# Regional Atmosphere-Biosphere-Hydrosphere Modeling:

## Current Potentials & Future Requirements

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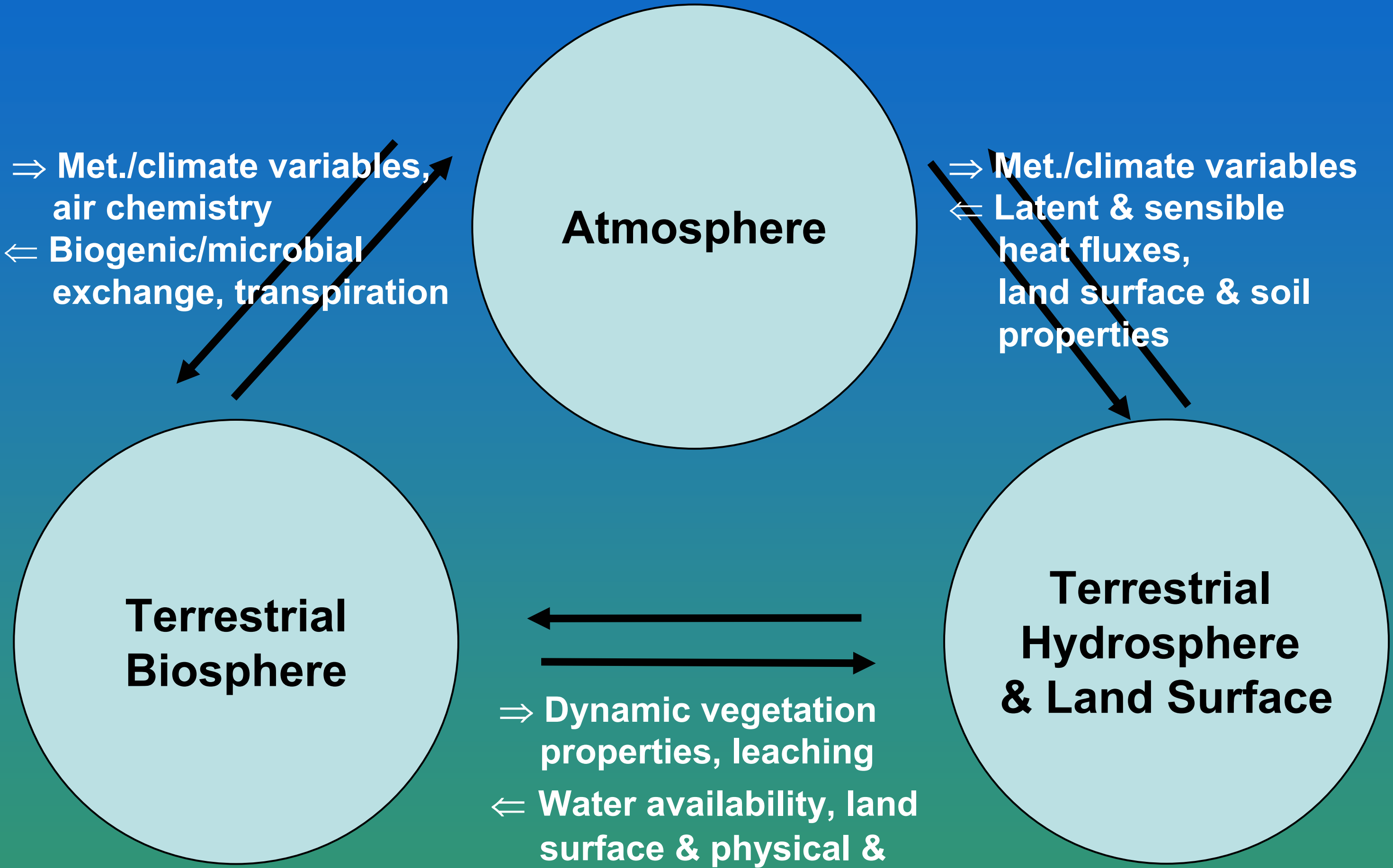
# Interdependent Systems: Brief Review



**Atmosphere**

⇒ Met./climate variables,
air chemistry
⇐ Biogenic/microbial
exchange, transpiration

⇒ Met./climate variables
⇐ Latent & sensible
heat fluxes,
land surface & soil
properties

**Terrestrial Biosphere**

**Terrestrial Hydrosphere & Land Surface**

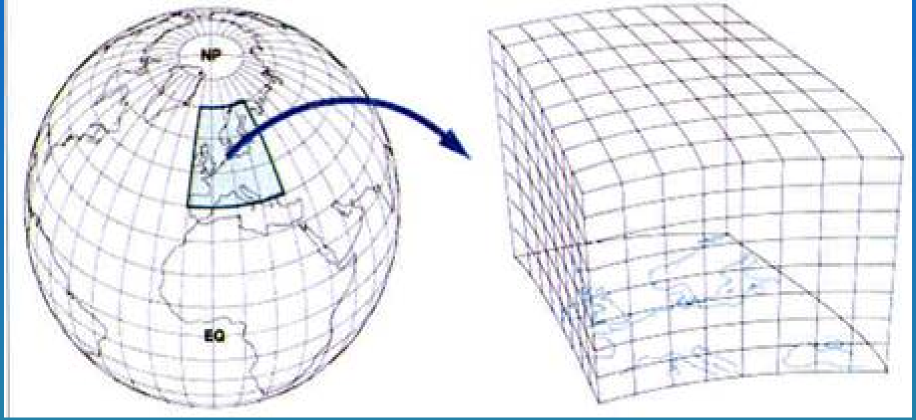
⇒ Dynamic vegetation
properties, leaching
⇐ Water availability, land
surface & physical &
chemical soil properties

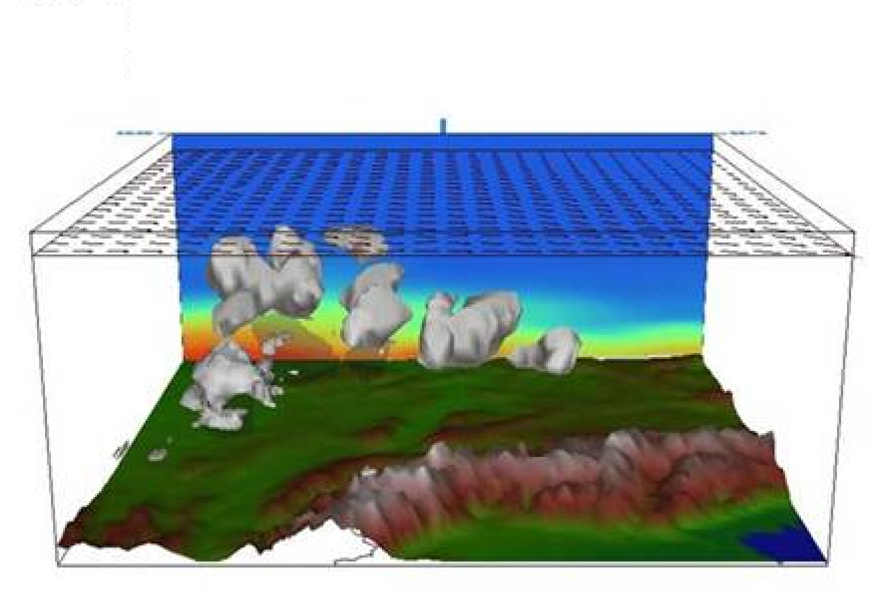
+ anthropogenic impact/management

# Current Potentials

# Regional Atmospheric Modeling

**Atmosphere**





Concept of dynamical downscaling

# Regional Atmospheric Modeling

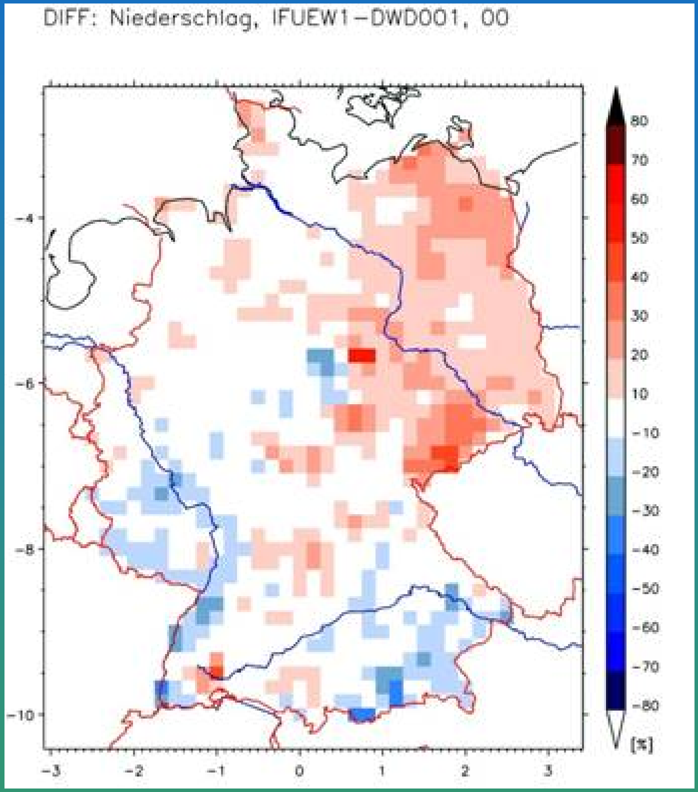
## Basic facts

**Atmosphere**

- Scales: 1 km (non-hydrostatic) < Δx < 50 km
  10-60 vertical layers for troposphere
  3 sec < Δt < 150 sec
- Boundary & initial cond. by global atmospheric model
- Nesting approach (successive refinement)
- Grid scale: general physical laws (conservation of energy, momentum, mass)
- Subgrid scale: parameterisations (turbulence, convection, cloud & precipitation physics)
- Requires land surface-, soil-, vegetation-properties, DEM, etc.

# Regional Atmospheric Modeling

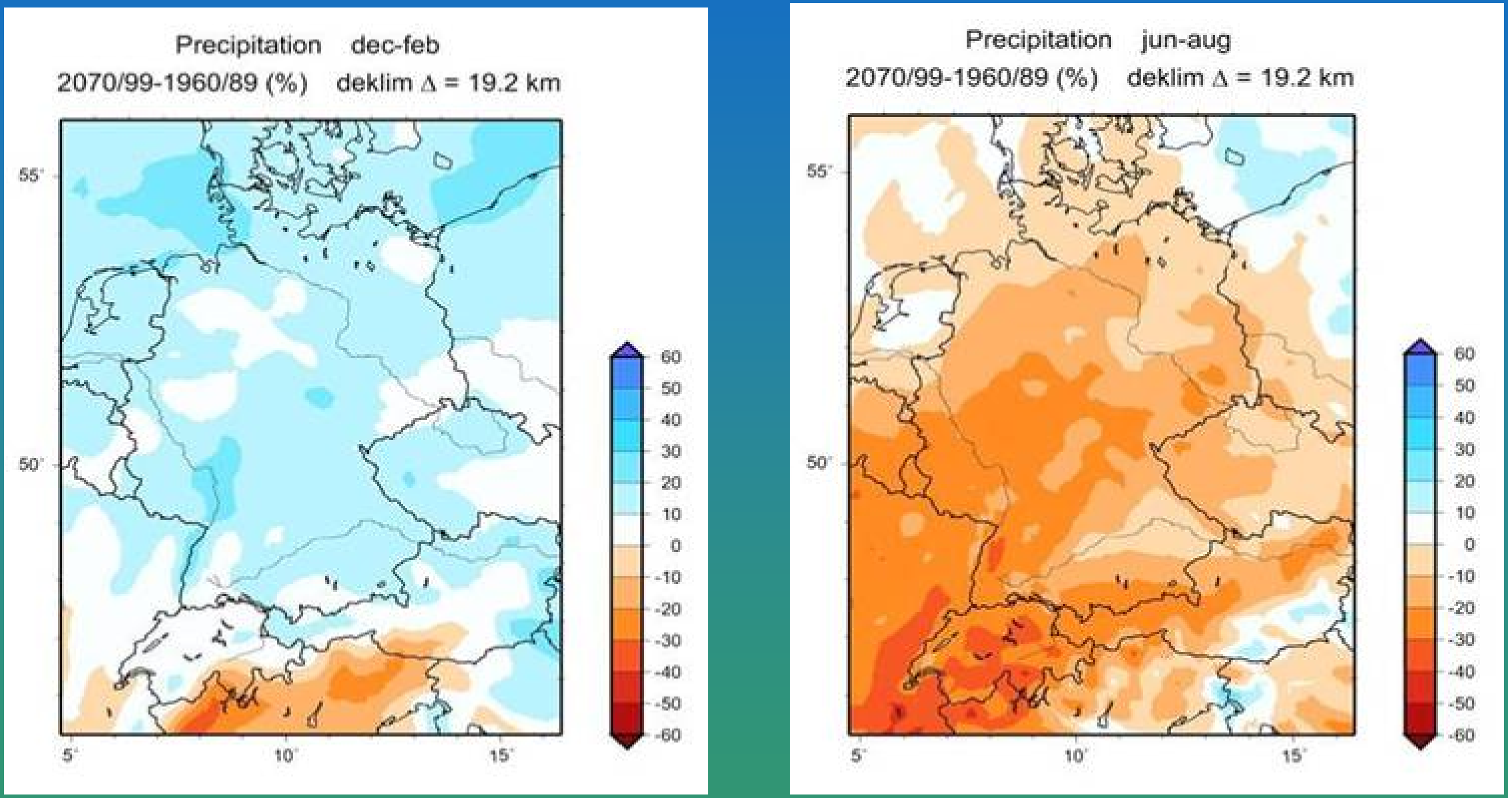
## Performance of Atmospheric Models



Difference MM5-ECMWF 19 km
vs. DWD gridded stations
1979-1993

# Regional Atmospheric Modeling

## Example: Regional Climate Modeling Impact of Climate Change on Precipitation



Precipitation dec-feb
2070/99-1960/89 (%) deklim Δ = 19.2 km

Precipitation jun-aug
2070/99-1960/89 (%) deklim Δ = 19.2 km

Expected precipitation change
MM5-ECHAM4, A2

# Regional Atmospheric Modeling

**Air chemistry models**

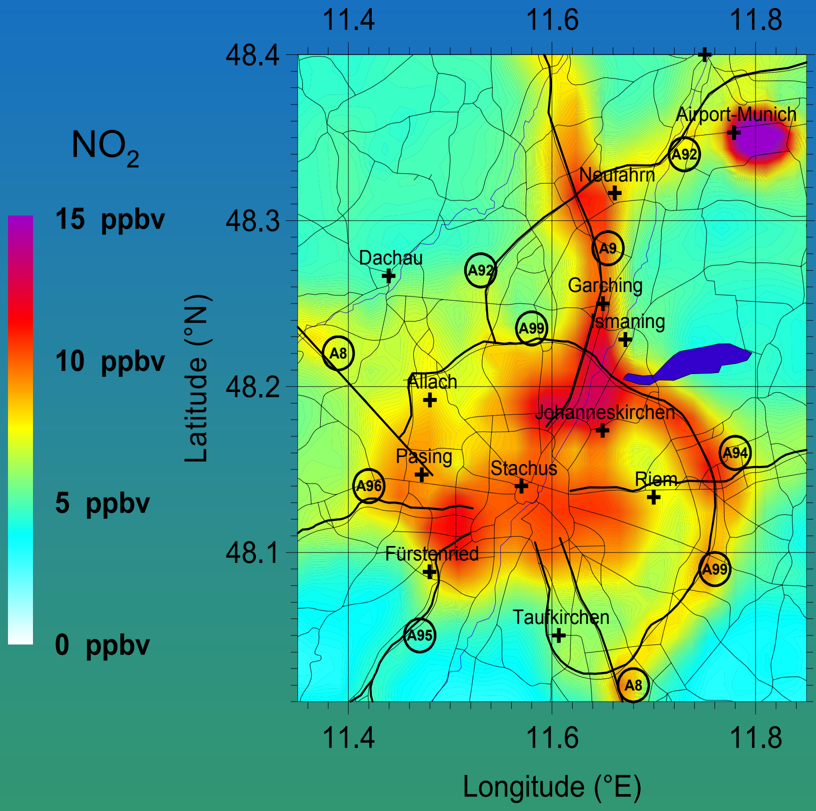
- Solving both for atmospheric transport & chemical kinetics
- Conservation laws (energy & mass) for all trace species (up to 200 species)
- Chemistry mechanisms defined by species & respective reaction paths
- Reducing complexity by lumping of similar species into groups
- Surface interaction both at lower boundary and particle surface
- Numeric:
  time splitting schemes
  ≈ factor 10 increased complexity compared to pure meteorological model
- Linking terrestrial biosphere: e.g. through canopy chemistry

**Requires met. variables at all grid points**

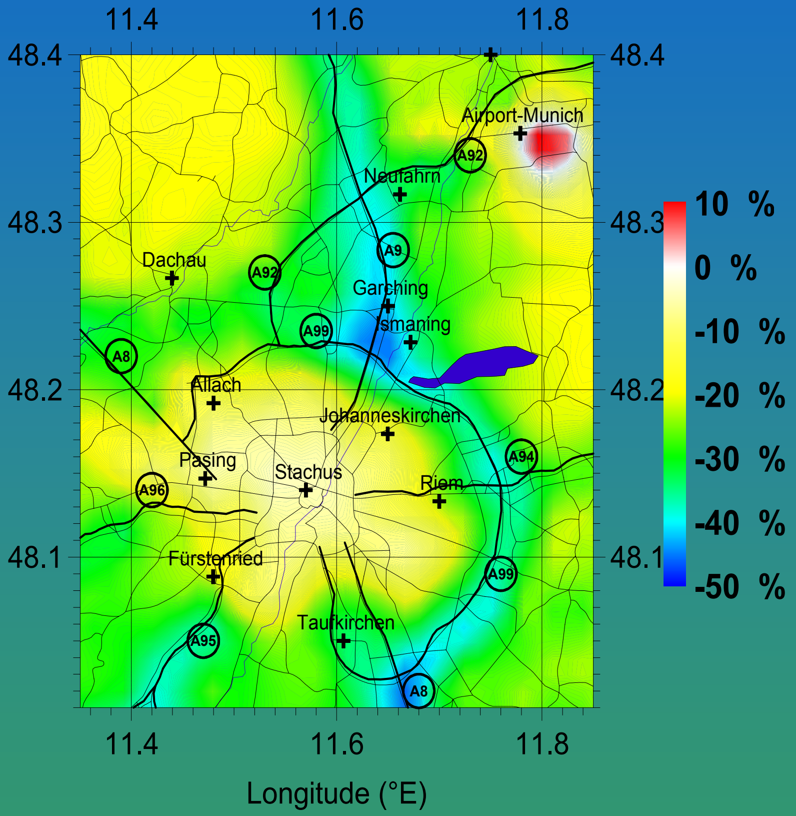
- Online vs. offline coupled codes

# Regional Atmospheric Modeling

## Example: Regional Meteorology-Chemistry Simulation Air Pollution in Metropolitan Areas



Air pollution distribution for the Munich area in summer 2000



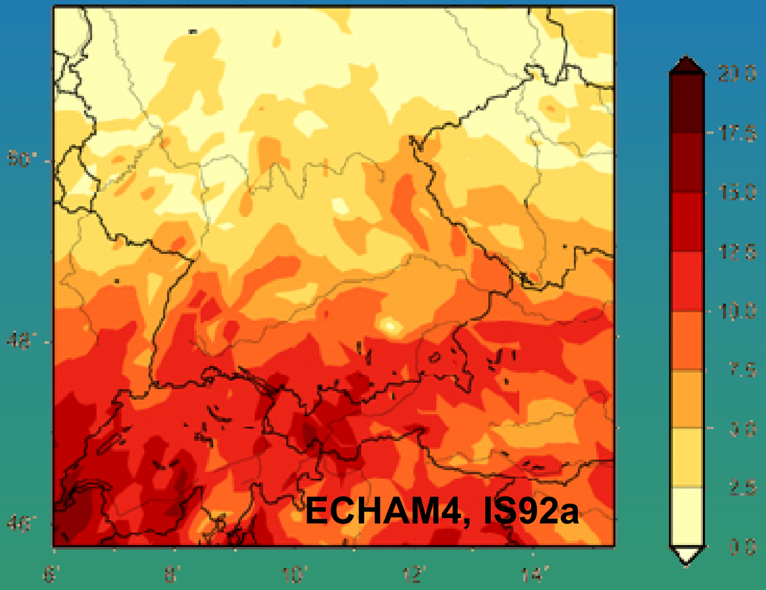
Air pollution difference due to emission projection in 2010

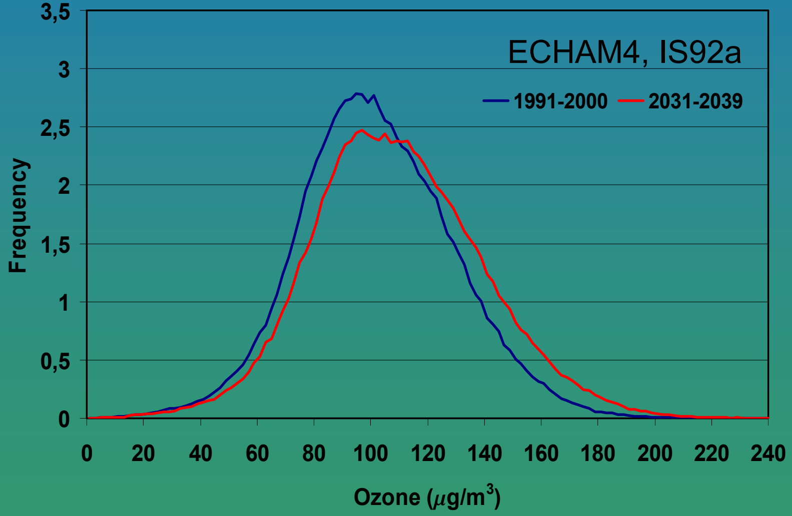
# Regional Atmospheric Modeling

## Example: Regional Climate-Chemistry Simulation
## Impact of Climate Change on Air Chemistry

Days with Threshold > 120 ug/m$^3$ Jun-Aug

Difference 2031/2039 - 1991/2000 uv20



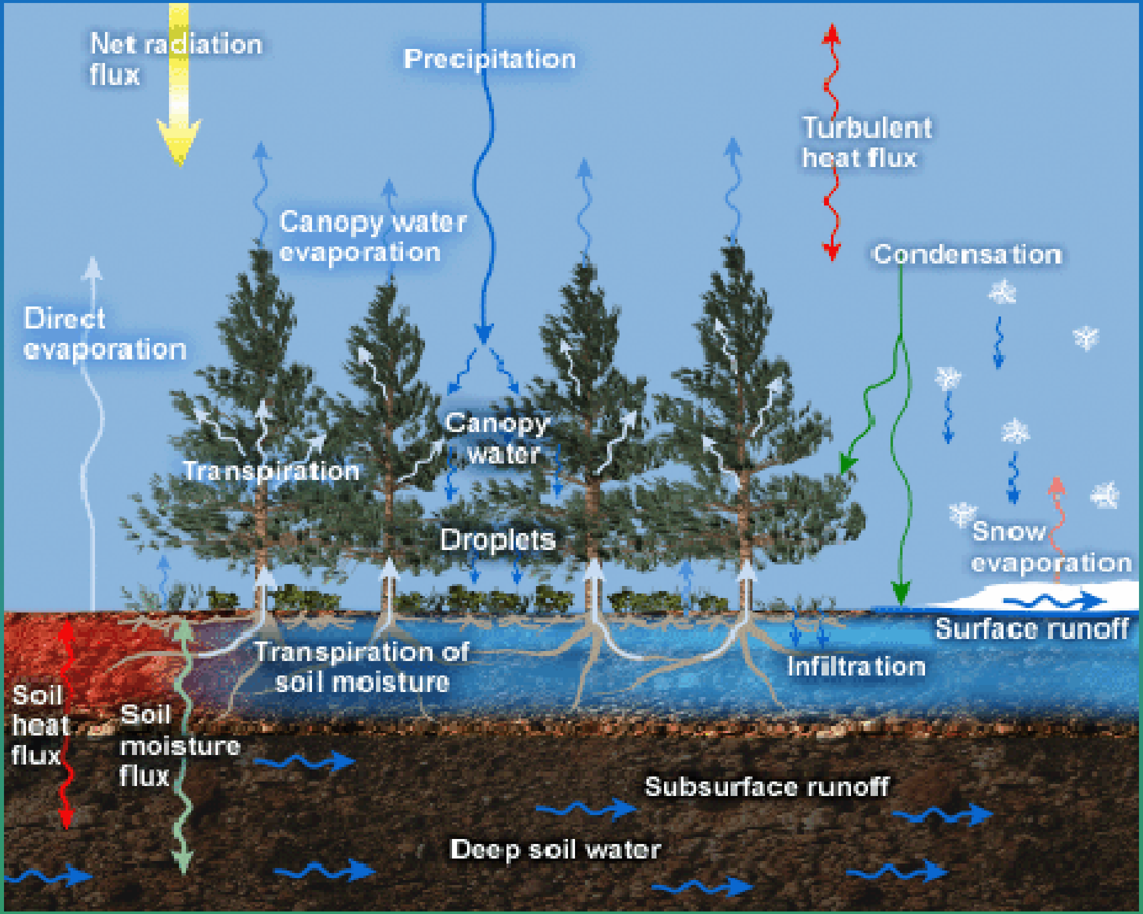


Increased occurrence of extreme value conditions

# Terrestrial Hydrological Modeling

## How does a standard atmospheric model account for terrestrial hydrology and vegetation?

**Terrestrial Hydrosphere & Land Surface**



Soil-Vegetation-Atmosphere-Transfer models

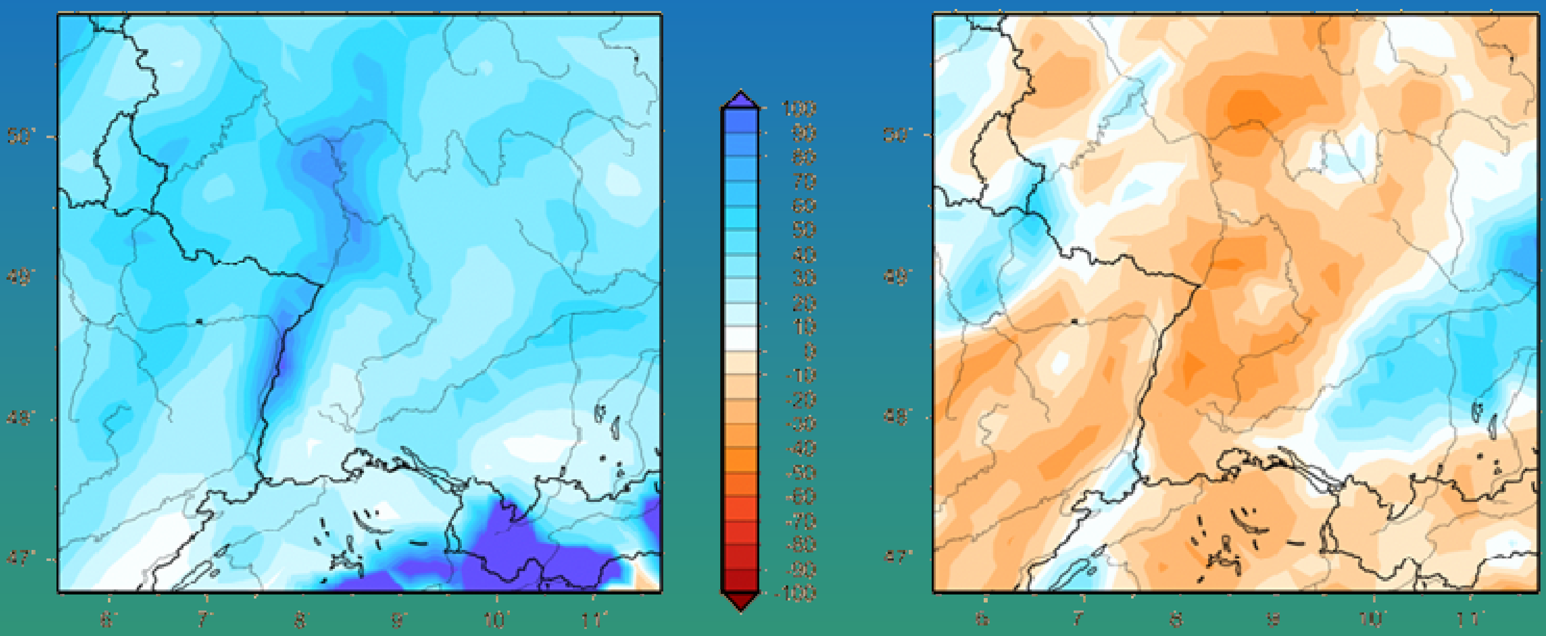
# Regional Atmospheric Modeling

## How does a standard atmospheric model account for terrestrial hydrology and vegetation?

- Vertical discretization: e.g. 4 soil layers till 2 m depth
- Solving **heat diff. equation** (soil temp.) & **Richards equation** (soil moisture)
- Canopy transpiration via **Penman-Monteith & resistance approach**
- Stability dependent **exchange coefficient** for sensible and latent heat fluxes
- Lower **boundary condition** for deep soil temperature & moisture
- **fixed vegetation** properties: e.g. vegetation type
- **seasonally fixed**: e.g. LAI, albedo, roughness length, water stress parameters

# Terrestrial Hydrological Modeling

## Example: Regional Climate Modeling
## Impact of Climate Change on Infiltration Excess



**DJF**

**JJA**

Change in infiltration excess [%] 2070-2099 vs. 1960-89, ECHAM4 & MM5, B2

# Terrestrial Hydrological Modeling

## Basic differences between SVAT-based hydrological models and “traditional” hydrological models

- **SVAT-Hydro Models (designed for atmospheric feedback purposes)**:

  full energy balance (soil heat & sensible heat fluxes)

  2-way interaction with PBL

- **“Traditional”-Hydro models (designed for pure hydrol. applications)**:

  lateral water fluxes, surface runoff routing

  deeper soils considered

  finer vertical & horizontal resolutions

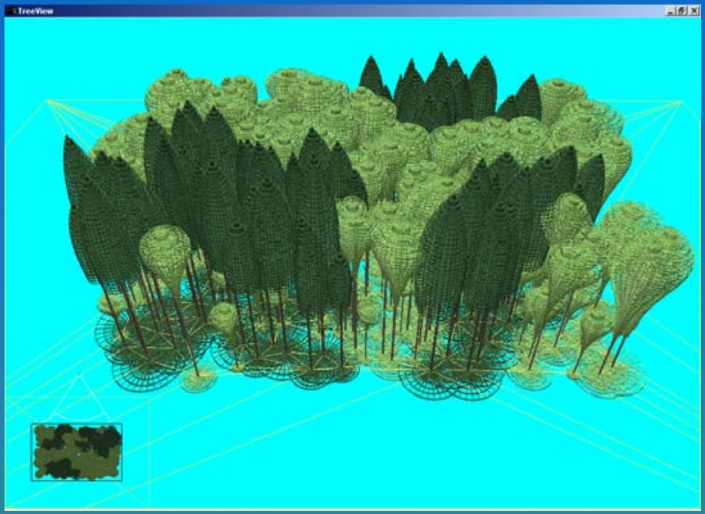
  often groundwater interaction

  often extensions for reactive flow & transport, erosion, etc.

  **but: depending on specific model choice**

# Biosphere Modeling

Biosphere



Macro-scale ecosystem

Micro-scale ecosystem

# Biosphere Modeling

**Biosphere**

## Basic facts (DNDC; MOBILE)

- 1-d column approach (soil & vegetation layers)
- 10 sec. < Δt < 1 day
- Driven by met./climate & air chemistry data
- **Macroscale ecosystem**

  1) Vegetation dynamics: e.g. stand level, foliage, LAI
  2) Soil-hydrology approaches: a) bucket b) SVAT
- **Microscale ecosystem**

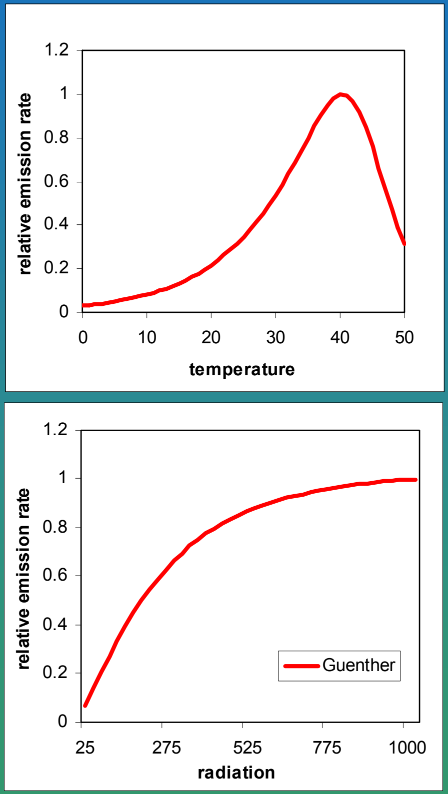
  1) Physiological (vegetation) & biogeochemical (soil) processes (C & N- fluxes & balances): mass fluxes, dissolution, decomposition, oxidation, adsorption, complexation, assimilation & reverse processes

  2) optionally (celluar level): biochemical processes C-metabolism (e.g. VOC emission)

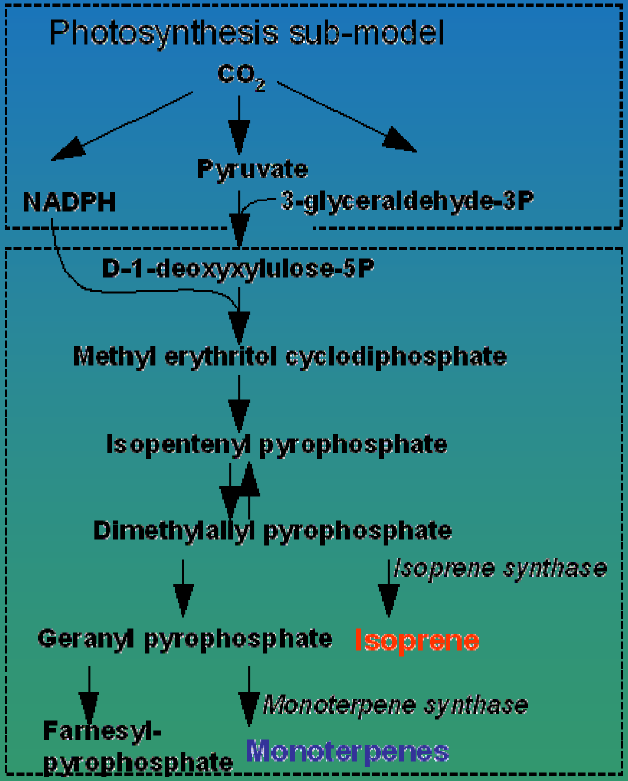
# Biosphere Modeling

## Process based vs. empirical approaches

### Example: VOC modeling



Empirical



Photosynthesis sub-model

$CO_2$

**Pyruvate**

**NADPH**

**3-glyceraldehyde-3P**

**D-1-deoxyxylulose-5P**

**Methyl erythritol cyclodiphosphate**

**Isopentenyl pyrophosphate**

**Dimethylallyl pyrophosphate**

*Isoprene synthase*

**Geranyl pyrophosphate**

**Isoprene**

*Monoterpene synthase*

**Farnesyl-pyrophosphate**

**Monoterpenes**

Process based

# Biosphere Modeling

## Process based vs. parameterized approaches

### Example: VOC modeling

### Empirical

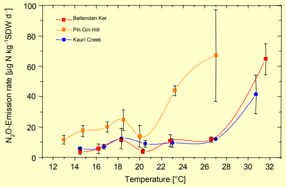
- Transparent relations
- Reliable within the parameterized range
- Requires data on time scale of prediction (often not available)

### Process-Based

- Better representation of variability
- Principally suitable for scenario studies (e.g. climate change & land use change)

# Biosphere Modeling

## Laboratory scale

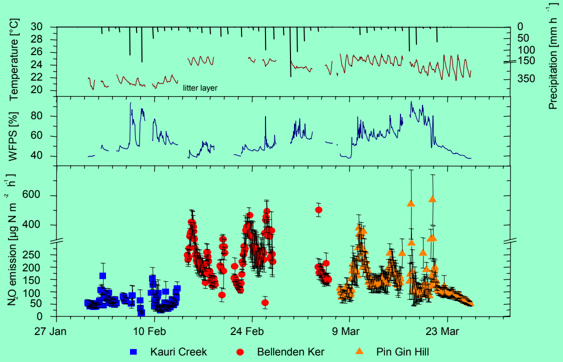


$$\text{fact\_moist}\ [l] = 1 - \frac{1}{1 + e^{\frac{\text{water}[l] - \text{W\_CRIT}}{\text{W\_DELTA}}}}$$

$$\text{fact\_temp}\ [l] = \left(\frac{\text{T\_MAX} - \text{temp}[l]}{\text{T\_MAX} - \text{T\_OPT}}\right)^{\text{T\_A}} * e^{\text{T\_A} * \frac{\text{temp}[l] - \text{T\_OPT}}{\text{T\_MAX} - \text{T\_OPT}}}$$

$$\frac{d\ \text{nitr\_akt}[l]}{d\ t} = \text{MUEMAX} * \left(\frac{\text{temp\_moist\_fact}}{\frac{\text{KM\_DOC} + \text{DOC}[l]}{\text{DOC}[l]} + \frac{\text{KM\_N} + n[l]}{n[l]}} - \text{nitr\_akt}[l]\right)$$

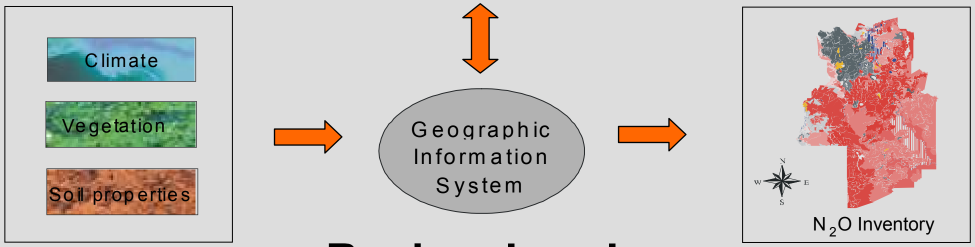
## Field scale



**Parametrisation**

**Calibration** **Validation**

**Process oriented biogeochemical model [PnET-N-DNDC]**



Climate

Vegetation

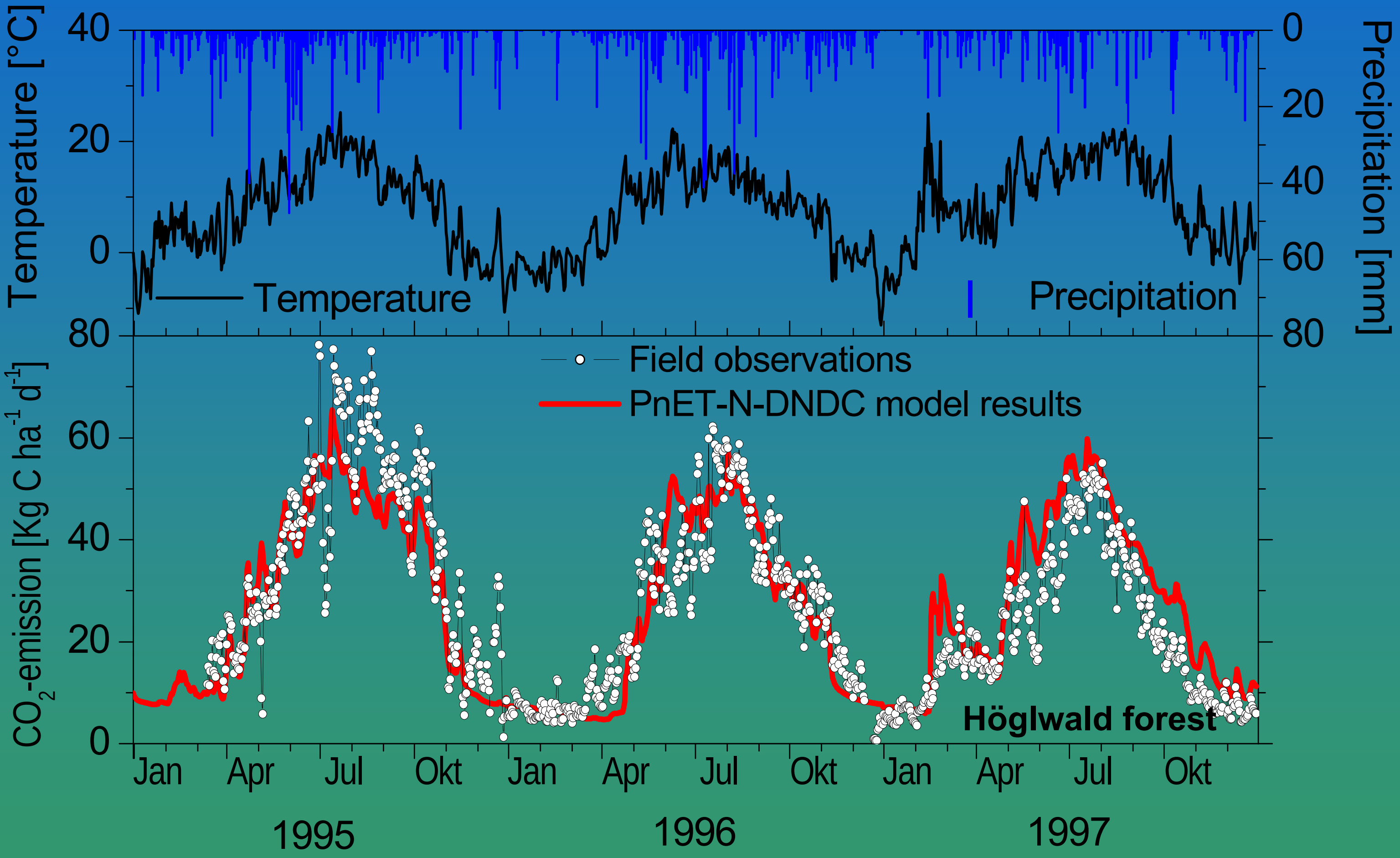
Soil properties

Geographic Information System

$N_2O$ Inventory

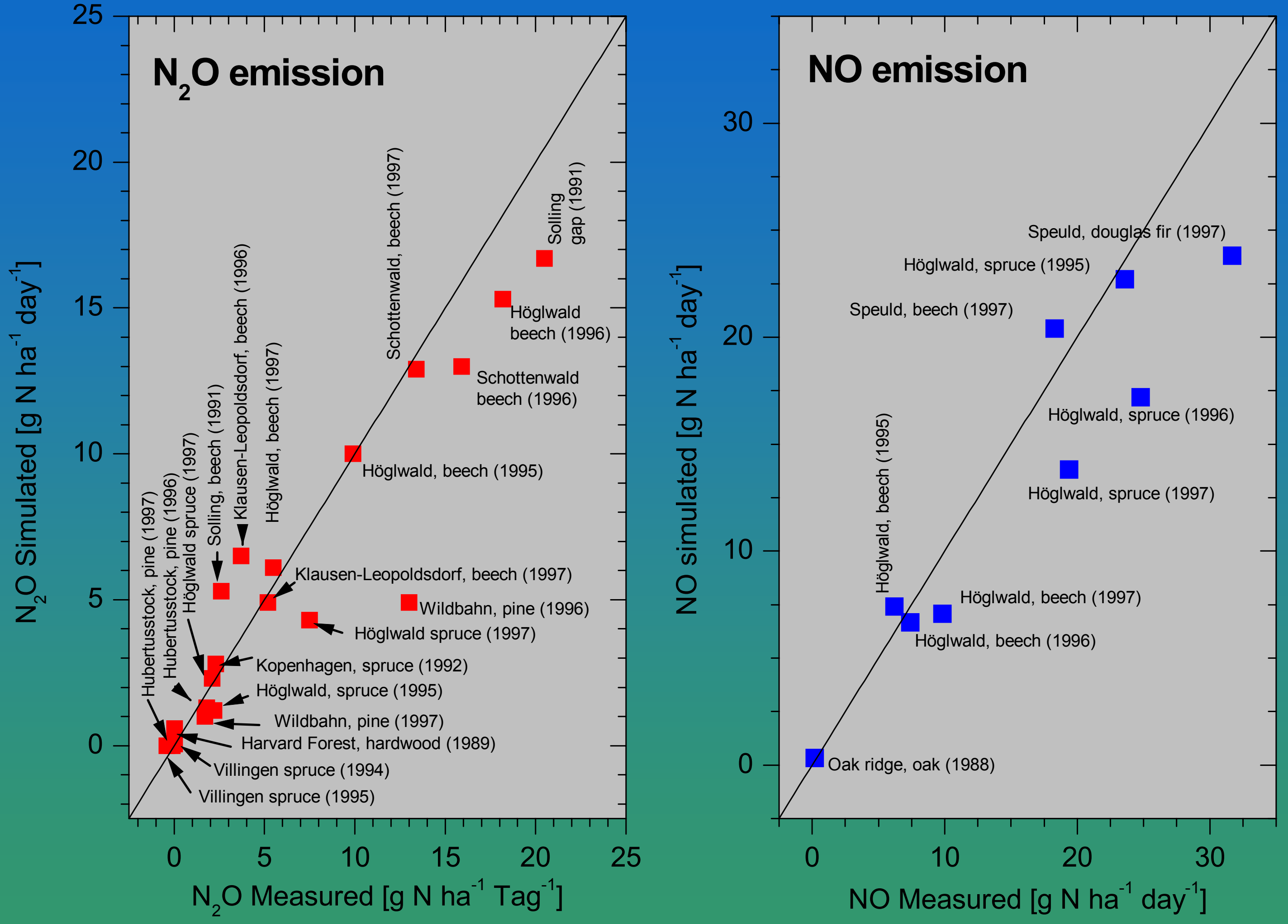
## Regional scale

# Biosphere Modeling



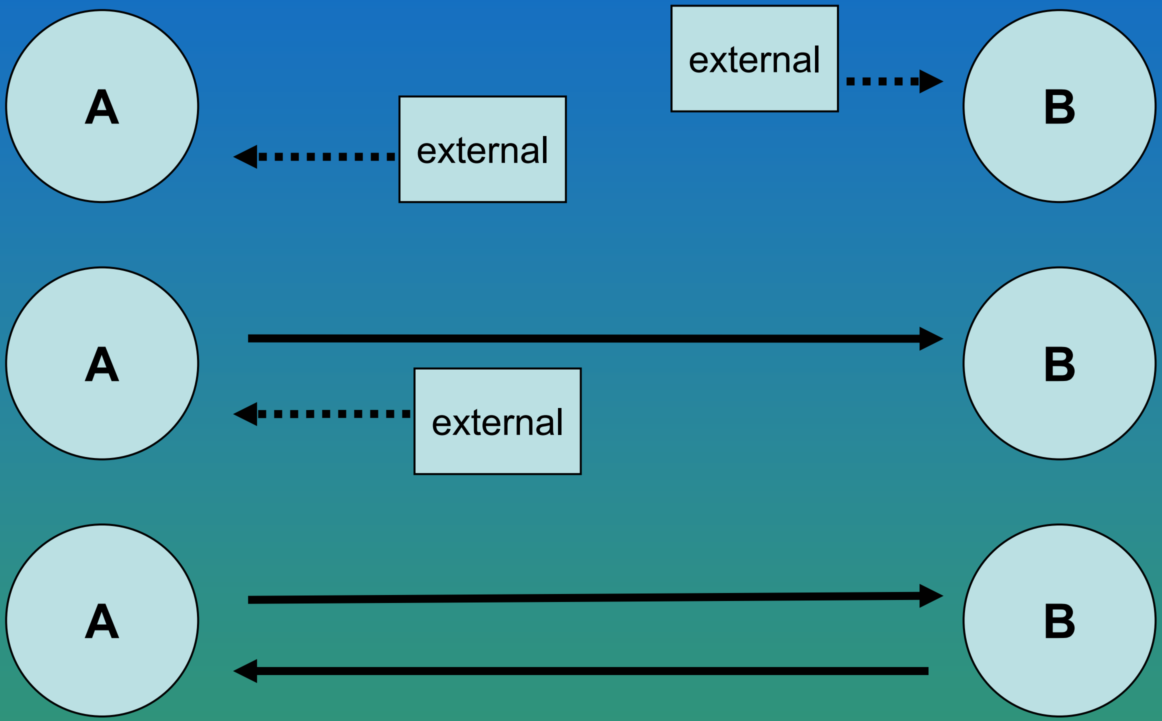
**Validation**

# Biosphere Modeling



**Validation for different European climate and vegetation regions**

# General Coupling Concepts

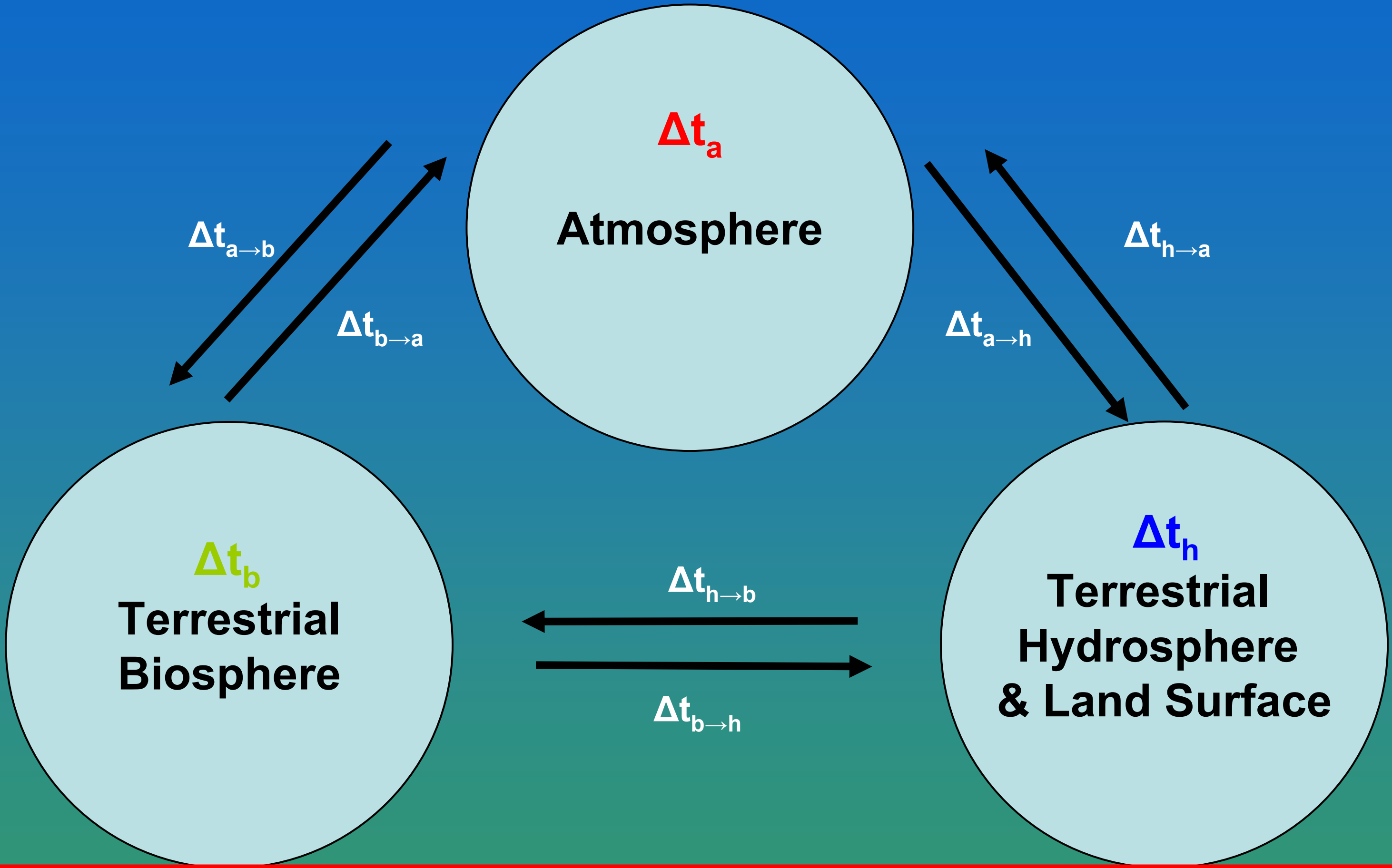


**Stand alone**
**No coupling**

**One-way coupling**

**Two-way coupling**

# General Coupling Considerations



$\Delta t_a$

**Atmosphere**

$\Delta t_b$

**Terrestrial Biosphere**

$\Delta t_h$

**Terrestrial Hydrosphere & Land Surface**

$\Delta t_{a \to b}$

$\Delta t_{b \to a}$

$\Delta t_{h \to a}$

$\Delta t_{a \to h}$

$\Delta t_{h \to b}$

$\Delta t_{b \to h}$

Relation between
- Process time scales $\Delta t_b$, $\Delta t_a$, $\Delta t_h$
- exchange time scales

⇒ determines coupling strategy & data exchange frequency

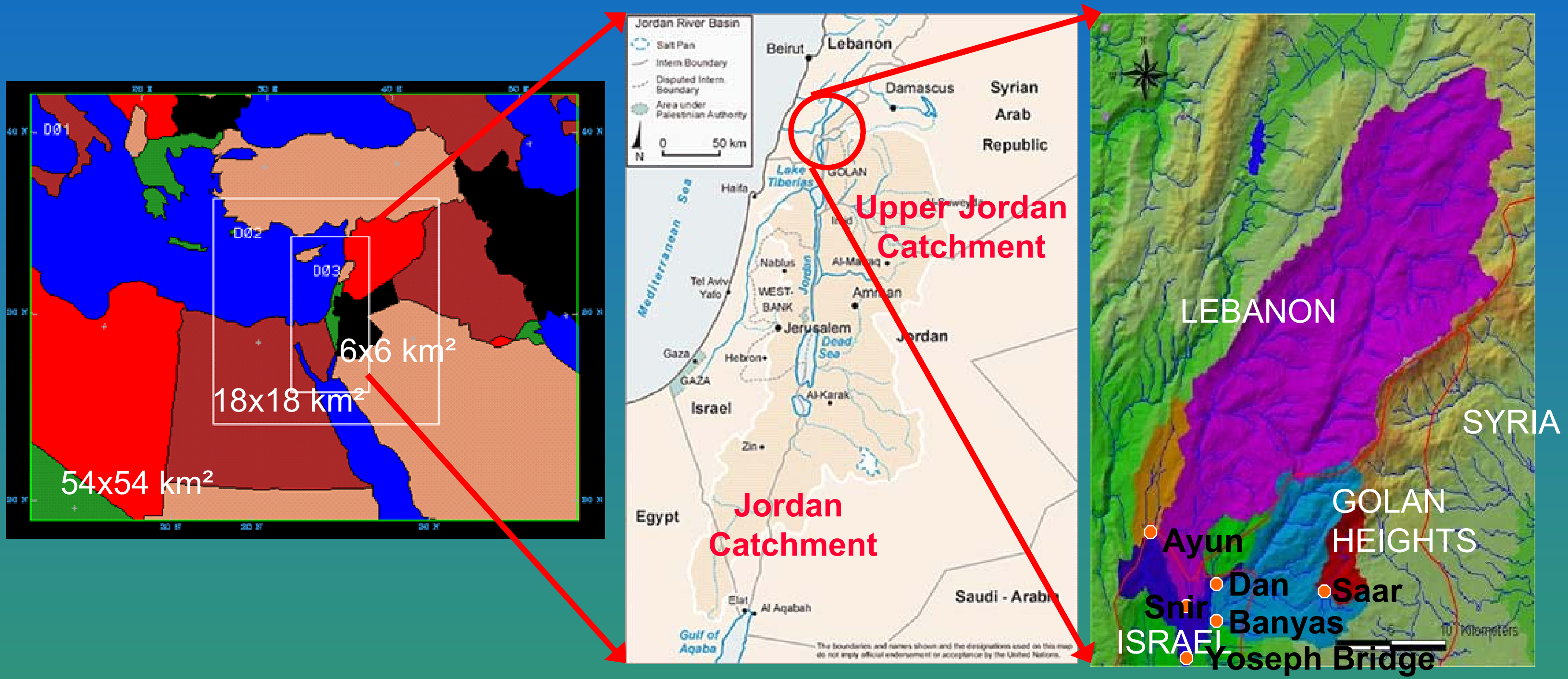
# Mutual System Interaction & Interfaces

| | **Atmosphere Models** | **Biosphere Models** | **Hydrological Models** |
|---|---|---|---|
| **Vegetation:**<br>type, LAI, $z_0$, $\alpha$ | External forcing<br>(Seasonally fixed) | Dynamic | External forcing<br>(Seasonally fixed) |
| **Emission:**<br>BVOC, $NO_x$ | External forcing | Dynamic | - |
| **Meteorology:**<br>T, P, p, v, RH | Dynamic | External forcing | External forcing |
| **Water redist.:**<br>Vertical&lateral | Dynamic<br>(3-d,1-d) | Dynamic<br>(1-d) | Dynamic<br>(2-d, 3-d) |

**Model coupling allows to introduce state variables where originally constant or externally provided parameters had to be applied**

# 1 Way Coupling

## Example: Climate-Hydrology Modeling
## Impact of Climate Change on Terrestrial Water Balance

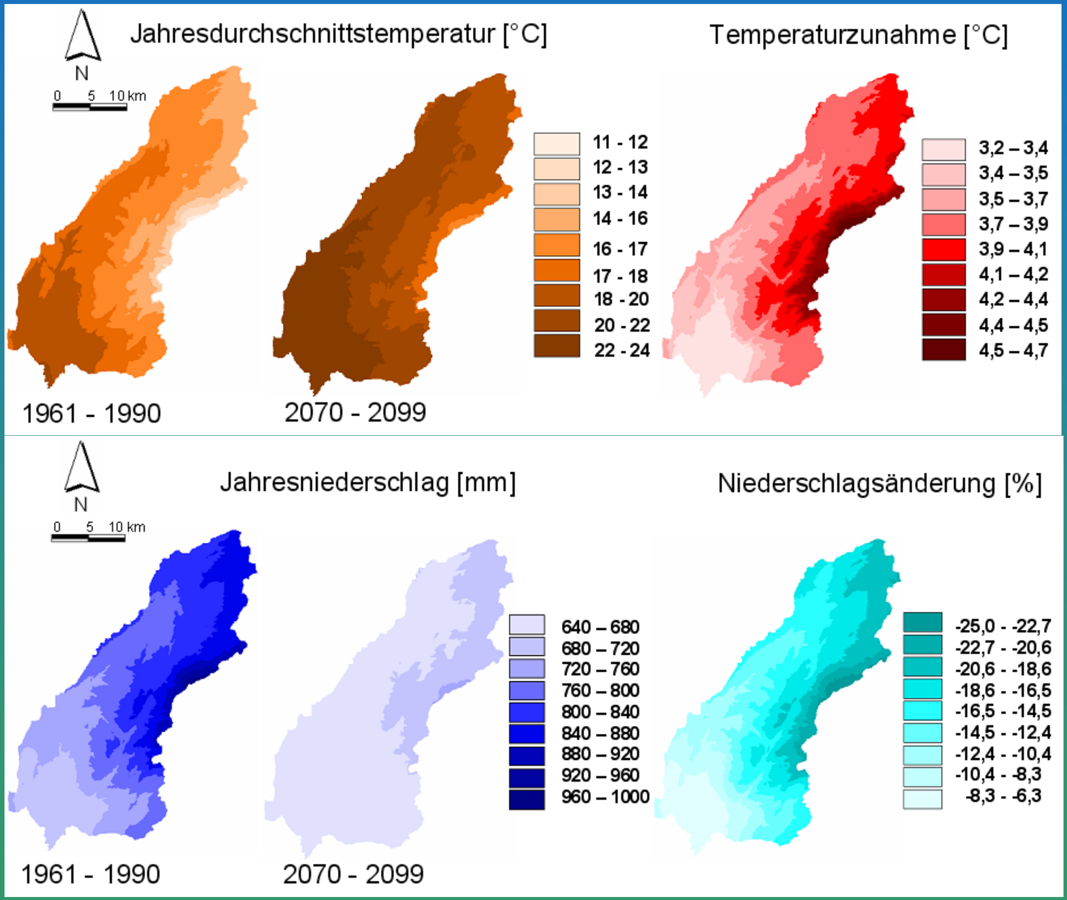


High resolution dynamical downscaling of global climate scenarios

Distributed hydrological modeling of surface and subsurface water balance in 90 m resolution

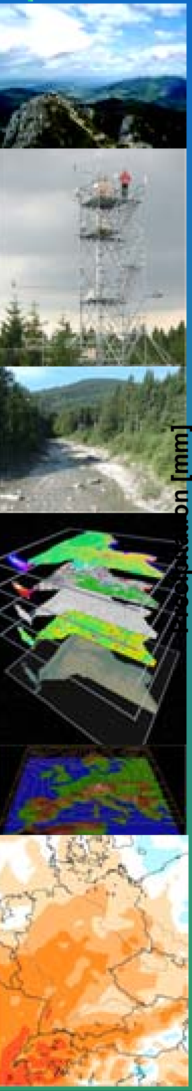
# 1 Way Coupling

## Example: Climate-Hydrology Modeling
## Impact of Climate Change, Near East/Upper Jordan River

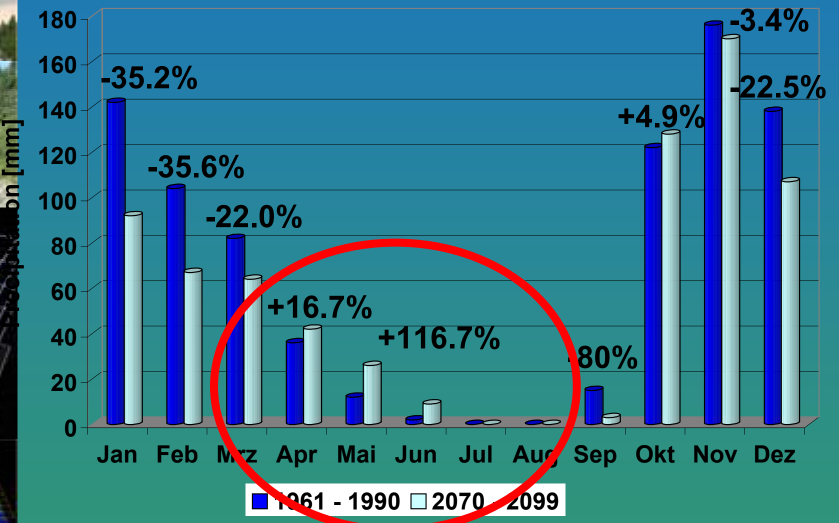


# 1 Way Coupling

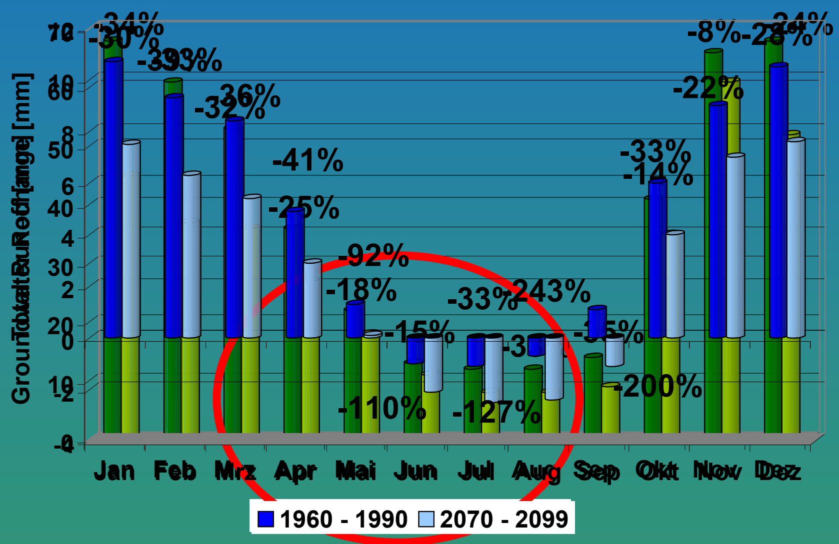
## Example: Climate-Hydrology Modeling
## Impact of Climate Change, Near East/Upper Jordan River



Precipitation



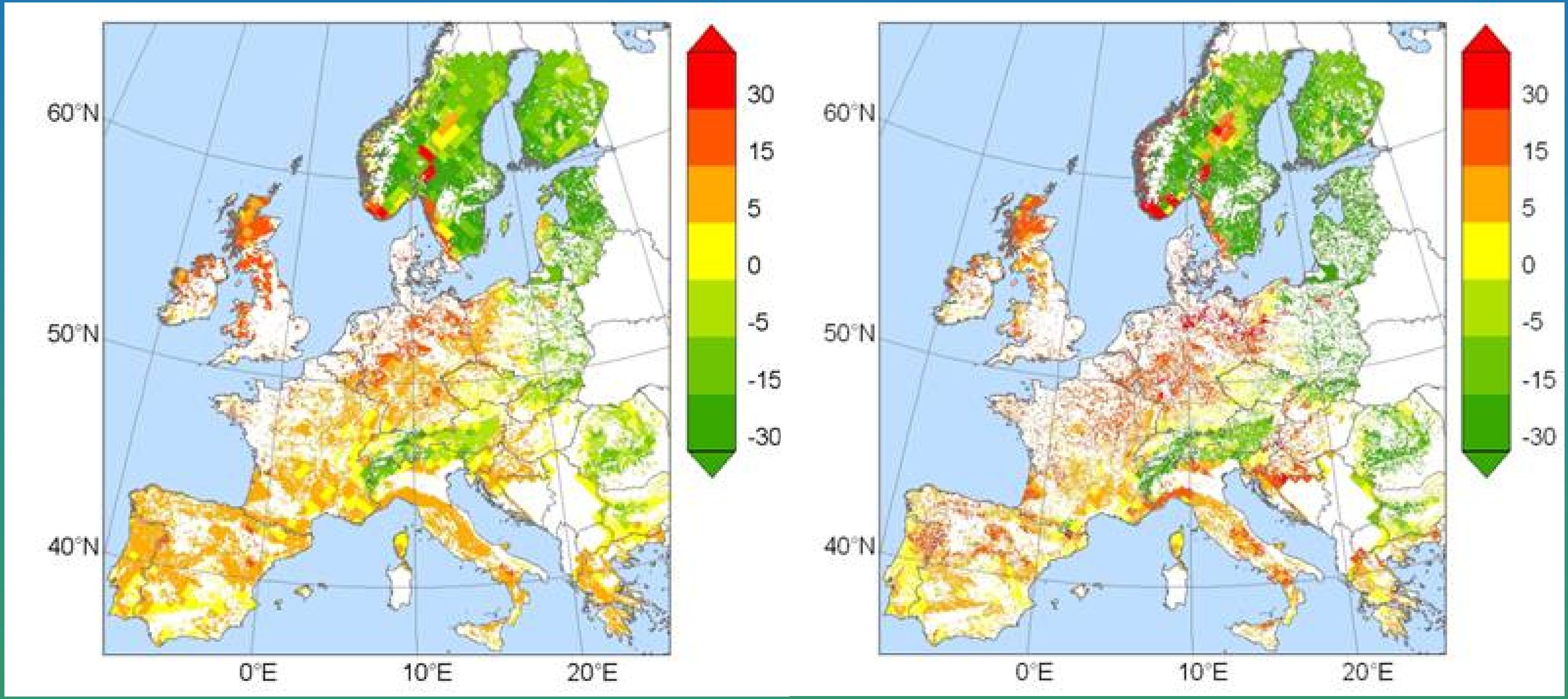
Runoff
Recharge



# 1 Way Coupling

## Example: Climate-Biosphere Modeling
## Impact of Climate Change on Biogeochemical Emissions

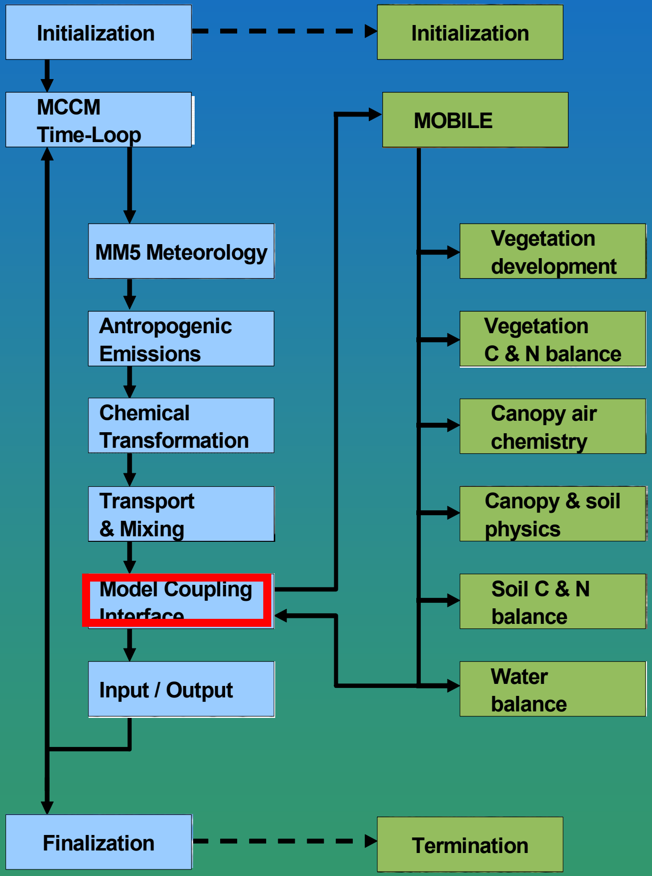
$N_2O$ emission change in % (future minus present)



# Towards fully dynamic 2-way coupled atmosphere-biosphere-hydrosphere modeling …

# 2 Way Coupling

## Example: Atmosphere-Biosphere-Hydrosphere Modeling



**Initialization** → **Initialization**

**MCCM Time-Loop**

**MM5 Meteorology**

**Antropogenic Emissions**

**Chemical Transformation**

**Transport & Mixing**

**Model Coupling Interface**

**Input / Output**

**Finalization** → **Termination**

**MOBILE**

**Vegetation development**

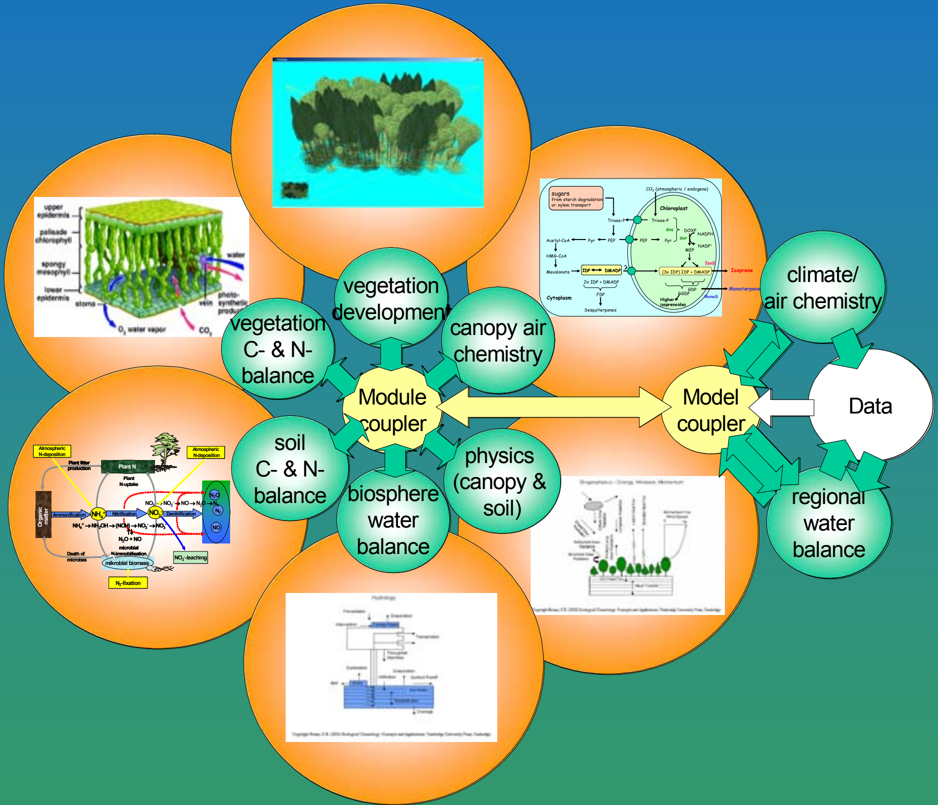
**Vegetation C & N balance**

**Canopy air chemistry**

**Canopy & soil physics**

**Soil C & N balance**

**Water balance**



vegetation development

vegetation C- & N-balance

canopy air chemistry

Module coupler

soil C- & N-balance

physics (canopy & soil)

biosphere water balance

Model coupler

climate/ air chemistry

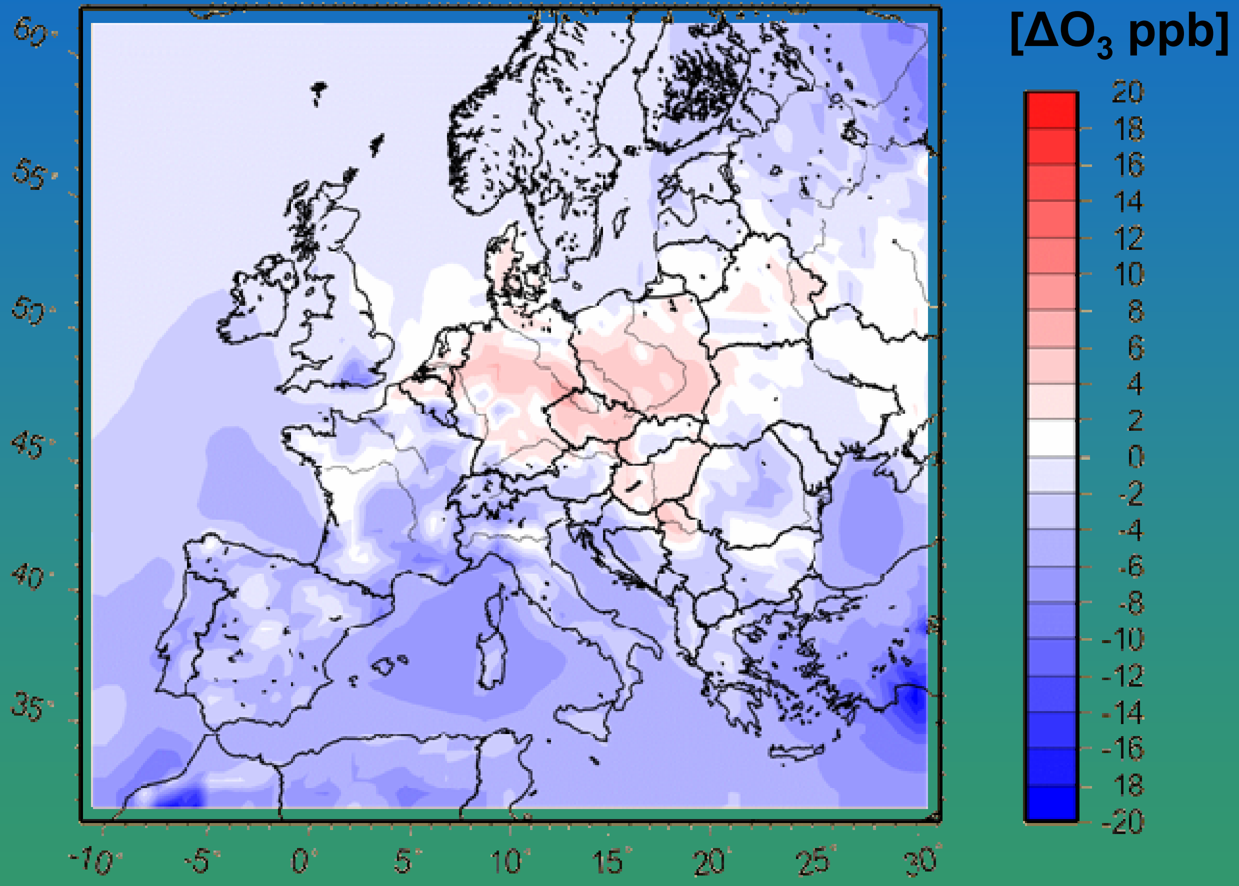
Data

regional water balance

Fully coupled model system, under development

# 2 Way Coupling

## Example: Atmosphere-Biosphere-Hydrosphere Modeling



Differences Atmo-Chemistry vs. Atmo-Bio-Hydro Model (August 2003)

# Future Requirements

# Challenges of Coupled Regional Model System(s)

1) Aggregation of stand alone 1d-modules to regional application:
**problem of scales & problem of regional validation**
usually only point measurements available
⇒ use of remote sensing techniques for areal validation necessary
- soil moisture dynamics
- sensible & latent heat fluxes (e.g. SEBAL method)
- areal vegetation dynamics, e.g. via LAI

but: coupling can provide new validation possibilities

2) **Parameter estimation** in coupled model system
- scale dependence of parameters
- non-uniqueness of solution due to large number of degrees of freedom
- multi-objective calibration of adjustable parameters & validation required

3) Specification of system parameters & initialization of state variables
(soil, vegetation, land surface, atmosphere, …)

4) Technical realization of data exchange between stand-alone modules!

# Final remarks

- Computational efficient realization of tight model coupling:
  parallelization and efficient implementation on HPC platforms
- Application and validation to different vegetation and climate zones
- Scaling laws? Often pragmatically neglected!
  laboratory scale ⇔ field scale ⇔ regional scale
  **Model coupling must be accompanied by scaling law investigation**
- Open model architecture & data exchange
- Community based approach
- Robustness required to ensure usability by all disciplines involved

# Thank you for your attention