RegCM4: Introduction to Main Computational Models

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www.pnl.gov

School on Parallel Programming and Parallel Architecture for HPC and Developer School for HPC applications in Earth Sciences + Symposium on HPC and Data-Intensive Applications in Earth Sciences

Trieste November 2014

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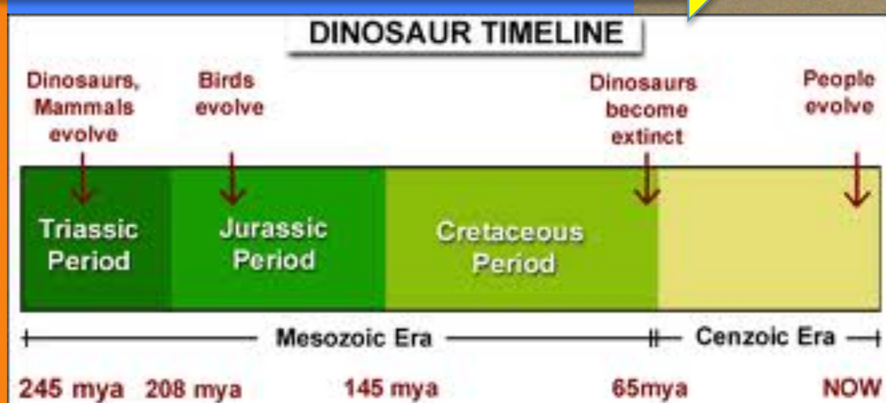
Regional Climate Modeling: Review of basic concepts

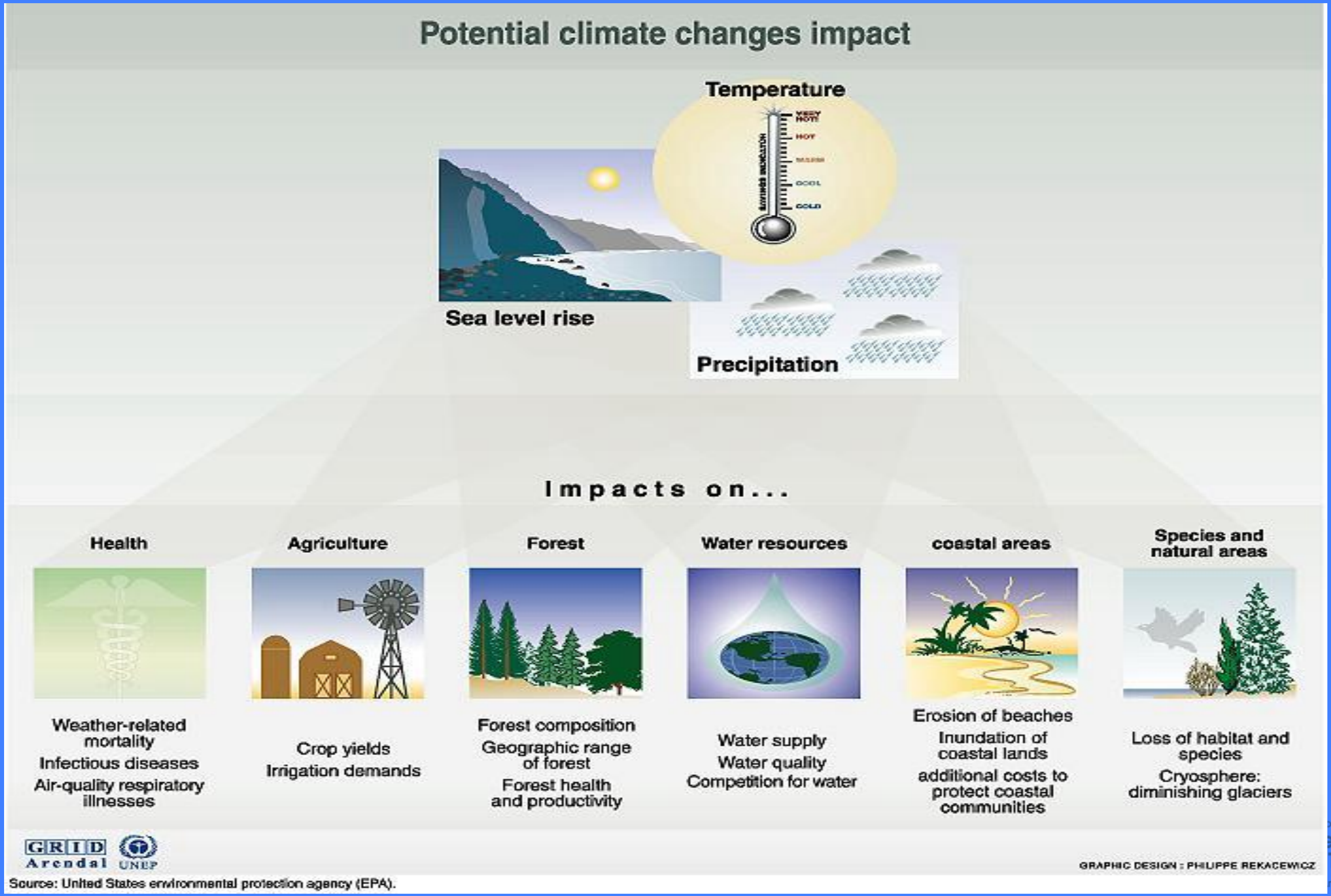
L. F. Richardson (b 1881)

2008: IBL Power 5+



250,000 Calculations

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



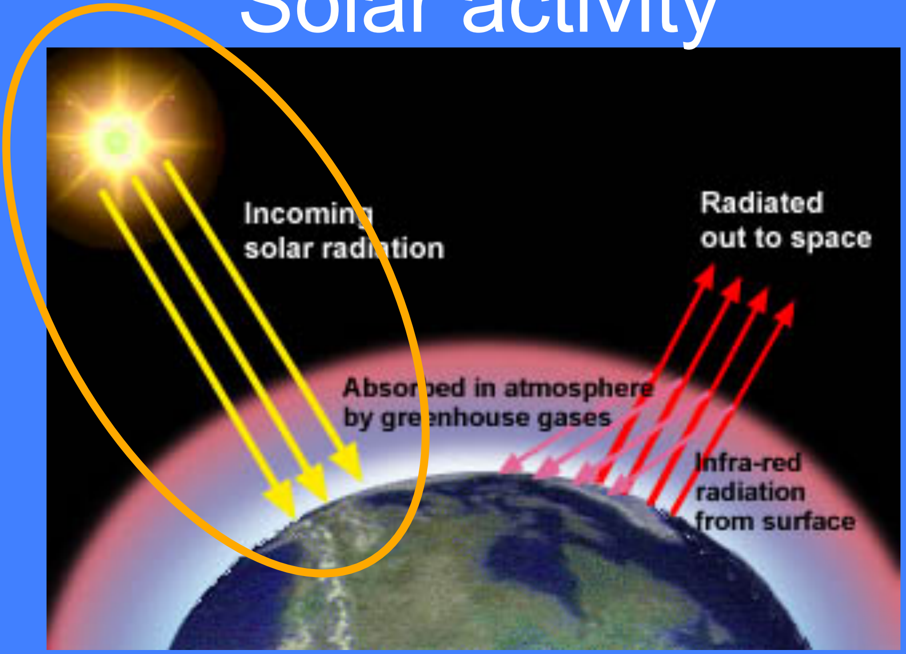
Regional climate modeling: Why?

- 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

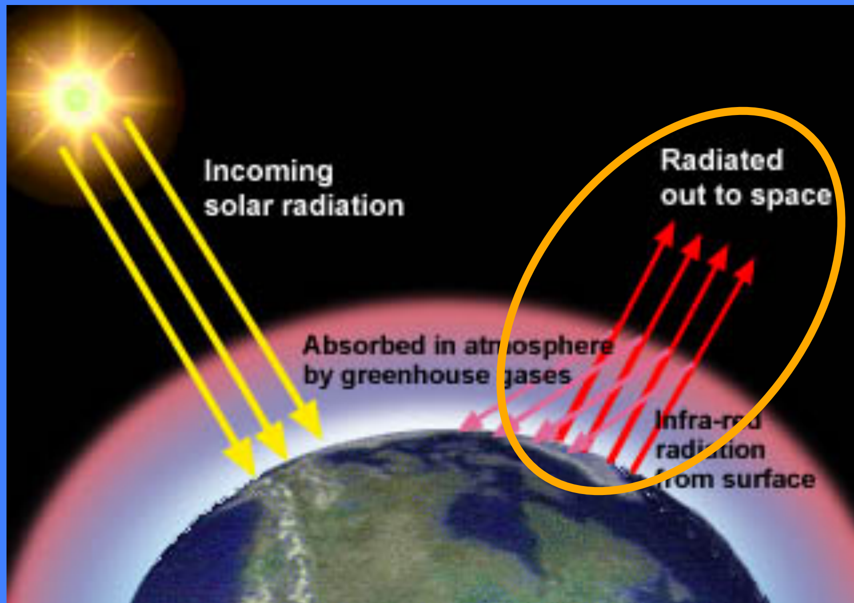
Large scale natural climatic forcings

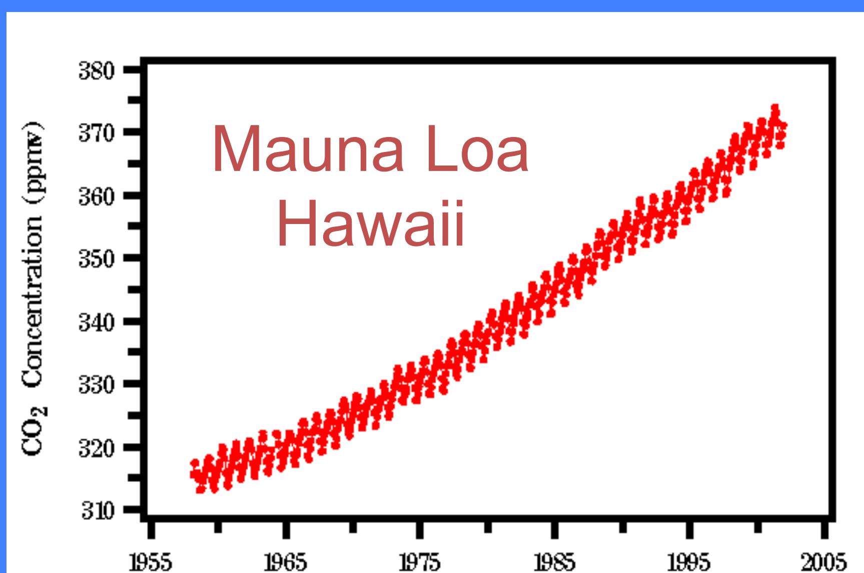
Volcanic eruptions

Solar activity



Large scale anthropogenic climatic forcings





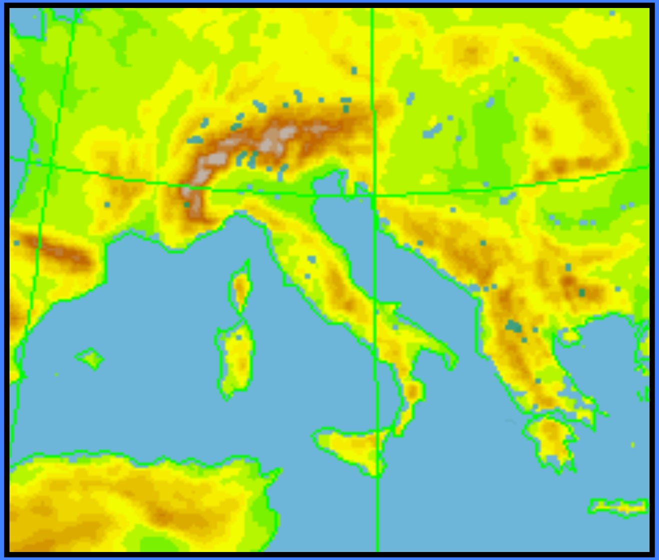
The Greenhouse effect

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.

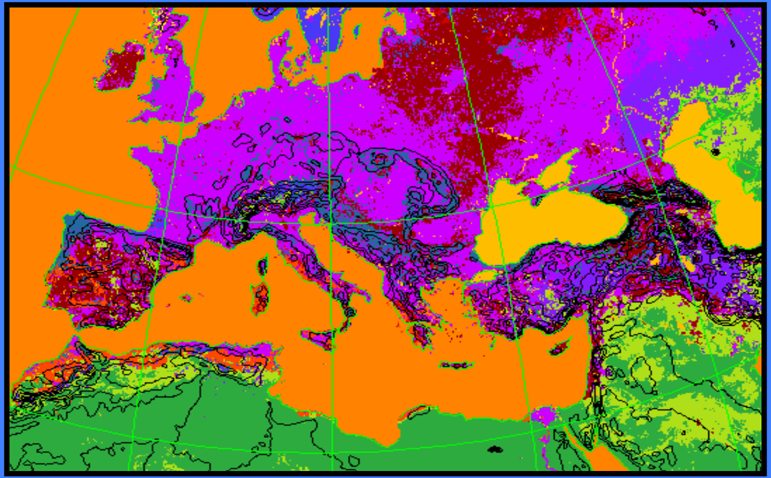
Extra CO_2 or other GHGs lead to a positive “forcing” of the climate system, an “excess greenhouse effect.”

Regional and local climatic forcings

Complex topography

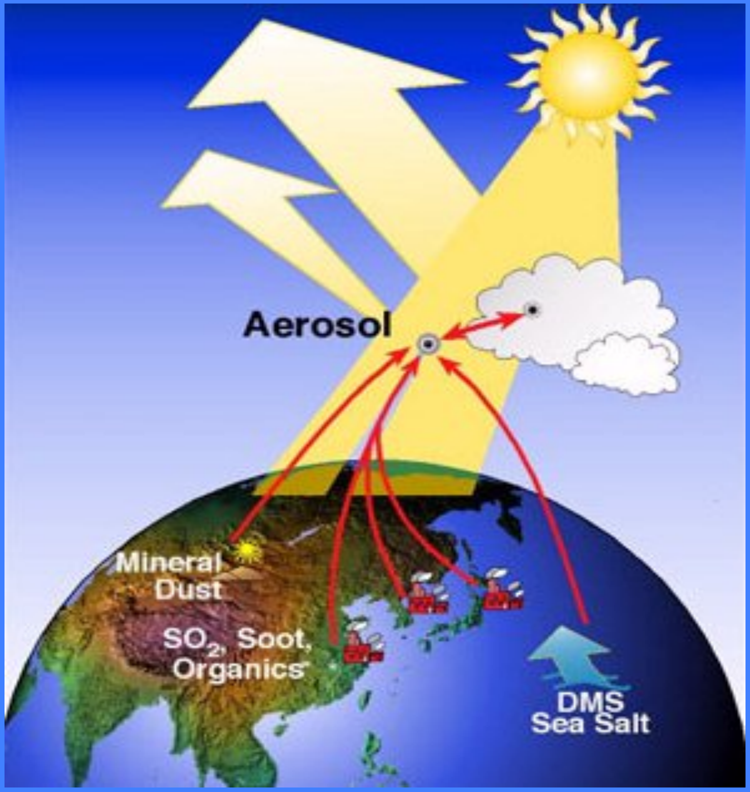


Complex landuse

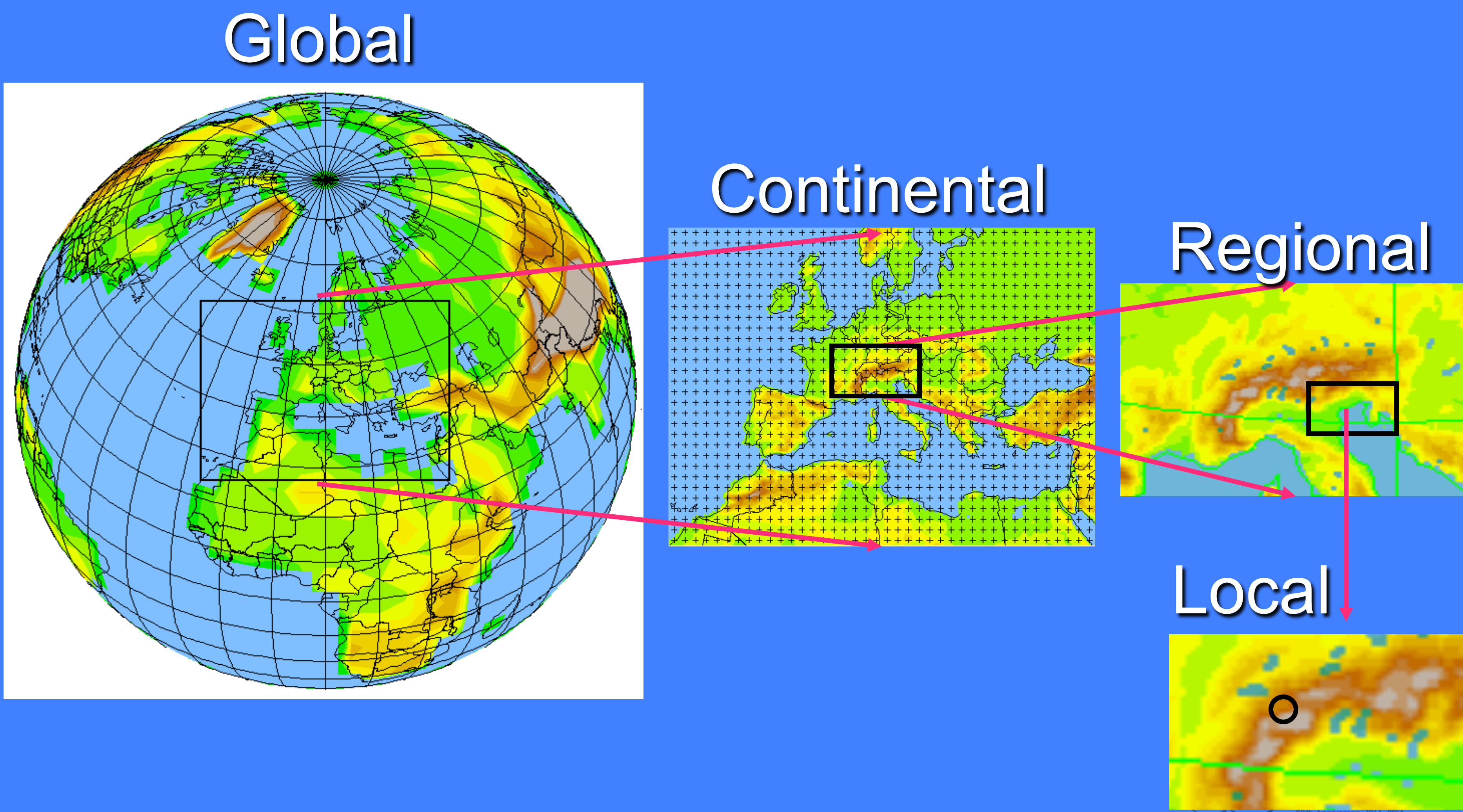


Aerosols

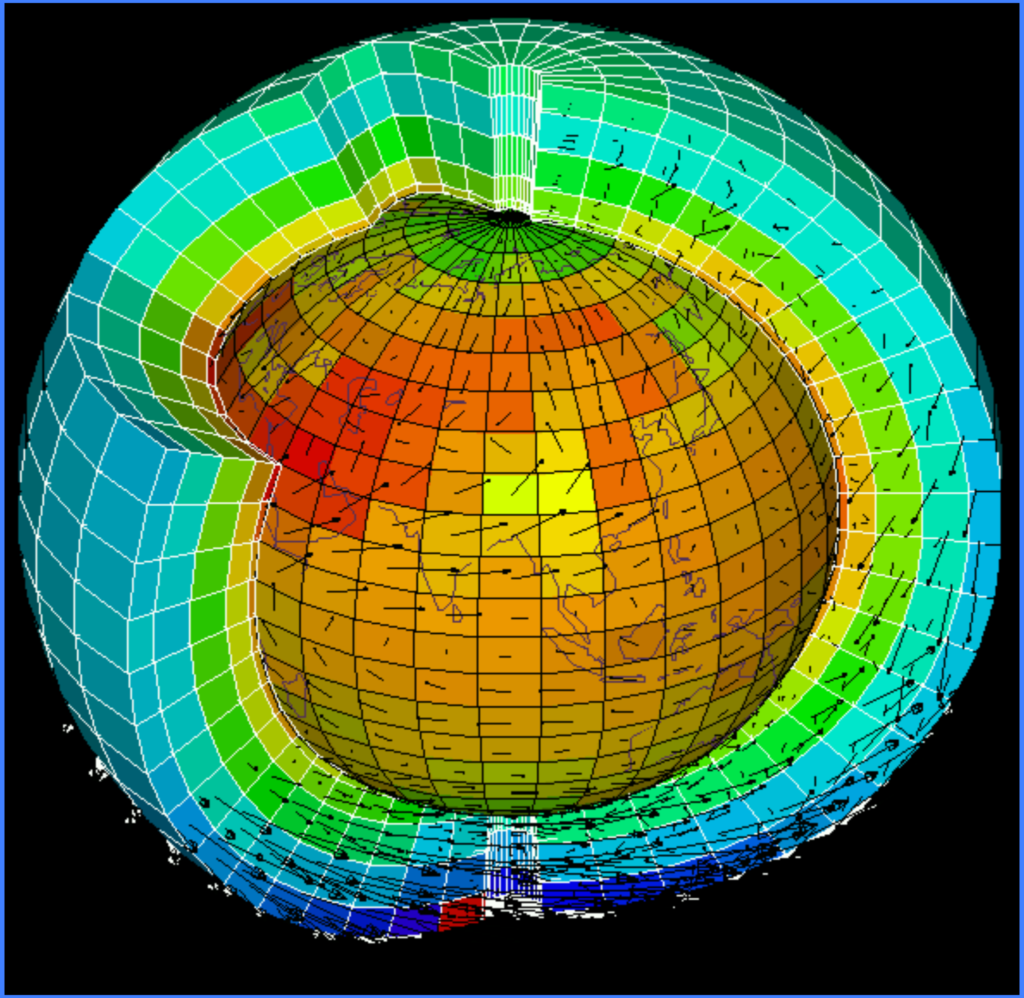
Direct and indirect effects



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

Conservation of momentum

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

Conservation of energy

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

Conservation of mass

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

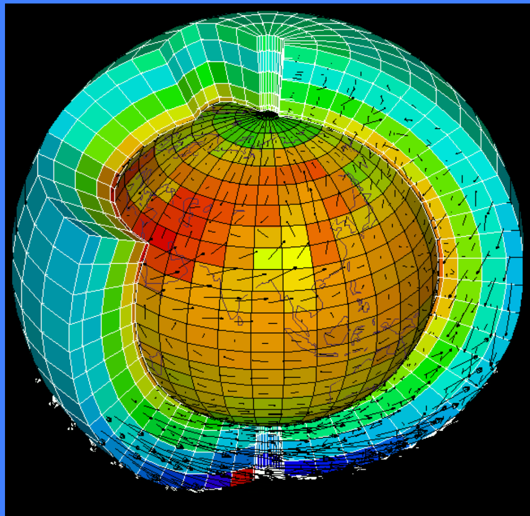
Physics

Conservation of water

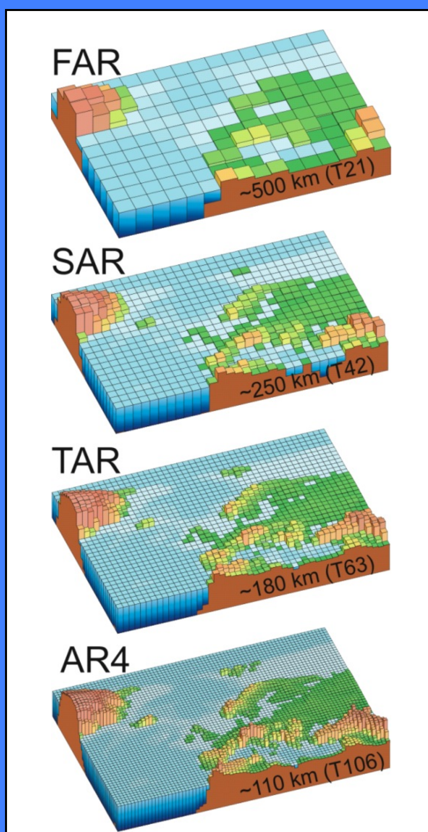
$$\frac{\partial q}{\partial t} + \overline{V} \cdot \nabla q = \frac{S_q}{\rho} + F_q$$

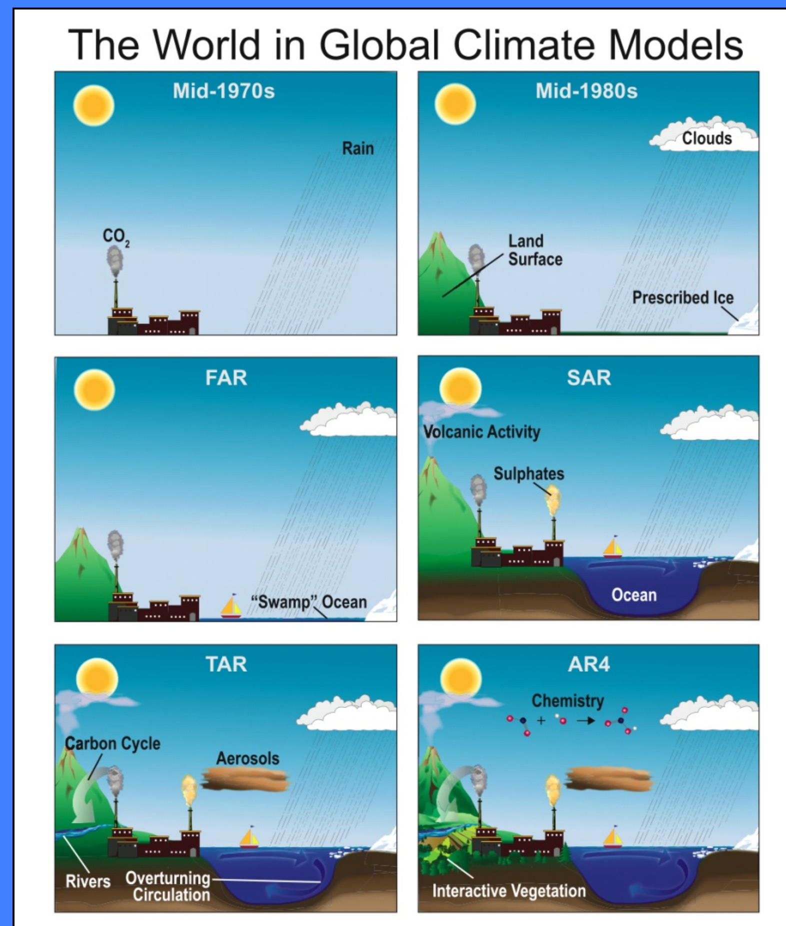
Equation of state

$$p = \rho R T$$

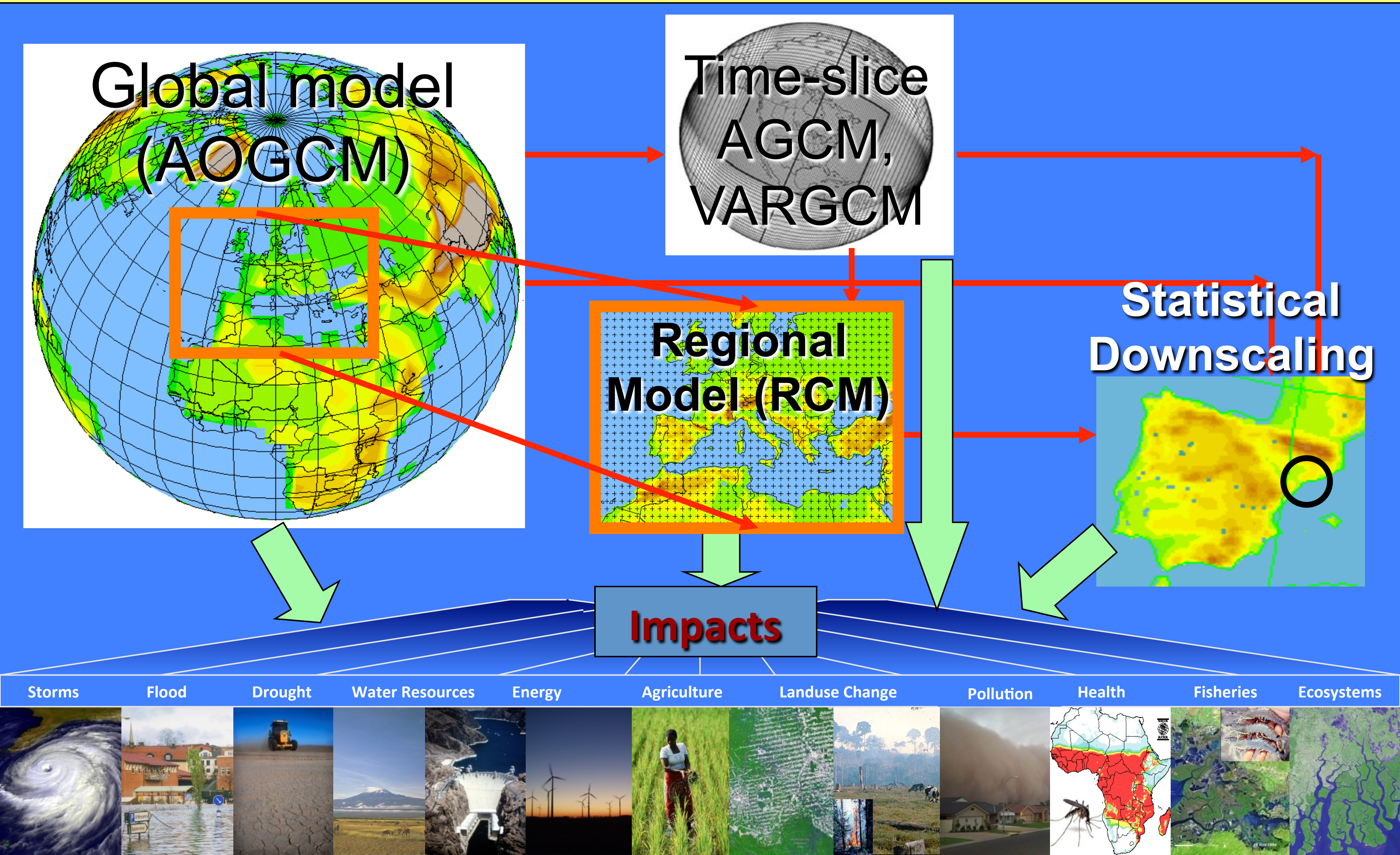


GCMs have evolved in terms of resolution and complexity





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



"Nested" Regional Climate Modeling: Technique and Strategy

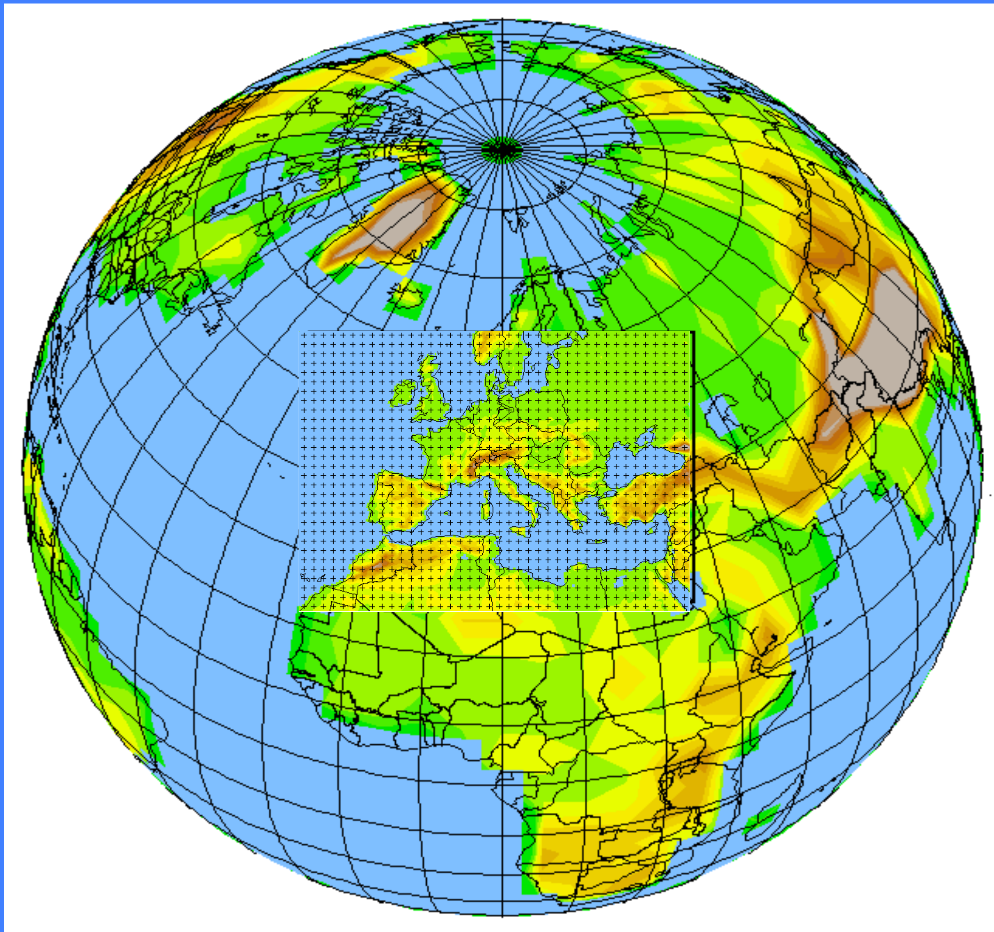
Motivation: The resolution of GCMs is still too coarse to capture regional and local climate processes

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).

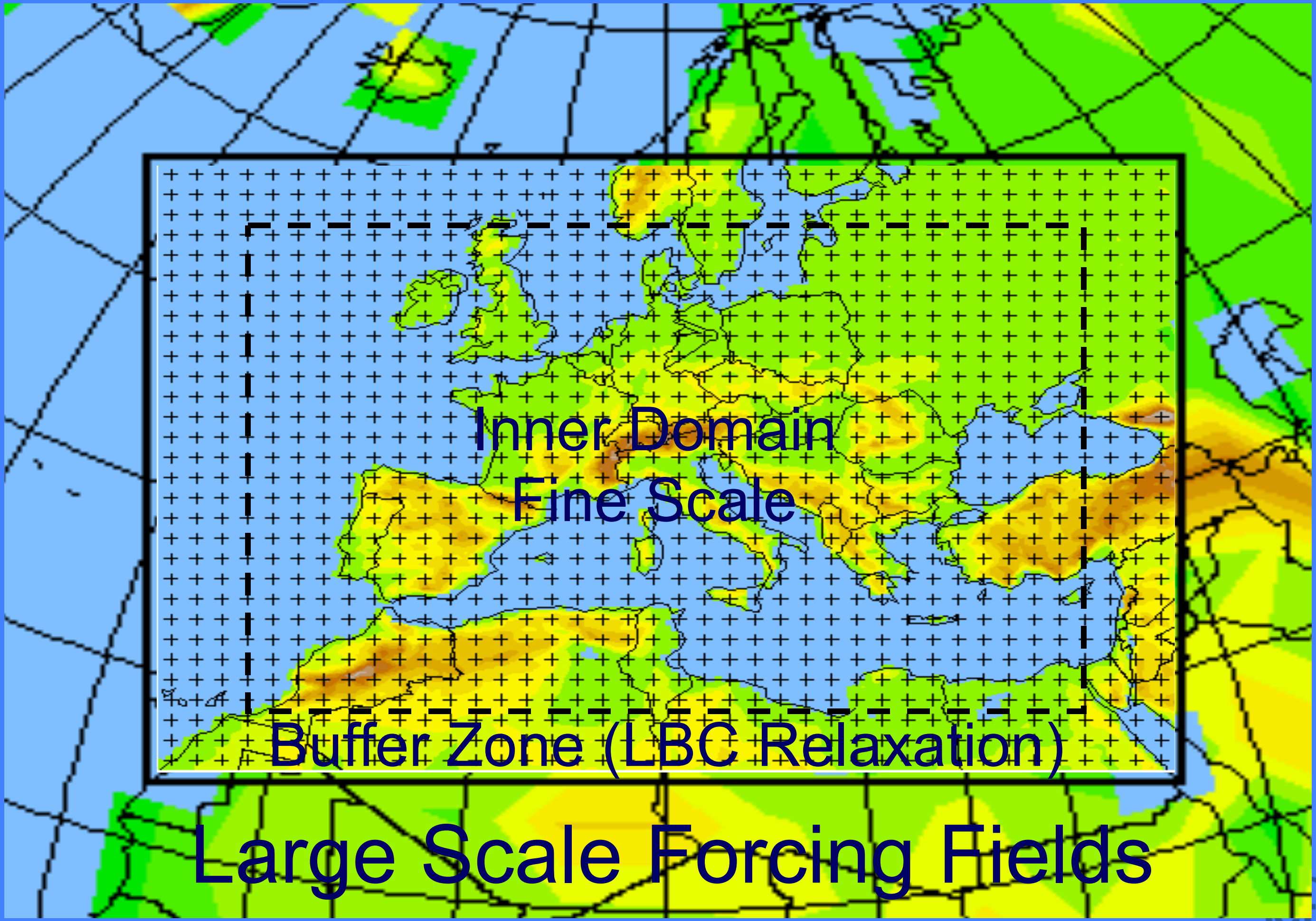
Strategy: The GCM simulates the response of the general circulation to the large scale forcings, the RCM simulates the effect of sub-GCM-grid scale forcings and provides fine scale regional information

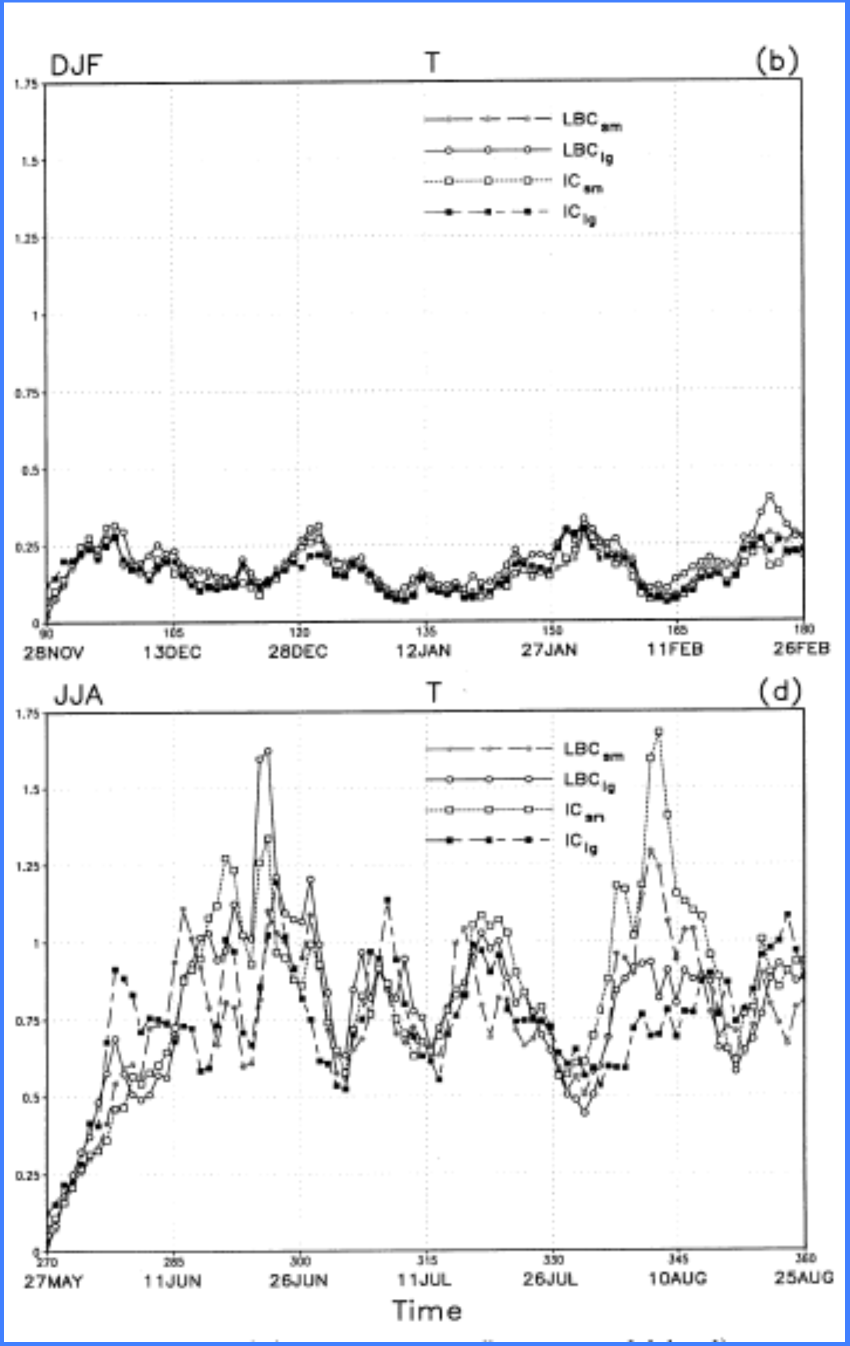
– Technique borrowed from NWP



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

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
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 10-50 km grid interval)

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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 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 - 30 km;
- Upgrade to non-hydrostatic, cloud-resolving frameworks under way in most models
- Decadal to centennial simulations the “accepted standard”
- Virtually all regions of the World have been simulated
- Some two-way nested experiments have been carried out
- Wide range of applications
  - Process studies, paleoclimate, climate change, seasonal prediction, impacts, climate-aerosol interactions,air-sea feedbacks, land-atmosphere feedbacks

Regional Climate Modeling Issues
Assimilation of LBC

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

Regional Climate Modeling Issues

Internal variability

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

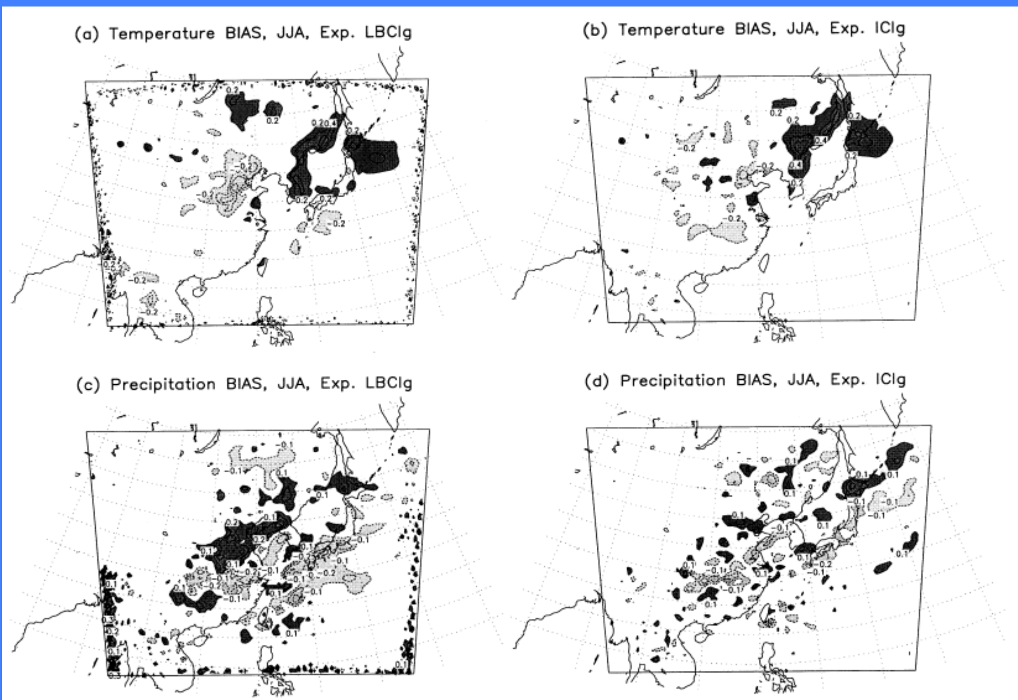


Figure 10. Bottom model level temperature (K) and precipitation (mm/day) BIAS for the LBC_{lg} and IC_{lg} perturbation experiments (not including the first 15 days of simulation). Season is JJA. (a) Temperature BIAS, Exp. LBC_{lg}; (b) temperature BIAS, Exp. IC_{lg}; (c) precipitation BIAS, Exp. LBC_{lg};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

Regional Climate Modeling Issues
"Garbage in, garbage out"

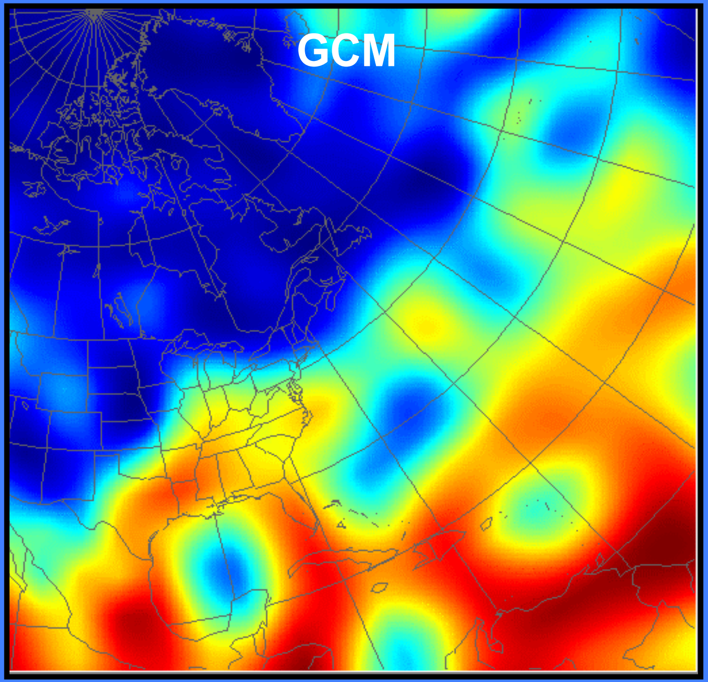
- RCMs are not intended to strongly modify the large scale circulation features in the forcing (GCM) fields
  - Failure of this condition might lead to inconsistencies at the lateral boundaries
- Due to the LBC forcing, large scale circulations are generally similar in the nested RCM and driving GCM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

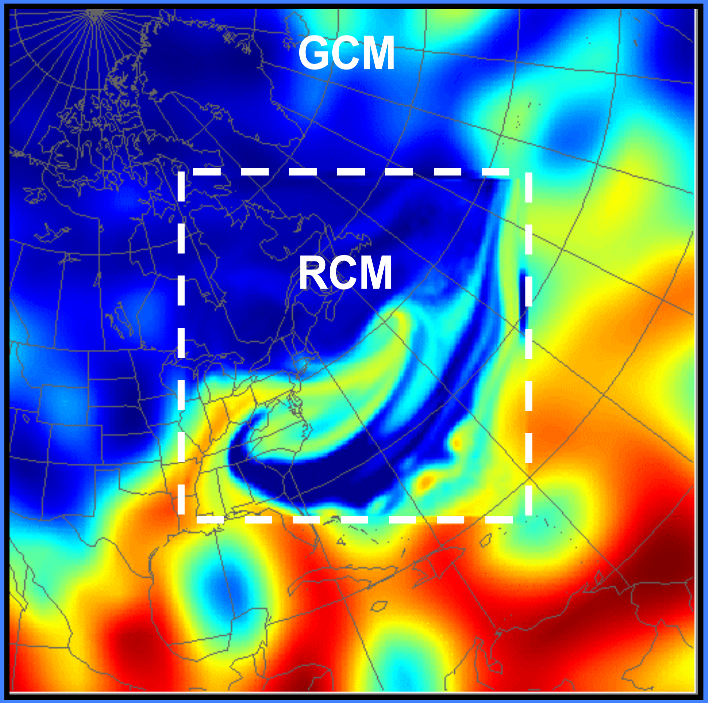
Regional Climate Modeling Issues
"Added value"

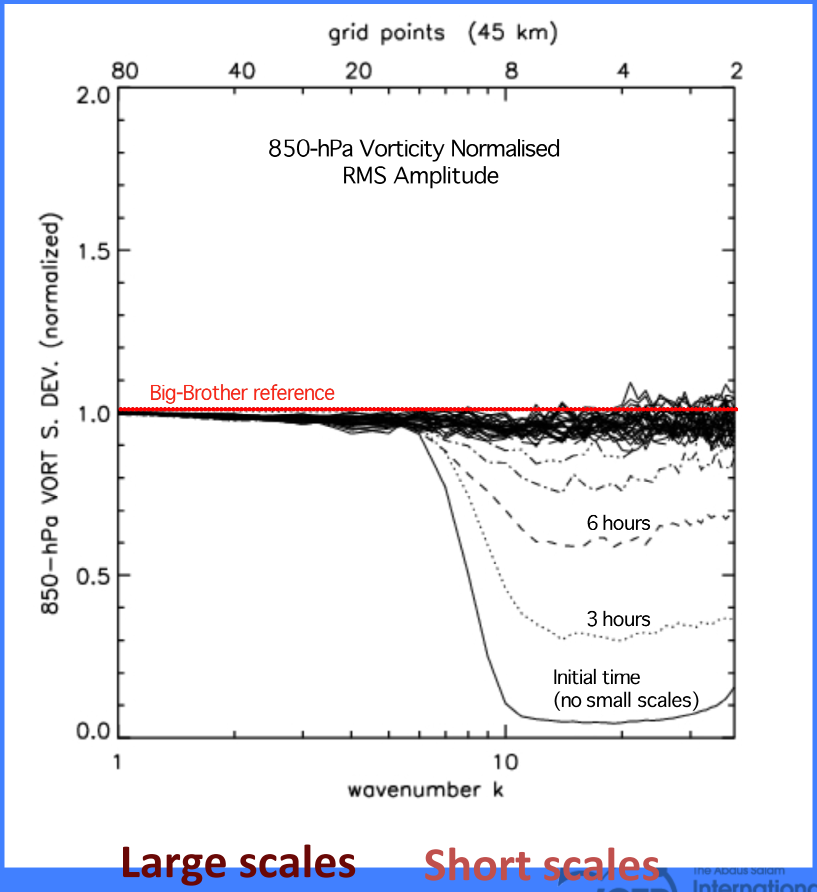
- What is the "added value" of the use of an RCM for our research problem?
- Increased resolution compared to the driving GCM
  - Fine scale forcings (e.g. topography)
  - Mesoscale circulations
- Tool for process studies
  - Aerosol effects, land-atmosphere interactions, regional feedbacks, circulations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

Dynamical Downscaling

Generation of small scales by a high-resolution RCM driven by low-resolution GCM data (900 hPa specific humidity)





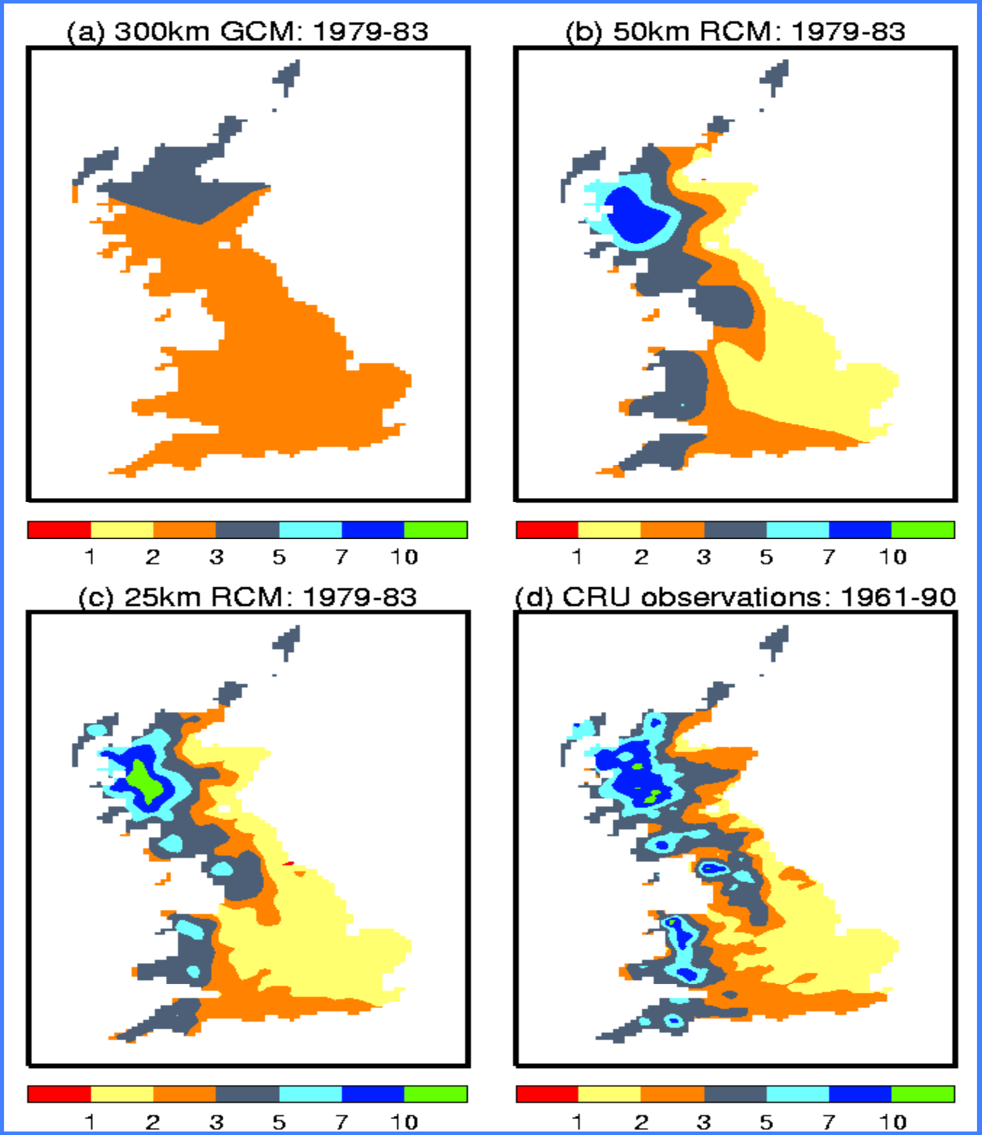


ADDED Value: Topographical detail

Winter precipitation over Great Britain

300km Global Model

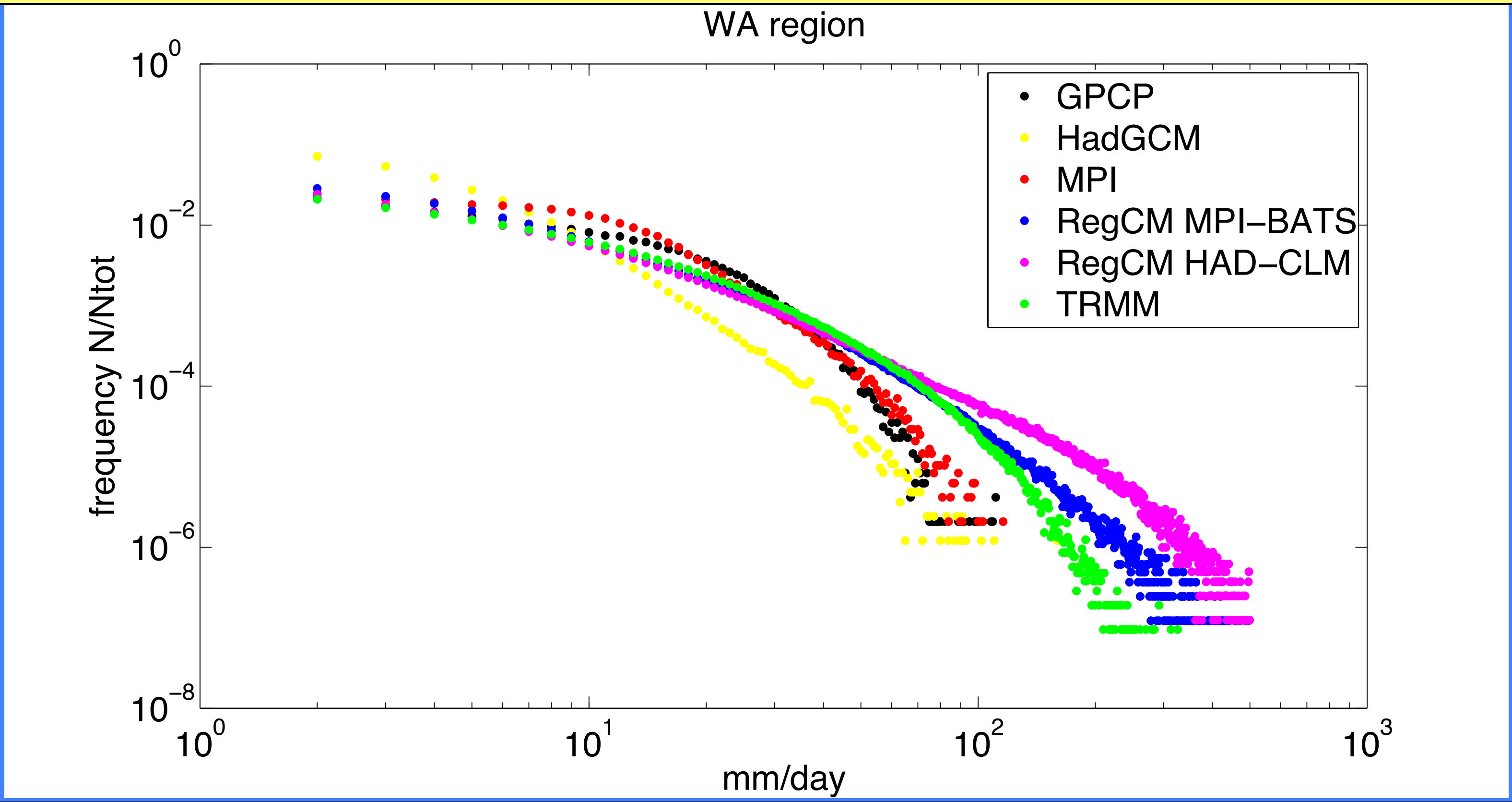
50km Regional Model



25km Regional Model

Observed

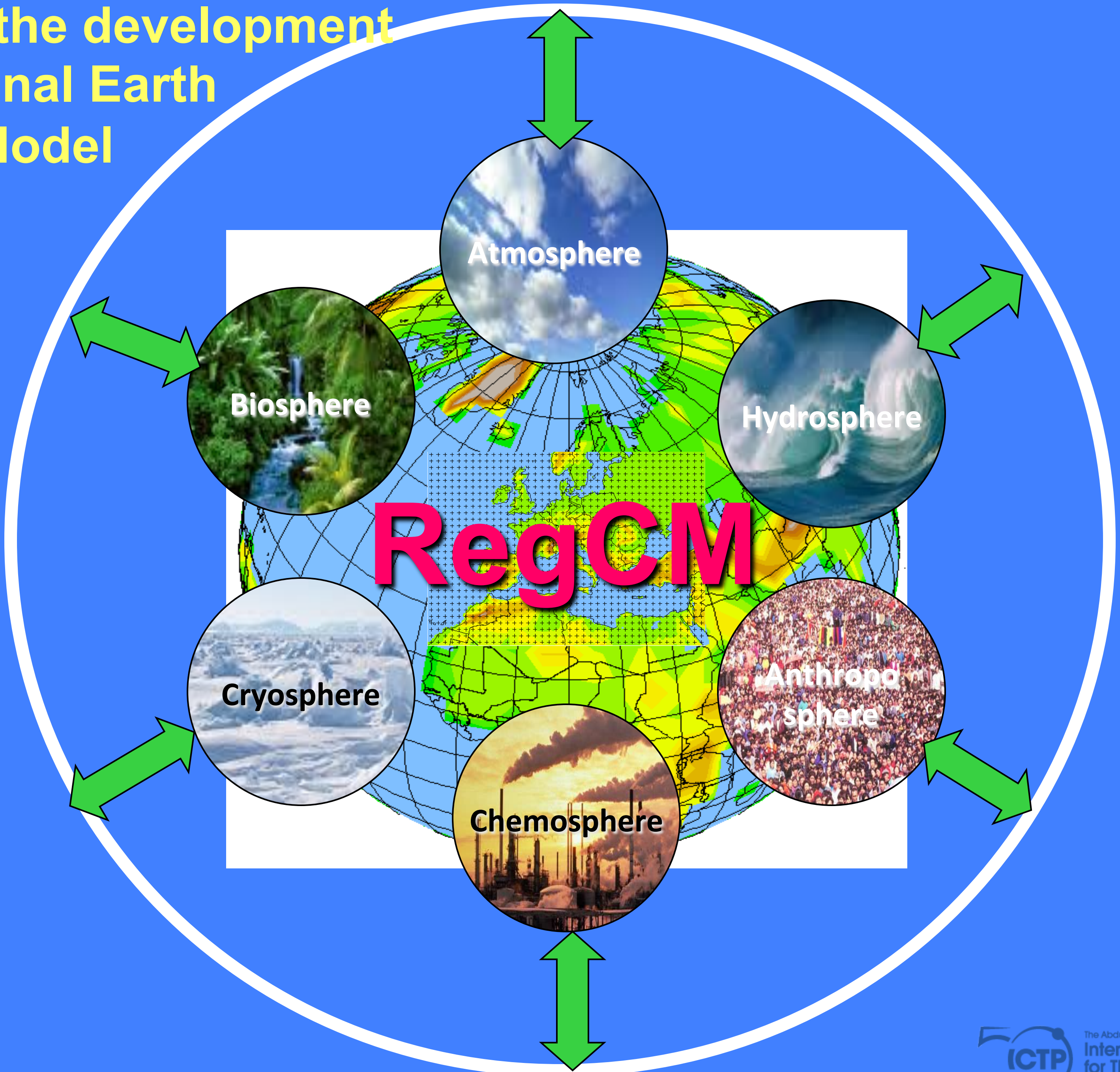
Added value: Extremes
Daily precipitation PDFs over West Africa



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 road to RegCM4 and beyond

Towards the development of a regional Earth System Model



The RegCM regional climate model system RegCM1 (1989)

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

The RegCM regional climate model system
RegCM2 (1993)

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

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The RegCM regional climate model system
RegCM2.5 (1999)

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

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

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

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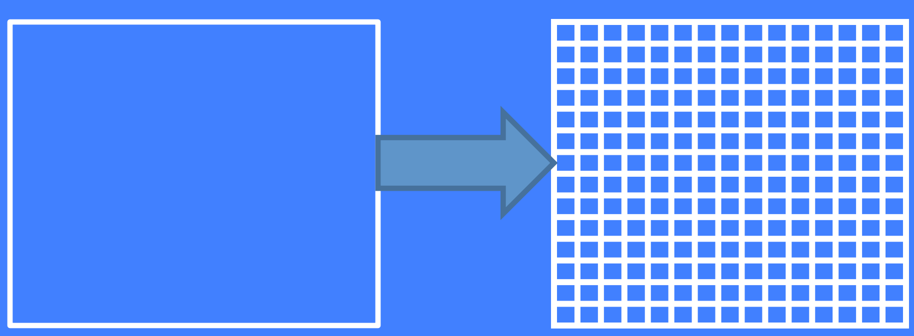
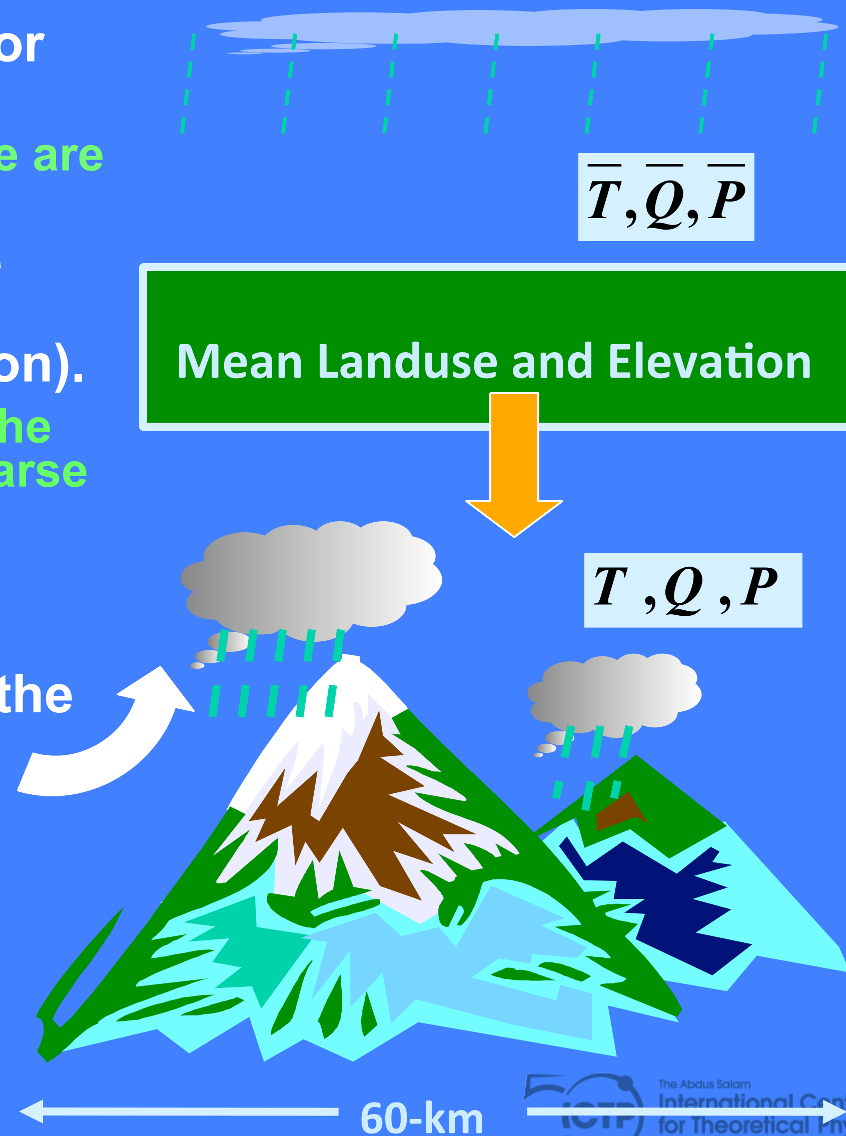
Land surface sub-grid model
Giorgi et al. (2003)

- **Define a regular fine scale sub-grid for each coarse scale model grid-box.**
  - **Landuse, topography, and soil texture are characterized on the fine grid.**
- **Disaggregate climatic fields from the coarse grid to the fine grid (e.g. temperature, water vapor, precipitation).**
  - **Disaggregation technique based on the elevation differences between the coarse grid and the fine grid.**
- **Perform BATS surface physics computations on the fine grid.**
- **Reaggregate the surface fields from the fine grid to the coarse grid.**



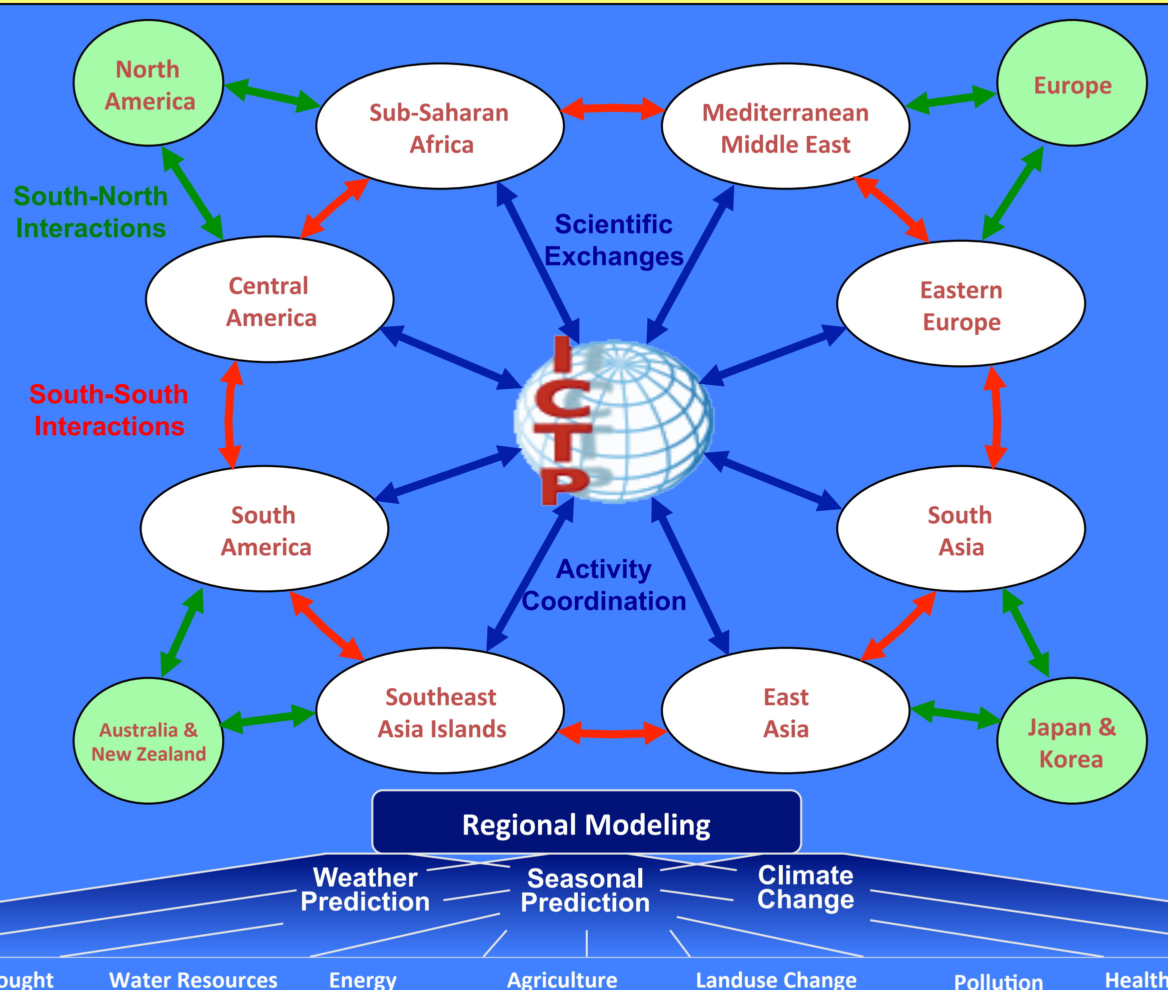


The ESP RegCM and Regional Climate research NETwork, RegCNET

Collaborative research projects

Use of ICTP model tools and datasets

Workshops at ICTP and on-site



E-mail list (over 800 p.)

Interactions with other international programs

Visitor program

The ICTP regional climate model system
RegCM4 (Giorgi et al. 2012, CR SI 2012)

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

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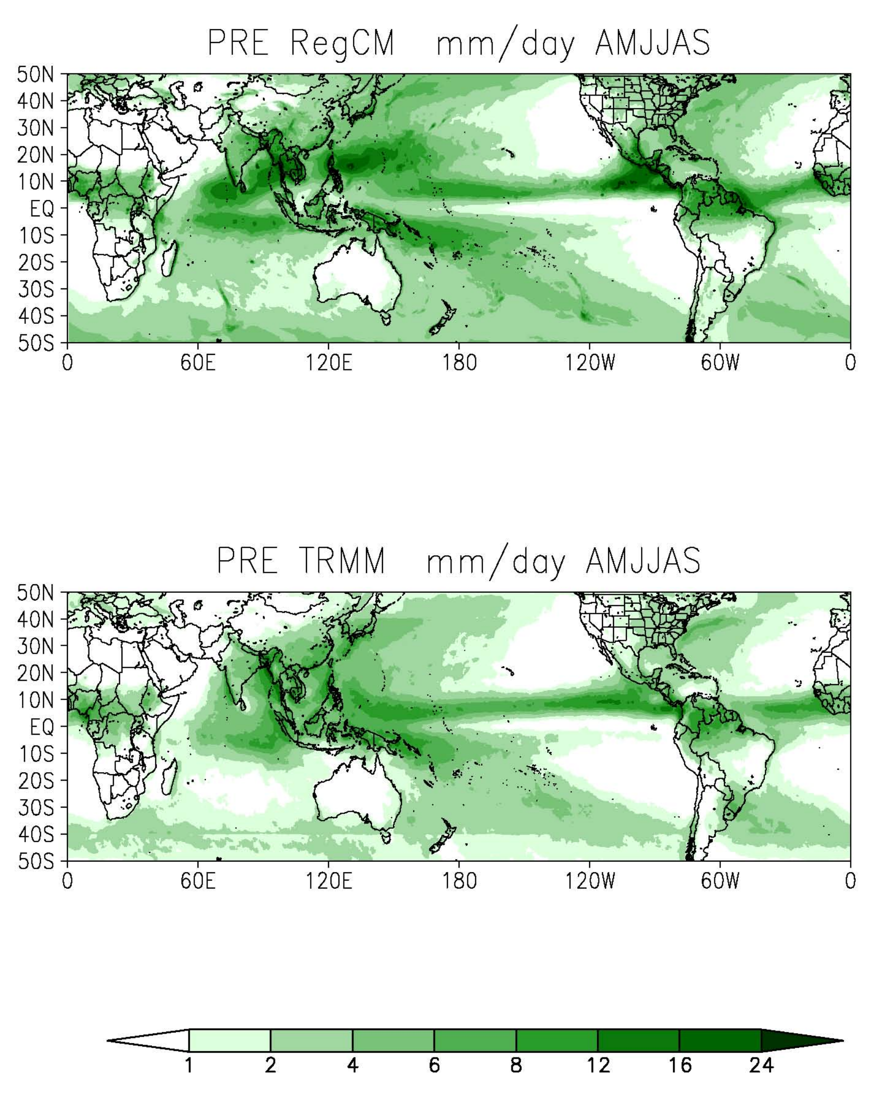
Tropical band configuration
(Coppola et al. 2012)



RegCM4

Precipitation
AMJJAS
1998-2002
ERA-Interim LBC

TRMM

The ICTP regional climate model system
RegCM4, coupled components

- **Coupled ocean**
  - **MIT ocean model (Artale et al. 2010)**
  - **ROMS (Ratnam et al. 2009)**
- **Interactive lake**
  - **1D thermal lake mode reactivated (Hostetler et al. 1994; Small et al. 1999)**
- **Interactive biosphere**
  - **Available in CLM but never tested**
- **Interactive hydrology**
  - **CHYM hydrological model available in "off line mode"**

- **Aerosols:**
  - OC-BC-SO4 (Solmon et al 2005)
  - Dust (Zakey et al 2006)
  - **Sea Salt (Zakey et al. 2009)**
- **Gas phase chemistry:**
  - **Various schemes and solvers tested**
  - **CBMZ + Sillmann solver implemented (Shalaby et al. 2012)**

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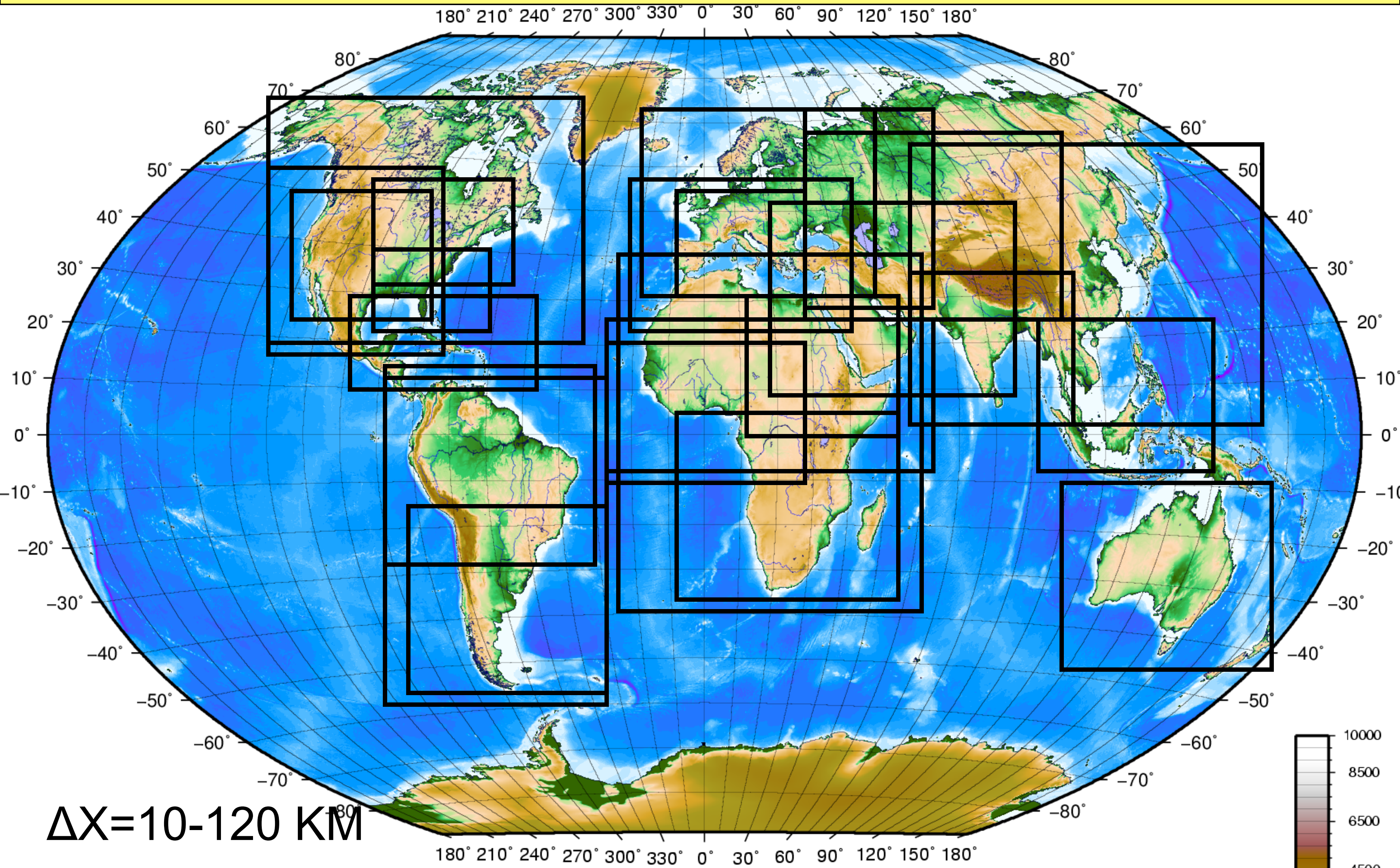
RegCM4: Climate Research Special Issue April 2012

- Fourteen papers using RegCM3 or RegCM4.
- Multiple regions
  - Africa, Europe, Mediterranean, East Asia, Central America, South America, Central Asia
- Range of resolutions (dx = 15 – 50 km)
- Multiple applications
  - Model validation
  - Parameterization testing
  - Climate change projections
  - Interactive aerosols
  - Coupled ocean

Updates to RegCM4 since 2012

- Cane-Fritsch cumulus convection scheme
- New cloud microphysics scheme
- CLM4.5 land surface scheme
  - Crops
  - Urban environments
  - Interactive vegetation
- “In house” coupling with MIT ocean model
- Implementation of MM5 non-hydrostatic dynamics under way

Sample of RegCM domains used

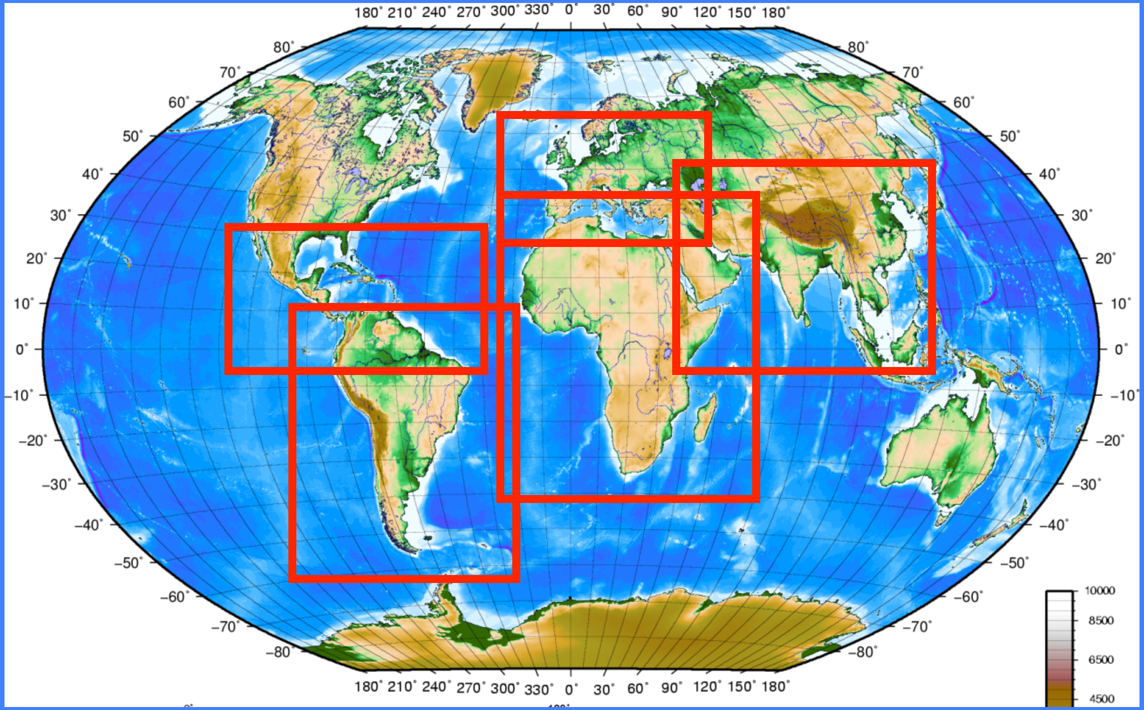


ΔX=10-120 KM

The RegCM regional climate model system
Participation to intercomparison projects

- PIRCS (US, ISU)
- NARCCAP (US, UCSC)
- PRUDENCE (Europe, ICTP)
- ENSEMBLES (Europe, ICTP)
- CECILIA (Central Europe, Central-Eastern European partners)
- AMMA (West Africa, ICTP, African partners)
- CLARIS (South America, U. Sao Paulo)
- RMIP (East Asia, CMA)
- CORDEX (Multiple domains, RegCNET)

The CORDEX RegCM hyper-MAtrix (CREMA) Phase I Experiment



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

CREMA Experiment set-up

- CORDEX domain specifications
- Simulation period
  - 1970-2100
  - Reference: 1976-2005
- Greenhouse gas scenarios
  - RCP8.5, RCP4.5
- Driving GCMs
  - HadGEM2-ES
  - MPI-ESMMR
  - GFDL-ESM
- Observations
  - CRU, GPCP, TRMM

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ICTP Regional Climate Model
CREMA Parameterization tested

- **Dynamics:**
  Hydrostatic (Giorgi et al. 1993a,b)
  Adaptable to any region
  Non-hydrostatic in progress
- **Radiation:**
  CCM3 (Kiehl 1996)
- **Large-Scale Clouds & Precipitaion:**
  SUBEX (Pal et al 2000)
- **Cumulus convection:**
  Grell (1993)
  Anthes-Kuo (1977)
  MIT (Emanuel 1991)
  Mixed convection
  Tiedtke (in progress)
- **Planetary boundary layer:**
  Modified Holtslag, Holtslag (1990)
  UW-PBL (O' Brien et al. 2011)
- **Land Surface:**
  BATS (Dickinson et al 1993)
  SUB-BATS (Giorgi et al 2003)
  CLM (Oleson et al. 2008)
- **Ocean Fluxes**
  BATS (Dickinson et al 1993)
  Zeng (Zeng et al. 1998)
  Diurnal SST
- **Configuration**
  Adaptable to any region
  Tropical belt configuration
- **Extensive code remake**

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Special Issue of Climate Change 2014

- Coppola et al.
  - Basic analysis of change and biases
- Giorgi et al.
  - Hydroclimatic extremes
- Diro et al.
  - Central America + Tropical storms
- Mariotti et al.
  - Changes in African monsoon
- Dash et al.
  - Weakening of the India monsoon
- Llopart et al.; Da Rocha et al.
  - Climate-land surface feedbacks over S. America
- Guttler et al.
  - Sensitivity of change signal to physics schemes

CREMA in numbers

- 200 Tera of data on the archives
- 1 year of simulation on a dedicated cluster (1000 processors)

WHAT HPC can help us for?

- model optimization
- higher scalability
- shorter simulation time

Picture from University of Bristol, U.K.