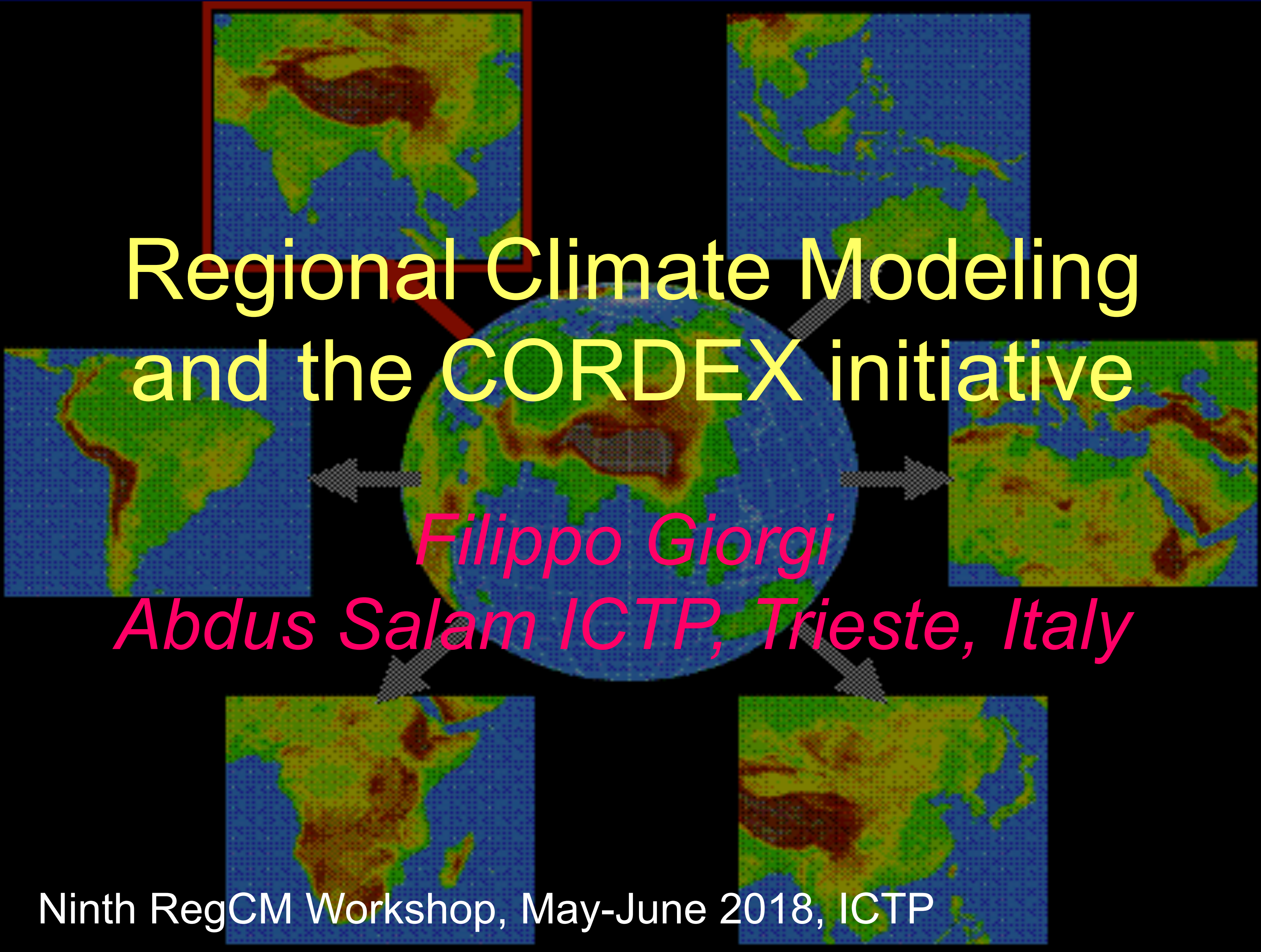

Regional Climate Modeling and the CORDEX initiative

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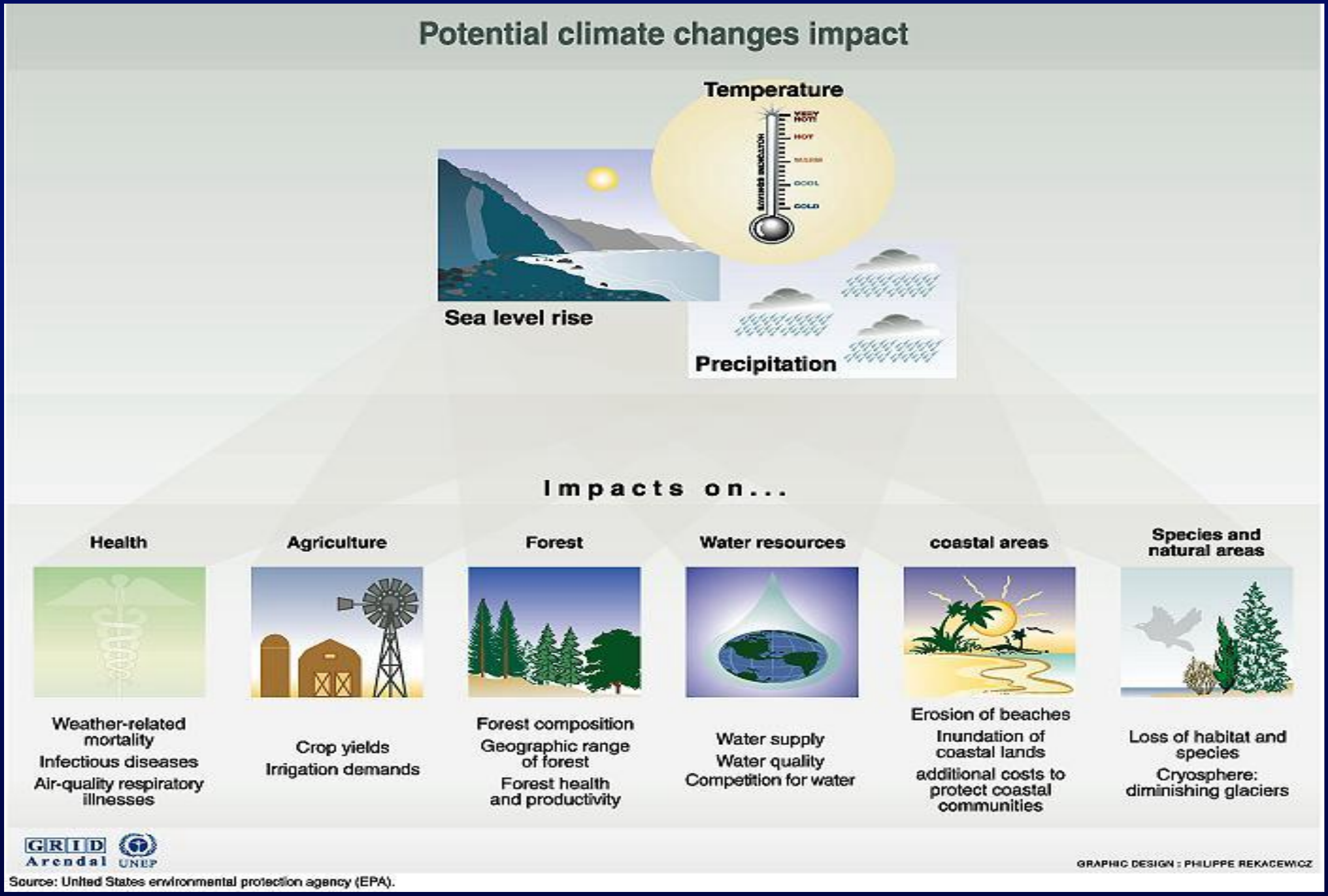
Abdus Salam ICTP, Trieste, Italy

Ninth RegCM Workshop, May-June 2018, ICTP

Lectures outline

- Basic notions and principles of regional climate modeling
- Some technical issues
- Brief history of the RegCM system
- Uncertainties in regional climate change projections
- The “COordinated Regional Downscaling EXperiment” (CORDEX)
- The CREMA II contribution to CORDEX-CORE

Regional climate information is needed for Vulnerability/Impact/Adaptation (VIA) assessment studies



Regional climate modeling: Why?

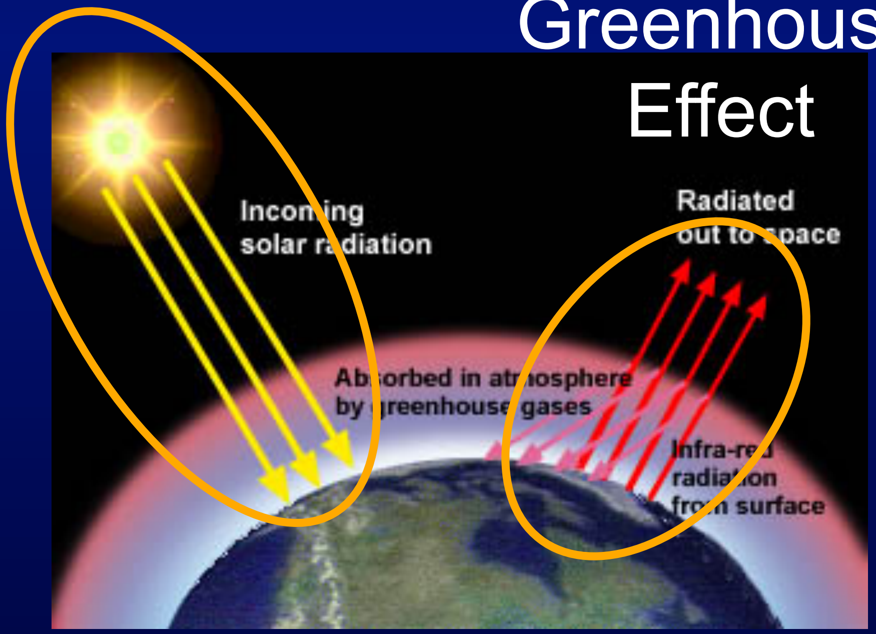
- Regional climates are determined by the interactions of planetary/large scale processes and regional/local scale processes
  - Planetary/large scale forcings and circulations determine the statistics of weather events that characterize the climate of a region
  - Regional and local scale forcings and circulations modulate the regional climate change signal, possibly feeding back to the large scale circulations
- In order to simulate climate (and more specifically climate change) at the regional scale it is thus necessary to simulate processes at a wide range of spatial (and temporal) scales

Large scale climatic forcings

Volcanic eruptions

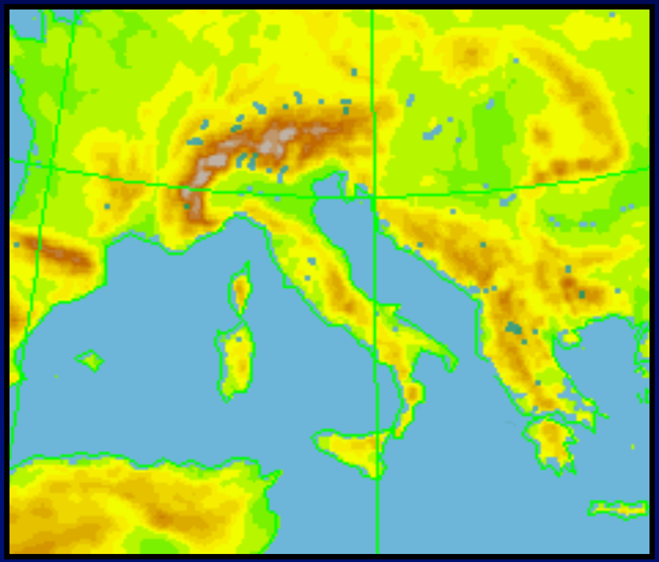
Solar activity

Greenhouse Effect

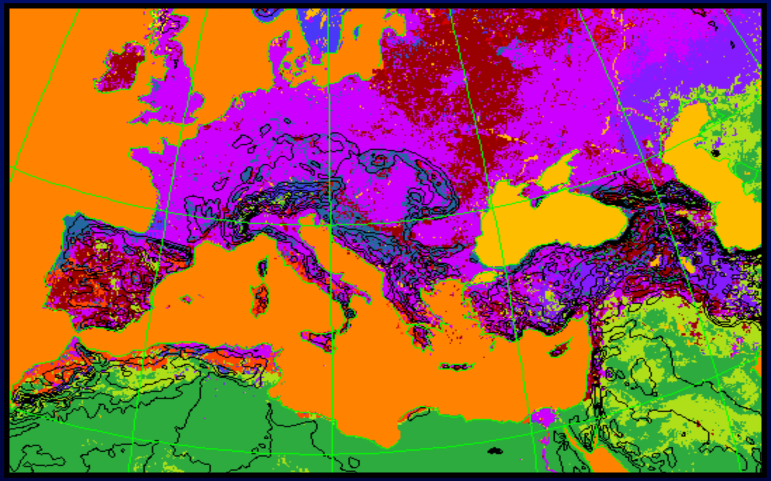


Regional and local climatic forcings

Complex topography

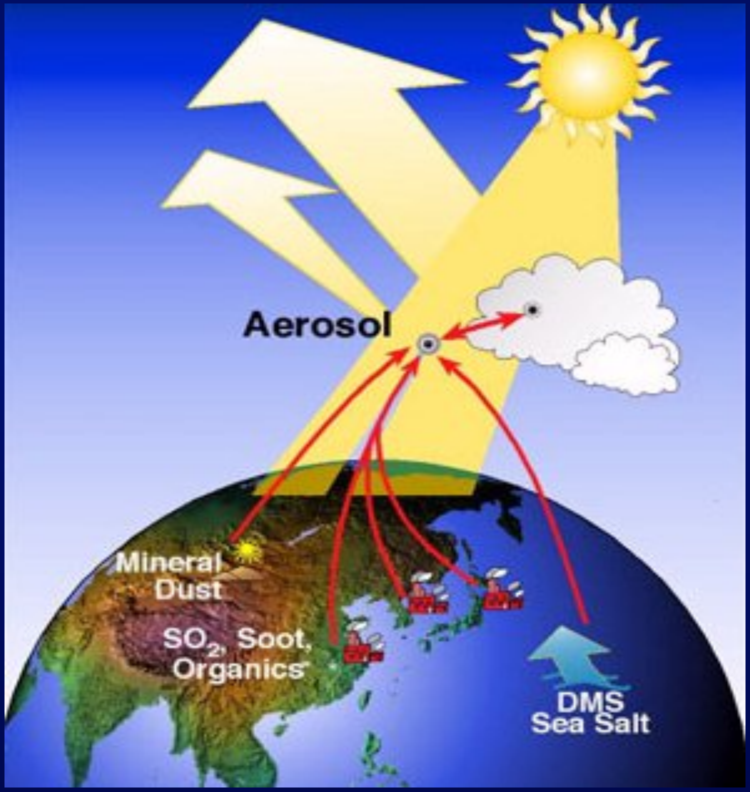


Complex landuse

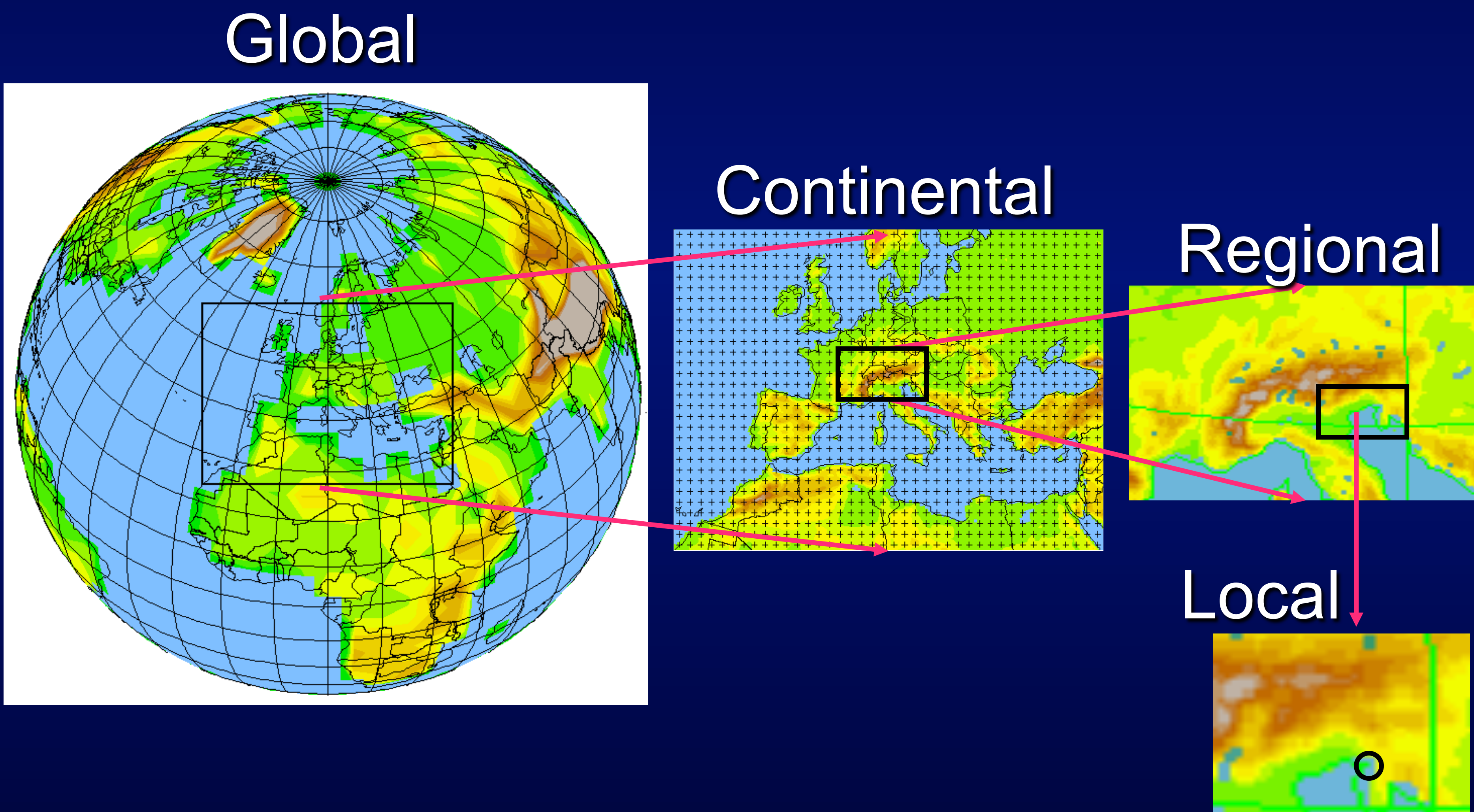


Aerosols

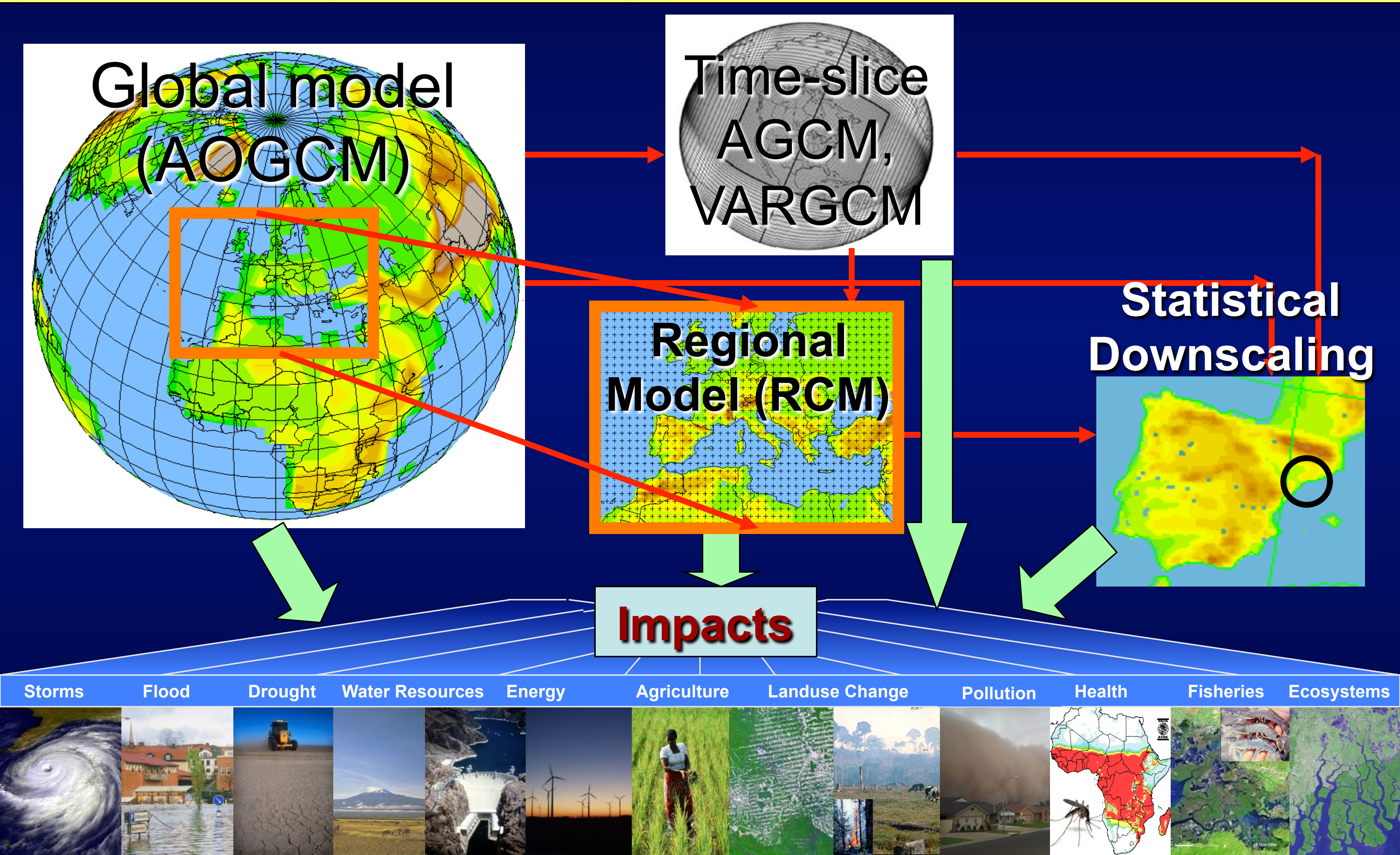
Direct and indirect effects



Climate change needs to be simulated at multiple spatial scales



Several tools are available for producing fine (sub-GCM) scale regional climate information



“Nested” Regional Climate Modeling: Technique and Strategy

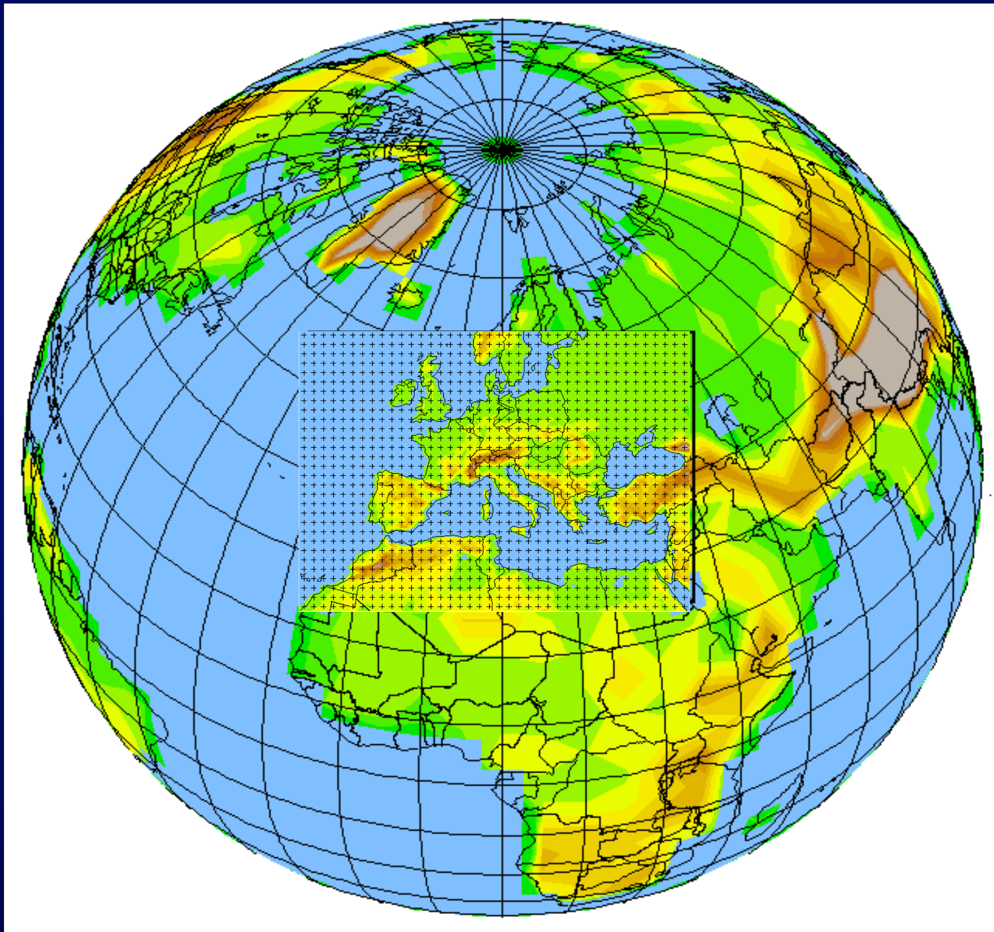
Motivation: The resolution of GCMs is still too coarse to capture regional and local climate processes

Technique:A “Regional Climate Model” (RCM) is “nested” within a GCM in order to locally increase the model resolution.

– Initial conditions (IC) and lateral boundary conditions (LBC) for the RCM are obtained from the GCM (“One-way Nesting”) or analyses of observations (perfect LBC).

Strategy: The GCM simulates the response of the general circulation to the large scale forcings, the RCM simulates the effect of sub-GCM-grid scale forcings and provides fine scale regional information

– Technique borrowed from NWP



The equations of a climate model

$$\frac{\partial \overline{V}}{\partial t} + \overline{V} \cdot \nabla \overline{V} = -\frac{\nabla p}{\rho} - 2\overline{\Omega} \times \overline{V} + \overline{g} + \overline{F}_{\overline{V}}$$

Conservation of momentum

$$C_p\left(\frac{\partial T}{\partial t} + \overline{V} \cdot \nabla T\right) = \frac{1}{\rho}\frac{dp}{dt} + Q + F_T$$

Conservation of energy

$$\frac{\partial \rho}{\partial t} + \overline{V} \cdot \nabla \rho = -\rho \nabla \cdot \overline{V}$$

Conservation of mass

$$\frac{\partial q}{\partial t} + \overline{V} \cdot \nabla q = \frac{S_q}{\rho} + F_q$$

Conservation of water

$$p = \rho R T$$

Equation of state

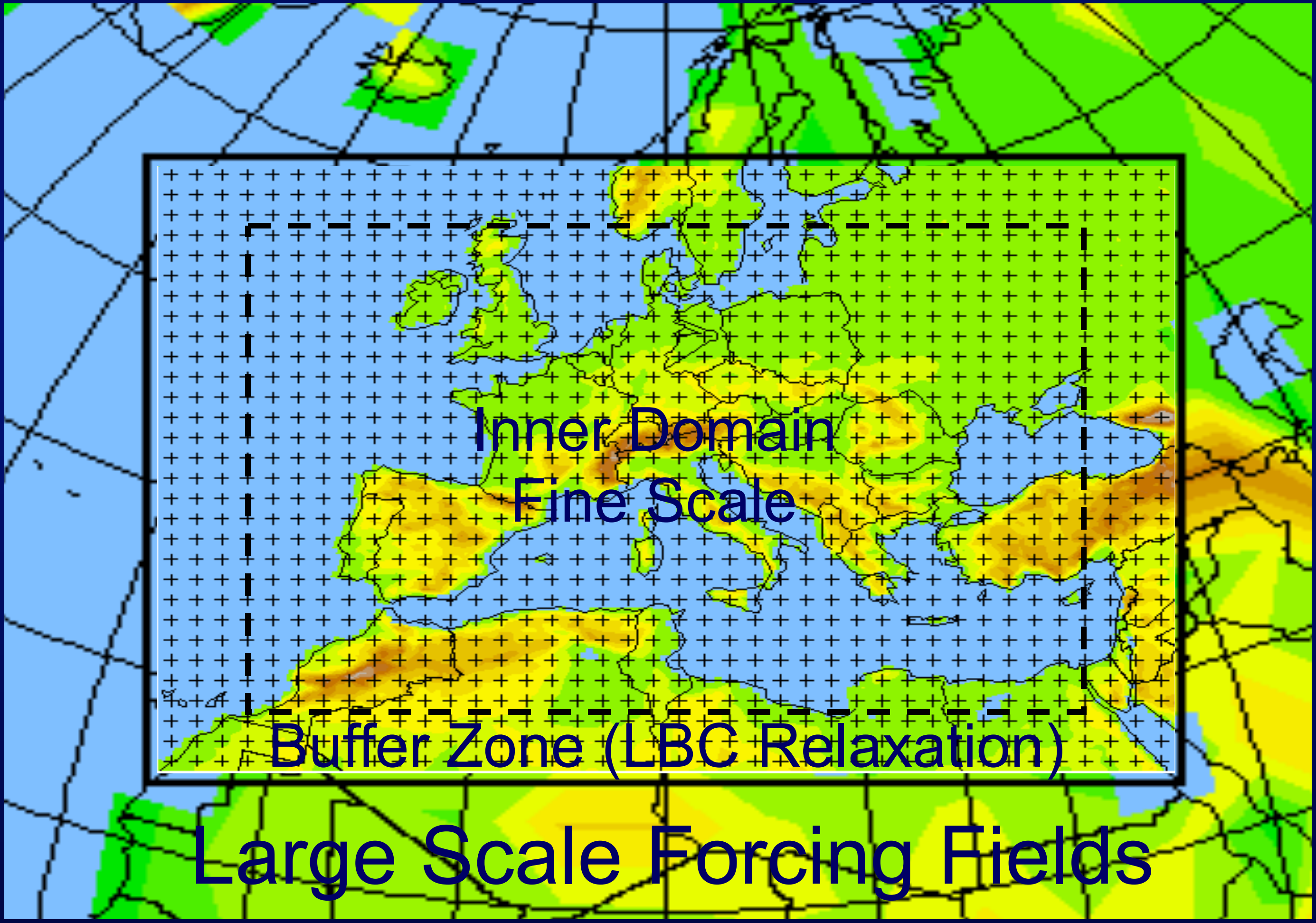
Physics

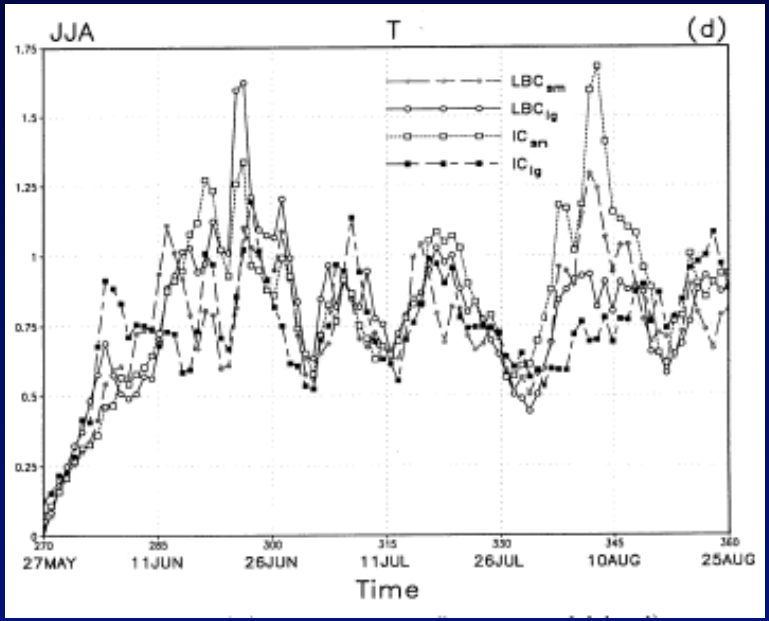
The components of a climate model

- Dynamics
  - Advection
  - Diffusion
  - Pressure gradient force
  - Coriolis force
  - Gravity
- Physics (parameterizations)
  - Radiative transfer
  - Planetary boundary layer
  - Resolvable scale clouds and precipitation
  - Convective clouds and precipitation
  - Land and ocean surface processes

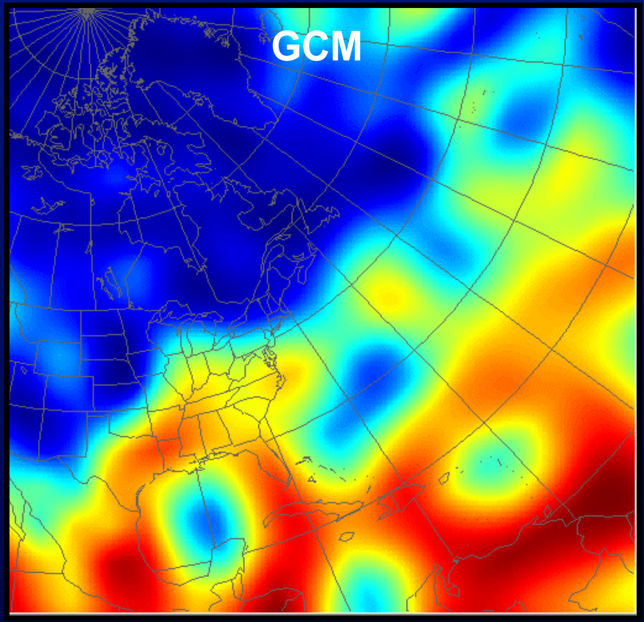
RCM Nesting procedure

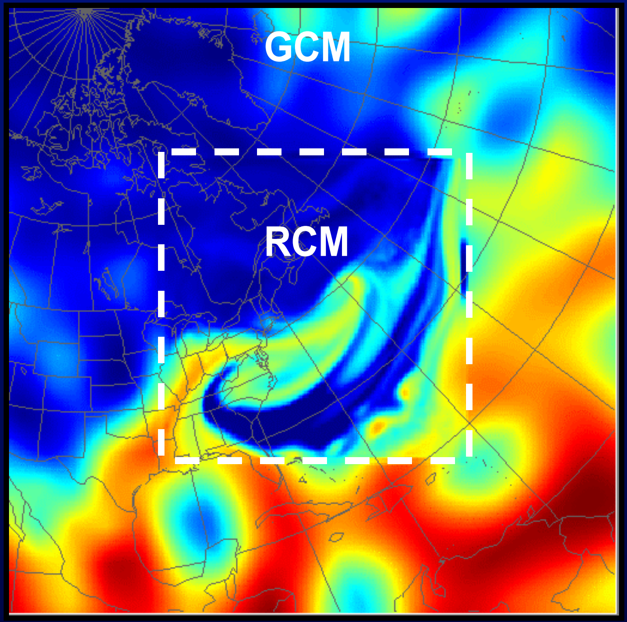
$$\frac{\partial \alpha}{\partial t} = F(n)F_1 \cdot (\alpha_{LBC} - \alpha_{mod}) - F(n)F_2 \cdot \Delta_2(\alpha_{LBC} - \alpha_{mod})$$





A dynamical equilibrium is reached in the interior domain between the information from the LBC and the model solution





900 Hpa specific humidity (Courtesy of R. Laprise)

Some key projects and literature

- Review papers: Giorgi and Mearns (1991), McGregor (1997), Giorgi and Mearns (1999), Giorgi et al. (IPCC 2001), Leung et al. (2003), Mearns et al. (2003), Wang et al. (2004), Giorgi (2006),Rummukainen (2010), Giorgi and Gutowski (2015)
- European projects: PRUDENCE, AMMA, ENSEMBLES, CECILIA, CLARIS, ACQWA, EUCP
- Intercomparison projects: PIRCS, RMIP, NARCCAP, NEWBALTIC, ARCMIP, PLATIN,ARC, NAMAP, QUIRCS,Transferability, CORDEX
- Special issues: JGR 1999; JMSJ 2004; TAC 2006; CC 2007; MAP 2004, 2008; CCH 2006; MET.-ZEIT. 2008; CR 2012; CC 2014.

Regional Climate Modeling
Applications

- Model development and validation
  - "Perfect Boundary Condition" experiments
  - Over 20 RCMs available Worldwide
  - Wide range of regional domains and resolutions (10-100 km)
- Process studies
  - Land-atmosphere interactions, topographic effects, cyclogenesis
  - Tropical storms, hurricanes
  - Regional hydrologic and energy budgets
- Climate change studies
  - Regional signals, variability and extremes
- Paleoclimate studies
- Regional climate system coupling
  - Chemistry/aerosol – atmosphere (Climatic effects of aerosols)
  - Ocean/sea ice-atmosphere
  - Biosphere-atmosphere
- Seasonal prediction
- Impact studies

Regional Climate Models: "State of the art"

- A number of RCMs today available, some of them "portable" and used by wide communities (e.g. RegCM, PRECIS, RSM, WRF)
- Grid spacing of ~10-25 km;
- Upgrade to non-hydrostatic, cloud-resolving frameworks under way in most models (1-5 km km grid size)
- Development of coupled regional Earth System models
- Decadal to centennial simulations the "accepted standard"
- Virtually all regions of the World have been simulated
- Some two-way nested experiments have been carried out
- Wide range of applications
  - Process studies, paleoclimate, climate change, seasonal prediction, impacts, climate-aerosol interactions,air-sea feedbacks, land-atmosphere feedbacks

Regional Climate Modeling Issues
Assimilation of LBC

- Standard relaxation technique
  - Only applied to a lateral buffer zone
  - Allows more freedom for the model to develop its own circulations in the interior of the domain
  - Different relaxation functions can be used to allow smoother blending of LBC and model fields
- Spectral nesting (or nudging)
  - Relaxation to the large scale forcing for the low wave number component of the solution throughout the entire domain
  - Standard boundary forcing for the high wave number component of the solution
  - Ensures full consistency between forcing and model produced large scale circulations
- Ratio of forcing fields resolution to model resolution should not exceed 6-8

Regional Climate Modeling Issues

Internal variability (IV)

RCMs are characterized by internal variability which may be misinterpreted as a real signal

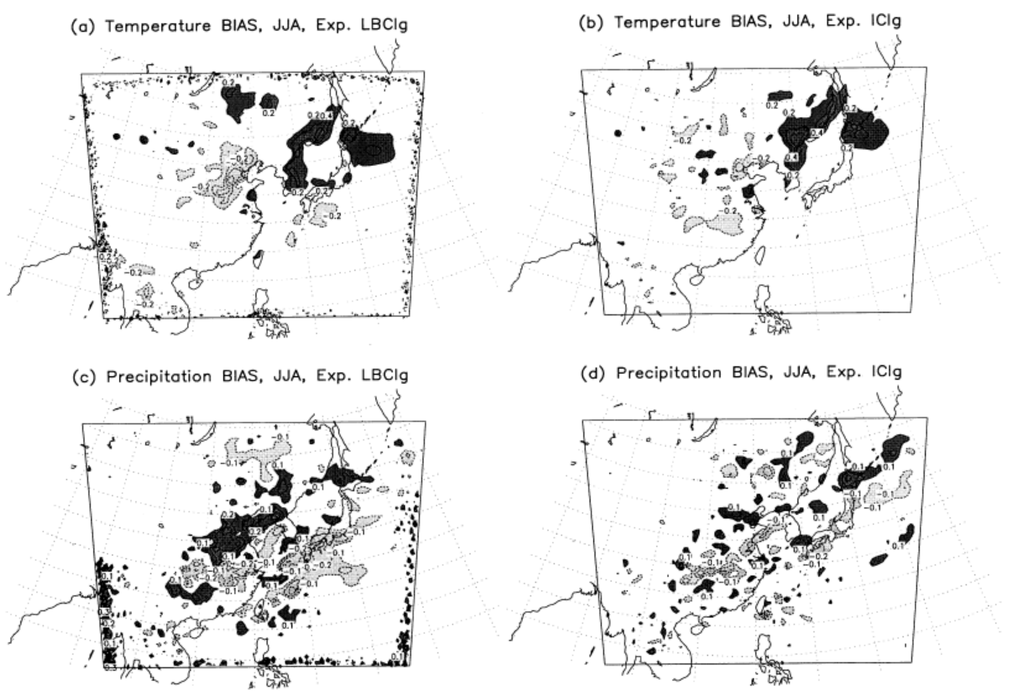


Figure 10. Bottom model level temperature (K) and precipitation (mm/day) BIAS for the LBC_{lg} and IC_{lg} perturbation experiments (not including the first 15 days of simulation). Season is JJA. (a) Temperature BIAS, Exp. LBC_{lg}; (b) temperature BIAS, Exp. IC_{lg}; (c) precipitation BIAS, Exp. LBC_{lg}; (d) precipitation BIAS, Exp. IC_{lg}. Light shading is for negative values and dark shading is for positive values.

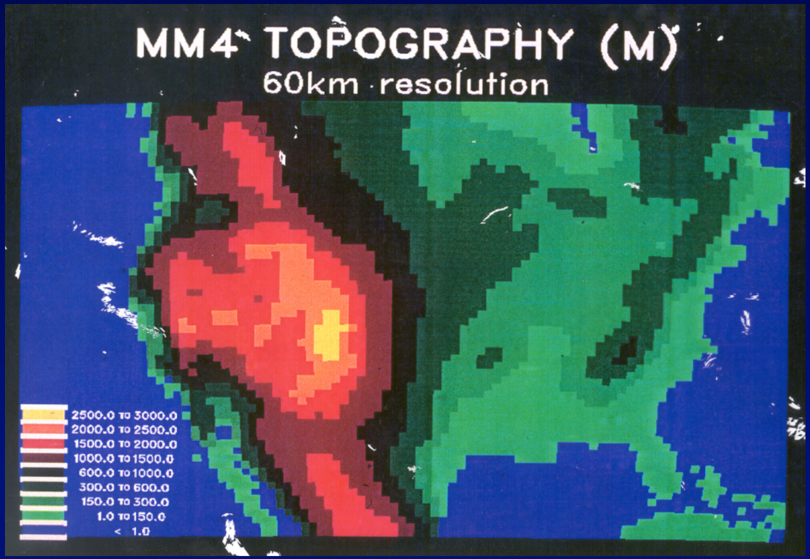
Giorgi and Bi (2000)

The internal variability depends on domain location and size, season, climate regime etc.

Regional Climate Modeling Issues
"Garbage in, garbage out"

- RCMs are not intended to strongly modify the large scale circulation features in the forcing (GCM) fields
  - Failure of this condition might lead to inconsistencies at the lateral boundaries
- Due to the LBC forcing, large scale circulations are generally similar in the nested RCM and driving GCM
  - The nested RCM cannot correct for errors transmitted from the large scale GCM fields through the lateral boundaries
- For a successful RCM simulation it is thus critical that the driving large scale LBC are of good quality
  - Examples: Correct location of jet streams and storm tracks
- <u>However the degree of forcing by the LBC depends on domain size, climate regime and LBC technique</u>
  - The LBC forcing is weaker in large and tropical domains and when using the standard relaxation technique

2CO2-Control Winter Precipitation

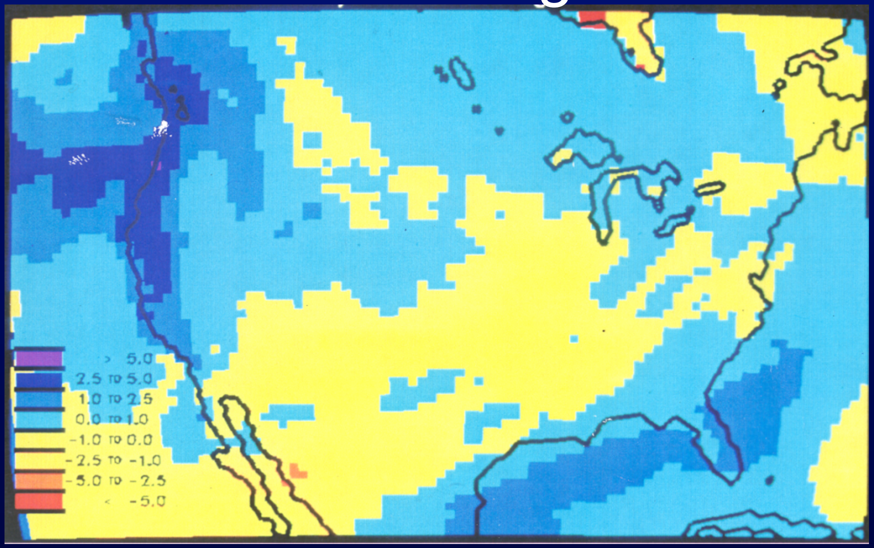


Model domain and topography

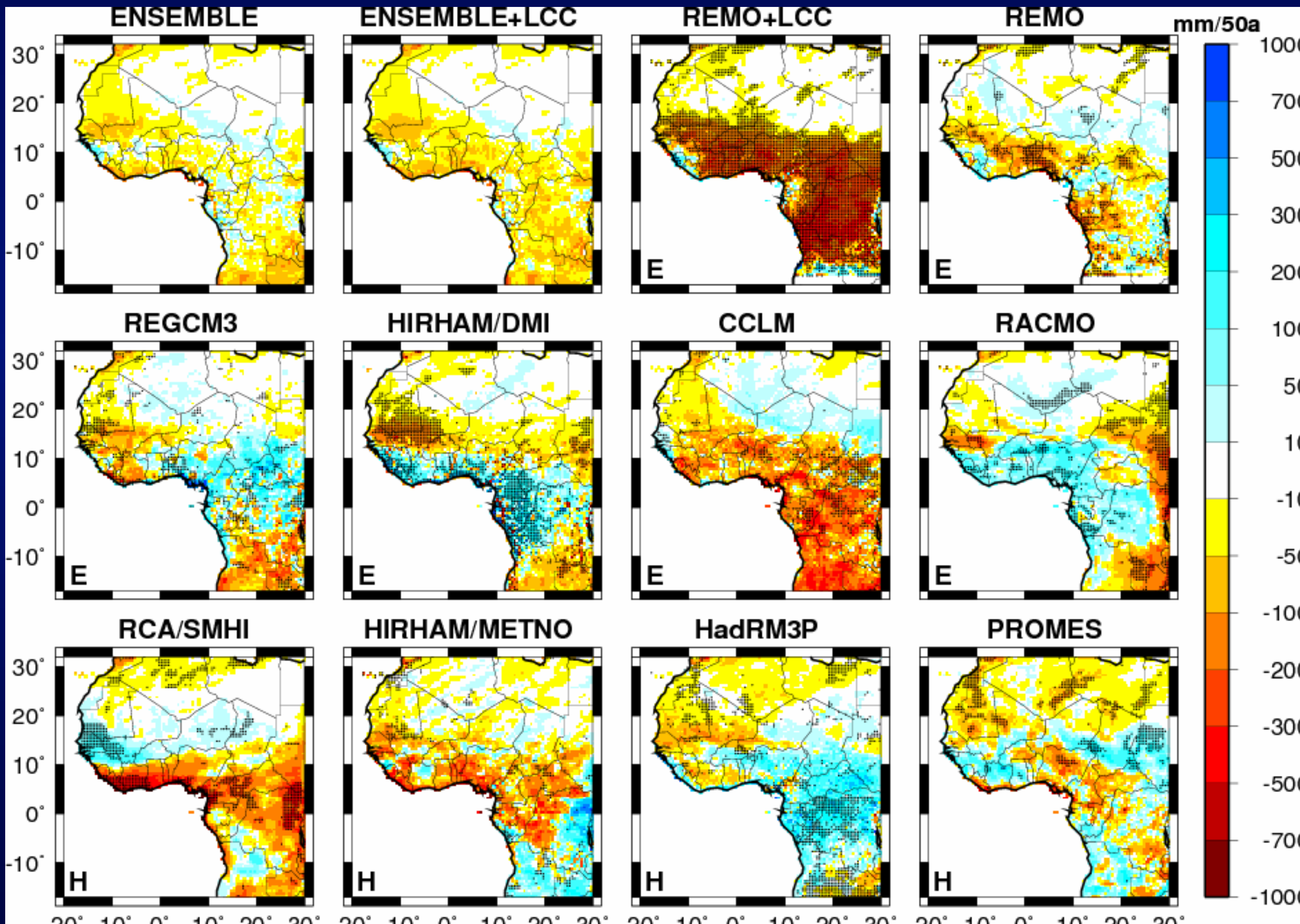
2CO2-Control DJF Precipitation

CCM

RegCM



Precipitation trend 1990-2050



ECHAM5 LBC

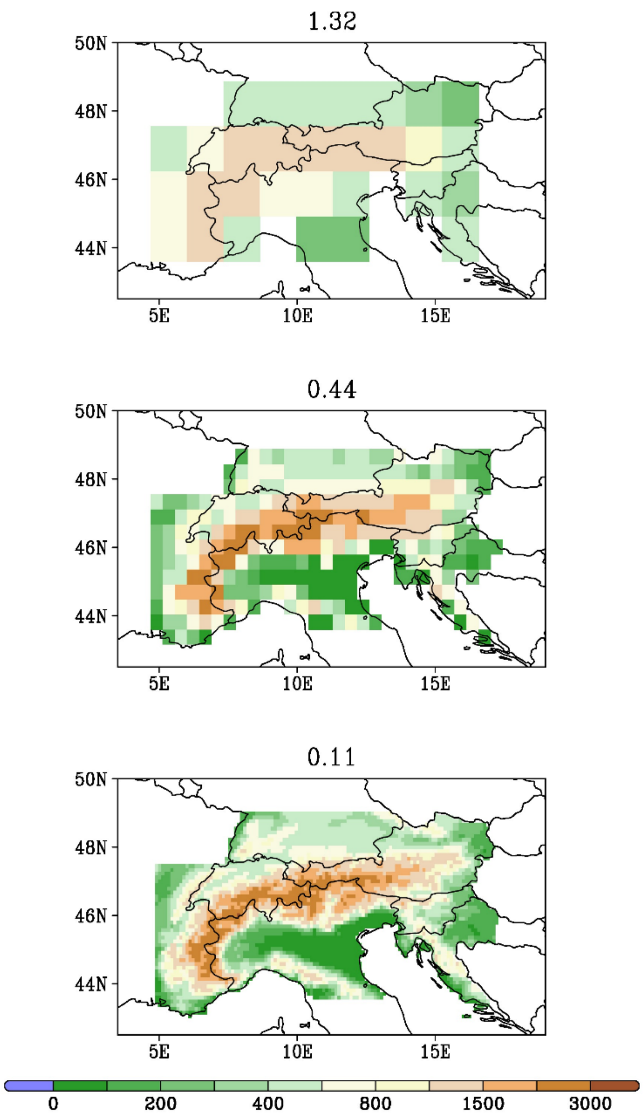
HadCM3 LBC

Regional Climate Modeling Issues
“Added value” (AV)

- What is the “added value” of the use of an RCM with respect of the driving GCM?
  - The added value is application-dependent and for some problems RCMs are not needed
- Examples of problems with high AV potential
  - Fine scale forcings (e.g. topography)
  - Mesoscale circulations
  - Extremes
- Tool for process studies and physics development
  - Aerosol effects, land-atmosphere interactions, regional feedbacks, circulations and processes etc.
  - Physics for high resolution applications

A study of added value over the Alps (Torma et al. 2015)

Horizontal resolutions: 1.32°, 0.44° and 0.11°



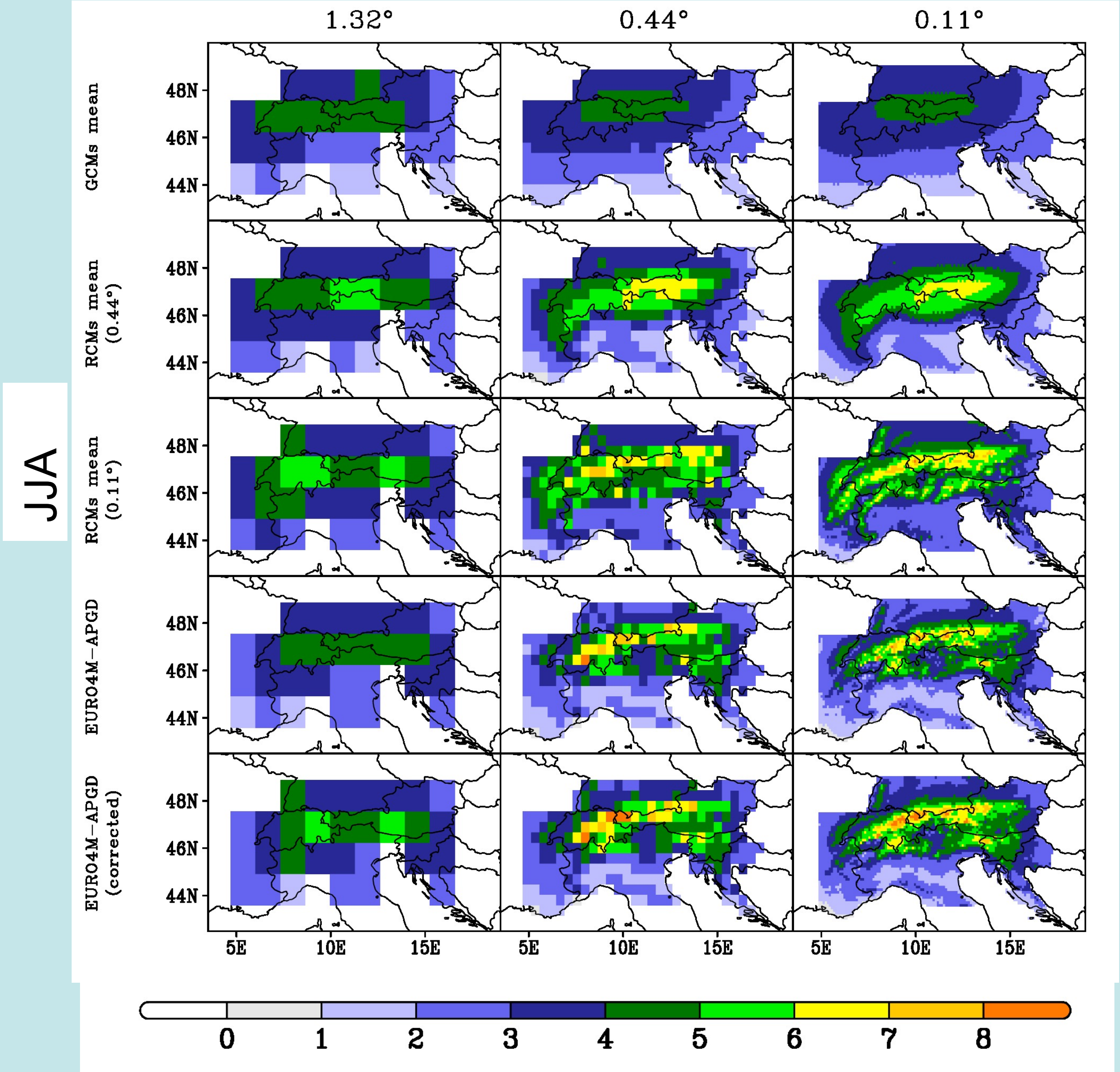
GCMs :
MPI-ES-MR
EC-EARTH
CNRM-CM5
HadGEM-ES

RCMs:
CCLM
RACMO
ALADIN
RegCM4.3
RCA4

Reference period: 1975-2004
Future period: 2070-2099

Observational data: EURO4M-APGD (Isotta et al., 2014)

Simulation of spatial patterns of precipitation - Summer

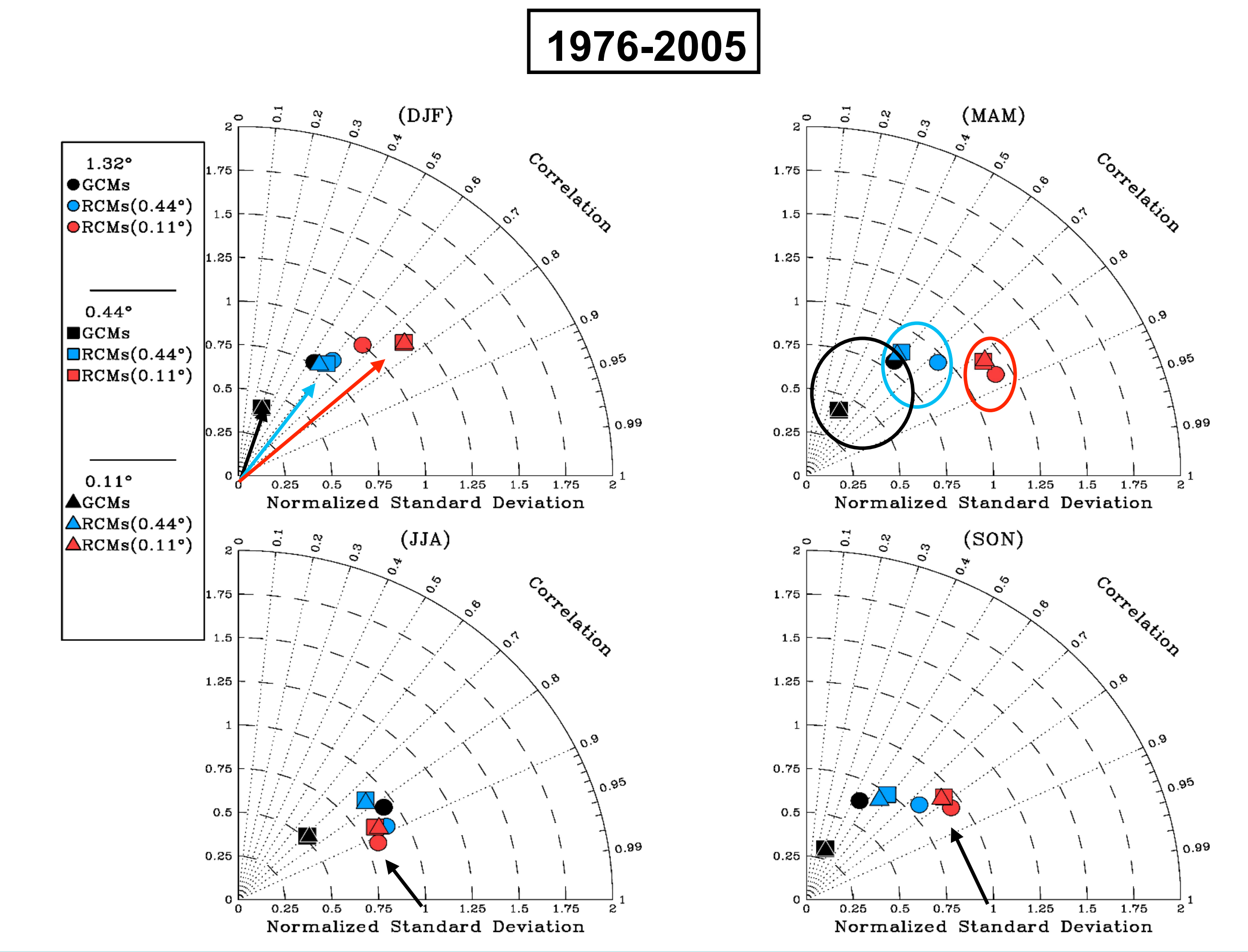


Higher resolution

Increasing details in precipitation spatial distribution

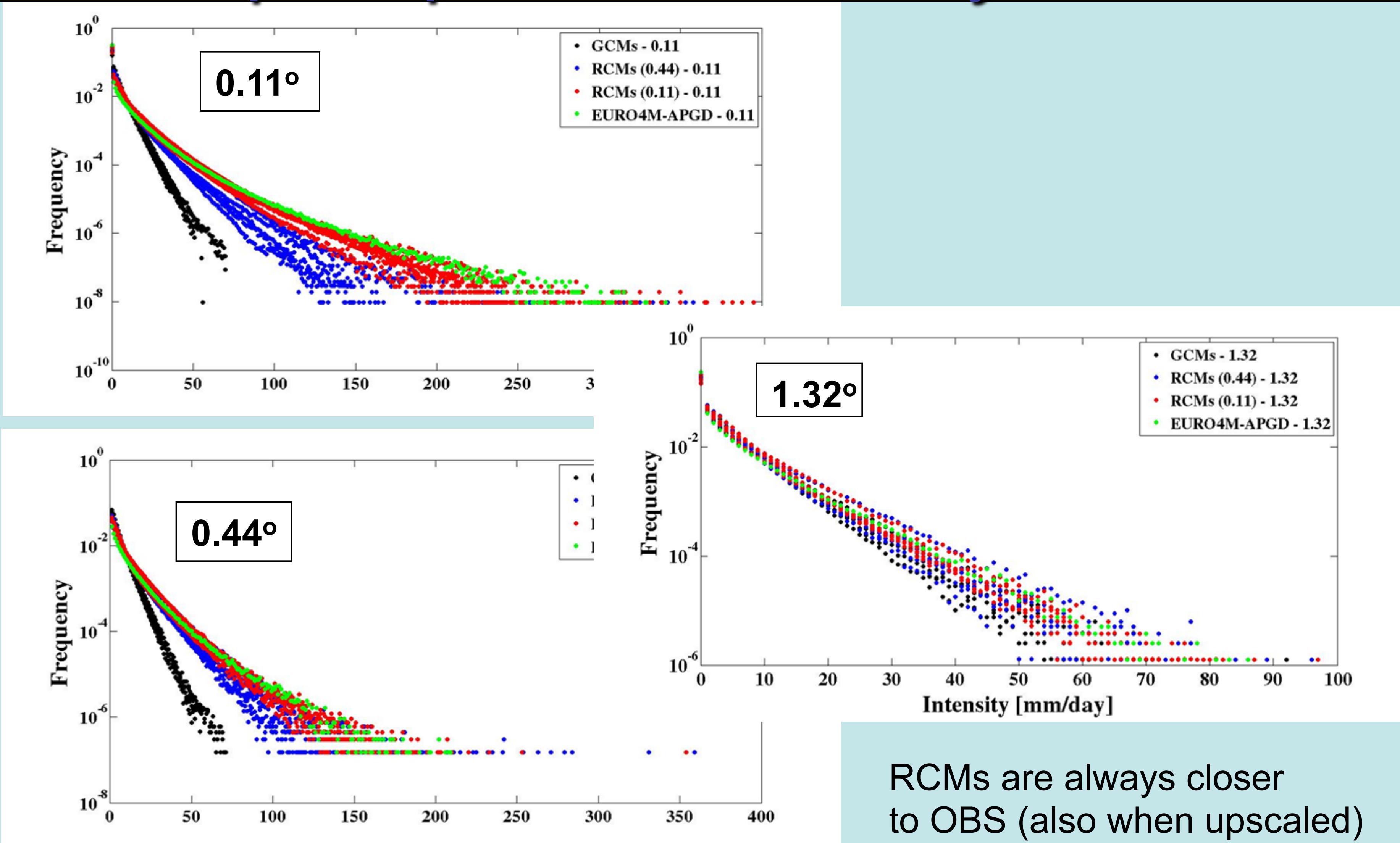
Fine scale AV

Taylor diagrams for mean seasonal precipitation



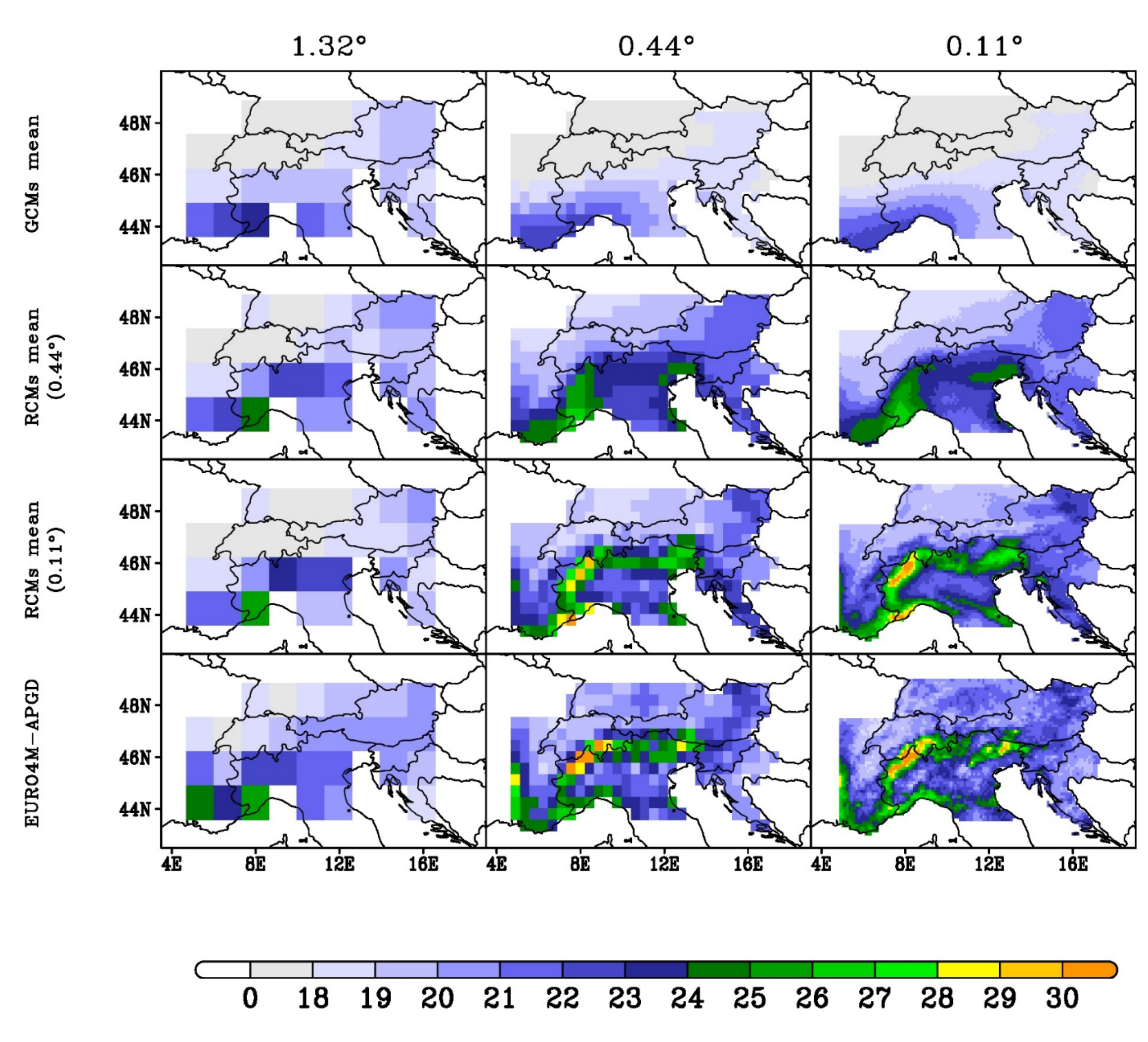
AV is found also when the data are upscaled at the GCM resolution

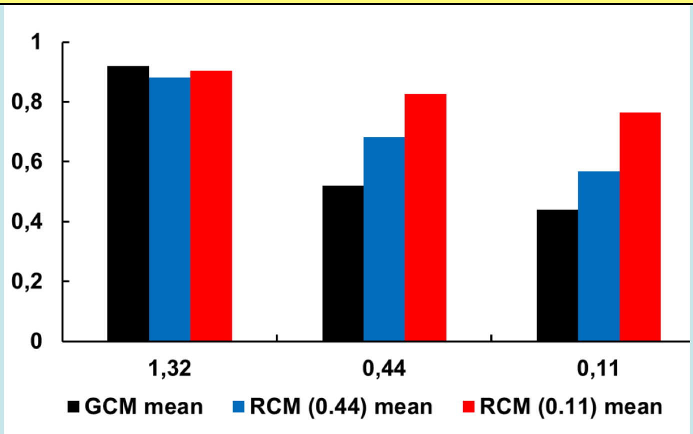
Added value: Simulation of daily precipitation intensity PDF



RCMs are always closer
to OBS (also when upscaled)

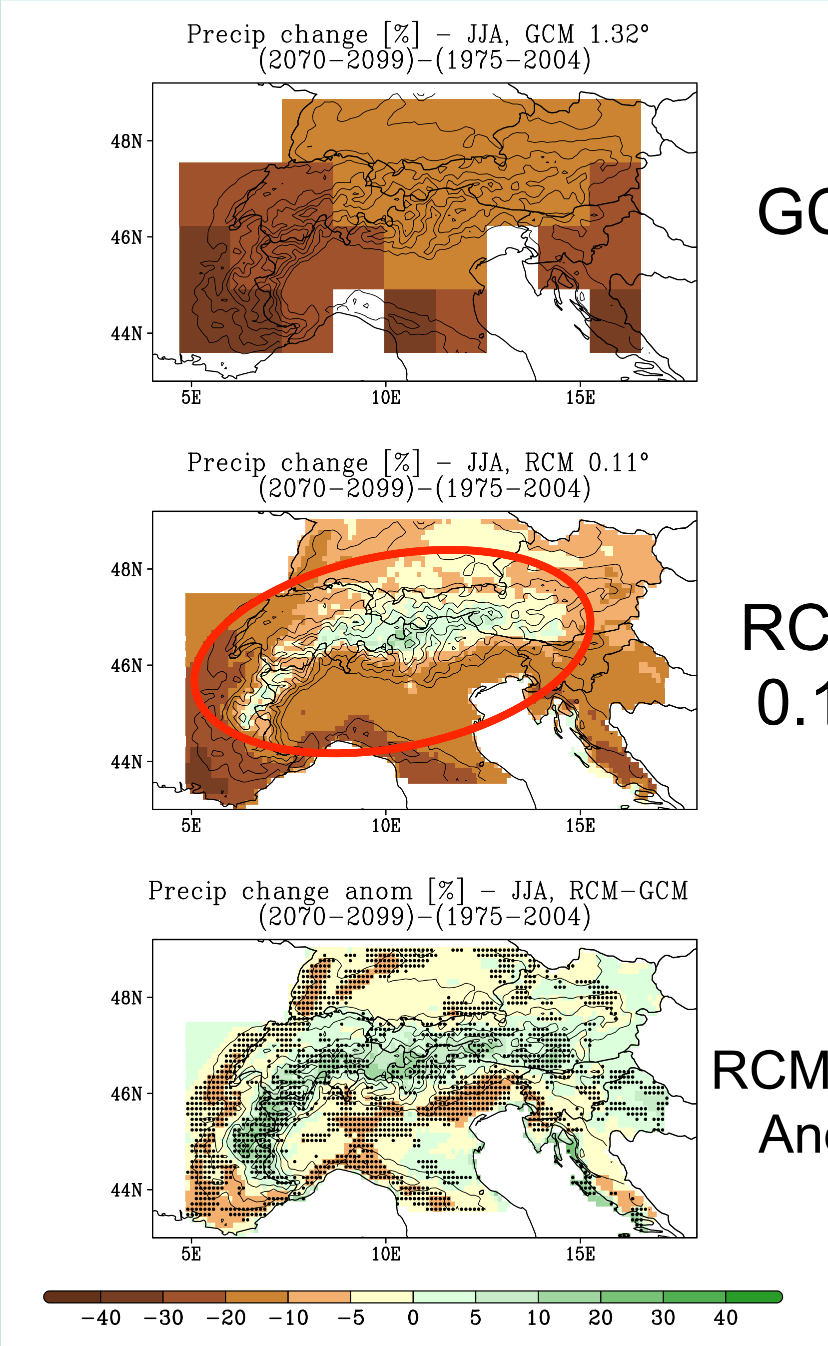
Fraction of precipitation above the 95th percentile





Correlation

Added value in climate change information: Summer precipitaiton change (Giorgi et al. 2015)



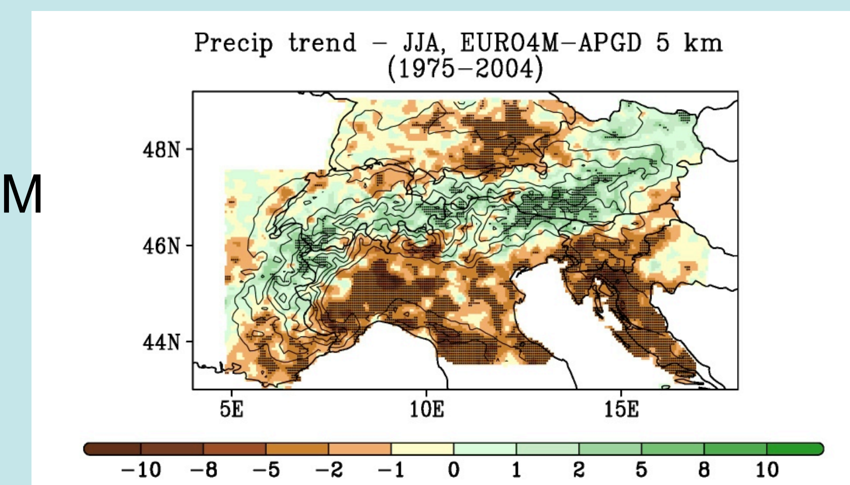
GCMs

RCMs
0.11°

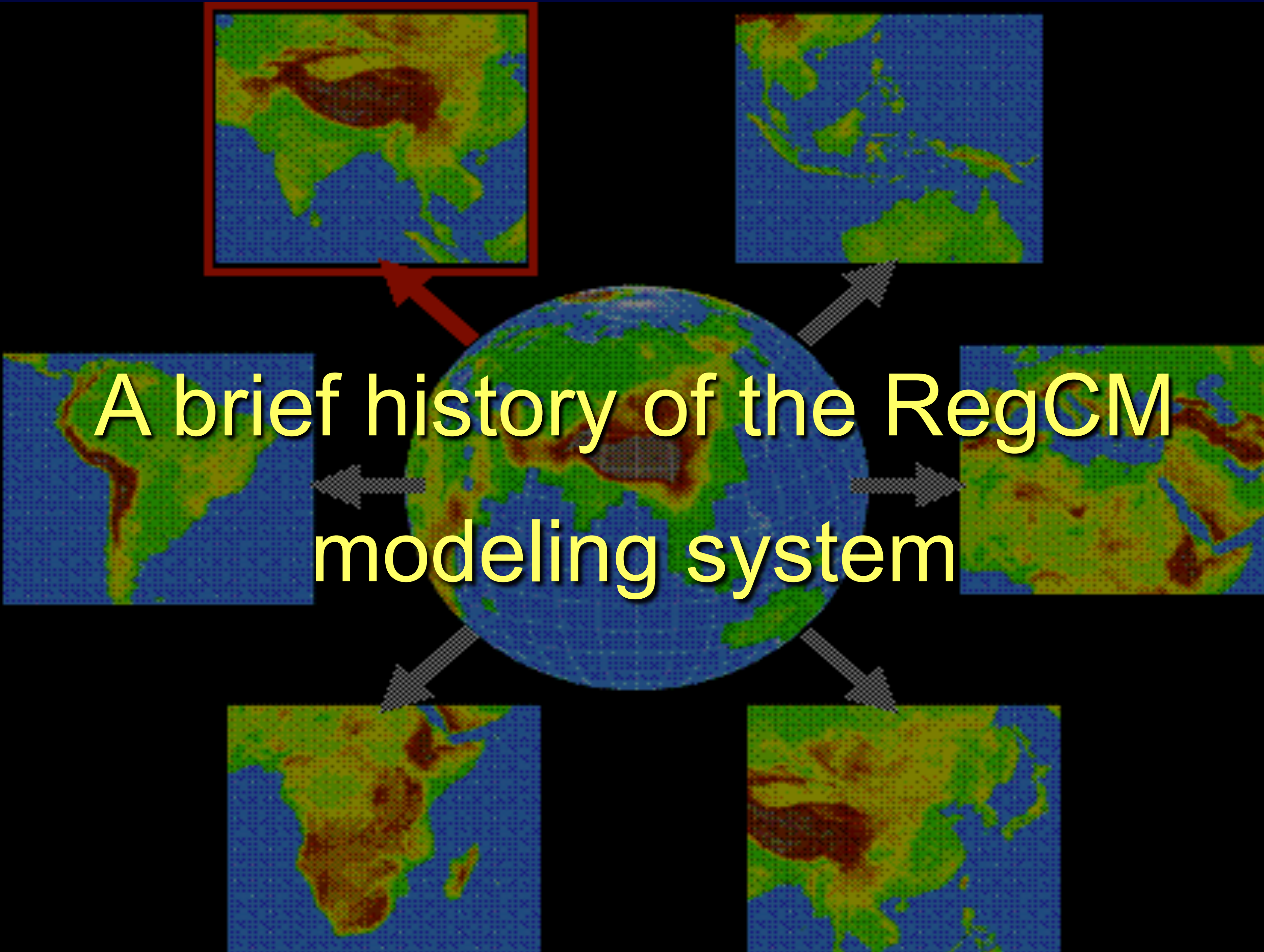
RCM – GCM
Anomaly

mm/day/century

Observed summer precipitation change (1975-2004)



A brief history of the RegCM modeling system



The RegCM regional climate model system

RegCM1 (1989)

- Documentation
  - Dickinson et al. (1989), Giorgi and Bates (1989), Giorgi (1990)
- General features
  - Horizontal grid spacing of 50-100 km
  - Adaptable to any region of the world
  - Driving fields from NCEP analyses or GCMs
- Model dynamics (based on mesoscale model MM4; Anthes et al. 1987)
  - Hydrostatic assumption
  - Sigma-p vertical coordinates; Staggered Arakawa B-grid
  - Explicit 3-level time-integration scheme
- Model Physics (based on MM4 and the CCM1 GCM)
  - CCM1 radiative transfer package (Kiehl et al. 1986)
  - Local stability-dependent PBL scheme (Blackadar et al. 1982)
  - Kuo-Anthes cumulus convections scheme (Anthes et al. 1977)
  - Implicit resolvable scale precipitation scheme
  - BATS1A land surface scheme (Dickinson et al. 1986)

The RegCM regional climate model system

RegCM2 (1993)

- Development
  - Giorgi et al. (1993a,b)
- General features
  - Horizontal grid spacing of 10-100 km
  - Adaptable to any region of the world
  - Driving fields from ECMWF and NCEP analyses or GCMs
- Model dynamics (based on hydrostatic mesoscale model MM5; Grell et al. 1994)
  - Sigma-p vertical coordinates; Staggered Arakawa B-grid
  - **Split explicit time-integration scheme** (doubling of time step)
- Model Physics (based on MM5 and the CCM2 GCM)
  - **CCM2 radiative transfer packa**ge (Kiehl et al. 1993)
  - **Non-local vertical diffusion PBL scheme** (Holtslag et al. 1990)
  - Kuo and Grell cumulus convections schemes (Grell 1993)
  - Implicit and **explicit** resolvable scale precipitation scheme (Hsie and Anthes 1984)
  - **BATS1E** land surface scheme (Dickinson et al. 1993)

The RegCM regional climate model system

RegCM2.5 (1999)

- Development
  - Giorgi et al. (1993a,b); Giorgi and Shields (1999); Small et al. (1999); Qian and Giorgi (1999); Special issue of JGR, April 1999.
- General features
  - Horizontal grid spacing of 10-100 km
  - Adaptable to any region of the world
  - Driving fields from ECMWF and NCEP analyses or GCMs
- Model dynamics (based on hydrostatic MM5; Grell et al. 1994)
  - Sigma-p vertical coordinates; Staggered Arakawa B-grid
  - Split explicit time-integration scheme
- Model Physics (based on MM5 and the CCM3 GCM)
  - **CCM3 radiative transfer package** (Kiehl et al. 1996)
  - Non-local vertical diffusion PBL scheme (Holtslag et al. 1990)
  - Kuo, Grell, **Zhang** cumulus schemes (Zhang et al. 1997)
  - **Simplified explicit precipitation scheme** (Giorgi and Shields 1999)
  - BATS1E land surface scheme (Dickinson et al. 1993)
  - **Coupled lake model** (Small et al. 1999)
  - **Coupled radiatively active aerosol model** (Qian and Giorgi 1999)

The ICTP regional climate model system
RegCM3, Pal et al. 2007, TAC SI 2006

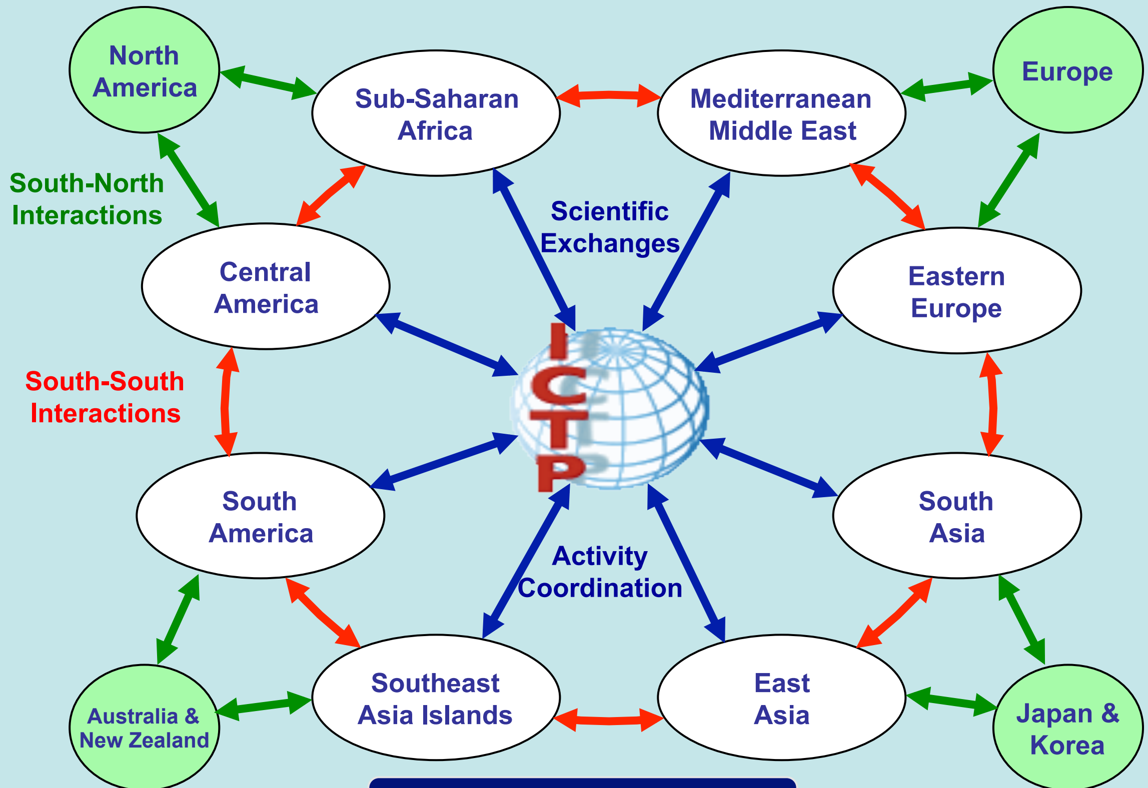
- **Dynamics:**
  MM5 Hydrostatic (Giorgi et al. 1993a,b)
- **Radiation:**
  CCM3 (Kiehl 1996)
- **Large-Scale Clouds & Precipitaion:**
  SUBEX (Pal et al 2000)
- **Cumulus convection:**
  Grell (1993)
  Anthes-Kuo (1977)
  MIT (Emanuel 1991)
- **Boundary Layer:**
  Non-local, Holtslag (1990)
- **Tracers/Aerosols:**
  Solmon et al 2005
  Zakey et al 2006
- **Land Surface:**
  BATS (Dickinson et al 1993)
  SUB-BATS (Giorgi et al 2003)
- **Ocean Fluxes**
  BATS (Dickinson et al 1993)
  Zeng (Zeng et al. 1998)
- **Computations**
  Parallel Code
  Multiple Platforms
  More User-Friendly Code

The ESP RegCM and Regional Climate research NETwork, RegCNET

Collaborative research projects

Use of ICTP model tools and datasets

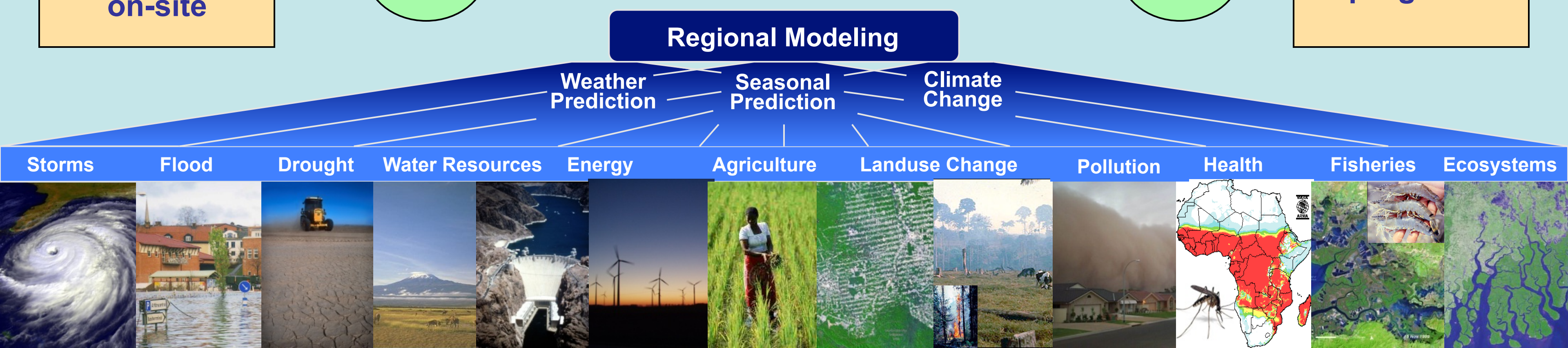
Workshops at ICTP and on-site



E-mail list (over 800 p.)

Interactions with other international programs

Visitor program



The ICTP regional climate model system

RegCM4 (Giorgi et al. 2012, CR SI 2012)

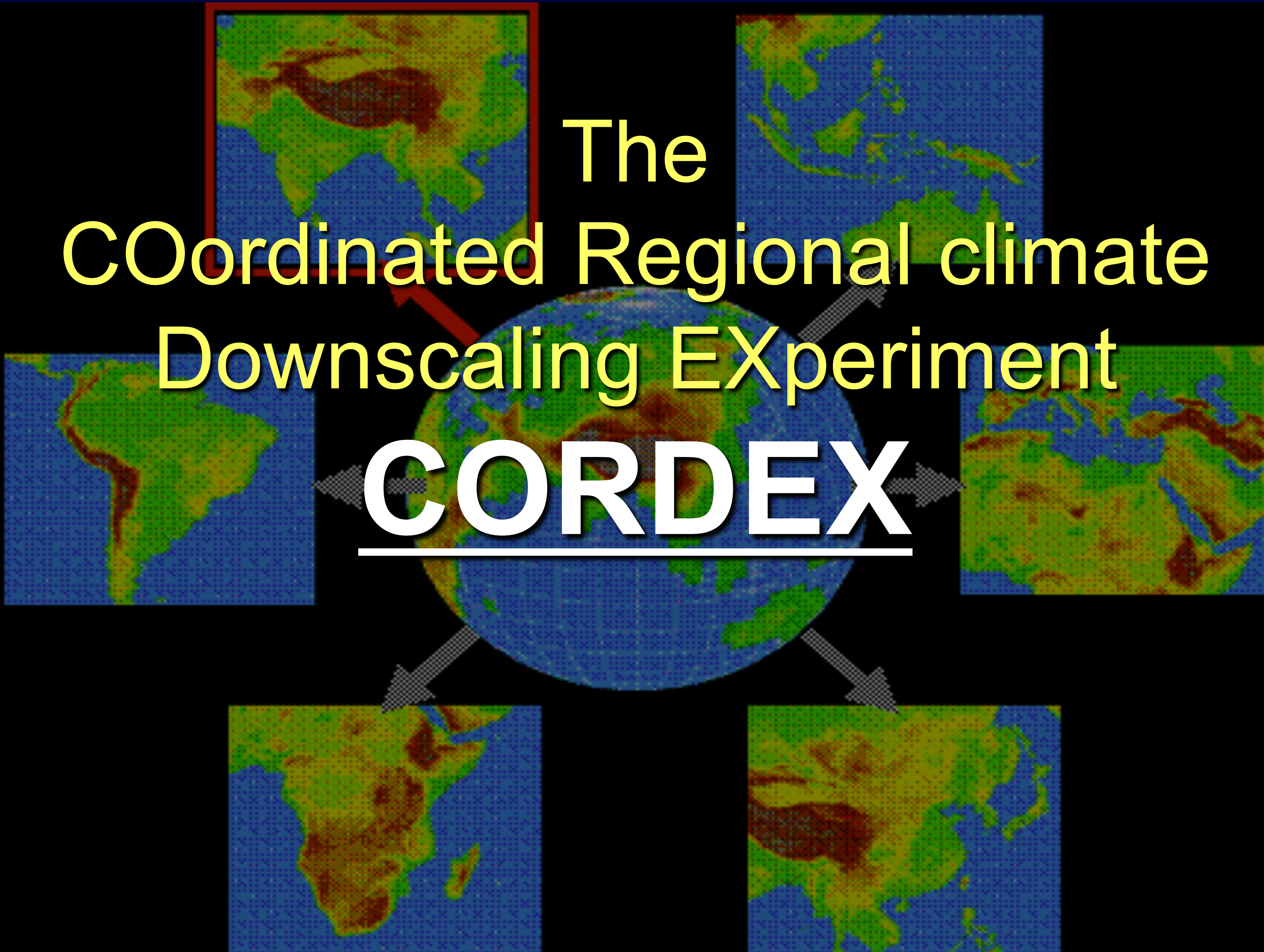
- **Dynamics:**
  Hydrostatic (Giorgi et al. 1993a,b)
  Adaptable to any region
- **Radiation:**
  CCM3 (Kiehl 1996)
  RRTM (Solmon)
- **Large-Scale Precipitation:**
  SUBEX (Pal et al 2000)
  Explicit microphysics (Nogherotto)
- **Cumulus convection:**
  Grell (1993)
  Anthes-Kuo (1977)
  MIT (Emanuel 1991)
  Mixed convection
  Tiedtke
  Kain-Fritsch
- **Planetary boundary layer:**
  Modified Holtslag, **Holtslag (1990)**
  UW-PBL (O' Brien et al. 2011)
- **Land Surface:**
  BATS (Dickinson et al 1993)
  SUB-BATS (Giorgi et al 2003)
  CLM3.5 (Steiner et al. 2009)
- **Ocean Fluxes**
  BATS (Dickinson et al 1993)
  Zeng (Zeng et al. 1998)
  Diurnal SST
- **Configuration**
  Adaptable to any region
  Tropical belt configuration
- **Extensive code remake**

The ICTP regional climate model system RegCM4, coupled components

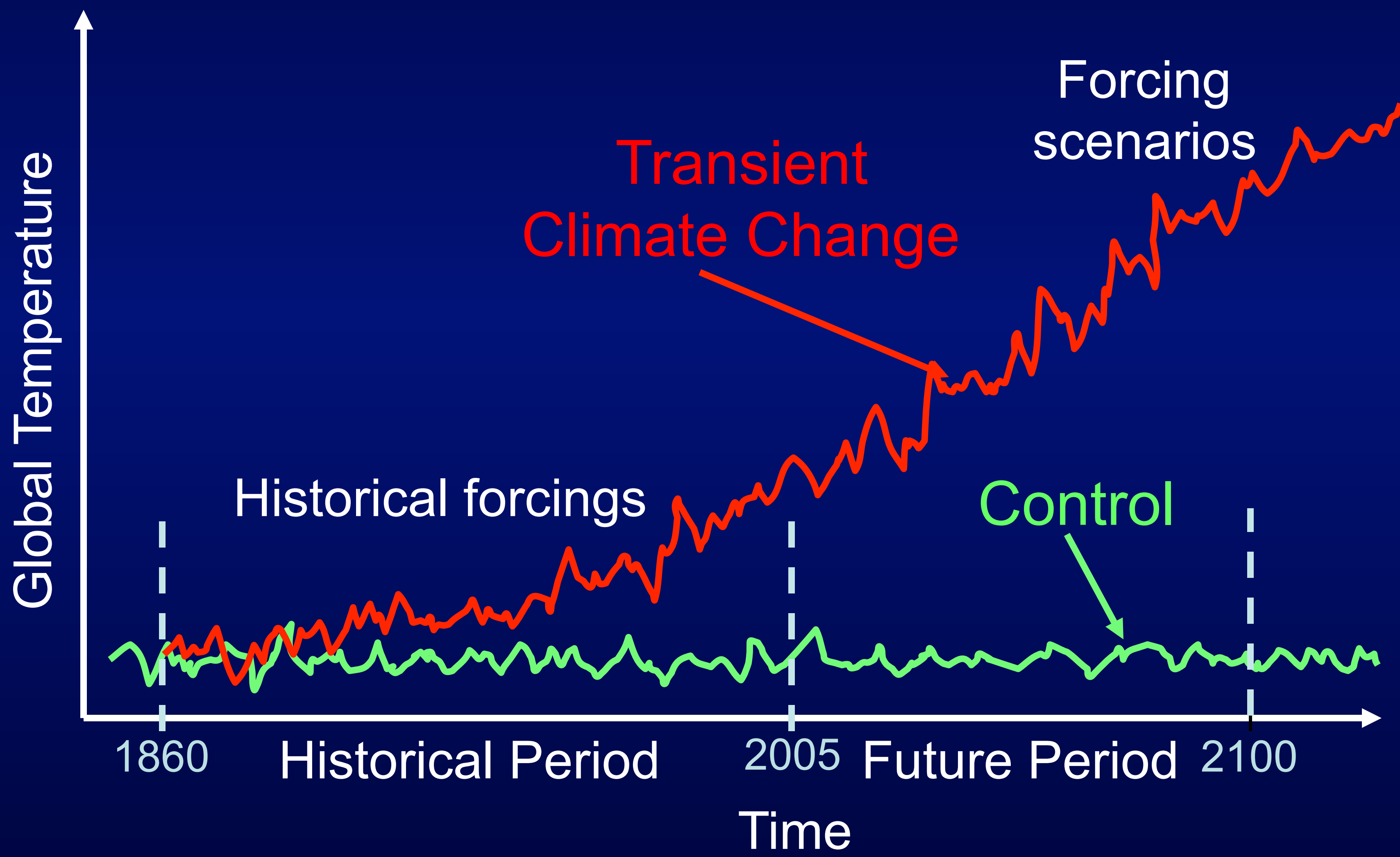
- **Coupled ocean**
  - MIT ocean model (Artale et al. 2010)
  - ROMS (Ratnam et al. 2009)
- **Interactive lake**
  - 1D thermal lake mode reactivated (Hostetler et al. 1994; Small et al. 1999)
- **Interactive biosphere**
  - Available in CLM but never tested
- **Interactive hydrology**
  - CHYM hydrological model available in “off line mode”
- **Aerosols:**
  - OC-BC-SO4 (Solmon et al 2005)
  - Dust (Zakey et al 2006)
  - Sea Salt (Zakey et al. 2009)
  - Pollen (Liu et al. 2016)
- **Gas phase chemistry:**
  - CBMZ + Sillmann solver implemented (Shalaby et al. 2012)
  - Nitrates

The COordinated Regional climate Downscaling EXperiment

CORDEX



Transient Climate Change "Projection"



The protocol for a regional climate change simulation:
Step I: Perfect LBC experiments

- IC and LBC from analyses of observations
  - NCEP, ECMWF
- Simulation of actual periods
  - Validation of the model against observations for the simulated period
- Identification and possibly minimization of systematic errors in the model configuration, dynamics and physics
  - "Customization of the model"

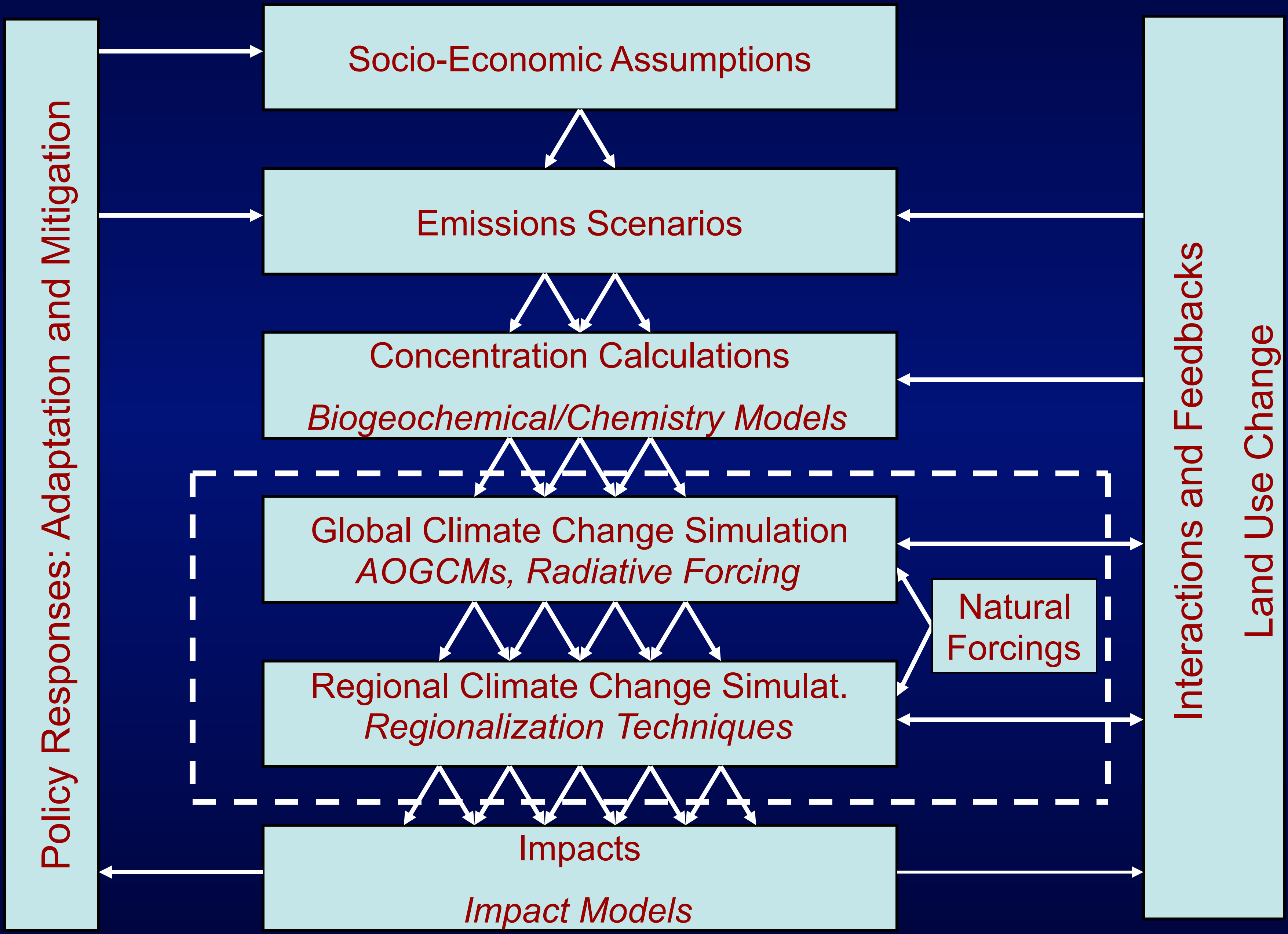
The protocol for a regional climate change simulation:
Step II: GCM-driven "Control" experiments

- IC and LBC from GCM simulations of present-day climate
- In-depth analysis of GCM forcing fields
  - Selection of best available forcing models
  - If errors in the GCM fields are too large, the value of the nested RCM experiment is doubtful
- Validation of model statistics against climatological observations
  - Need of long simulations to obtain robust statistics
- Identification of errors due to the GCM LBC vs. errors due to the model physics and configuration
- Assessment of added fine scale information provided by the RCM ("Added value")

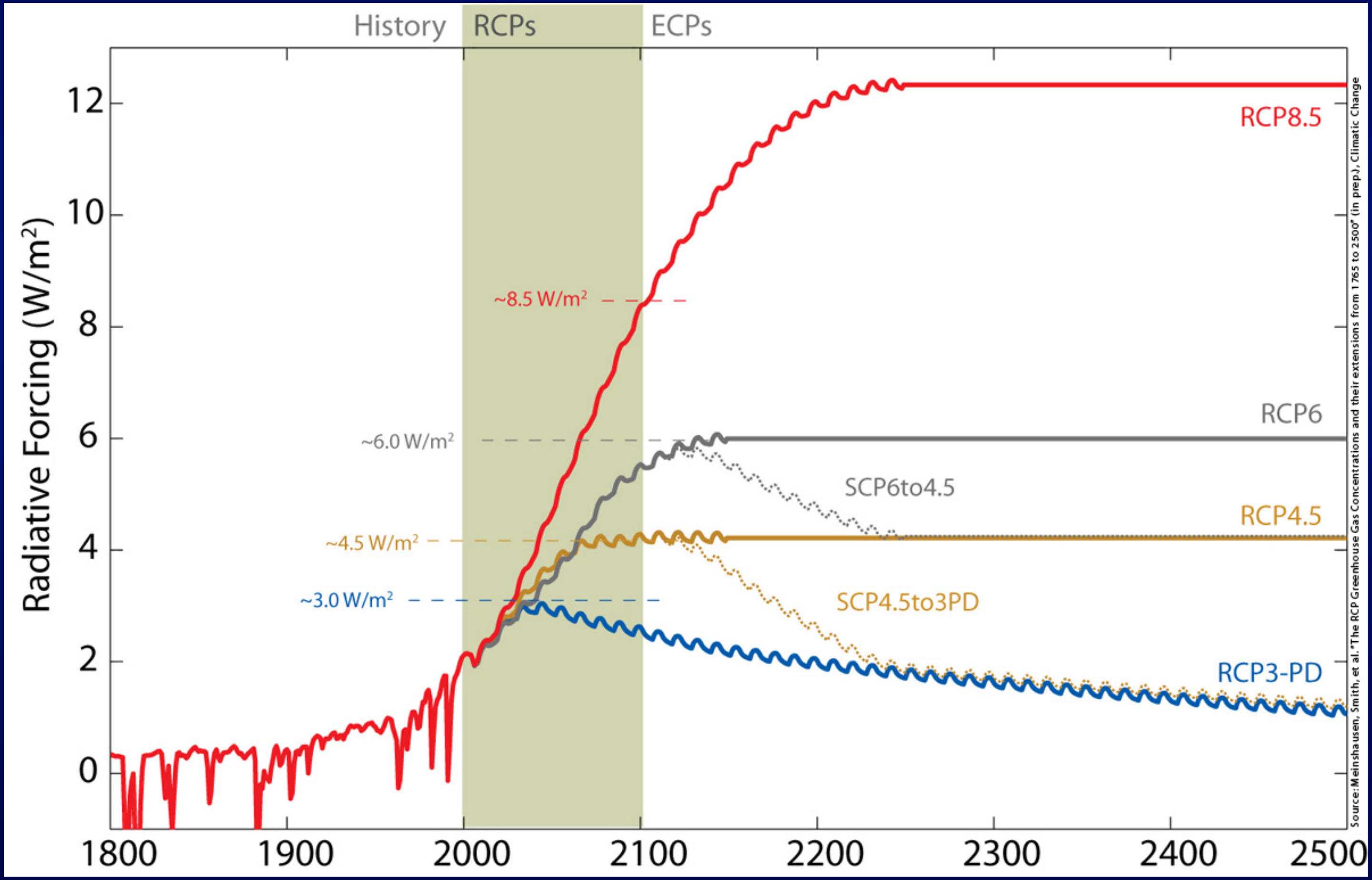
The protocol for a regional climate change simulation:
Step III: GCM-driven experiments of “future” climate conditions

- IC and LBC from GCM simulations of present day and “future” climate conditions
  - Transient (e.g. 1960-2100)
  - Time slices (e.g. 1961-1990; 2071-2100)
- Comparison of “future” and present day “climate statistics” in order to identify the change signal
- Use in impact assessment
  - Direct use of model output
  - Post-processing of model output (e.g. bias correction)

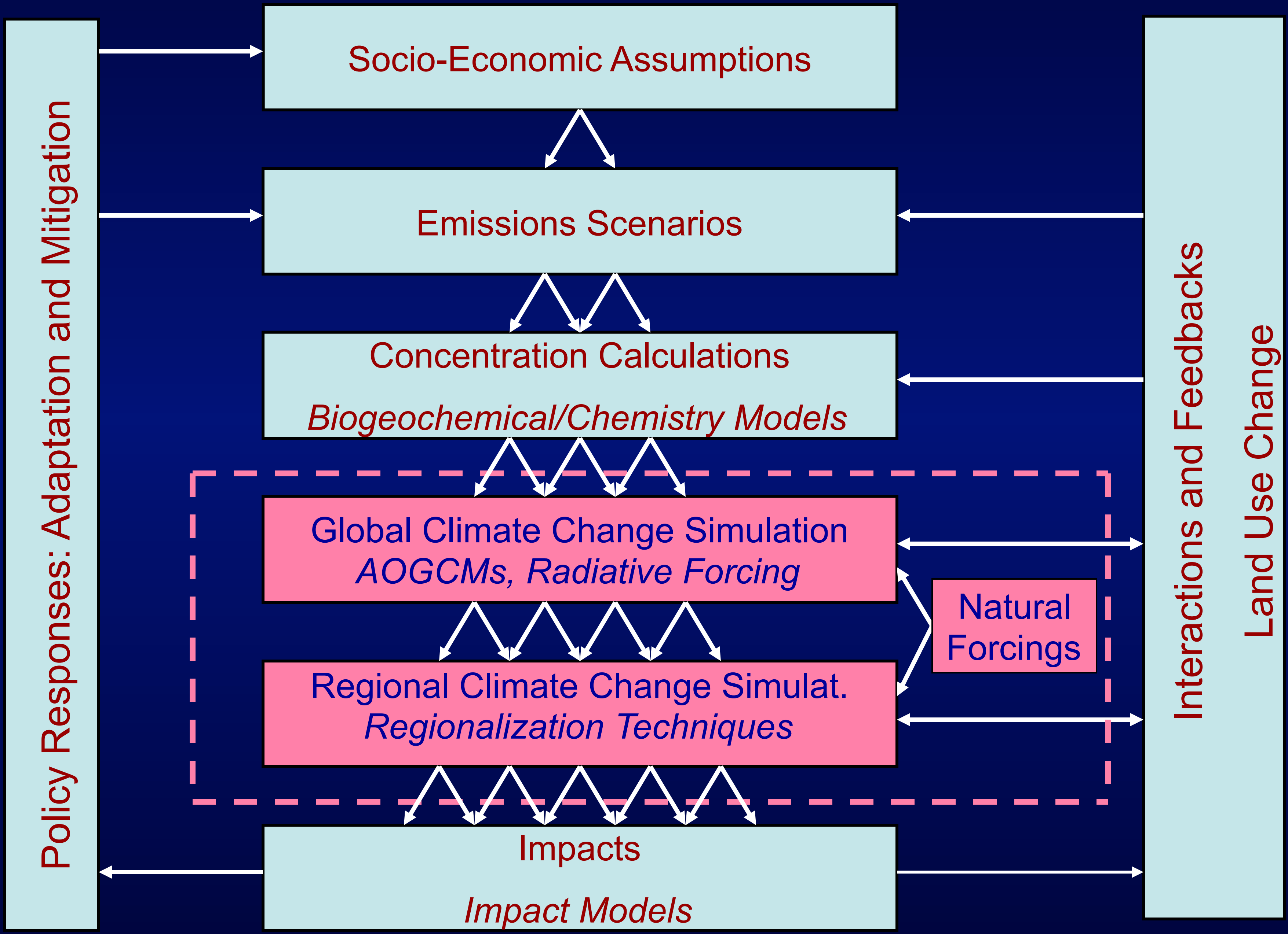
Cascade of uncertainty in climate change prediction



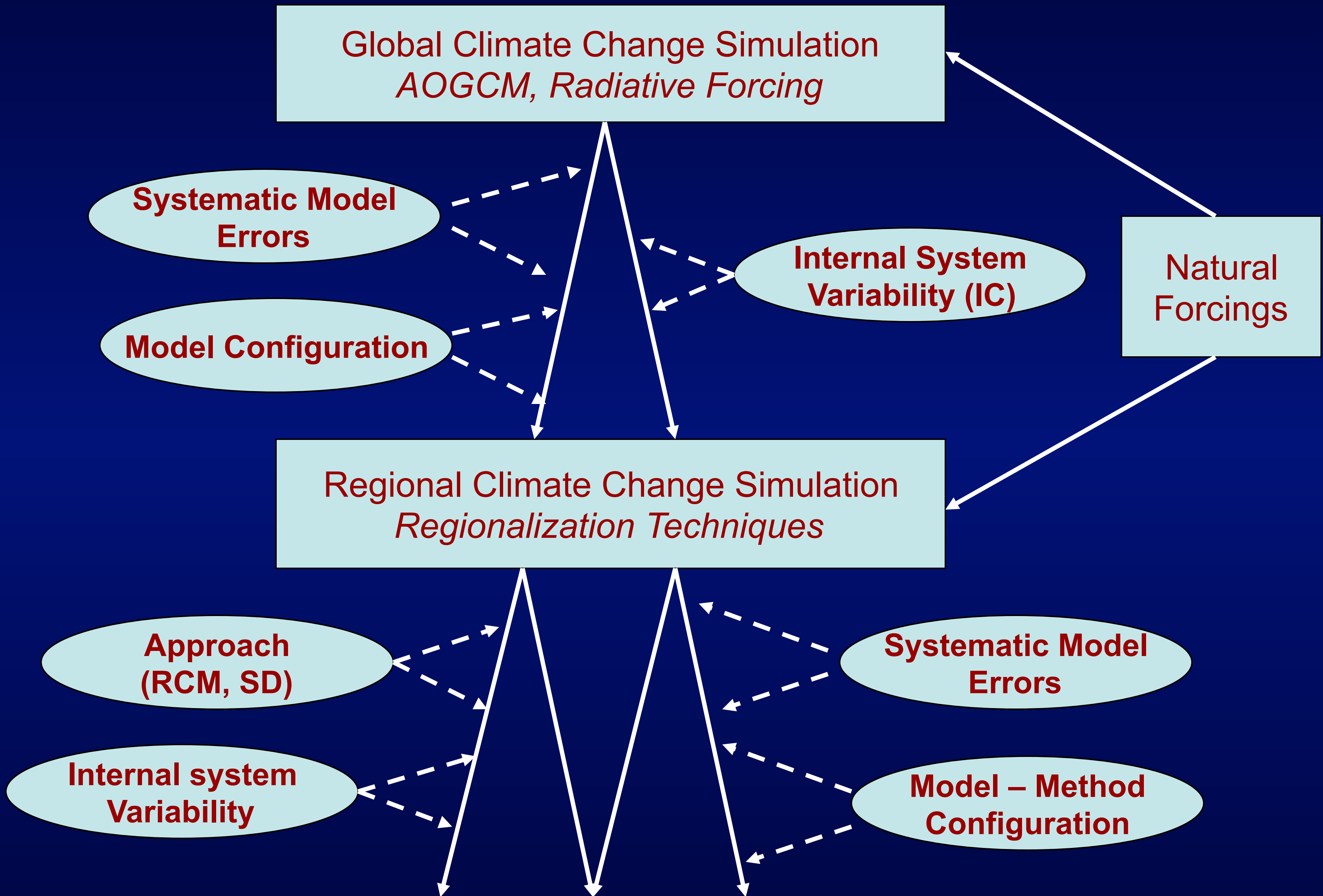
Scenario Uncertainty



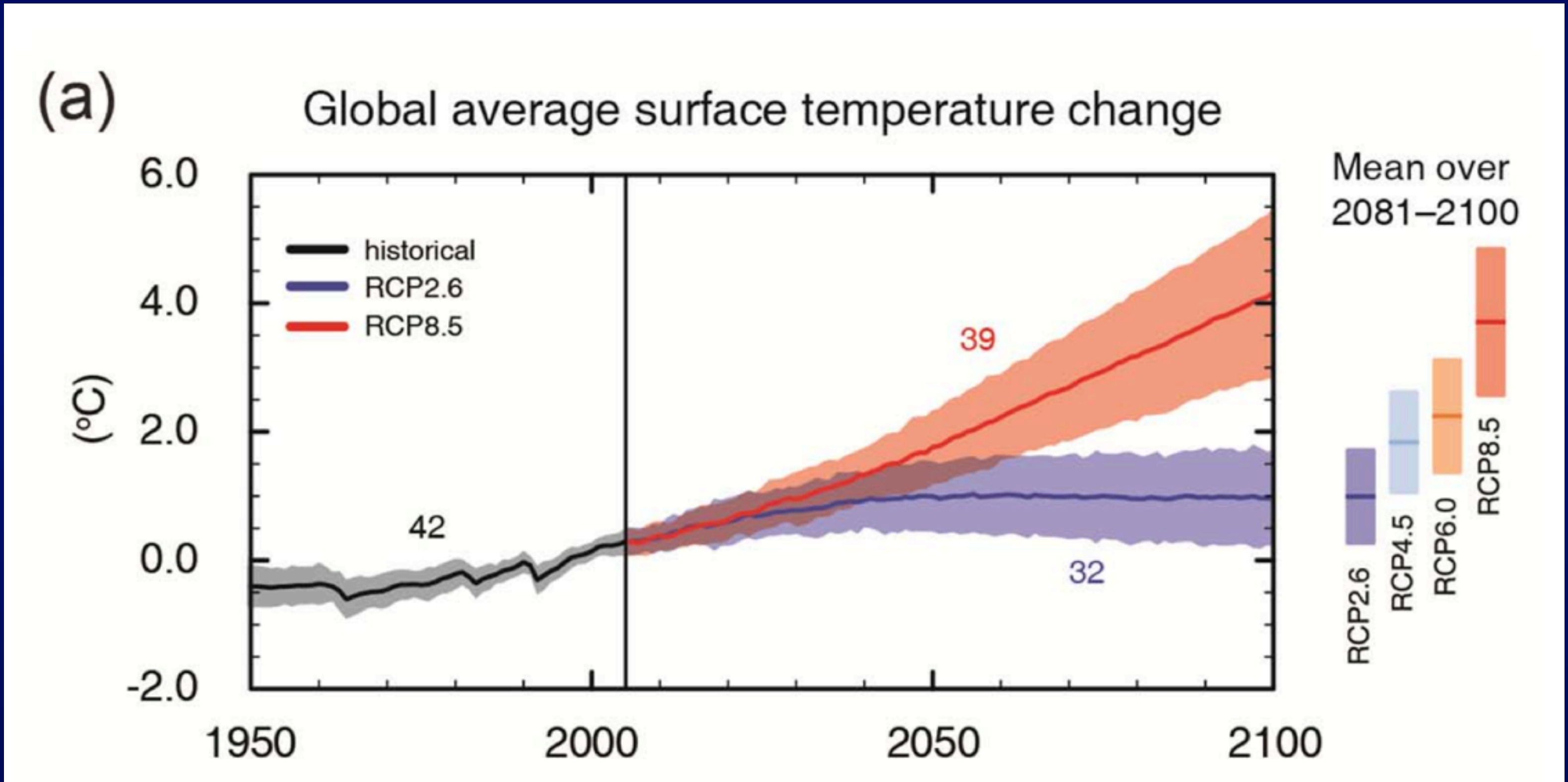
Cascade of uncertainty in climate change prediction



Climate Simulation Segment of the Uncertainty Cascade

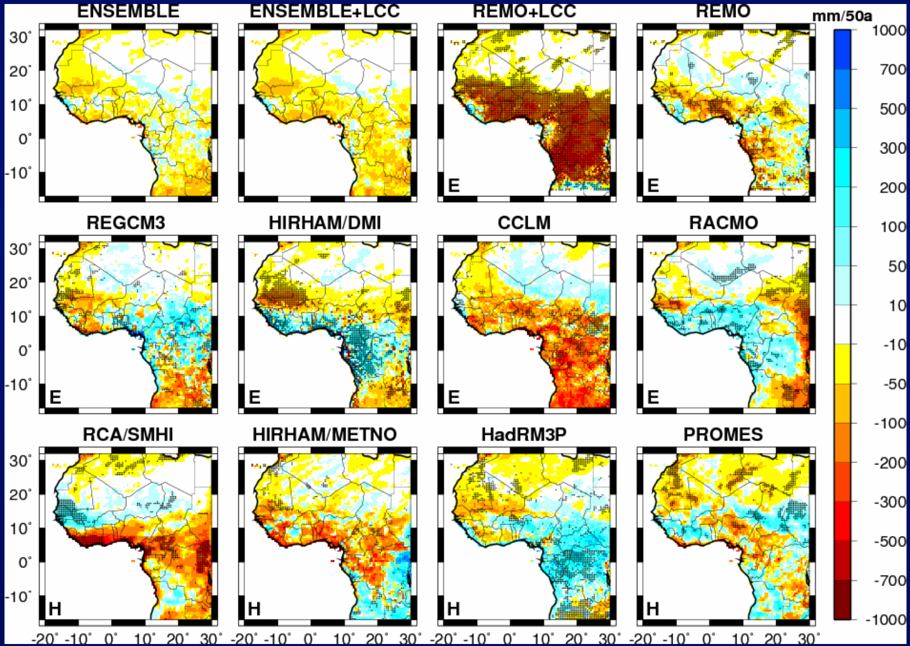


IPCC – 2013: Global temperature change projections for the 21st century



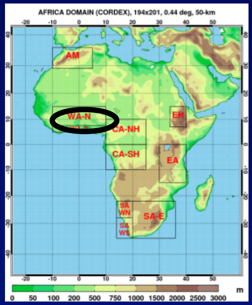
Uncertainties in regional projections

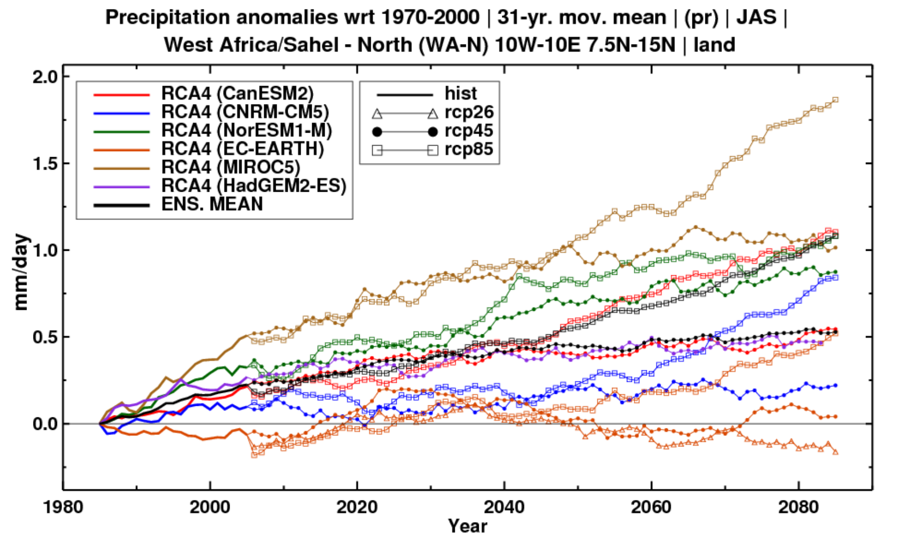
Trend in precipitation, 2001-2050 A1B Scenario



From Paeth et al. 2010

Trend in Sahel precipitation (G. Nikulin, SMHI)



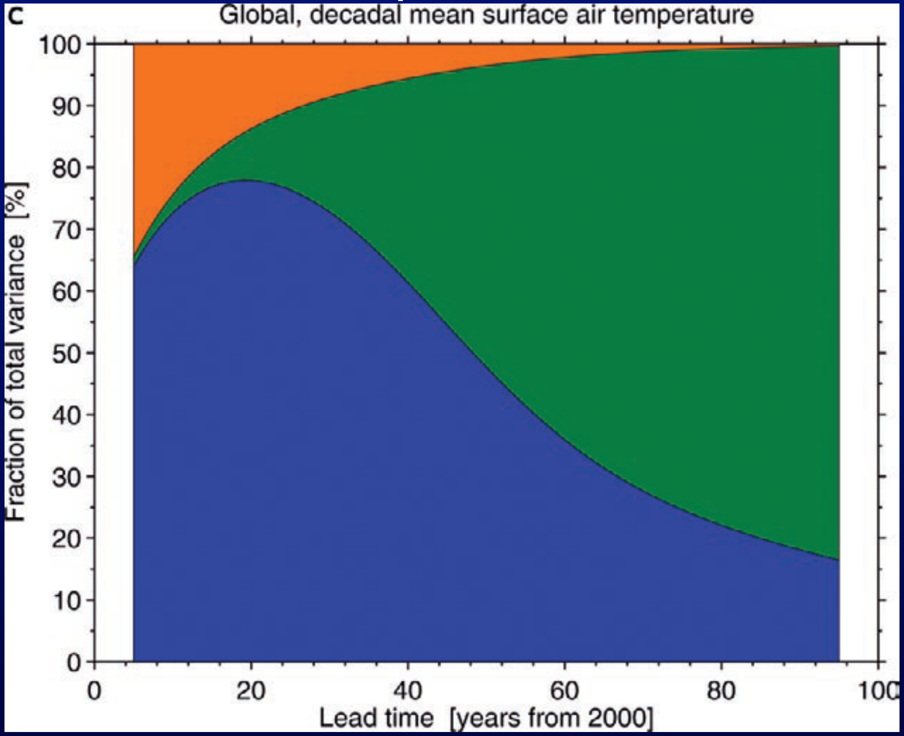


Fraction of uncertainty explained by different sources as a function of lead time

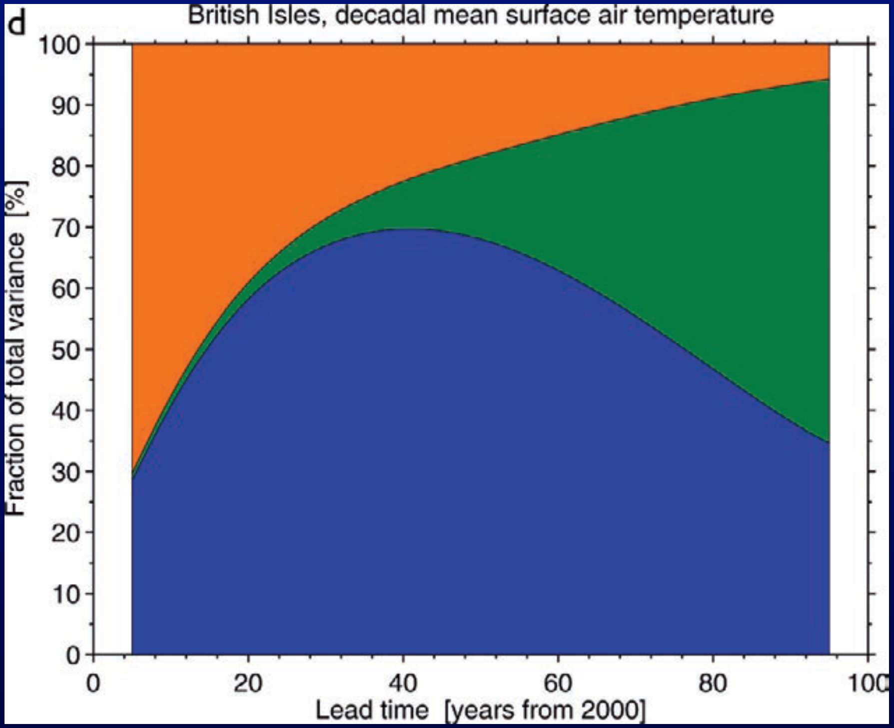
Internal variability
Scenario uncertainty
Model configuration uncertainty

Hawkins and Sutton 2009

Decadal temperature - Global

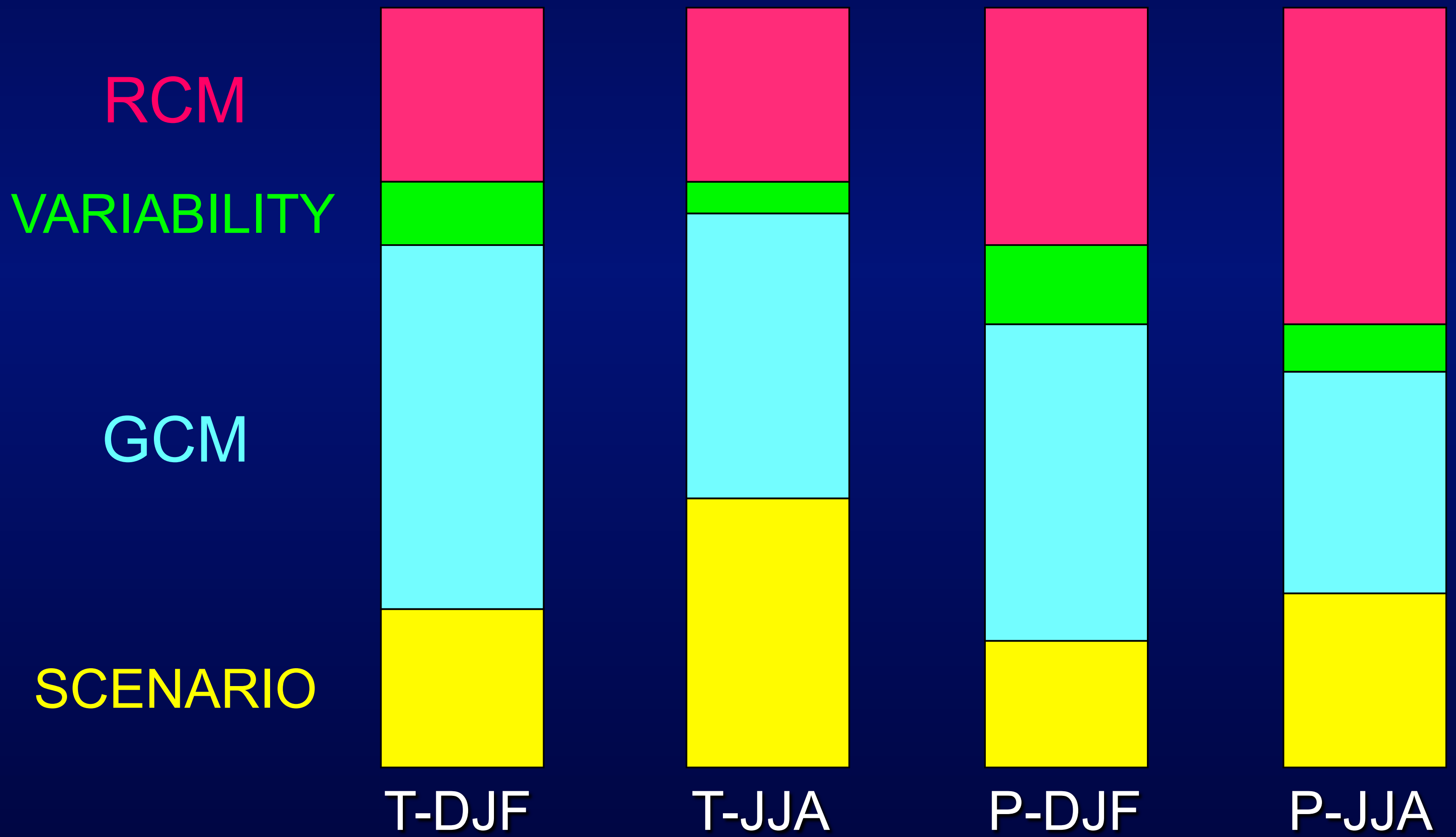


Decadal temperature – British Isles

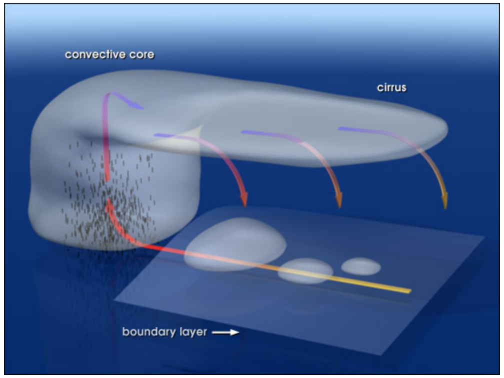


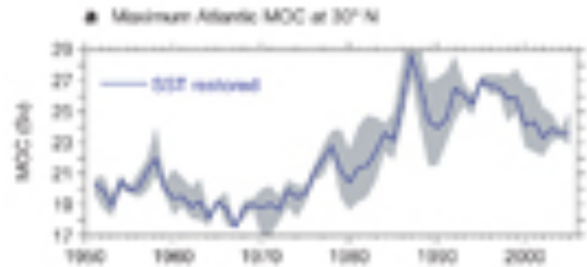
Sources of uncertainty in the simulation of temperature and precipitation change (2071-2100 minus 1961-1990) by the ensemble of PRUDENCE simulations (whole Europe)

(Note: the scenario range is about half of the full IPCC range, the GCM range does not cover the full IPCC range) (Adapted from Deque et al. 2006)



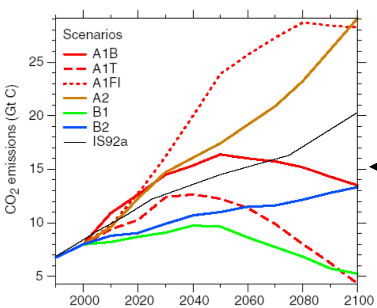
Regional Climate Change "Hyper-Matrix Framework" (HMF)





RCD Configuration

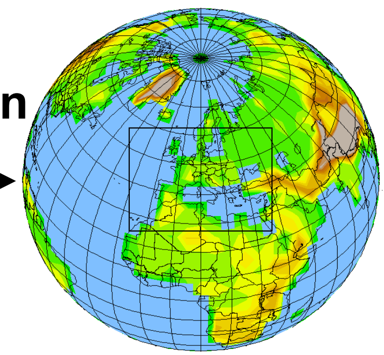
Internal Variability



Forcing Scenario

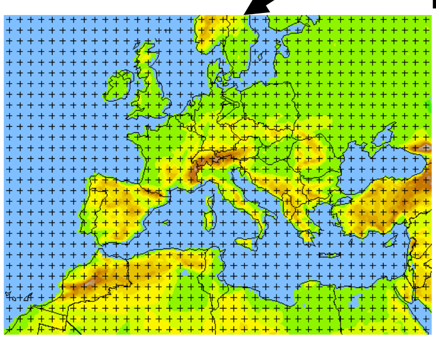
Experiment (i,j,k …)

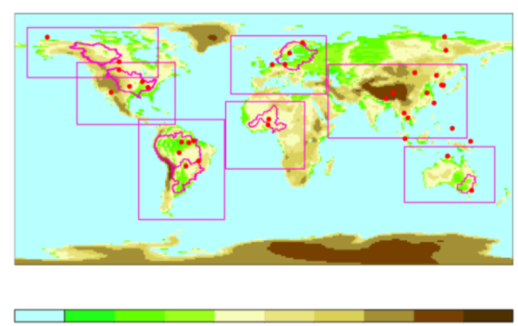
GCM Configuration



RCD Approach

Geographic Region





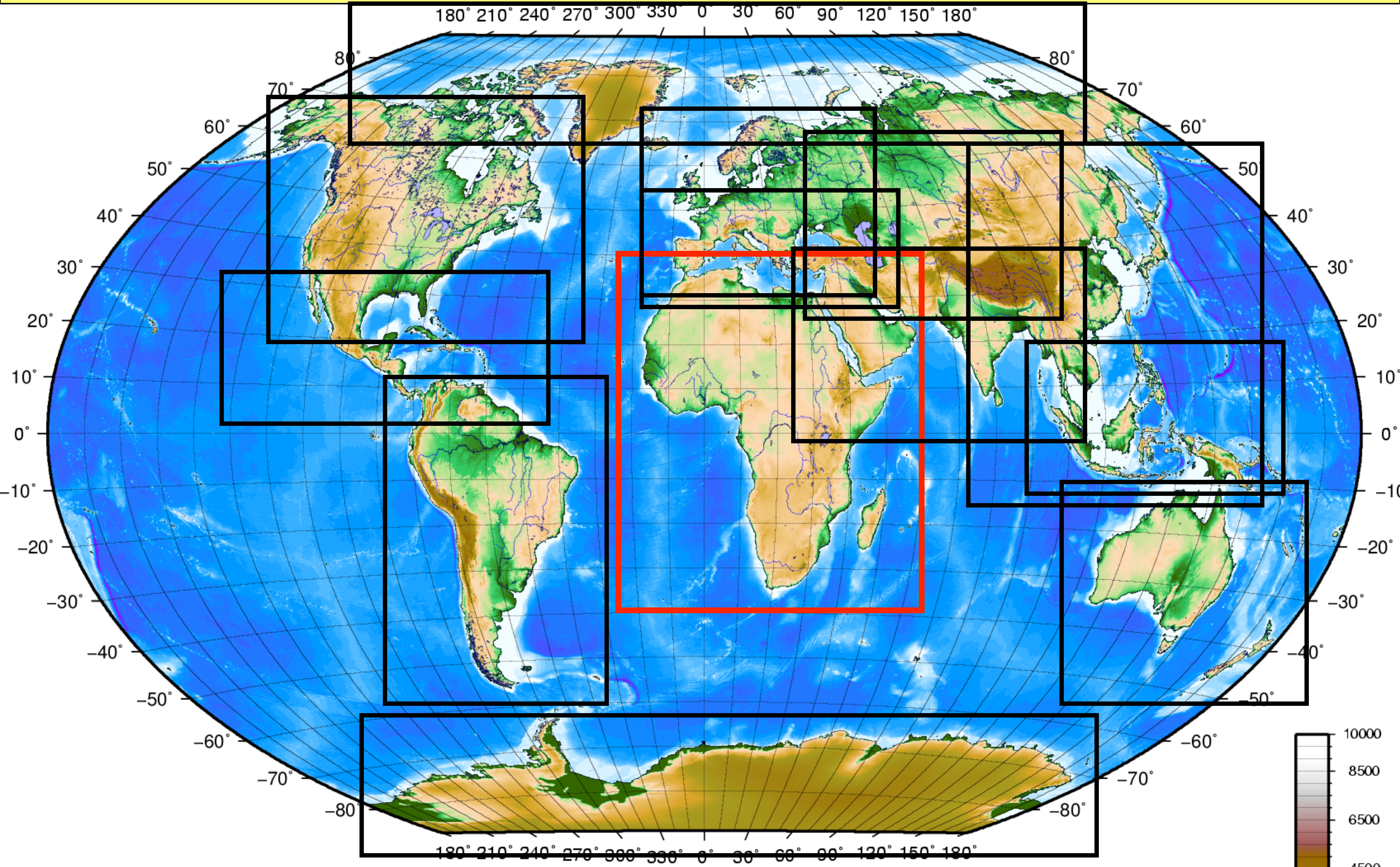
Giorgi et al. EOS 2008

CORDEX Vision and Goals

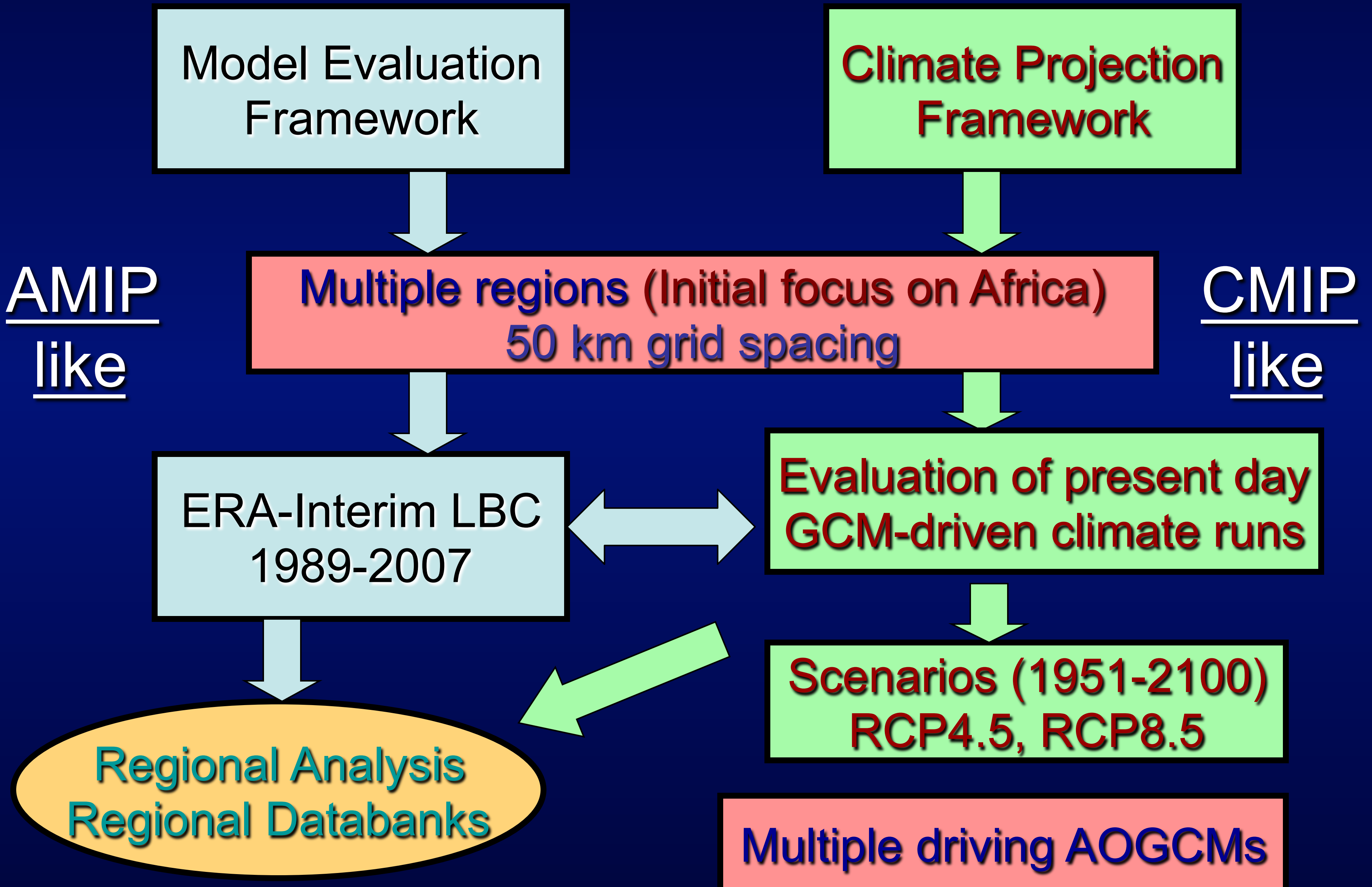
The CORDEX vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships

- To better understand relevant regional/local climate phenomena, their variability and changes through downscaling
- To evaluate and improve regional climate downscaling models and techniques (RCM, ESD, VAR-AGCM, HIR-AGCM)
- To produce large coordinated sets of regional downscaled climate projections worldwide
- To foster communication and knowledge exchange with users of regional climate information

CORDEX domains



CORDEX Phase I experiment protocol



Ensembles of projections are available for most domains

CORDEX-S. ASIA

CORDEX-South Asia Multi Models Output

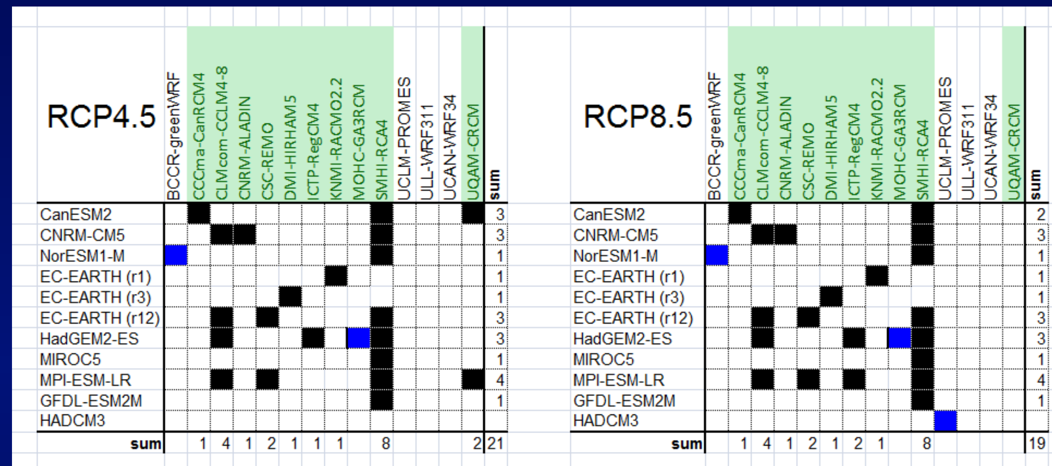
Historical (1950 – 2005) | Evaluation Run (1989 – 2008) | RCP 4.5

Variable name (Monthly and Daily)	SMHI-RCA4	IITM-RegCM4-GFDL	IITM-RegCM4-LMDZ	COSMO-CLM	IITM-LMDZ
Institute's / Data Providers	Rossby Centre, SMHI	CCCR-IITM, Pune	CCCR-IITM, Pune	Goethe Inst - Univ. of Frankfurt	CCCR-IITM, Pune
Rainfall (pr)	✓	✓	✓	✓	✓
Surface Air Temperature (tas)	✓	✓	✓	✓	✓
Surface Air Temp. Maximum (tasmax)	✓	✓	✓	--	✓
Surface Air Temp. Minimum (tasmin)	✓	✓	✓	--	✓
Sea-level Pressure (psl)	✓	✓	✓	--	✓
Surface Specific Humidity (huss)	✓	✓	✓	--	✓
Surface Zonal Wind (uas)	✓	✓	✓	--	✓
Surface Meridonial Wind (vas)	✓	✓	✓	--	✓
Downward Shortwave Radiation (rsds)	--	✓	✓	--	--

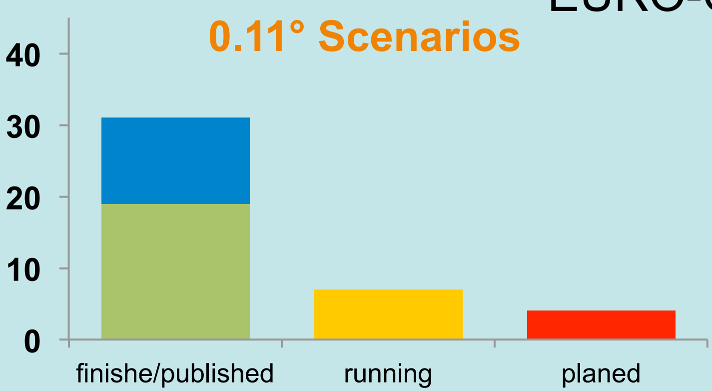
To download the data please click here

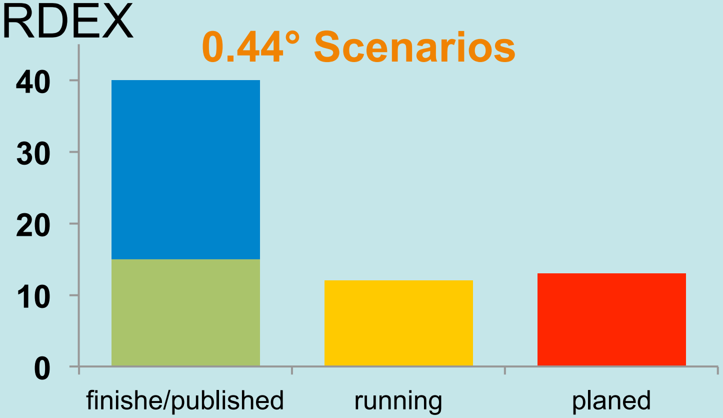
Regridding script example, click here to download | script

CORDEX-AFRICA

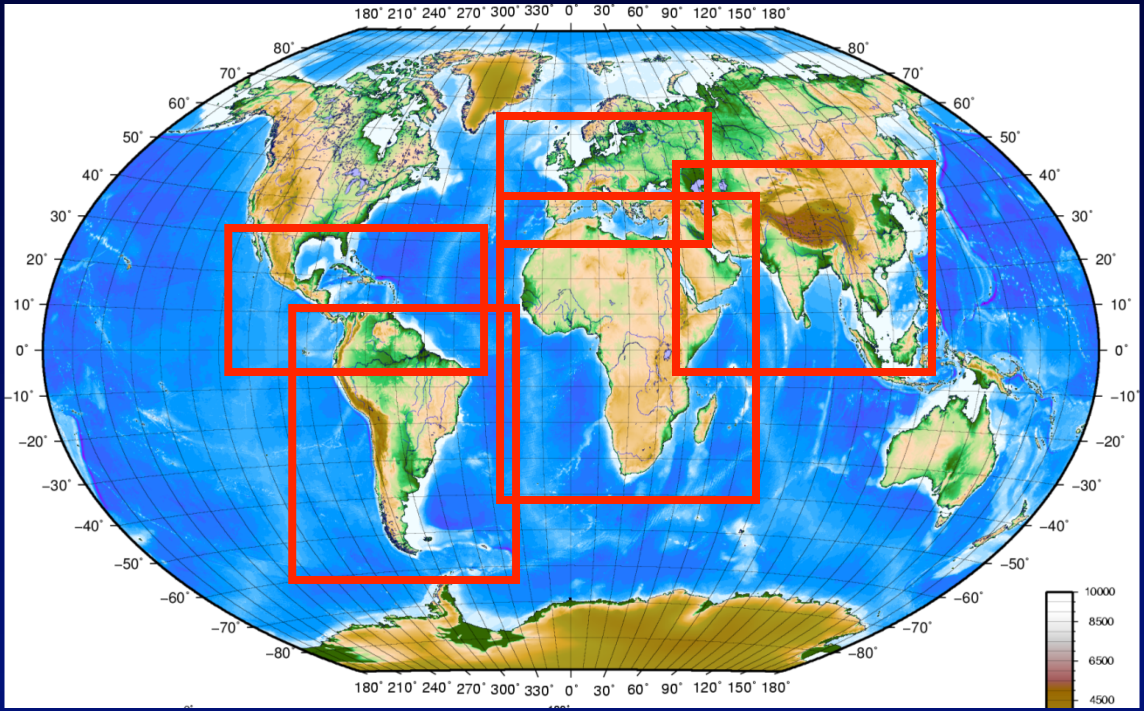


EURO-CORDEX





The CREMA Phase I Experiment



Contribution to the Coordinated Regional Downscaling Experiment (CORDEX) by the RegCM community

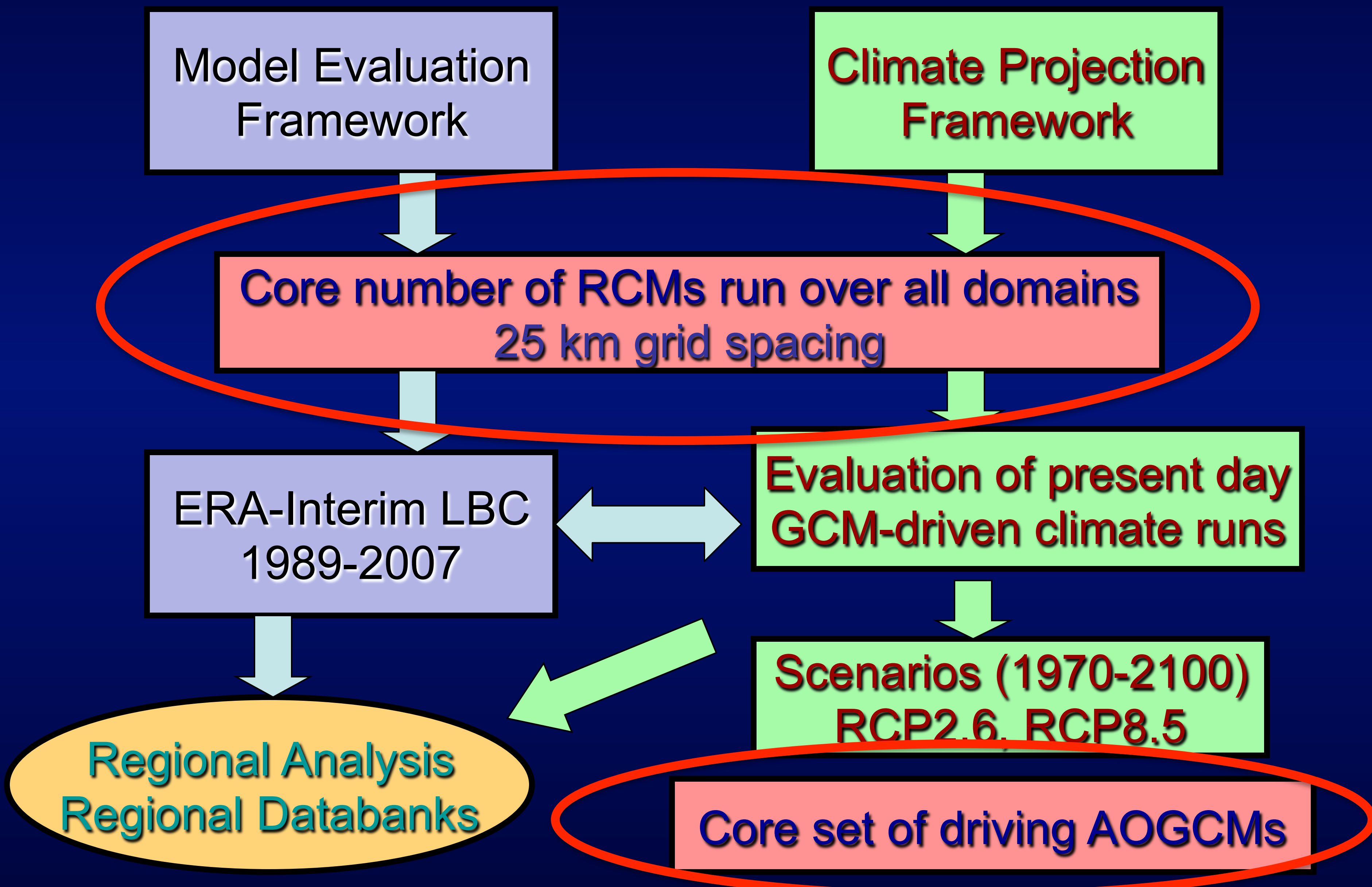
Collaboration across
ICTP
U. San Paolo (Brazil)
CICESE (Mexico)
Indian Institute of technology
U. Dakar (Senegal
DHMZ (Croatia)

Special Issue of
Climatic Change (2014)

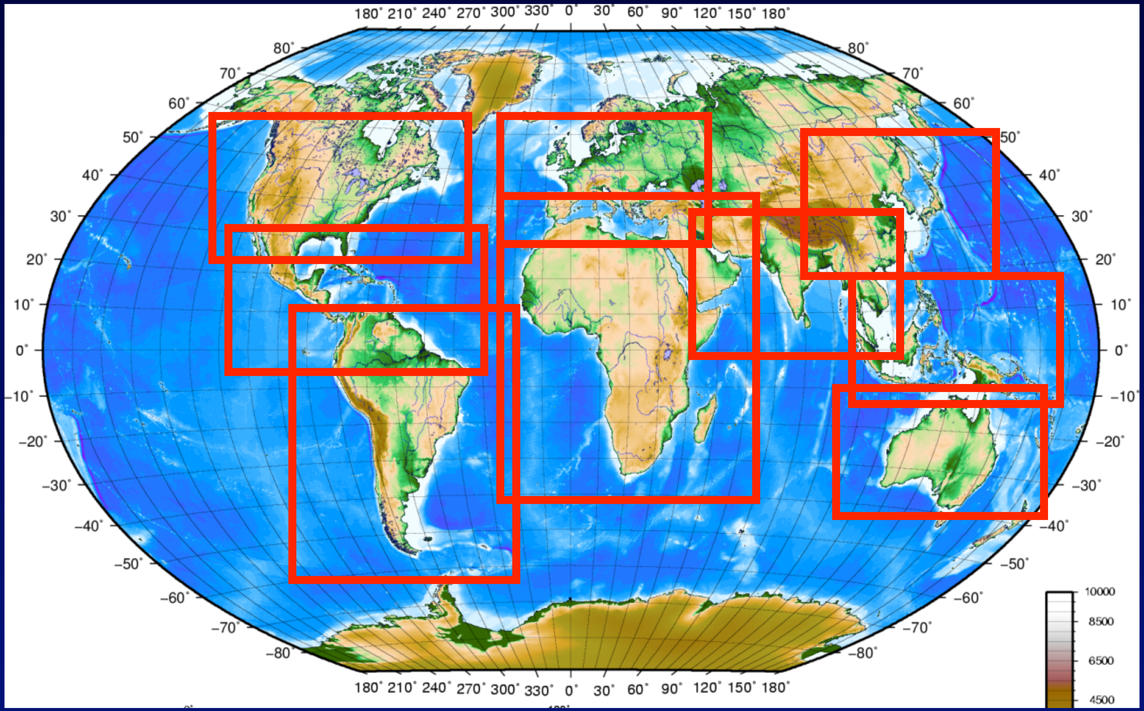
34 Scenario simulations (1970-2100) over 5 CORDEX domains with RegCM4 driven by three GCMs, 2 GHG scenarios (RCP4.5/8.5) and different physics schemes

3 months dedicated time on ~700 CPUs at the ARCTUR HPC
~200 Tbytes of data produced

CORDEX CORE experiment protocol



The CREMA Phase II Experiment



Contribution to the CORDEX-CORE program by the RegCM community

6 Scenario simulations (1970-2100)
9 CORDEX domains
RegCM4 at dx=25 km
3 driving CMIP5 GCMs
(MPI,HADGEM, NorESM)
2 GHG scenarios (RCP2.6/8.5)
CORE set of variables stored

Most simulations completed at the CINECA supercomputing centre
~1 Pbytes of data produced ?

Simulations done by
ICTP
Gao-IAP
Ashfaq-ORNL
Others?

Special Issue of
Int. J. Climatology (2019/20?)

Issues to be discussed at the workshop

- Timeline for completing the simulations
- Policy for collecting, distributing and using the data
- Planning of analyses and papers for the Special Issue
- Special needs for analyses in different domains
- Timeline for the special issue
- Follow up “paper writing” workshop in 2019
- Any other issue?

Current status of the CREMA II simulations

- South America: Six scenarios almost finished (Taleena)
- Australia: Six scenarios at mid 21st century (Taleena)
- North America: Historical periods finished (Taleena)
- Central America: Best configuration almost there (Abraham)
- Africa: Historical periods under way (Francesca)
- Southeast Asia: Still working on it (Paolo)
- Europe: Slowly proceeding, 12 km (James)
- South Asia: Configuration given to Moetasim (?)
- East Asia: Gao?


Thank You