Notes concerning the climate modelling exercises:

- **Please send the solutions for both exercises to me (*sven.kotlarski@env.ethz.ch*) until 15 January 2015 (copy to Prof. Ramanathan)**
- **For each exercise please provide one solution for each student**
  (in case you teamed up with somebody for the Panoply/CDO exercises you can provide the same plots in your respective solutions)

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

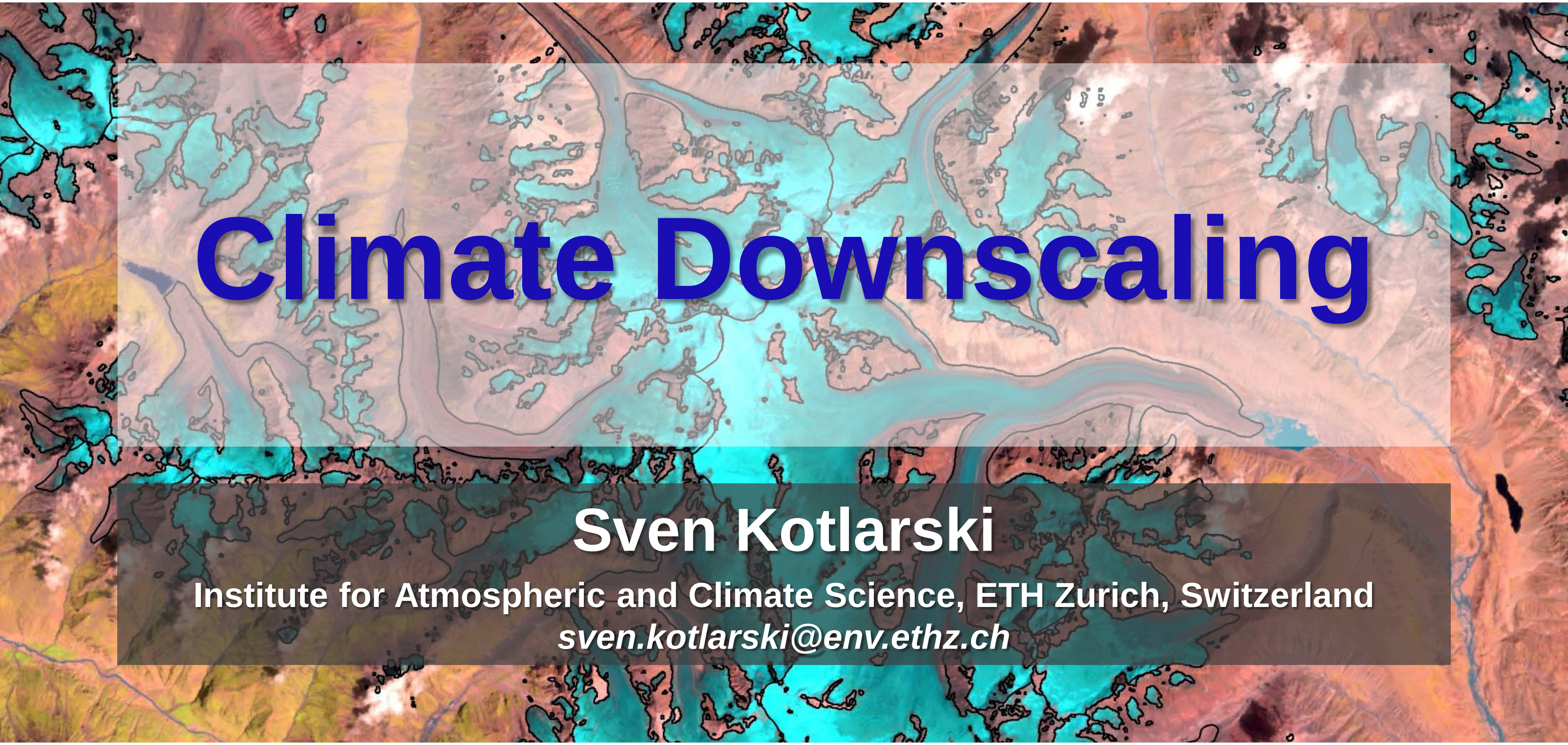
METEODAT

UNIVERSITÄT BERN

UNIVERSITAS FRIBURGENSIS

UNIVERSITÉ DE GENÈVE

University of Zurich[UZH]



Climate Downscaling

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IHCAP – Indian Himalayas Climate Change Adaptation Programme

2nd Indo-Swiss Capacity Building Programme, Level II (Jan 5 – Feb 13, 2015)

STRUCTURE OF THIS COURSE

Lecture 1: **Global climate modelling**

Exercises 1: **Postprocessing and visualization of climate model output**

Lecture 2: **Climate downscaling**

Exercises 2: **Analysis of regional climate change signals**

OUTLINE

1. CLIMATE DOWNSCALING: THE RATIONALE
2. REGIONAL CLIMATE MODELLING
3. THE CORDEX INITIATIVE

BREAK

4. STATISTICAL DOWNSCALING
5. LINKING IMPACT MODELS
6. REPRESENTING GLACIERS IN REGIONAL CLIMATE MODELS

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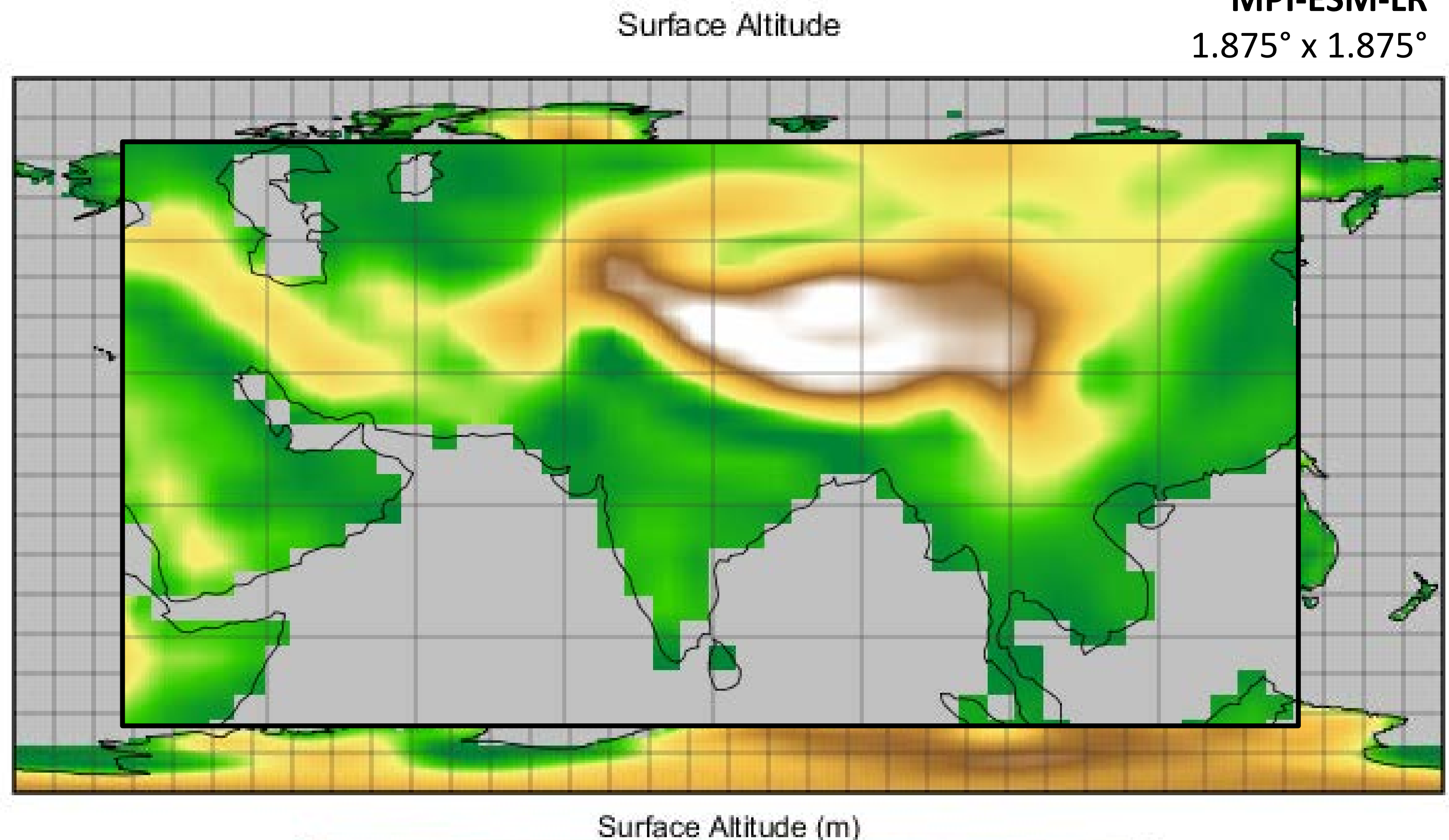
Piz Daint
CSCS Lugano
Cray XC30

blizzard
DKRZ Hamburg
IBM power6, 4224 dual cores

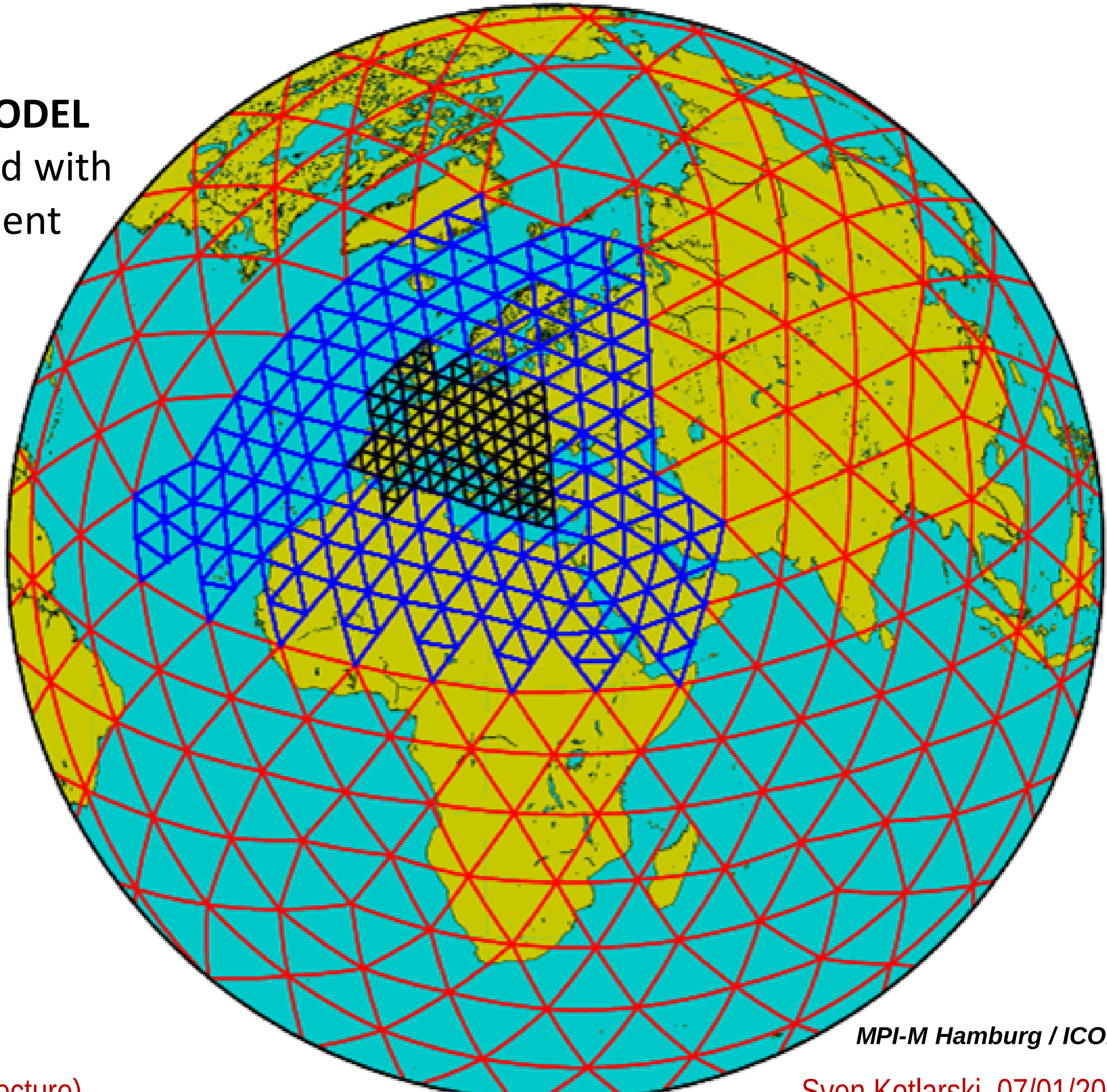
MPI-ESM-LR
1.875° x 1.875°



- Limited computing ressources restrict current GCM resolution to **100-300 km**
- but: (1) **Mesoscale circulations** not resolved
  (2) **Regional scale feedback processes** poorly represented
  (3) Climate change impacts are mainly experienced on **regional / local scales**

OPTION A: VARIABLE RESOLUTION GCM

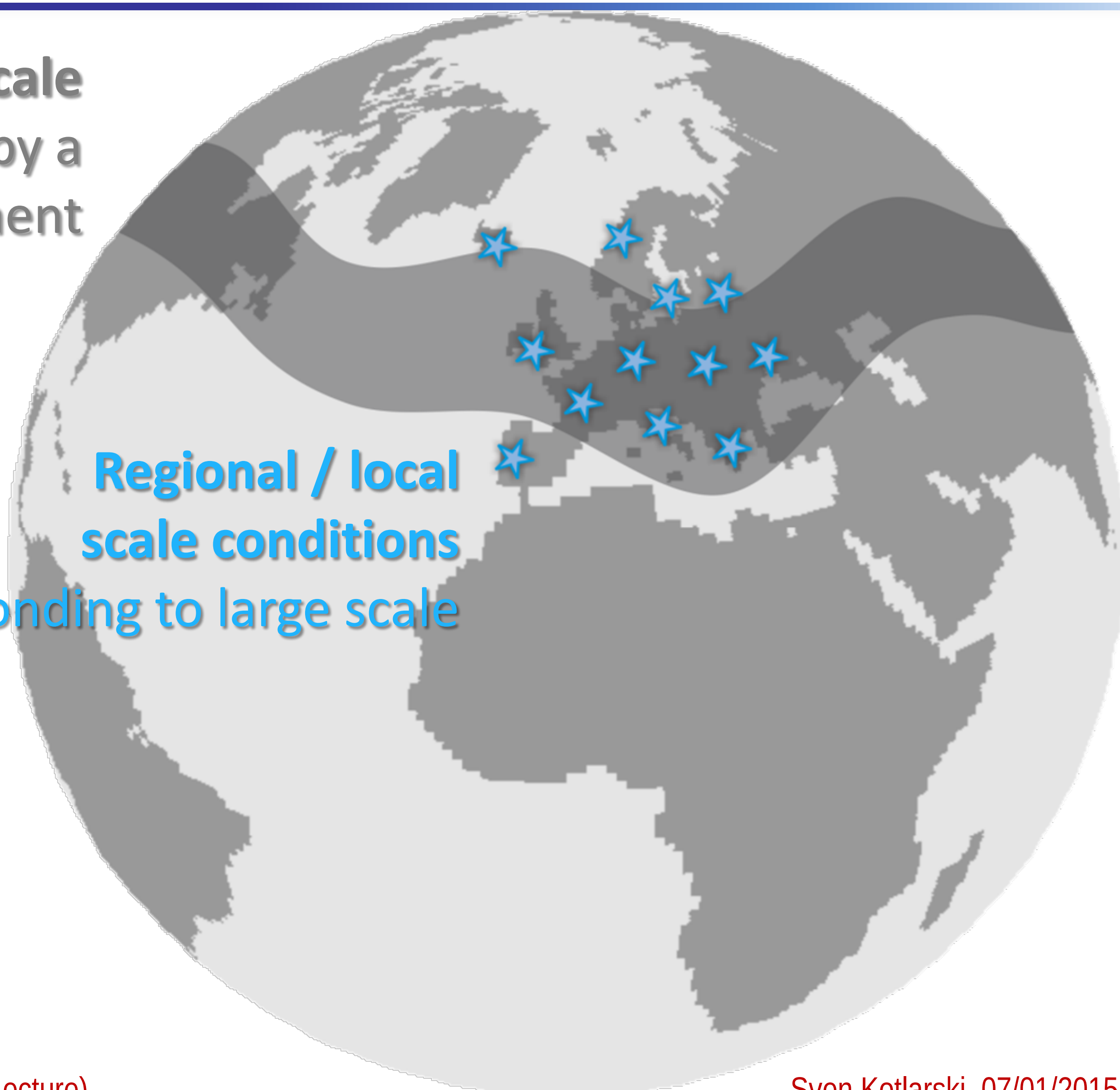
THE ICON MODEL
triangular grid with
local refinement



MPI-M Hamburg / ICON

OPTION B: EXPLICIT DOWNSCALING

Large scale
as provided by a
GCM experiment



Regional / local
scale conditions
corresponding to large scale

WHAT IS CLIMATE DOWNSCALING?

- Downscaling attempts to **resolve the scale discrepancy** between climate change scenarios and the resolution required for impact assessment
- It is **based on the assumption that large-scale weather exhibits a strong influence on local scale weather**
- In general sense, downscaling **disregards any reverse effects** from local scales upon global scales

Maraun et al, Rev. Geophys., 2010

Which types of downscaling exist

?

TYPES OF DOWNSCALING

STATISTICAL – EMPIRICAL DOWNSCALING	DYNAMICAL DOWNSCALING
Establishing **statistical relationships** between large-scale predictors and local weather conditions **based on observations** **Extrapolation** of relationships into the future (using large-scale predictors from GCM experiments)	Nesting a **regional climate model** (RCM) at higher resolution into a coarse-resolution GCM RCMs typically developed from numerical weather prediction models

SUMMARY CHAPTER 1
(Climate Downscaling: The Rationale)

- **Spatial resolution of global climate models restricted by available computing power**
- **Higher spatial resolution required for many applications**
- **Climate downscaling addresses this need by translating large-scale information to local conditions**

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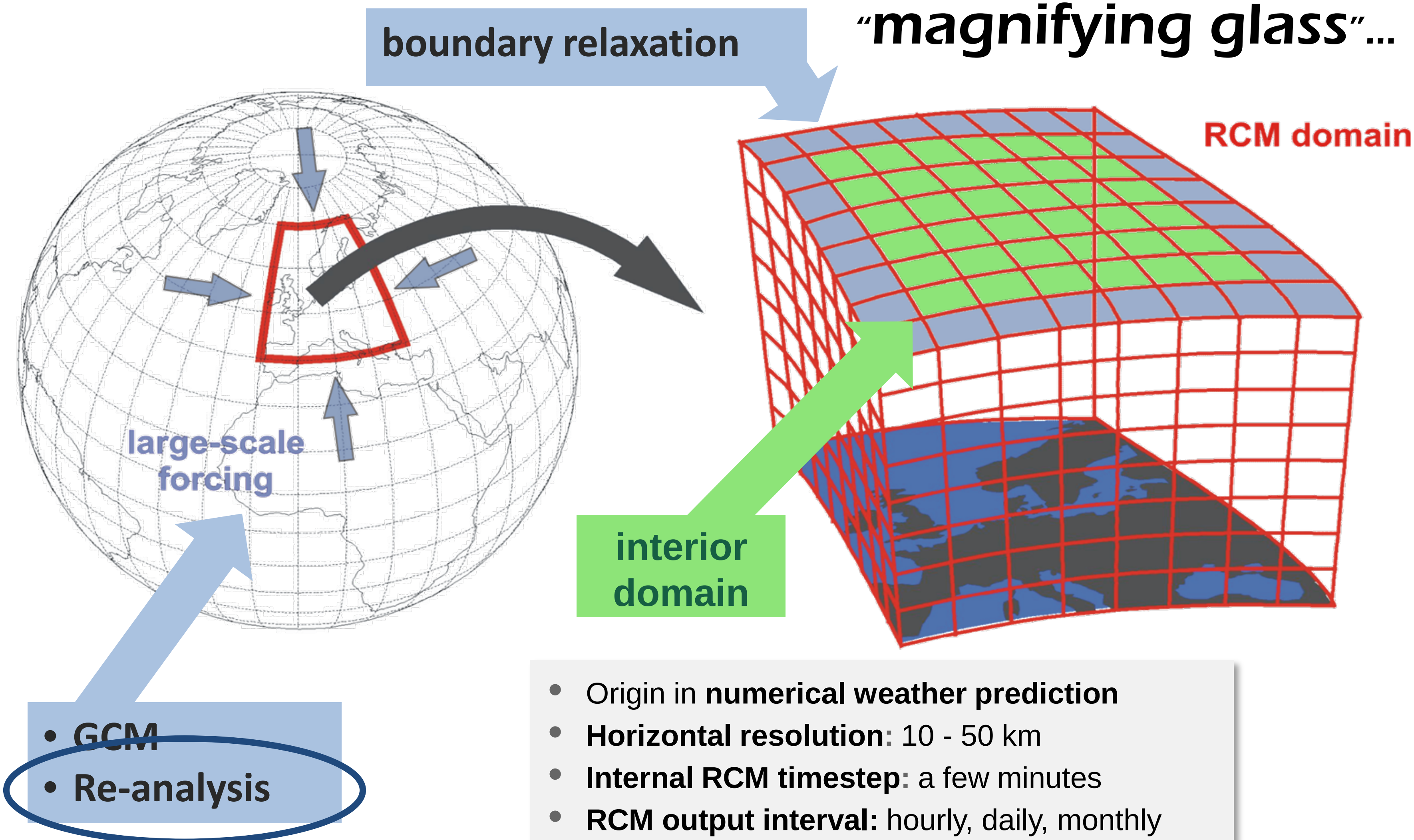
REGIONAL CLIMATE MODELLING

Apply a limited area model (**regional climate model, RCM**) as a "**magnifying glass**"...



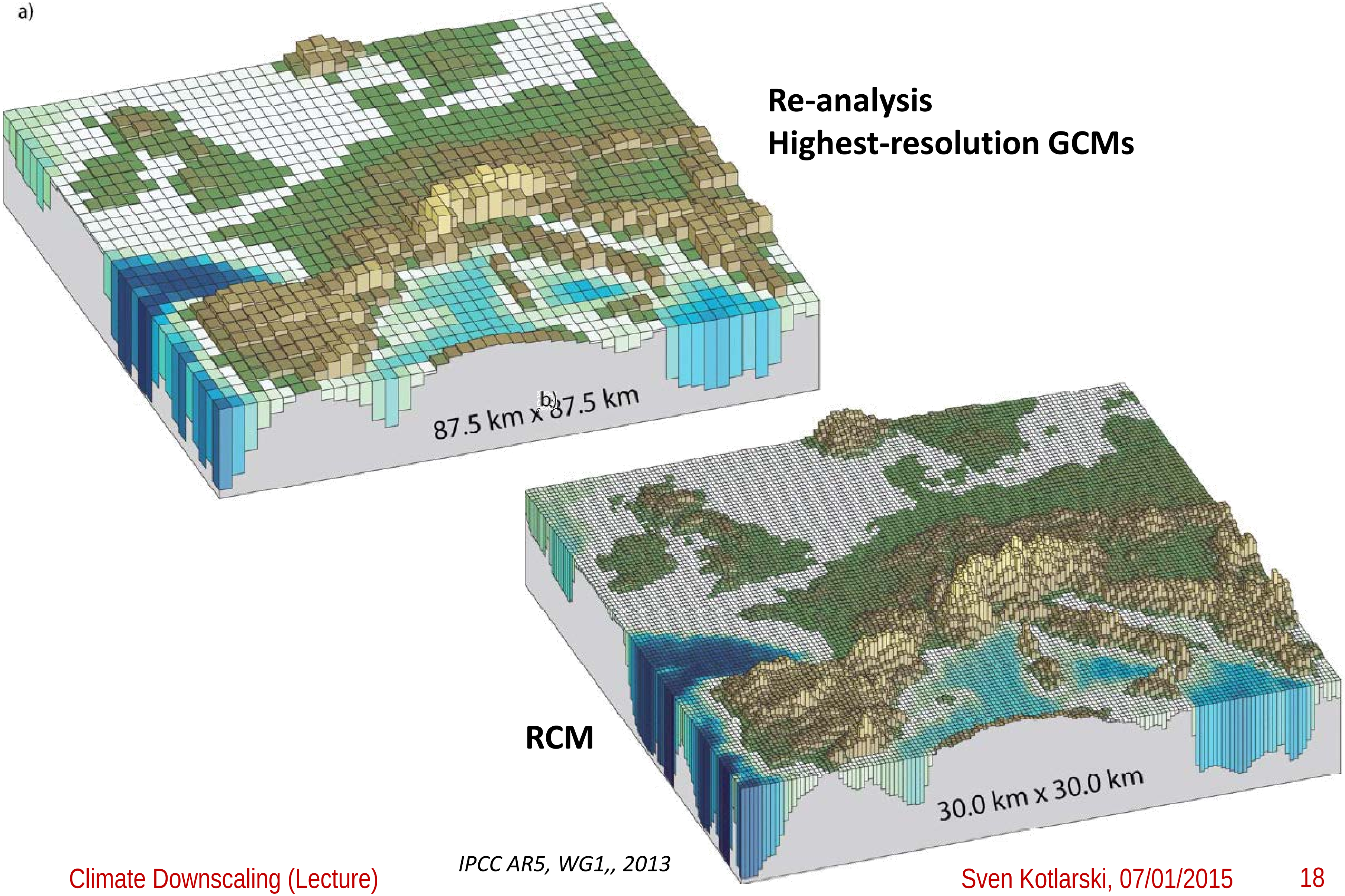
- Origin in **numerical weather prediction**
- **Horizontal resolution**: 10 - 50 km
- **Internal RCM timestep**: a few minutes
- **RCM output interval:** hourly, daily, monthly
- Typically **one-way nesting** only

RE-ANALYSES

- Systematic approach to **produce data sets for climate monitoring and research**
- Idea: Continuously assimilate observations (surface, radio sondings, remote sensing) into a **weather/climate model and run this model forward in time** -> reprocessing observational data spanning an extended historical period using a consistent modern analysis system
- Apply **unchanging assimilation schemes and models** («frozen»)
- Most reanalyses are **global**, but **regional** products at higher resolutions exist as well
- Besides atmospheric reanalyses further types exist (e.g., oceanic reanalyses)
- Several purposes, including **validation** of GCMs and RCMs and **provision of boundary forcing**

More on this in the gridded climate data lecture …

GRID SPACINGS …



Re-analysis
Highest-resolution GCMs

RCM

IPCC AR5, WG1,, 2013

PROS and CONS of dynamical downscaling

+

- **Physically consistent response, including climate feedbacks**
- **Application of models for future periods possible (in principle)**

–

- **Computationally expensive**
- **Advanced expertise required**
- **Limited number of realizations**
- **Limited spatial resolution** (does not target the site scale)
- **Strongly depends on driving GCM** (*garbage in – garbage out*)
- **"Added value" wrt. GCM not always apparent** (found, e.g., in high-order statistics reflecting intense and localized events)

ADDED VALUE

- **An RCM won't improve all aspects of a GCM simulation**
- Added value often hard to find for time-averaged quantities or on large spatial scales
- Most likely in **frequency distributions and high-order statistics reflecting intense and localized events** (e.g. tails of daily precipitation intensity distribution; e.g. Jacob et al. 2013)
- Added value on scales that are common to both the RCM and the driving GCM?

→

- **RCMs are complementary to GCMs by adding further detail to global climate projections**
- **They allow to study climate processes in higher (spatial) detail than global models allow**

http://climate4impact.eu/impactportal/general

ROTATED RCM GRIDS

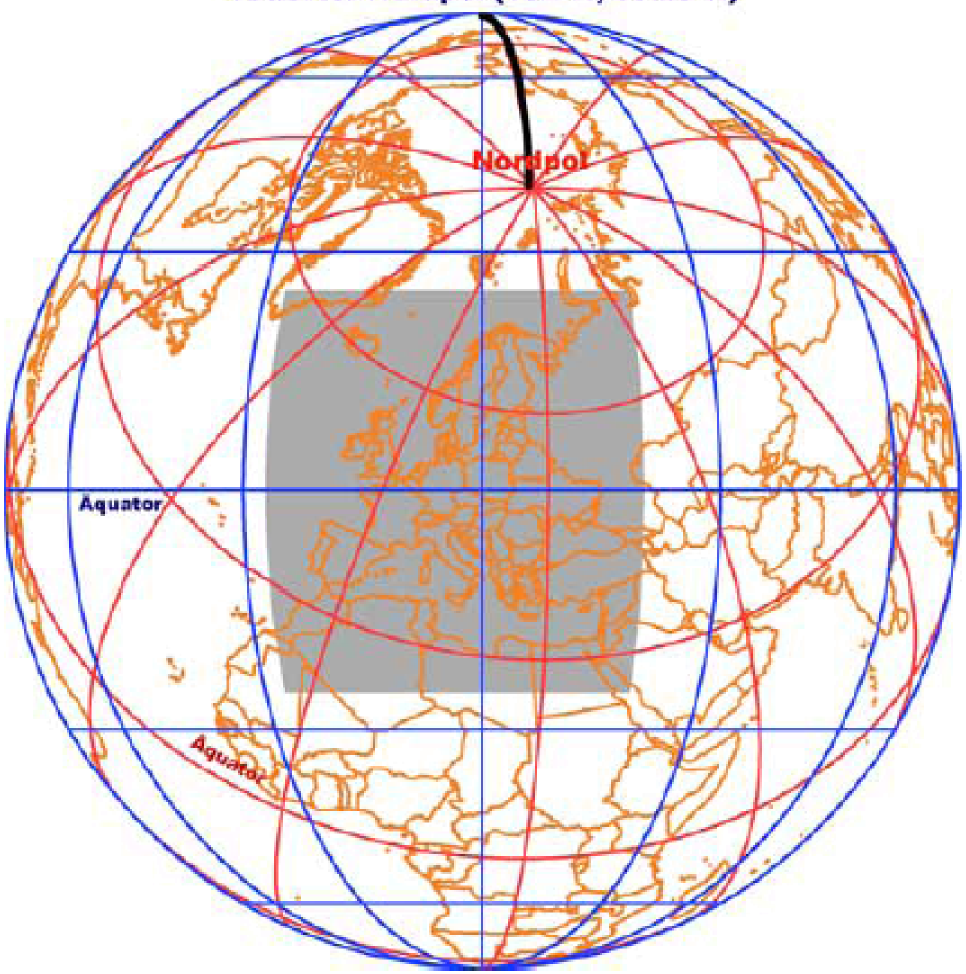


Abbildung 8: Rotierte Länge und Breite (blaue Linien) für ein sphärisches Koordinatensystem mit dem rotierten Nordpol bei 162° W und 39,25° N. Rote Linien: Länge und Breite des unrotierten geographischen Systems. Grau eingezeichnet ist das ENSEMBLES Modellgebiet.

Göttel 2008

- RCM grid cells often defined in a lat/lon system
- meridional convergence towards the poles
- grid rotation necessary (equator passes approx. the center of model domain)
- rotated grid not regular in real-world lat-lon

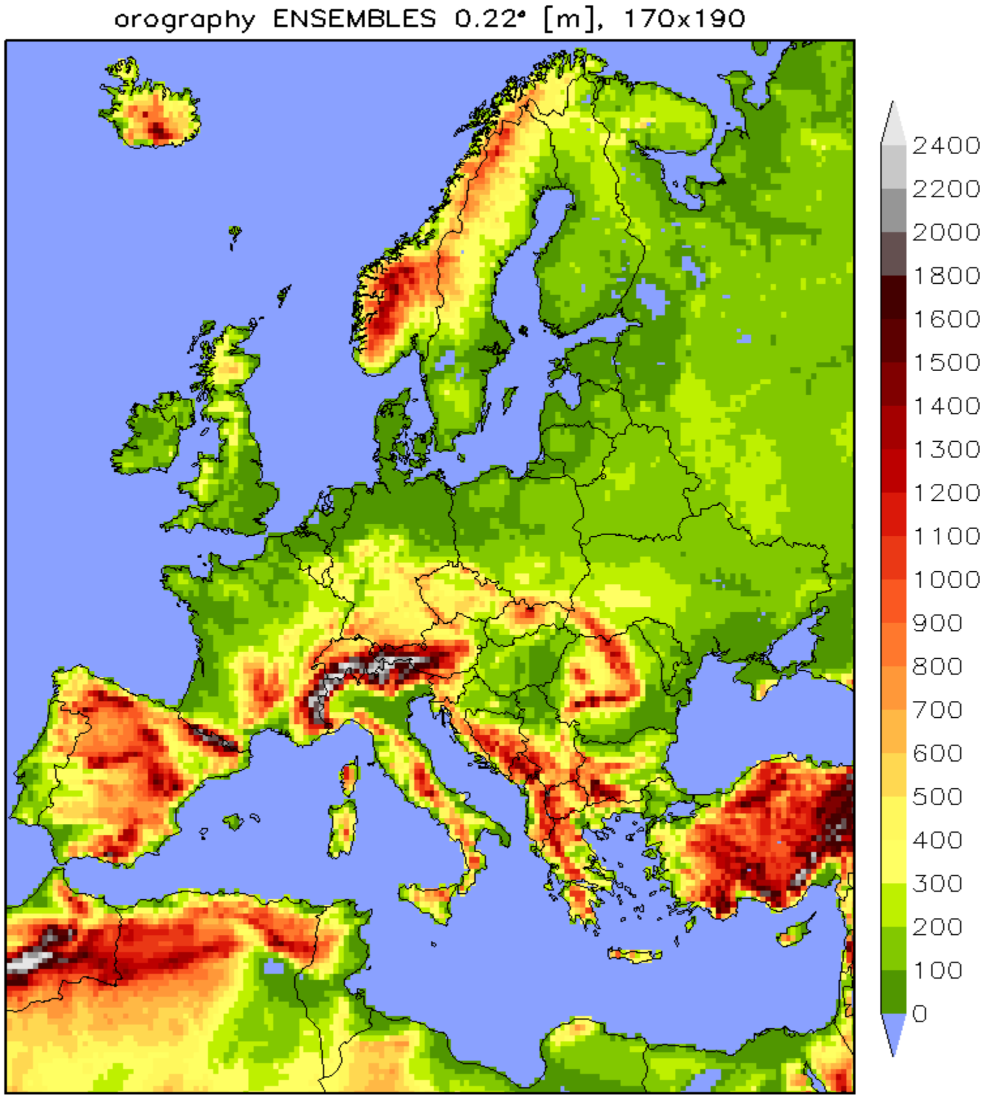
COSMO-CLM

COSMO model in CLimate Mode

- Regional atmospheric circulation model
- Scale: 1 km to 50 km
- Based on NWP model COSMO (**DWD, MeteoSwiss**)
- Development and application: **CLM community**

THE ENSEMBLES PROJECT

- 5-year research programme (EU FP6)
  www.ensembles-eu.metoffice.com
- **Objective**: Setup of an ensemble prediction system for climate change in Europe
- **Regional component:**
  16 RCMs at 25 km (and 50 km) resolution
- **Evaluation runs** and **climate change scenarios** until 2050/2100 (multiple GCMs, SRES A1B)



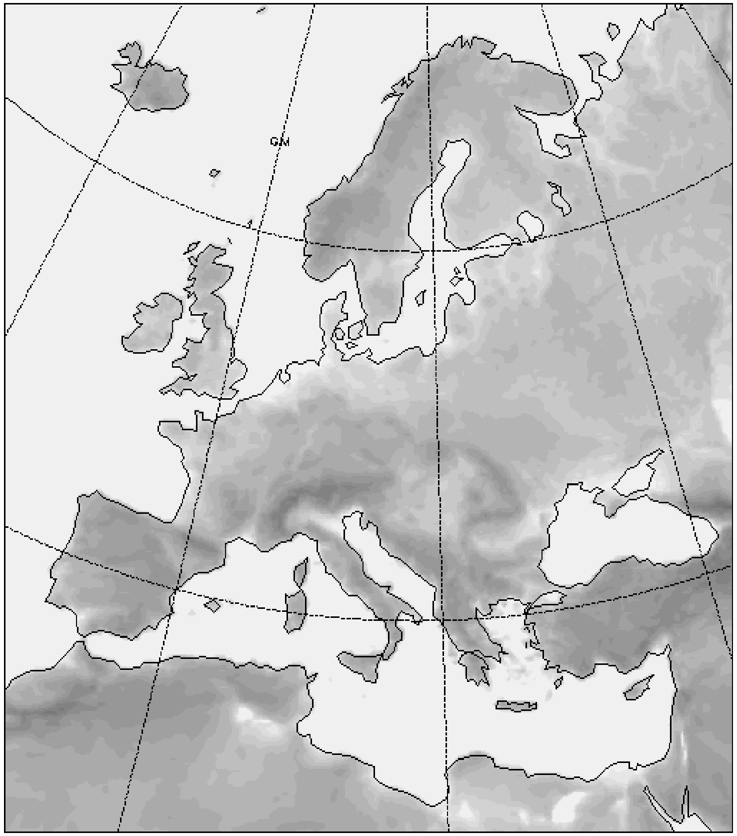
TYPES OF RCM EXPERIMENTS

boundary forcing (global)

Re-analysis
(perfect boundaries)

→

RCM



→

Evaluation of downscaling

WHY RCM EVALUATION?

Does the model work for the purpose it has been built for?

Model = incomplete representation of the climate system

Structural and parametric uncertainties

Good evaluation = basic requirement for trust in regional climate scenarios

Model selection and weighting

If selection necessary: Evaluation can inform choice to some extent

Basis for excluding models with major deficiencies

Model setup and calibration

Choosing a specific setup

Calibration within a specific setup

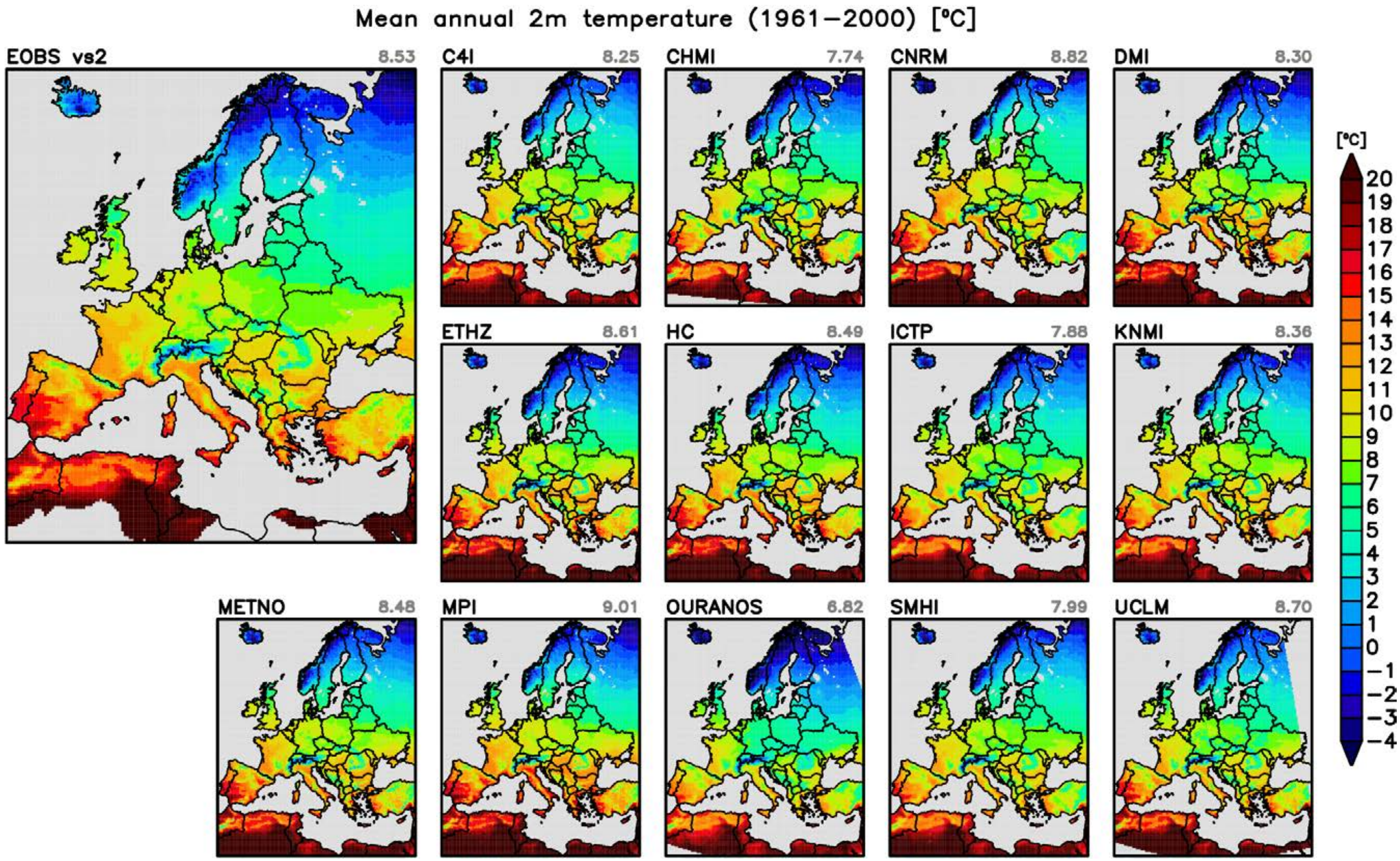
Added value analysis

Is RCM application, or very high resolution really required?

Identification of model deficiencies

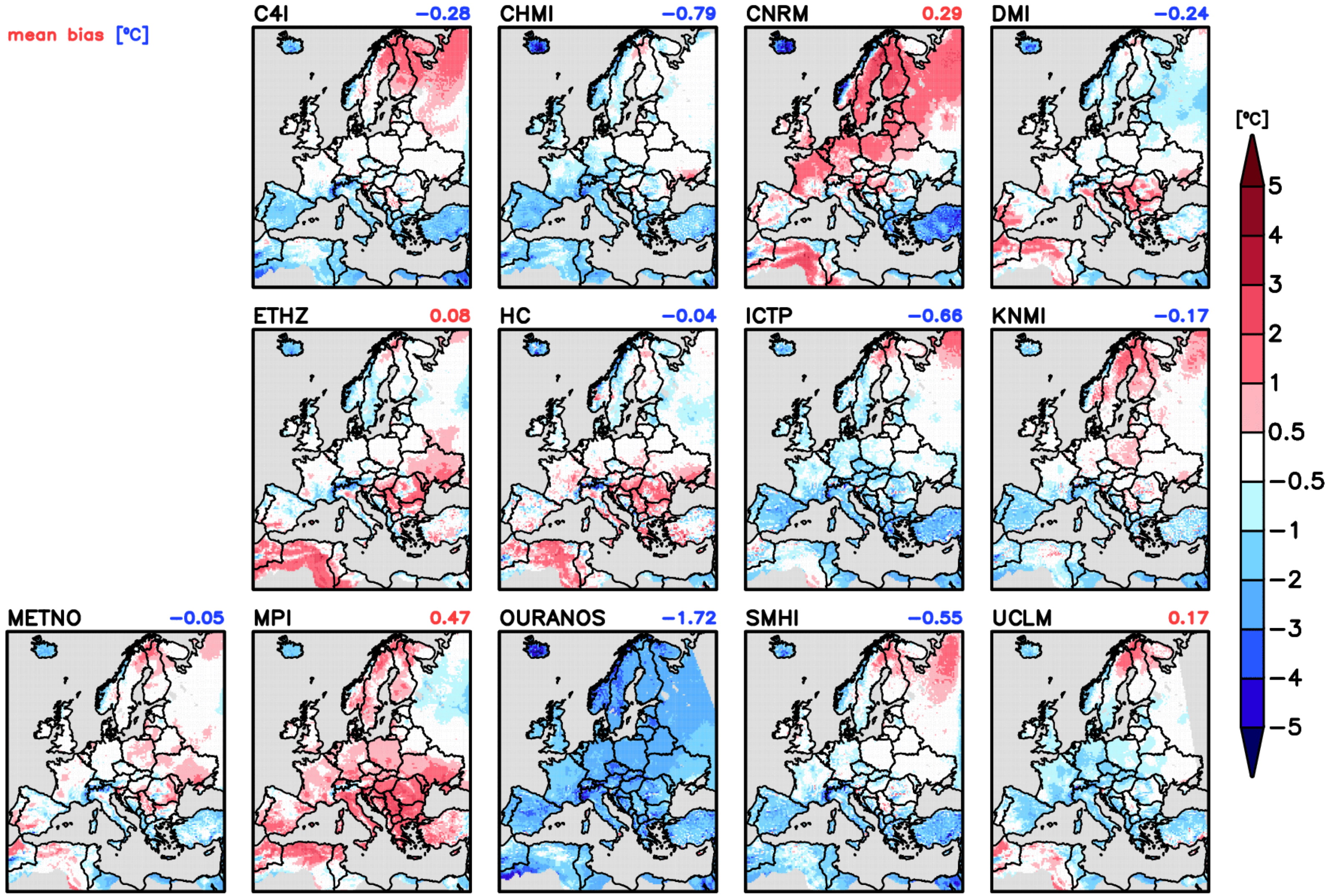
Model development

VALIDATION (1)



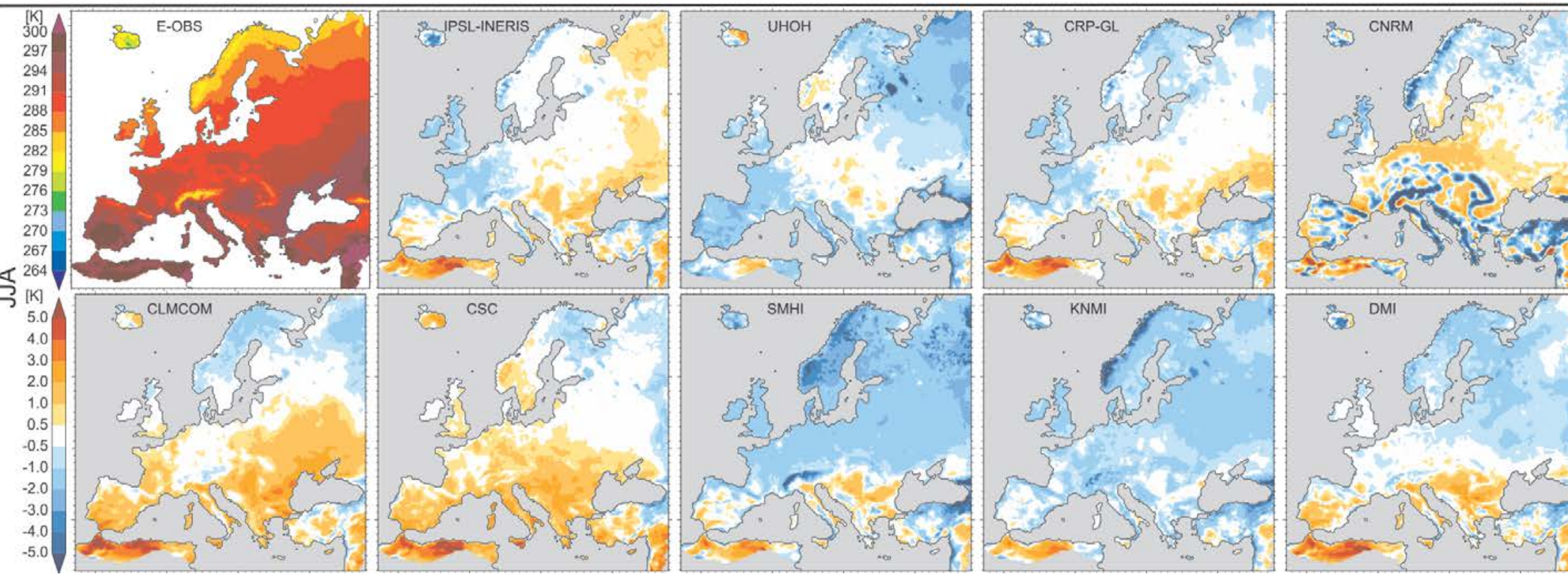
VALIDATION (2)

Mean annual 2m temperature bias wrt EOBS (1961–2000) [°C]

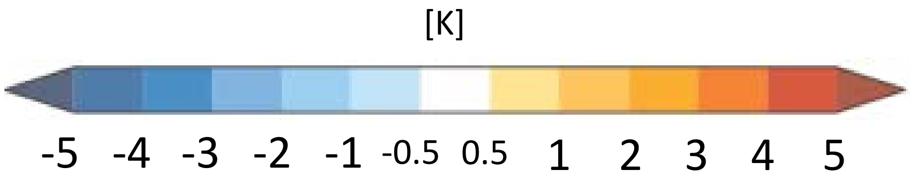


VALIDATION (3)

Summer temperature bias of nine regional climate models (ERA-Interim driven, 1989-2008)

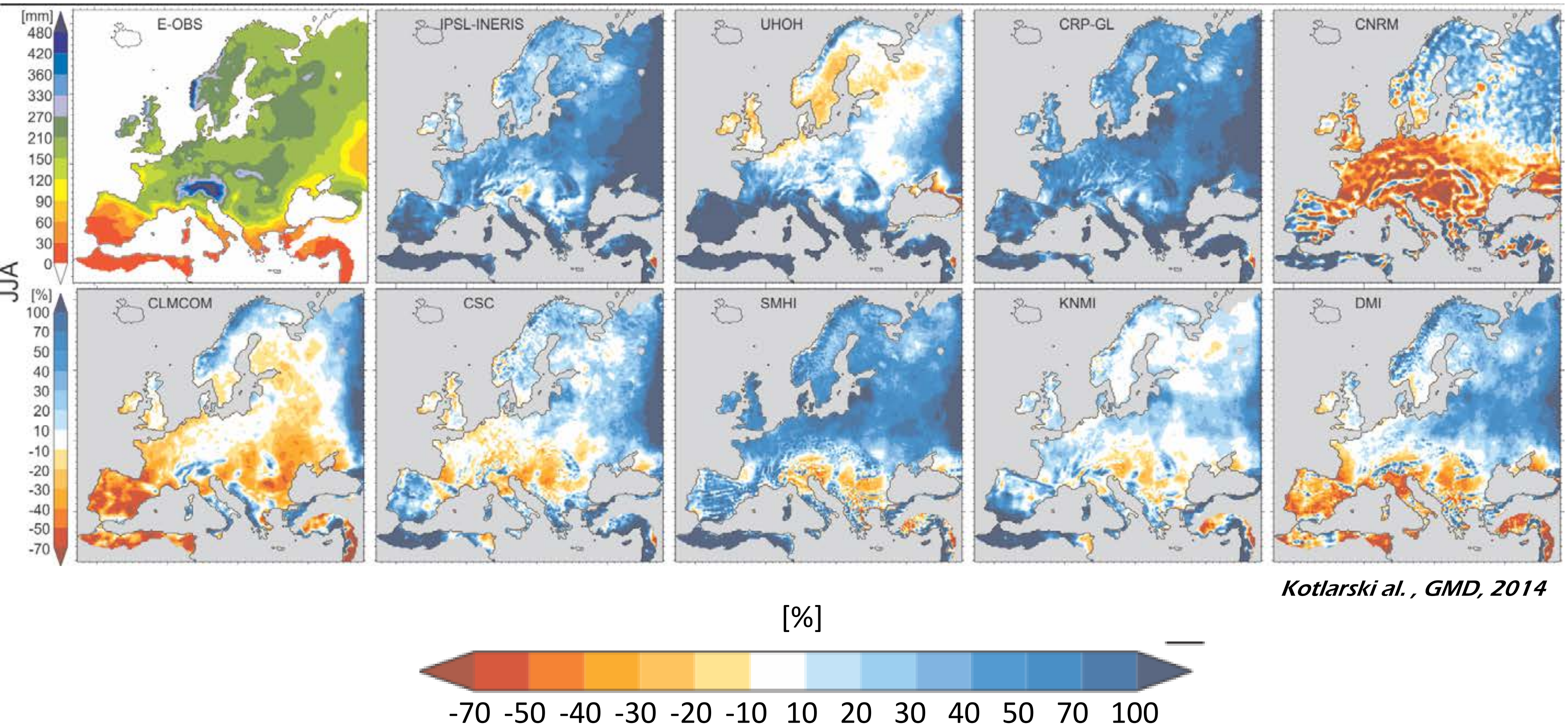


Kotlarski al. , GMD, 2014



VALIDATION (4)

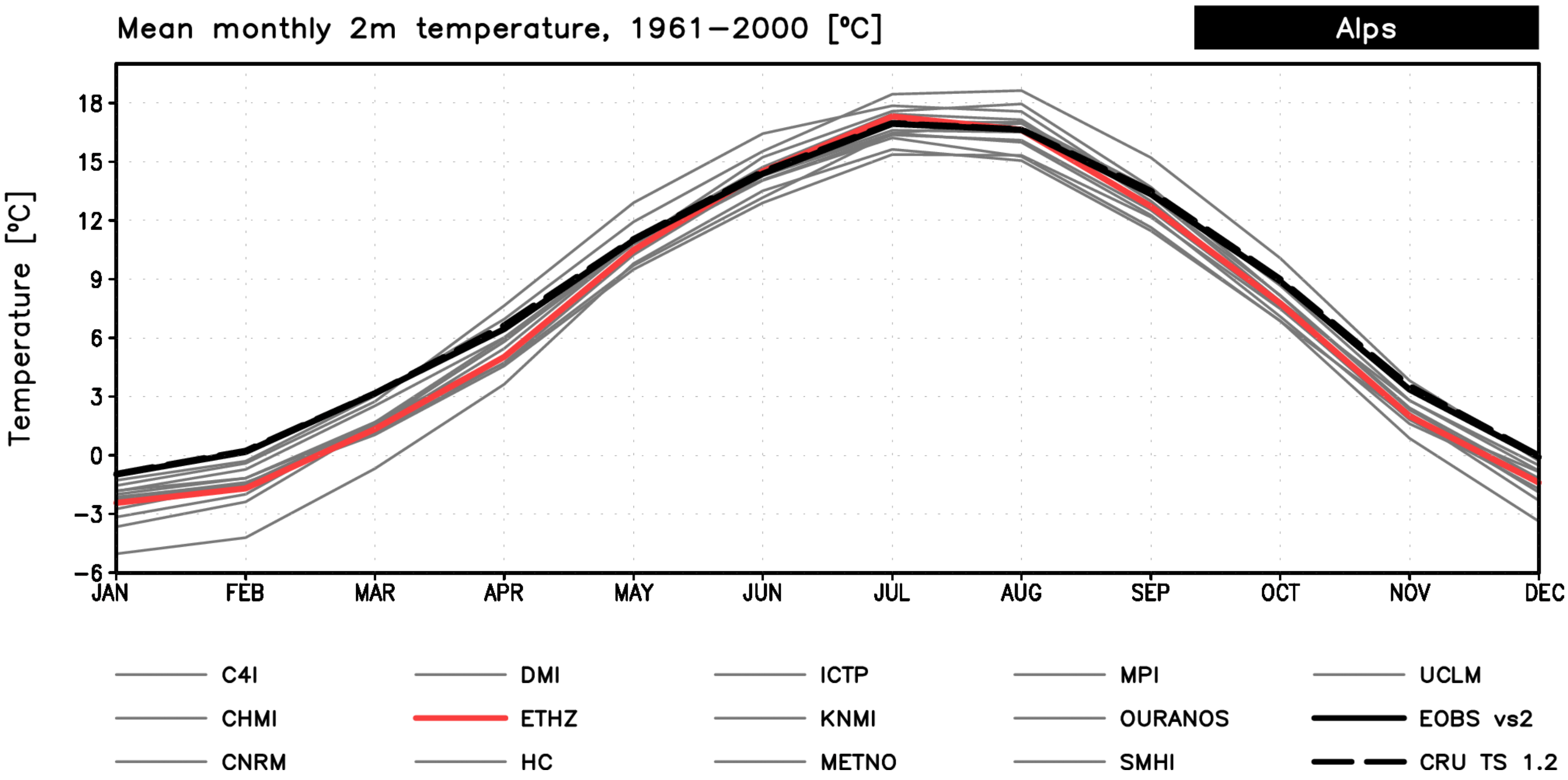
Summer precipitation bias of nine regional climate models (ERA-Interim driven, 1989-2008)



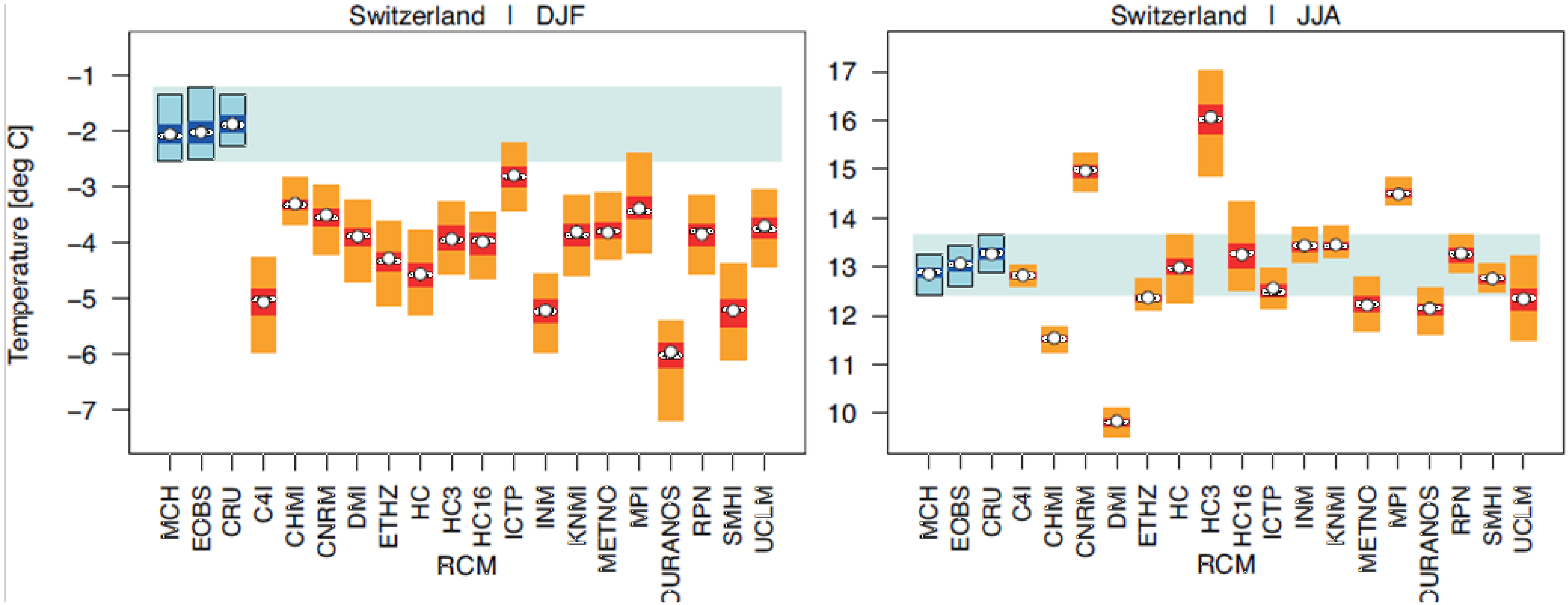
Kotlarski al. , GMD, 2014

Take care: E-OBS not corrected for systematic undercatch

VALIDATION (5)



VALIDATION (6)



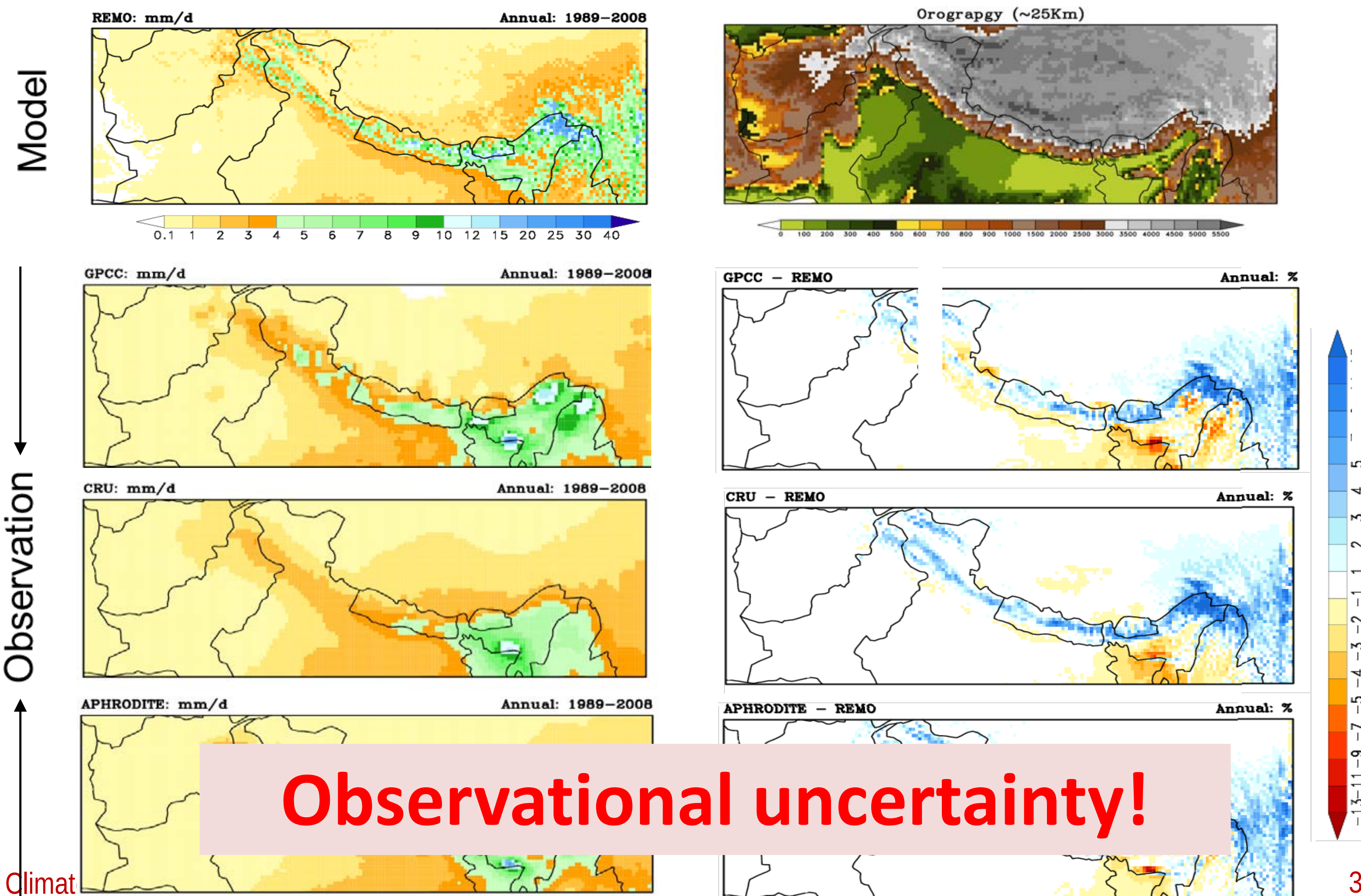
Jan Rajczak, ETH Zurich

Observational uncertainty!

VALIDATION (7)

Pankaj Kumar, MPI-M Hamburg

Observation and Model Precipitation annual mean 1989-2008



Observational uncertainty!

VALIDATION (7)

Note: **Skill in the present does not imply skill in the future** (compensating errors, different/ further relevant processes in the future, …)

But: **Model has to reflect the behaviour of the real system in order to be suitable for scenario development.**

TRAPS IN EVALUATION

TAKE CARE!

- Observational uncertainty
- Scale mismatch
- Compensating biases
- Infinite number of performance metrics
- Is evaluation independent of calibration?
- Internal variability
- Present-day performance vs. climate change signal
- Non-stationarity of model biases

TYPES OF RCM EXPERIMENTS

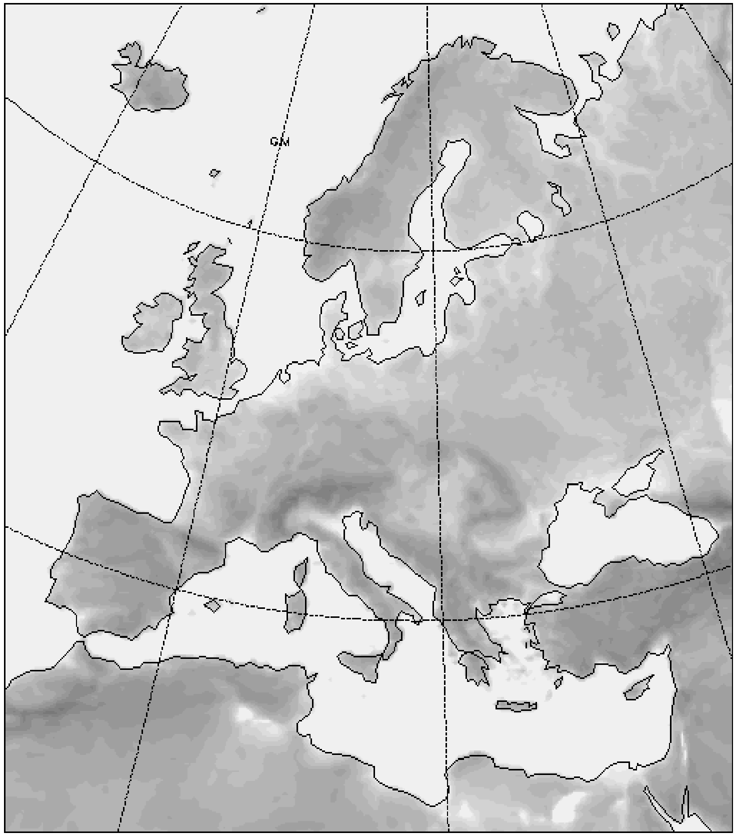
boundary forcing (global)

Re-analysis
(perfect boundaries)

GCM
historical GHG

GCM
future GHG

RCM



Evaluation of downscaling

Evaluation of GCM-RCM chain

Climate change

TYPES OF RCM EXPERIMENTS

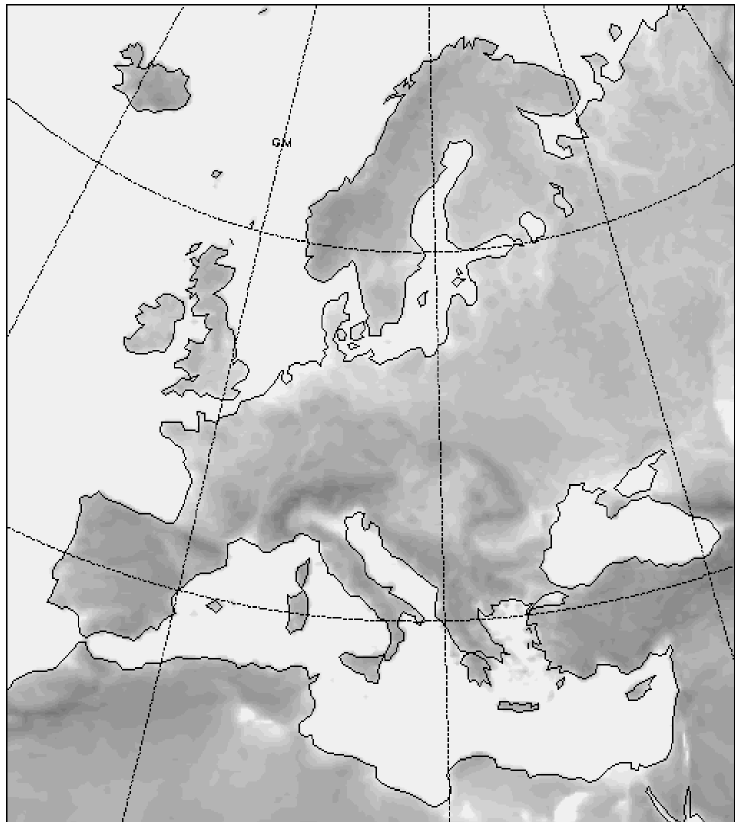
boundary forcing (global)

RCM

Re-analysis
(perfect boundaries)

GCM
historical GHG

GCM
future GHG



Evaluation of downscaling

Evaluation of GCM-RCM chain

Climate change

Greenhouse Gas Emission Scenarios
SRES scenarios, RCPs

TYPES OF RCM EXPERIMENTS

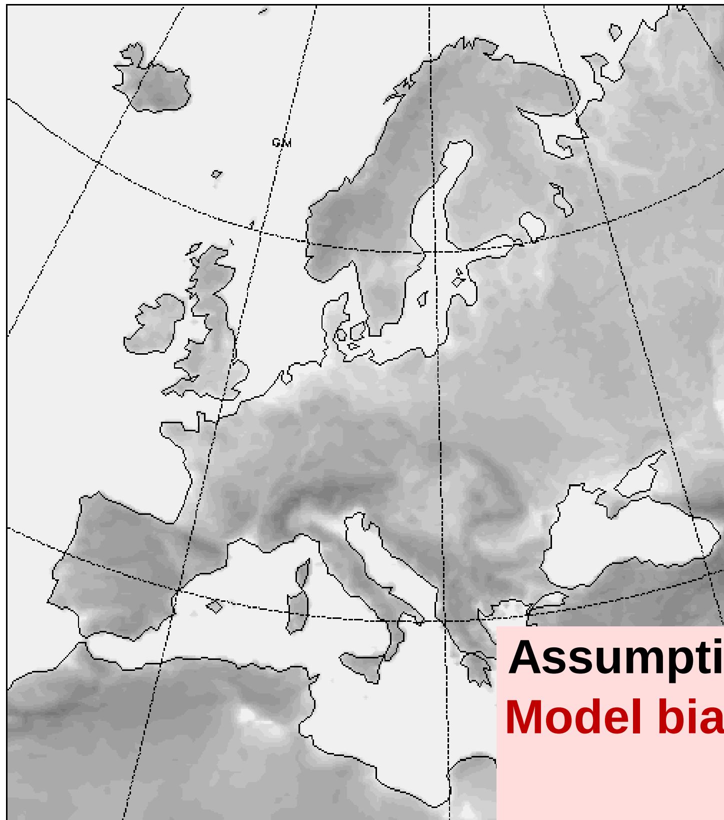
boundary forcing (global)

Re-analysis
(perfect boundaries)

GCM
historical GHG

GCM
future GHG

RCM



Evaluation of downscaling

Evaluation of GCM-RCM chain

Climate change

Greenhouse Gas Emission Scen
SRES scenarios, RC

Assumption:
Model bias constant in time
⬍
Climate change signal not affected by model bias

TYPES OF RCM EXPERIMENTS

boundary forcing (global)

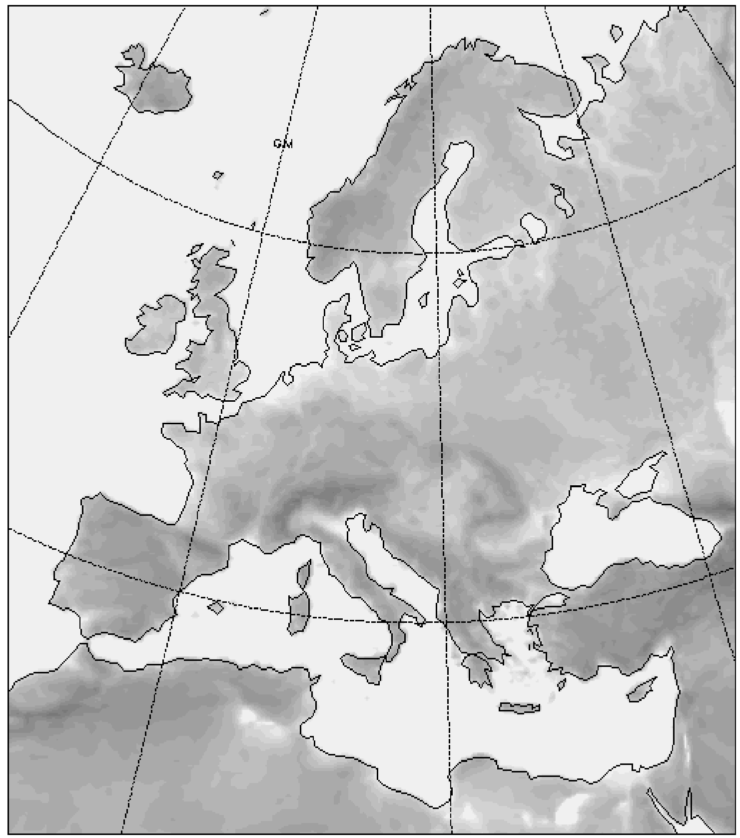
Re-analysis
(perfect boundaries)

GCM
historical GHG

GCM
future GHG

analysis of individual years not possible !!

RCM



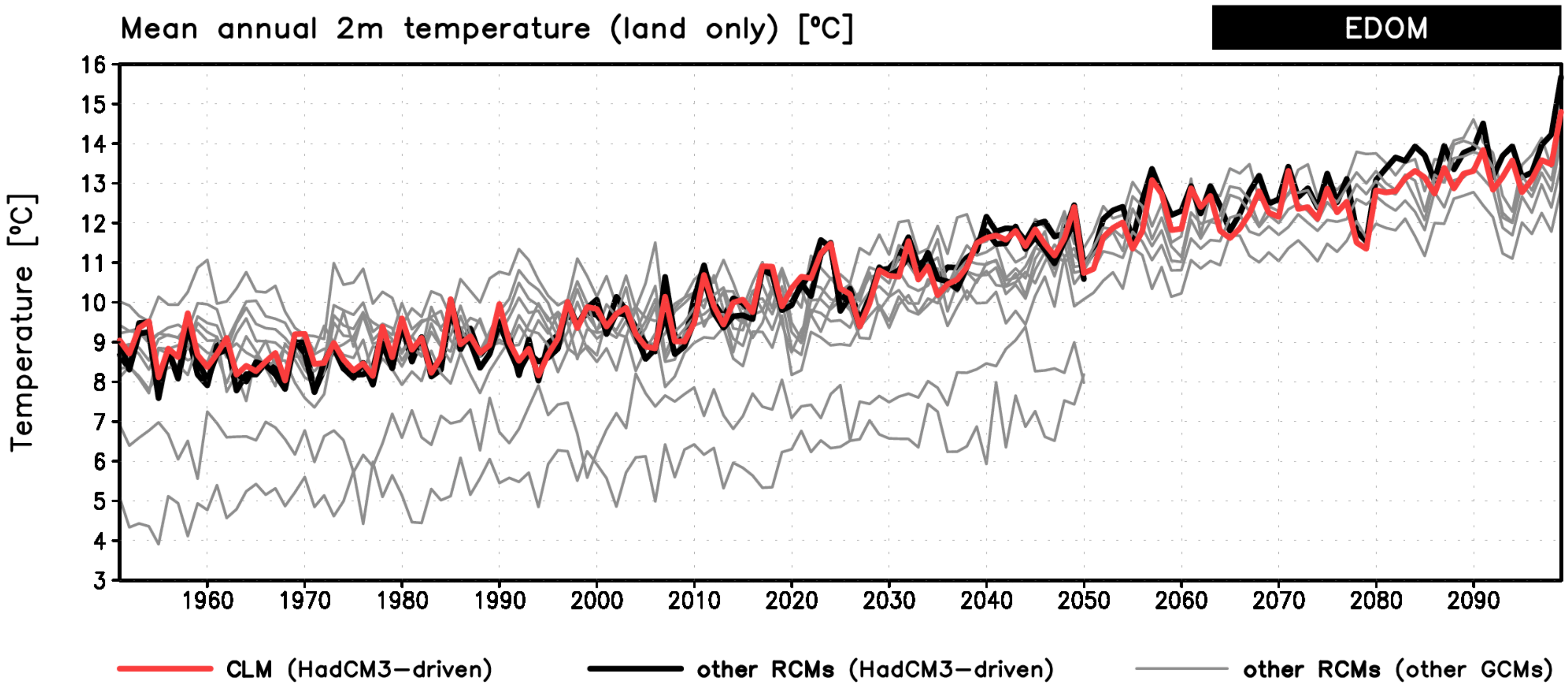
Evaluation of downscaling

Evaluation of GCM-RCM chain

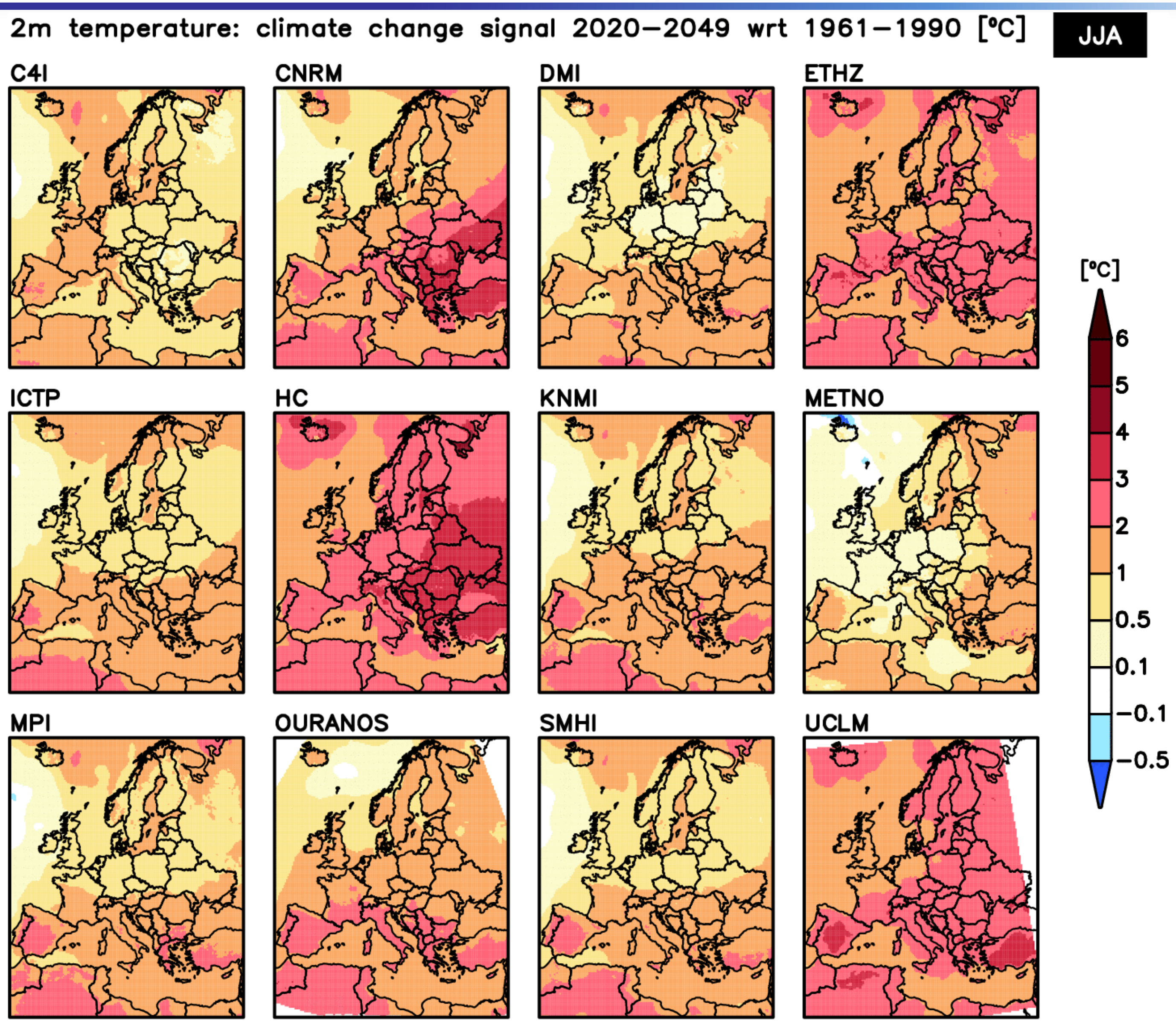
Climate change

REGIONAL CLIMATE SCENARIOS (1)

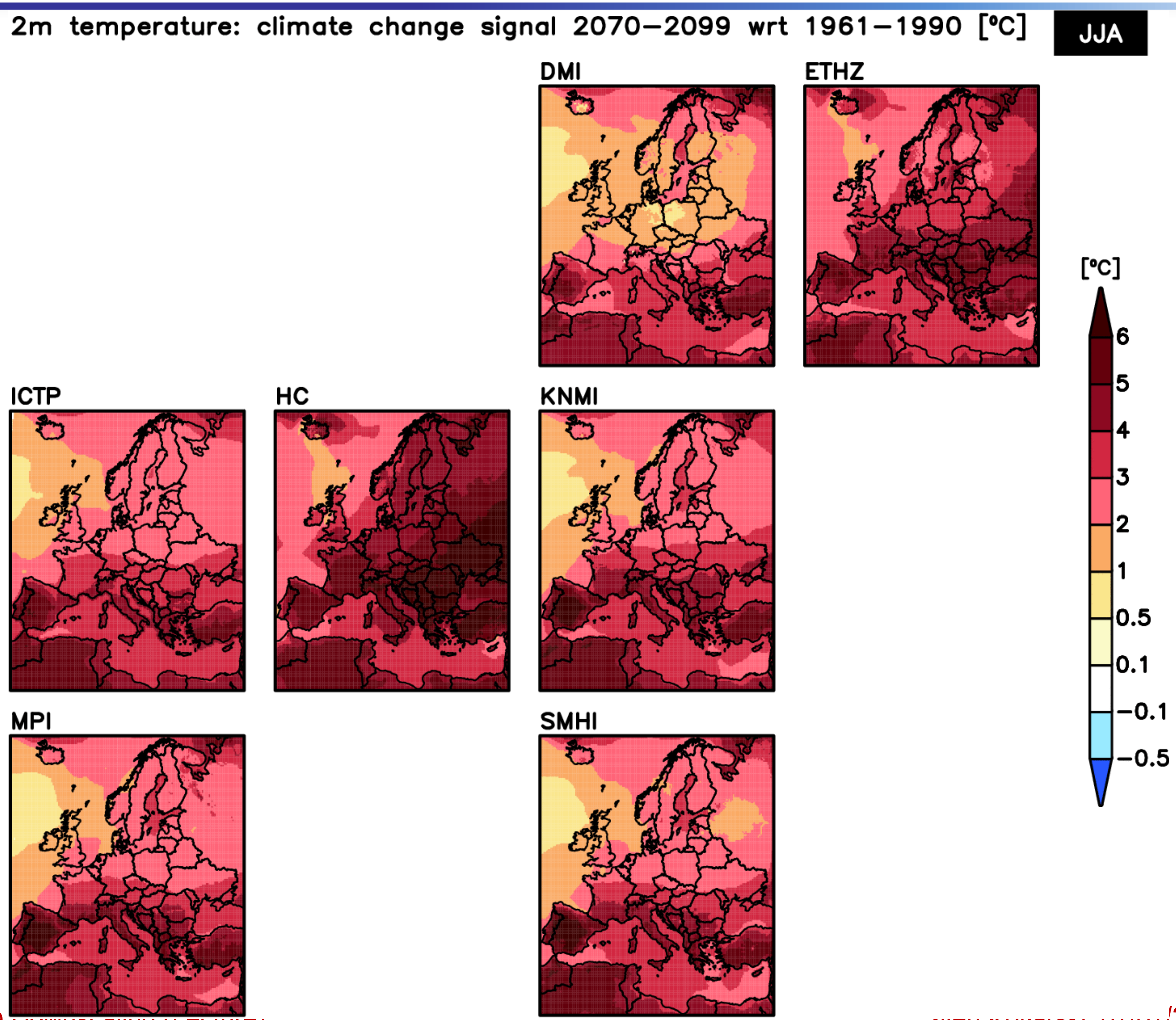
Multi-GCM multi-RCM ensemble



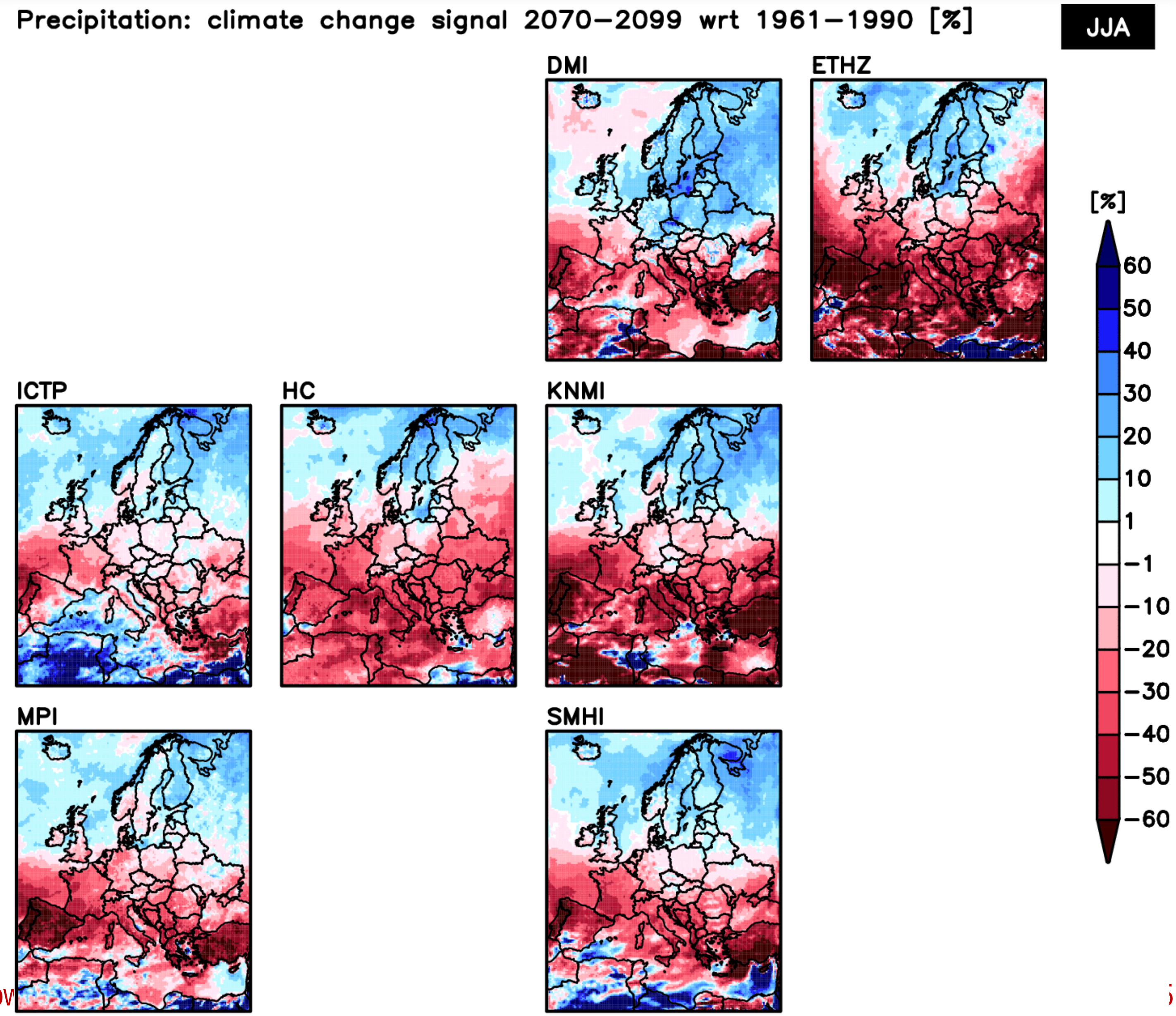
REGIONAL CLIMATE SCENARIOS (2)



REGIONAL CLIMATE SCENARIOS (3)

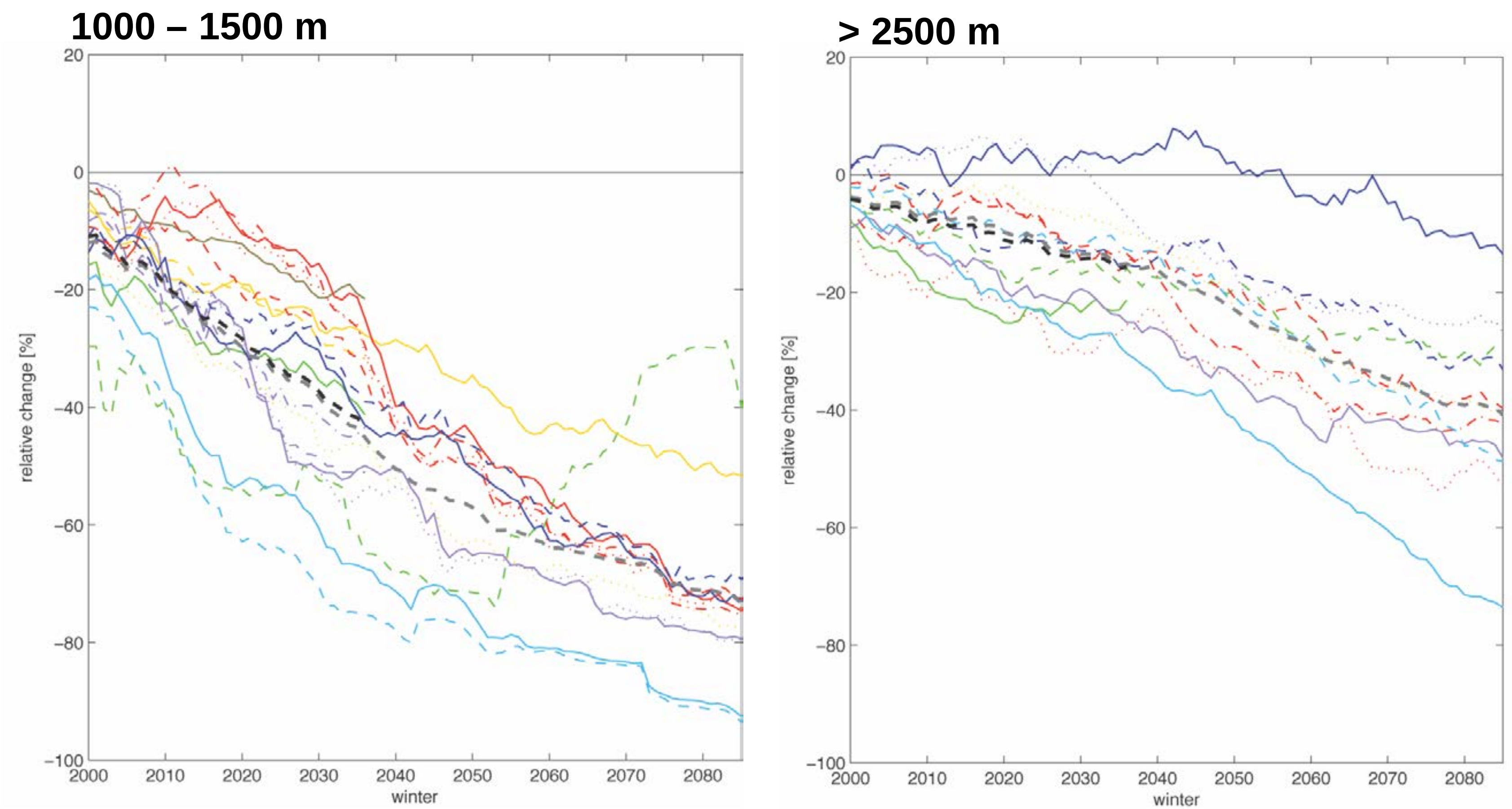


REGIONAL CLIMATE SCENARIOS (4)



REGIONAL CLIMATE SCENARIOS (5)

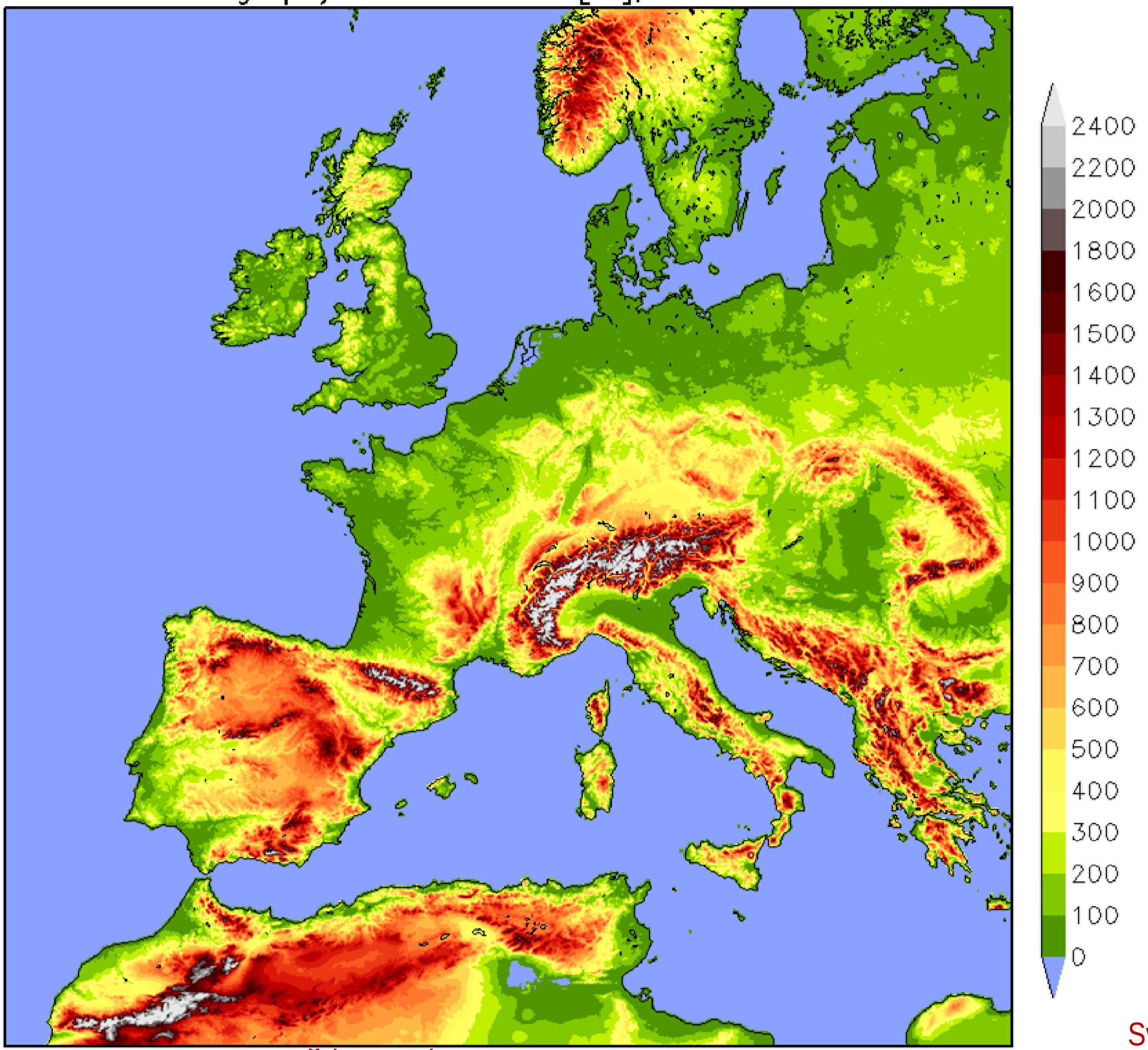
Change of mean winter SWE in the European Alps [% wrt. 1971-2000]
30-year running means



Steger et al., Climate Dynamics, 2013

COMING UP: HIGH-RESOLUTION SCENARIOS

orography CCLM 2.2 km [m], 1542x1542



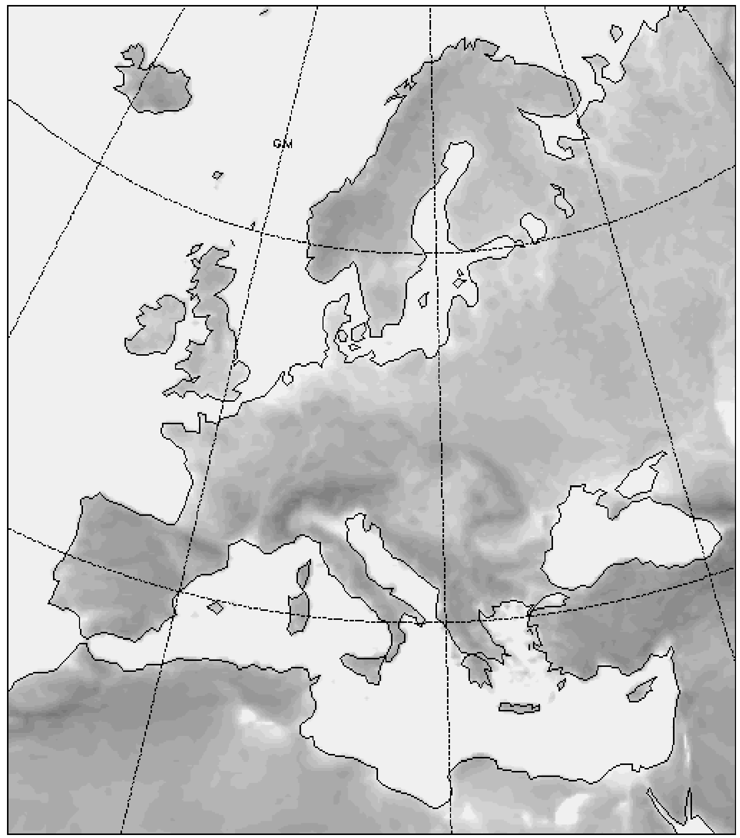
Kilometer-scale resolution required to avoid uncertainties and inaccuracies due to convection parameterisation

European-scale simulations **extremely expensive**, but simulations for smaller domains (Ban et al., 2014; Kendon et al. 2014) and prototype versions for European domains already available (Leutwyler et al., in prep)

TYPES OF RCM EXPERIMENTS

boundary forcing (global)

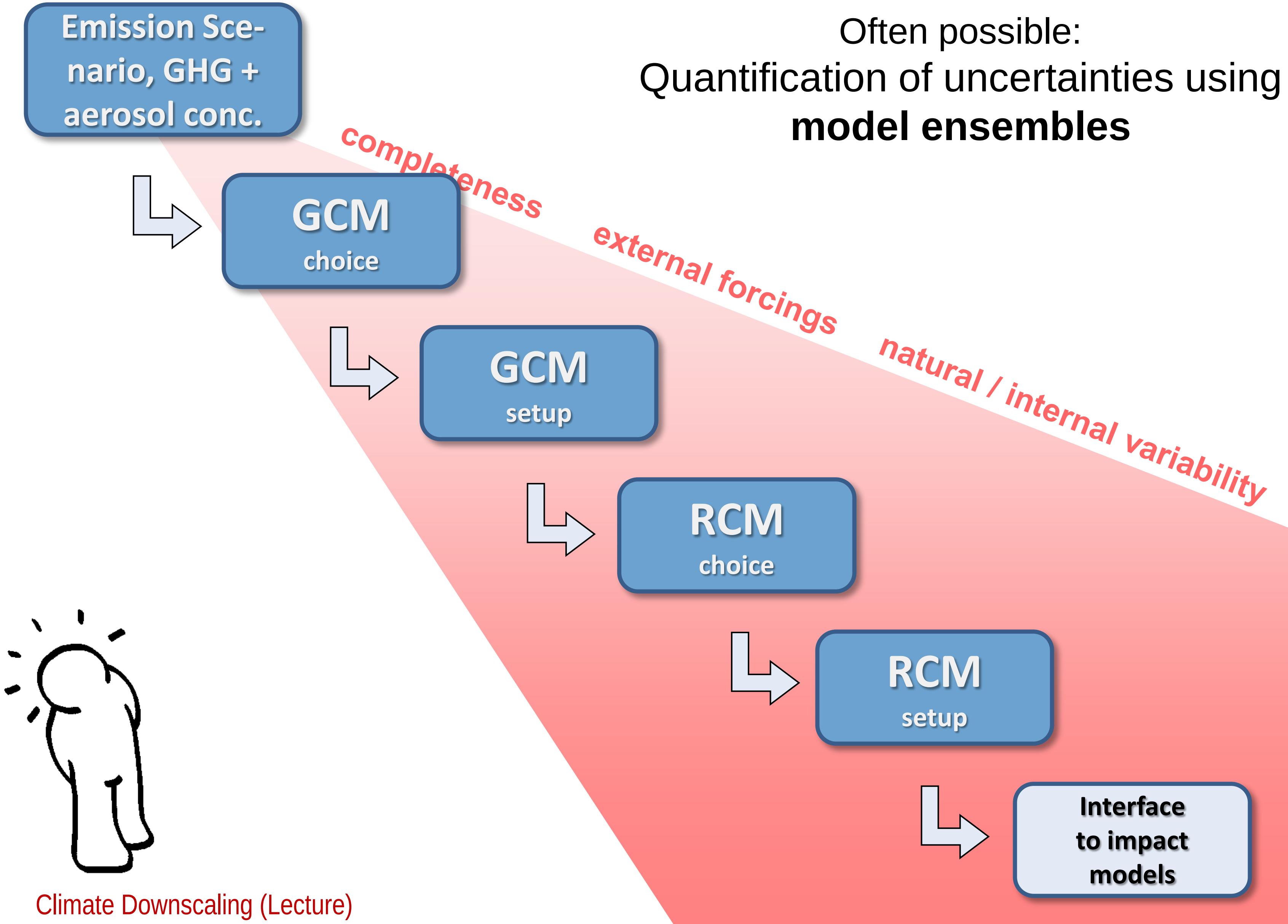
RCM



boundary forcing (global)	RCM	
Re-analysis (*perfect boundaries*)	→	**Evaluation of downscaling**
GCM historical GHG	→	**Evaluation of GCM-RCM chain**
GCM future GHG	→	**Climate change**
Re-analysis/GCM Idealized setups	→	**Sensitivities, process understanding**

THE UNCERTAINTY CASCADE

Often possible:
Quantification of uncertainties using **model ensembles**



SUMMARY CHAPTER 2 (Regional Climate Modelling)

- **Regional climate models (RCMs) to bridge the scale gap between coarse-resolution global models and local climate impacts**
- **Physically-based translation of large-scale boundary forcing into local/regional conditions**
- **Different types of experiments**
- **Validation essential**
- **Mind uncertainties and analyse ensembles whereeever possible**

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CORDEX: OVERVIEW

Coordinated Regional Climate Downscaling Experiment

- **International framework for next generation of regional climate change projections for all terrestrial regions of the globe.**
- **Input to IPCC AR5.**
- **Includes dynamical and statistical downscaling approaches.**
- ***http://wcrp-cordex.ipsl.jussieu.fr***

Model evaluation framework

Coordinate evaluation and possibly improvement of downscaling techniques.

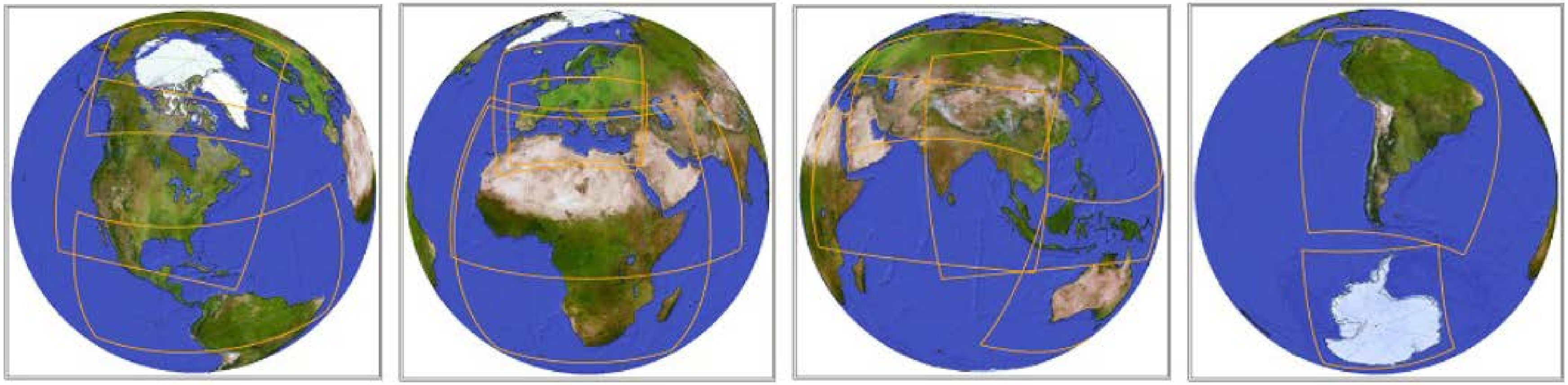
Climate projection framework

Coordinate the production of regional climate scenarios over regions worldwide, as input for impact and adaptation studies.

Communication / Interface

Promote interaction between GCM, downscaling and end user communities.

THE CORDEX DOMAINS



The CORDEX community has grown to now include 14 domains;

- Arctic CORDEX
- North America CORDEX
- Central America CORDEX
- EURO-CORDEX
- MED-CORDEX
- CORDEX Africa
- MENA-CORDEX
- Central Asia CORDEX
- South Asia CORDEX
- East Asia CORDEX
- South East Asia CORDEX*NEW
- Australasia CORDEX
- South America CORDEX
- CORDEX Antarctica

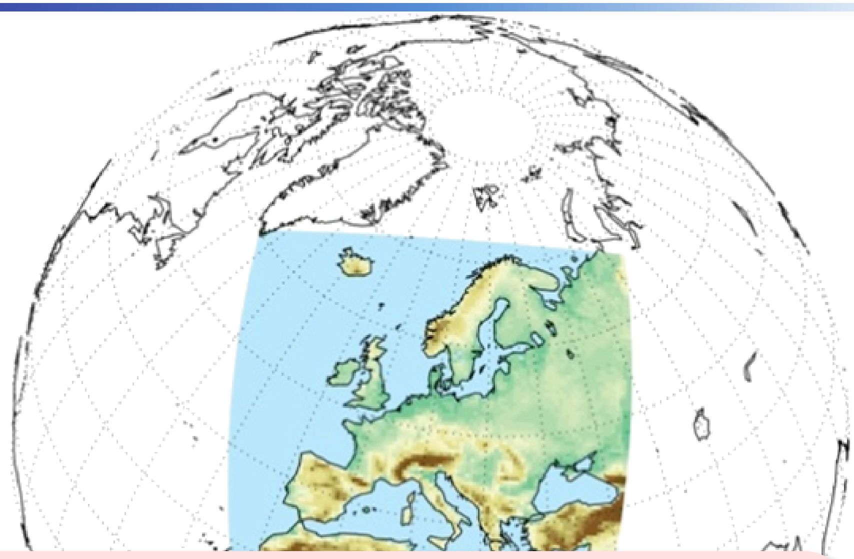
Focus domain: Africa

Baseline RCM resolution: 50 km

Data access: ESGF ***(http://cordexesg.dmi.dk/)***

EURO-CORDEX

- European branch of CORDEX
  http://www.euro-cordex.net
- Community currently consists of **29 modelling centers** applying **10 different RCMs**
- Experiments at **50 km** <u>and</u> **12 km** for European domain



Evaluation runs

forcing:
ERA-Interim (1989-2008)

Climate scenarios

forcing: CMIP5 GCMs (1951-2100)

<u>50km</u>: **66** simulations (10 RCMs, 12 GCMs, 3 RCPs)

<u>12 km</u>: **42** simulation (9 RCMs, 7 GCMs, 3 RCPs)

About 1/3 of experiments currently available on ESGF archive
(e.g. *http://esgf-data.dkrz.de*)

SUMMARY CHAPTER 3 (CORDEX)

- **Recent WCRP initiative on climate downscaling**
- **14 regions with standardized RCM experiments**
- **RCM ensembles driven by the CMIP5 GCMs are already (or will soon be) available for use in climate impact research**

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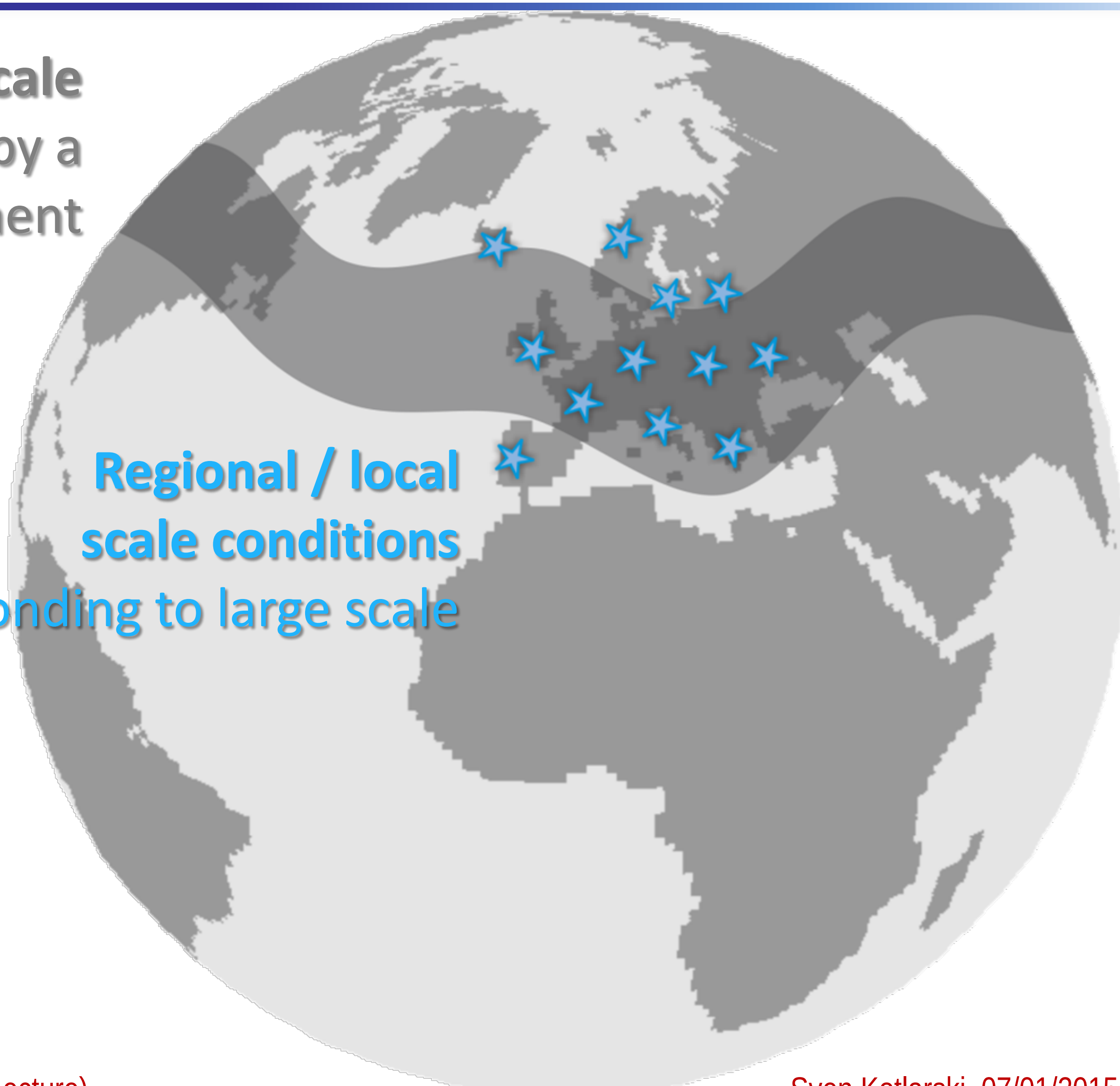
TYPES OF DOWNSCALING

STATISTICAL – EMPIRICAL DOWNSCALING	DYNAMICAL DOWNSCALING
Establishing **statistical relationships** between large-scale predictors and local weather conditions **based on observations** **Extrapolation** of relationships into the future (using large-scale predictors from GCM experiments)	Nesting a **regional climate model** (RCM) at higher resolution into a coarse-resolution GCM RCMs typically developed from numerical weather prediction models

THE IDEA…

Large scale
as provided by a
GCM experiment



Regional / local
scale conditions
corresponding to large scale

VARIANTS OF STATISTICAL DOWNSCALING

Perfect Prog: Establish relationships between synoptic-scale predictors and local weather conditions based on observed evidence and transfer relations into the future

MOS (Model Output Statistics):
Apply transfer functions to simulated parameters to match observations

Weather generators: Stochastic modeling of (daily) local weather sequence conditioned

COMPARISON TO DYNAMICAL DOWNSCALING

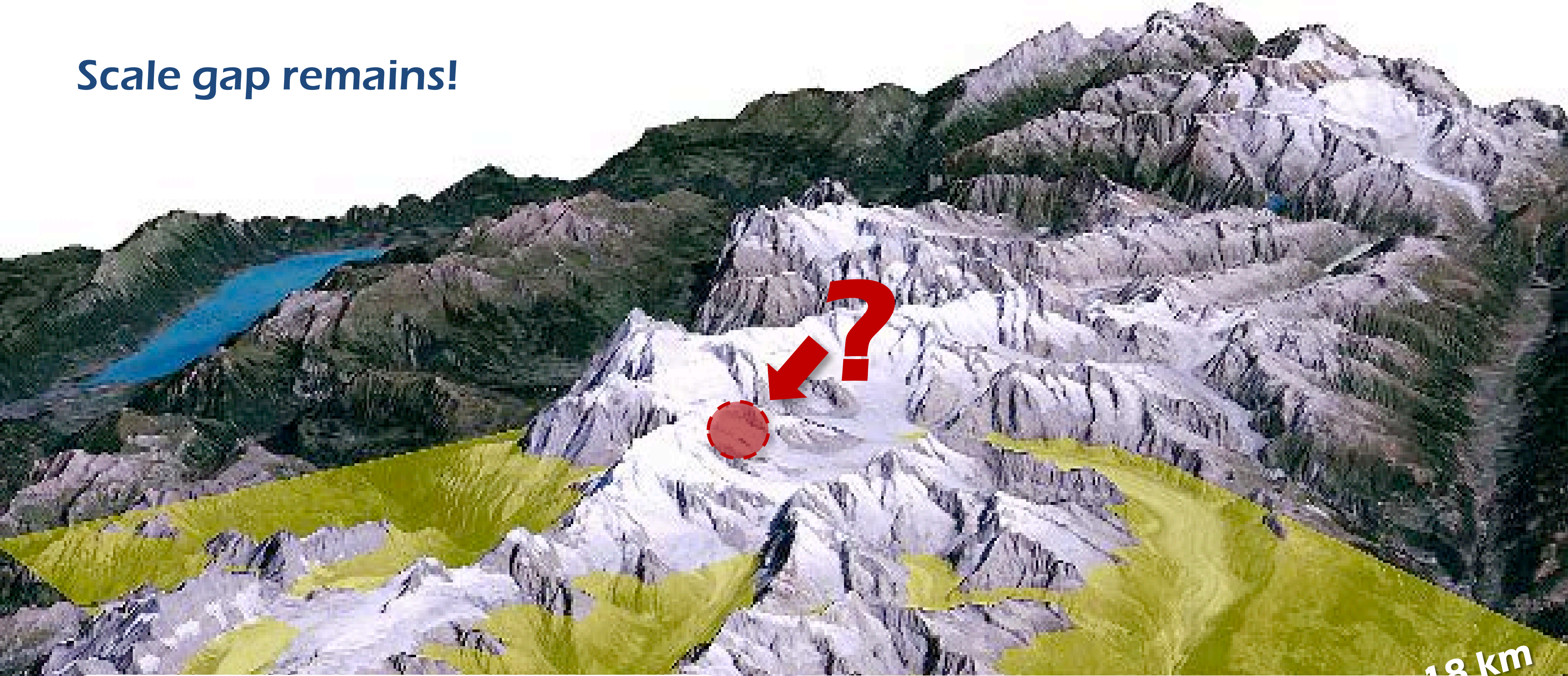
SD

- Cheap & efficient
- Targets the site scale
- Stationarity of transfer relation assumed
- New feedbacks not accounted for
- Problems relating to spatial and temporal consistency and inter-parameter consistency

DD

- Physically consistent responses
- Limited spatial resolution (typically still beyond impacts scale)
- Relation between RCM bias and climate change signals not ultimately clear
- Computationally expensive, limited number of realisations possible

Scale gap remains!



Impact models typically require a **higher spatial resolution** than delivered by an RCM

↓

further downscaling necessary

RCM output is biased and does not yield realistic control conditions

↓

Model bias needs to be accounted for

Statistical downscaling and bias correction

Figure: **S. Gruber, Univ. Zurich**

SUMMARY CHAPTER 4 (Statistical Downscaling)

- **Methods to transfer large-scale information into local conditions based on empirical evidence**
- **Large variety of methods exist that target specific parameters/problems**
- **Own strengths and weaknesses compared to RCMs**
- **Combination of statistical and dynamical downscaling often advisable**

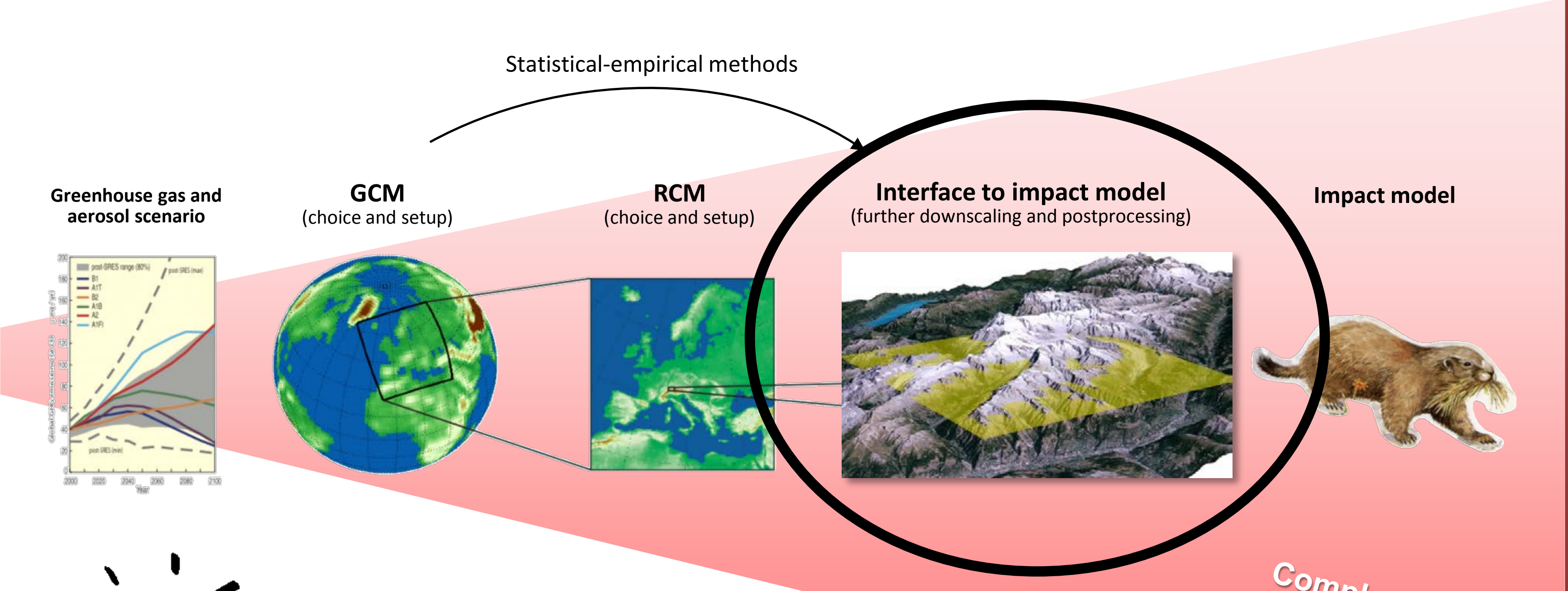
OUTLINE

1. CLIMATE DOWNSCALING: THE RATIONALE
2. REGIONAL CLIMATE MODELLING
3. THE CORDEX INITIATIVE

BREAK

4. STATISTICAL DOWNSCALING
5. **LINKING IMPACT MODELS**
6. REPRESENTING GLACIERS IN REGIONAL CLIMATE MODELS

THE UNCERTAINTY CASCADE



Ensemble **approaches**

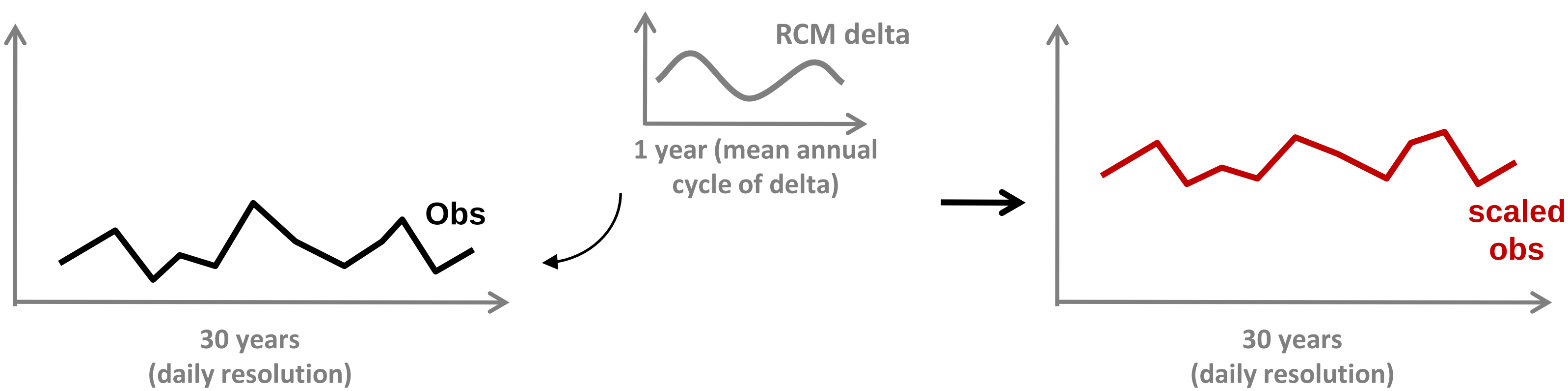
to quantify and constrain uncertainties

THE DELTA CHANGE APPROACH

Historical observations
(region, specific site)

Climate model derived change signal
SCEN - CTRL

Future climate



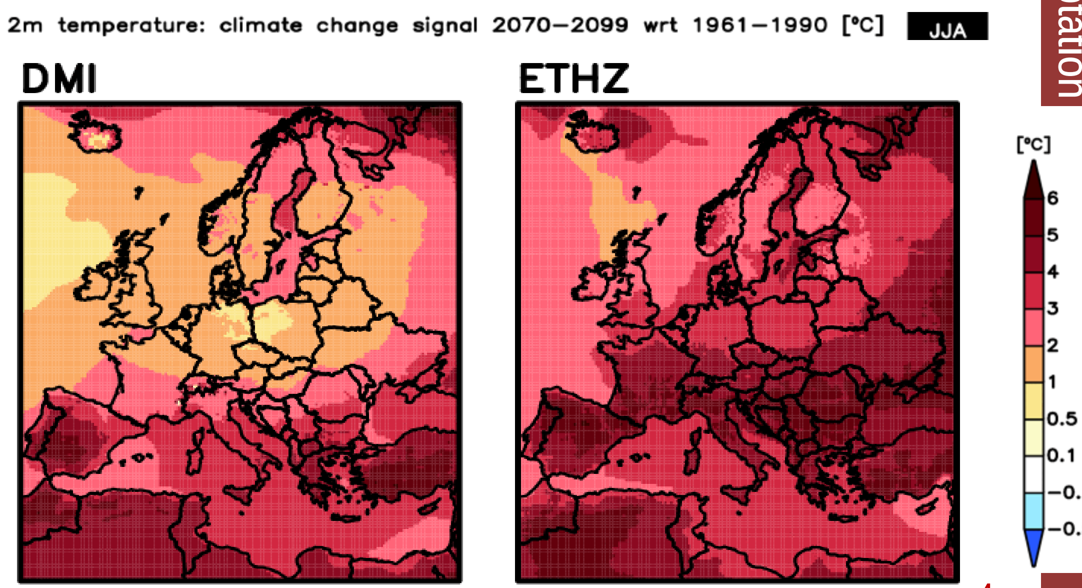
THE DELTA CHANGE APPROACH

Historical observations
(region, specific site)

Climate model derived change signal
SCEN - CTRL

Future climate

- **Easy and robust** (e.g., spatial and temporal variability based on observations)
- Climate change signal less variable in space than climate itself
- *Based on time slices*
- *Ignores changes in variability*
- *Assumes constant model bias*



Is the constant bias assumption fulfilled on the spatial and temporal scales considered?

BIAS CORRECTION (MOS)

Climate model CONTROL

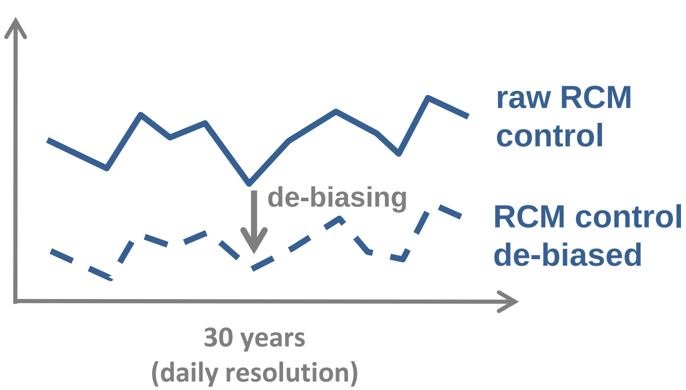
Calibrate transfer function
(bias correction and downscaling)

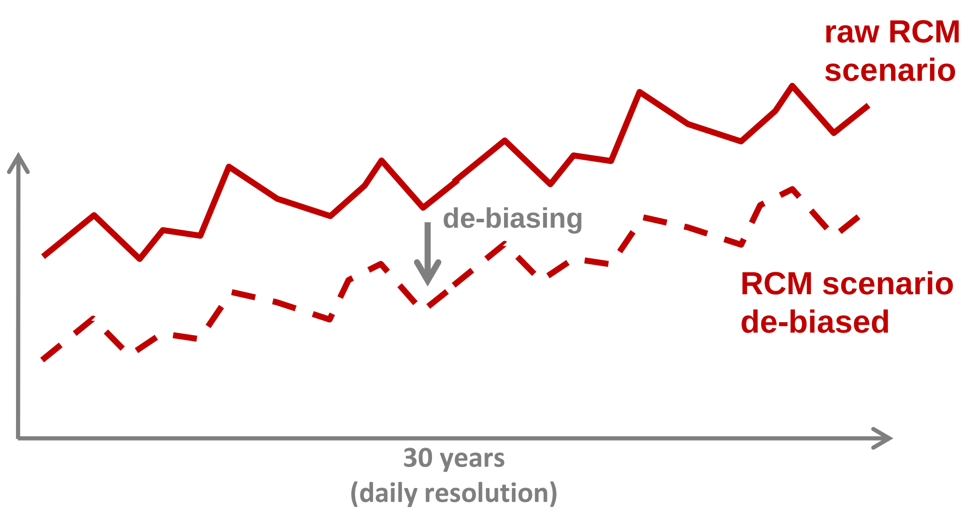
Historical observations
(region, specific site)

Climate model SCENARIO series

Apply transfer function

Future climate series





BIAS CORRECTION (MOS)

Climate model CONTROL

↕ Calibrate transfer function (bias correction <u>and</u> downscaling)

Historical observations (region, specific site)

Climate model SCENARIO series

↓ Apply transfer function

Future climate series

e.g., Quantile Mapping (Boé et al. 2007, Themessl et al. 2011, Gudmundsson et al. 2012)

Matching simulated onto observed distribution by applying a percentile-specific correction

- Changes in variability accounted for
- Transient scenario series
- Can account for non-stationary model biases to some extent

- Cannot correct for all kinds of biases («bias adjustment»)
- Inconsistencies likely (spatial, temporal, inter-parameter)

SUMMARY CHAPTER 5
(Linking Impact Models)

- **Delta change approach** vs. **Bias approach**
- **Sometimes possible: Directly analyze climate model output for «secondary» parameters (e.g. snow, glaciers)**
- **Choice of method adds further uncertainty to estimated climate change impact**

OUTLINE

1. CLIMATE DOWNSCALING: THE RATIONALE
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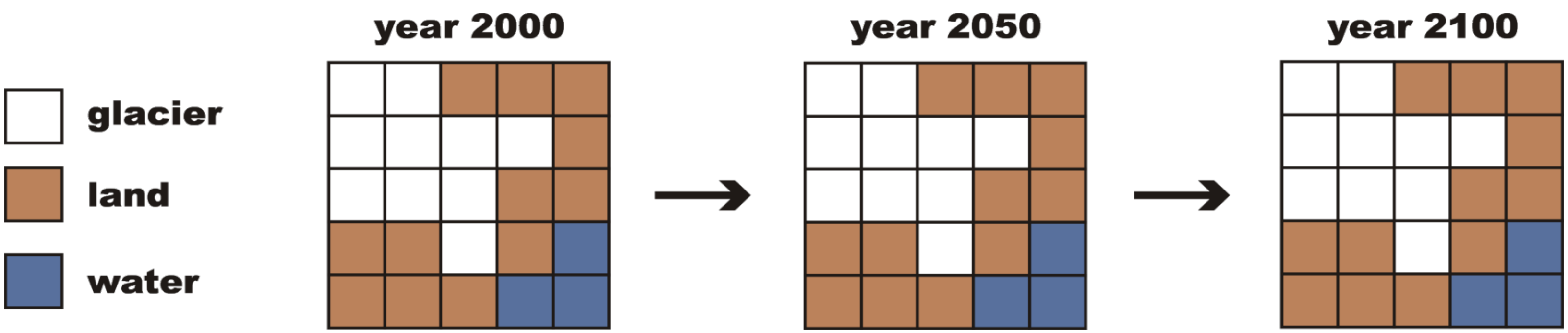
6. **REPRESENTING GLACIERS IN REGIONAL CLIMATE MODELS**

Kotlarski et al., Clim. Dyn., 2010

MOTIVATION (1)

- Interactive role of glaciers in the climate system
- **Direct** and **indirect** feedback mechanisms
- Poor representation in today's climate models:



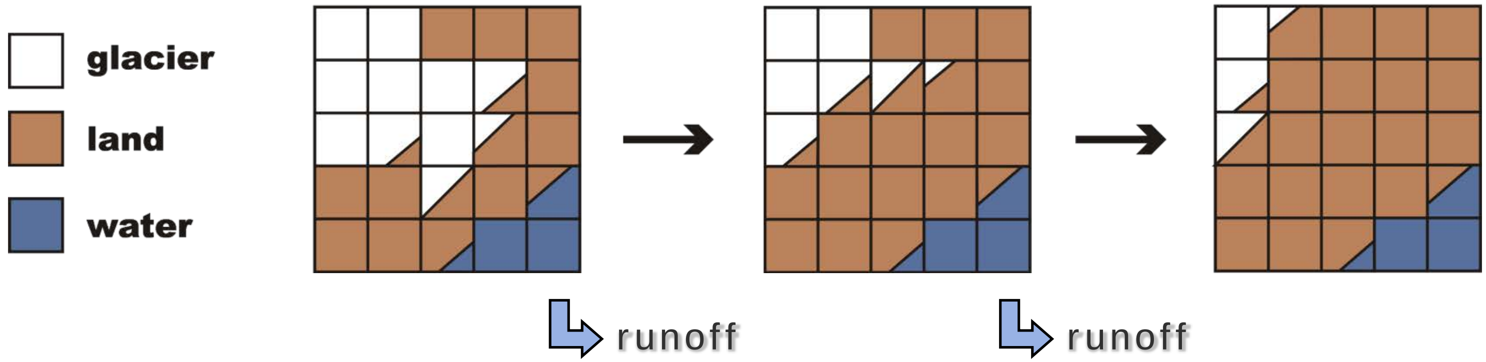
  - **Static glacier masks**
  - No changes in ice extent, no feedback to atmosphere
  - No consideration of water volume stored
  - No / simplified runoff generation
  - Exception: Ice sheet models in ESM

MOTIVATION (2)

more sophisticated approach necessary if

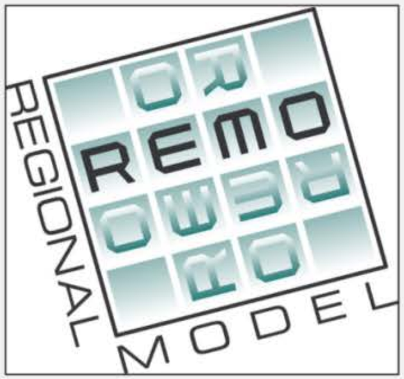
- contribution of glacial meltwater to SLR is important (longterm, coupled experiments)
- regional climatic changes in glacierized areas are to be assessed
- focus on discharge in glacierized river basins

- Interactive glacier scheme for regional climate modelling
- Glacier mass balance and area changes on a subgrid scale, accounting for direct physical feedback mechanisms



- Applicable for entire mountain ranges and computationally effective, target resolution: RCM grid cell
- Simplified description and minimum of input data

GENERAL CONCEPT



Jacob, 2001

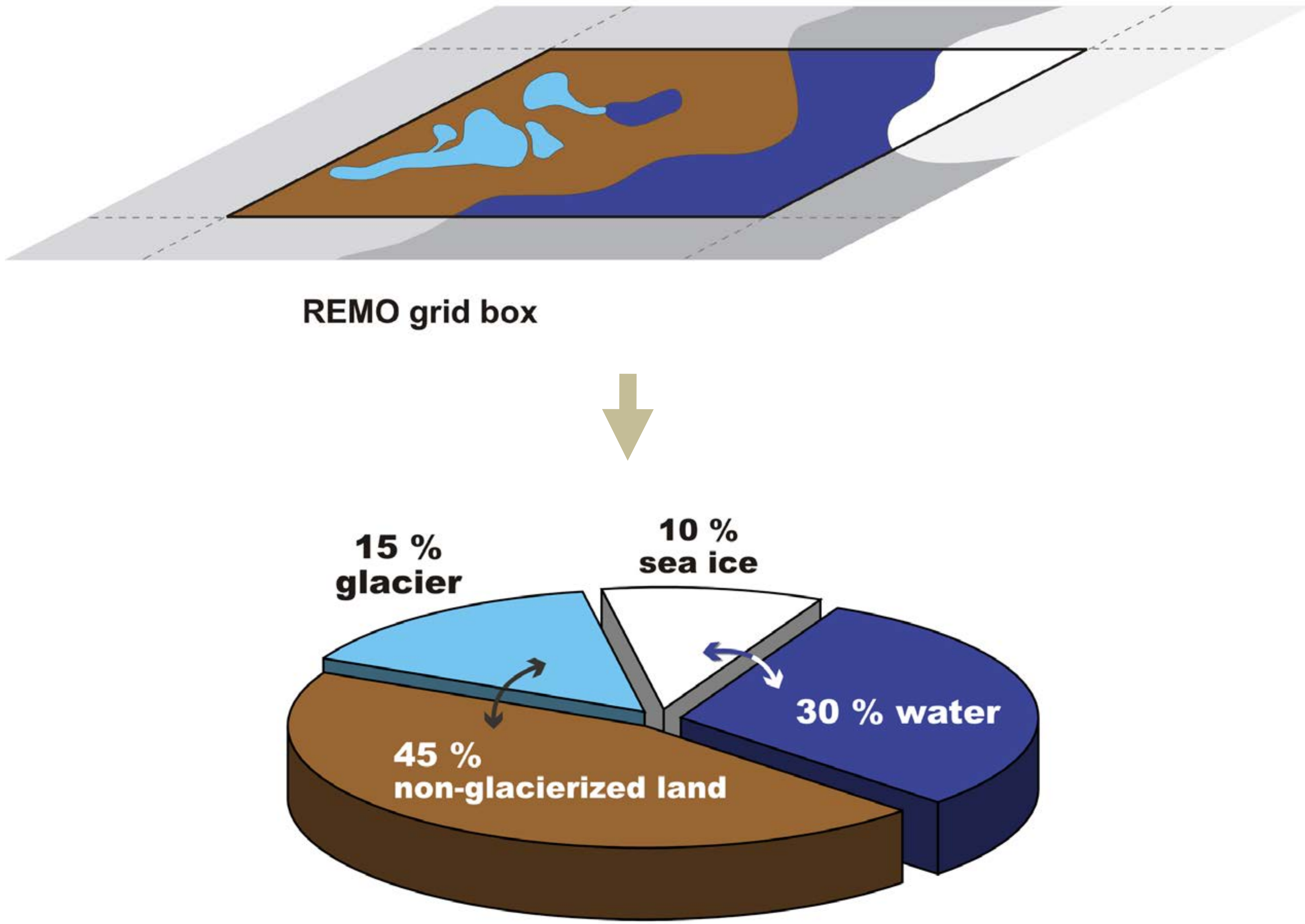
atmospheric forcing

surface characteristics and runoff

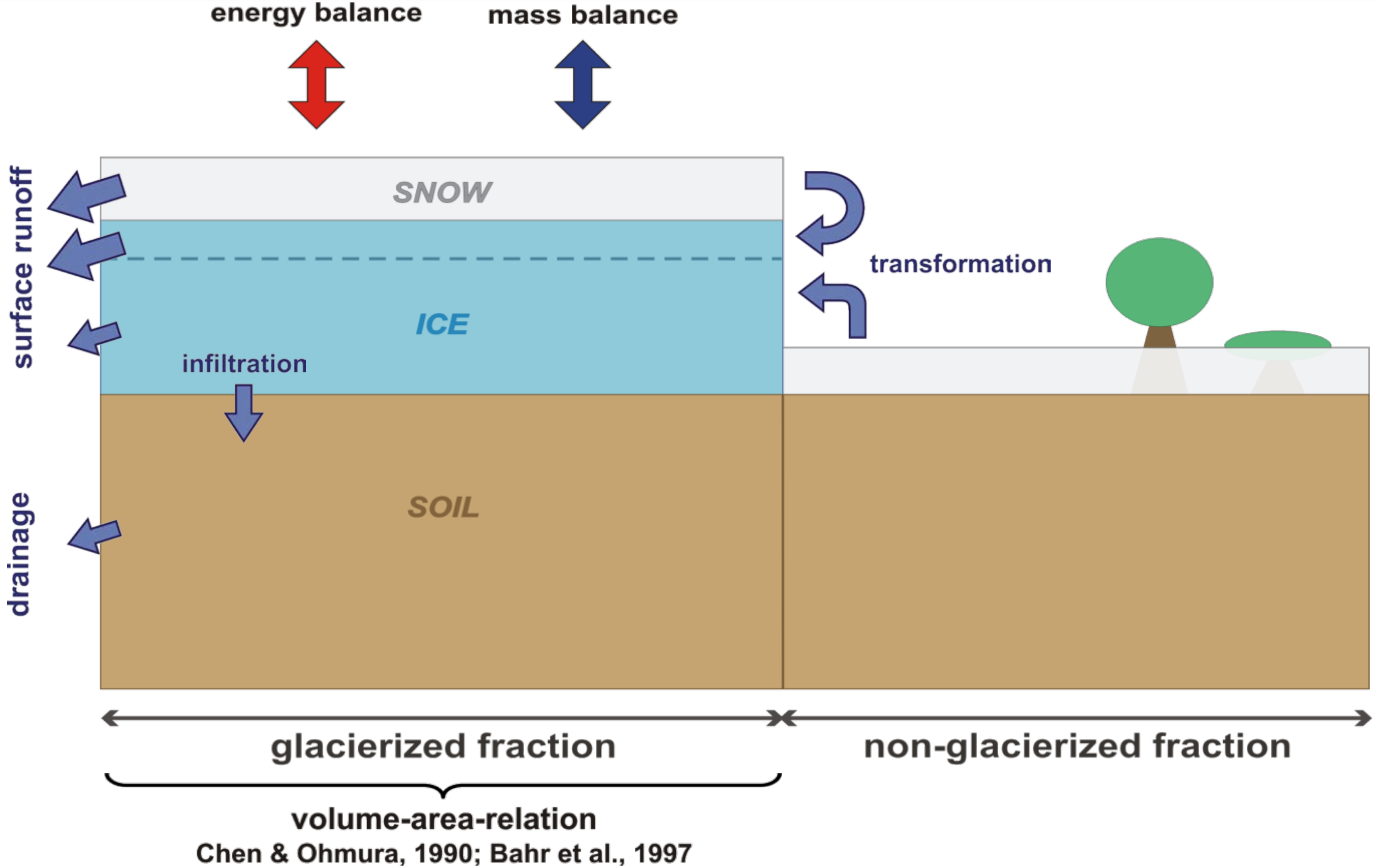
GLACIER SCHEME

- surface energy balance
- mass balance
- subgrid variability of snow-fall and solar radiation

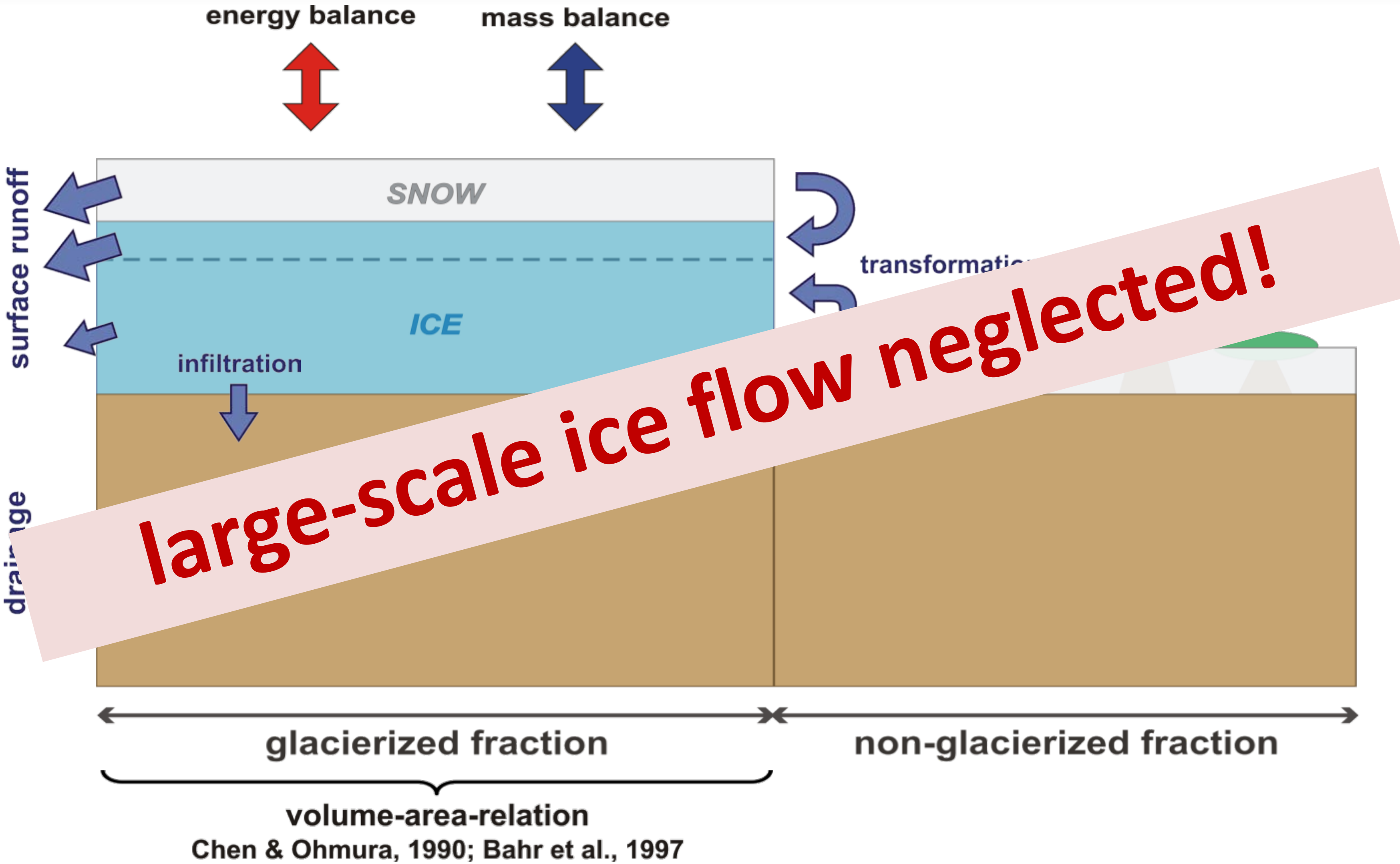
THE TILE APPROACH



GRID BOX CROSS SECTION



GRID BOX CROSS SECTION



SETUP

ERA40 Re-analysis / ECMWF analysis

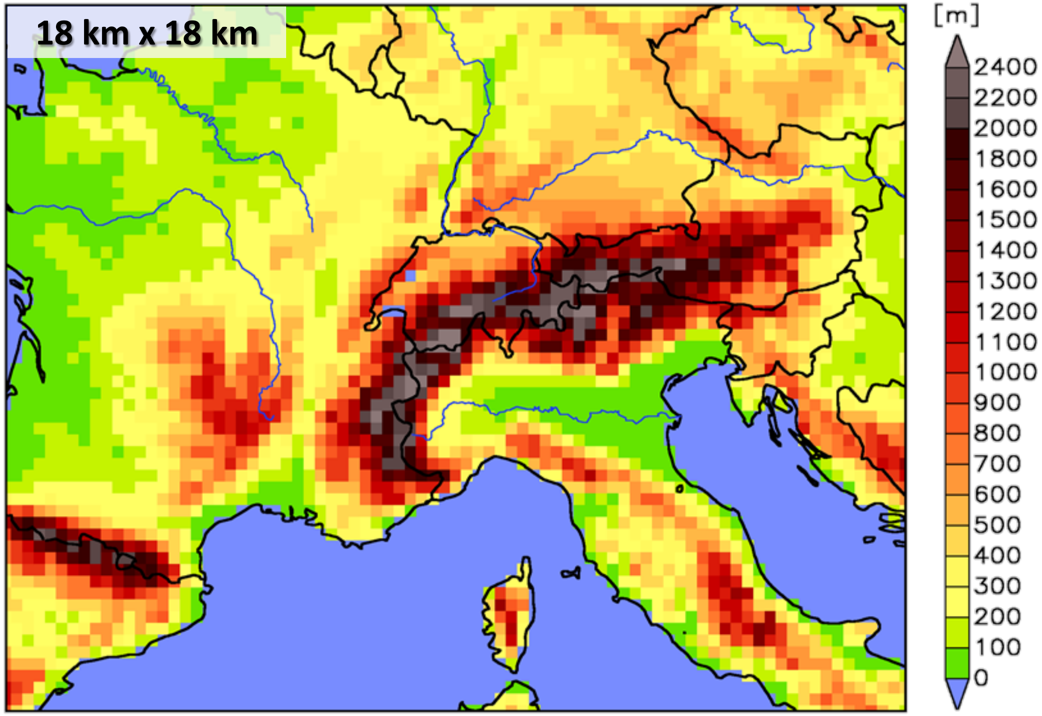
1958 - 2003

ECHAM5 / MPI-OM

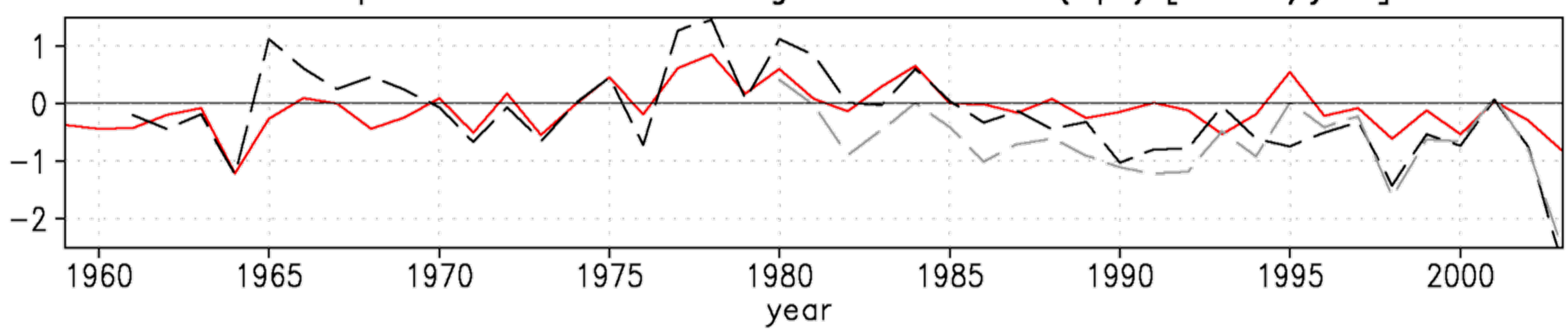
2004 - 2100
SRES A2

via REMO 50 km

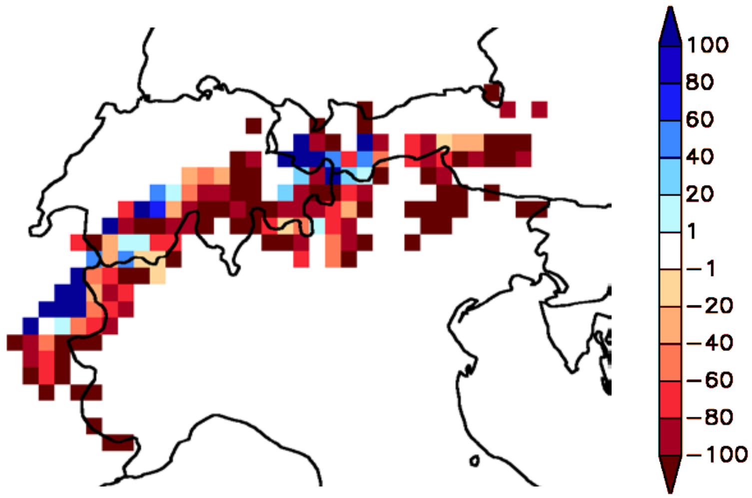
REMO$_{glacier}$



MODEL EVALUATION

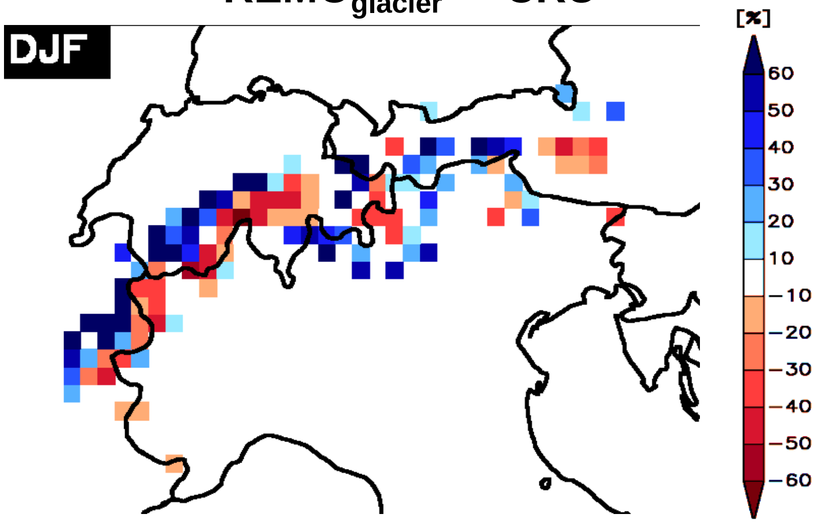


Simulated glacier area change 1958 - 2003 [%]



Bias winter precipitation 1958 - 2000 [%]

REMO$_{glacier}$ - CRU

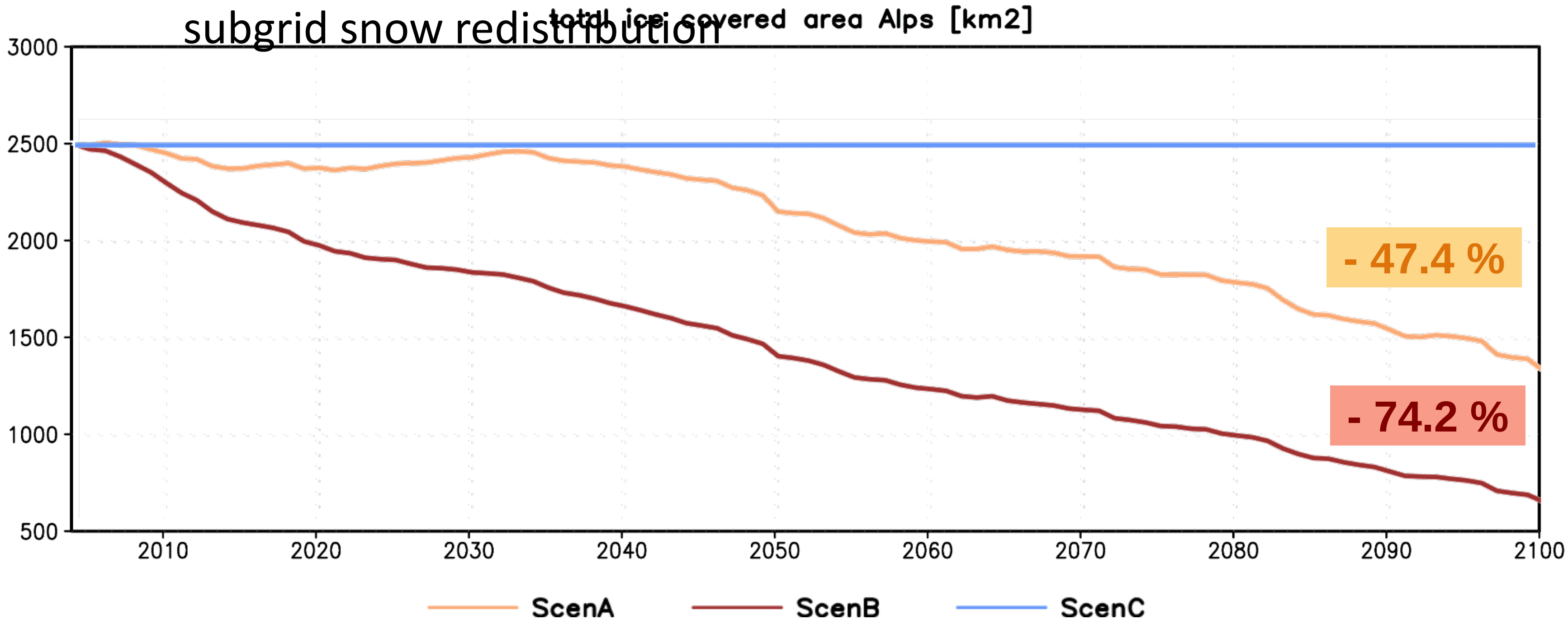


IHCAP – Indian Himalayas Climate Change Adaptation Programme: Level II

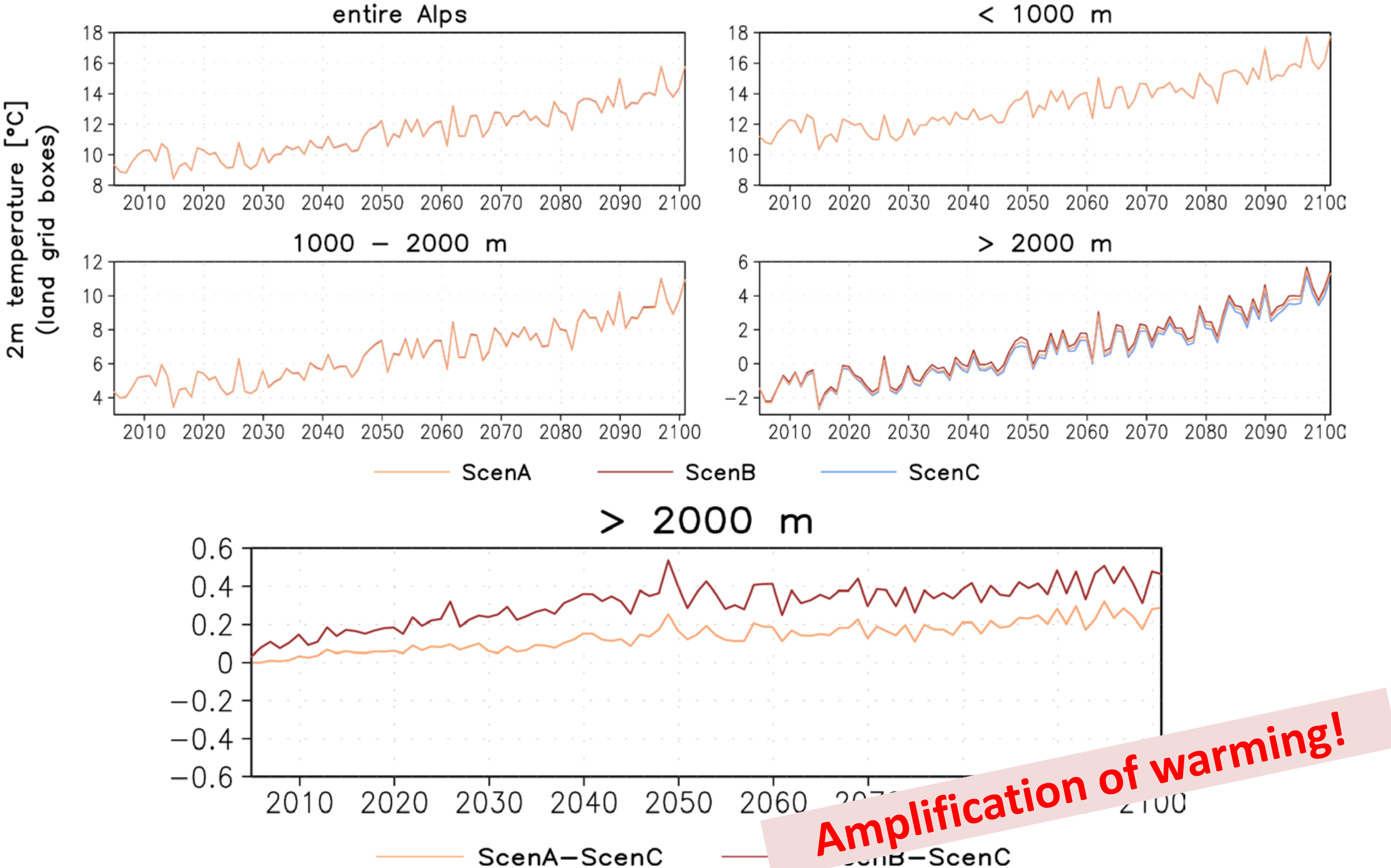
SCENARIO (1)

Scen A	Scen B	Scen C
κ = 2.0	κ = 1.5	κ = 2.0
		no glacier area change

subgrid snow redistribution



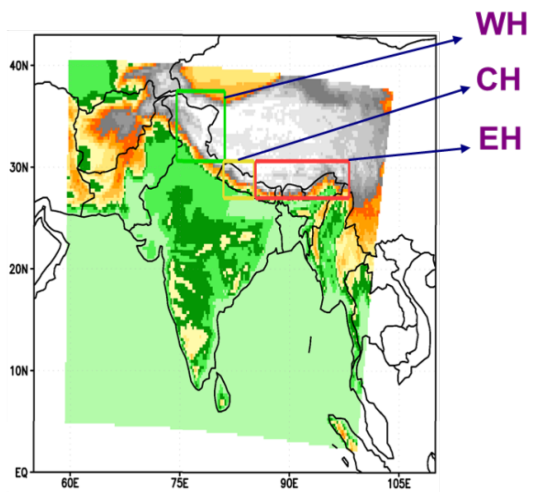
SCENARIO (2)

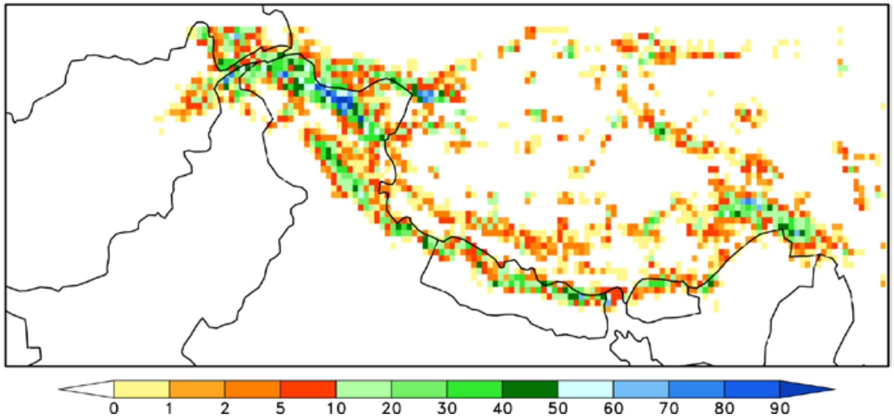


2m temperature [°C]
(land grid boxes)
entire Alps
< 1000 m
1000 – 2000 m
> 2000 m
ScenA
ScenB
ScenC
> 2000 m
ScenA−ScenC
ScenB−ScenC
Amplification of warming!

APPLYING REMOglacier OVER THE HIMALAYAS (1)

RCM Experiment Setup	
RCM	**REMO-Glacier**
Resolution	**0.22x0.22 deg (~25 km)**
Domain	**60.125E - 100.125E & 4.125N - 40.125N**
Period	**1989-2008; 1960-2100**
Forcing	**ERAI; ECHAM5/MPI OM; HadCM3**





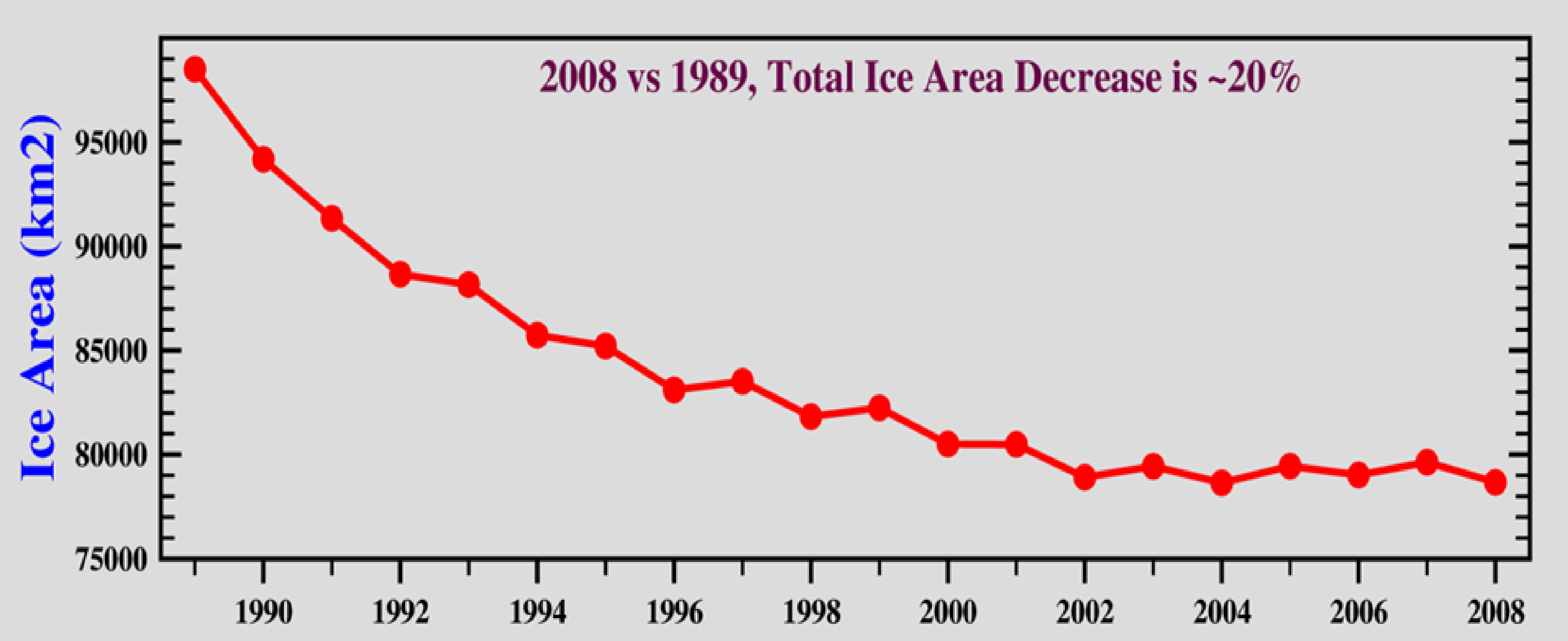
Glacier Inventory

Pankaj Kumar, MPI-M Hamburg

APPLYING REMOglacier OVER THE HIMALAYAS (2)

Glacier Area

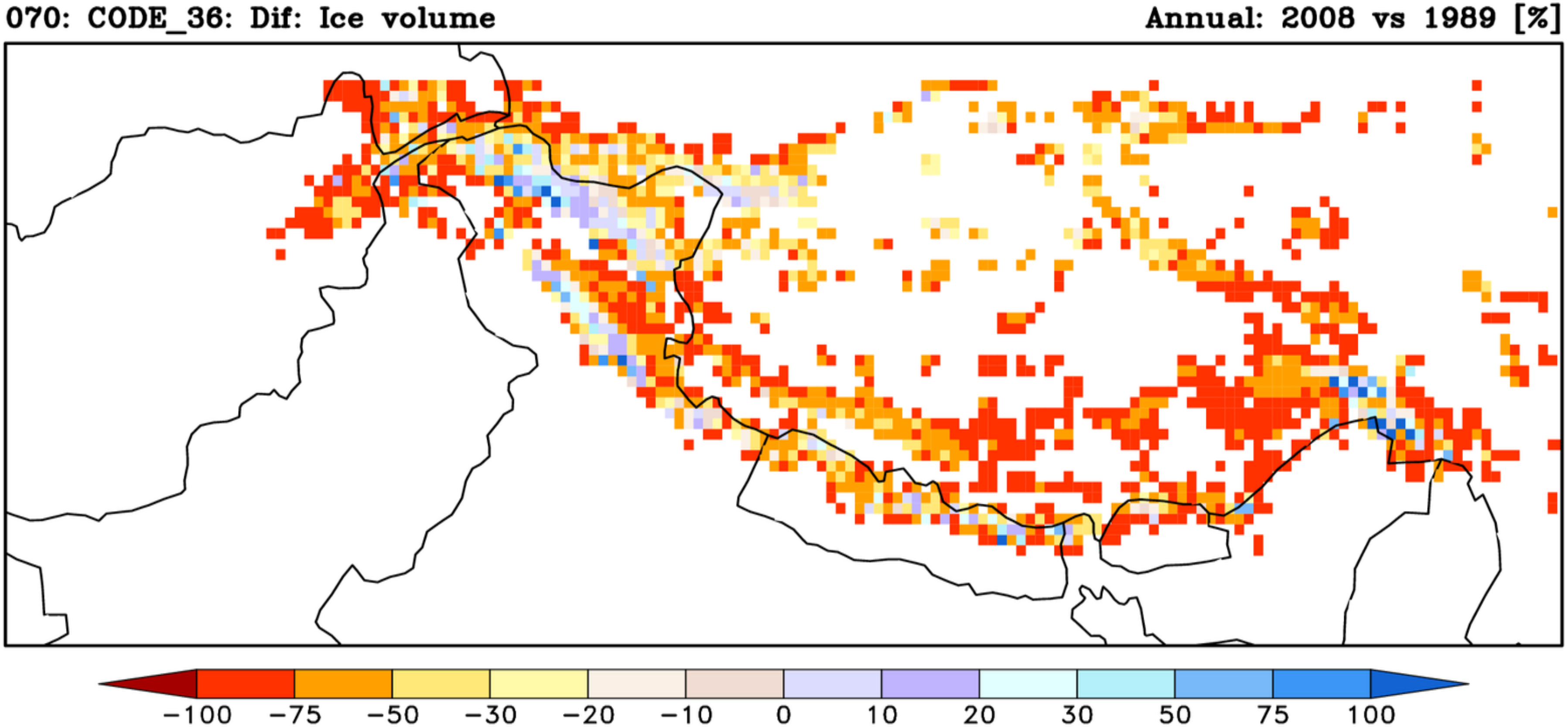
Preliminary results show a simulated decrease of glacier area (1989-2008) of ~20% with respect to 1989,



Pankaj Kumar, MPI-M Hamburg

APPLYING REMOglacier OVER THE HIMALAYAS (3)

Glaciers mean ice volume change, 1989-2008 w.r.t. 1989 in %

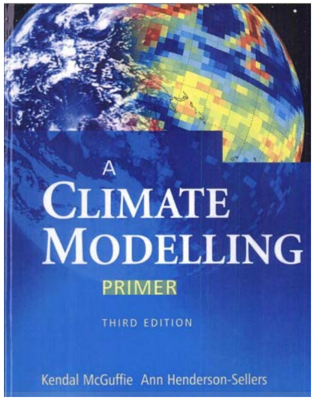


Pankaj Kumar, MPI-M Hamburg

SUMMARY CHAPTER 6
(Representing Glaciers in Regional Climate Models)

- **Possibility to account for glaciers on a subgrid scale within a climate model**
- **Motivation: Explicitly incorporate the impact of changing glacier area on the regional climate**
- **Use of extremely simplified concepts**
- **Results not accurate in every sense, but broadly comparable to observations and to studies applying specific glacier models (mass balance and ice flow)**

LITERATURE



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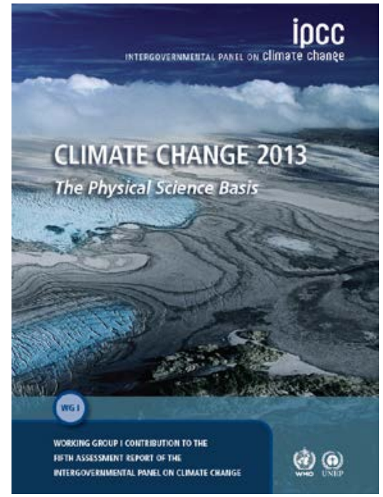

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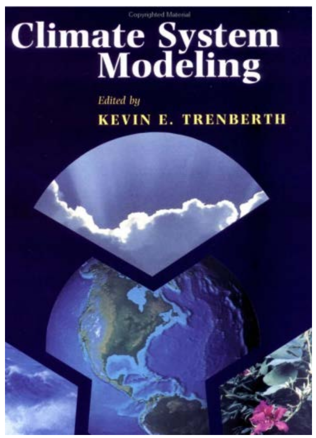

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THANK YOU FOR LISTENING!