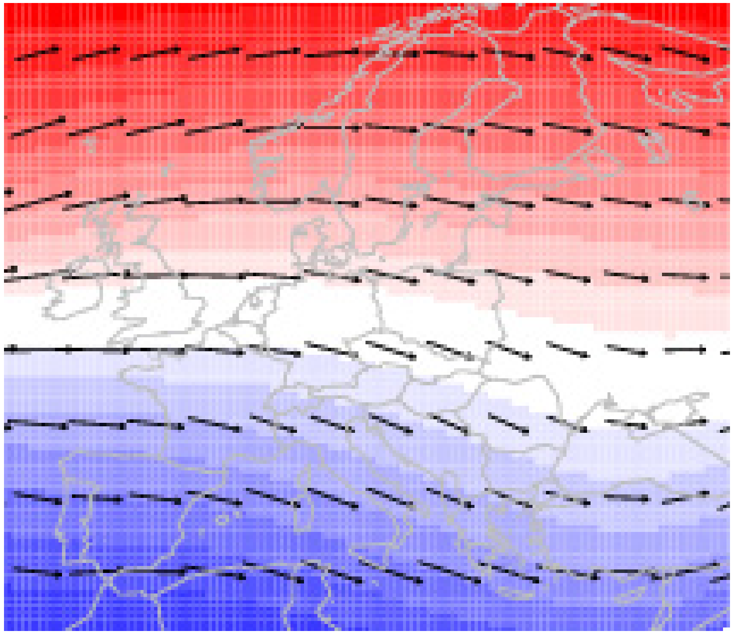


Select an appropriate WRF setup for long-term simulations

WRF regional climate simulations: example Germany

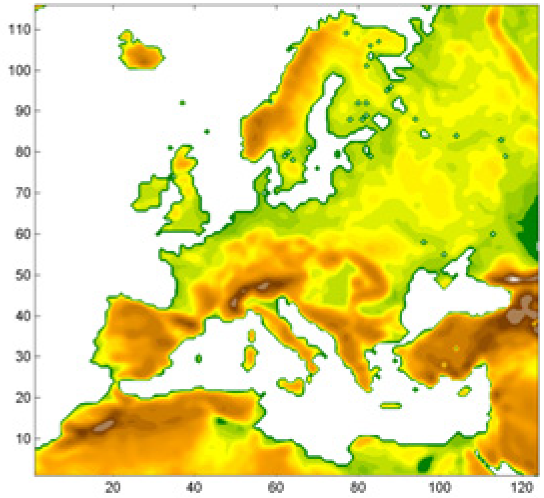
- Simulation periods:
- ERA40 run: 1971-2000
- ECHAM5 control period: 1971-2000
- ECHAM5 scenario: 2021-2050
- For each simulation: 3 years spinup

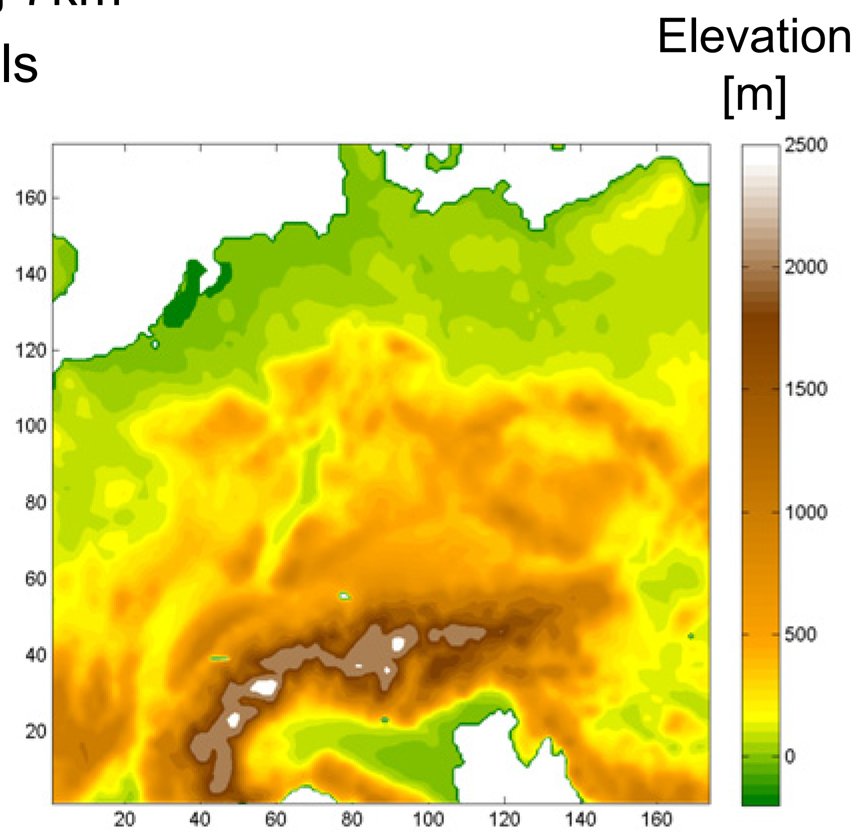
Example: WRF 50 km geoptential height@500hPa and wind field using ERA40



WRF regional climate simulations: example Germany

- **Nesting strategy:**
  - **Domain1:** 125 x 117 gridpoints, 42 km
  - **Domain2**: 175 x 175 gridpoints, 7km
  - **Both domains:** 40 vertical levels





WRF regional climate simulations: example Germany

Karlsruhe Institute of Technology

High performance computing characteristics of this study:

- For robust long-term simulations integration time step has to be selected comparatively small to satisfy Courant-Friedrichs-Lewy (CFL) stability:

$$CFL = \frac{u * \Delta t}{\Delta x} \leq CFL_{\max}$$

with ***u*** = velocity
Δt = time step
Δx = length interval
CFL_{max} = 1 (typically)

→ 46 million integration steps for 614250 grid cells for domain1

→ 69 million integration steps for 1286250 grid cells for domain2

→ more than 10 degrees of freedom (momentum, mass, pressure, mixing ratios for moisture, etc.) on each grid cell

Shows necessity to run regional climate simulations on a suitable high performance computing (HPC) environment

WRF regional climate simulations: example Germany

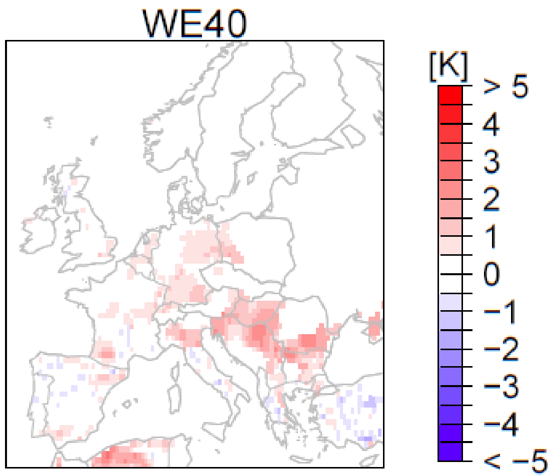
- High performance computing characteristics of this study:

	Global driving data	Period	Wall clock time [days]	CPU number	CPU time [hours]
Run 1	ECHAM5 CTR	1968-2000	58.13	96	133926
Run 2	ECHAM5 A1B	2018-2050	57.98	96	133595
Run 3	ERA40	1968-2000	59.49	96	137074

In addition to simulations themselves, a lot of preparatory work (mainly preparation of global forcing data) and postprocessing is required

WRF ERA40 long-term reanalysis simulations: example Germany

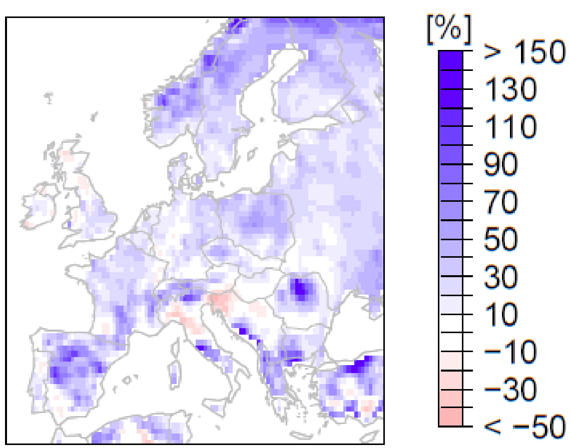
Temperature Bias [K]:



Averaged over Germany [K]:

	DJF	MAM	JJA	SON	Annual
WE40	-0.1	0.5	2.3	1.0	0.9

Precipitation Bias [%]:



Averaged over Germany [%]:

	DJF	MAM	JJA	SON	Annual
WE40	37	29	-8	8	14

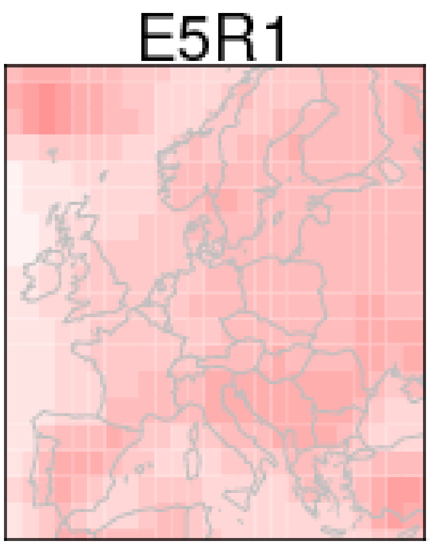
Berg P, Wagner S, Kunstmann H, Schädler G (2011) ***High resolution regional climate model simulations for Germany: Part I - validation.*** Climate Dynamics submitted.

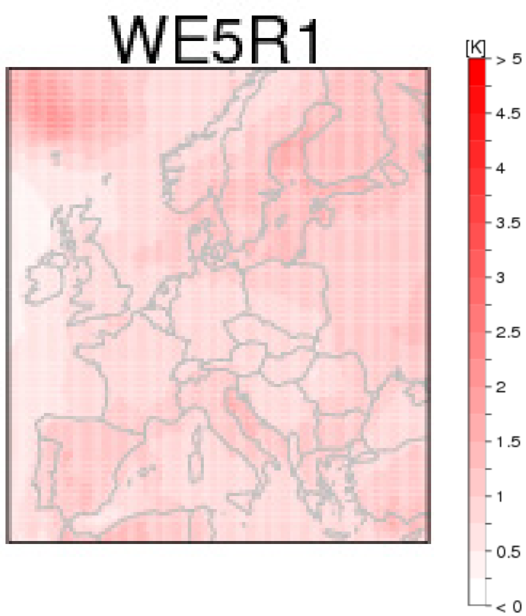
WRF regional climate simulations: example Germany

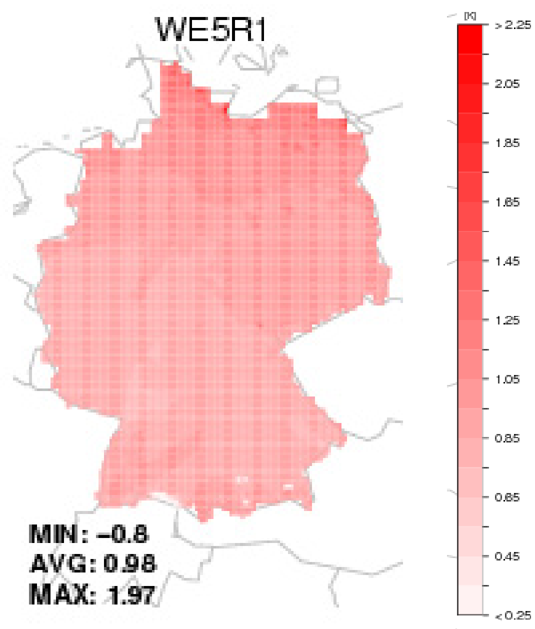
Karlsruhe Institute of Technology

Projected Temperature change [K]:

GCM: **RCM@42km:** **RCM@7km:**





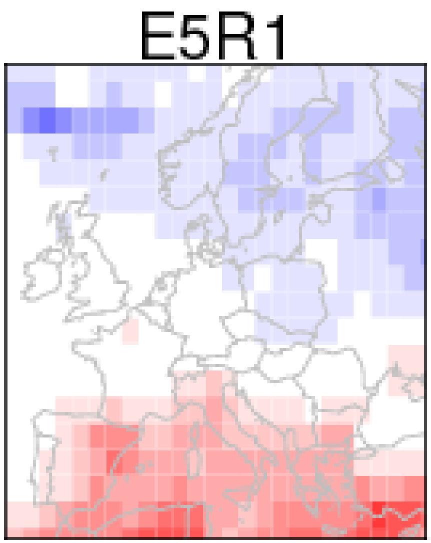


Wagner S, Berg P, Schädler G, Kunstmann H (2011) ***High resolution regional climate model simulations for Germany: Part II - projected climate changes.*** Clim. Dyn. submitted.

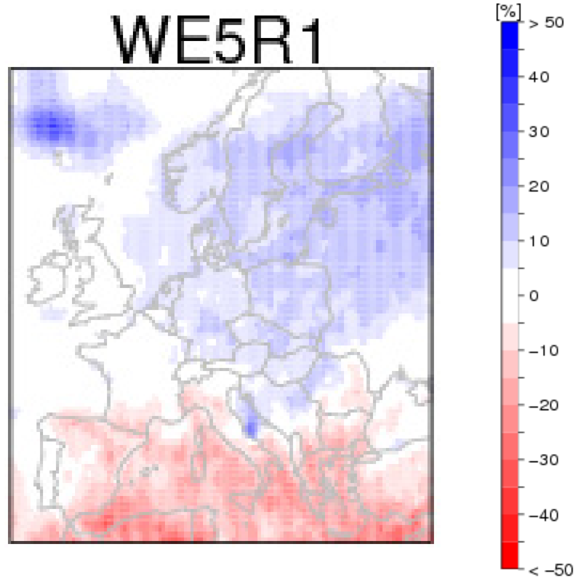
WRF regional climate simulations: example Germany

Projected Precipitation Change [%]:

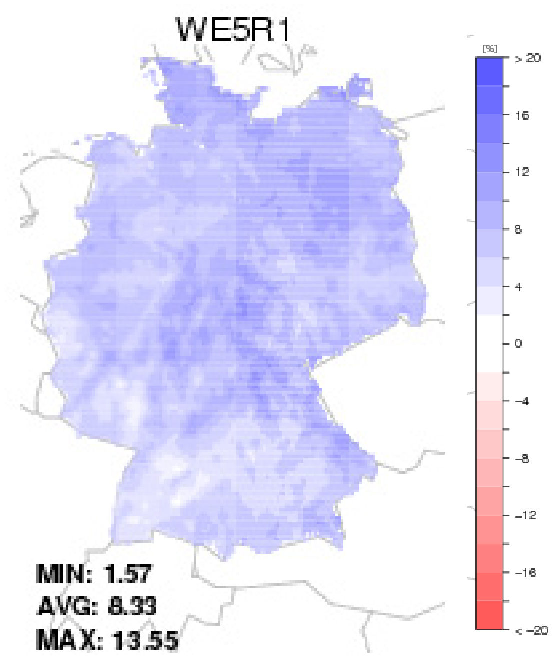
GCM:



RCM@42km:



RCM@7km:



Wagner S, Berg P, Schädler G, Kunstmann H (2011) ***High resolution regional climate model simulations for Germany: Part II - projected climate changes.*** Clim. Dyn. submitted.

CEDIM

KIT Karlsruhe Institute of Technology

GFZ Helmholtz Centre Potsdam

CEDIM-Project *„Flood Hazards in a Changing Climate “*

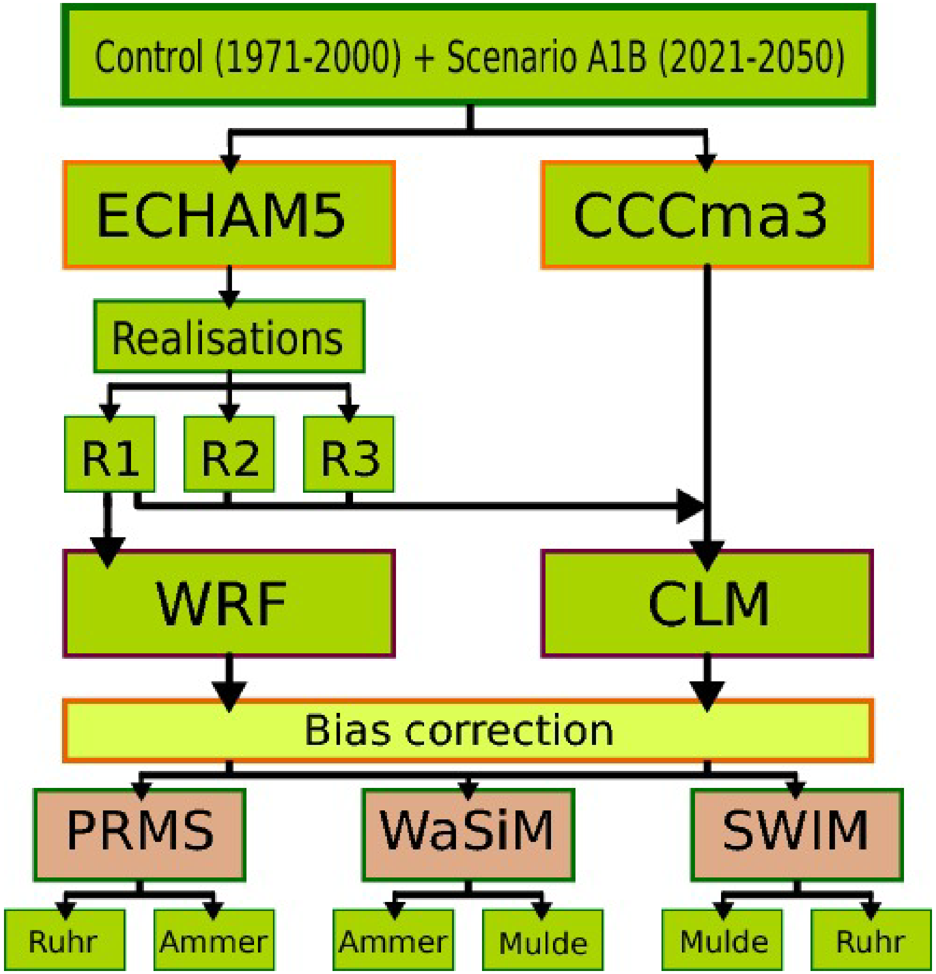
KIT: IMK-TRO: P. Berg, H. Feldmann, G. Schädler
IWG: J. Ihringer, J. Liebert
IMK-IFU: H. Kunstmann, I. Ott, S. Wagner
GFZ: Section 5.4: D. Duethmann, B. Merz

Project Report: Flood Hazards in a Changing Climate
Schädler et al., 2012

http://www.cedim.de/download/Flood_Hazards_in_a_Changing_Climate.pdf

Methodology: Schematic of model chain

ERA40 WRF & CLM simulations &



Ensemble approach

Further Literature:

Berg P, Wagner S, Kunstmann H, Schädler G (2011) ***High resolution regional climate model simulations for Germany: Part I - validation.*** Climate Dynamics submitted.

Wagner S, Berg P, Schädler G, Kunstmann H (2011) ***High resolution regional climate model simulations for Germany: Part II - projected climate changes.*** Clim. Dyn. submitted.

Berg, P., H. Feldmann, and H.-J. Panitz (2012) ***Bias correction of high resolution regional climate model data***. J. Hydrol., 448-449, 80-92.

Ott I, Düthmann D, Liebert J, Berg P, Feldmann H, Ihringer J, Kunstmann H, Merz B, Schädler G, Wagner S (2012) ***High resolution climate change impact analysis on medium sized river catchments in Germany: an ensemble assessment***. Journal of Hydrometeorology, submitted.

Take Home Messages

- WRF simulation results can be affected by
  - domain setup:

  number of domains, size of domains, horizontal and vertical resolution

  →domain edges: avoid steep topography; away of target region

  - input data:

  →Choose suitable input data set (meteorological, land use, …)

  - model physics:

  →Literature review: which parameterization have other people used for WRF simulations in same area of interest?

  → Choose suitable physic options & combinations

Be confident with your WRF setup before starting RCM simulations

→ can usually not be repeated

Take Home Messages

Regional climate simulations and climate impact studies:

- Do long-term reanalysis simulations to assess performance of RCM WRF
- RCM simulations show some bias and range of projected temperature and precipitation changes
- Benefit of high resolution RCM in simulating spatial patterns & precipitation intensity distributions
- Benefit of ensemble simulations

- Data requirements of subsequent climate impact studies have to be know before
- Possibly, bias correction methods are required
- Apply ensemble simulations to incorporate main sources of uncertainties from scenarios, GCMs, realisations, and RCMs and impact model