Hydrology in the Community Land Model

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Terrestrial Sciences Section

The **Community Land Model** is a... ?

a) Hydrology model

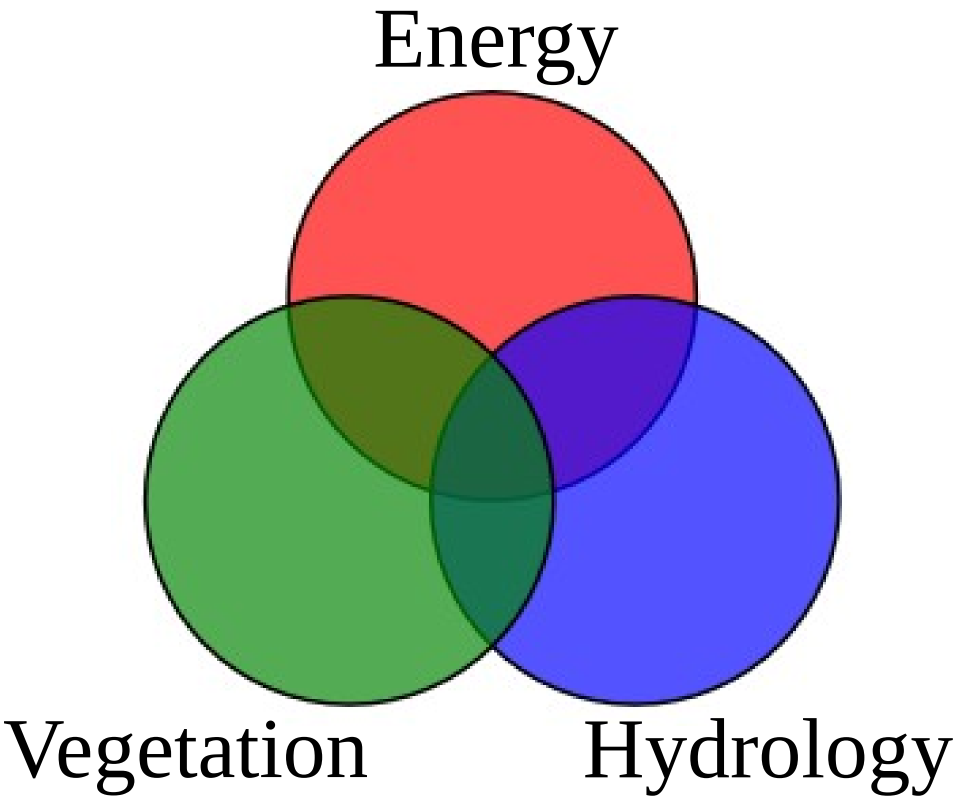
b) Land Surface model

c) Terrestrial Processes model

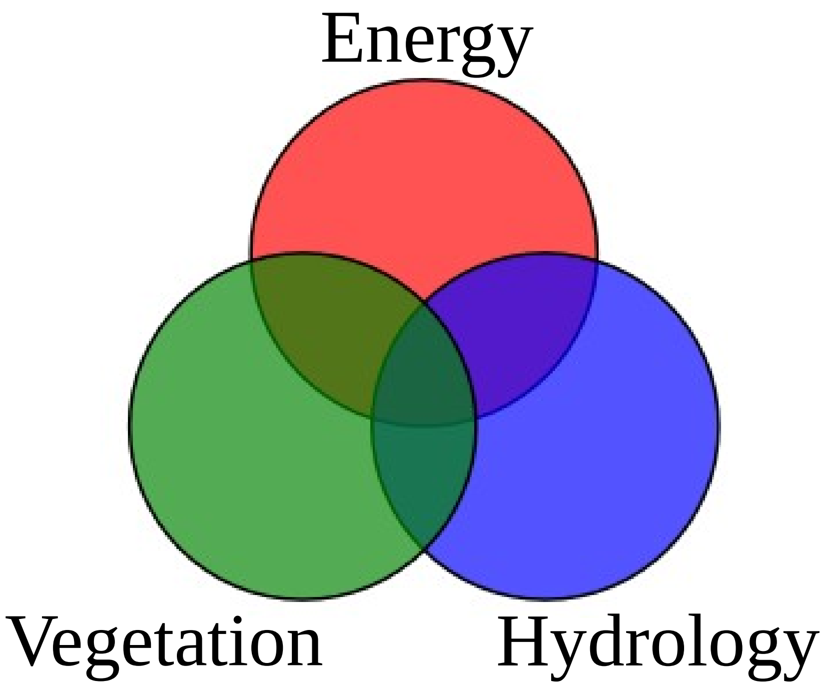
d) Biogeochemical cycling model

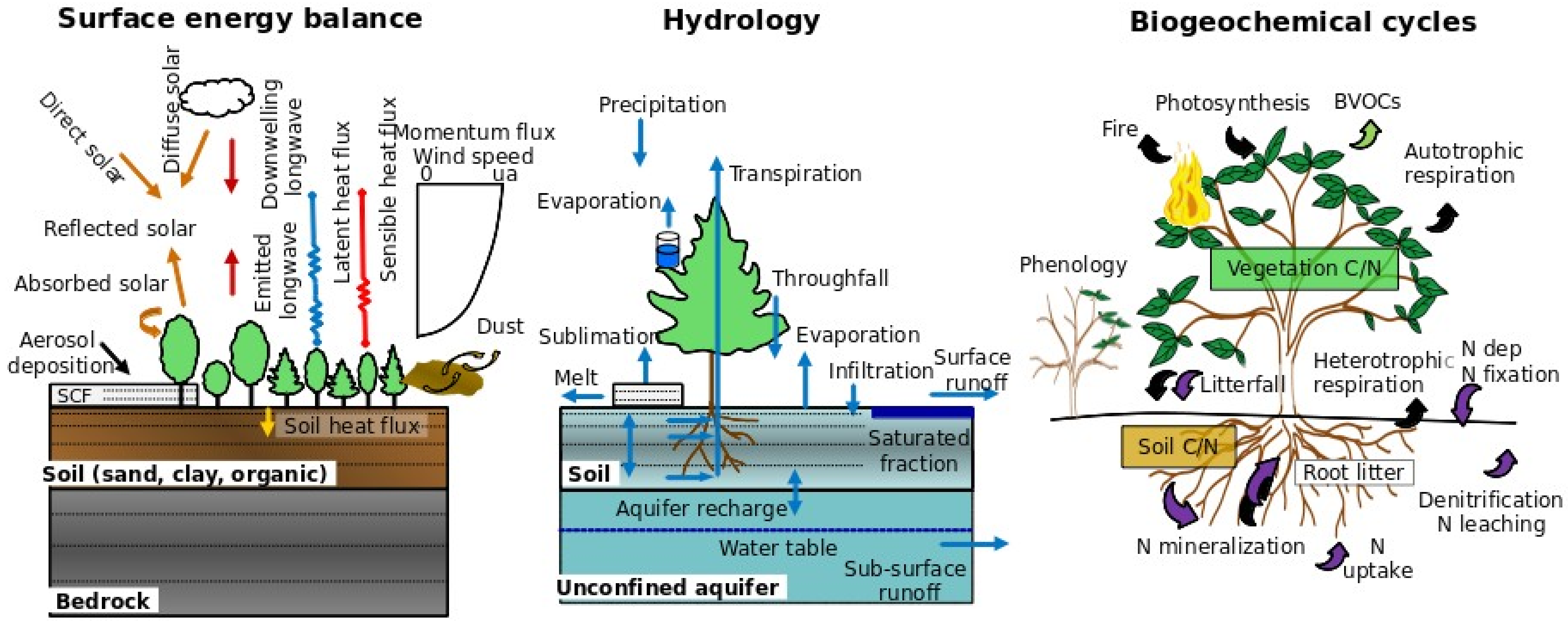
e) Atmospheric lower boundary condition

The movement of **water** is inextricably linked to the flow of **energy** and the life cycle of **vegetation**



The ***modeling*** of the movement of water is inextricably linked to the ***modeling*** of the flow of energy and the ***modeling*** of the life cycle of vegetation




Surface energy balance
Direct solar
Diffuse solar
Downwelling longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
ua
Reflected solar
Absorbed solar
Emitted longwave
Aerosol deposition
Dust
SCF
Soil heat flux
Soil (sand, clay, organic)
Bedrock
Hydrology
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Melt
Infiltration
Surface runoff
Saturated fraction
Soil
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Biogeochemical cycles
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
Litterfall
Heterotrophic respiration
N dep
N fixation
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake

The Water Balance

$$P = E + R + \Delta S$$

P = Precipitation
E = Evapotranspiration
R = Runoff
S = Storage

Different Models, *Different Foci*

Flood Forecasting ⇒ **R**

NWP, Climate Prediction ⇒ **E**

Drought Monitoring, Groundwater ⇒ **S**

Different Foci, *Different Models*

1-D ⇒ Darcy Flow (Infiltration/Recharge)

2-D ⇒ River Routing

3-D ⇒ Saturated Flow (Groundwater)

CLM is tasked with simulating ***all*** of these phenomena...

...therefore, ***trade-offs*** will be made.

CLM Water Balance Operations

Precipitation

⇒ Partitioning between rain and snow, or between stratiform and convective

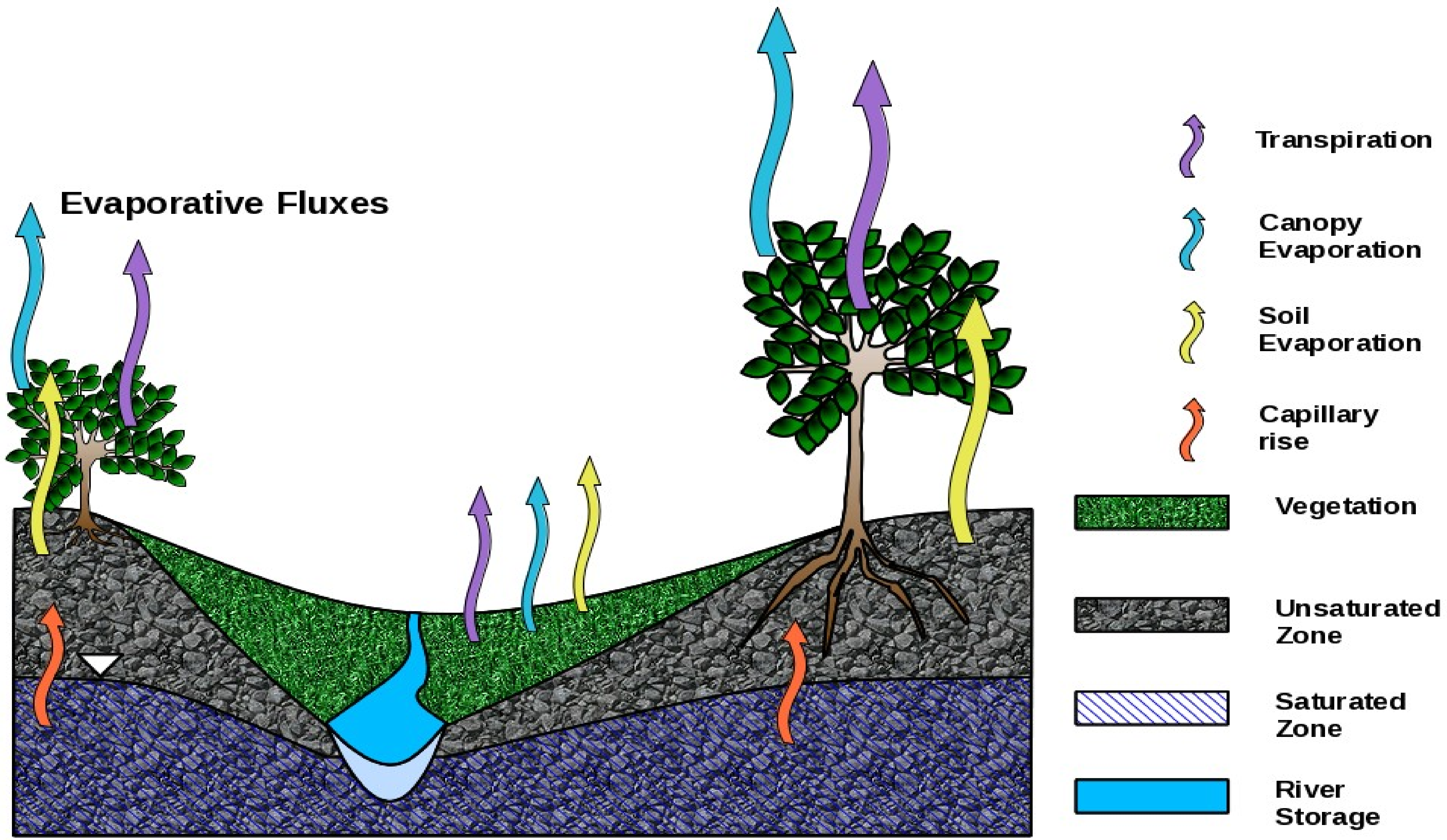
⇒ Canopy interception, storage, and throughfall

CLM Water Balance Operations

Evaporation

⇒ Evaporation from Soil / Canopy / Snow / Surface Water

⇒ Transpiration from vegetation


Evaporative Fluxes
Transpiration
Canopy Evaporation
Soil Evaporation
Capillary rise
Vegetation
Unsaturated Zone
Saturated Zone
River Storage

CLM Water Balance Operations

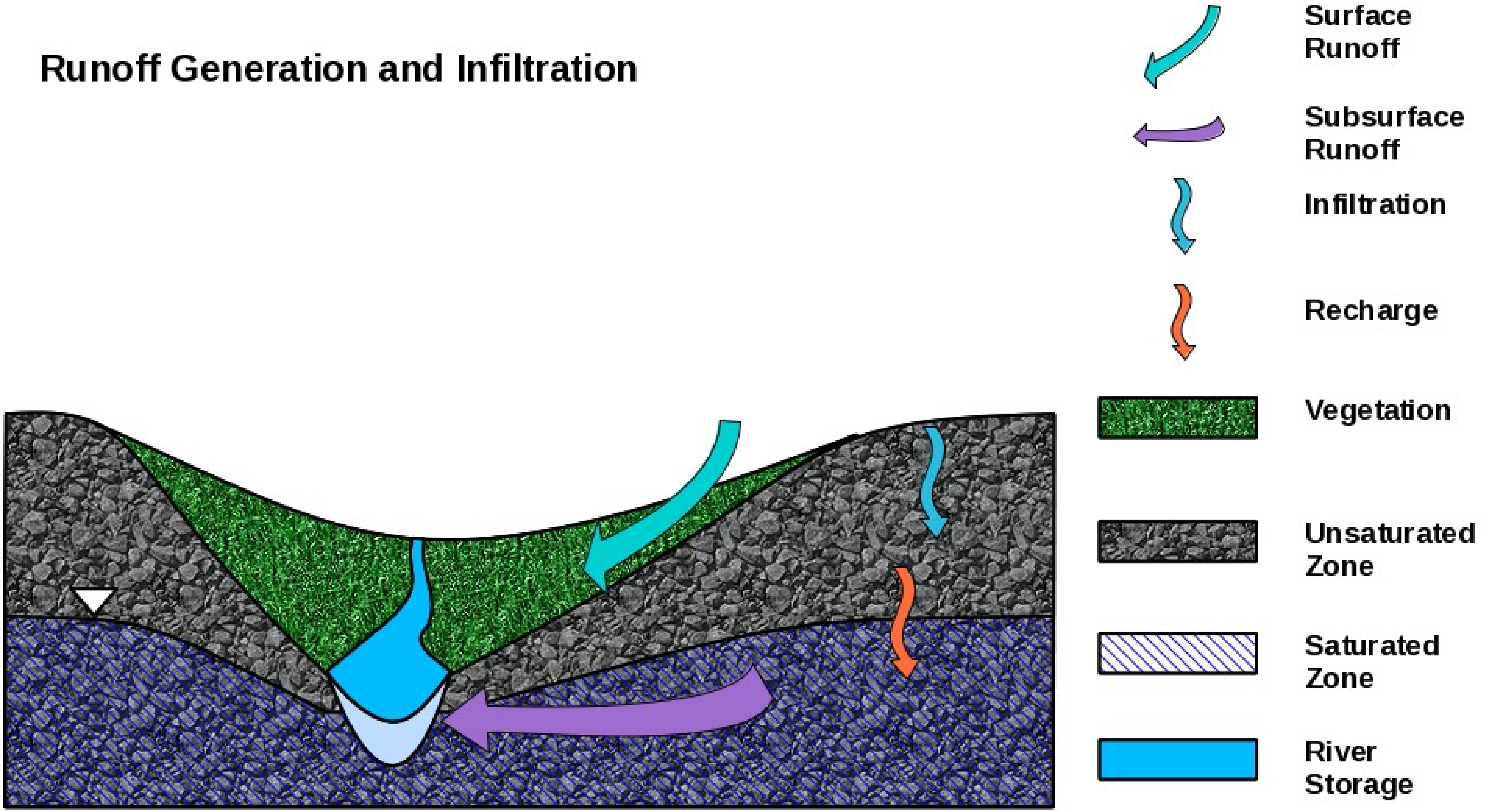
Runoff

⇒ Surface Runoff (Infiltration and/or Saturation Excess)

⇒ Subsurface Runoff (Baseflow)

⇒ River Routing

Runoff Generation and Infiltration



CLM Water Balance Operations

Storage

⇒ Soil Moisture

⇒ Groundwater and water table depth

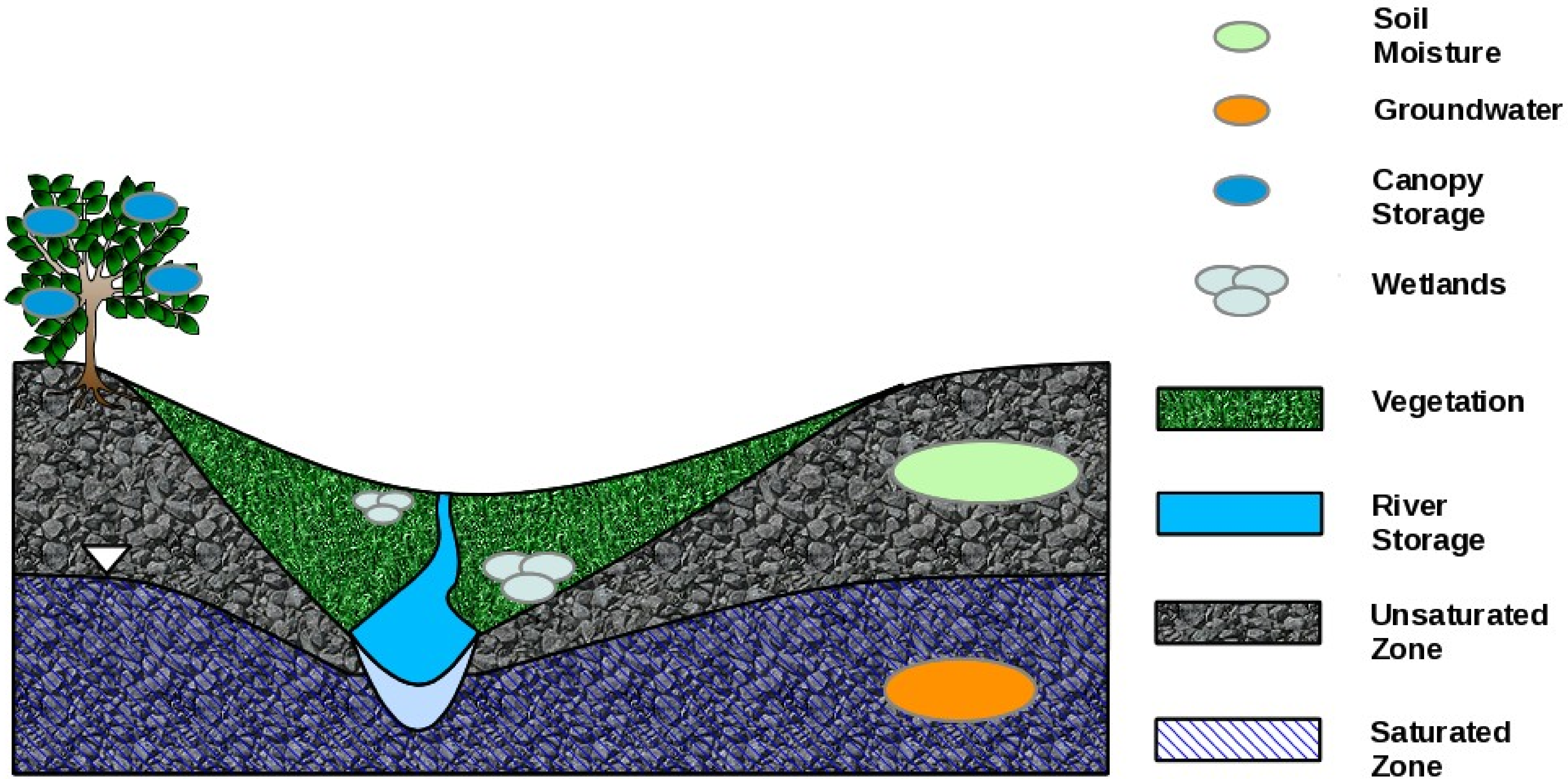
⇒ Perched water table

⇒ Canopy water

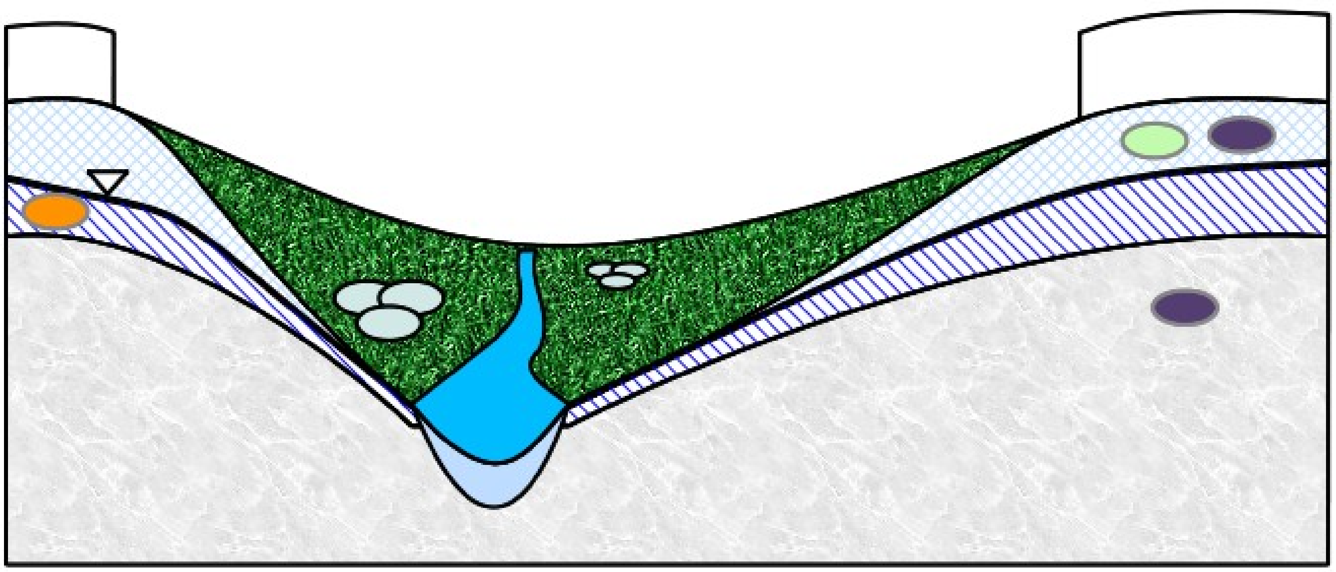
⇒ Surface water

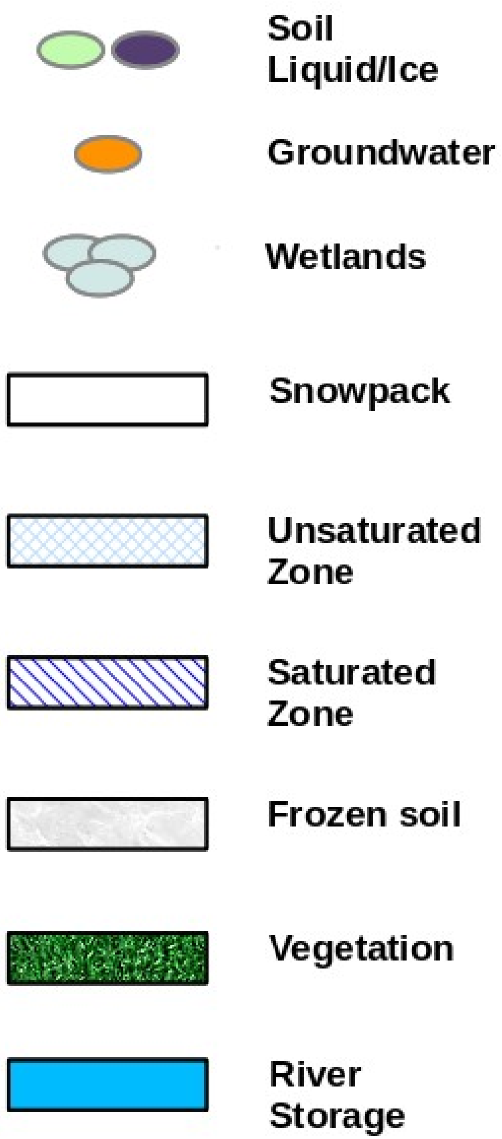
⇒ Snow

Storage Components



Cold Region Storage Components





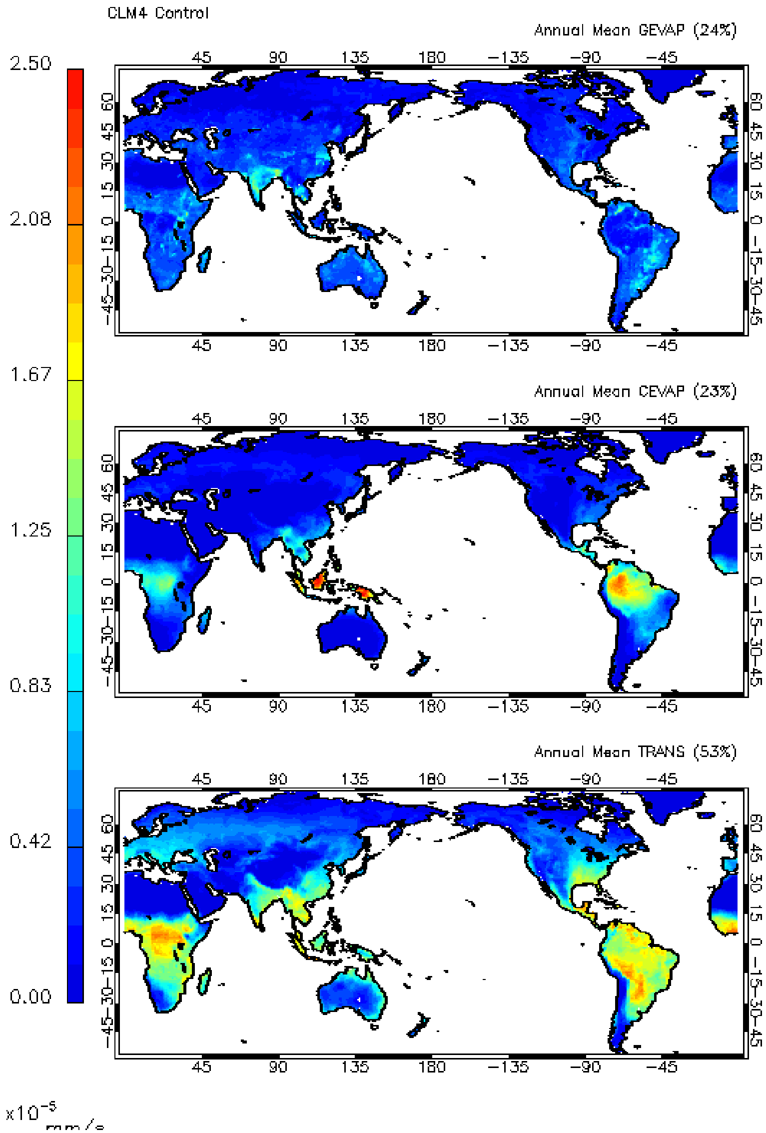
Surface Processes

- Precipitation partitioning
- Canopy hydrology
- Snow hydrology
- Surface runoff
- Infiltration
- Surface water (wetlands)
- Flooding
- River routing

Canopy Hydrology

- Interception / throughfall
- Leaf water storage and wetted fraction
- Evaporation from leaf surfaces

Canopy Hydrology And Evapotranspiration Partitioning

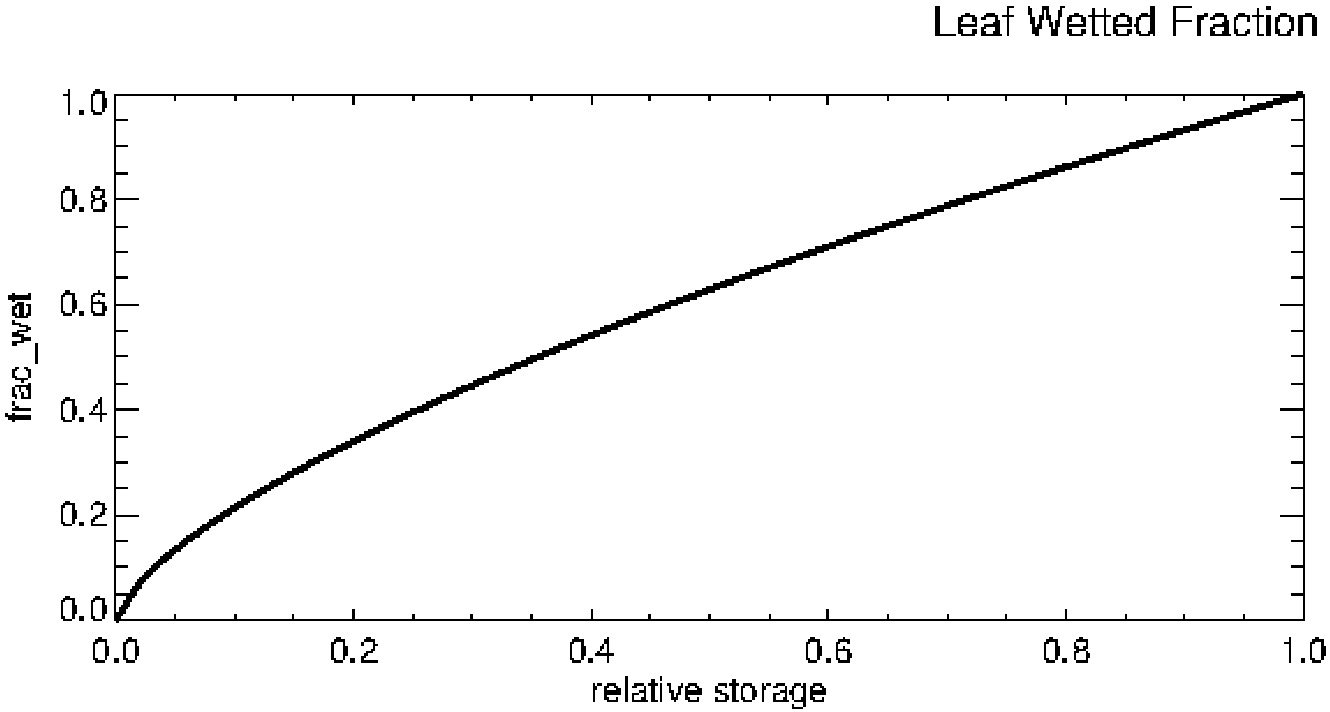


Ground Evaporation: 24%

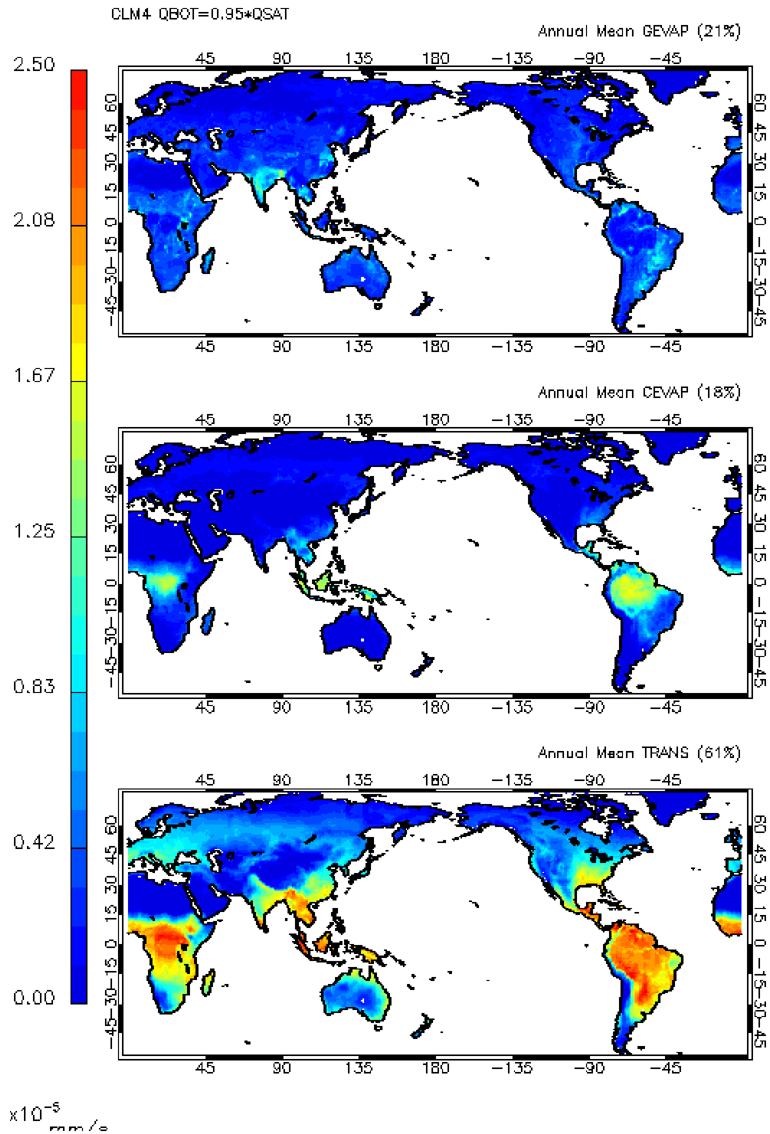
Canopy Evaporation: 23%

Transpiration: 53%

Leaf Wetted Area



Canopy Hydrology And Evapotranspiration Partitioning



Ground Evaporation: 21%

Canopy Evaporation: 18%

Transpiration: 61%

Snow Hydrology

- Density of new snow.
- Interception and canopy storage
- Multi-layer structure
- Compaction and metamorphosis
- Radiative transfer including aerosol effects
- Fractional snow covered area
- Subgrid surface energy and moisture fluxes

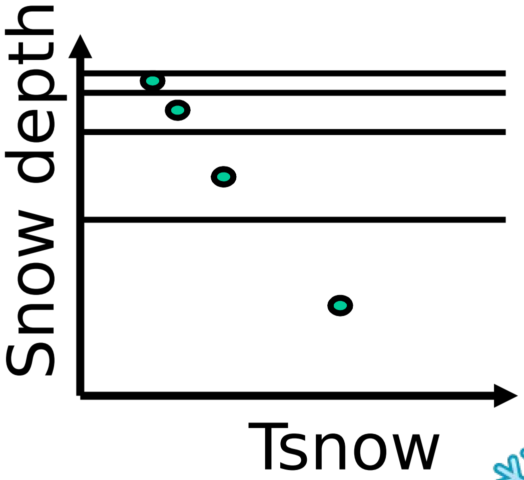
Snow model

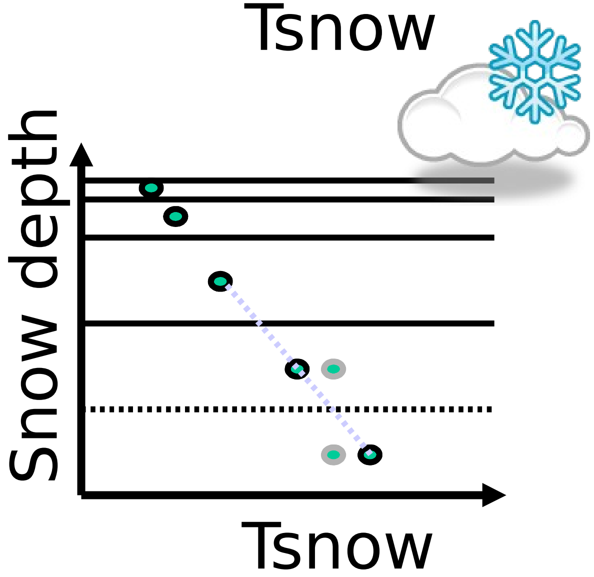
Treats processes such as:

- Accumulation
- Snow melt and refreezing
- Snow aging
- Water transfer across layers
- Snow compaction:
  - destructive metamorphism due to wind
  - overburden
  - melt-freeze cyclesI

- Sublimation
- Aerosol deposition

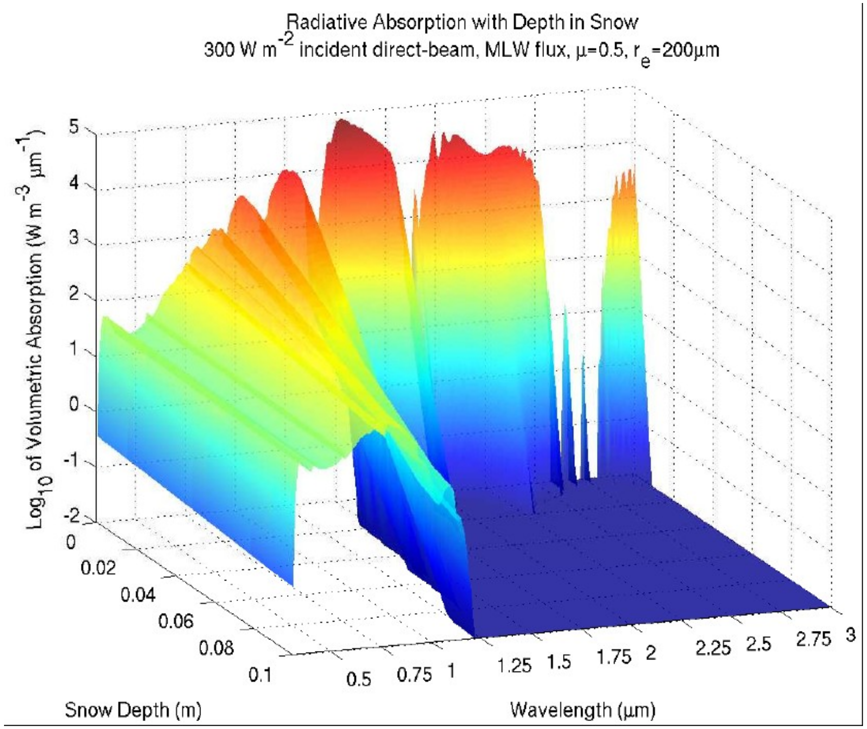
Up to 5-layers of varying thickness





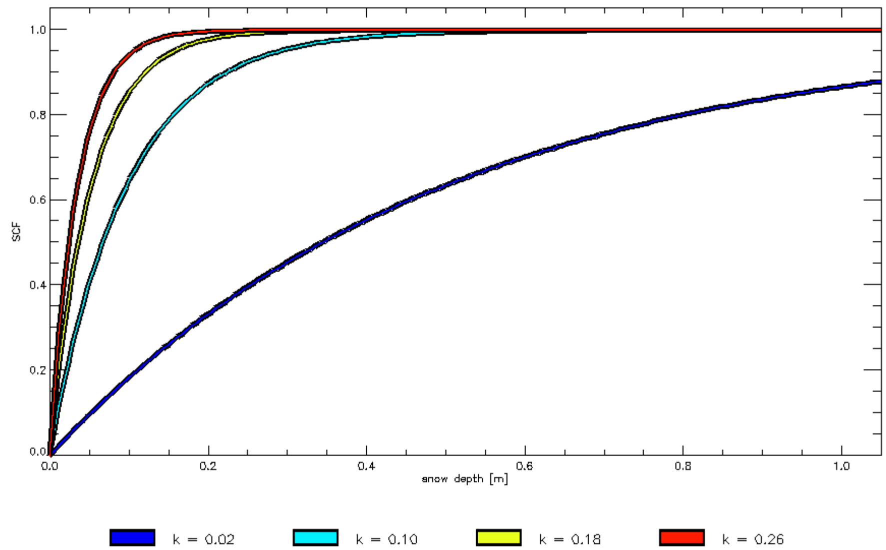
Snow Radiative Transfer (SNICAR)

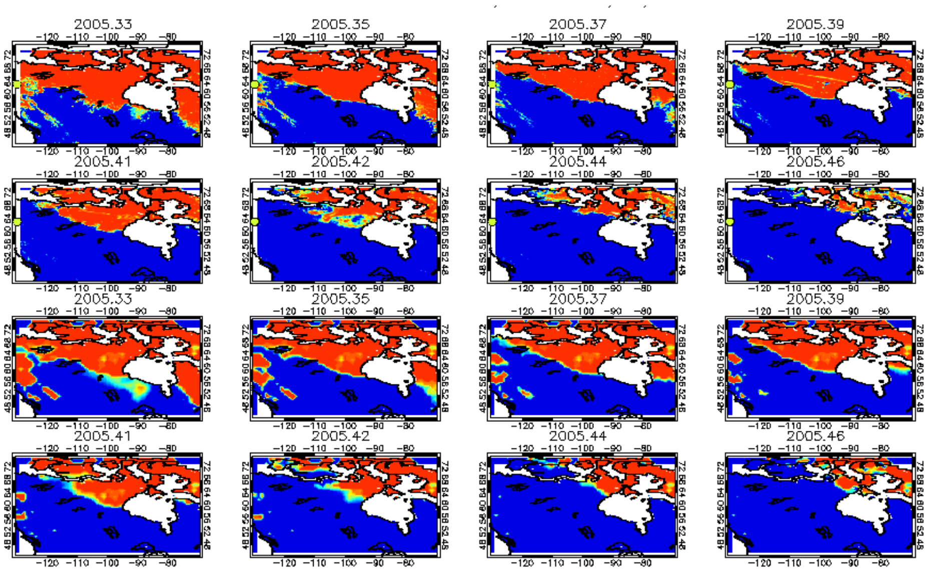
- Snow darkening from deposited black carbon, mineral dust, and organic matter
- Vertically-resolved solar heating in the snowpack
- Snow aging (evolution of effective grain size) based on:
  - Snow temperature and temperature gradient
  - Snow density
  - Liquid water content and
  - Melt/freeze cycling

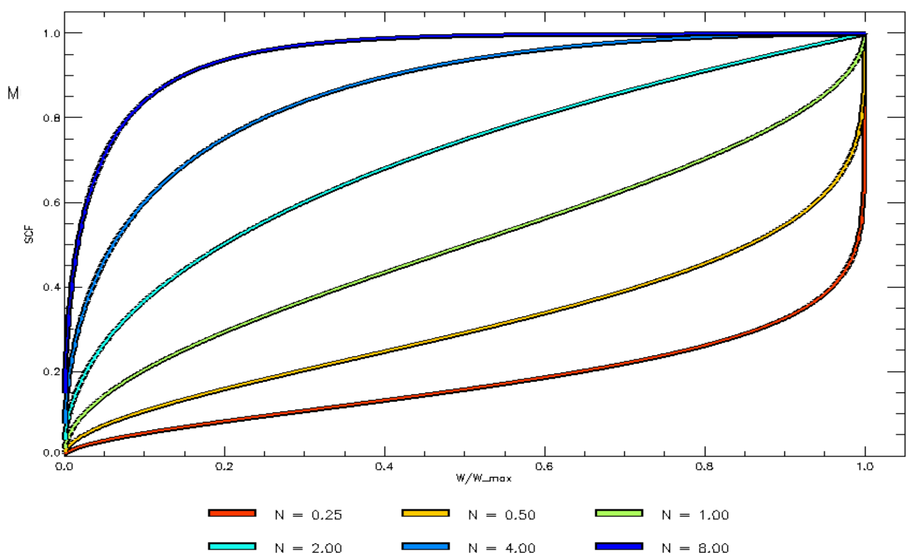


Fractional Snow Covered Area

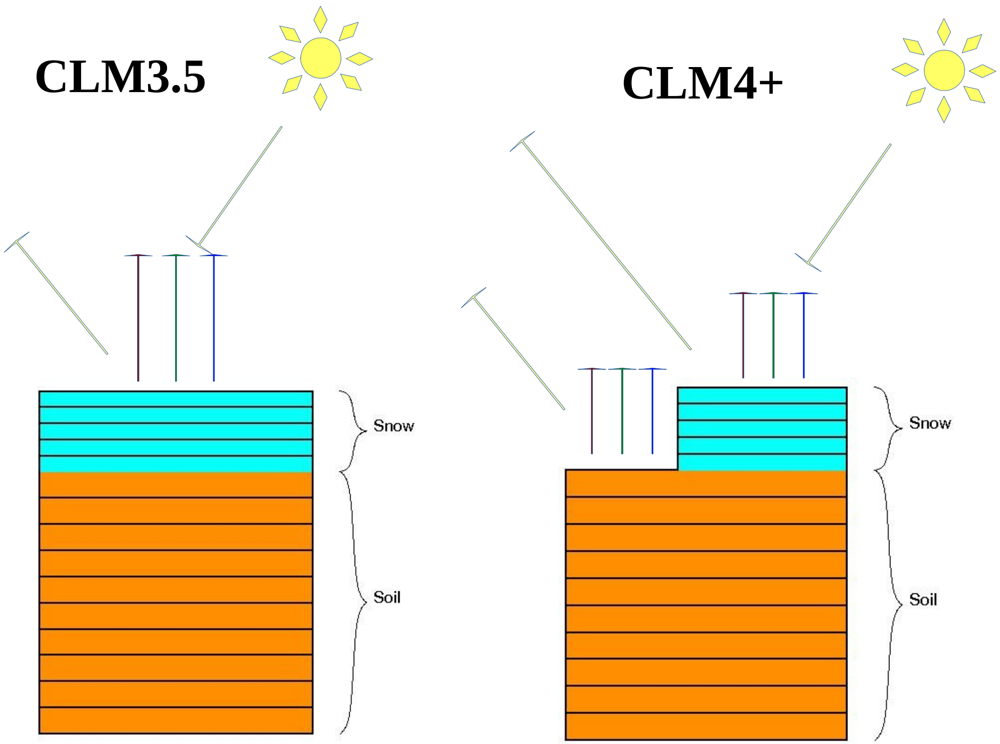
- Describes sub-gridscale snow cover
- Based on snow water equivalent (SWE)
- Dependent on snow history
- Dependent on snow trajectory

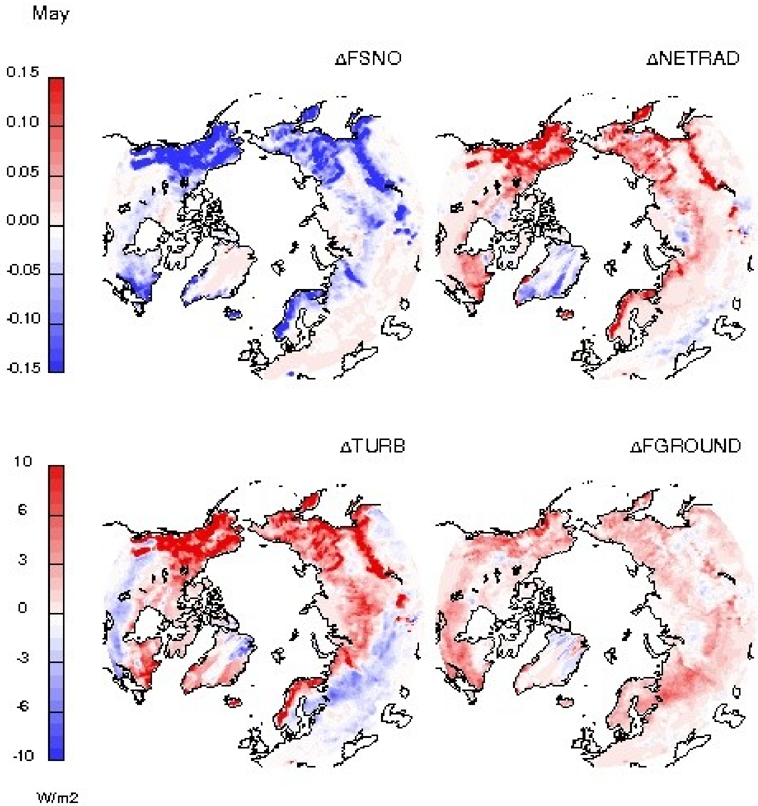






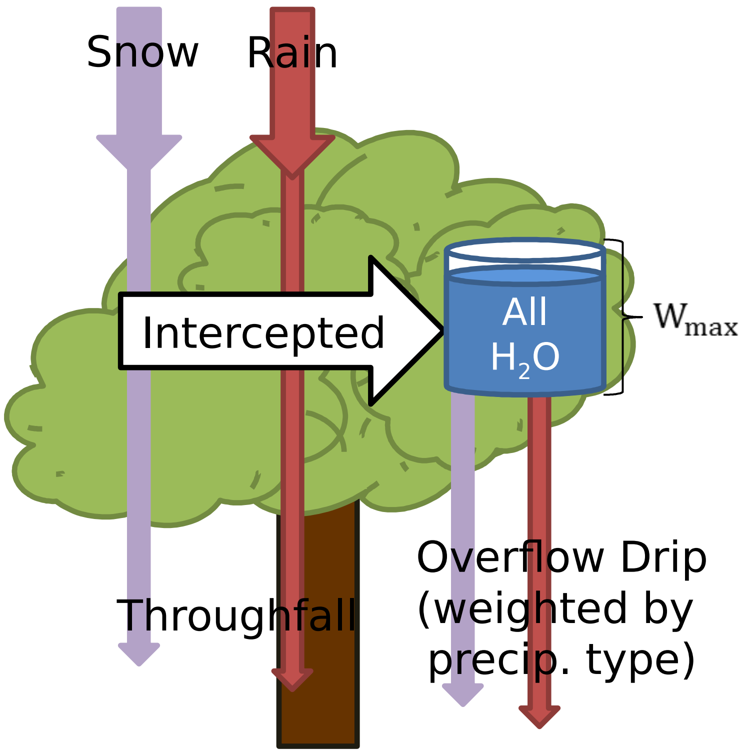
Subgrid Snowpack and Surface Fluxes



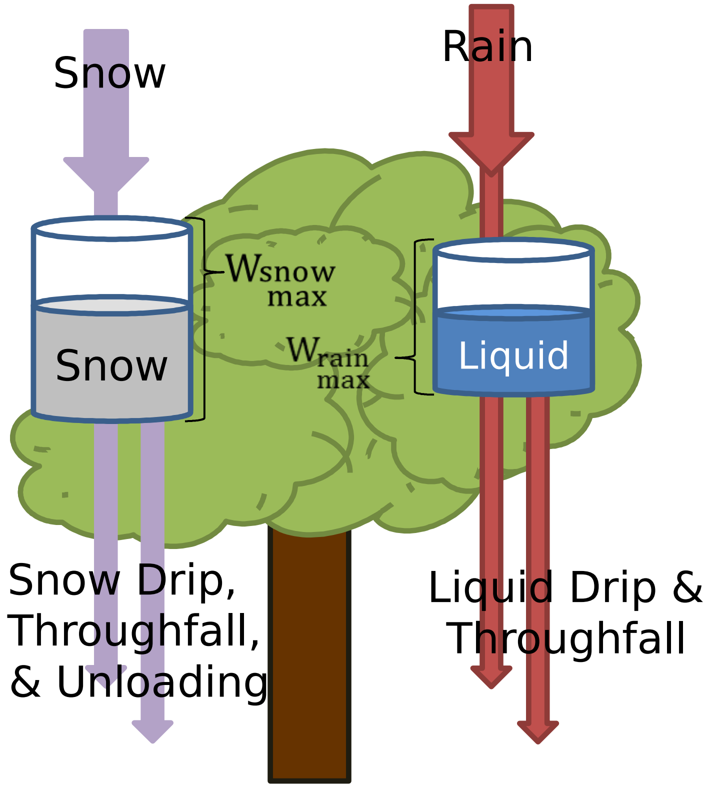


CLM Canopy Snow Treatment

- Introduced canopy snow storage variable, and related fluxes



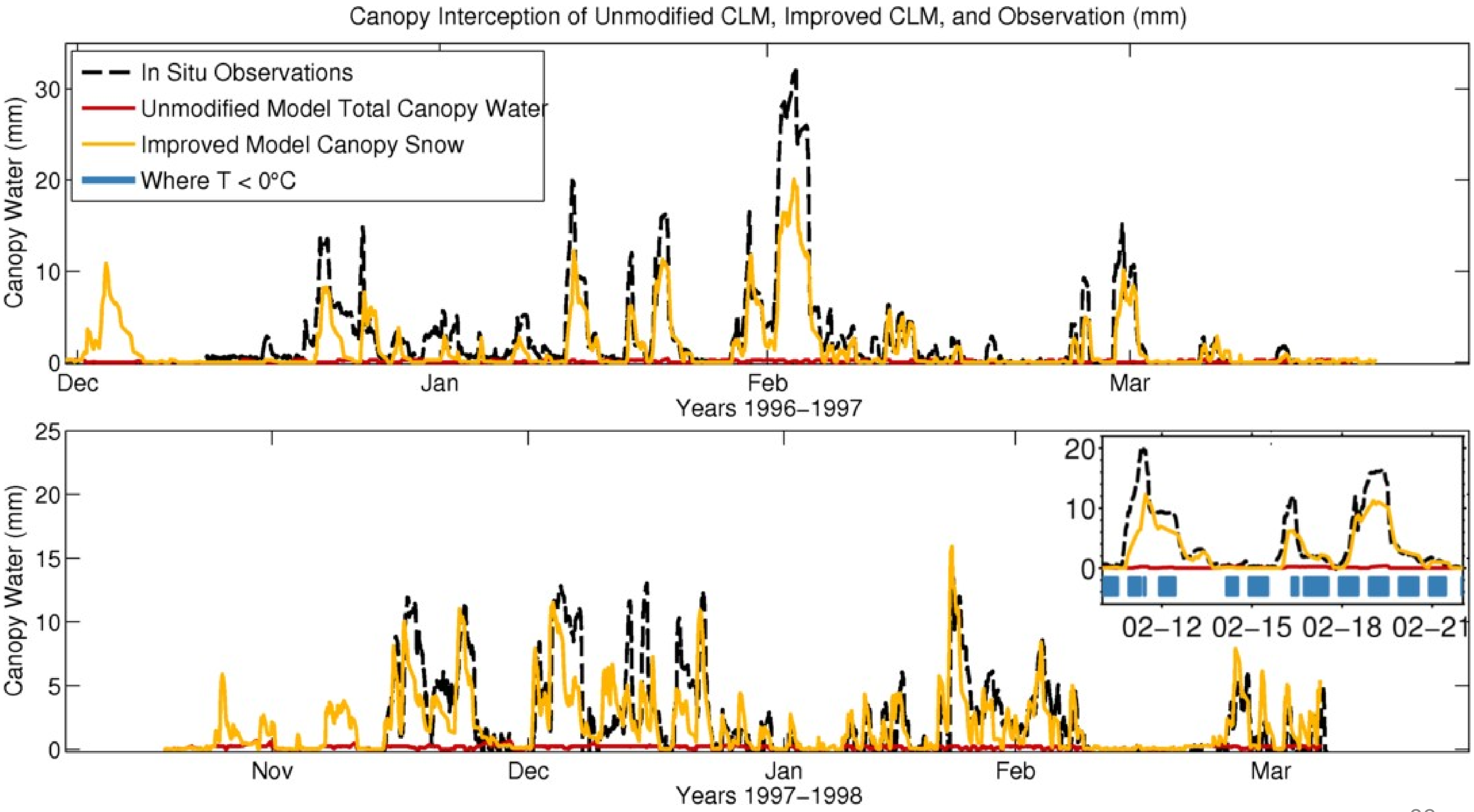
Current Canopy Hydrology



Snow Veg. Implementation

Evergreen Snow Interception Measurements

- More representative of in-situ snow canopy storage
- (previous snow albedo present only in freezing temps.

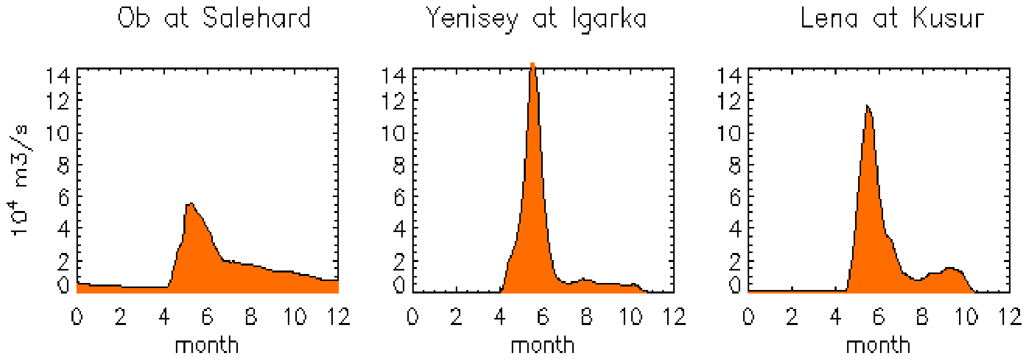


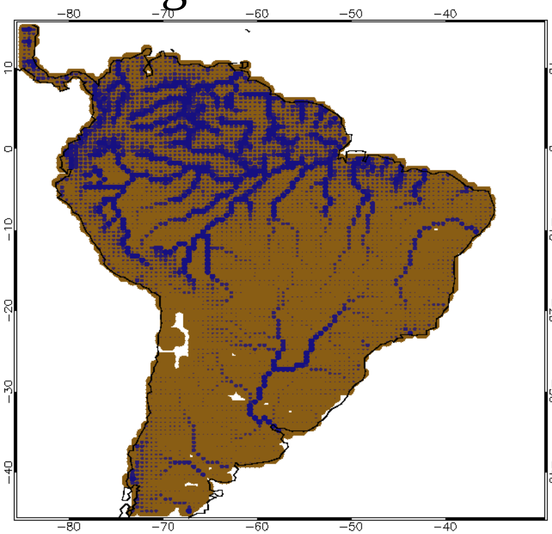
Surface Water Processes

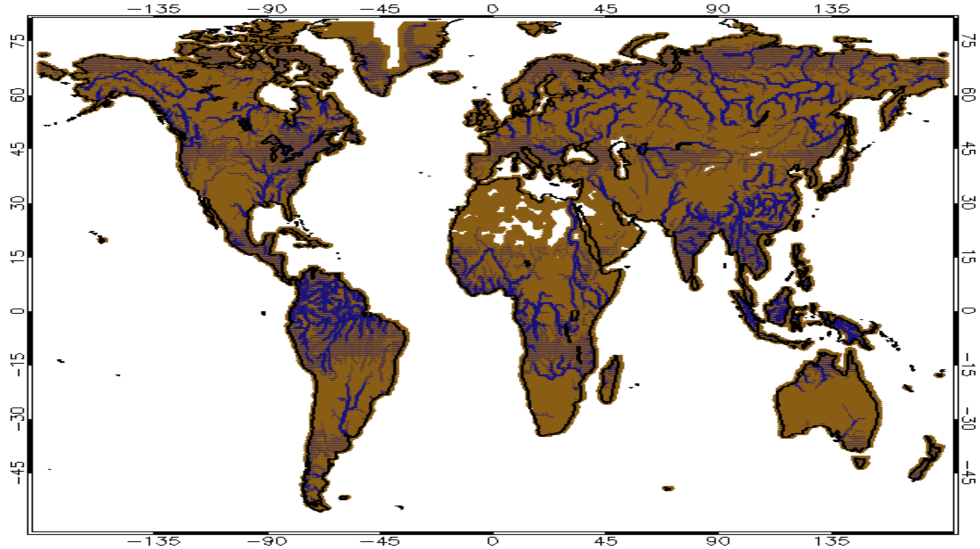
- Surface runoff
- River routing
- Infiltration
- Surface water (wetlands)
- Flooding

River model

- Routes runoff to the oceans
- Flow directions are obtained from an input dataset
- Calculates water volume and discharge

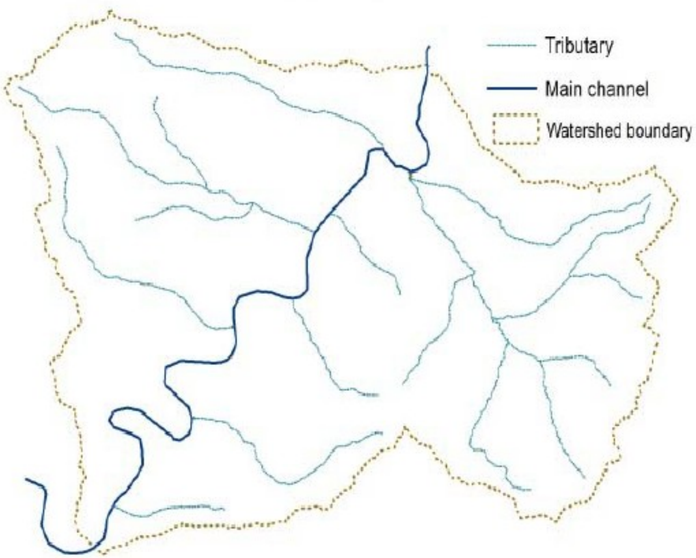




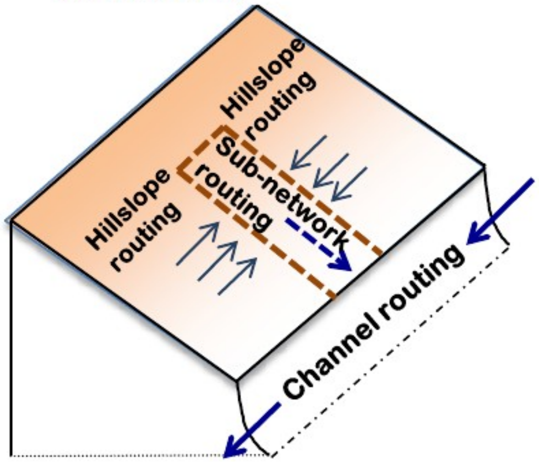


Model for Scale Adaptive River Transport

Real river network



Conceptualized network



- Hillslope routing accounts for event dynamics and impacts of overland flow on soil erosion, nutrient loading, etc.
- Sub-network routing: scale adaptive across different resolutions to reduce scale dependence
- Main channel routing: explicit estimation of in-stream status (velocity, water depth, etc).

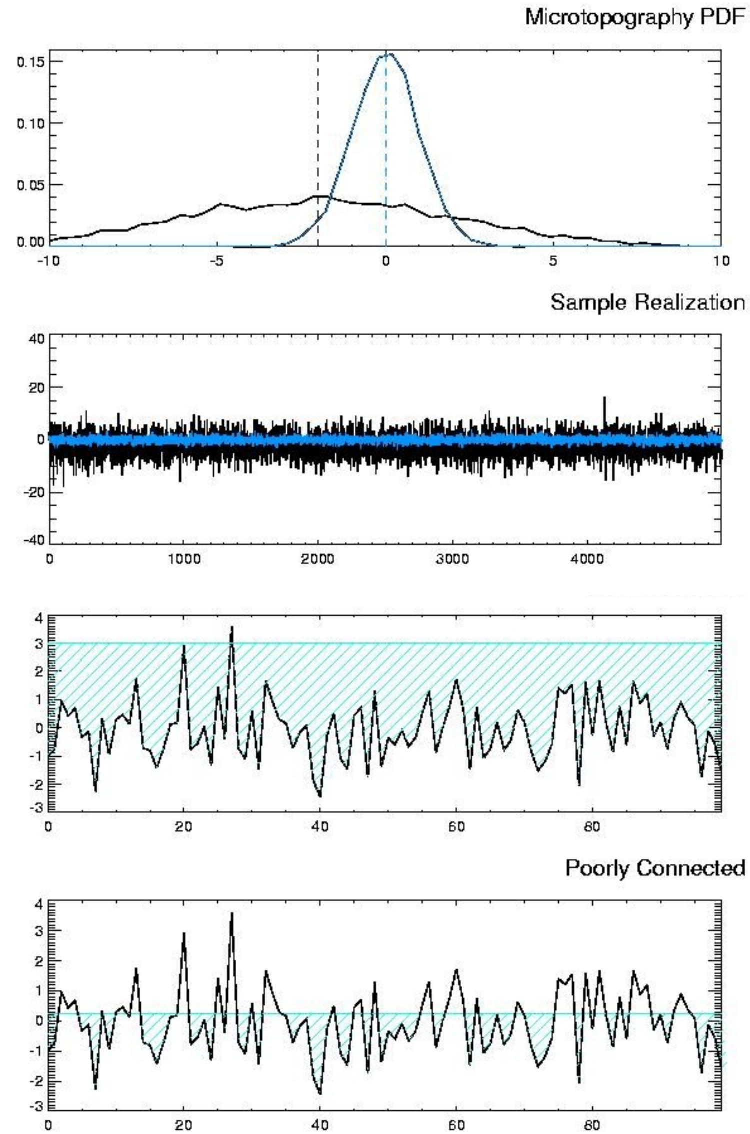
(Li et al., JHM, 2013)

(Subgrid-scale) Surface Water Storage

- Uses a statistical description of the **microtopography** to determine volume/area relations and connectivity

- When storage is large, inundated areas are well connected, and surface runoff is high.

- When storage is small, inundated areas are generally not connected, and surface runoff is low.



Subsurface Processes

- Soil evaporation
- Rooting distribution and transpiration
- Soil moisture redistribution
- Recharge
- Groundwater and water table
- Lateral subsurface flow

Soil Moisture Redistribution

- Hydrostatic equilibrium form of Richards equation
- Moisture form of Richards equation with adaptive sub-stepping

Soil model

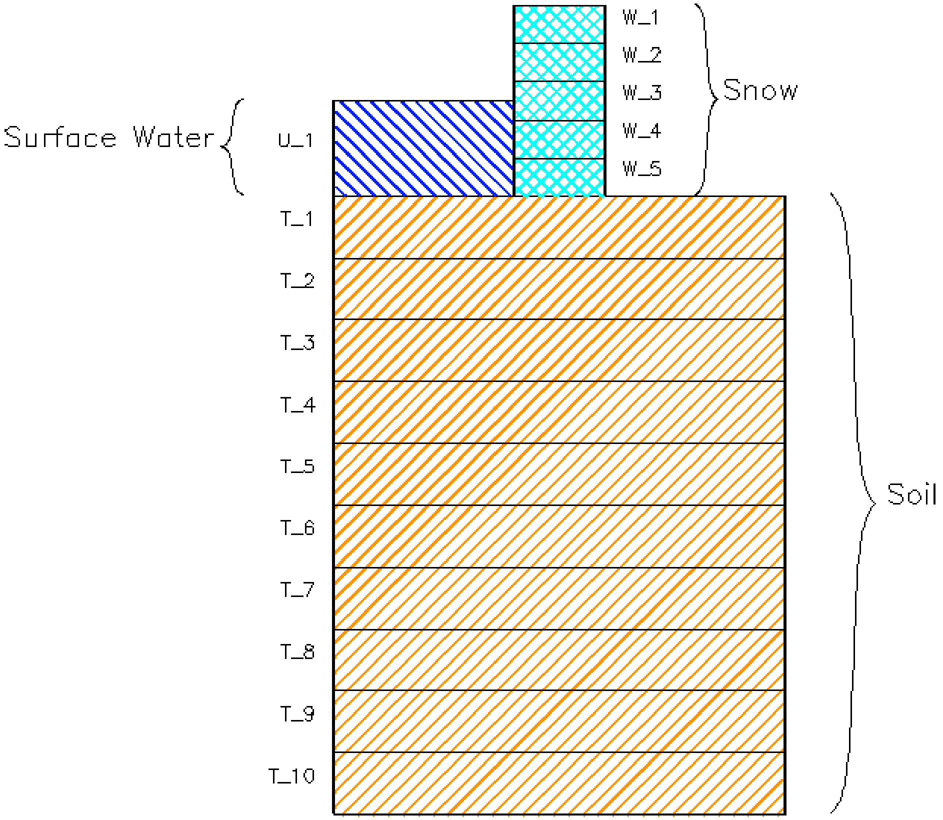
Treats processes such as:

- Soil moisture redistribution
  - Infiltration
  - Darcy flow
  - Recharge

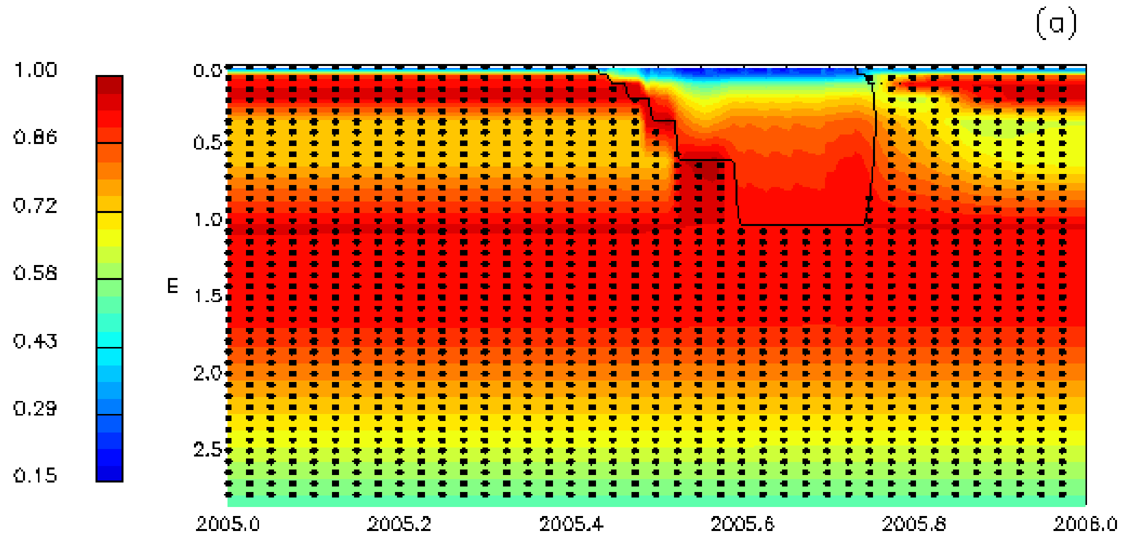
- Soil moisture phase change
- Soil temperature redistribution

Default structure has 20 layers of variable thickness, spanning about 8 meters depth

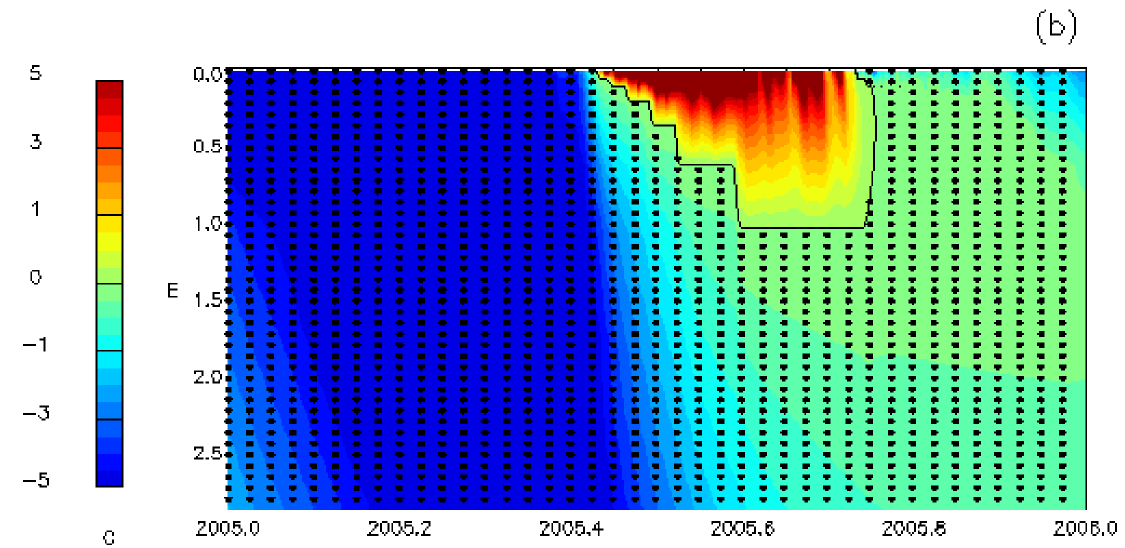
- Thermal calculations use additional deep layers



a) Soil moisture (% saturation)



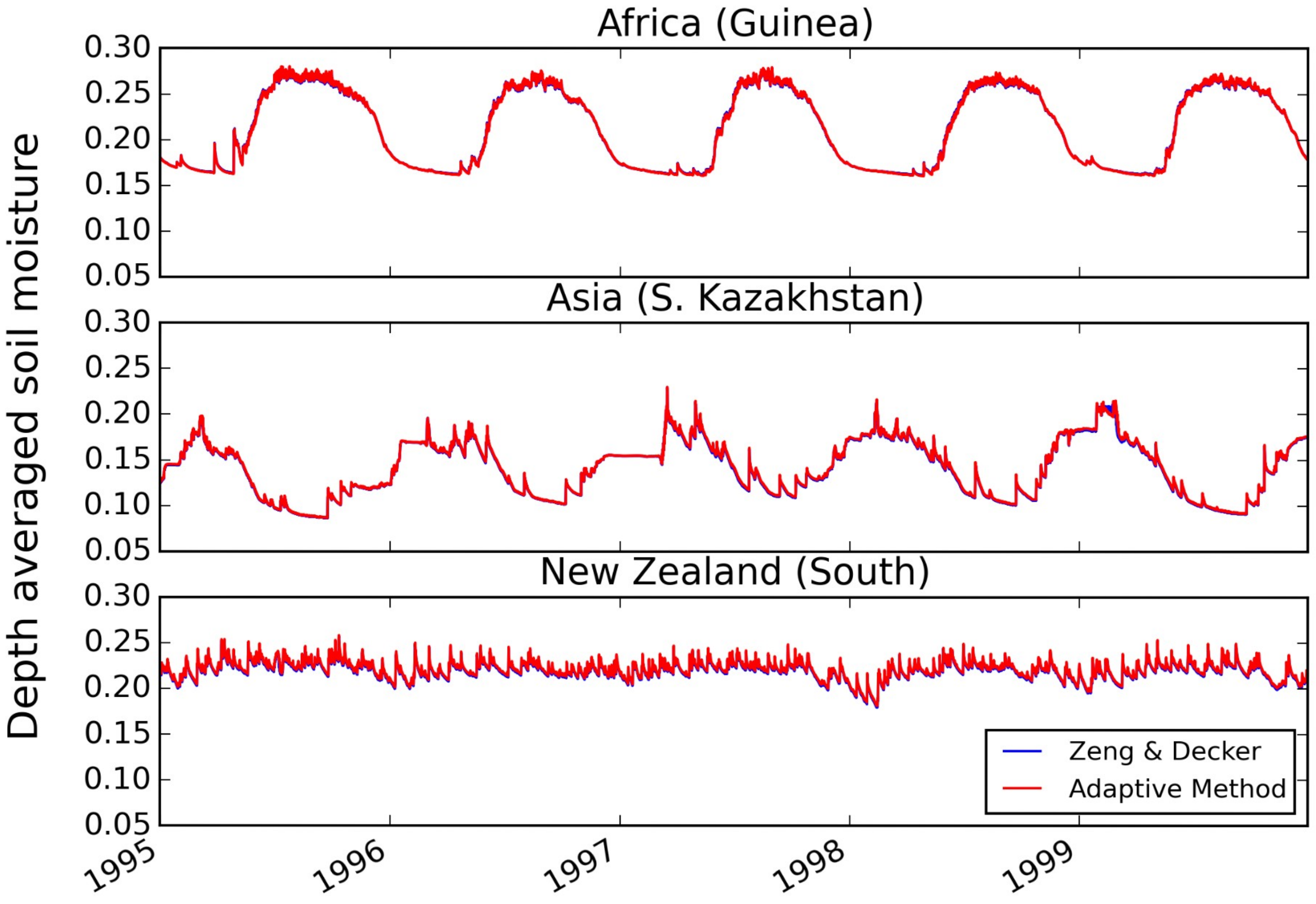
b) Soil temperature ($^\circ$C)



Stippling indicates frozen soil

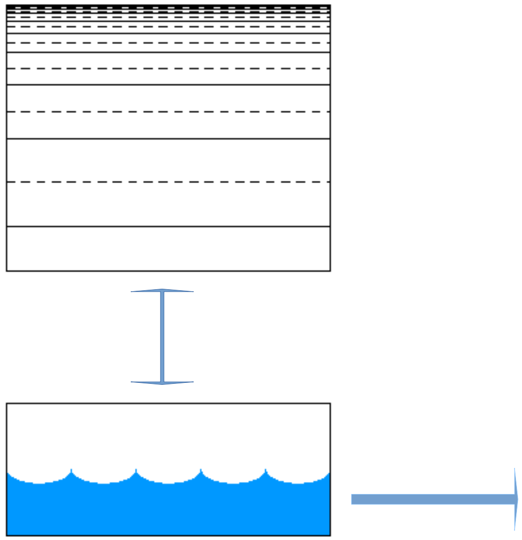
Adaptive time stepping method for soil water distribution

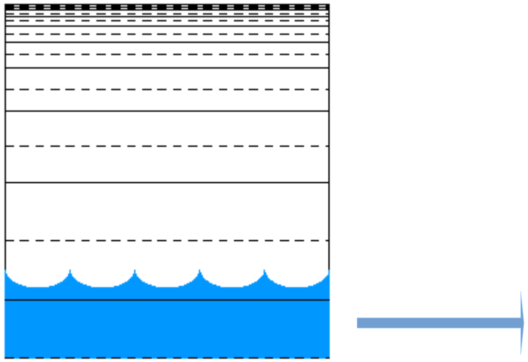
- Similar results to Zeng & Decker method
- Tested globally and at points with relatively high numerical error



Groundwater and Water Table Dynamics

- bulk aquifer layer
- bedrock (zero vertical flux) lower boundary

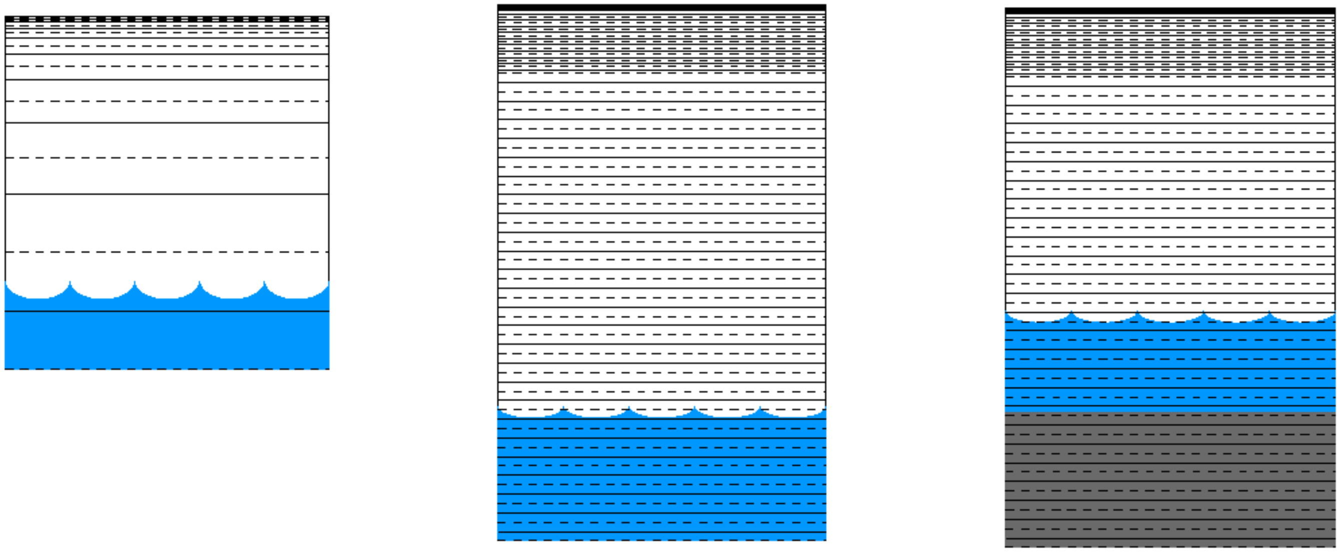




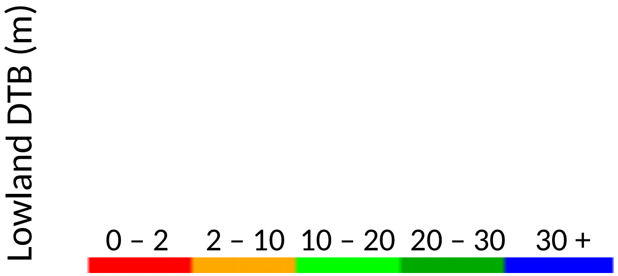
zero flux

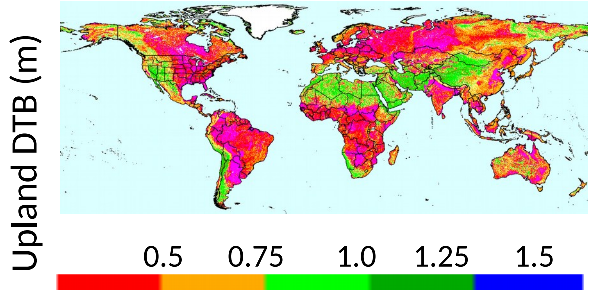
Soil Depth

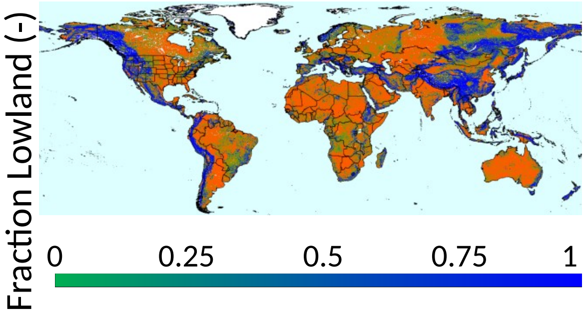
- deep soil / variable soil depth
- high vertical resolution soil



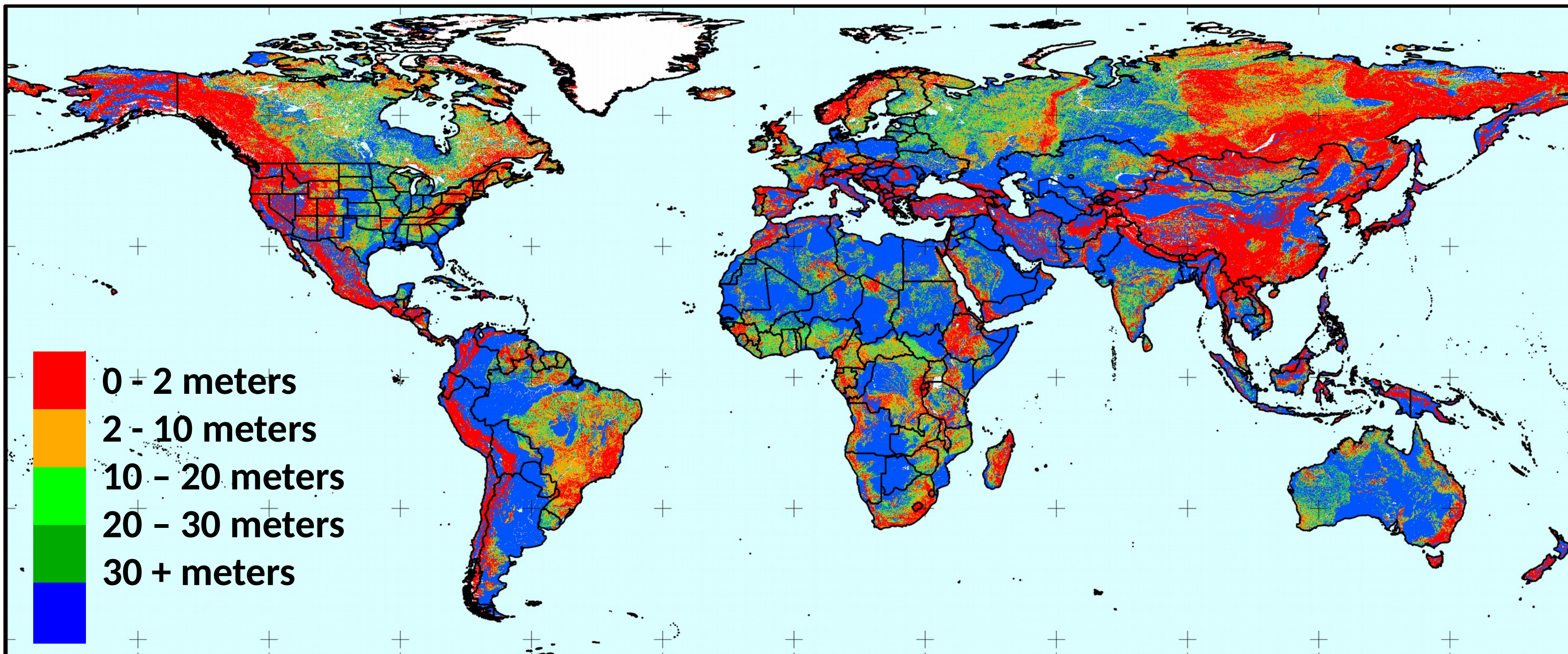
PRELIMINARY GLOBAL MAP OF DTB ESTIMATES







Overall Depth to Bedrock (~1 km resolution)



Slide courtesy M.Brunke, U. Arizona

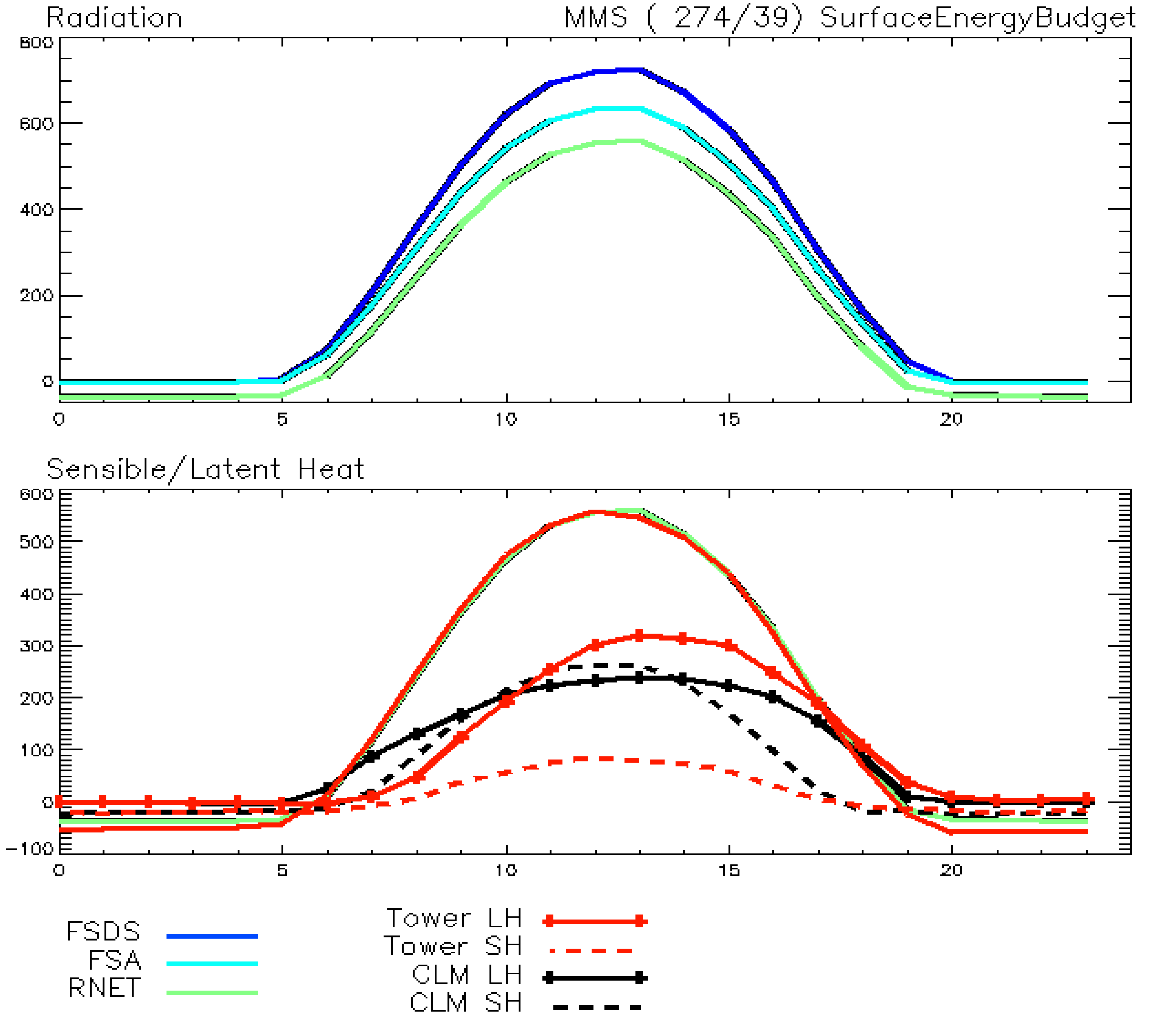
Model Validation Tools

Ideally, should be:

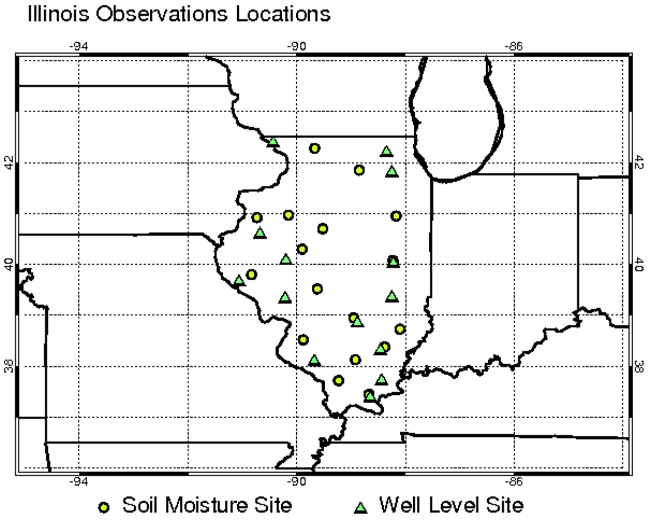
- Global
- Directly comparable to modeled process/state/flux
- Same spatial / temporal scale
- High accuracy
- Long record

In reality, no datasets meeting these criteria exist...

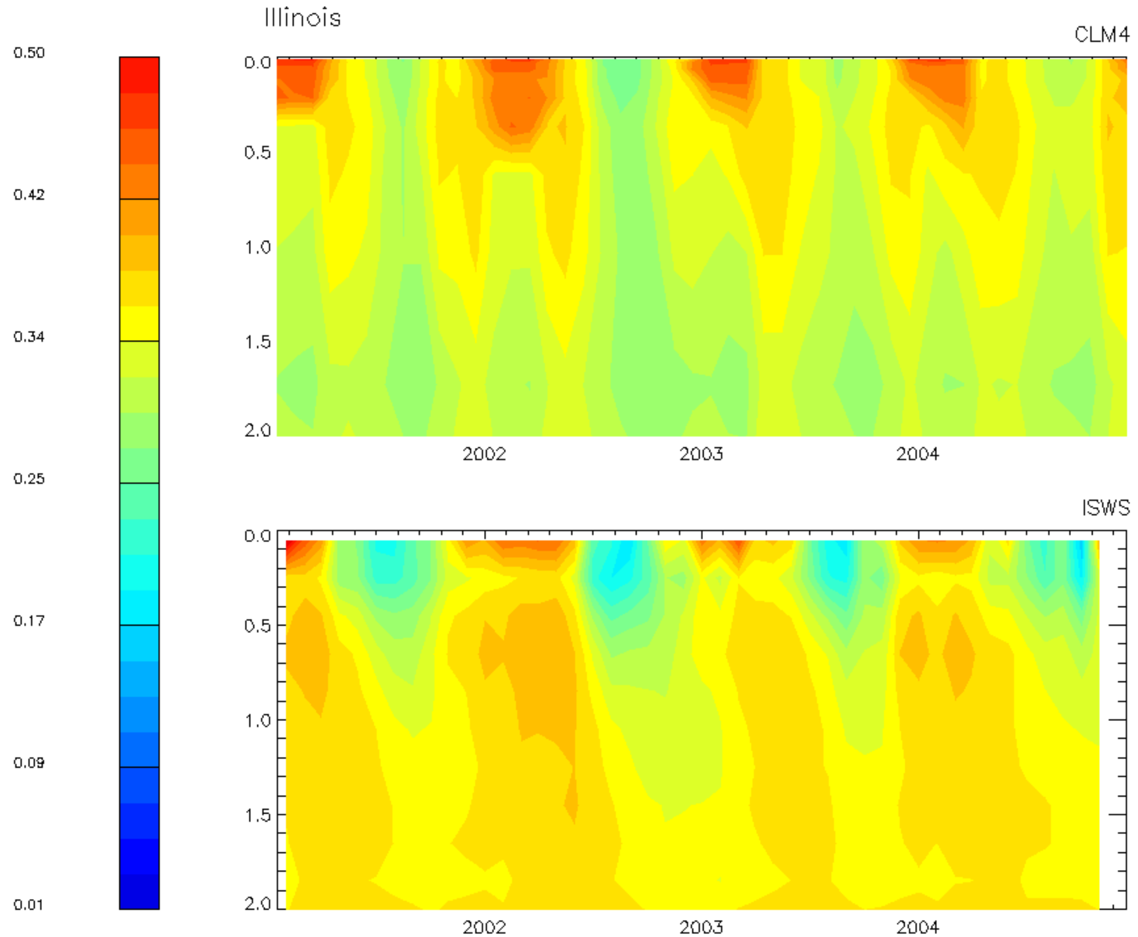
Flux Towers


Radiation
MMS (274/39) SurfaceEnergyBudget
800
600
400
200
0
0
5
10
15
20
Sensible/Latent Heat
600
500
400
300
200
100
0
−100
0
5
10
15
20
FSDS
FSA
RNET
Tower LH
Tower SH
CLM LH
CLM SH

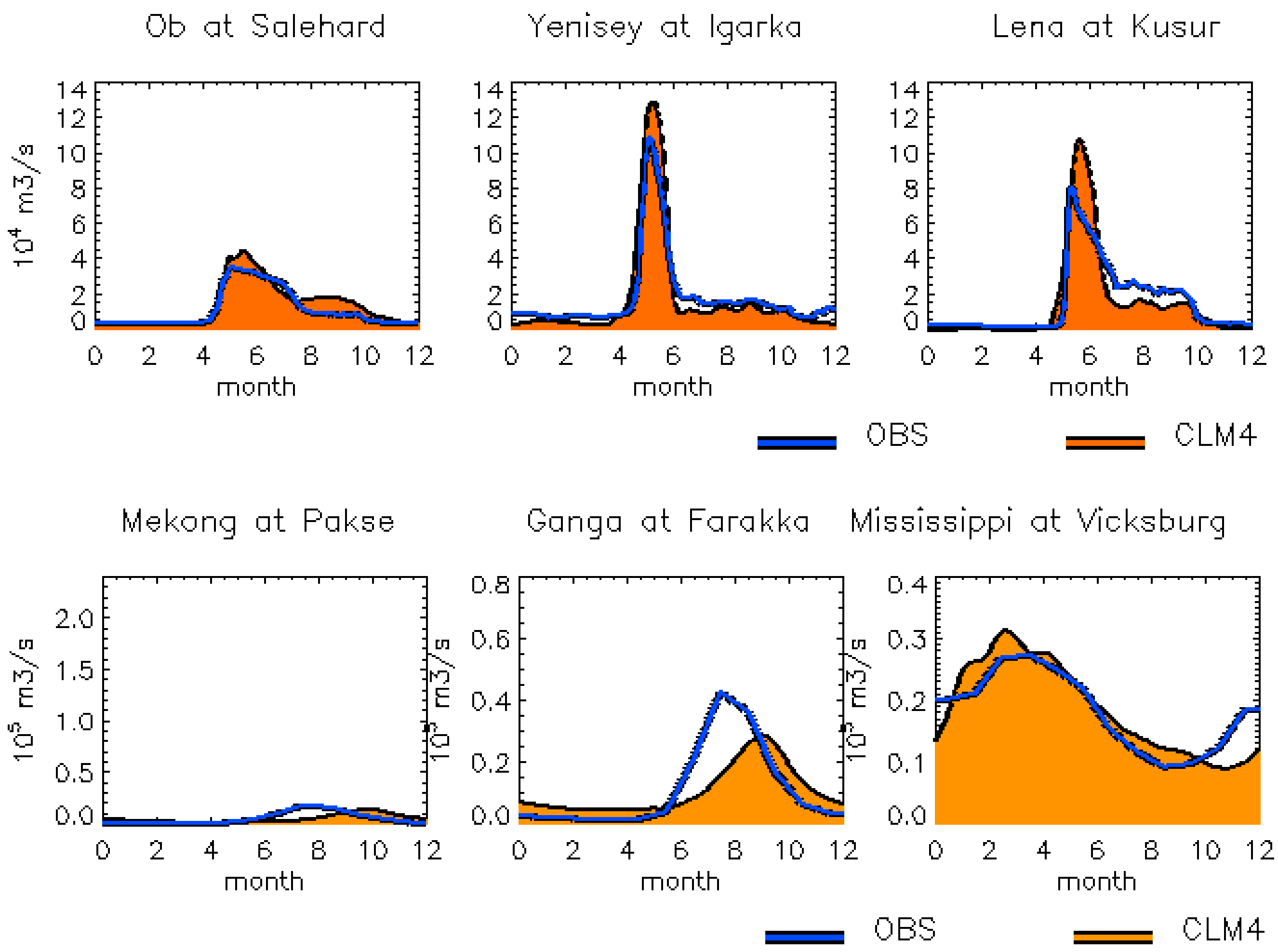
Soil Moisture Networks



Top panel: CLM soil moisture
Bottom: Observed soil moisture



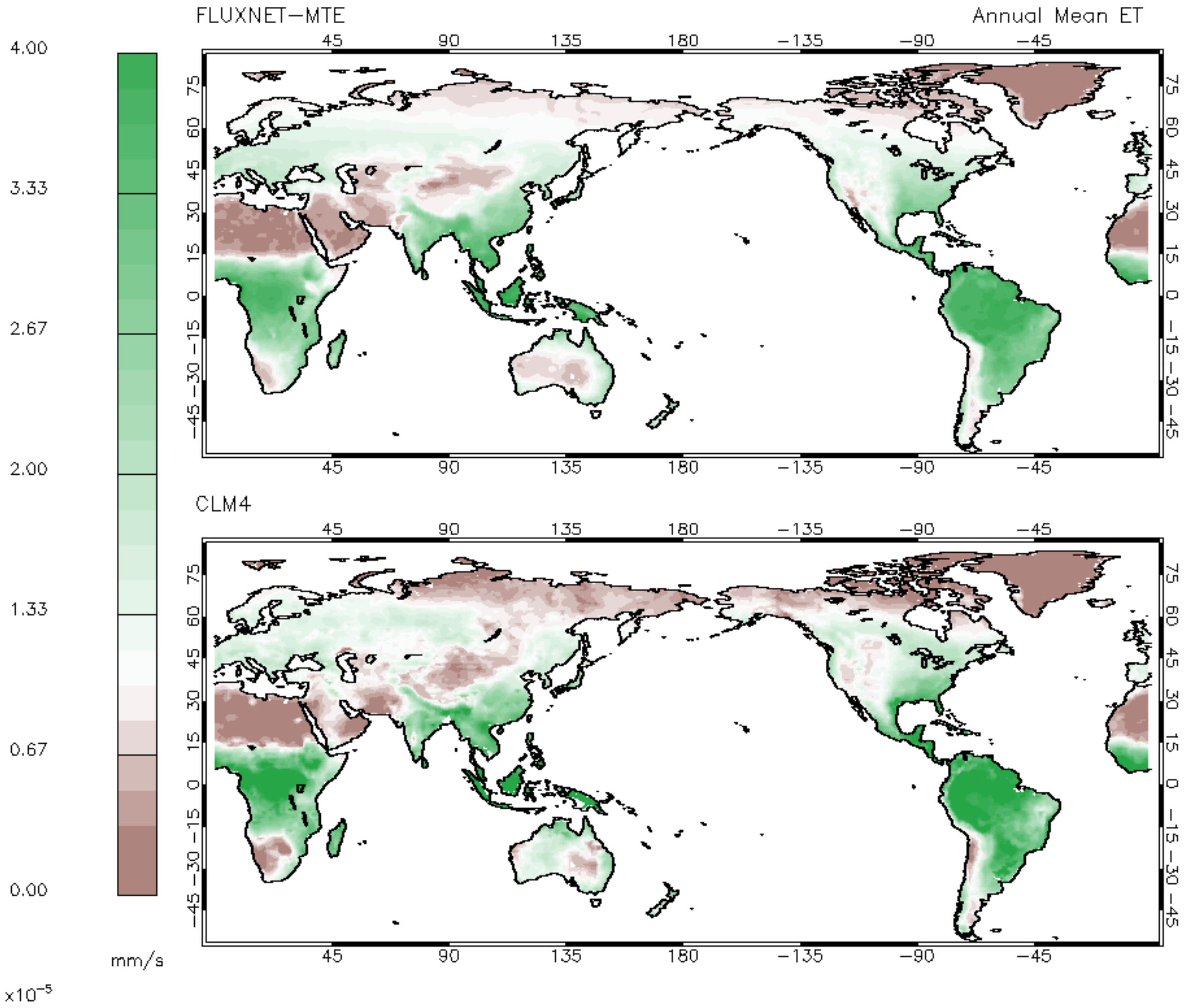
River Discharge



FLUXNET-MTE

Annual Mean Evapotranspiration

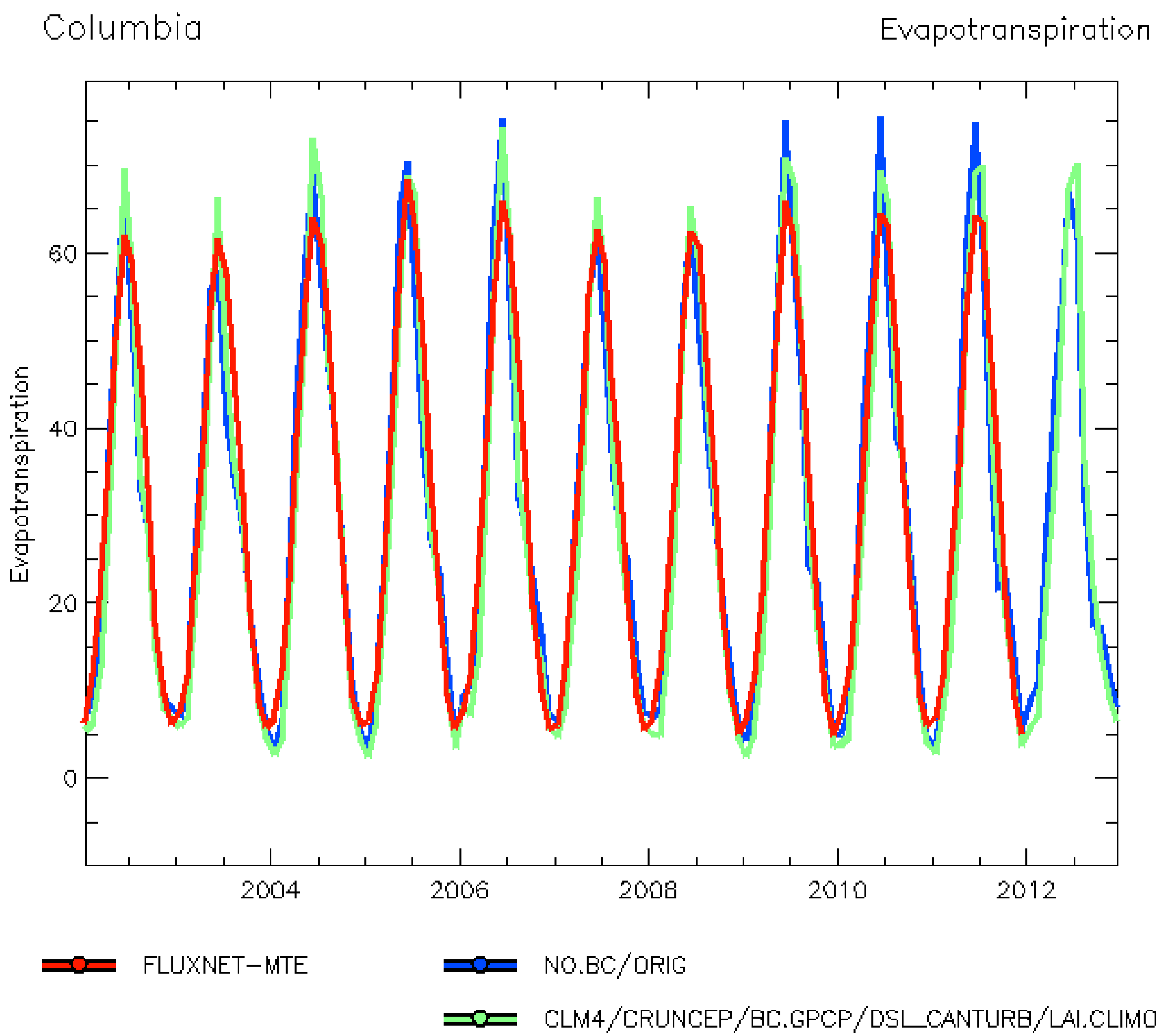
Top panel: FLUXNET-MTE
Bottom: CLM



FLUXNET-MTE

Columbia River Basin
Evapotranspiration

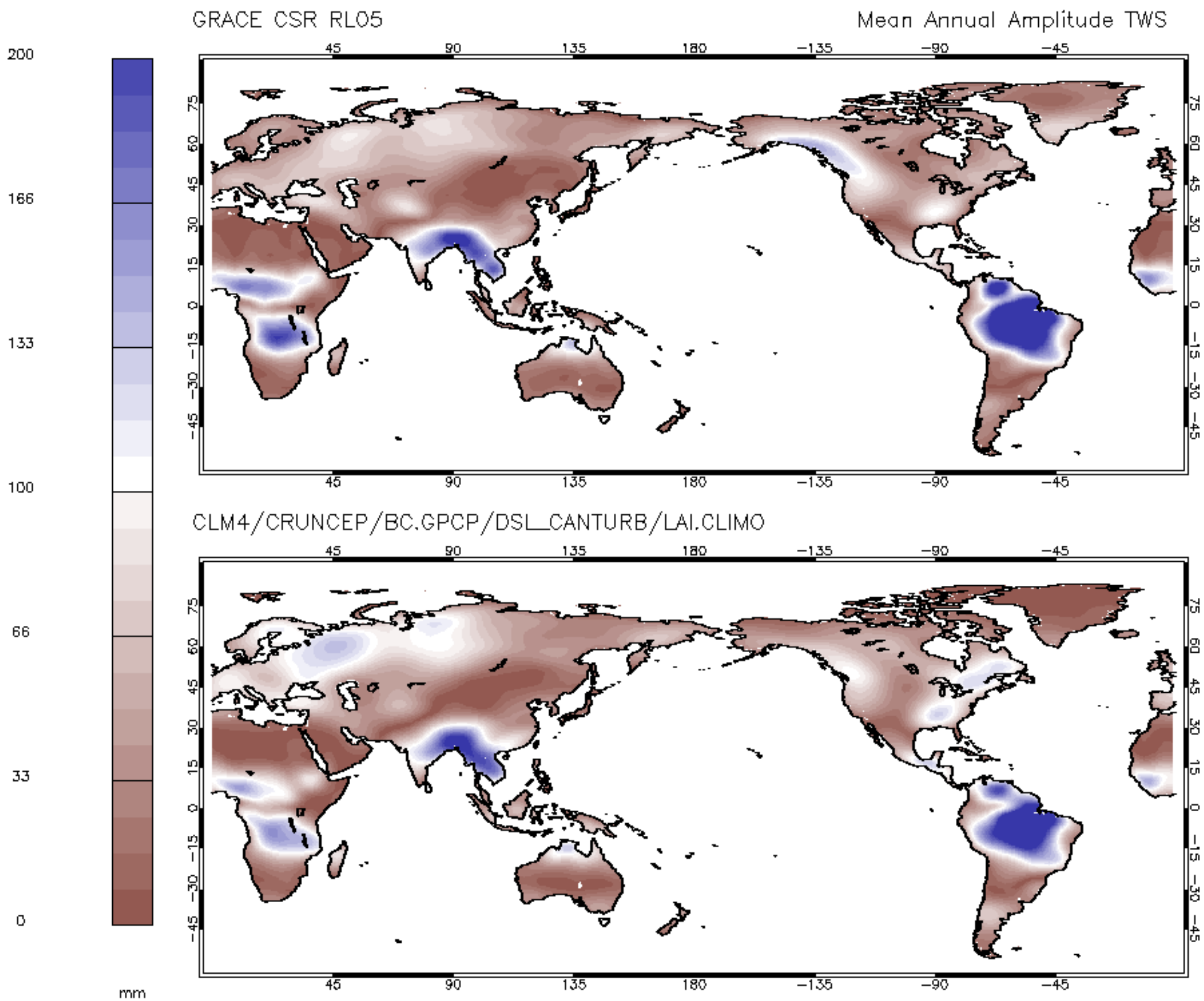
Red: FLUXNET-MTE
Blue/Green: CLM



GRACE Total Water Storage

Mean Annual Amplitude of Total Water Storage

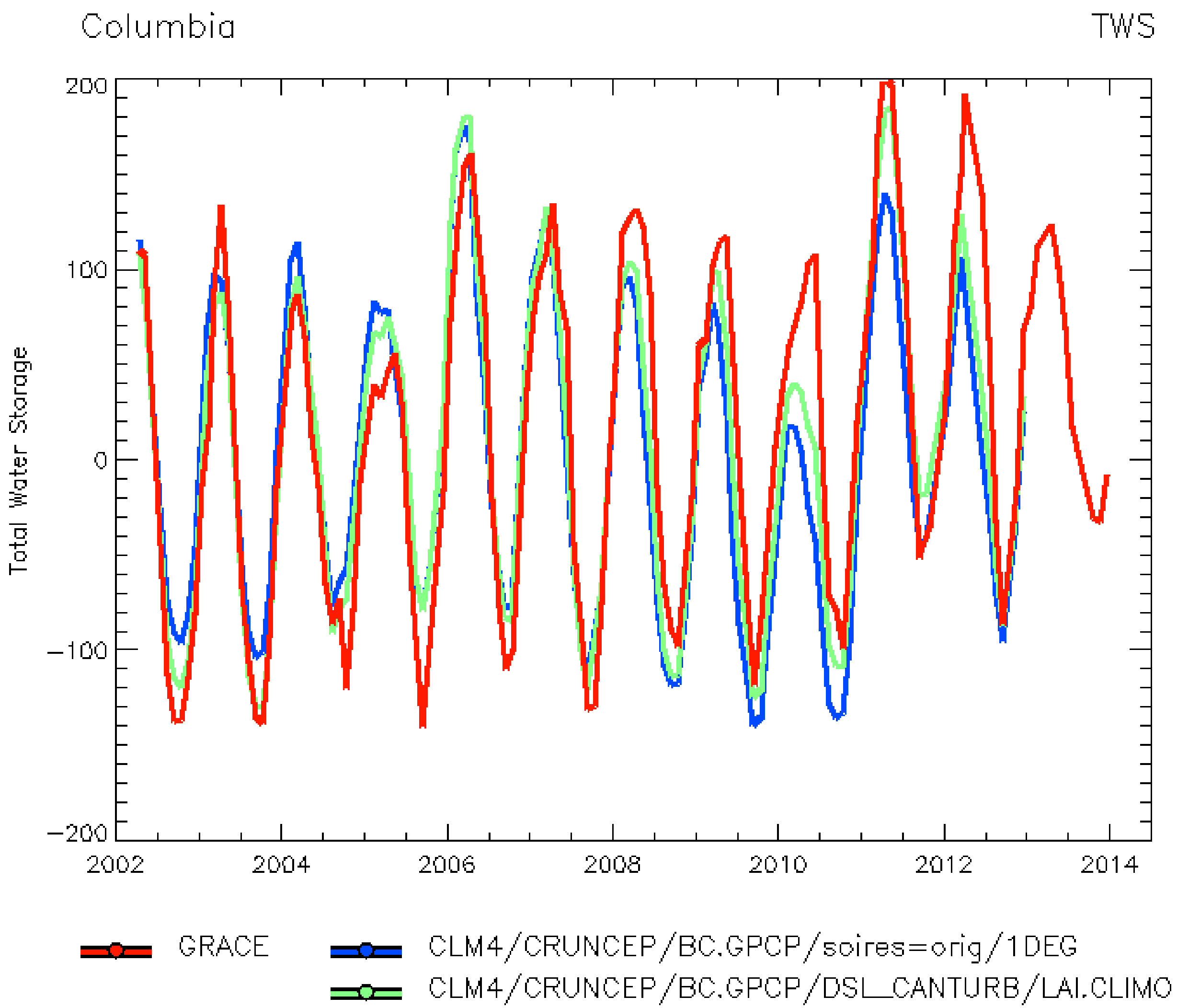
Top panel: GRACE
Bottom: CLM



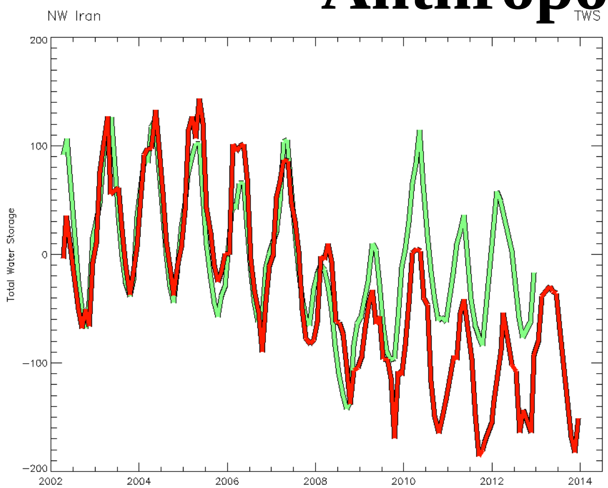
GRACE Total Water Storage

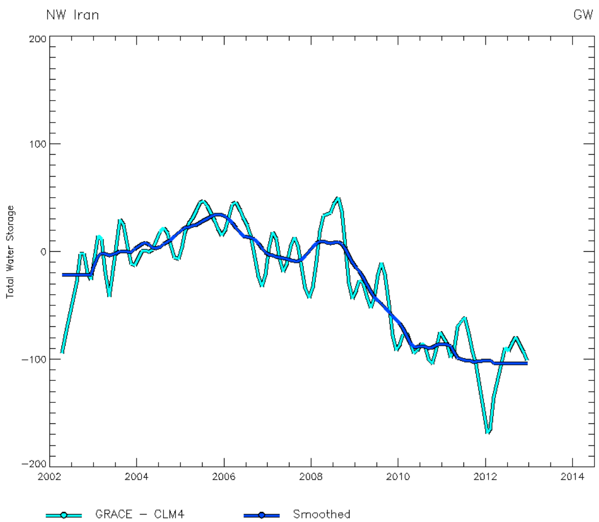
Columbia River Basin
Total Water Storage

Red: GRACE
Blue/Green: CLM



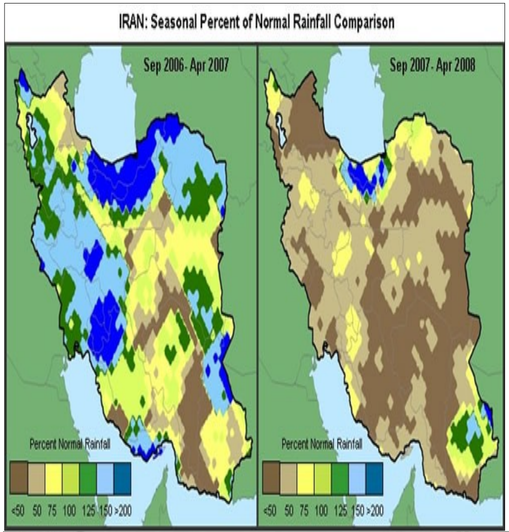
CLM Application Example: Anthropogenic Groundwater Withdrawal



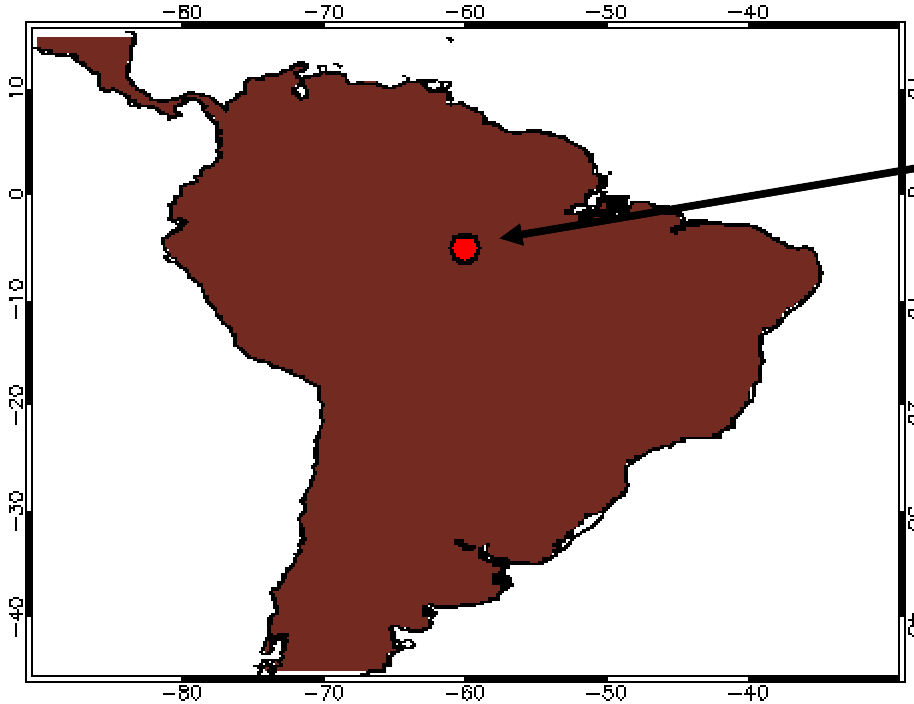


Human-induced groundwater changes can be estimated by removing the CLM estimate of TWS from the GRACE estimate of TWS

- **GRACE TWS**
- **CLM TWS**
- **Groundwater**

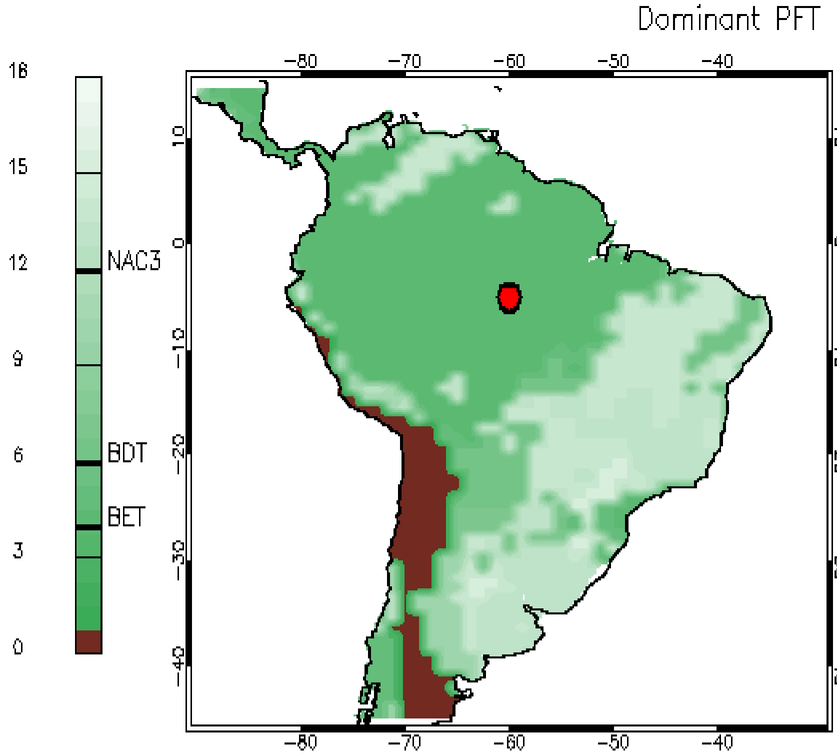


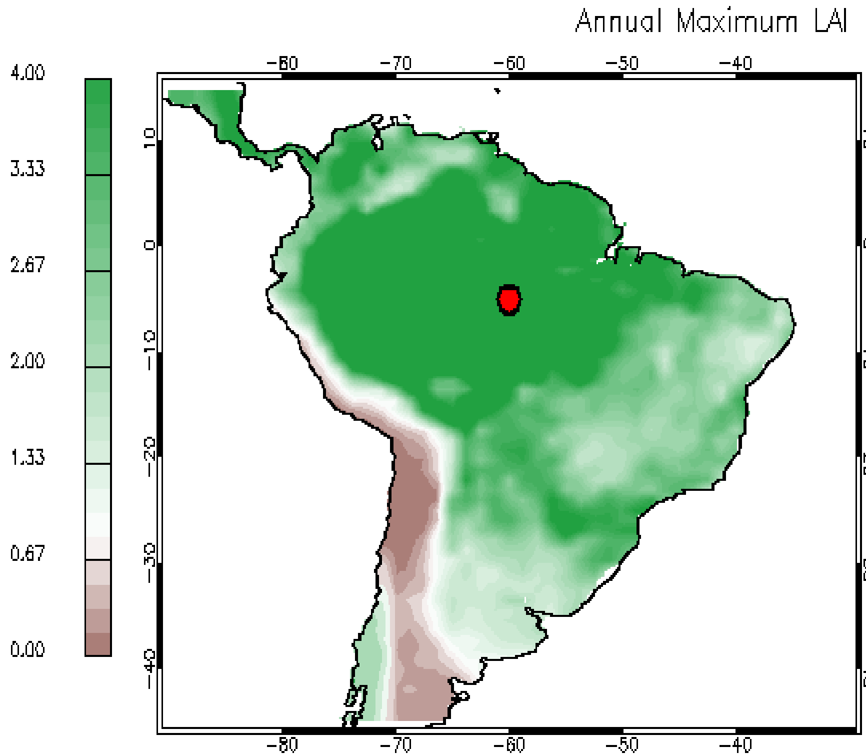
Example I
Effects of Parameter Change



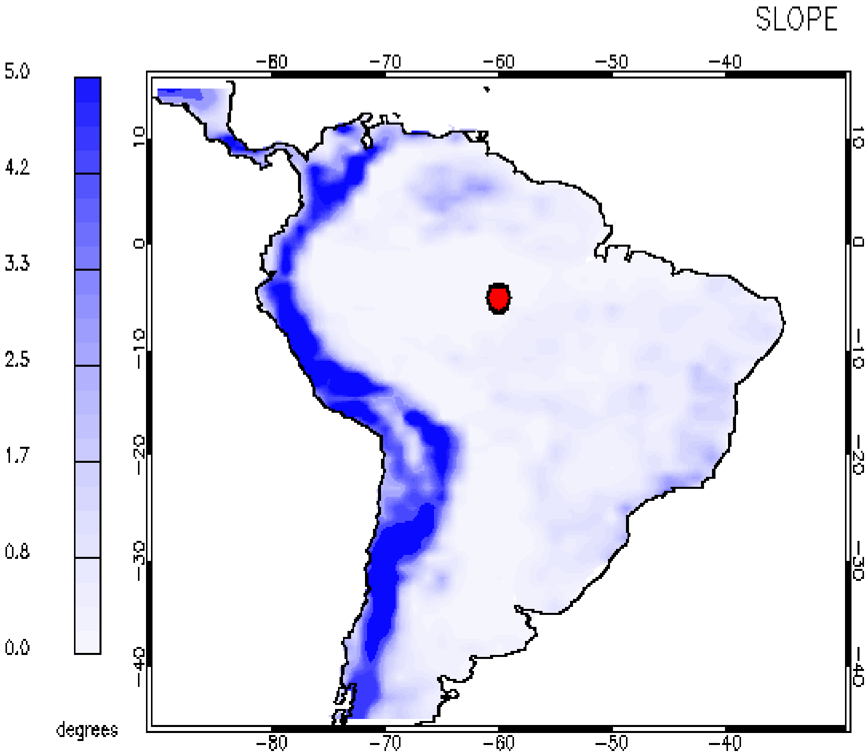
60W / 5S

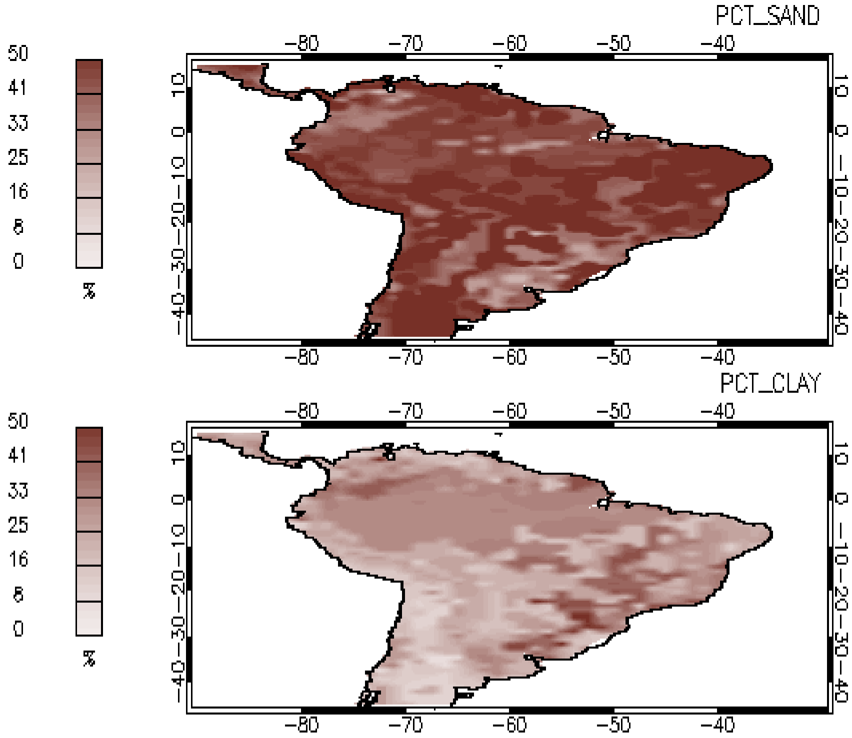
Hydrological ly Relevant Surface Data



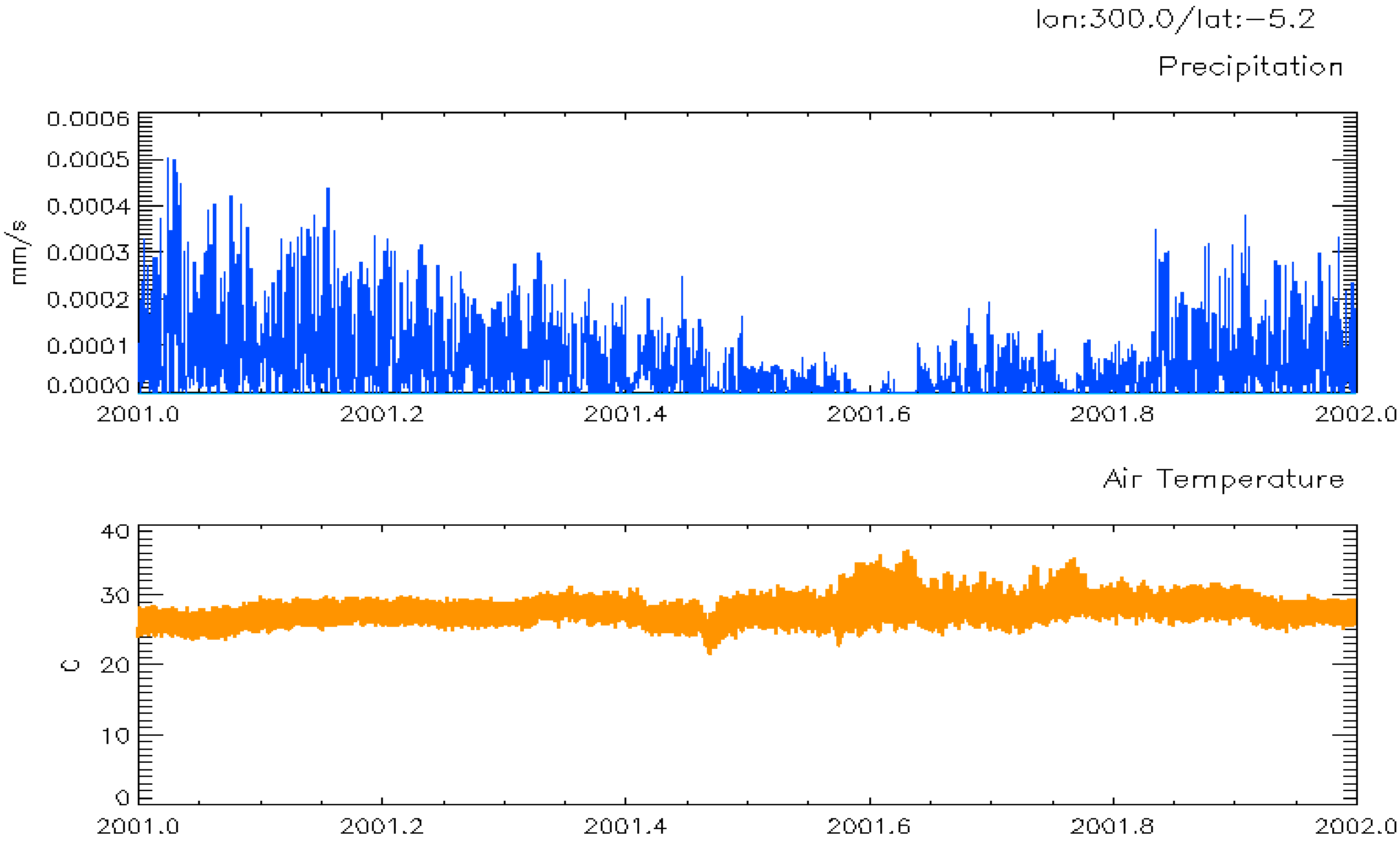


Hydrological Relevant Surface Data





Time Series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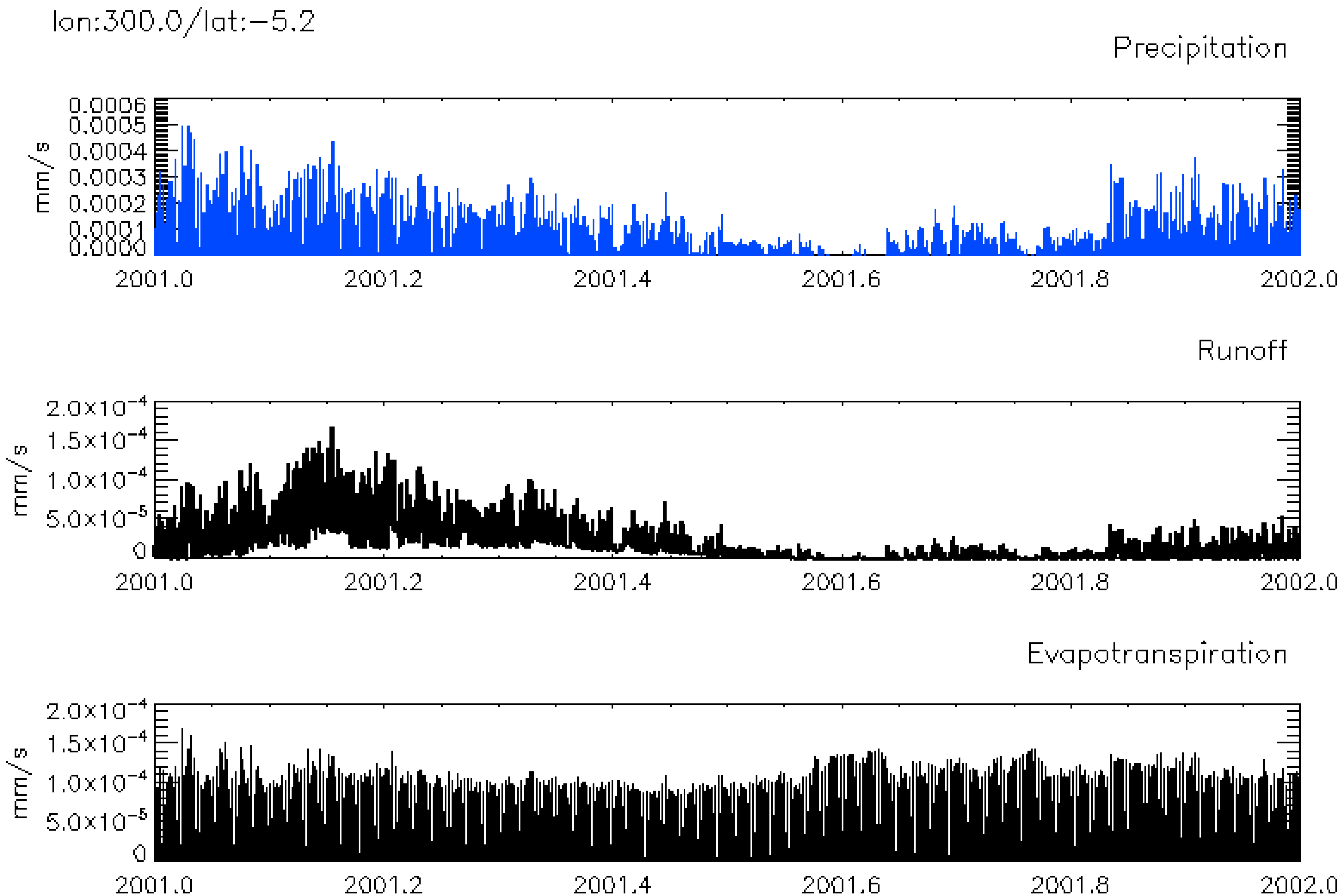
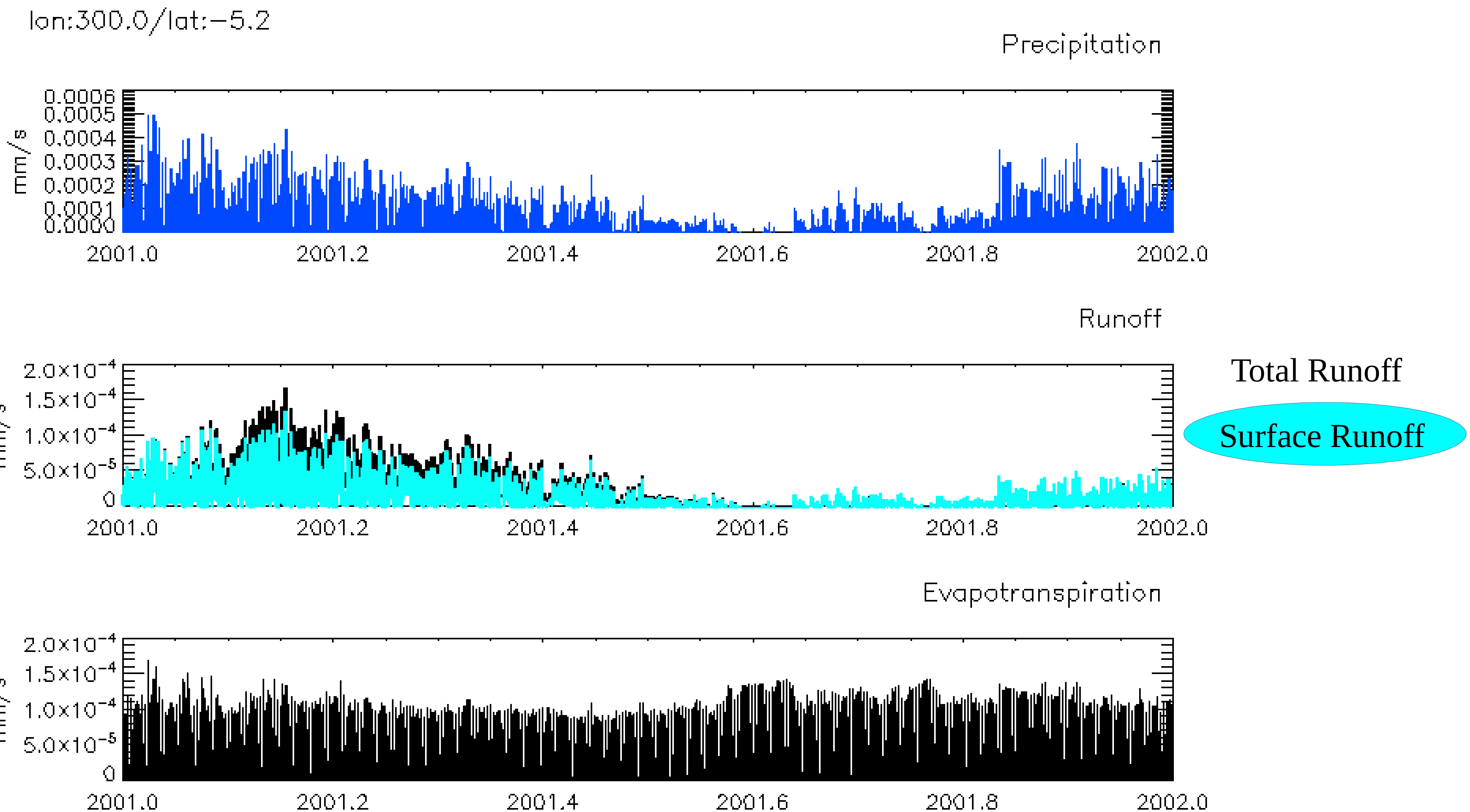
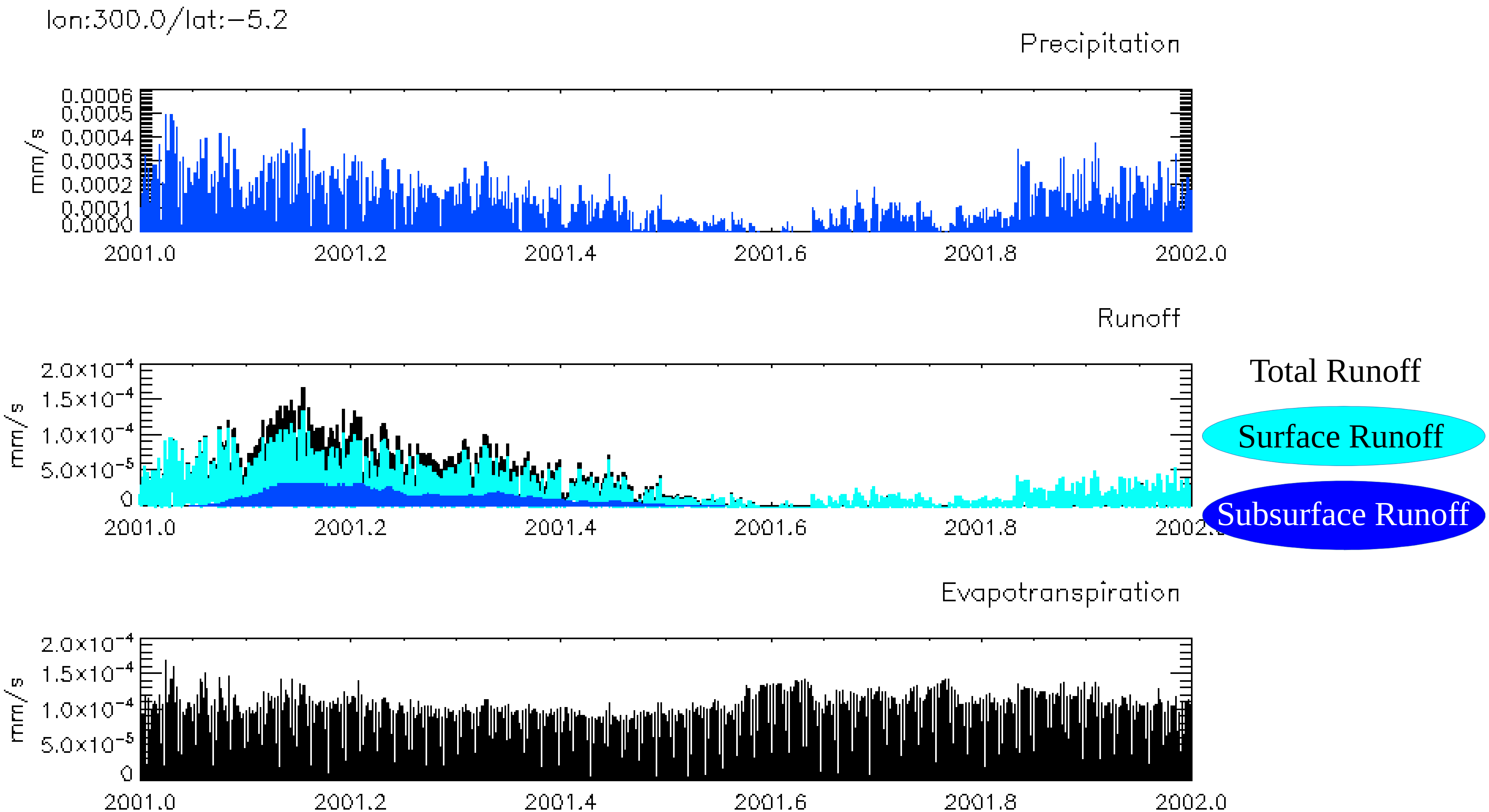
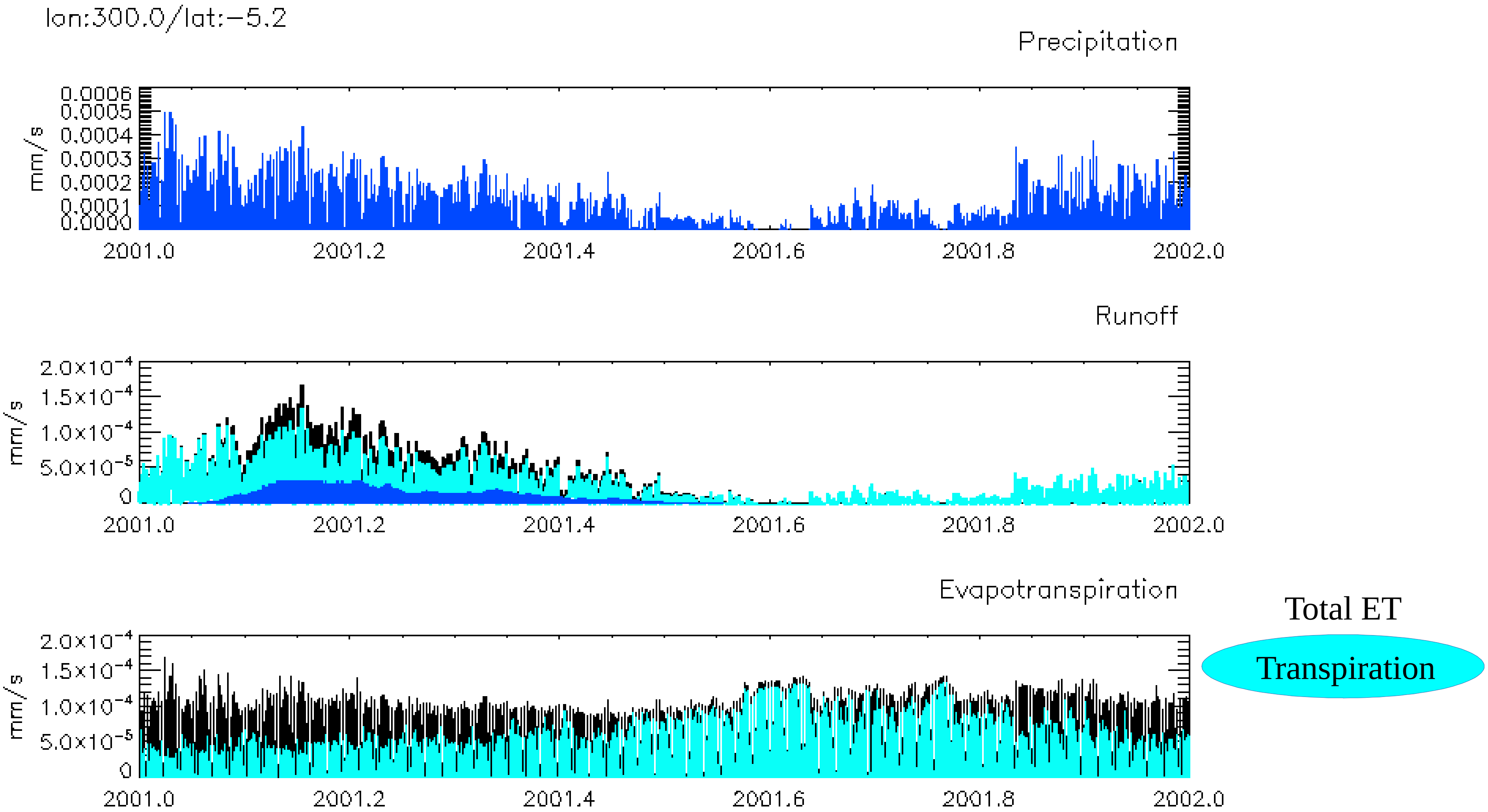
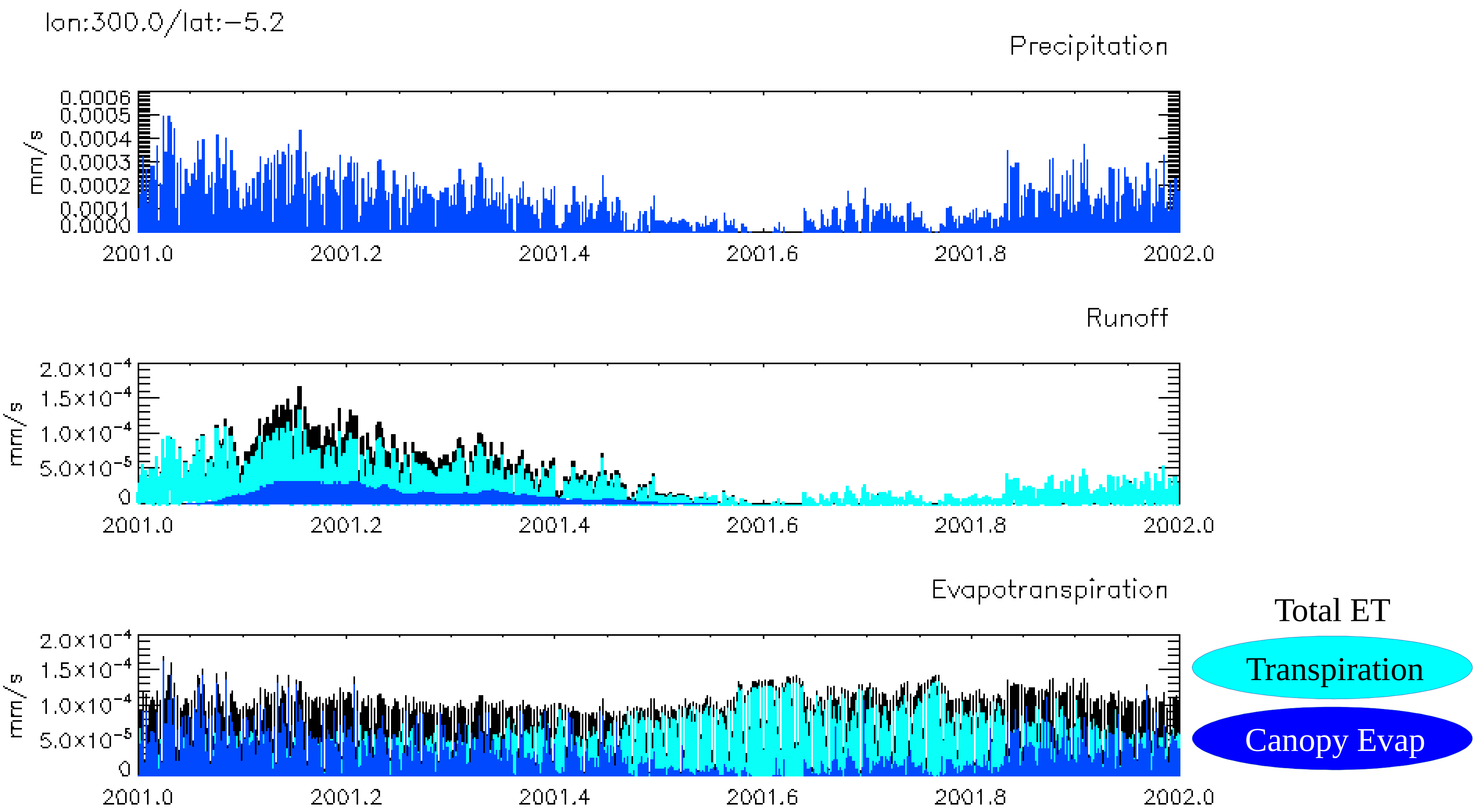
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Air Temperature
C
40
30
20
10
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0


lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0x10^-4
1.5x10^-4
1.0x10^-4
5.0x10^-5
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Evapotranspiration
mm/s
2.0x10^-4
1.5x10^-4
1.0x10^-4
5.0x10^-5
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0

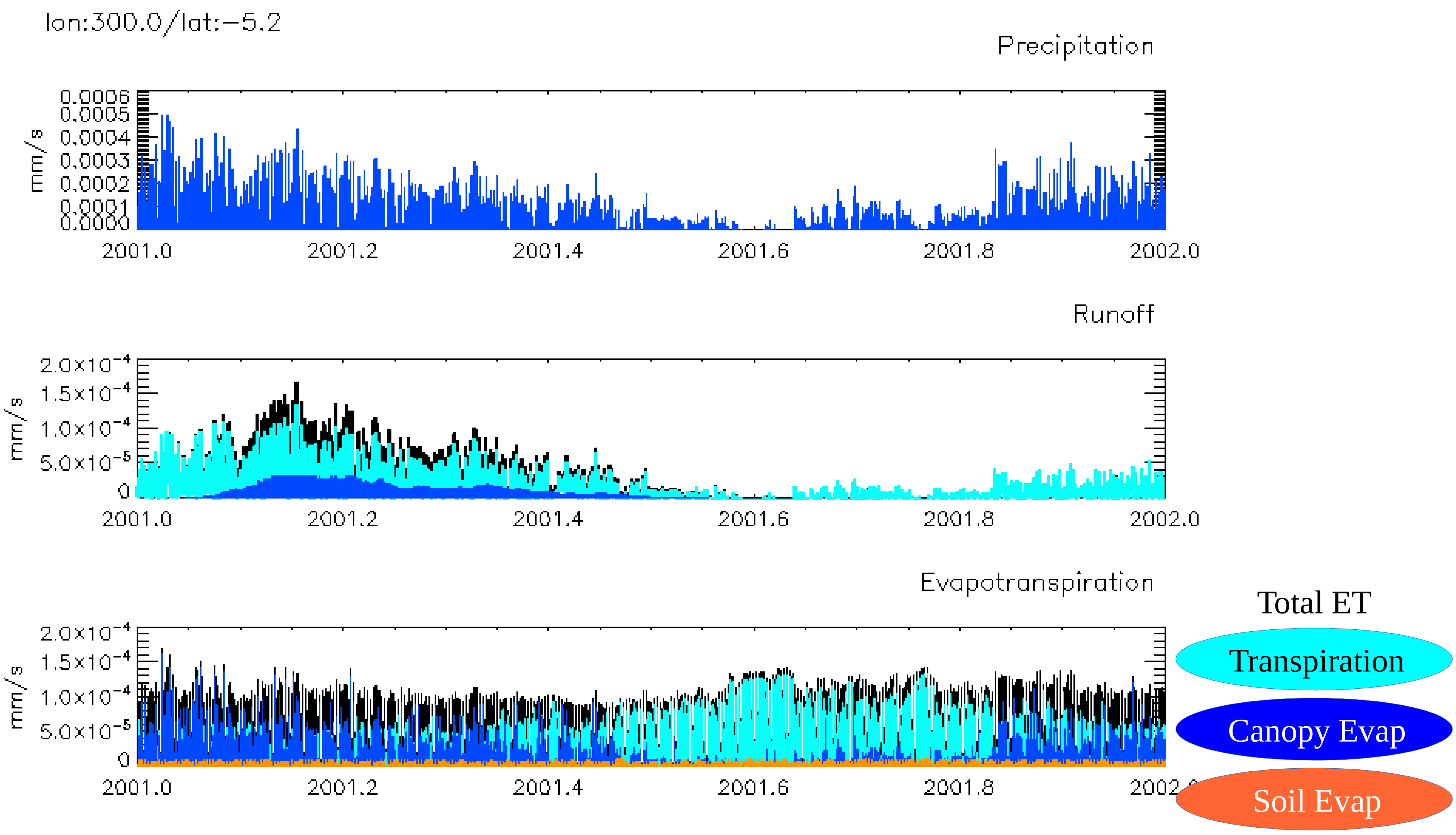

lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0×10^{-4}
1.5×10^{-4}
1.0×10^{-4}
5.0×10^{-5}
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Total Runoff
Surface Runoff
Evapotranspiration
mm/s
2.0×10^{-4}
1.5×10^{-4}
1.0×10^{-4}
5.0×10^{-5}
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0

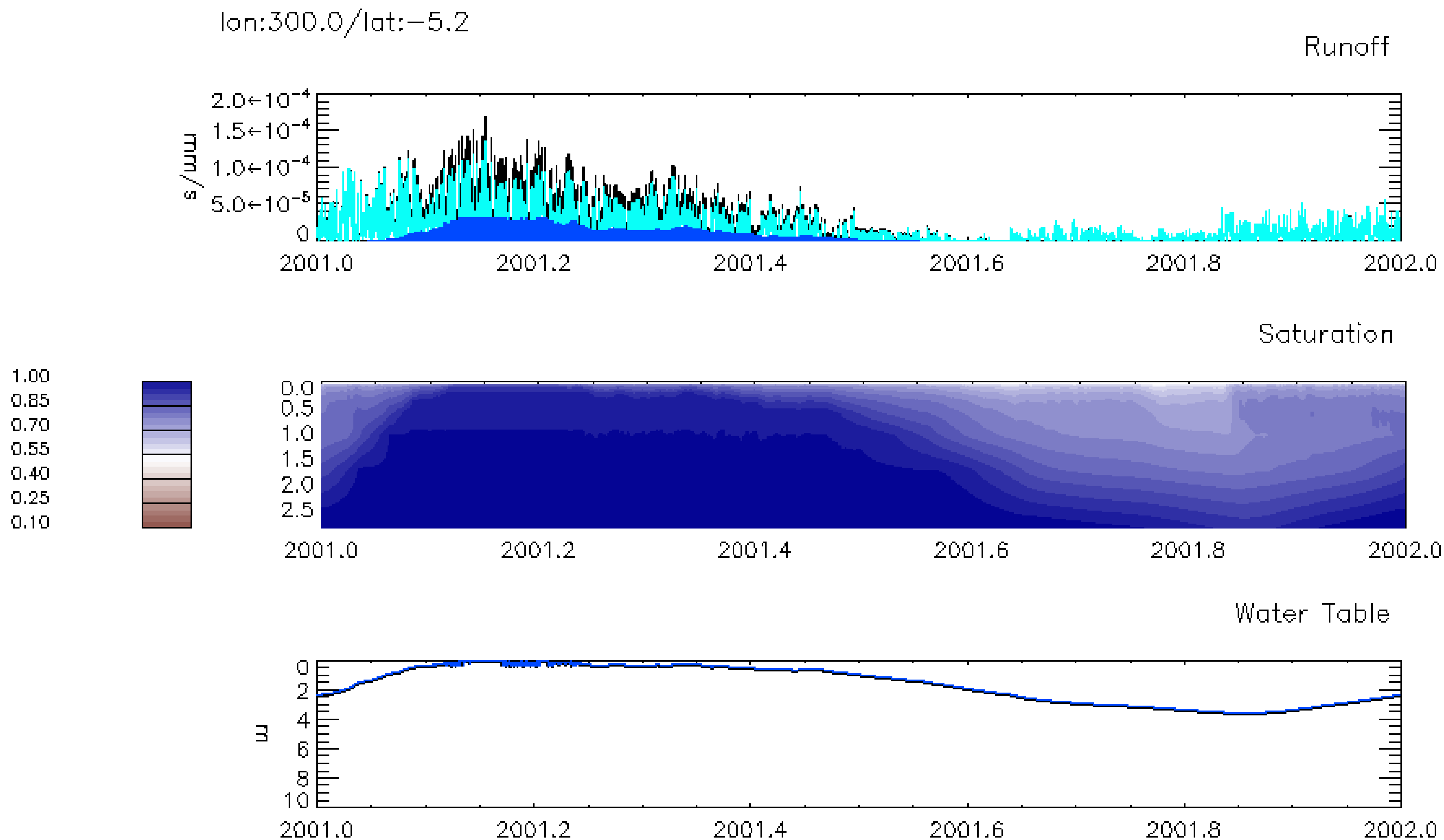

lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
Total Runoff
Surface Runoff
Subsurface Runoff
mm/s
2.0x10^{-4}
1.5x10^{-4}
1.0x10^{-4}
5.0x10^{-5}
0
Evapotranspiration
mm/s
2.0x10^{-4}
1.5x10^{-4}
1.0x10^{-4}
5.0x10^{-5}
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0


lon:300.0/lat:-5.2
Precipitation
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
mm/s
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
2.0x10^-4
1.5x10^-4
1.0x10^-4
5.0x10^-5
0
mm/s
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Evapotranspiration
2.0x10^-4
1.5x10^-4
1.0x10^-4
5.0x10^-5
0
mm/s
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Total ET
Transpiration

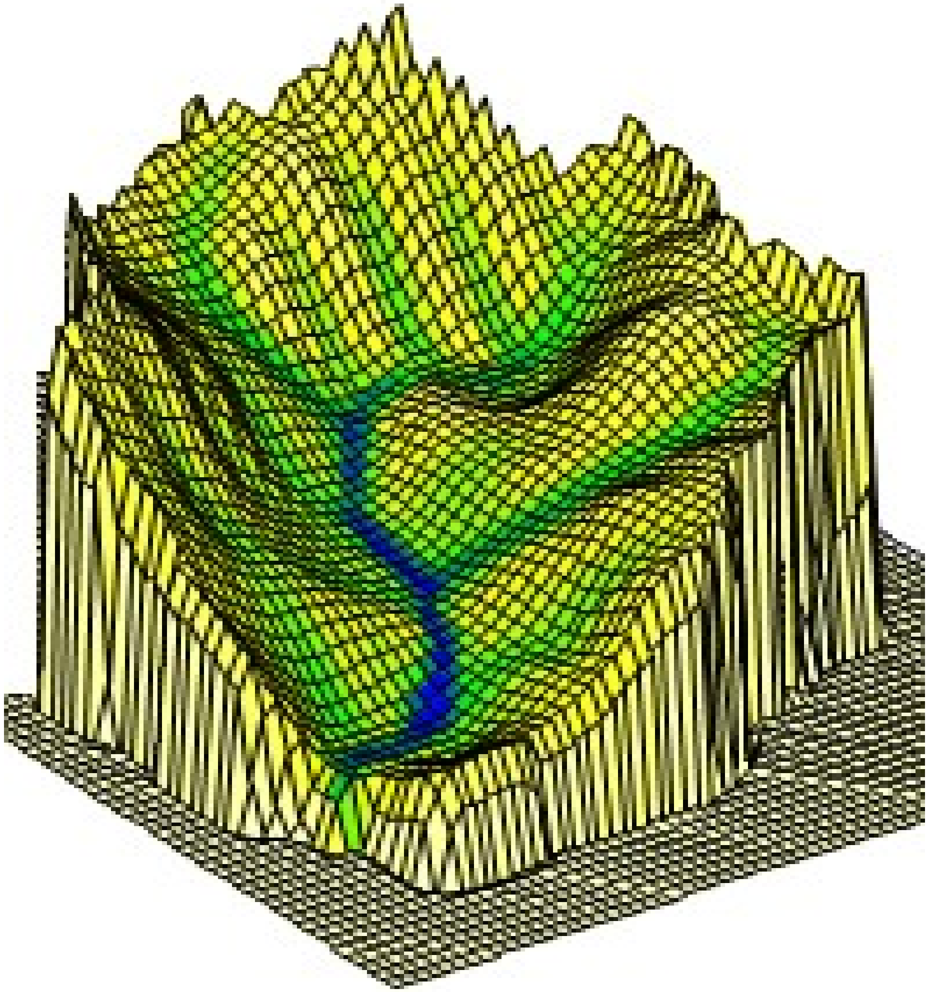


lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Evapotranspiration
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Total ET
Transpiration
Canopy Evap


lon:300.0/lat:−5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Evapotranspiration
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0
2001.0
2001.2
2001.4
2001.6
2001.8
Total ET
Transpiration
Canopy Evap
Soil Evap



lon:300.0/lat:-5.2
Runoff
mm/s
2.0×10^-4
1.5×10^-4
1.0×10^-4
5.0×10^-5
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Saturation
1.00
0.85
0.70
0.55
0.40
0.25
0.10
0.0
0.5
1.0
1.5
2.0
2.5
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Water Table
m
0
2
4
6
8
10
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0



The water table determines the fraction of the area that is saturated

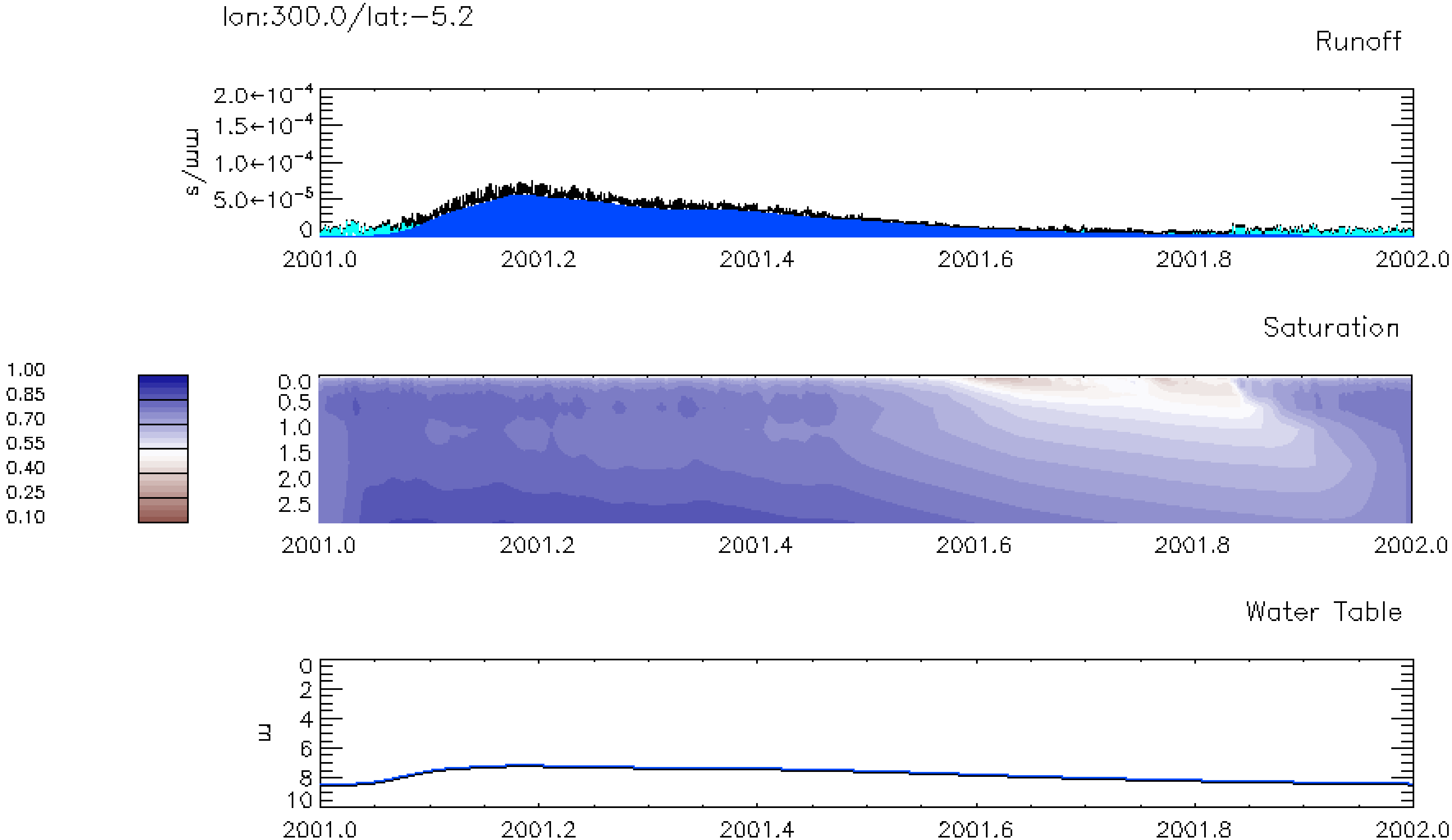
Saturated areas produce surface runoff

Example: Effects of Modifying the Water Table

$$\Delta ZWT = Qdrainage - Qrecharge$$

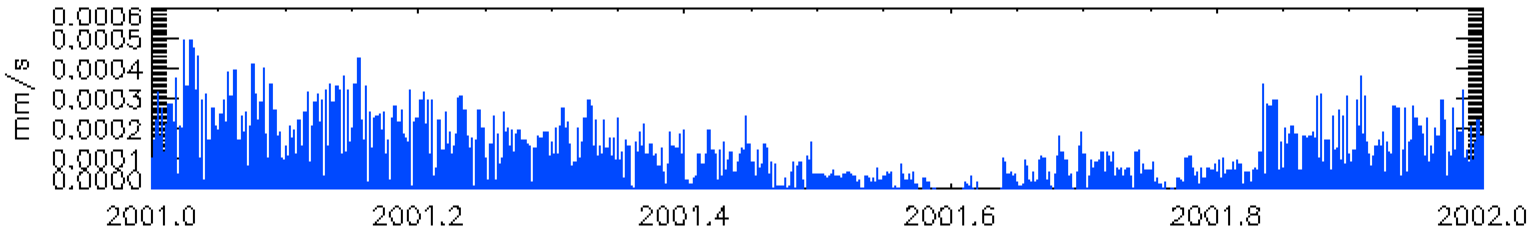
$$Qdrainage = A \exp(-f\ z)$$

$$Qsurface = F \exp(-g\ z)\ Pthroughfall$$

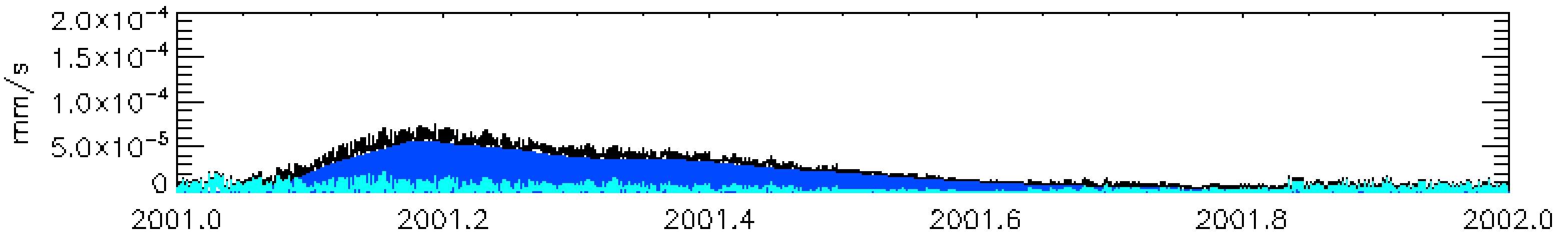

lon:300.0/lat:-5.2
Runoff
2.0×10^-4
1.5×10^-4
1.0×10^-4
5.0×10^-5
0
mm/s
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Saturation
1.00
0.85
0.70
0.55
0.40
0.25
0.10
0.0
0.5
1.0
1.5
2.0
2.5
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Water Table
0
2
4
6
8
10
m
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0

lon:300.0/lat:-5.2

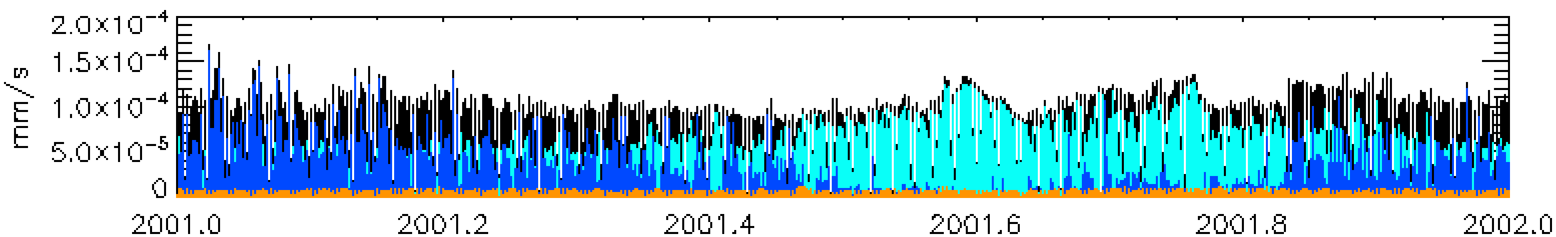
Precipitation



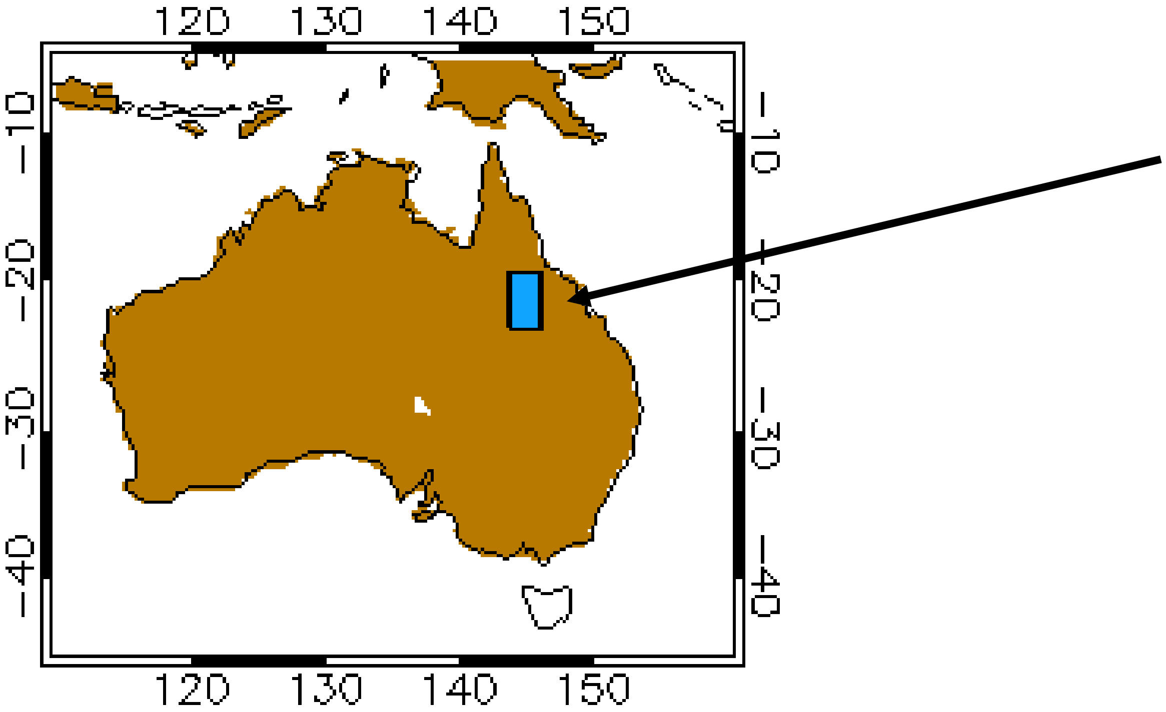
Runoff



Evapotranspiration

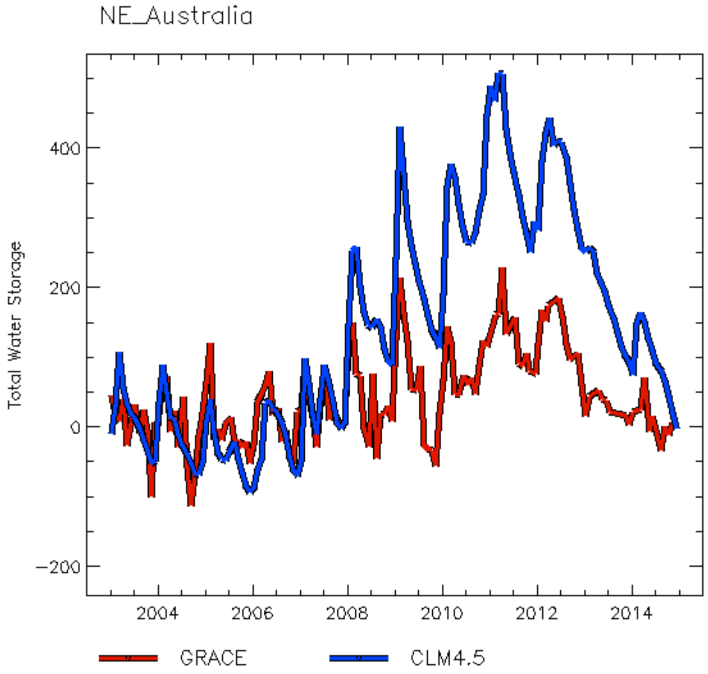


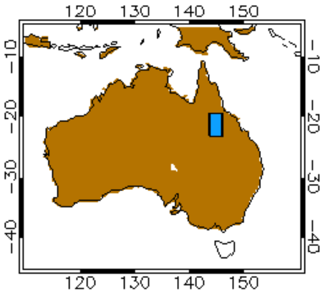
Example II
Model Structural Change



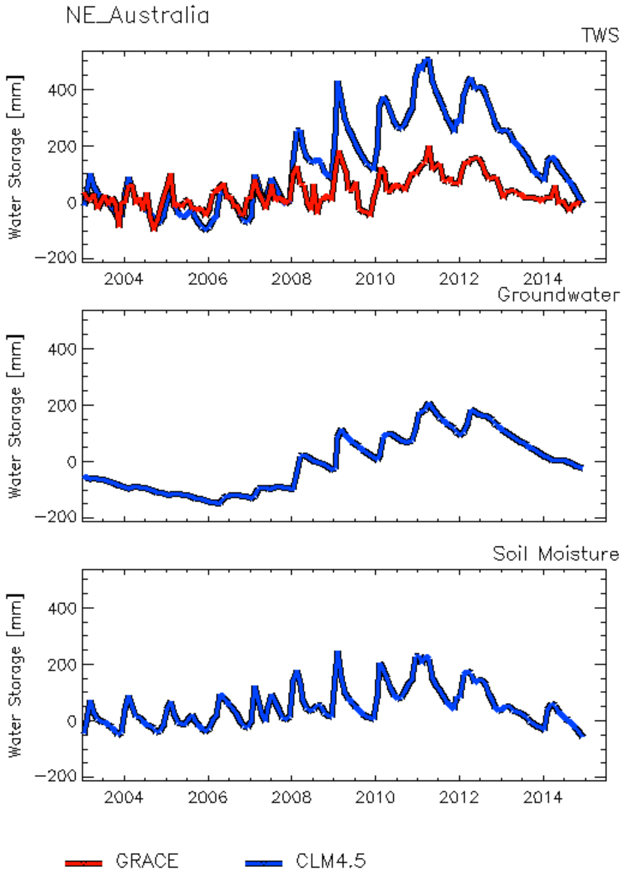
NE Australia

GRACE Water Storage Comparison





GRACE Water Storage Comparison

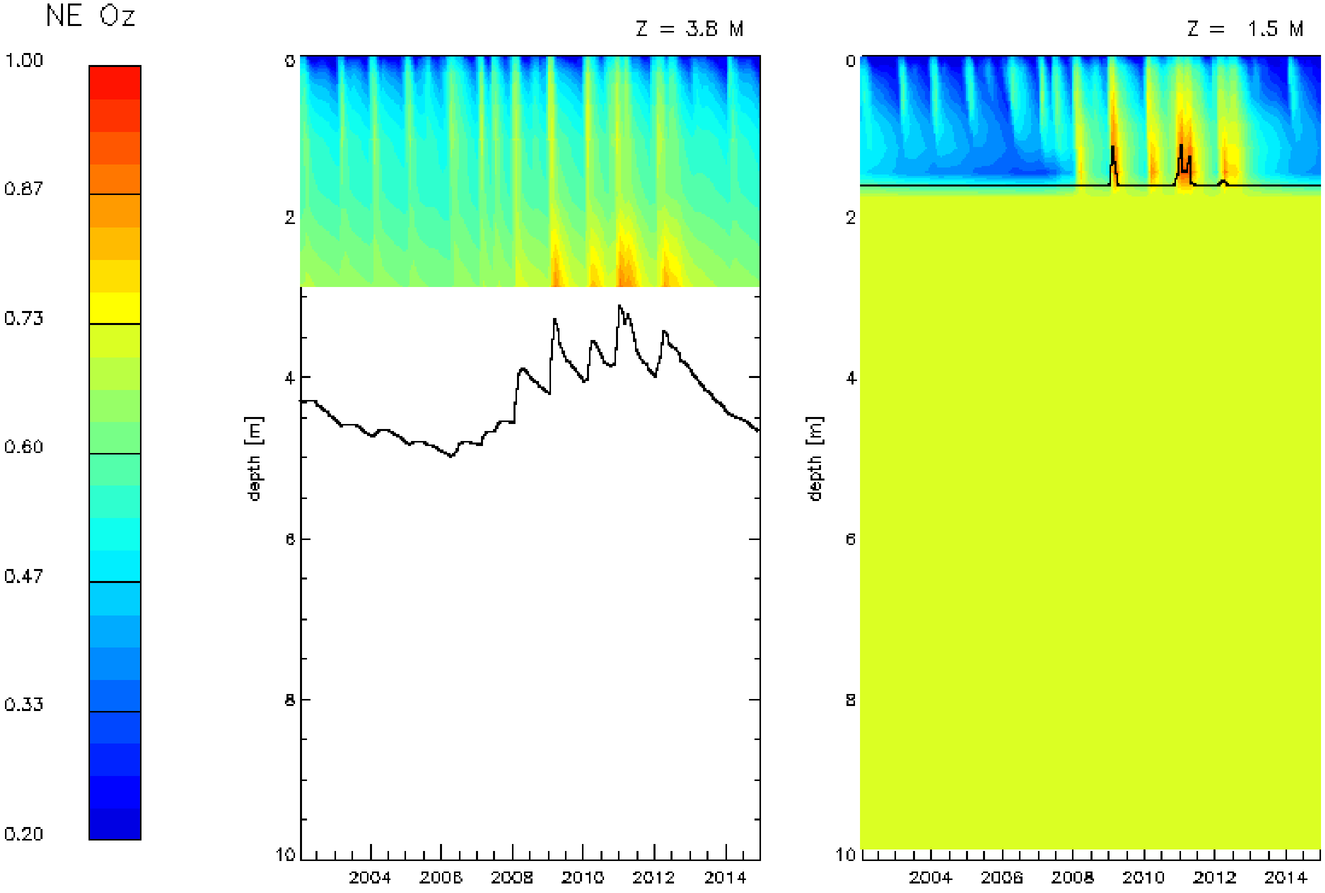


Total Water Storage

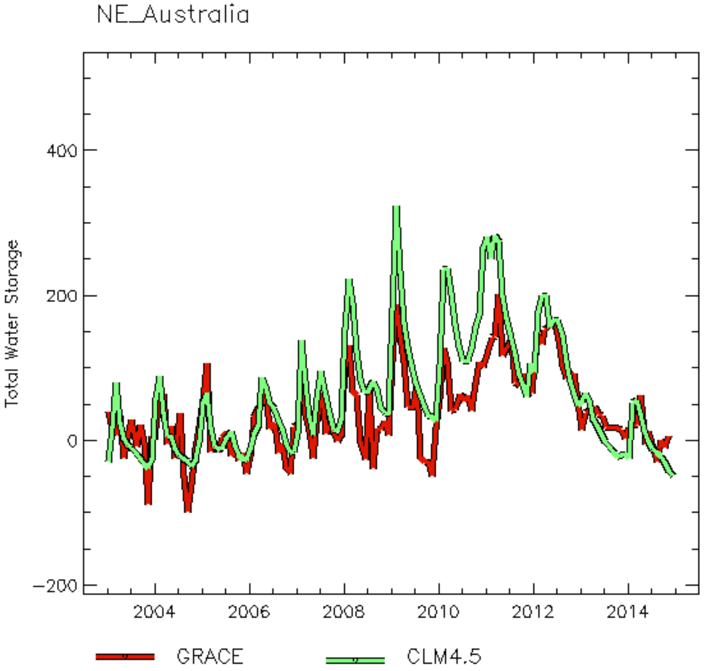
Groundwater Storage

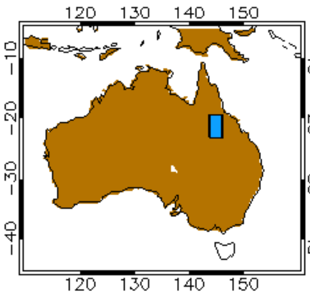
Soil Water Storage

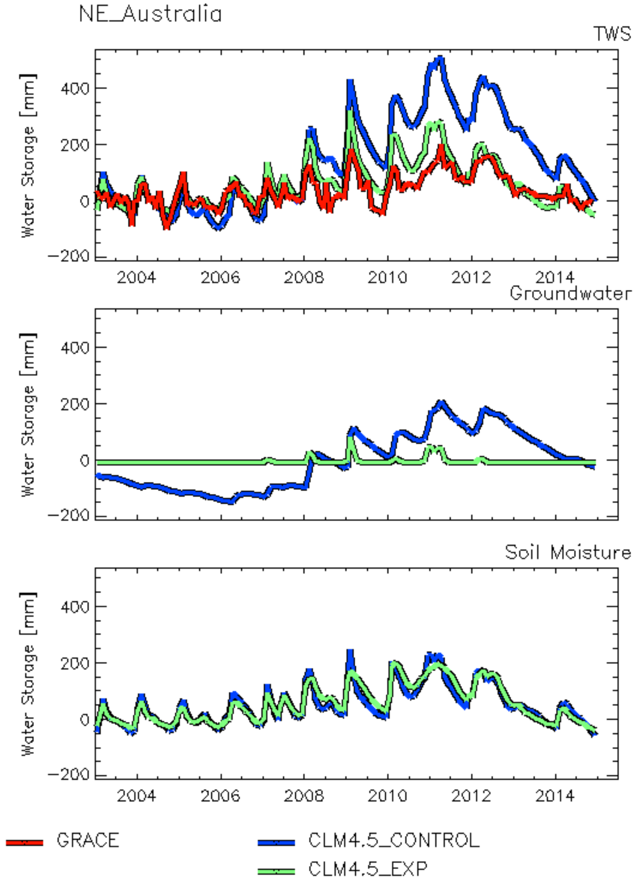
Spatially Variable Soil Depth



GRACE Water Storage Comparison







Current and Future Challenges

- Subgrid heterogeneity and covariance of vegetation, soil moisture, surface water and snow
- Within-canopy turbulent fluxes
- Human management and withdrawals
- Groundwater dynamics
- Dynamic lakes
- Hydrological response to land cover change