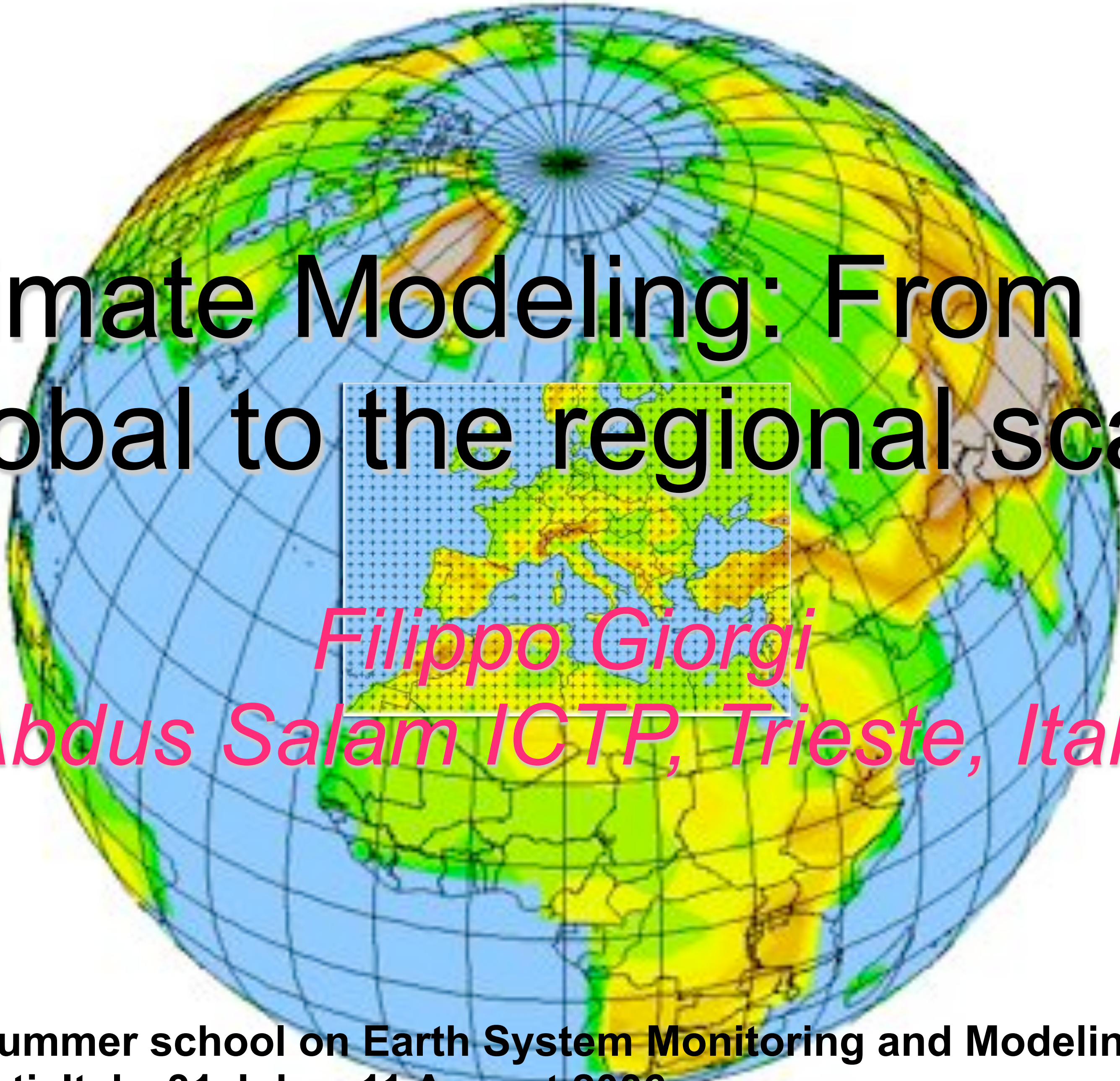


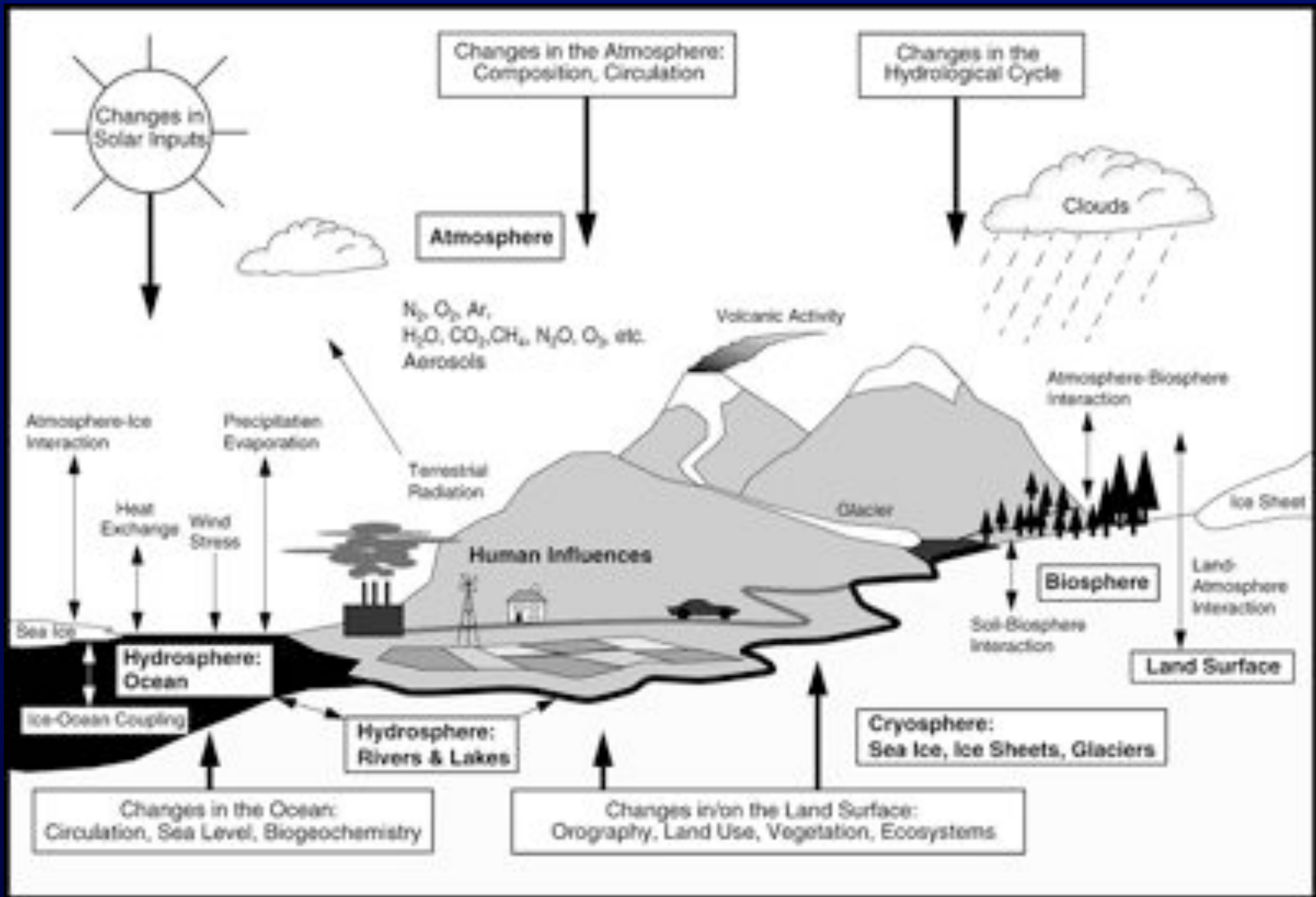
Climate Modeling: From the global to the regional scale

Filippo Giorgi
Abdus Salam ICTP, Trieste, Italy

ESA summer school on Earth System Monitoring and Modeling
Frascati, Italy, 31 July – 11 August 2006

The coupled Climate System

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



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

The "dynamical core" of a climate model

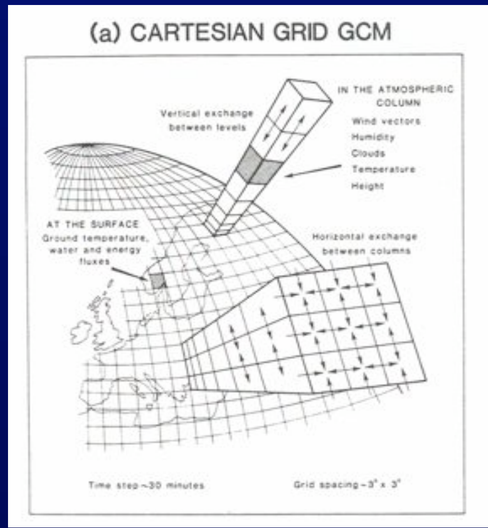
$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{\nabla p}{\rho} - 2\vec{\Omega} \times \vec{V} + \vec{g} + \vec{F}_V$$

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

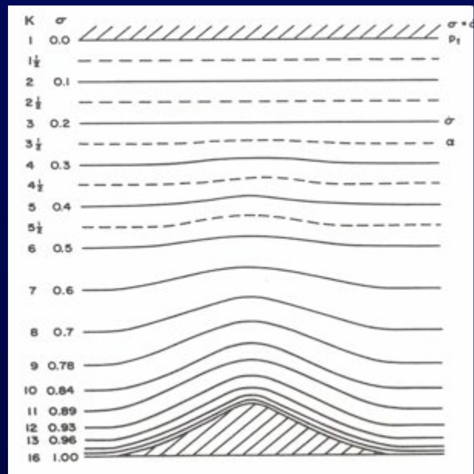
$$\frac{\partial \rho}{\partial t} + \vec{V} \cdot \nabla \rho = -\rho \nabla \cdot \vec{V}$$

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

$$p = \rho R T$$



Numerical solution
Finite differences
Spectral
Semi-Lagrangian



Vertical discretization
Terrain following (σ)
Height (z)
Pressure (p)
Hybrid

The “Physics” of a climate model

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

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

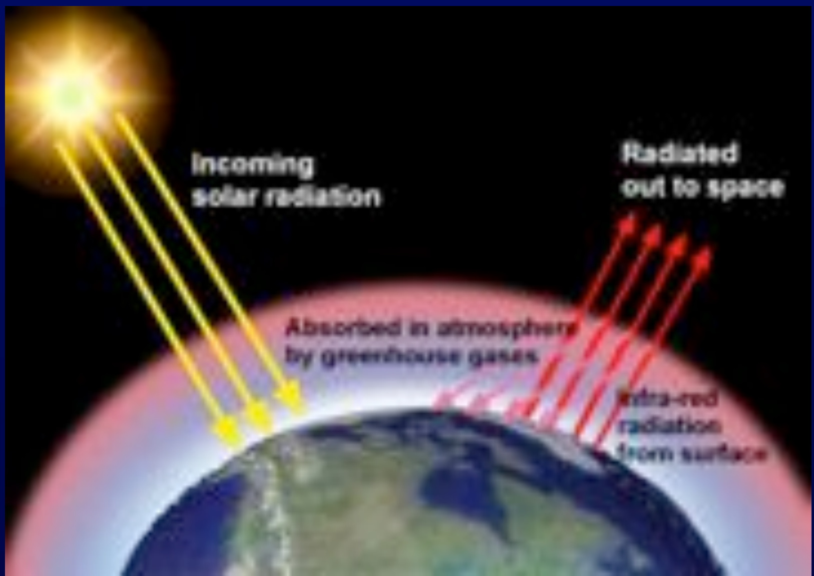
$$\frac{\partial \rho}{\partial t} + \overline{V} \cdot \nabla \rho = -\rho \nabla \cdot \overline{V}$$

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

$$p = \rho R T$$

The "Physics" of a climate model: Radiative Transfer

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



Scattering and absorption of solar and infrared radiation

O_3, H_2O, GHG

Clouds

Aerosols

The “Physics” of a climate model
Clouds and precipitation

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

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

Resolvable scale precipitation
(explicit schemes)
Prognostic equations for cloud variables
Parameterization of cloud microphysics

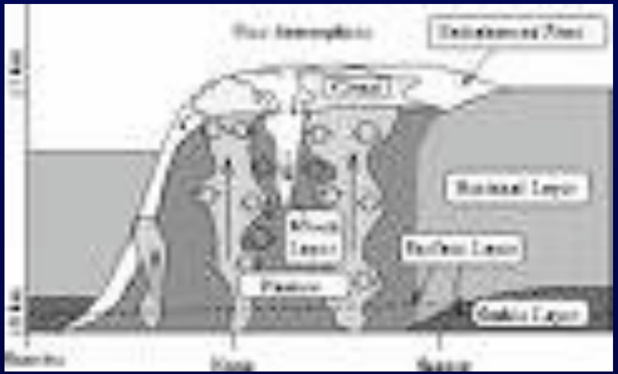
Convective (sub-grid scale) precipitation
Parameterization of deep moist convection
Many schemes available

The “Physics” of a climate model
Planetary boundary layer processes

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

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

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



Transport of momentum, energy
and water vapor from the surface
to the free troposphere

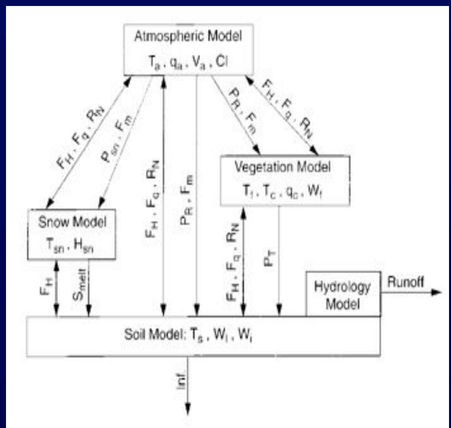
Stability-dependent vertical turbulent transport
Mostly “turbulent diffusion” schemes
Local and non-local schemes

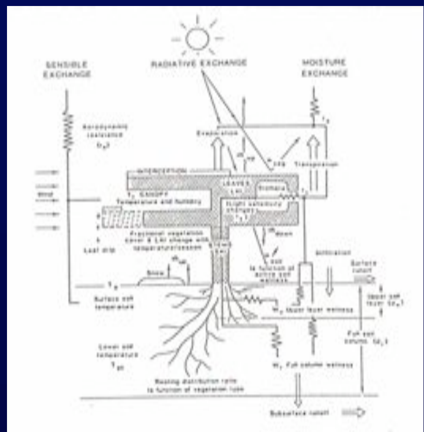
The “Physics” of a climate model
Land surface processes

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

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

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





Surface-atmosphere exchanges of momentum, energy and water vapor

Vegetation module

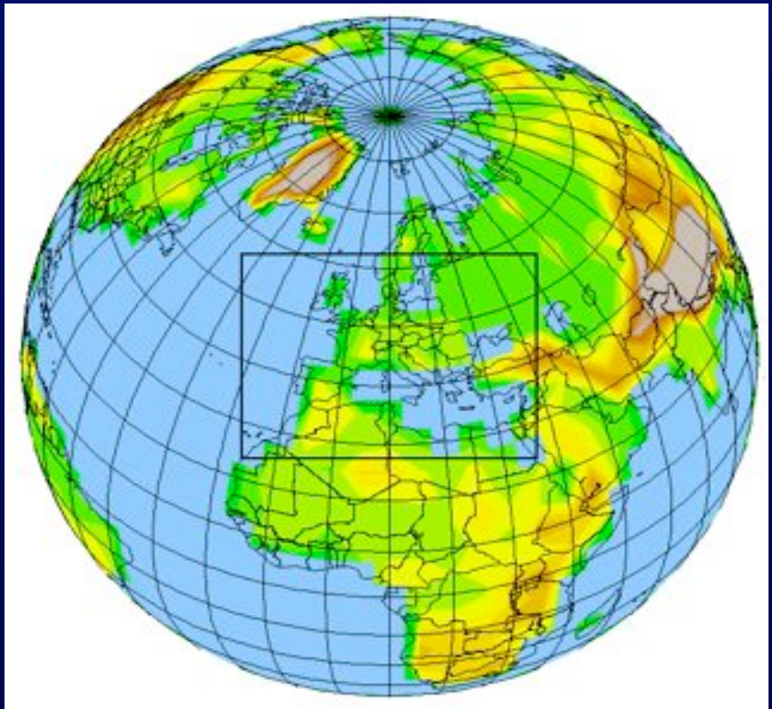
Soil module

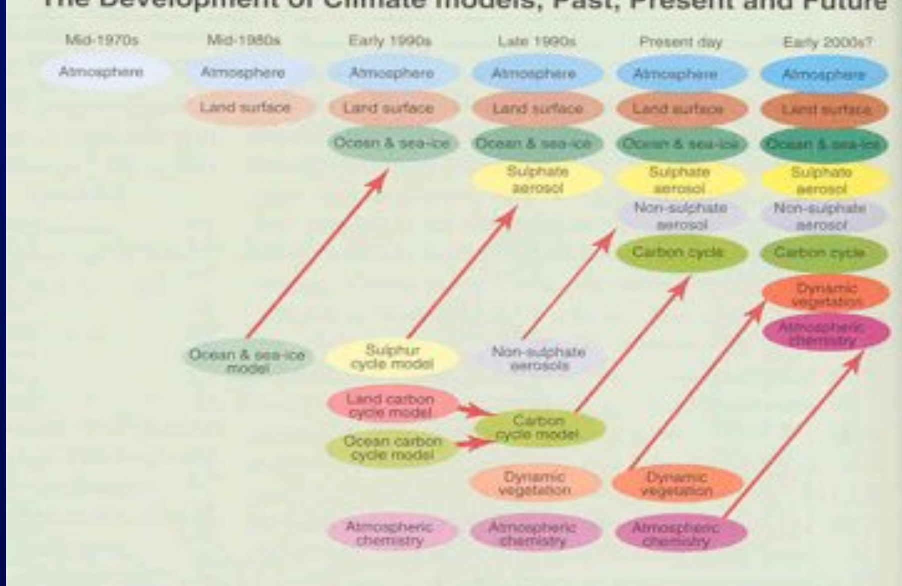
Surface hydrology module

Snow module

The basic tool for climate modeling

Coupled Atmosphere-Ocean General Circulation Model or AOGCM



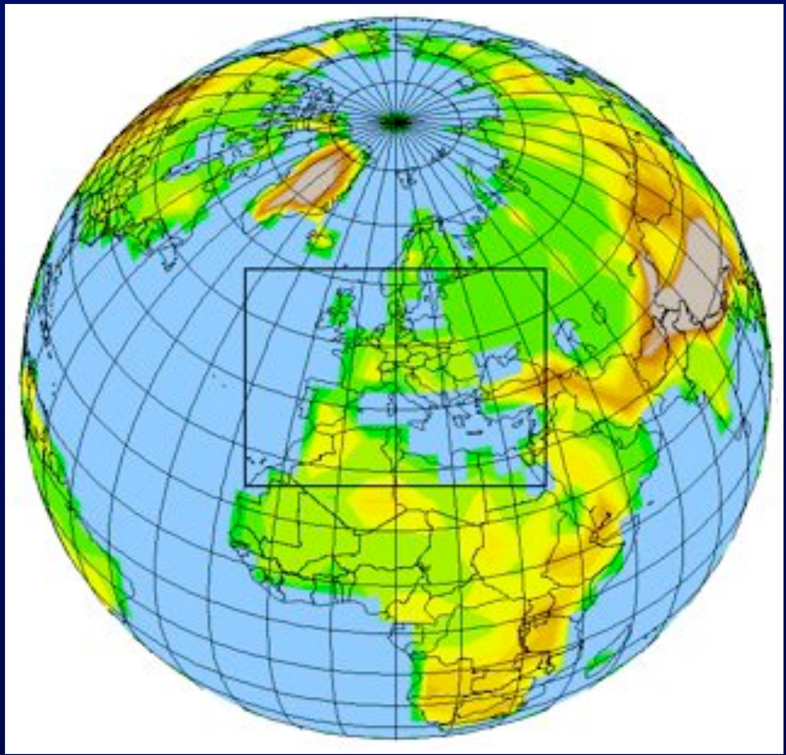


Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive climate models.

AOGCMs are numerical representations of the global climate

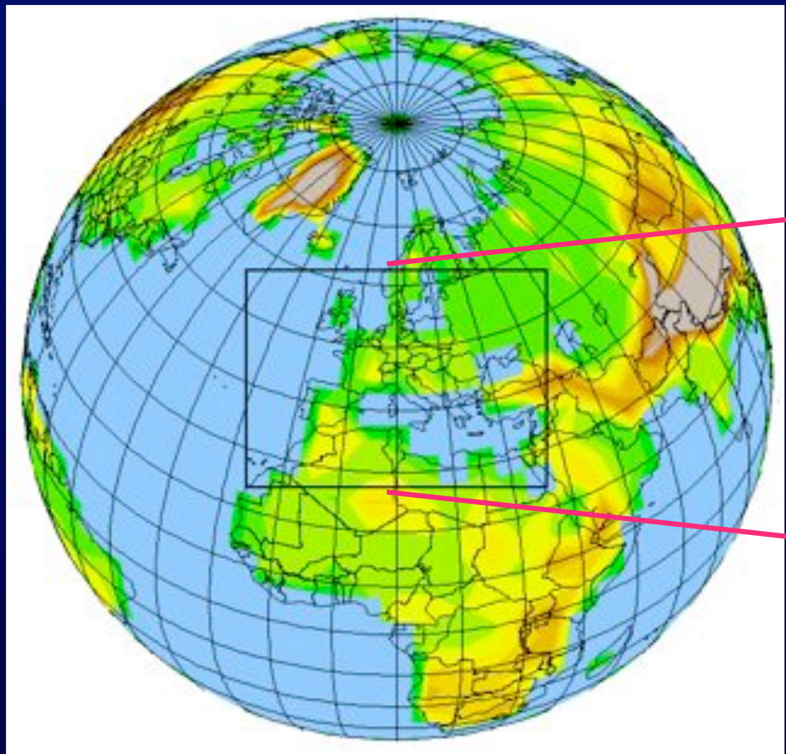
From global to regional climate modeling
The spatial scales of climate processes

Global

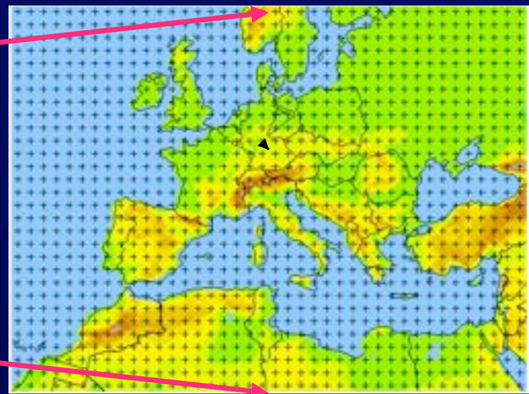


From global to regional climate modeling
The spatial scales of climate processes

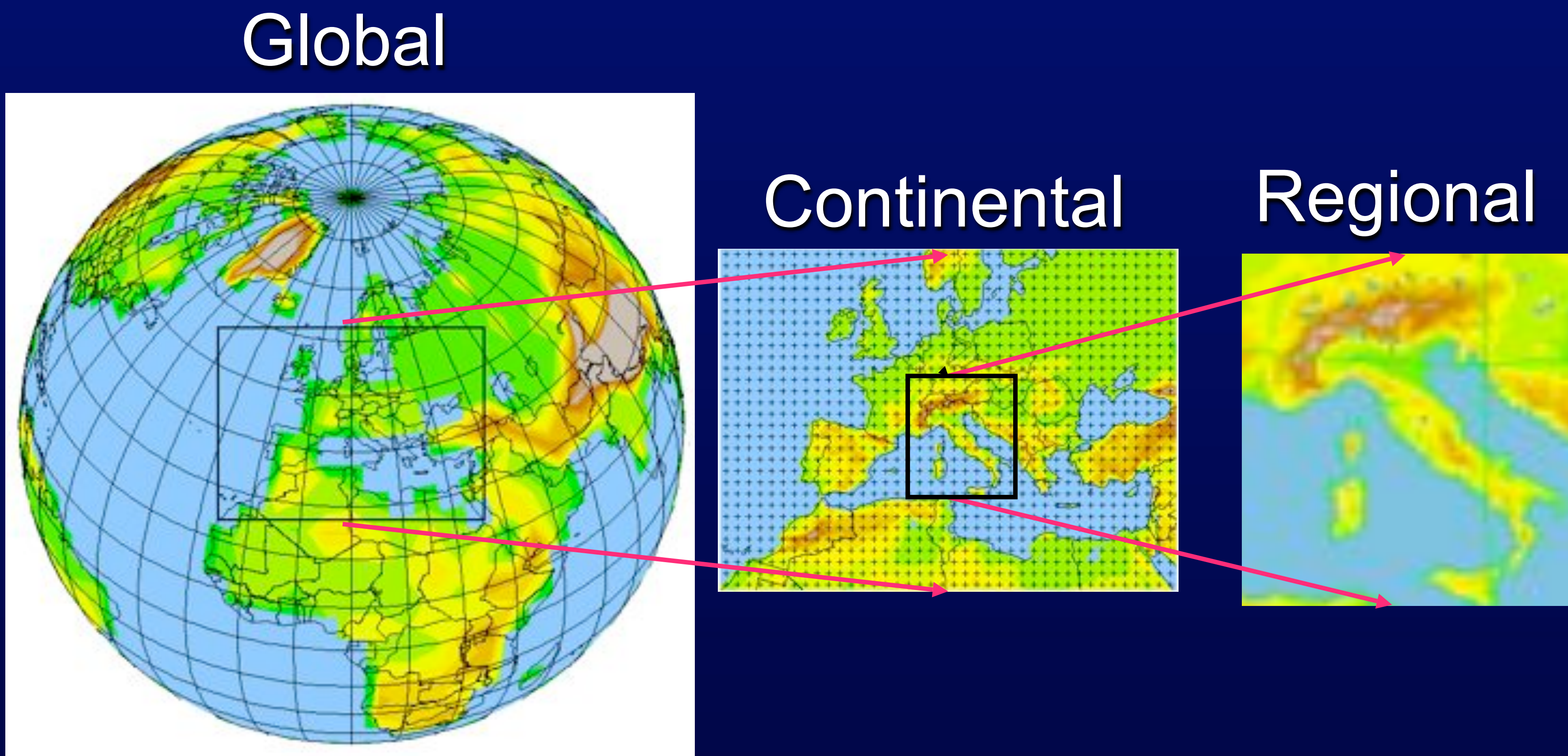
Global



Continental

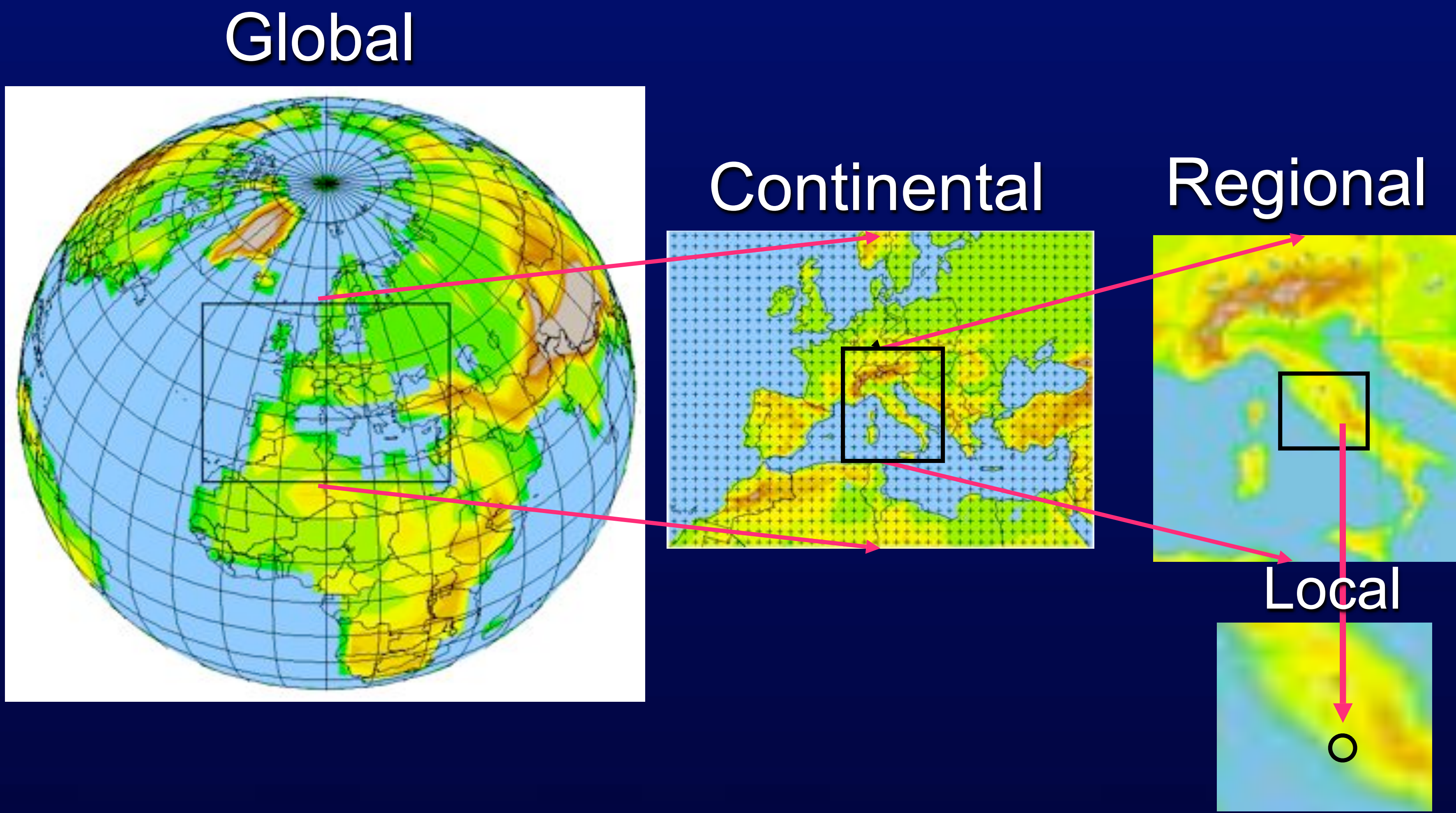


From global to regional climate modeling
The spatial scales of climate processes



From global to regional climate modeling

The spatial scales of climate processes



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

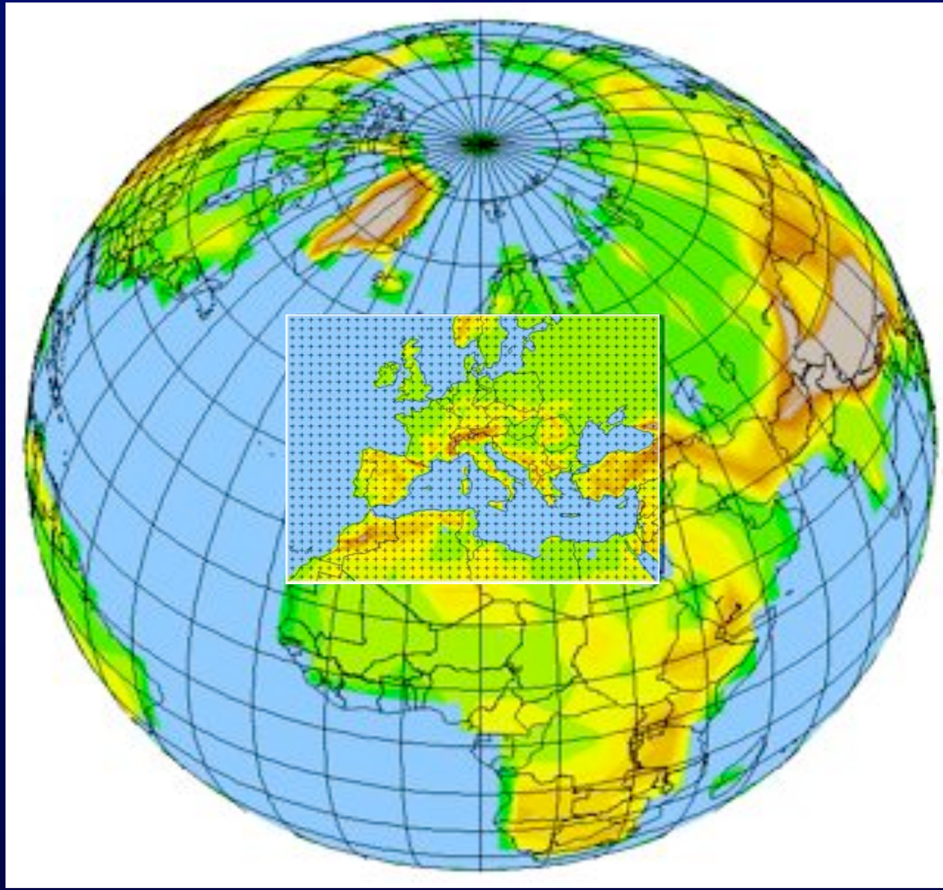
"Nested" Regional Climate Modeling: Technique and Strategy

Motivation: The resolution of AOGCMs is still too coarse to capture regional and local climate processes (e.g. topography, coastlines)

Technique: A limited area "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").

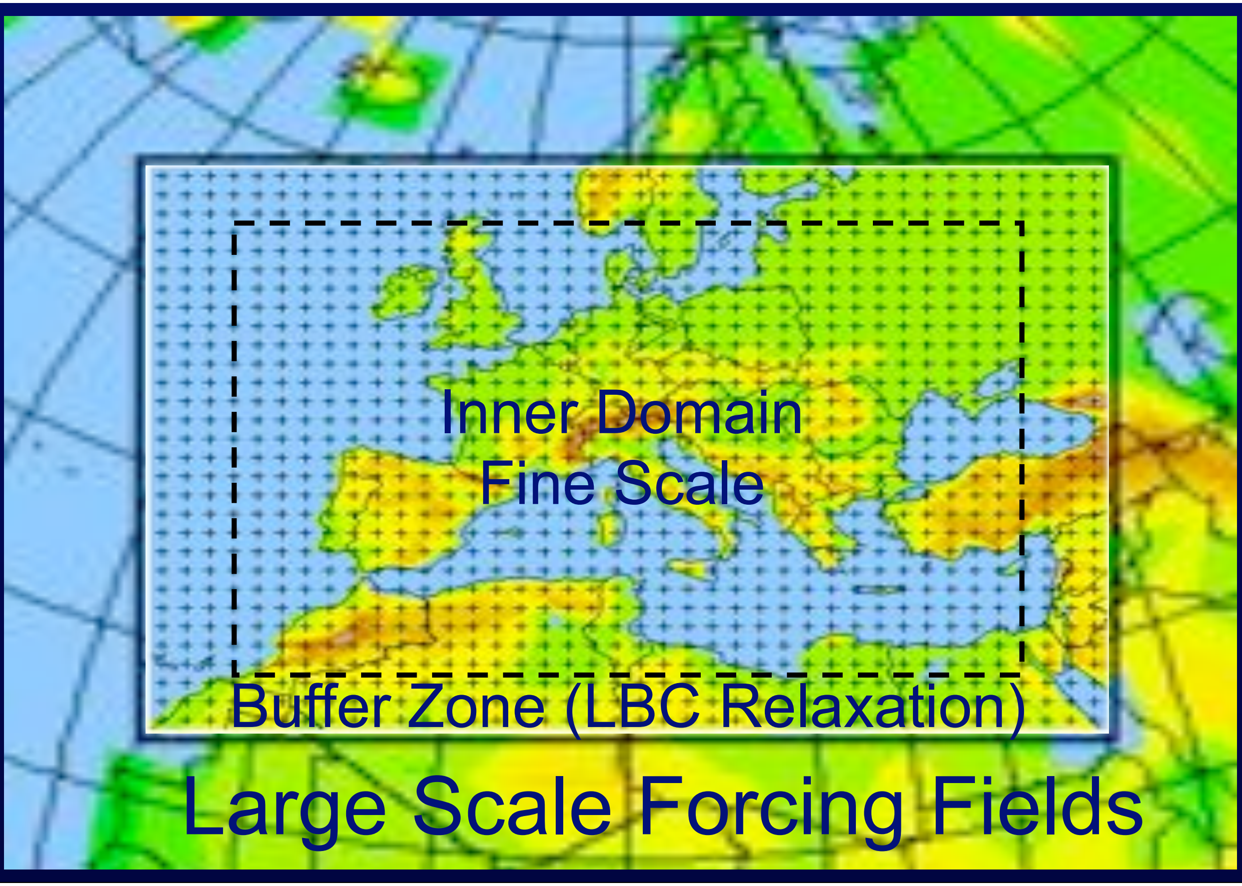
Strategy: The GCM simulates the response of the general circulation to the large scale forcings (e.g. GHG), the RCM simulates the effect of sub-GCM-grid scale forcings and provides fine scale regional information



RCM Nesting procedure

Different model prognostic variables are "relaxed" toward the large scale forcing fields in a lateral "buffer zone"

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



Regional Climate Modeling
Advantages

- Physically based downscaling
  - Comprehensive climate modeling system
- Wide variety of applications
  - Process studies
  - Paleoclimate
  - Climate change
  - Seasonal prediction
- High resolution through multiple nesting (currently up to a few km grid interval)
- Usable on PCs

Regional Climate Modeling
Limitations

- One-way nesting
  - No regional-to-global feedbacks
- Technical issues in the nesting technique
  - Domain, LBC procedure, physics, etc.
- Not intended to correct systematic errors in the large scale forcing fields
  - Always analyse first the forcing fields
- Computationally demanding

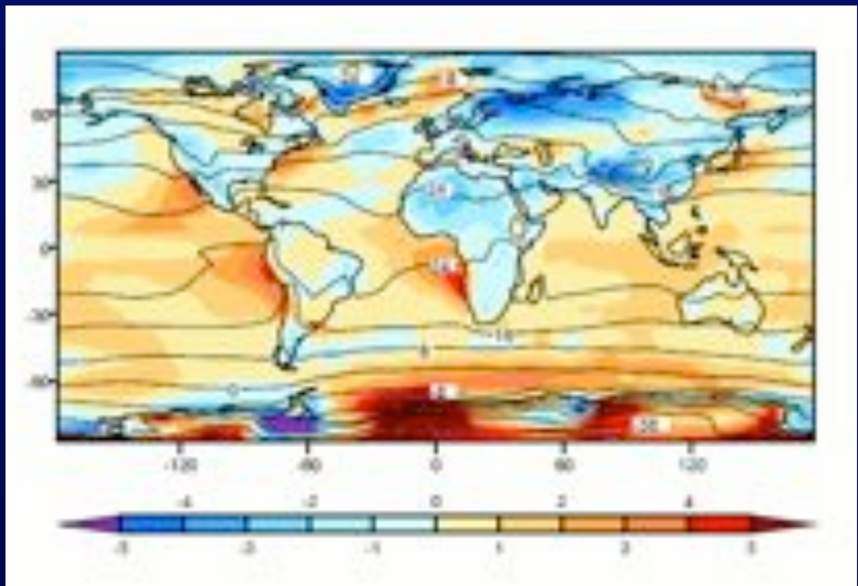
Regional Climate Modeling
Applications

- 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 changes, variability and extremes
- Paleoclimate studies
- Regional climate system coupling
  - Chemistry/aerosol – atmosphere (Climatic effects of aerosols)
  - Ocean/sea ice-atmosphere
  - Biosphere-atmosphere
- Seasonal prediction

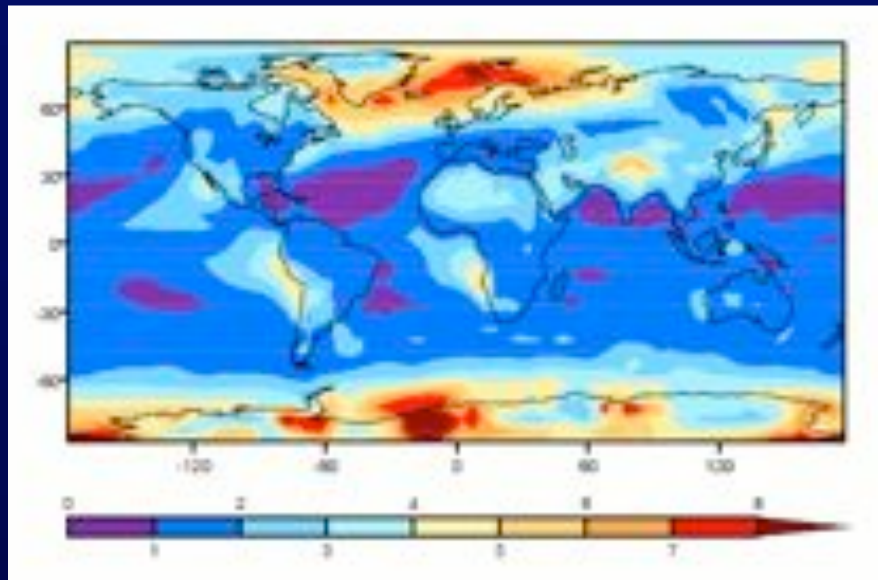
The performance of

Performance of AOGCMs
Annual temperature, 20 models

Observed annual temperature (lines) and multi-models ensemble bias (colors)

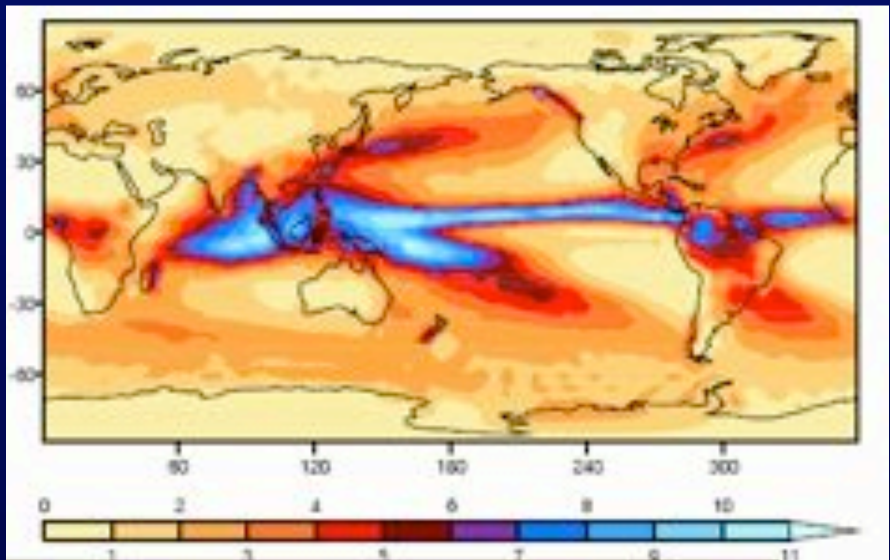


Annual temperature multi-model ensemble Average root mean square error

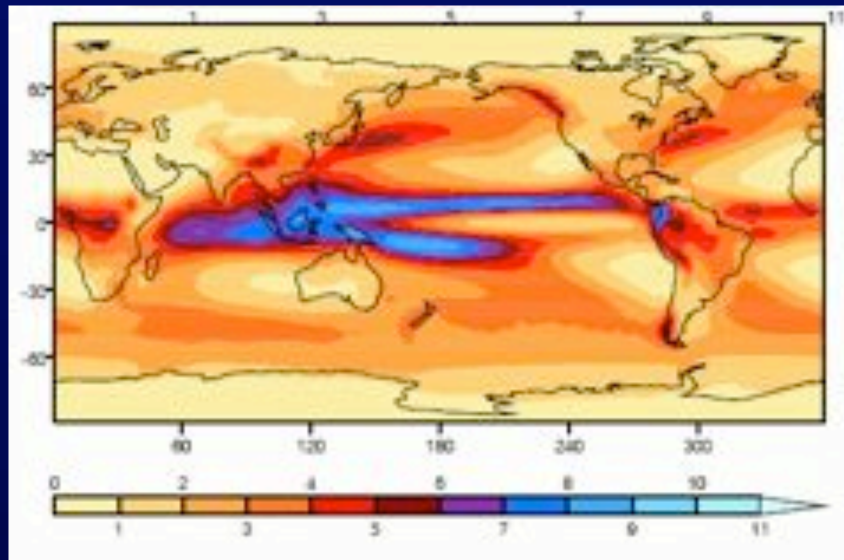


Performance of AOGCMs
Annual precipitation, 20 models

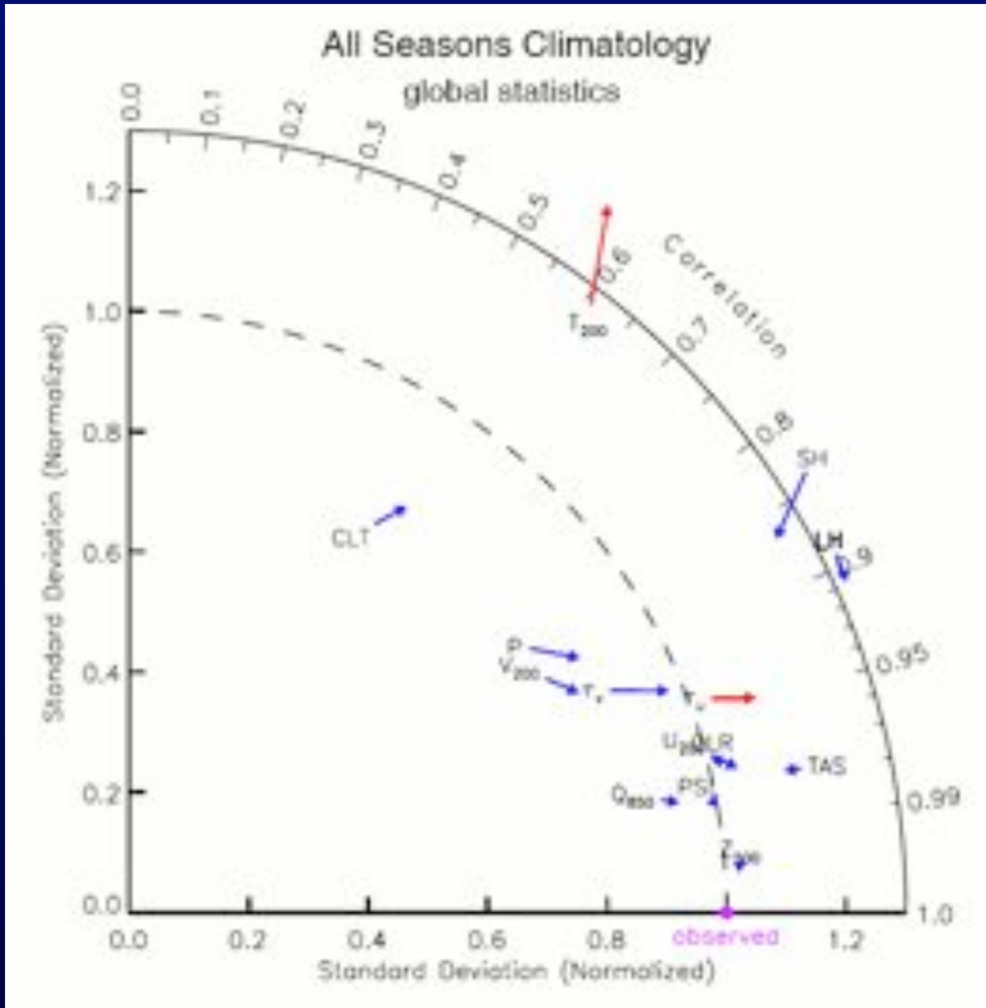
Observations



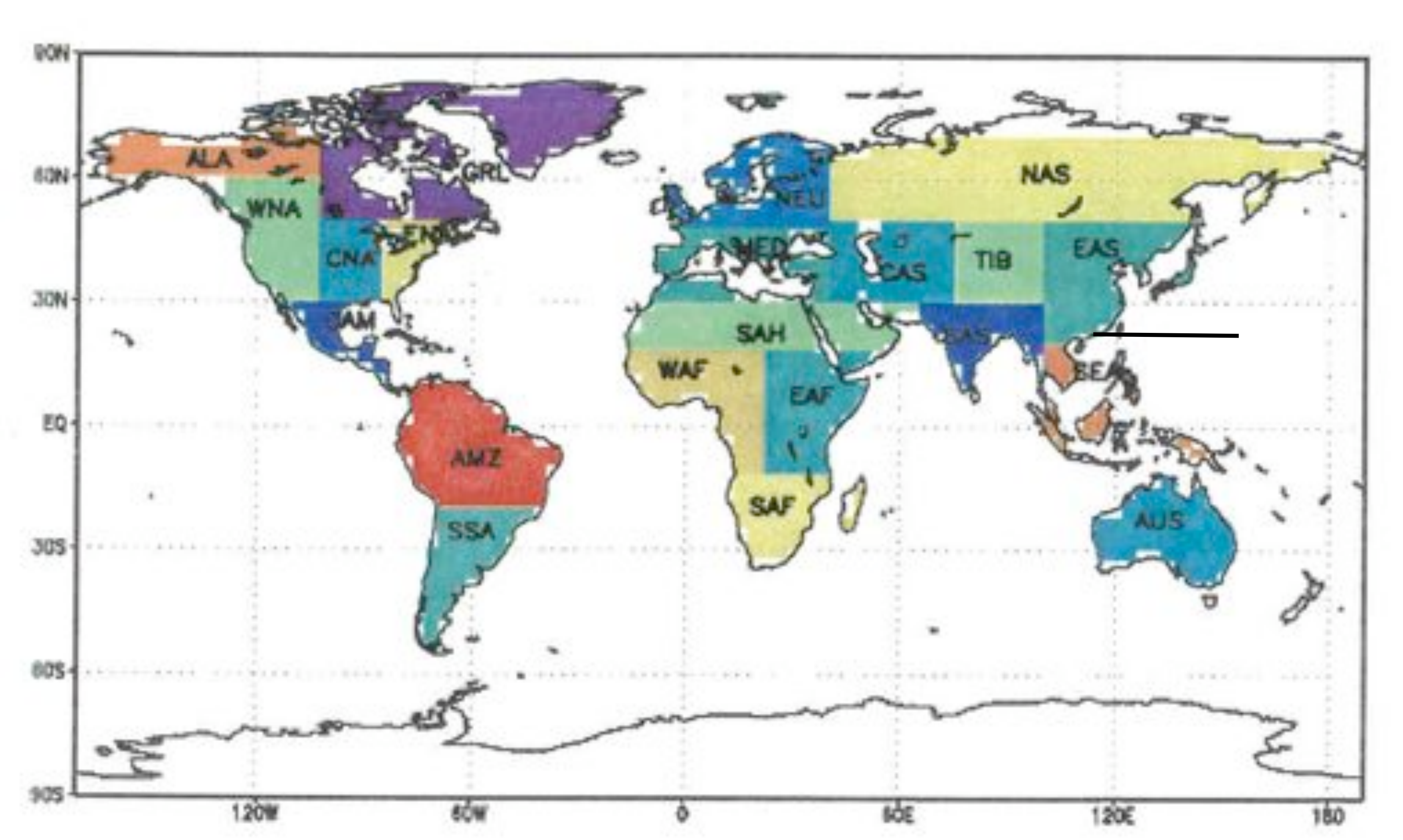
Model ensemble mean



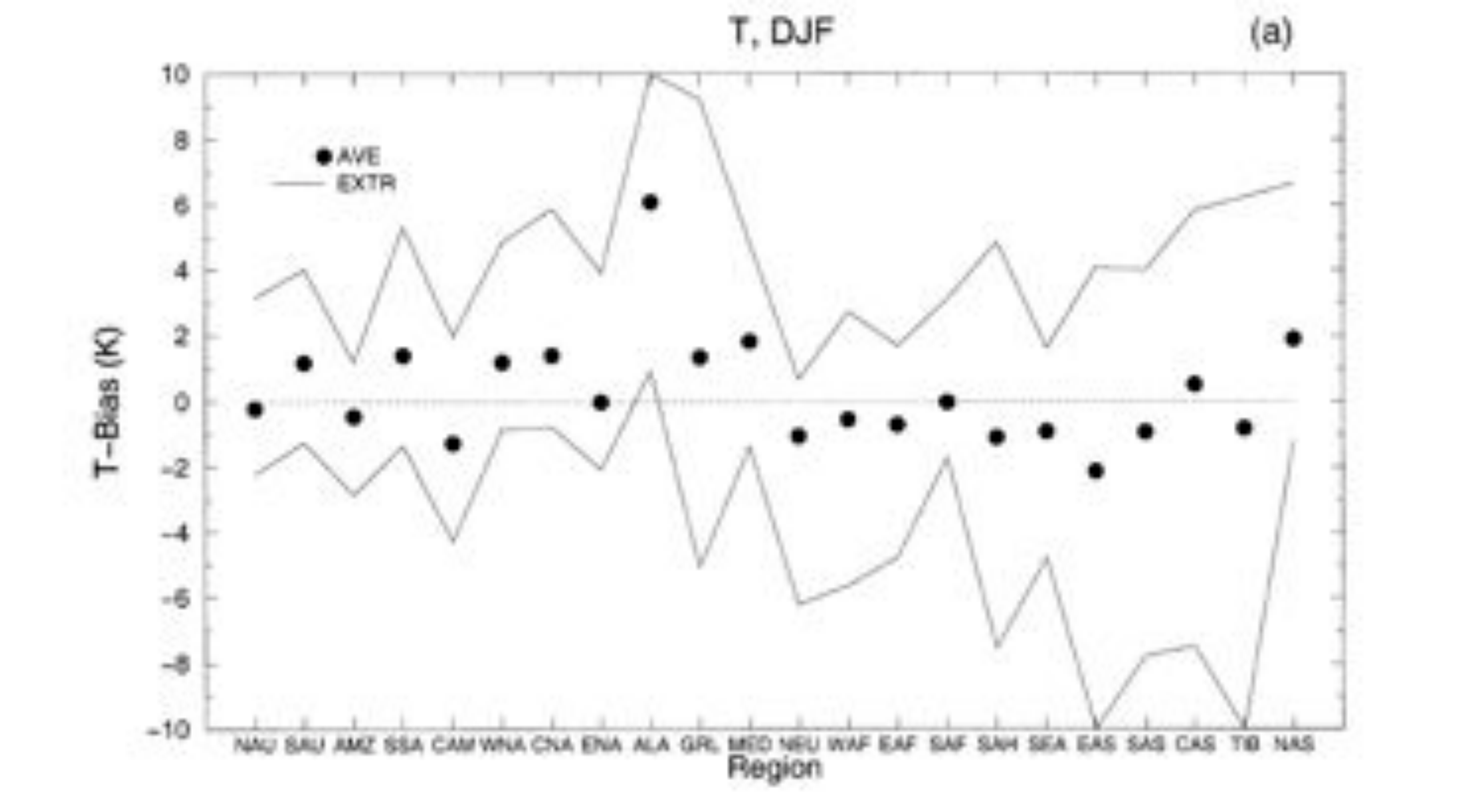
Global Performance of AOGCMs
20 models



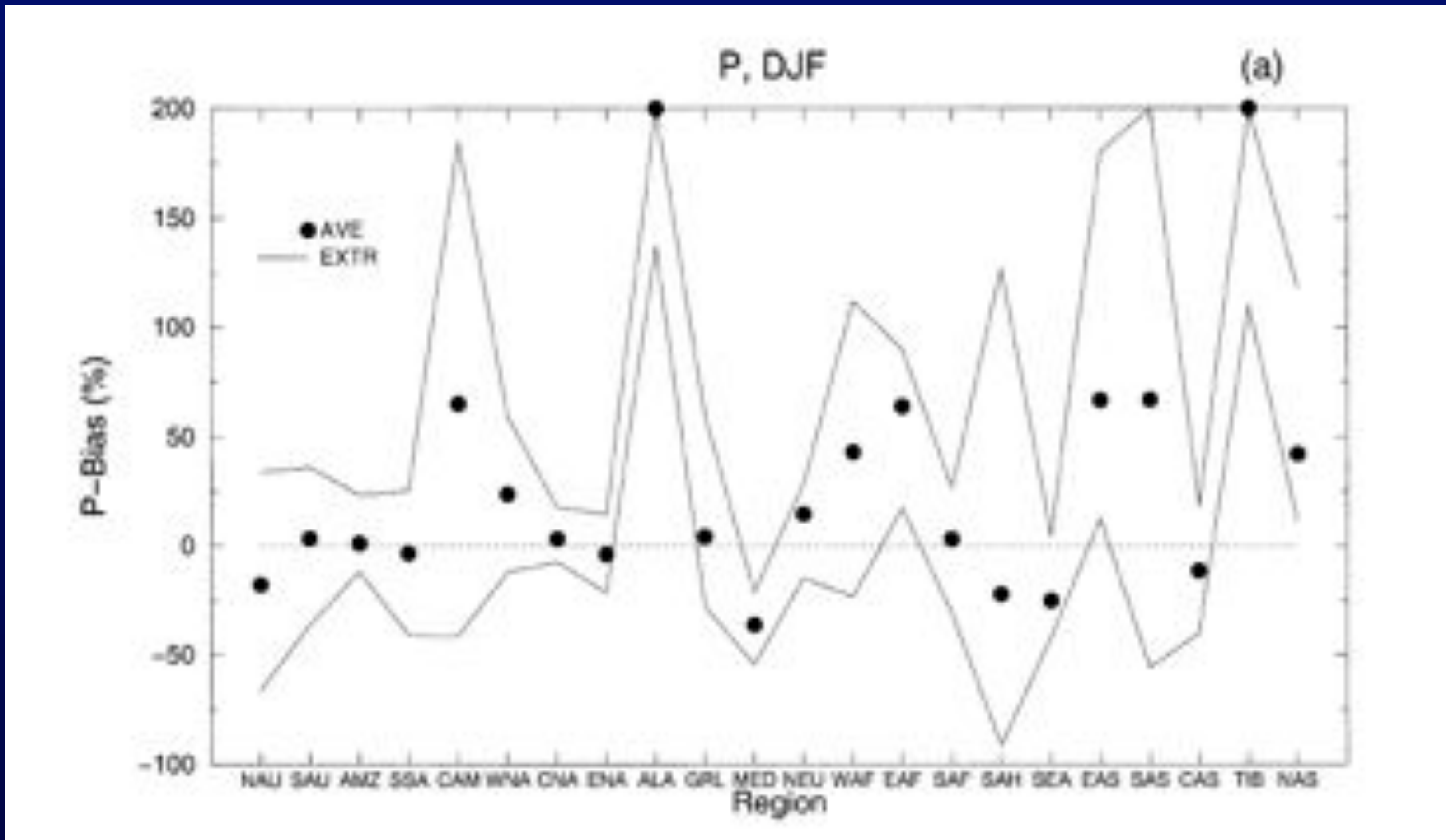
Regional performance of AOGCMs



Regional performance of AOGCMs
Temperature Bias, 9 AOGCMs

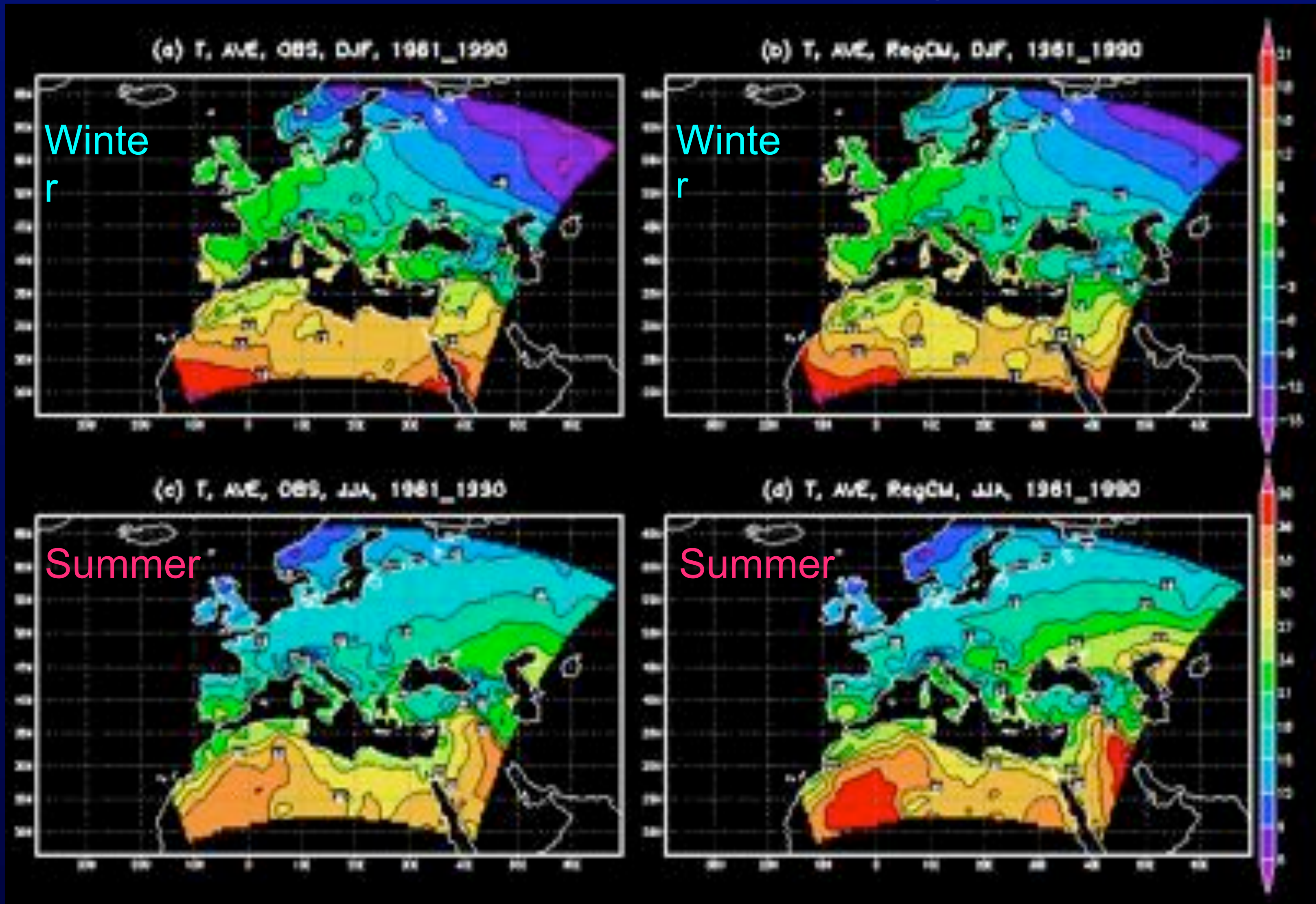


Regional performance of AOGCMs
Precipitation Bias, 9 AOGCMs



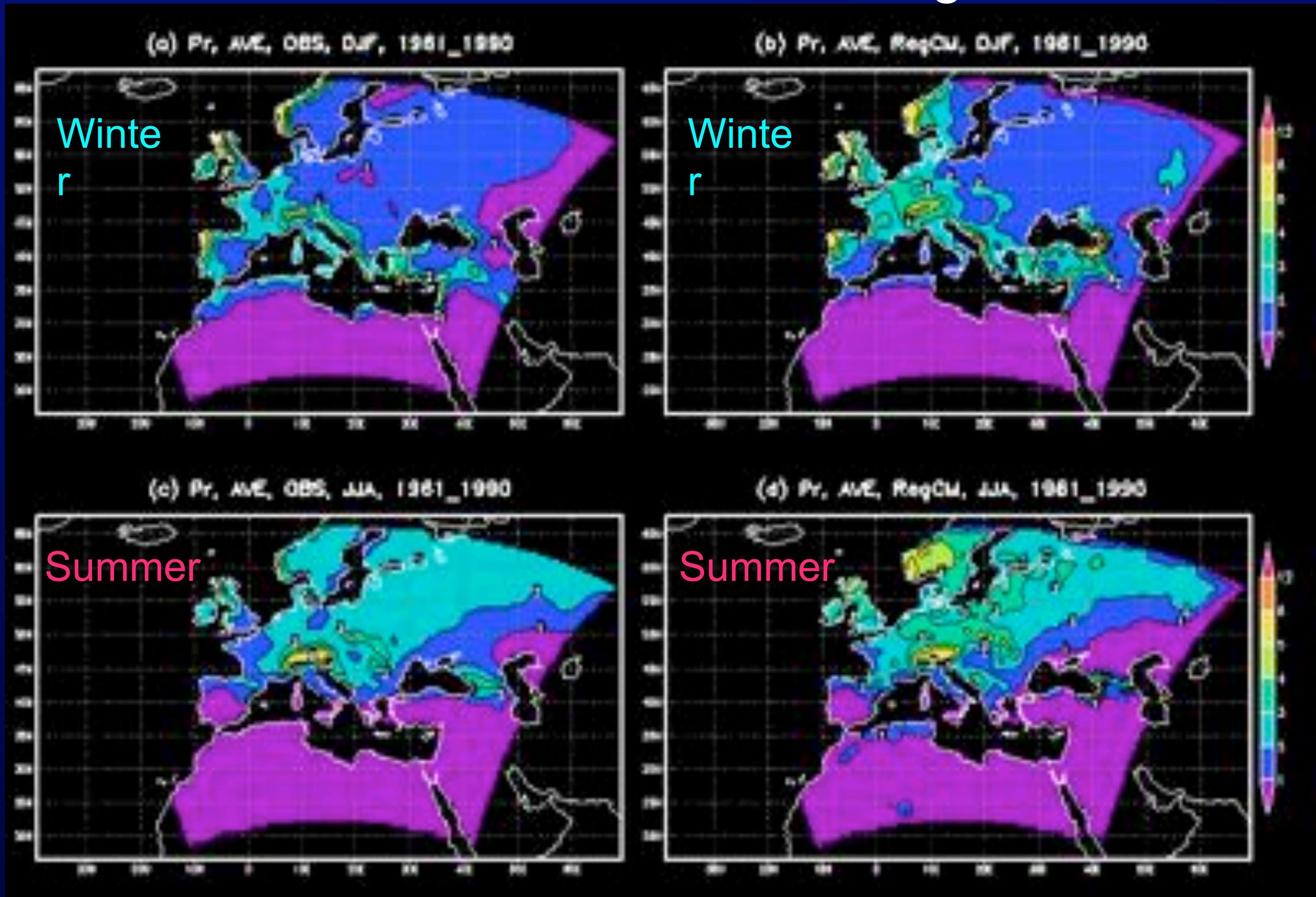
Performance of RCMs, temperature

Observations RegCM



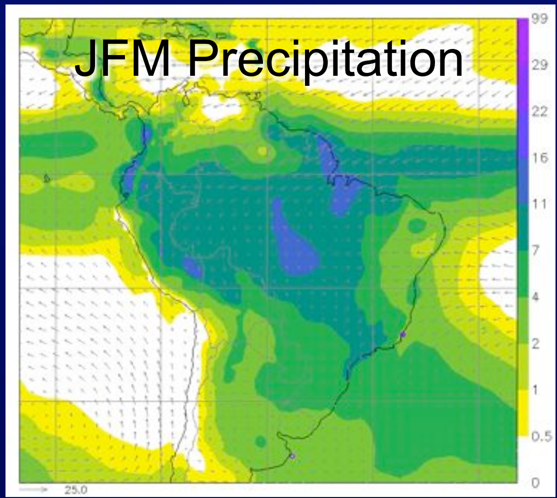
Performance of RCMs, precipitation

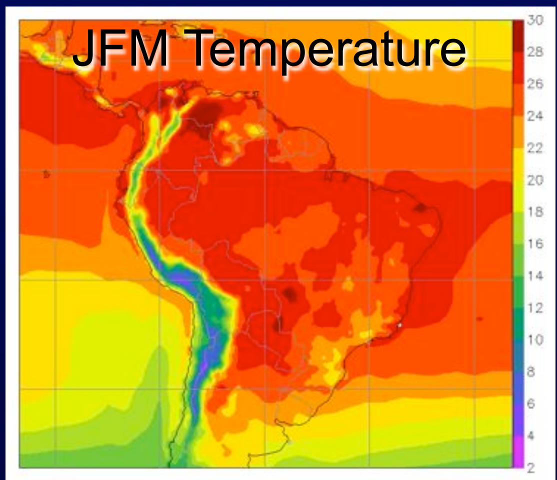
Observations RegCM



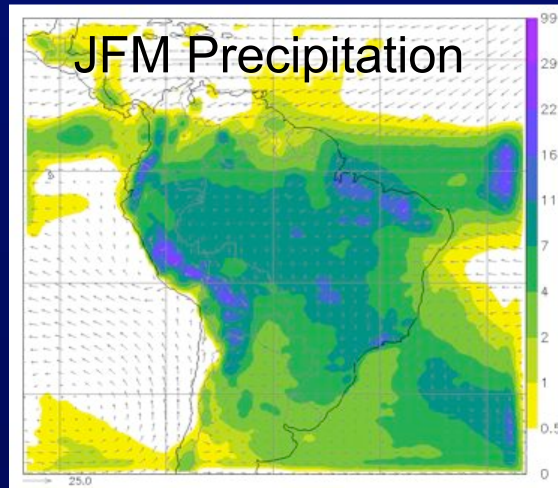
Performance of RCMs (1987-2000)

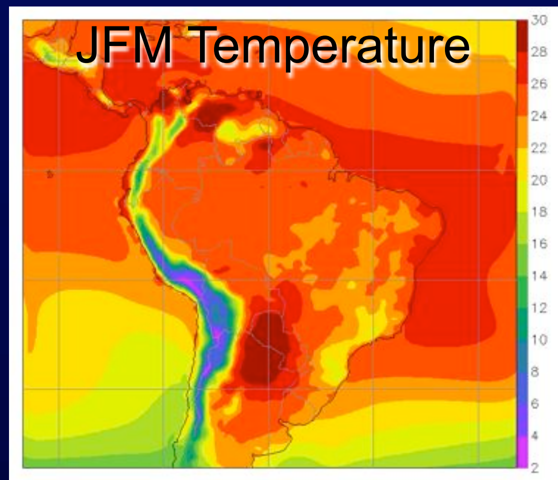
Observations





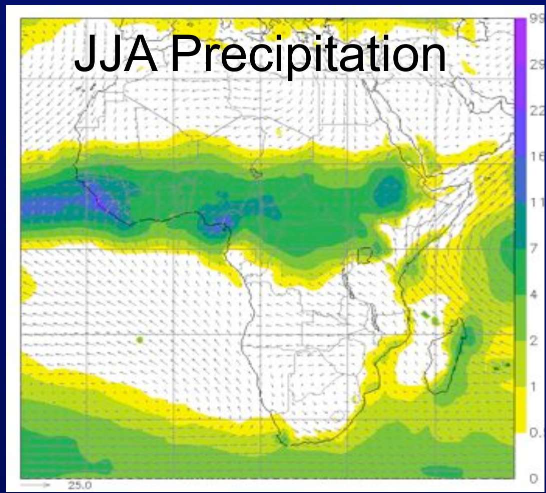
RegCM3

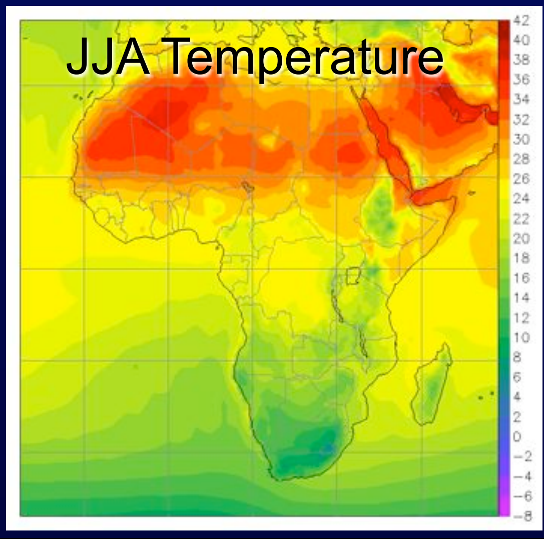




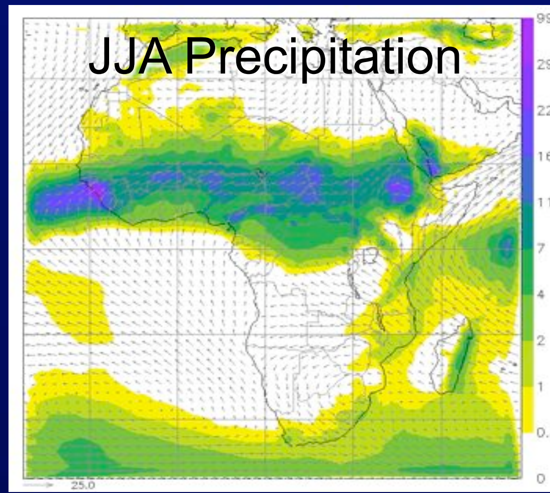
Performance of RCMs (1987-2000)

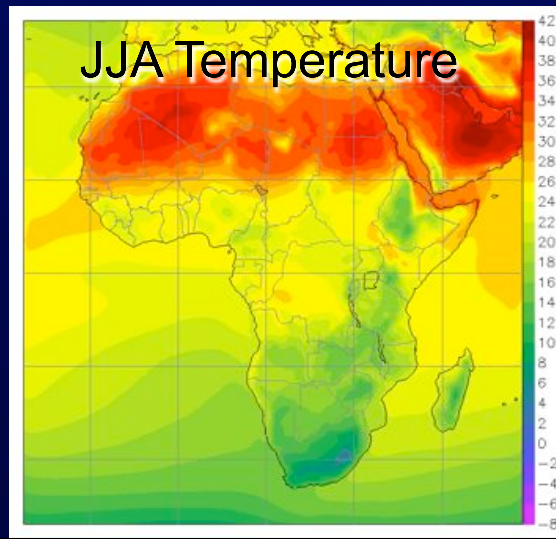
Observations





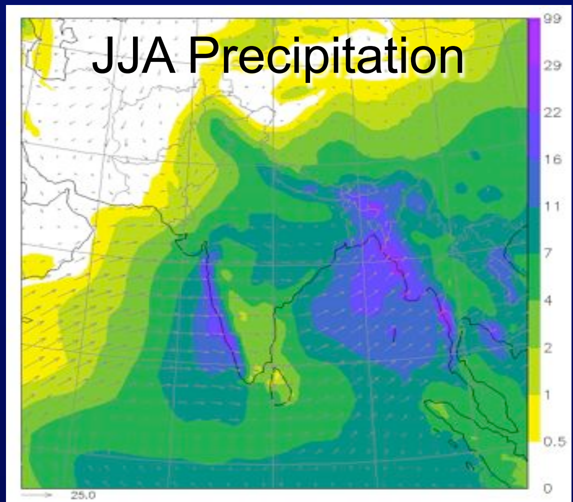
RegCM3

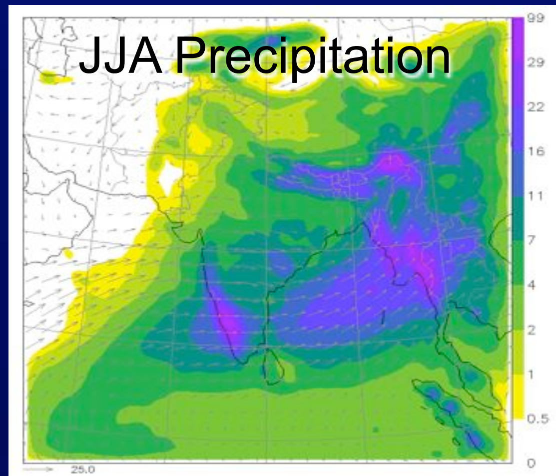


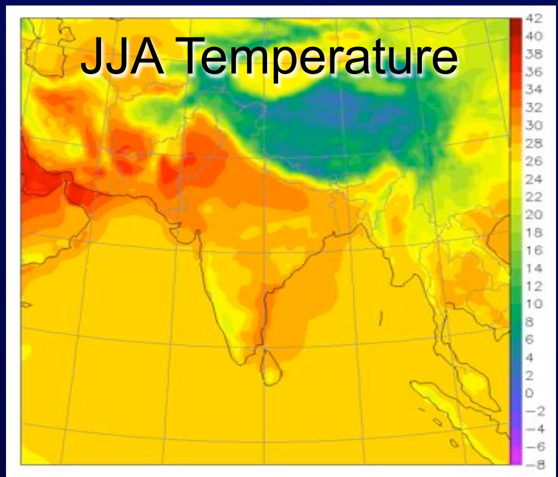


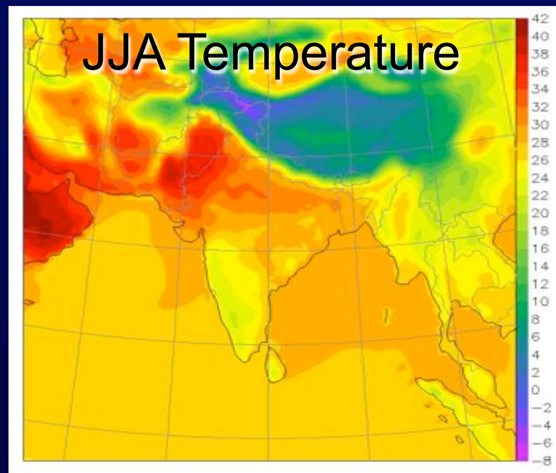
Performance of RCMs (1987-2000)

Observations | RegCM3







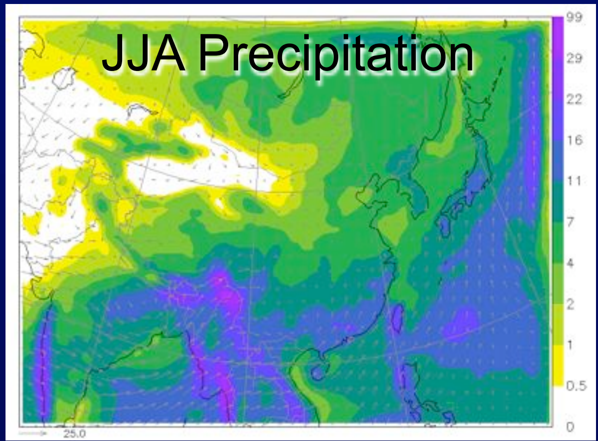


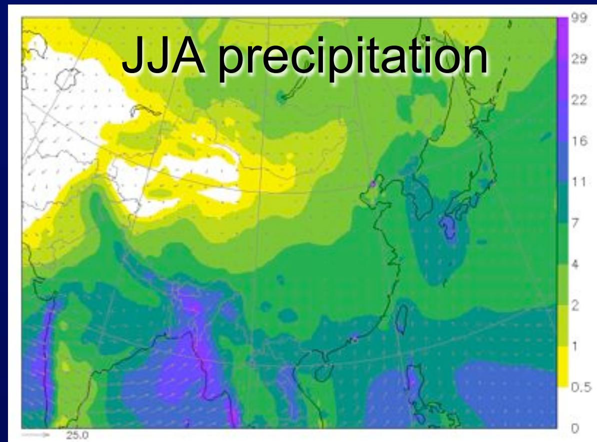
Performance of RCMs

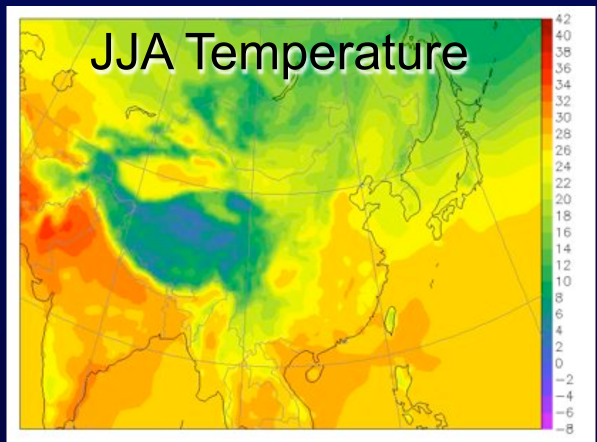
Precipitation and Winds (1987-2000)

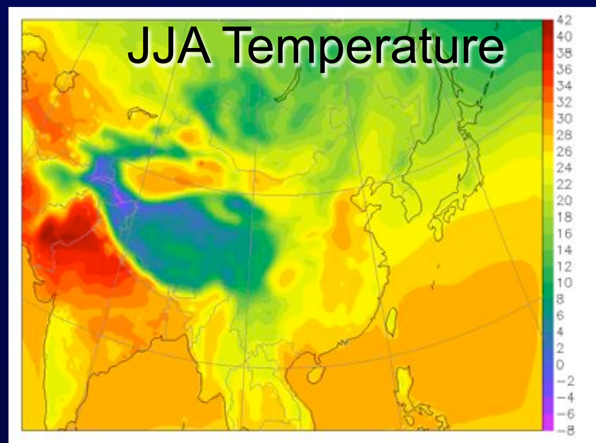
Observations

RegCM3

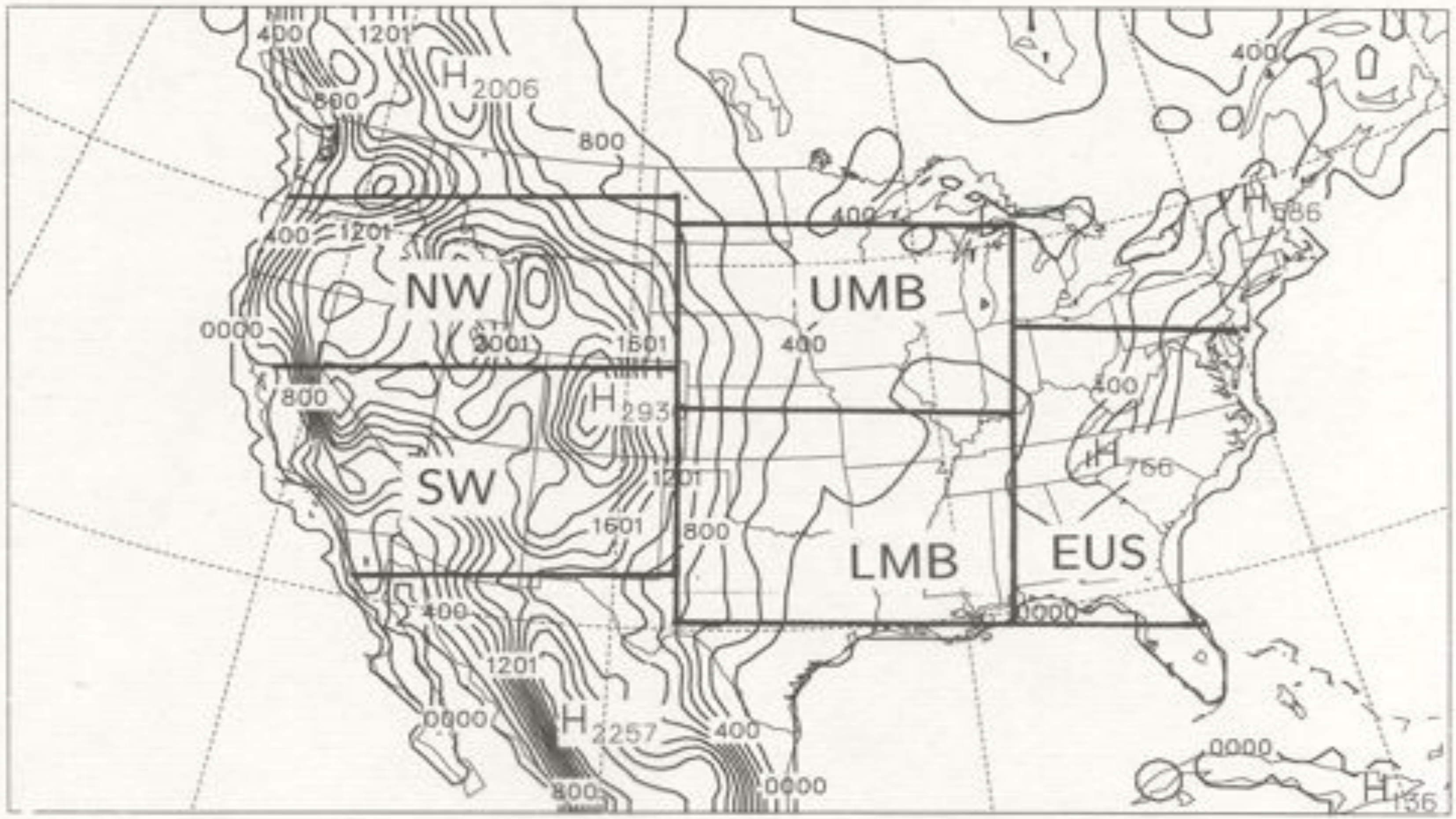




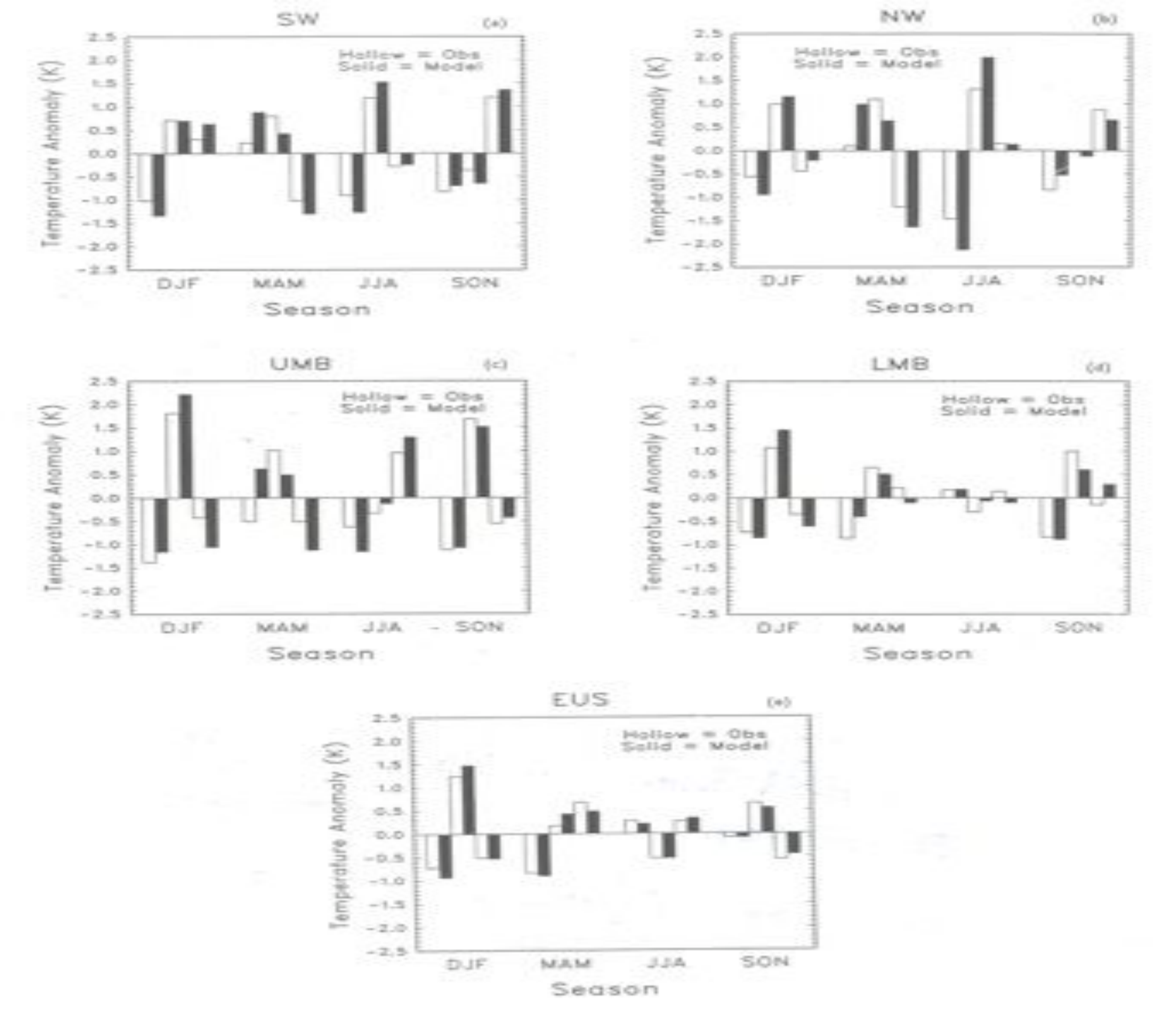




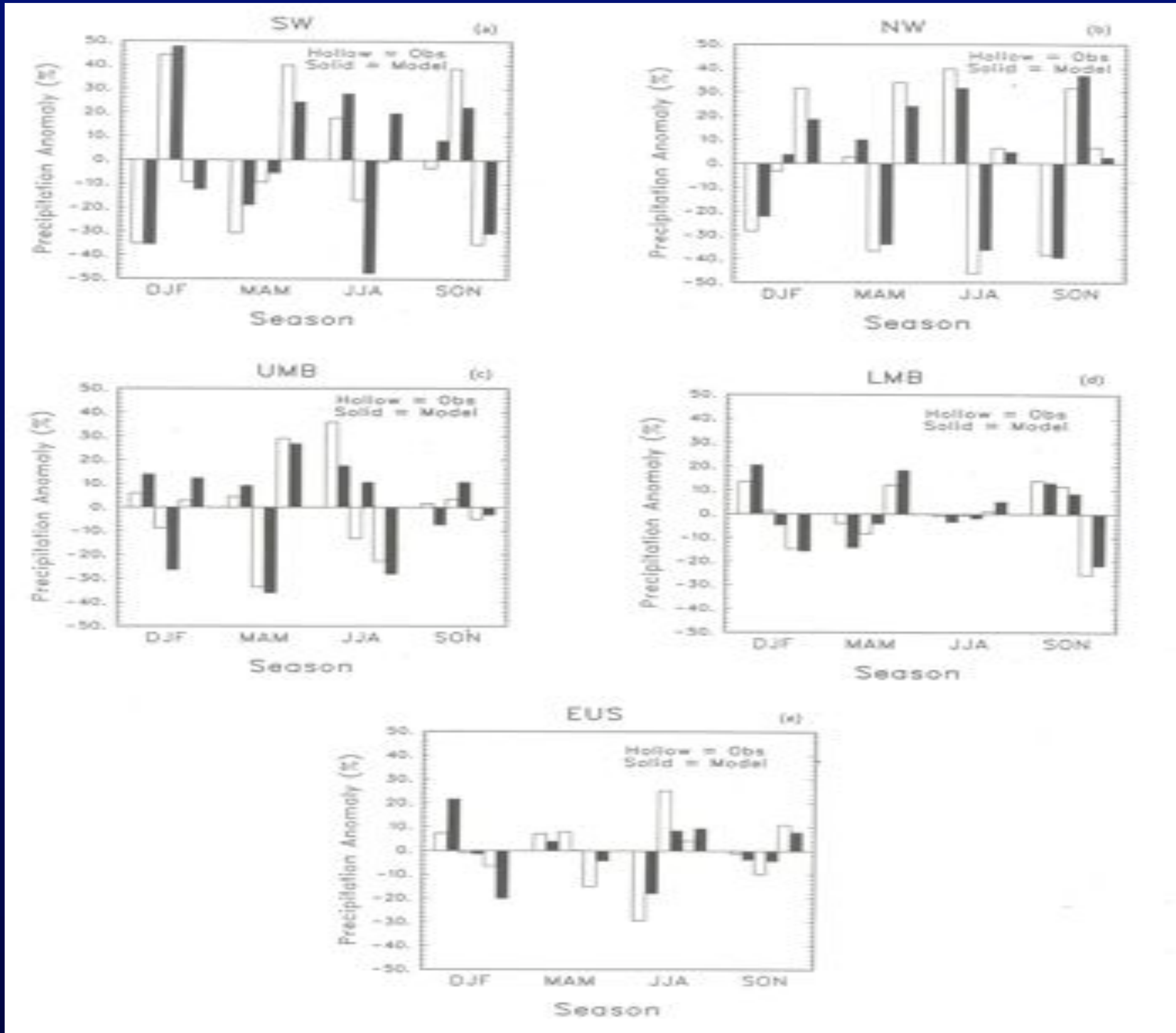
Three-year Simulation (1993-1995), Model Domain



Temperature Interannual Variability

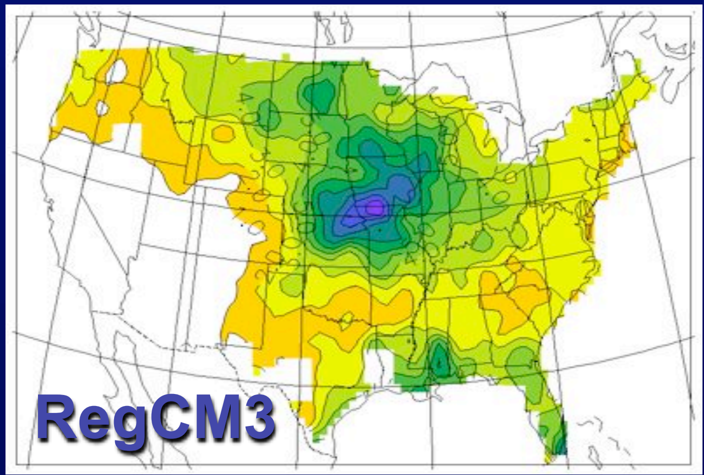


Precipitation Interannual Variability

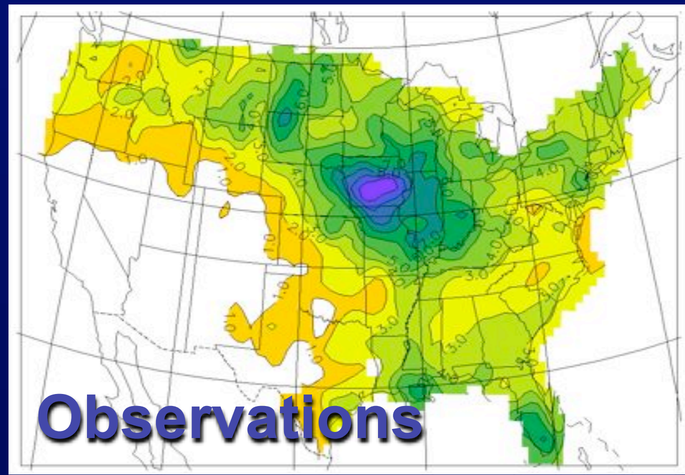


Simulation of extreme precipitation

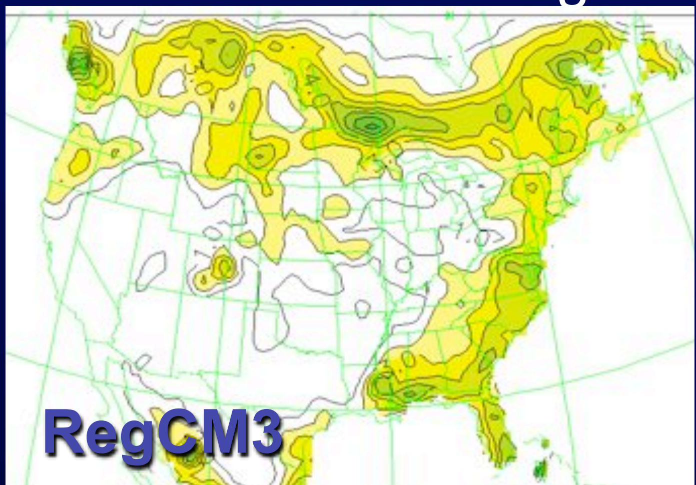
Summer 1993 Flood



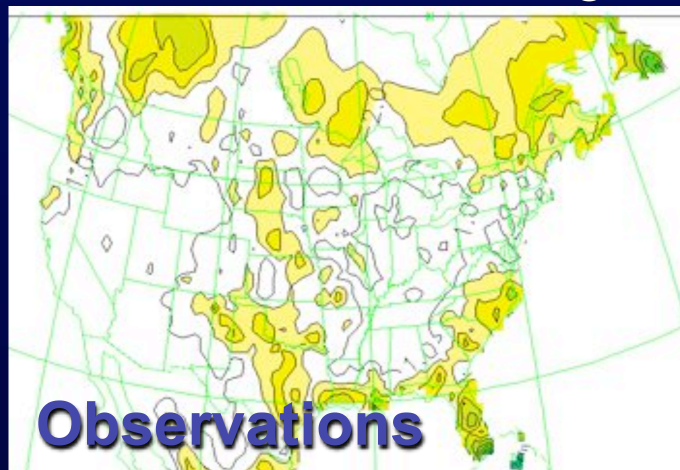
Summer 1993 Flood



Summer 1988 Drought

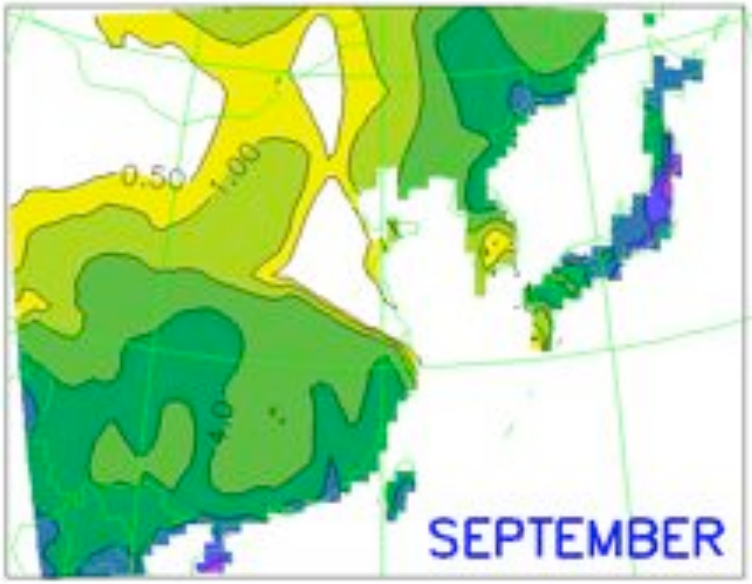


Summer 1988 Drought

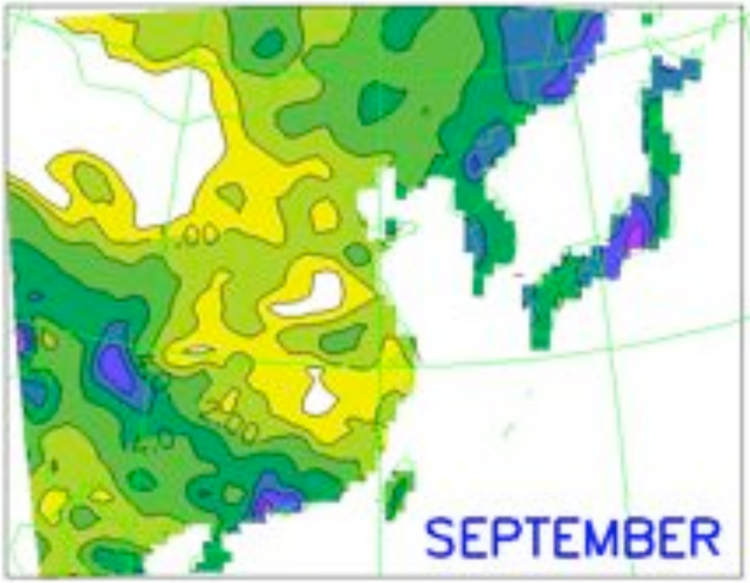


Precipitation over East Asia
Sept 1994 thru August 1995

CRU Obs



RegCM

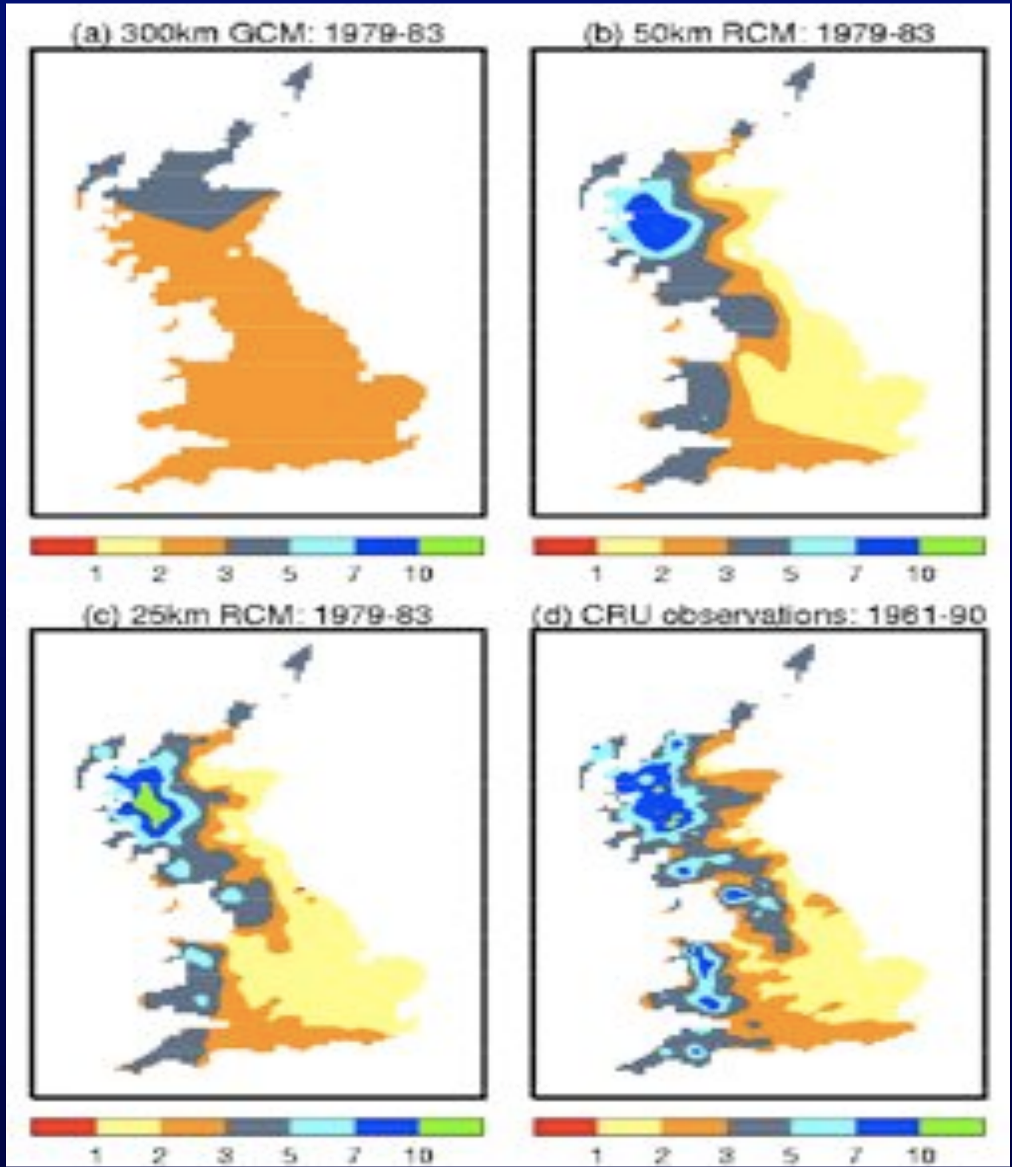


Examples of the added

WINTER PRECIPITATION OVER BRITAIN

300km Global Model

50km Regional Model



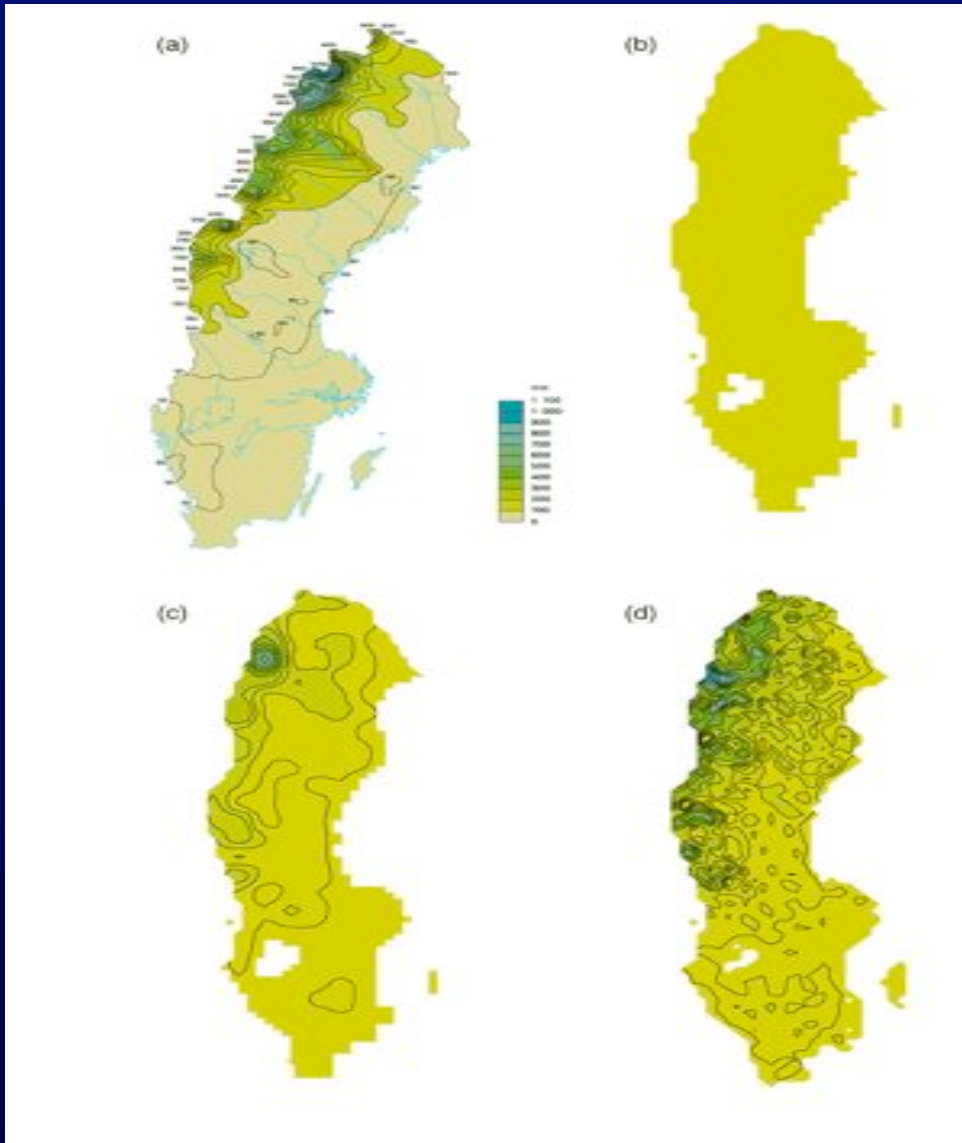
25km Regional Model

Observed

Summer Runoff in Sweden

Observations

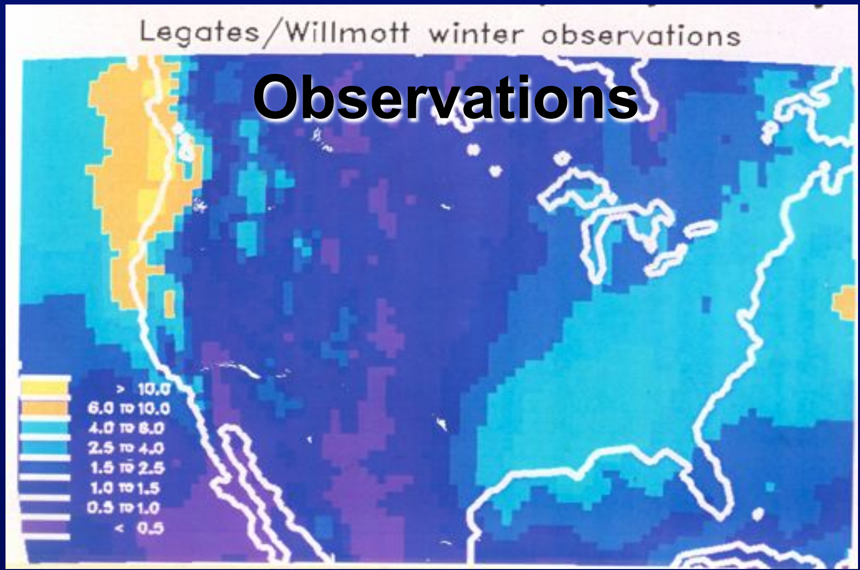
GC
M

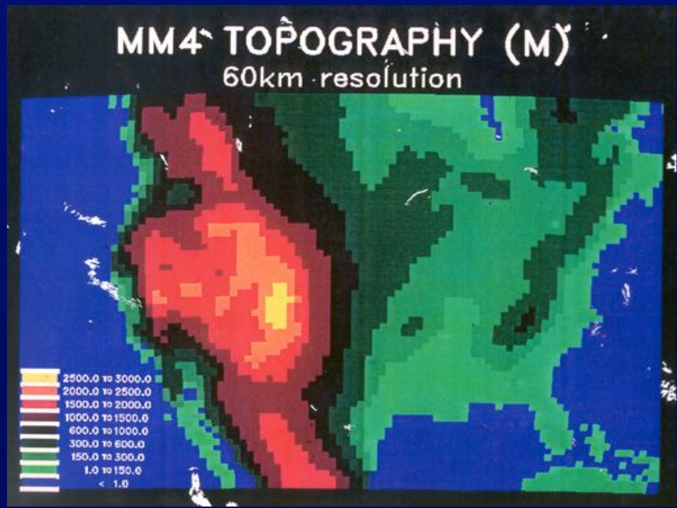


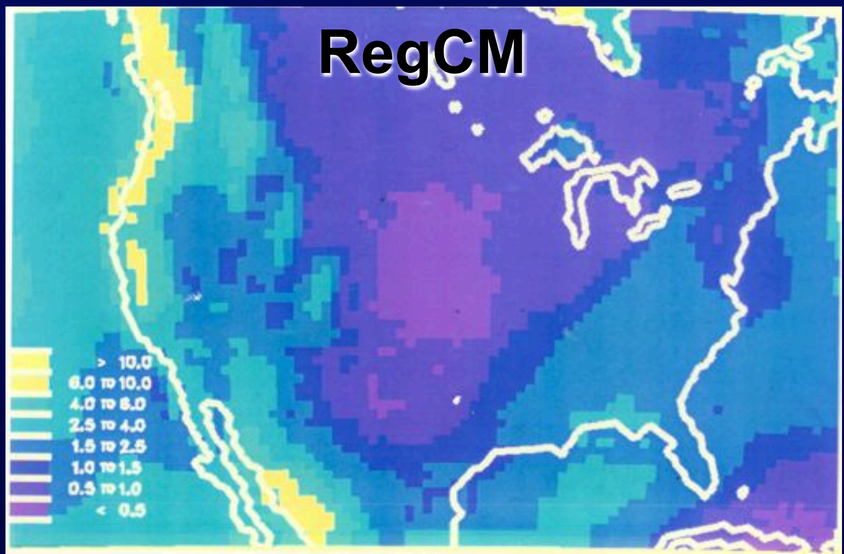
RCM – 55 km

RCM - 18 km

Present day winter precipitation



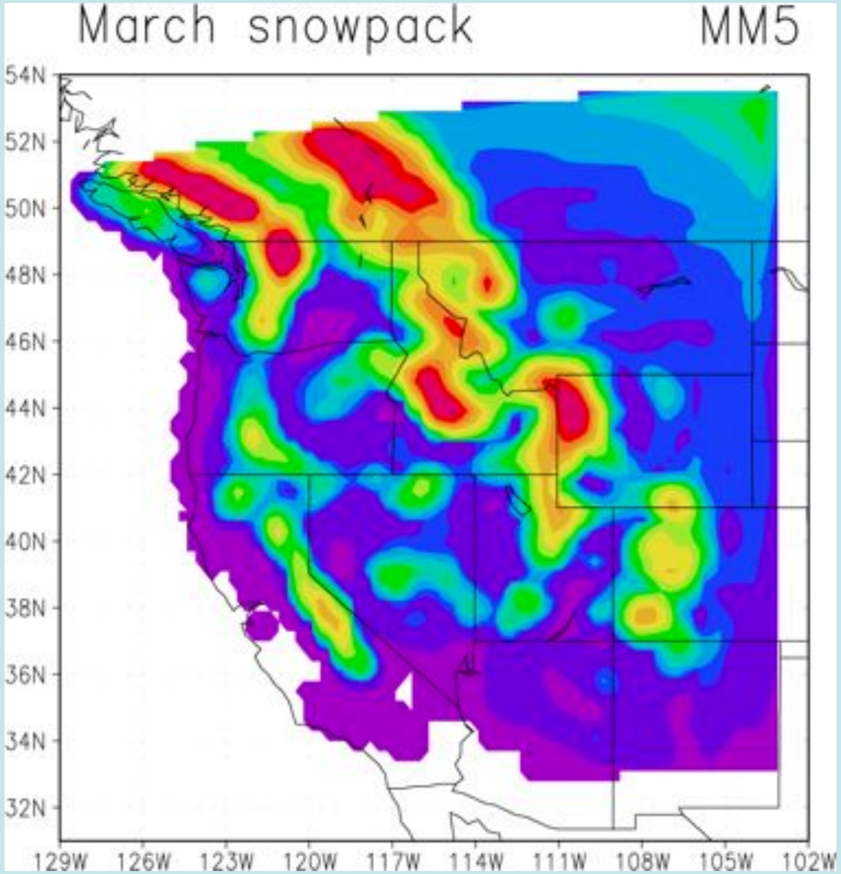




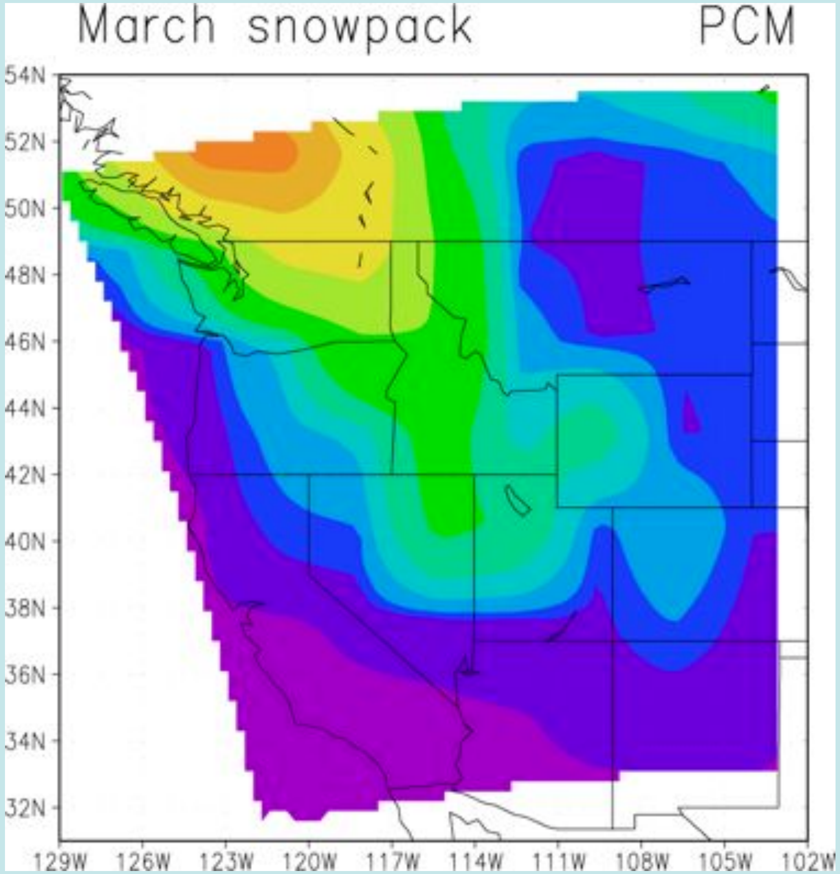
Global and Regional Simulations of Snowpack

GCM under-predicts and misplaces snow

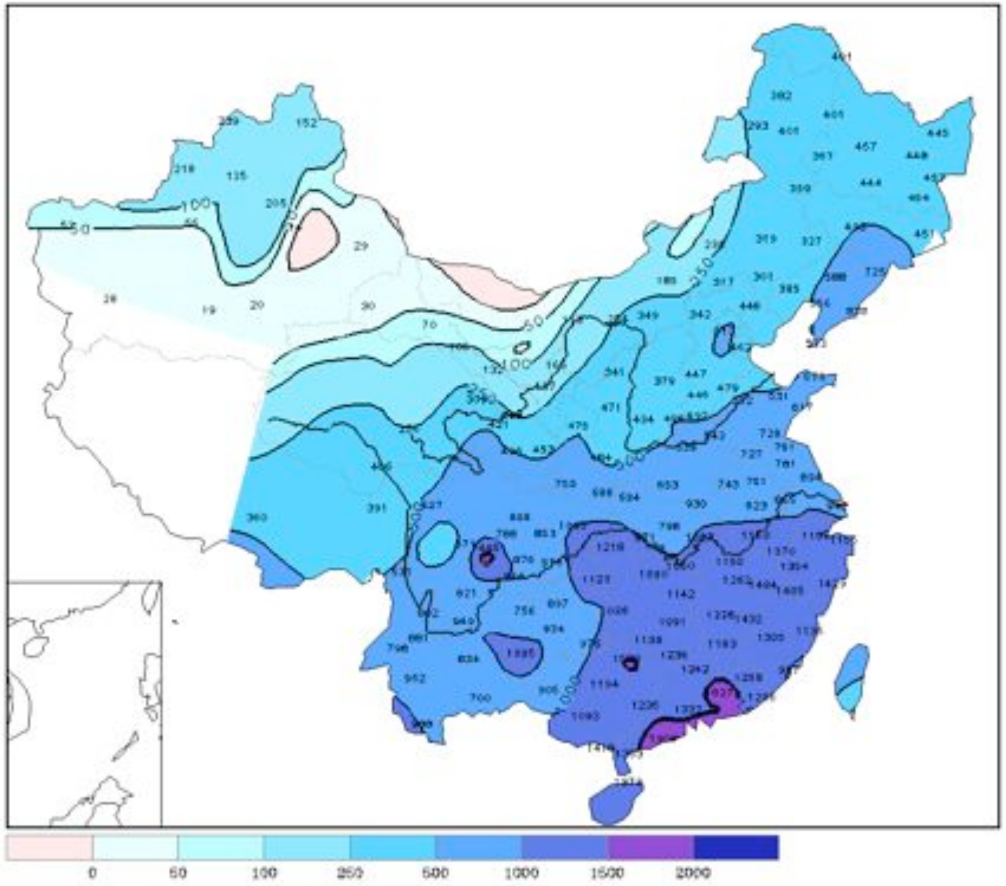
Regional Model Simulation



Global Model Simulation

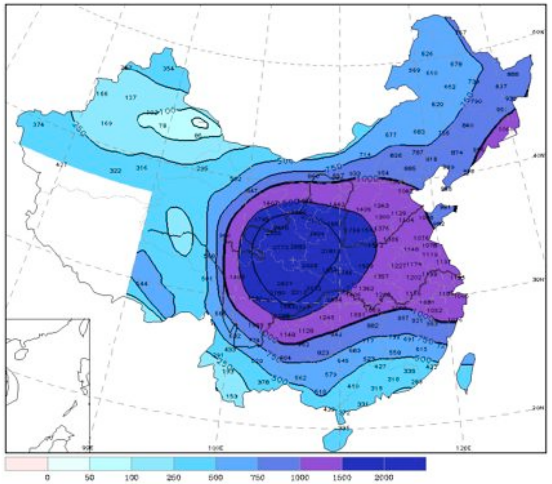


Observed Annual Mean Precipitation in China (unit: mm)

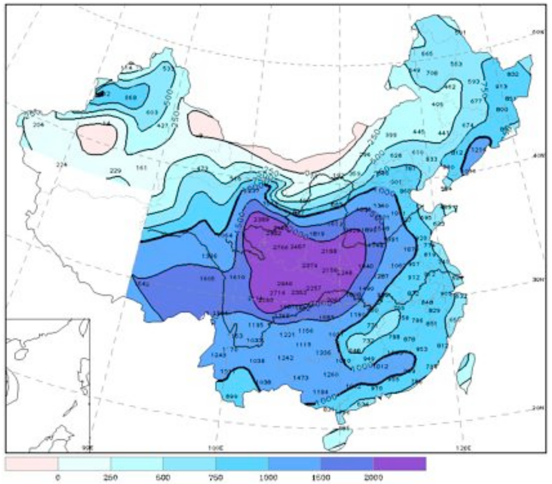


From Gao et al. 2006

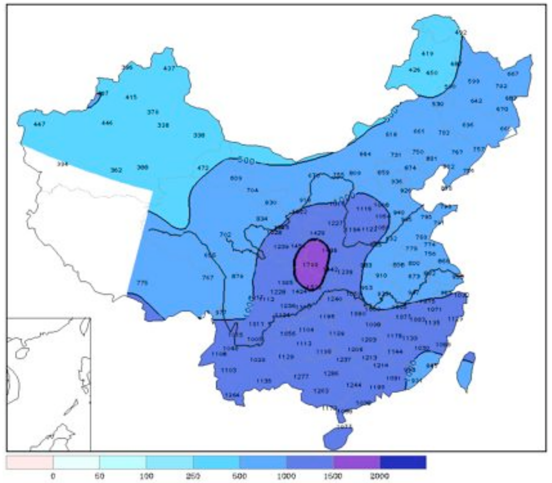
Simulation of east Asia monsoon precipitation by GCMs has been traditionally very difficult



NCAR CCM

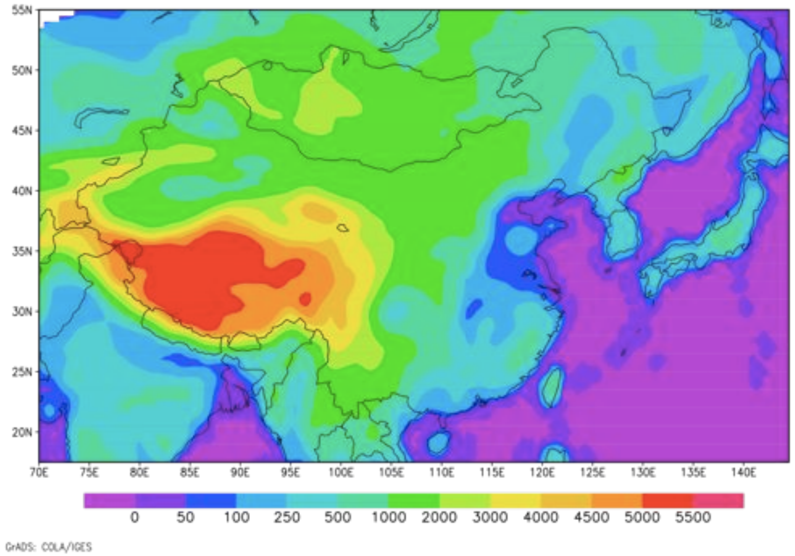


T63 NCC GCM

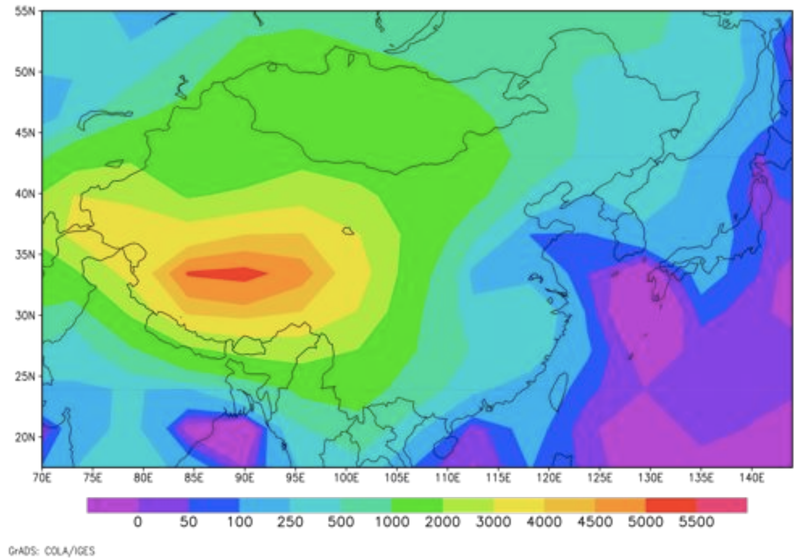


CSIRO GCM

Model representation of the Himalaya system

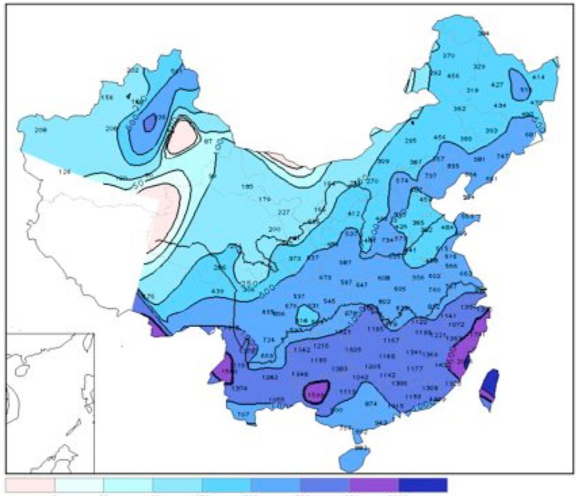


RCM 60 km

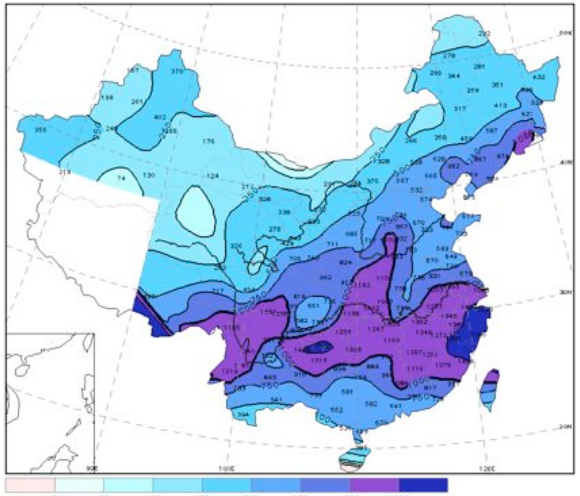


CSIRO GCM (360 km)

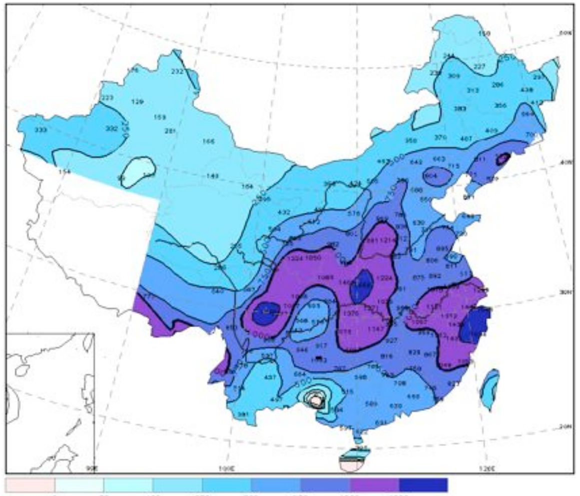
Mean annual precipitation (mm/day)



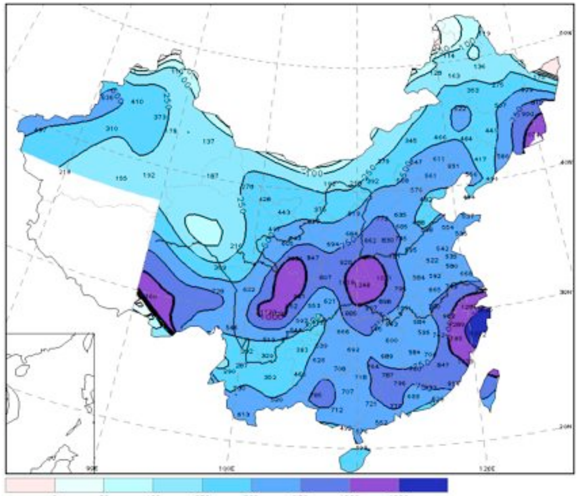
60 km



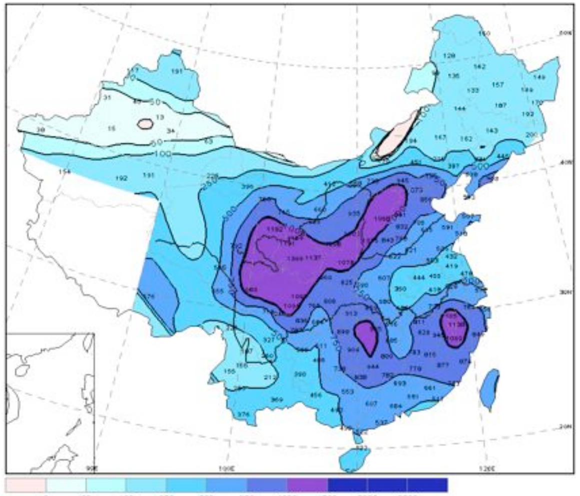
90 km



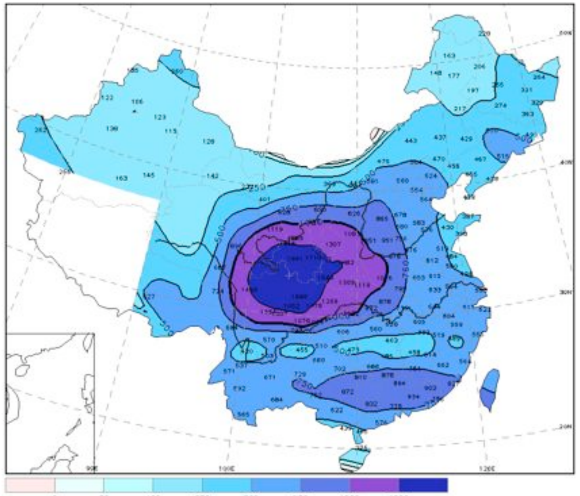
120 km



180 km

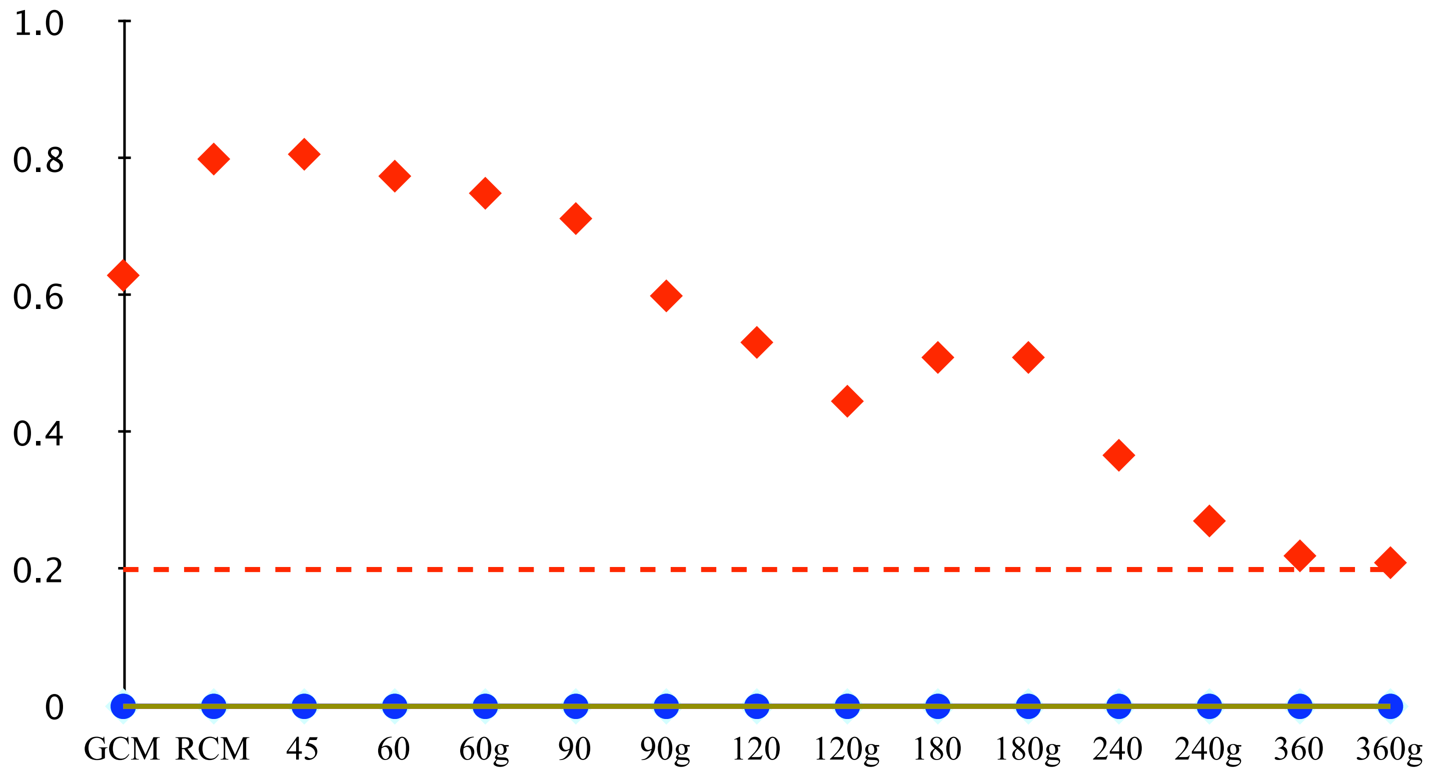


240 km

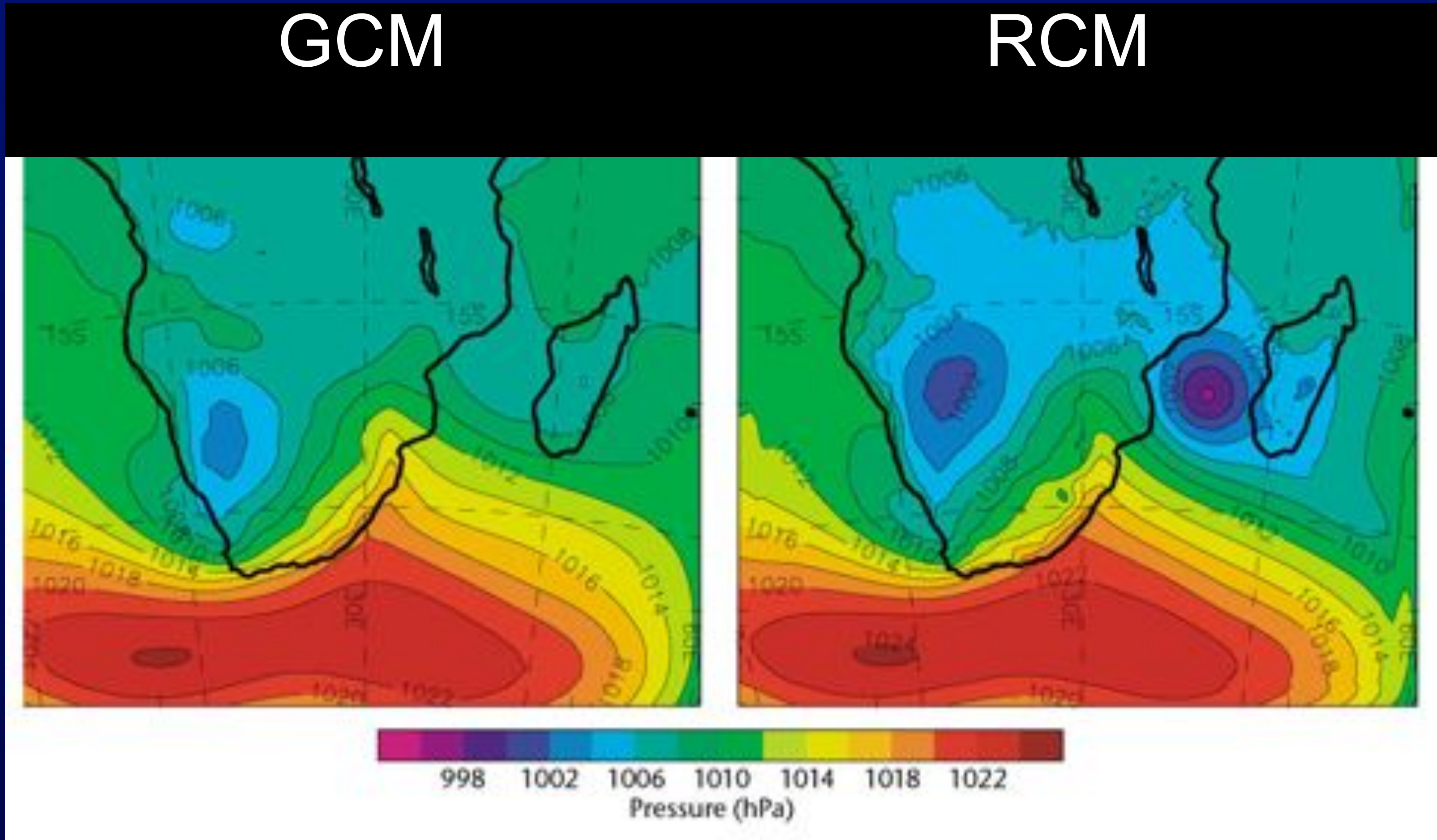


360km

Spatial correlation coefficient between simulated and observed annual mean precipitation

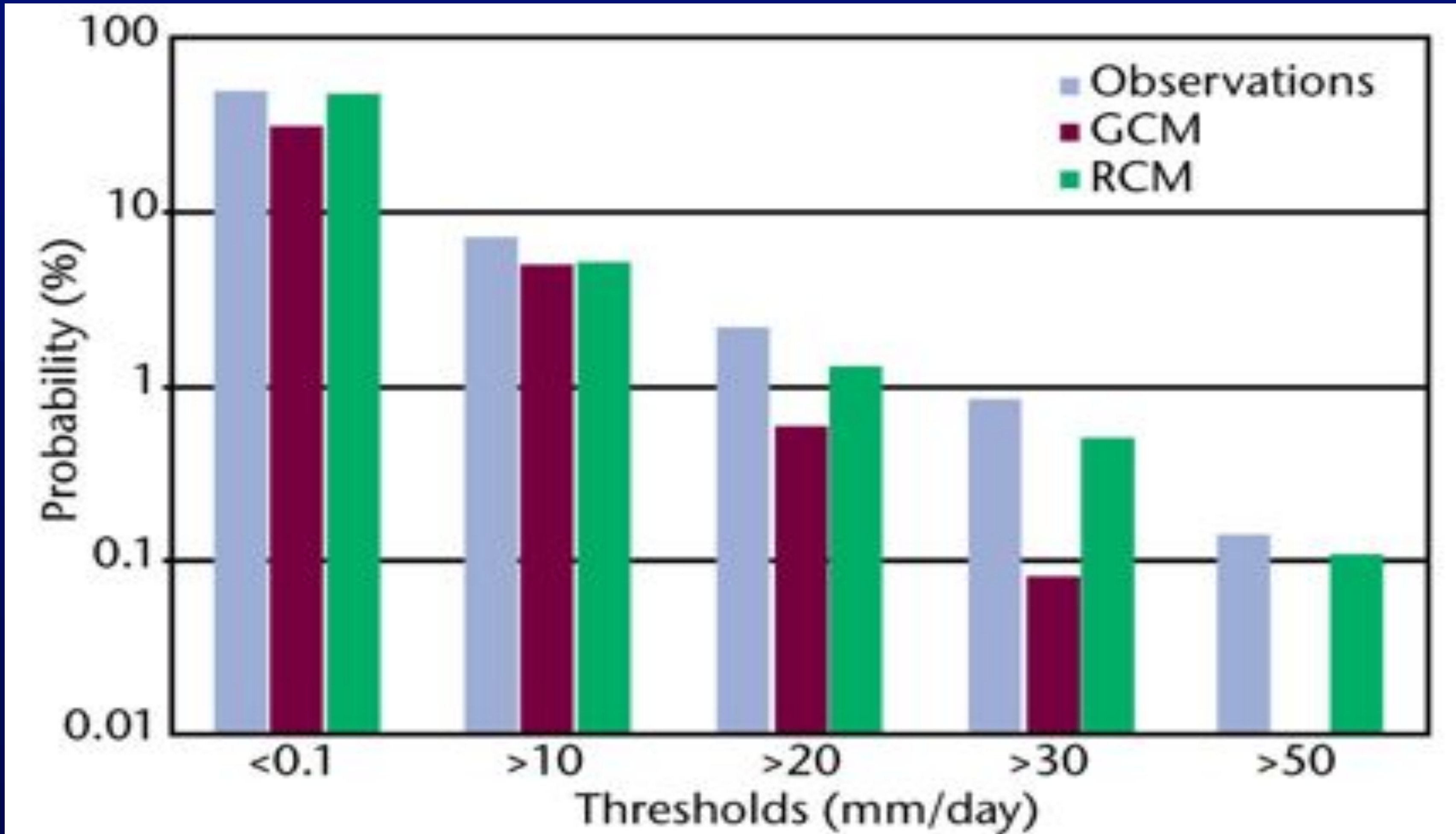


SIMULATION OF A TROPICAL CYCLONE



RCMs can simulate circulation features not resolved by GCMs

WINTER DAILY RAINFALL OVER THE ALPS

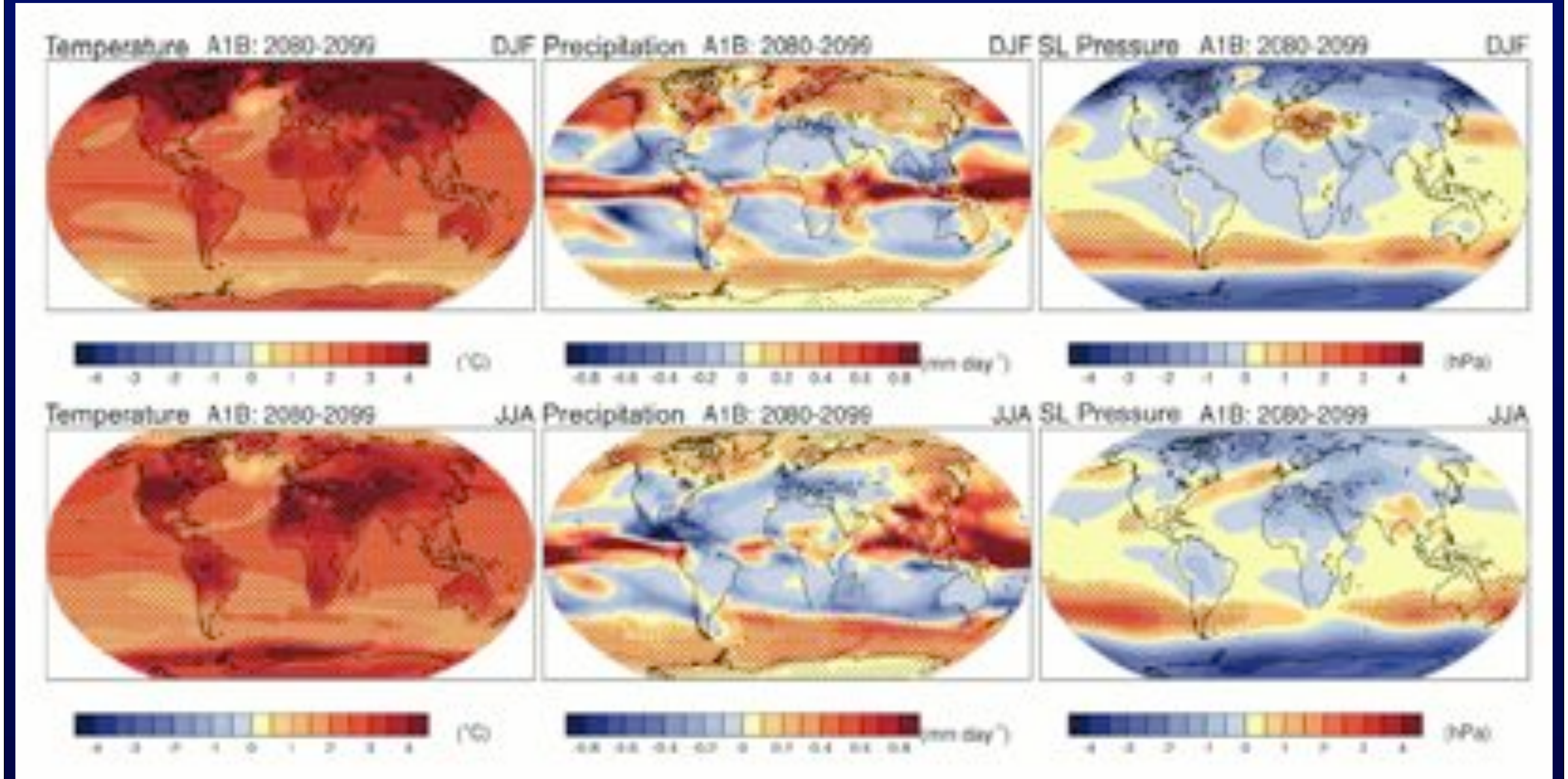


RCMs simulate extreme rainfall much better than GCMs

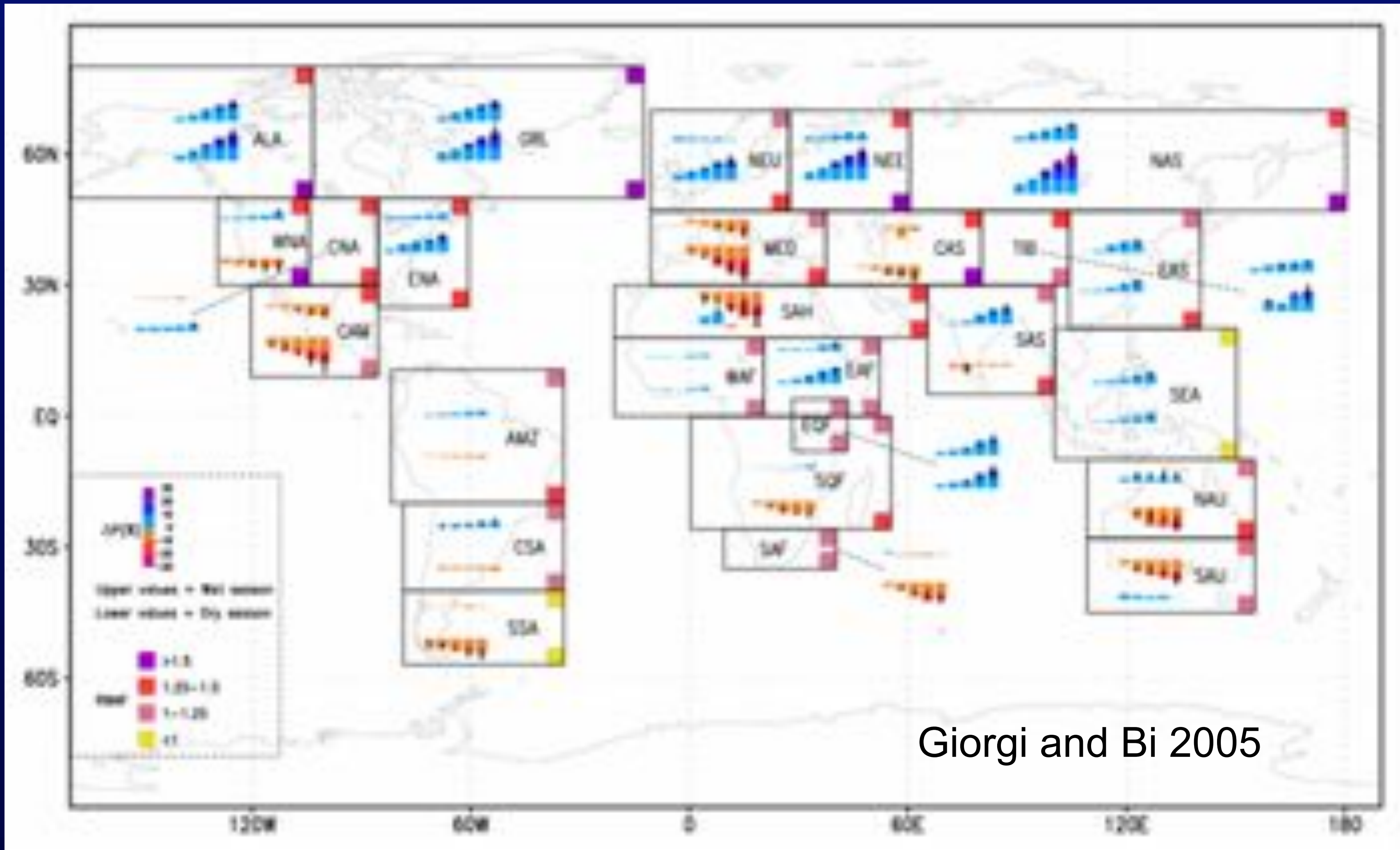
Examples of Application:

Ensemble average changes

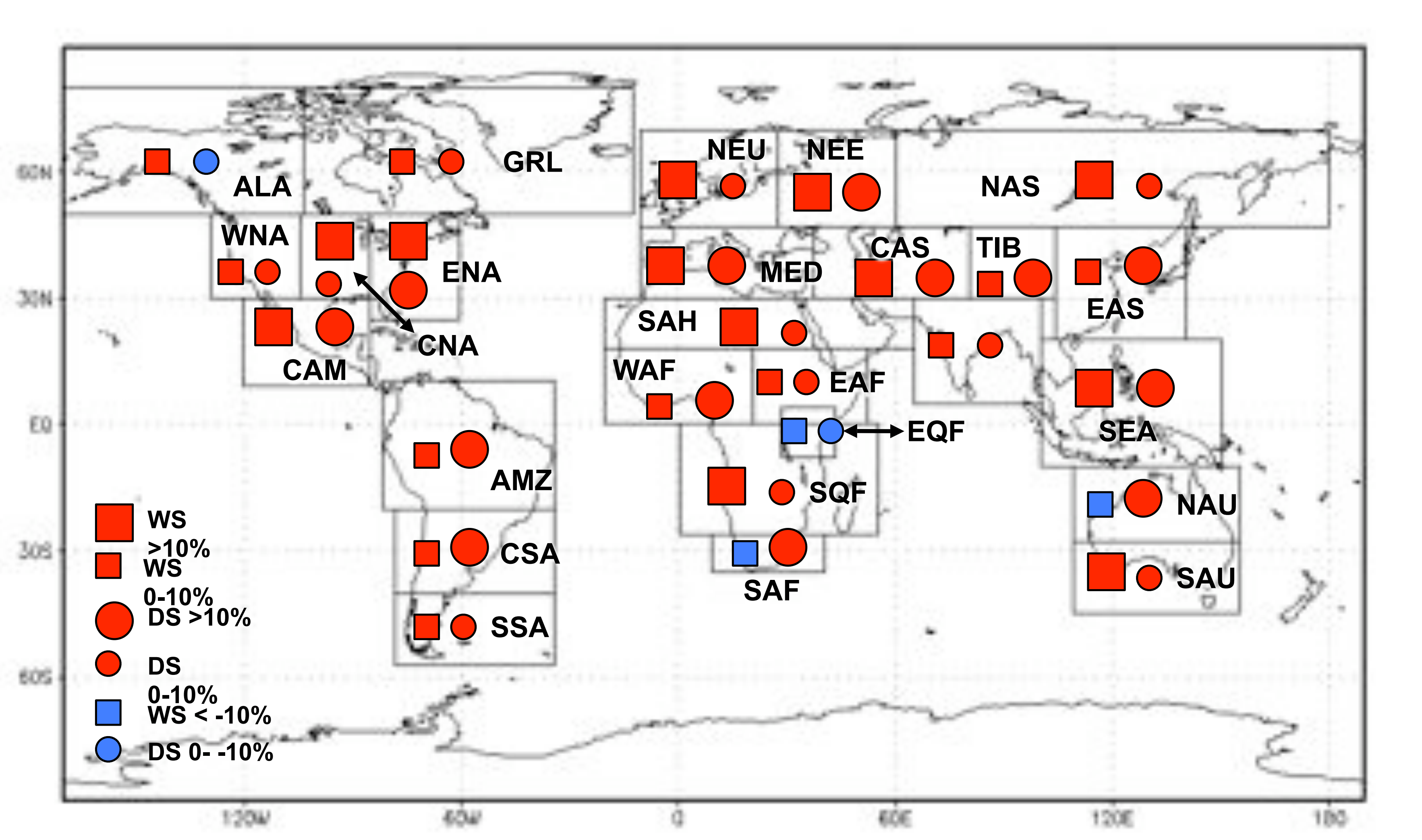
A1B scenario, 20 AOGCMs



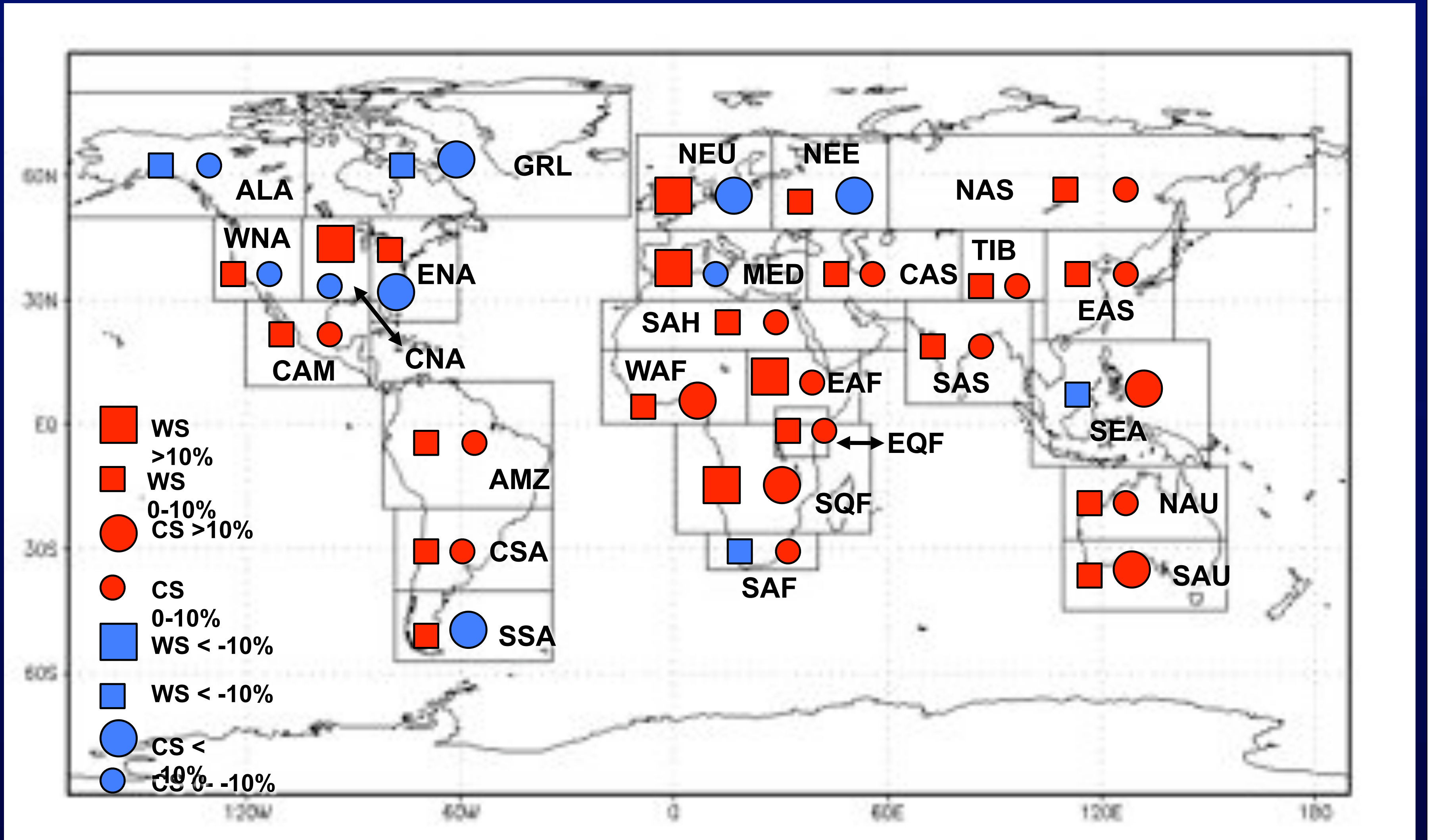
Regional temperature and precipitation change for the 21st century (ensemble average 20 AOGCMs)



Change in precipitation interannual variability (CV, 2080-2099 minus 1960-1979, A1B-A2-B1)



Change in temperature interannual variability (SD, 2080-2099 minus 1960-1979, A1B-A2-B1)

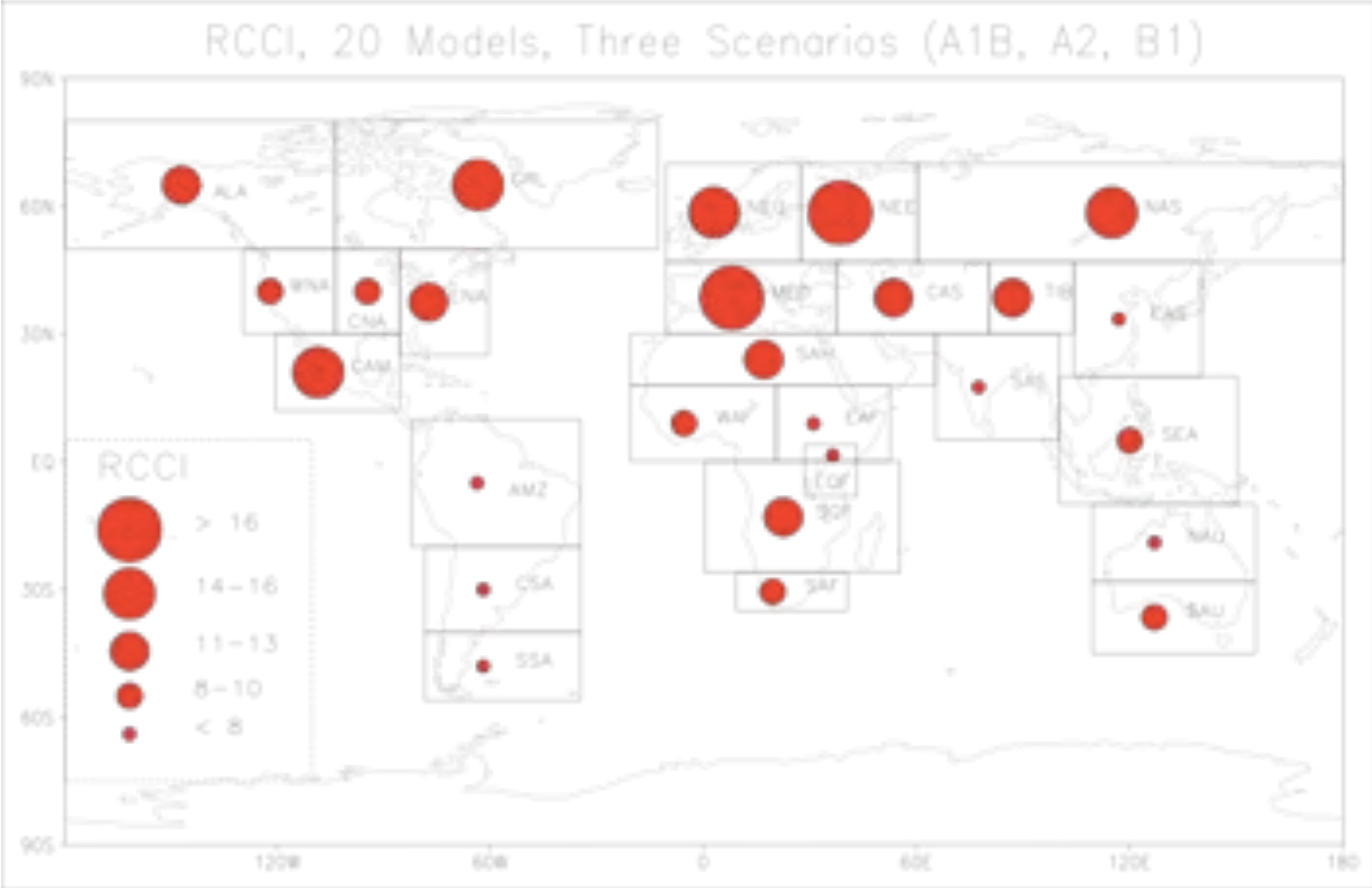


Regional Climate Change Index (RCCI)
The RCCI is a comparative index

$$RCCI = [n(\Delta P) + n(\Delta\sigma_P) + n(RWAF) + n(\Delta\sigma_T)]_{WS} +$$

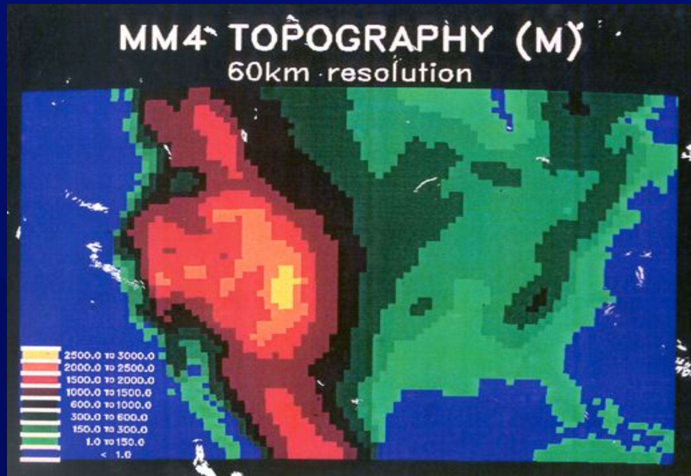
$$[n(\Delta P) + n(\Delta\sigma_P) + n(RWAF) + n(\Delta\sigma_T)]_{DS}$$

n	ΔP	$\Delta\sigma_P$	RWAF	$\Delta\sigma_T$
0	$< 5\%$	$< 5\%$	< 1.1	$< 5\%$
1	$5-10\%$	$5-10\%$	$1.1-1.3$	$5-10\%$
2	$10-15\%$	$10-20\%$	$1.3-1.5$	$10-15\%$
4	$> 15\%$	$> 20\%$	> 1.5	$> 15\%$



From Giorgi, GRL, 2006

Effect of topography on the precipitation change signal

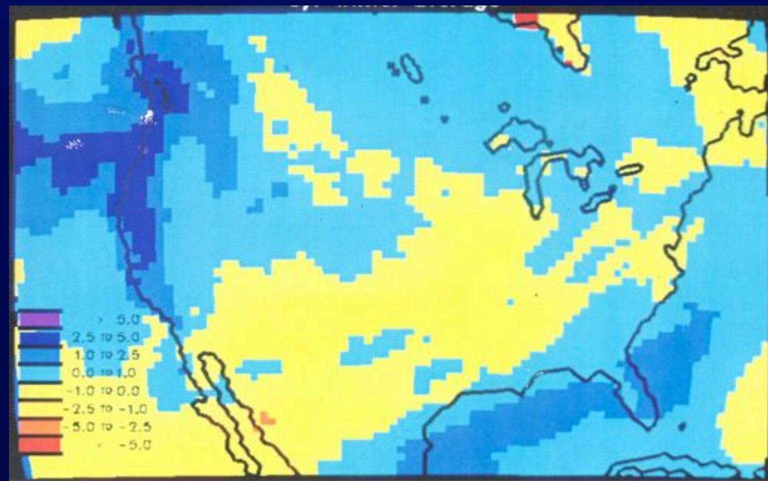


Model domain and topography

2CO2-Control
DJF Precipitation

CCM

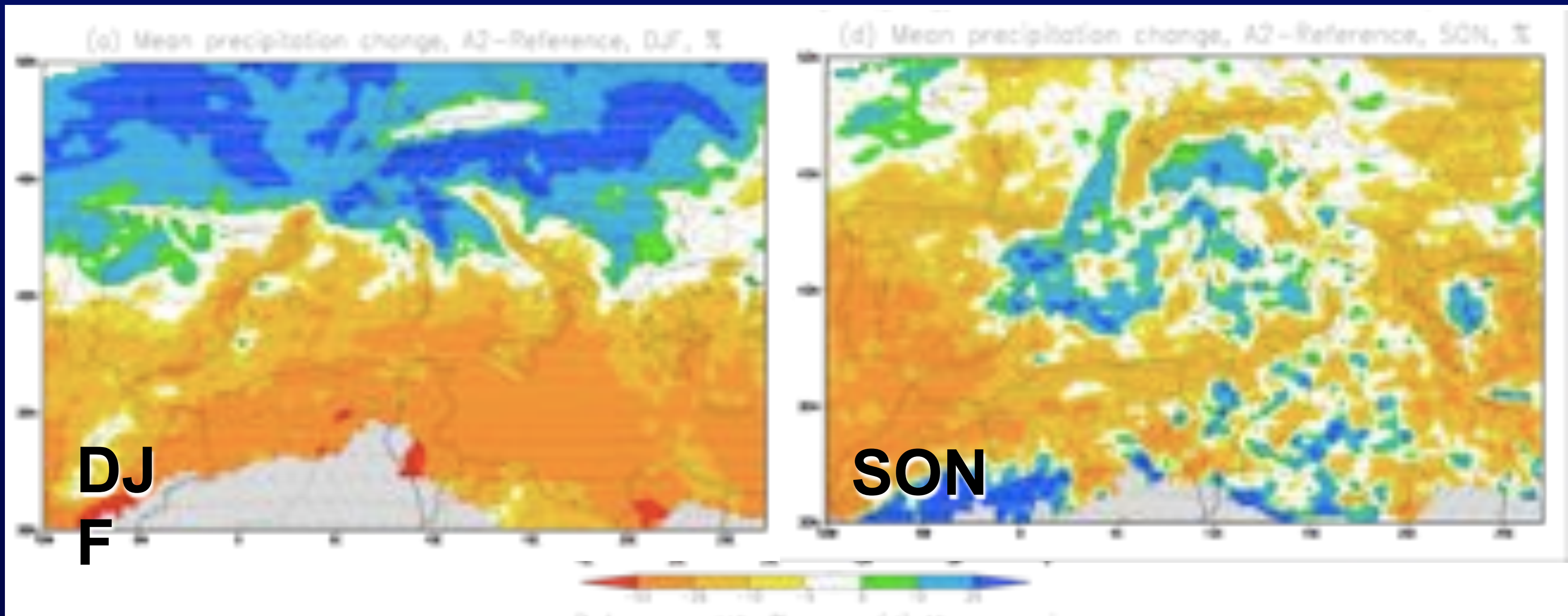
RegCM



Topographical barriers affect the precipitation change signal

Effect of topography on the precipitation change signal

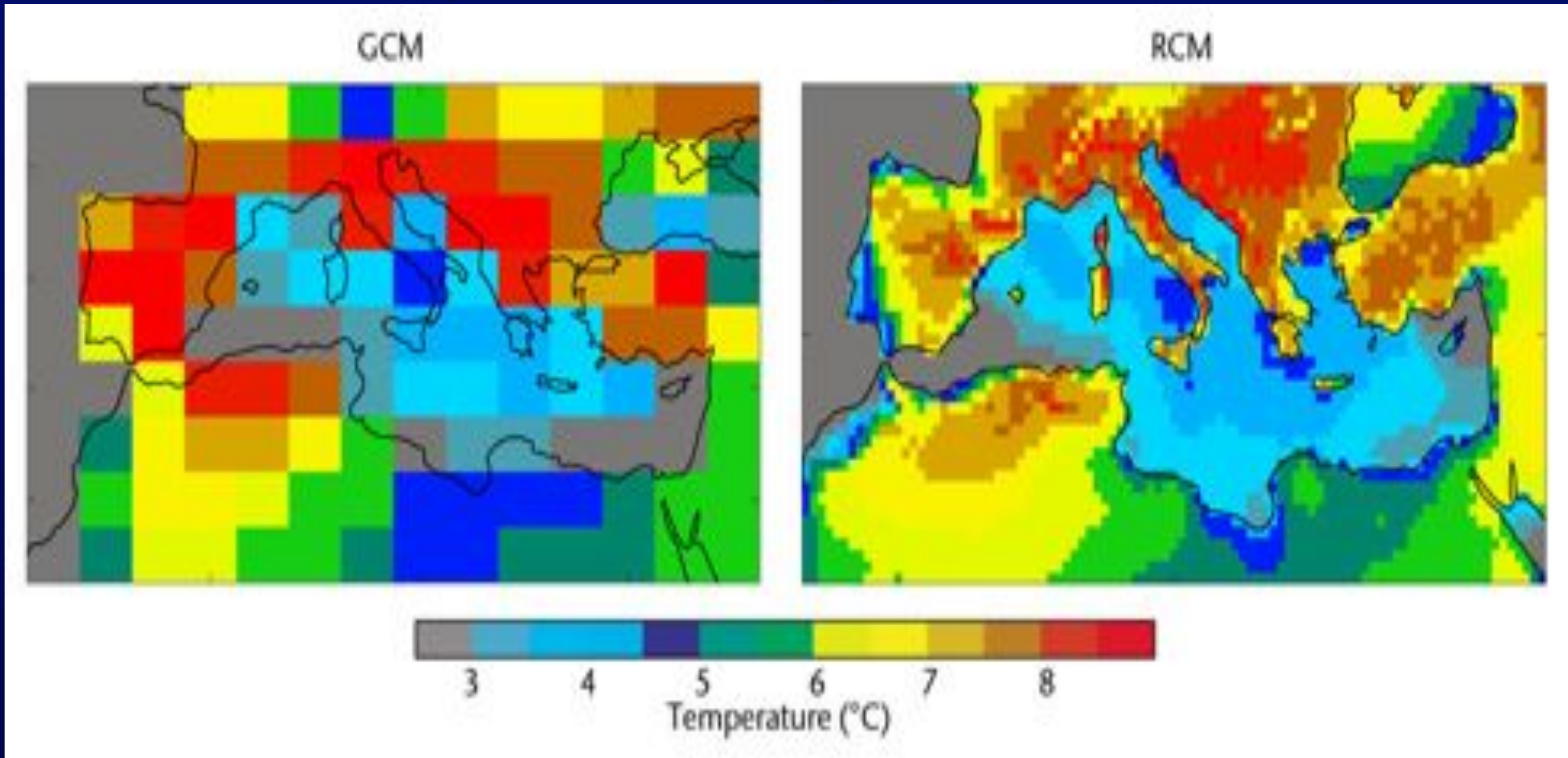
Mean precipitation change, A2 - control



Topographical barriers affect the precipitation change signal

Effect of topography on the temperature change signal

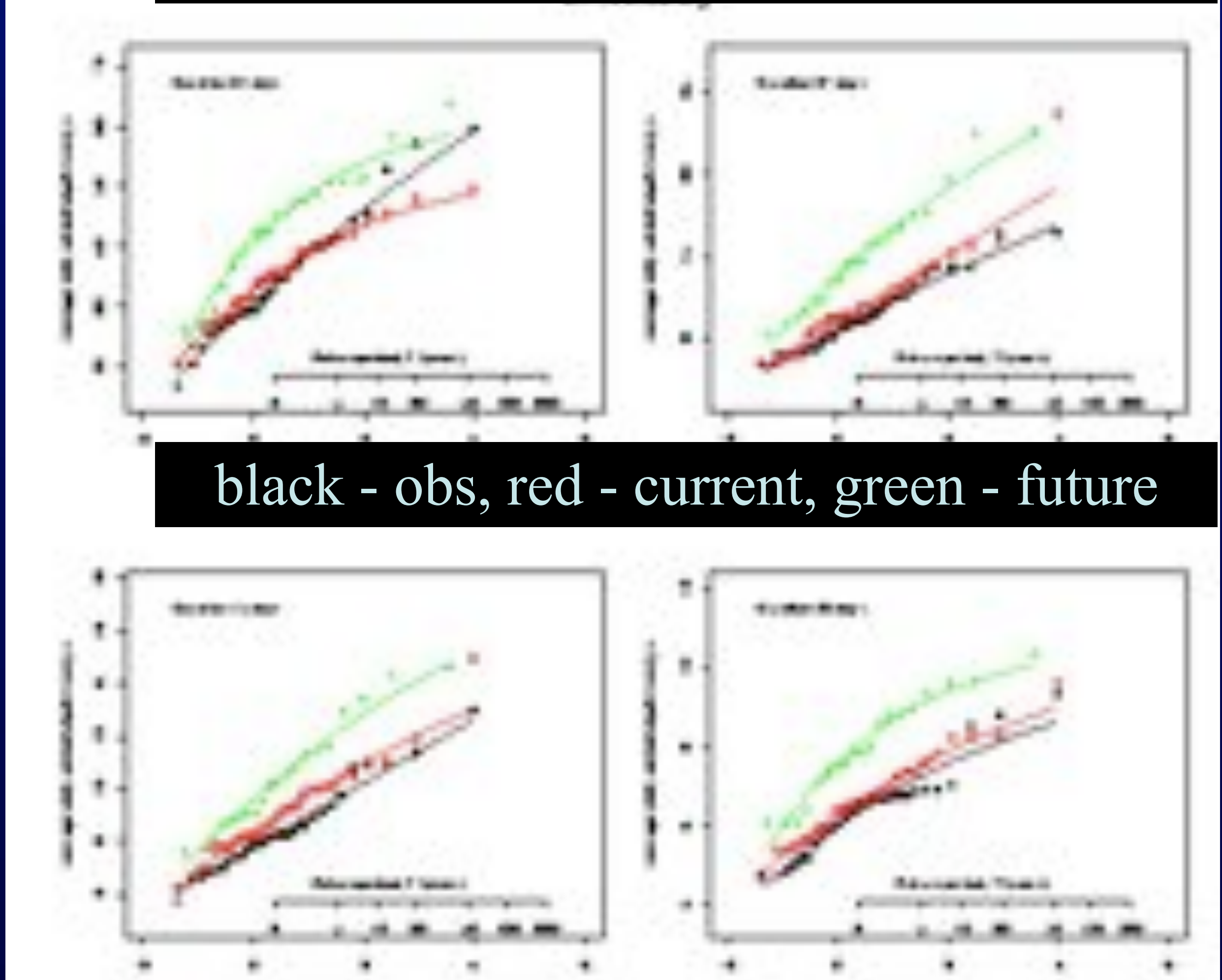
Temperature change, A2 - control



Climate on islands changes very differently to the surrounding Mediterranean Sea, and can only be

Simulation of changes in extreme precipitation
Central England gridbox

1, 7, 15 and 30 day event annual maxima



black - obs, red - current, green - future

Global to regional climate modeling
Summary

- The latest generation coupled AOGCMs show a good performance in simulating large scale features of the general circulation
  - Improvements in p the representation of physical processes
  - Increase in horizontal resolution (currently 100-200 km)
- Most AOGCMs today include atmosphere, ocean, sea ice, simple chemistry/aerosol, carbon cycle components
- An increasing number of AOGCMs is being applied in a coordinated way to climate change simulations, which allows us to use the compounded information from ensembles of models (see Lecture 2)
- The field of regional climate modeling has substantially matured in the last decade
  - The quality of RCMs has improved
  - The quality of GCMs simulations necessary to run the RCMs has improved
- RCMs can provide significant added value compared to coarser resolution GCMs
  - Climatic signal of complex topography
  - Extremes
- Many RCMs are today available and more coordinated projects are being conducted
  - Considerable improvement in understanding of the potentials and limitations of RCMs
- We can today start to use with some confidence global and regional climate models to provide more reliable climate change information


GRAZIE