Regional Climate and Hydrology Research at KIT/IMK-IFU

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The IMK-IFU Institute

- … is a **remote lab of KIT** …
- Around **100 employees**
- Research focus on **Biosphere-Hydrosphere-Atmosphere Interactions**
- Further **labs on Mount Zugspitze (atmospheric sounding)**
- Setup and operation of **TERENO prealpine observatory**
- **High performance computing**: e.g. regional climate & hydrological simulations
- **Employees & students from all continents** (except Antarctica)
- Budget of ≈ 5+2.5 Mio €/a (based funds + third party funding)

Regional Climate and Water Research

Specific Research Questions

- Closing the regional water cycle:
  development of ***fully coupled atmosphere-hydrosphere model systems***

- Observation & distributed modeling of ***joint water and energy fluxes***
  in complex terrain

- Quantification of **spatio-temporal precipitation variability** in complex terrain
  and poorly gauged regions

- ***Experimental hydrological process analysis*** *using microwave devices*
  (precipitation analysis) *and stable isotopes* (water origin and process separation)

Regional Climate and Water Research

Methods: Modeling Approaches

- **Dynamical Downscaling** of global meteorological fields (reanalyses, forecasts, climate scenarios): *WRF, COSMO-CLM*

- **Statistical Downscaling**: Copula-based multivariate methods, Canonical Correlation Analysis, Circulation Pattern Analyses

- **Distributed water- and energy flux modeling**: *WaSIM-ETH, NDHMS, GEOtop*

- **Coupled Atmospheric-Hydrological Model Systems**: *WRF-Hydro, WRF-NoahLSM-HMS*

Regional Climate and Water Research

Methods: Measurement Techniques

- **Water and energy fluxes** via *TERENO infrastructure:*
  EC-Flux stations, climate stations, lysimeters

- **Precipitation-Radar**: *DWD Hohenpeissenberg & TERENO*

- **Microwave links**: from *commercial cell phone companies (Ericsson) & own fully polarimetric phase coherent devices*

- **Stable water isotopes**: *Picarro Analyser for δ18O and δD*

Institute of Meteorology and Climate Research

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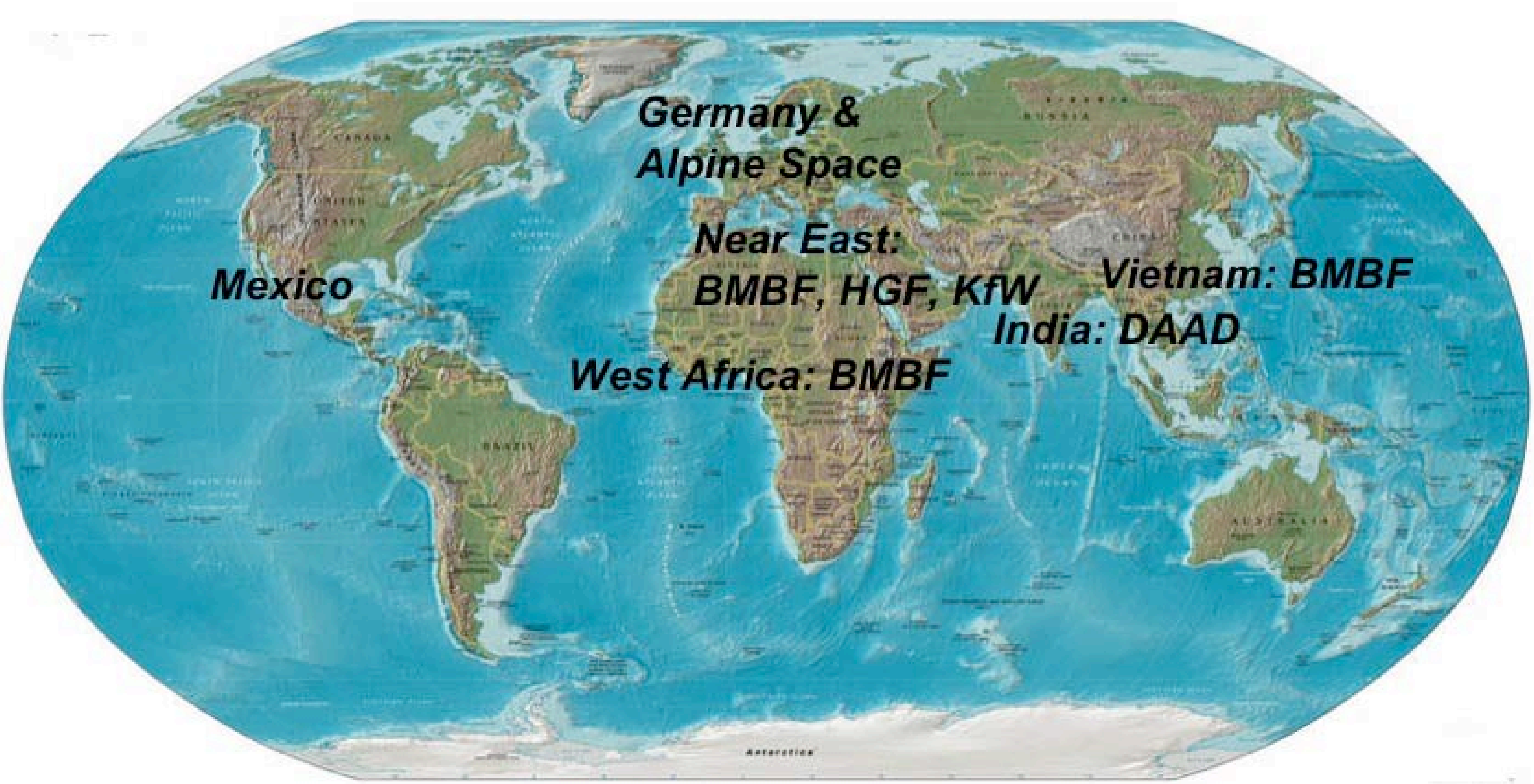
Active in climate and water sensitive regions worldwide



Recent Third-Party Funded Projects

DFG-NSFC: *"Long Term Land Use - Precipitation Feedbacks in the Hai River and Poyang Lake Regions" (PreFeed), 2010-2013*

DFG-Priority Programme 1257*, "The Global Continental Water Balance Using GRACE Spaceborn Gravimetry and High Resolution Consistent Geodetic-Hydrometeorological Data Analysis", 2007-2013*

Helmholtz Gemeinschaft, Virtual Institute*: "Regional Precipitation Observation by Cellular Network Microwave Attenuation and Application to Water Resources Management", 2008-2012*

Helmholtz Gemeinschaft: *"Regionale Klimainitiative" (REKLIM), 2010-2013*

BMBF: *"West African Science Service Centre for Climate Change and Adapted Land Use" (WASCAL), 2010-2014*

BMBF: *"Decadal Prediction of African Rainfall and Atlantic Hurricane Activity", 2011-2015*

BMBF: *"Food Security in Eastern Africa: Steering Rice Production towards Climate Resilience" (RICE-EA), Demonstration Project, 2012*

BMBF: *"Landuse and Climate Change Interactions in Central Vietnam" (LUCCi), 2010-2014*

BMBF: *"GLOWA-Jordan River: An International Study of the Future of the Water Scarce Jordan River Basin under the Impact of Climate and Global Change" , 2006-2011*

StMUG & Nationalparkverwaltung Berchtesgaden: *"Water Balance and Physically Based Snow Modeling for the National Park Berchtesgaden", 2008-2012*

CEDIM: *"Flood Hazards in a Changing Climate", 2008-2011*

KfW: *"Impact of Climate Change on the Figeh-Spring, Damascus/Syria", 2010-2012*

Case study:
Climate simulations for Central Vietnam

- LUCCi Project
- WP3: Climate simulations
- Further activities

Land Use and Climate Change interactions in Central Vietnam (LUCCi)

Project duration: July 2010 – July 2015
2010-2013: Research phase
2013-2015: Implementation phase

Coordination:
Institute for Technology and Resources Management in the Tropics and Subtropics, ITT, at the Cologne University of Applied Sciences

Main German partners of the consortium:

- Department for Remote Sensing, Friedrich-Schiller University of Jena
- Department of Geoinformatics, Hydrology and Modelling, Friedrich-Schiller-University of Jena
- Institute of Environmental Engineering and Ecology, Ruhr University Bochum
- Karlsruhe Institute of Technology (KIT, IMK-IFU)
- Secretariat for the International Hydrological Programme (IHP) of UNESCO and the Hydrology and Water Resources Programme (HWRP)

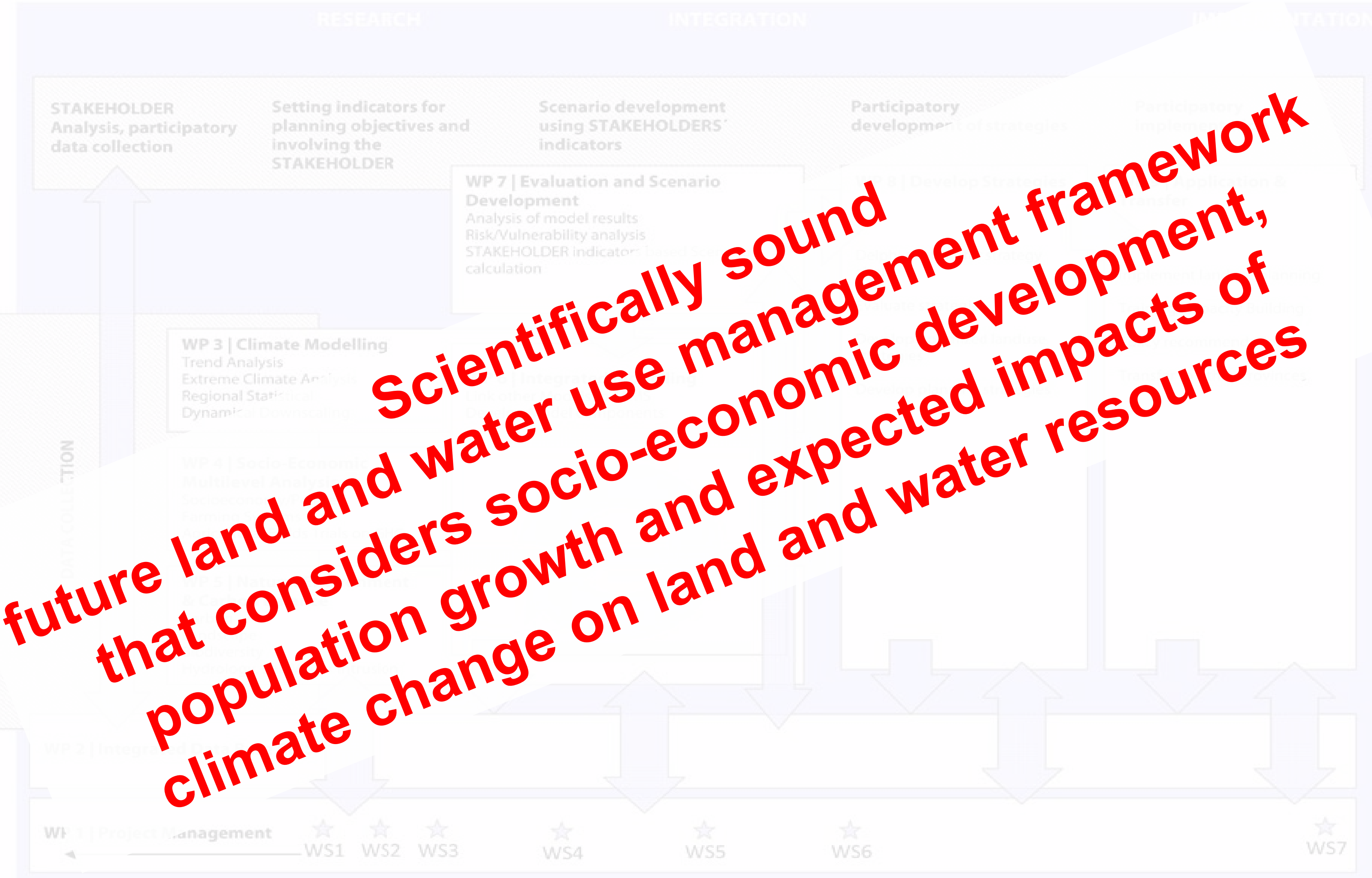
Main Vietnamese partners:

- Vietnam Academy for Water Resources, Centre for Training and International Cooperation
- Hue University of Agriculture and Forestry
- Ministry of Agriculture and Rural Development (MARD)
- Ministry of Natural Resources and Environment (MONRE)
- Ministry of Science and Technology (MOST)

International institutions:

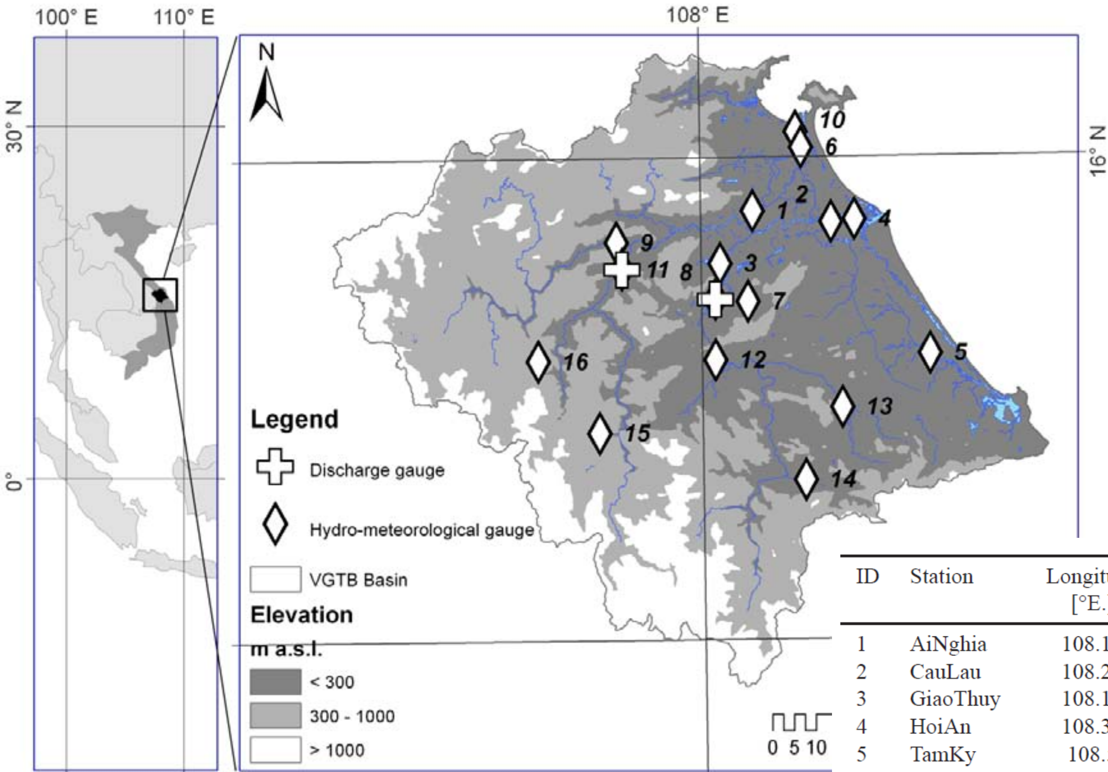
- International Rice Research Institute, IRRI, CGIAR
- UN REDD, Hanoi at MARD
- UNDP Disaster Risk Management Programme

LUCCi objective



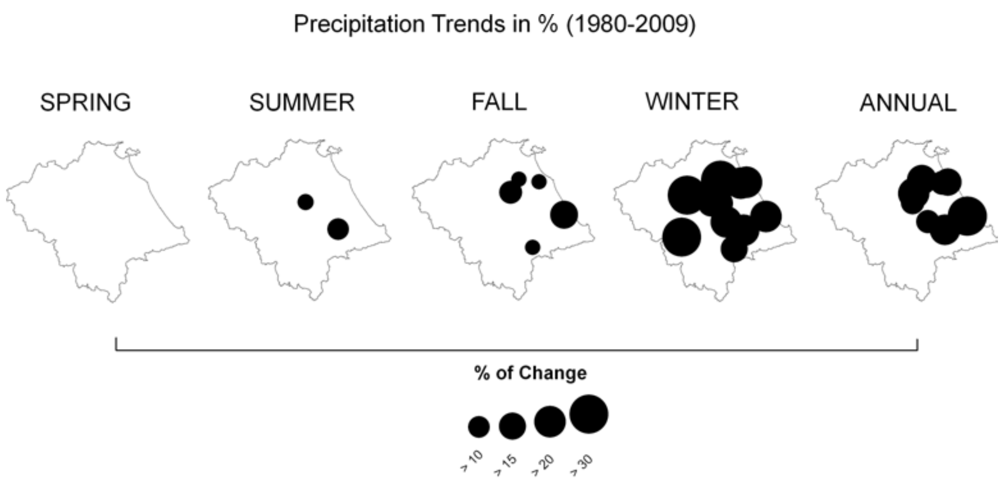
Scientifically sound future land and water use management framework that considers socio-economic development, population growth and expected impacts of climate change on land and water resources

WP3 activities: Analysis of observation data

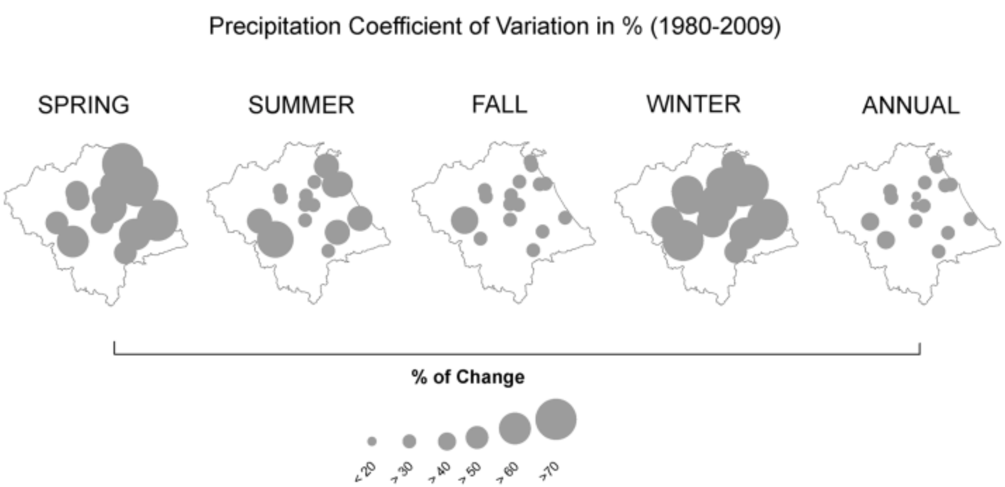


ID	Station	Longitude [°E.]	Latitude [°N.]	Altitude [m a.s.l.]	Data Availability Precipitation	Temperature	Discharge
1	AiNghia	108.12	15.88	6	1976-2009		
2	CauLau	108.28	15.85	5	1976-2009		
3	GiaoThuy	108.13	15.85	5	1976-2009		
4	HoiAn	108.33	15.87	5	1976-2009		
5	TamKy	108.5	15.55	5	1977-2009	1977 - 2009	
6	CamLe	108.2	16.00	6	1976-2009		
7	QueSon	108.1	15.70	7	1977-2006		
8	NongSon	108.03	15.70	9	1976-2009		1976-2009
9	HoiKhach	107.82	15.82	18	1976-2009		
10	DaNang	108.18	16.03	23	1976-2009	1976-2009	
11	ThanhMy	107.83	15.77	24	1976-2009		1976-2009
12	SonTan	108.03	15.57	53	1976-2009		
13	TienPhuoc	108.3	15.48	58	1977-2009		
14	TraMy	108.25	15.33	135	1977-2009	1977-2009	
15	KhamDuc	107.78	15.43	393	1978-2009		
16	Hien (Trao)	107.65	15.59	420	1978-2009		

Historical trend analysis (P, T_{min}, T_{max}, R)



→ **Significant increase of P**
→ **Magnitude higher at coasts**
→ **Signal dominant in winter (DJF)**



$$C_V = \frac{\sigma}{\mu}$$

→ **Variability highest during winter (DJF) and Spring (MAA)**

Decadal trend analysis

ID	Station	Sen's slope [mm/year]		
		1980-1989	1990-1999	2000-2009
1	AiNghia	-127*	117	116
2	CauLau	-73	64	98
3	GiaoThuy	-103	14	54
4	HoiAn	-59	49	19
5	TamKy	-116	203*	77
6	CamLe	-121+	145	NA
7	QueSon	-115	82*	-219
8	NongSon	-148*	175*	35
9	HoiKhach	-114*	NA	60
10	DaNang	-101	59+	32
11	ThanhMy	-103*	189*	4
12	SonTan	-128+	129+	79
13	TienPhuoc	-69	166*	NA
14	TraMy	-126	112	111
15	KhamDuc	-200	140	190
16	Hien (Trao)	-286**	34	146

significant at p=0.10 (+), p=0.05 (*), and p=0.01 (**)

→ Decadal differences:

Decrease in 1980s
High increase in 1990s
Increase in 2000s (n.s.)

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Motivation: why do we need process-based RCM simulations?

- **Sparse observation network of hydrometeorological data**
  - ➢ Few hydrometeorological stations (located in lowlands)
  - ➢ Low sampling rates (daily)

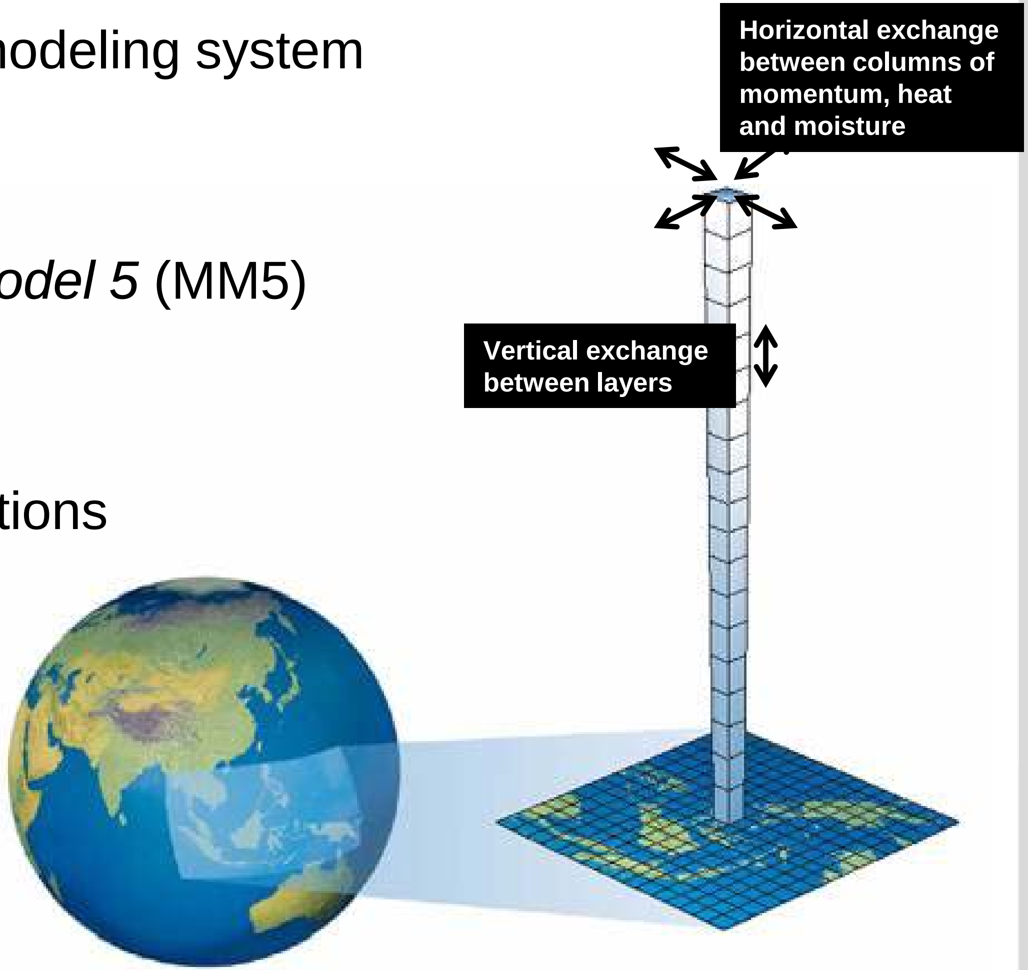
- **Stakeholders demand delineation of climate change adaptation strategies**
  - ➢ Flood protection measures (adaptation of infrastructure)
  - ➢ Future hydropower potential (low flows)
  - ➢ Water availability for agriculture

→ High resolution representation of hydrometeororological variables (P, T, etc.) for past and future

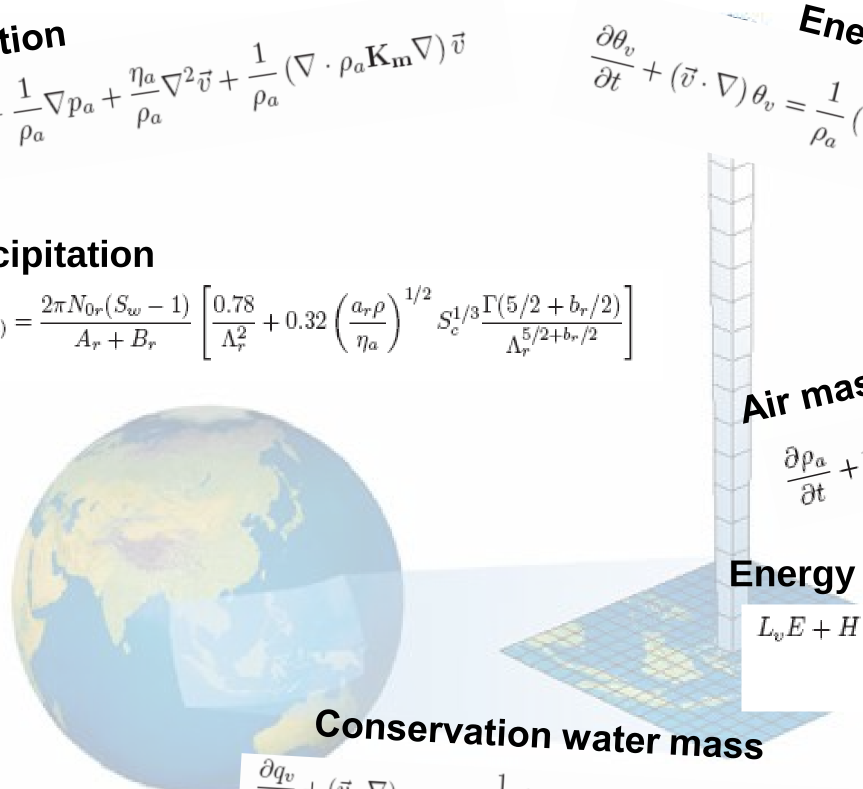
WRF (*<u>W</u>eather <u>R</u>esearch and <u>F</u>orecast Model*)

- Next generation atmospheric modeling system
- Developed at NCAR
- Non-hydrostatic
- Successor of the *Mesoscale Model 5* (MM5)
- Various applications:
  - ✓ Weather forecasts
  - ✓ (Long-term) climate simulations
  - ✓ Different scales
- Atmospheric and (sub)surface compartments:

Atmospheric compartment



Atmosphere – explicit calculation of



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

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

Precipitation

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

Air mass conservation

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

Gas law

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

Energy conservation at land surface

$$\begin{aligned} L_vE + H + G &= SW_{net} + LW_{net} \\ &= (1-\alpha)SW\downarrow + LW\downarrow - \epsilon\,\sigma_B\,T_{surf}^4 \end{aligned}$$

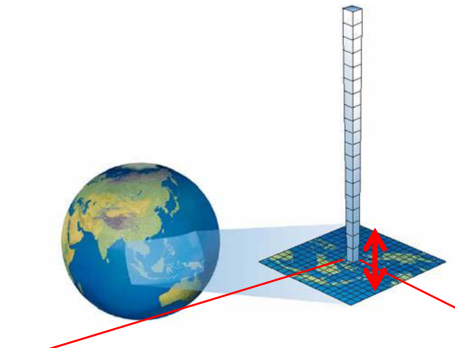
Conservation water mass

$$\begin{aligned}
\frac{\partial q_v}{\partial t} + (\vec{v}\cdot\nabla)\,q_v &= \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_v + R_{evap} - R_{cond} - R_{iini} - R_{idep/sub} \\
\frac{\partial q_c}{\partial t} + (\vec{v}\cdot\nabla)\,q_c &= \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_c + R_{cond} + R_{iini} + R_{idep/sub} - R_{aconv} - R_{accr} \\
\frac{\partial q_r}{\partial t} + (\vec{v}\cdot\nabla)\,q_r &= \frac{1}{\rho_a}(\nabla\rho_a\mathbf{K_h}\nabla)\,q_r - R_{evap} + R_{aconv} + R_{accr} - \frac{\partial V_f\rho_a g q_r}{\partial z} \qquad (2.32)
\end{aligned}$$

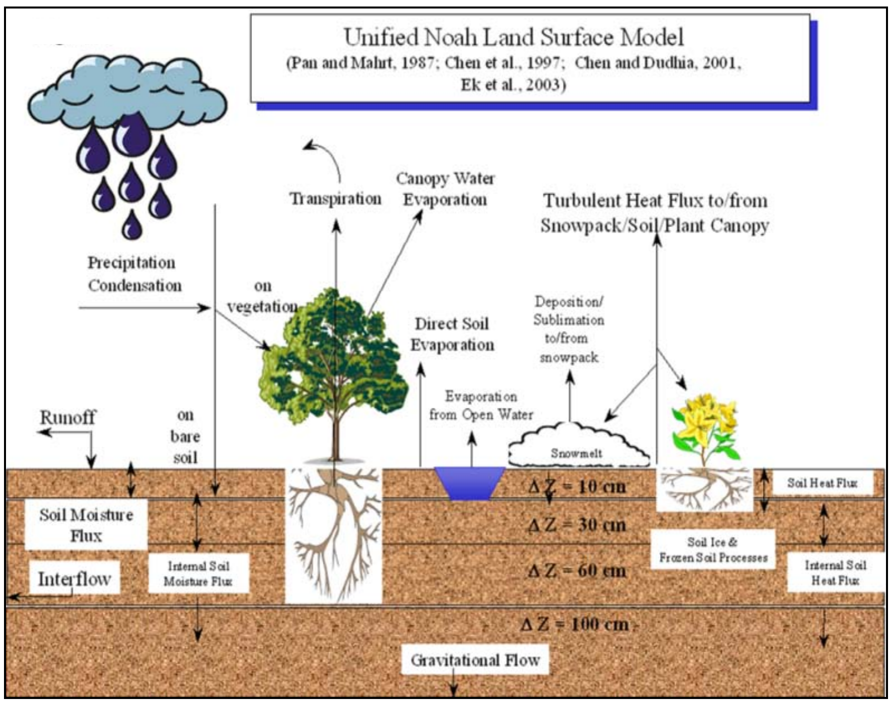
Soil temperature diffusion

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

WRF – (sub)surface compartment

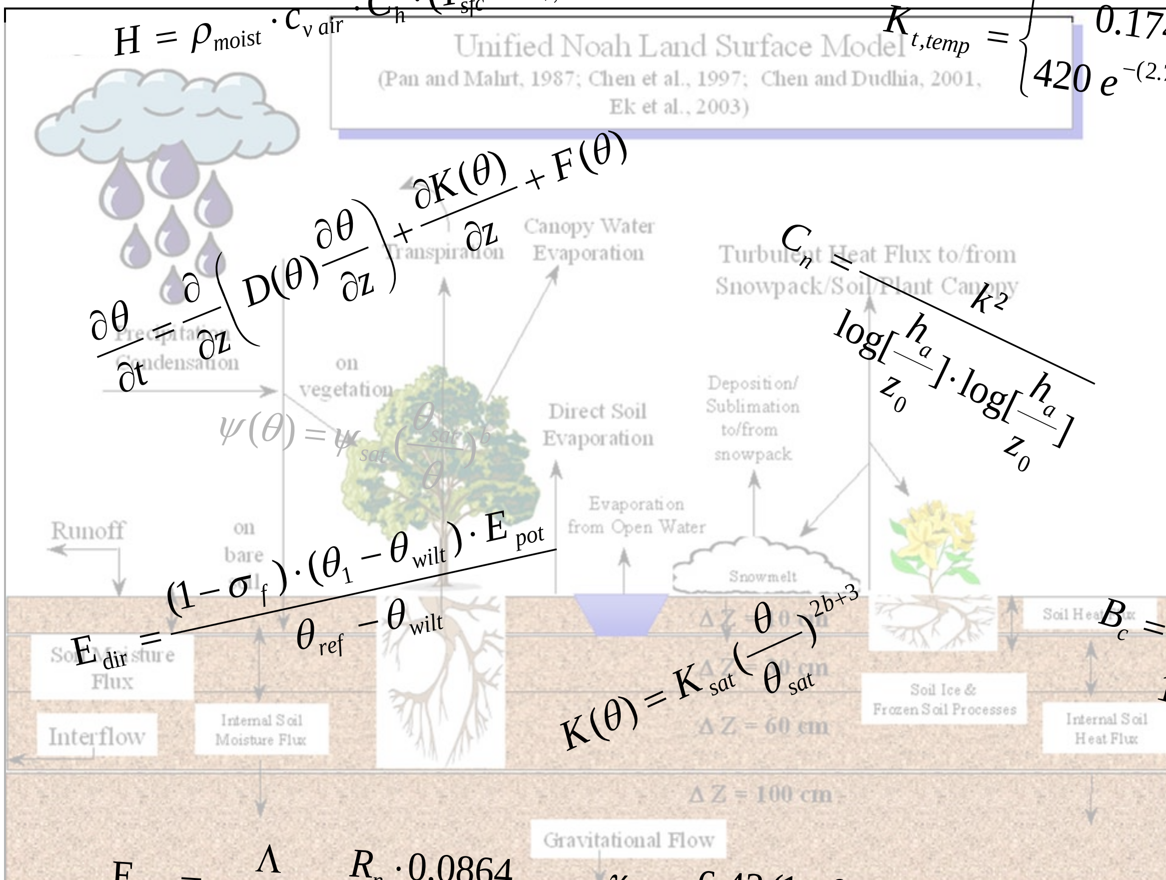


Surface and subsurface compartment



- Lower boundary: SVAT-model for surface and subsurface water budgets
- **Joint atmospheric-terrestrial water budget calculations**

Model Equations NOAH LSM



$$H = \rho_{moist} \cdot c_{v\,air} \cdot C_h \cdot (T_{sfc} - T_{v,a})$$

$$K_{t,temp} = \begin{cases} 0.174 & If[P_f > 5.1 \; or \; P_f < 0] \\ 420\, e^{-(2.7+P_f)} & else \end{cases}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} + F(\theta)$$

$$C_h = \frac{k^2}{\log[\frac{h_a}{z_0}] \cdot \log[\frac{h_a}{z_0}]}$$

$$\psi(\theta) = \psi_{sat}\left(\frac{\theta_{sat}}{\theta}\right)^b$$

$$D(\theta) = K(\theta)\frac{\partial \psi}{\partial \theta}$$

$$E_{dir} = \frac{(1-\sigma_f)\cdot(\theta_1 - \theta_{wilt})\cdot E_{pot}}{\theta_{ref} - \theta_{wilt}}$$

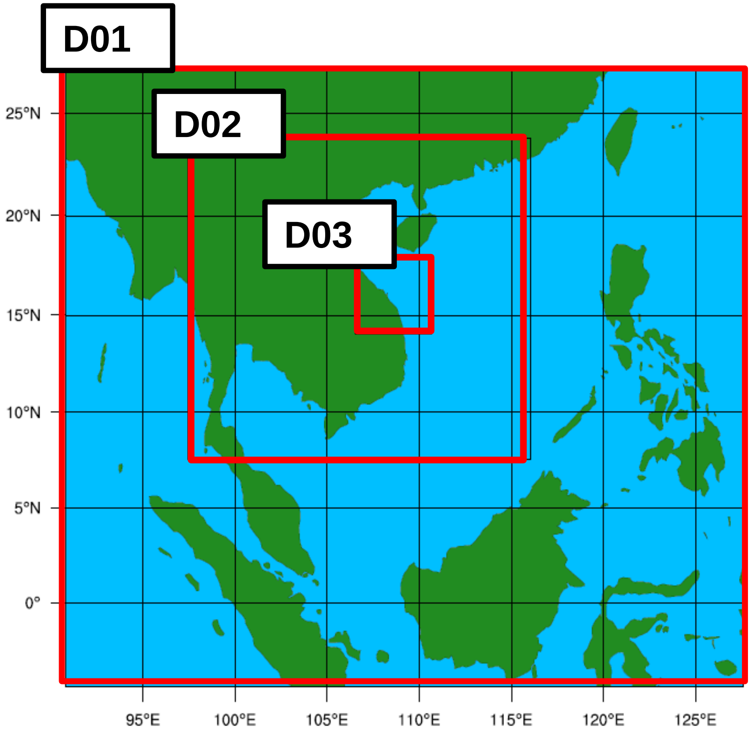
$$K(\theta) = K_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{2b+3}$$

$$B_c = \frac{1 + \frac{\Lambda_{q_{sat}}}{R_r}}{1 + R_c \cdot C_h + \frac{\Lambda_{q_{sat}}}{R_r}}$$

$$E_{pot} = \frac{\Lambda}{(\Lambda+\gamma)} \cdot \frac{R_n \cdot 0.0864}{\lambda} \cdot + \frac{\gamma}{(\Lambda+\gamma)} \cdot \frac{6.43\,(1+0.536\, v_a)}{\lambda}(e_{sat} - e)$$

$$C_v(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[K_i(\theta)\frac{\partial T}{\partial z}\right]$$

WRF Setup



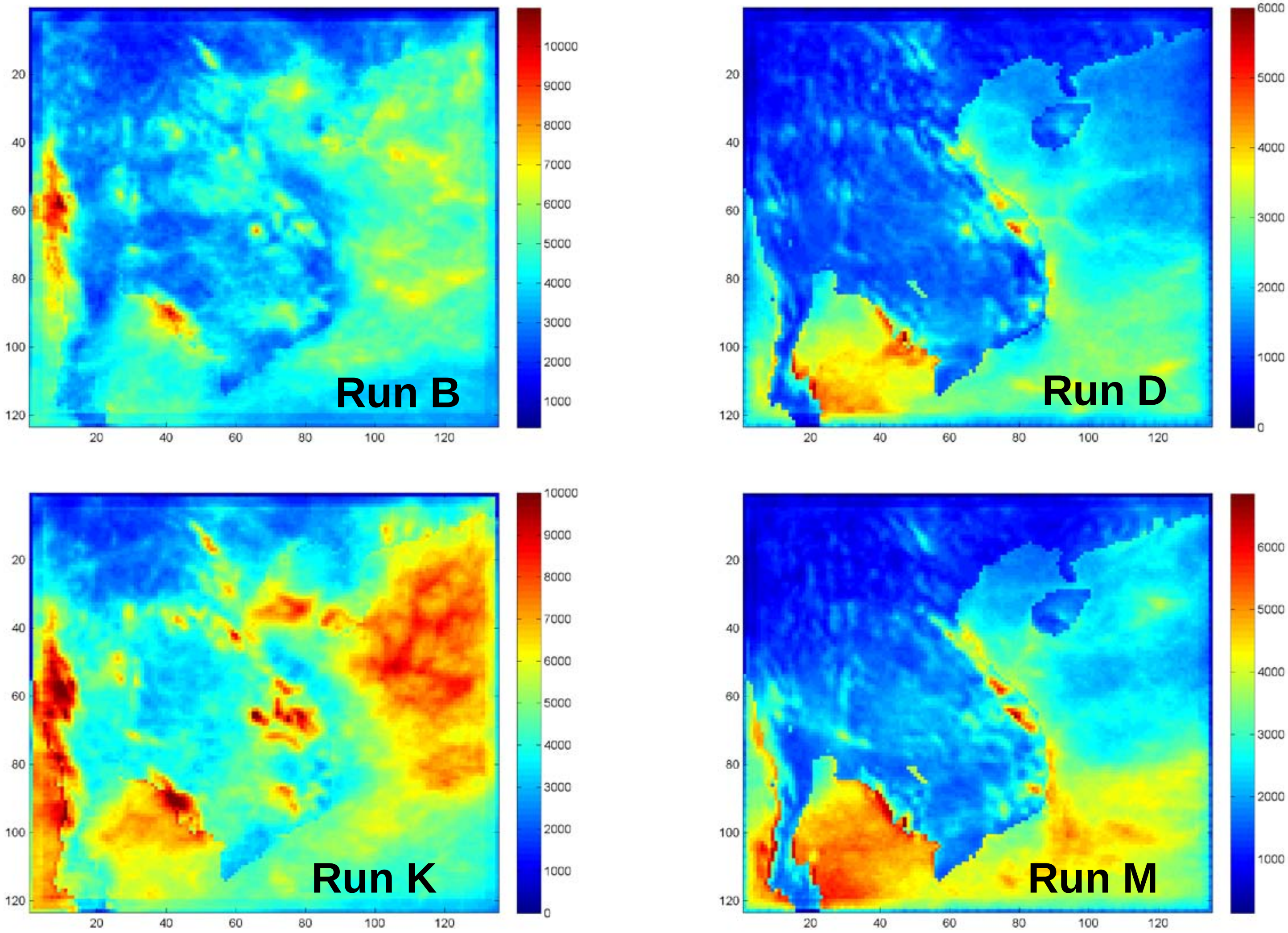
Domain1:
- horizontal: 99 x 99 grid points with a resolution of **45 km**
- vertical: 50 layers up to 5000 Pa
- time step: 180 s

Domain2:
- horizontal: 142 x 145 grid points with a resolution of **15 km**
- vertical: 50 layers up to 5000 Pa
- time step: 120 s

Domain3:
- horizontal: 66 x 75 grid points with a resolution of **5 km**
- vertical: 50 layers up to 5000 Pa
- time step: 40 s

Transient WRF simulation from 1960 - 2050
WRF results strongly depend on subgridscale parameterizations

Comparison Parameterization Runs: P



Systematic WRF Experiments: Focus on P

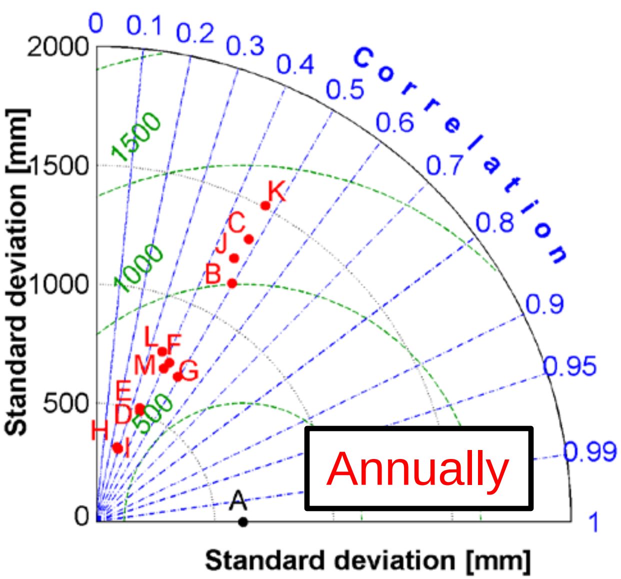
- 12 Combinations using 3 MP, 2 PBL and 2 CU schemes
- 2 Combinations using NCEP & ERA40 Reanalyses

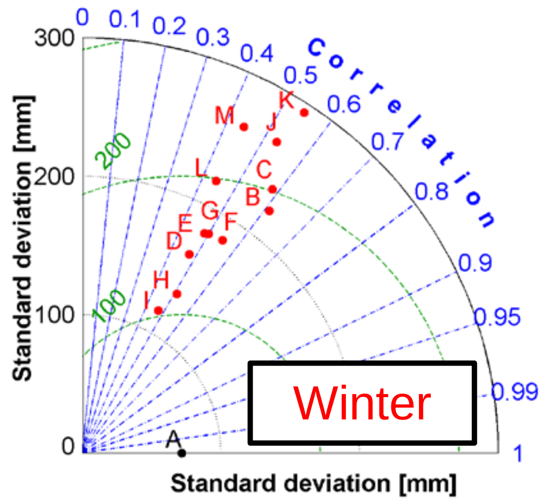
→ 2 x 12 = **24 WRF simulation for 2000**

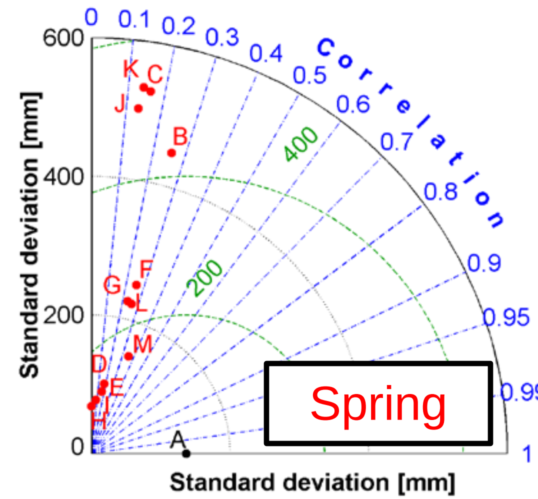
Run	Microphysic schemes	PBL physic schemes	Cumulus physic schemes
B	Lin et al.	Hong et al.	Betts-Miller-Janjic
C	Lin et al.	Nakanishi and Niino	Betts-Miller-Janjic
D	Lin et al.	Nakanishi and Niino	New SAS
E	Lin et al.	Hong et al.	New SAS
F	WRF Single-Moment 3-class	Hong et al.	Betts-Miller-Janjic
G	WRF Single-Moment 3-class	Nakanishi and Niino	Betts-Miller-Janjic
H	WRF Single-Moment 3-class	Hong et al.	New SAS
I	WRF Single-Moment 3-class	Nakanishi and Niino	New SAS
J	WRF Double-Moment 6-class	Hong et al.	Betts-Miller-Janjic
K	WRF Double-Moment 6-class	Nakanishi and Niino	Betts-Miller-Janjic
L	WRF Double-Moment 6-class	Nakanishi and Niino	New SAS
M	WRF Double-Moment 6-class	Hong et al.	New SAS

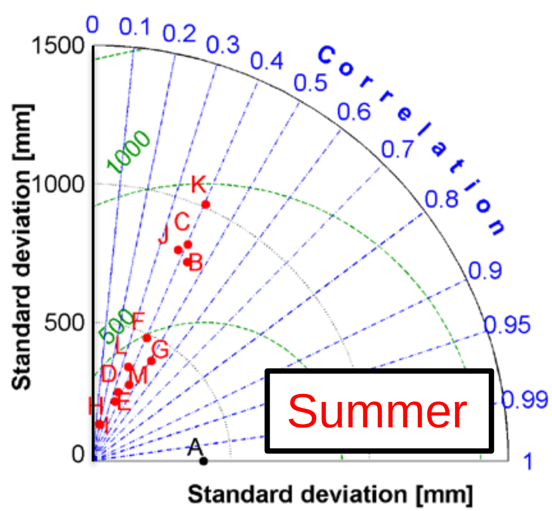
Validation ERA40-WRF 2000 Experiments: P

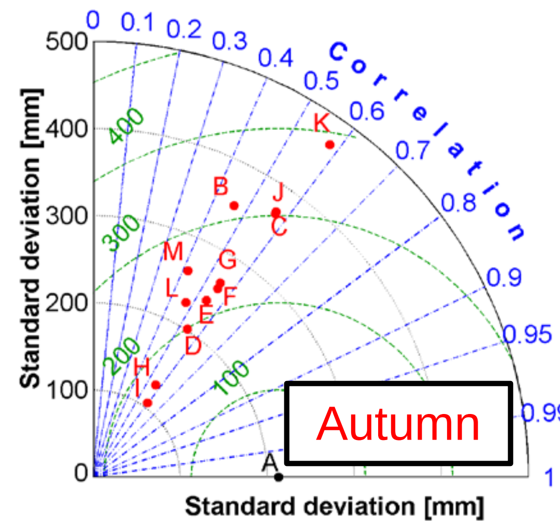
A: APHRODITE data







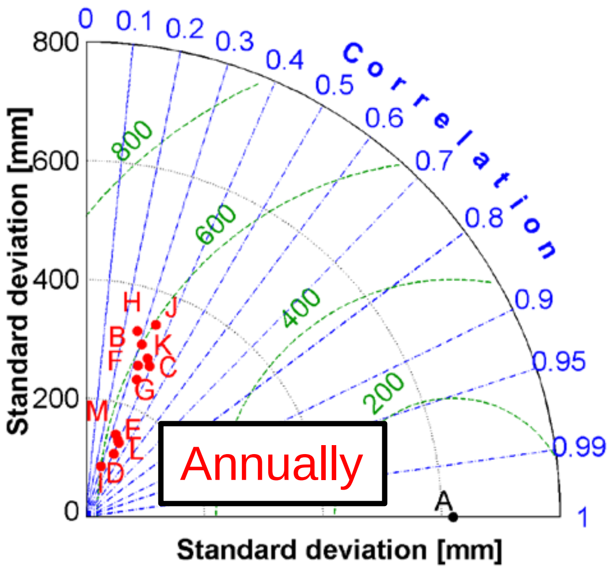


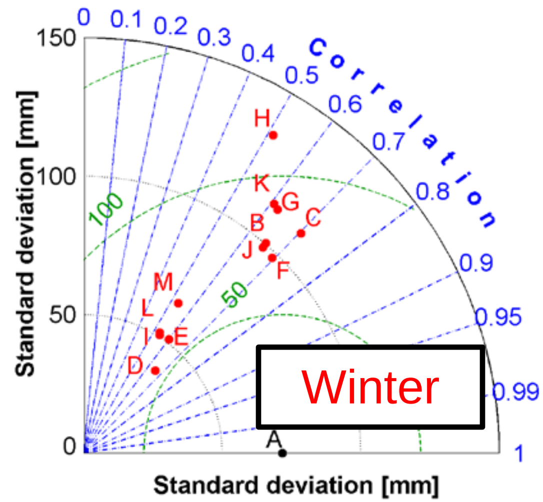


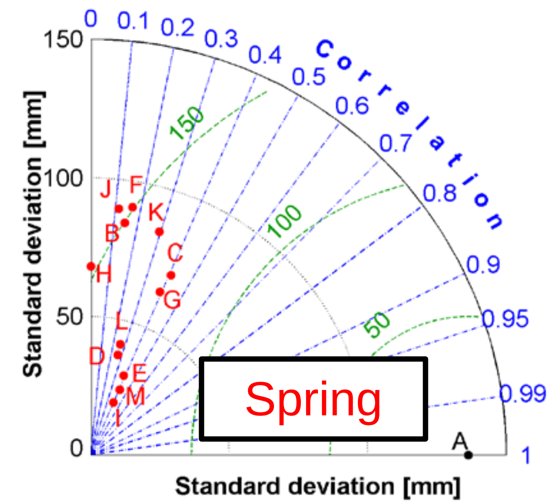
Pearson Correlation Coefficient
Root Mean Squared Error
Standard Deviation

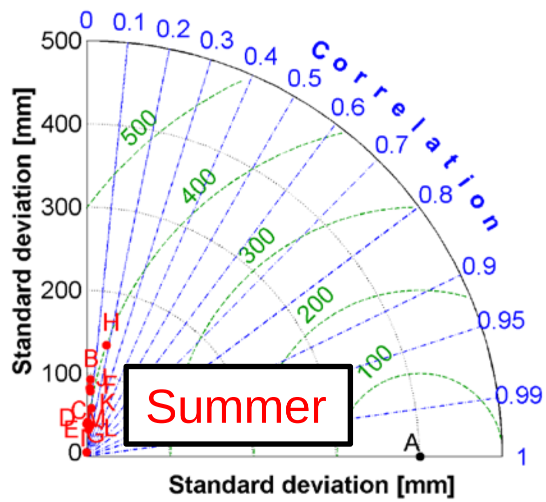
Validation NCEP-WRF 2000 Experiments: P

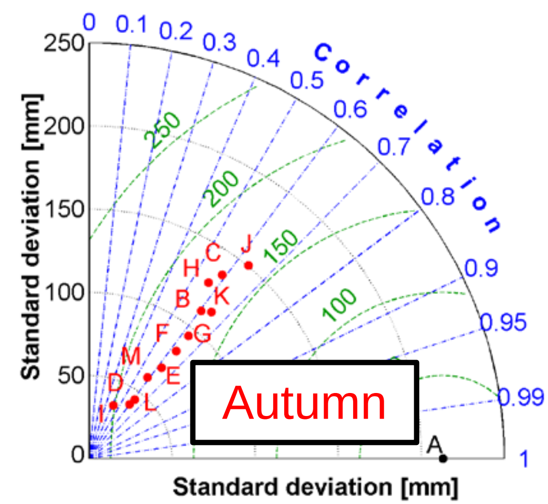
A: APHRODITE data











Pearson Correlation Coefficient
Root Mean Squared Error
Standard Deviation

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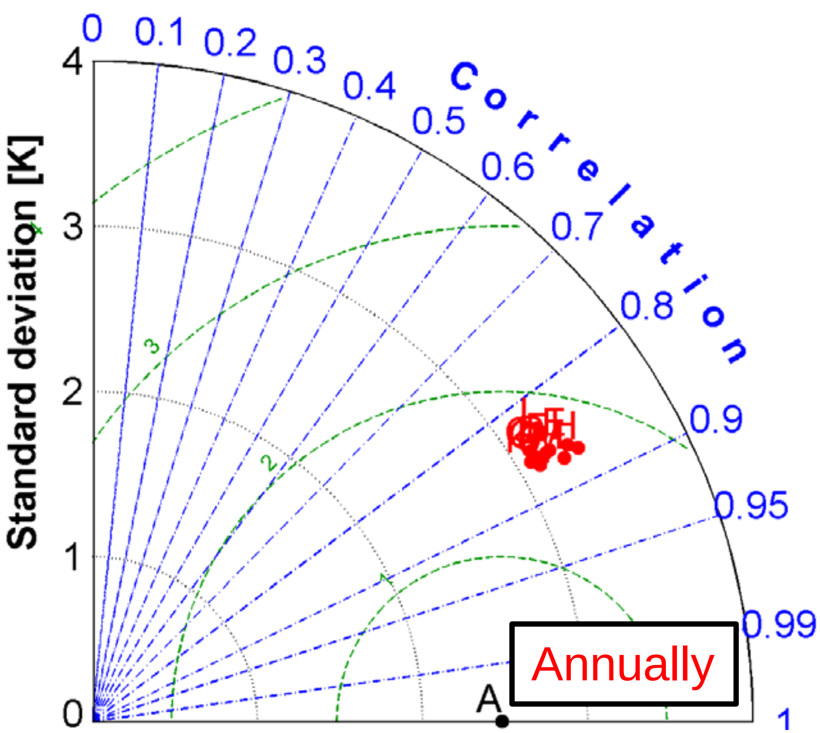
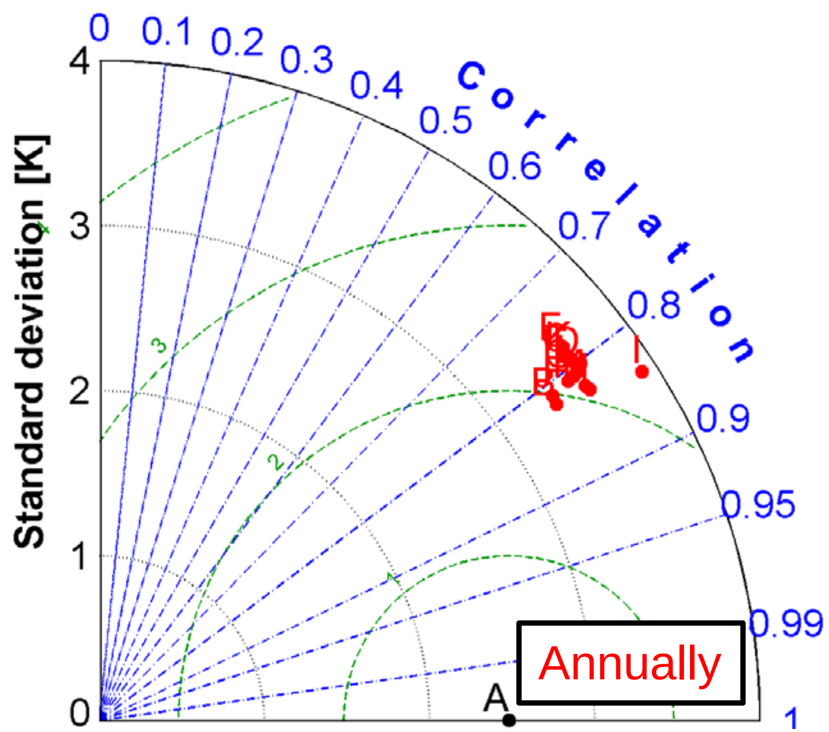
Validation WRF 2000 Experiments: T2

A: CRU data



ERA40



NCEP

Final Decision (based on simulated T, P)

- **ERA40 Reanalysis**
  - Lower bias in T
  - Higher pattern correlation of P (summer)

Run	Microphysic schemes	PBL physic schemes	Cumulus physic schemes
B	Lin et al.	Hong et al.	Betts-Miller-Janjic
C	Lin et al.	Nakanishi and Niino	Betts-Miller-Janjic
D	Lin et al.	Nakanishi and Niino	New SAS
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G	**WRF Single-Moment 3-class**	**Nakanishi and Niino**	**Betts-Miller-Janjic**
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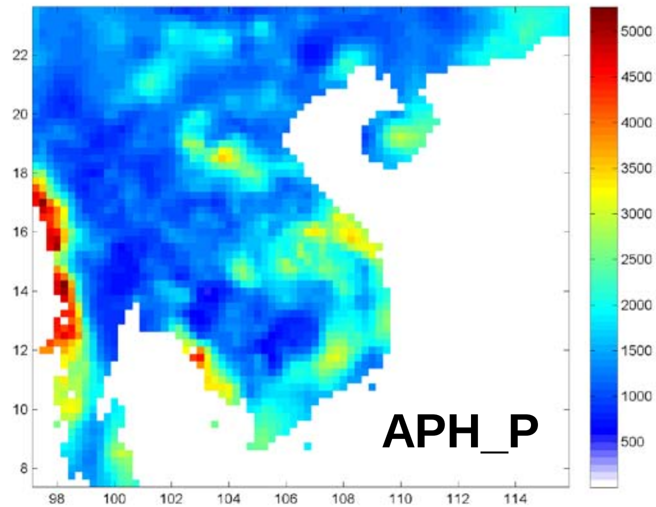
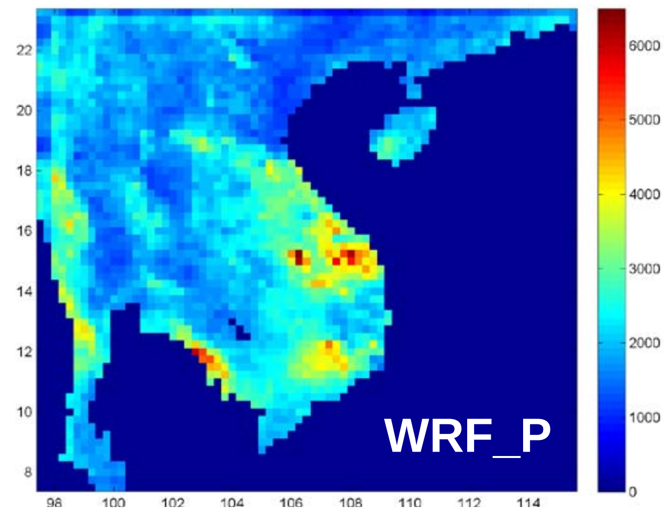
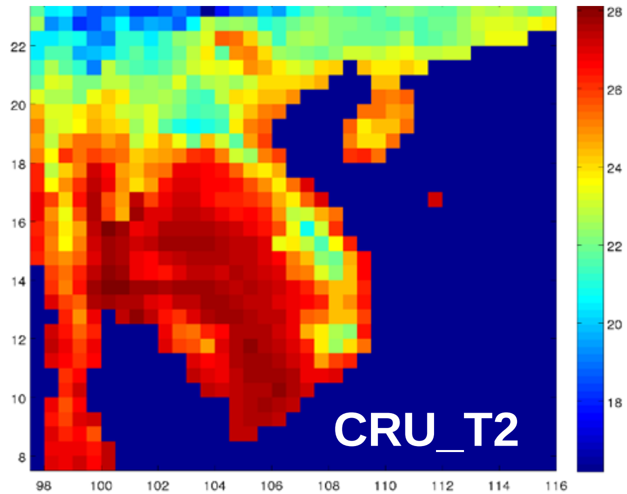
ERA40-WRF vs. OBSERVATIONS DOM2 (P, T2)

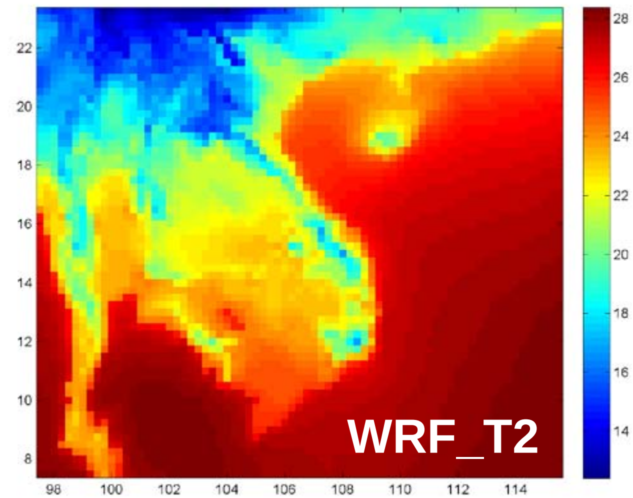
Karlsruher Institut für Technologie



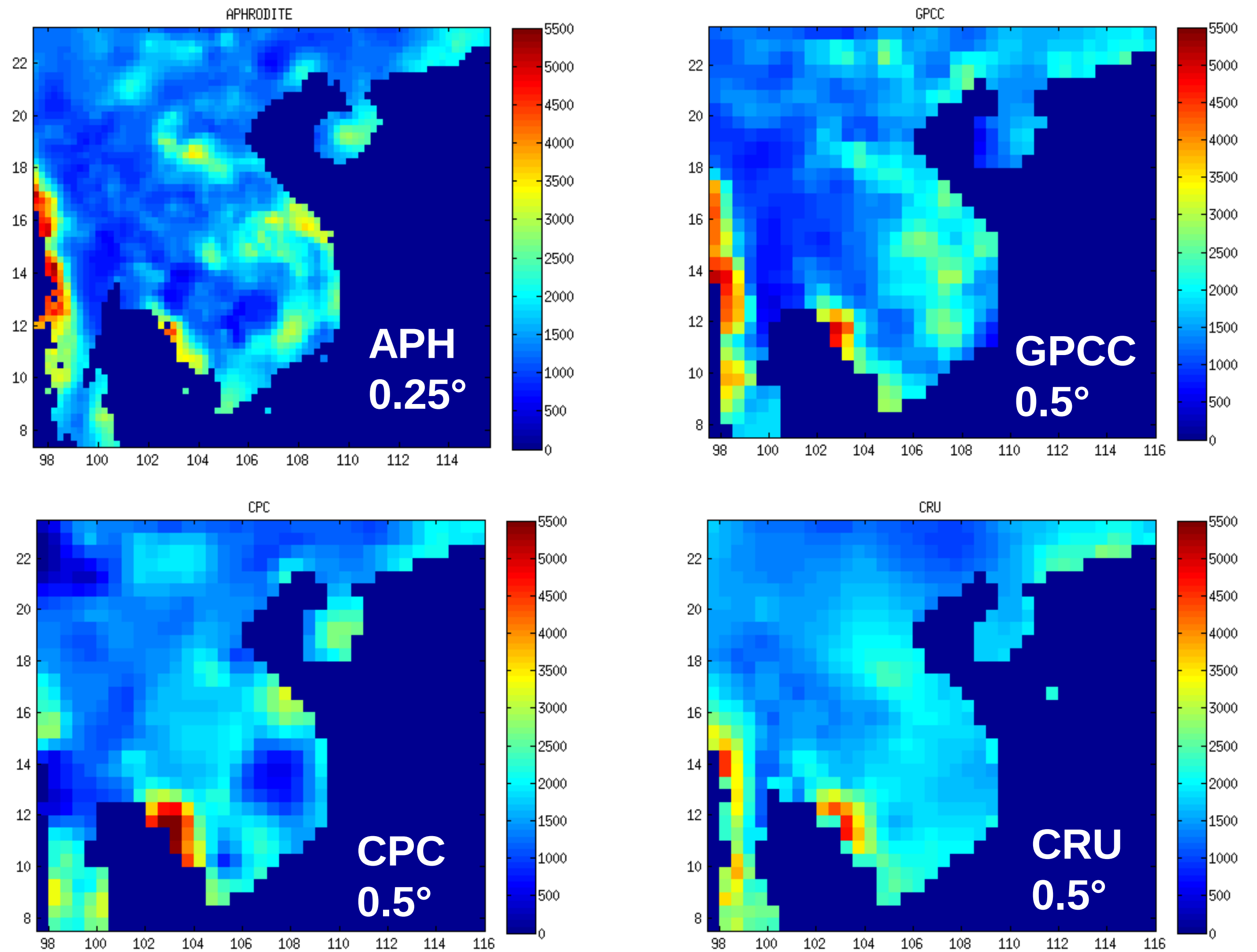


Year 2000





Different Reference Datasets: P



LUCCi Progress Report of WP3

- **Collection of hydrometeorological observation data**
- **Plausibility analysis and correction of data**
- **Statistical analysis**
- **Transient climate simulations in three nesting steps with resolutions of 45 km, 15 km and 5 km**
  - Preliminary work: computing and storage facilities, experimental simulations, final setup of WRF
  - WRF Simulations: 10 out of 90 years

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Future activities of WP3 *Climate Modeling*

- **04/2012 PhD thesis (IHP & KIT): Impact of LUC on climate and vice versa (Mrs. Nguyen Phuong)**
- **09/2012 PhD DAAD scholarship (KIT): Impact of CC on terrestrial water balance as well as flood and drought characteristics (Mr. Dang Thinh)**
- **Statistical Downscaling & Bias Correction: Estimation of GCM and scenario inherent uncertainties**

Potential collaborations with HMO-VNU

- **Aggregation of available CC information for Vietnam to allow for improved uncertainty estimation (PDFs)**
  - Multi-model multi-scenario (different GCMs, emission scenarios)
  - Different RCMs (PRECIS, RegCM3, WRF)

- **Validation strategies (methodologies, data sources, etc.)**

- **Extreme value analysis based on EV theory**
  - Assessment of future climate indices
  - Return periods of floods and droughts

- **Joint scientific publications**

Cảm ơn

Thank you for your attention

Preparation RCM Simulations: HPC Environment

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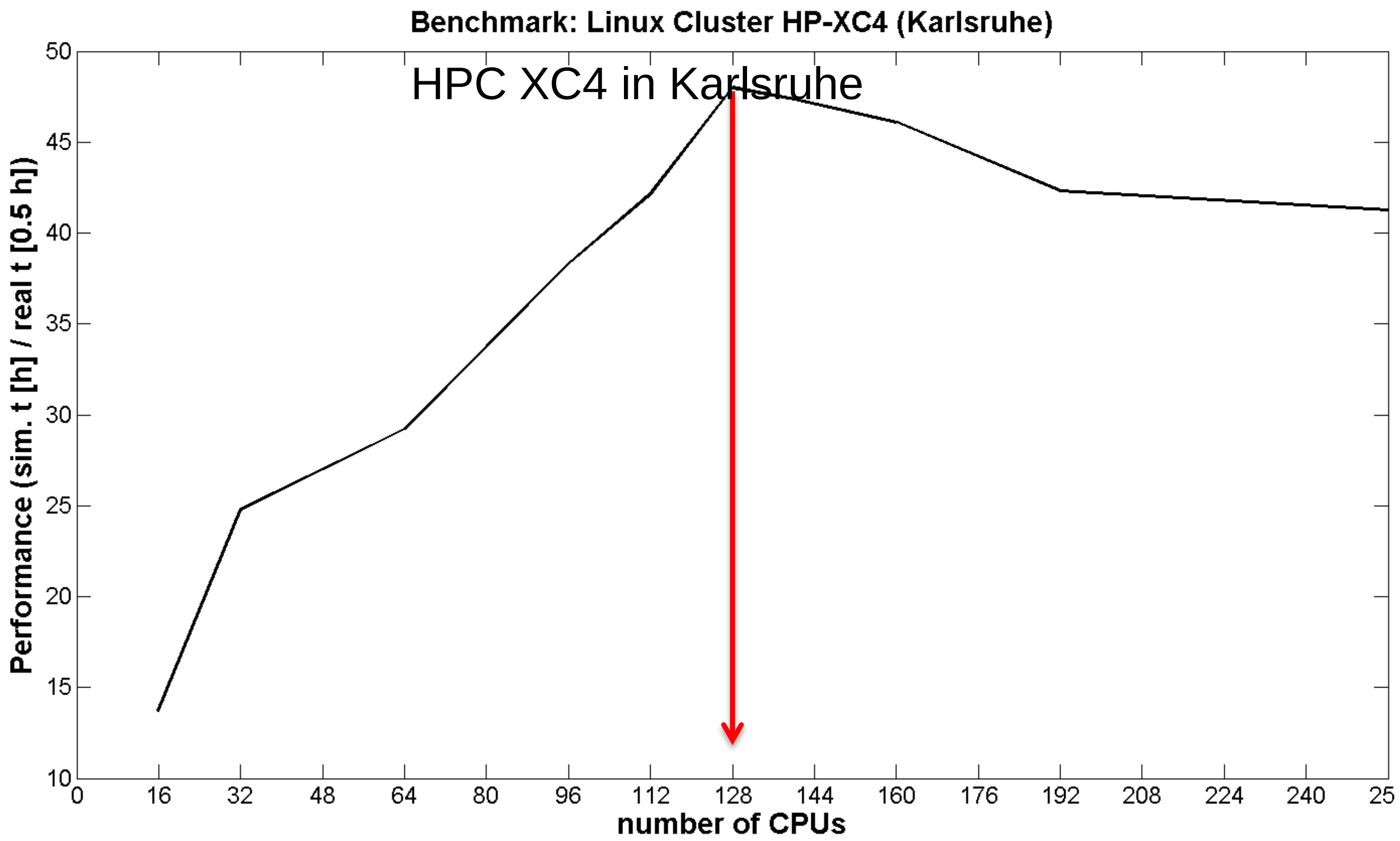
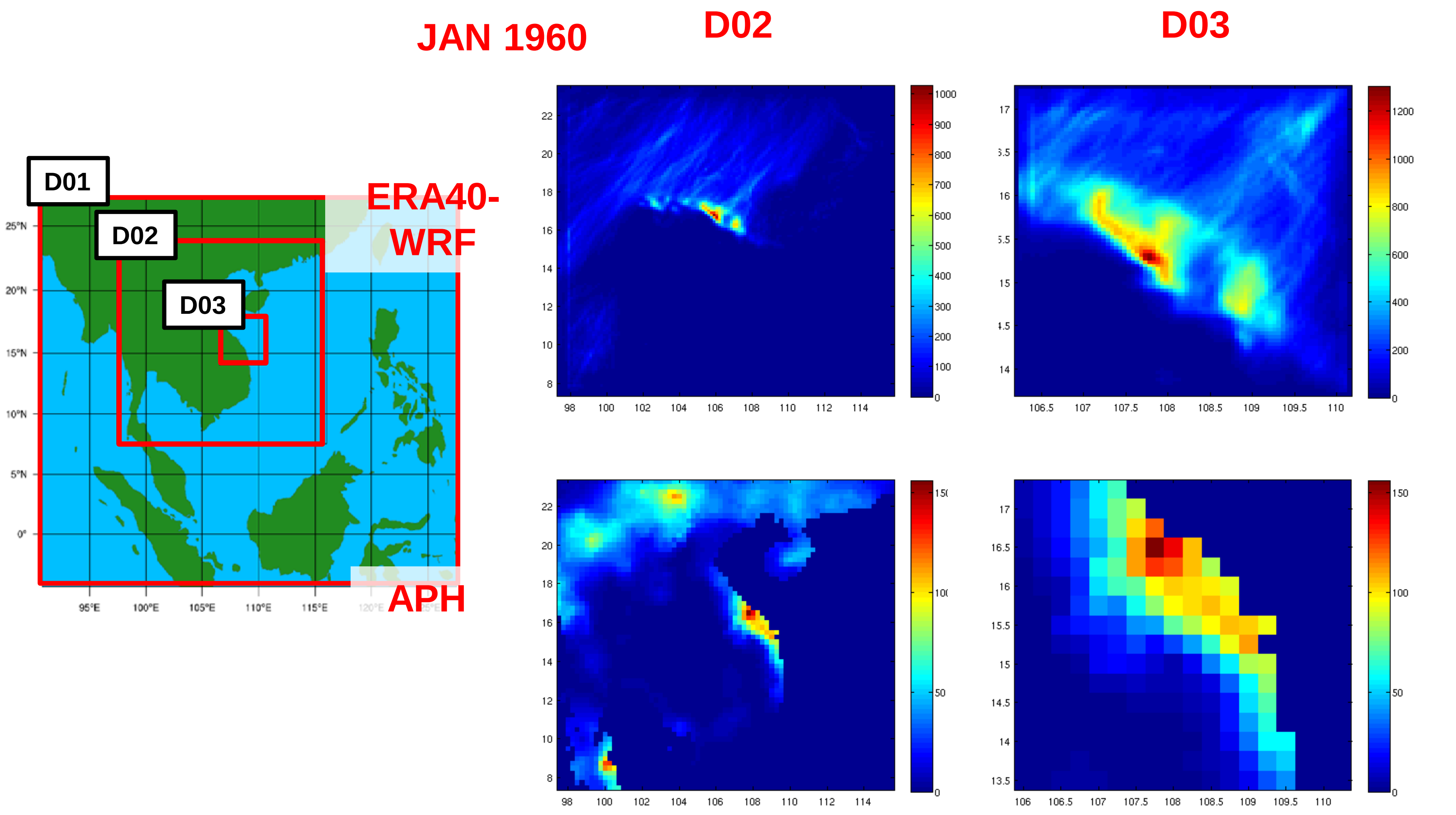


- **Peak performance using 128 CPUs**
- **Depends on CPUs, Compiler (options), but also WRF setup**

Motivation: why do we need RCM simulations?



How to derive Regional Climate Projections?

Population Growth Economic Development
Technological Progress

⇩

Emission Scenarios
Greenhouse Gas Concentrations

⇩

Global Climate Models

⇩

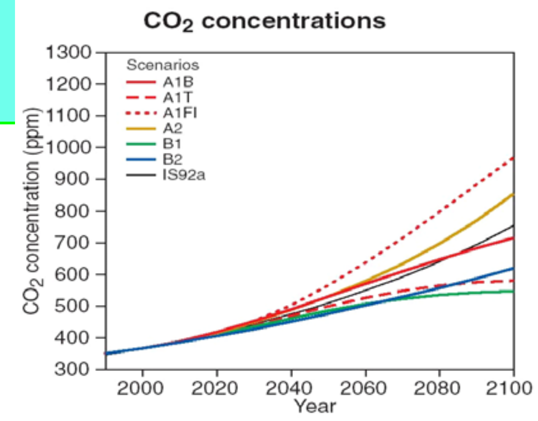
Global Climate Scenarios

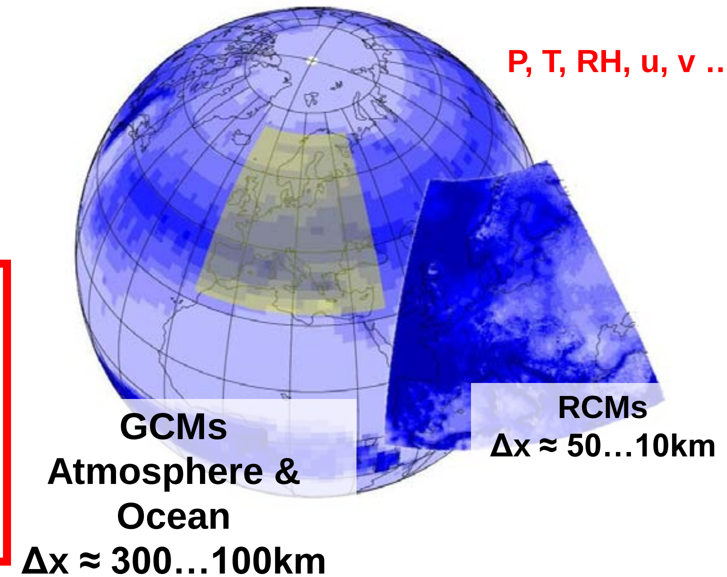
⇩

Downscaling Methods

⇩

Regional Climate Scenarios





WP3: Climate modeling (Project LUCCi)

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- **Analysis of observation data**
- **Process-based RCM simulations**
- **Progress Report of WP3 “*Climate Modeling*”**
- **Further activities of WP3 “*Climate Modeling*”**

WRF Modeling System

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