Sources of uncertainty in regional climate "prediction"

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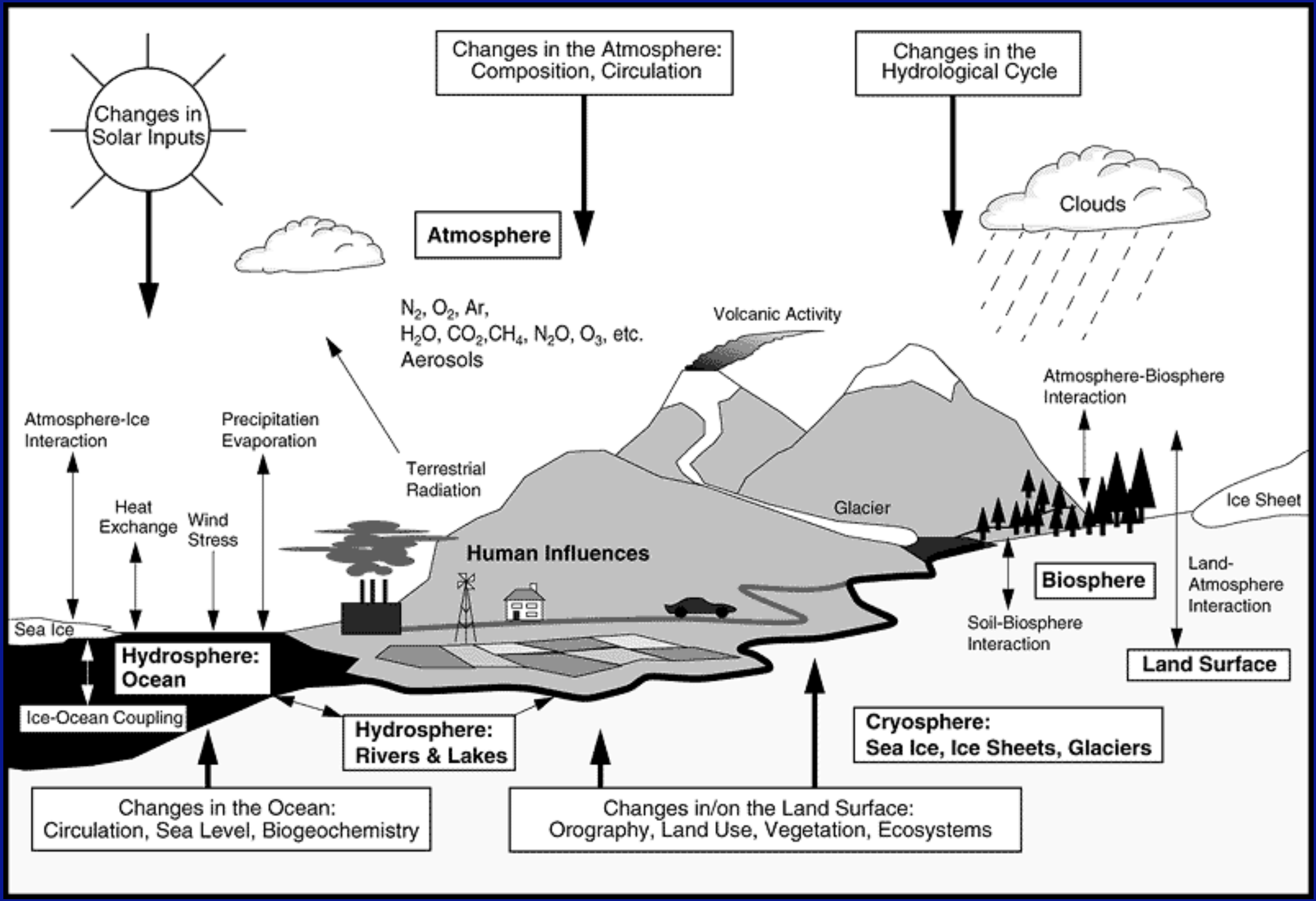
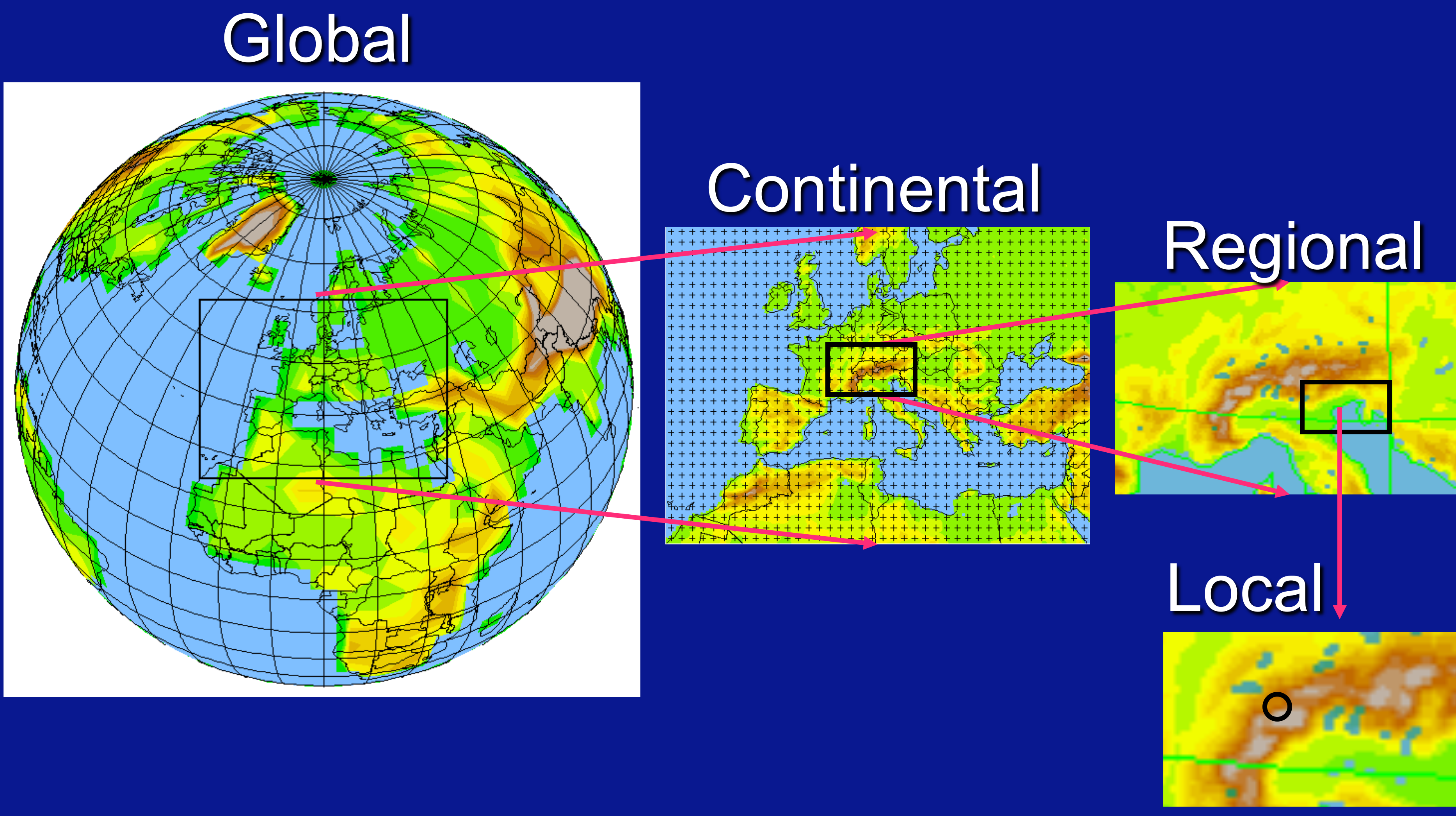
The Earth system is one of the most complex entities in science

We live in a highly non-linearly coupled Climate System characterized by a range of spatial and temporal scales



Climate change needs to be simulated at multiple spatial scales

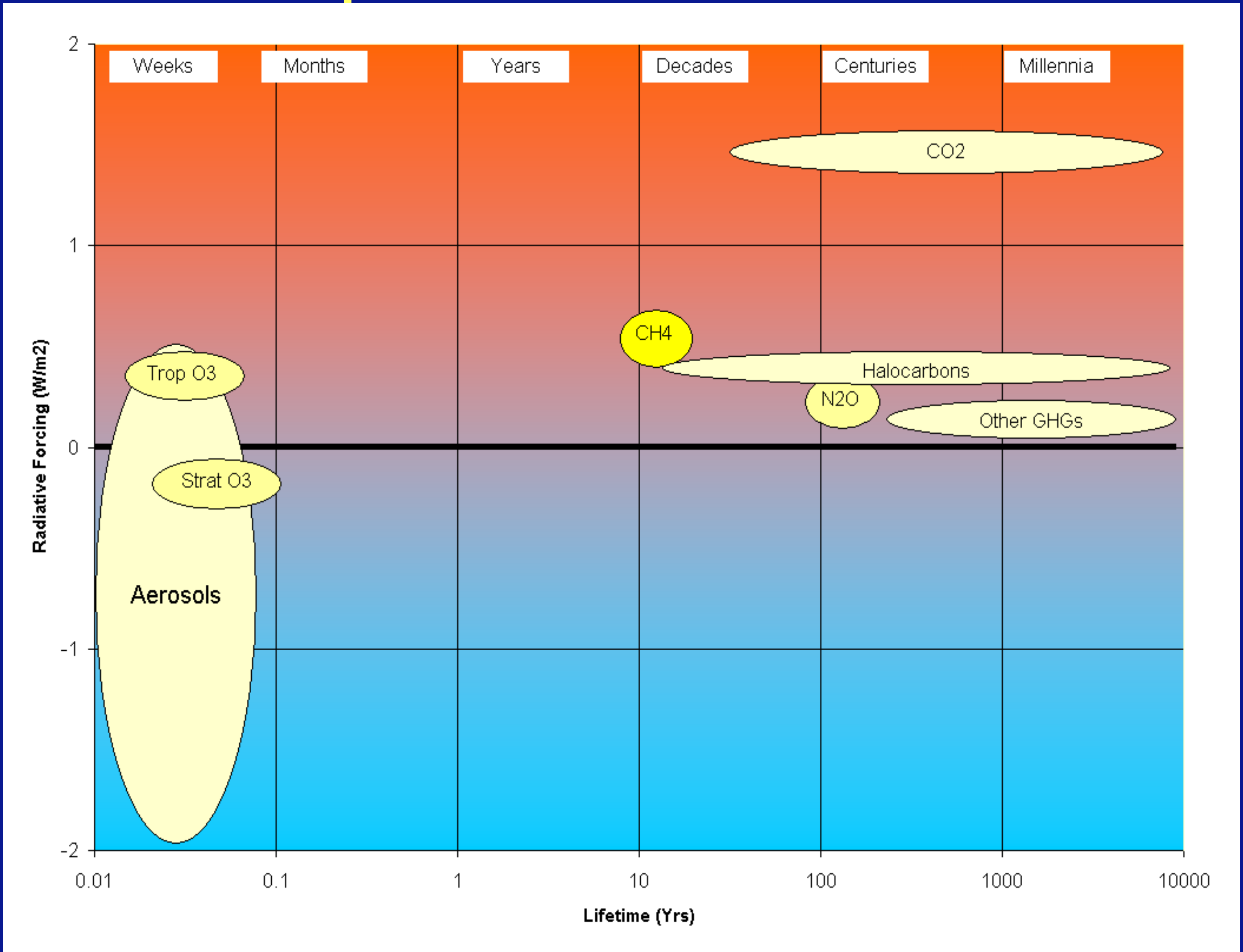


Climate forcings act on multiple temporal scales

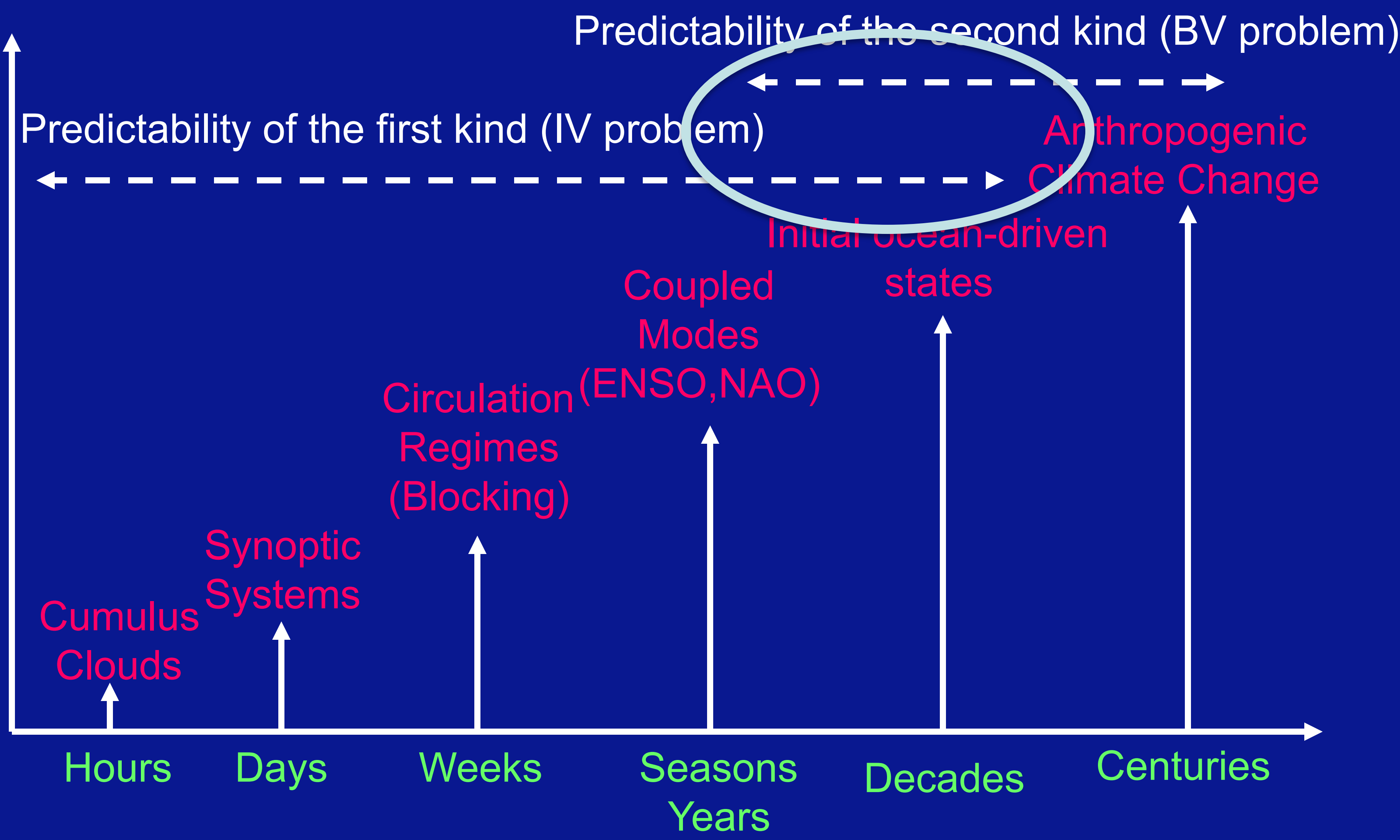
Many key warming agents live for decades or more

All known cooling agents are relatively short-lived

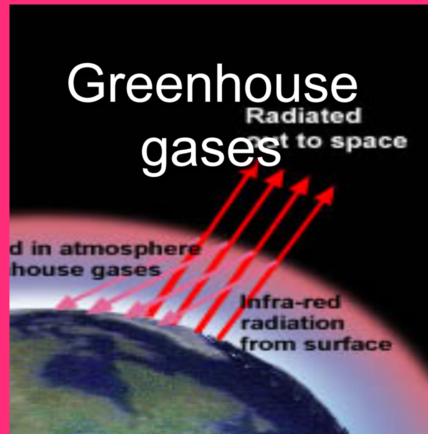
-> implications for short and long-term effects and options

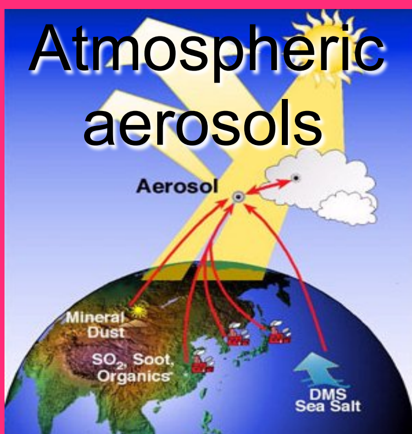


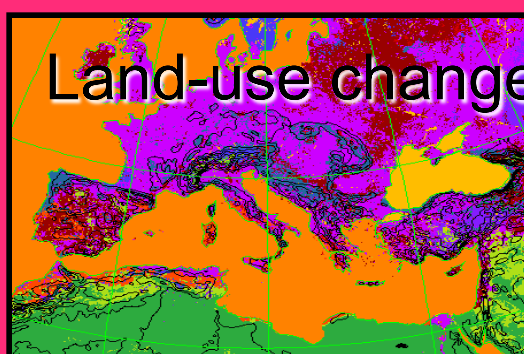
Range of Predictability for Different Phenomena



Human factors

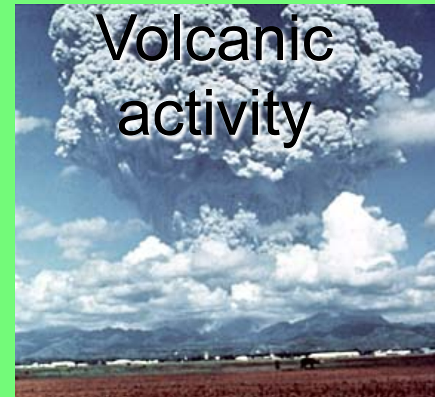


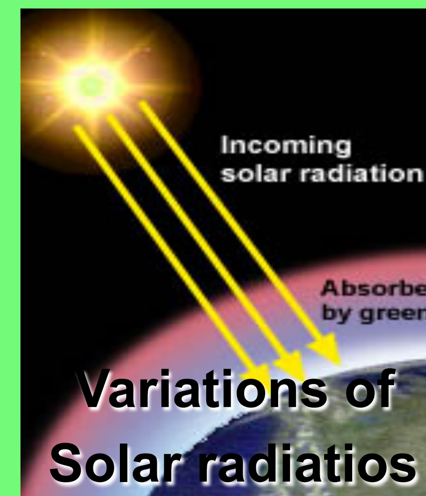


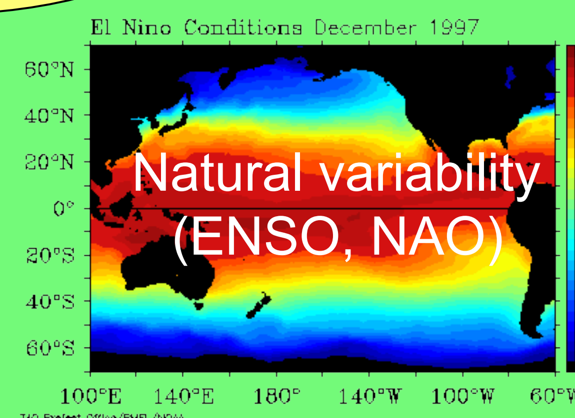


The earth's climate can change because of anthropogenic or natural factors

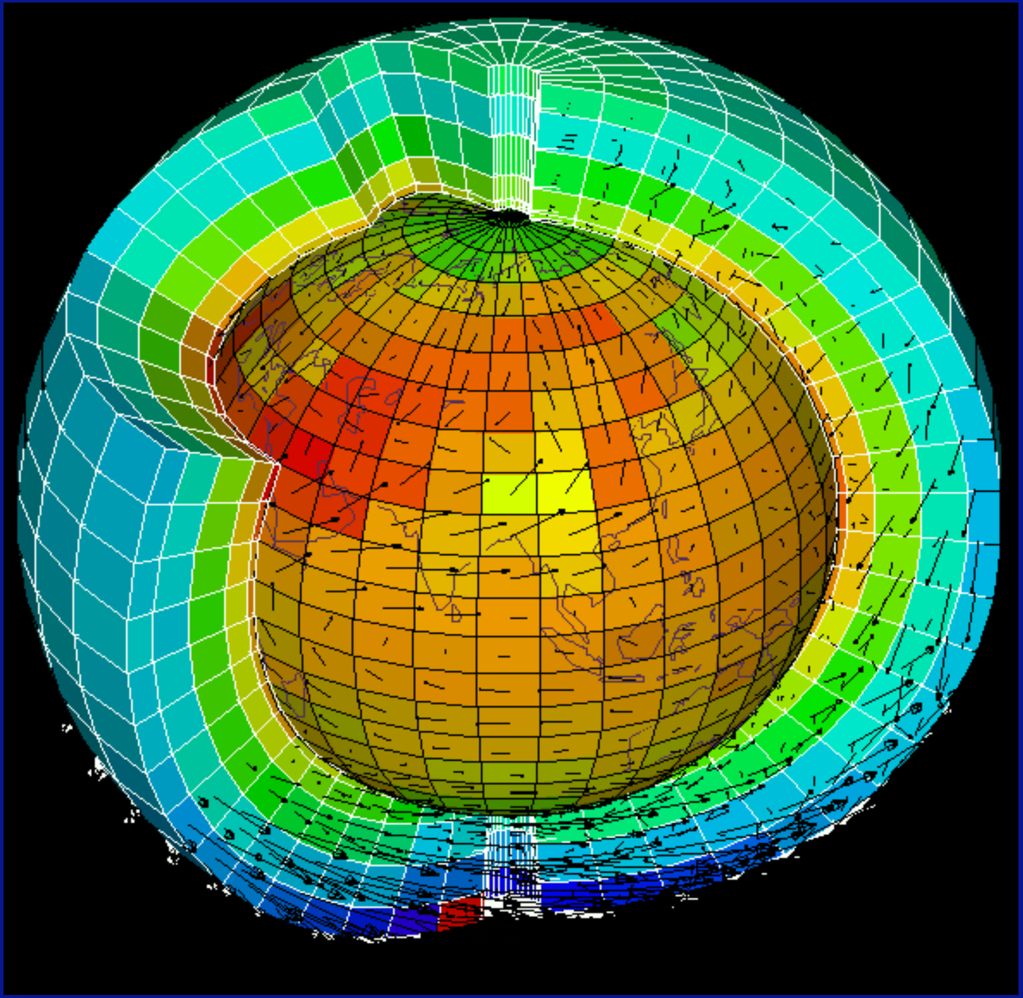
Natural factors







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

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

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

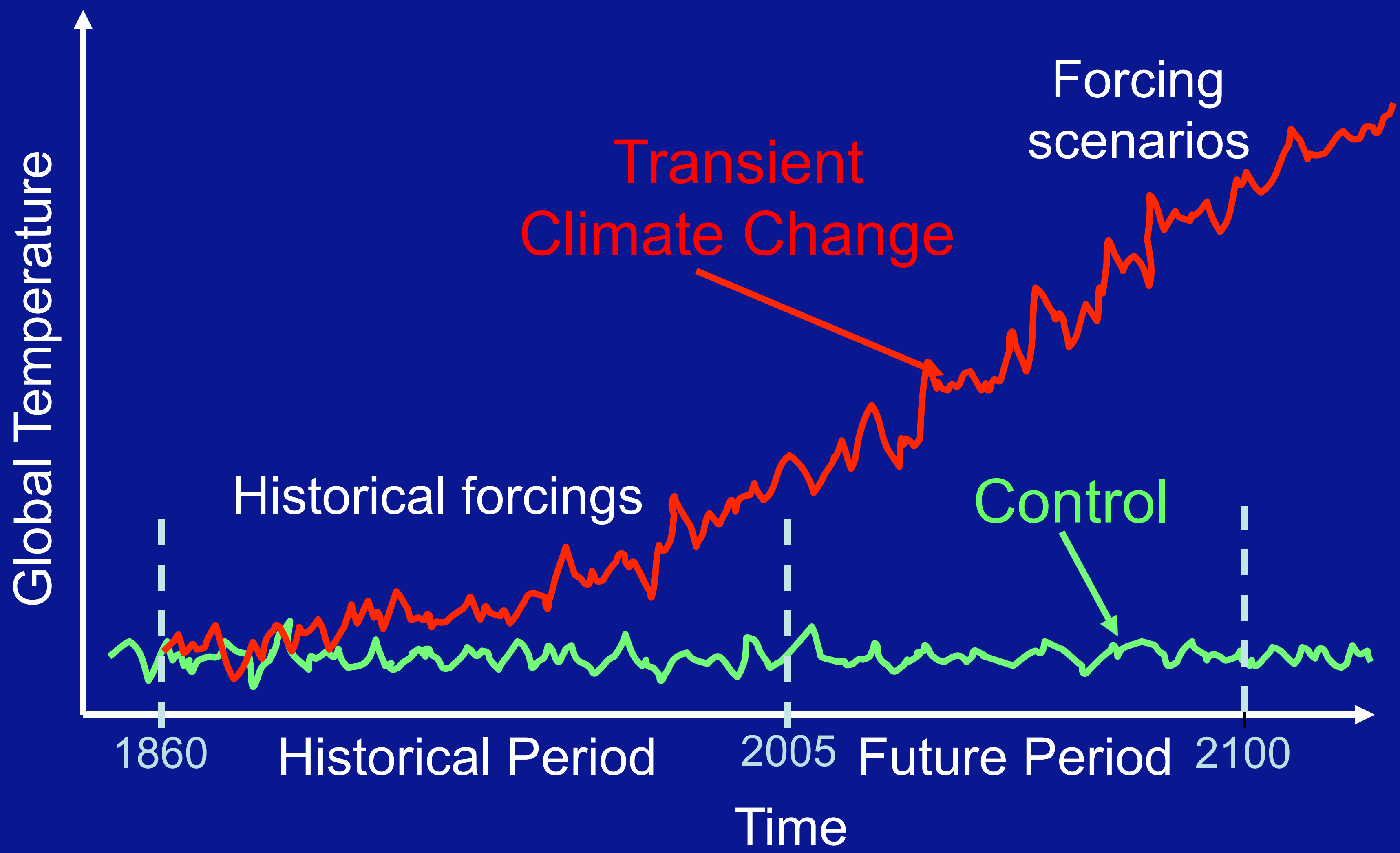
$$\frac{\partial q}{\partial t} + \overline{V} \cdot \nabla q = \frac{S_q}{\rho} + F_q$$

Conservation of water

$$p = \rho R T$$

Equation of state

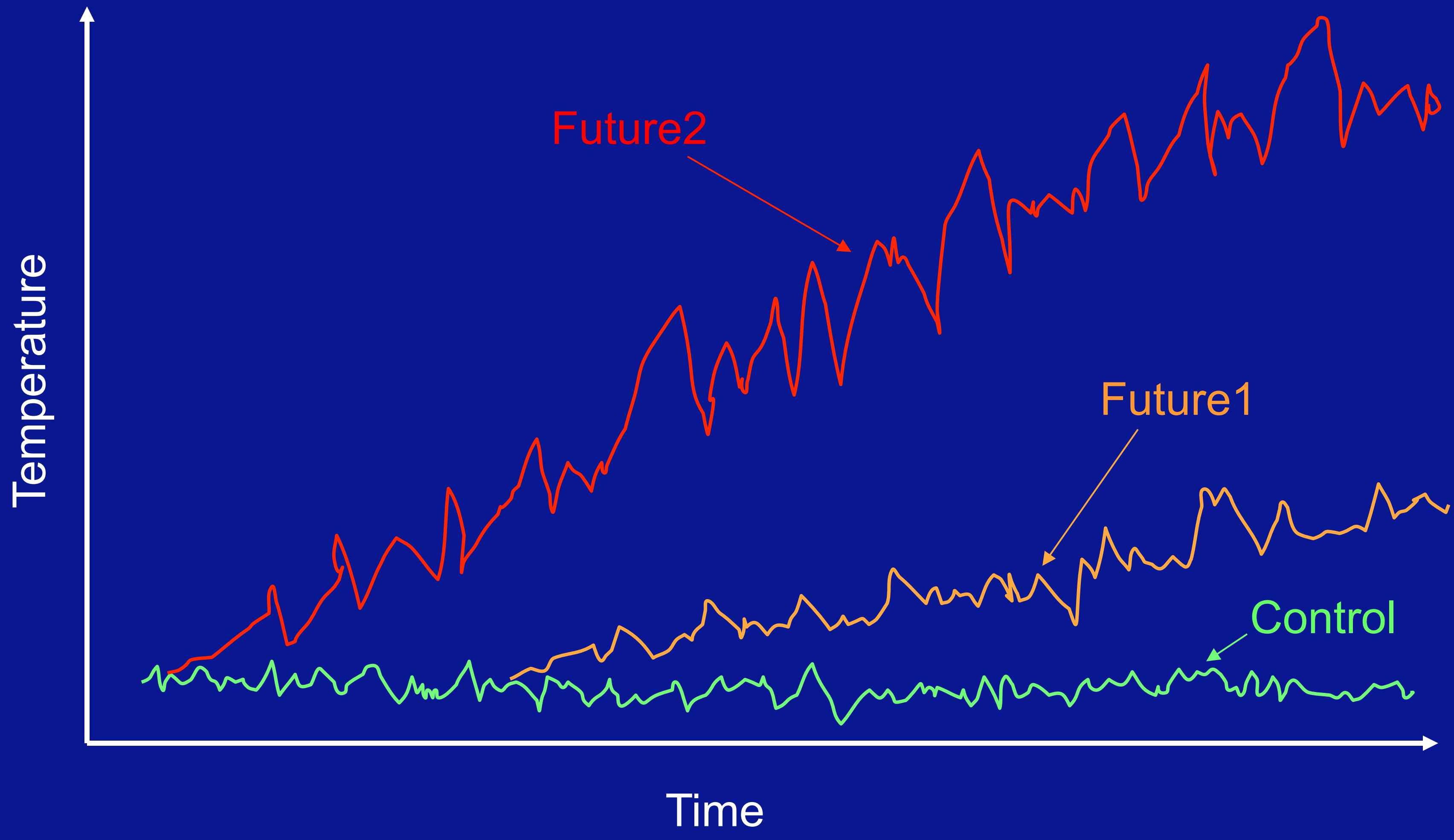
Transient Climate Change Simulation



Intrinsic Uncertainties in Climate Change Prediction:
Initial Conditions of the Climate System

- We do not know with good accuracy what the initial conditions of the climate system were at the beginning of the "Industrialization Experiment"
  - Initial ocean state
  - Initial biosphere state
  - Initial cryosphere state

Climate can evolve differently depending on the initial conditions of its slow components



Intrinsic Uncertainties in Climate Change Prediction: Unpredictability of External Forcings

- Unpredictable Natural Forcings
  - Volcanic activity
  - Solar activity
- Unpredictable, or little predictable, anthropogenic forcings (e.g. GHG and aerosol emissions, land-use change)
  - Social and economic development
  - Technological advances
- Development of scenarios rather than predictions of forcings
  - "Projection" vs. "Prediction" of climate change

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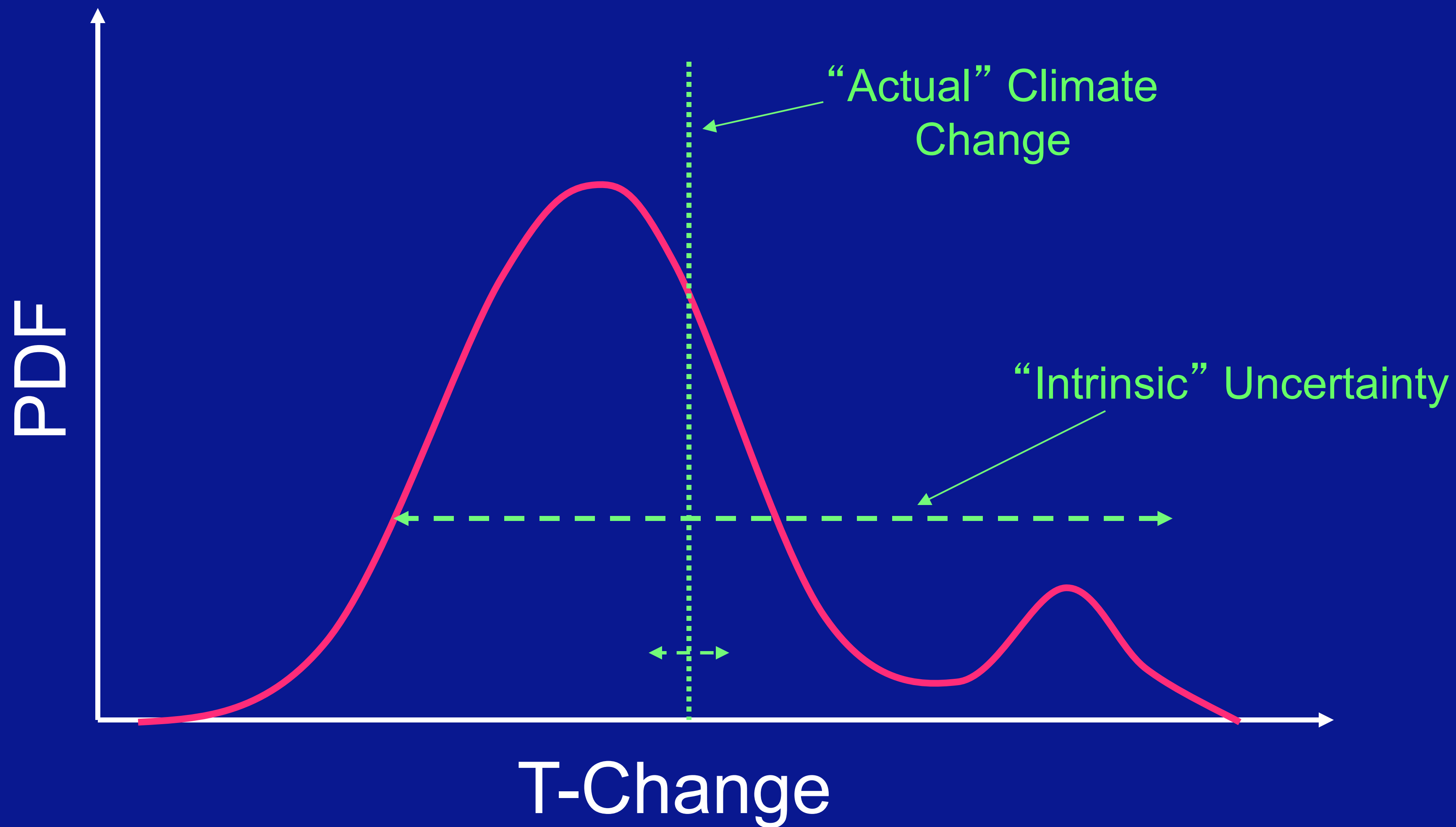
Intrinsic Uncertainties in Climate Change Prediction:
Non-linearities,Thresholds and Feedbacks

- Feedbacks within the climate system can enhance its non-linearity and thus decrease predictability
  - Cloud feedback
  - Tropical convection
  - Snow and sea-ice albedo feedback
  - Biogeochemical / hydrologic feedbacks
  - Adaptation / mitigation feedbacks
- Threshold behaviors also enhance nonlinearity and decrease predictability
  - Shut down of the Thermohaline Circulation
  - Melting of Greenland and Antarctic Ice Sheets

The Climate Change Prediction Problem

Because of the internal variability and non-linearity of the climate system, the presence of feedbacks, and the random component of the external natural and anthropogenic forcings, the “actual” climate change is only one (essentially unpredictable) realization within a range of possible realizations, each characterized by a certain likelihood to occur

Climate Change PDF



The Climate Change Prediction Problem

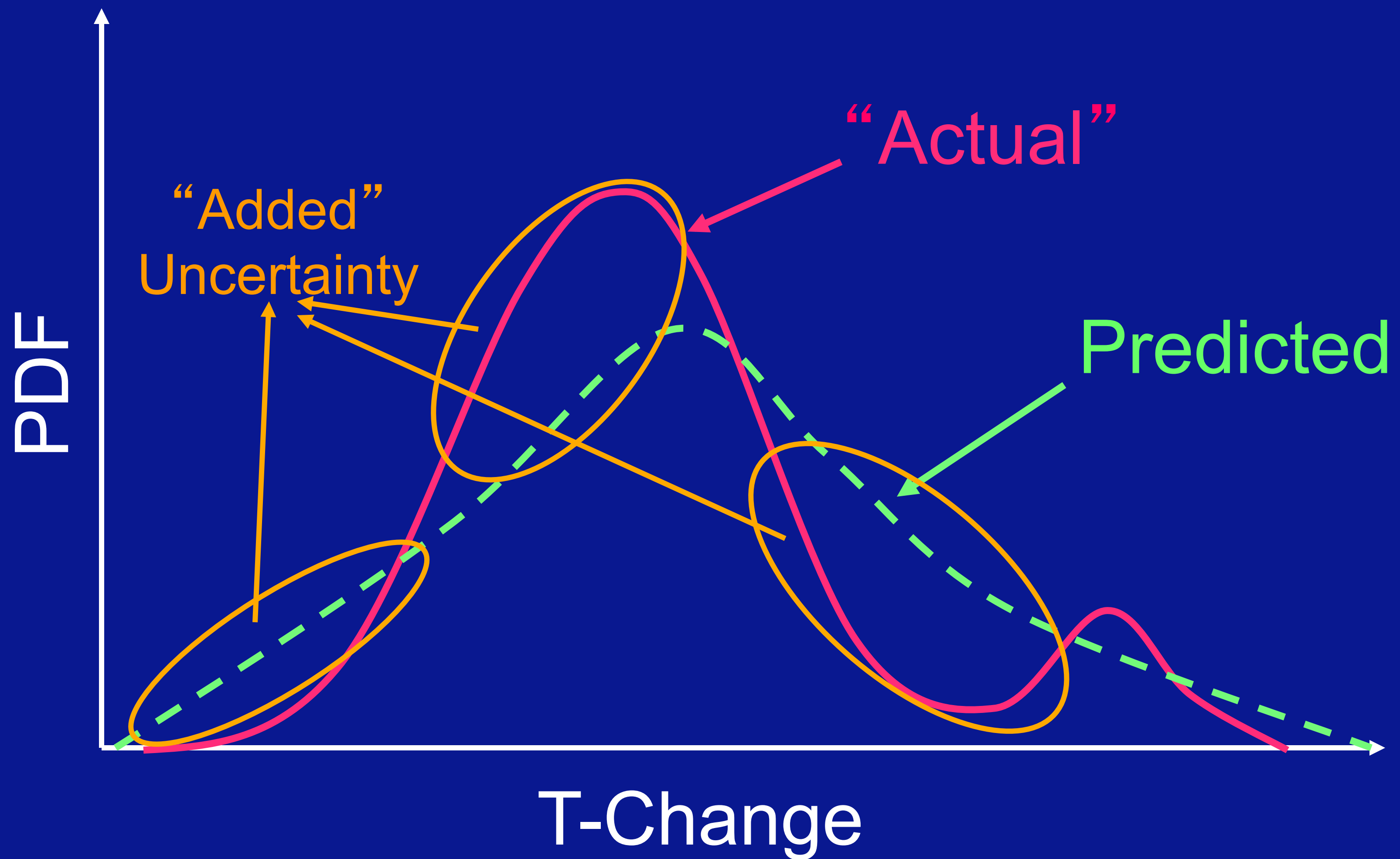
The purpose of climate prediction is not to predict what will be the exact climate of the future, but to reconstruct as closely as possible the PDF of possible future climates. This implies that:

Climate change prediction needs to be approached in a probabilistic way.

There are also many sources of "added" uncertainty:

- Imperfect knowledge of processes
- Imperfect observations
- Imperfect models
- Imperfect analyses and approaches
- And probably many more ...

Predicted vs. “Actual” Climate Change PDF



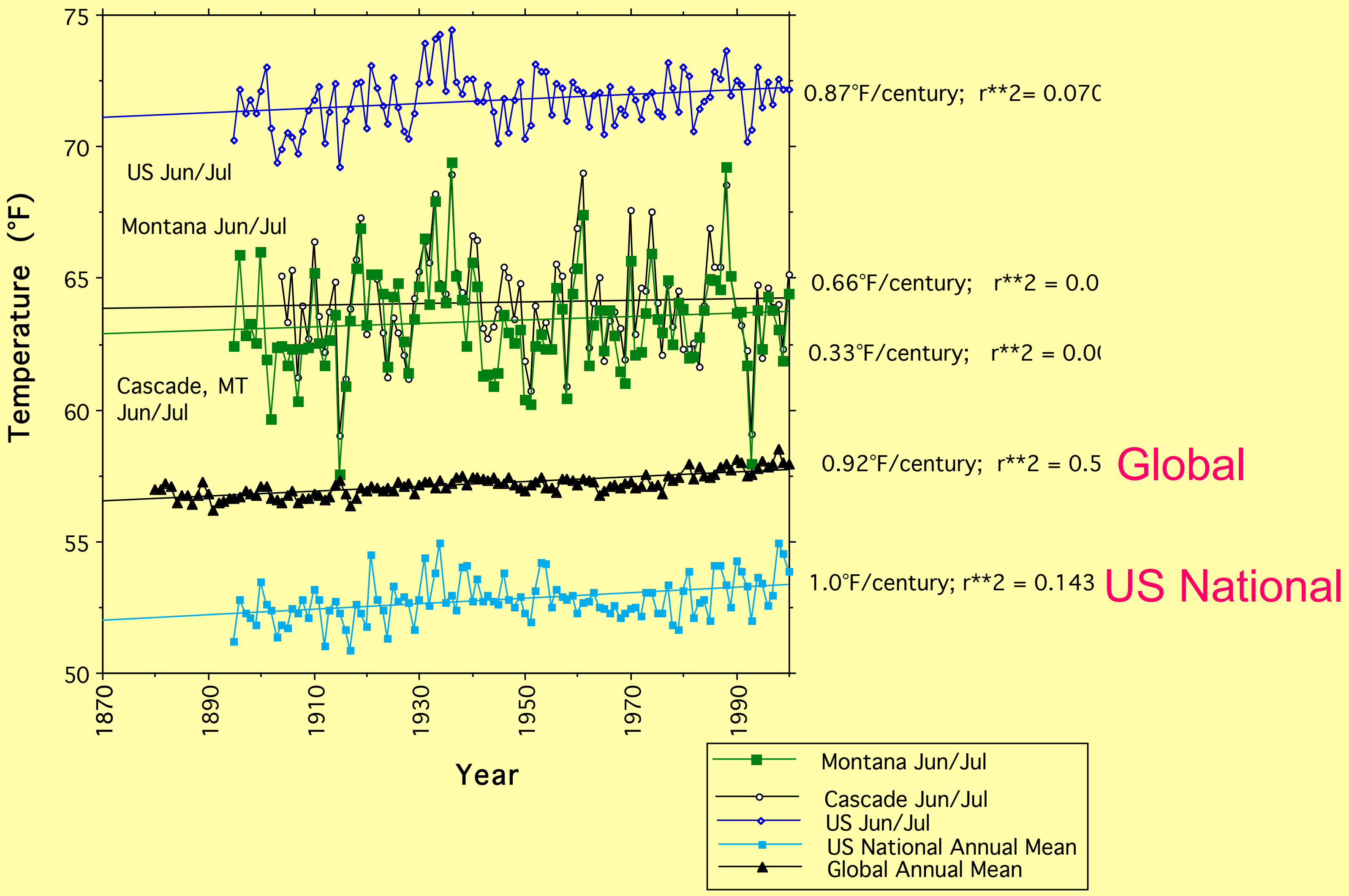
The uncertainty "dilemma"

- We need to characterize as much as possible the "intrinsic" uncertainty
  - Wide PDF
- But we need to reduce as much as possible the "added" uncertainty
  - Narrow PDF
- We do not have specific case studies to test our anthropogenic climate change "predictions", e.g. as in weather and seasonal forecast, and as a result it is critical to evaluate and possibly quantify their reliability
  - Process understanding
  - Model fidelity
  - Seemless prediction
  - Inter-model agreement
  - Consistency with observed trends
  - <u>Multiple evidence</u>

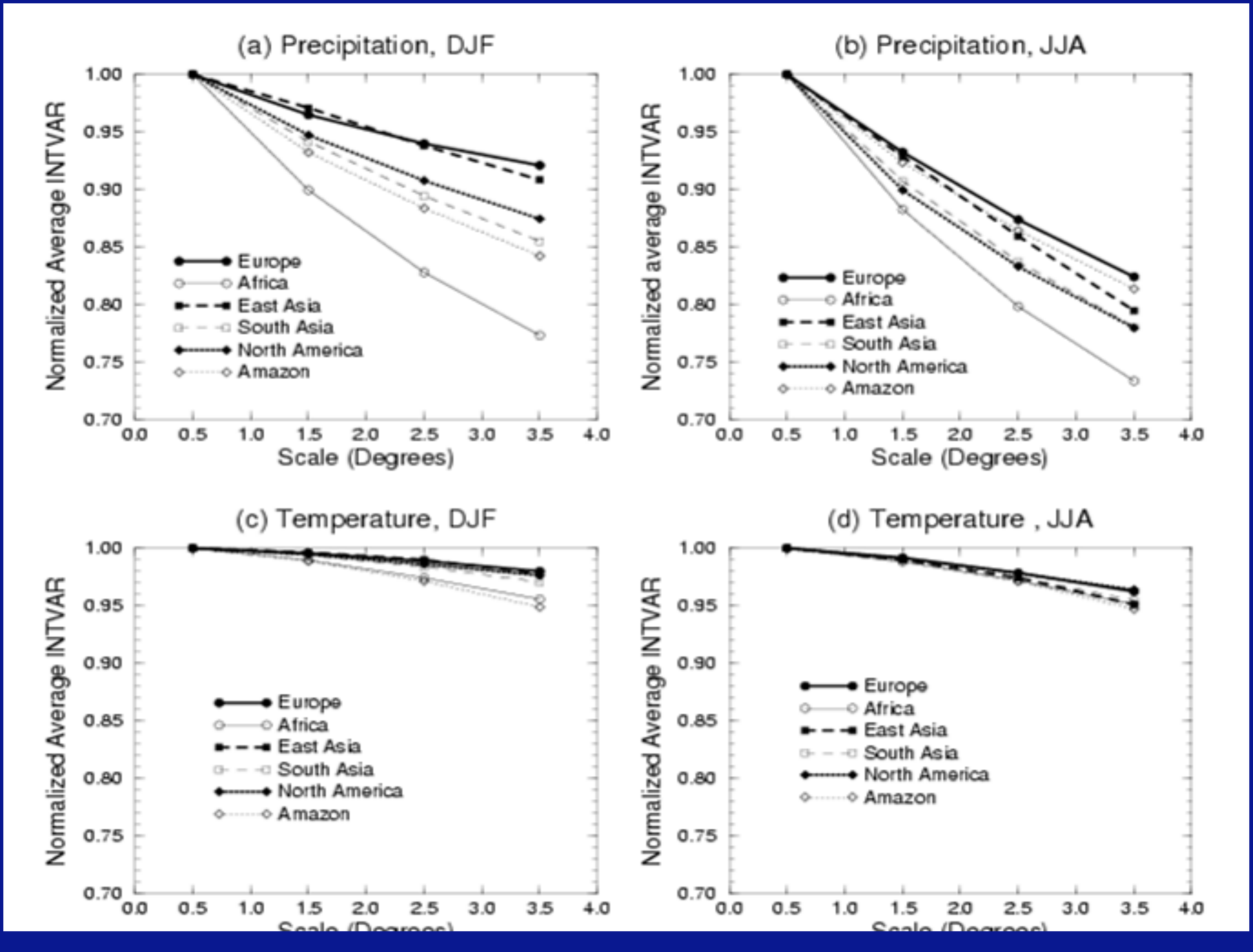
Regional vs. Global Climate Change Prediction

- Climate change prediction is more difficult at the regional than the global scale
  - Natural variability increases at finer scales, which makes the extraction of the change signal from the underlying noise more difficult
  - Changes in circulation structure, regimes and natural climate modes are more important at the regional scale: regional climate is more non-linear
  - Regional climates are affected by local scale forcings and processes that are not adequately resolved by climate models

Observed Temperature Trend

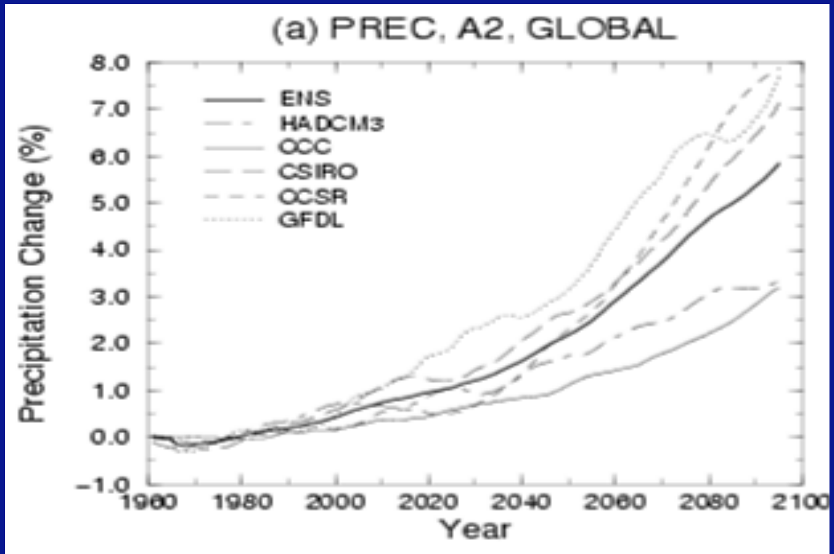


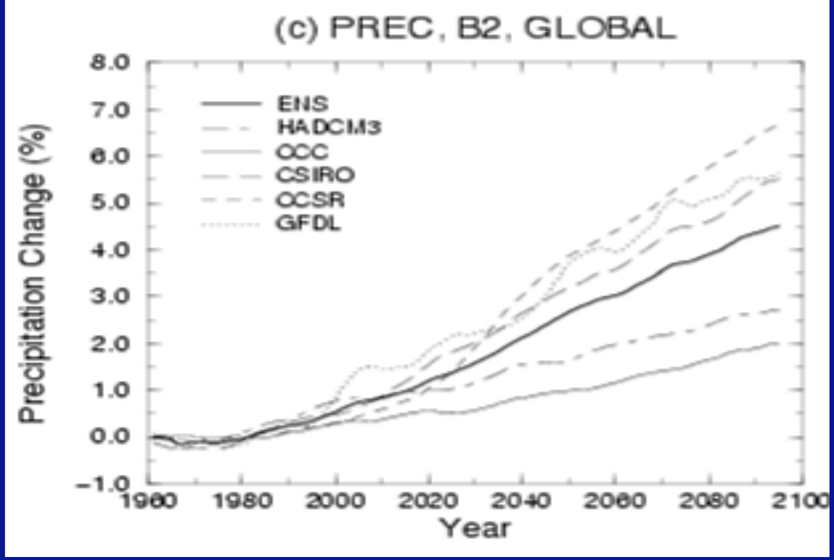
Sensitivity of interannual variability to spatial scale (Giorgi 2003)



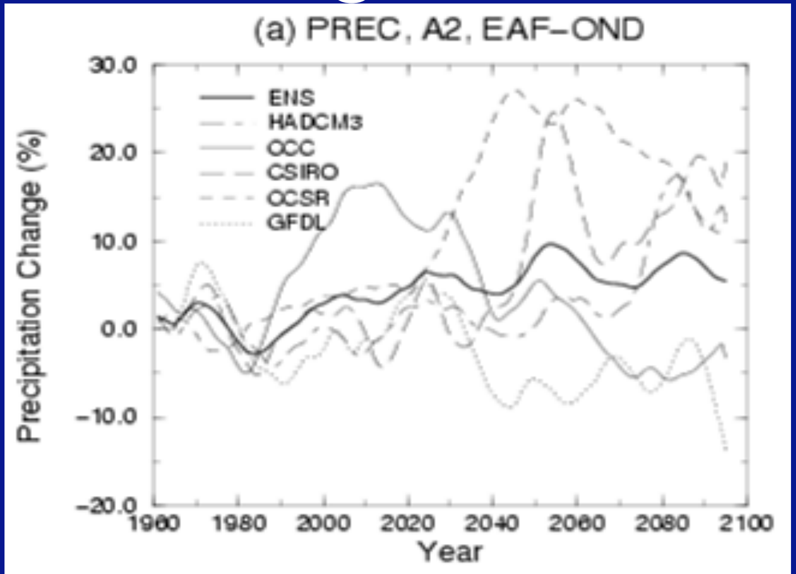
Precipitation change

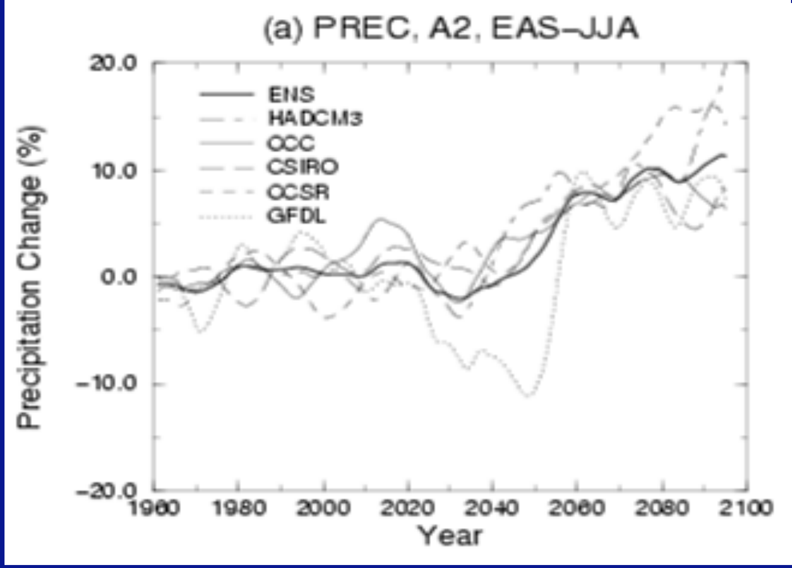
Global



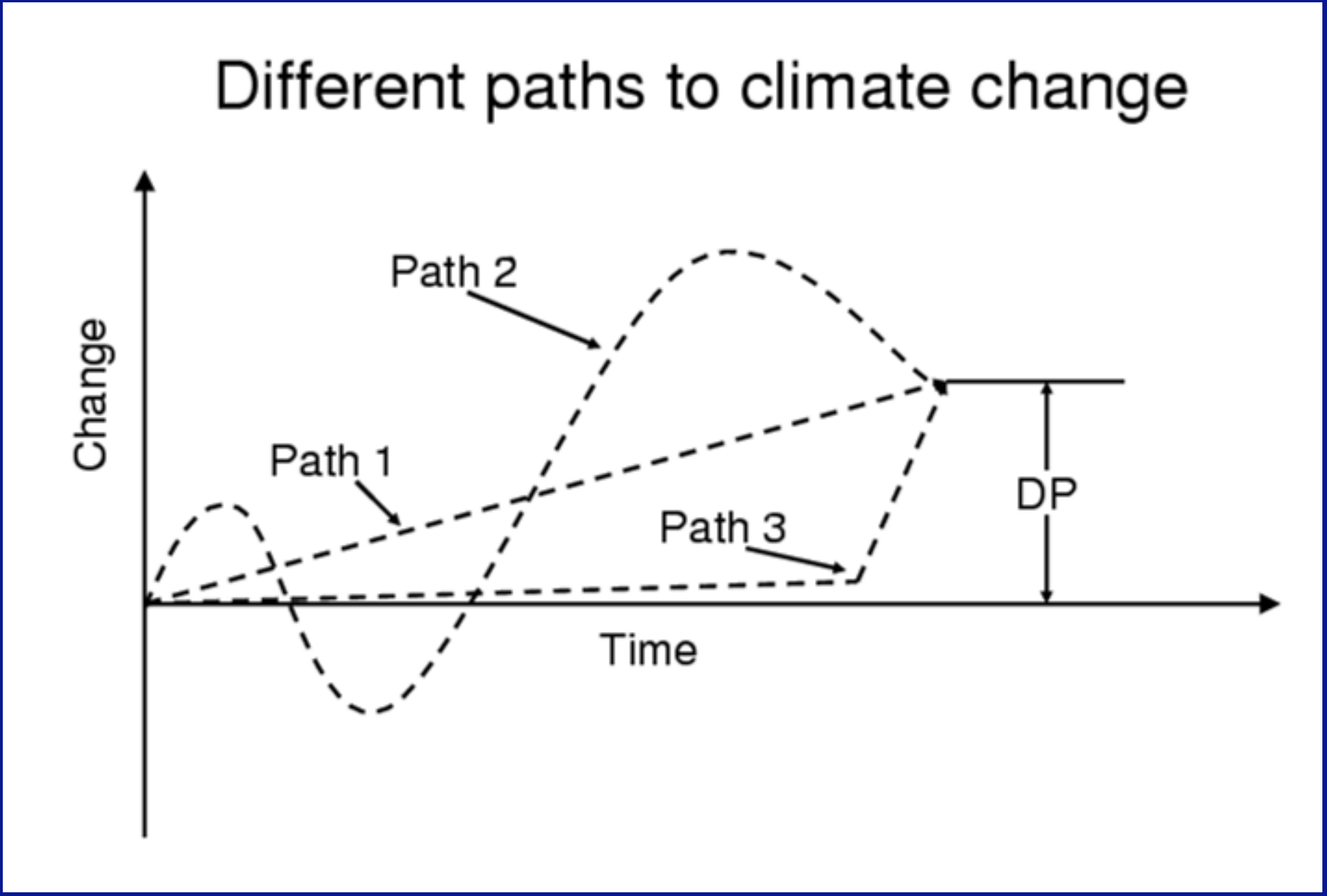


Regional





The "path" to regional climate change may be important for impacts



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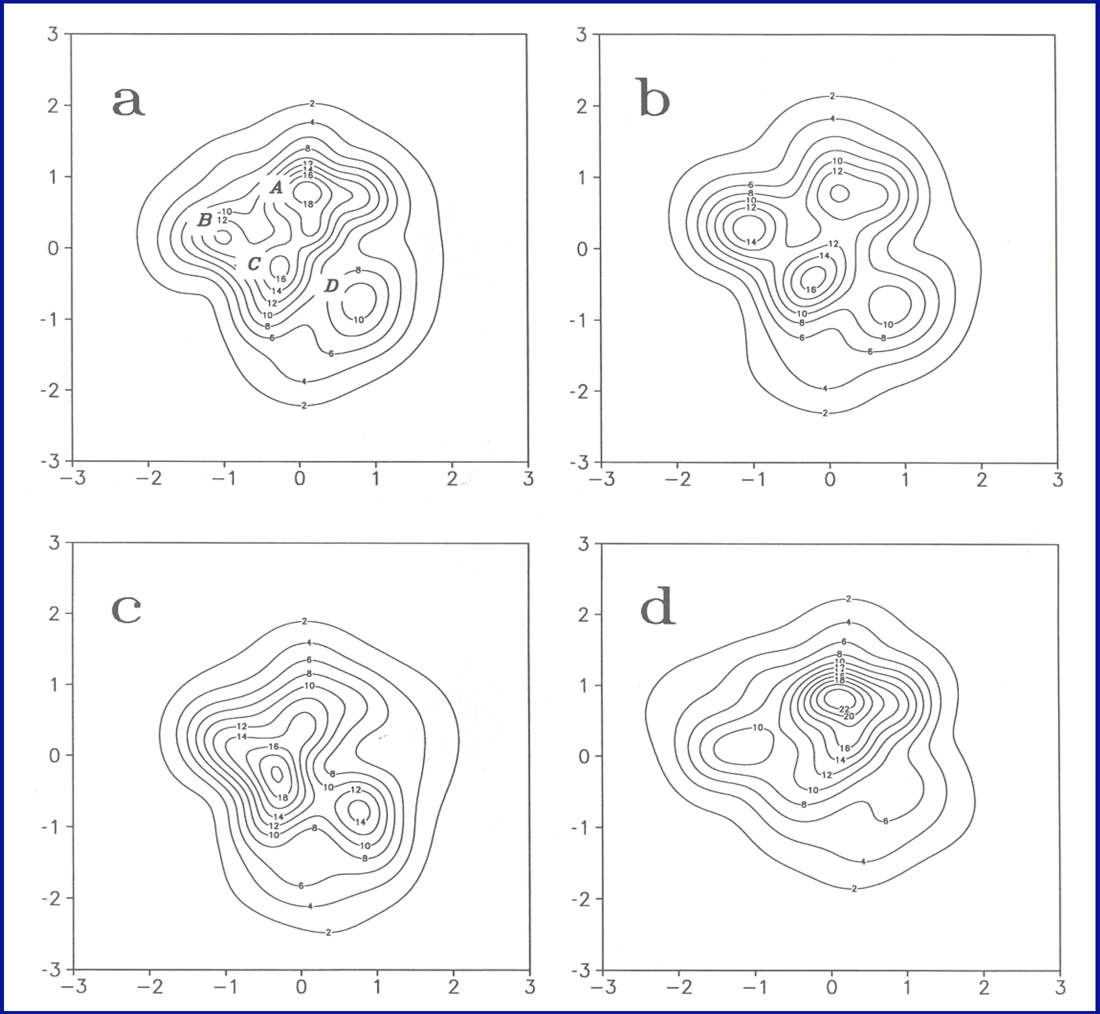
PDF of 500 Hpa Height (Corti et al. 1999)

1949 / 94

1949 / 94
No EN-LN



1949 / 71

1971 / 94

Climate Change can modify the frequency and/or structure of weather regimes

Regional vs. Global Climate Change Prediction

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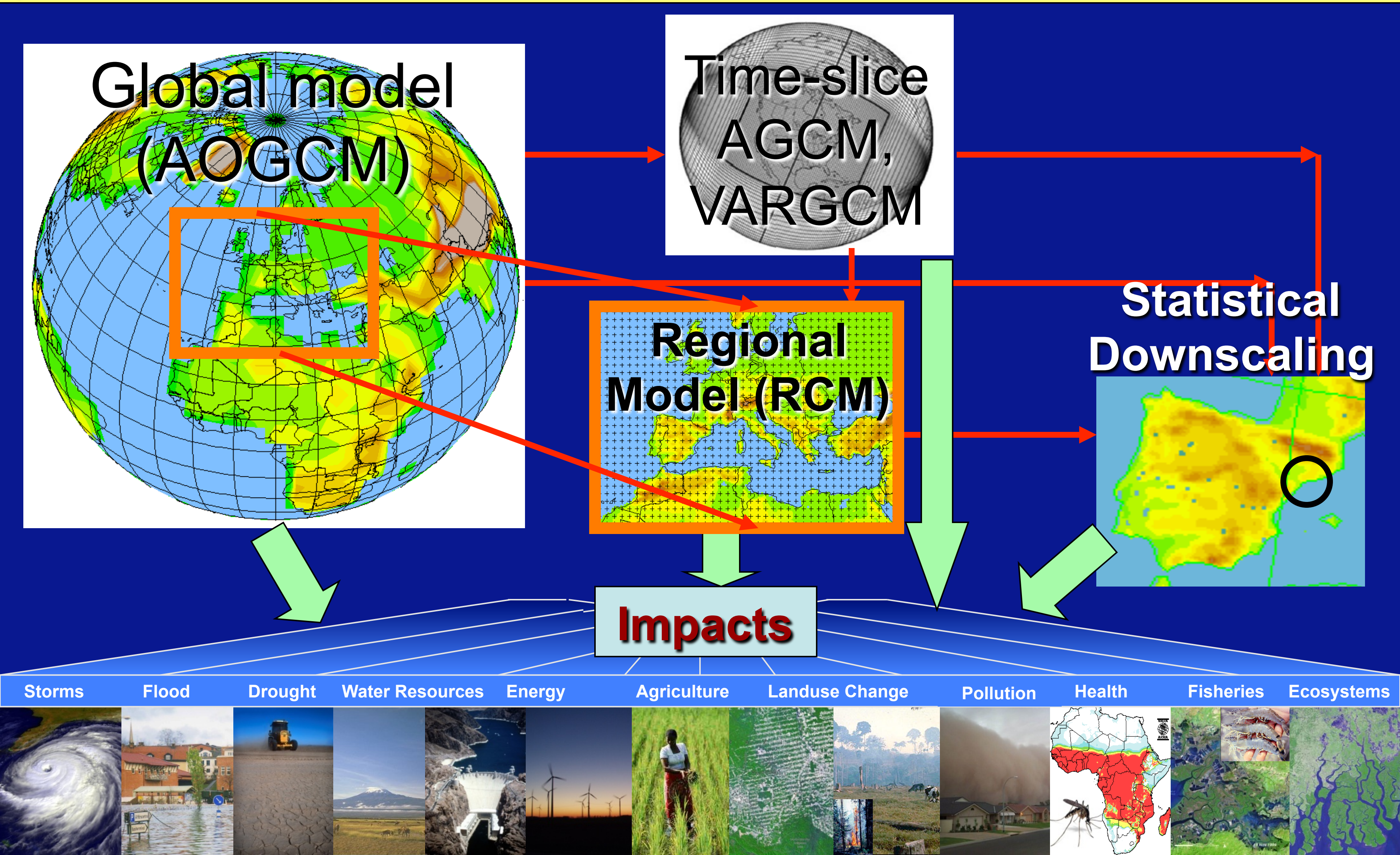
  - Changes in circulation structure, regimes and natural climate modes are more important at the regional scale: regional climate is more non-linear
  - Regional climates are affected by local scale forcings and processes that are not adequately resolved by global climate models (topography, landuse, aerosols, extremes etc.)

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



“Nested” Regional Climate Modeling: Technique and Strategy

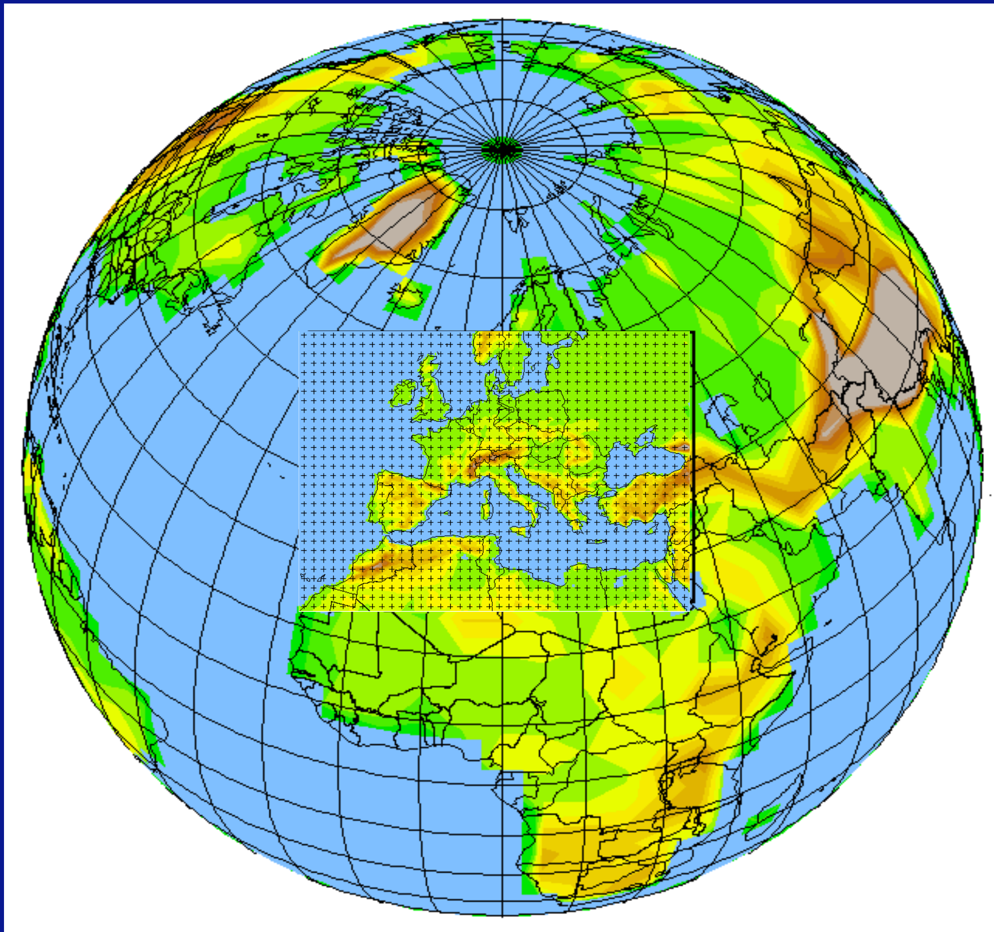
Motivation: The resolution of GCMs is still too coarse to capture regional and local climate processes

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

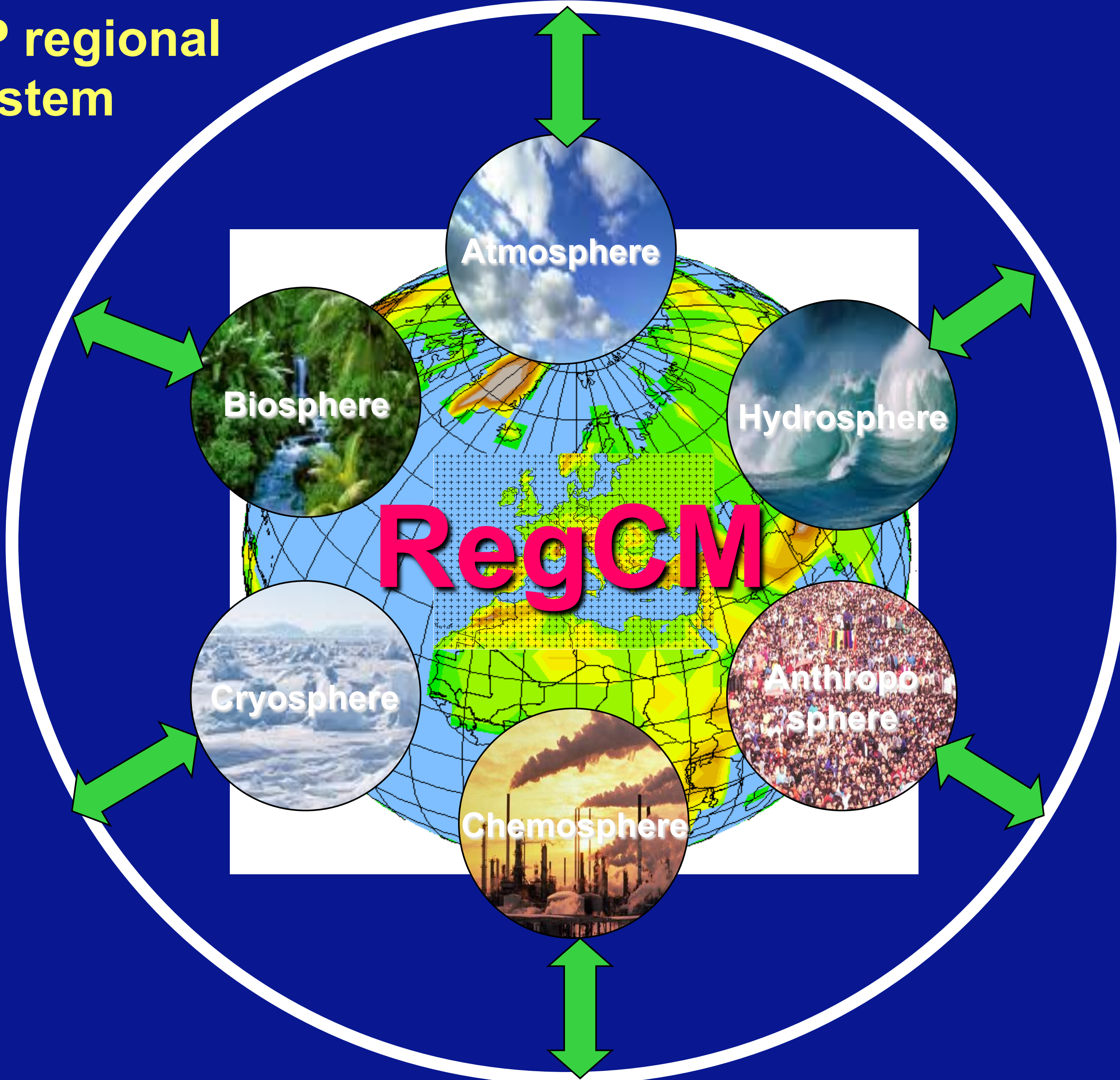
- Initial conditions (IC) and lateral boundary conditions (LBC) for the RCM are obtained from the GCM (“One-way Nesting”) or analyses of observations (perfect LBC).

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

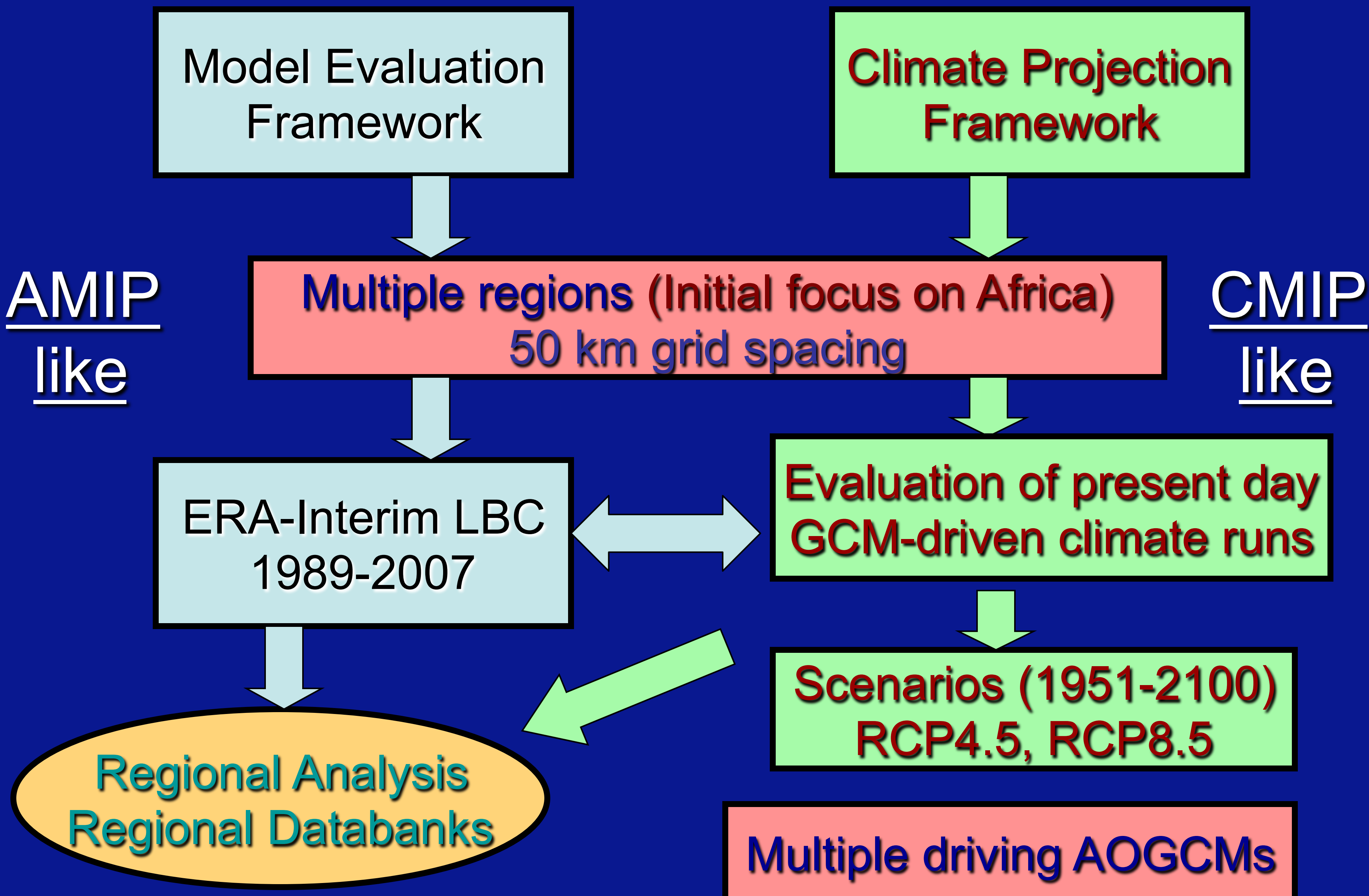
- Technique borrowed from NWP



The ICTP regional Earth System Model

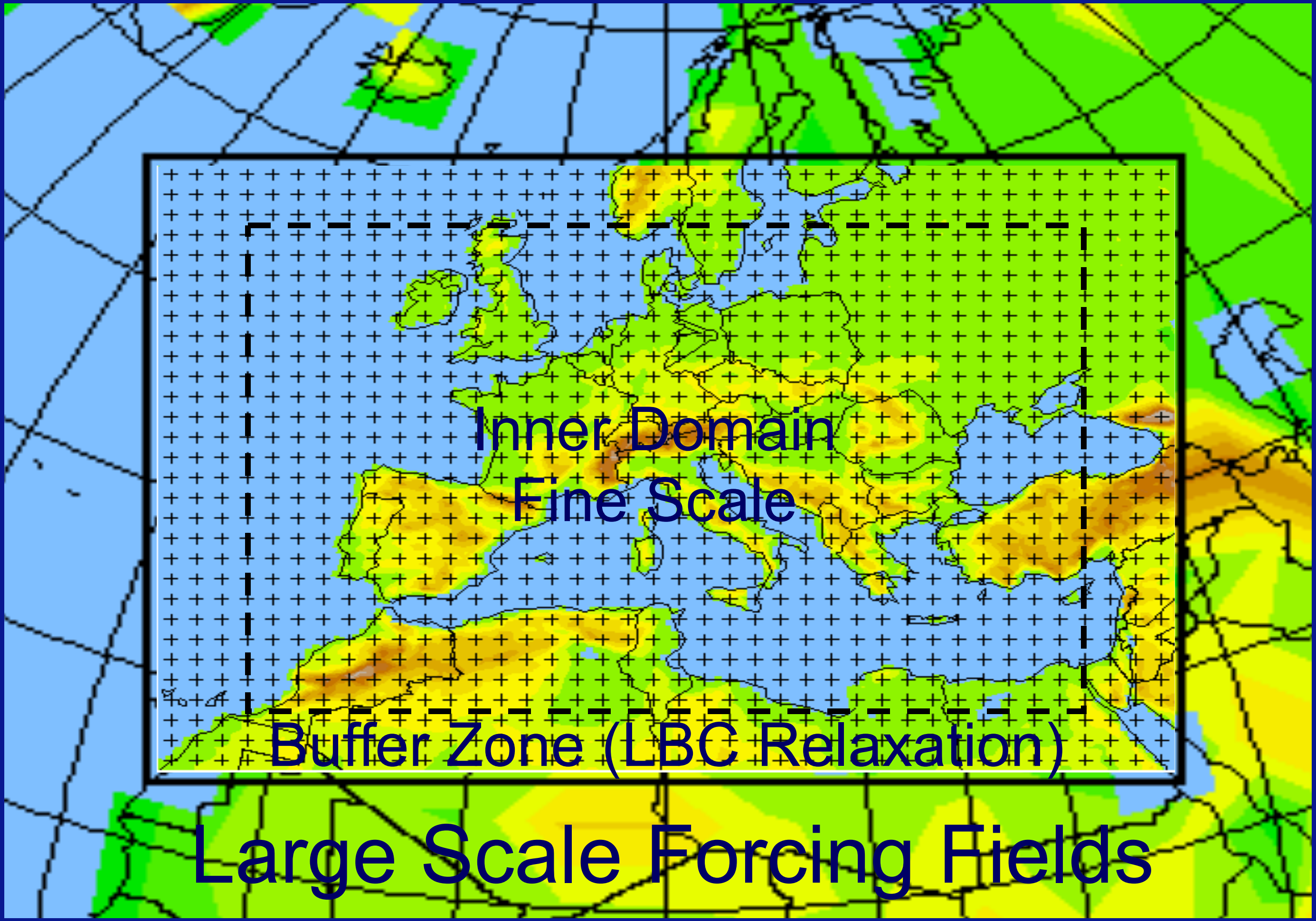


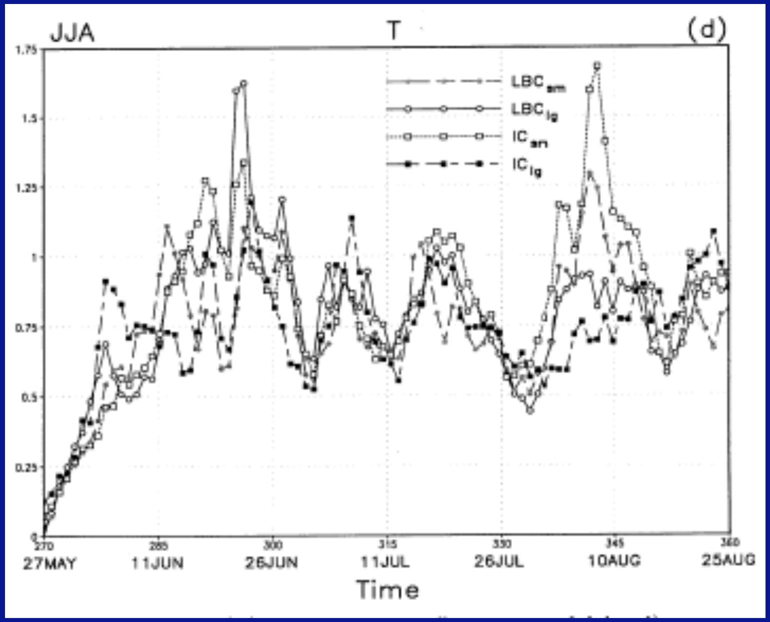
CORDEX Phase I experiment protocol



RCM Nesting procedure

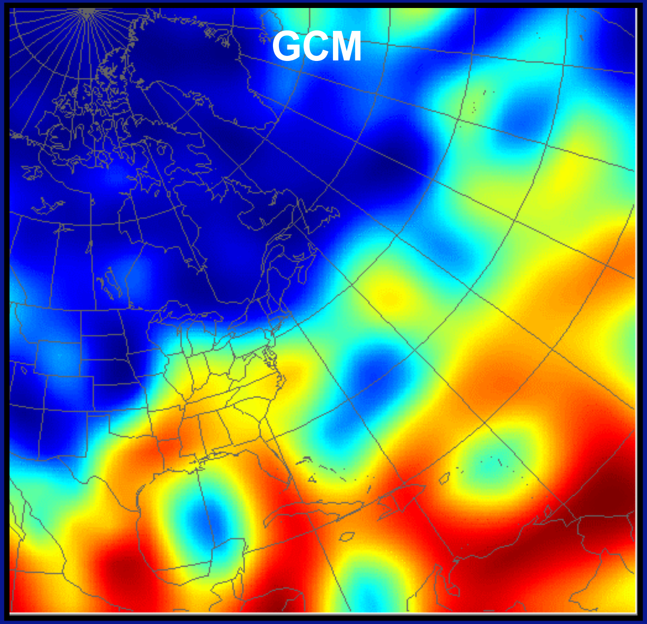
$$\frac{\partial \alpha}{\partial t} = F(n)F_1 \cdot (\alpha_{LBC} - \alpha_{mod}) - F(n)F_2 \cdot \Delta_2(\alpha_{LBC} - \alpha_{mod})$$

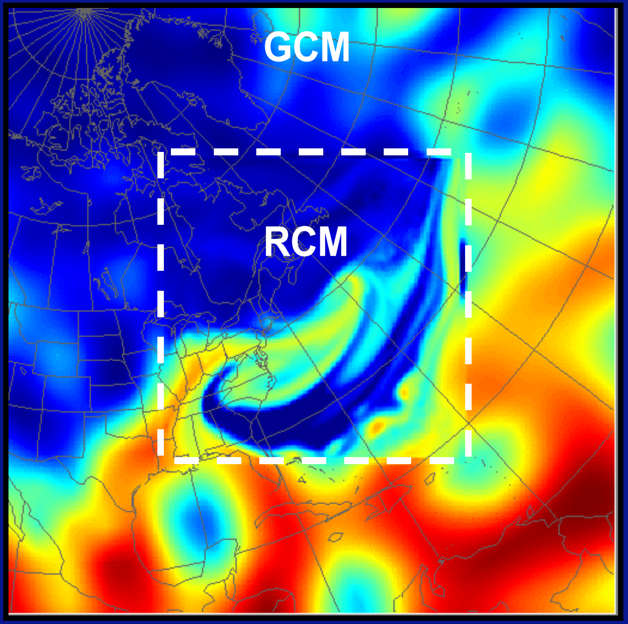




A dynamical equilibrium is reached in the interior domain between the information from the LBC and the model solution

<u>RCMs are not intended to correct large scale circulation errors in the driving GCMs</u>





900 Hpa specific humidity (Courtesy of R. Laprise)

Added value of RCMs
Where to look for it?

- Complex fine scale surface forcings: Topography, coastlines, land surface gradients, lakes/islands, etc.
- Strong regional forcings: Aerosols
- Precipitation intensity distributions and extreme events
- Regional circulations: sea breeze, slope circulations
- Synoptic scale and mesoscale processes: tropical storms, mesoscale convectiove processes, tropical convection

High quality, high resolution observations are needed to assess added value

The case of the European Alps
(Torma, Giorgi, Coppola, JGR 2015)

- Area characterized by complex, fine scale topographical features which strongly modulate local climate characteristics
- Availability of a high quality, high resolution gridded dataset: EURO4M-APGD (Isotta et al. 2014)
  - Daily precipitation gridded onto a 5 km regular grid
  - Homogenized data from more than 8000 stations
  - Long period of coverage: 1971-2008
- Availability of ensembles of RCM projections from EURO-CORDEX and MED-CORDEX
  - Multiple driving GCMs and nested RCMs
  - Two nominal resolutions: 0.11°, 0.44°
  - Easy accessible open data

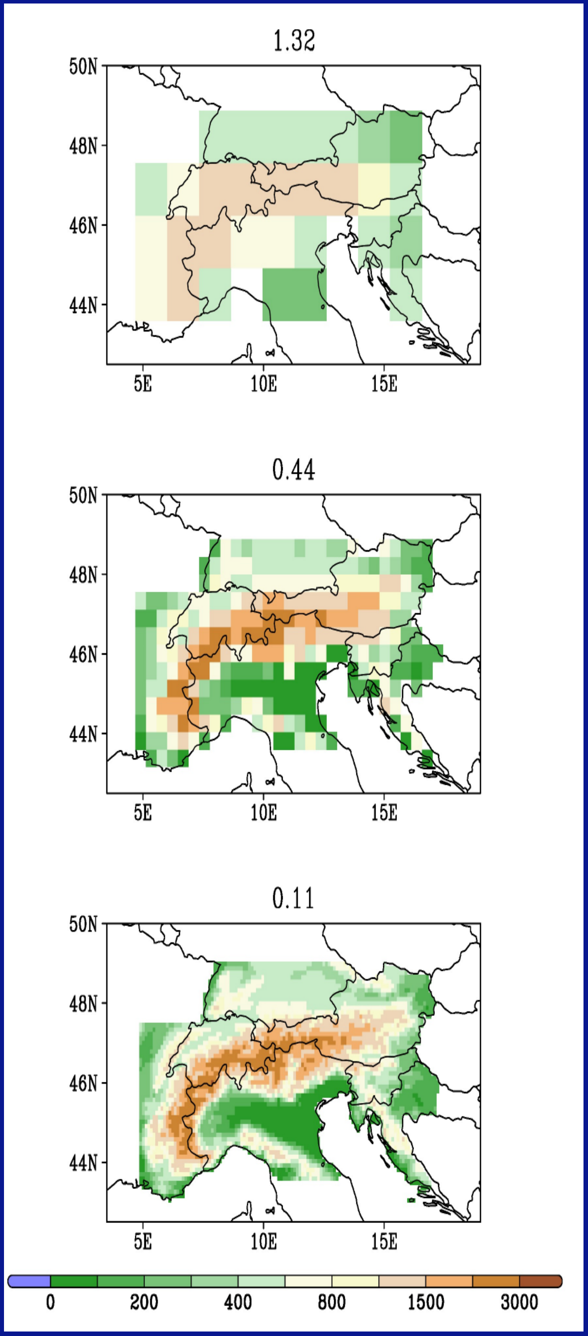
Added value questions examined

- Do the RCMs improve the representation of given present day precipitation statistics compared to the driving GCMs?
  - Downscaling to fine scales
  - Upscaling to GCM-like scales
- Is the RCM climate change signal different from that of the driving GCMs?
- Statistics examined:
  - Spatial distribution of precipitation
  - Daily precipitation intensity PDFs
  - Daily precipitation intensity extremes

Added value metrics used

- All data are intercompared on common grids of different resolutions: 1.32°, 0.44°, 0.11°
  - Historical period: 1976-2005
  - Future period: 2070-2099
- Spatial precipitation pattern: Taylor diagram
  - Spatial correlation
  - Spatial standard deviation
  - Centered RMSE
- Daily precipitation intensity PDF
  - Kolmogorov-Smirnov (KS) Distance
- Daily precipitation extremes: R95 (fraction of total precipitation above the 95th percentile on an annual basis)
  - Mean
  - Correlation coefficient

Analysis grids (topography)

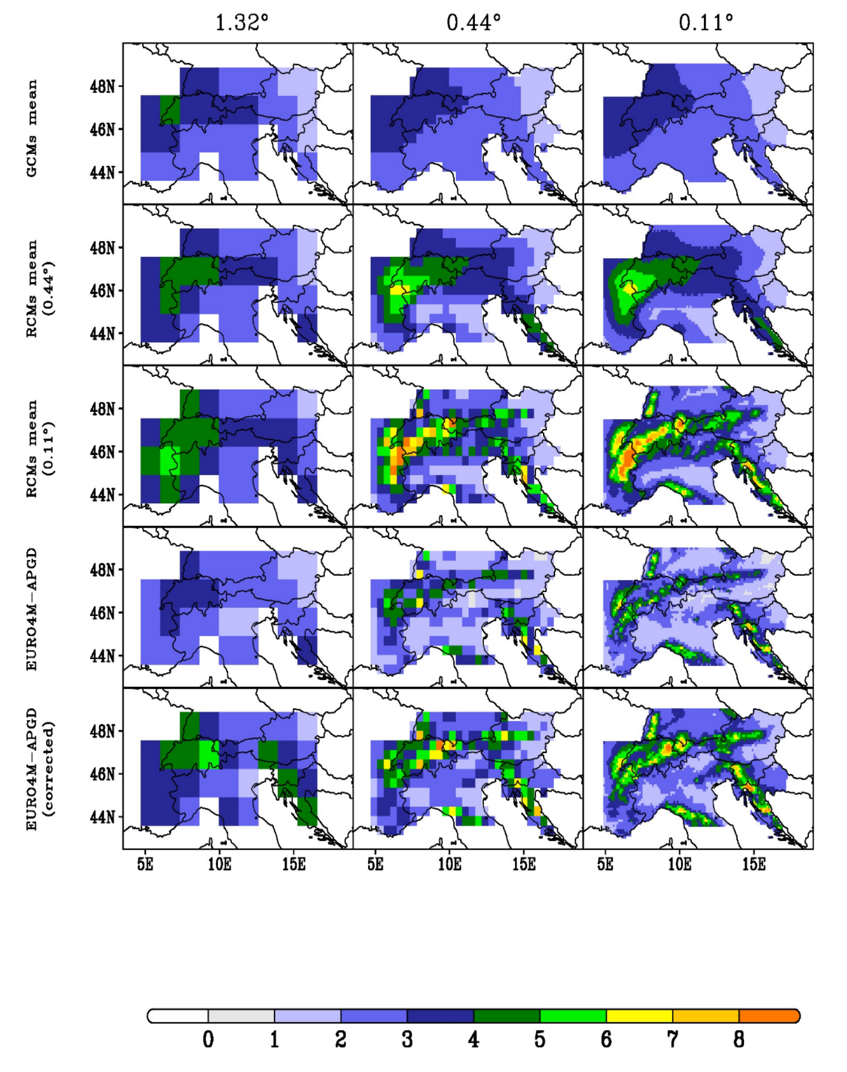


Model ensembles

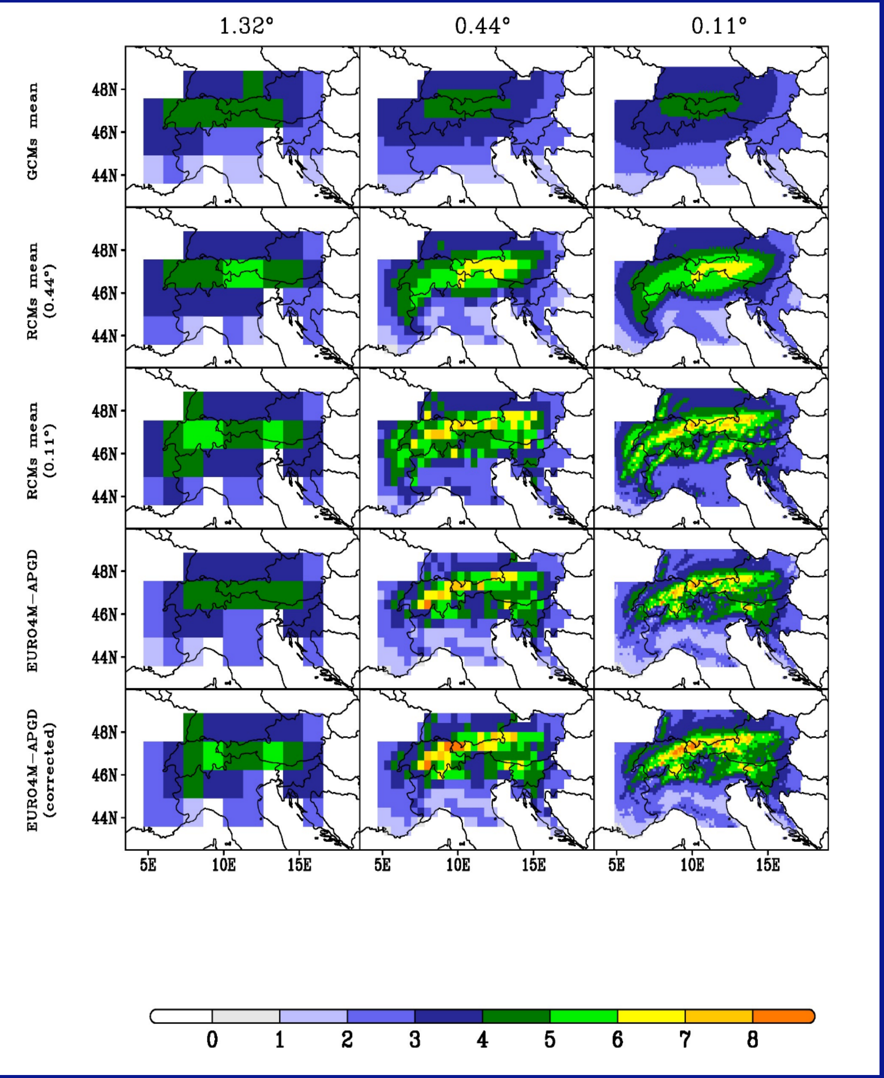
Model	Modelling group	Resolution	Reference
a, CNRM-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherches et de Formation Avancee en Calcul Scientifique, France	1.40625 º x 1.40625 º	Voldoire et al., 2012
b, EC-EARTH	Irish Centre for High-End Computing, Ireland	1.125 º x 1.125 º	Hazeleger et al., 2010
c, HadGEM2-ES	Met Office Hadley Centre, UK	1.875 º x 1.2413 º	Collins et al., 2011
d, MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.875 º x 1.875 º	Jungclaus et al., 2010
ALADIN (a-MC)	Centre National de Recherches Meteorologiques, France	0.44 º/0.11 º	Colin et al., 2010
CCLM (d-EC)	Climate Limited-area Modelling Community, Germany	0.44 º/0.11 º	Rockel et al., 2008
RCA4 (c-EC)	Swedish Meteorological and Hydrological Institute, Rossby Centre, Sweden	0.44 º/0.11 º	Kupiainen et al., 2011
RACMO (b-EC)	Royal Netherlands Meteorological Institute, The Netherlands	0.44 º/0.11 º	Meijgaard van et al., 2012
RegCM4 (c-MC)	International Centre for Theoretical Physics, Italy	0.44 º/0.11 º	Giorgi at al., 2012

Ensemble mean seasonal precipitation (1976-2005)

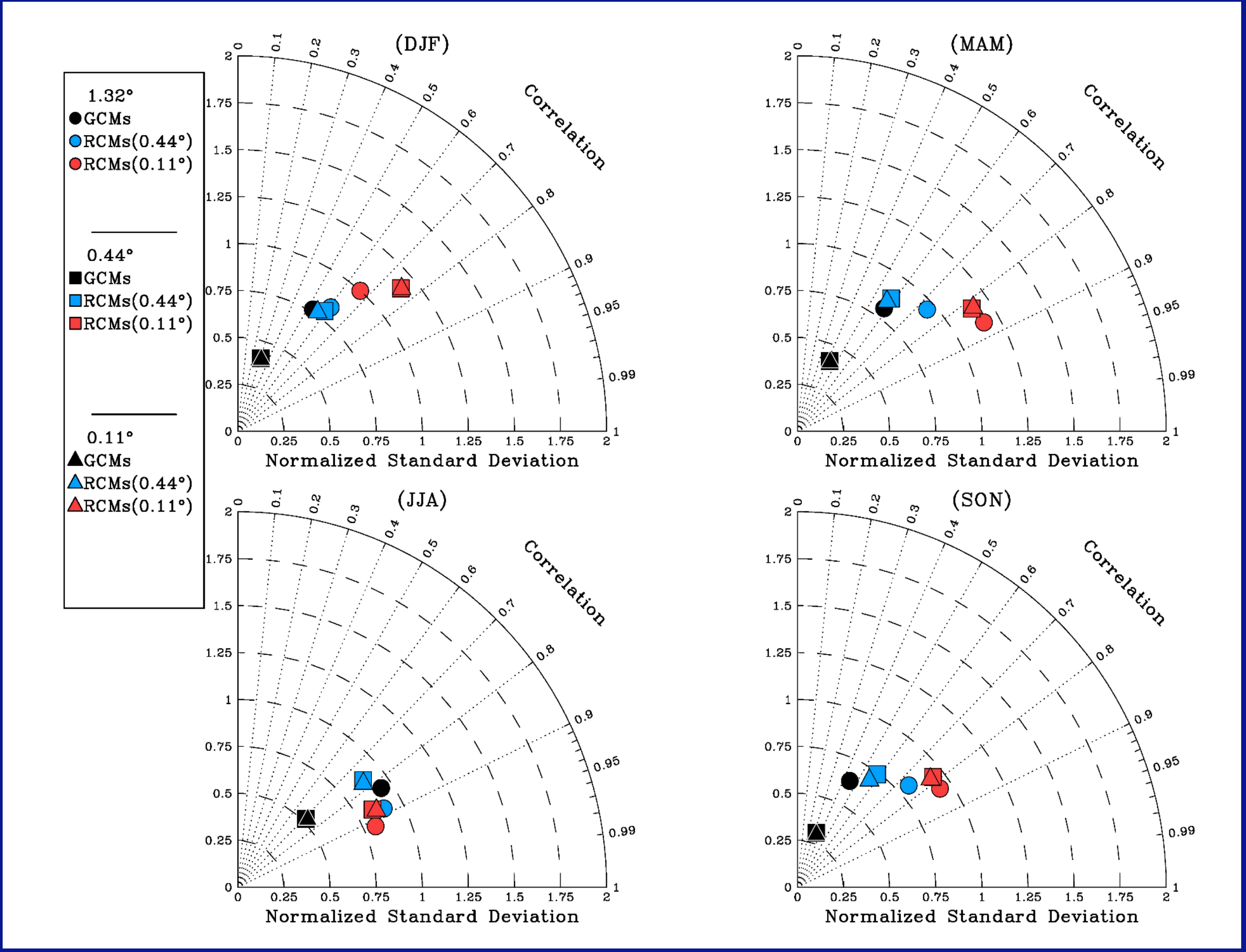
Winter (DJF)



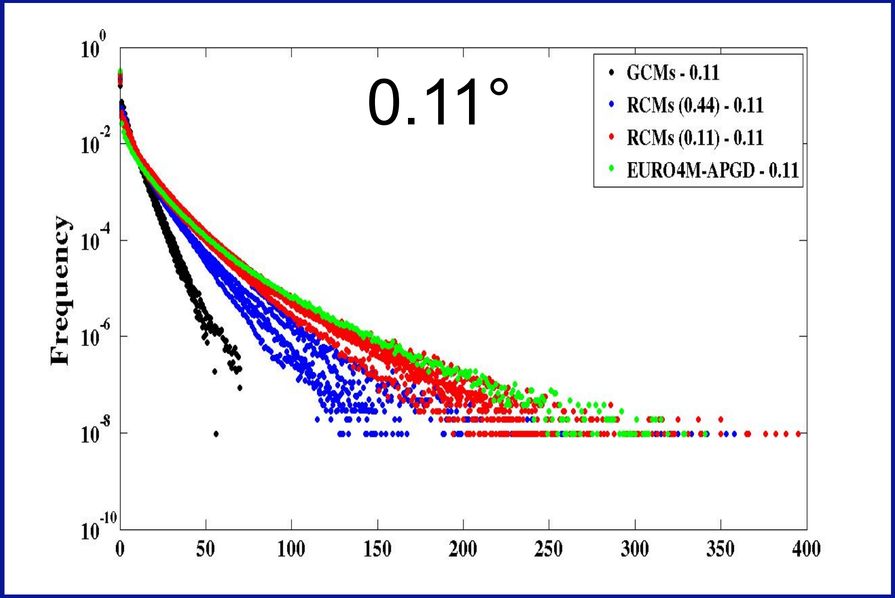
Summer (JJA)

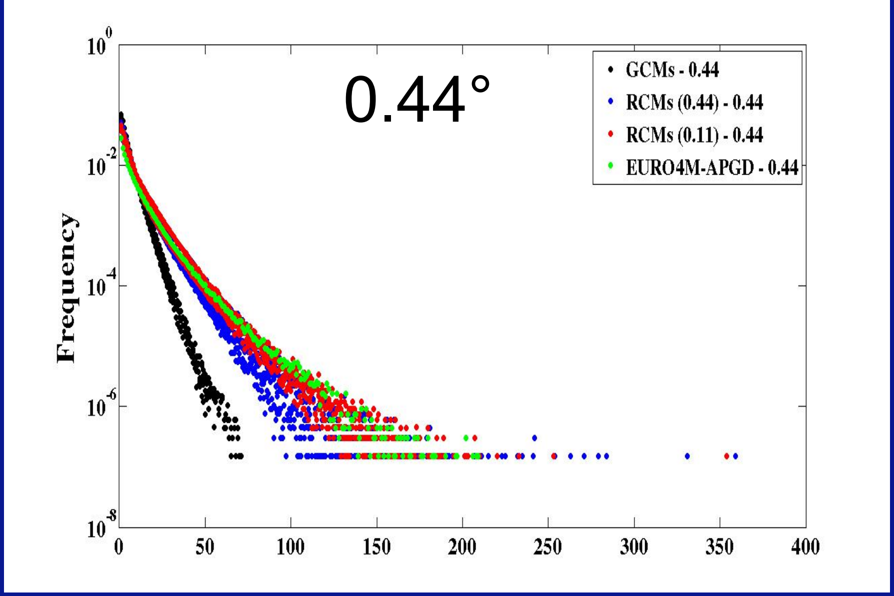


Taylor diagram of mean seasonal precipitation (model vs. obs, 1976-2005)

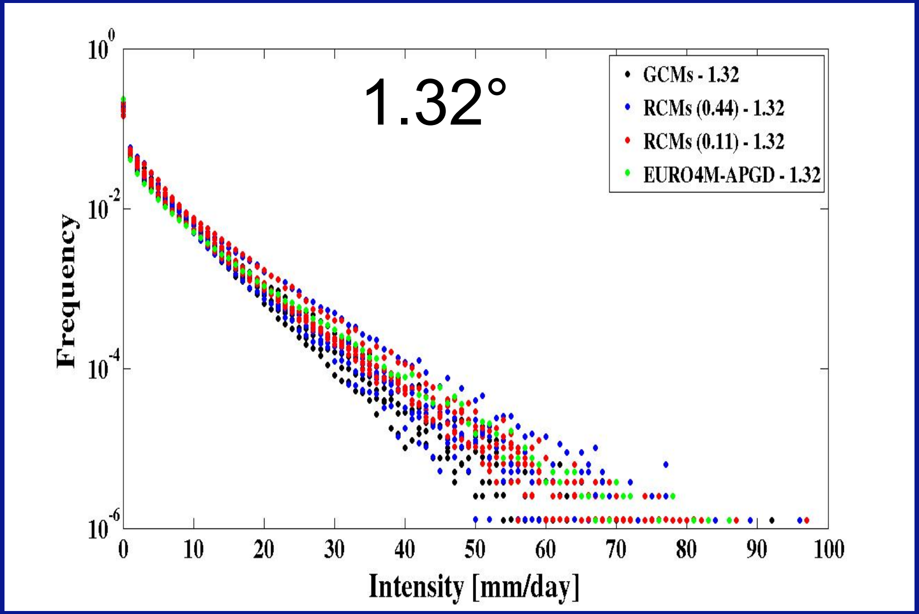


Daily precipitation PDFs on different grids

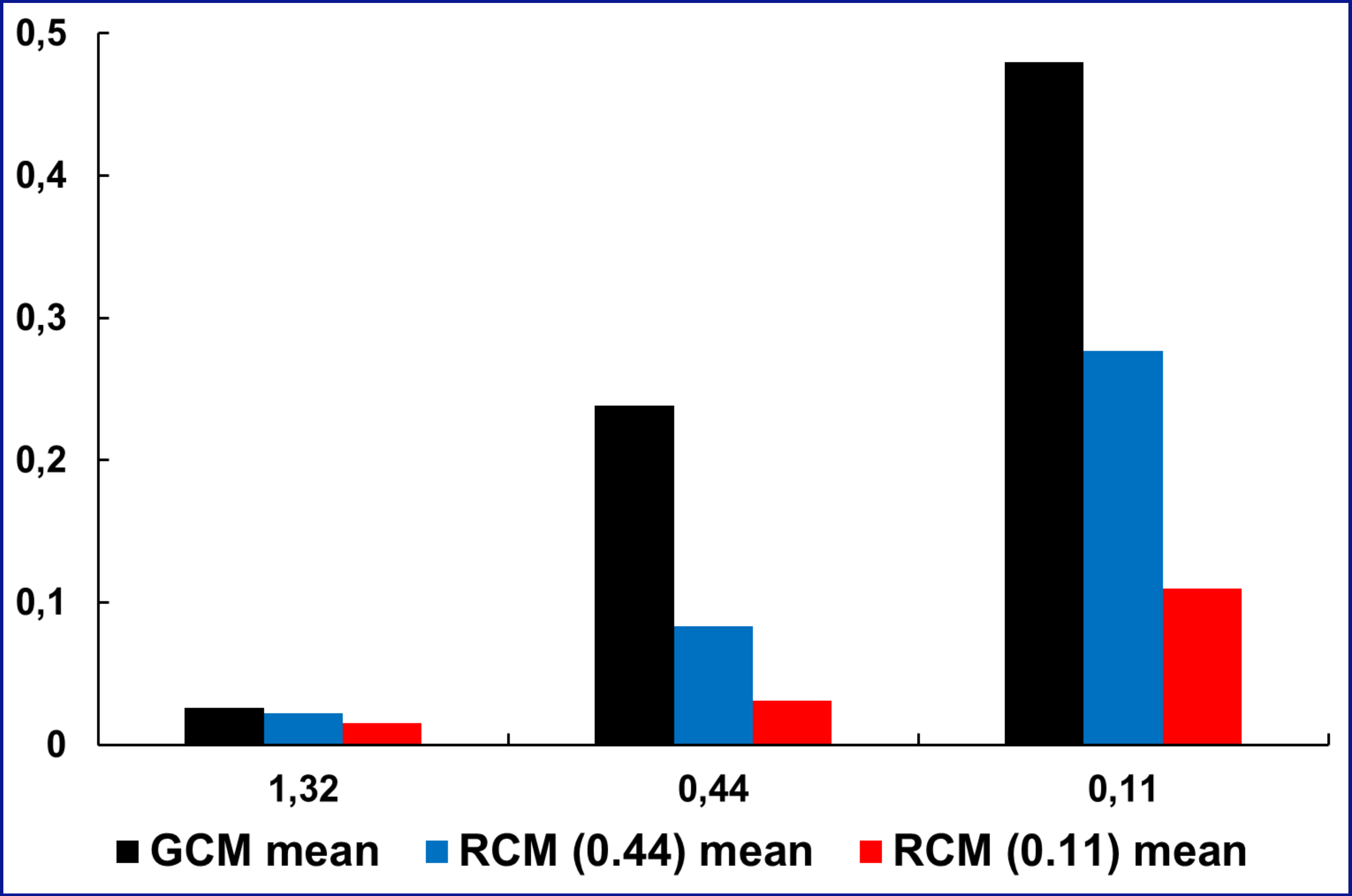




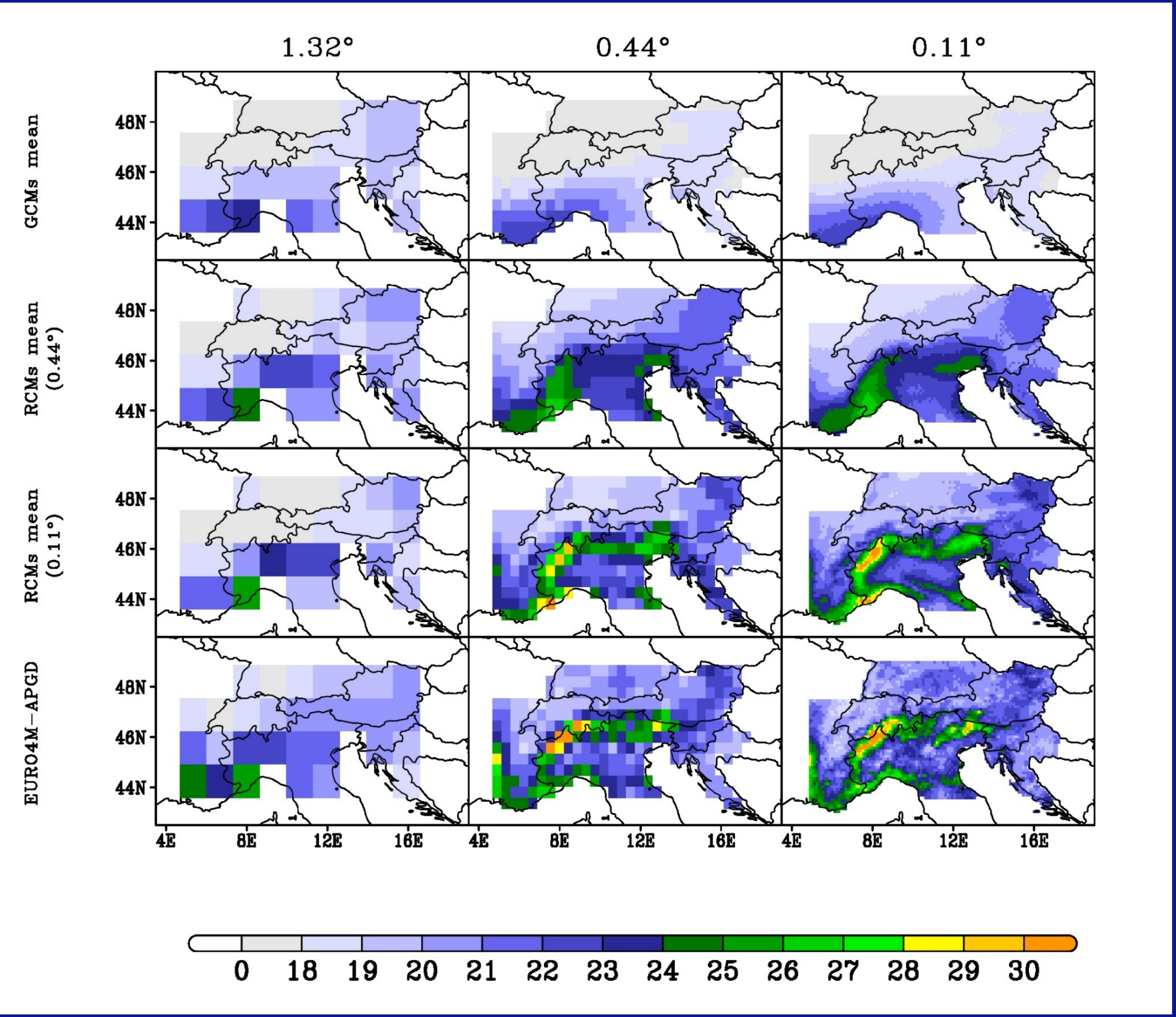
1976-2005



Ensemble mean KS distance for different resolution grids (1976-2005)



Ensemble mean R95 for different resolution grids (1976-2005)



Mean

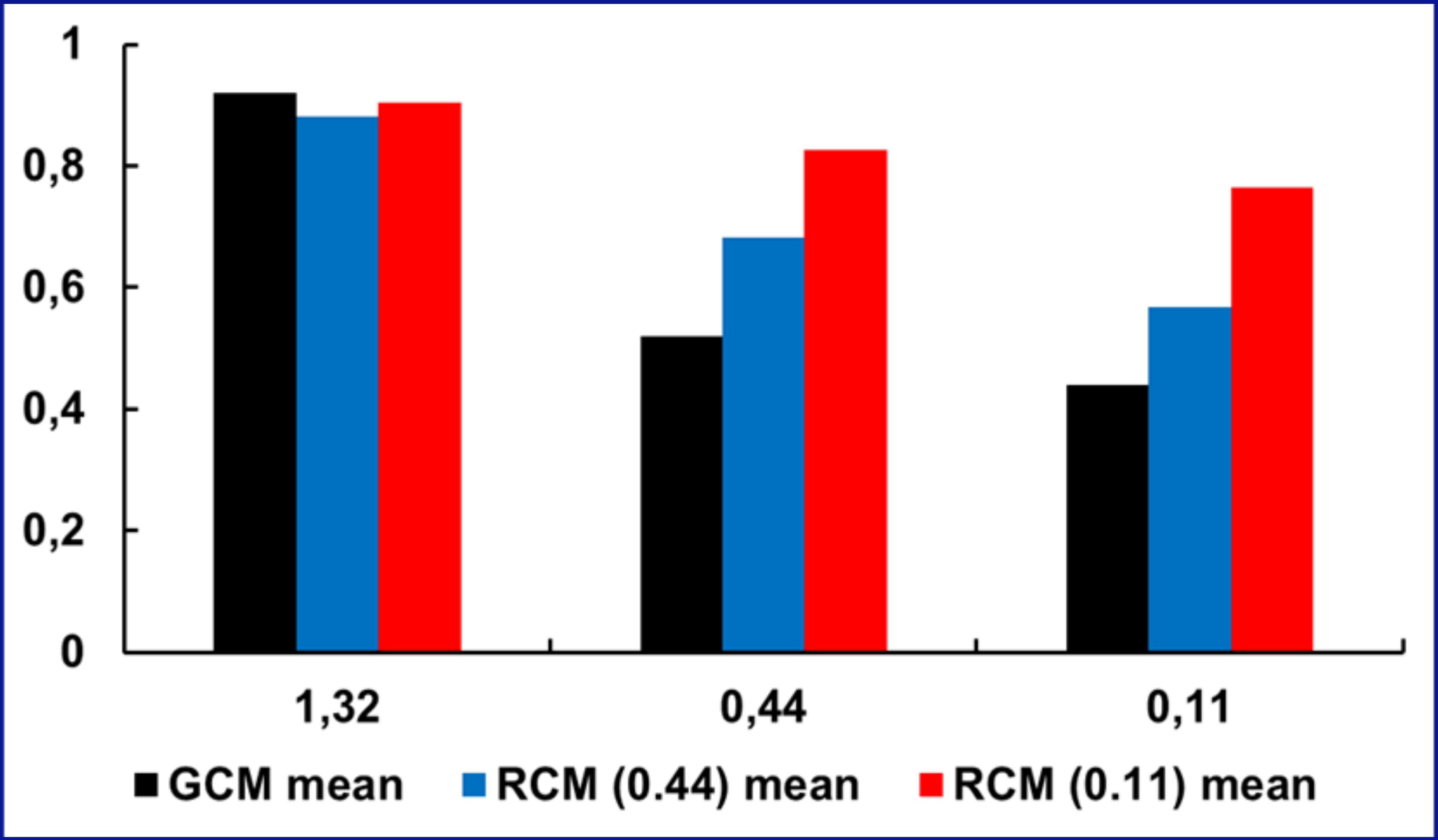
19.5

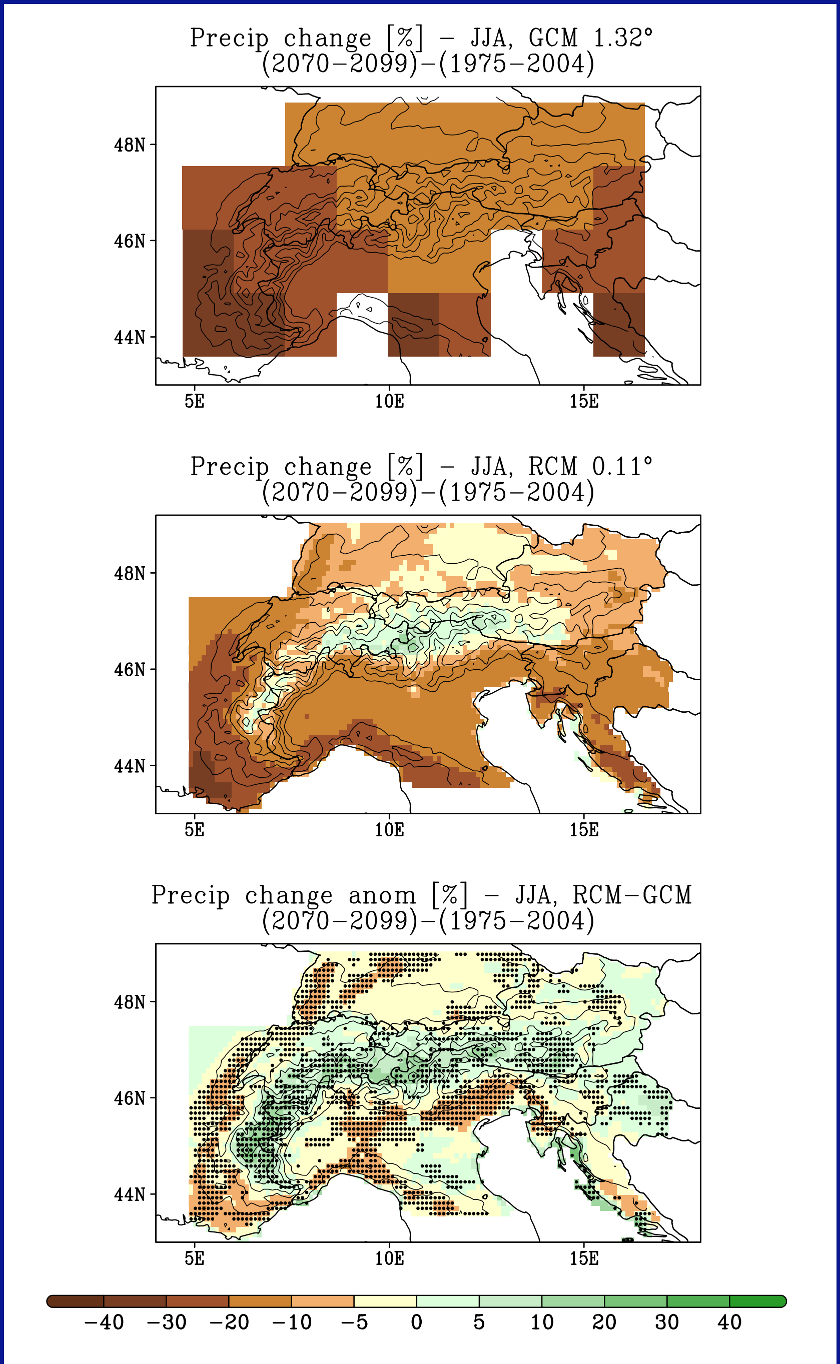
21.5

22.1

22.2

Correlation between simulated and observed R95 for different resolution grids (1976-2005)





mm/day/century

GCMs

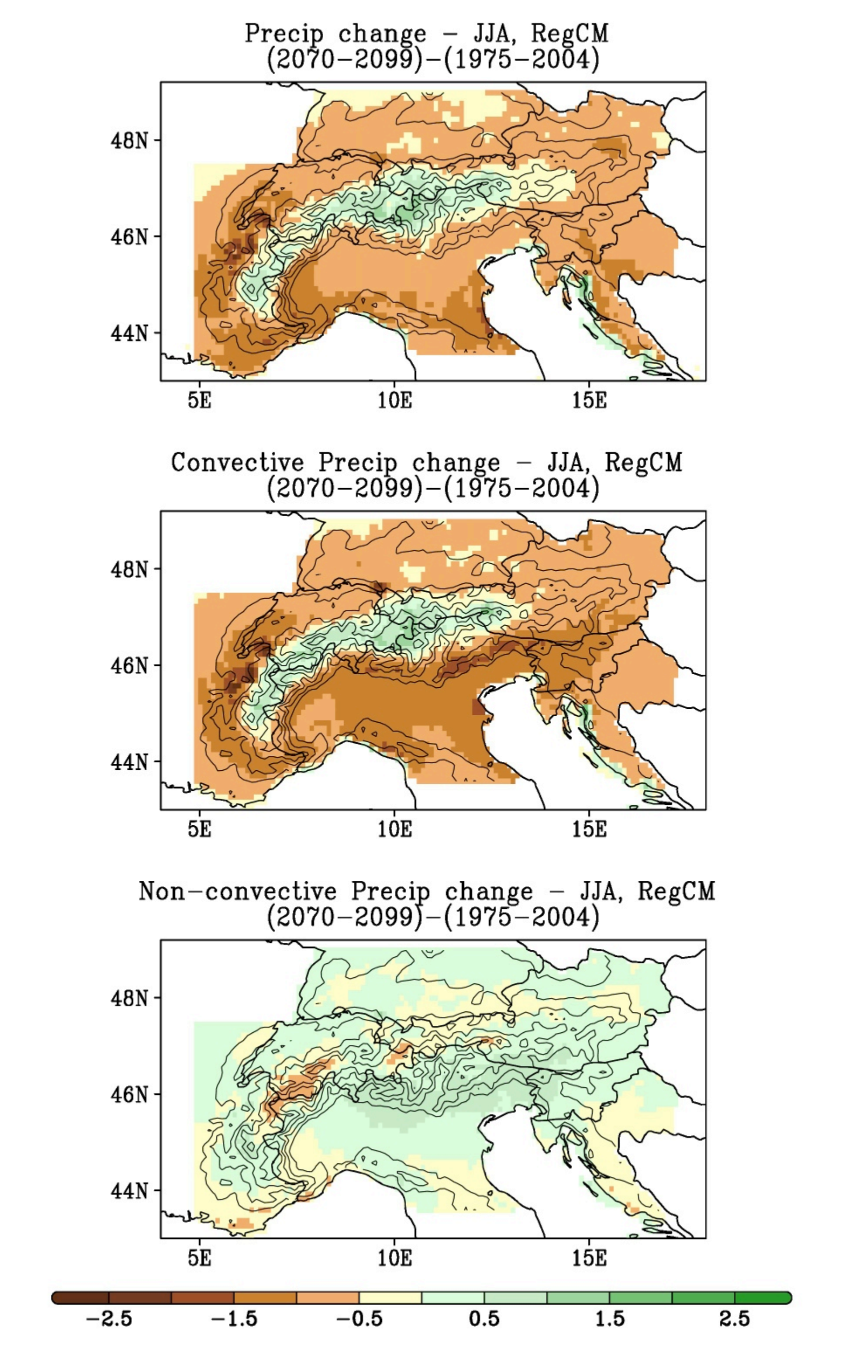
RCMs
0.11°

RCM – GCM
Anomaly

Is added value reflected in the climate change projection?

Summer precipitation change

Summer precipitation change RegCM (0.11°)



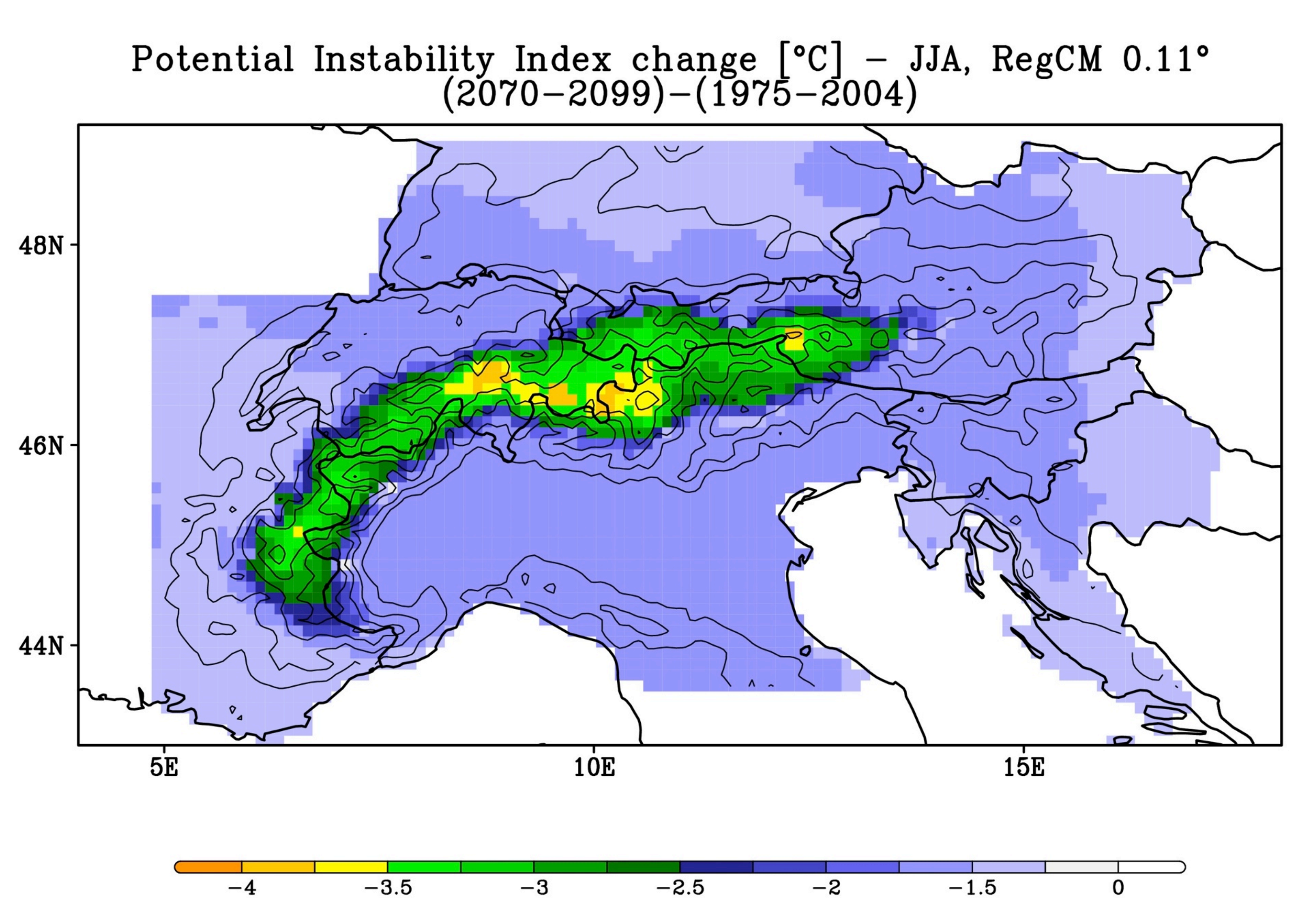
mm/day/century

Total

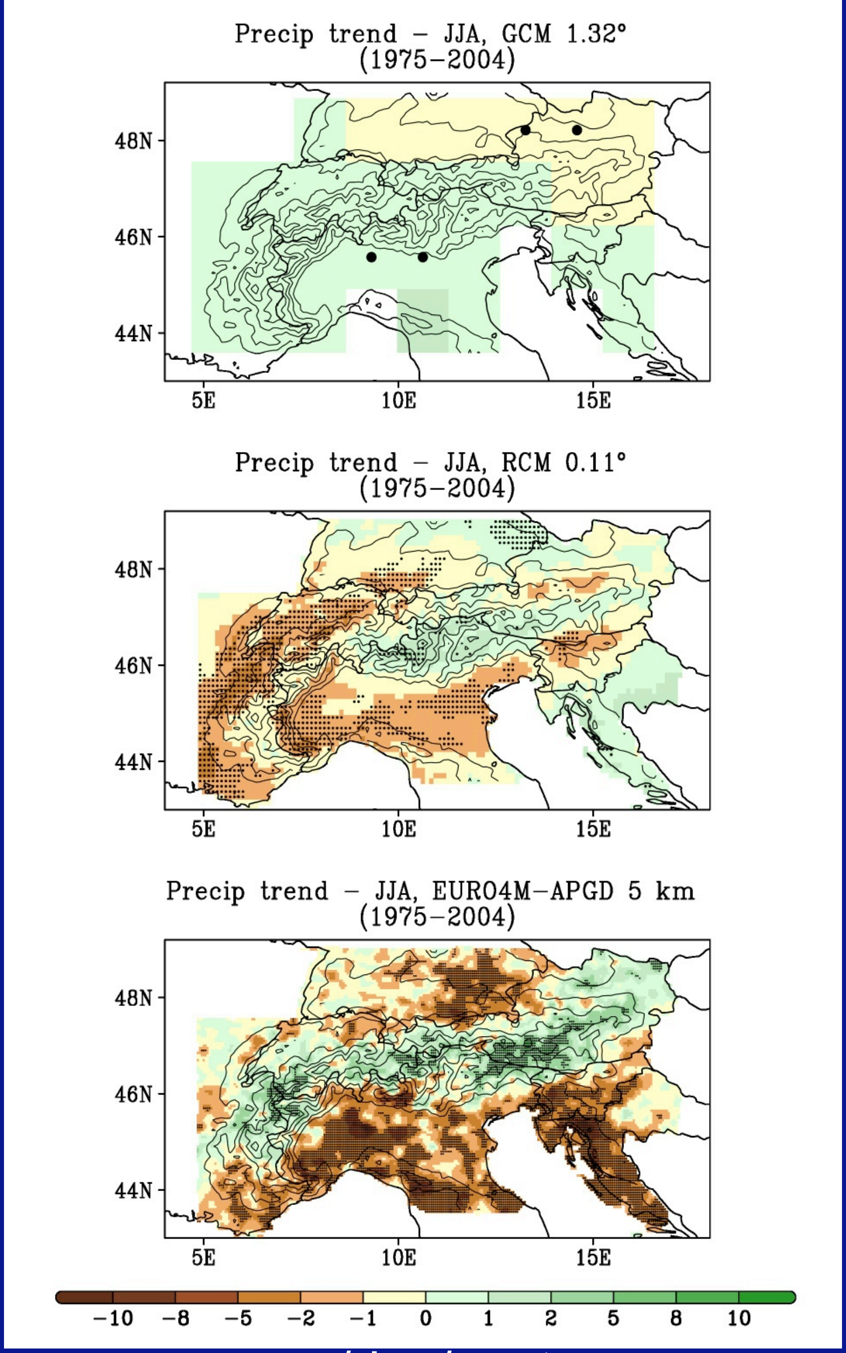
Convective

Non-Convective

Change in potential instability index



Summer precipitation trend during 1975-2004



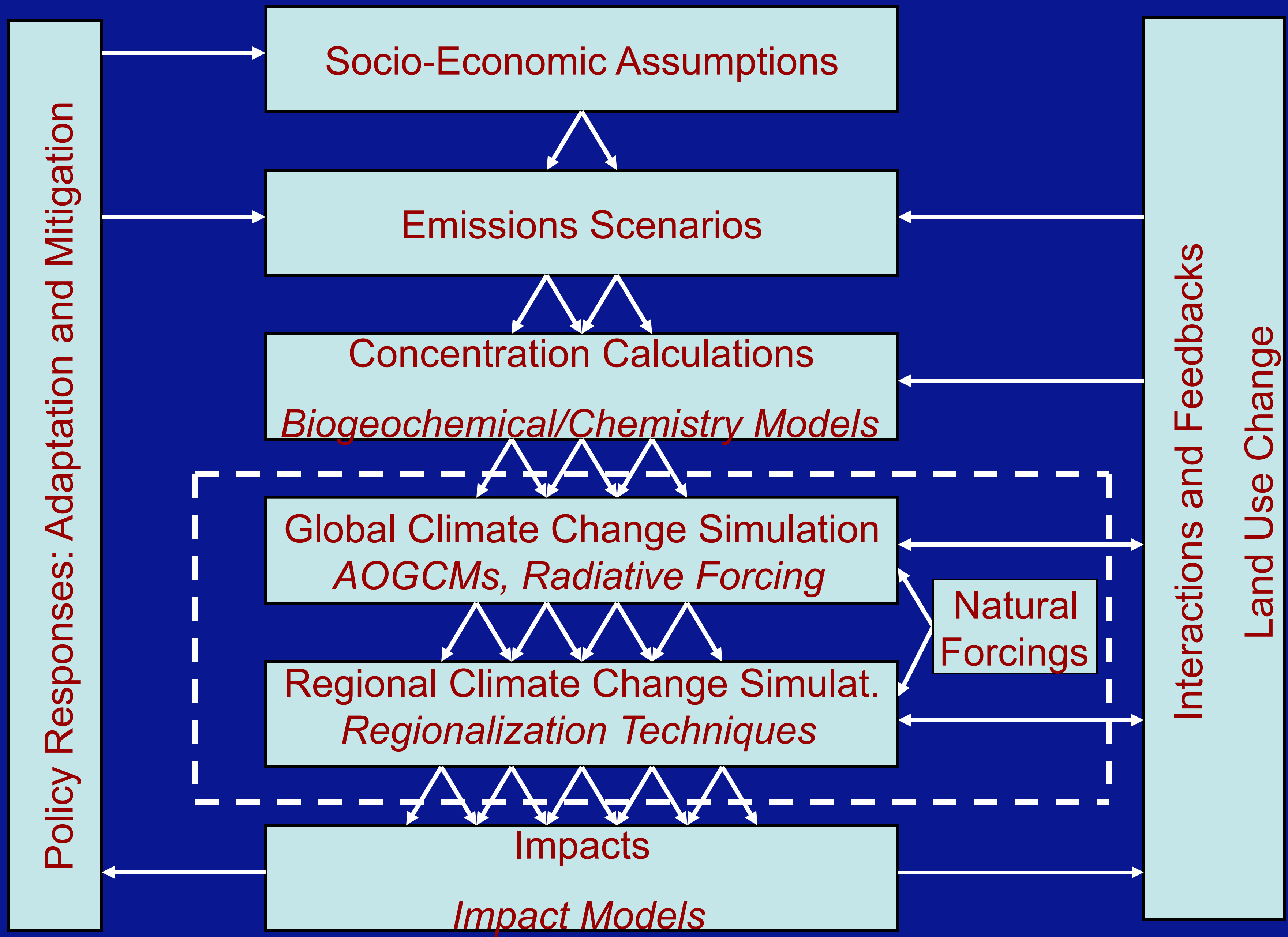
mm/day/century

GCMs

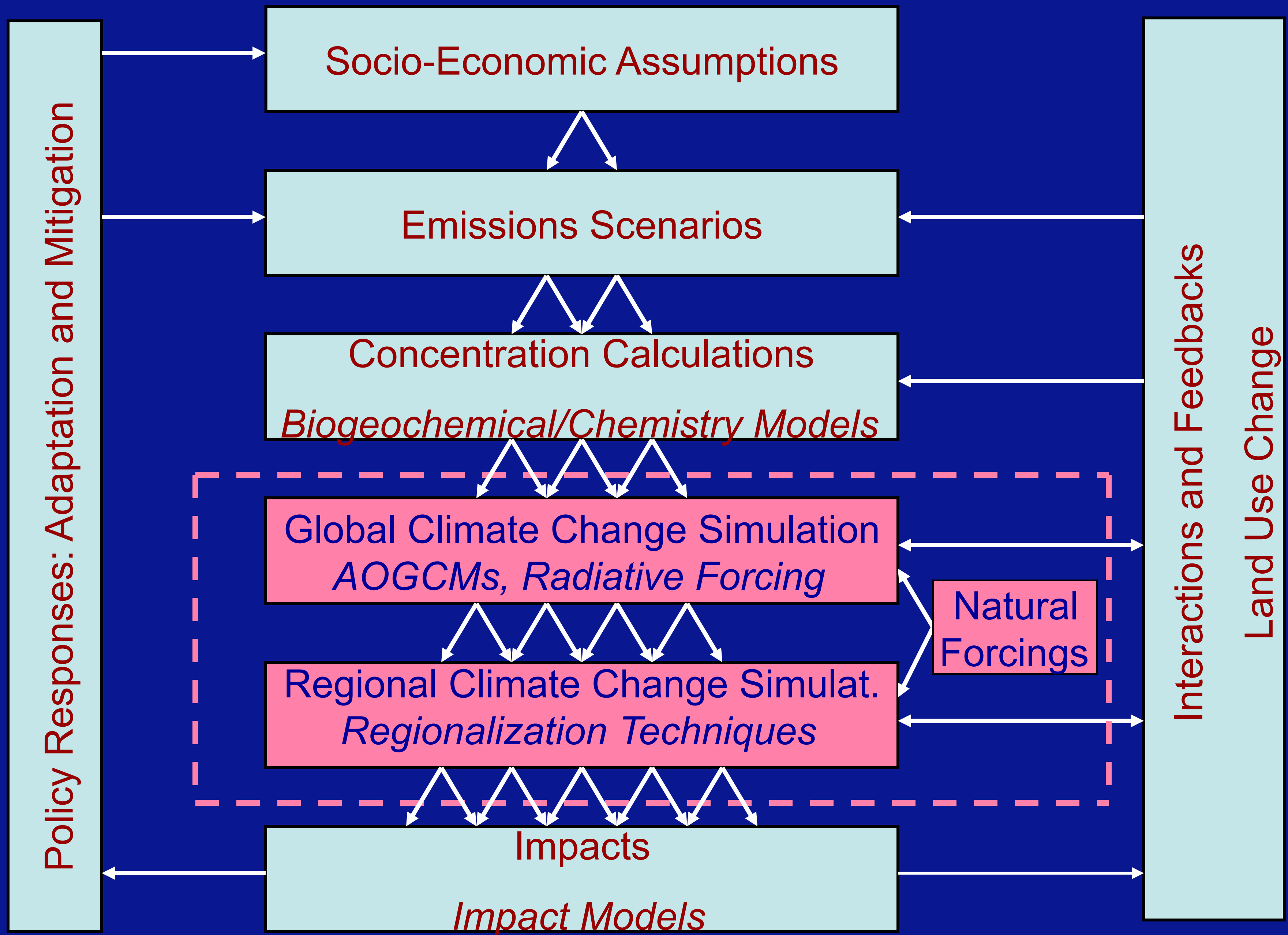
RCMs 0.11°

Observations EURO4M-APGD

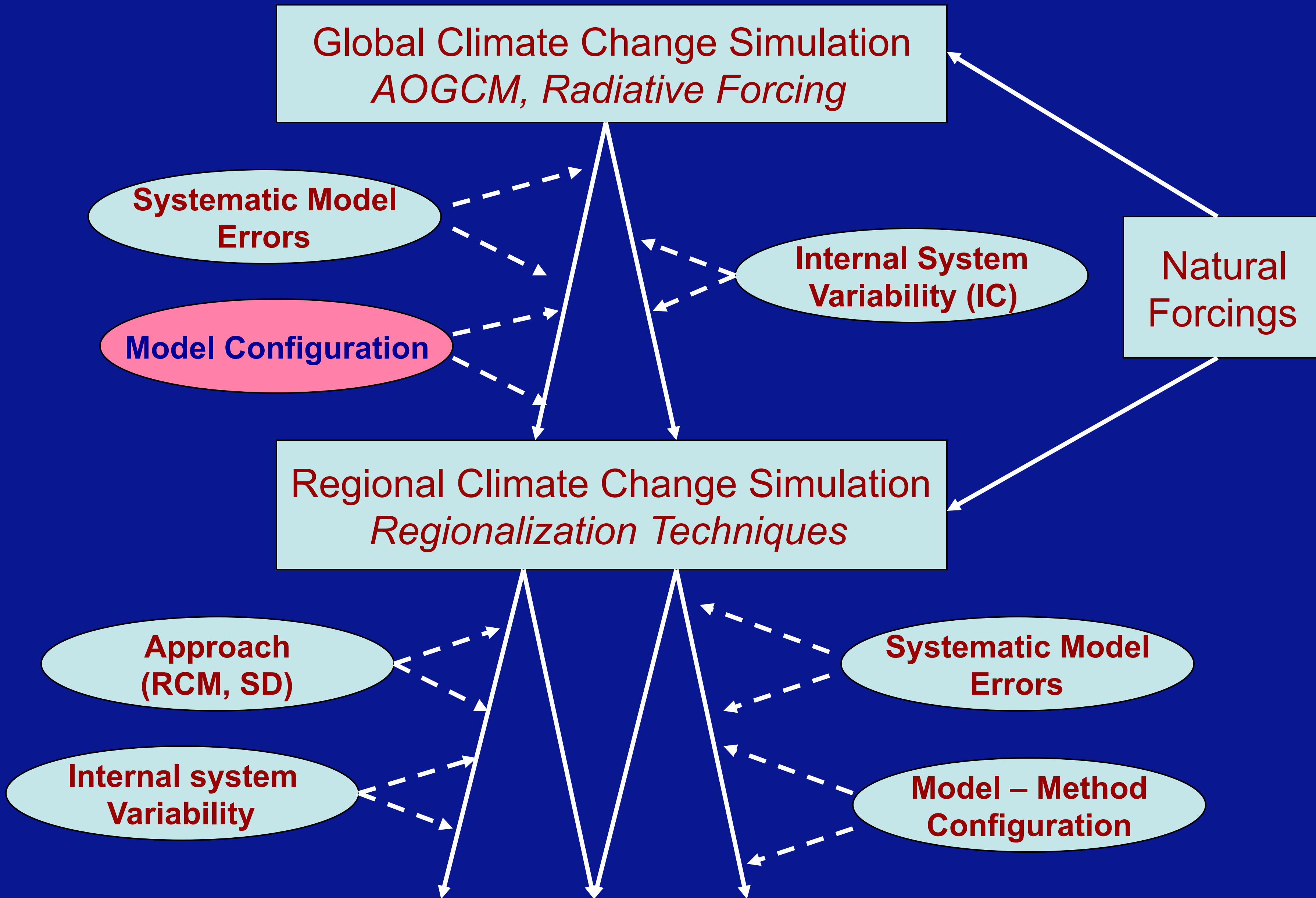
Cascade of uncertainty in climate change projections



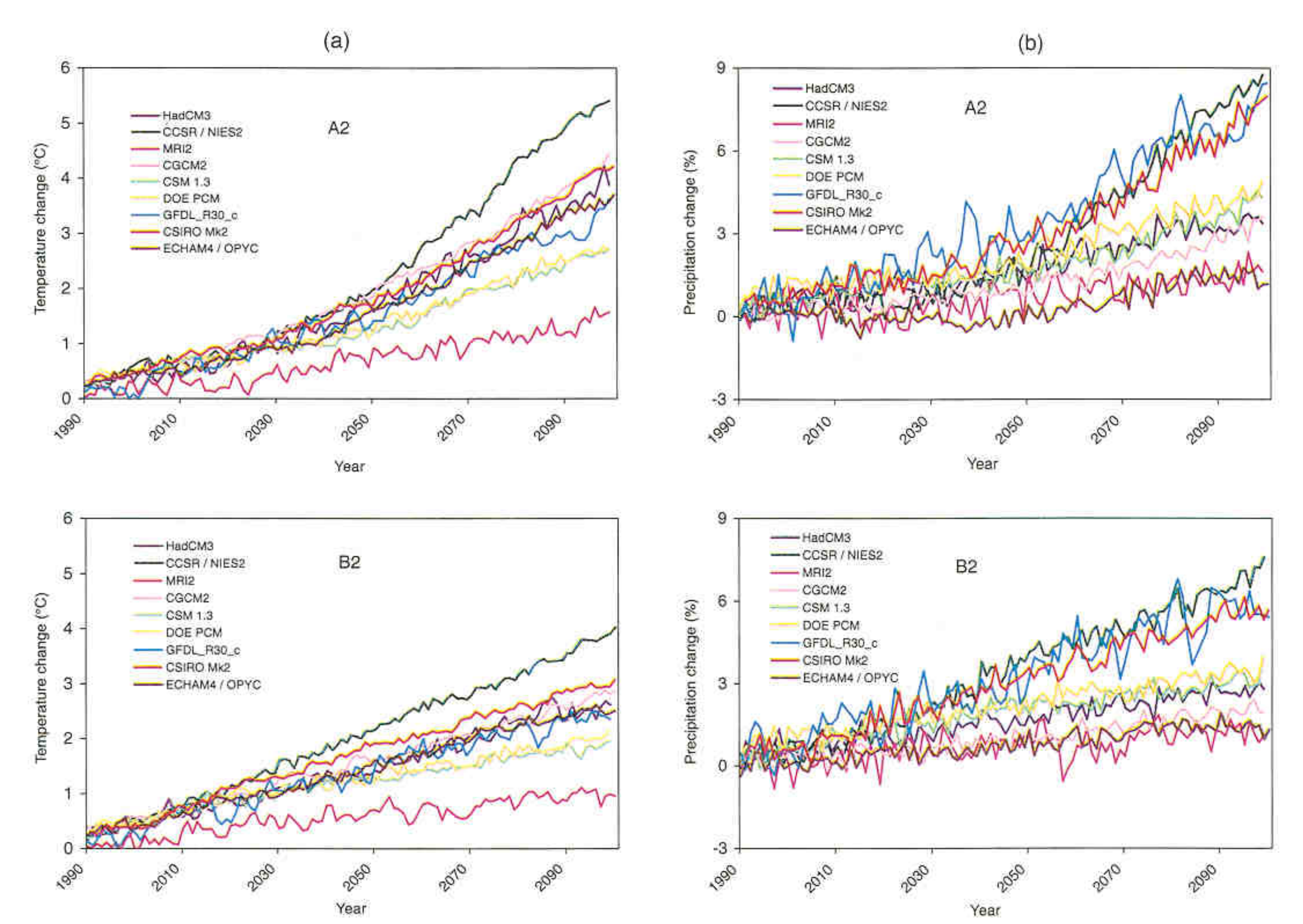
Cascade of uncertainty in climate change projections



Climate Simulation Segment of the Uncertainty Cascade



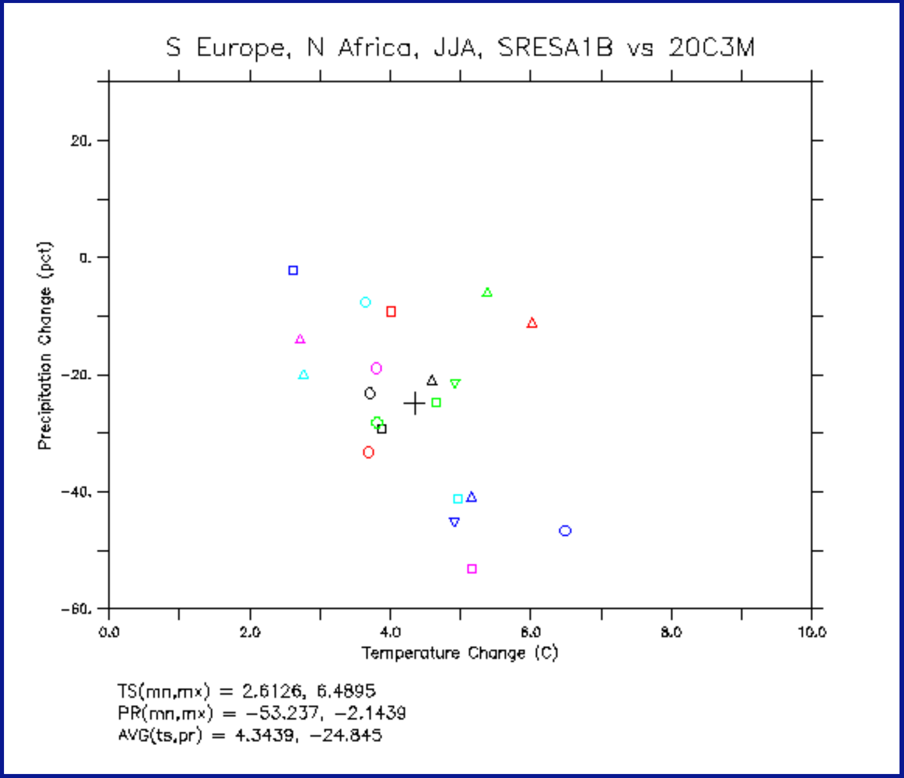
Model configuration uncertainty at the global scale



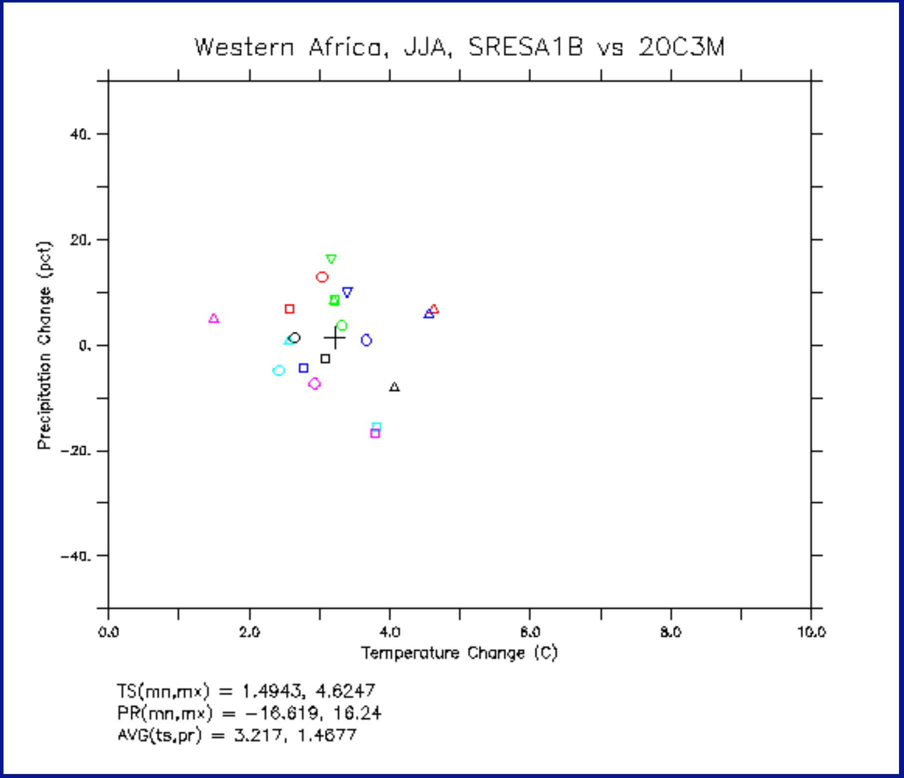
Model configuration uncertainty at the regional scale (AOGCMs)

Regional precipitation vs. temperature change

Mediterranean warm season



West Africa monsoon season

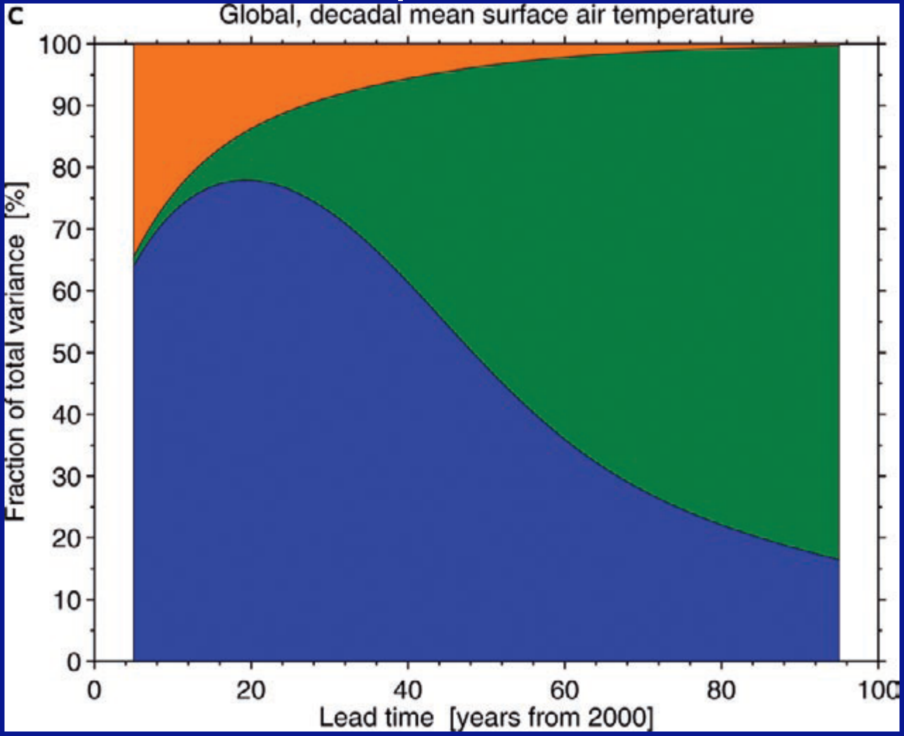


Fraction of uncertainty explained by different sources as a function of lead time

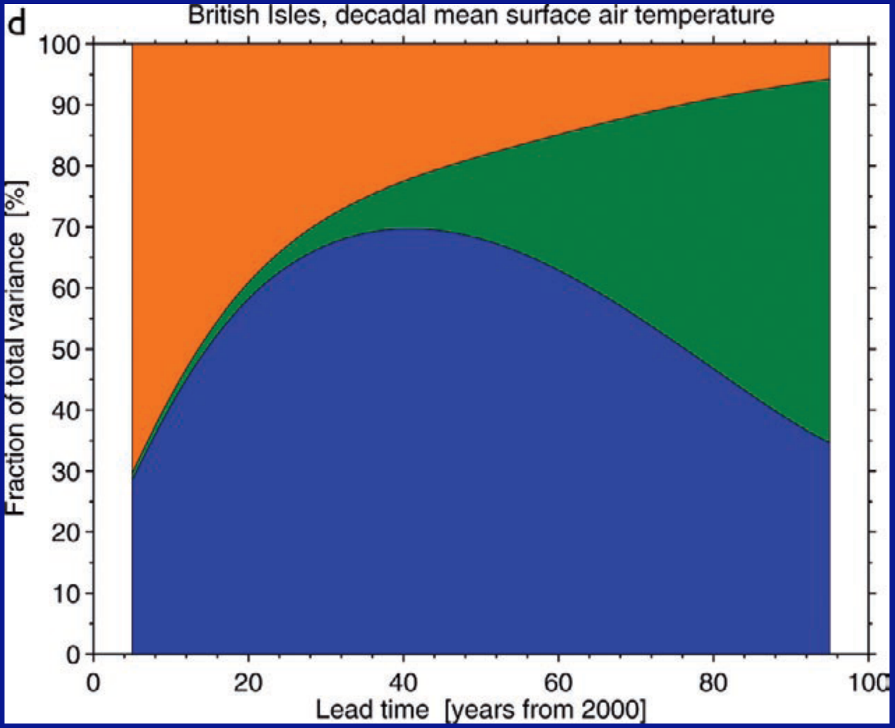
Internal variability
Scenario uncertainty
Model configuration uncertainty

Hawkins and Sutton 2009

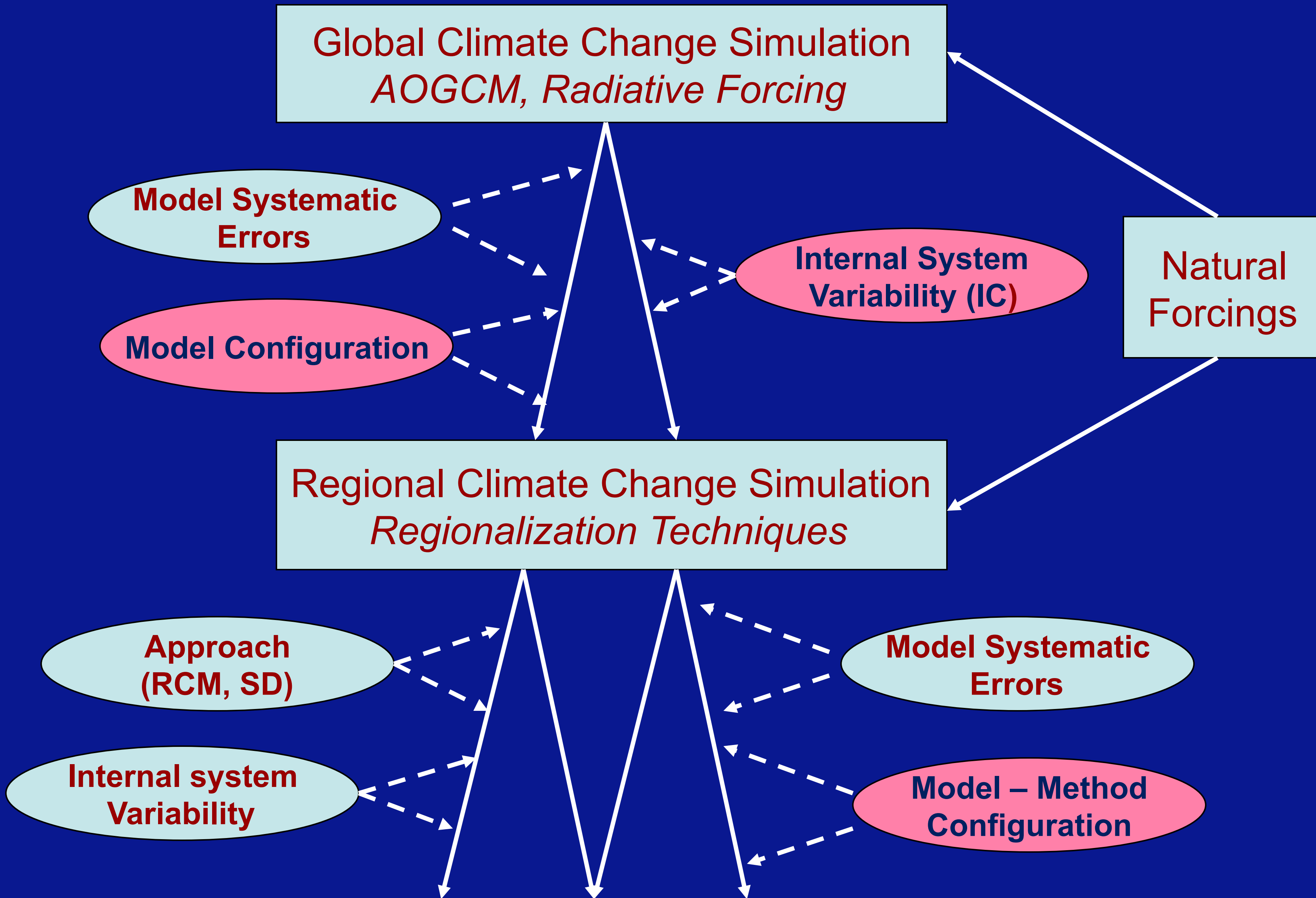
Decadal temperature - Global



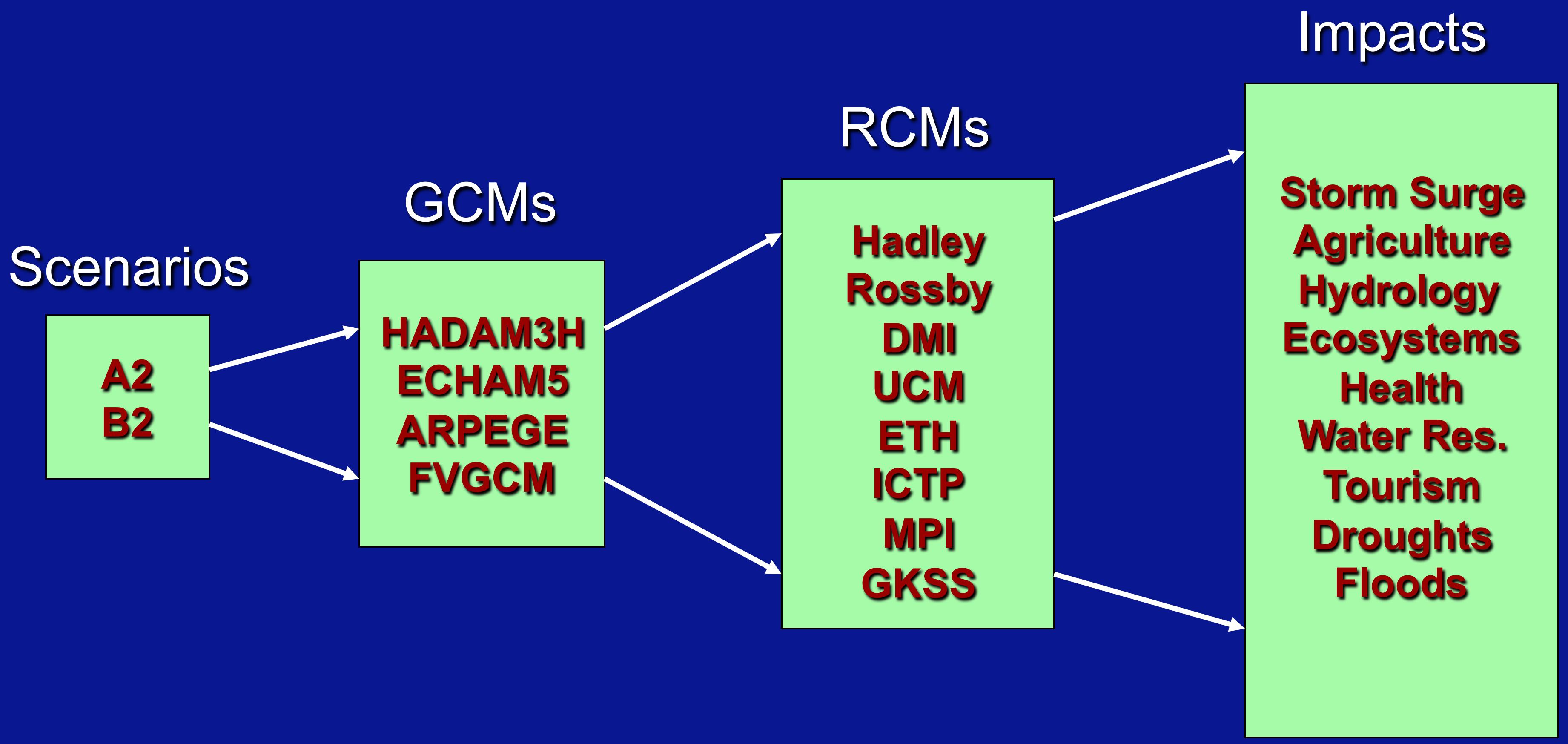
Decadal temperature – British Isles



Climate Simulation Segment of the Uncertainty Cascade

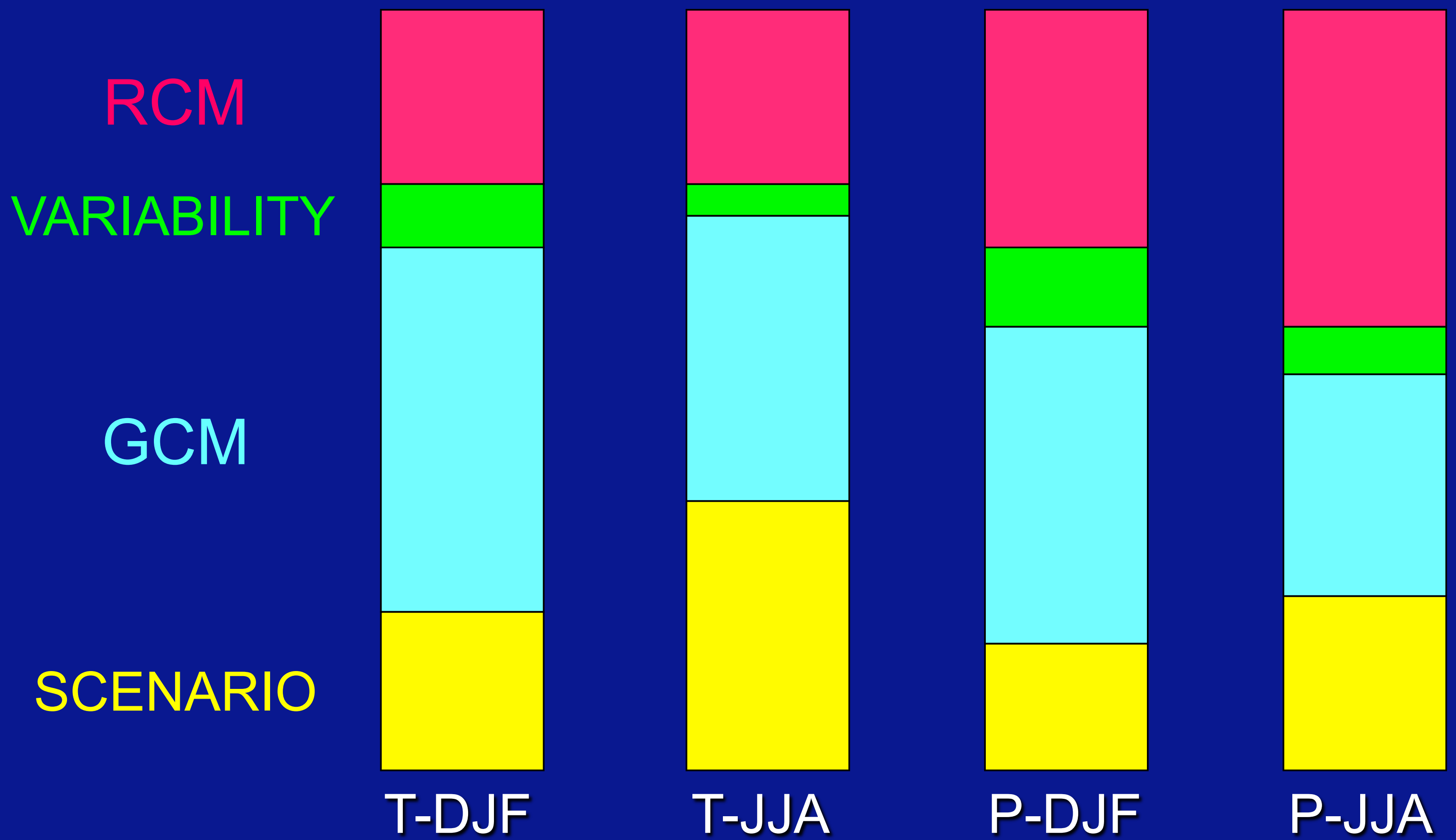


Uncertainties in regional climate change projections: The PRUDENCE strategy

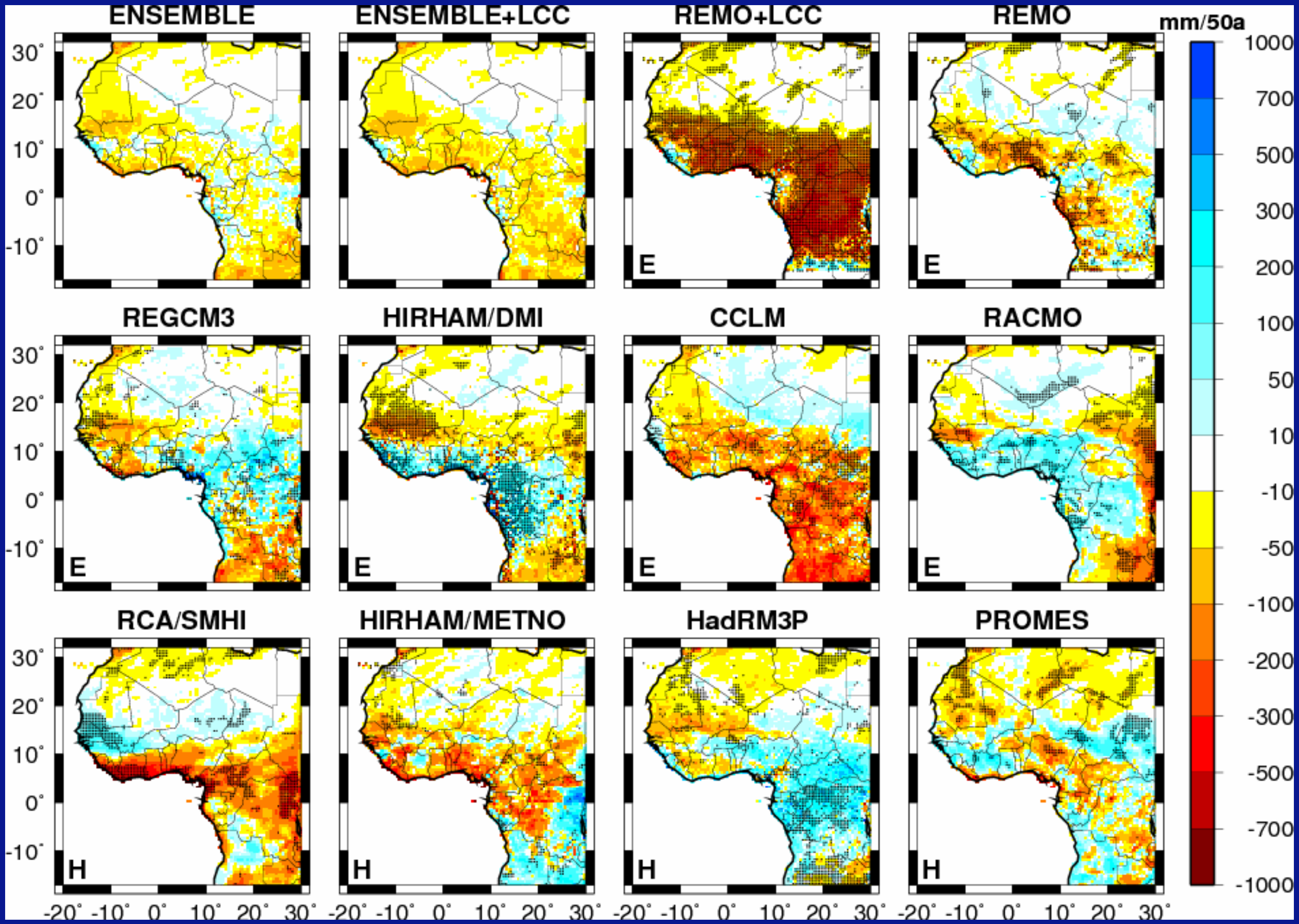


Sources of uncertainty in the simulation of temperature and precipitation change (2071-2100 minus 1961-1990) by the ensemble of PRUDENCE simulations (whole Europe)

(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)



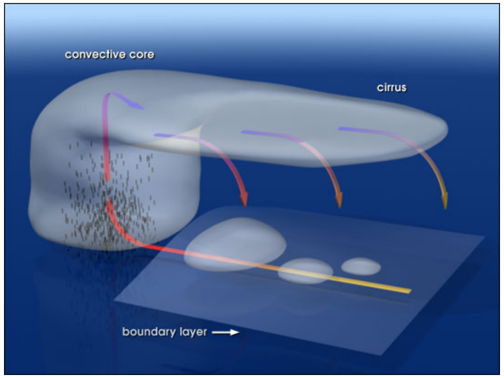
Precipitation trend 1990-2050
(AMMA Project, Paeth et al. 2011)

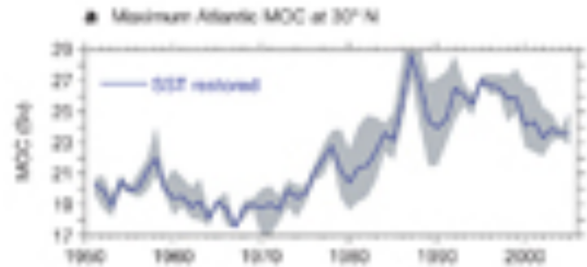


ECHAM5 LBC

HadCM3 LBC

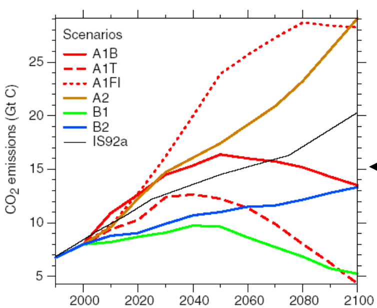
Large ensembles are needed to explore the uncertainty space





RCD Configuration

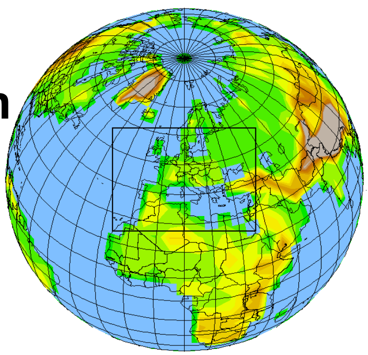
Internal Variability



Forcing Scenario

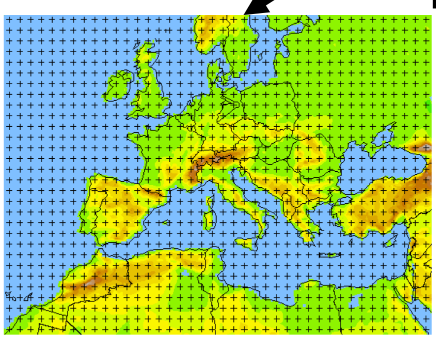
Experiment (i,j,k …)

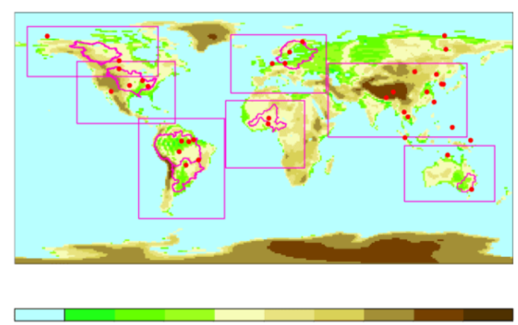
GCM Configuration



RCD Approach

Geographic Region





Giorgi et al. EOS 2008

Conclusions

- Climate change prediction (or projection) is characterized by an intrinsic uncertainty (to be fully characterized) and by an added uncertainty due to deficiences in the prediction process (to be minimized)
- Because of this nature, climate prediction needs to be approached in a probabilistic way
- Uncertainties increase at the regional to local scales
- Large ensembles of simulations are needed in order to fill the phase space of possible future climates (and climate change paths) and to produce meaningful PDFs
  - Use of downscaling techniques can enhance the uncertainty in regional projections
- Good criteria are needed to assess the reliability (credibility) of climate change projections
- A clear understanding of uncertainties and underlying processes is critical


Thank You

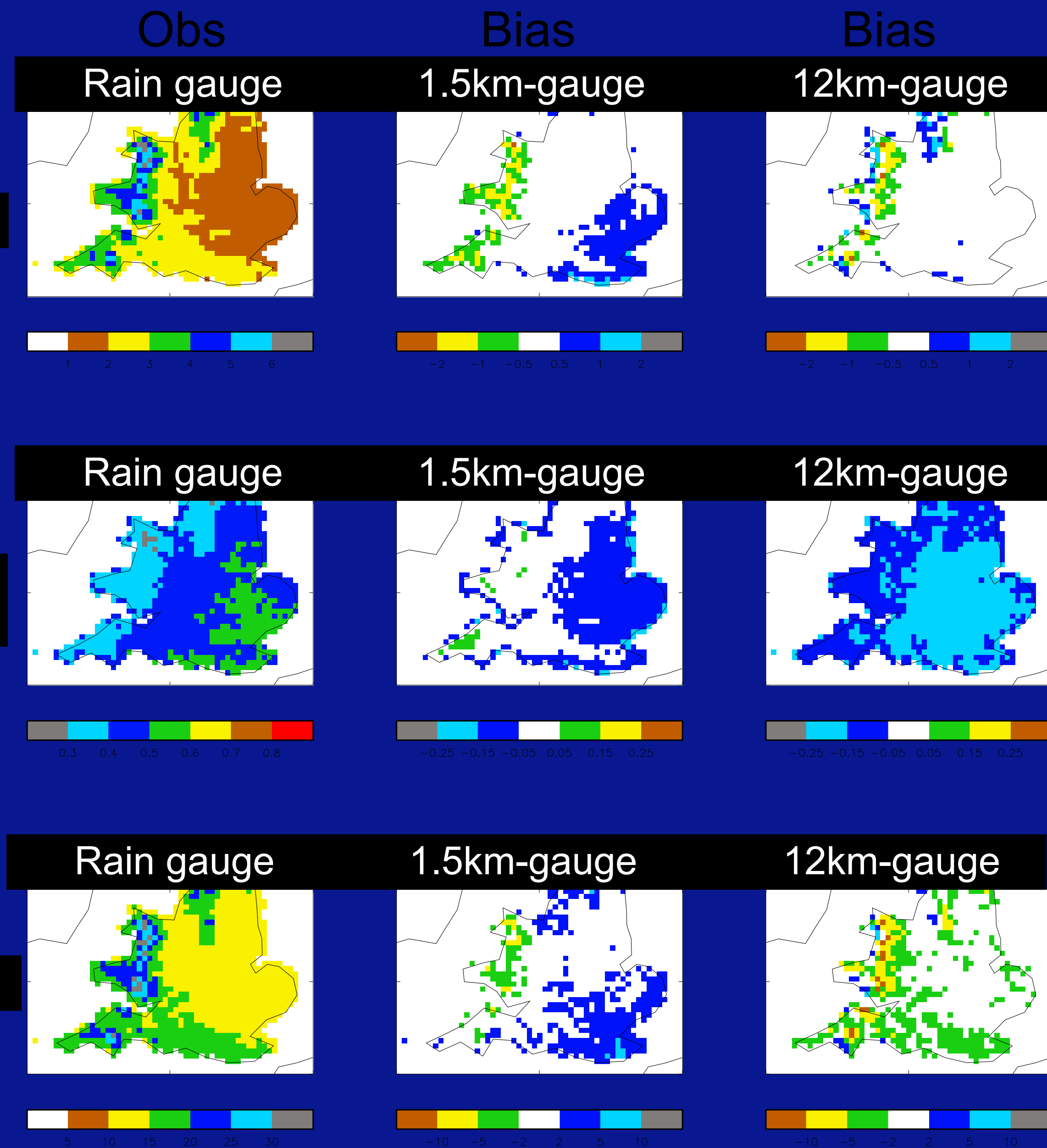
Very high resolution modeling

Daily precipitation (1990-2003)

Mean precip

Dry day occurrence

Heavy precip



Courtesy of E. Kendon UKMO