Summer School
“Land Cover and Climate Change in West Africa”

Impact on terrestrial hydrology in the Volta basin

Integration of MODIS derived land surface properties into a water balance simulation model

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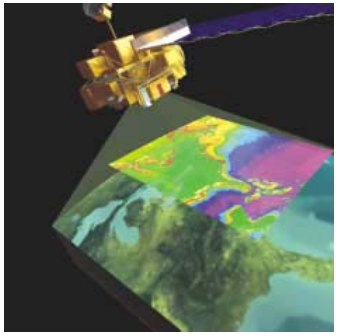
Outline

- Remote sensing in hydrology
- Regional hydrological modeling
- Potential evapotranspiration: Penman-Monteith approach
- Land surface properties in hydrological model
  a) standard
  b) remote sensing (MODIS) data
- Study area: White Volta basin
  a) Albedo comparison
  b) LAI comparison
- Impact of MODIS albedo and LAI on water balance estimations
  a) time series
  b) spatial distribution
- Summary

Remote sensing in hydrology

Remote sensing produces

- areal measurements in place of point measurements
- all information is collected & stored at one place
- it offers high resolution in space & time
- data are available in digital form
- …



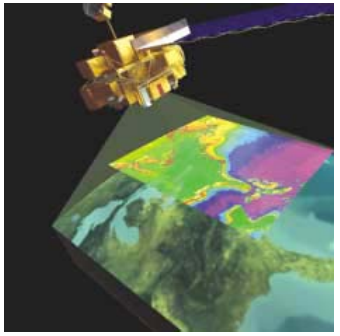
Remote sensing in hydrology

- better define soils and land covers over a watershed
  → required for the determination of infiltration, evapotranspiration, runoff
- correct errors in input data based on point measurements
- estimate evapotranpiration (ET) & soil moisture fields

Schultz, G. A. 1998. Remote sensing in hydrology. Journal of Hydrology, 124, 1071–1107.
Singh, V. P. (ed). 1995. Computer Models of Watershed Hydrology. Water Resources Publications.
…

Remote sensing in this study

For hydrological modeling in poorly gauged basins & regions with a weak infrastructure (White Volta basin)



- Remote sensing (RS) is valuable data source
  - RS satisfies several data requirements
  - RS provides data near real time!!
  → no delay due to data collection, digitalization,…

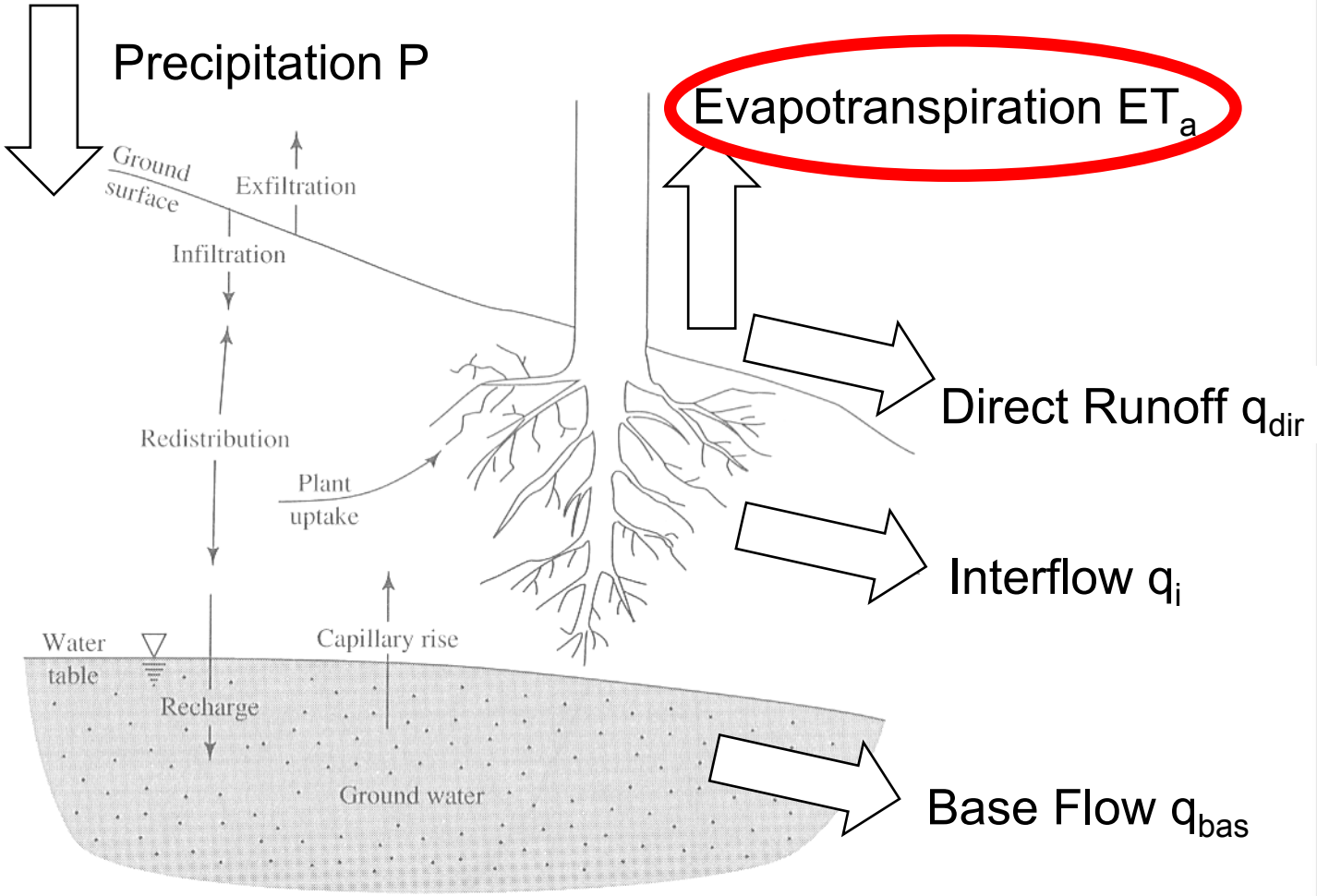
In this study

- RS products are used for a better description of land surface parameters in hydrological modeling
- Land surface properties **albedo & LAI (Leaf Area Index)** from the space-borne remote sensing system MODIS are employed

Integration of MODIS derived land surface properties into a water balance simulation model

Regional hydrological modeling

Terrestrial Water Balance & Runoff components



Potential evapotranspiration

- **Definition:** maximum quantity of water capable of being evaporated from the soil to the atmosphere by evaporation and plant transpiration of a specified region (climate)

- Penman-Monteith:

$$\lambda E = \frac{3.6 \cdot \frac{\Delta}{\gamma_p}(\boldsymbol{R_N} - G) + \frac{\rho \cdot c_p}{\gamma_p \cdot r_a}(e_s - e) \cdot t_i}{\frac{\Delta}{\gamma_p} + 1 + \frac{\boldsymbol{r_s}}{r_a}}$$

with

$$R_N = (1 - \boldsymbol{\alpha}) \cdot RG - R_L$$

and

$$\frac{1}{r_s} = \frac{(1 - A)}{r_{sc}} + \frac{A}{r_{ss}}$$

$$A = f^{\boldsymbol{LAI}}$$

- α albedo
- LAI leaf area index

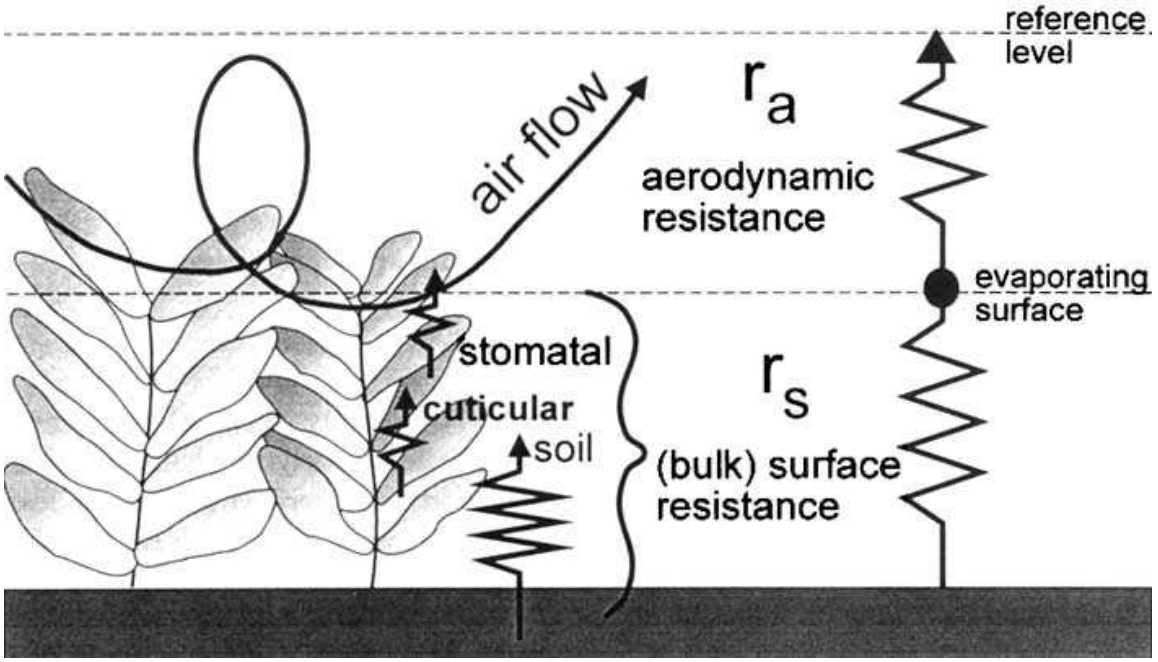
Potential evapotranspiration

- **List of symbols**

λ	$[kJ/kg]$	latent vaporization heat: $\lambda = 2500.8 - 2.372 \cdot T[°C]$
E	$[mm/m^2]$	latent heat flux: $[mm/m^2] \equiv [kg/m^2]$
Δ	$[hPa/K]$	tangent of saturated vapour pressure curve $\Delta = \frac{\partial e_s}{\partial T}$
$\boldsymbol{R_N}$	$[\boldsymbol{Wh/m^2}]$	**net radiation**
G	$[Wh/m^2]$	soil heat flux, here: $0.1 \cdot R_N$
ρ	$[kg/m^3]$	density of dry air
c_p	$[kJ/(kg \cdot K)]$	specific heat capacity of dry air at constant pressure: $c_p = 1.005$
e_s	$[hPa]$	saturation vapour pressure at temperature T
e	$[hPa]$	actual vapour pressure (observed)
t_i	$[-]$	number of seconds within a time step
γ_p	$[hPa/K]$	psychometric constant
$\boldsymbol{r_s}$	$[s/m]$	**bulk-surface resistance**
r_a	$[s/m]$	bulk-aerodynamic resistance
R_N	$[Wh/m^2]$	net radiation
$\boldsymbol{\alpha}$	$[-]$	**surface albedo**
RG	$[Wh/m^2]$	global radiation: $RG = R_{sun} + R_{sky}$ with shortwave direct R_{sun} and diffuse R_{sky} radiation
R_L	$[Wh/m^2]$	longwave radiation: $R_L = R_{out} - R_{in}$

Potential evapotranspiration

- r_a: aerodynamic resistance
- r_s: bulk surface resistance



http://www.fao.org/docrep/x4090/x4090e06.htm

Potential evapotranspiration

Surface albedo [ ]

- **Definition:** reflectance of incident energy by the surface; determined by surface reflectance properties, which vary for different forms of surface materials and wetness

- Penman-Monteith:

$$\lambda E = \frac{3.6 \cdot \frac{\Delta}{\gamma_p}(\boldsymbol{R_N} - G) + \frac{\rho \cdot c_p}{\gamma_p \cdot r_a}(e_s - e) \cdot t_i}{\frac{\Delta}{\gamma_p} + 1 + \frac{\boldsymbol{r_s}}{r_a}}$$

with $$R_N = (1 - \boldsymbol{\alpha}) \cdot RG - R_L$$

- increase of α values ➔ decrease of λE

Potential evapotranspiration

LAI: Leaf area index [ ]

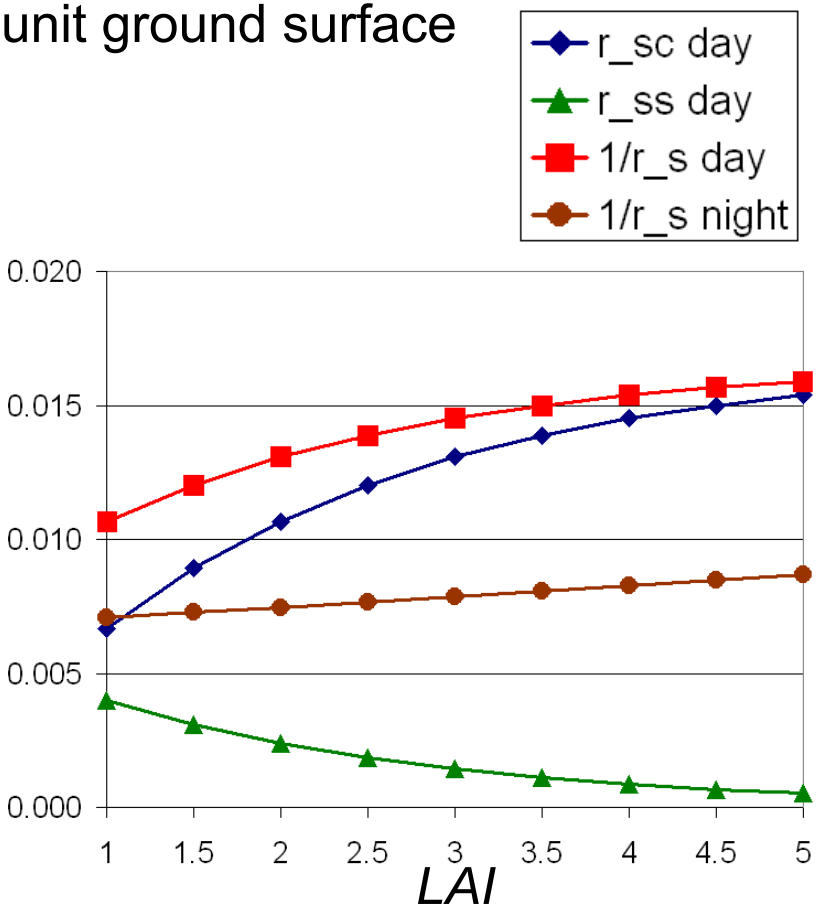
- **Definition:** total one-sided leaf area per unit ground surface

- Penman-Monteith:

$$\lambda E = \frac{3.6 \cdot \frac{\Delta}{\gamma_p}(\boldsymbol{R_N} - G) + \frac{\rho \cdot c_p}{\gamma_p \cdot r_a}(e_s - e) \cdot t_i}{\frac{\Delta}{\gamma_p} + 1 + \frac{\boldsymbol{r_s}}{r_a}}$$

with $$\frac{1}{r_s} = \frac{(1-A)}{r_{sc}} + \frac{A}{r_{ss}}$$

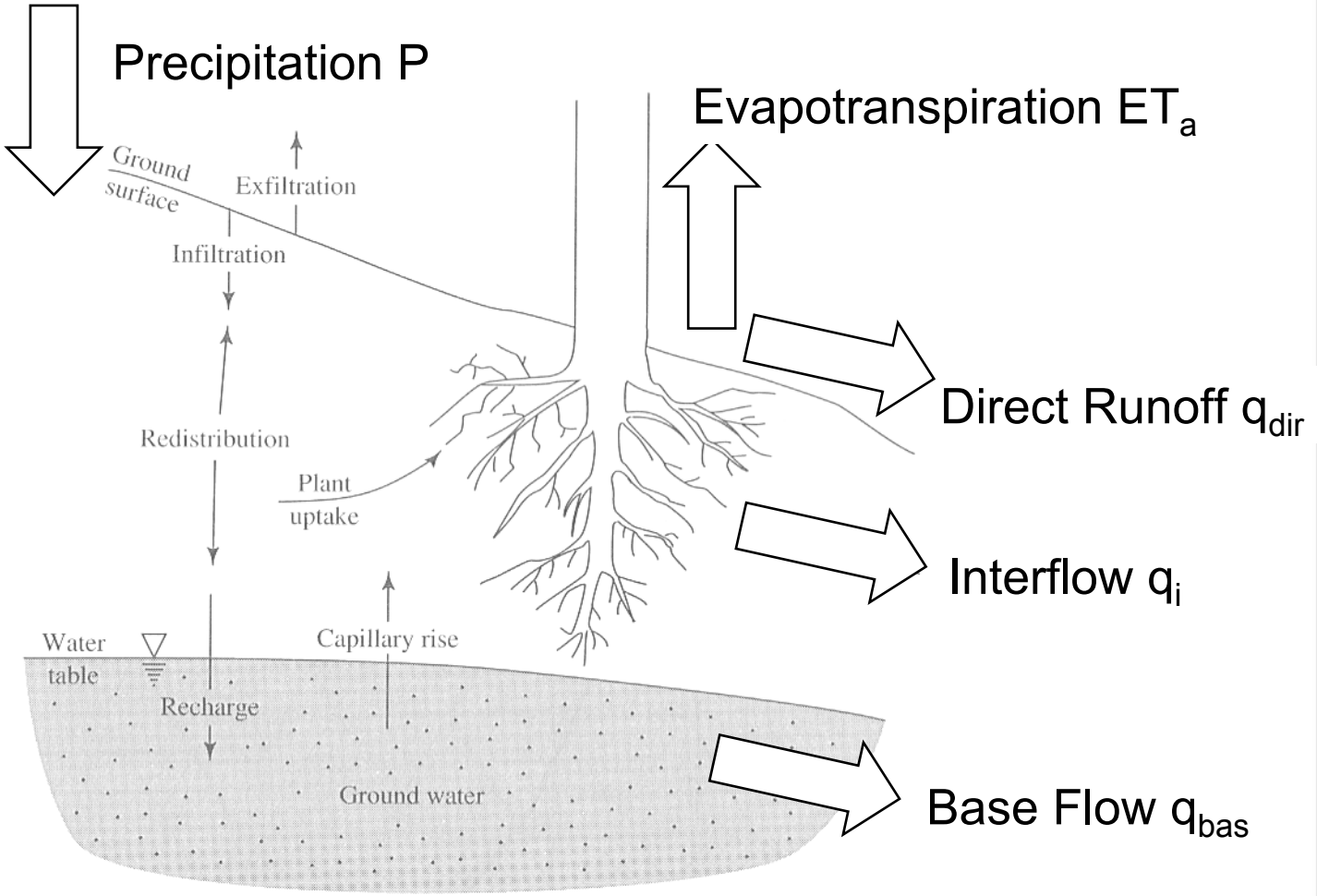
$$A = f^{\boldsymbol{LAI}}$$



increase of LAI values ➔ increase of λE

Regional hydrological modeling

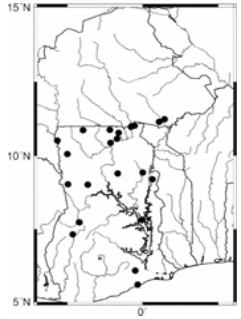
Terrestrial Water Balance & Runoff components

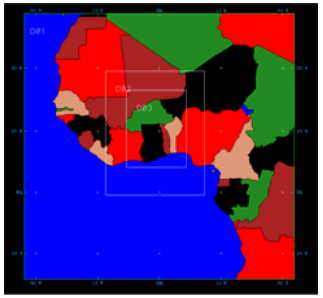


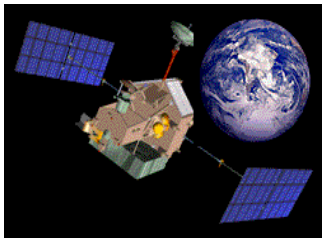
Regional hydrological modeling

meteorological input

1. observation data
2. meteorological model
3. satellite data

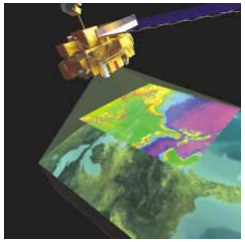




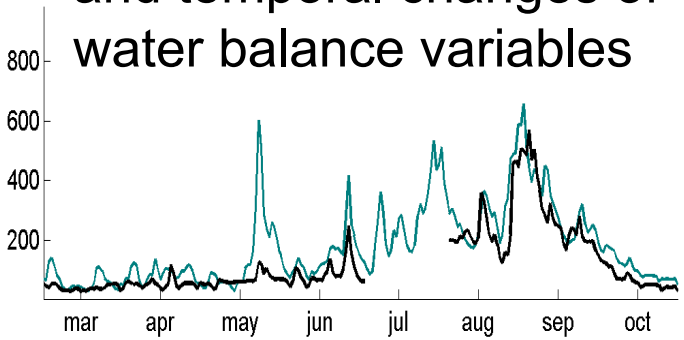


hydrological model

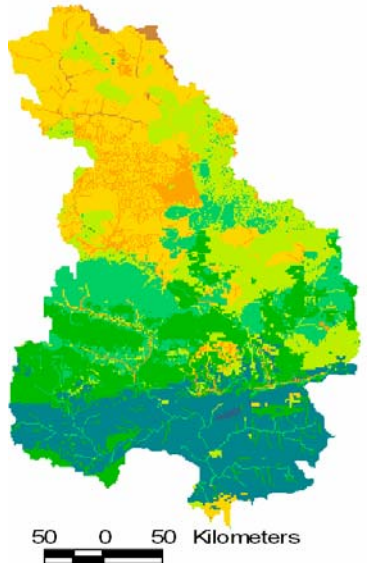
- digital elevation model
- soil & land use grid
- soil & land surface properties



Information about spatial and temporal changes of water balance variables



Surface Runoff [m³/s]

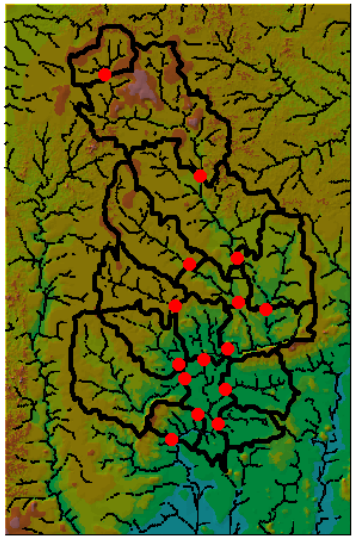


Evapotranspiration [mm/a]

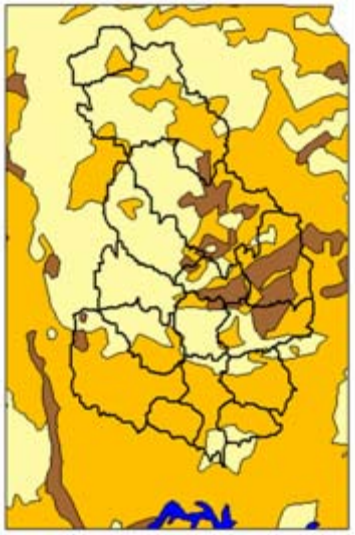
Regional hydrological modeling

Regional hydrological modeling

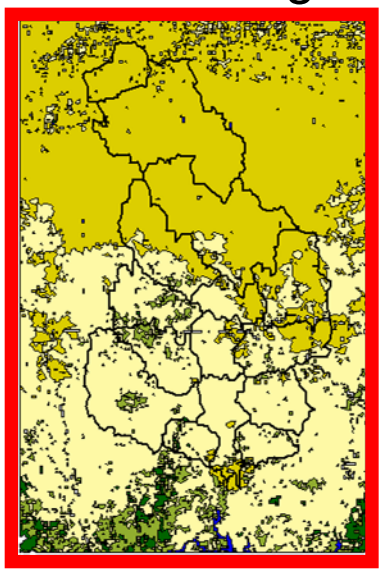
DEM

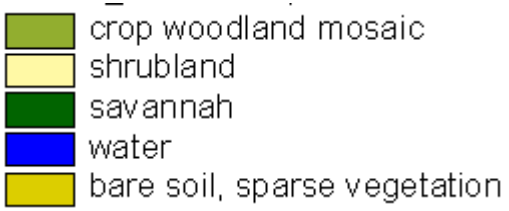


Soil grid



Land Use grid





+ Tables with Soil and Land Use properties

Example: Land Use Table

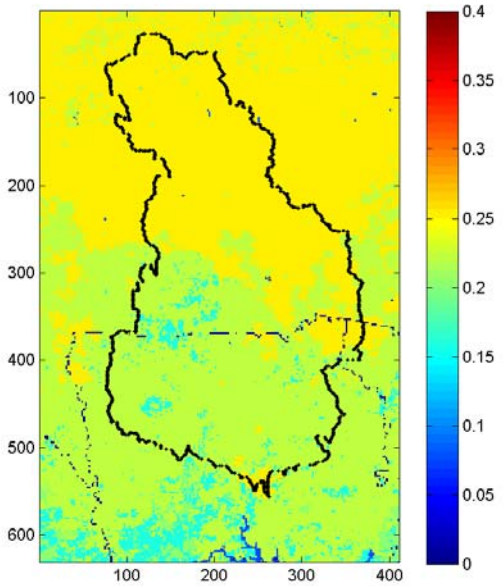
Code	Name	Albedo	surface resistance [monthly]	DOY's 1 … 4	LAI 1 …4	veg. height 1 …4	veg. covering 1 …4	root depth 1 …4
8	shrubland							
19	bar.sparse.veg.							

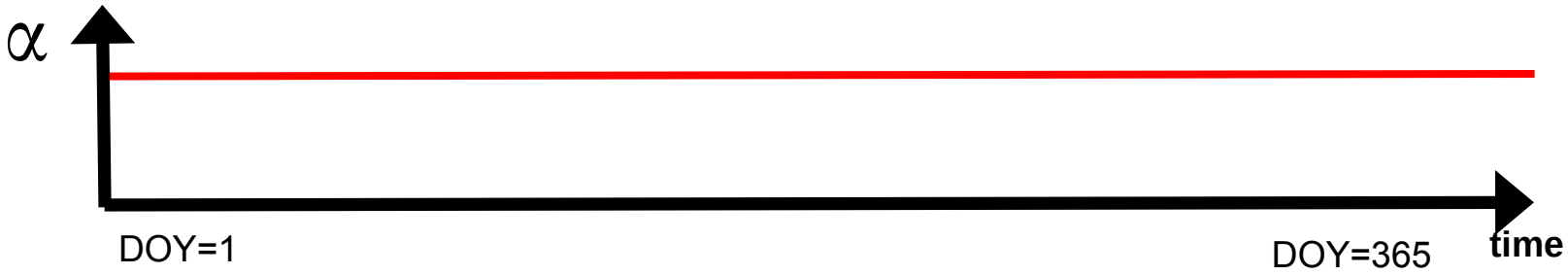
Land surface properties in hydrological model

- Standard → WHITE VOLTA basin

Albedo

Code	Name	Albedo	surface resistance [monthly]	DOY's 1 … 4	LAI 1 …4
8	shrubland	0.22			
10	savanna	0.20			
19	bar.sparse.veg.	0.25			





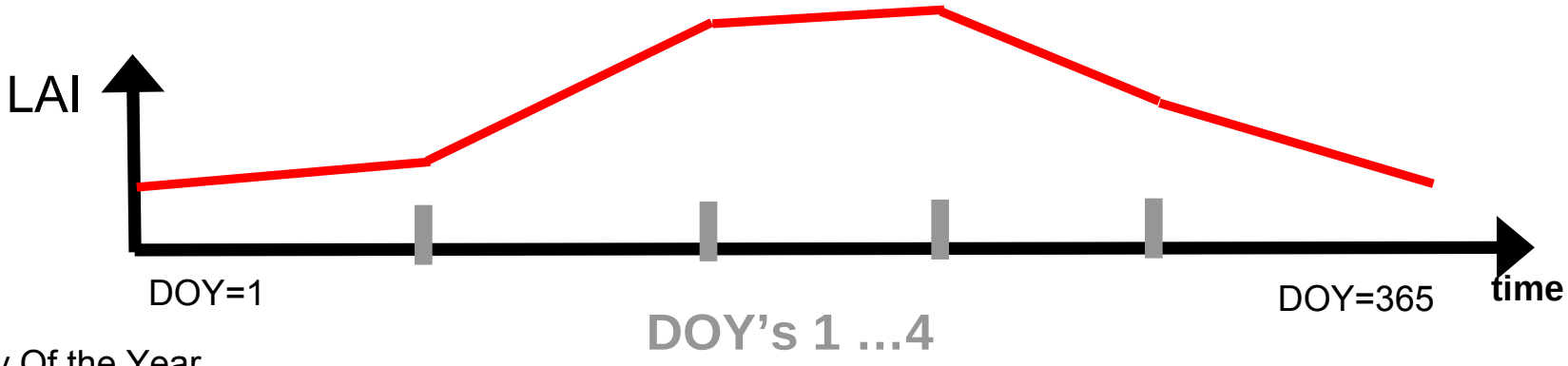
DOY=Day Of the Year

Land surface properties in hydrological model

- Standard → WHITE VOLTA basin

LAI

Code	Name	Albedo	surface resistance [monthly]	DOY's 1 … 4	LAI 1 …4	…
8	shrubland	0.22		120, 180, 240, 304	1.5, 2.5, 2.5, 2.5	
10	savanna	0.20		120, 180, 240, 304	1.5, 2.0, 2.0, 2.0	
19	bar.sparse.veg.	0.25		120, 180, 240, 304	0.5, 1.5, 1.5, 1.5	



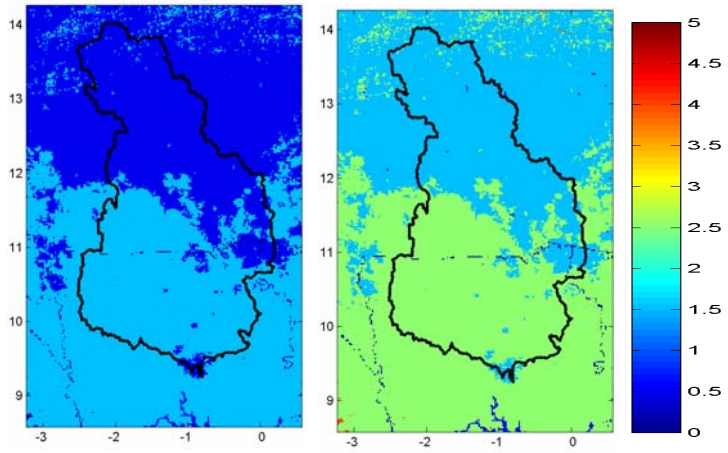
DOY=Day Of the Year

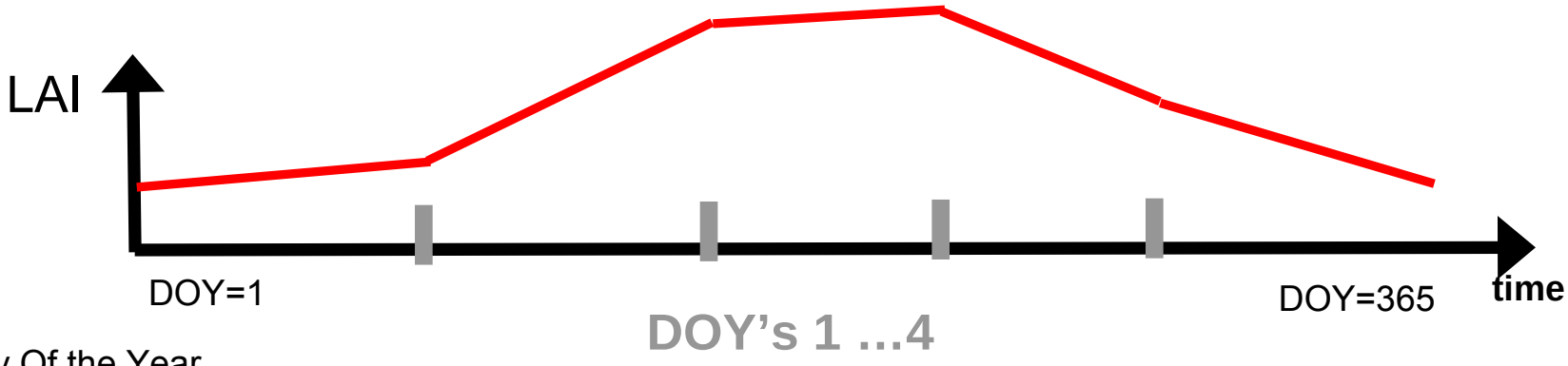
Land surface properties in hydrological model

- Standard → WHITE VOLTA basin: two seasons – dry season
  – rainy season

LAI

Code	Name	DOY's 1 … 4	LAI 1 …4
8	shrubland	120, 180, 240, 304	1.5, 2.5, 2.5, 2.5
10	savanna	120, 180, 240, 304	1.5, 2.0, 2.0, 2.0
19	bar.sparse.veg.	120, 180, 240, 304	0.5, 1.5, 1.5, 1.5





DOY=Day Of the Year

Land surface properties in hydrological model

- Satellite derived: MODIS
- Satellites provide worldwide spatially information on land surface properties

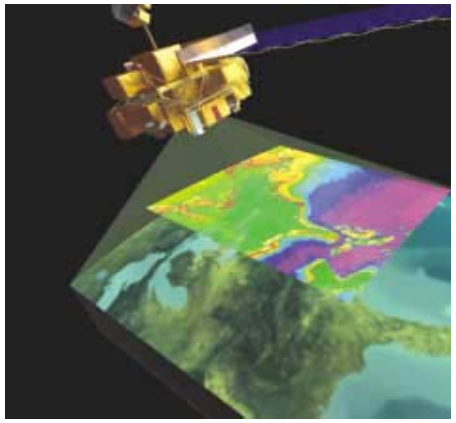
  (e.g. MODIS entire earth every 2 days)
- ADVANTAGES:

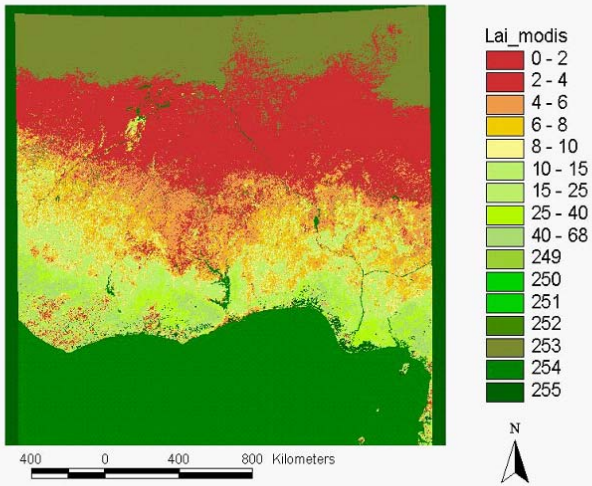
  - more detailed spatial and temporal description of land surface variables

  - one data source

  - allows inter-annual investigations

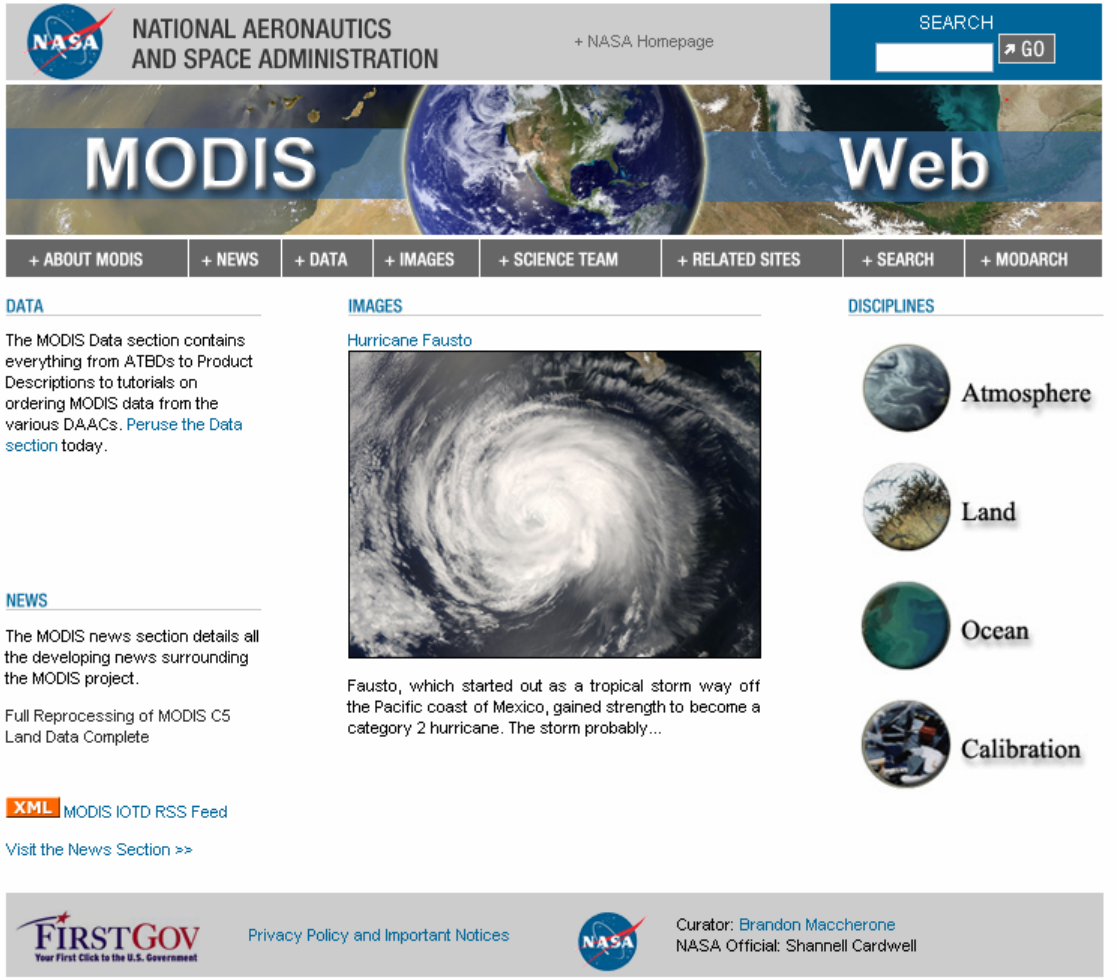
  - …





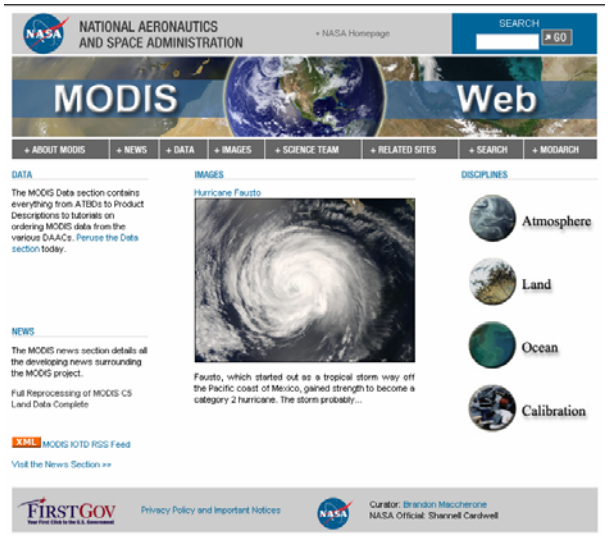
MODIS

- **http://modis.gsfc.nasa.gov/index.php**



MODIS

- http://modis.gsfc.nasa.gov/index.php
- Moderate Resolution Imaging Spectroradiometer
- Terra (EOS AM) & Aqua (EOS PM) satellites
- global coverage within 1 to 2 days
- 36 spectral bands: 0.4 – 14 µm
- goal: improve understanding of global dynamics & processes on land, oceans, lower atmosphere
- 44 data products (250 – 1000 m)



MODIS – 44 data products

Calibration
(see also: http://www.mcst.ssai.biz/mcstweb/index.html)

* MOD 01 - Level-1A Radiance Counts
* MOD 02 - Level-1B Calibrated Geolocated Radiances
* MOD 03 - Geolocation Data Set

Atmosphere
(see also: http://modis-atmos.gsfc.nasa.gov/)

* MOD 04 - Aerosol Product
* MOD 05 - Total Precipitable Water (Water Vapor)
* MOD 06 - Cloud Product
* MOD 07 - Atmospheric Profiles
* MOD 08 - Gridded Atmospheric Product
* MOD 35 - Cloud Mask

Land
(see also: http://edcdaac.usgs.gov/dataproducts.asp and ht

* MOD 09 - Surface Reflectance
* MOD 11 - Land Surface Temperature & Emissivity
* MOD 12 - Land Cover/Land Cover Change
* MOD 13 - Gridded Vegetation Indices (Max NDVI & Inte
* MOD 14 - Thermail Anomalies, Fires & Biomass Burning
* MOD 15 - Leaf Area Index & FPAR
* MOD 16 - Evapotranspiration
* MOD 17 - Net Photosynthesis and Primary Productivity
* MOD 43 - Surface Reflectance
* MOD 44 - Vegetation Cover Conversion

Cryosphere
(see also: http://nsidc.org/daac/modis/index.html)

* MOD 10 - Snow Cover
* MOD 29 - Sea Ice Cover

Ocean
(Details about ocean products are best obtained by going

* MOD 18 - Normalized Water-leaving Radiance
* MOD 19 - Pigment Concentration
* MOD 20 - Chlorophyll Fluorescence
* MOD 21 - Chlorophyll_a Pigment Concentration
* MOD 22 - Photosynthetically Available Radiation (P
* MOD 23 - Suspended-Solids Concentration
* MOD 24 - Organic Matter Concentration
* MOD 25 - Coccolith Concentration
* MOD 26 - Ocean Water Attenuation Coefficient
* MOD 27 - Ocean Primary Productivity
* MOD 28 - Sea Surface Temperature
* MOD 36 - Total Absorption Coefficient
* MOD 37 - Ocean Aerosol Properties
* MOD 39 - Clear Water Epsilon

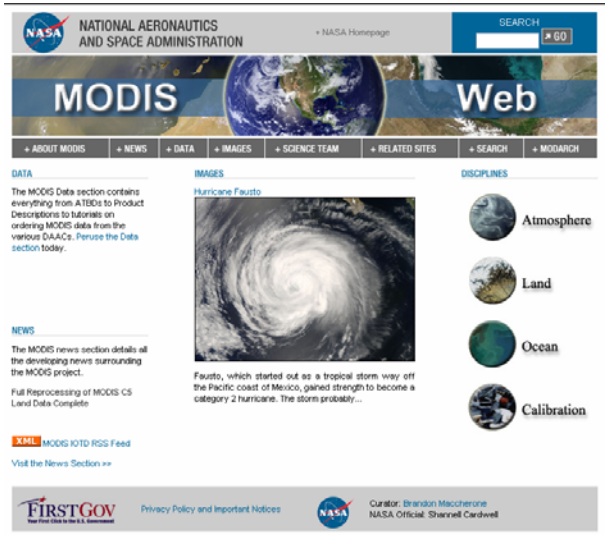
MODIS

MODIS LAND:

- MOD 43: Surface Reflectance BRDF/Albedo Parameter
  - spatial resolution: 1km
  - temporal resolution: 16 days

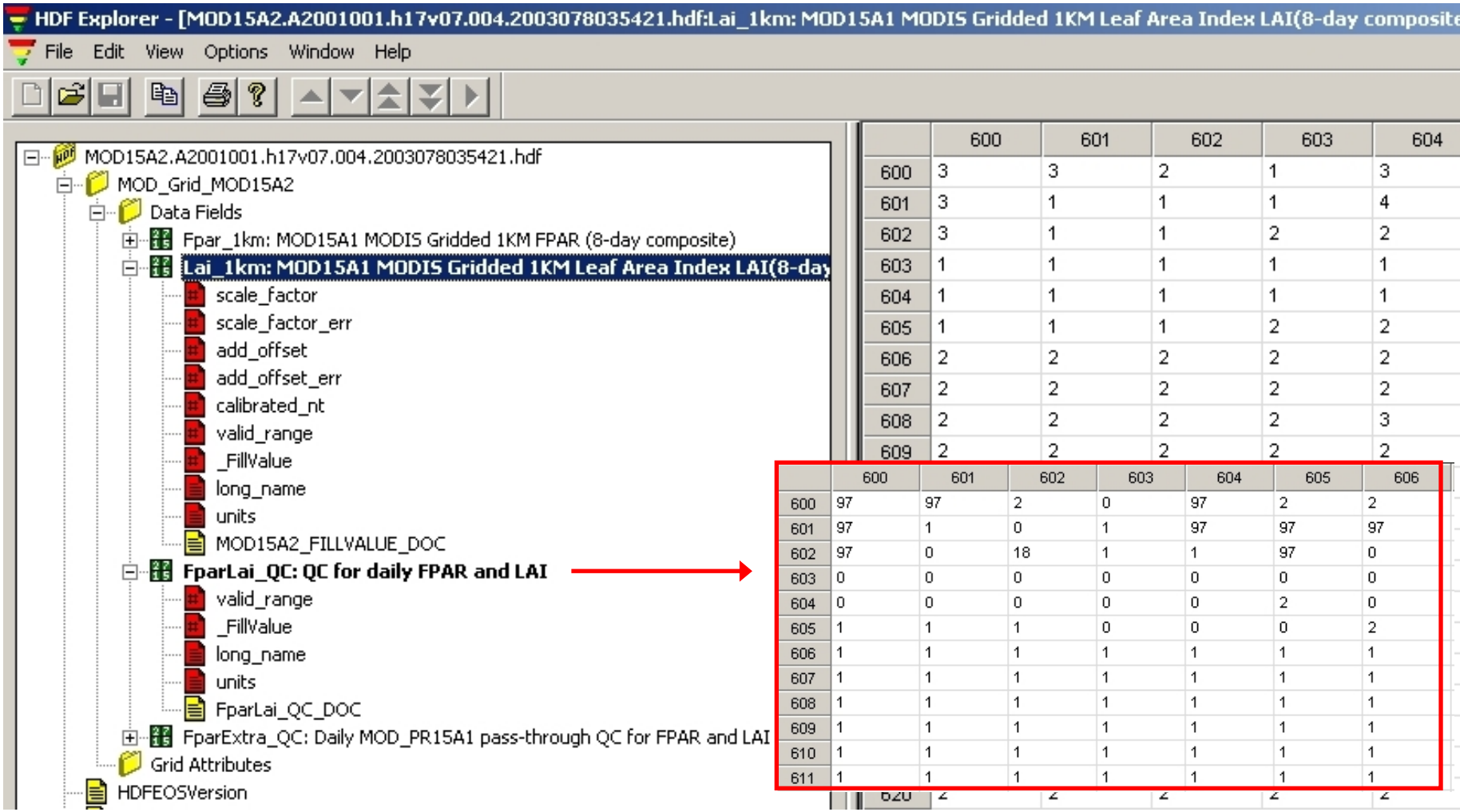
- MOD 15: Leaf Area Index (LAI) and Fractional Photosynthetically Active Radiation (FPAR)
  - spatial resolution: 1km
  - temporal resolution: 8 days

- *detailed description: MODIS_albedo_43.pdf & MODIS_LAI_43.pdf*



MODIS-data, HDF Explorer

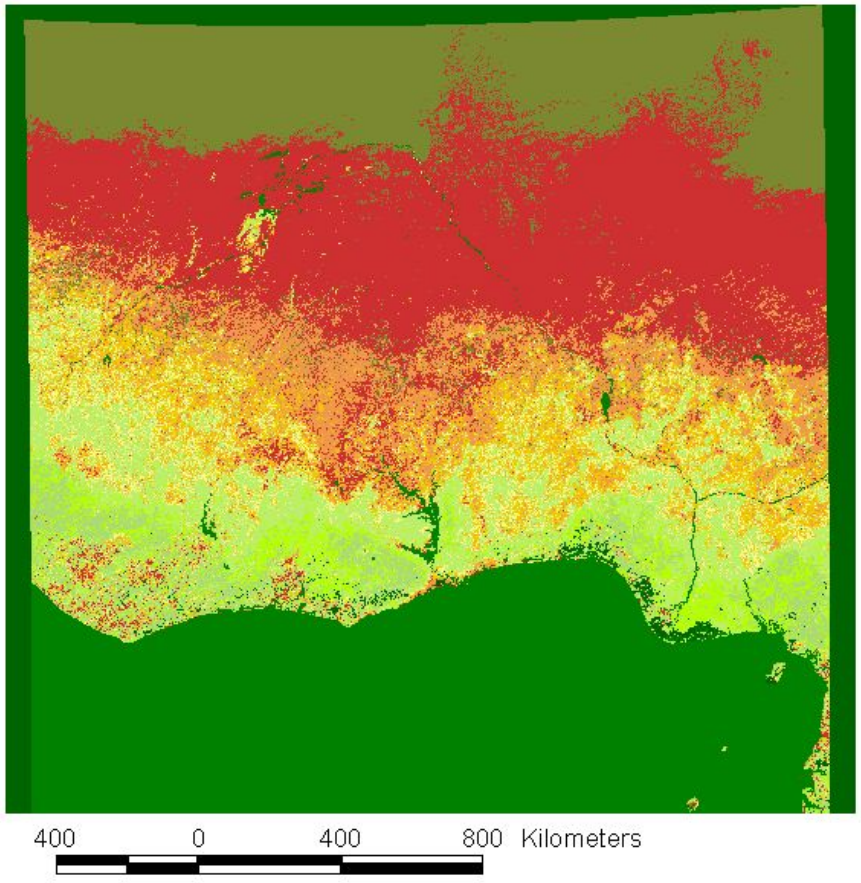
tile



	600	601	602	603	604
600	3	3	2	1	3
601	3	1	1	1	4
602	3	1	1	2	2
603	1	1	1	1	1
604	1	1	1	1	1
605	1	1	1	2	2
606	2	2	2	2	2
607	2	2	2	2	2
608	2	2	2	2	3
609	2	2	2	2	2

	600	601	602	603	604	605	606
600	97	97	2	0	97	2	2
601	97	1	0	1	97	97	97
602	97	0	18	1	1	97	0
603	0	0	0	0	0	0	0
604	0	0	0	0	0	2	0
605	1	1	1	0	0	0	2
606	1	1	1	1	1	1	1
607	1	1	1	1	1	1	1
608	1	1	1	1	1	1	1
609	1	1	1	1	1	1	1
610	1	1	1	1	1	1	1
611	1	1	1	1	1	1	1

MODIS-data example: LAI (Jan. 2003)



Lai_modis
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 15
15 - 25
25 - 40
40 - 68
249
250
251
252
253
254
255

N

MOD15A2.A2001001.h17v07.004.2003078035421.hdf:MOD15A2

MOD15A1 FILL VALUE LEGEND
255 : _Fillvalue: not-computed or outside projection...
254 : water (ocean or inland)
253 : barren, very sparsely vegetated
252 : perennial snow,ice on pixel
251 : permanant wetlands,marshes
250 : urban,built-up
249 : unclassifiedl

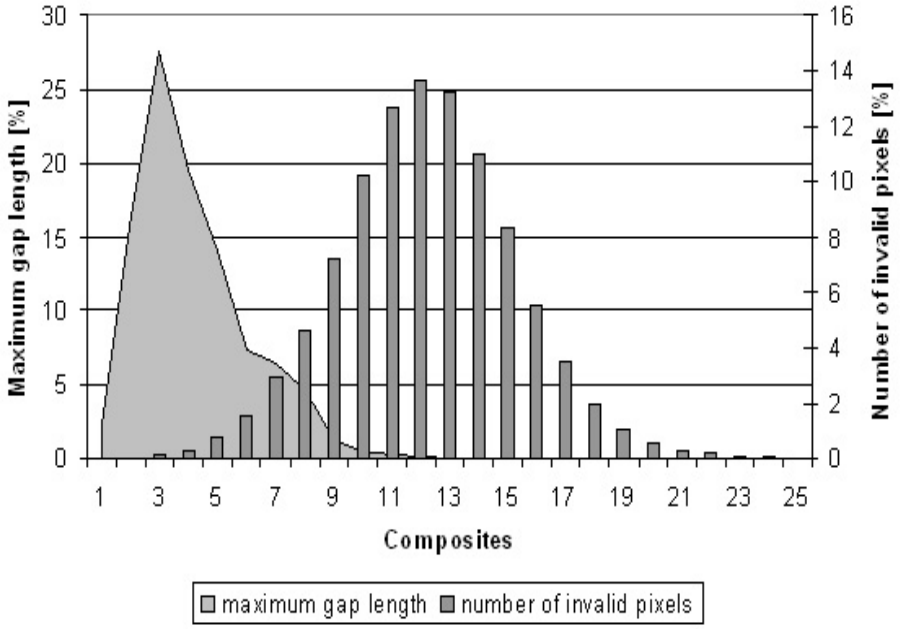
Integration of MODIS products in a hydrological model

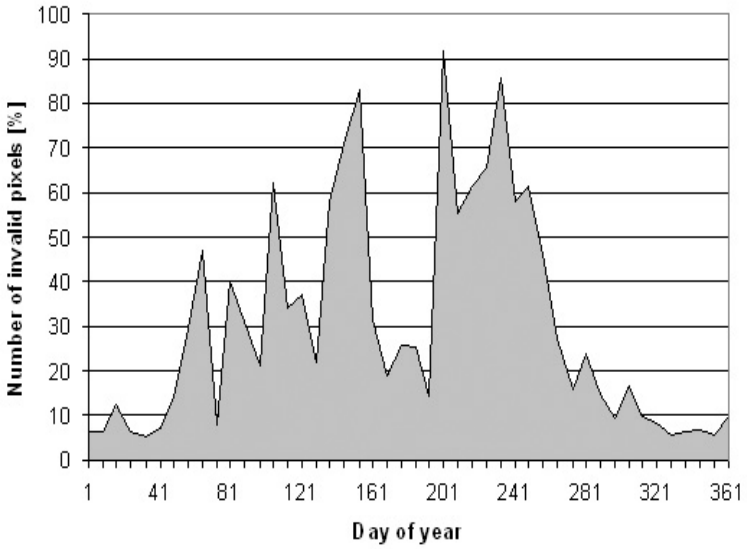
- MODIS time series generation (TiSeG)
  - done by C. Conrad & R. R. Colditz (University Wuerzburg)
    → topic tomorrow

  - analysis of Quality Assurance Science Data Set (QA-SDS)
    → number of invalid pixels & maximum gap length
  - invalid pixels are either masked or spatial/temporal interpolated

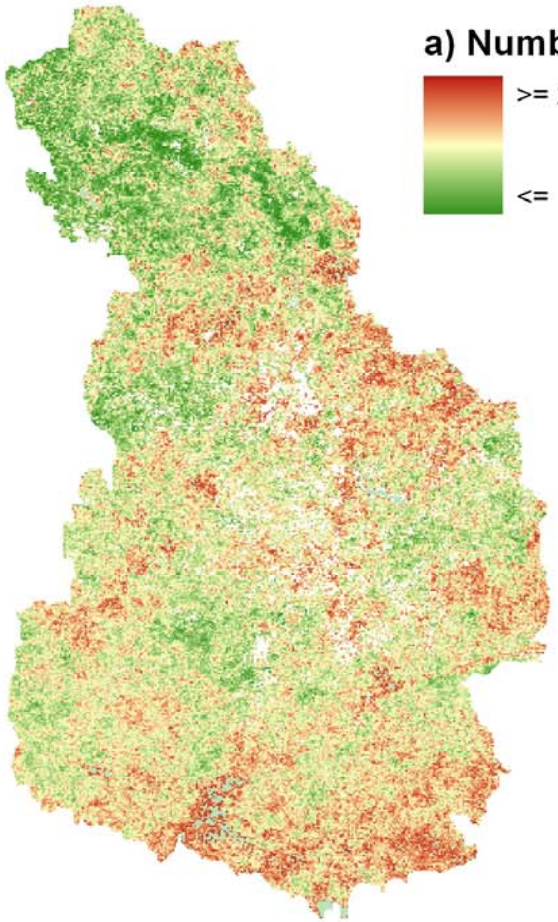
- Composites of Albedo (16 days) and LAI (8 days) grids
  - analysed (quality checked)
  - aggregated to monthly means
  - monthly grids are imported into hydrological model
  - imported MODIS grids replace the internally generated standard grids

TiSeG results (2004)





TiSeG results (2004)

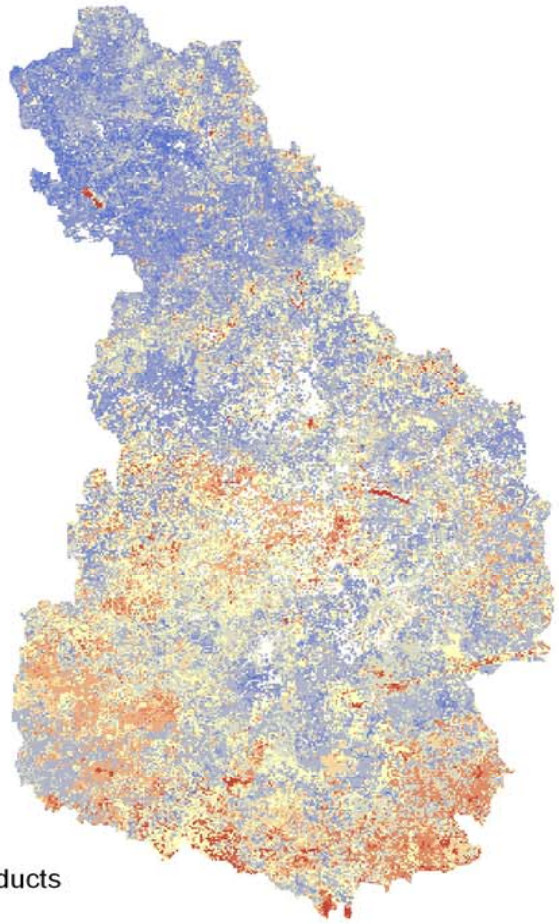


a) Number of invalid LAI values 2004

>= 20

<= 5

Mask of MOD15
Collection 4 LAI Products



b) Maximum gap length

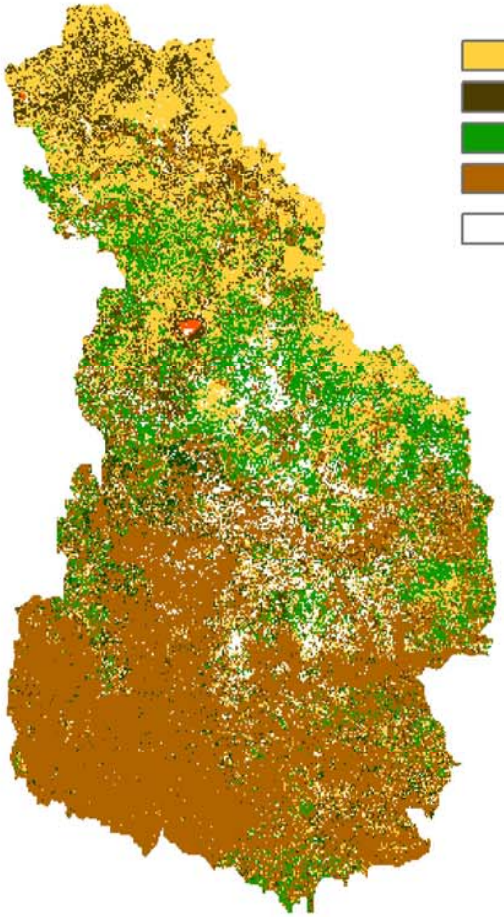
>= 10

0

Mask of MOD15
Collection 4 LAI Products

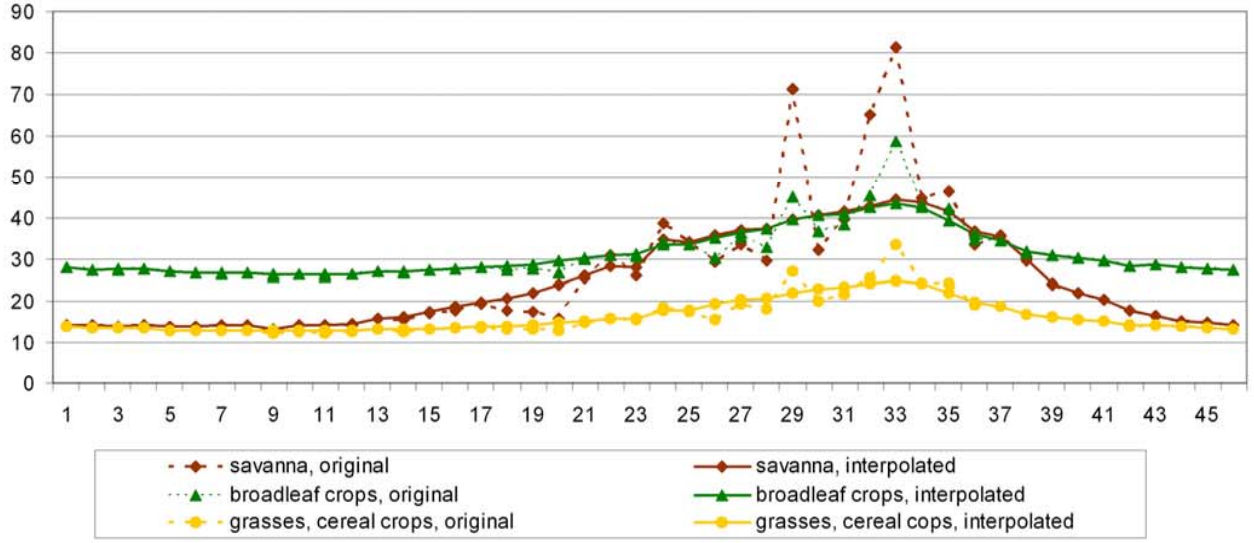
TiSeG results (2004)

a)



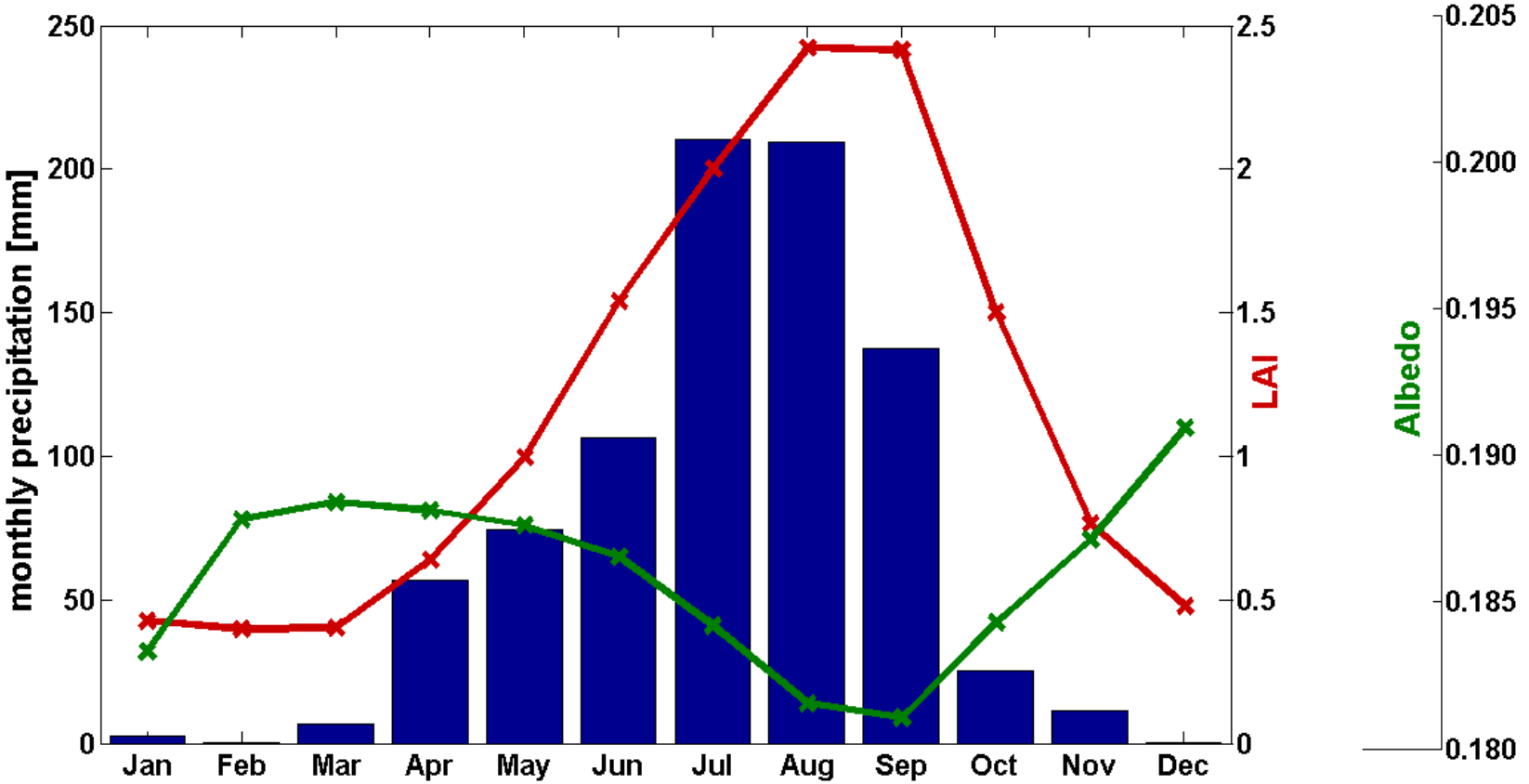
Grasses/cereal crops
Shrubs
Broadleaf crops
Savanna
Broadleaf forest
Needleleaf forest
Unvegetated
Urban
Mask of MOD15 Collection 4 LAI Products

b)



MODIS albedo & LAI, rain

seasonal cycle for the White Volta basin

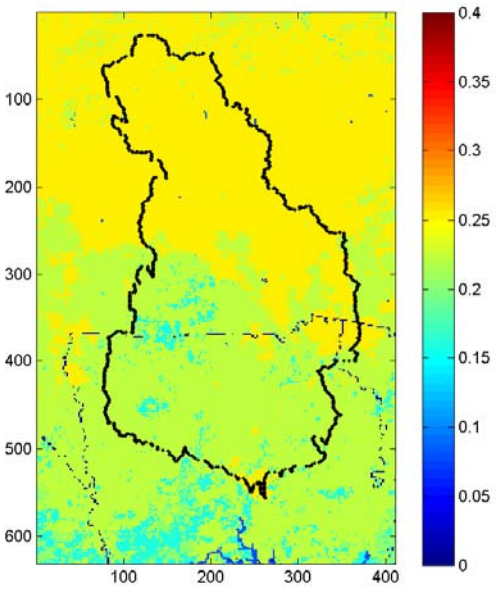


Albedo

standard literature versus MODIS 2004

standard literature

albedo depending on LU type



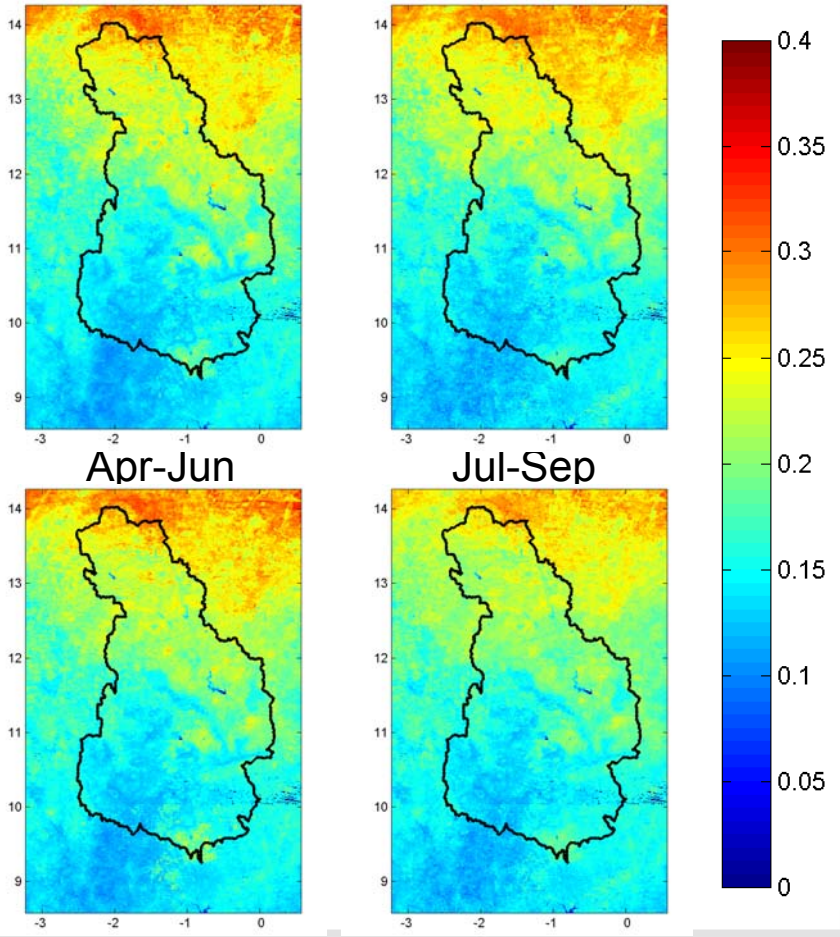
MODIS 3 month-mean

Jan-Mar

Oct-Dec

Apr-Jun

Jul-Sep

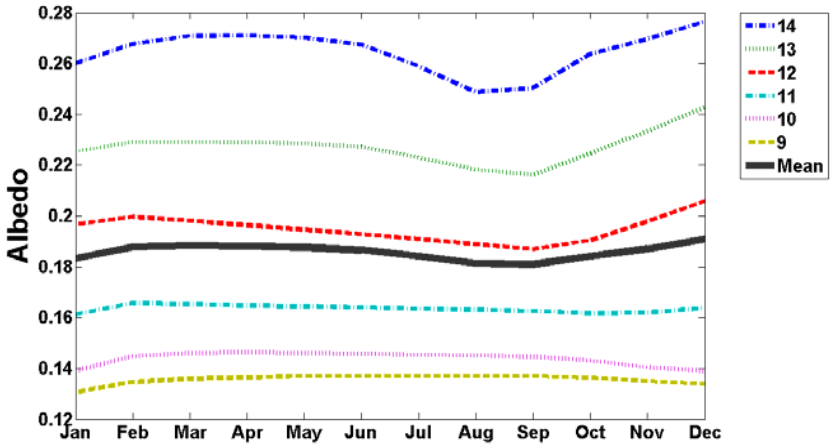


Albedo

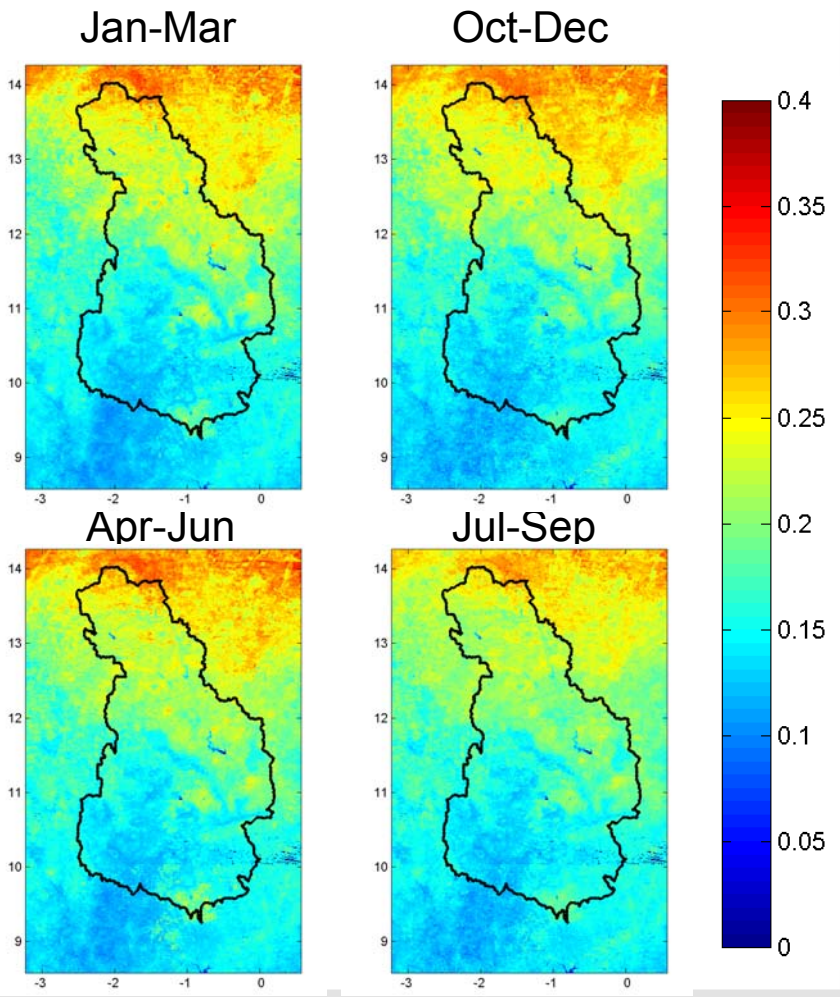
standard literature versus MODIS 2004

MODIS:

Latitudinal profile of monthly means

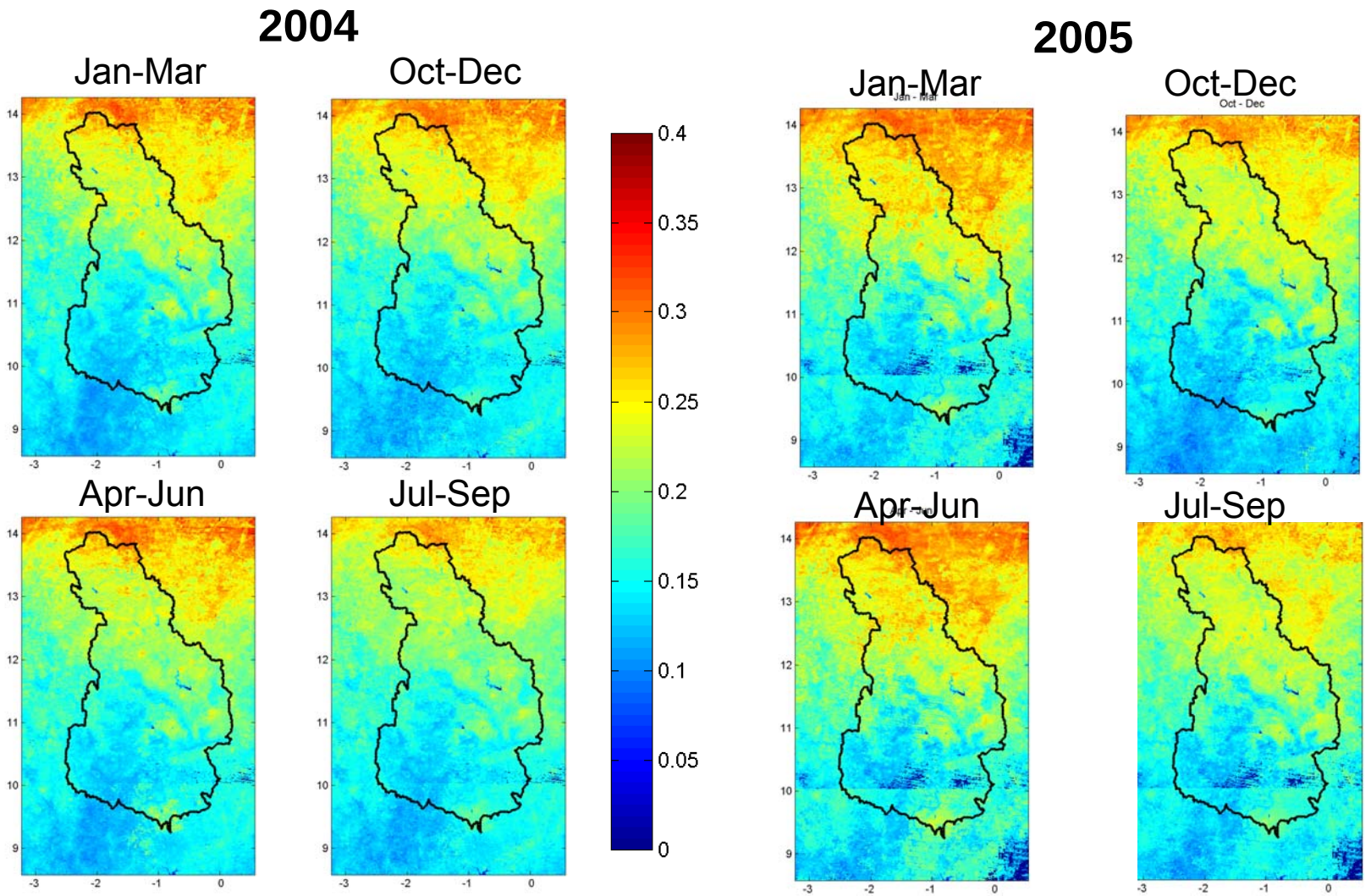


MODIS 3 month-mean



Albedo

Inter-annual variability: MODIS 2004 & 2005



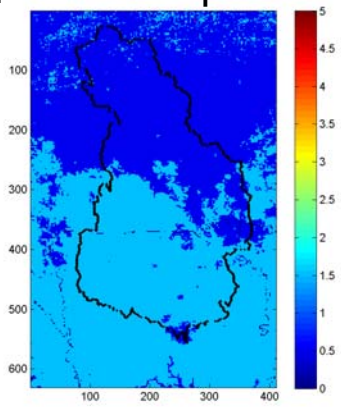
Leaf Area Index- LAI

standard literature versus MODIS 2004

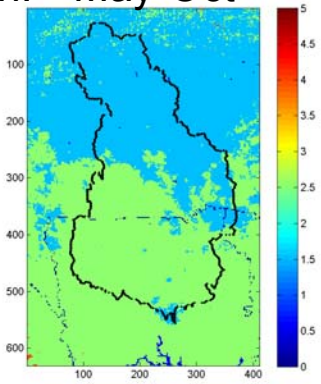
standard literature

LAI depending on LU type

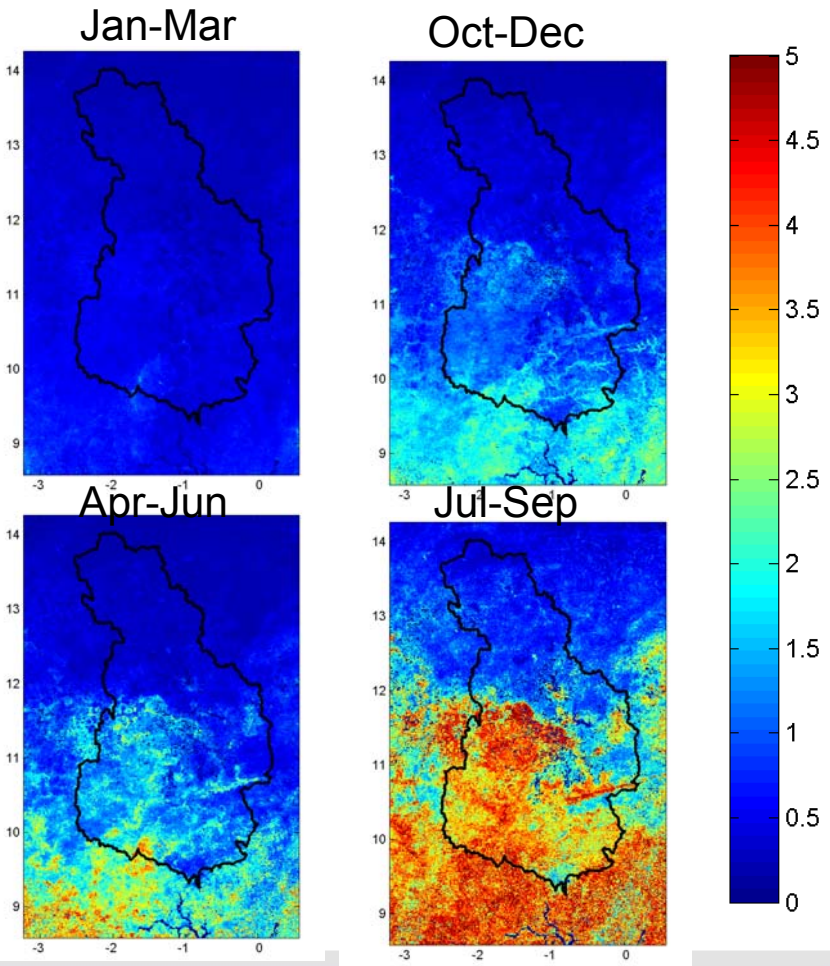
dry season: Nov-Apr



rainy season: May-Oct



MODIS 3 month-mean

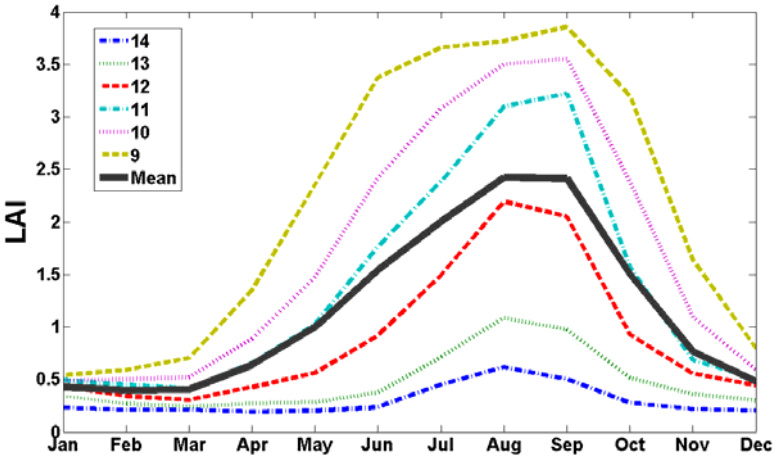


Leaf Area Index- LAI

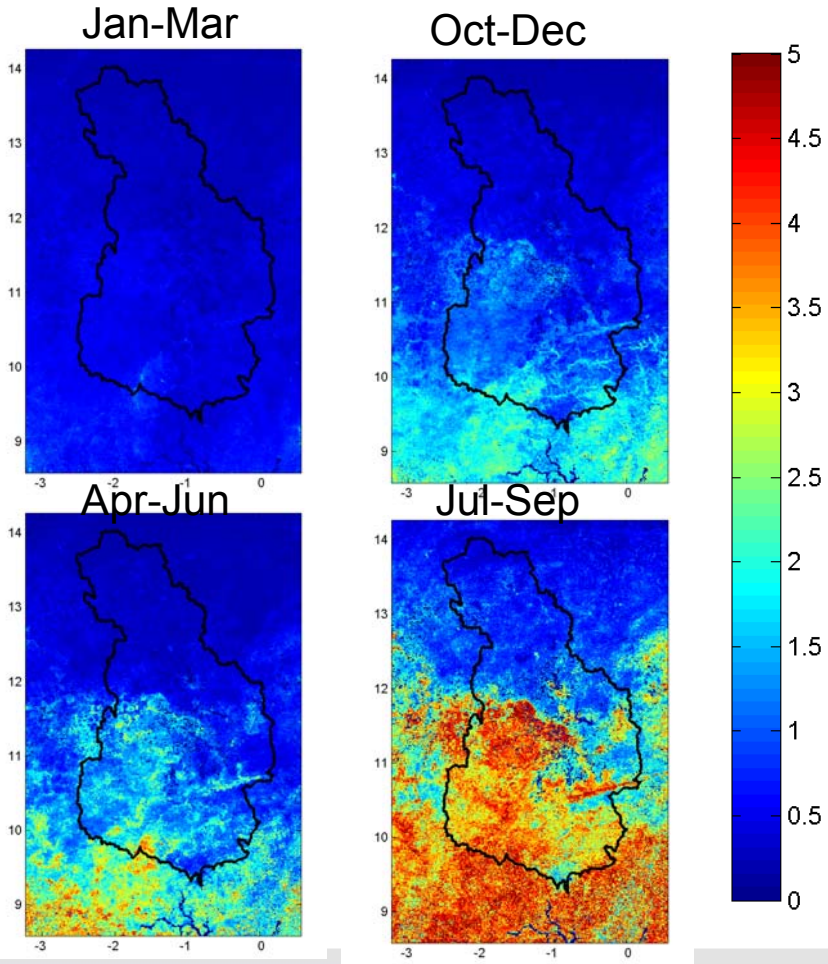
standard literature versus MODIS 2004

MODIS:

Latitudinal profile of monthly means

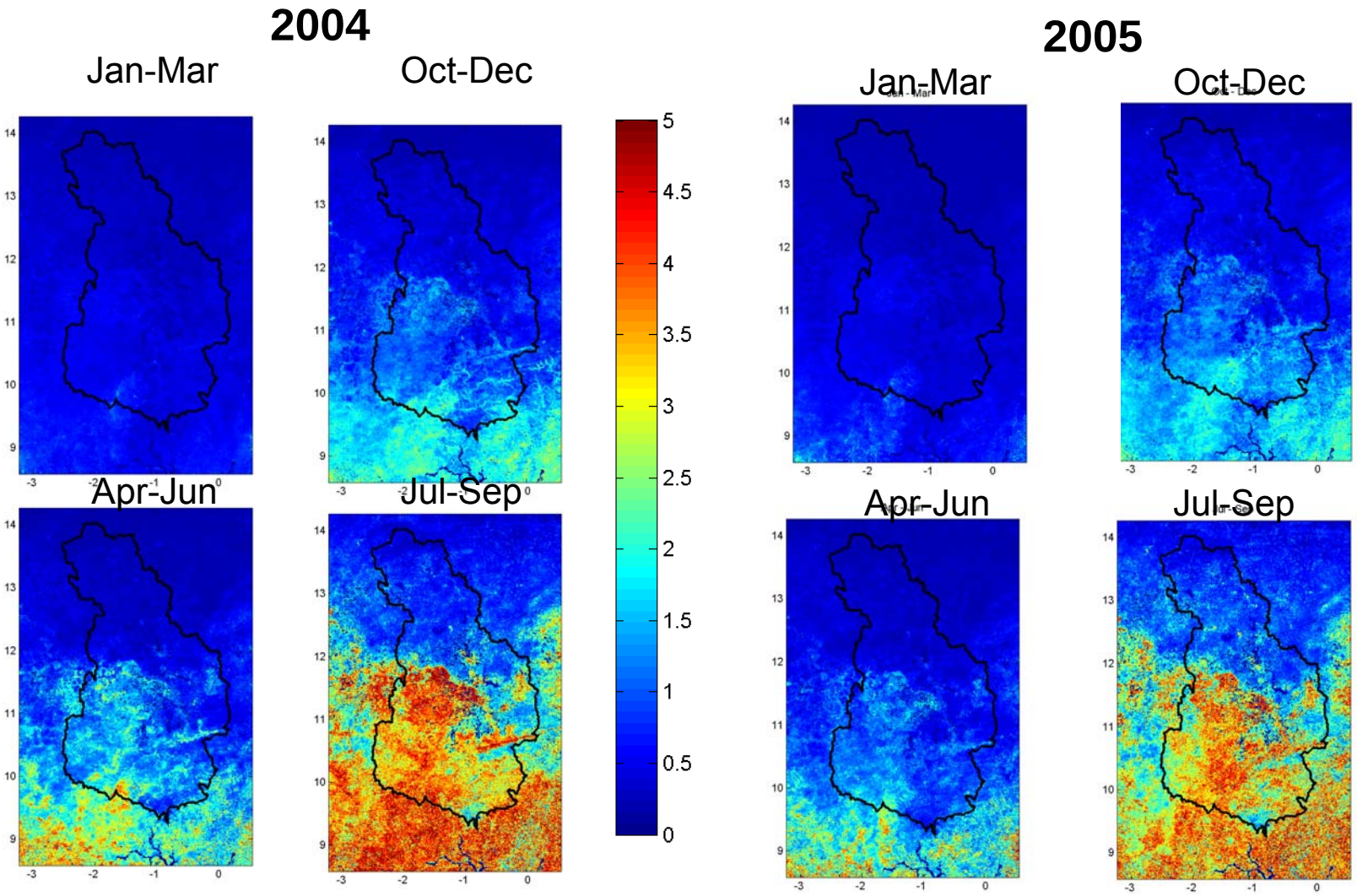


MODIS 3 month-mean



Leaf Area Index- LAI

Inter-annual variability: MODIS 2004 & 2005



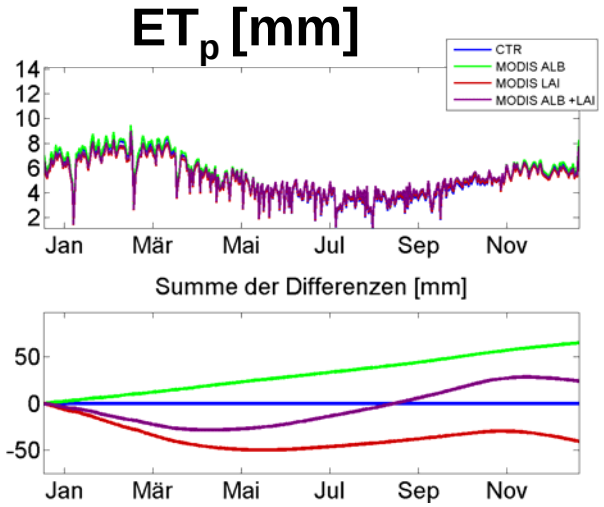
Impact of MODIS albedo and LAI on water balance estimations

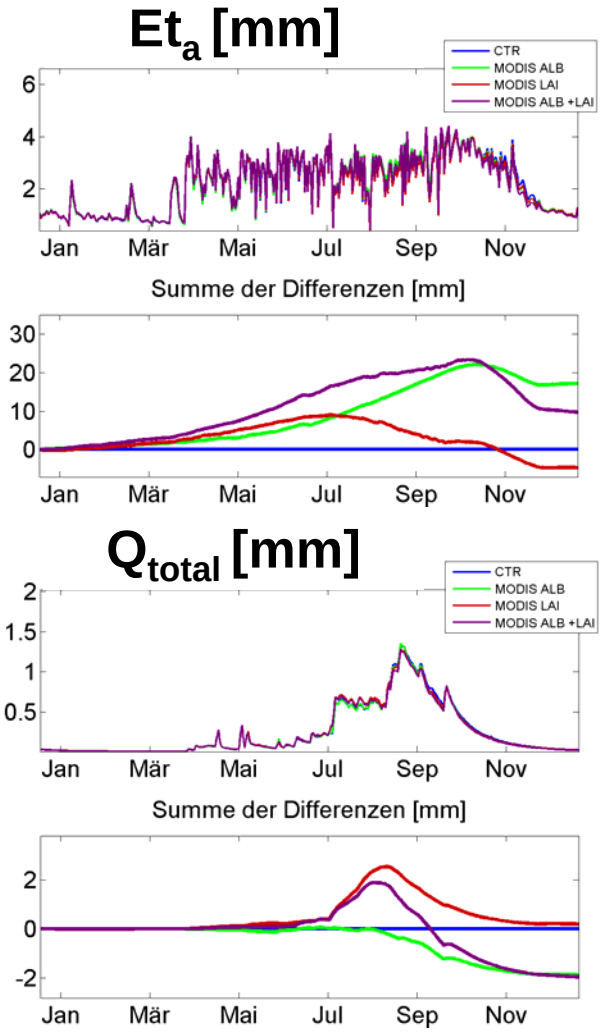
a) time series of spatially aggregated variables

b) spatial distribution of annual sums

Impact of MODIS albedo and LAI : time series

2004:





legend:

Control-Run

MODIS Albedo

MODIS LAI

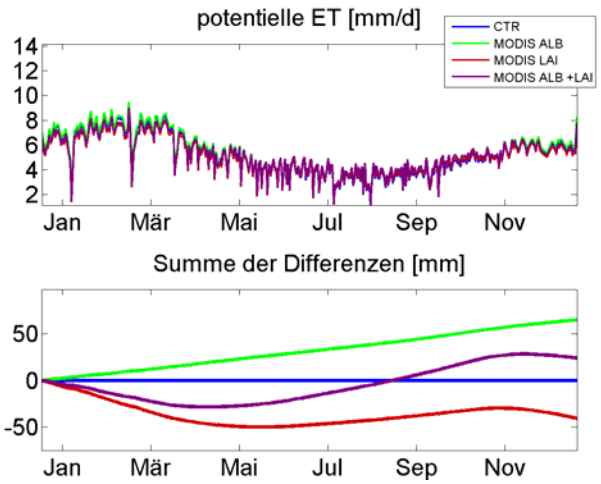
MODIS Albedo & LAI

Impact of MODIS albedo and LAI : time series

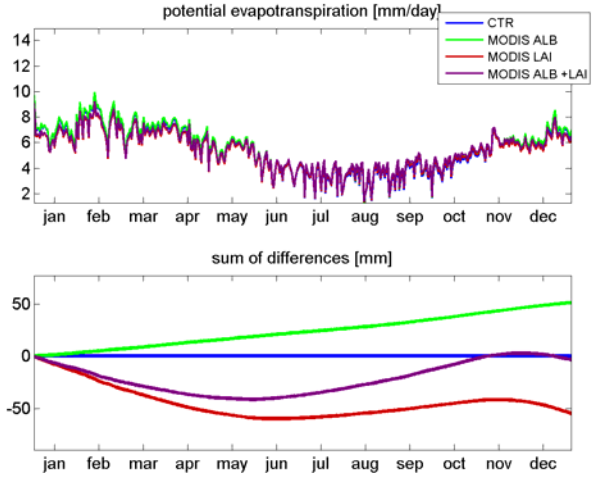
inter-annual variability

ET_p [mm]

2004:



2005:



legend:

Control-Run

MODIS Albedo

MODIS LAI

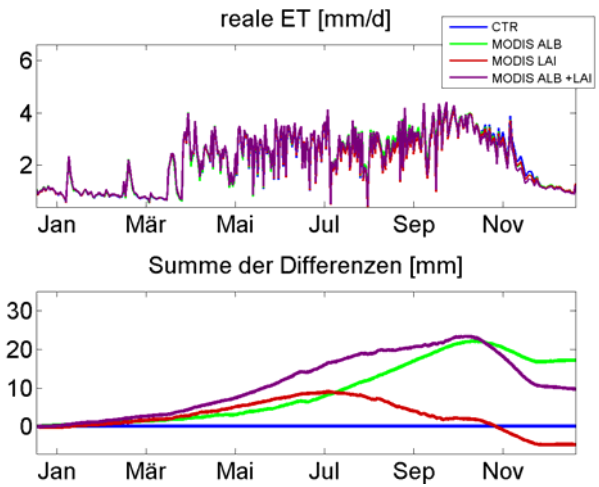
MODIS Albedo & LAI

Impact of MODIS albedo and LAI : time series

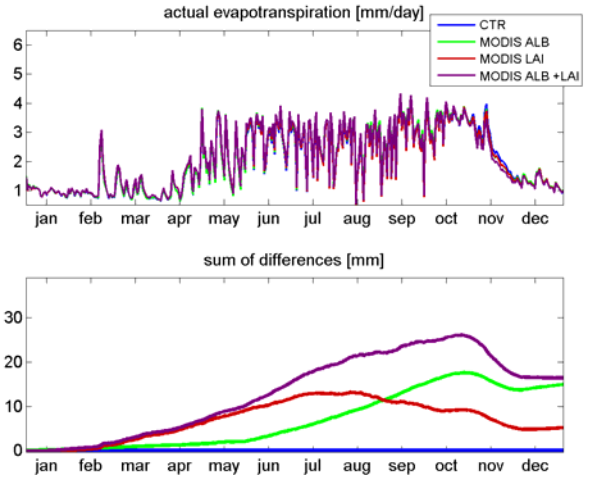
inter-annual variability

ET_a [mm]

2004:



2005:



legend:

Control-Run

MODIS Albedo

MODIS LAI

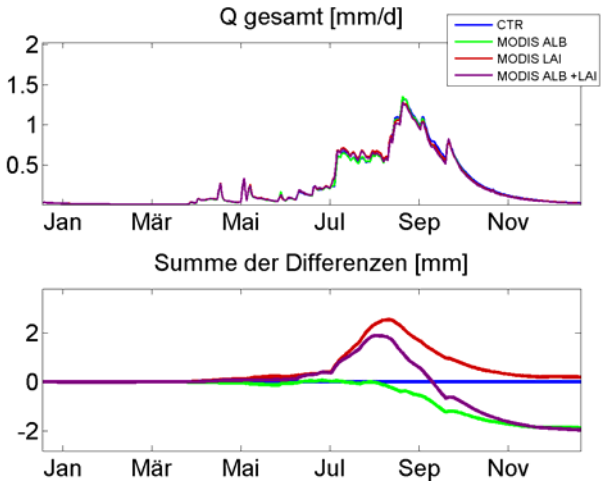
MODIS Albedo & LAI

Impact of MODIS albedo and LAI : time series

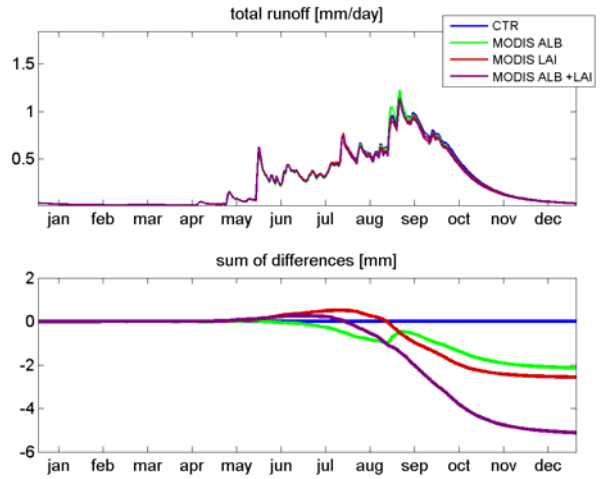
inter-annual variability

Q_{total} [mm]

2004:



2005:



legend:

Control-Run

MODIS Albedo

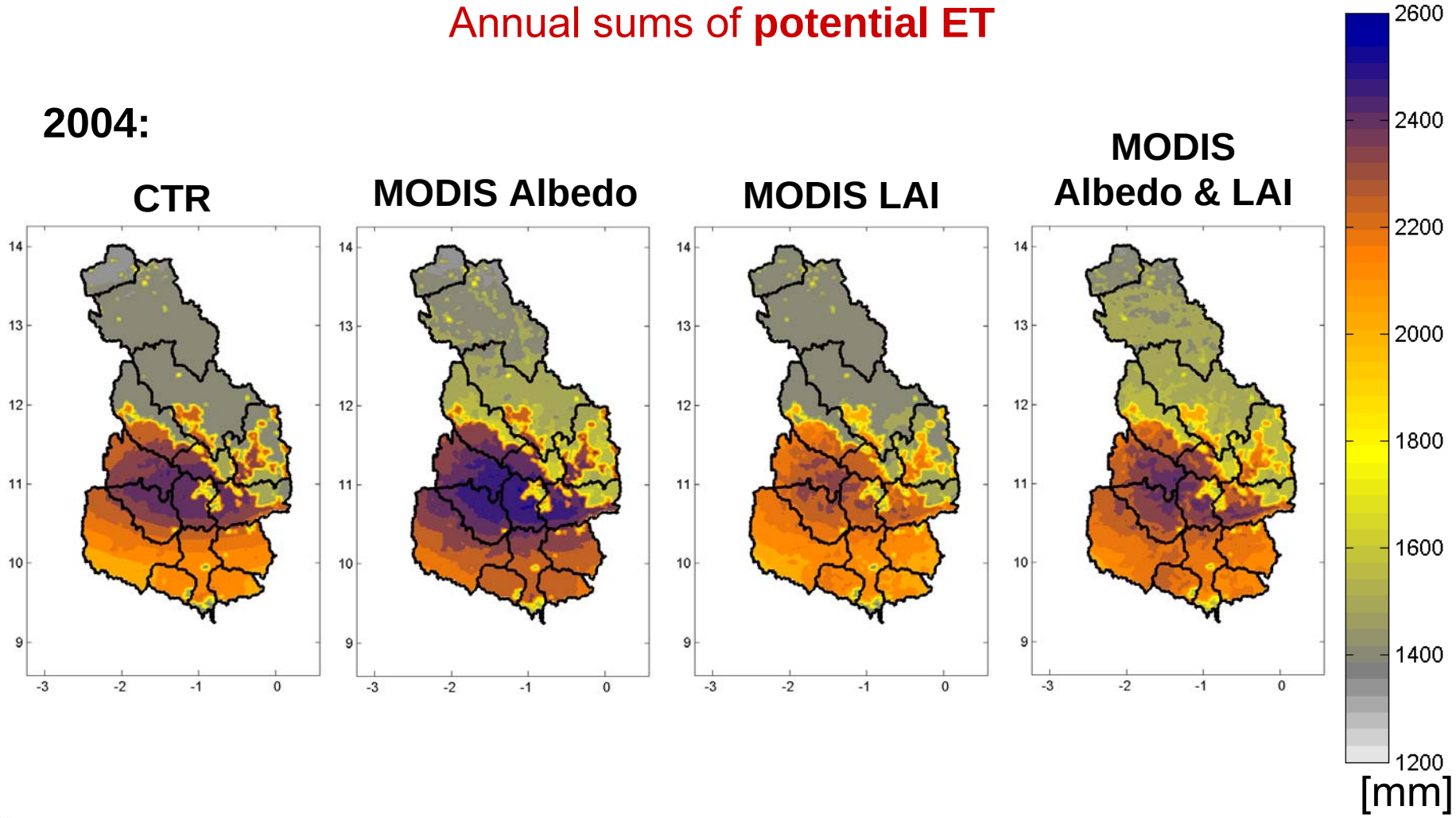
MODIS LAI

MODIS Albedo & LAI

Impact of MODIS albedo and LAI : spatial distribution

Annual sums of **potential ET**

2004:

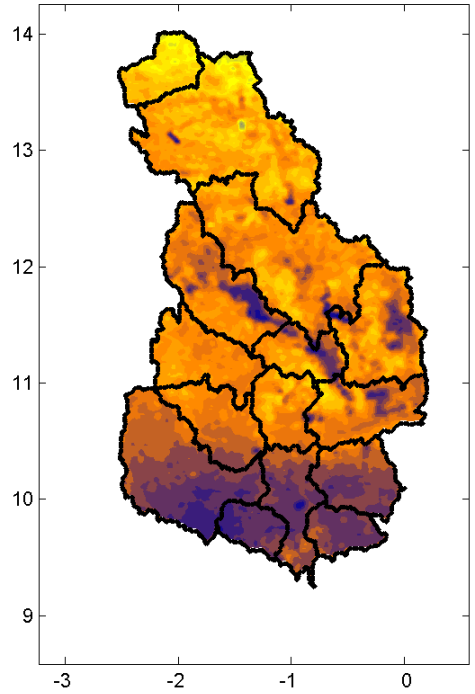


Impact of MODIS albedo and LAI : spatial distribution

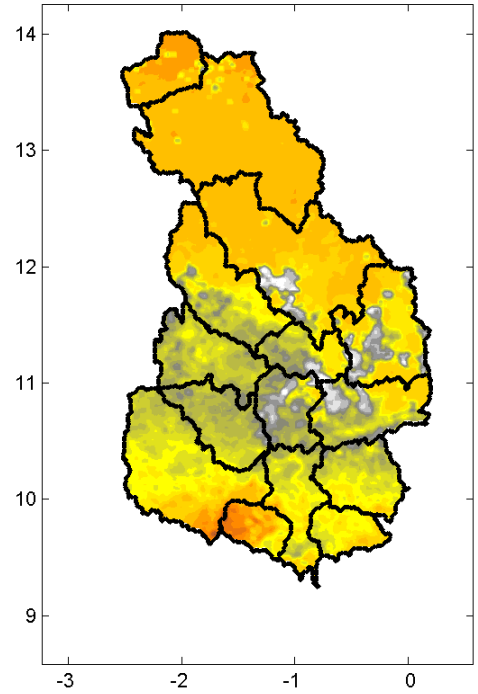
Differences of annual sums of **potential ET**
with respect to simulations using static tabulated values

2004:

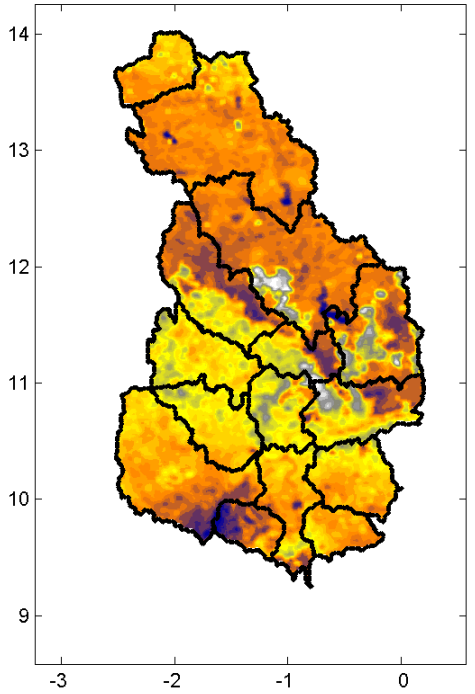
MODIS Albedo

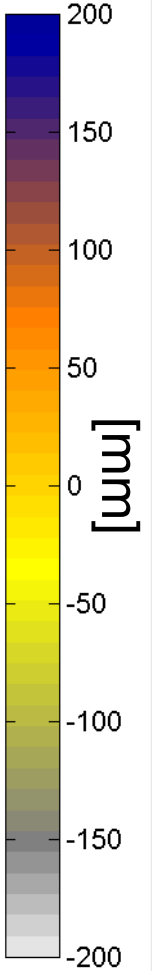


MODIS LAI



MODIS Albedo & LAI

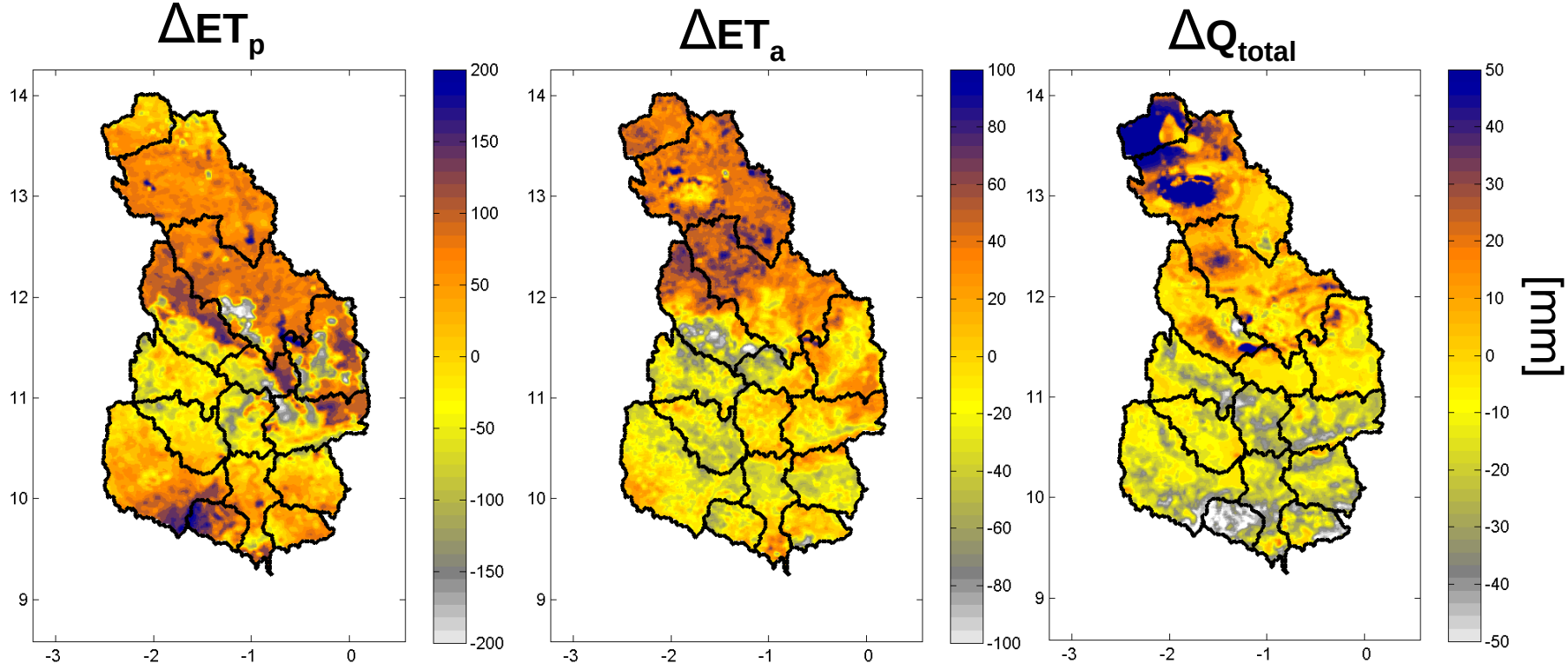




Impact of MODIS albedo and LAI : spatial distribution

Differences of annual sums – MODIS Albedo & LAI
with respect to simulations using static tabulated values

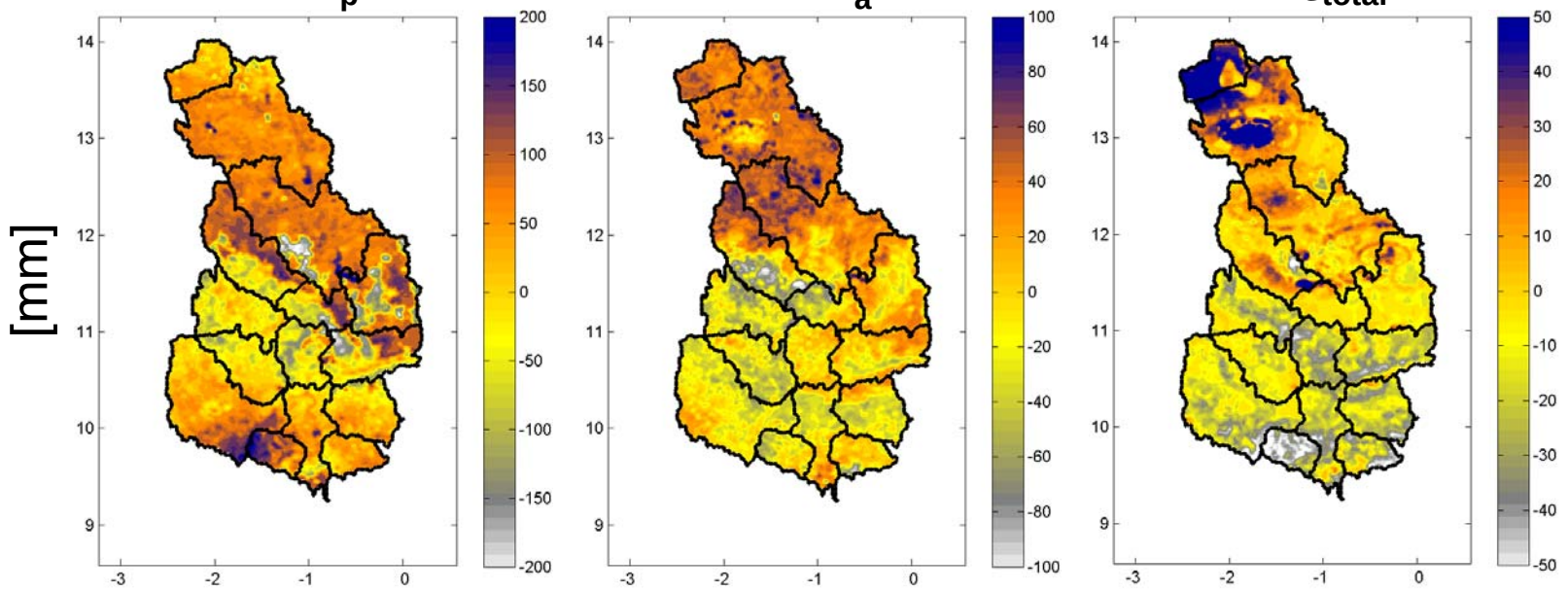
2004:



Impact of MODIS albedo and LAI : spatial distribution

Differences of annual sums – MODIS Albedo & LAI
with respect to simulations using static tabulated values

2004:



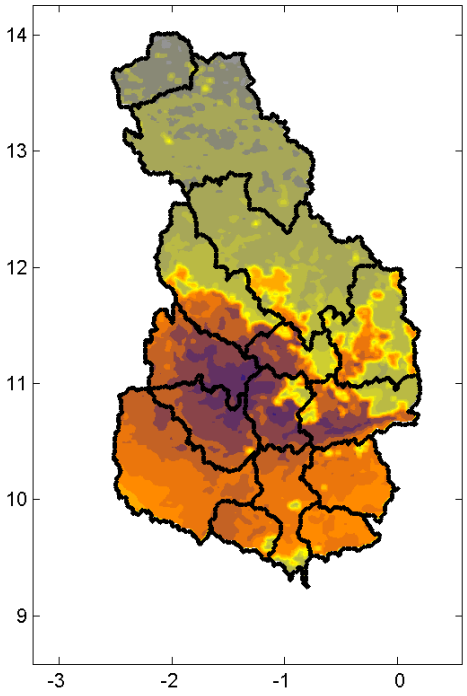
	ΔET_p	ΔET_a	ΔQ_{total}
total basin:	+2%	+1%	-1%
sub basin:	-2% – +5%	-4% – +7%	-26% – +35%*

Impact of MODIS albedo and LAI : spatial distribution

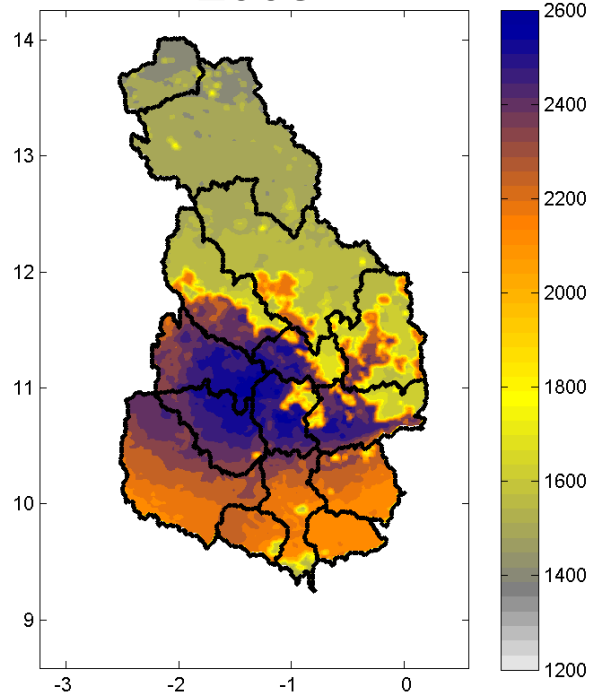
inter-annual variability:
Annual sums – MODIS Albedo & LAI

ET_p:

2004



2005



Impact of MODIS albedo and LAI : spatial distribution

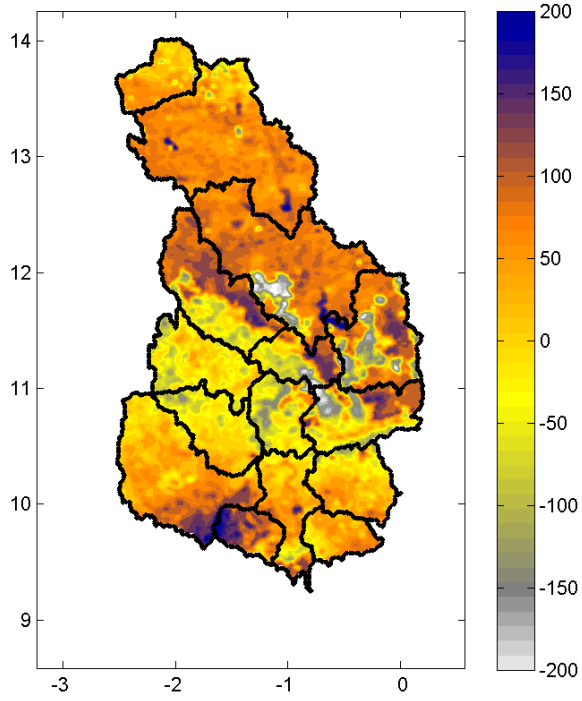
inter-annual variability:

Differences of annual sums – MODIS Albedo & LAI

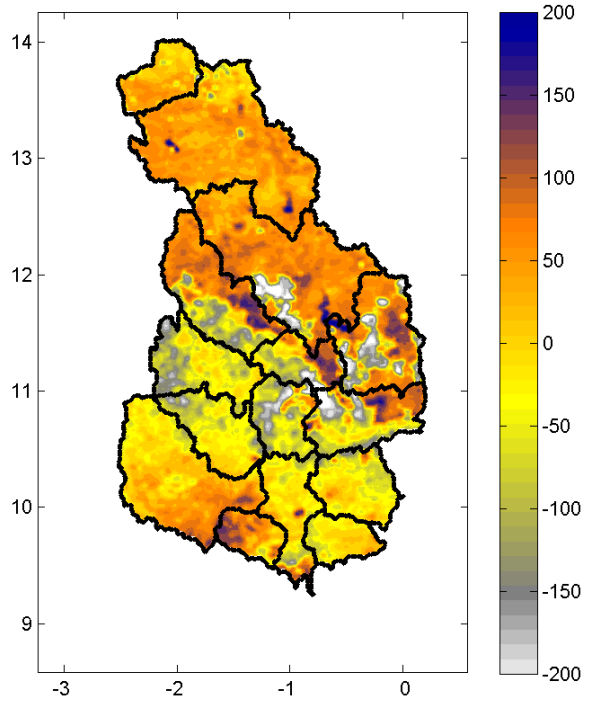
with respect to simulations using static tabulated values

ΔET_p:

2004



2005



Impact of MODIS albedo and LAI : spatial distribution

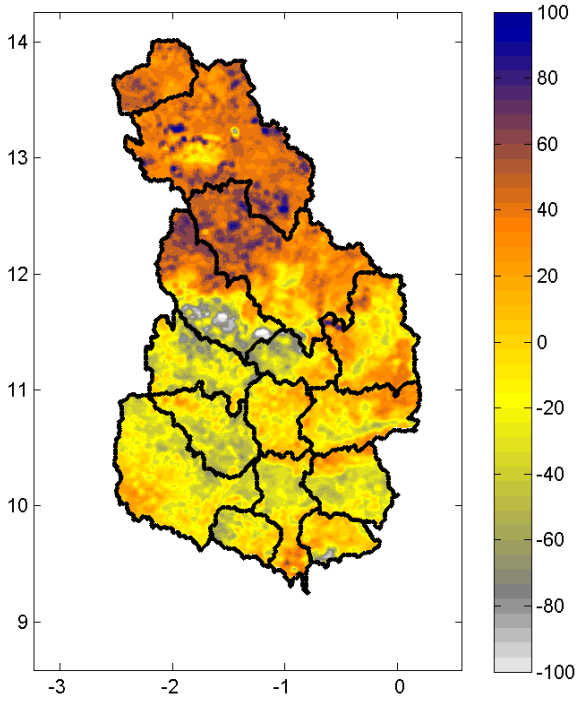
inter-annual variability:

Differences of annual sums – MODIS Albedo & LAI

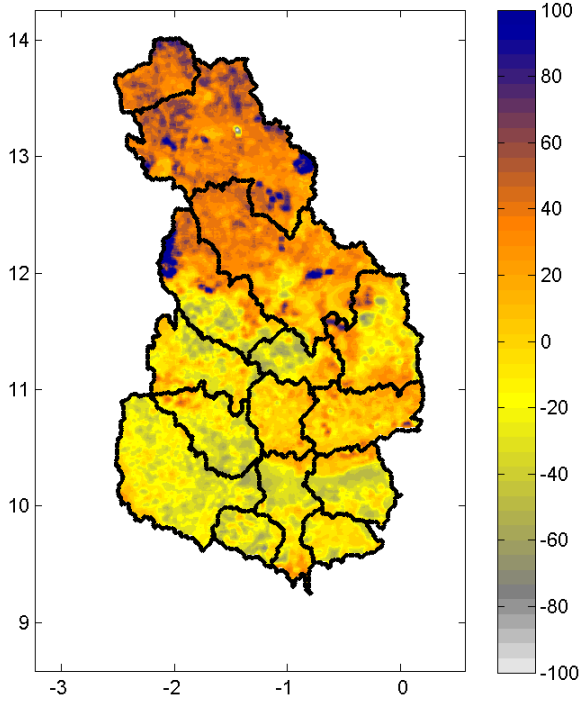
with respect to simulations using static tabulated values

ΔET_a:

2004



2005



Impact of MODIS albedo and LAI : spatial distribution

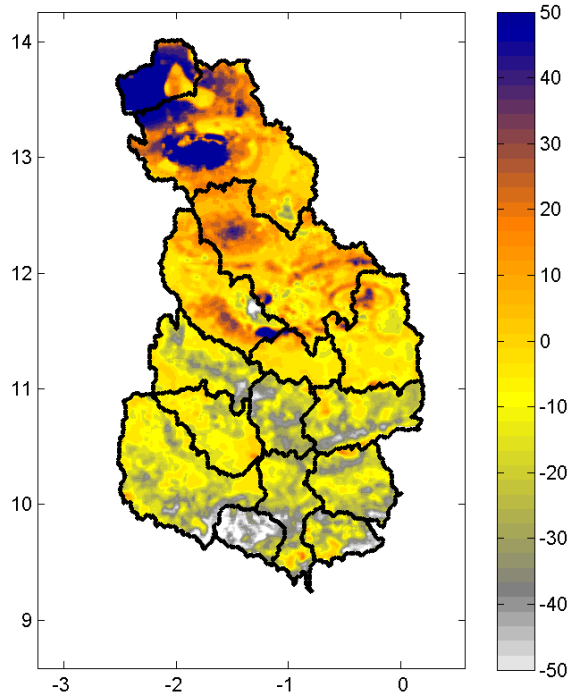
inter-annual variability:

Differences of annual sums – MODIS Albedo & LAI

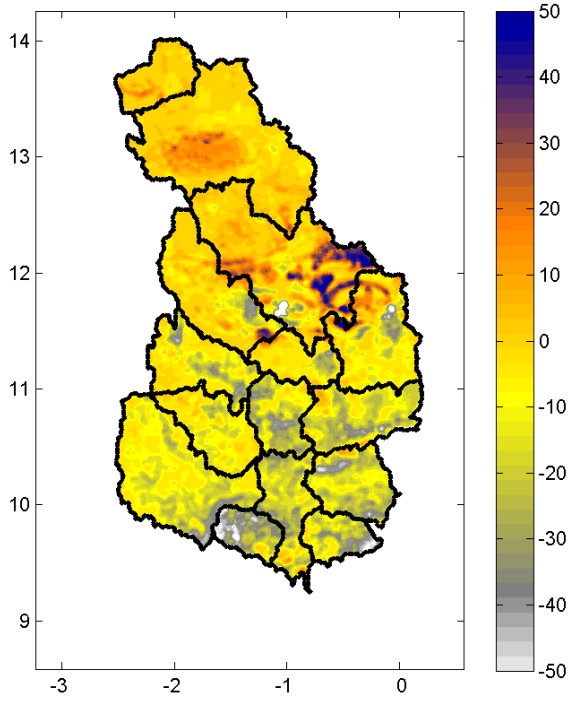
with respect to simulations using static tabulated values

ΔQ_{total}:

2004



2005



Impact of MODIS albedo and LAI : spatial distribution

2004 Tables 2005

annual sums:

	ET_p	ET_a	Q_{total}
Tabulated	1879	770	81
MODIS ALB	1961	785	79
MODIS LAI	1851	763	81
MODIS ALB & LAI	1916	779	80

	ET_p	ET_a	Q_{total}
Tabulated	1966	734	85
MODIS ALB	2035	741	83
MODIS LAI	1926	739	83
MODIS ALB & LAI	1962	744	81

Standard deviation within subcatchments:

	ET_p	ET_a	Q_{total}
Tabulated	214	83	66
MODIS ALB & LAI	173	80	62

	ET_p	ET_a	Q_{total}
Tabulated	234	87	60
MODIS ALB & LAI	193	82	57

Summary

- Integration of MODIS albedo & LAI into a hydrological model
- Comparison MODIS albedo & LAI versus standard literature values
  - albedo: increased level of detail in spatial dimension
  - LAI: additional better representation of temporal development
- MODIS application allows inter-annual comparisons
  - further advantage: all data are based on same data source & time
- Impact of MODIS albedo & LAI on hydrological simulation results
  - minor on daily time series of spatially aggregated variables, occurring differences agree well with theoretical impact (Penman-Monteith) & the differences in albedo & LAI grids
  - clear on spatial distribution of water balance variables

Further readings:
Wagner, S., Kunstmann, H. Bárdossy, A., Conrad, C., Colditz, R., Water balance estimation of a poorly gauged catchment in West Africa using dynamical downscaling of meteorological fields and remote sensing information J. Phys.Chem. Earth (2008), doi:10.1016/j.pce.2008.04.002

Wagner, S. Water Balance in a Poorly Gauged Basin in West Africa Using Atmospheric Modelling and Remote Sensing Information, Dissertation