Regional Climate Modeling

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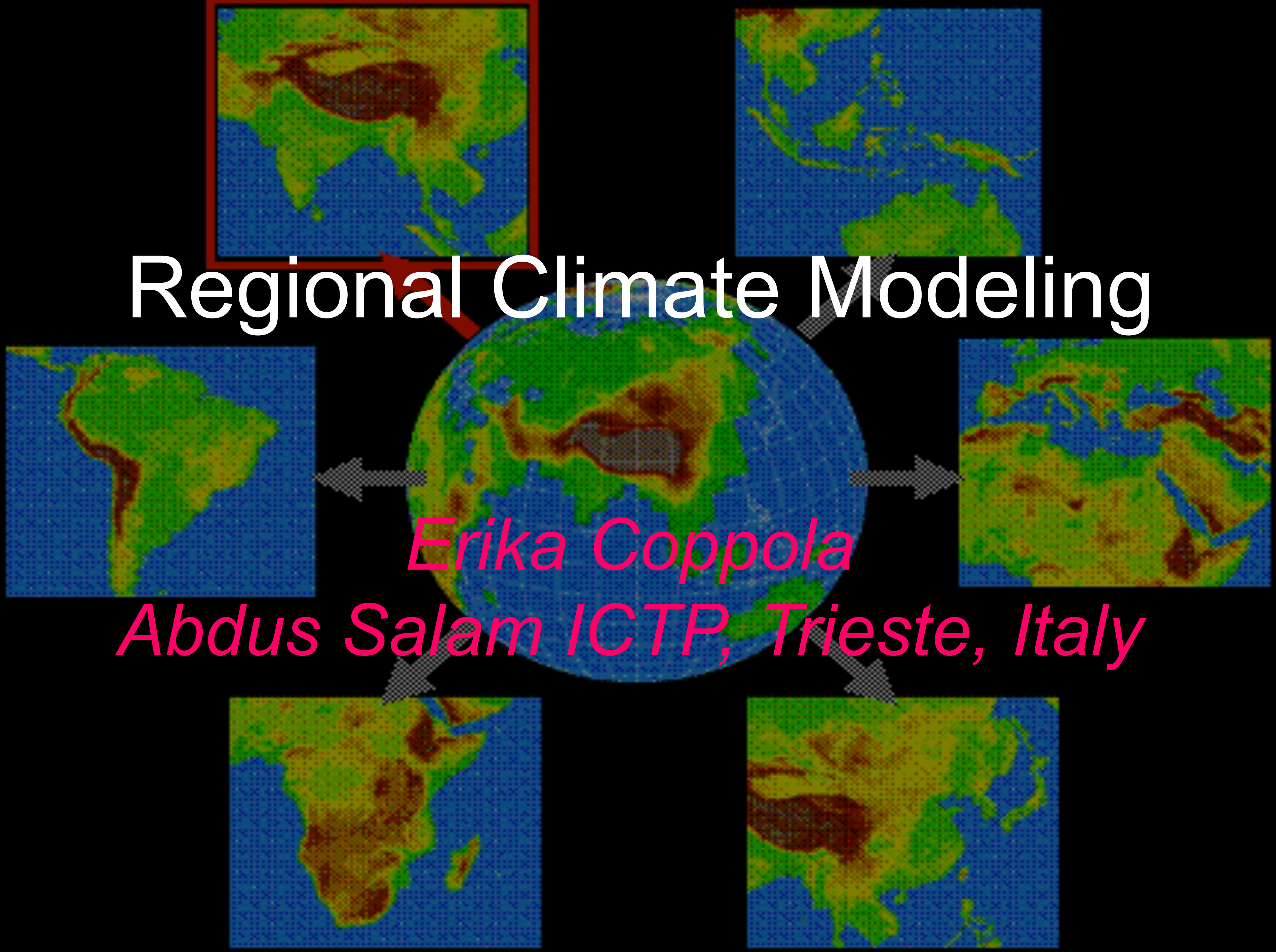
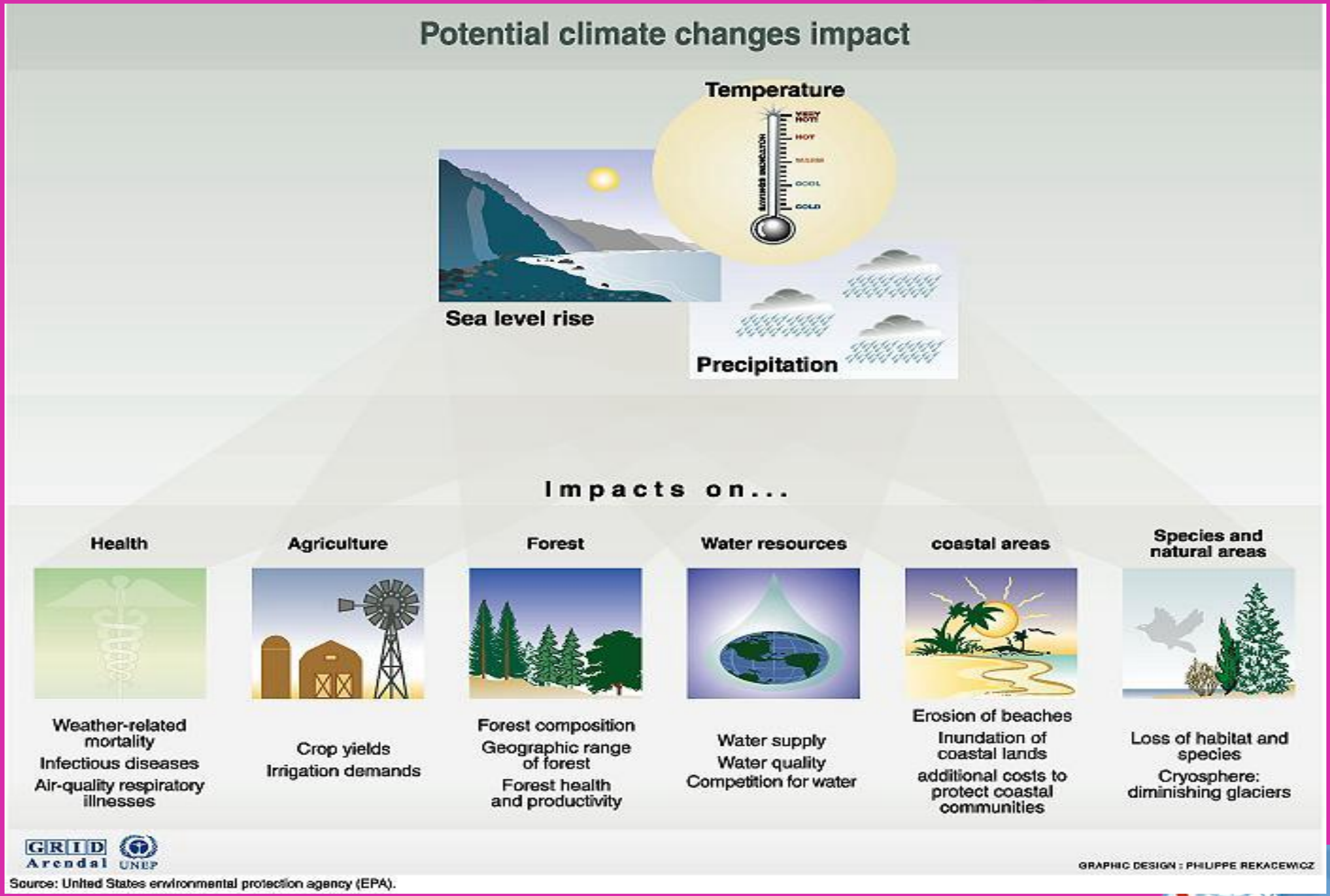


Regional climate information is critical to assess impacts

Information is needed at the regional scale



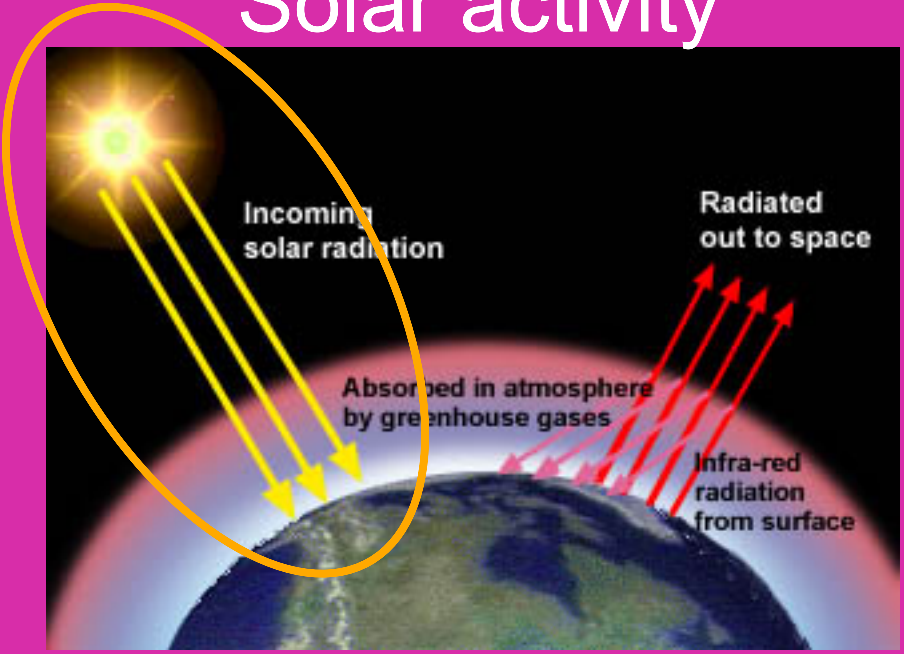
Regional climate modeling: Why?

- 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

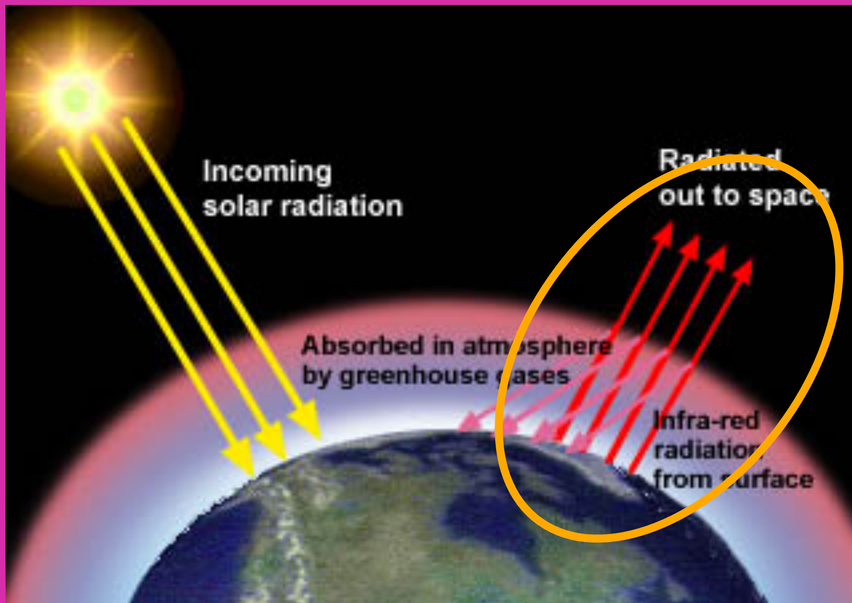
Large scale natural climatic forcings

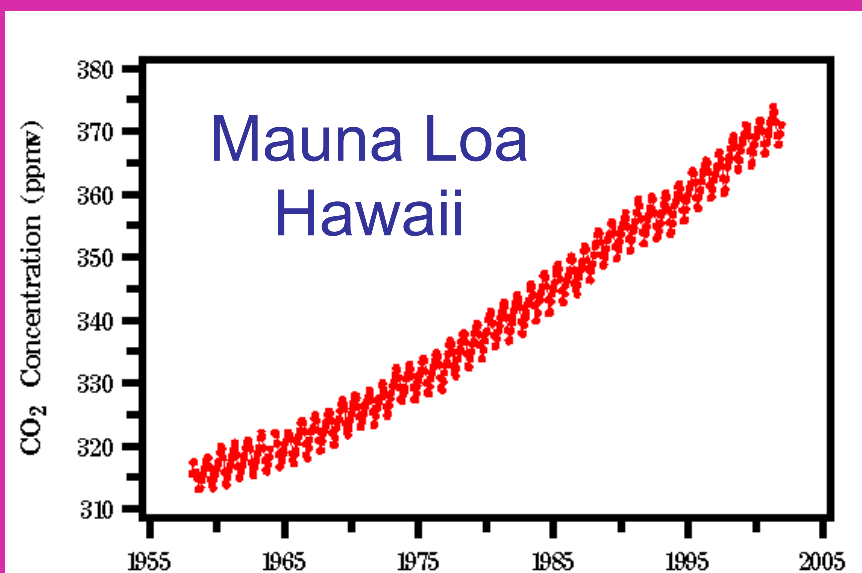
Volcanic eruptions

Solar activity



Anthropogenic climatic forcings





The Greenhouse effect

Like the sun, the Earth emits radiation. It is much cooler than the sun, though, so it emits in the infrared. Some of that infrared energy may be absorbed by molecules in the atmosphere, affecting the global energy balance.

Extra CO_2 or other GHGs lead to a positive “forcing” of the climate system, an “excess greenhouse effect.”

Regional and local climatic forcings

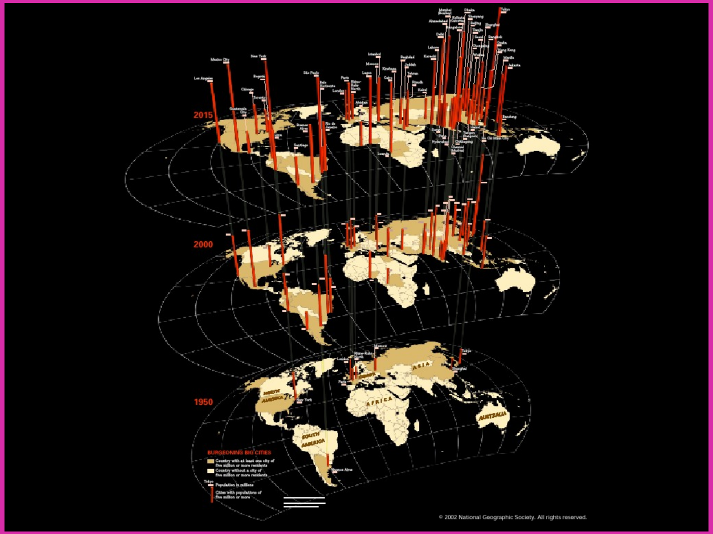
Aerosols

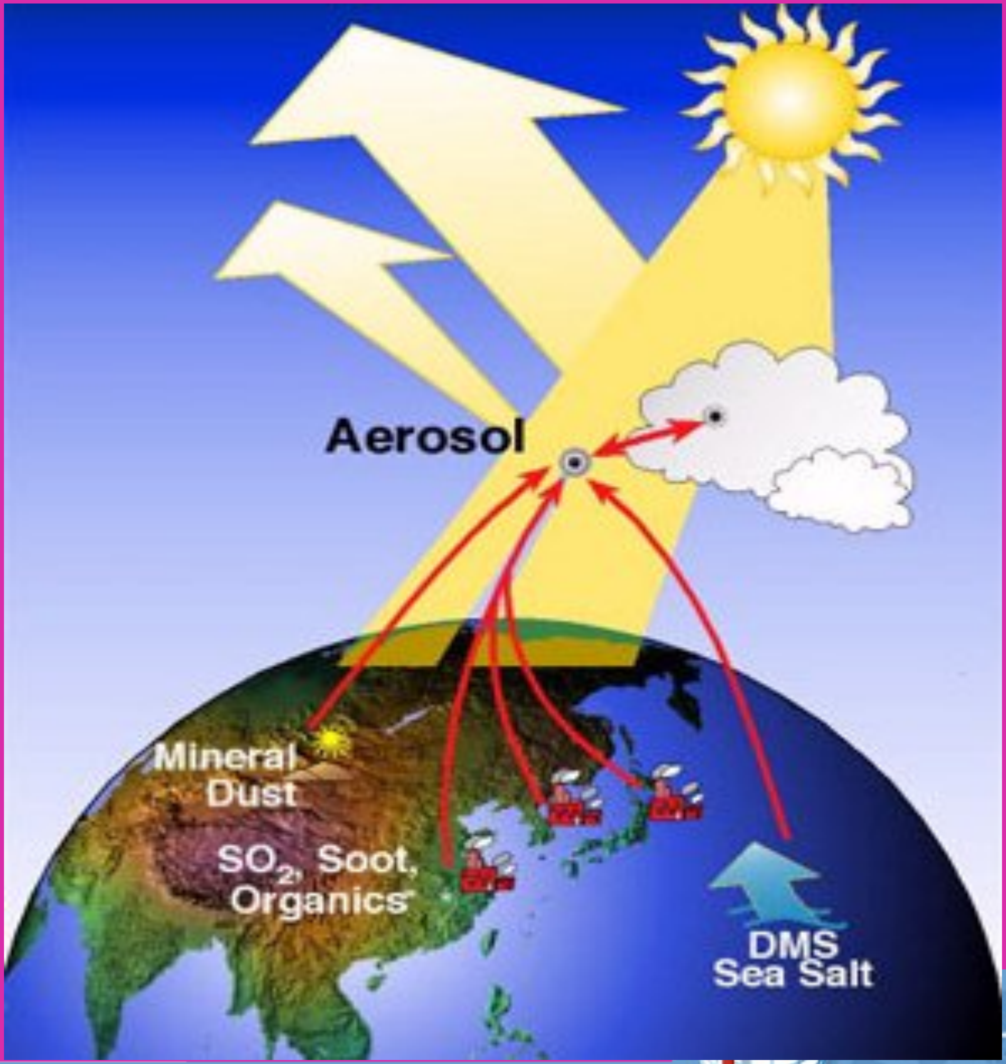
Direct effects

Aerosols absorb and reflect solar radiation

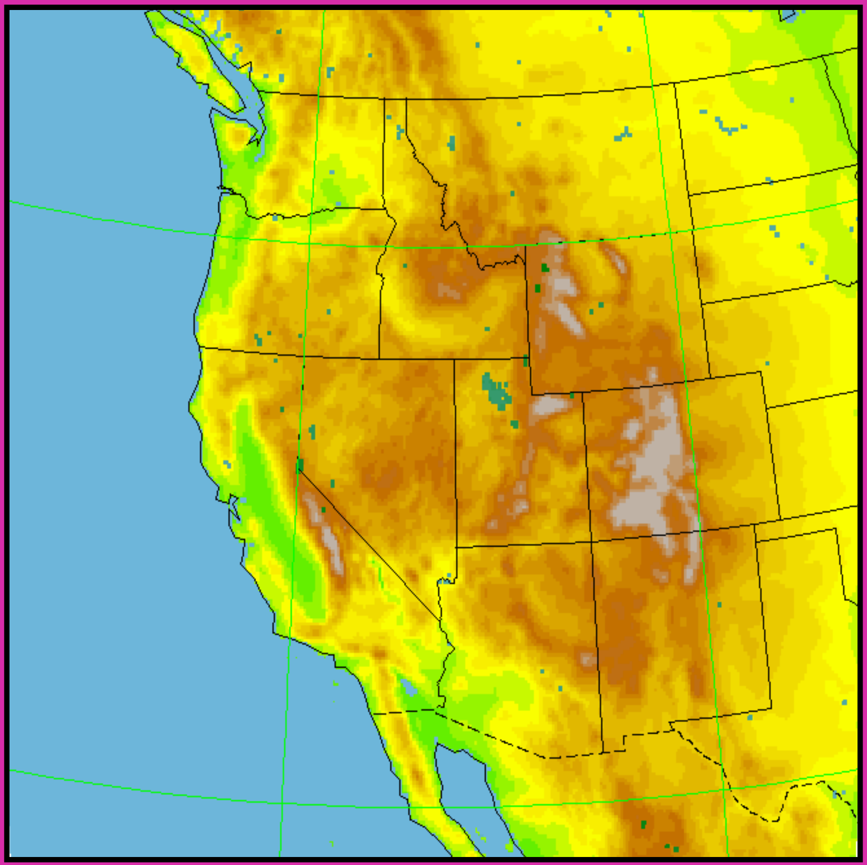
Indirect effects

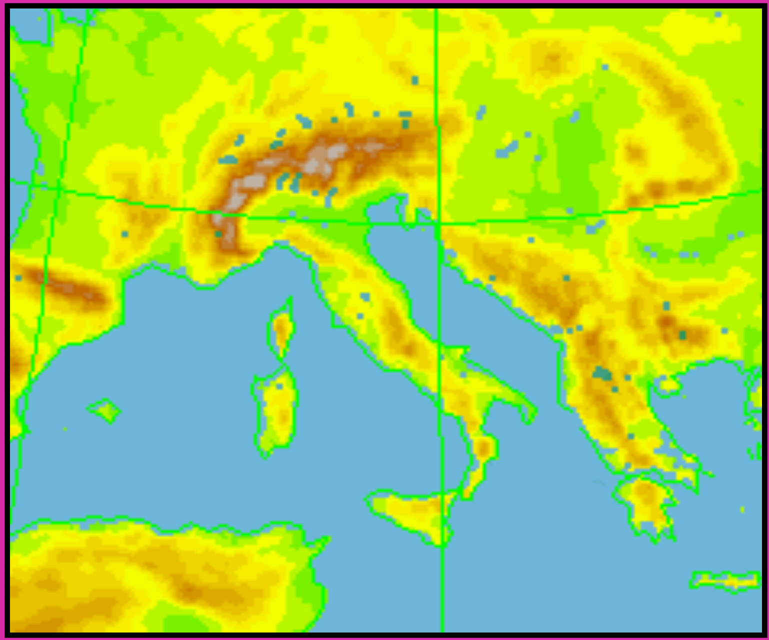
Aerosols change the properties of clouds

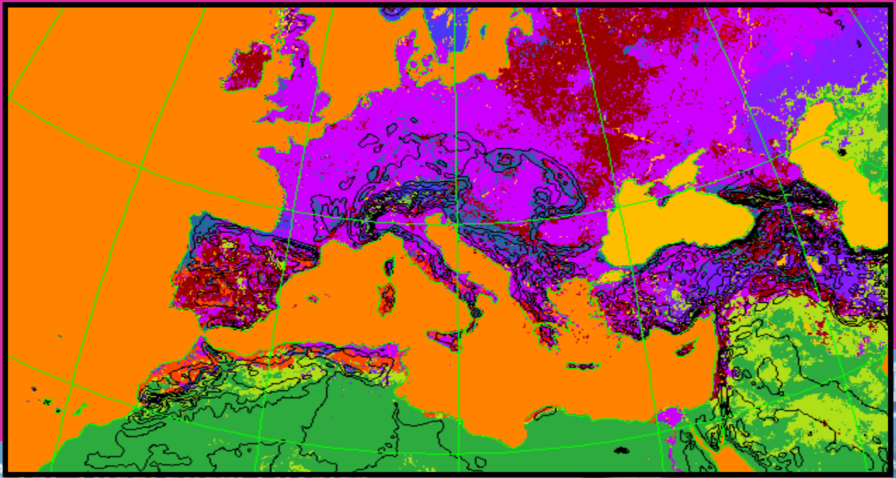




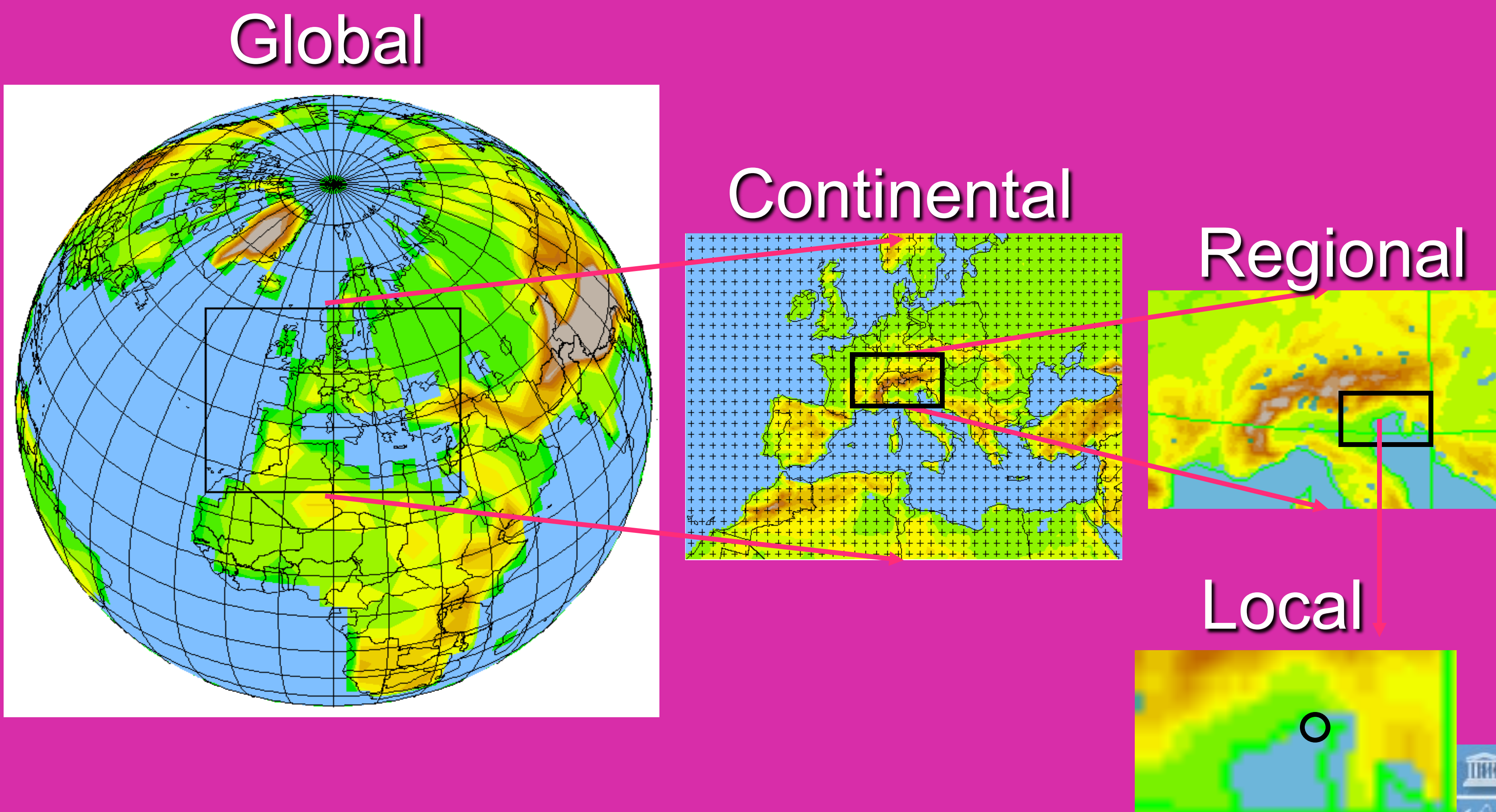
Regional and local climatic forcings:
Topography and vegetation





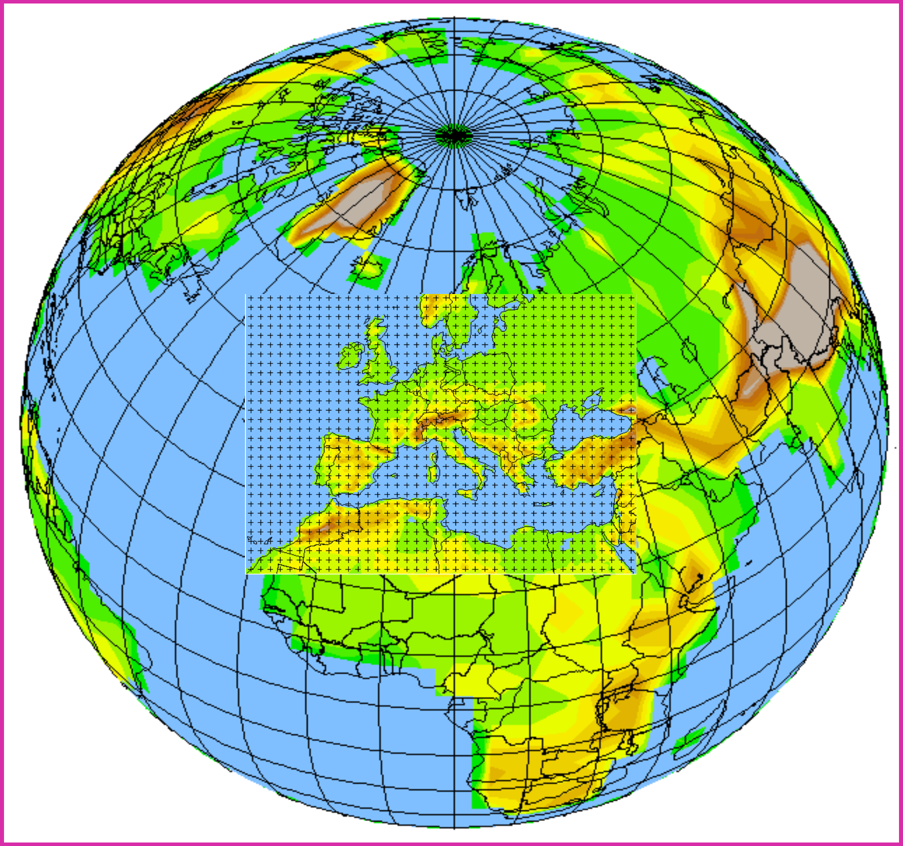


The scales of climate change



"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.
- 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

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

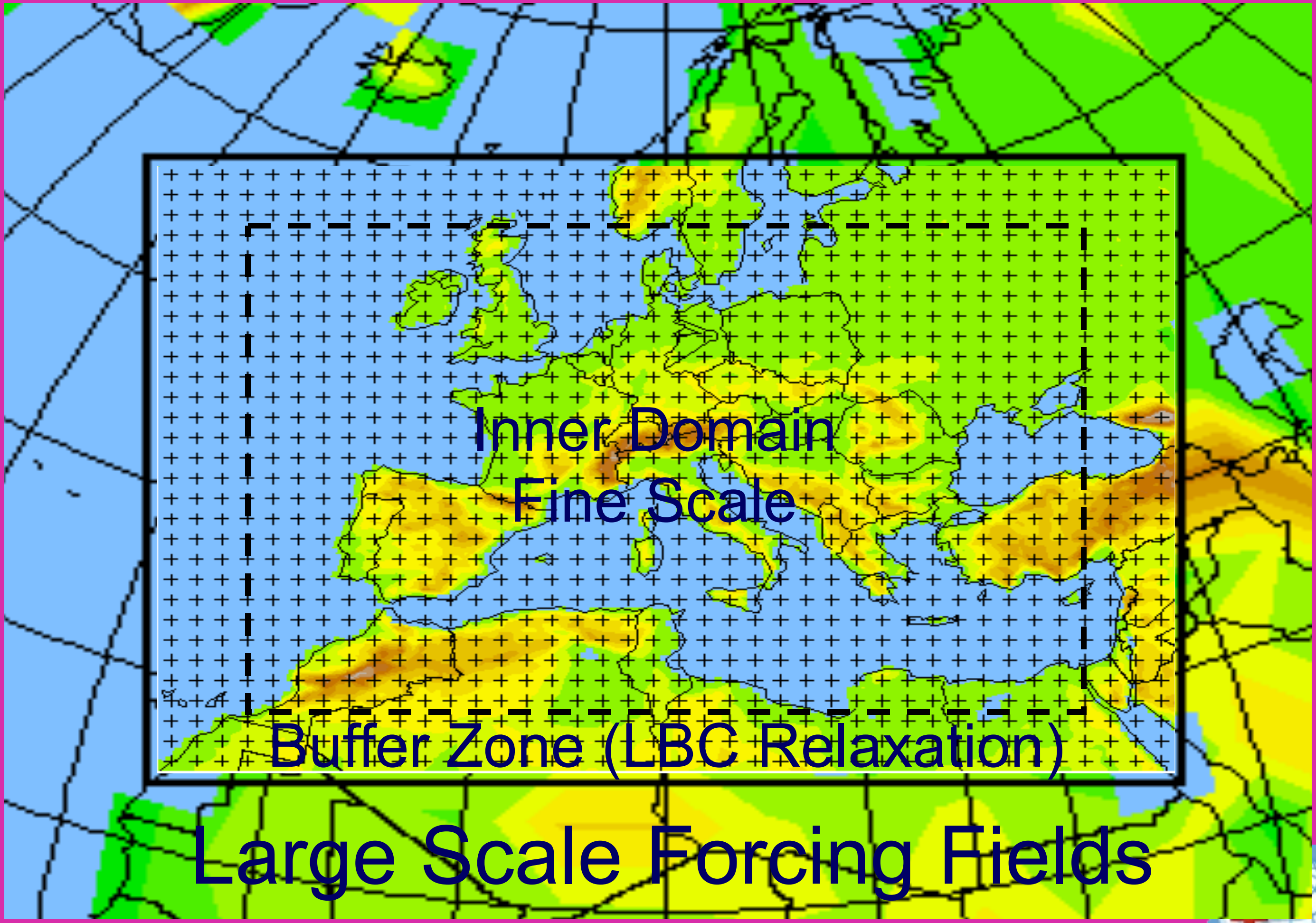
Conservation of water

$$p = \rho R T$$

Equation of state

RCM Nesting procedure

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



“Regionalization” techniques to enhance the AOGCM information

- High Resolution “Time-Slice” AGCM Experiments
- Variable Resolution AGCM
- “Nested” Regional Climate Model (RCM)
- Empirical/Statistical and Statistical/ Dynamical Downscaling
- Combined use of different techniques (e.g. RCM nested in high resolution AGCM)

Regional Climate Modeling
Advantages

- Physically based downscaling
  - Comprehensive climate modeling system
- Nesting within different GCMs or analyses of observations ("perfect boundary conditions experiments")
- Wide variety of applications
  - Process studies and validation
  - Paleoclimate
  - Climate change
  - Seasonal prediction
- High resolution through multiple nesting (currently 10-50 km grid interval)
- Usable on PCs

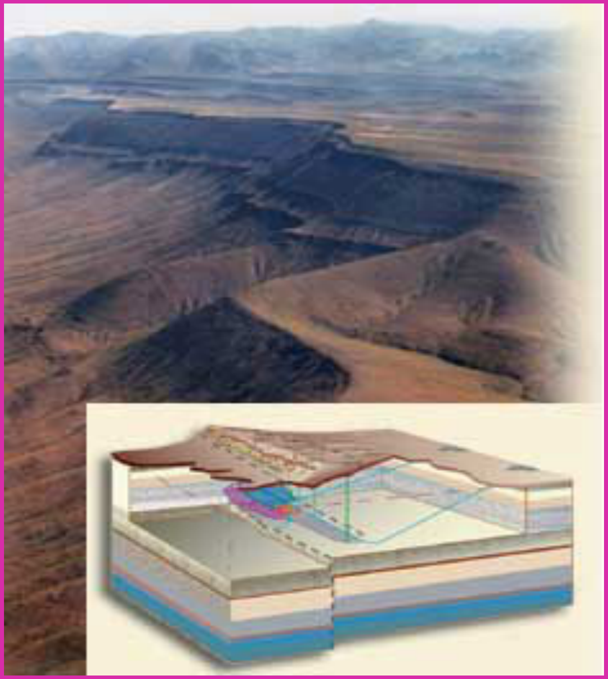
Regional Climate Modeling Limitations

- 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

Regional Climate Modeling:
A Brief Historical Overview

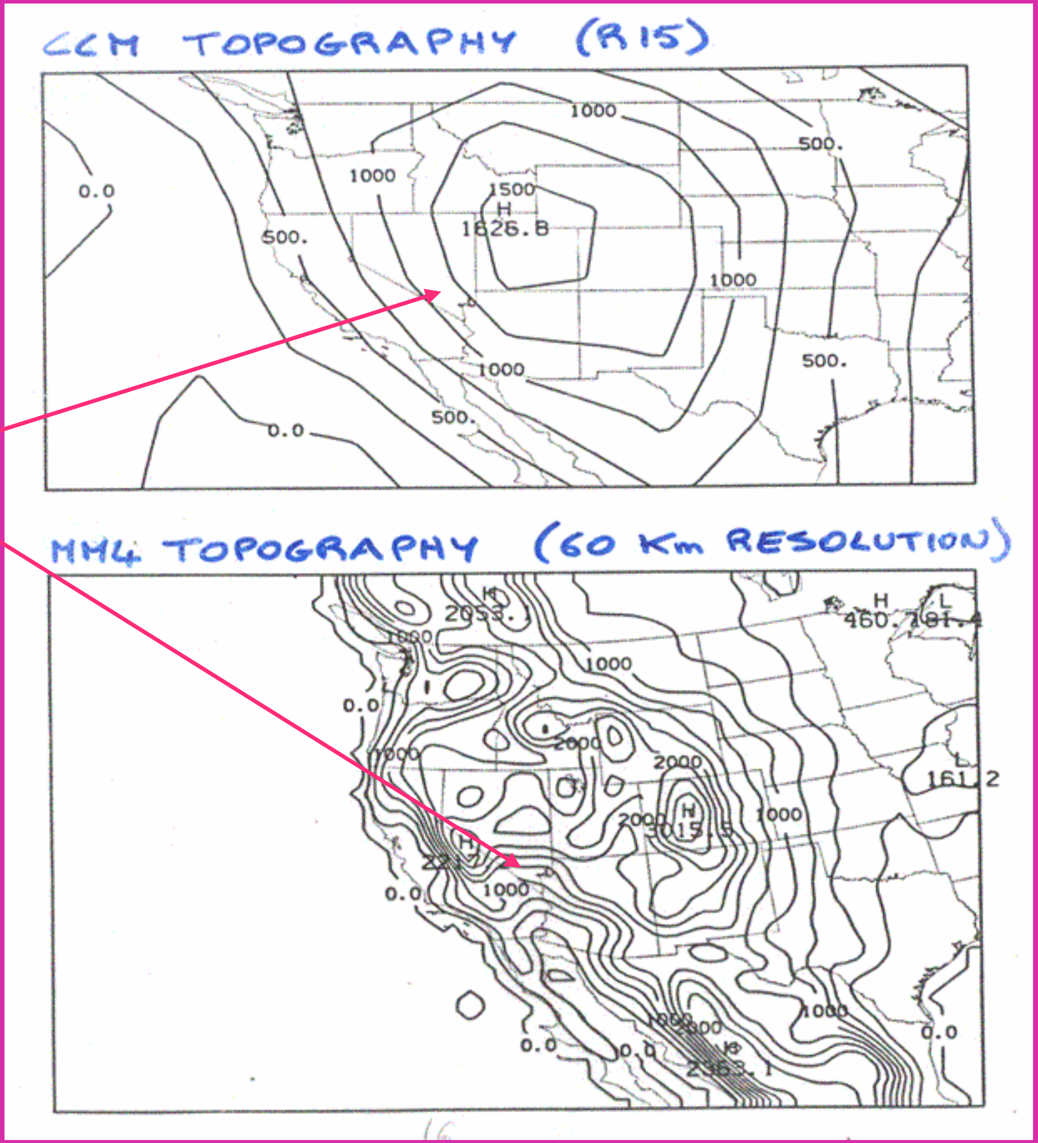
The birth of regional climate modeling

The Yucca Mountain Project (1987)



Model domain for the Yucca Mountain Project

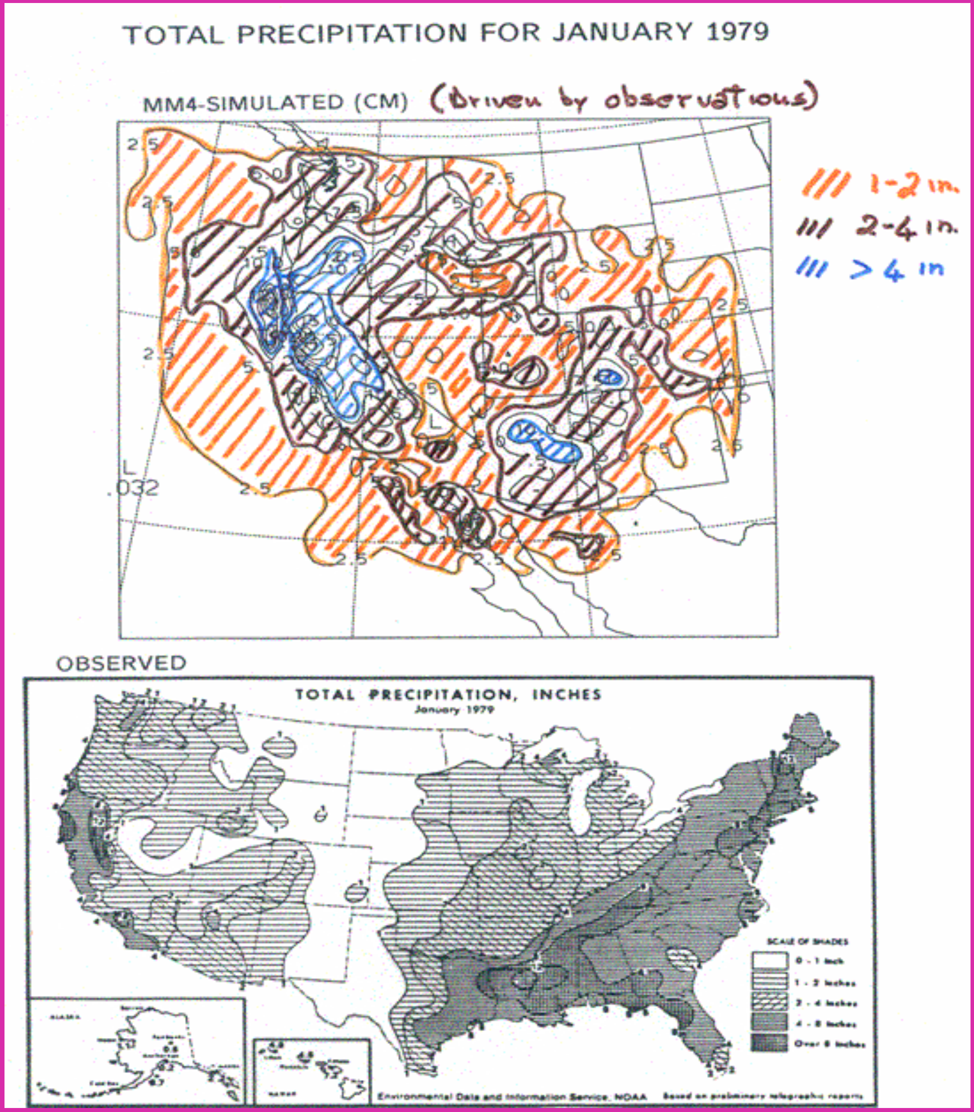
Yucca Mountain



The first Regional Climate Model RegCM (1989)

- Traditionally, limited area models (LAMs) had been used for numerical weather prediction involving simulations of 1-5 days in length.
- Dickinson et al. (1989) proposed to adopt the "nesting" approach to climate problems by generating statistics of large numbers of short LAM simulations driven by GCM fields
  - The model used was a suitably modified version of the NCAR/Penn State mesoscale model MM4
- Giorgi and Bates (1989) and Giorgi (1990) completed the first LAM simulations in "climate mode" (1-month long) driven by ECMWF analyses of observations and by GCM fields, respectively.
- This lead to the generation of the first version of RegCM, which was based on MM4 with suitably modified radiative transfer and land surface process schemes

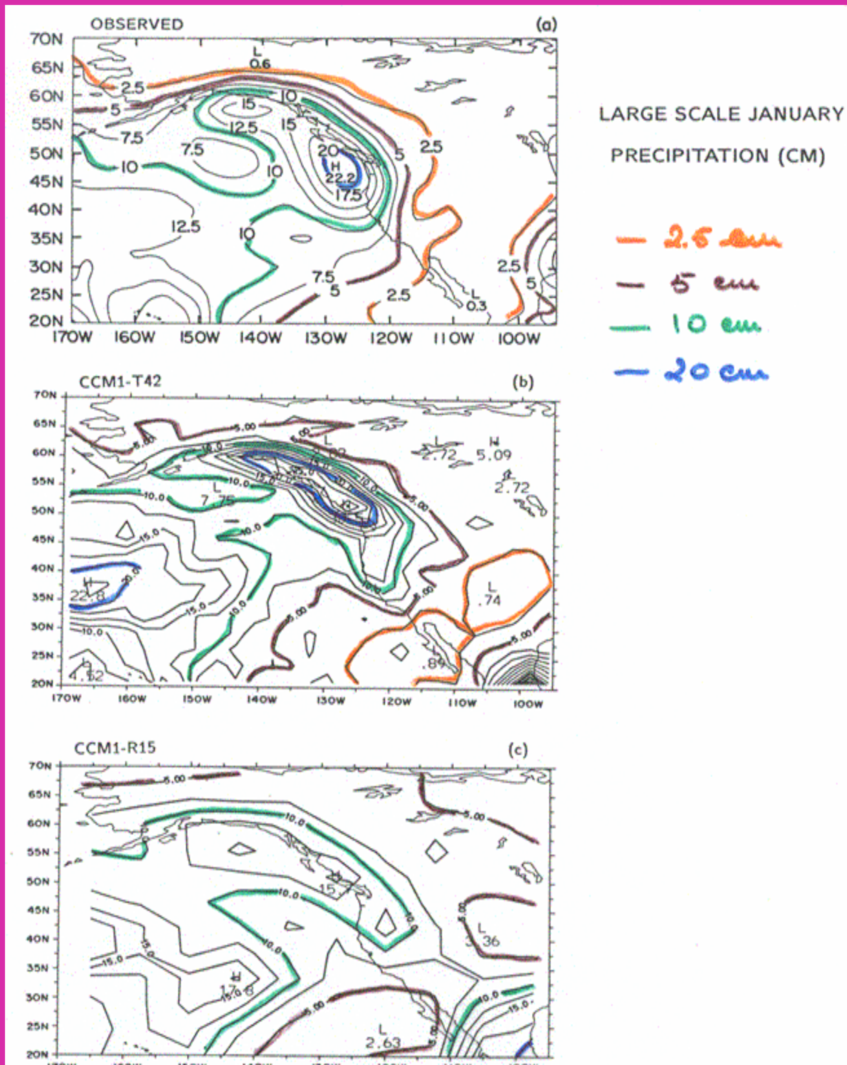
The first LAM Experiment in "climate mode"
When LAMs became RCMs

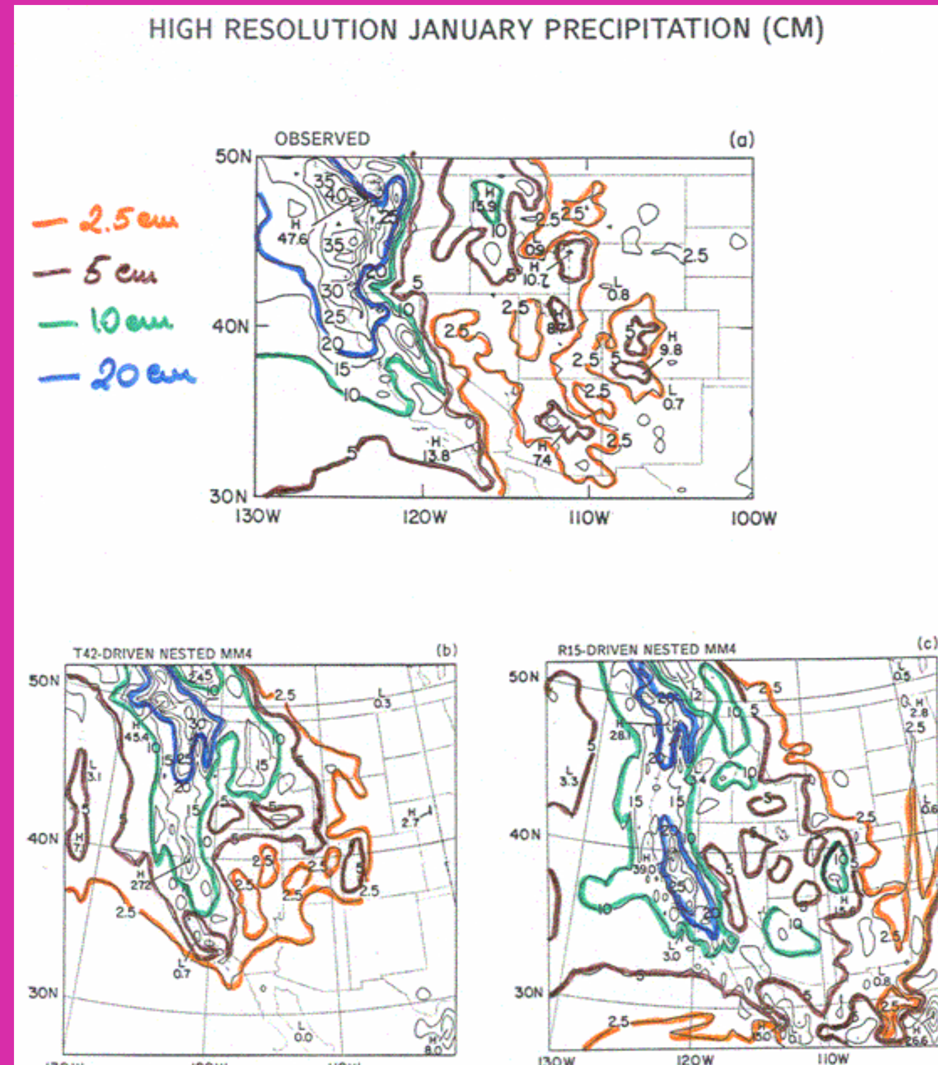


From
Giorgi and Bates (1989)

The first GCM-driven regional climate simulation

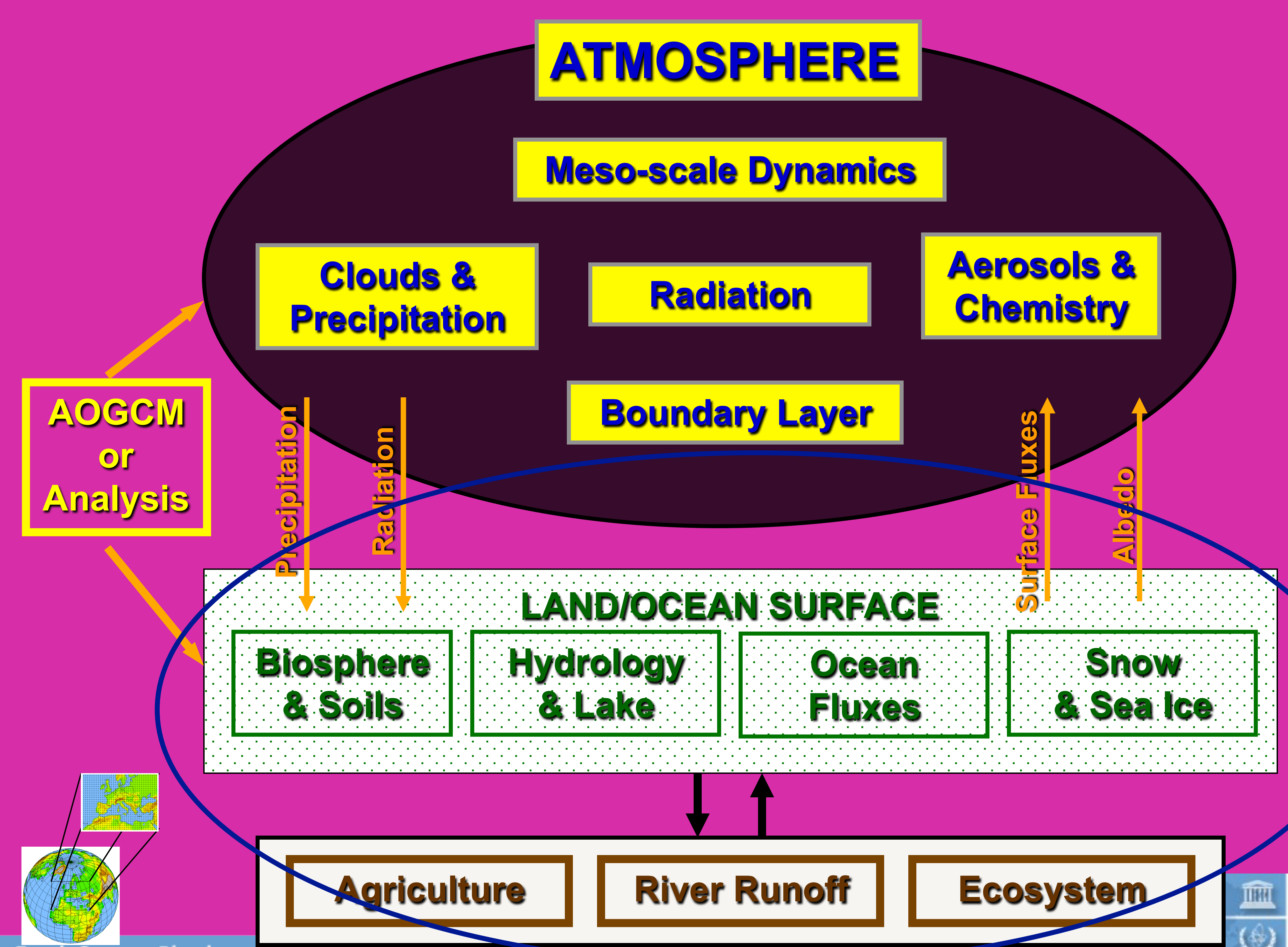
Giorgi (1990)





The Regional Climate Model RegCM
An example of RCM development

- RegCM1: Dickinson et al (1989), Giorgi and Bates (1989), Giorgi (1990)
  - Dynamics from the NCAR/PSU MM4 (Anthes et al. 1987)
  - Physics from the NCAR CCM1 (Williamson et al. 1987) and MM4
- RegCM2: Giorgi et al. (1993a,b)
  - Dynamics from the hydrostatic NCAR/PSU MM5 (Grell et al. 1994)
  - Physics from the NCAR CCM2 (Hack et al. 1993) and MM5
- RegCM2.5: Giorgi and Mearns (1999), RegCM special issue of JGR (1999)
  - Dynamics from the hydrostatic MM5
  - Physics from the NCAR CCM3 (Kiehl et al. 1996) and MM5
  - Coupled lake model
  - Coupled tracer transport scheme
- RegCM3: Pal et al. (2007), RegCNET Special Issue of TAC
  - Dynamics from the hydrostatic MM5
  - Physics upgrades for convective and non-convective precipitation, air sea fluxes
  - Coupled with a simple chemistry/aerosol scheme
  - Sub-grid land surface scheme


ATMOSPHERE
Meso-scale Dynamics
Clouds & Precipitation
Radiation
Aerosols & Chemistry
Boundary Layer
AOGCM or Analysis
Precipitation
Radiation
Surface Fluxes
Albedo
LAND/OCEAN SURFACE
Biosphere & Soils
Hydrology & Lake
Ocean Fluxes
Snow & Sea Ice
Agriculture
River Runoff
Ecosystem

Regional Climate Modeling: Research landmarks

- RCMs were born in the late 80s and early 90s when mesoscale models used in NWP were modified for long-term integrations (Dickinson et al. 1989; Giorgi 1990; Giorgi et al 1994)
- Milestone review papers: Giorgi and Mearns (1991), McGregor (1997), Giorgi and Mearns (1999), Giorgi et al. (IPCC 2001), Leung et al. (2003), Wang et al. (2004)
- The European "Thrust"
  - Christensen et al. (1995, 1997, 1998), Jones et al. (1995, 1997), Machenauer et al. (1996, 1998)
  - The Rossby Center
  - The Baltex project
  - The Swiss "extremes" (ETH, U. Fribourg)
  - C21C->MERCURE->PRUDENCE->ENSEMBLES
- Intercomparison projects: PIRCS , RMIP, NARCCAP etc.
- The transferability project (Takle et al. 2007)
- The West Coast "Wave": PNL, UCSC, Scripps, LLNL, U. Alaska (Arcsym)
- The Canadian RCM ("Big Brother" experiment, Denis et al. 2002)
- The Australian DARLAM (first 140-year simulation, Mc Gregor et al. 1999)
- RCM special issues (JGR 1999; JMSJ 2004; TAC 2006; CC 2007)
- Two-way nesting (Lorenz et al. 2005)

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 Modeling:
Some basic issues

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
- 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
"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 severe 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 boundary conditions be of good quality
  - Examples: Correct location of jet streams and storm tracks; realistic simulation of monsoons and ICTZ

Regional Climate Modeling Issues
Model physics

- Should the physics schemes in the nested RCM and driving GCM be the same?
  - Same physics would lead to a better interpretation of model results
  - Same physics would maximize consistency between LBC and RCM
  - GCM physics (e.g. convection) may not be suitable for fine scales. Each model uses schemes developed for their respective resolutions
  - A given scheme may behave very differently at different resolutions
- Simulations of comparable quality have been conducted with RCMs having wither the same or different physics schemes from the driving GCM (PRUDENCE)

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
- RCMs are characterized by a certain level of internal variability due to the model non-linearities

Regional Climate Modeling Issues
"Added value"

- What is the "added value" of the use of an RCM for our research problem?
- Increased resolution compared to the driving GCM
  - Fine scale forcings (e.g. topography)
  - Mesoscale circulations
- Tool for process studies
  - Aerosol effects, land-atmosphere interactions, regional feedbacks, circulations and processes etc.
- Tool for parameterization development and testing

Regional Climate Modeling
Examples of “Added Value”

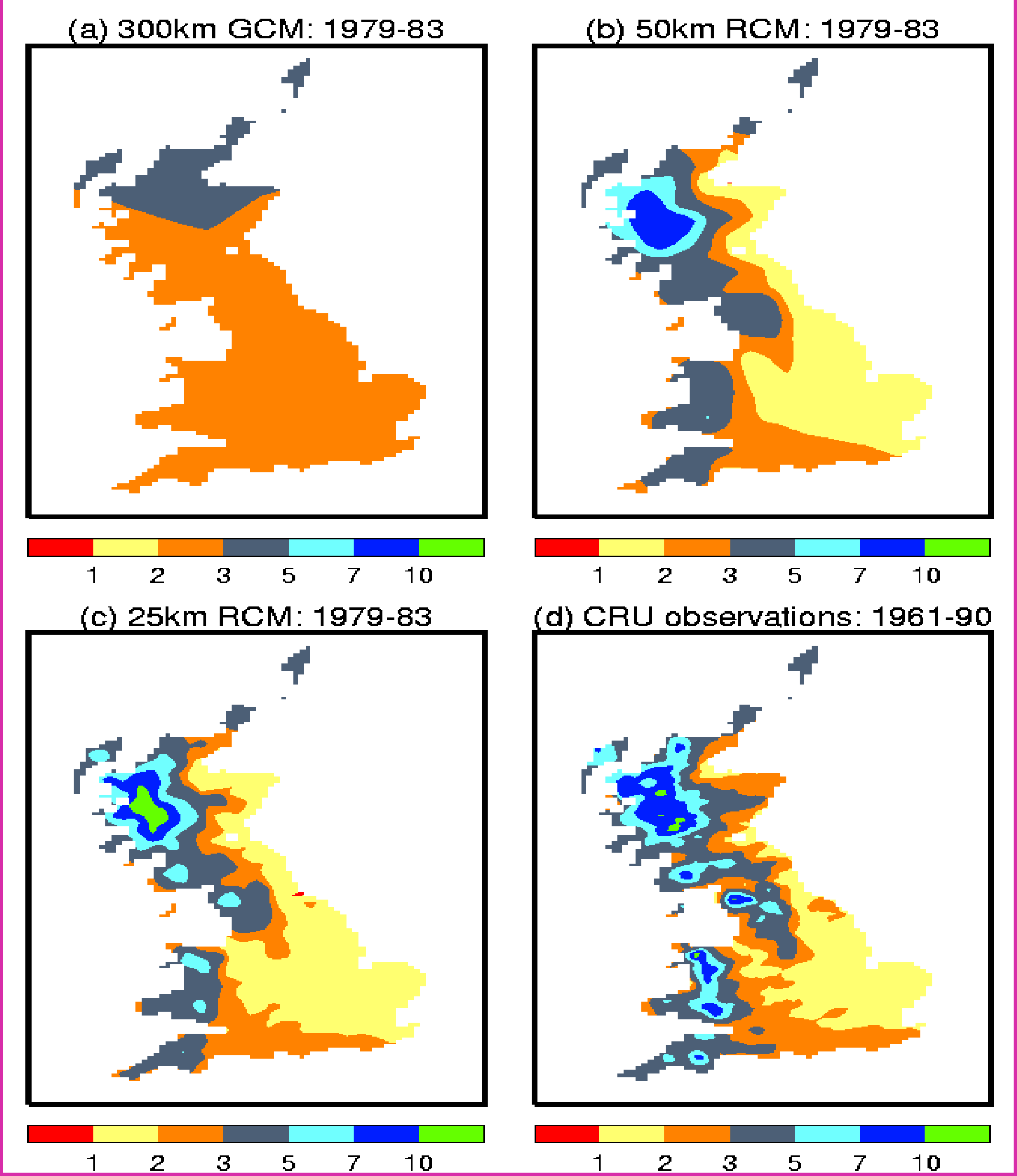
WINTER PRECIPITATION OVER BRITAIN

300km Global Model

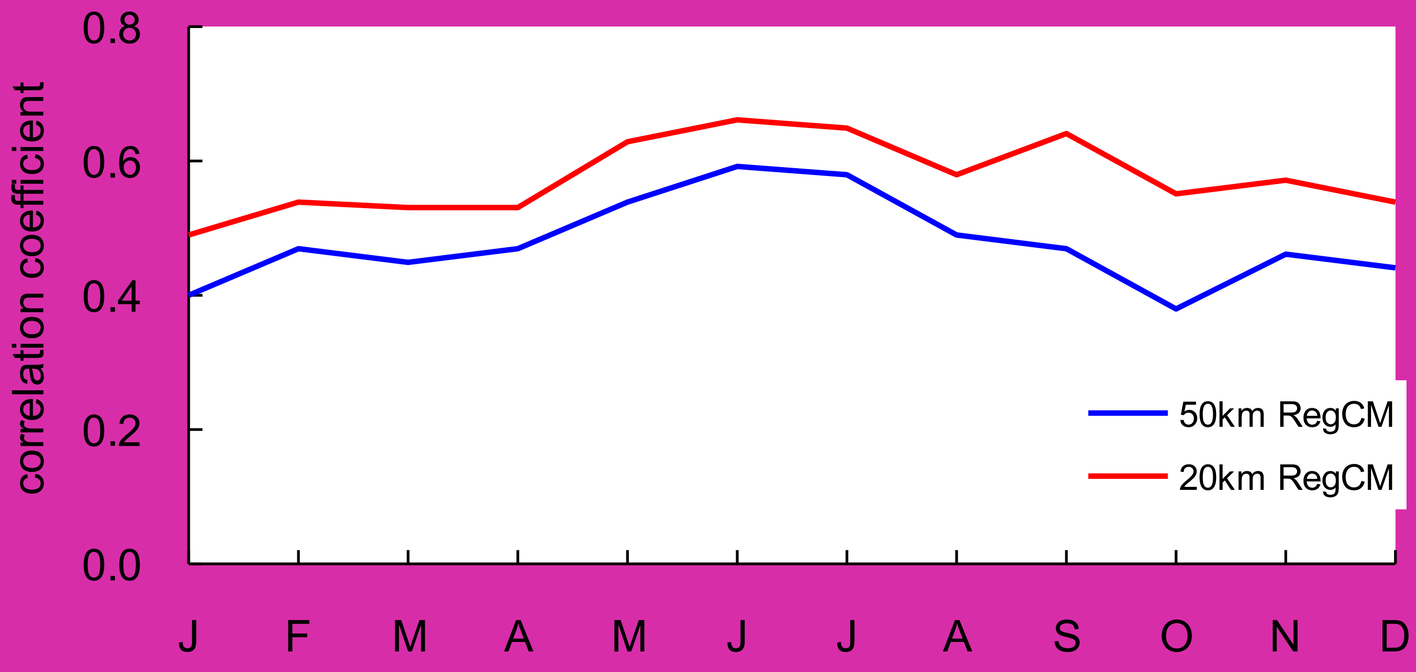
50km Regional Model

25km Regional Model

Observed



Spatial Correlation Coefficient between precipitation simulation and Frei & Schär data



Mean of the 12 Months: **0.58** vs **0.48**

Example of regional vs. global model performance over Europe

- Precipitation spatial correlation between simulated and observed (high resolution) data:

	Winter	Spring	Summer	Fall
RegCM	0.73	0.67	0.53	0.52
CCM	0.54	0.08	-0.06	0.38

- Comparison with the UKMO experiment:

– Surface air temperature bias (whole Europe, units °C):

	Winter	Spring	Summer	Fall
RegCM	2.0	-1.7	1.3	0.03
UKMO	-0.9	-1.8	-1.1	-1.5

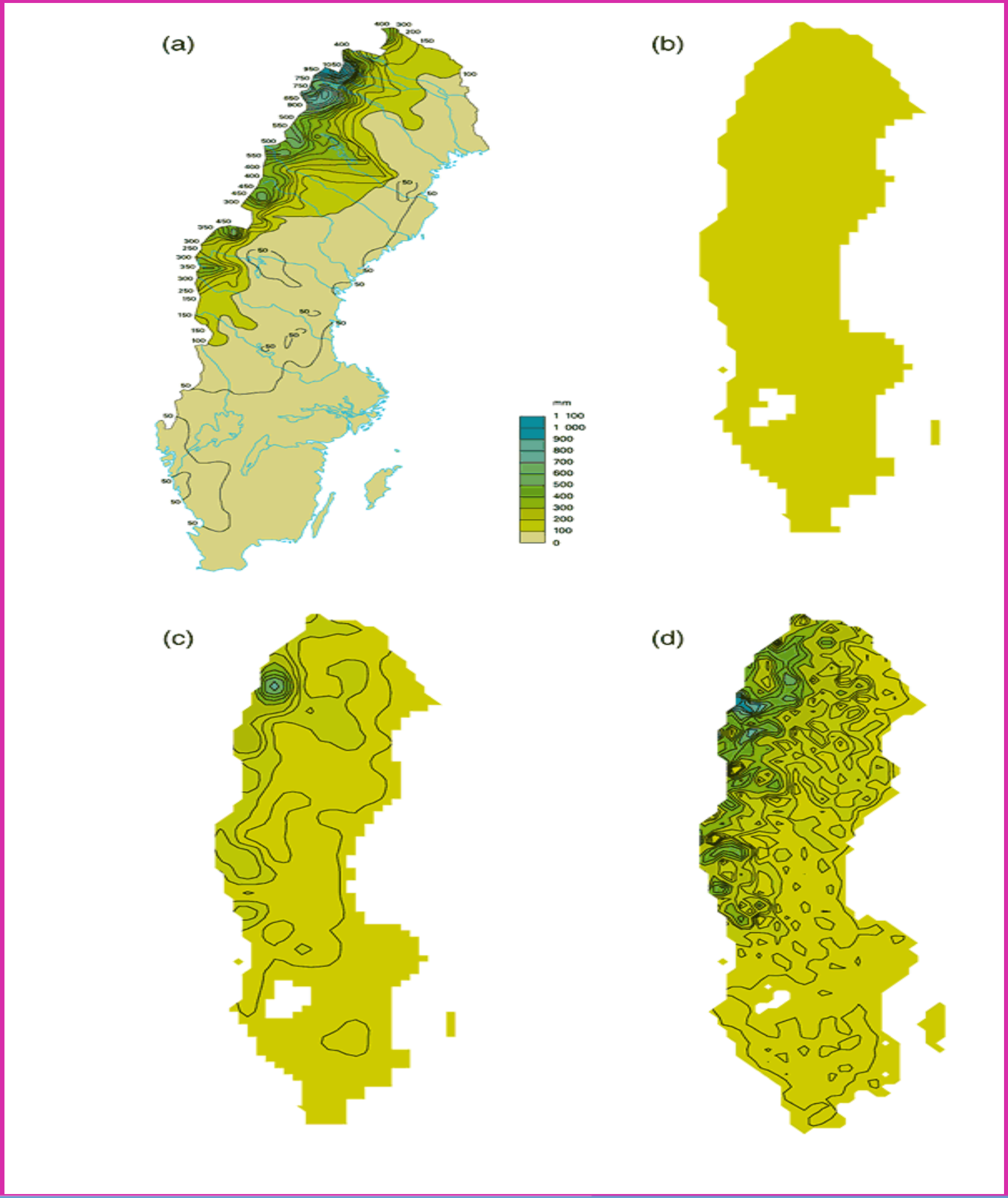
– Precipitation bias (whole Europe, units % of observed):

	Winter	Spring	Summer	Fall
RegCM	-16.8	-4.8	-27.3	-5.0
UKMO	16.8	45.0	-0.6	25.0

Summer Runoff in Sweden

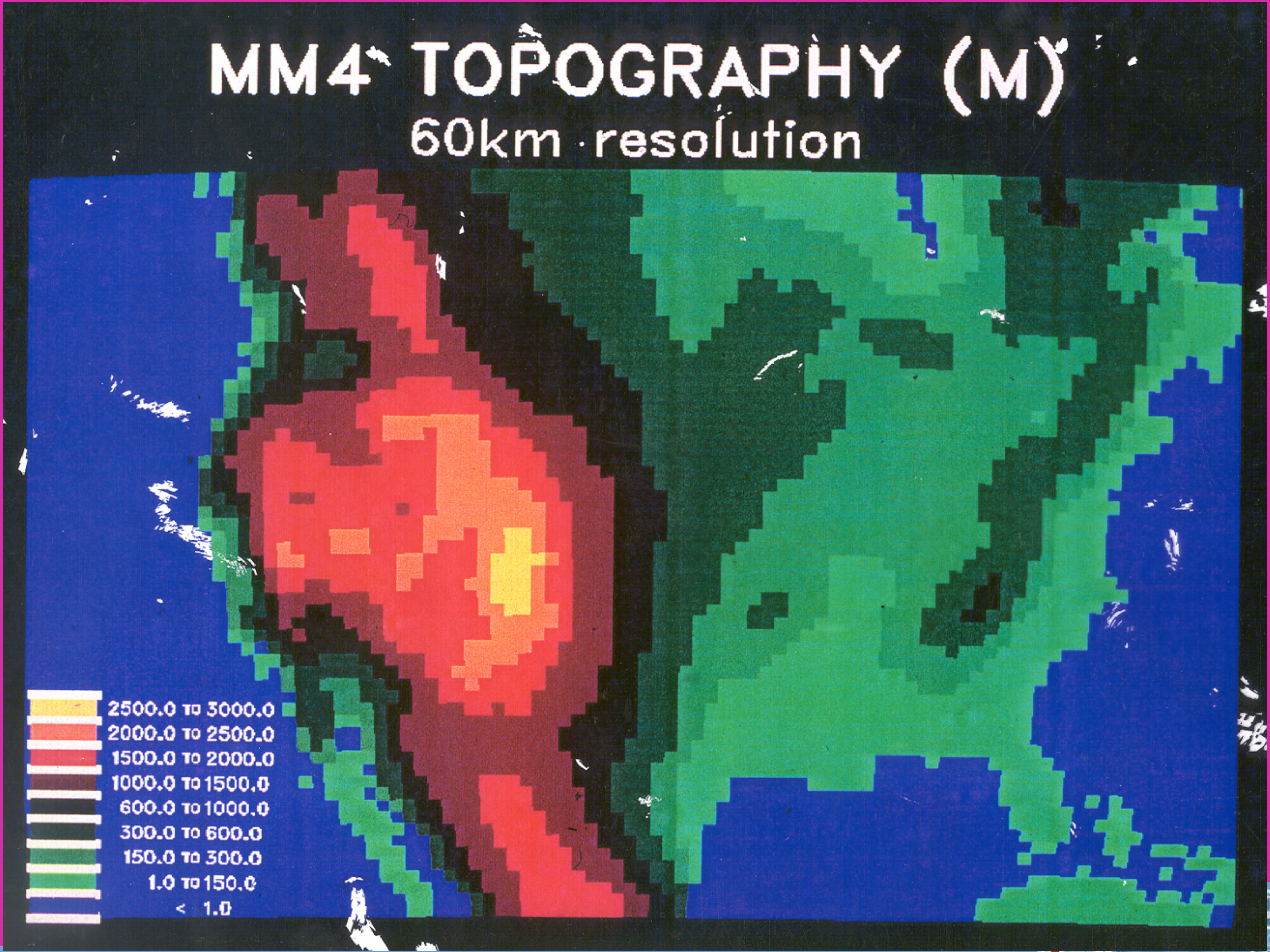
Observations

GCM

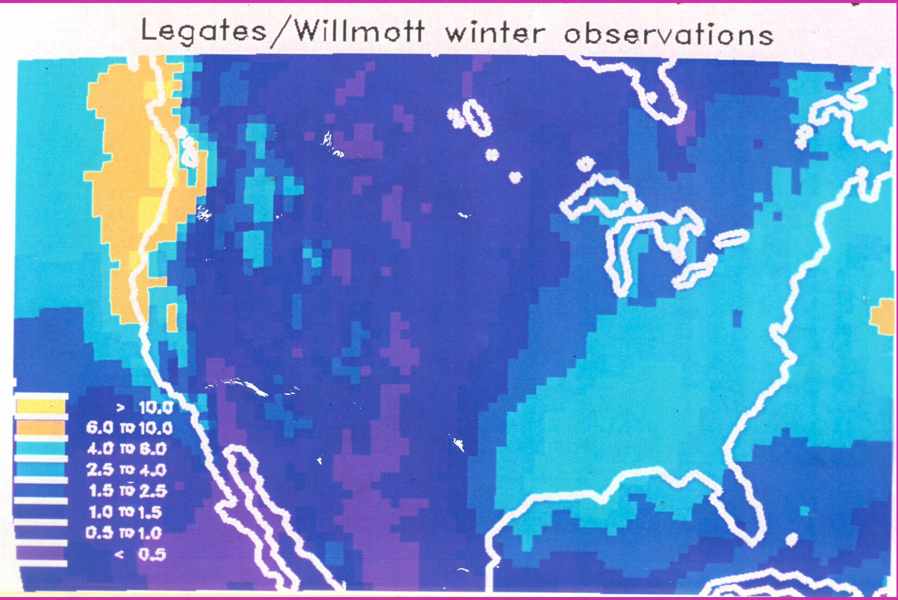


RCM – 55 km

RCM - 18 km

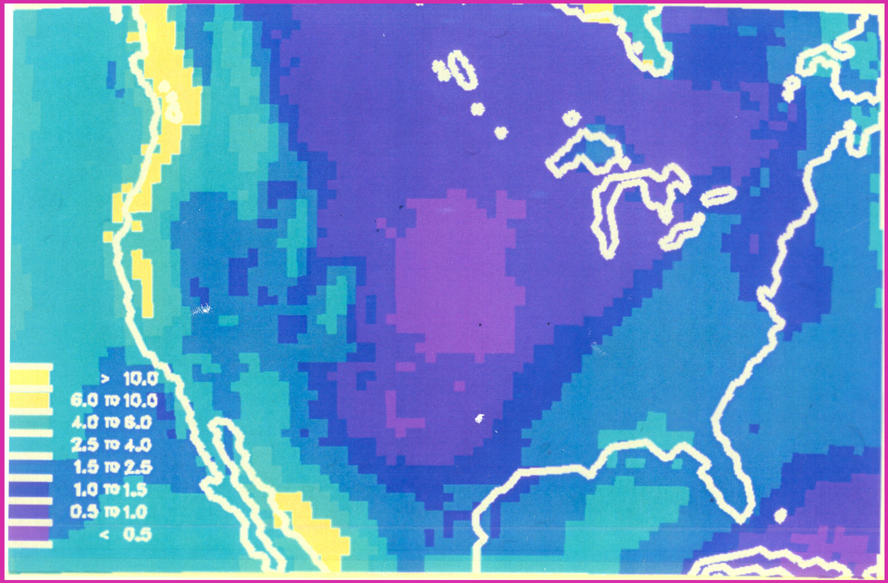

MM4 TOPOGRAPHY (M)
60km resolution
2500.0 TO 3000.0
2000.0 TO 2500.0
1500.0 TO 2000.0
1000.0 TO 1500.0
600.0 TO 1000.0
300.0 TO 600.0
150.0 TO 300.0
1.0 TO 150.0
< 1.0

Observations



Winter Precipitation Present Day

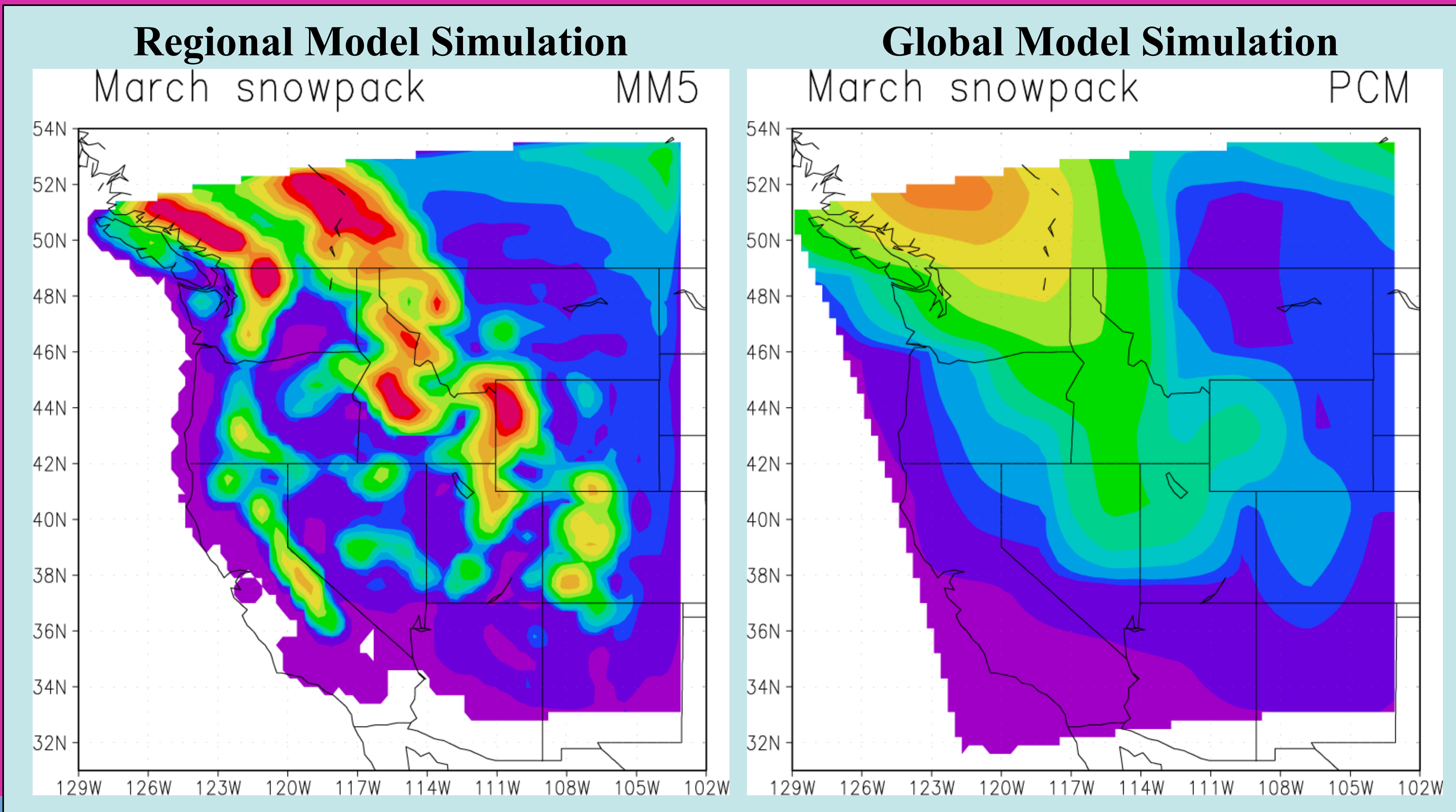
RegCM



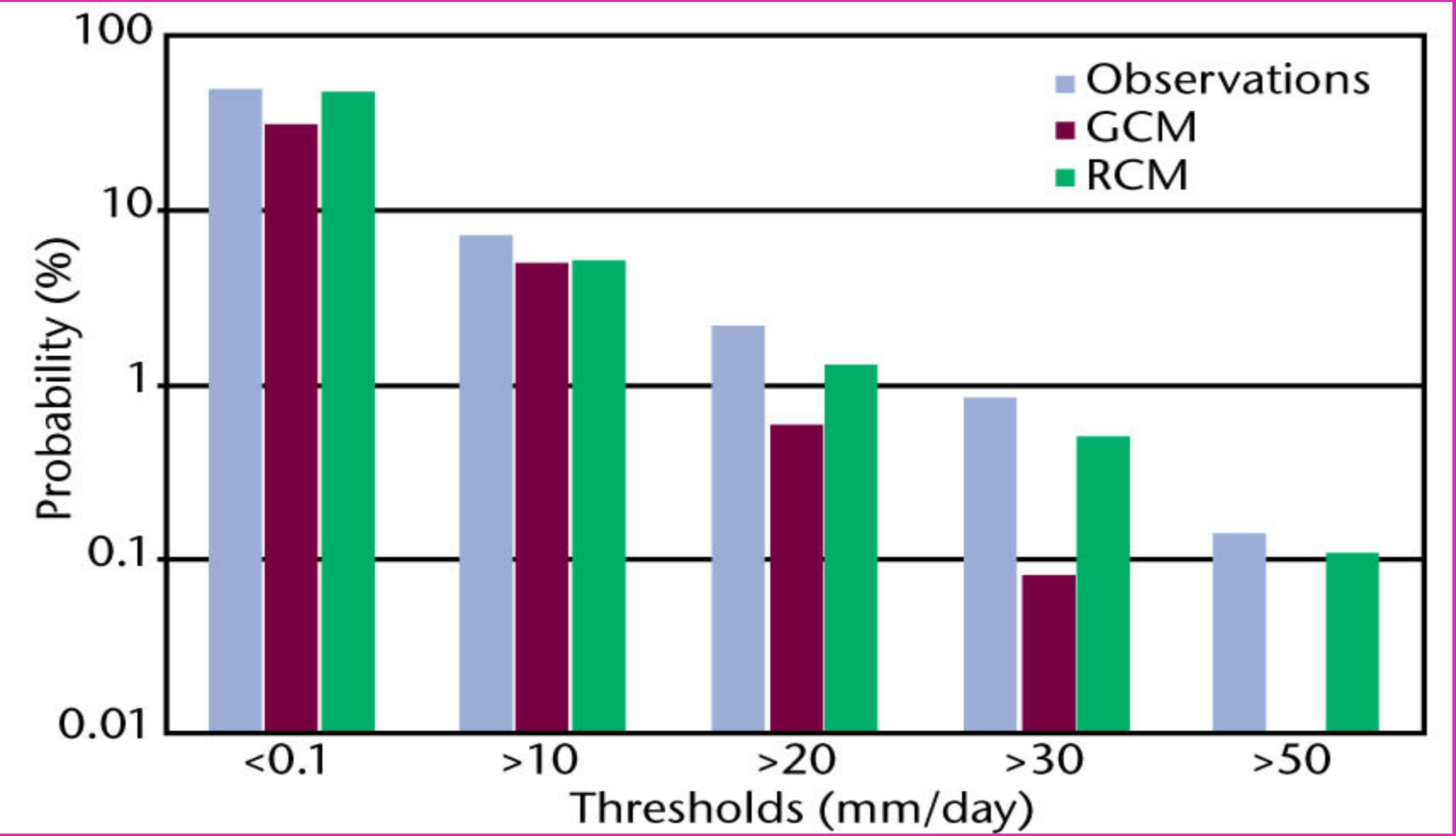
CCM1

Global and Regional Simulations of Snowpack

GCM under-predicts and misplaces snow

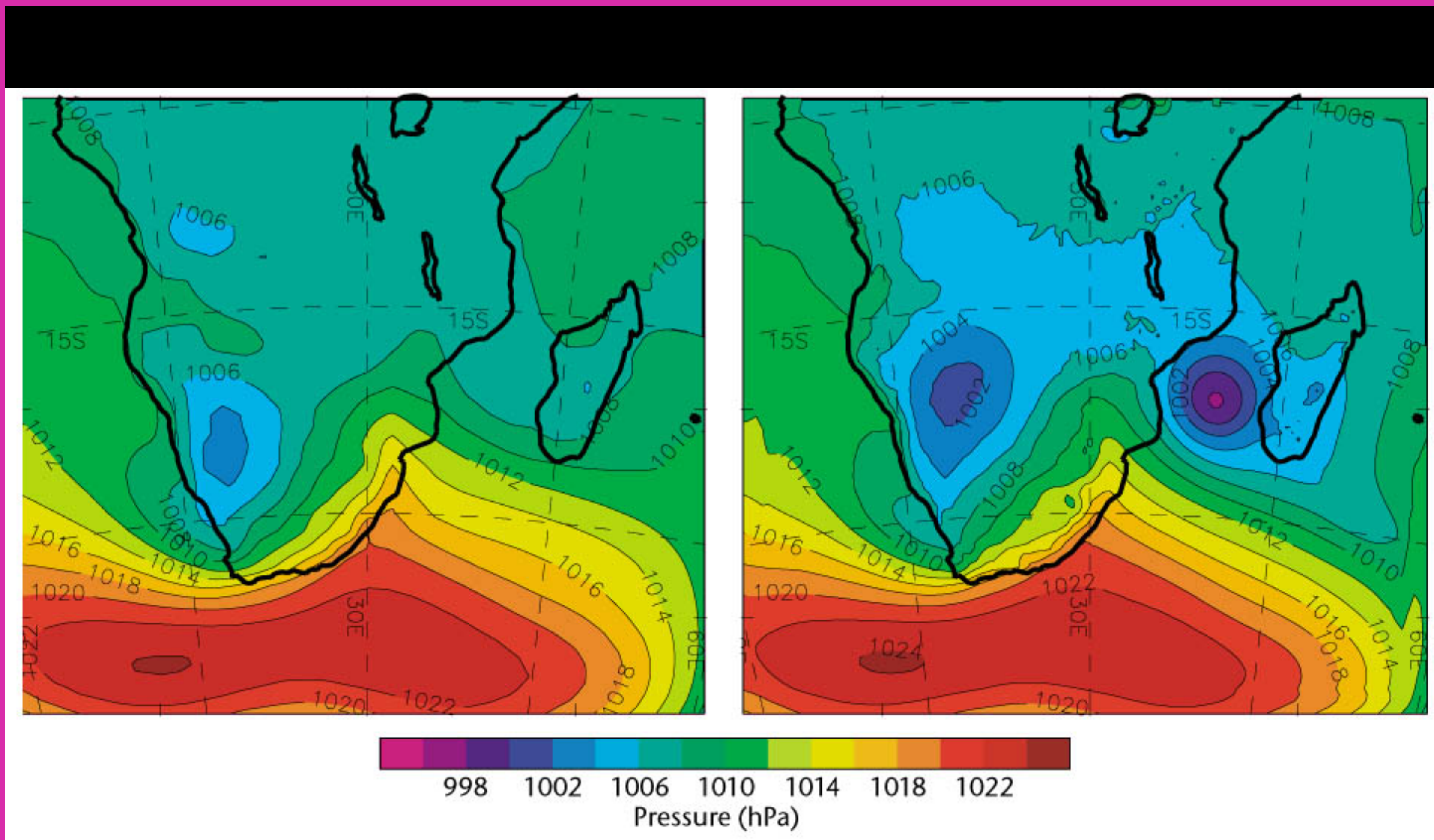


WINTER DAILY RAINFALL OVER THE ALPS



RCMs simulate extreme rainfall much better than GCMs

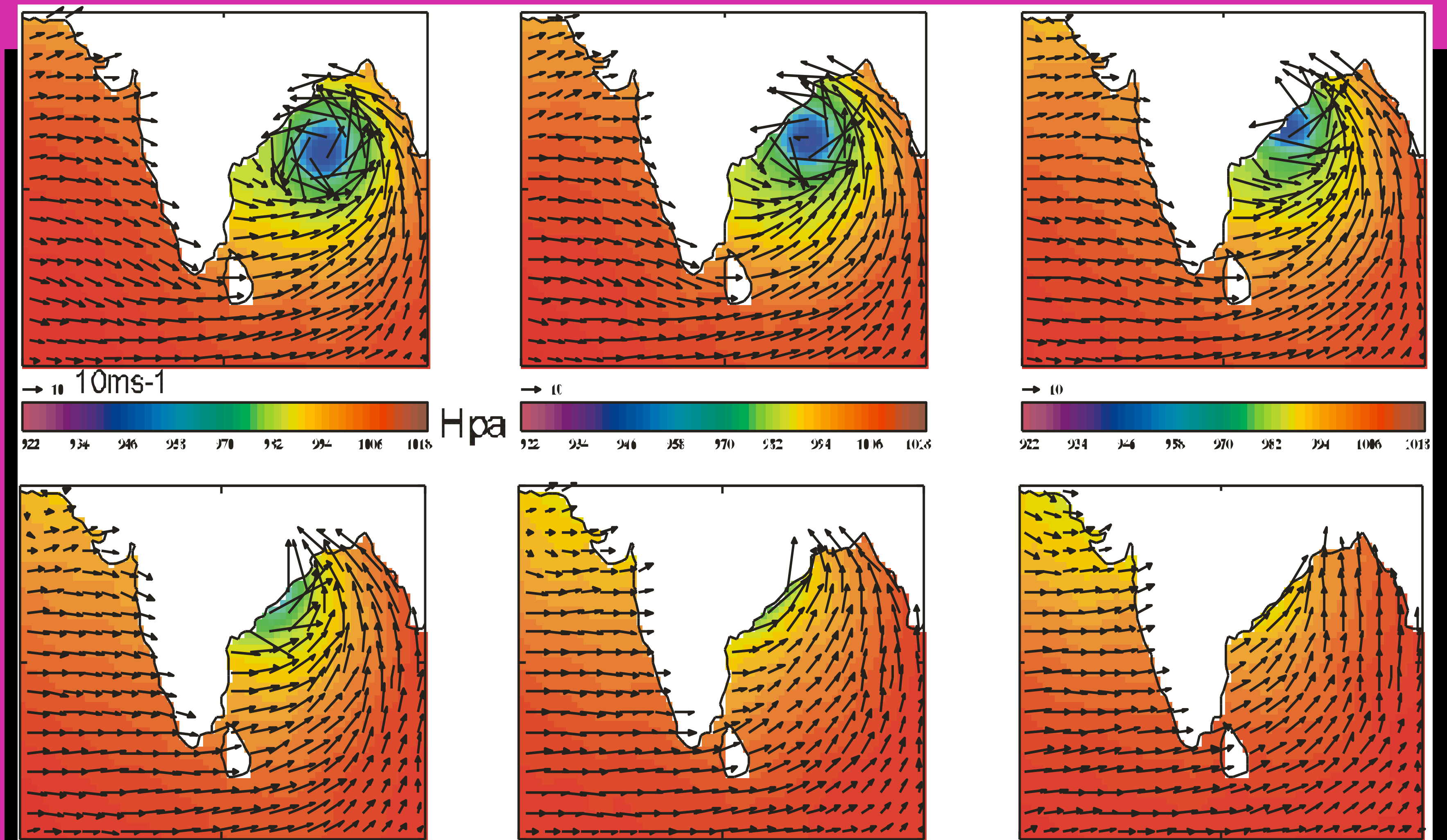
SIMULATION OF A TROPICAL CYCLONE

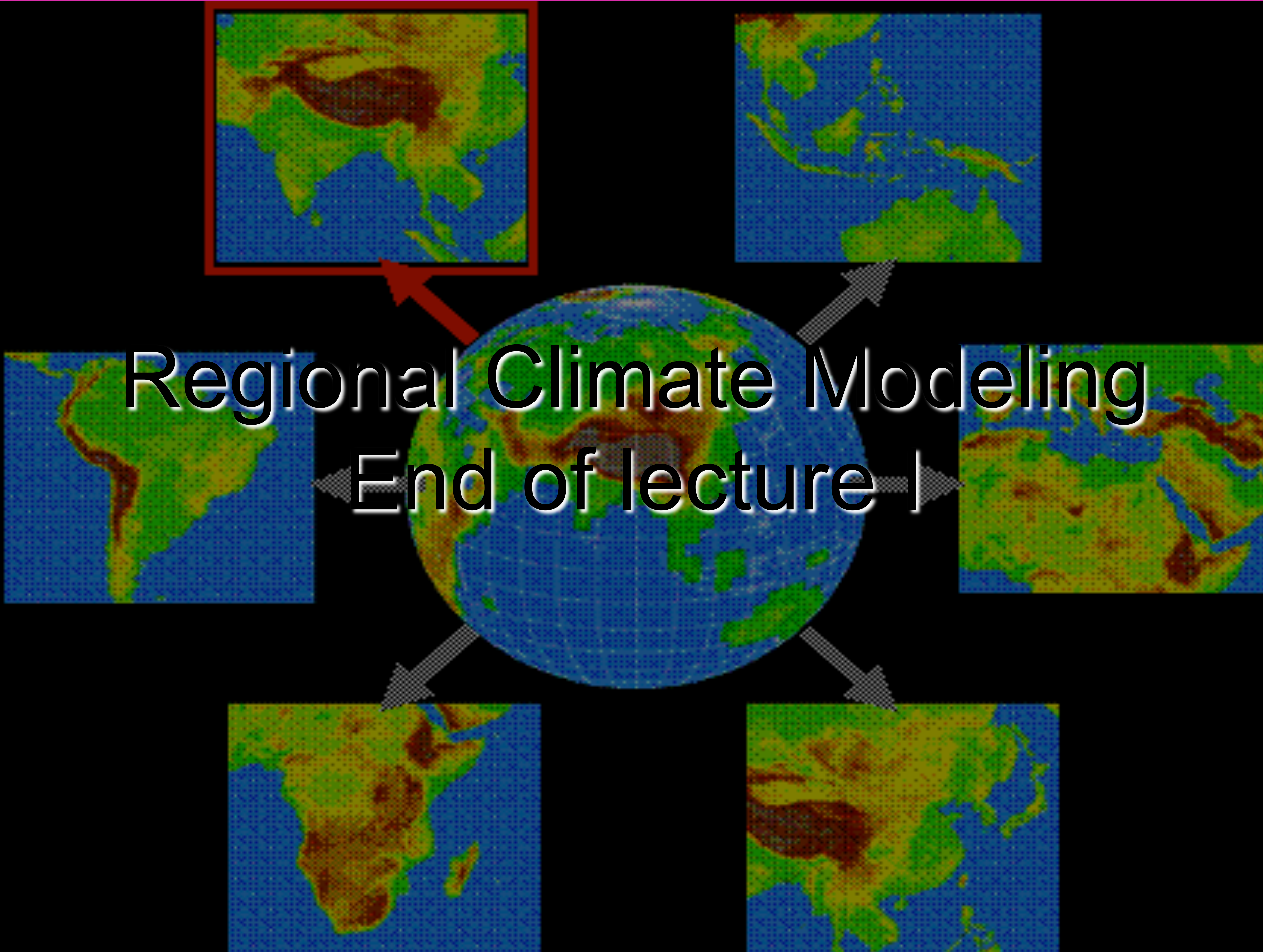


RCMs can simulate circulation features not resolved by GCMs

CYCLONE SIMULATION with an RCM

Pressure (hPa) and wind fields (m/s) every 6h from control run




Regional Climate Modeling
End of lecture I