Capabilities and Limitations of Regional Climate Modeling for Hydrological Impact Analysis

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Motivation

Stakeholders demand delineation of climate change adaptation strategies

- Flood protection measures (adaptation of infrastructure)
- Future hydropower potential (low flows)
- Water availability for agriculture
- Tourism (Skiing…)

Requirements in hydrological climate change impact investigations

- High resolution spatial and temporal distribution of future temperature & precipitation

How well are current regional climate predictions suited for that purpose?

Joint Atmosphere & Terrestrial Hydrology Analysis

Atmosphere is primary driver of hydrological processes: brief review

- Spatial and temporal distribution of precipitation and temperature
- Global warming impacts water vapor carrying capacity & evaporation/condensation
- Projections of future terrestrial water availability must consider future atmospheric state
- Close linkage atmosphere, precipitation & land surface:
  energy & water fluxes at land surface: latent & sensible heat fluxes
  terrain elevation: e.g. precipitation generation by orographic blocking
  soil: long term memory of previous precipitation & temperature
- **Interlinked atmosphere & land surface process description & analysis necessary**

Climate Modeling: Looking into the Future…

Population Growth Economic Development
Technological Progress

⇩

Emission Scenarios
Greenhouse Gas Concentrations

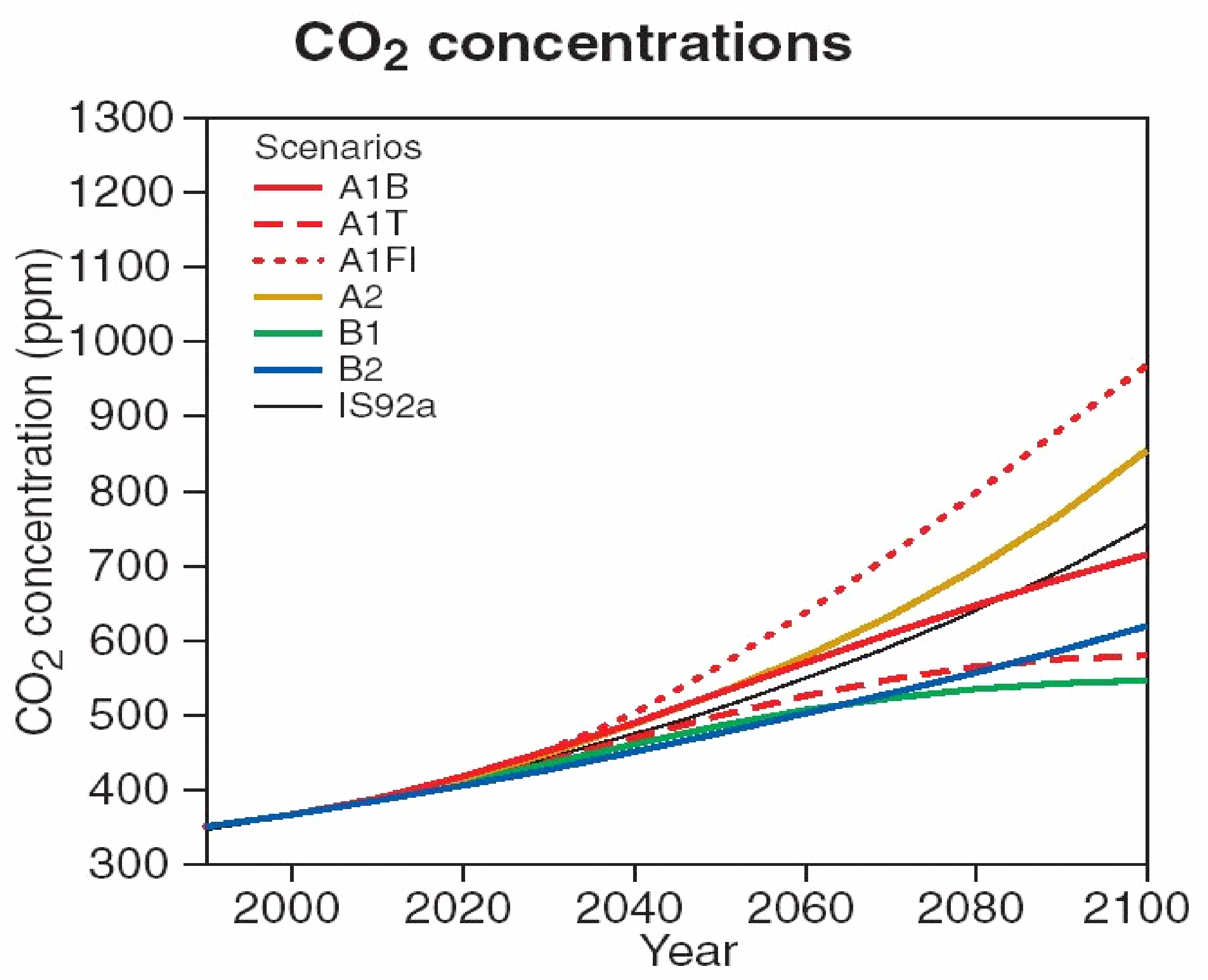
⇩

Global Climate Models

⇩

Global Climate Scenarios

Climate Modeling: Looking into the Future…



From Global to Regional Climate Modeling

Global climate models

- physically based (e.g. conservation laws for energy, momentum, water/humidity variables)
  but: parameterizations for subgridscale processes (turbulence, convective precipitation, …)

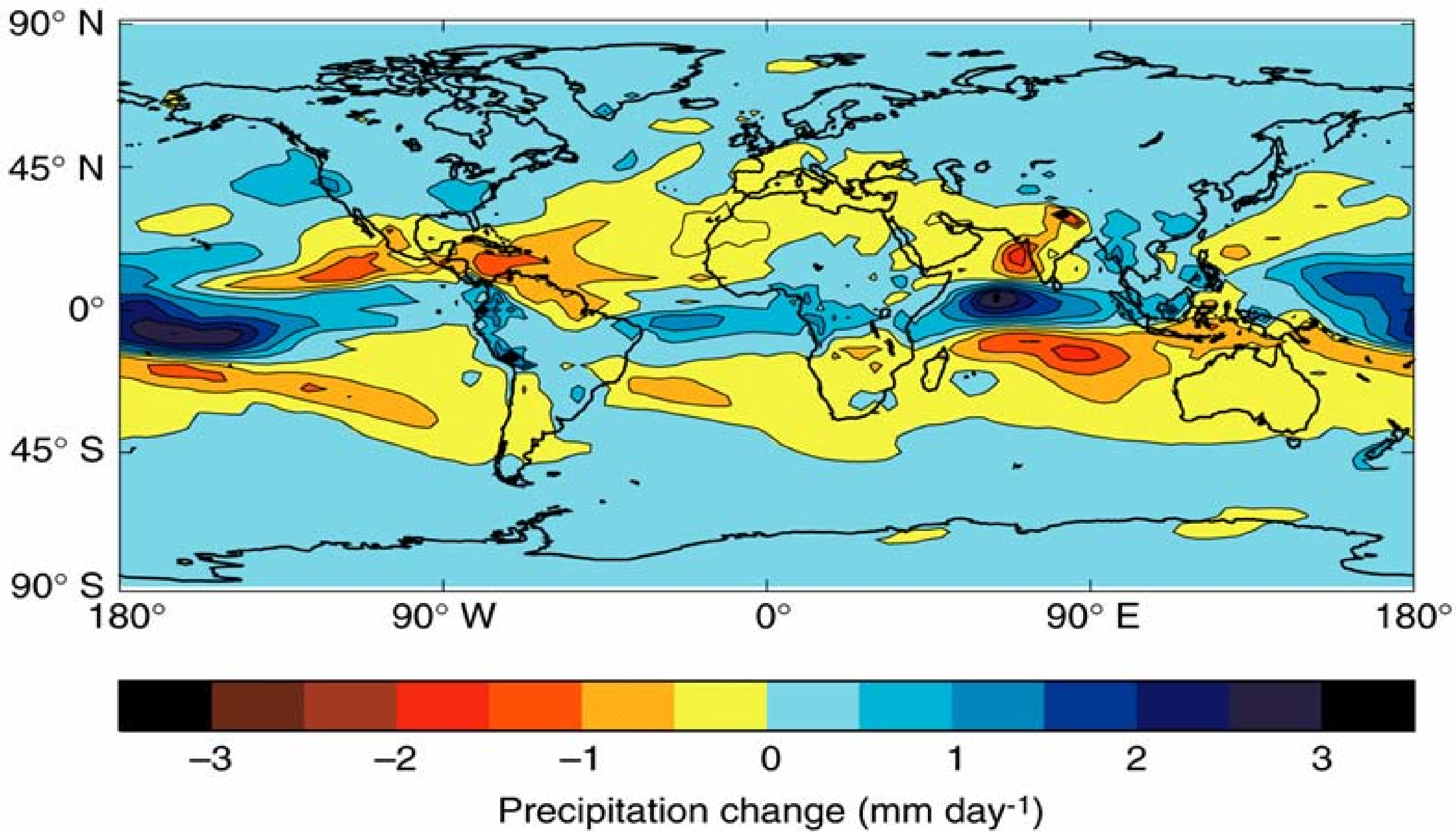
- resolution usually ≈ 100-300 km

- designed to reproduce & project global trends

- limited potential for regional analysis

Climate Modeling: Looking into the Future…

Global Climate Scenarios:
Projected Changes in Annual Precipitation for the 2050s



Hadley Centre for Climate Prediction and Research

⇒ **Resolution too coarse for regional impact analysis !**

Climate Modeling: Looking into the Future…

Population Growth Economic Development
Technological Progress

⇩

Emission Scenarios
Greenhouse Gas Concentrations

⇩

Global Climate Models

⇩

Global Climate Scenarios

⇩

Downscaling Methods

⇩

Regional Climate Scenarios

Regionalization Techniques

Statistical downscaling

- statistical relations between large scale forcing & station observed variables
- e.g. via multiple regression, canonical correlation analysis, circulation pattern analysis
- computationally efficient
- climate change information derived only at station locations
- gridded fields obtained by spatial interpolation between station locations
- persistence of statistical relations under changing climate conditions assumed

Regionalization Techniques

Dynamical downscaling

- 3-dim regional atmospheric models (RCM) based on
  conservation laws, physical relations, parameterizations for subgridscale processes

- nested approach: global model provides lateral boundaries of regional model

- computationally expensive

- examples: *nonhydrostatic* CLM, MM5, WRF
  hydrostatic REMO, RegCM, HIRHAM, PRECIS

- usually coupled atmosphere-land surface modeling systems

Regional Climate Modeling

Momentum conservation

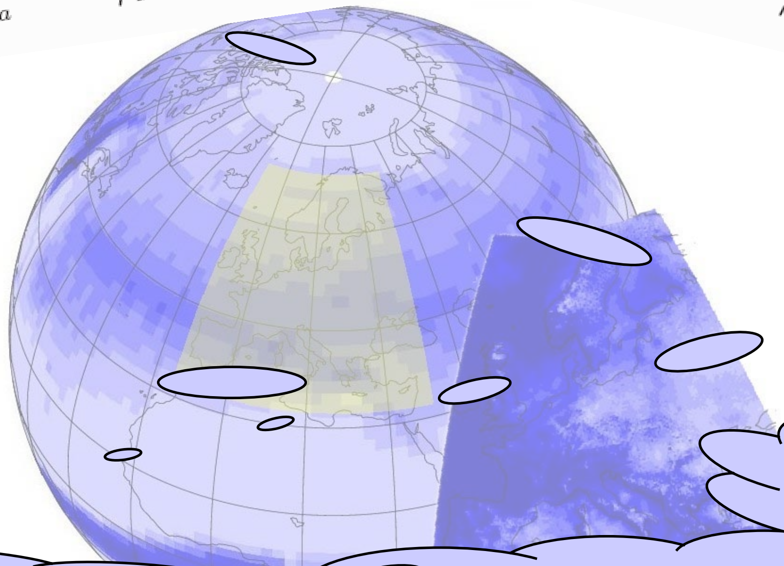
$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\,\vec{v} = -f\vec{k}\times\vec{v} - \nabla\Phi - \frac{1}{\rho_a}\nabla p_a + \frac{\eta_a}{\rho_a}\nabla^2\vec{v} + \frac{1}{\rho_a}(\nabla\cdot\rho_a\mathbf{K_m}\nabla)\,\vec{v}$$

Energy conservation

$$\frac{\partial \theta_v}{\partial t} + (\vec{v}\cdot\nabla)\,\theta_v = \frac{1}{\rho_a}(\nabla\cdot\rho_a\mathbf{K_h}\nabla)\,\theta_v + \frac{\theta_v}{c_{p,d}T_v}\sum_{n=1}^{N}\frac{dQ_n}{dt}$$

Gas law

$$p = \frac{nR^*T}{V}$$



Air mass conservation

$$\frac{\partial \rho_a}{\partial t} + \nabla\cdot(\vec{v}\rho_a) = 0$$

Conservation water mass

$$\frac{\partial q_v}{\partial t} + (\vec{v}\cdot\nabla)\,q_v = \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_v + R_{evap} - R_{cond} - R_{iini} - R_{idep/sub}$$

$$\frac{\partial q_c}{\partial t} + (\vec{v}\cdot\nabla)\,q_c = \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_c + R_{cond} + R_{iini} + R_{idep/sub} - R_{aconv} - R_{accr}$$

$$\frac{\partial q_r}{\partial t} + (\vec{v}\cdot\nabla)\,q_r = \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_r - R_{evap} + R_{aconv} + R_{accr} - \frac{\partial V_f\rho_a g q_r}{\dots}$$

Energy conservation at land surface

$$L_vE + H + G = SW_{net} + LW_{net} = (1-\alpha)SW\downarrow + LW\downarrow - \epsilon\,\sigma_B\,T^4_{\dots}$$

Soil temperature diffusion

$$C(\Theta)\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z}\left[K_t(\Theta)\frac{\partial T_s}{\dots}\right]$$

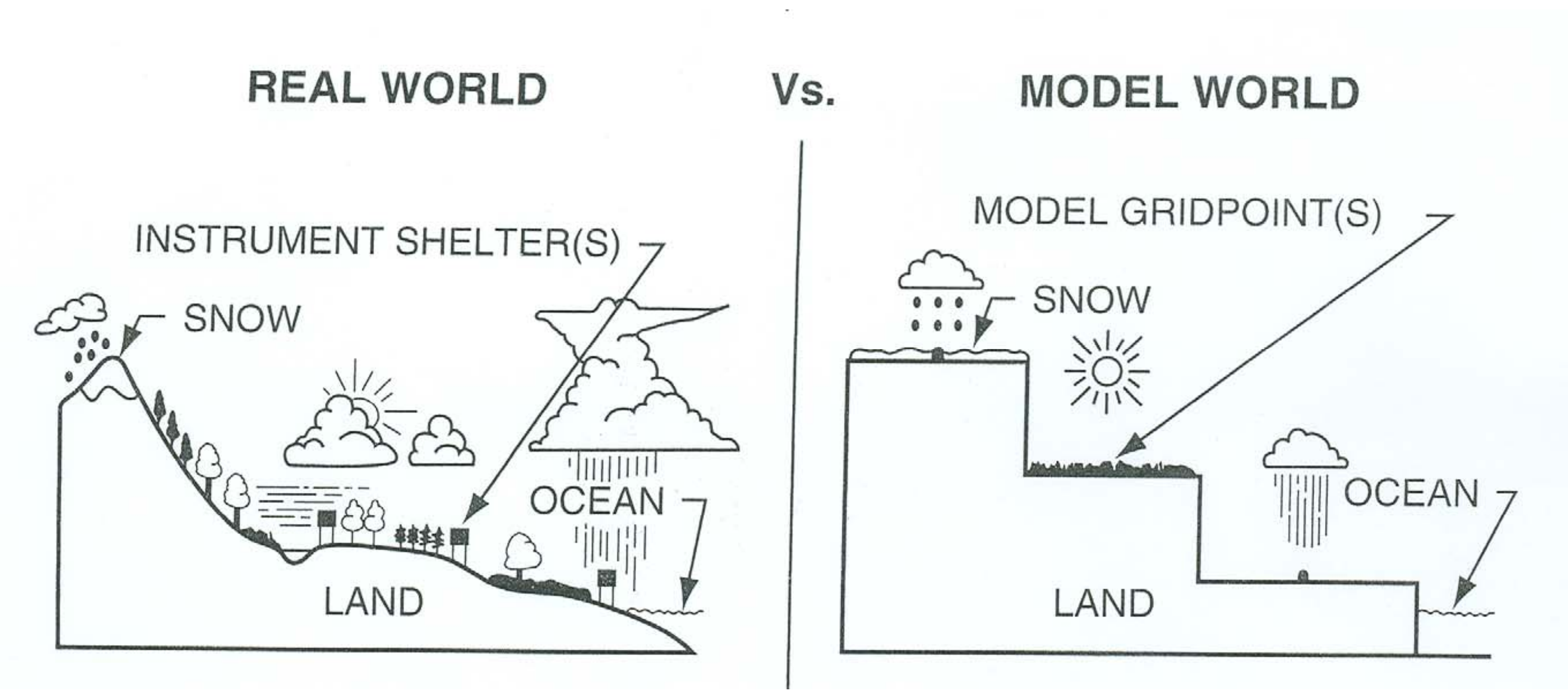
Precipitation physics

$$R_{evap\ (rain)} = \frac{2\pi N_{0r}(S_w-1)}{A_r+B_r}\left[\frac{0.78}{\Lambda_r^2} + 0.32\left(\frac{a_r\rho}{\eta_a}\right)^{1/2} S_c^{1/3}\frac{\Gamma(5/2+b_r/2)}{\Lambda_r^{5/2+b_r/2}}\right]$$

Soil water infiltration

$$\frac{\partial\Theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\Theta)\frac{\partial\Theta}{\partial z}\right] + \frac{\partial k(\Theta)}{\partial z}$$

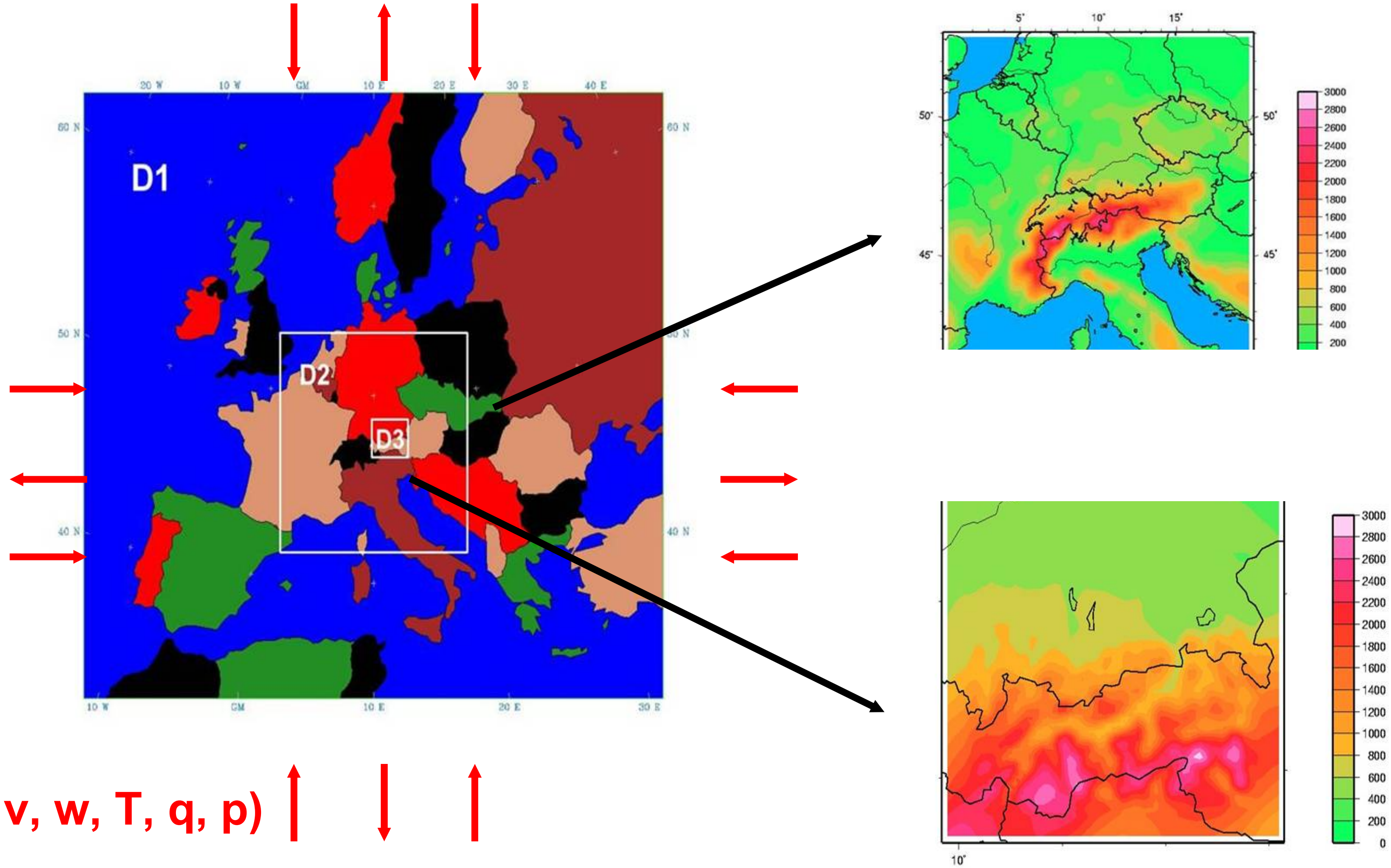
Regional Climate Modeling



Dynamical Downscaling: Nested Simulations

RCM: forced by global model (boundary- & initial value problem)

High spatial resolution ⇒ detailed consideration of elevation



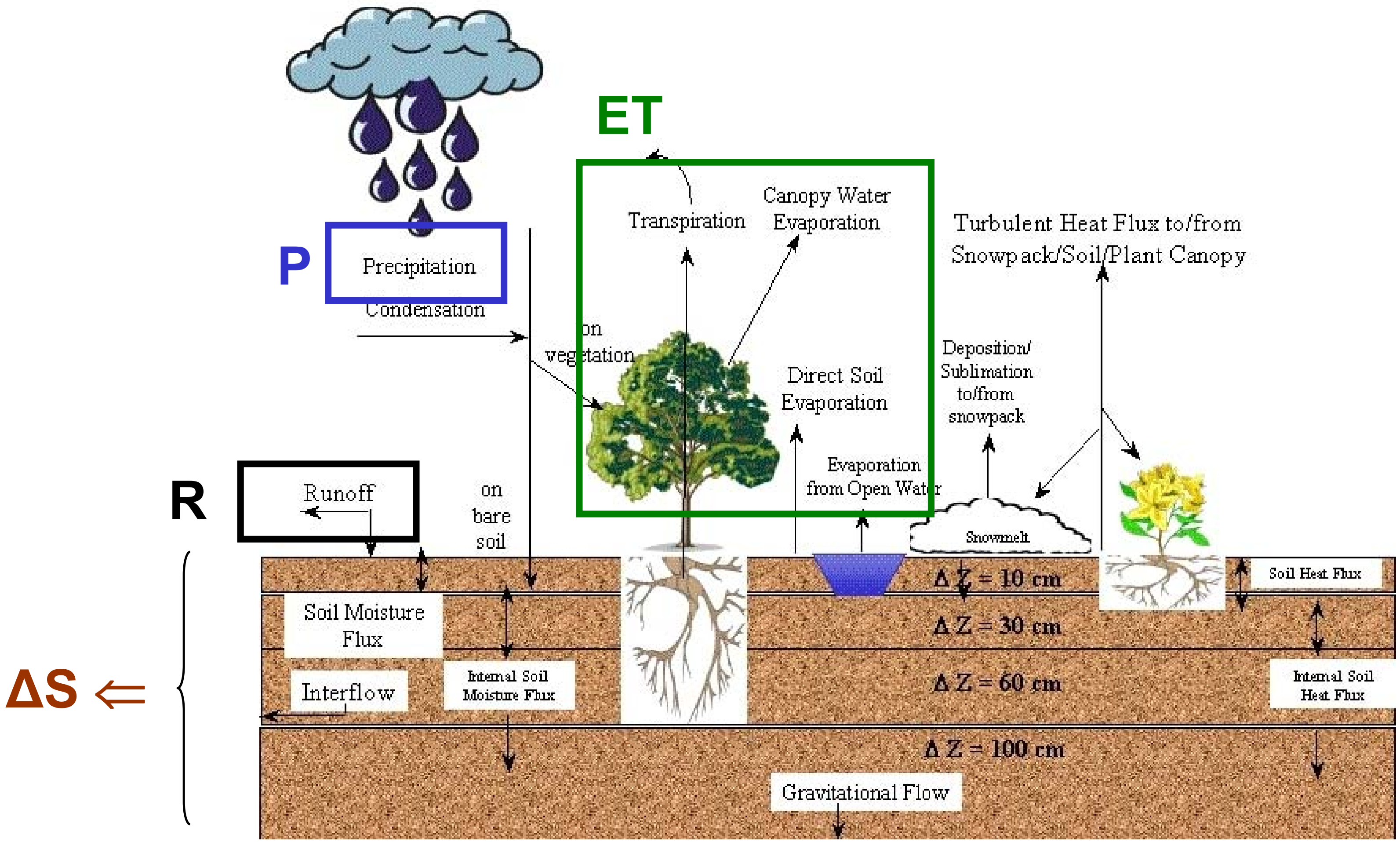
Elevation in 20x20 km^2 resolution

Elevation in 4x4 km^2 resolution

(u, v, w, T, q, p)

Land Surface Processes in Regional Climate Models

Dynamical downscaling: SVAT model as lower boundary at every grid point



Soil-Vegetation-Atmosphere-Transfer (SVAT) Model

SVAT-Models vs. Traditional Hydrological Models

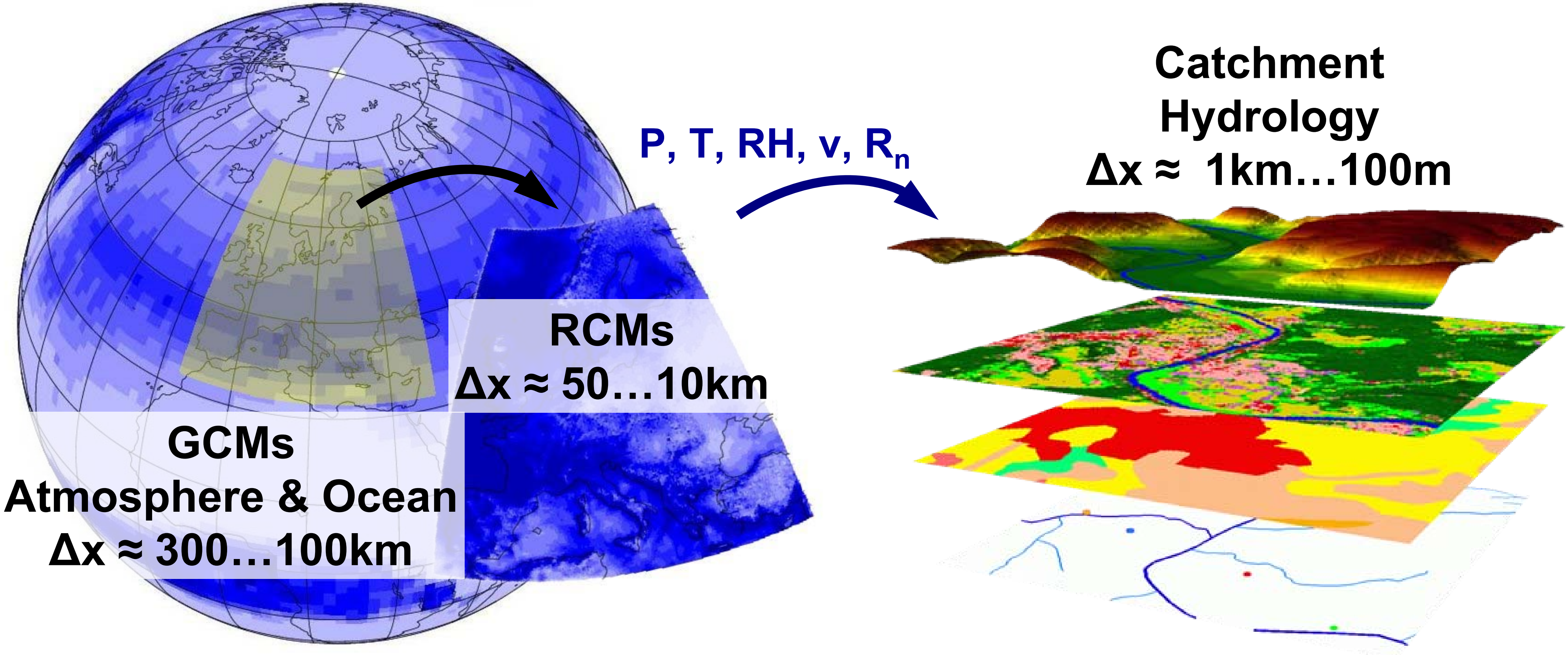
SVAT- hydro models (designed for atmospheric feedback purposes)

- full energy balance (soil heat & sensible heat fluxes)
- 2-way interaction with PBL
- focus on vertical water fluxes (soil moisture, ET)

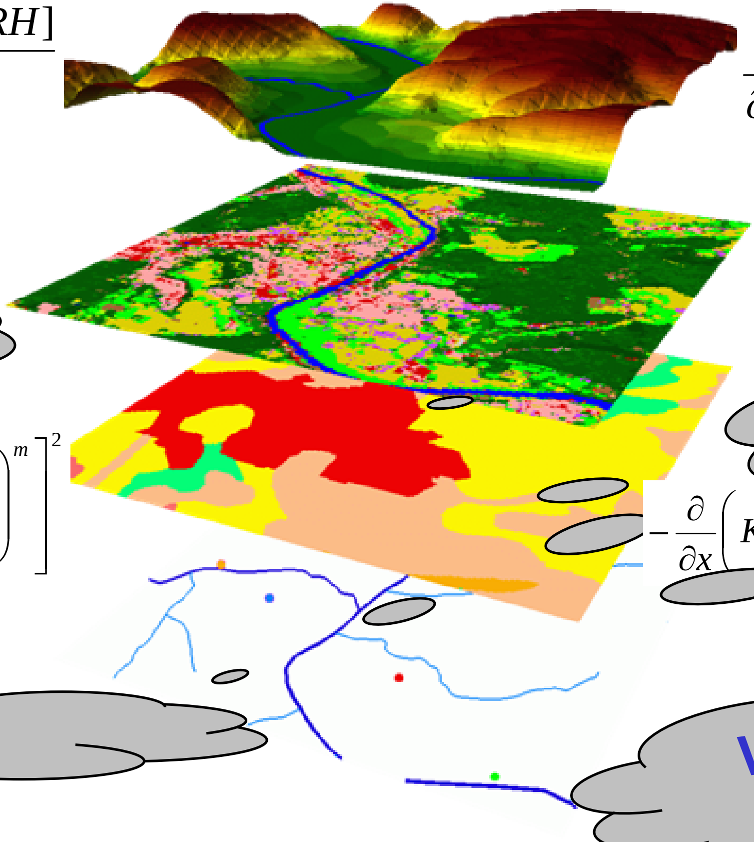
“Traditional”- hydro models (designed for pure hydrological applications):

- vertical + lateral water fluxes, surface runoff routing
- deeper soils considered, finer vertical & horizontal resolutions
- often groundwater interaction, often extensions for reactive flow & transport, erosion, etc.
- **but of course: depending on specific model choice**

Joint Regional Climate – Hydrology Modeling



Regional Hydrological Modeling



Evapotranspiration

$$E = \frac{s(T_a)[K+L] + \gamma K_E \rho_w \lambda_v v_a e_{sat}(T_a)[1-RH]}{\rho_w \lambda_v [s(T_a)+\gamma]}$$

Infiltration

$$\frac{\partial}{\partial z'}\left(K_h(\theta)\frac{\partial \Psi(\theta)}{\partial z'}\right) - \frac{\partial K_h(\theta)}{\partial z'} = \frac{\partial \theta}{\partial t}$$

Conductivity

$$K_h(\theta) = K_{h,sat}\sqrt{\frac{\theta-\theta_{res}}{\phi-\theta_{res}}}\left[1-\left(1-\left(\frac{\theta-\theta_{res}}{\phi-\theta_{res}}\right)^{1/m}\right)^m\right]^2$$

Groundwater Flow

$$-\frac{\partial}{\partial x}\left(K_{hx}\frac{\partial h}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_{hy}\frac{\partial h}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_{hz}\frac{\partial h}{\partial z}\right) + R = -S_s\frac{\partial h}{\partial t}$$

Routing

$$v_h = M\left(\frac{Q_h / v_h}{B_h + \frac{2Q_h}{v_h\, B_h}}\right)^{2/3}\sqrt{I}$$

Wave Retention

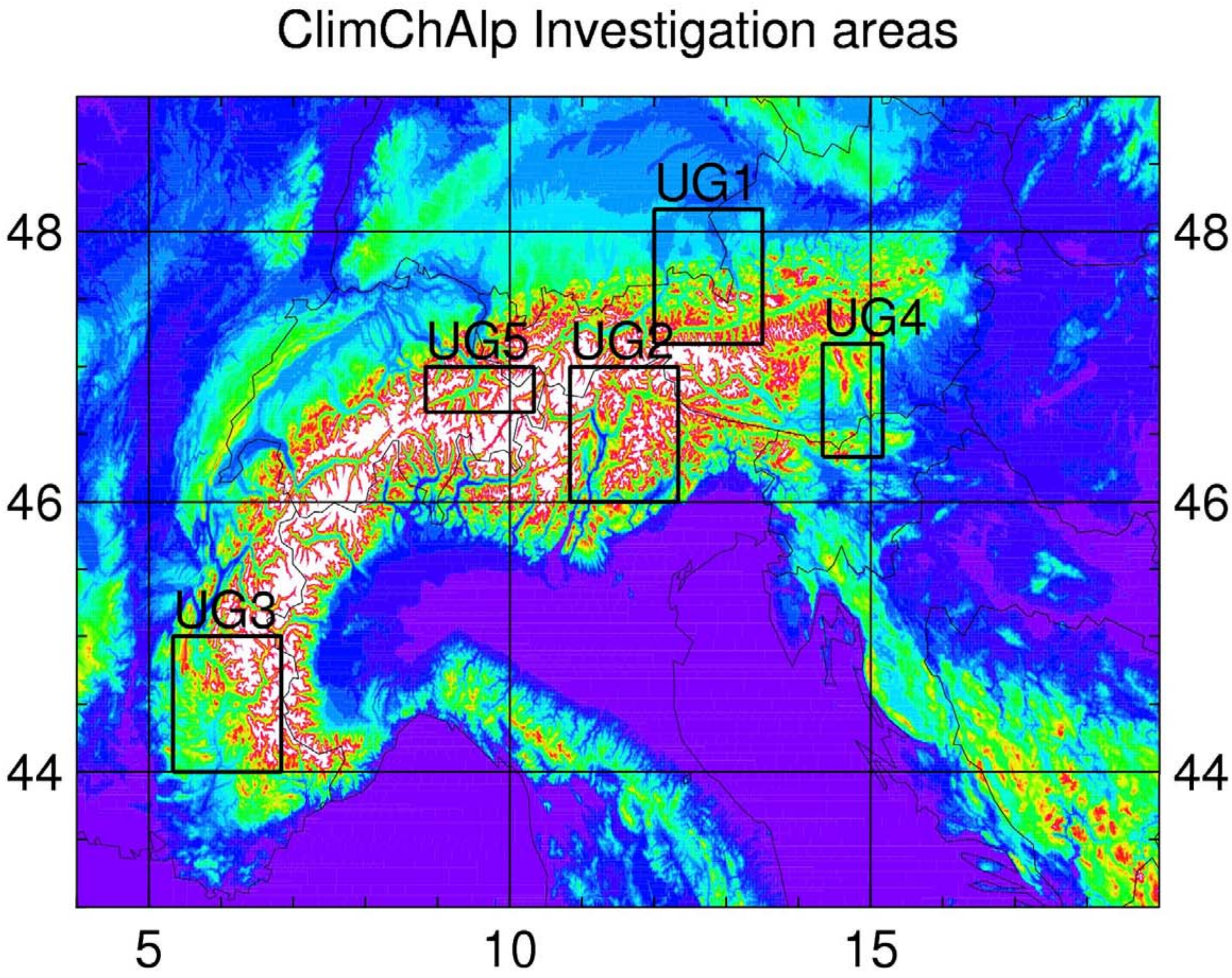
$$Q_{out} = \left(Q_{v,t-1}\cdot e^{-\Delta t/k_v} + Q_{v,t}\cdot(1-e^{-\Delta t/k_v})\right) + \left(Q_{h,t-1}\cdot e^{-\Delta t/k_h} + Q_{h,t}\cdot(1-e^{-\Delta t/k_h})\right)$$

Δx, Δy = 100m-1km, Δt =1h-1d

How well do RCMs reproduce observed climate?

An example from the Alps

Investigation Areas



Greater Alpine Region (GAR)

Available High Resolution Data (Δx < 20km)

SRES	GCM	RCM	SDM	Ensembles
SRES B1	ECHAM5	CLM		2?
	ECHAM5	REMO		1
	PCM		TYN	1
	Had3		TYN	1
	CSIRO2		TYN	1
	CGCM		TYN	1
SRES B2	Had3	RegCM		1
	PCM		TYN	1
	Had3		TYN	1
	CSIRO2		TYN	1
	CGCM		TYN	1
SRES A1B	ECHAM5	CLM		2?
	ECHAM5	REMO		1
SRES A1FI	PCM		TYN	1
	Had3		TYN	1
	CSIRO2		TYN	1
	CGCM		TYN	1
SRES A1	PCM		TYN	1
	Had3		TYN	1
	CSIRO2		TYN	1
	CGCM		TYN	1
SRES A2	Had3	HIRHAM		1
	Had3	ReGCM		1
	EGHAM5	REMO		1
	PCM		TYN	1
	Had3		TYN	1
	CSIRO2		TYN	1
	CGCM		TYN	1

CLM - Germany (2001-2100)
hourly data, Δx≈18km

HIRHAM - DMI, Denmark(2070-2099)
daily data in the Internet (PRUDENCE)
Δx≈13km

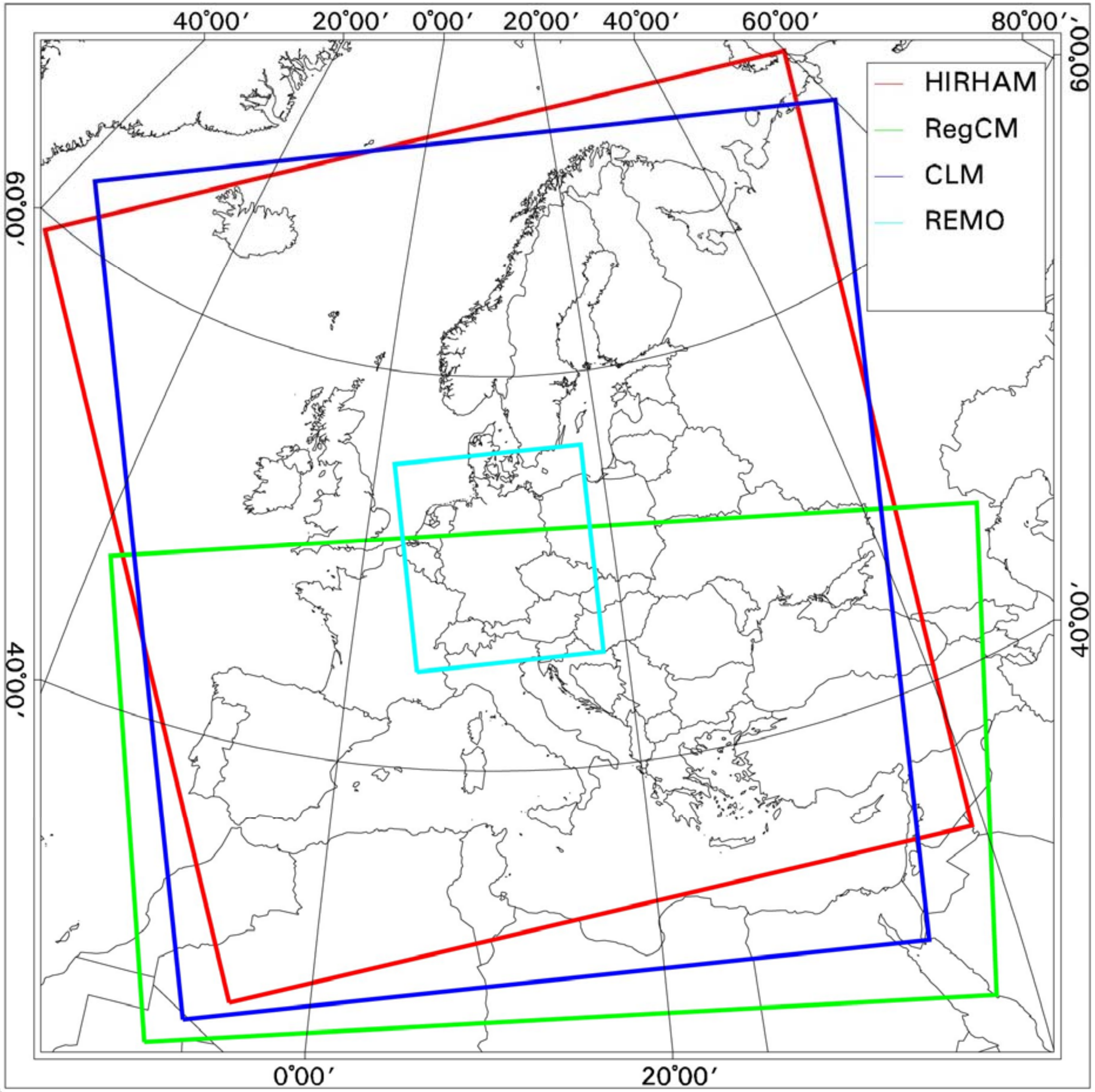
RegCM - ICTP, Italy (2070-2099)
daily data, Δx≈20km

REMO - MPI, Germany (2001-2100)
hourly data, Δx≈10km

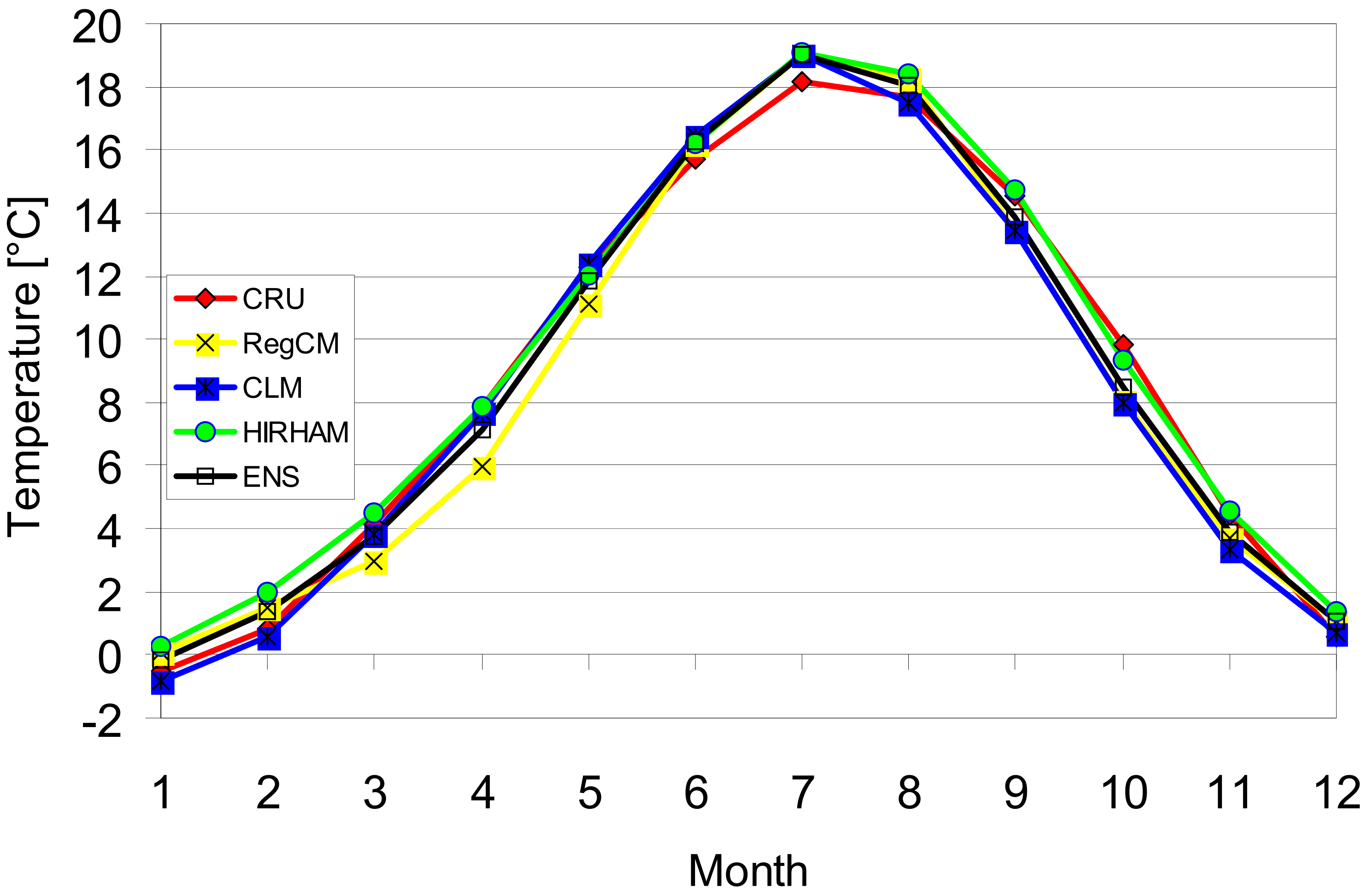
TYN – Tyndall Centre,UK, statistical downscaling

Different GCMs & different scenarios !

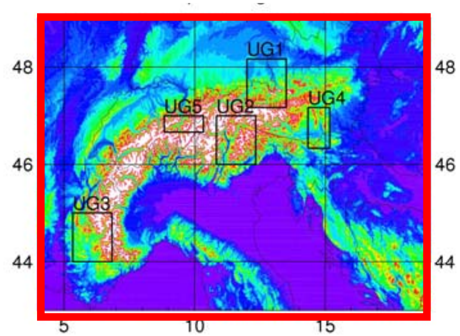
Extent of High Resolution Data



Performance Present Climate: GAR (Greater Alpine Region)



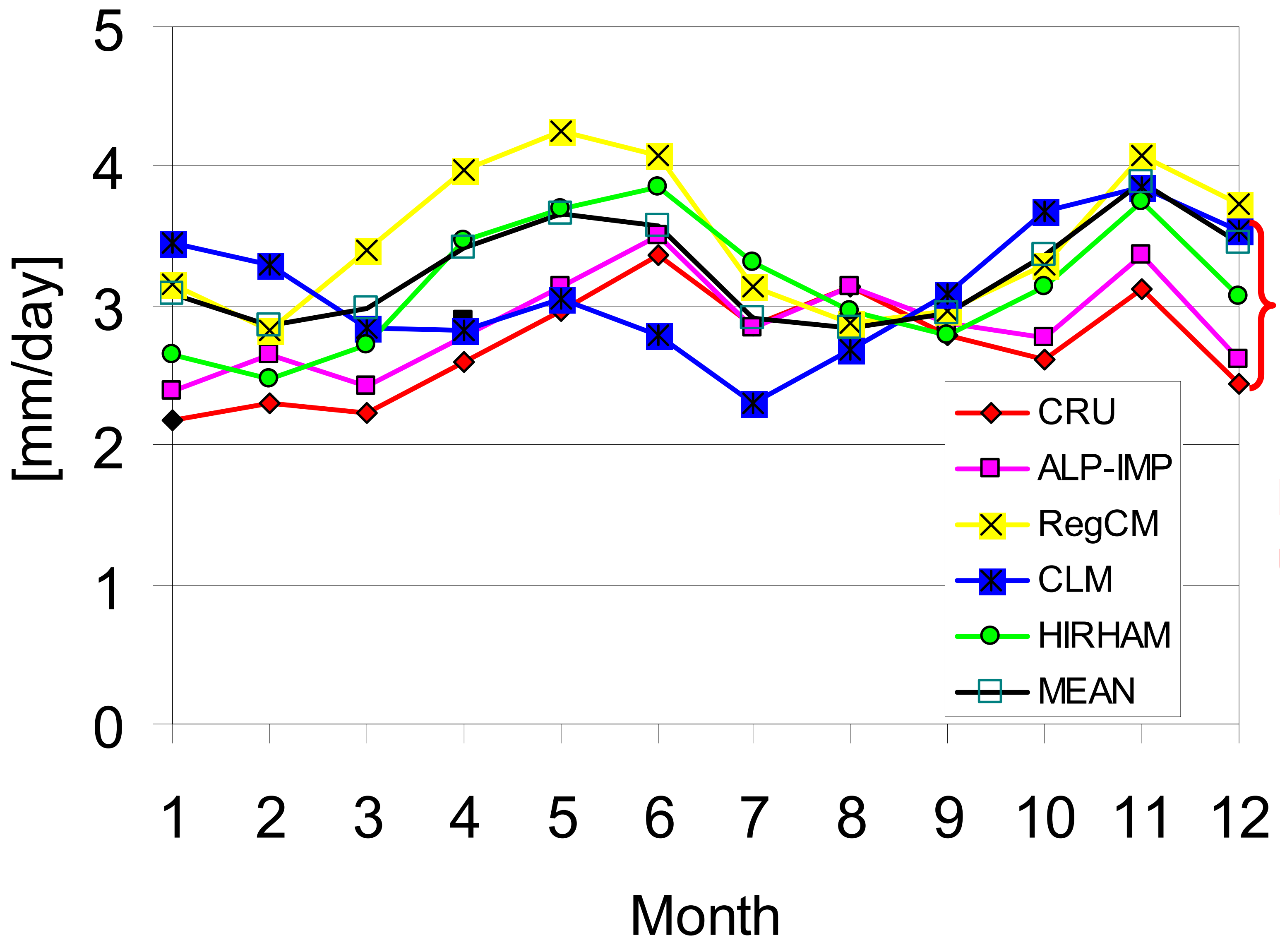
GAR



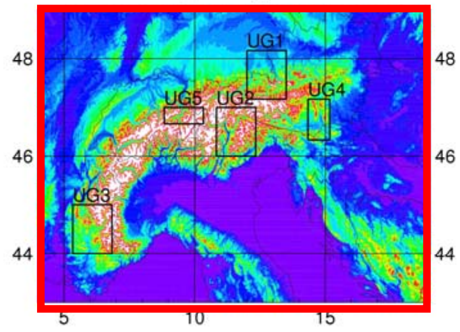
Mean monthly temperature bias +/- 1°C

1961-90

Performance Present Climate: GAR



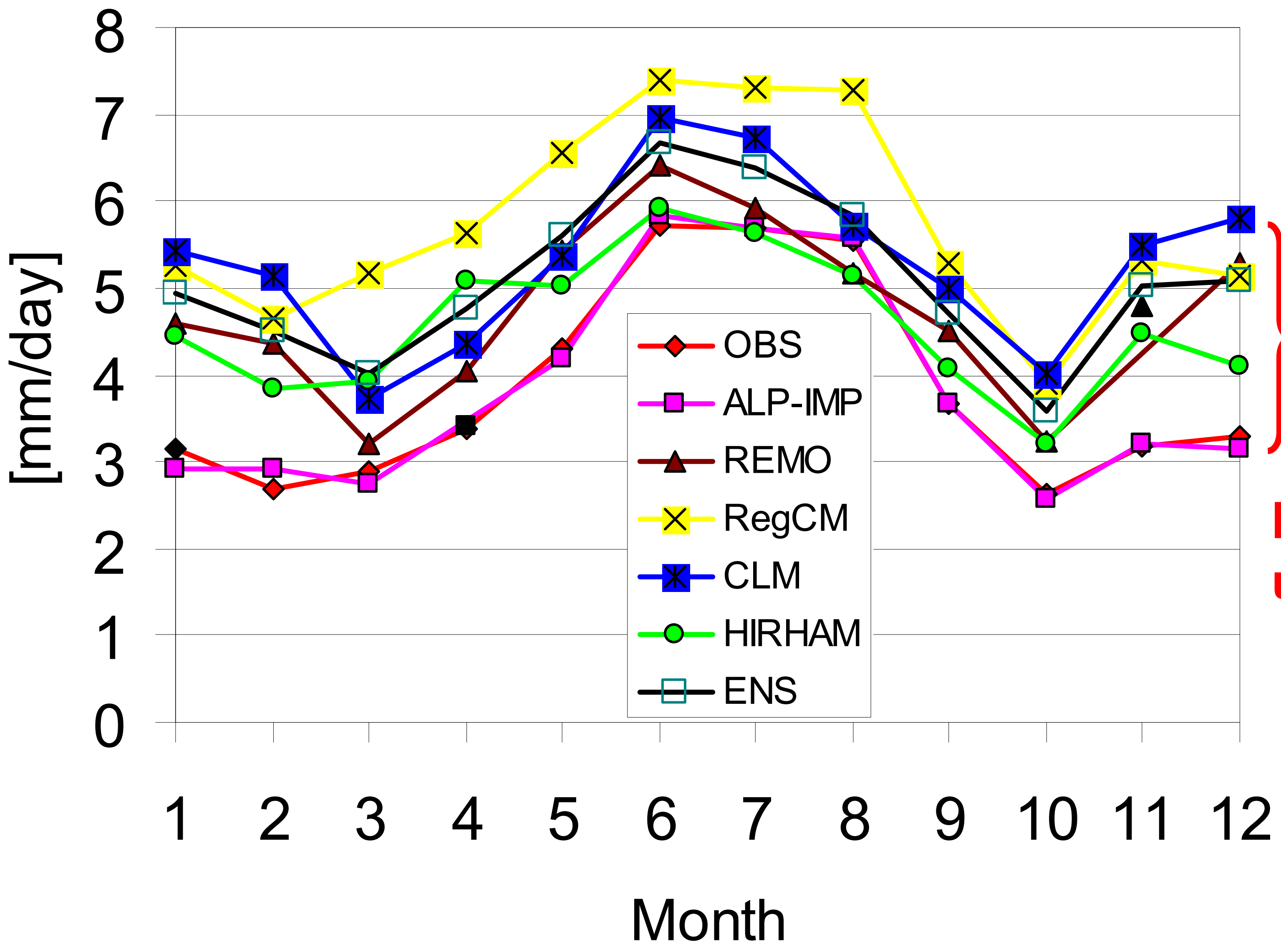
GAR



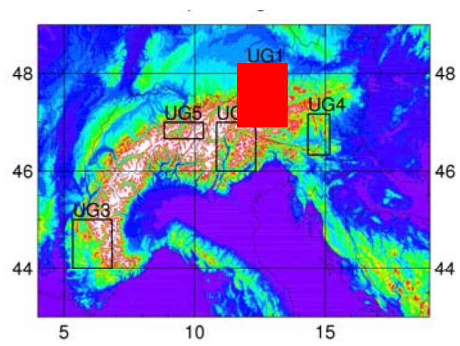
Precipitation bias up to 1.5 mm/day

1961-90

Performance Present Climate: UG1



UG1



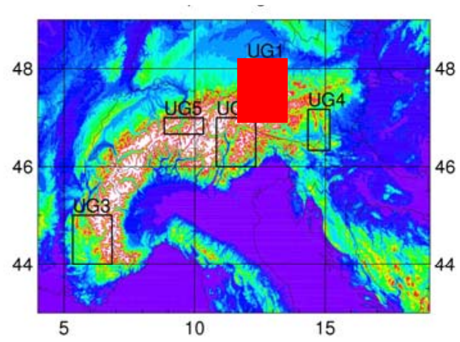
Precipitation bias up to +2.5 mm/day!

1961-90

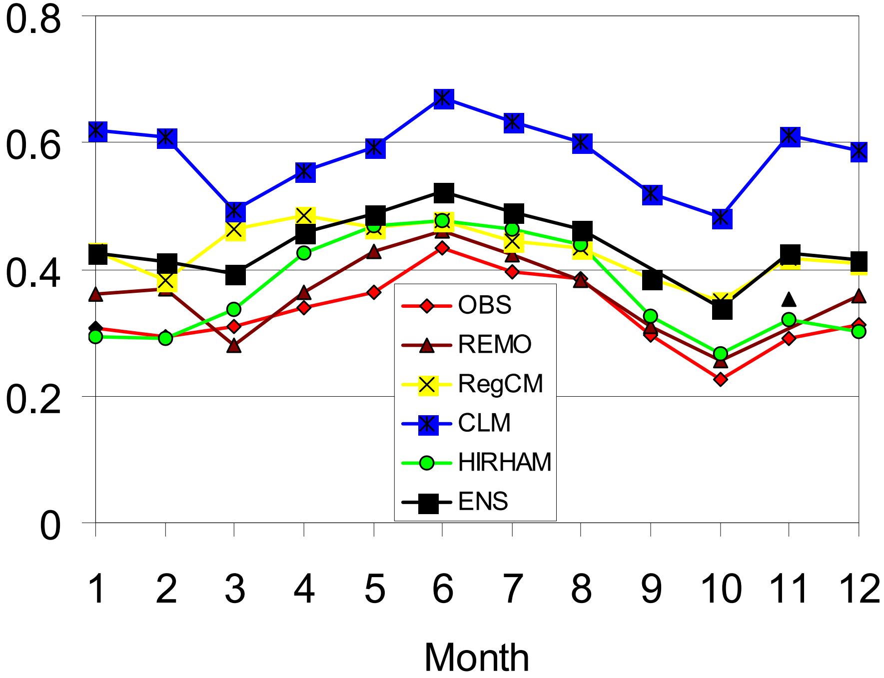
Performance Present Climate: UG1

FRE: Frequency (fraction) of days with

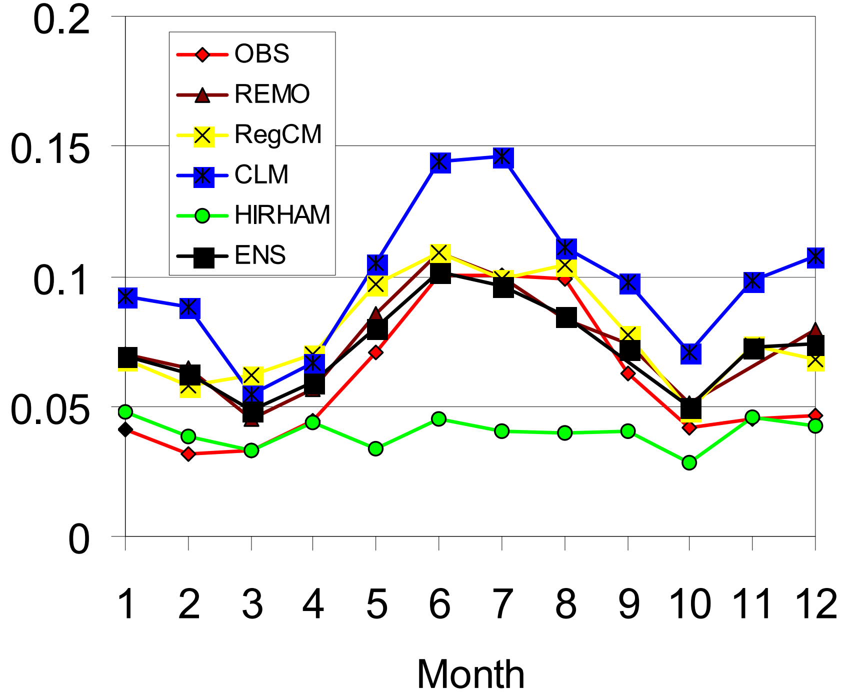
UG1



FRE 1: P > 1mm



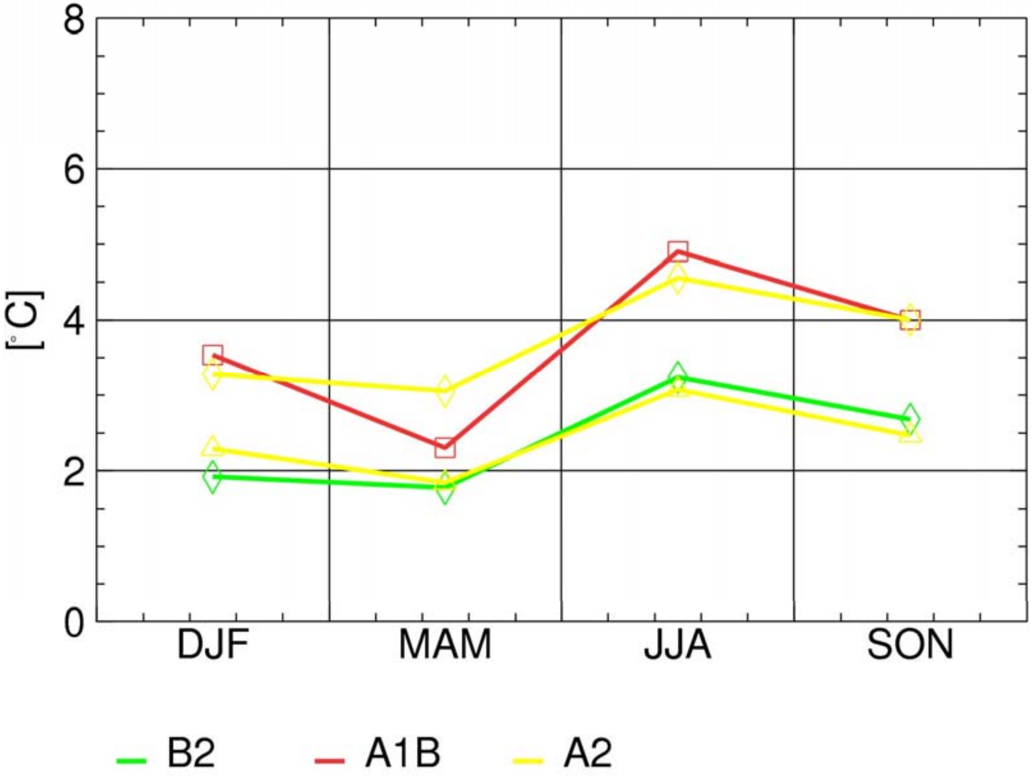
FRE 15: P > 15mm



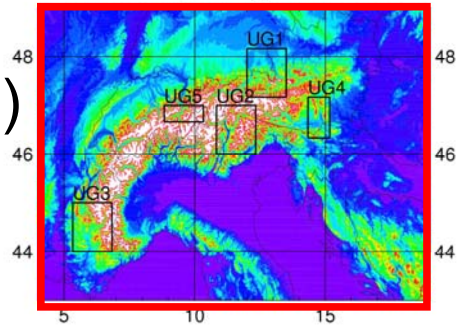
Future Climate: GAR

Temperature

GAR Ts-Tc

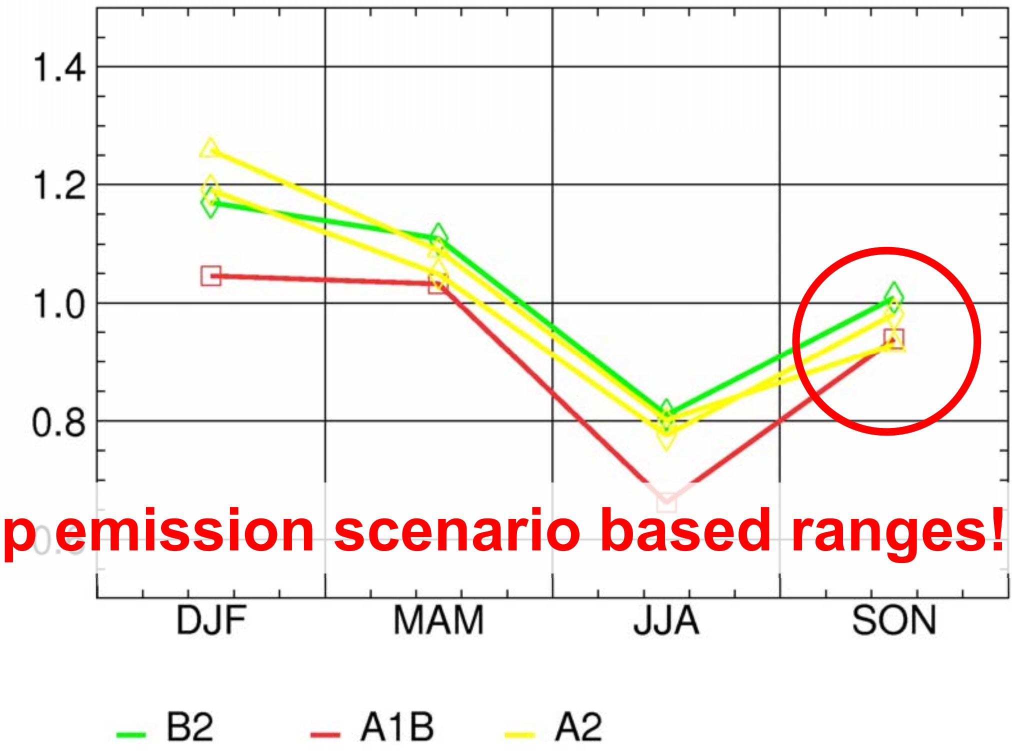


Δ: HIRHAM (HadCM3)
□: CLM (ECHAM5)
◊: RegCM (HadCM3)



Precipitation

GAR Ps/Pc



RCM ranges overlap emission scenario based ranges!

c - control run (1961 – 1990)
s - scenario run (2071 – 2100)

From RCM from hydrological impact analysis…

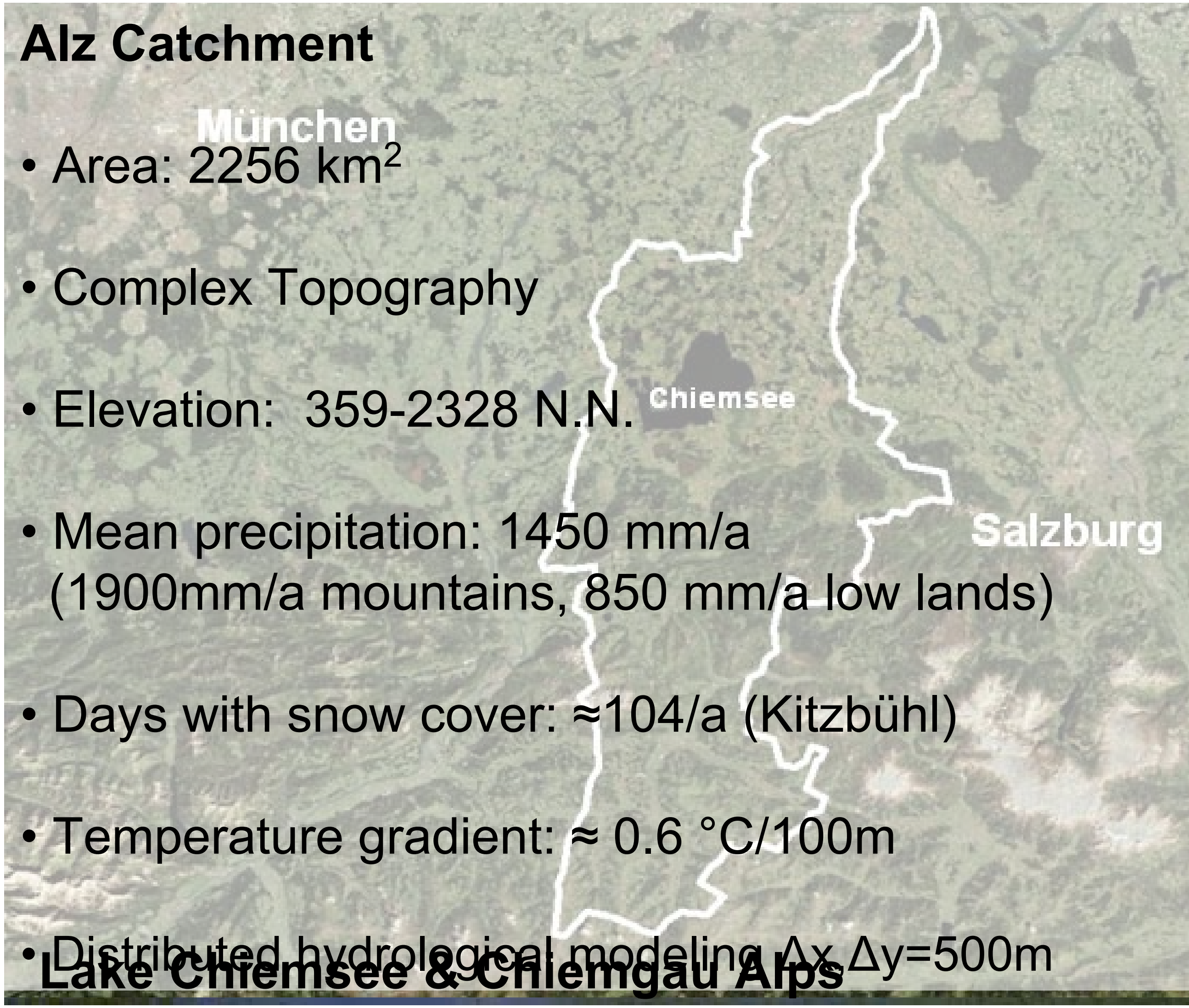
An example from the Alps

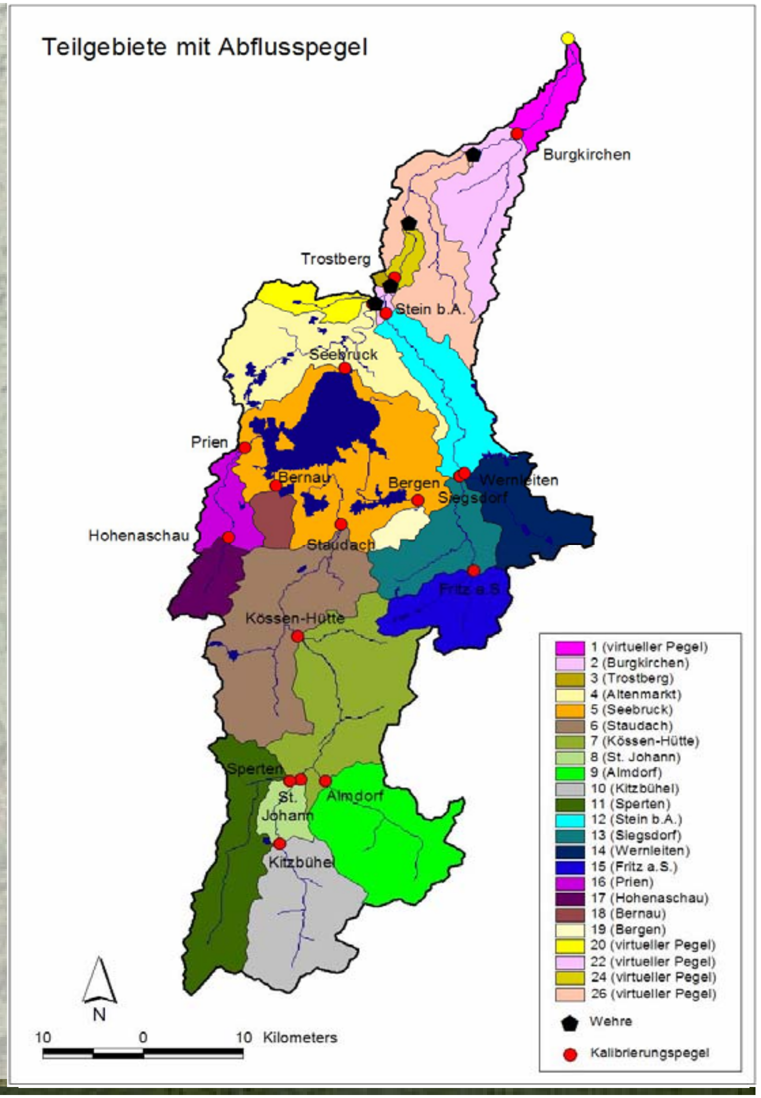
Regional Climate Modeling & Hydrological Impact Analysis

Regional Climate Modeling

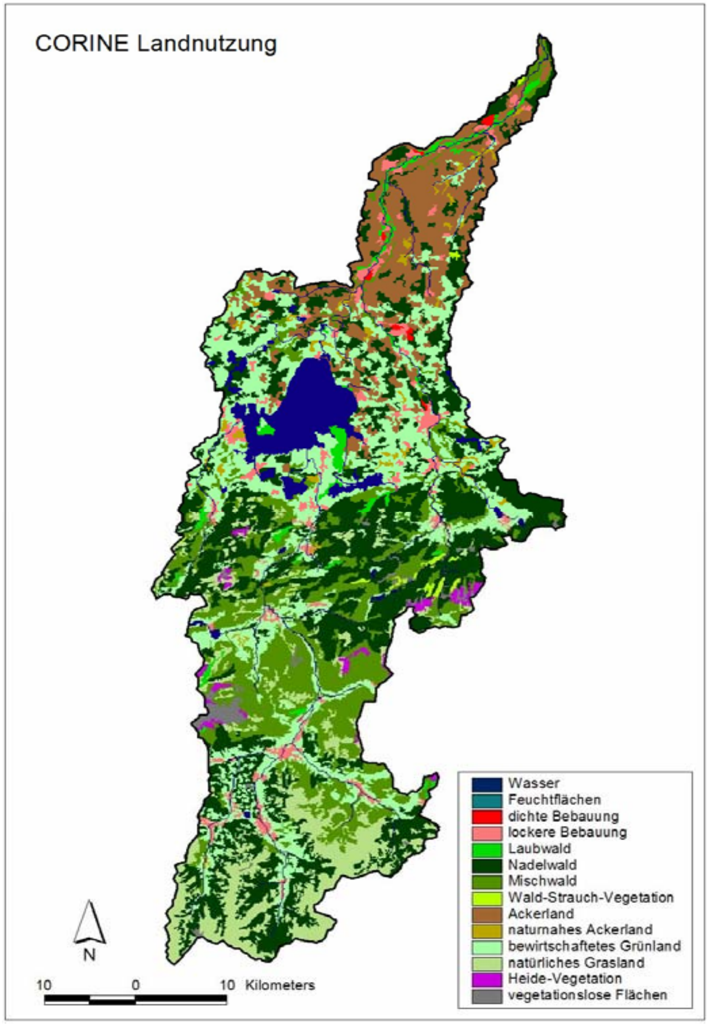
Alz Catchment

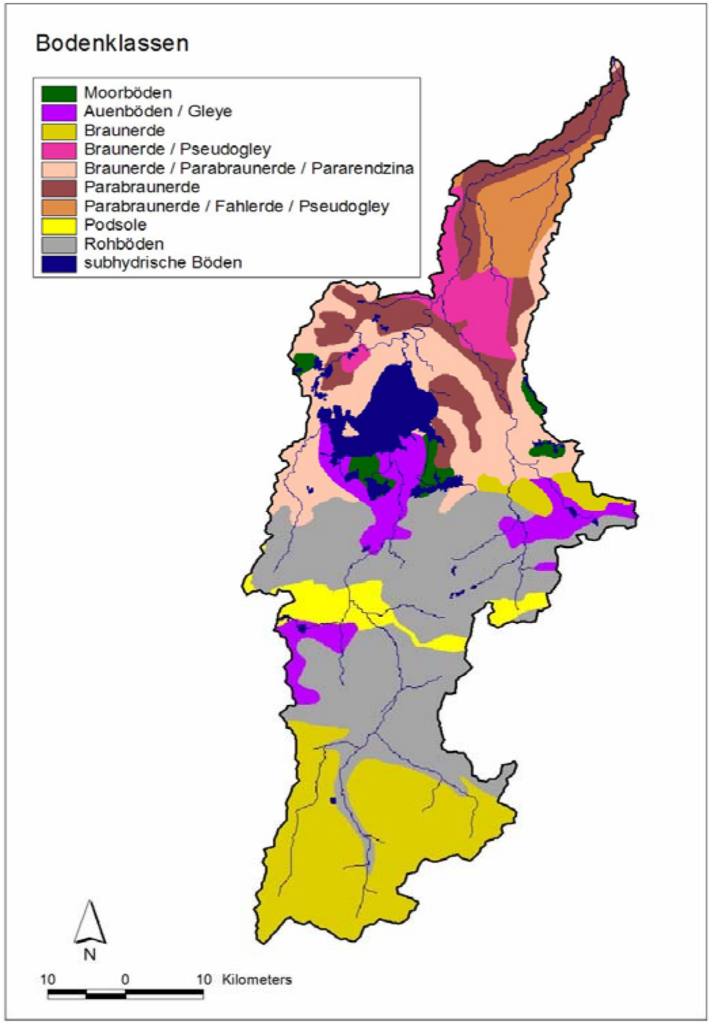
- Area: 2256 km^2
- Complex Topography
- Elevation: 359-2328 N.N.
- Mean precipitation: 1450 mm/a (1900mm/a mountains, 850 mm/a low lands)
- Days with snow cover: ≈104/a (Kitzbühl)
- Temperature gradient: ≈ 0.6 °C/100m
- Distributed hydrological modeling Δx,Δy=500m





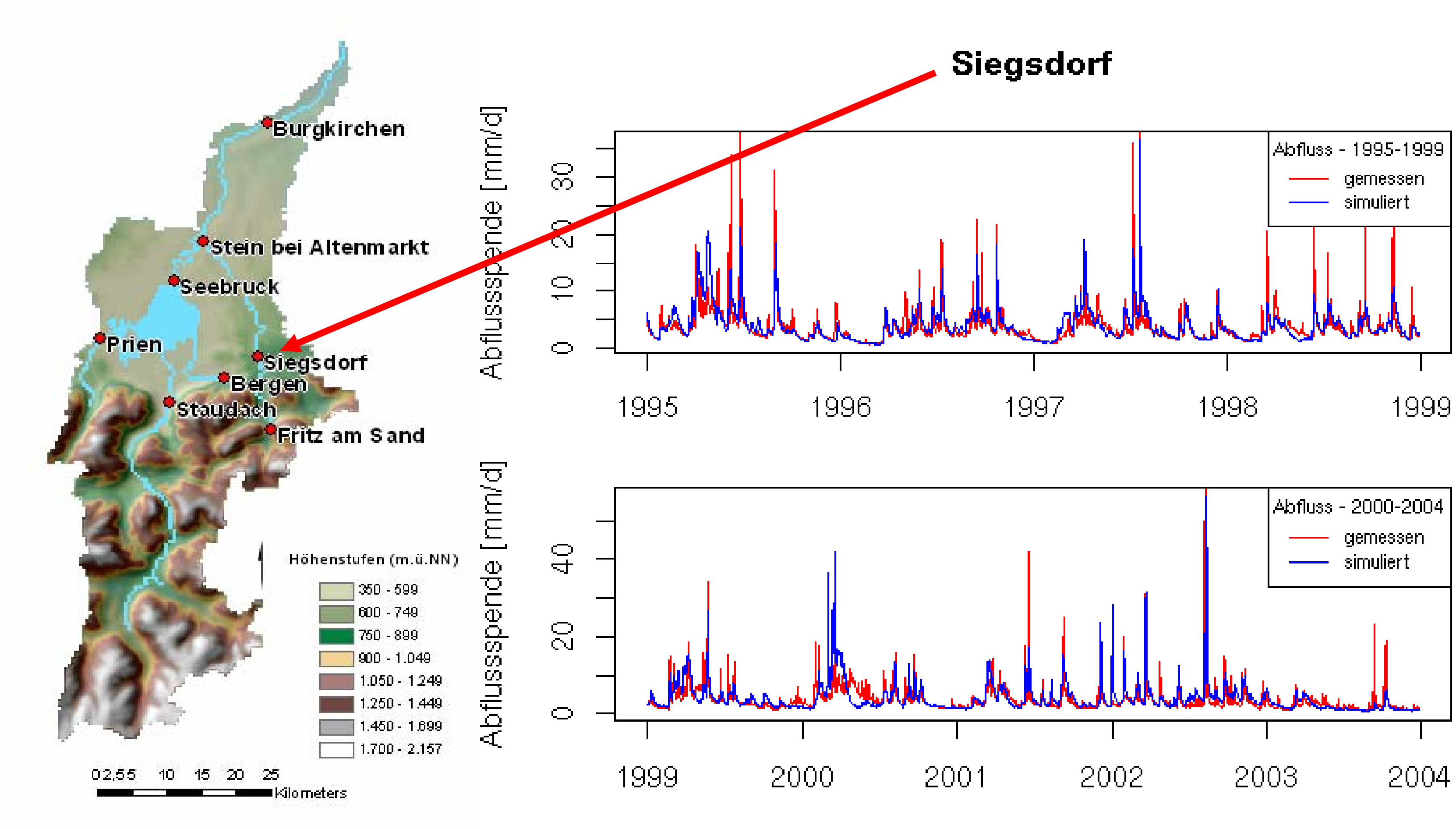
Time Invariant Data for Hydrological Model



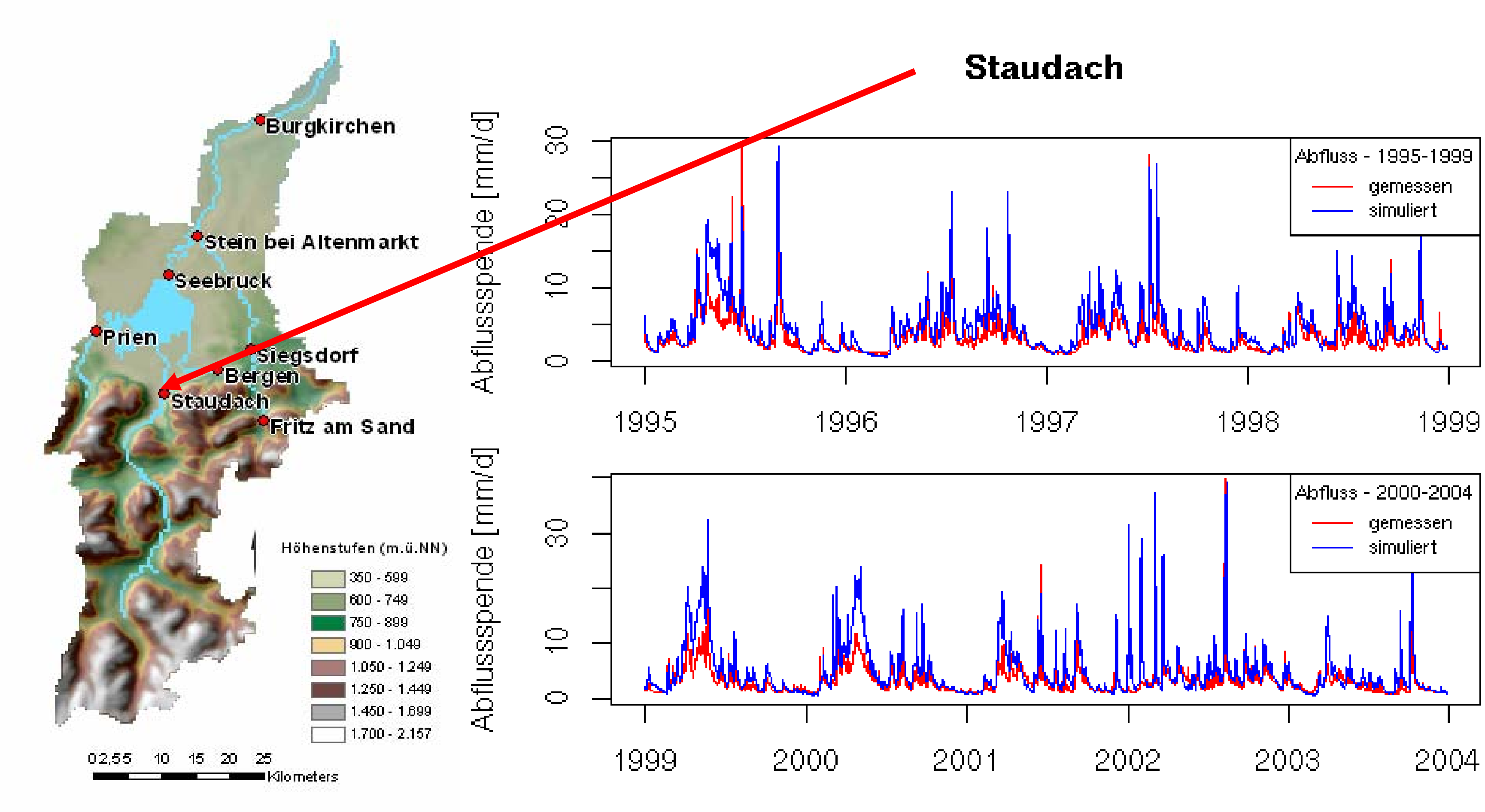


Performance Hydrological Model

Water balance simulation with WaSiM

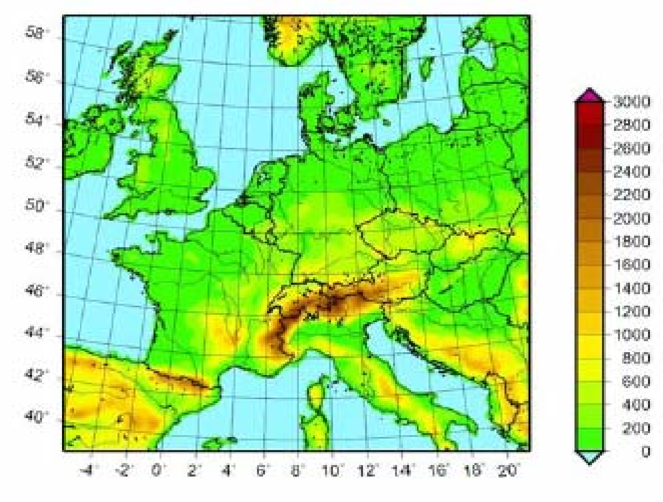


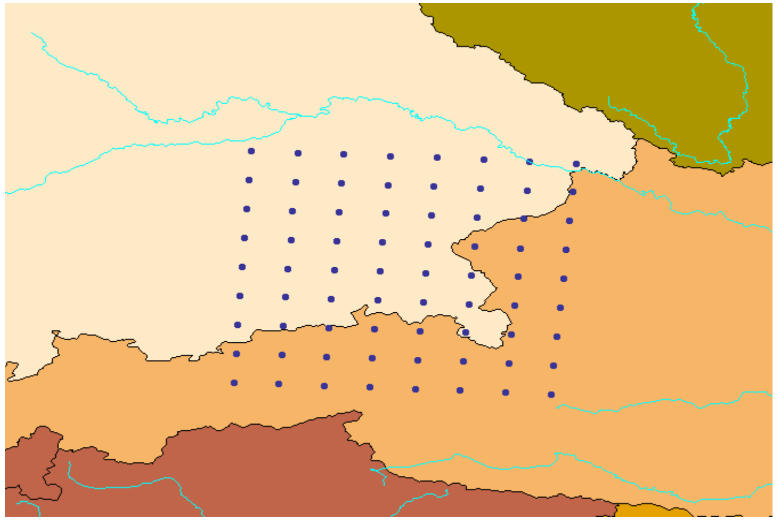
Water balance simulation with WaSiM



Model Chain for Hydrological Impact Analysis

Model Chain ECHAM4(B2) – MM5@18km – WaSiM@500m

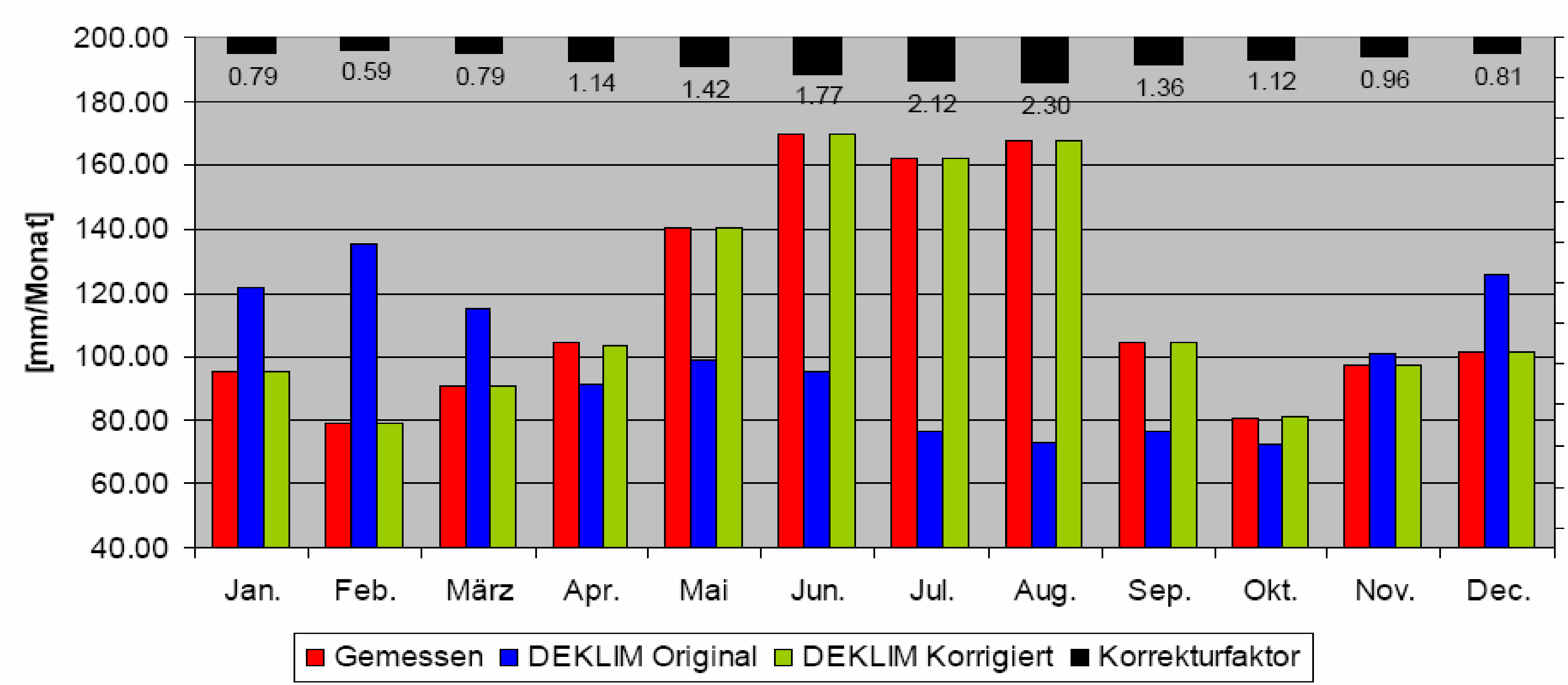




Position of Grid Points

Method & Bias-Correction after
Kunstmann et al., 2004 (HESS, Ammer EZG),
Kunstmann et al., 2007 (PCE, Volta EZG),
Kunstmann et al., 2007 (IAHS, oberes Jordan EZG)

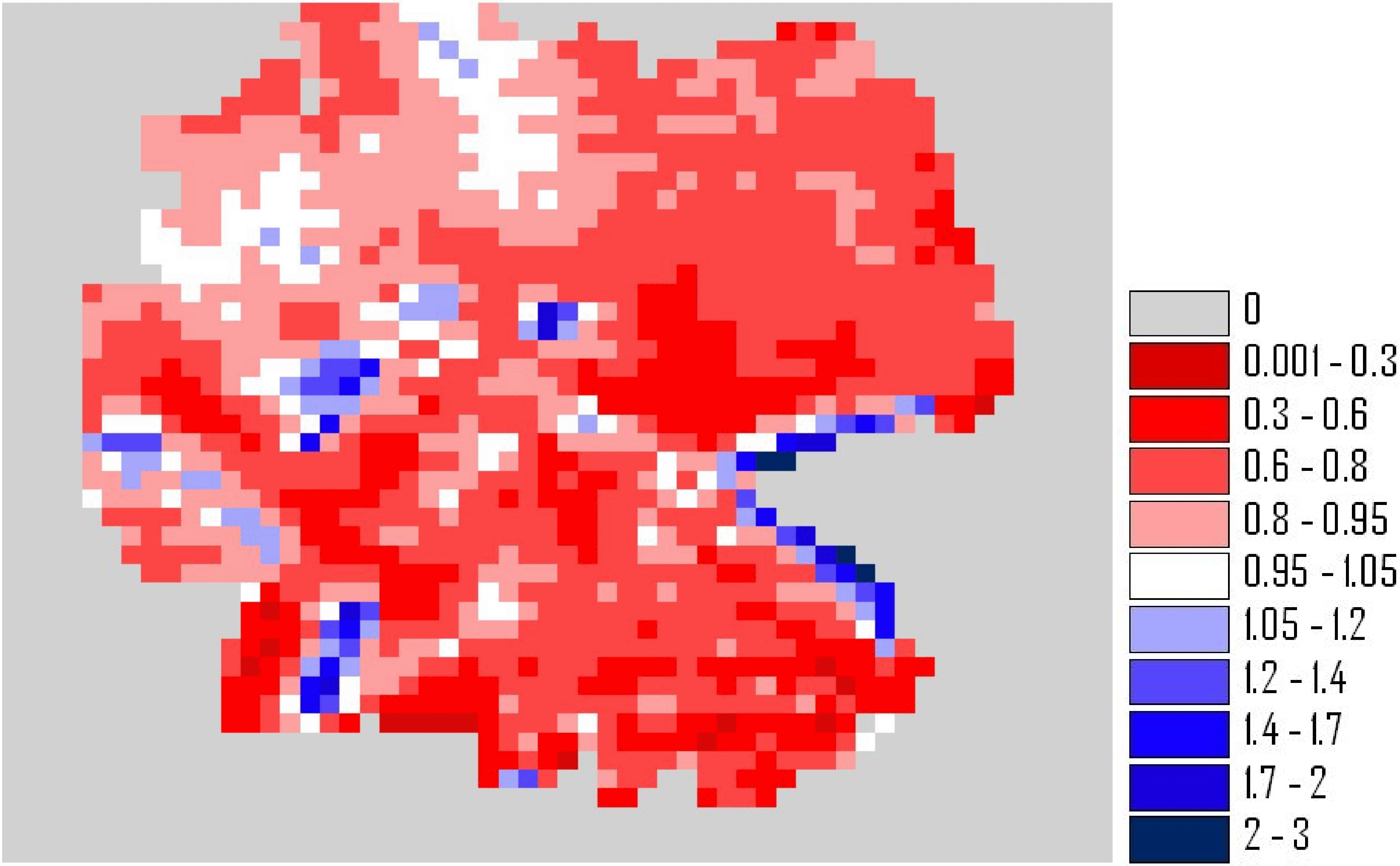
Bias & Bias Correction



Alz catchment:
Monthly bias-correction factors for ECHAM4-MM5@19km: CTRL vs. climatology

Bias & Bias Correction

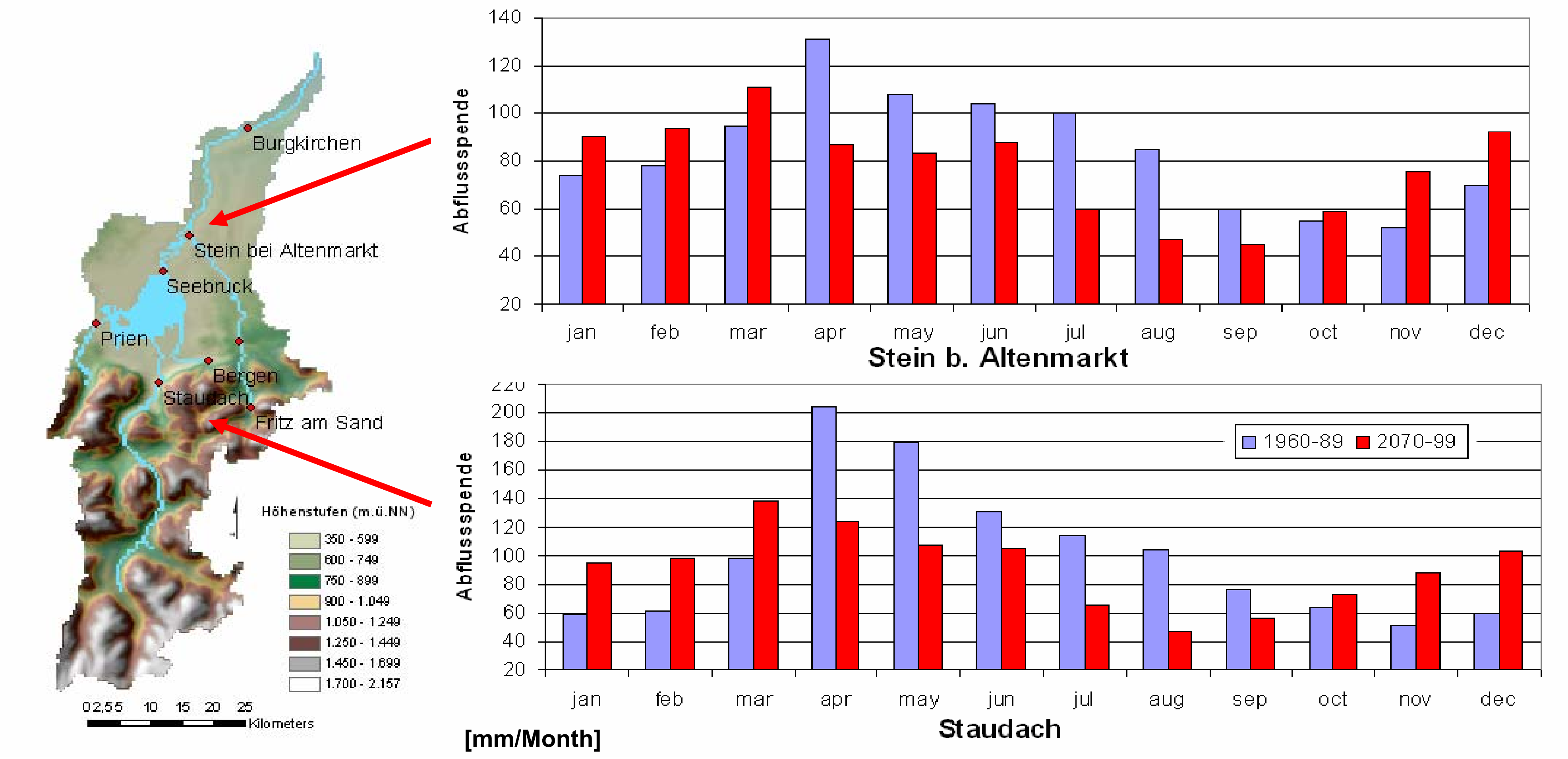
Area:
Germany+
Austrian part of
Alz catchment



Monthly bias-correction factors for ECHAM5-CLM@18km: CTRL vs. climatology

Expected Climate Change

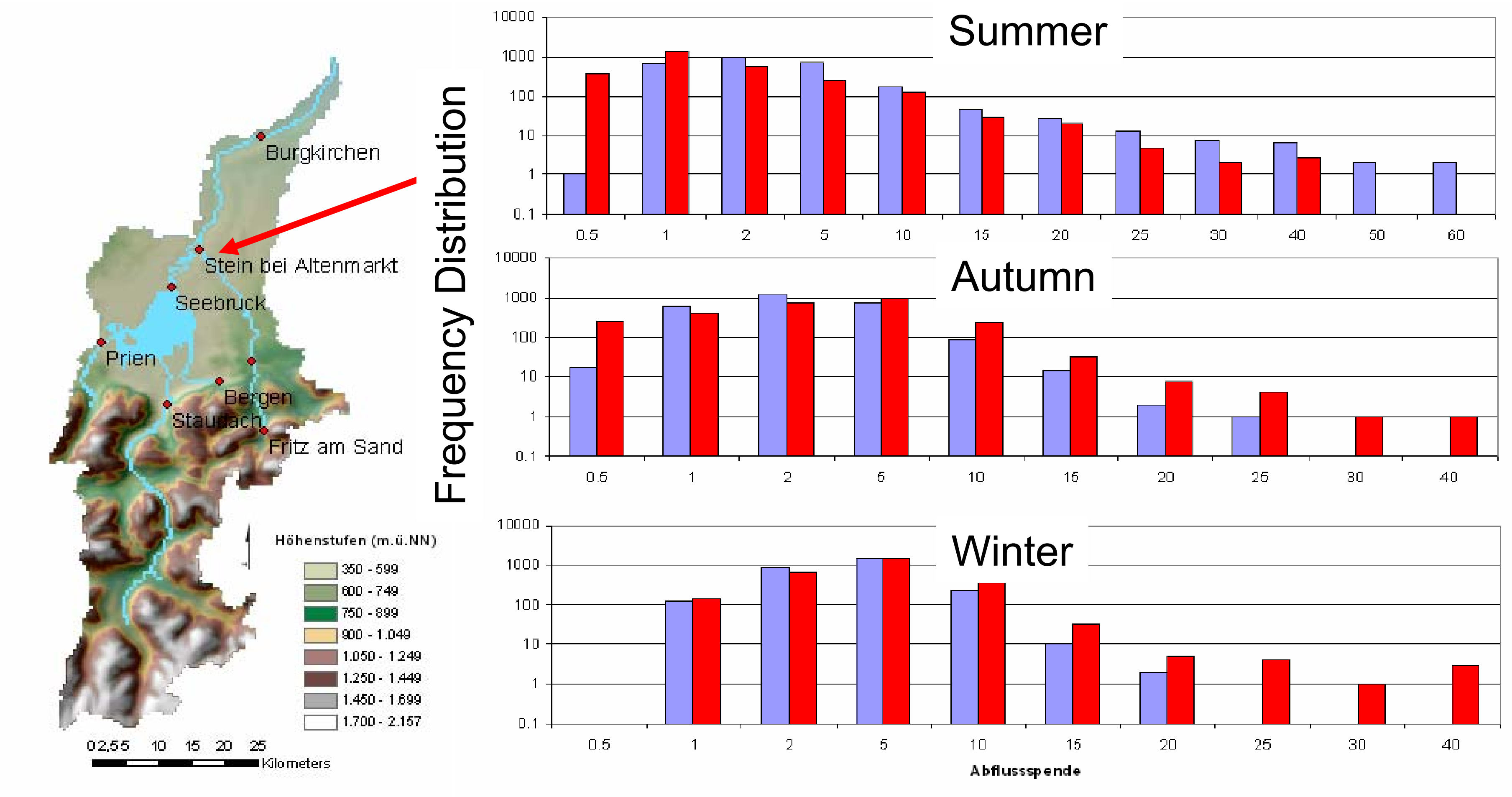
Joint Model System ECHAM4(B2) – MM5@18km – WaSiM@500m



Decrease of summer, increase of winter runoff

Expected Climate Change

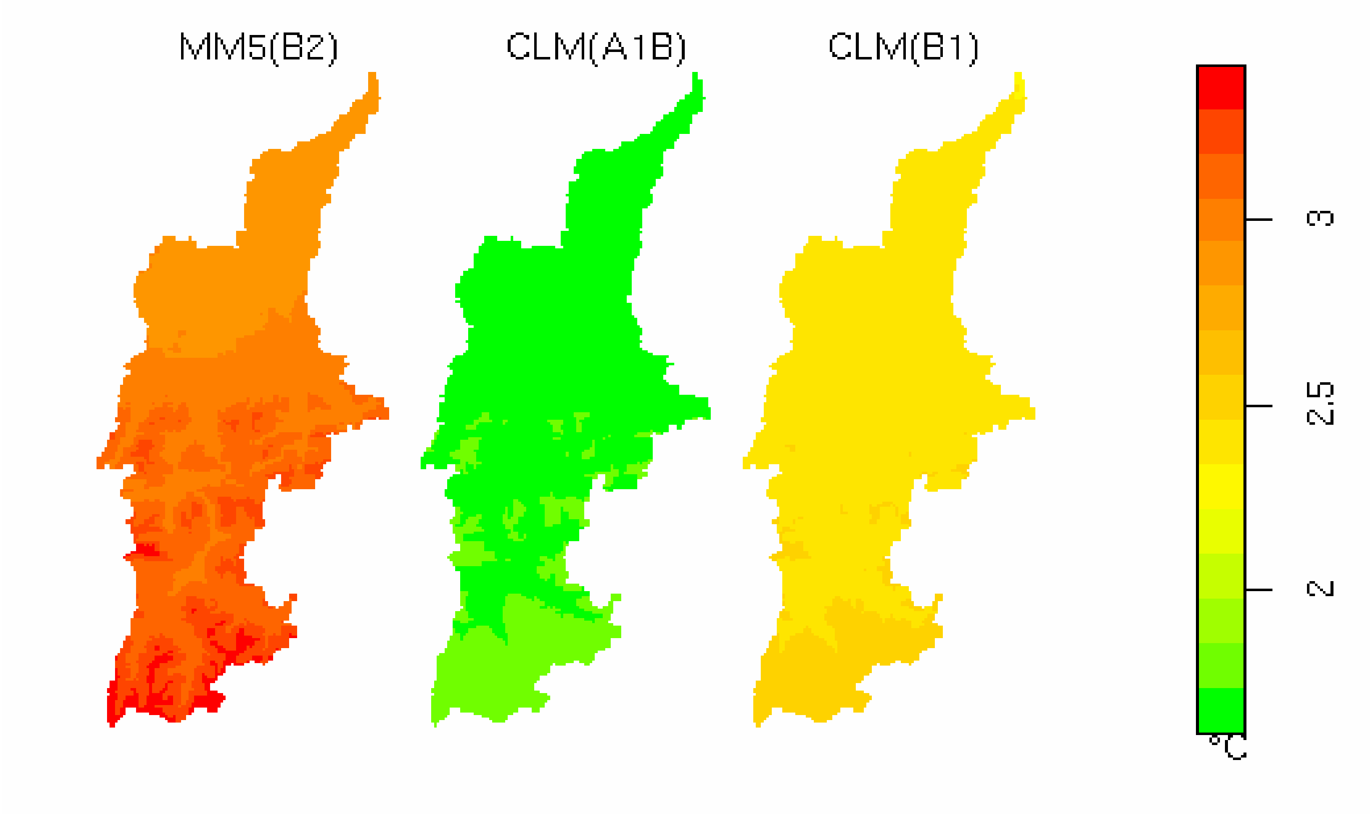
Joint Model System ECHAM4(B2) – MM5@18km – WaSiM@500m



Changes in frequencies: Increase of both low flow & high flow situations!

Expected Climate Change: Joint Uncertainties

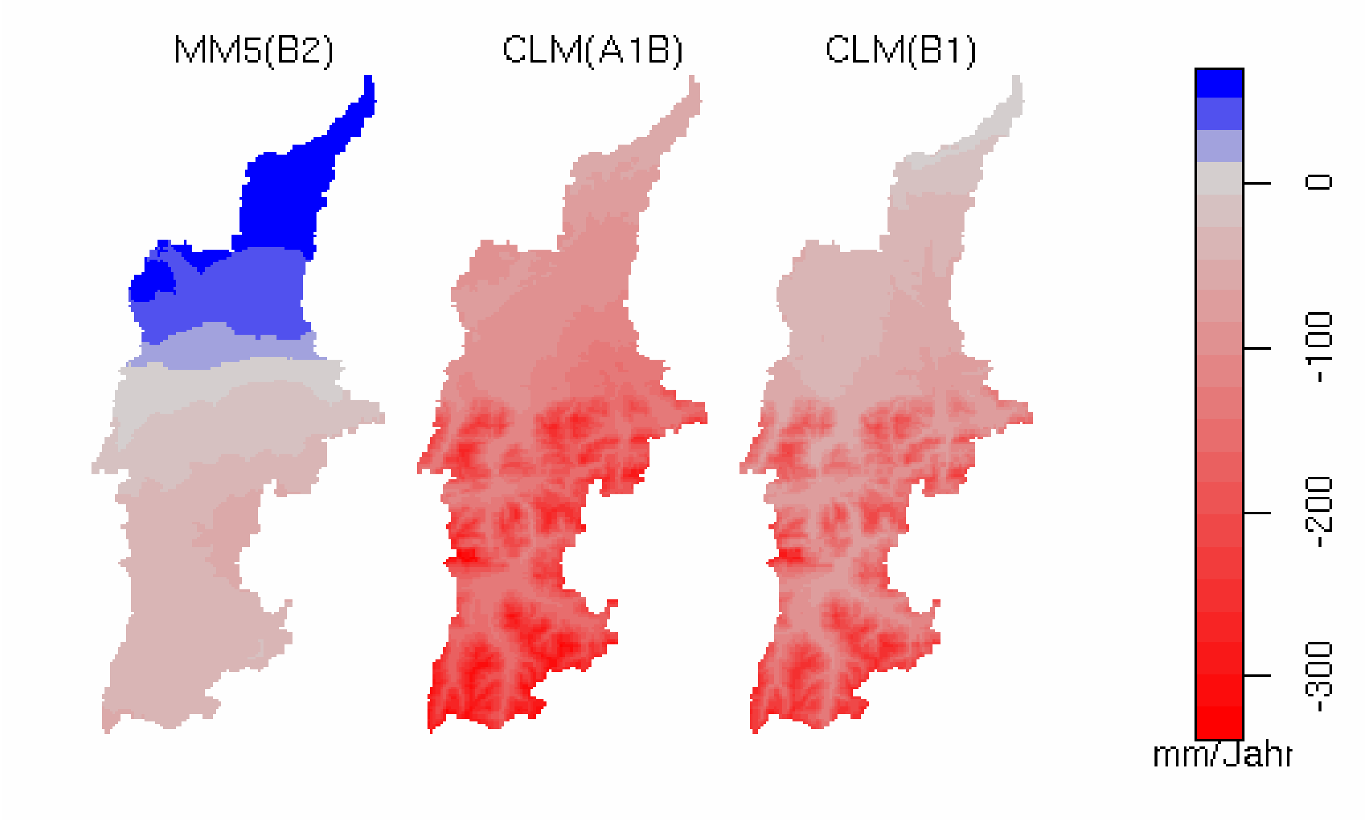
ECHAM4-MM5@18km vs. ECHAM5-CLM@19km – WaSiM@500m



Temperature Change 2070-99 minus 1960-89

Expected Climate Change: Joint Uncertainties

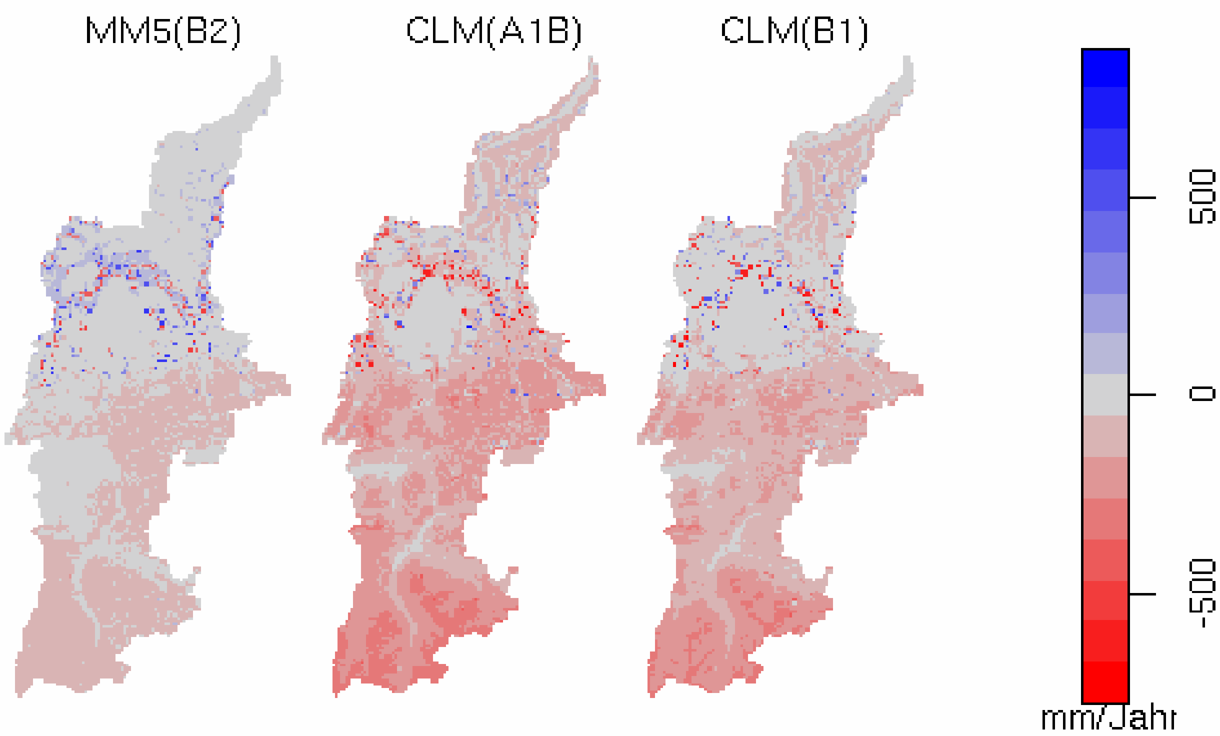
ECHAM4-MM5@18km vs. ECHAM5-CLM@19km – WaSiM@500m



Precipitation Change 2070-99 minus 1960-89

Expected Climate Change: Joint Uncertainties

ECHAM4-MM5@18km vs. ECHAM5-CLM@19km – WaSiM@500m



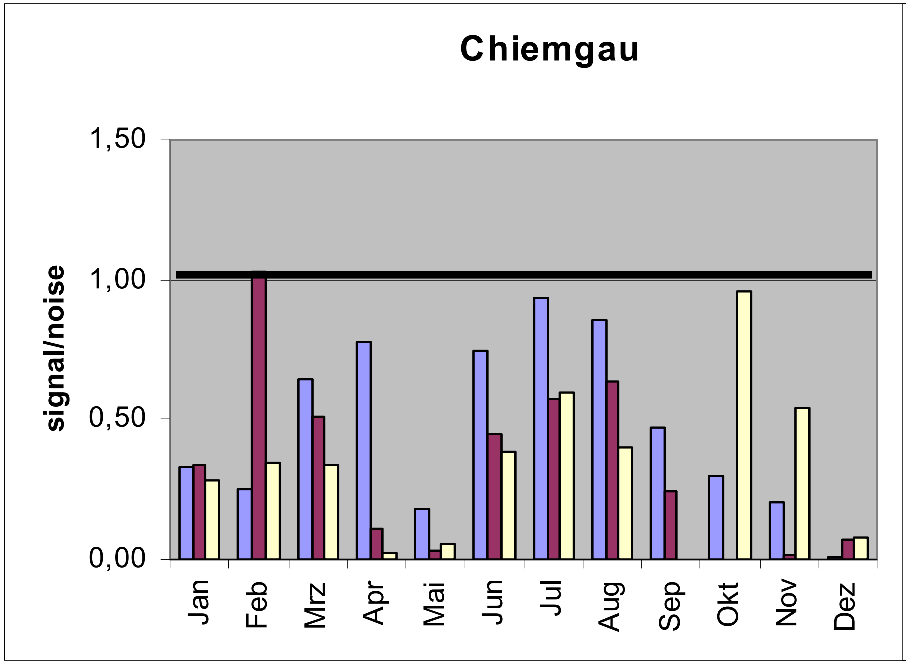
Total Runoff Change 2070-99 minus 1960-89

Expected Climate Change: Trend vs. Natural Variability

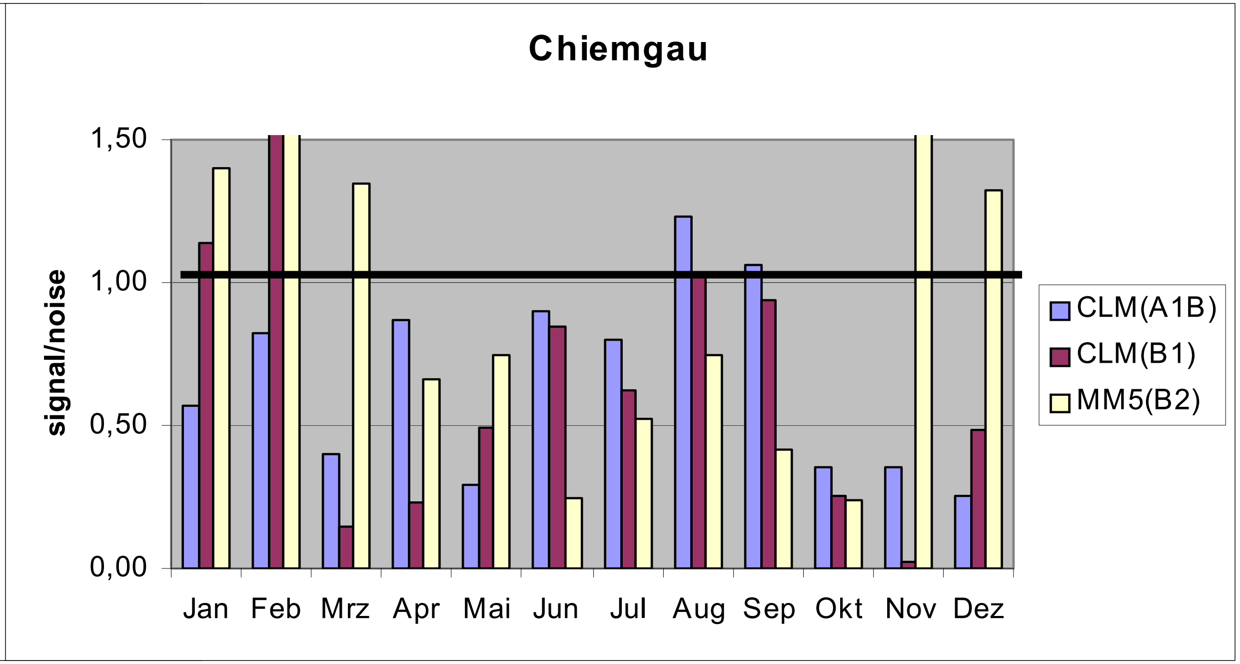
Model Chain ECHAM4/5 - MM5@18km/CLM@19km - WaSiM@500m

Signal to Noise ratio:

$$SN = \frac{|\overline{X}_{fut} - \overline{X}_{pres}|}{\sigma} > 1?$$



SN for Precipitation



SN for Discharge

Signal climate change mostly within inter-annual variability!

Summary: Current Capabilities & Limitations

- Regional climate models: spatial resolutions down to 5-10km for climate runs
- Non-hydrostatic models for $\Delta x < 10$ km
- **No single model can be identified as best**:
  performance depends on selected variable and area
  $\Rightarrow$ Hydrological impact studies by ensemble data set
- There is further a clear need for high resolution RCM data
- More detailed climatology needed (daily station-statistics)
- **Significant biases in precipitation detected!**
  $\Rightarrow$ Biases in precipitation usually require statistical correction techniques
- **RCM ranges overlap emission scenario based ranges!**

… How about the Philippines?


Thank you for your attention