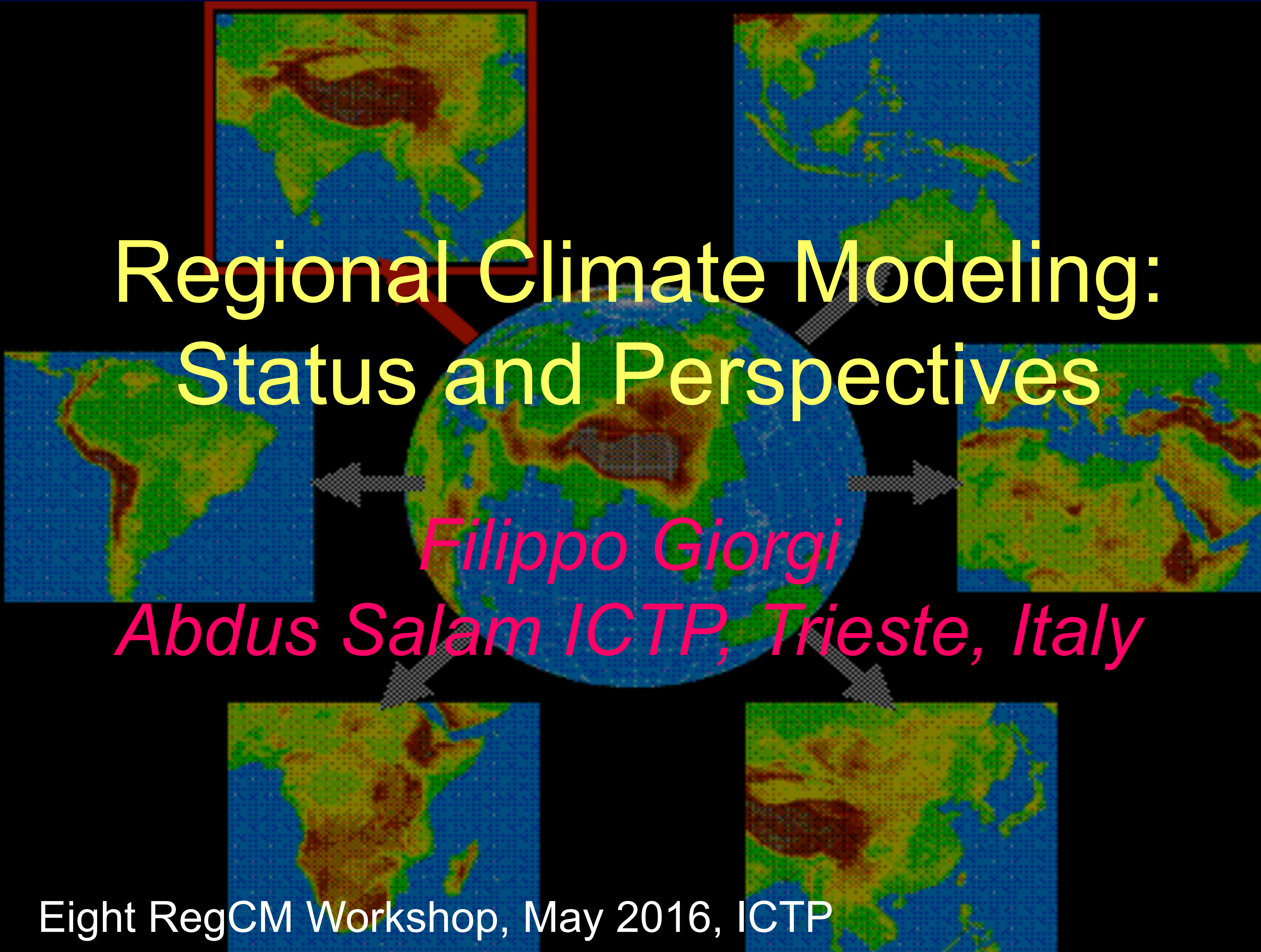


Regional Climate Modeling: Status and Perspectives

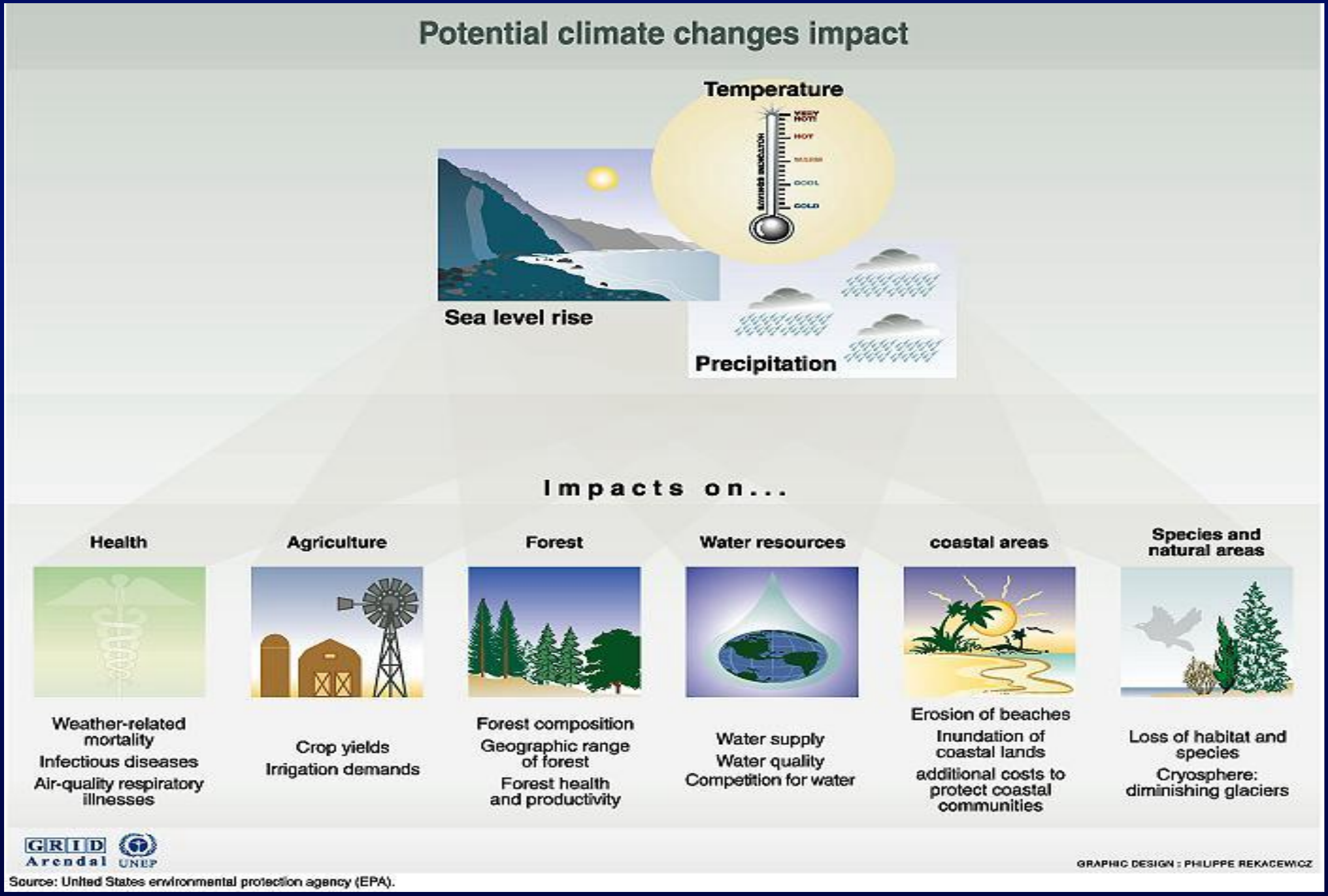
Filippo Giorgi
Abdus Salam ICTP, Trieste, Italy

Eight RegCM Workshop, May 2016, ICTP

Lecture outline

- Basic notions and principles of regional climate modeling
- Some technical issues
- Uncertainties in regional climate change projections
- The “COordinated Regional Downscaling EXperiment” (CORDEX)
- Final consideraitons

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



Regional climate modeling: Why?

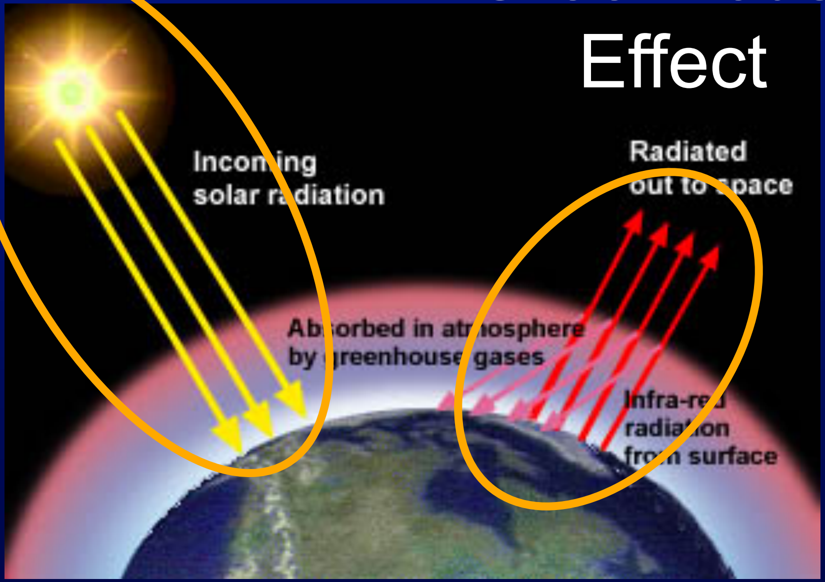
- Regional climates are determined by the interactions of planetary/large scale processes and regional/local scale processes
  - Planetary/large scale forcings and circulations determine the statistics of weather events that characterize the climate of a region
  - Regional and local scale forcings and 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

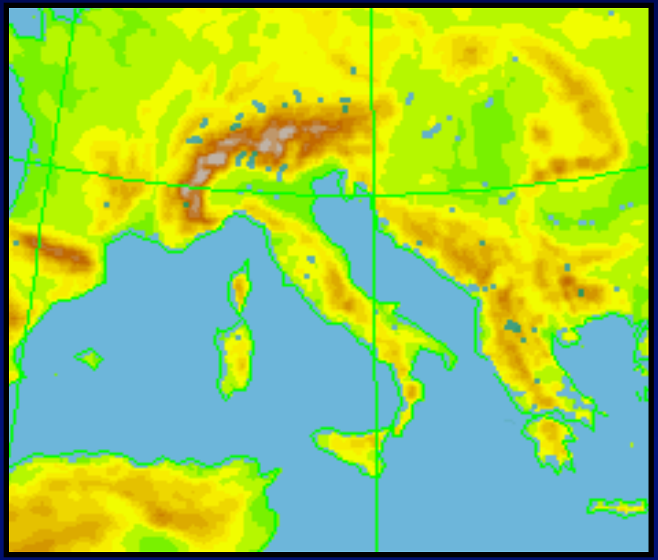
Solar activity

Greenhouse Effect

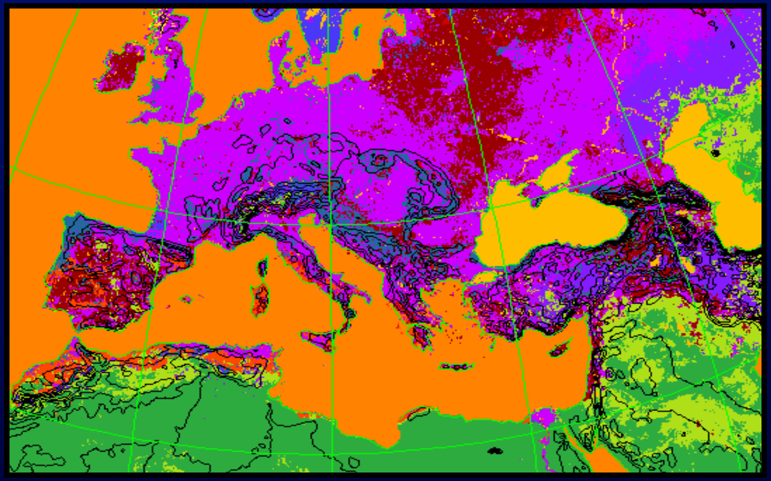


Regional and local climatic forcings

Complex topography

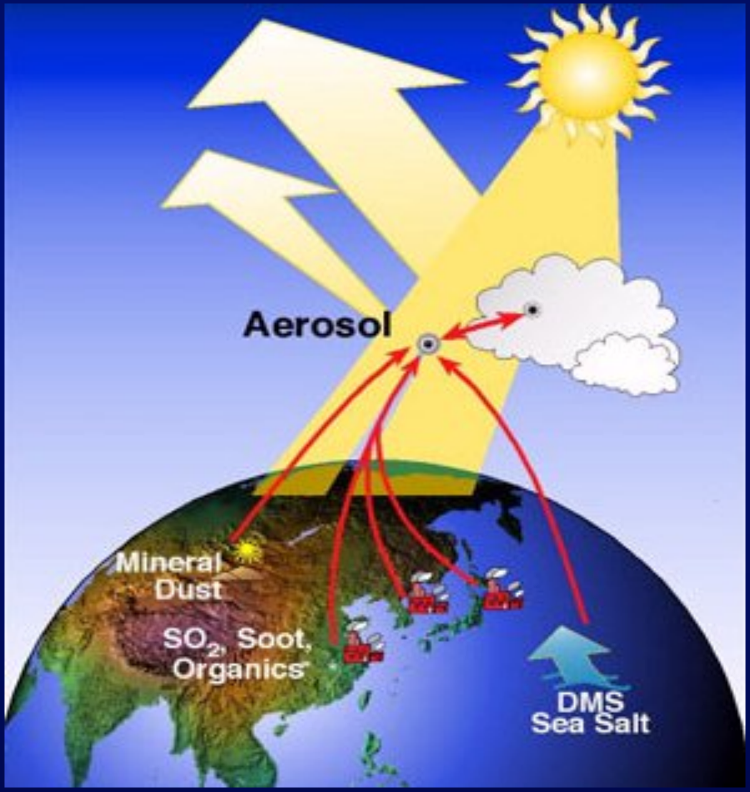


Complex landuse

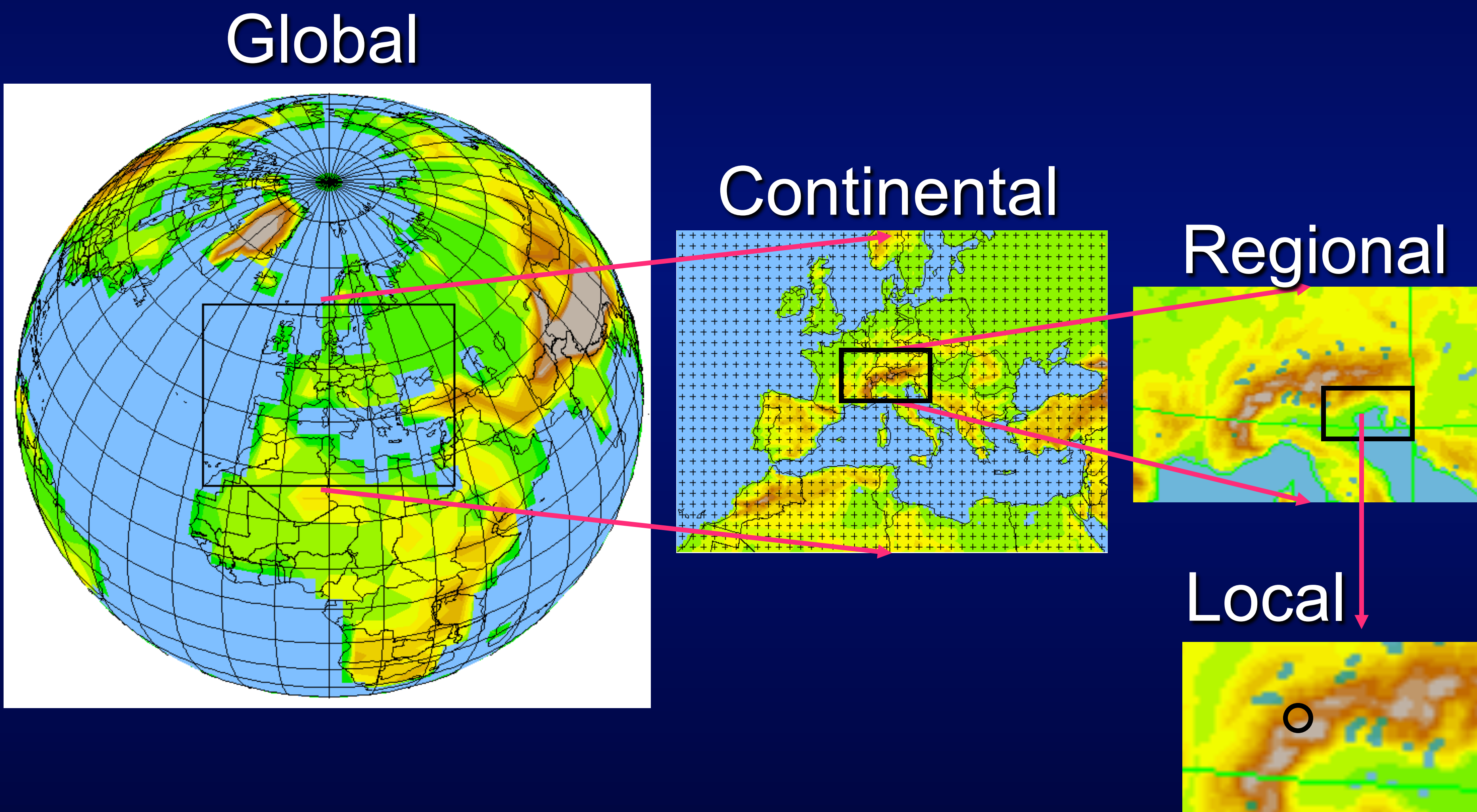


Aerosols

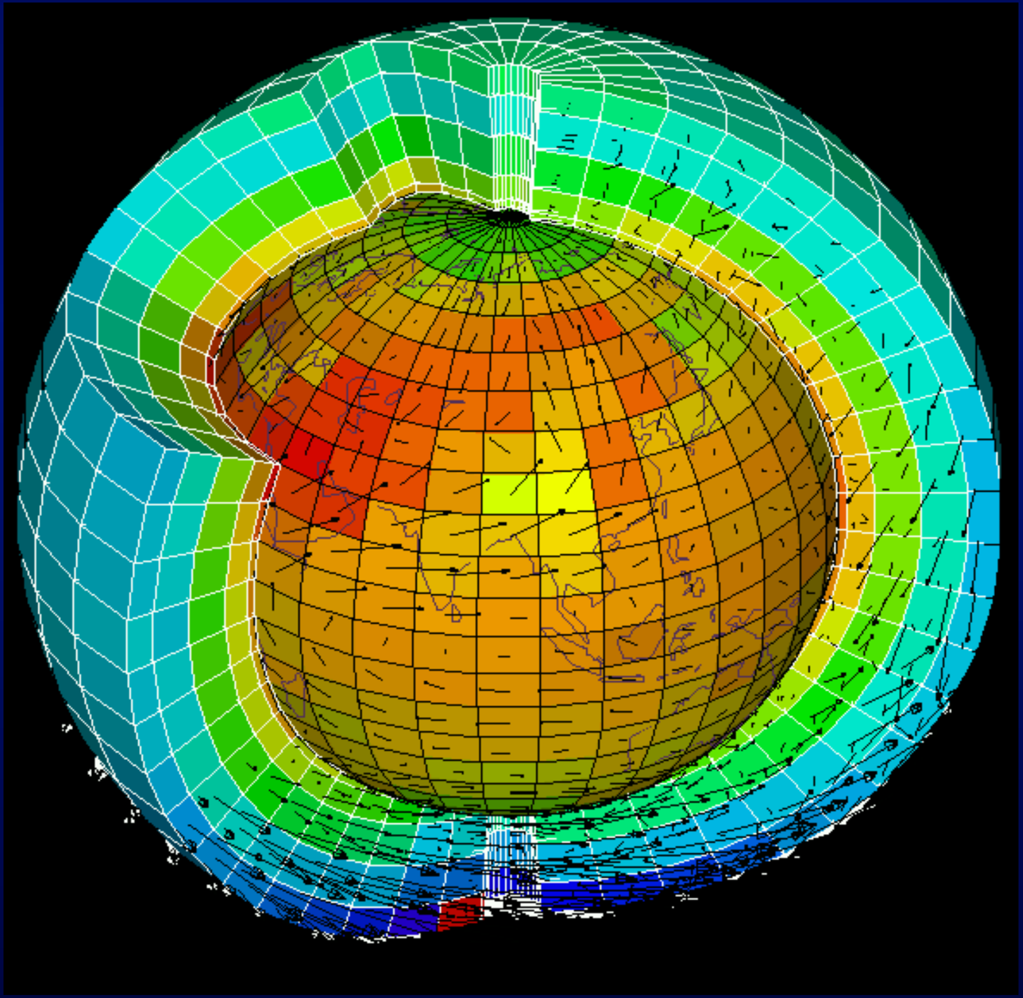
Direct and indirect effects



Climate change needs to be simulated at multiple spatial scales



The primary tools available today for simulating climate change are Global Climate (System) Models (GCMs)



GCMs are numerical representations on a three-dimensional grid of the processes that determine the evolution of the Earth's climate

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

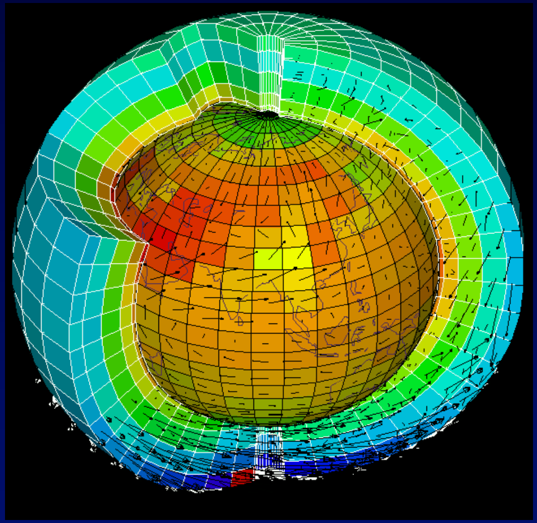
Physics

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

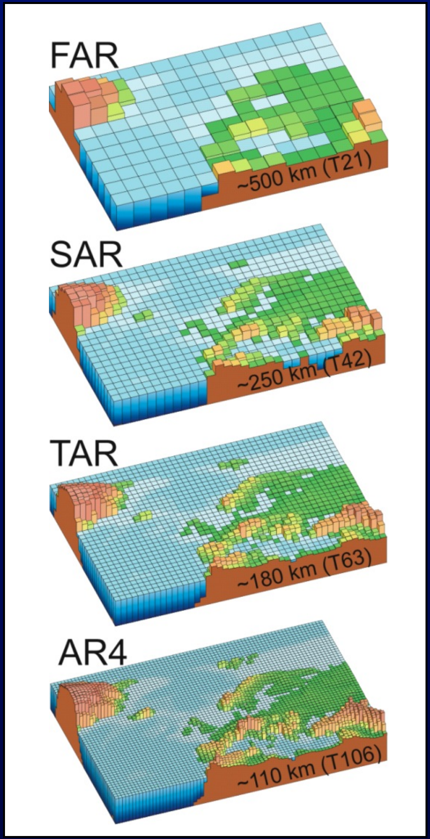
Conservation of water

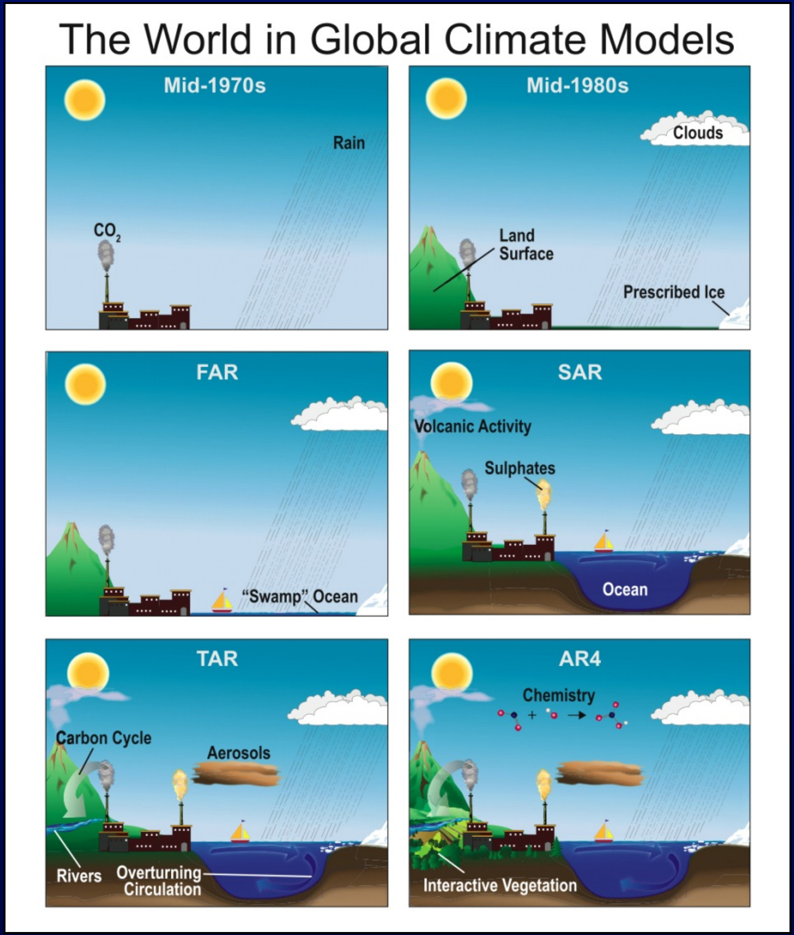
$$p = \rho R T$$

Equation of state

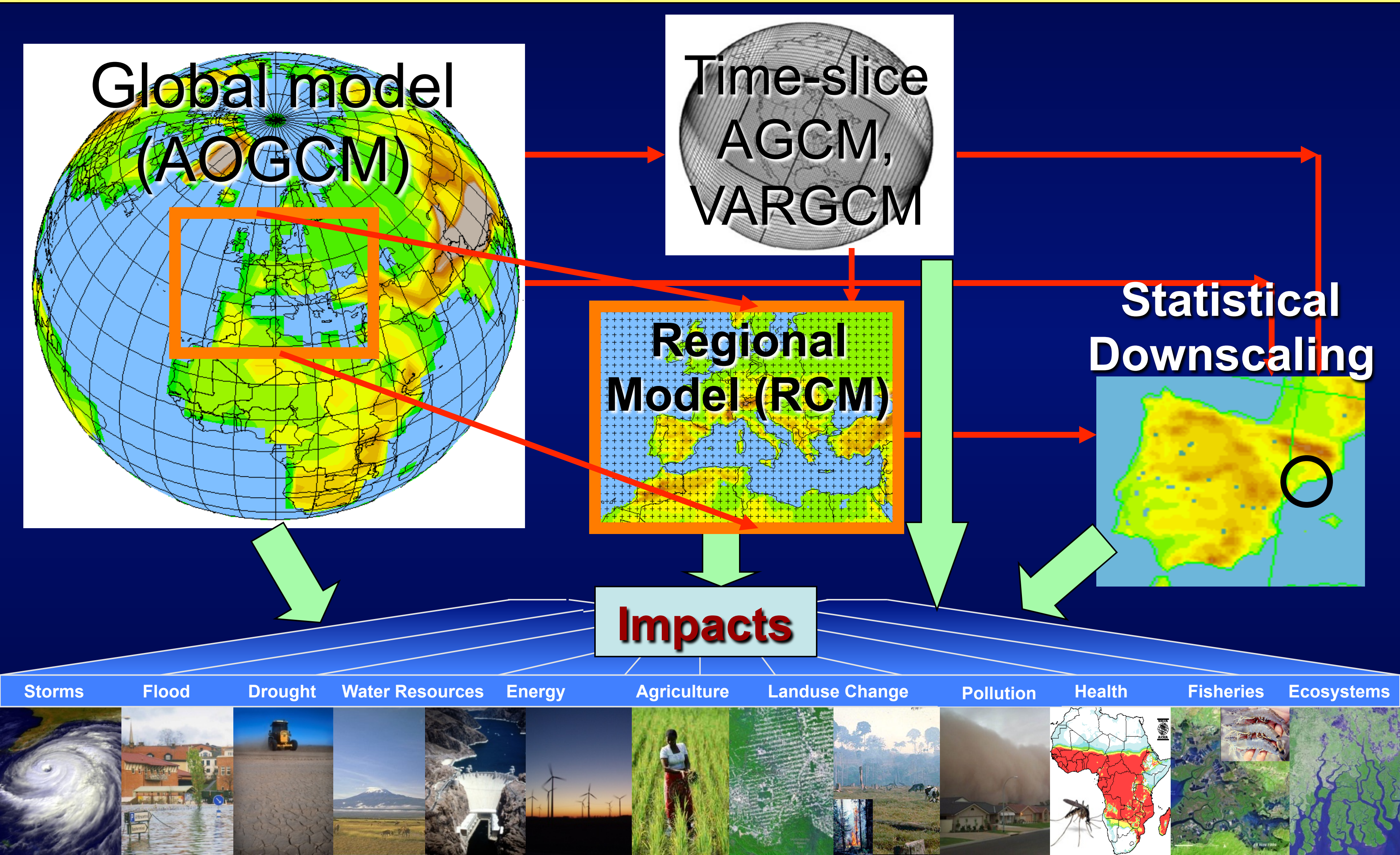


GCMs have evolved in terms of resolution and complexity





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



“Nested” Regional Climate Modeling: Technique and Strategy

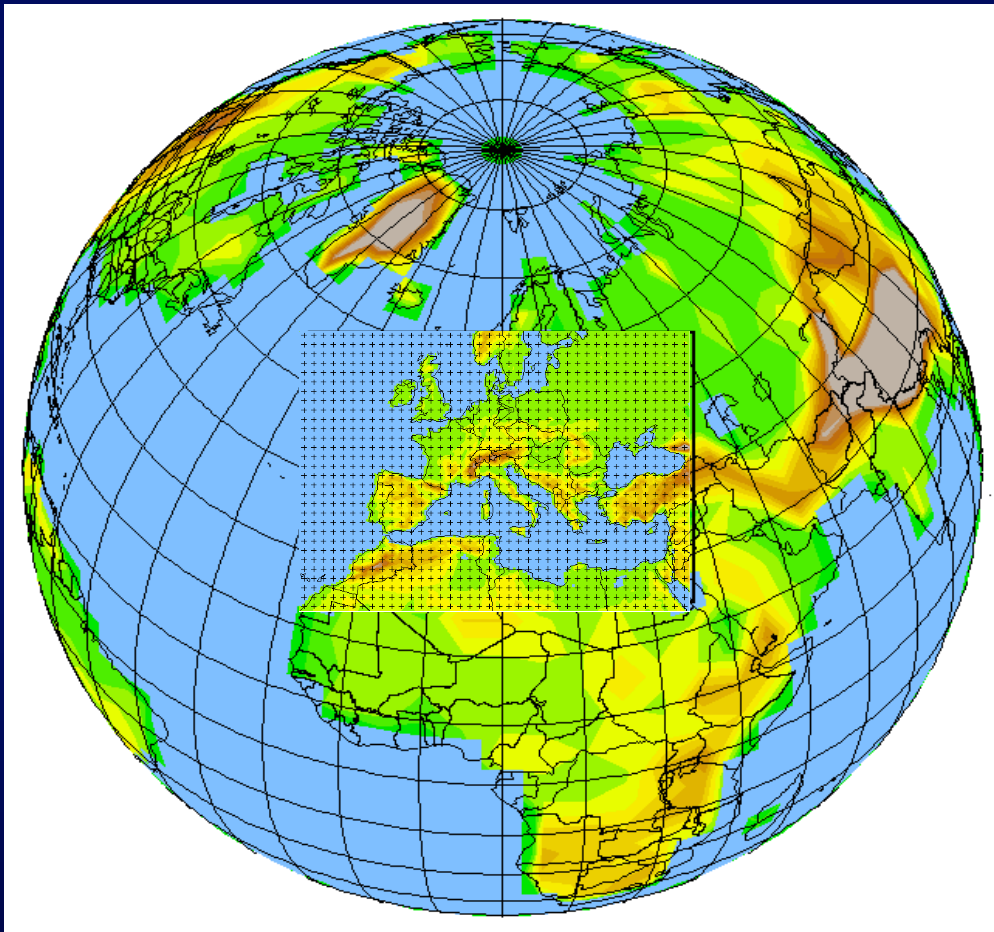
Motivation: The resolution of GCMs is still too coarse to capture regional and local climate processes

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).

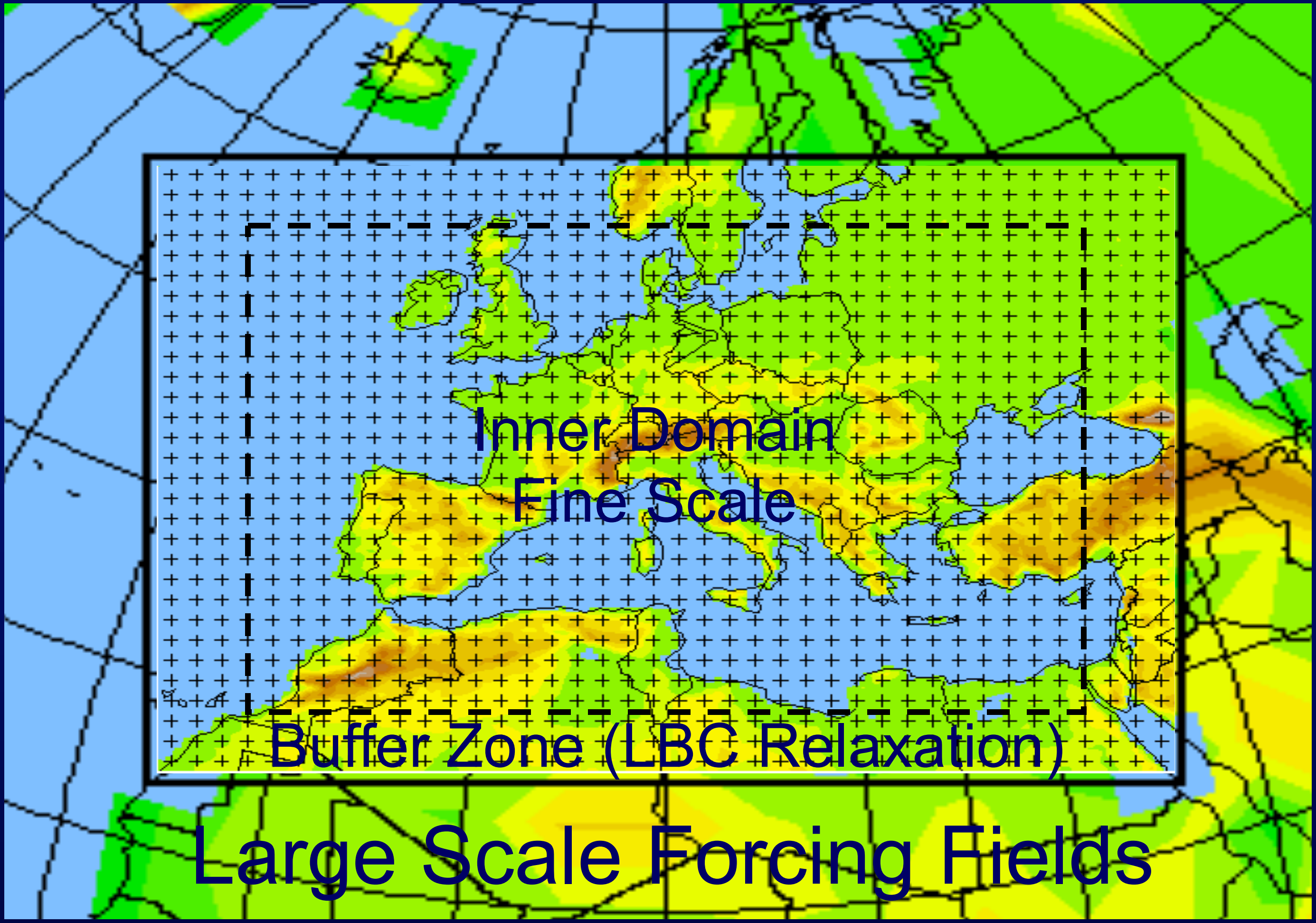
Strategy: The GCM simulates the response of the general circulation to the large scale forcings, the RCM simulates the effect of sub-GCM-grid scale forcings and provides fine scale regional information

– Technique borrowed from NWP

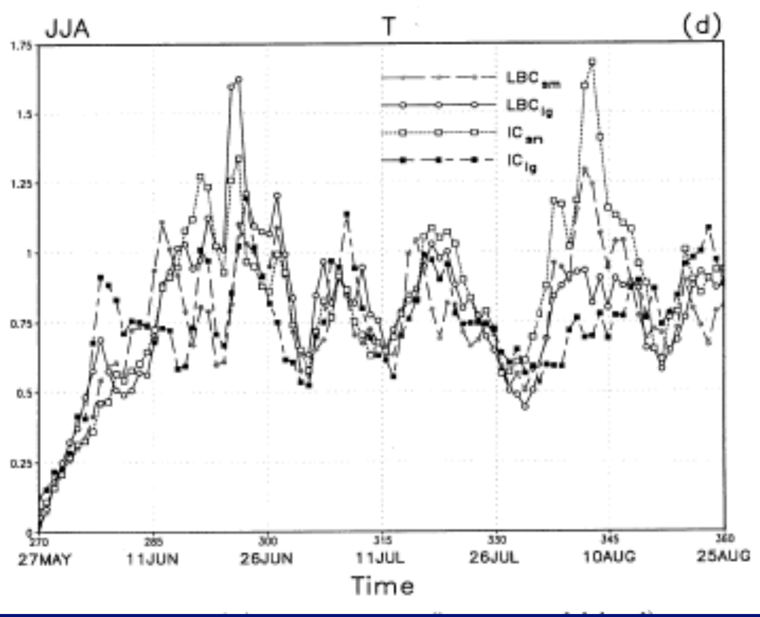


RCM Nesting procedure

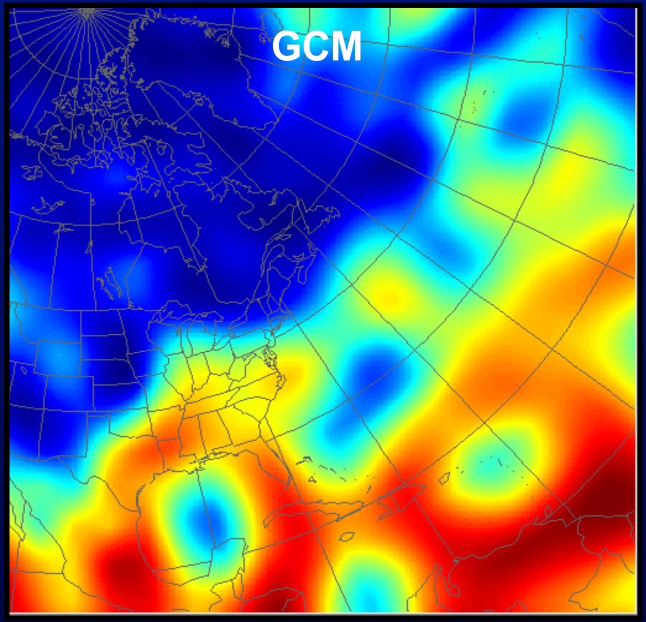
$$\frac{\partial \alpha}{\partial t} = F(n)F_1 \cdot (\alpha_{LBC} - \alpha_{mod}) - F(n)F_2 \cdot \Delta_2(\alpha_{LBC} - \alpha_{mod})$$

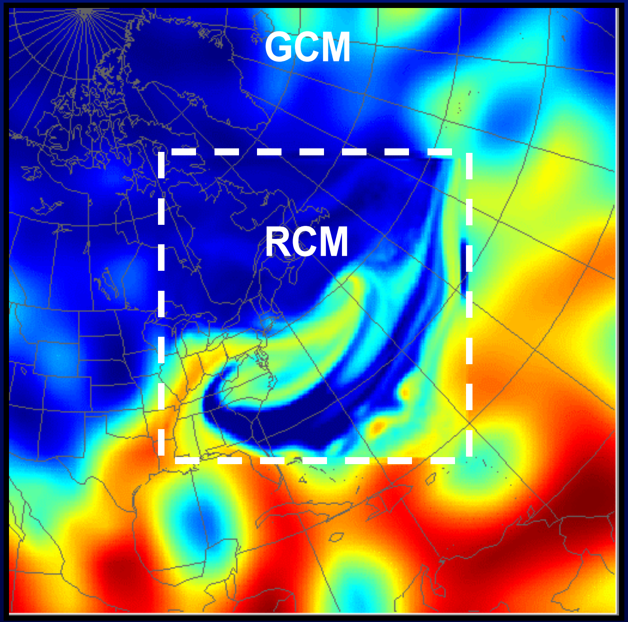


A dynamical equilibrium is reached in the interior domain between the information from the LBC and the model solution



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
- Intercomparison projects: PIRCS, RMIP, NARCCAP, NEWBALTIC, ARCMIP, PLATIN,ARC, NAMAP, QUIRCS,Transferability
- Special issues: JGR 1999; JMSJ 2004; TAC 2006; CC 2007; MAP 2004, 2008; CCH 2006; MET.-ZEIT. 2008; CR 2012;CC 2014.

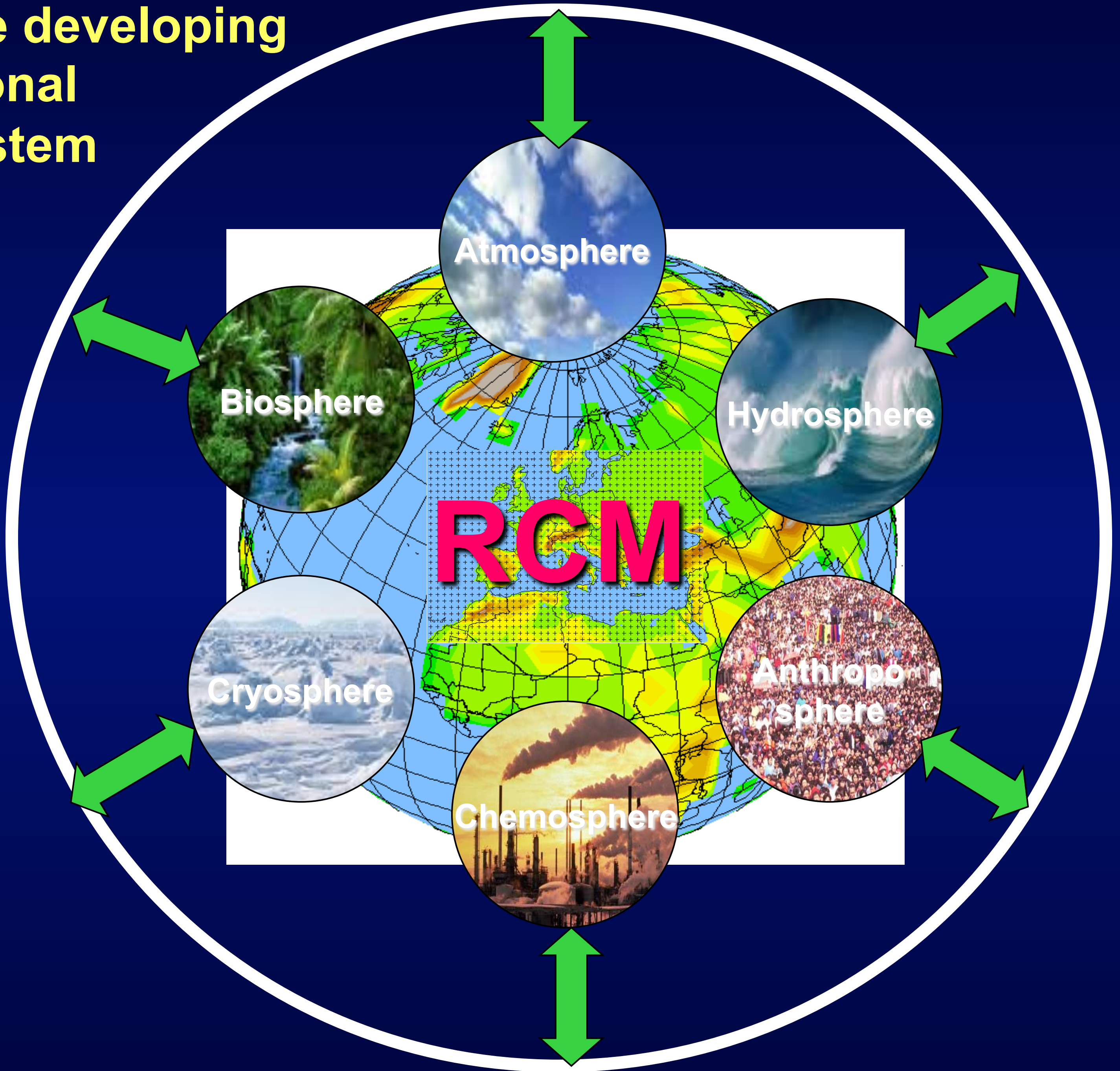
Regional Climate Modeling Applications

- 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”

- Many 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)
- 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

RCMs are developing into regional Earth System Models



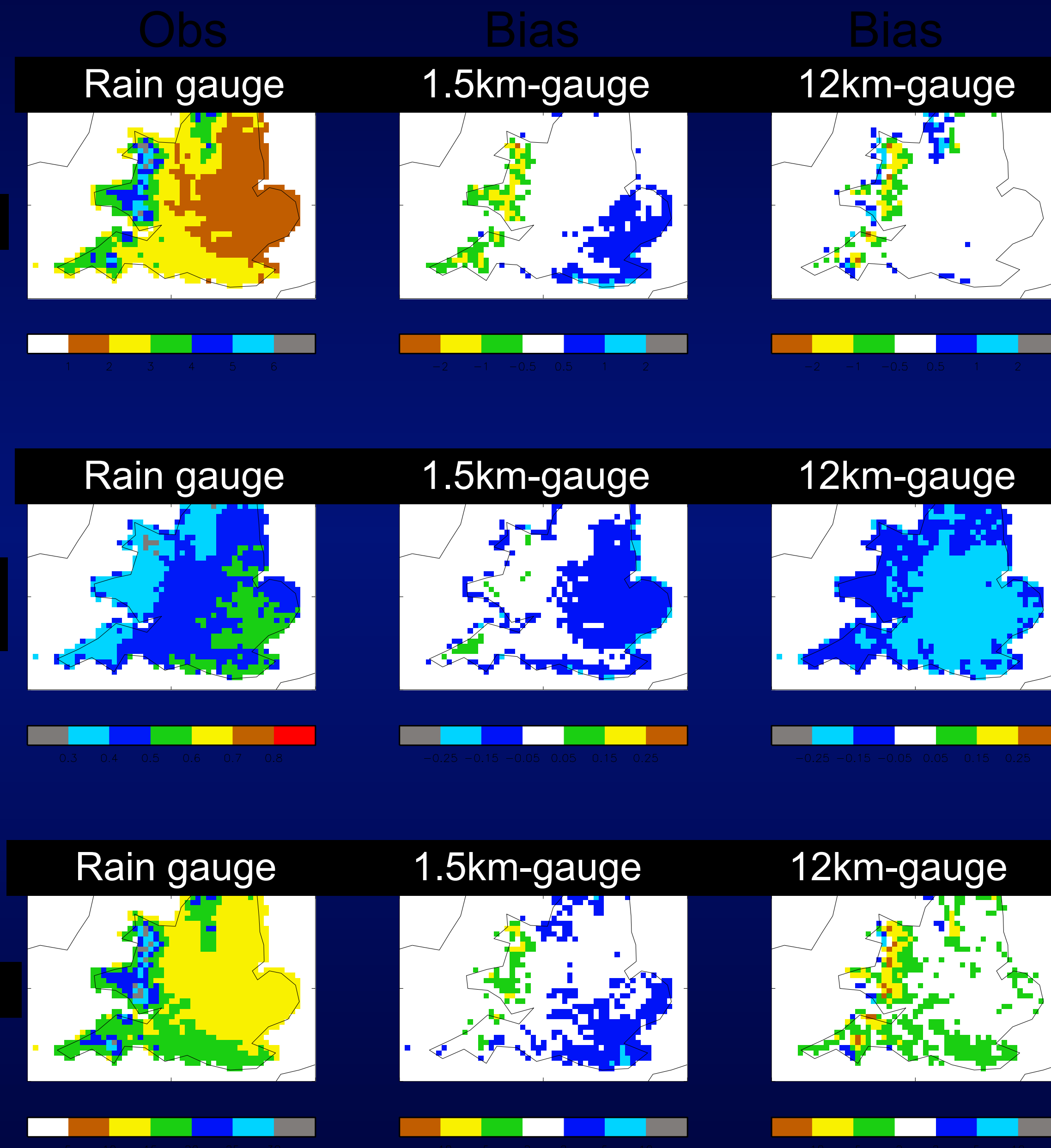
Convection permitting modeling

Daily precipitation
(1990-2003)

Mean precip

Dry day occurrence

Heavy precip



Courtesy of E. Kendon
UKMO

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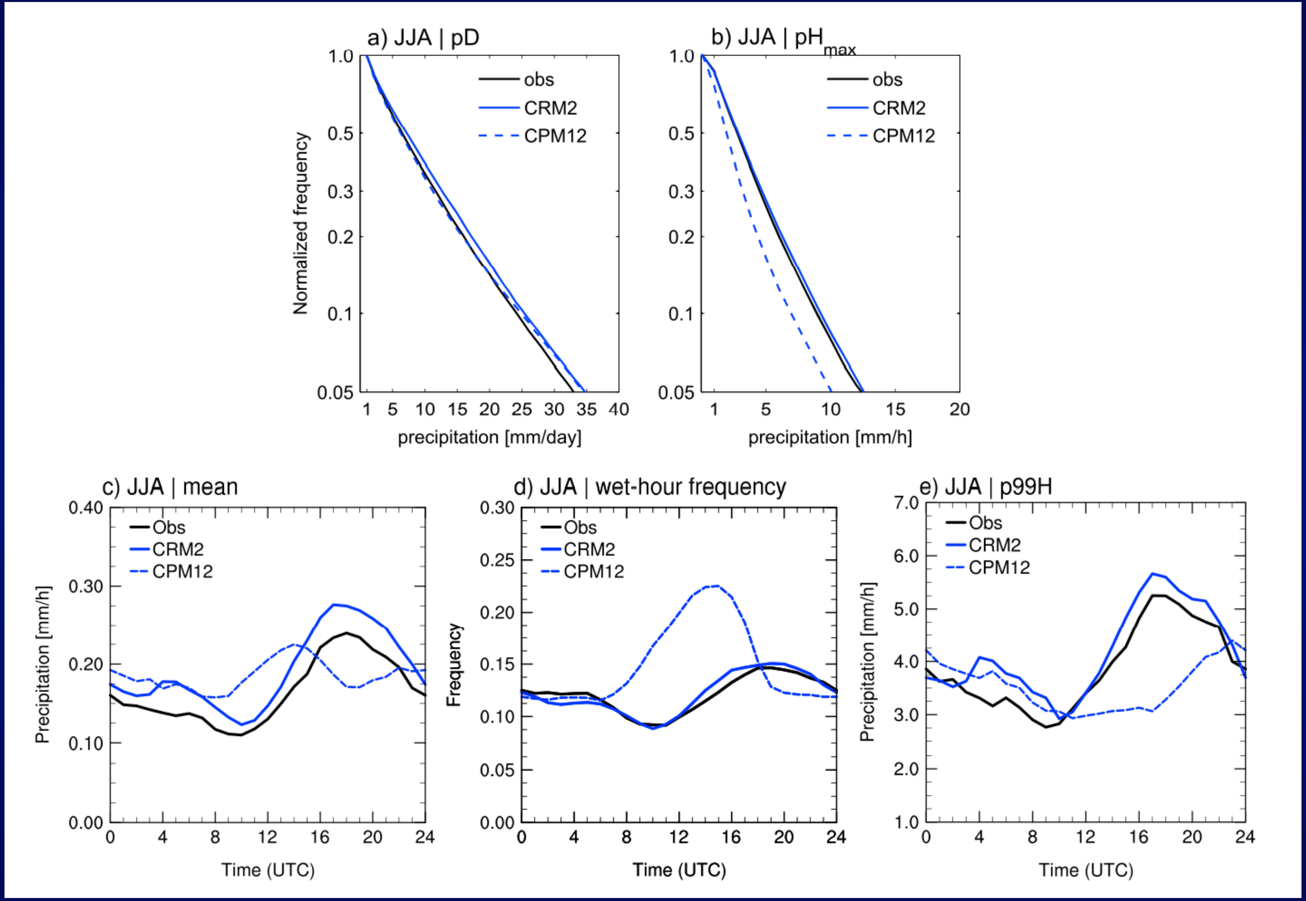
Convection permitting modeling



Improvement of the diurnal cycle of precipitation

From Ban et al. GRL (2015)

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

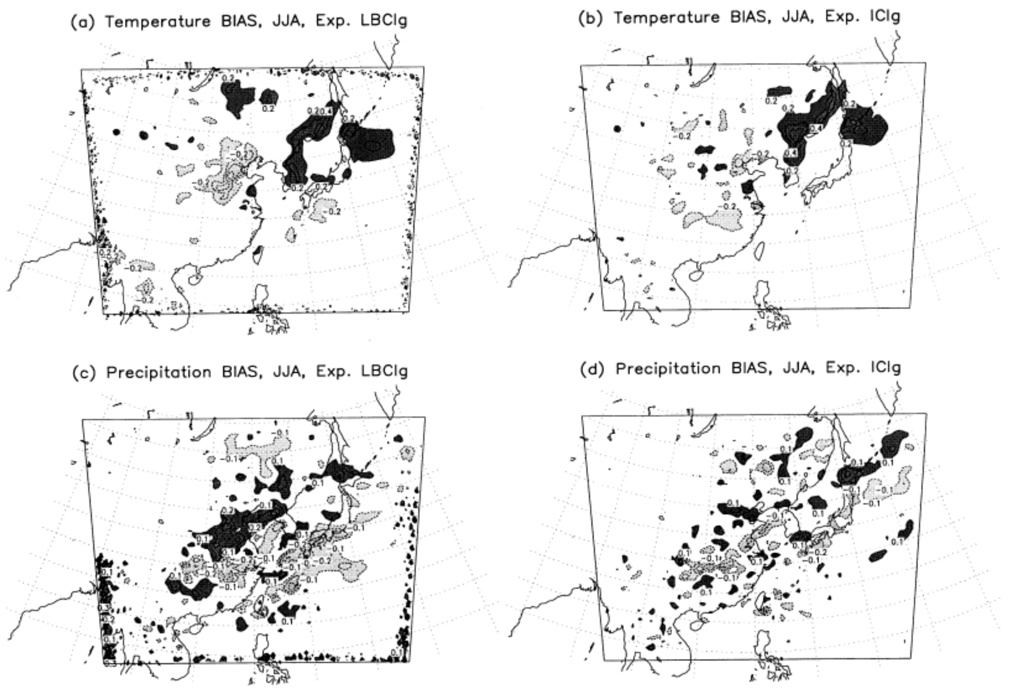


Figure 10. Bottom model level temperature (K) and precipitation (mm/day) BIAS for the LBC_{lg} and IC_{lg} perturbation experiments (not including the first 15 days of simulation). Season is JJA. (a) Temperature BIAS, Exp. LBC_{lg}; (b) temperature BIAS, Exp. IC_{lg}; (c) precipitation BIAS, Exp. LBC_{lg};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

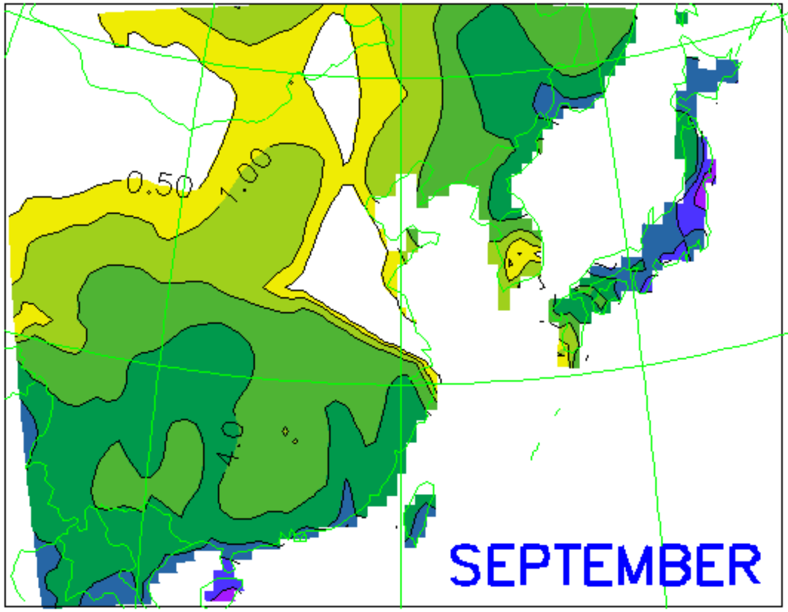
Regional Climate Modeling Issues
Model configuration

- Domain selection
  - The model domain should be large enough to include relevant circulations and forcings and to allow the model to fully develop its own internal dynamics
- Resolution selection
  - The model resolution should be sufficient to capture relevant forcings and to provide useful information for given applications
- A compromise needs to be generally reached between model domain size and resolution
  - The model results generally depend on the model configuration (although this dependence should be made minimal)
  - There are no precise rules for the choice of model configuration
- A regional model simulation generally depends to some extent on the selected domain

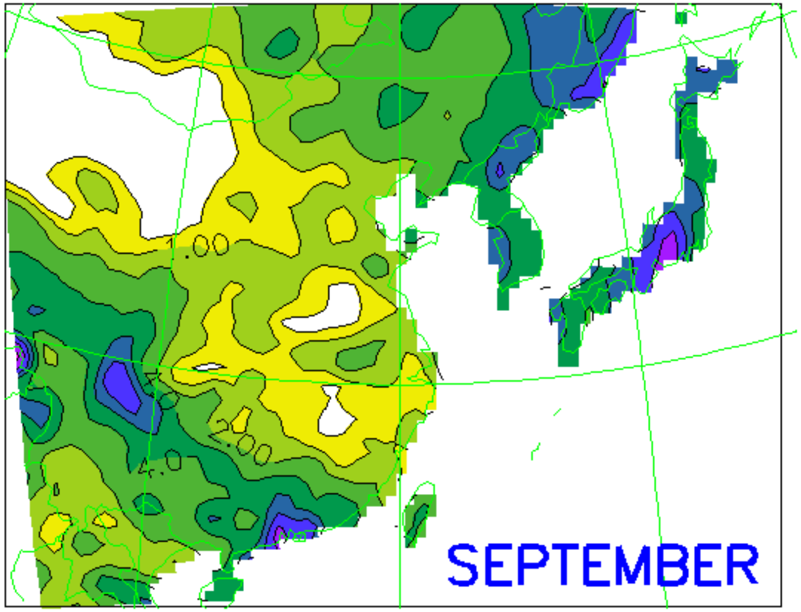
Intraseasonal variability: Precipitation over East Asia

Sept 1994 thru August 1995

CRU Obs



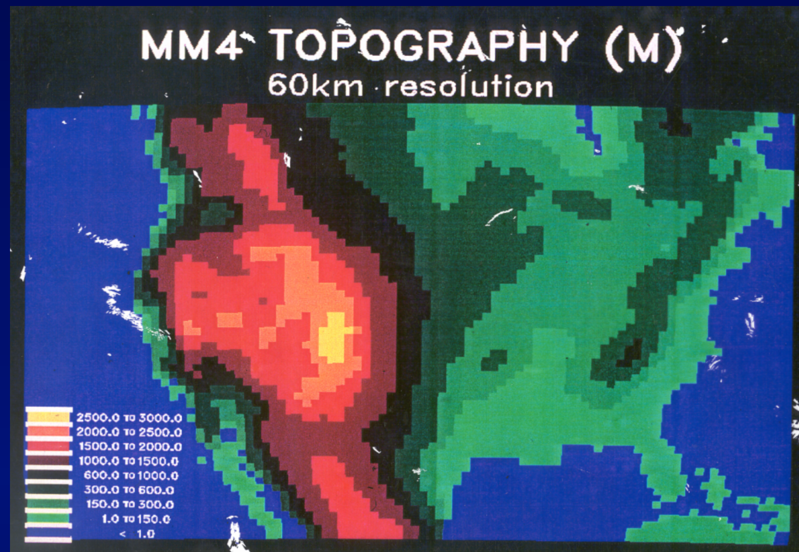
RegCM



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
- However the degree of forcing by the LBC depends on domain size, climate regime and LBC technique
  - The LBC forcing is weaker in large and tropical domains and when using the standard relaxation technique

2CO2-Control Winter Precipitation

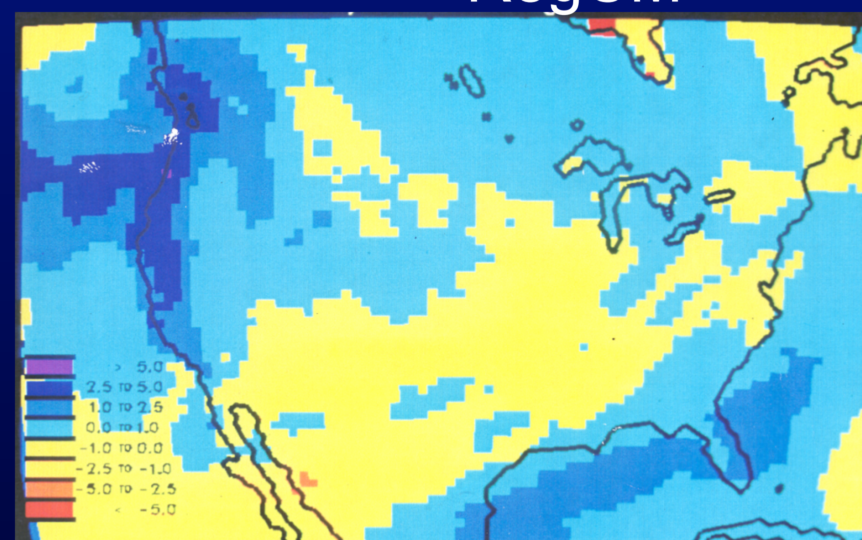


Model domain and topography

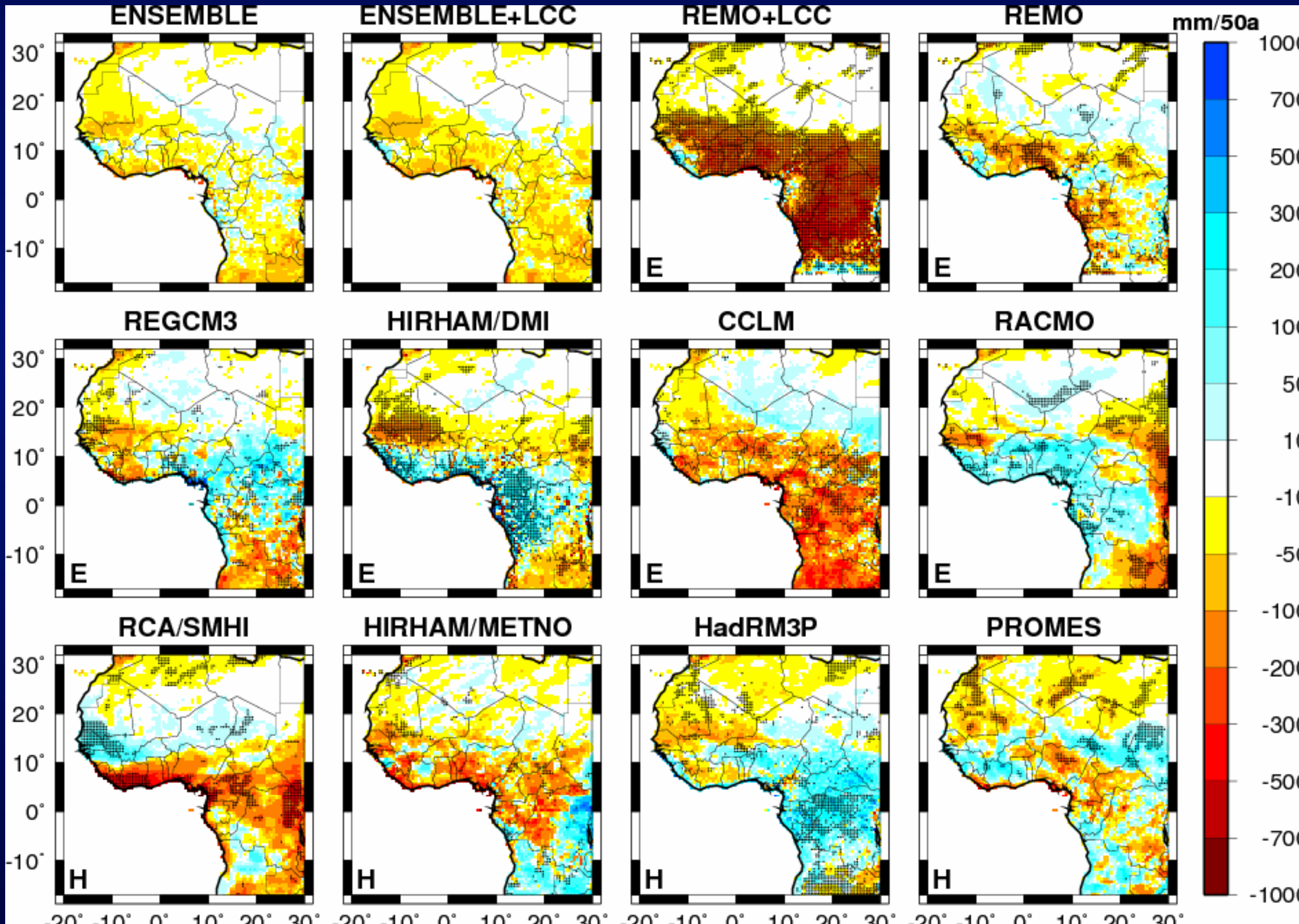
2CO2-Control
DJF Precipitation

CCM

RegCM



Precipitation trend 1990-2050



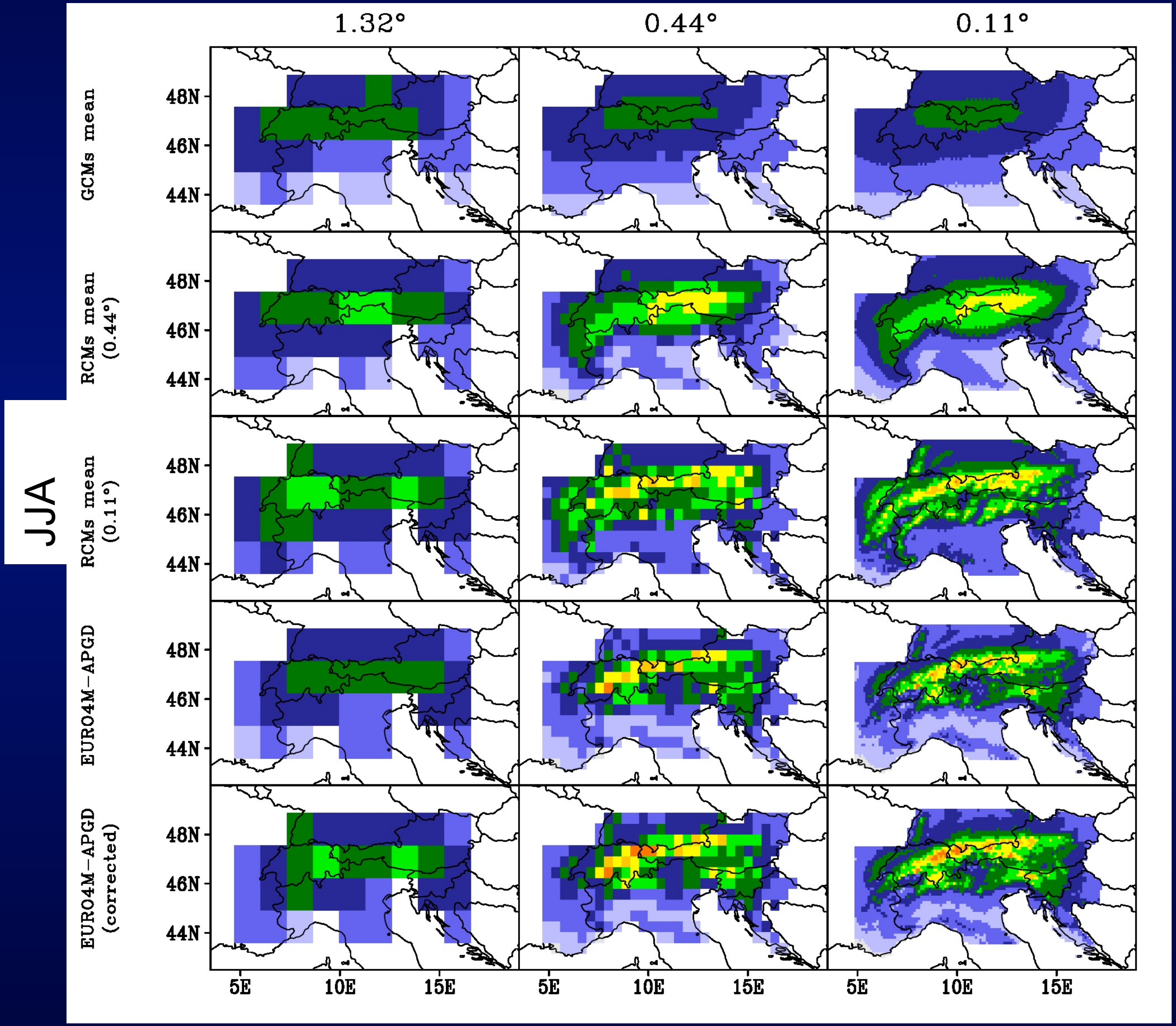
ECHAM5 LBC

HadCM3 LBC

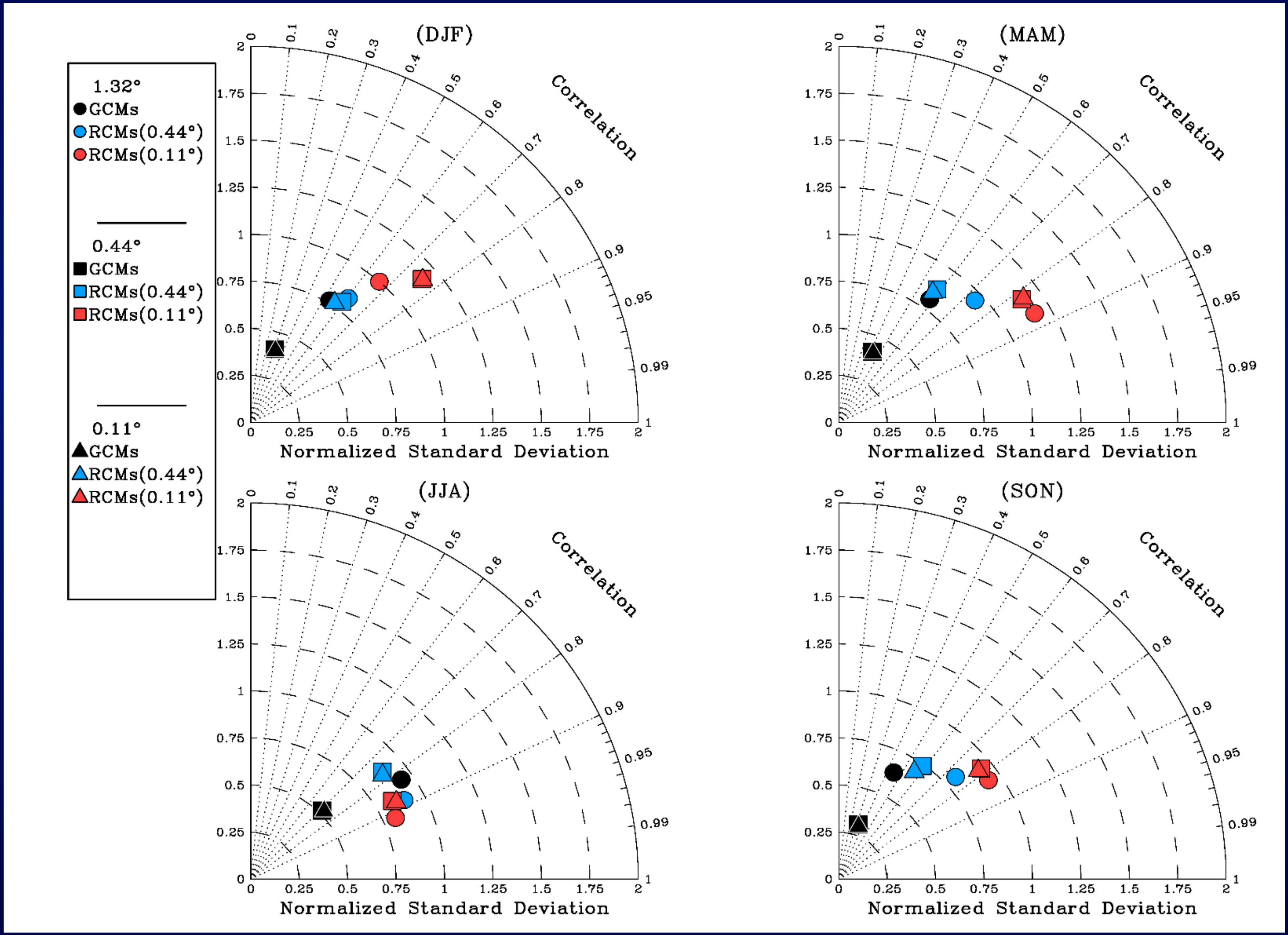
Regional Climate Modeling Issues
"Added value" (AV)

- 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

Seasonal mean precipitation (June-July-August, 1976-2005)

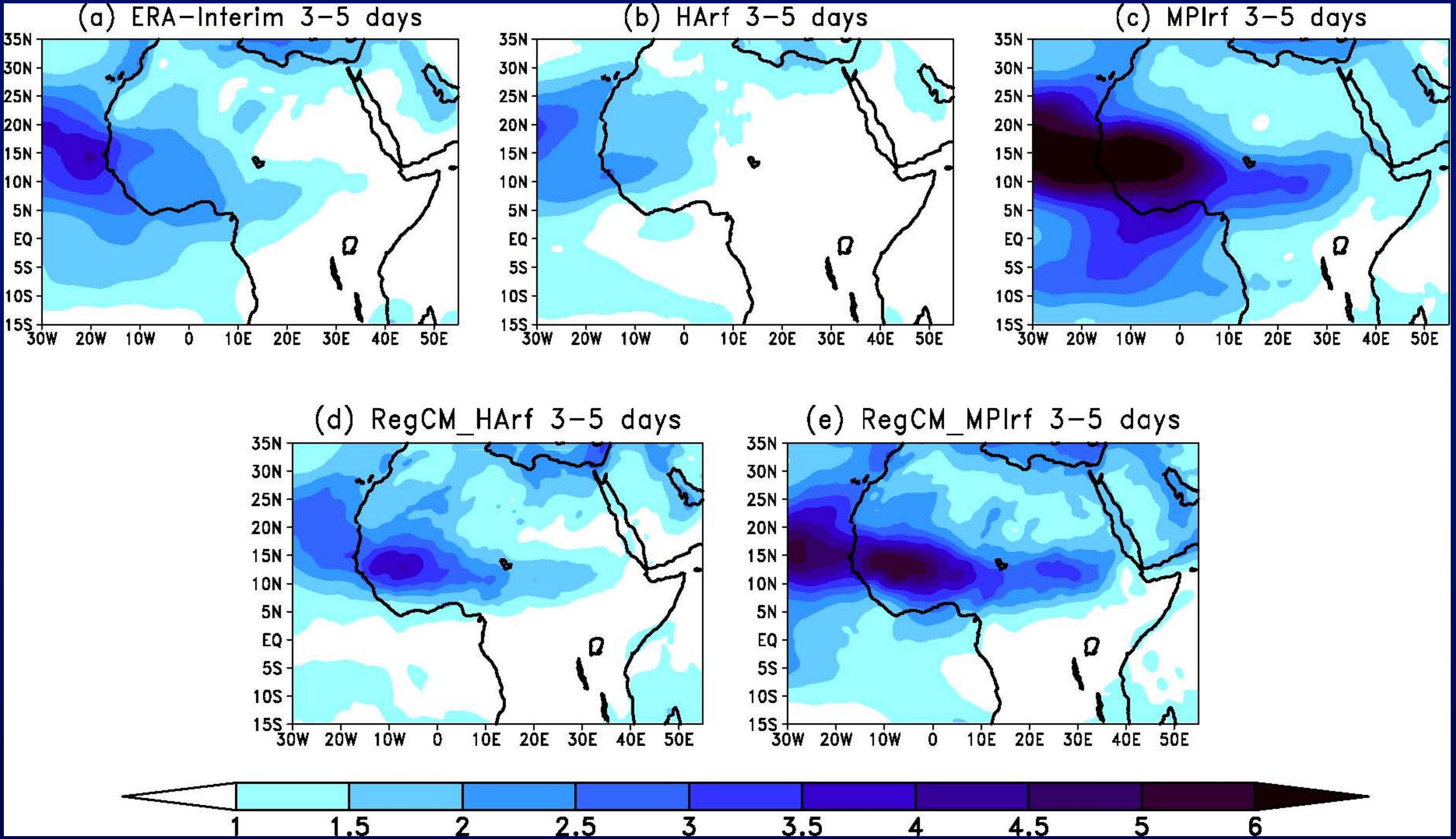


Taylor diagram of seasonal precipitation (1976-2005)



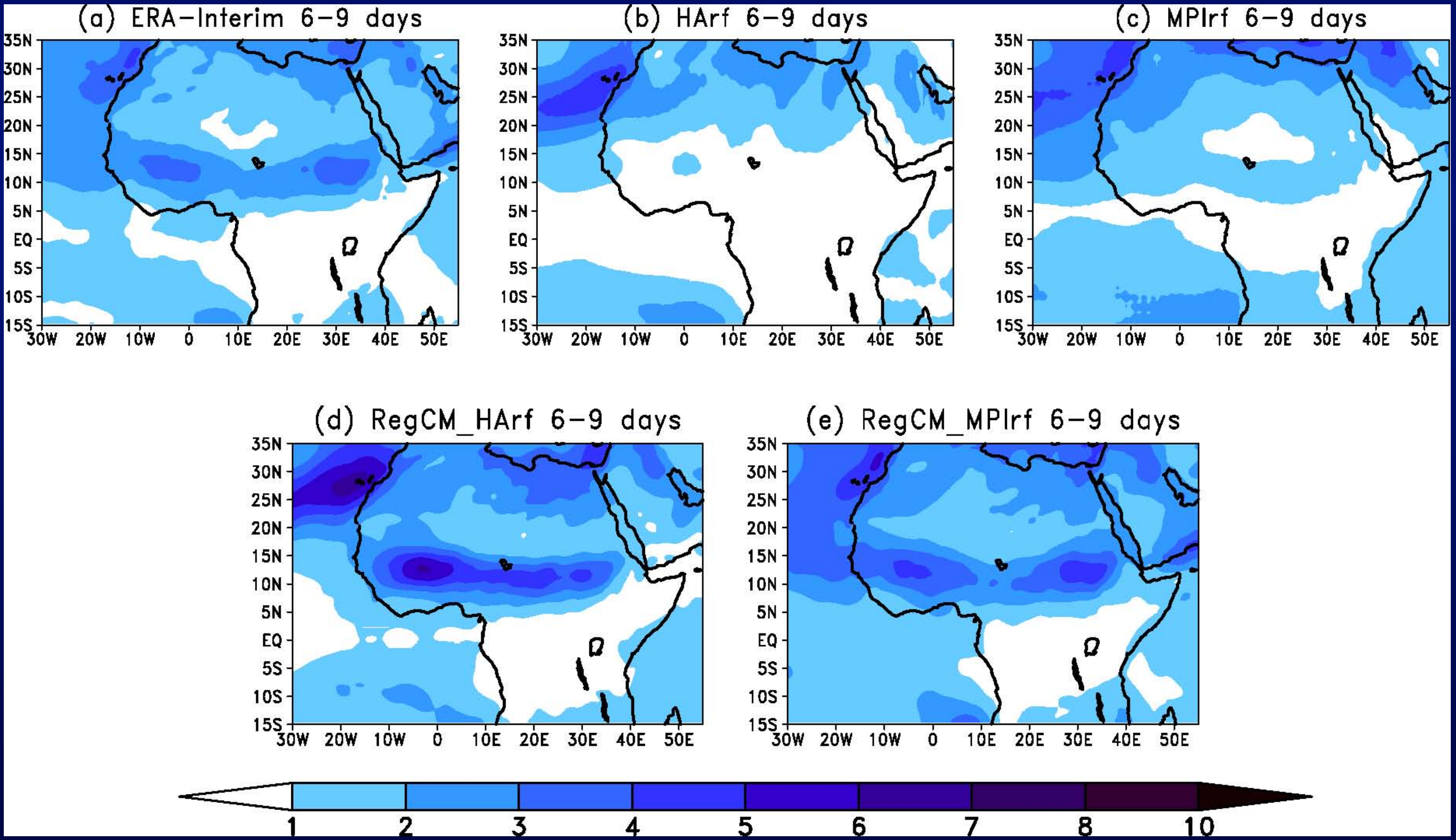
Added value: Regional circulations
AEW activity over the Sahel

Variance in 700 hPa meridional wind, JJA, 3-5 days filter

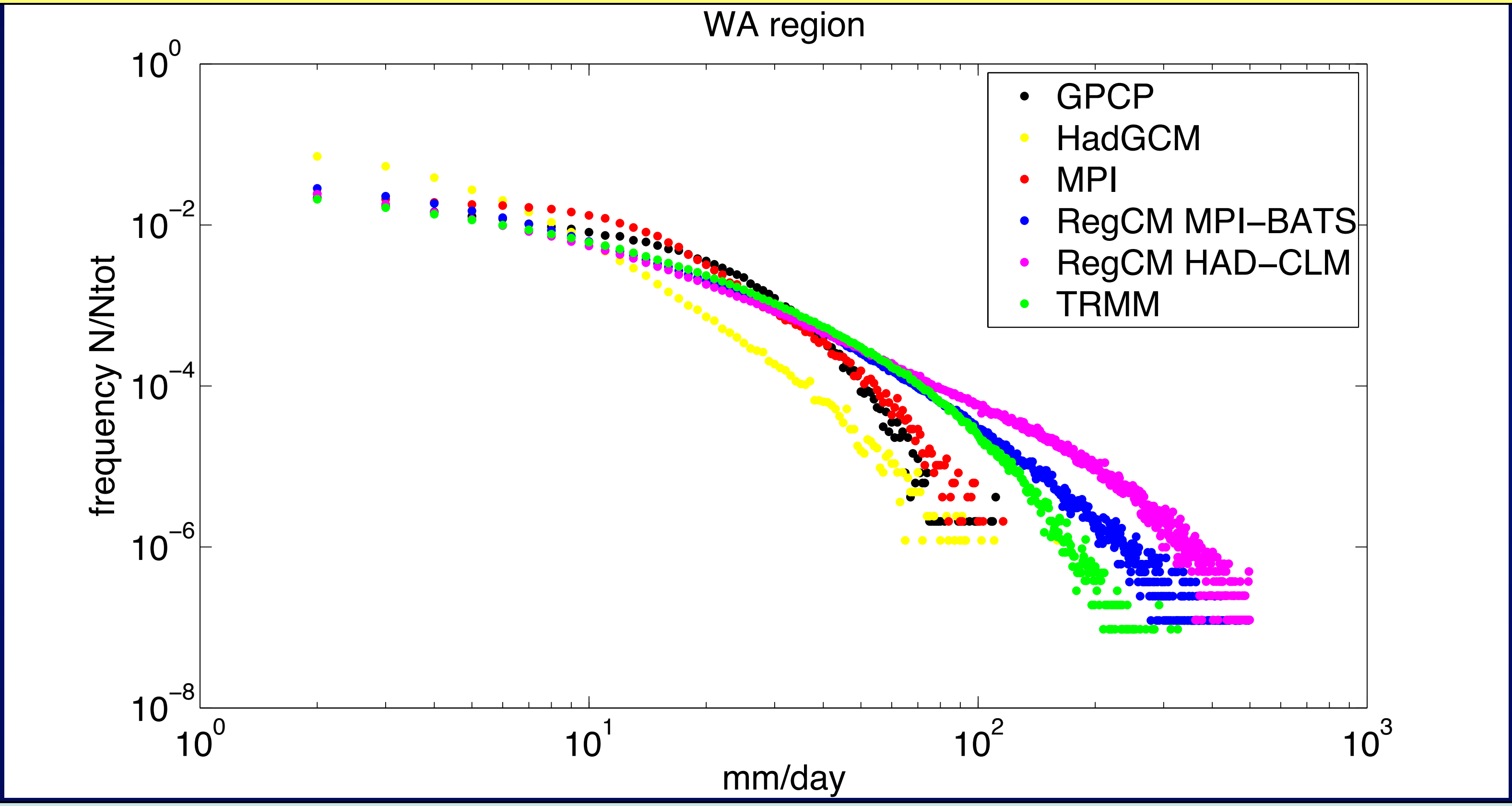


Added value: Regional circulations
AEW activity over the Sahel

Variance in 700 hPa meridional wind, JJA, 6-9 days filter

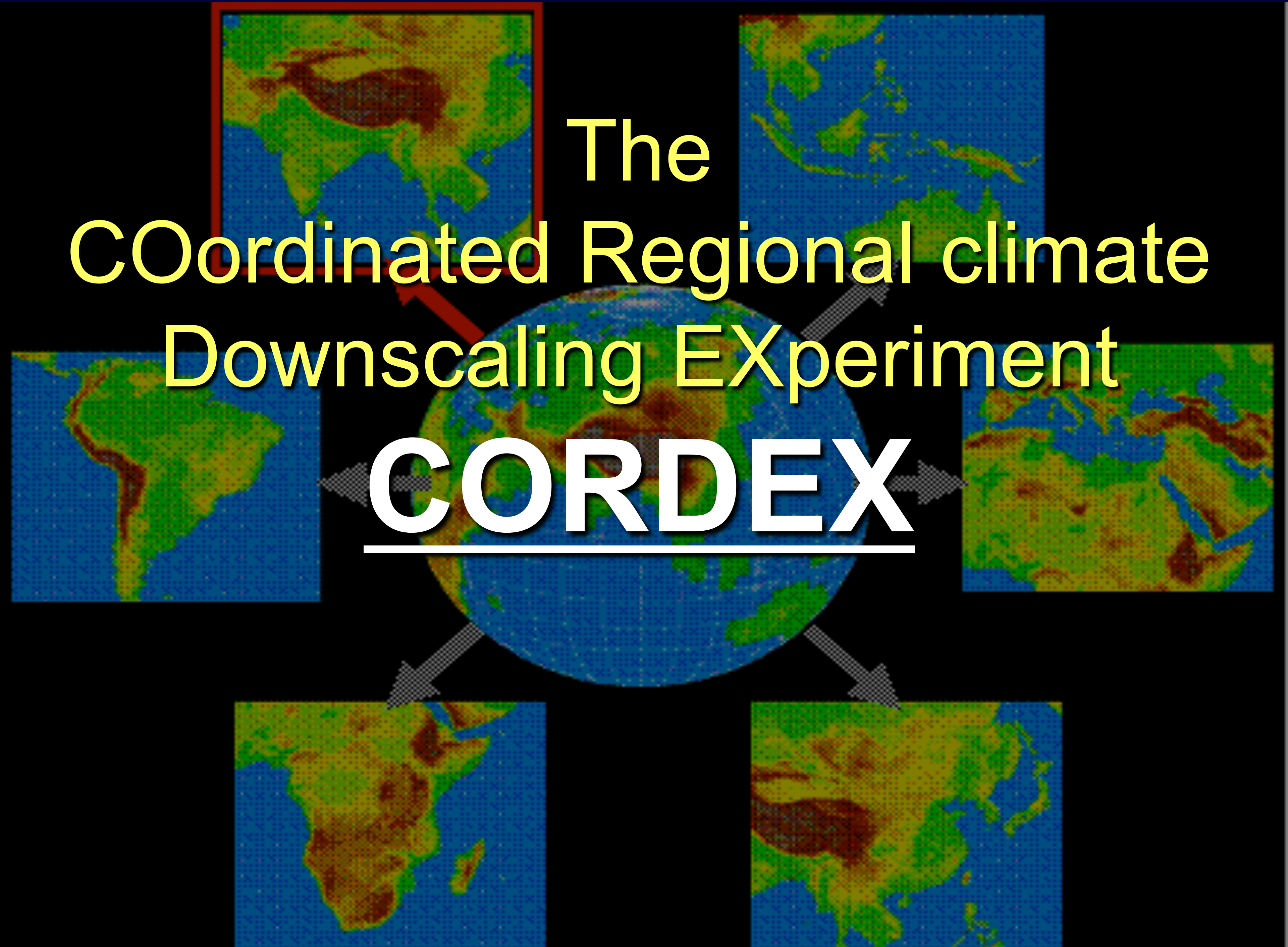


West Africa: Daily precipitation PDF in GCMs and RCMs

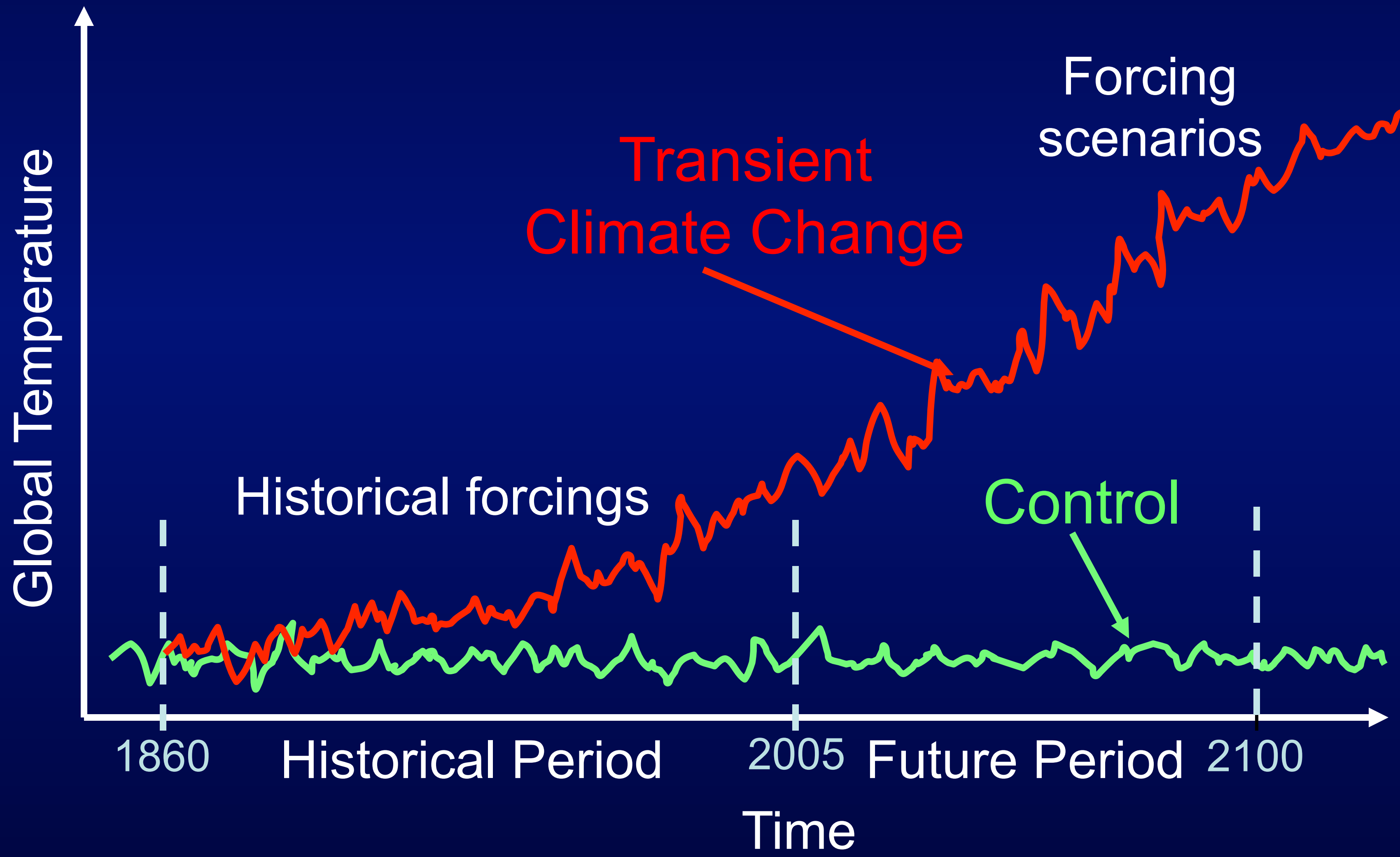


The GCM is close to the coarse resolution data, the RCMs to the high resolution data

<u>This is what we expect from a downscaling exercise</u>


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"

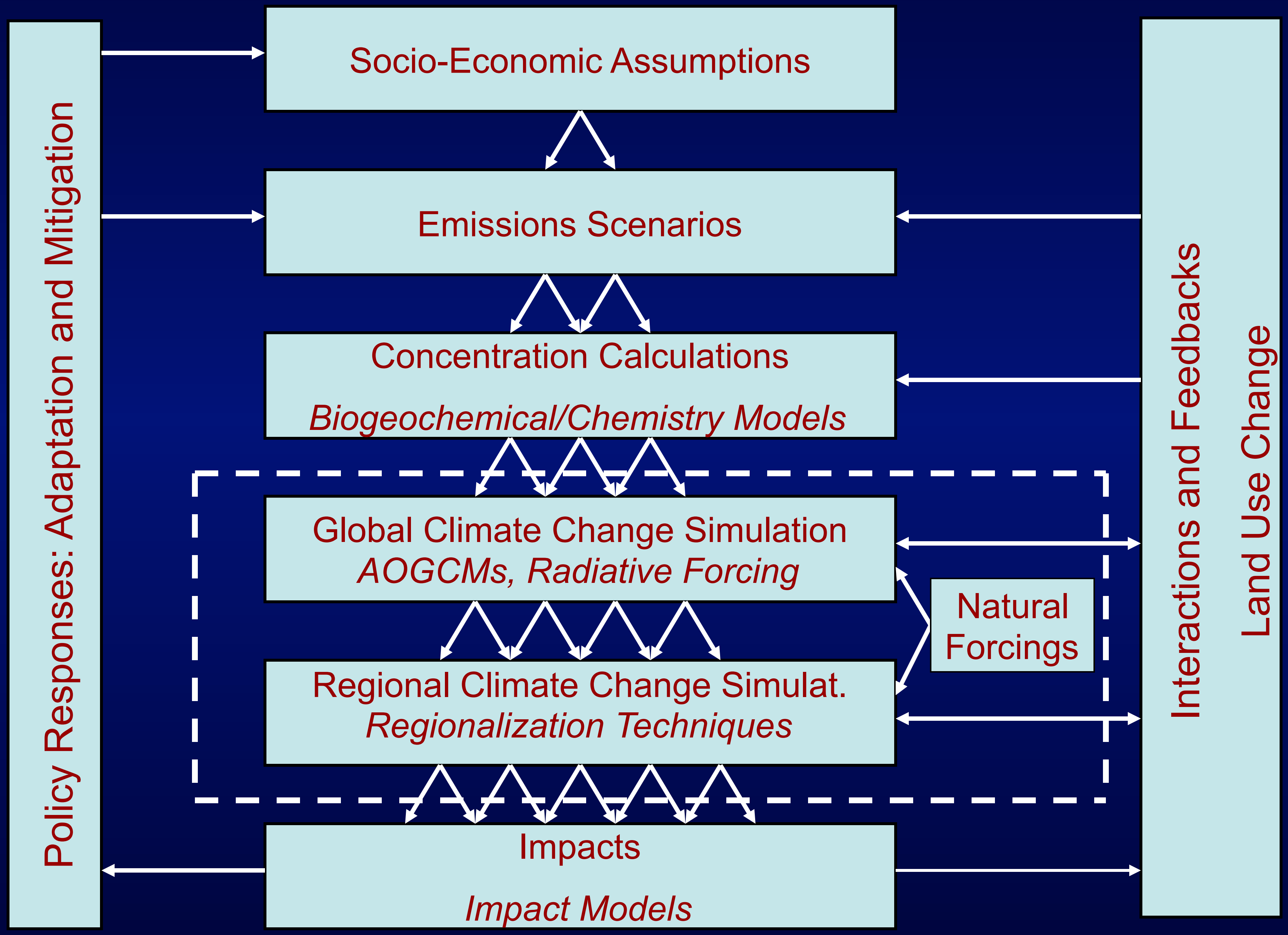
The protocol for a regional climate change simulation:
Step II: GCM-driven "Control" experiments

- 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")

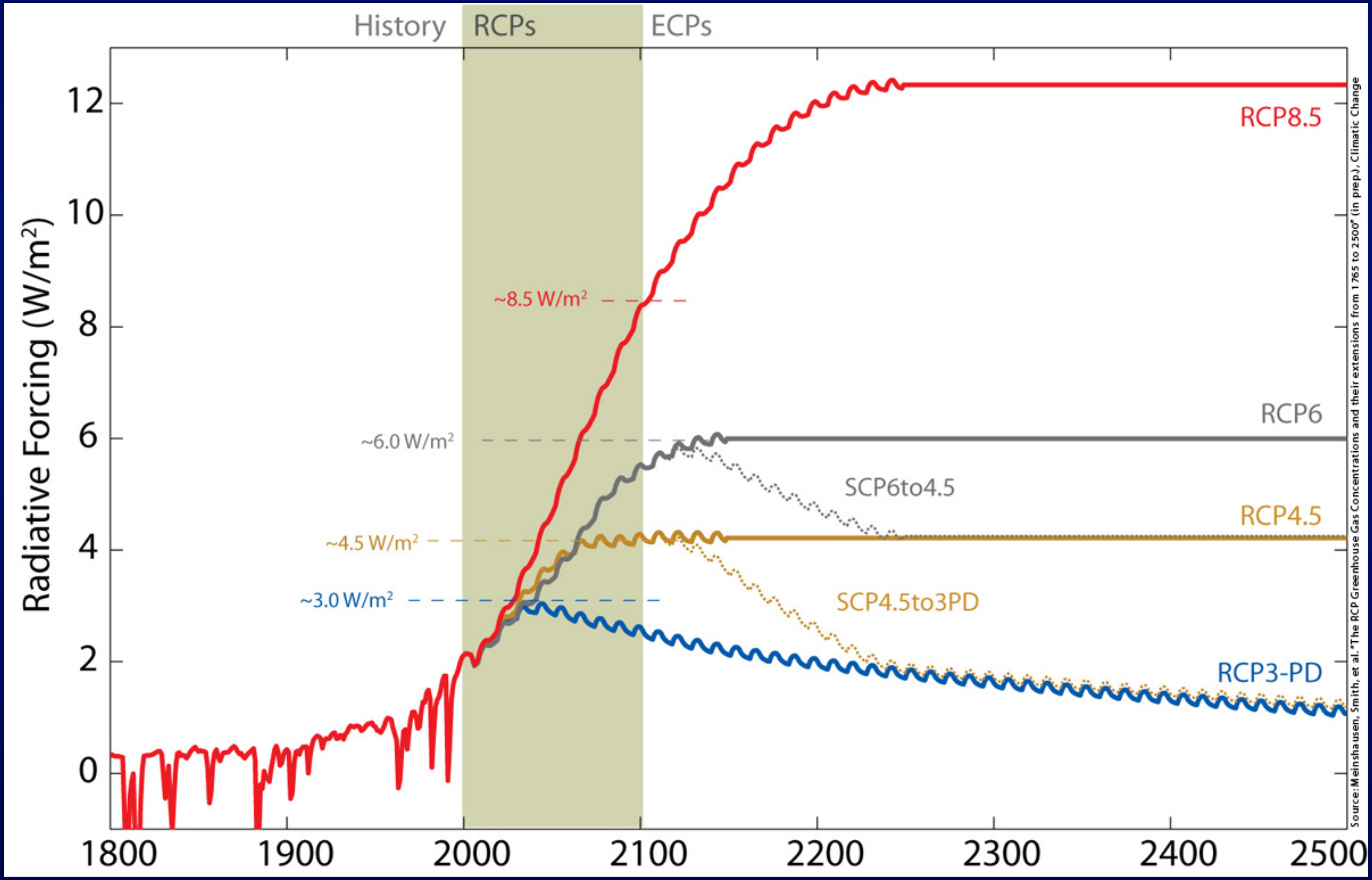
The protocol for a regional climate change simulation:
Step III: GCM-driven experiments of “future” climate conditions

- 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)

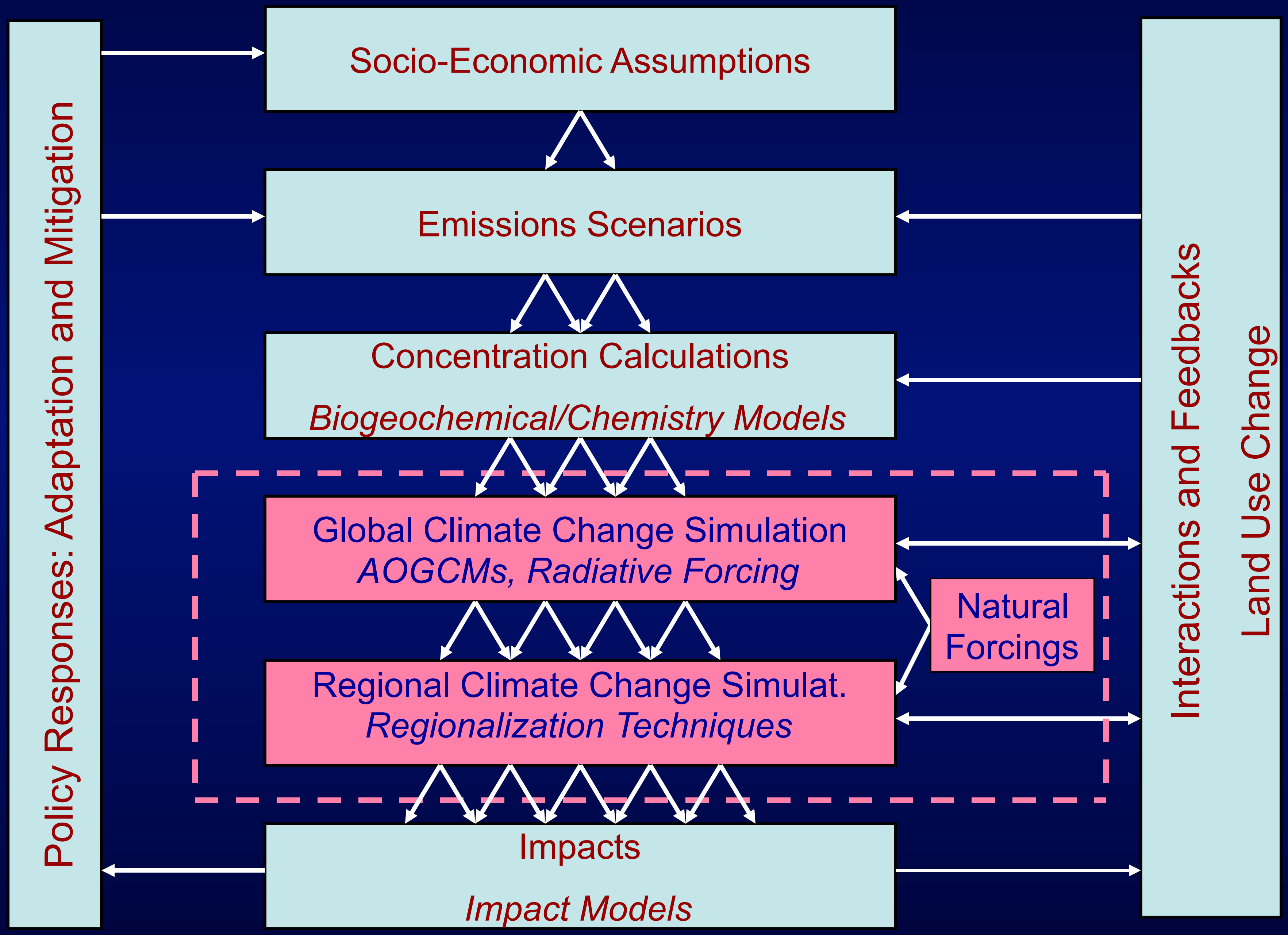
Cascade of uncertainty in climate change prediction



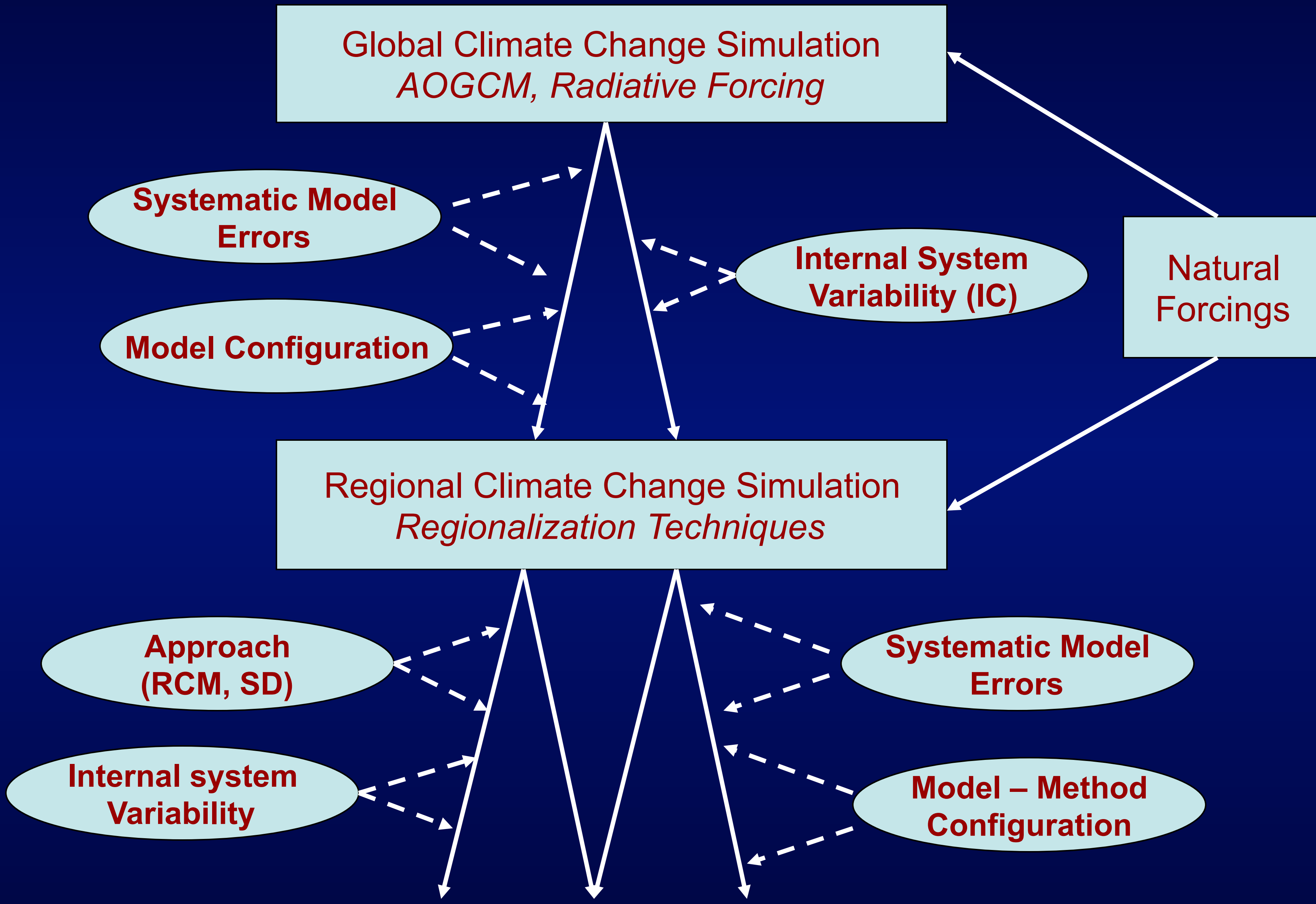
Scenario Uncertainty



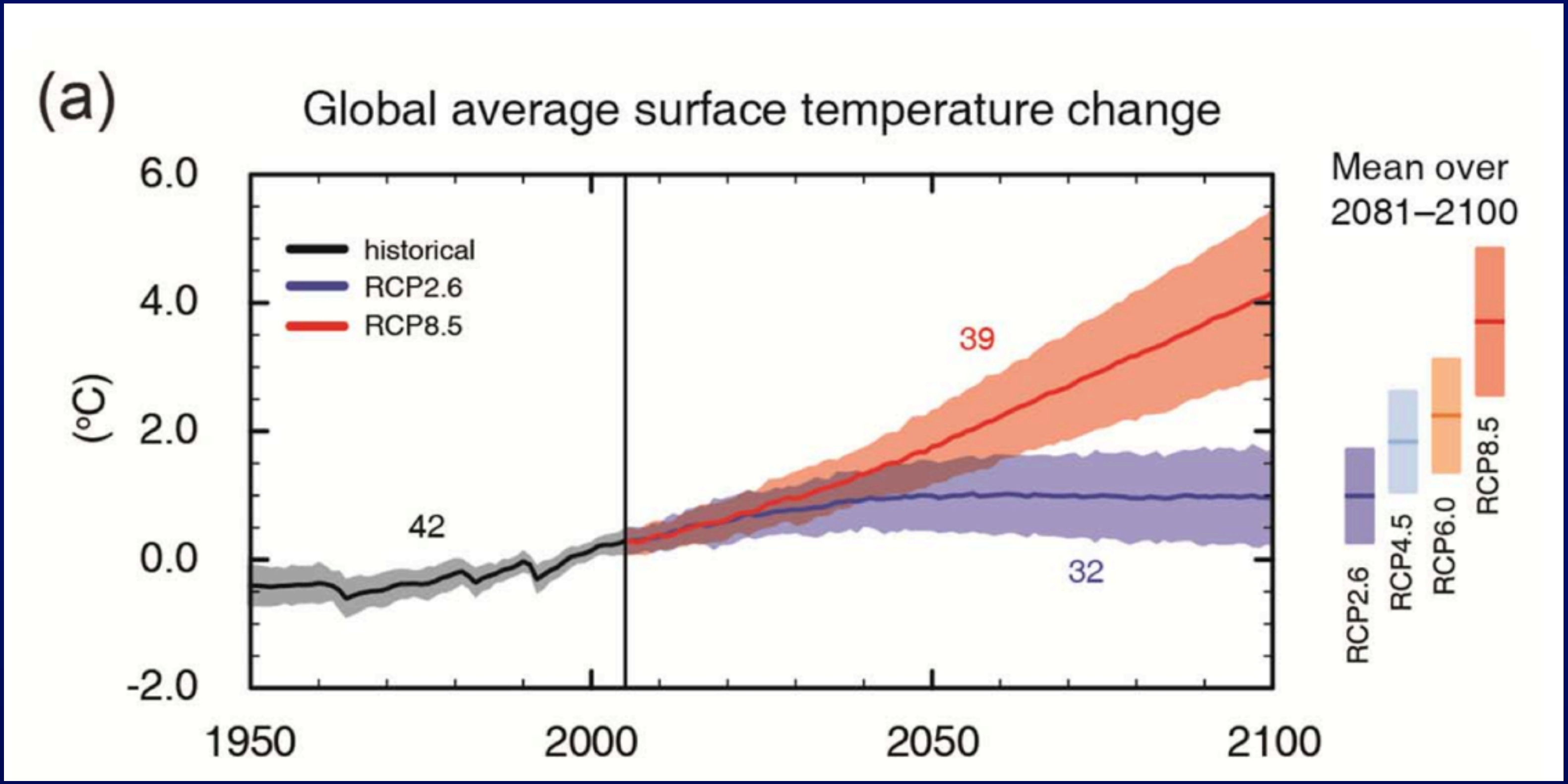
Cascade of uncertainty in climate change prediction



Climate Simulation Segment of the Uncertainty Cascade

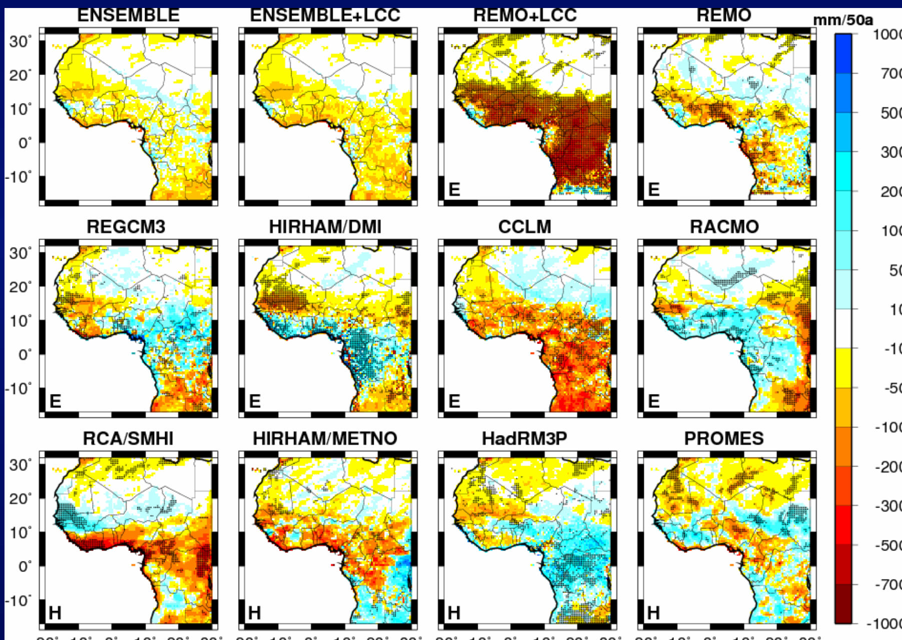


IPCC – 2013: Global temperature change projections for the 21st century



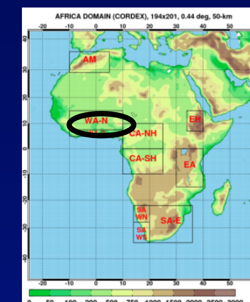
Uncertainties in regional projections

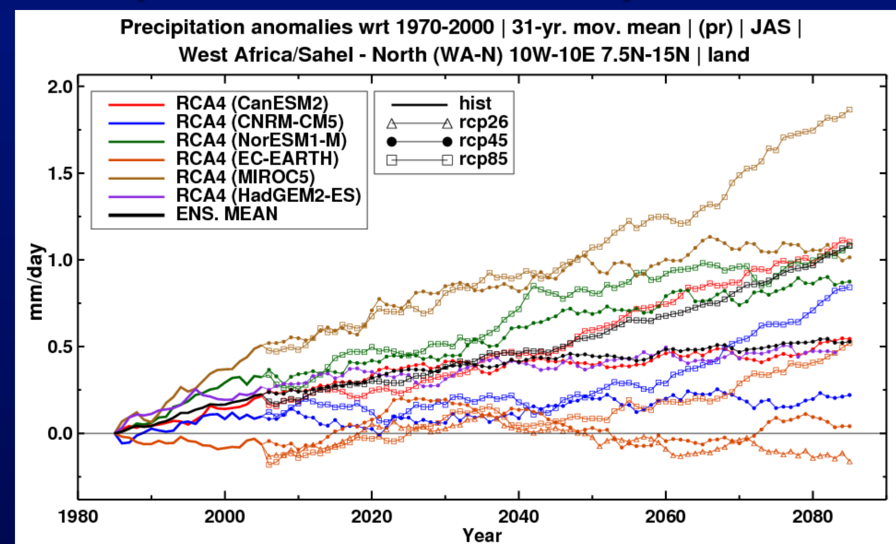
Trend in precipitation,
2001-2050 A1B Scenario



From Paeth et al. 2010

Trend in Sahel
precipitation
(G. Nikulin, SMHI)



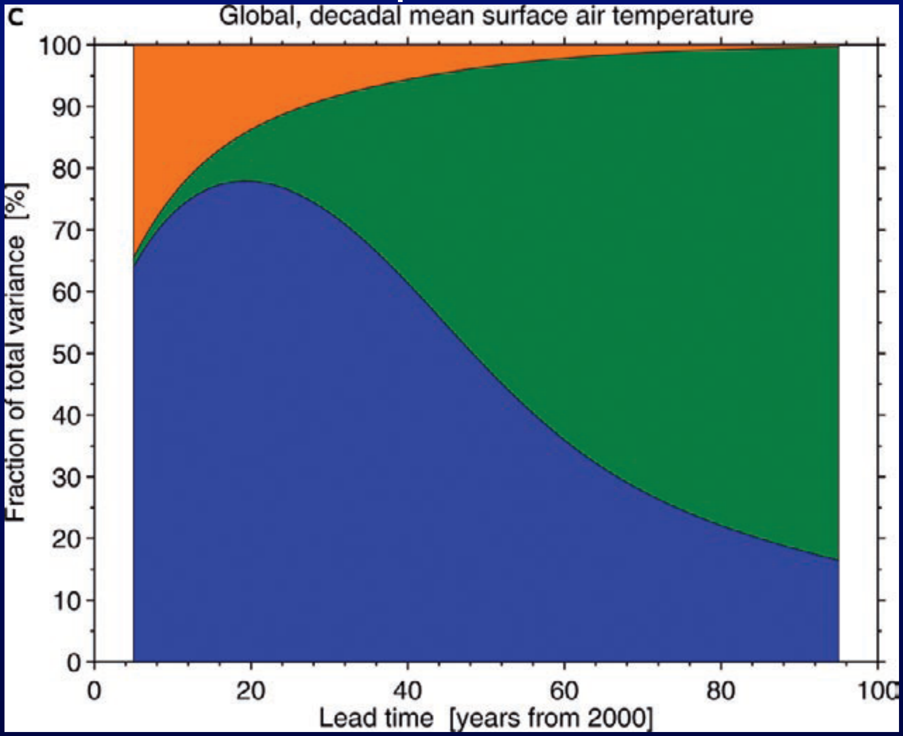


Fraction of uncertainty explained by different sources as a function of lead time

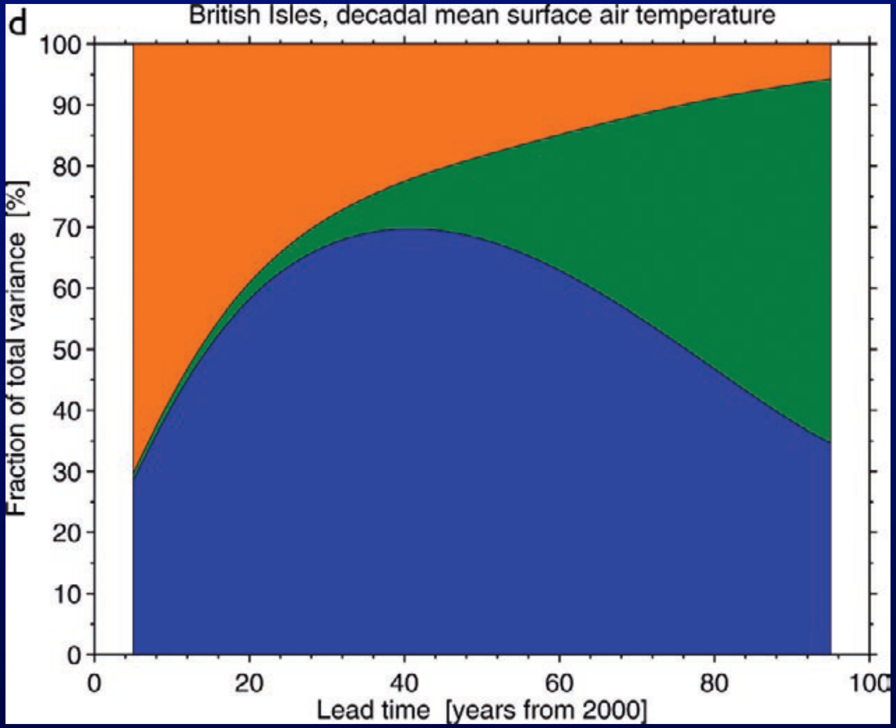
Internal variability
Scenario uncertainty
Model configuration uncertainty

Hawkins and Sutton 2009

Decadal temperature - Global

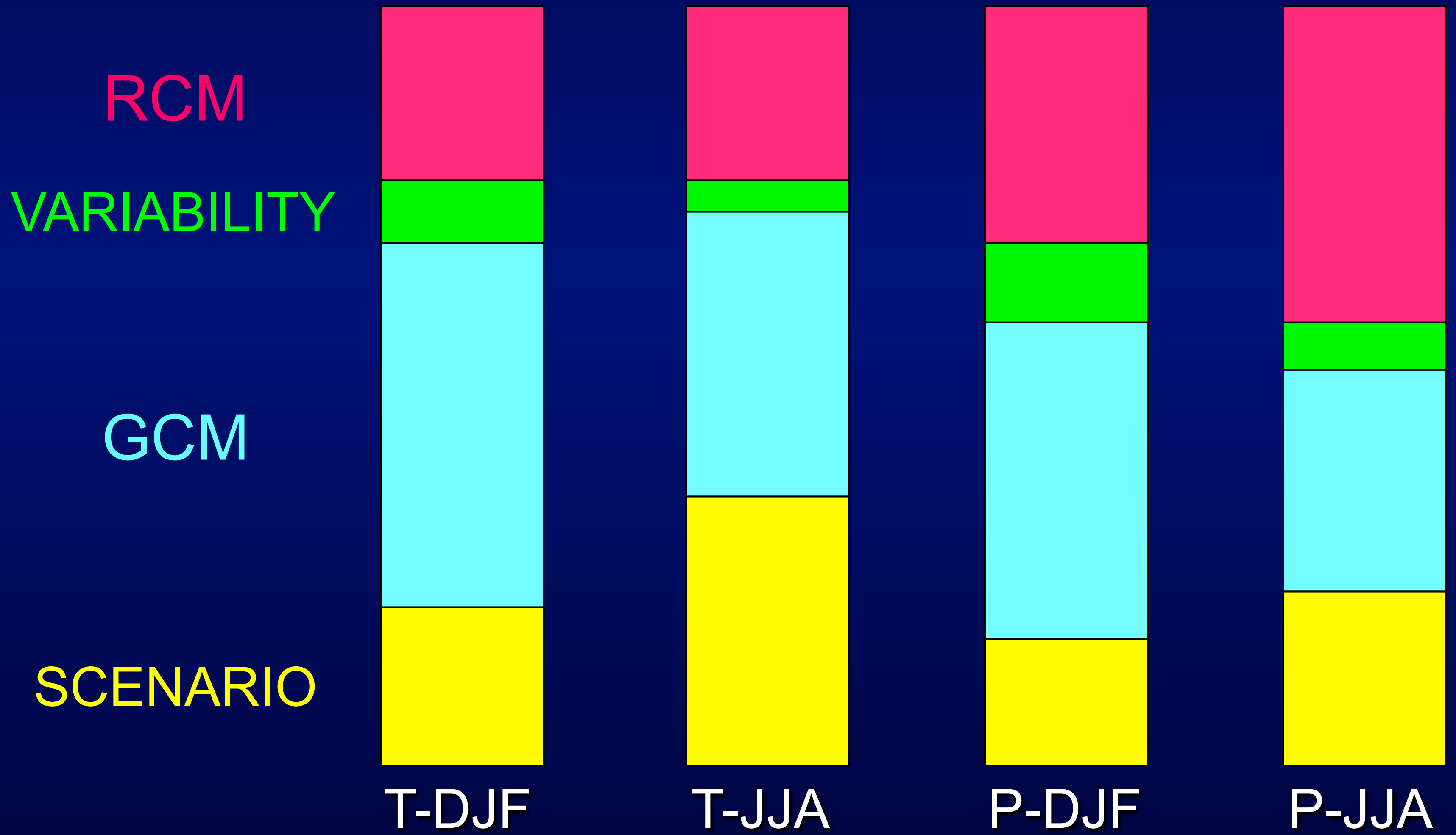


Decadal temperature – British Isles

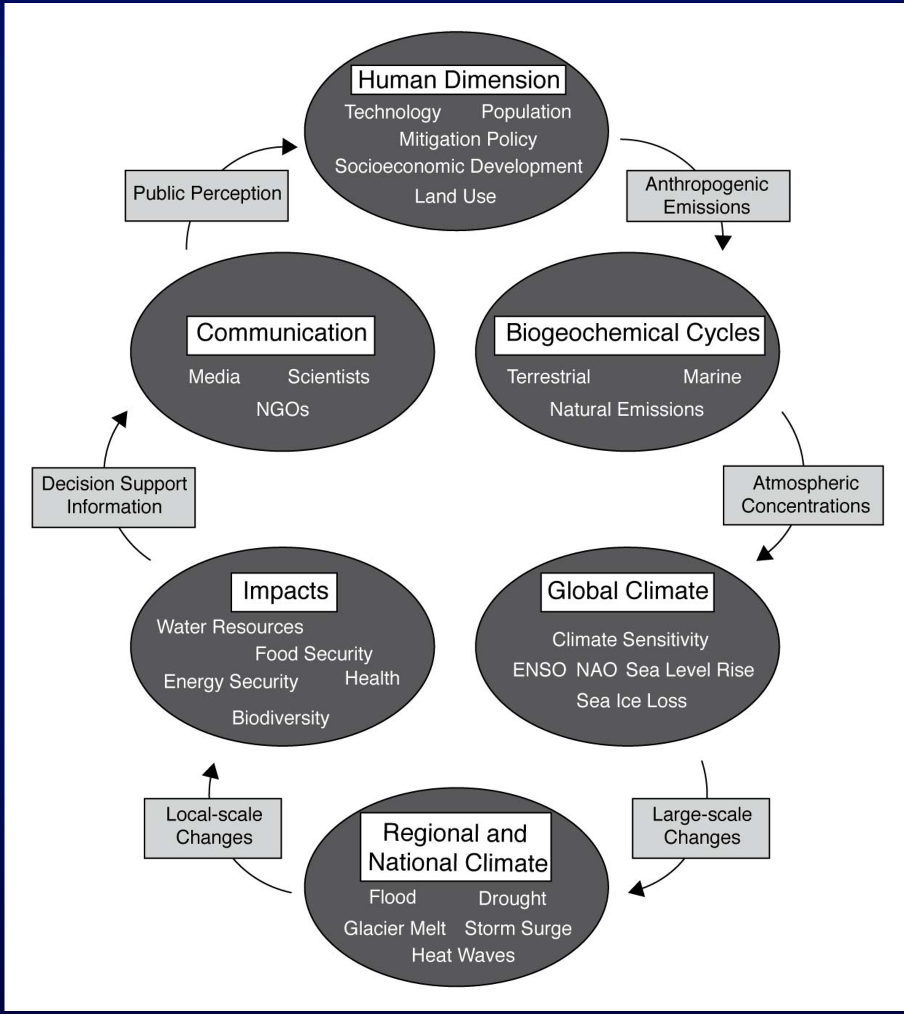


Sources of uncertainty in the simulation of temperature and precipitation change (2071-2100 minus 1961-1990) by the ensemble of PRUDENCE simulations (whole Europe)

(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)



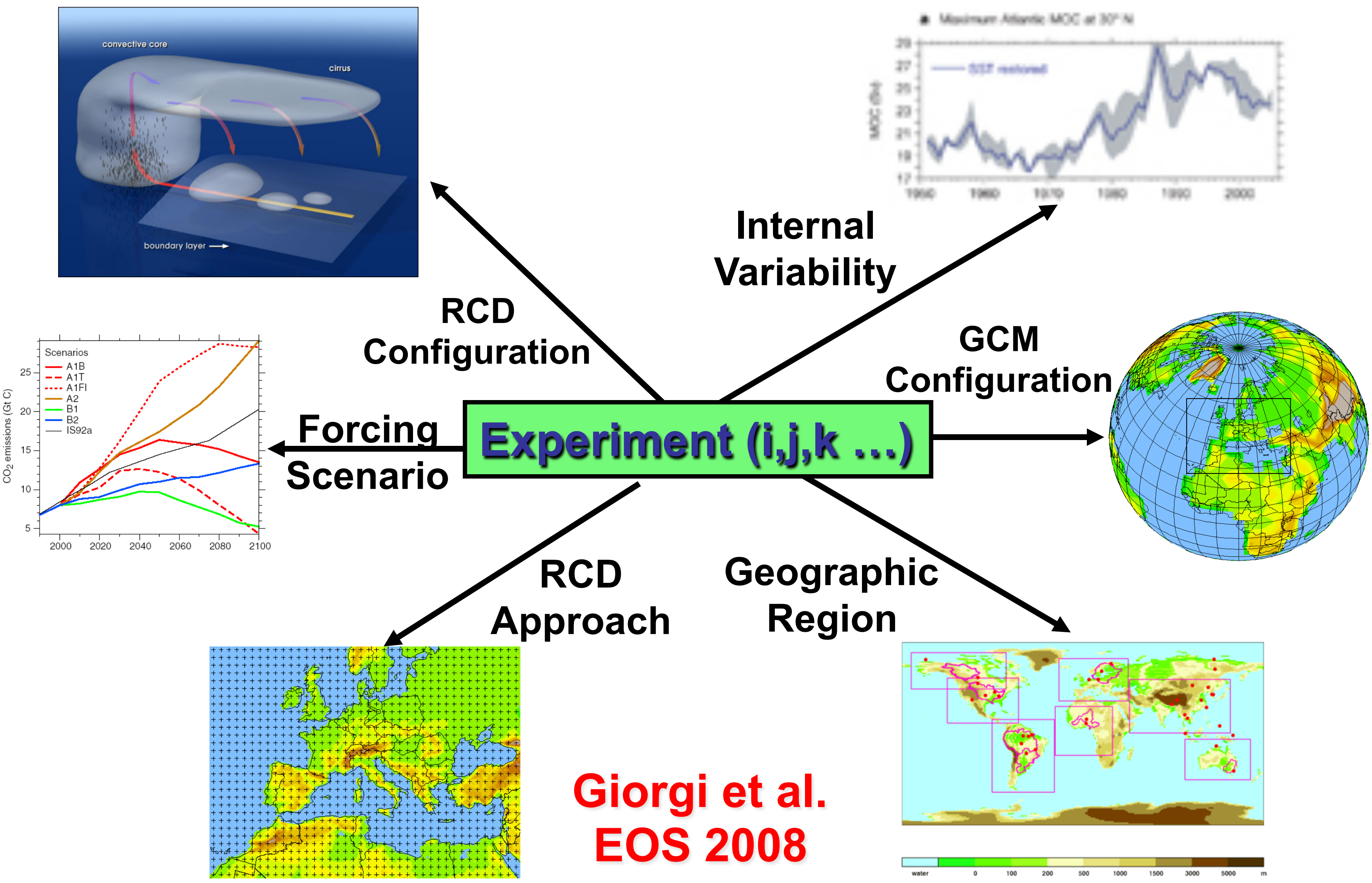
The generation of climate change scenarios for impact/adaptation work requires proper characterization of uncertainties



<u>To date RCM studies have not been coherent and comprehensive enough to sufficiently characterize uncertainties in climate change projections</u>

Exceptions are Europe (PRUDENCE, ENSEMBLES) and (maybe) US (NARCCAP)

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



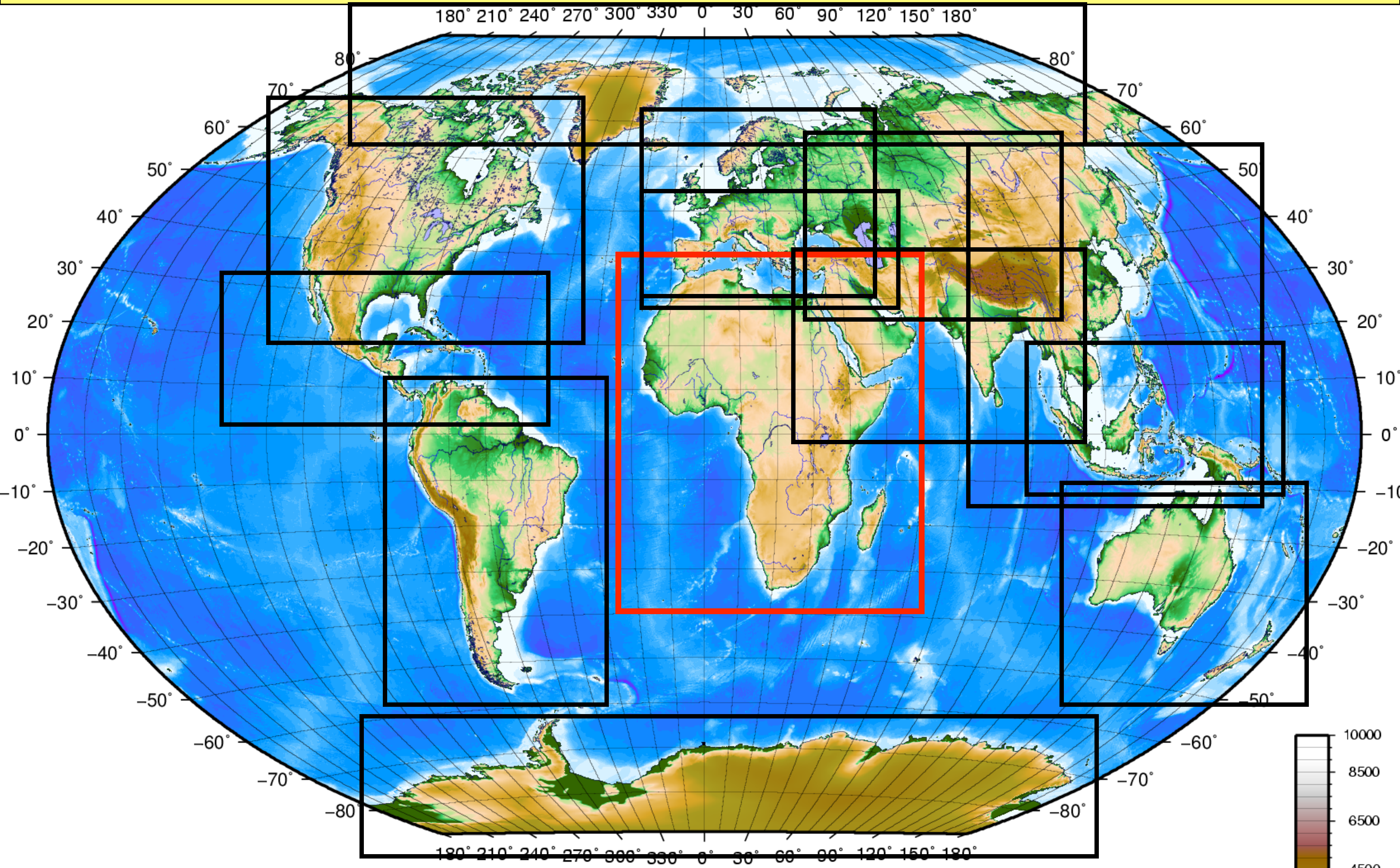
Giorgi et al.
EOS 2008

CORDEX Vision and Goals

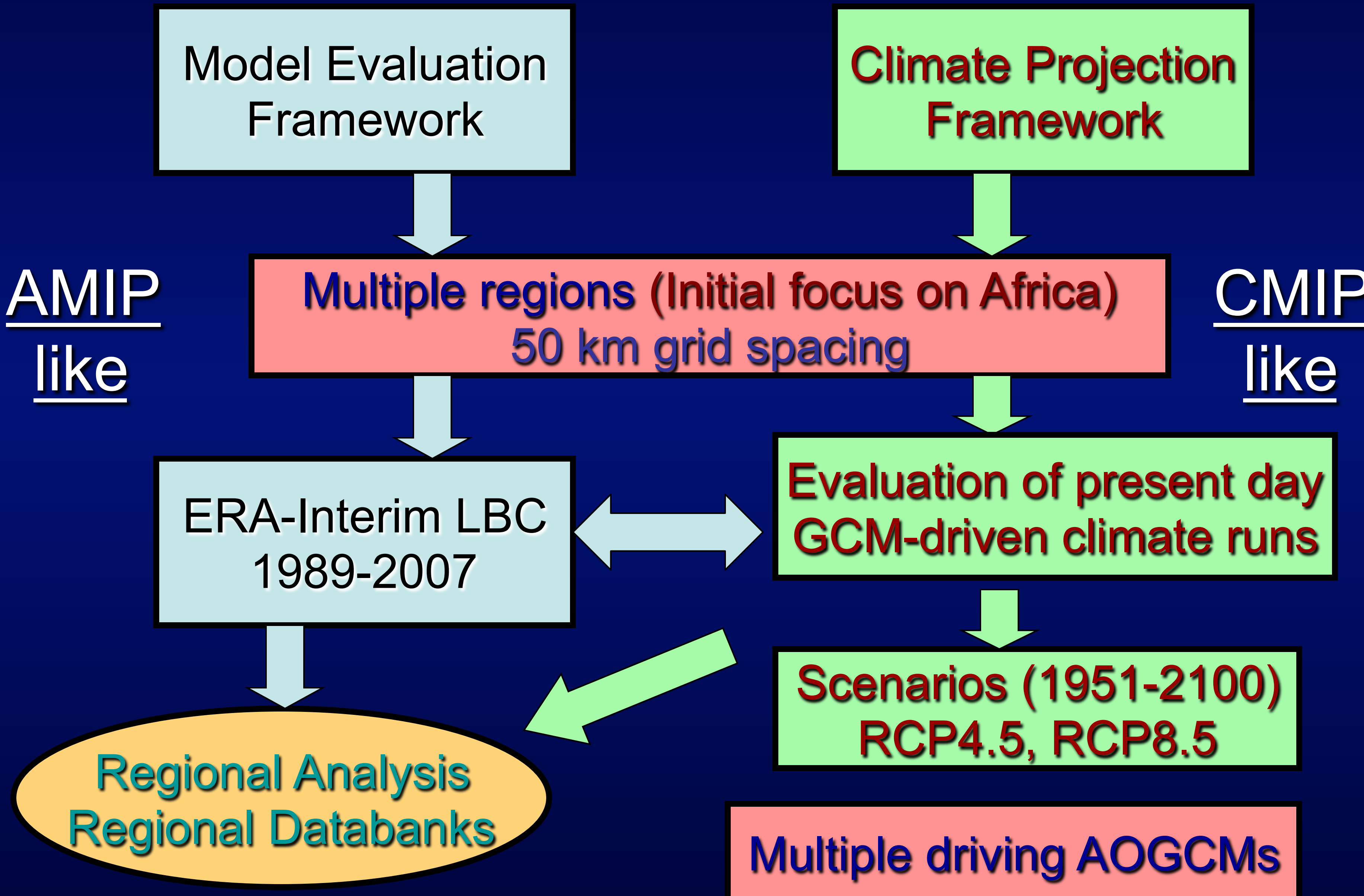
The CORDEX vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships

- 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)	--	✓	✓	--	--

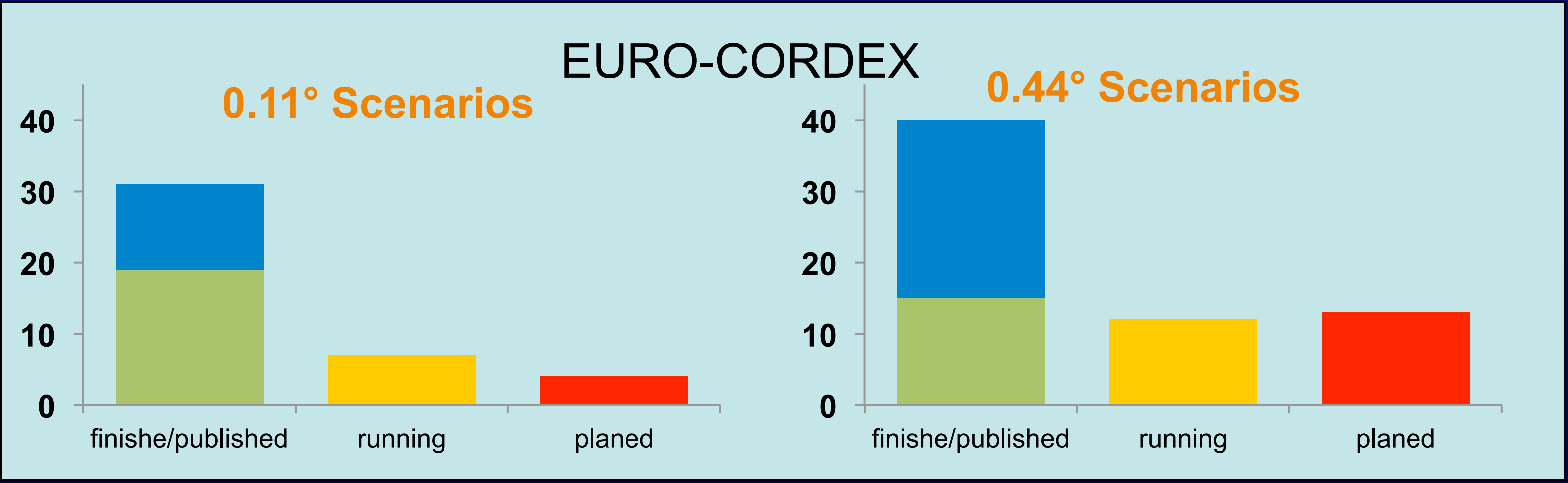
To download the data please click here

Regridding script example, click here to download | script

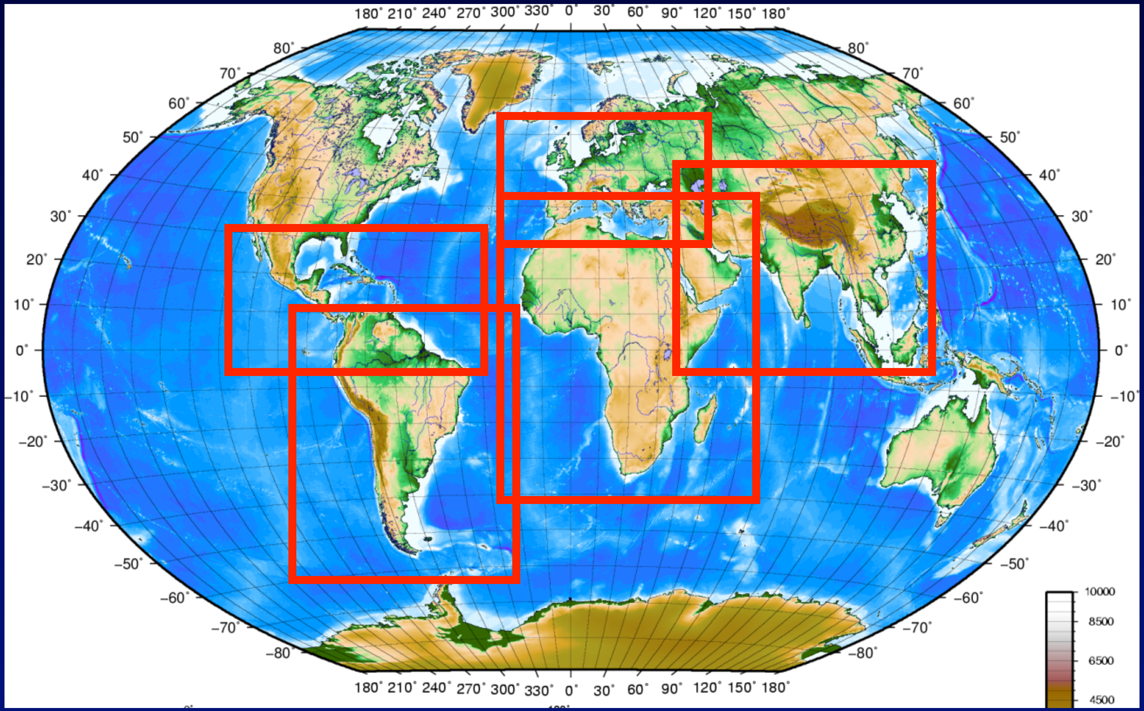
CORDEX-AFRICA

RCP4.5	BCCR-greenWRF	CCCma-CanRCM4	CLMcom-CCLM4-8	CNRM-ALADIN	CSC-REMO	DMI-HIRHAM5	ICTP-RegCM4	KNMI-RACMO2.2	MOHC-GA3RCM	SMHI-RCA4	UCLM-PROMES	ULL-WRF311	UCAN-WRF34	UQAM-CRCM	sum
CanESM2		■								■				■	3
CNRM-CM5			■	■						■					3
NorESM1-M	■ (blue)									■					1
EC-EARTH (r1)								■							1
EC-EARTH (r3)						■									1
EC-EARTH (r12)			■		■					■					3
HadGEM2-ES			■				■		■ (blue)	■					3
MIROC5										■					1
MPI-ESM-LR			■		■					■				■	4
GFDL-ESM2M										■					1
HADCM3															
sum		1	4	1	2	1	1	1		8				2	21

RCP8.5	BCCR-greenWRF	CCCma-CanRCM4	CLMcom-CCLM4-8	CNRM-ALADIN	CSC-REMO	DMI-HIRHAM5	ICTP-RegCM4	KNMI-RACMO2.2	MOHC-GA3RCM	SMHI-RCA4	UCLM-PROMES	ULL-WRF311	UCAN-WRF34	UQAM-CRCM	sum
CanESM2		■								■					2
CNRM-CM5			■	■						■					3
NorESM1-M	■ (blue)									■					1
EC-EARTH (r1)								■							1
EC-EARTH (r3)						■									1
EC-EARTH (r12)			■		■					■					3
HadGEM2-ES			■				■		■ (blue)	■					3
MIROC5										■					1
MPI-ESM-LR			■		■		■			■					4
GFDL-ESM2M										■					1
HADCM3											■ (blue)				
sum		1	4	1	2	1	2	1		8					19



The CREMA Phase I Experiment



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

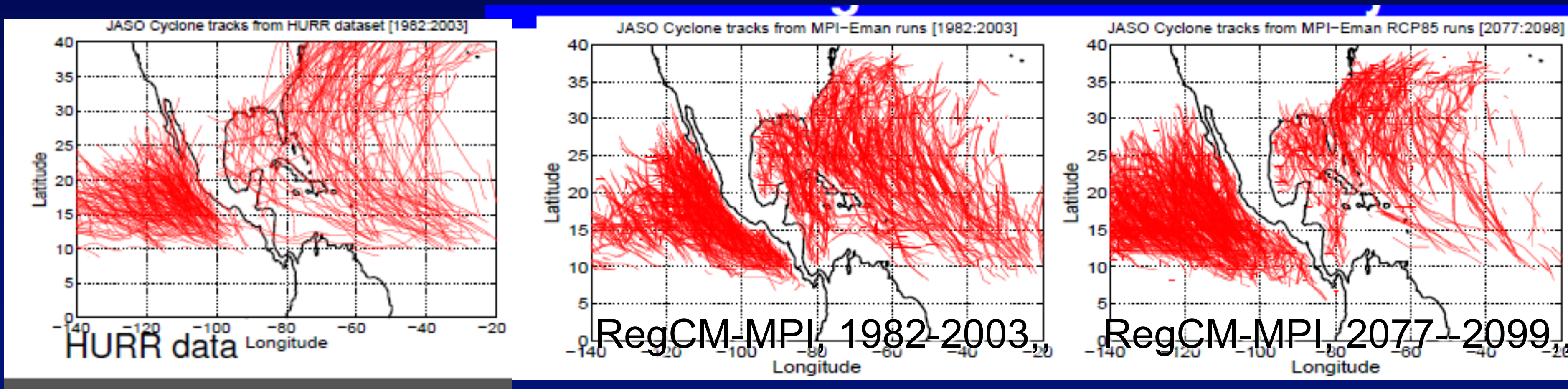
Collaboration across
ICTP
U. San Paolo (Brazil)
CICESE (Mexico)
Indian Institute of technology
U. Dakar (Senegal
DHMZ (Croatia)

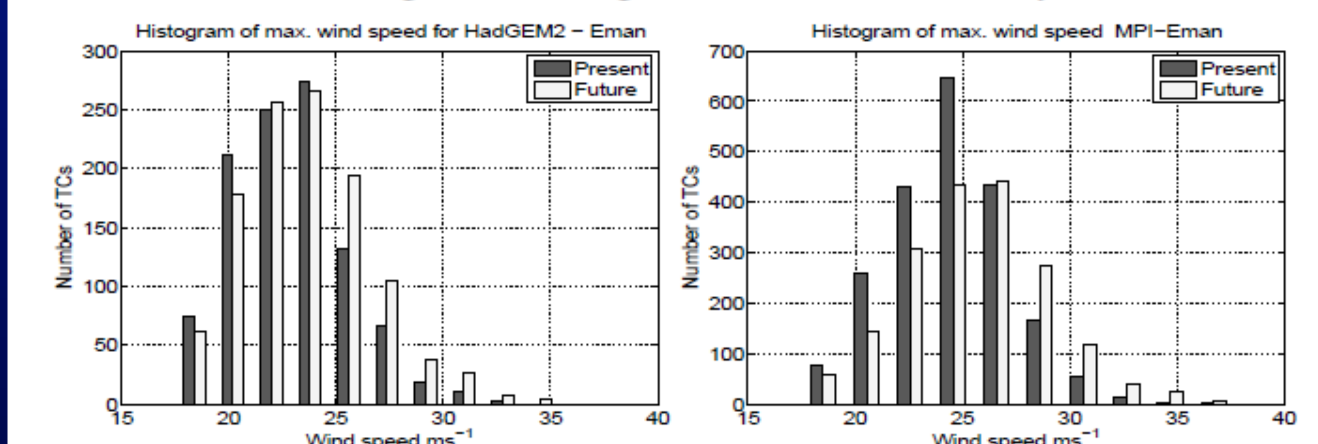
Special Issue of Climatic Change (2014)

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

Change in tropical cyclones
(Diro, Fuentes-Franco et al. 2014)





A decrease in the weak TCs but an increase in the frequency of the strongest TCs

Emerging scientific challenges

- ✧ **Added value**

Internal variability & added value as functions of scale; Very high resolution modeling; Bias correction uncertainties and consistency

- ✧ **Human element**

Coupling of regional climate and urban development (e.g. coastal megacities); Land use change; Aerosol effects.

- ✧ **Coordination of regional coupled modelling**

Ocean-ice-atmosphere; Lakes; Dynamic land surface; Natural fires; Atmospheric chemistry; Carbon cycle; Aerosols; Marine biogeochemistry

- ✧ **Precipitation**

Extremes; Convective systems; Coastal storm systems; MJO/Monsoon

- ✧ **Local wind systems**

Wind storms; Strong regional winds; Wind energy

Future plans, CORDEX2: Flagship Pilot Studies

Effects of regional forcings
Land-use change
Urbanization
Aerosols

Intercomparison of different downscaling techniques (e.g. RCM, ESD)

Interactions with other WCRP projects (e.g. GEWEX)

Modeling (Added Value) at multiple scales, down to convection permitting.
Model development

Availability/production of high quality, high resolution, multiple variable observations

Development of coupled Regional Earth System Models (RESMs)

Relevance for VIA and adaptation/policy applications
Input to WGRC
FRONTIER PROJECTS

Production of large ensembles for uncertainty characterization

Study of phenomena relevant for regional climate and impacts through targeted experiments (e.g MCS, TC, extremes, monsoon)

Future plans CORDEX2: The COmmon Regional Experiment (CORE) Framework

- Main motivations
  - Call by IPCC for a greater role in the next report, and in particular for the production of a CORDEX based “Atlas like” product. (June 2020)
  - Call by IPCC to contribute to the 1.5C special report (March 2018)
  - Natural evolution of CORDEX1
- Main issues with the present (CORDEX1) framework
  - Large inhomogeneity of information (experiments) across different domains (Europe vs. Australia and Central Asia)
  - Relatively coarse resolution, in particular vs. the planned CMIP6 GCM experiments
  - Need of reasonably comprehensive and representative M^n ensembles

The COmmon Regional Experiment (CORE)

- Current thinking:
  - Step 1: Use a core set of RCMs to downscale a core set of GCMs over all (or most) CORDEX regions for a core set of scenarios (Core^3)
  - Step 2: Incrementally augment the Core^3 ensemble with further models/ experiments (i.e. open process).

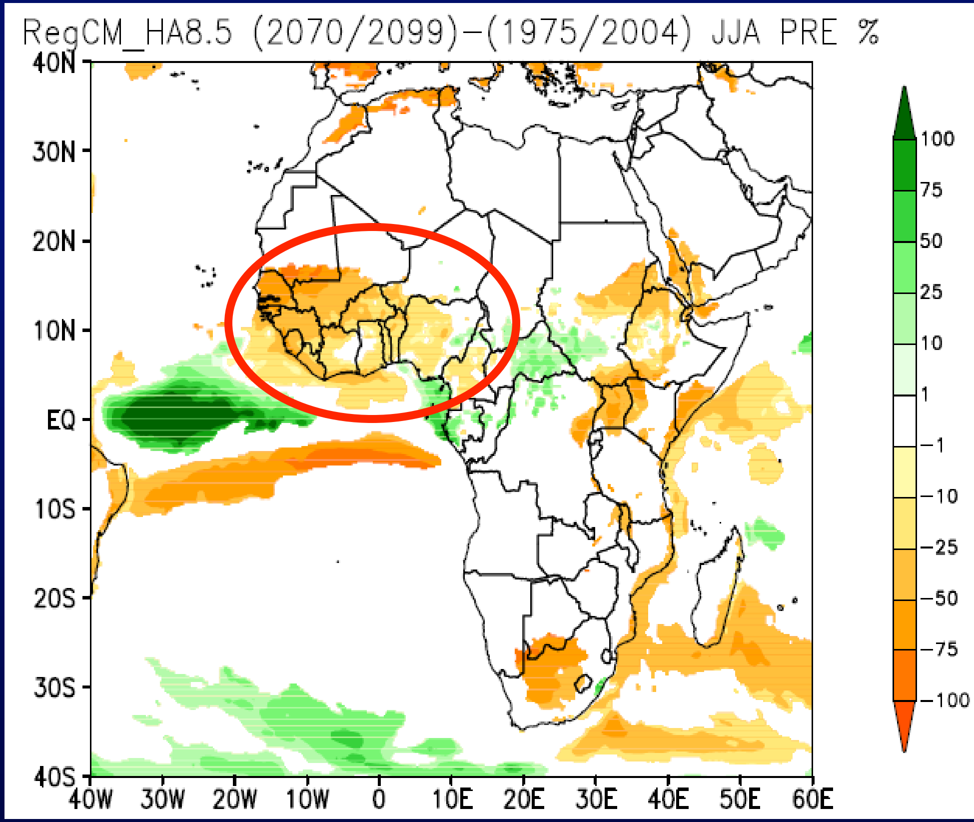
Main CORE issues to be discussed

- How many RCMs? (Community RCMs? ~5?)
- How many GCMs? (5-6?)
- Resolution? (Somewhere between 10 and 25 km).
- Priority scenarios? (RCP2.6, RCP8.5)
- CMIP5 or CMIP6 GCMs?
- How to choose GCMs? Common for all regions?
- What data to be stored? (Minimum set)
- How to incorporate ESD?
- Resources?
- Timeline?
- We need to discuss these issues in our RegCM community

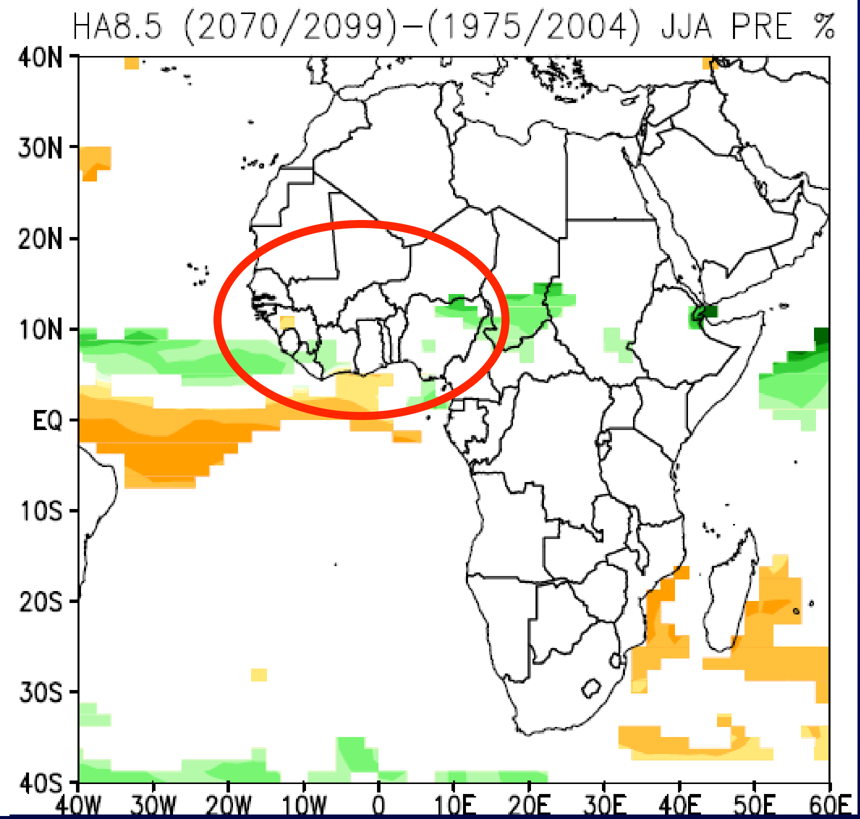

Thank You

West Africa:
JJA precipitation change

HAD-RegCM4



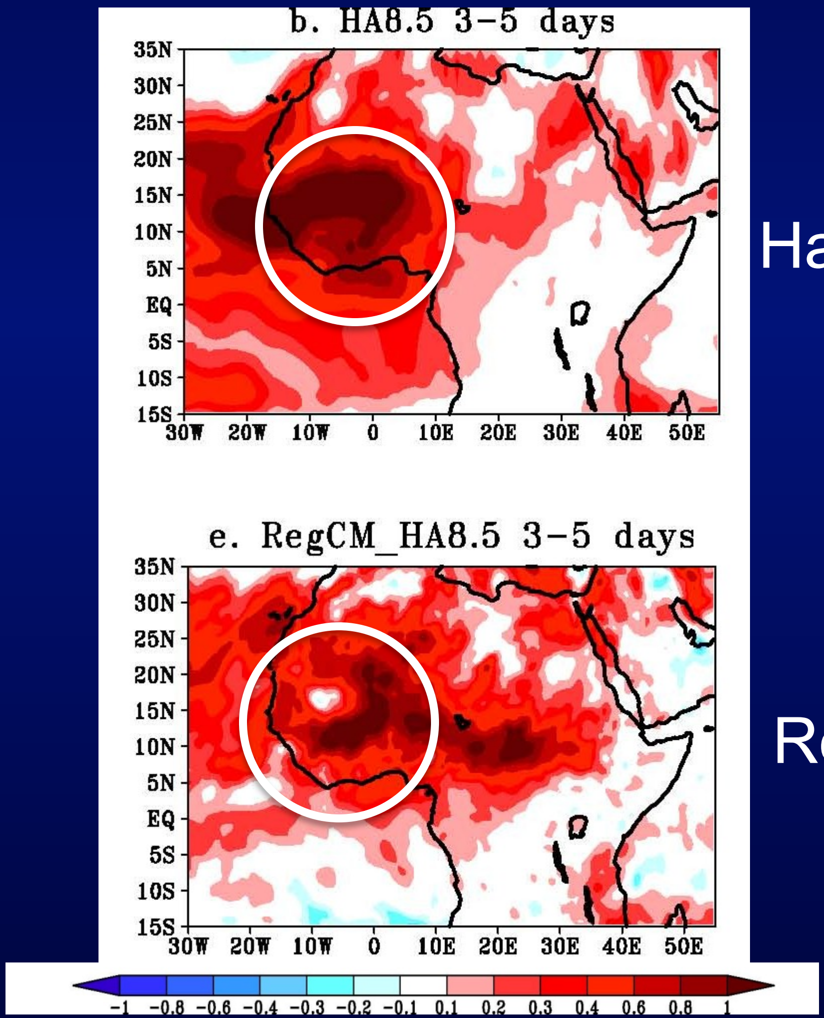
HADGEM



West Africa: Change in AEW activity

Change, 3-5 days filter

Change, 6-9 days filter



HadGEM

RegCM4