Hydrology in the Community Land Model

Sean Swenson
Terrestrial Sciences Section

What is Hydrology?

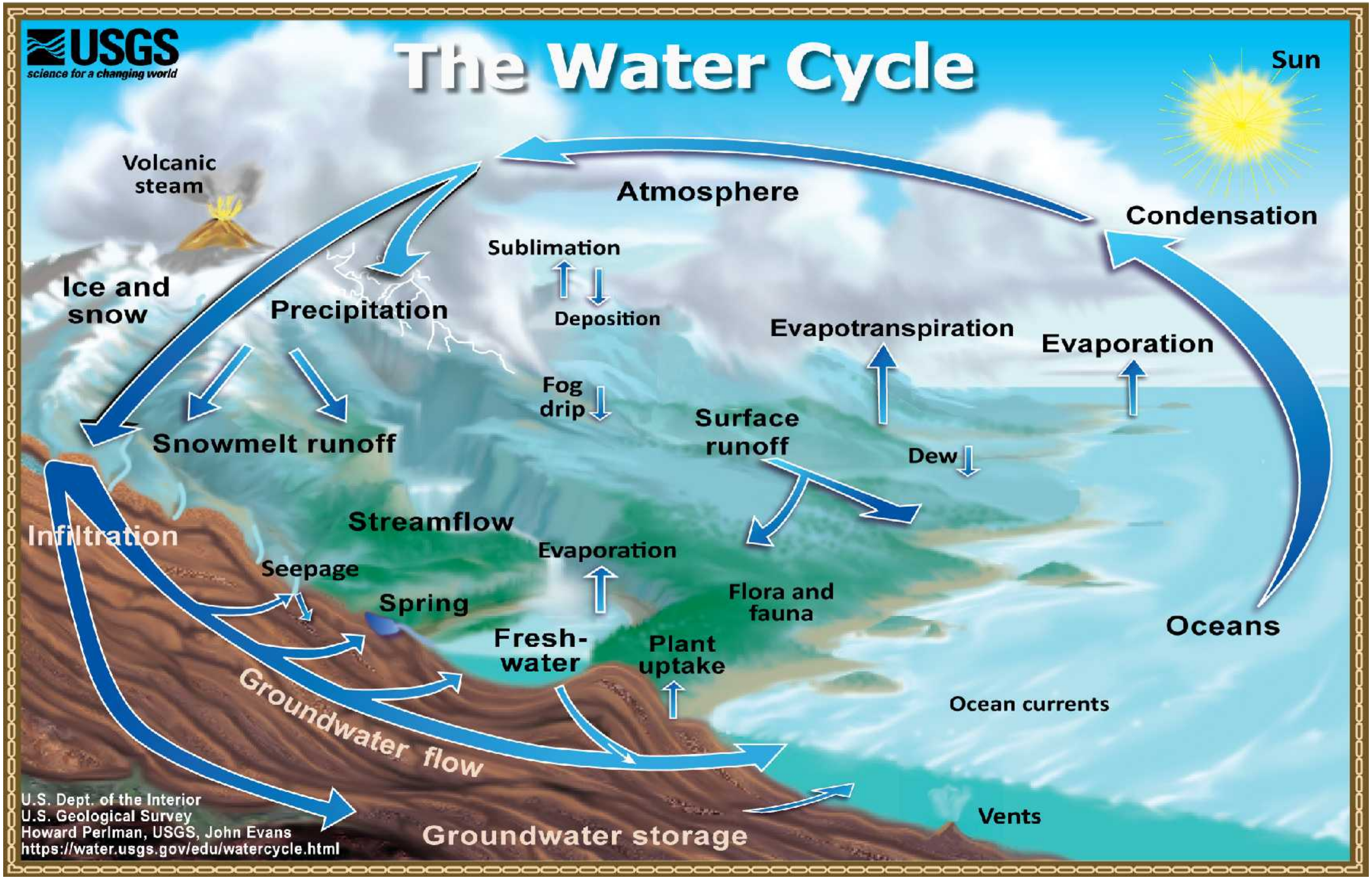
a) the study of water

What is Hydrology?

a) the study of water

b) the science that encompasses the occurrence, distribution, movement and properties of the waters of the Earth and their relationship with the environment within each phase of the hydrologic cycle. *

* U.S. Geological Survey

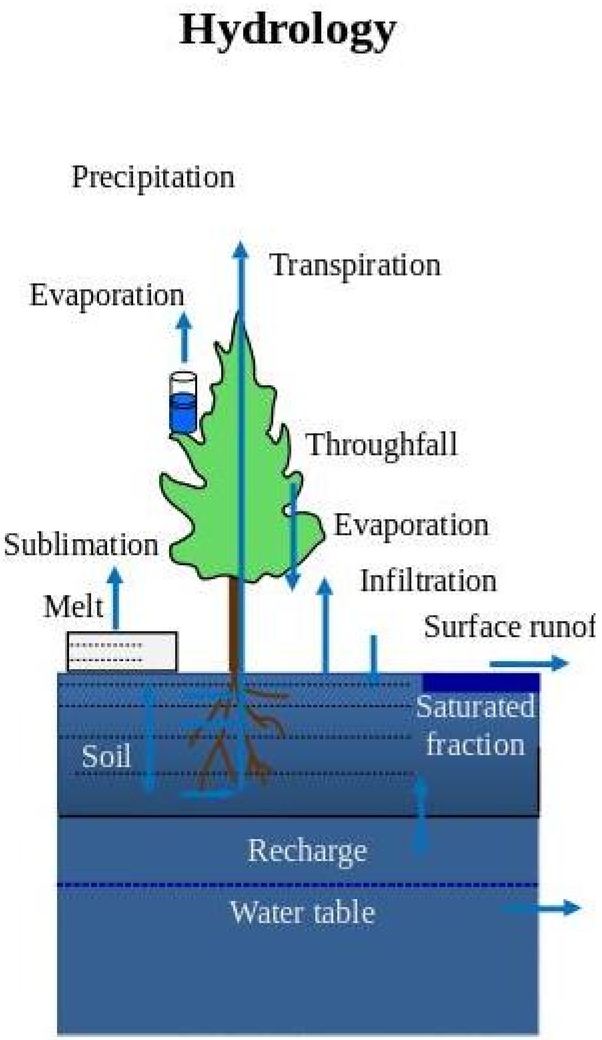

USGS
science for a changing world
The Water Cycle
Sun
Volcanic steam
Atmosphere
Condensation
Sublimation
Deposition
Ice and snow
Precipitation
Evapotranspiration
Evaporation
Fog drip
Surface runoff
Dew
Snowmelt runoff
Streamflow
Infiltration
Evaporation
Seepage
Spring
Flora and fauna
Oceans
Fresh-water
Plant uptake
Groundwater flow
Ocean currents
Vents
Groundwater storage
U.S. Dept. of the Interior
U.S. Geological Survey
Howard Perlman, USGS, John Evans
https://water.usgs.gov/edu/watercycle.html

What is Hydrology in CTSM?

a) the fluxes of water into and out of the land

b) the redistribution of water within the land

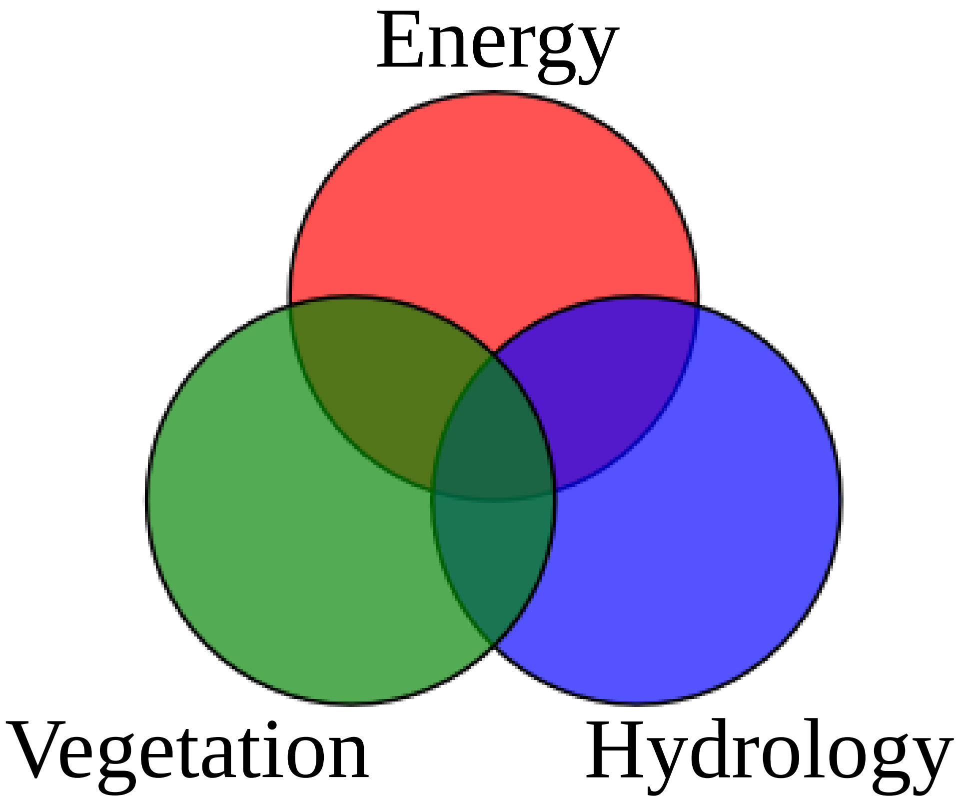
What is Hydrology in CTSM?

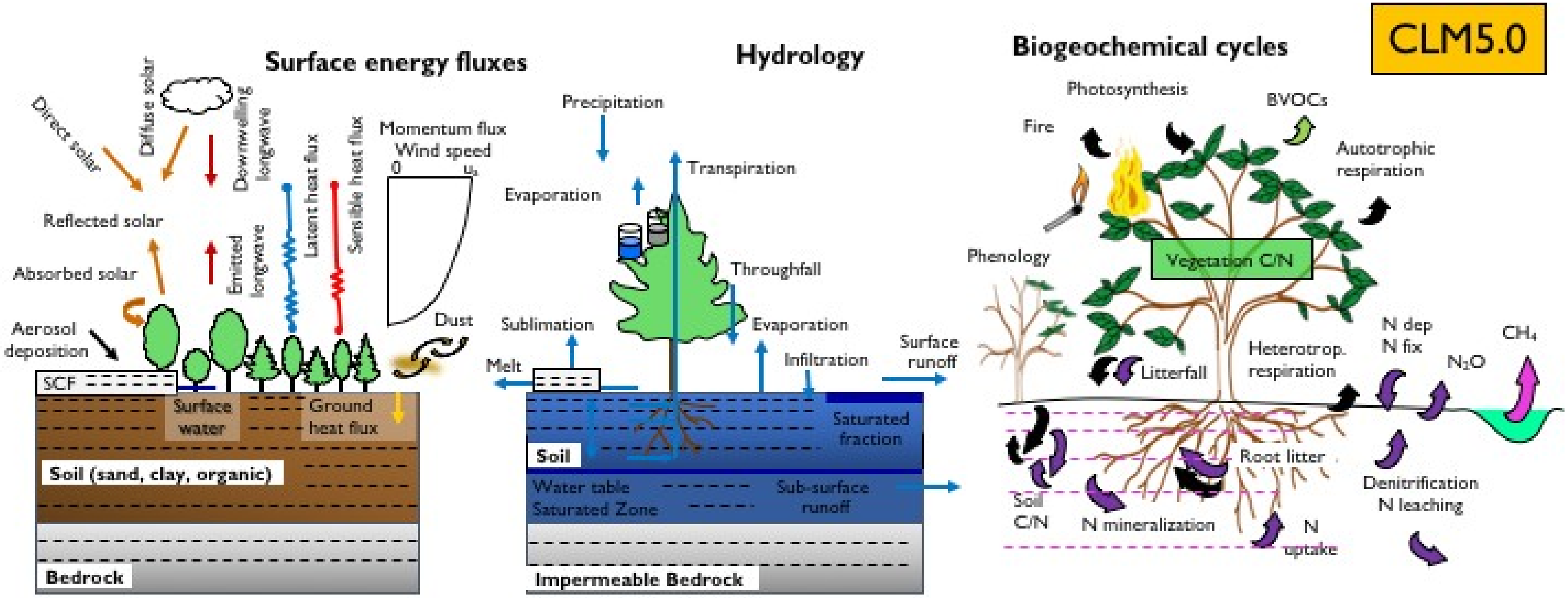


a) the fluxes of water into and out of the land

b) the redistribution of water within the land

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





From: *Technical Description of version 5.0 of the Community Land Model (CLM)*

The Water Balance

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

P = Precipitation

E = Evapotranspiration

R = Runoff

S = Storage

Hydrologic models have different objectives

Flood Forecasting ⇒ **R**

NWP, Climate Prediction ⇒ **E**

Drought Monitoring, Groundwater ⇒ **S**

Different objectives lead to different model structures

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

CLM Water Balance Operations

Runoff

⇒ Surface Runoff (Infiltration and/or Saturation Excess)

⇒ Subsurface Runoff (Baseflow)

⇒ River Routing

CLM Water Balance Operations

Storage

⇒ Soil Moisture

⇒ Groundwater and water table depth

⇒ Perched water table

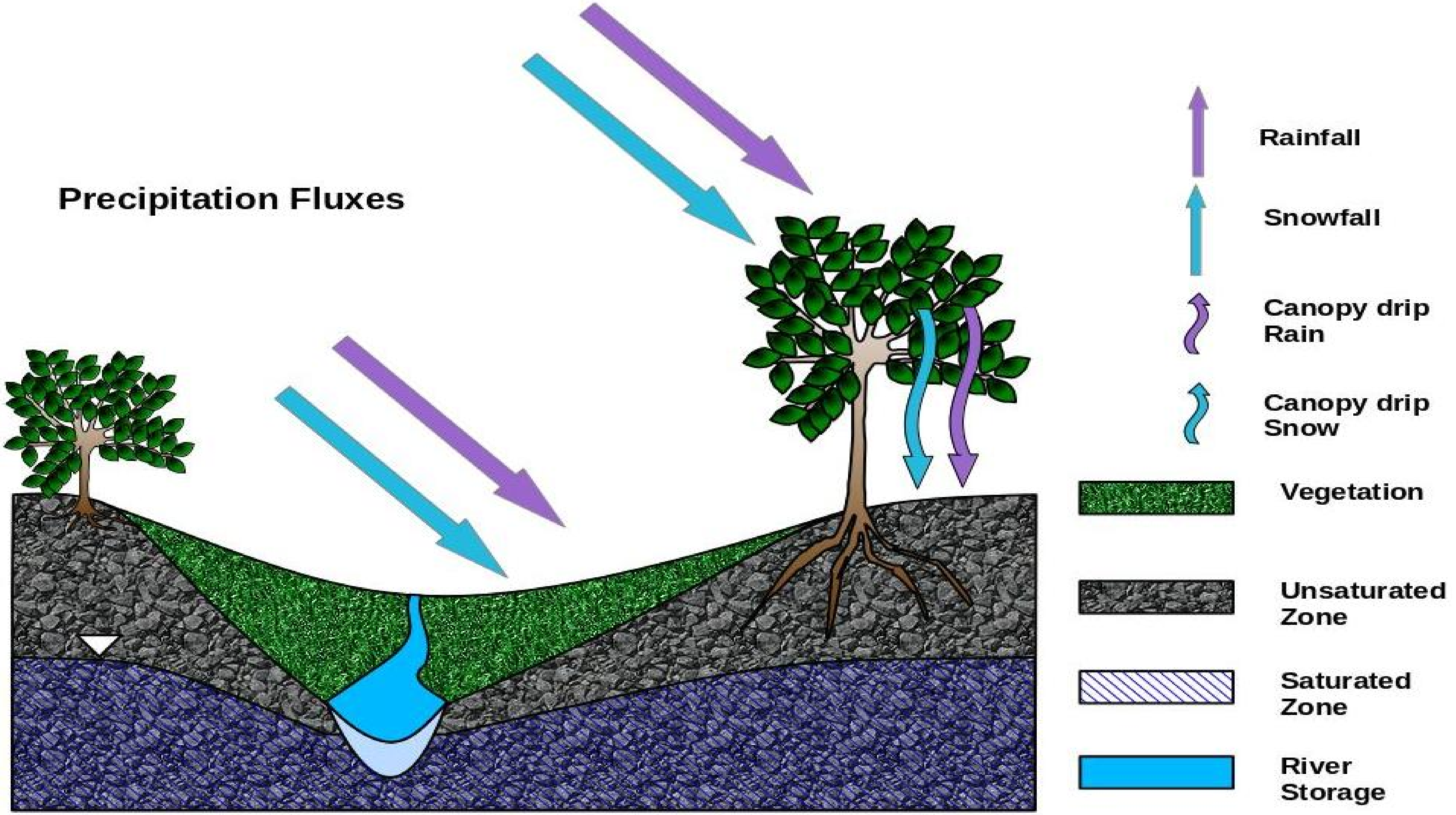
⇒ Canopy water

⇒ Surface water

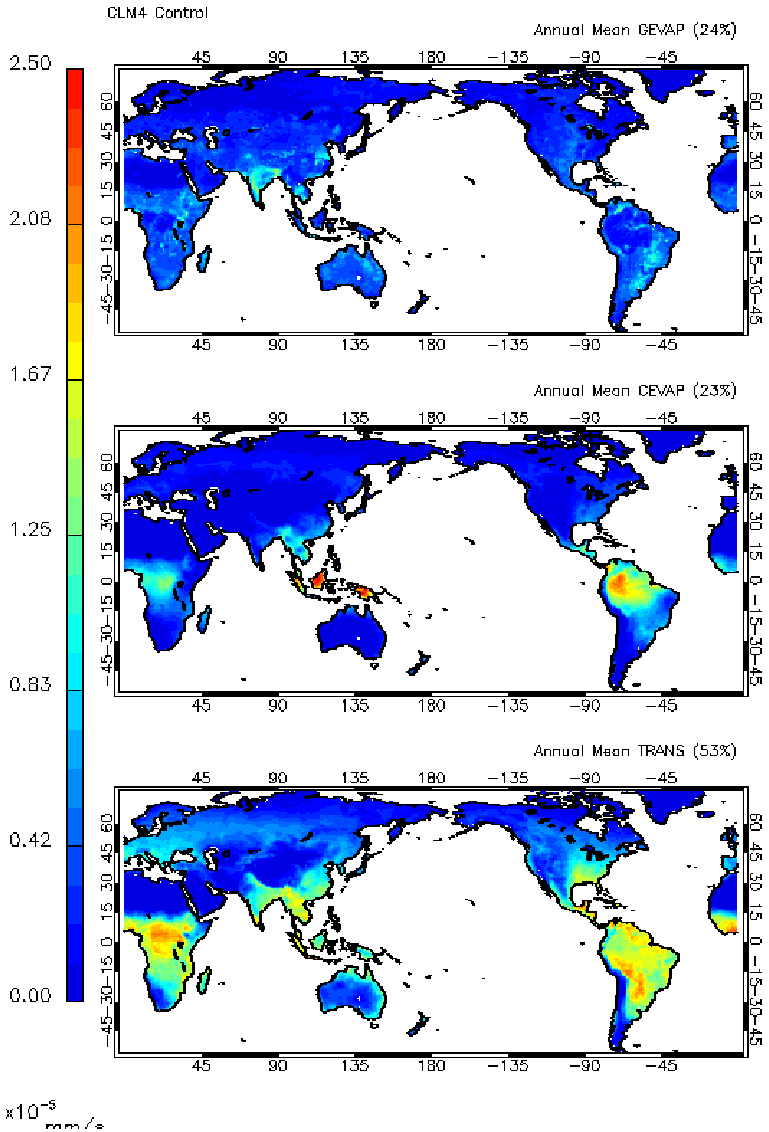
⇒ Snow

Canopy Hydrology

- Section 2.7.1 of the CLM Tech Note
- Interception / throughfall
- Leaf water storage and wetted fraction
- Evaporation from leaf surfaces


Precipitation Fluxes
Rainfall
Snowfall
Canopy drip Rain
Canopy drip Snow
Vegetation
Unsaturated Zone
Saturated Zone
River Storage

Canopy Hydrology And Evapotranspiration Partitioning

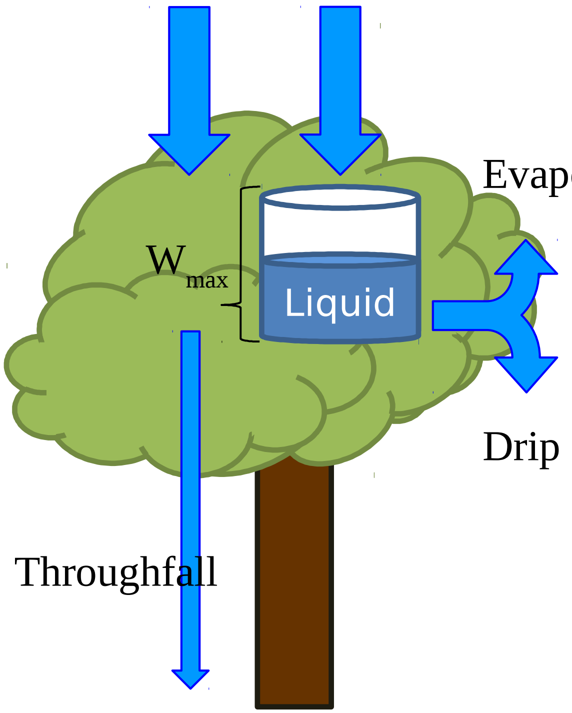


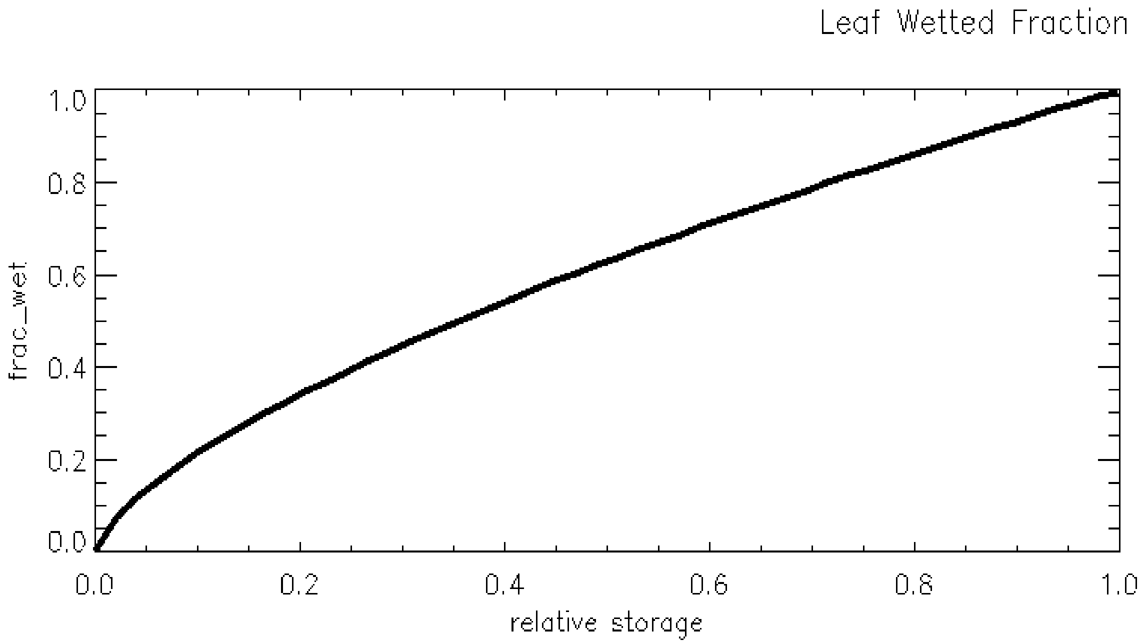
Ground Evaporation: 24%

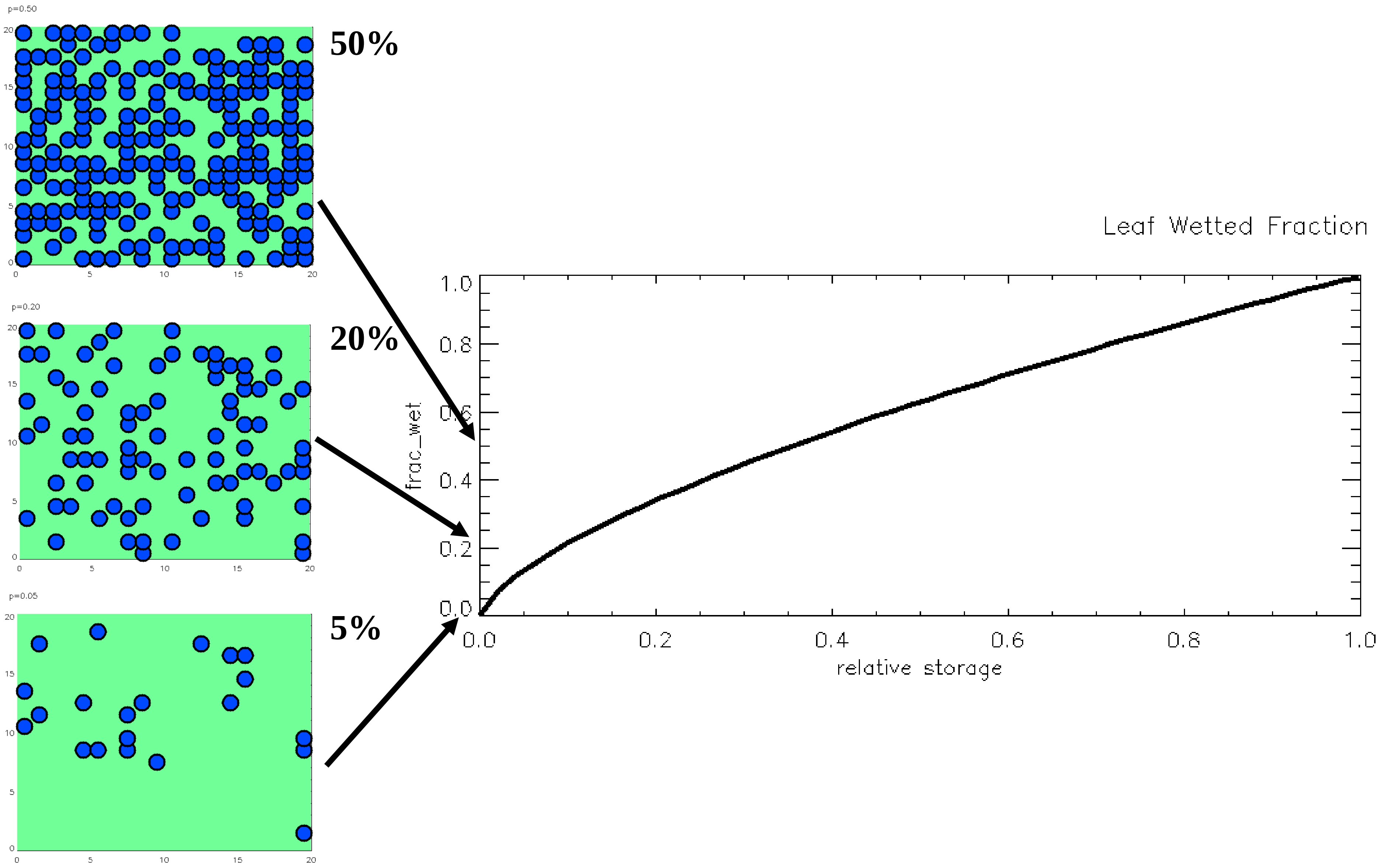
Canopy Evaporation: 23%

Transpiration: 53%

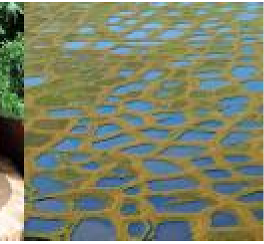
Leaf Wetted Area

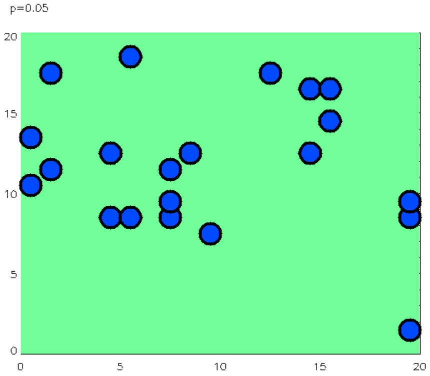


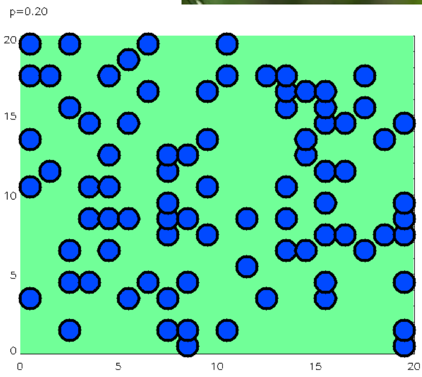


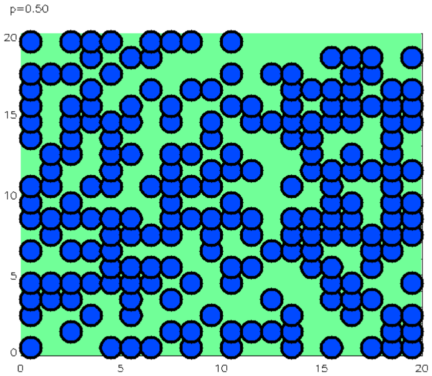


p=0.50
50%
p=0.20
20%
p=0.05
5%
Leaf Wetted Fraction
frac_wet
relative storage

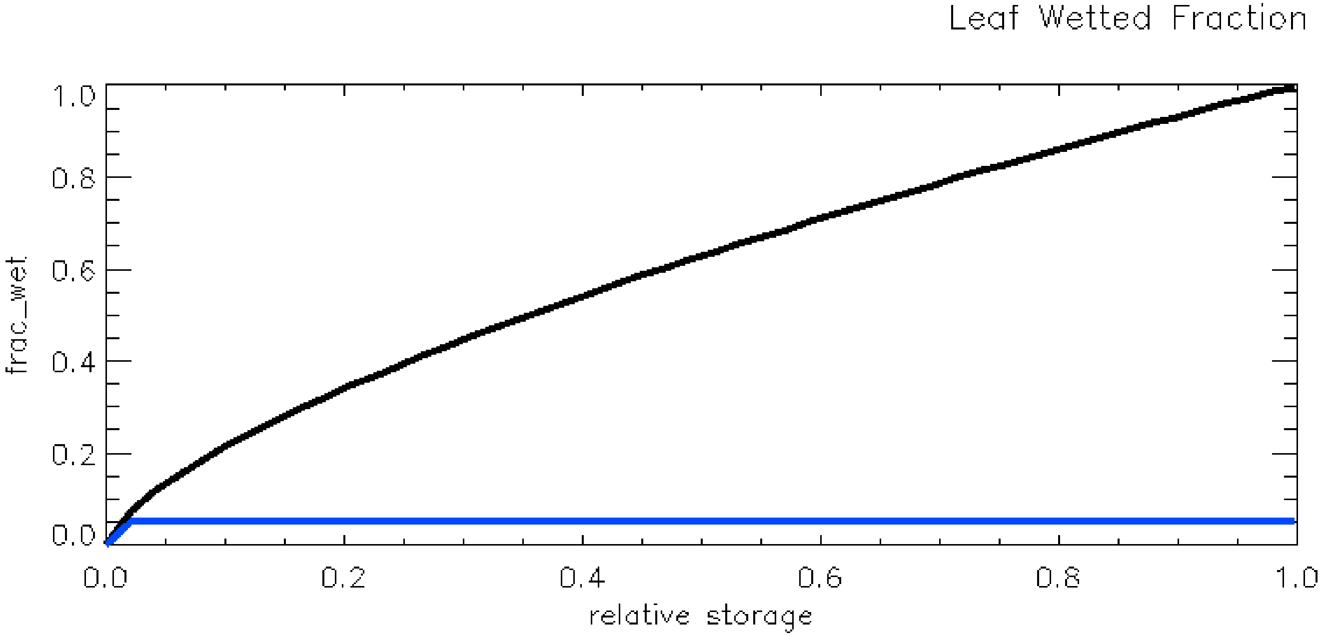



p=0.05
0
5
10
15
20

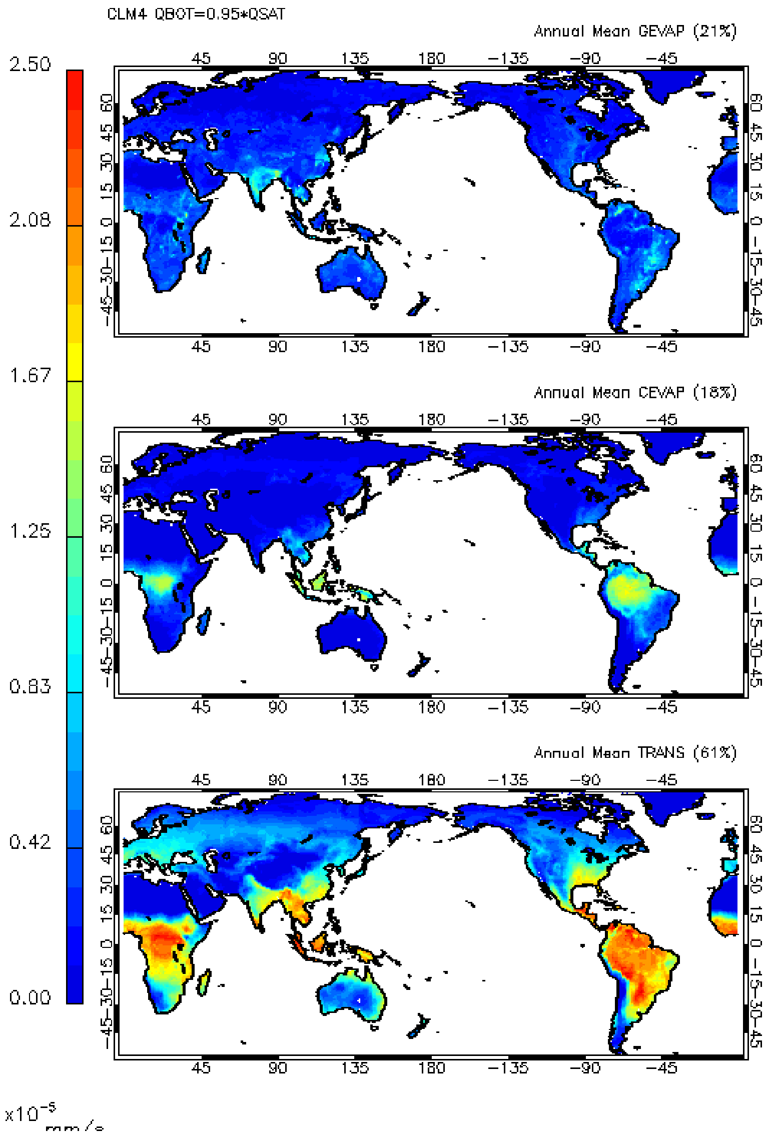

p=0.20
0
5
10
15
20


p=0.50
0
5
10
15
20

Leaf Wetted Area



Canopy Hydrology And Evapotranspiration Partitioning



Ground Evaporation: 21%

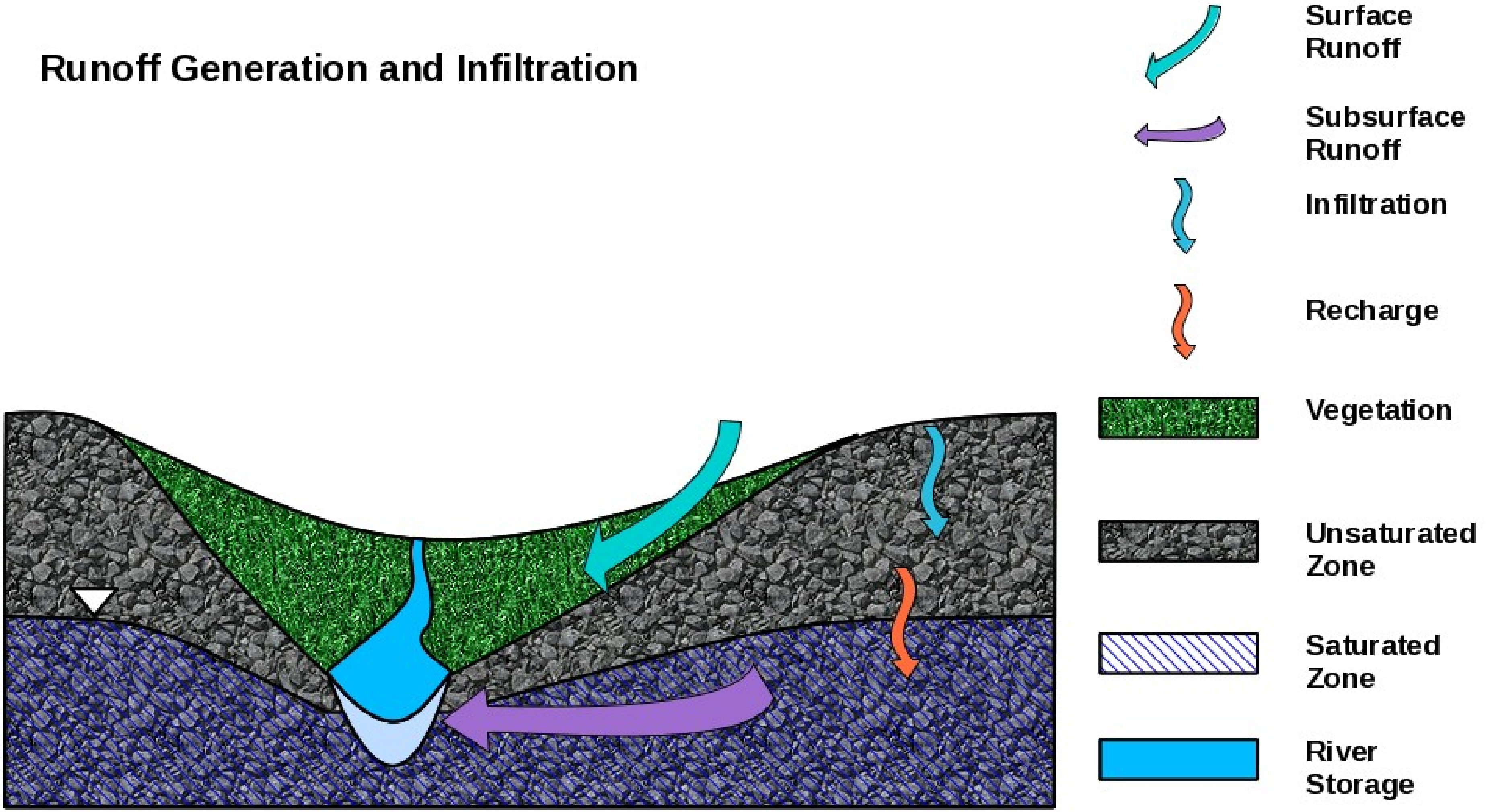
Canopy Evaporation: 18%

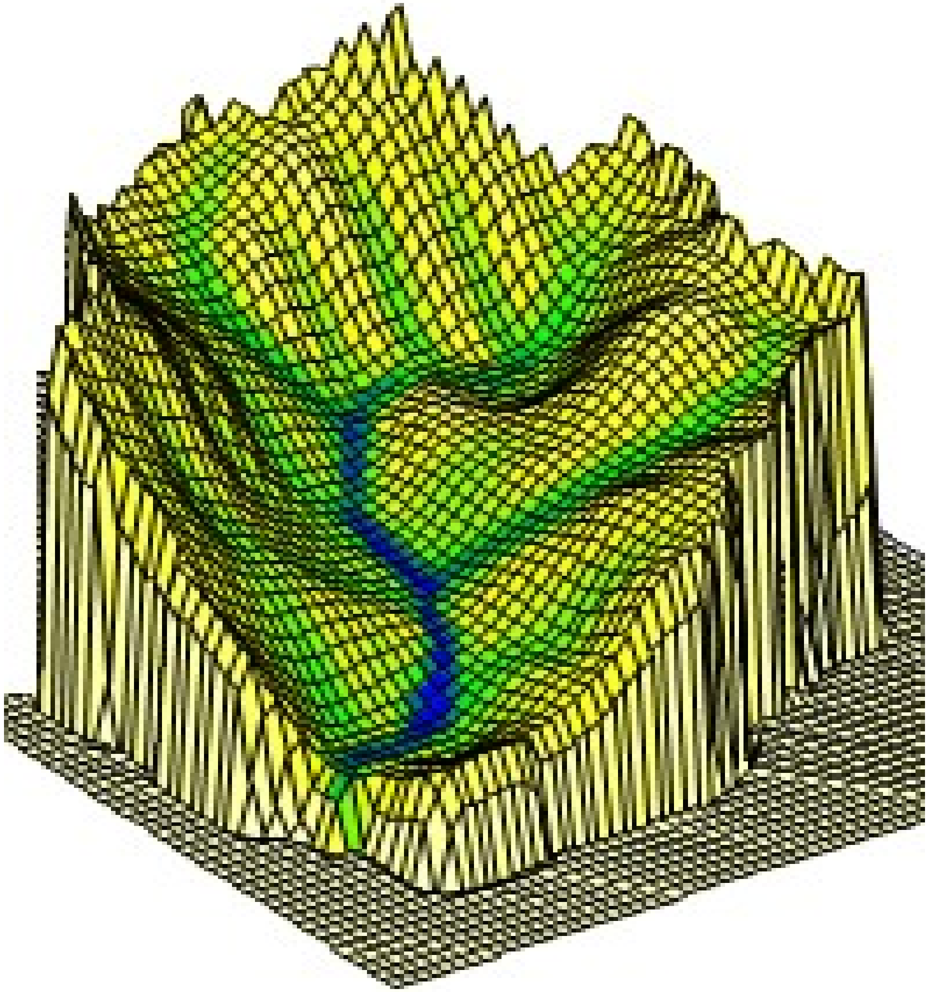
Transpiration: 61%

Runoff and Surface Water Processes

- Section 2.7.2 of the CLM Tech Note
- Surface runoff
- Saturated area
- Subsurface runoff
- River routing
- Surface water (wetlands)

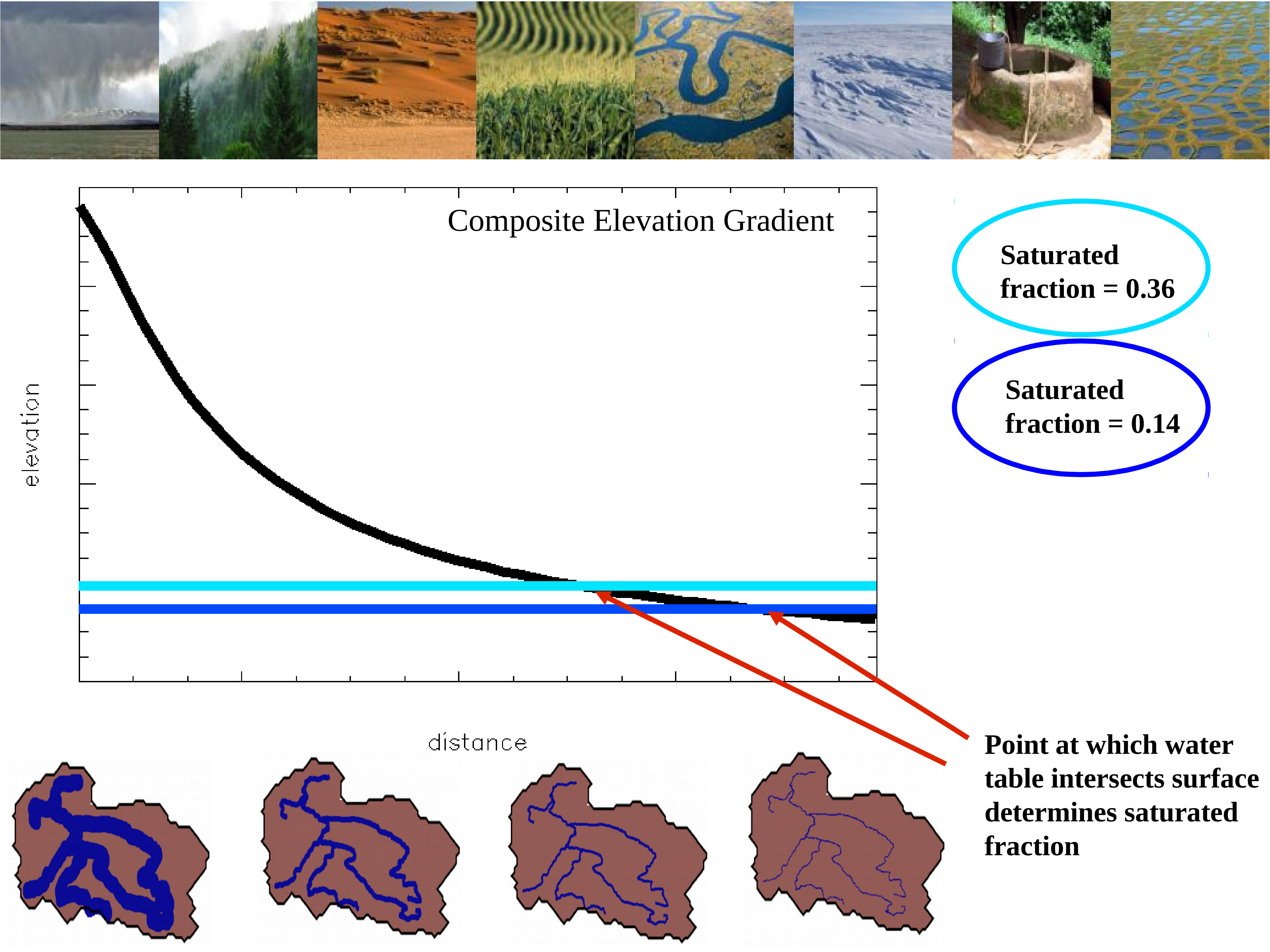
Runoff Generation and Infiltration





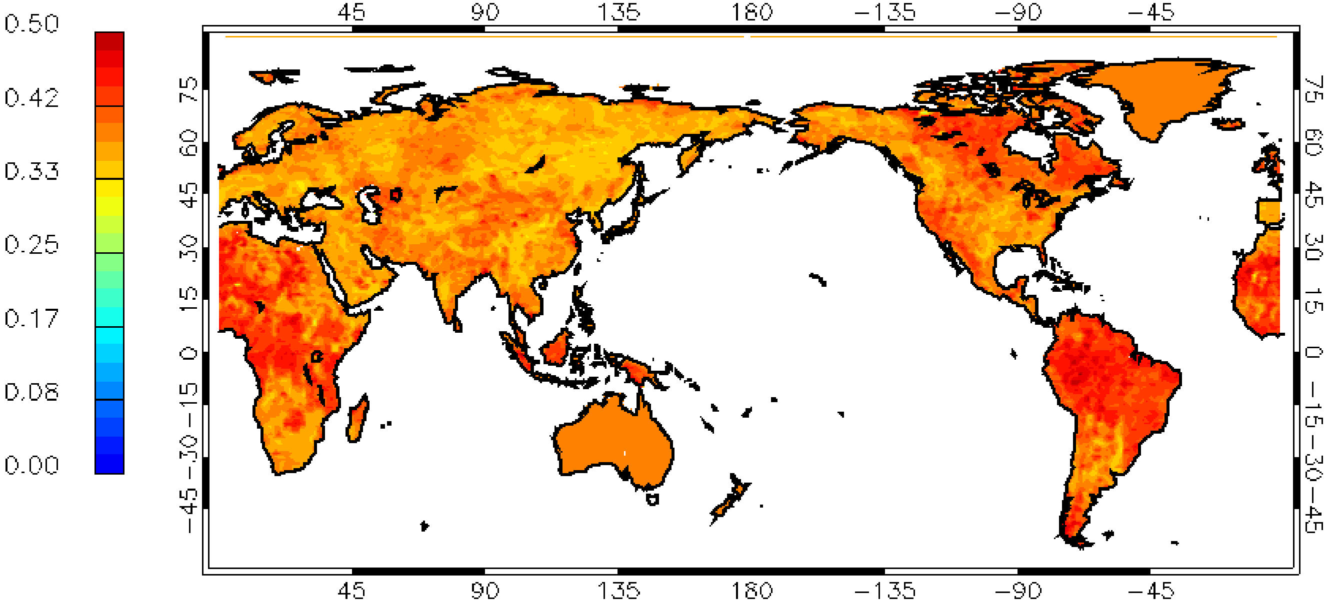
The water table determines the fraction of the area that is saturated

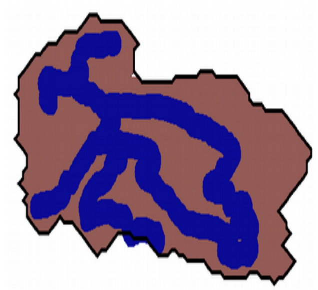
Saturated areas produce surface runoff



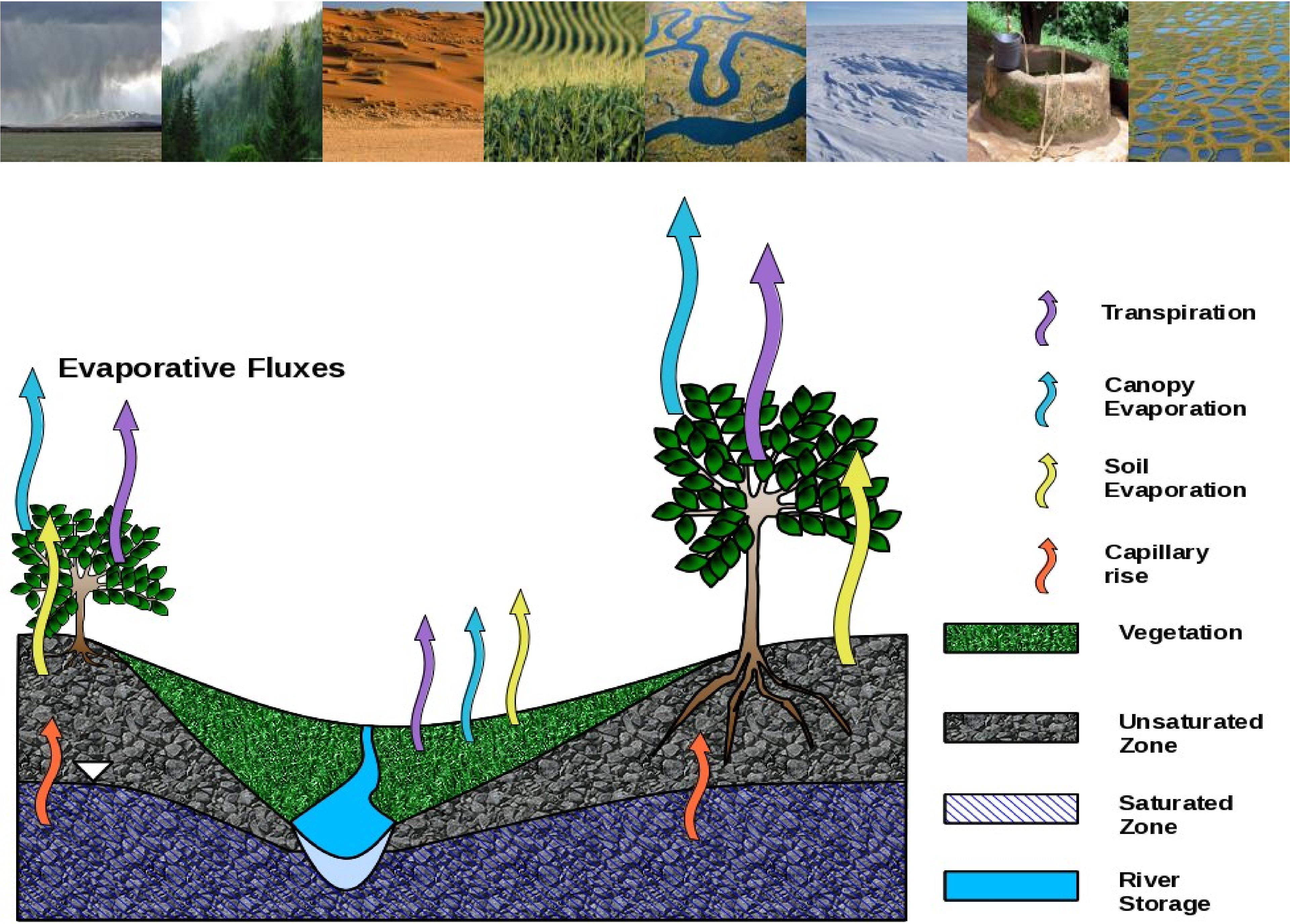
Composite Elevation Gradient
elevation
distance
Saturated fraction = 0.36
Saturated fraction = 0.14
Point at which water table intersects surface determines saturated fraction

Fmax

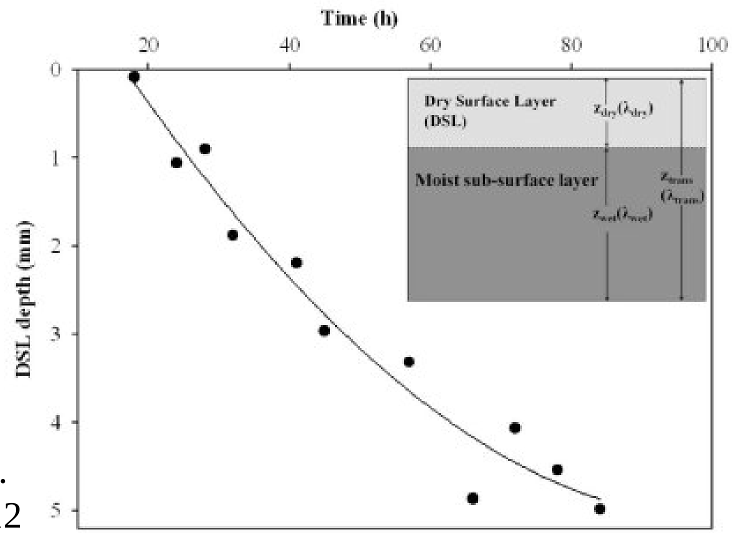




Fmax variable on surface data file determines maximum saturated fraction

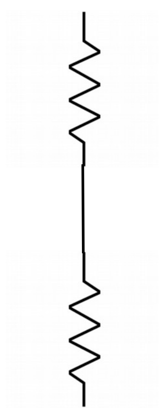

Evaporative Fluxes
Transpiration
Canopy Evaporation
Soil Evaporation
Capillary rise
Vegetation
Unsaturated Zone
Saturated Zone
River Storage

Dry Surface Layer (DSL)



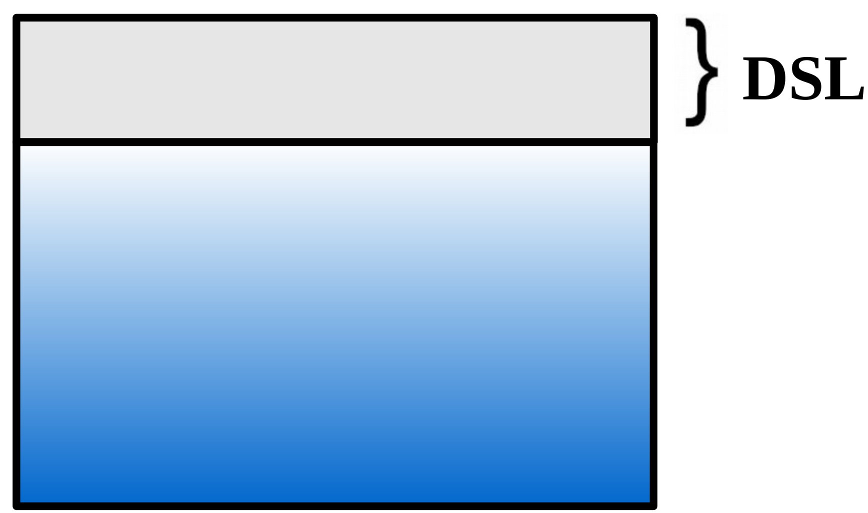
Deol et al.
WRR,2012

Figure 9. Estimated thickness of the dry surface layer (DSL) during transient evaporation. The line indicates the approximate trend. Inset: Conceptual structure of near-surface transition layer used for estimating thickness of the dry surface layer (DSL) with thickness (z) and thermal conductivity (λ).



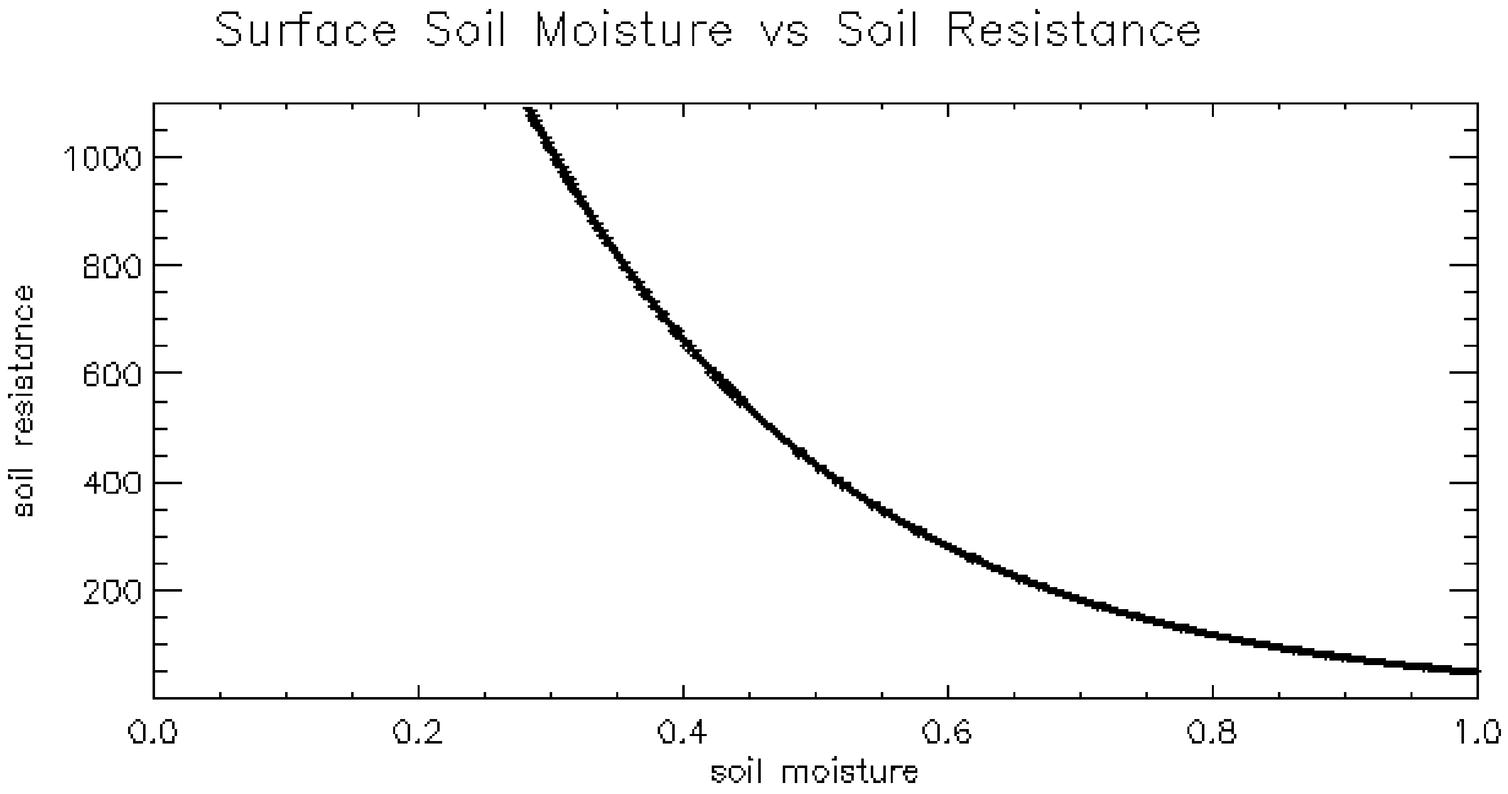
Vapor Diffusion

Liquid Diffusion

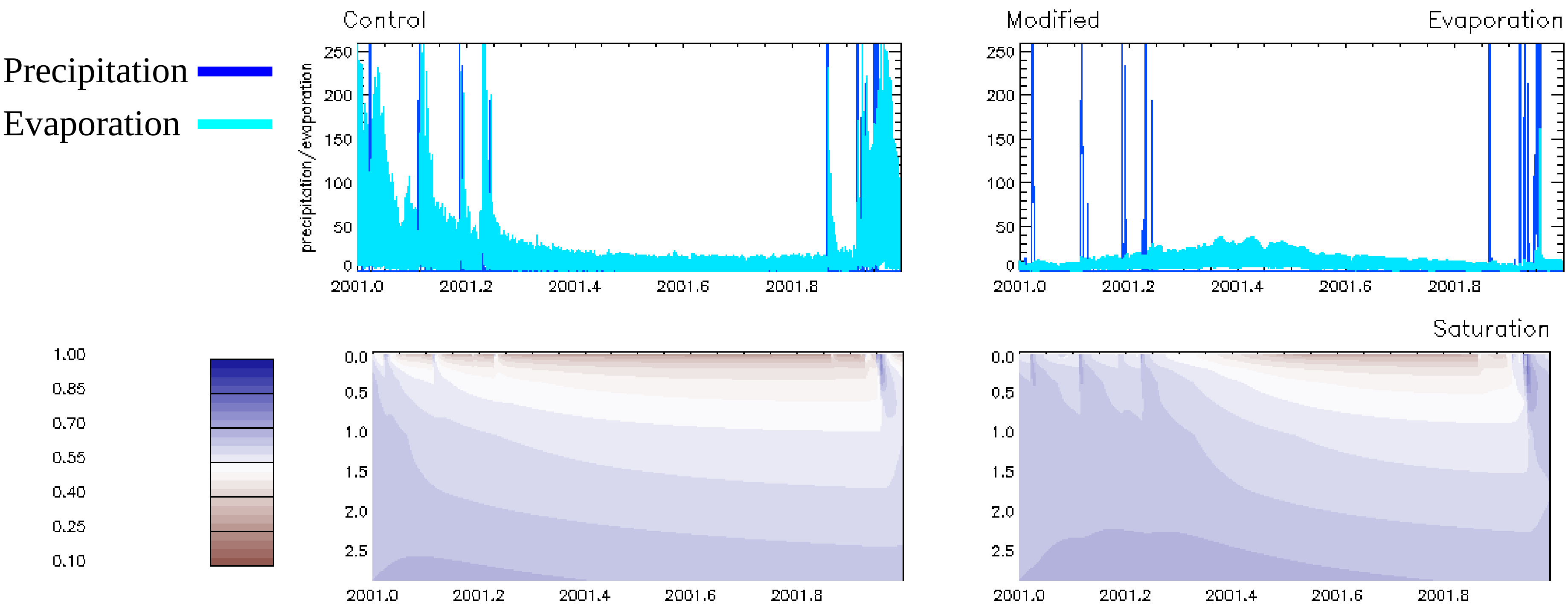


Vapor Diffusion < Liquid Diffusion

Soil Evaporative Resistance



Section 2.5.2 of CLM Tech Note



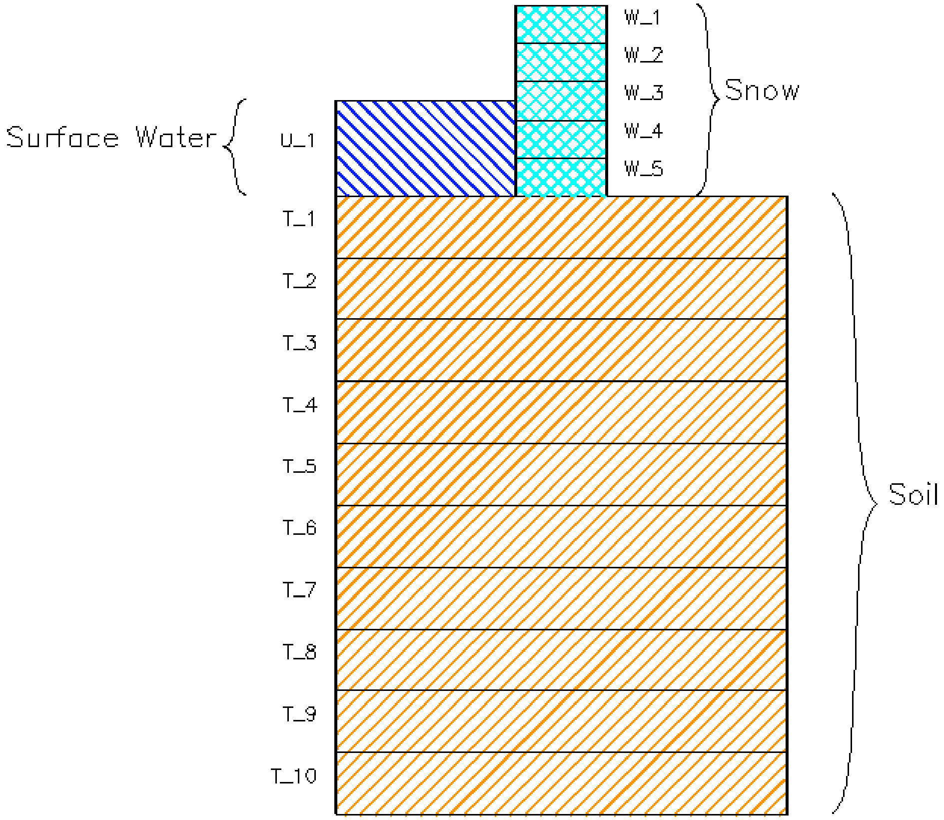
Little infiltration – precipitation rapidly returned to atmosphere

Larger infiltration events during winter – evaporation peaks during summer

Soil Moisture Redistribution

- Section 2.7.3 of the CLM Tech Note
- Moisture form of Richards equation with adaptive sub-stepping
- Water moves due to gravity and gradients in soil matric potential

Soil model



Treats processes such as:

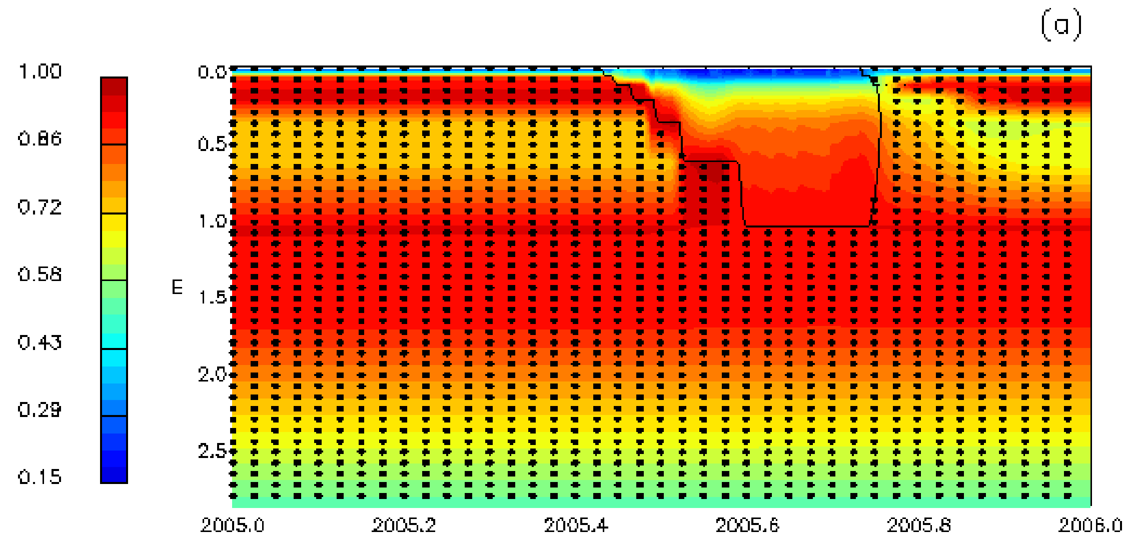
- Soil moisture redistribution
  - Infiltration
  - Darcy flow
  - Recharge

- Soil moisture phase change
- Soil temperature redistribution

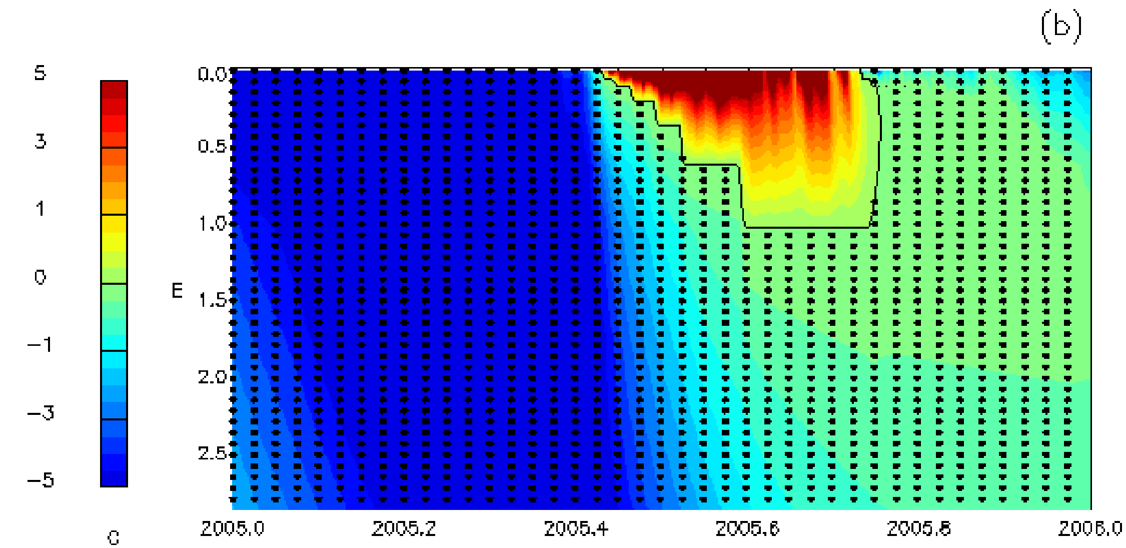
Default structure has 20 layers of variable thickness, spanning about 8 meters depth

- Thermal calculations use additional deep layers

a) Soil moisture (% saturation)



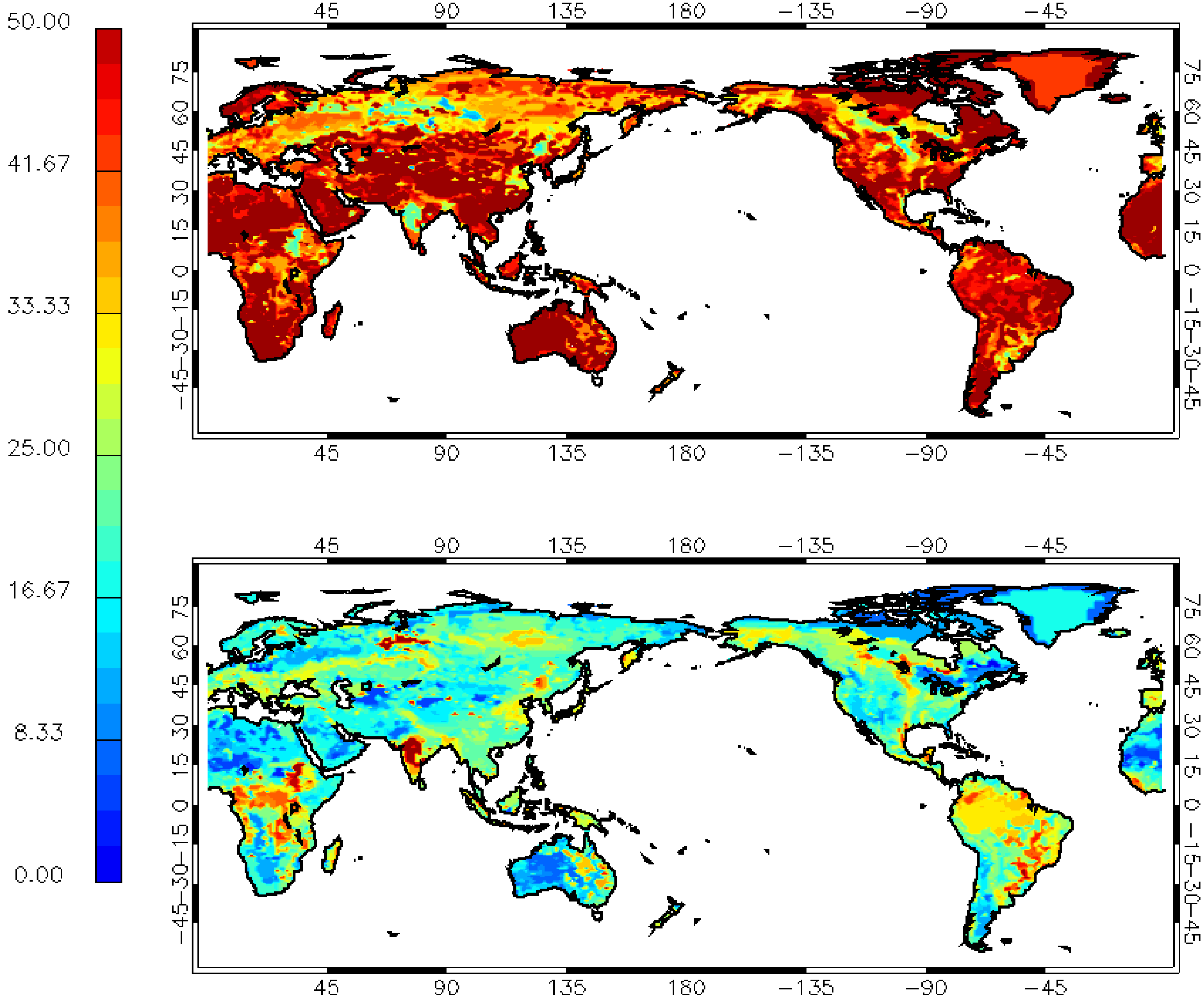
b) Soil temperature (∘C)



Stippling indicates frozen soil

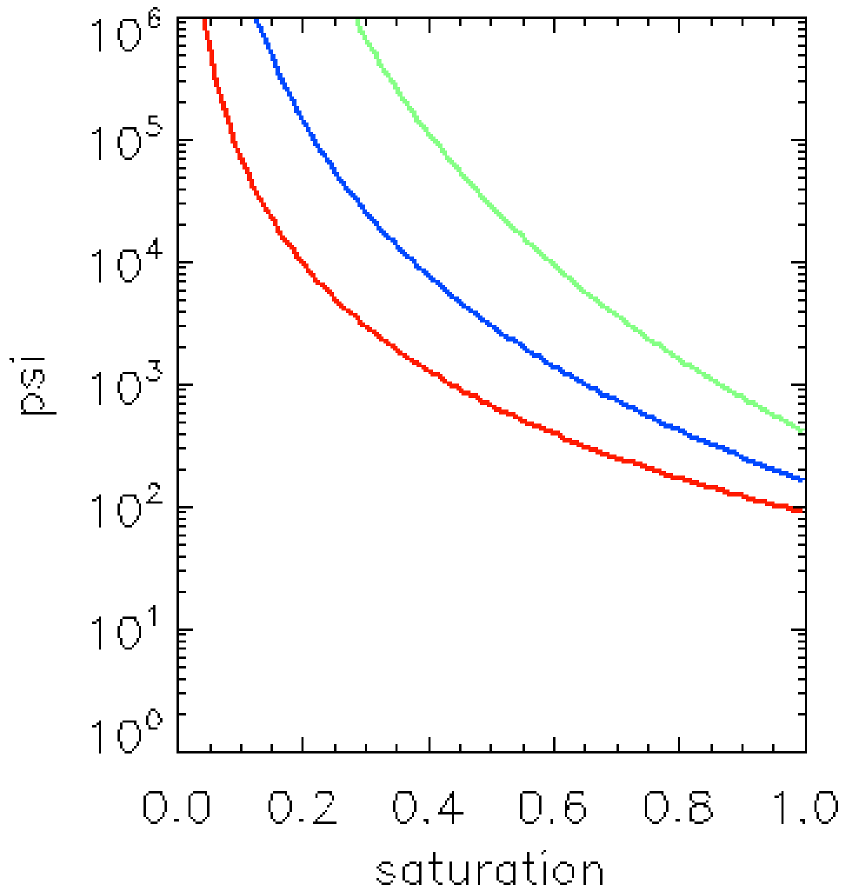
Percent sand

Percent clay

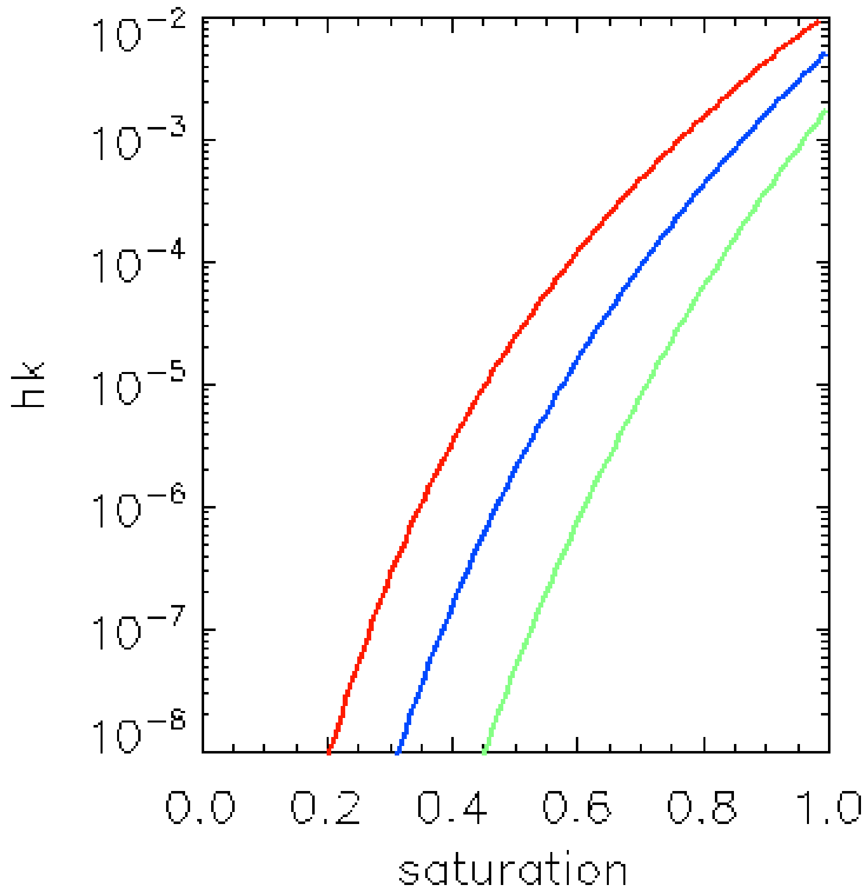


Soil Hydraulic Properties

Soil Matric Potential



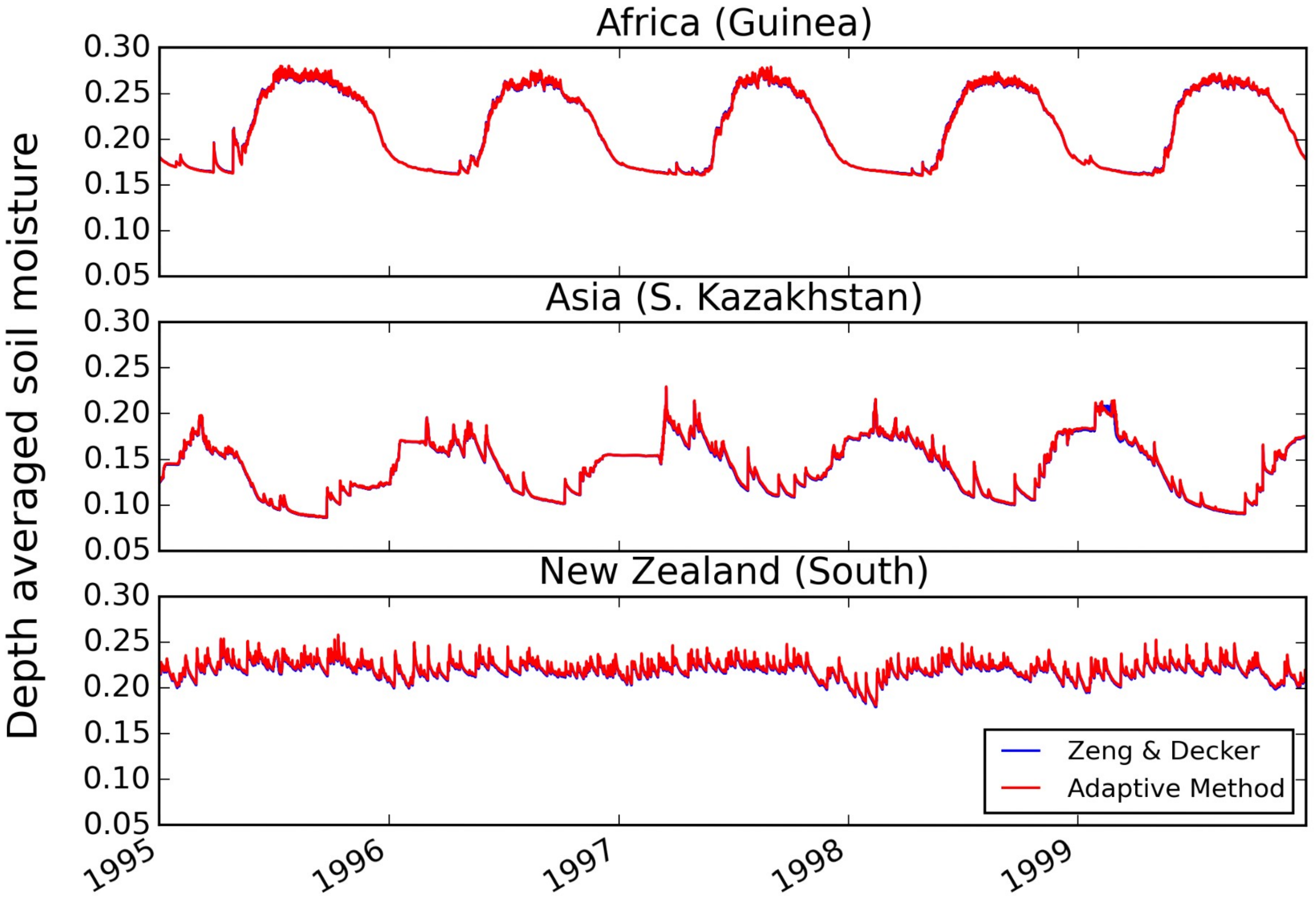
Soil Hydraulic Conductivity



Adaptive time stepping method for soil water distribution

Variable time step length depending on solution error

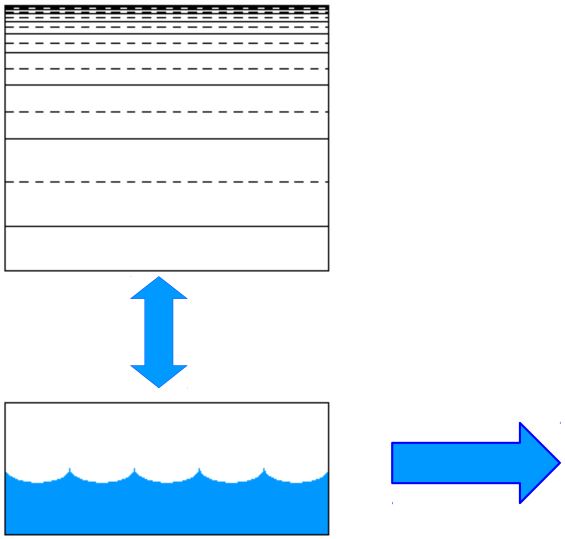
Eliminates numerical instabilities in Richards equation solution

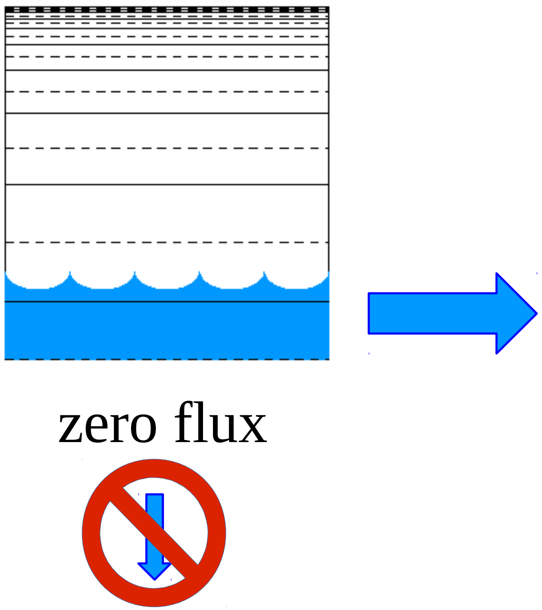


Slide courtesy J.Volk, U. Nevada

Groundwater and Water Table Dynamics

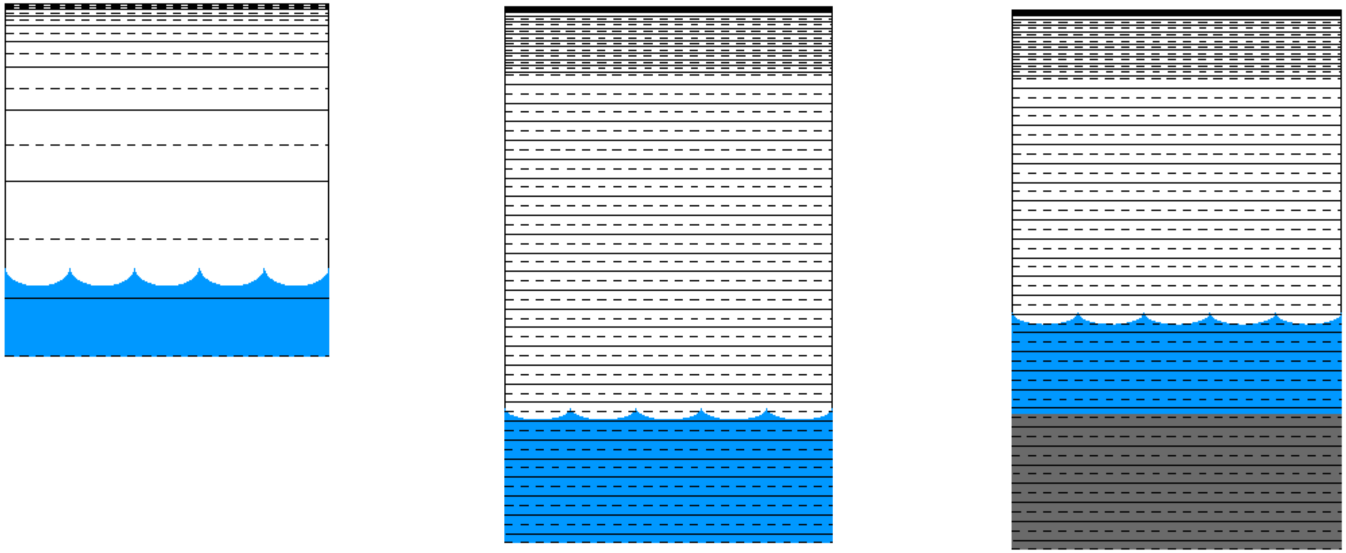
- bulk aquifer layer
- bedrock (zero vertical flux) lower boundary
- subsurface discharge depends on water table depth



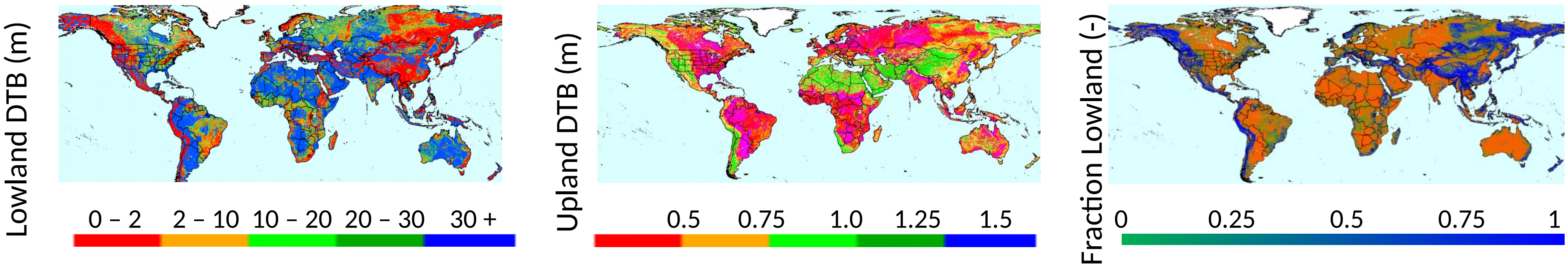


Soil Depth

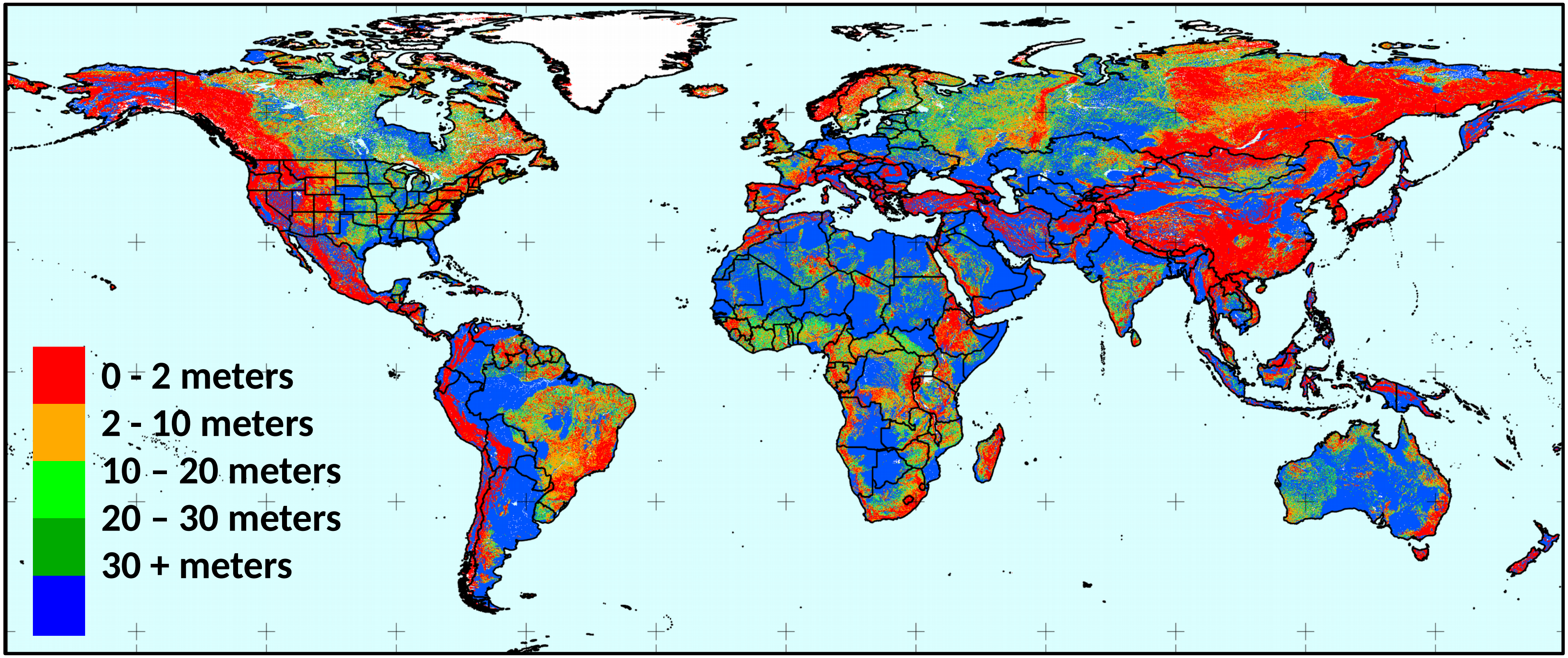
- deep soil / variable soil depth
- high vertical resolution soil



PRELIMINARY GLOBAL MAP OF DTB ESTIMATES



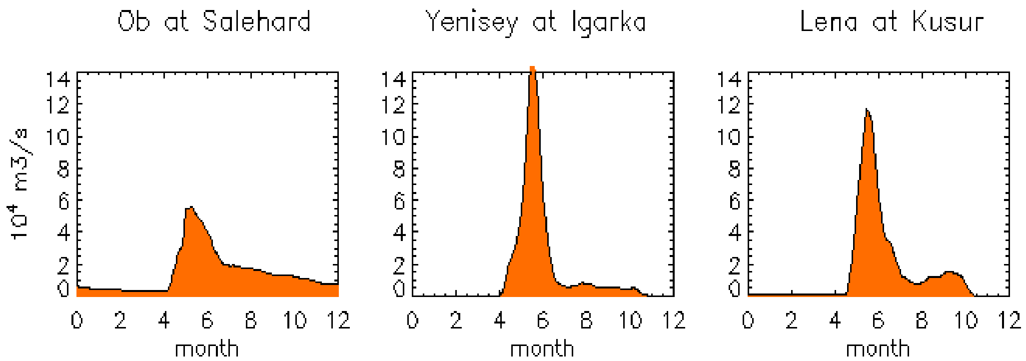
Overall Depth to Bedrock (~1 km resolution)

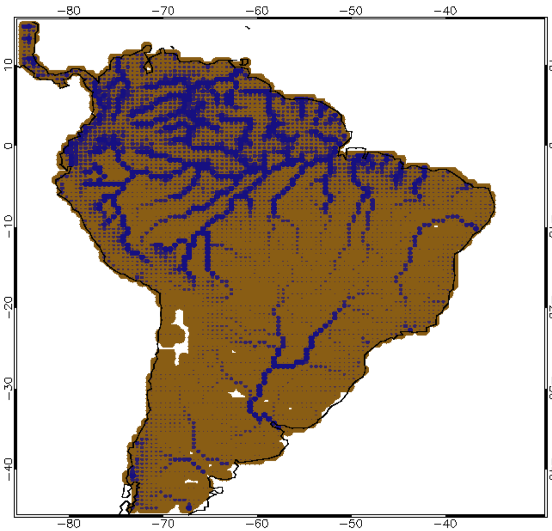


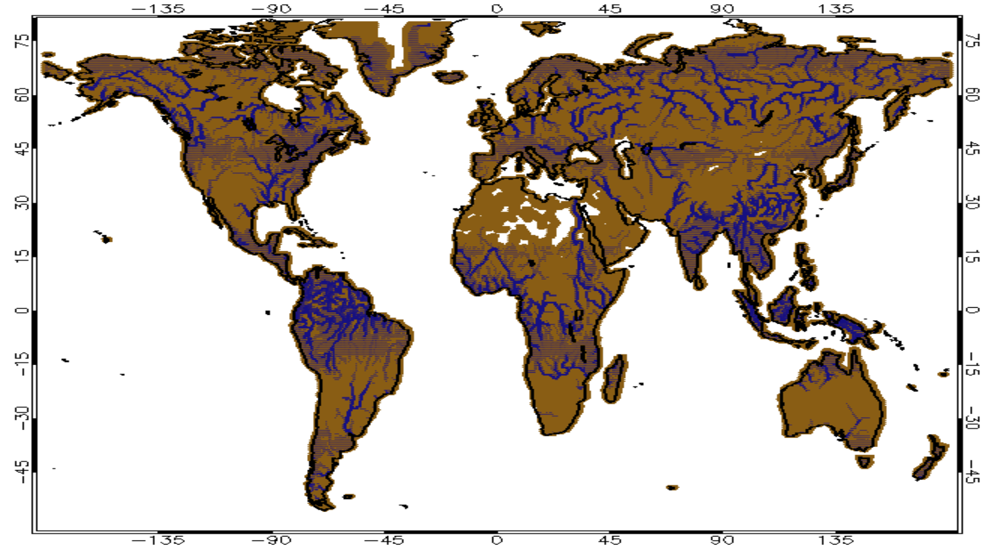
Slide courtesy M.Brunke, U. Arizona

River model

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

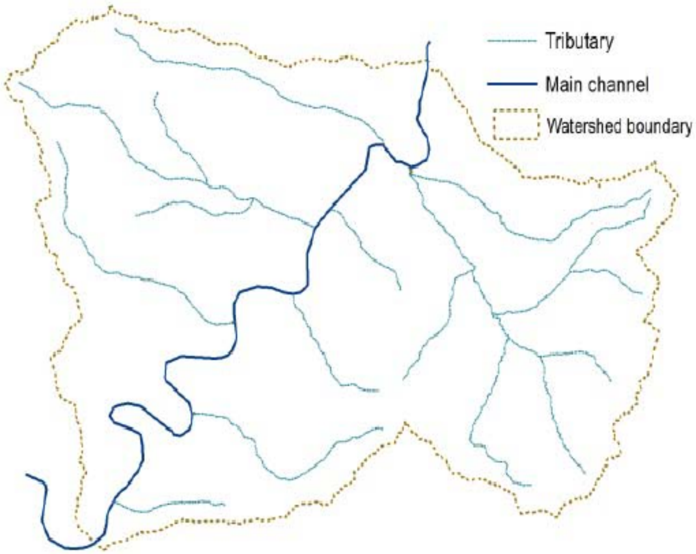




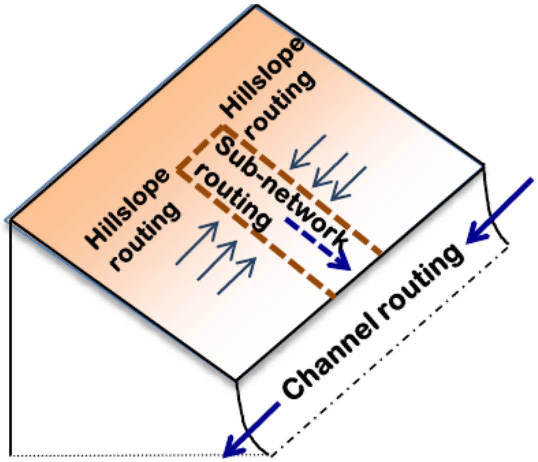


Model for Scale Adaptive River Transport

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)

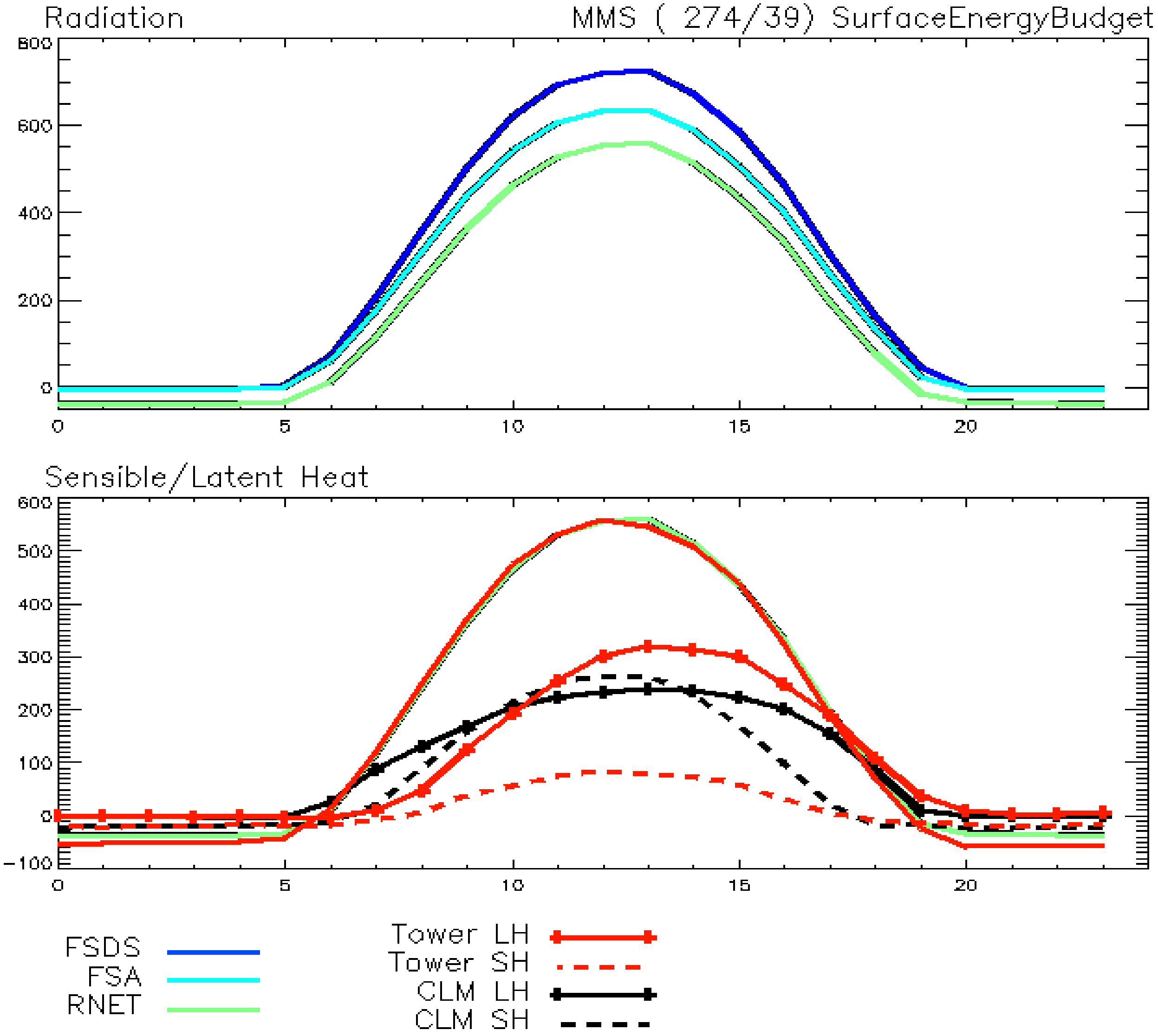
Model Validation Tools

Ideally, should be:

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

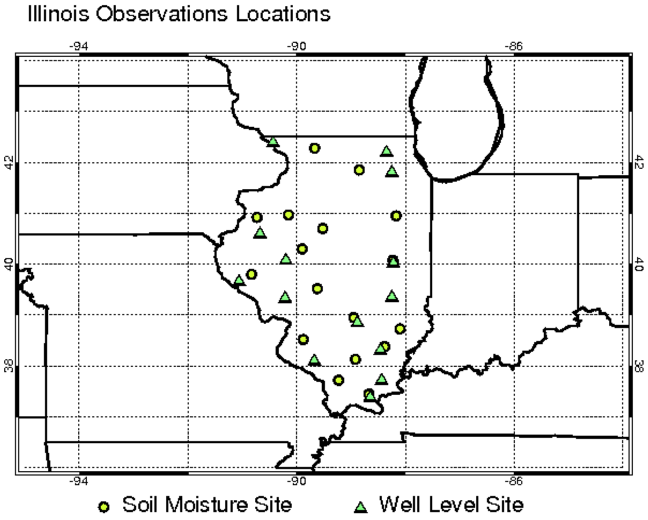
In reality, no datasets meeting these criteria exist...

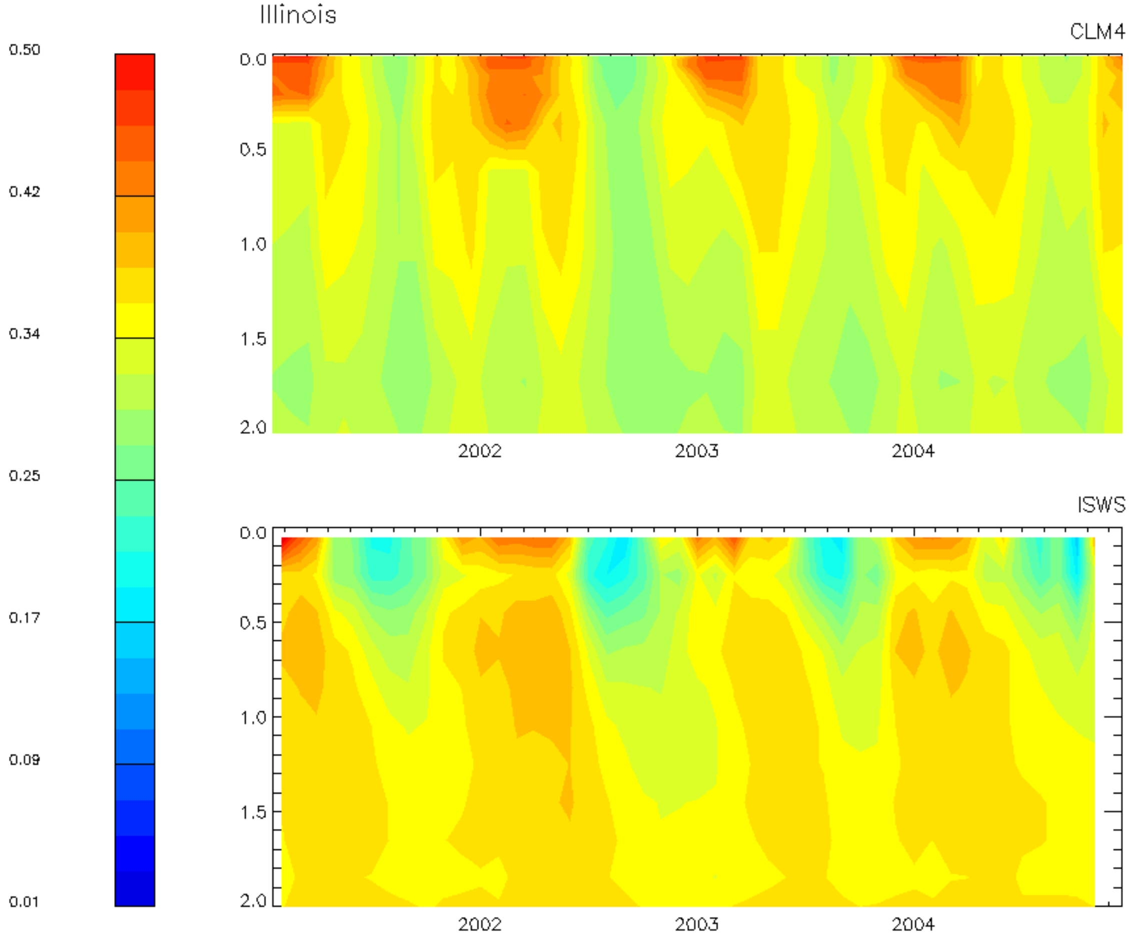
Flux Towers



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

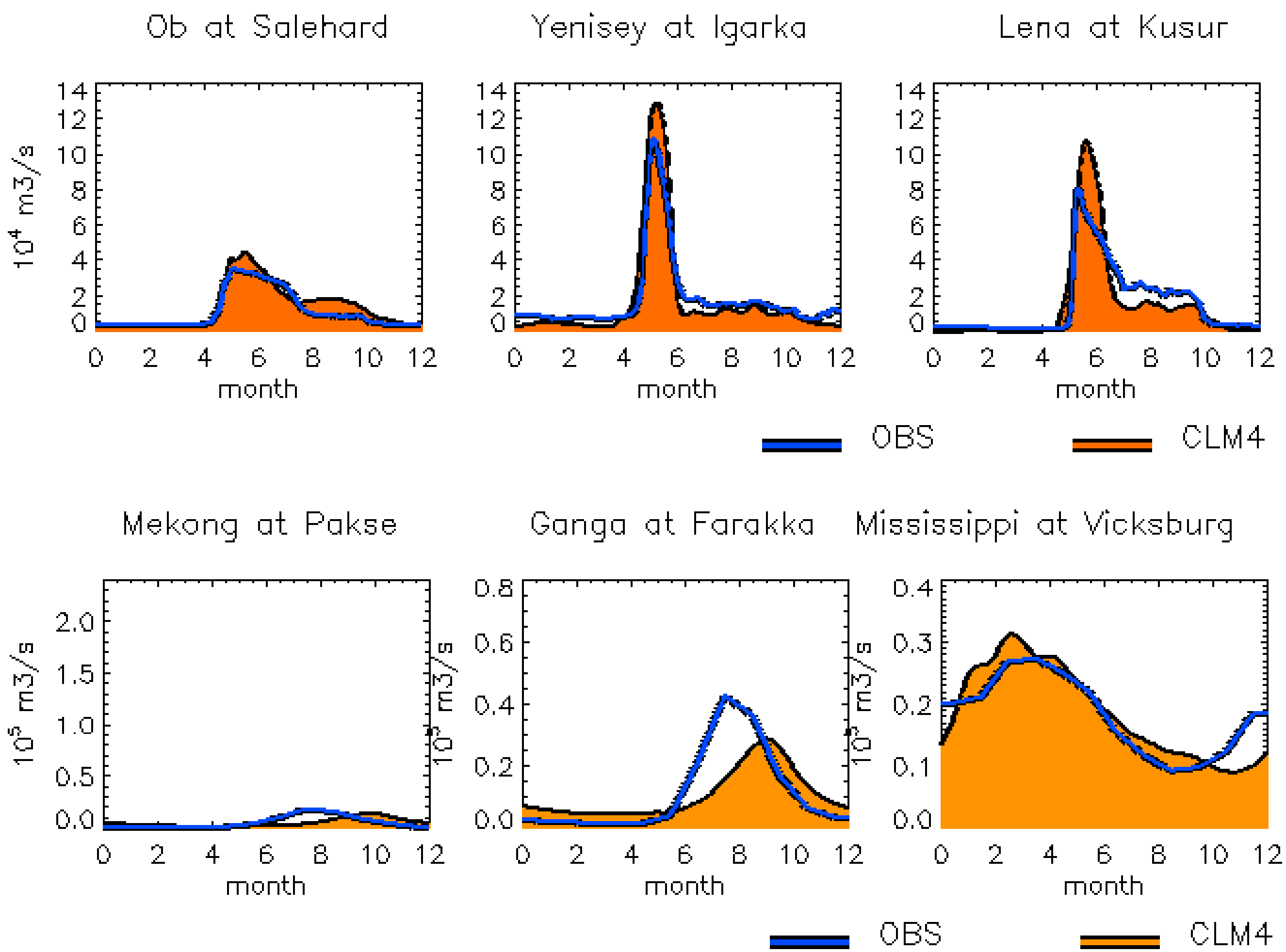
Soil Moisture Networks





Top panel: CLM soil moisture
Bottom: Observed soil moisture

River Discharge

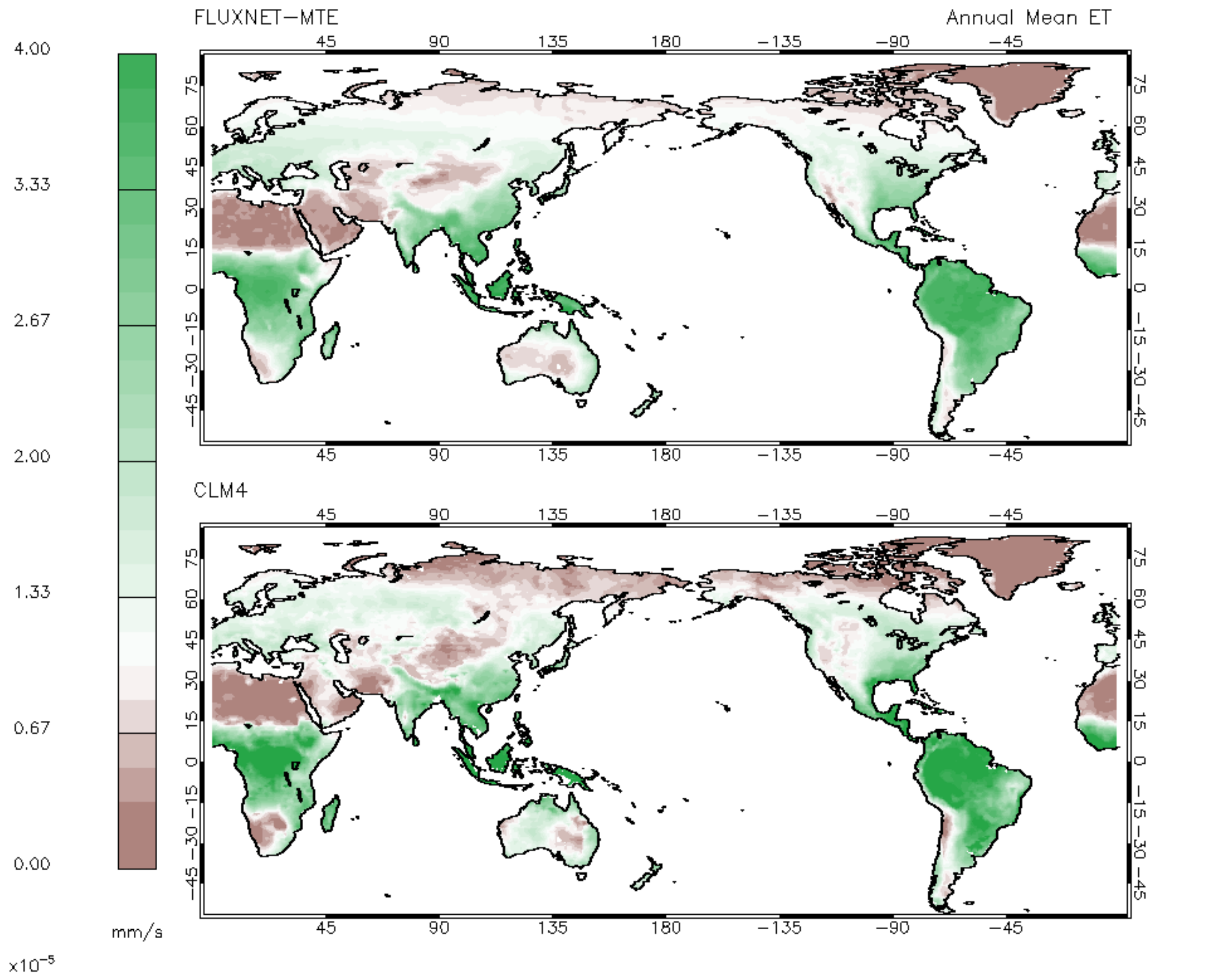


Gridded Model-Data Synthesis Products

Examples: FLUXNET-MTE, FLUXCOM

Top panel: FLUXNET-MTE
Bottom: CLM

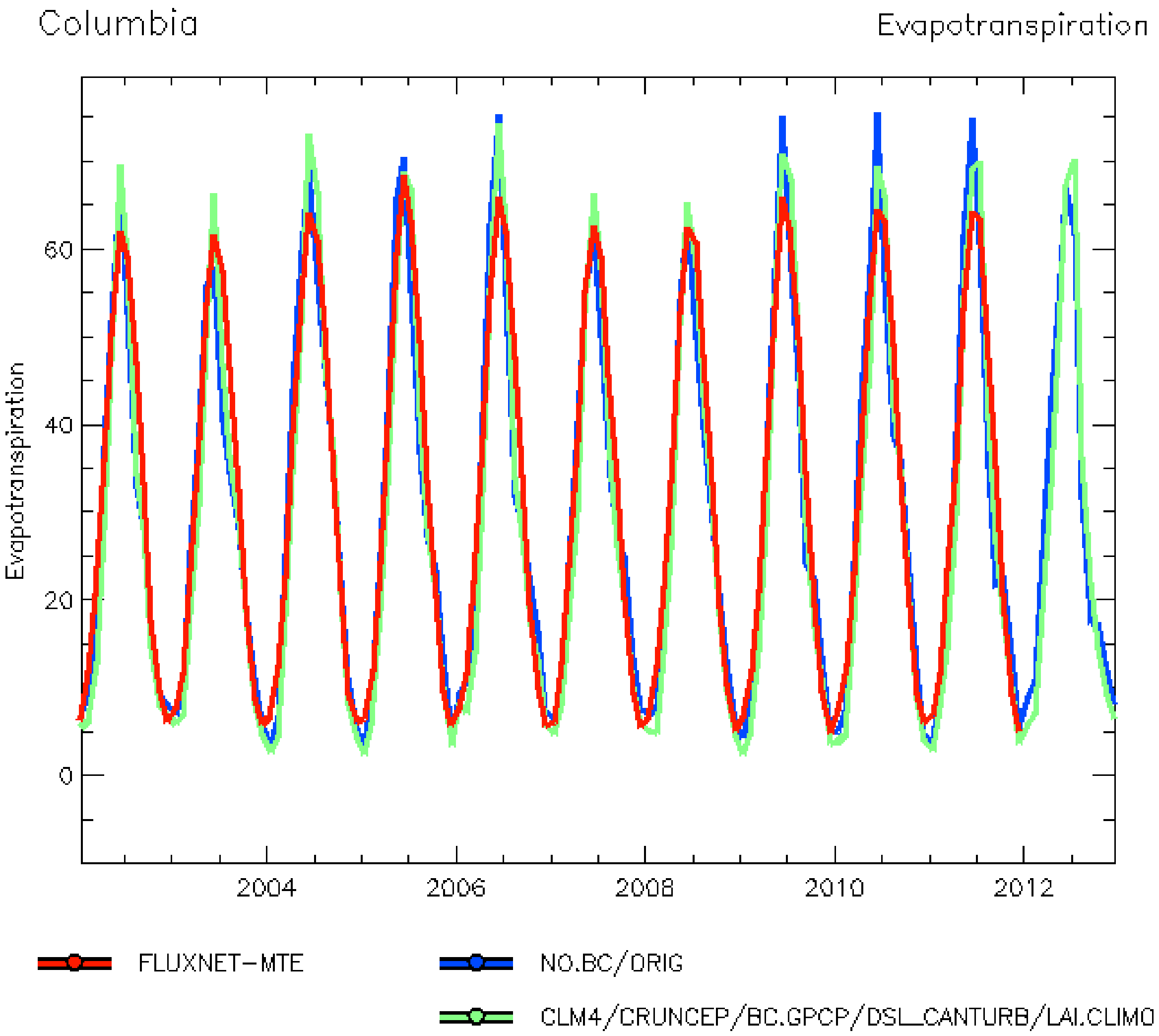
Annual Mean Evapotranspiration



FLUXNET-MTE

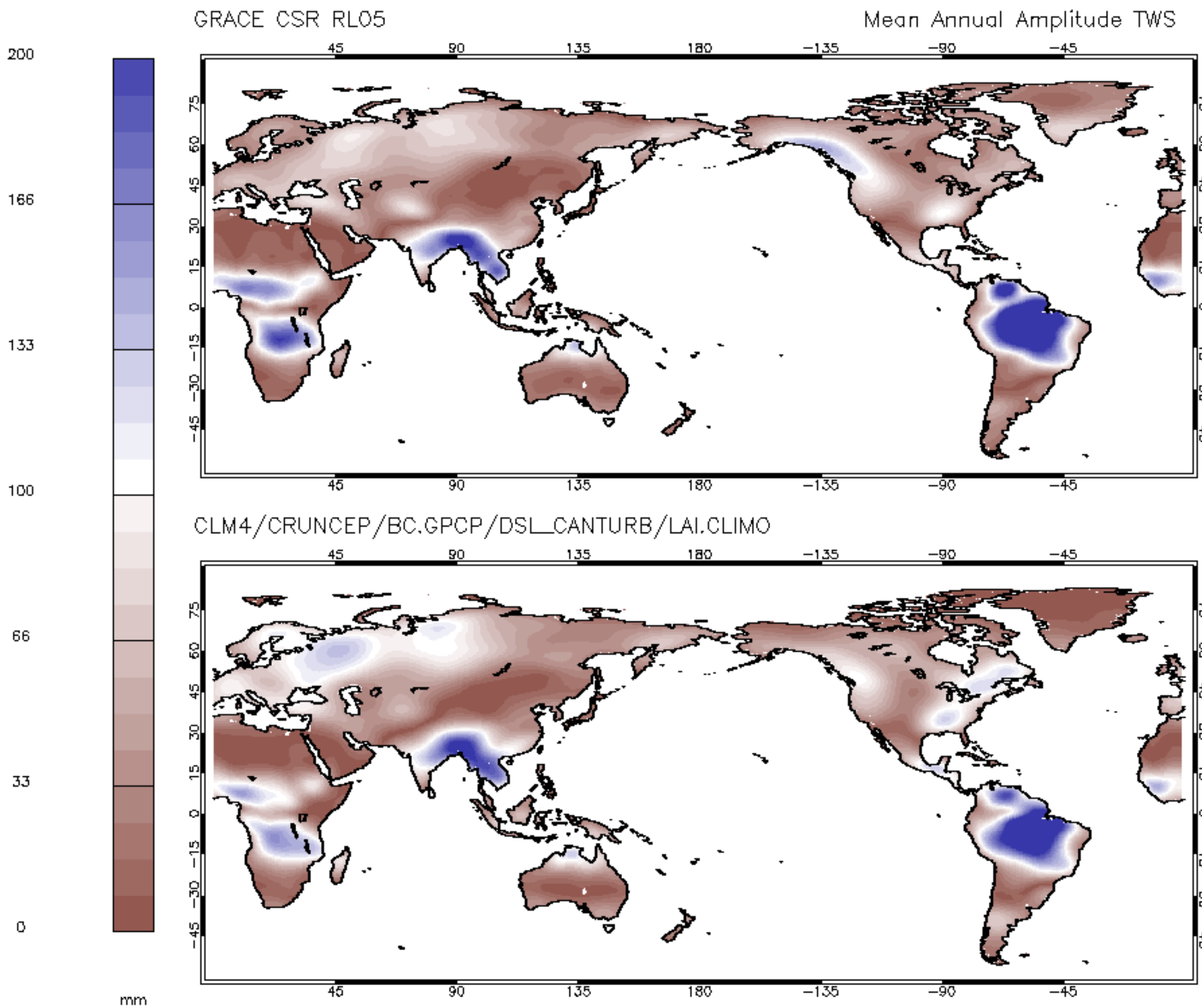
Columbia River Basin
Evapotranspiration

Red: FLUXNET-MTE
Blue/Green: CLM



GRACE Total Water Storage

Mean Annual Amplitude of Total Water Storage

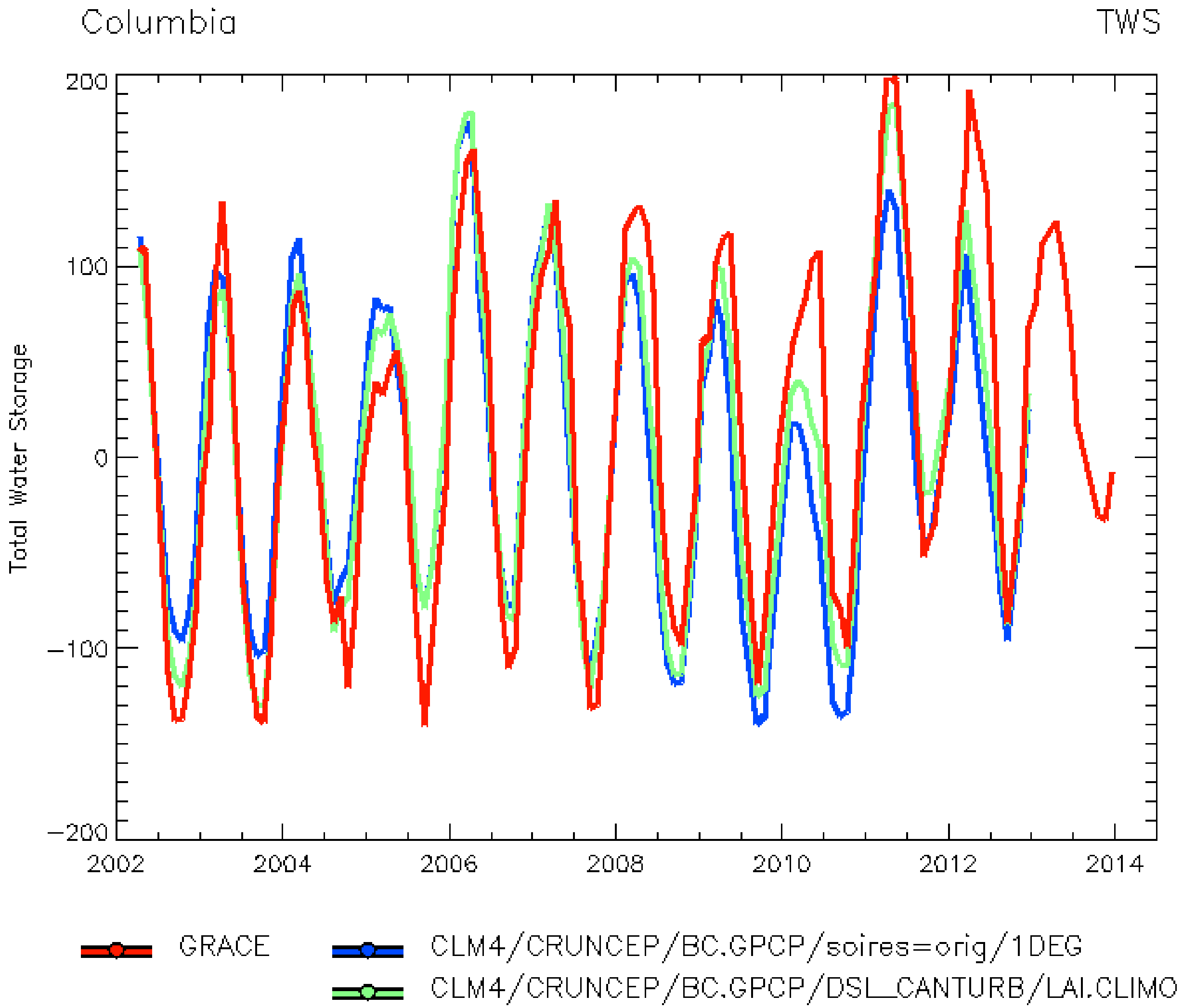


Top panel: GRACE
Bottom: CLM

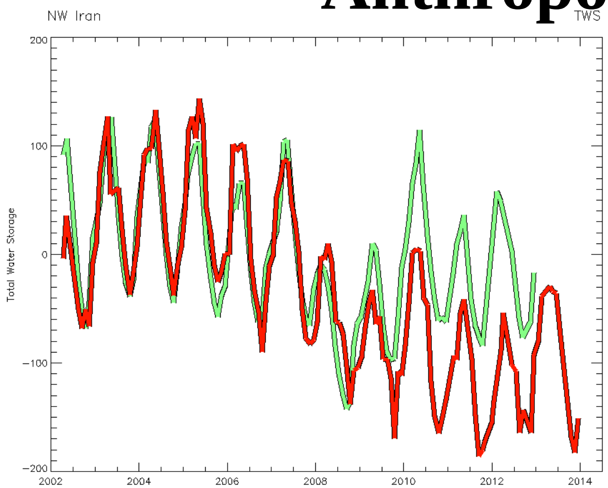
GRACE Total Water Storage

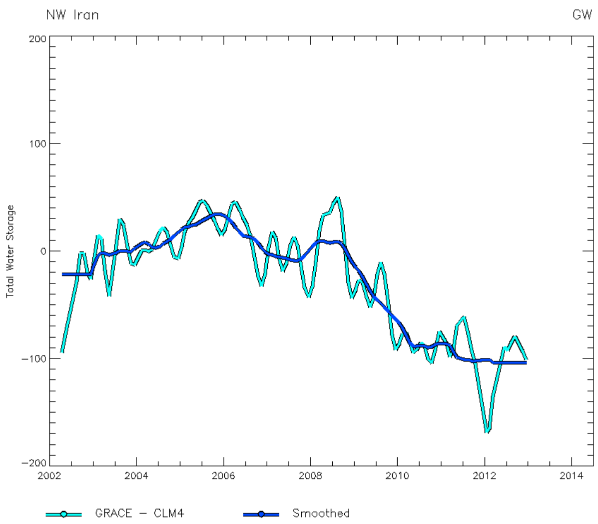
Columbia River Basin Total Water Storage

Red: GRACE
Blue/Green: CLM



CLM Application Example: Anthropogenic Groundwater Withdrawal



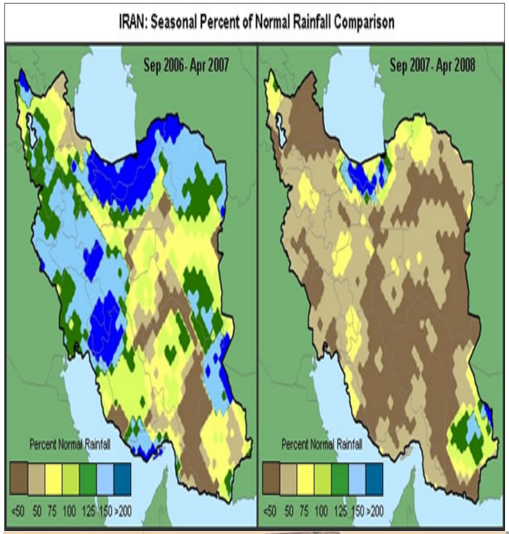


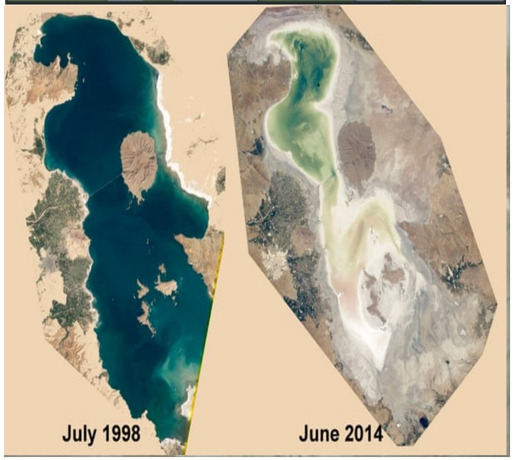
Human-induced groundwater changes can be estimated by removing the CLM estimate of TWS from the GRACE estimate of TWS

GRACE TWS

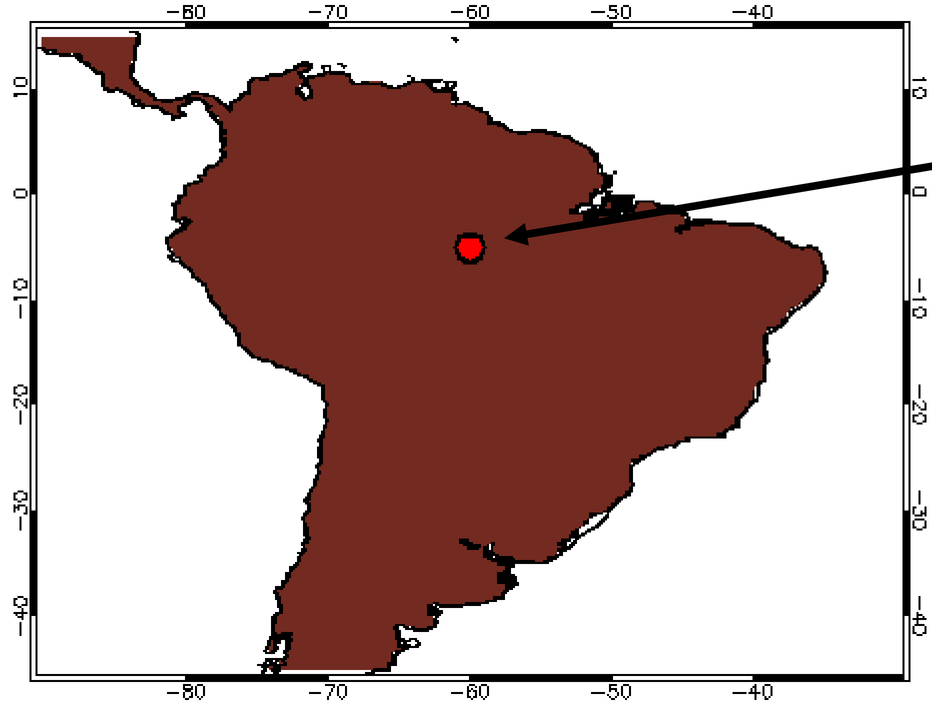
CLM TWS

Groundwater



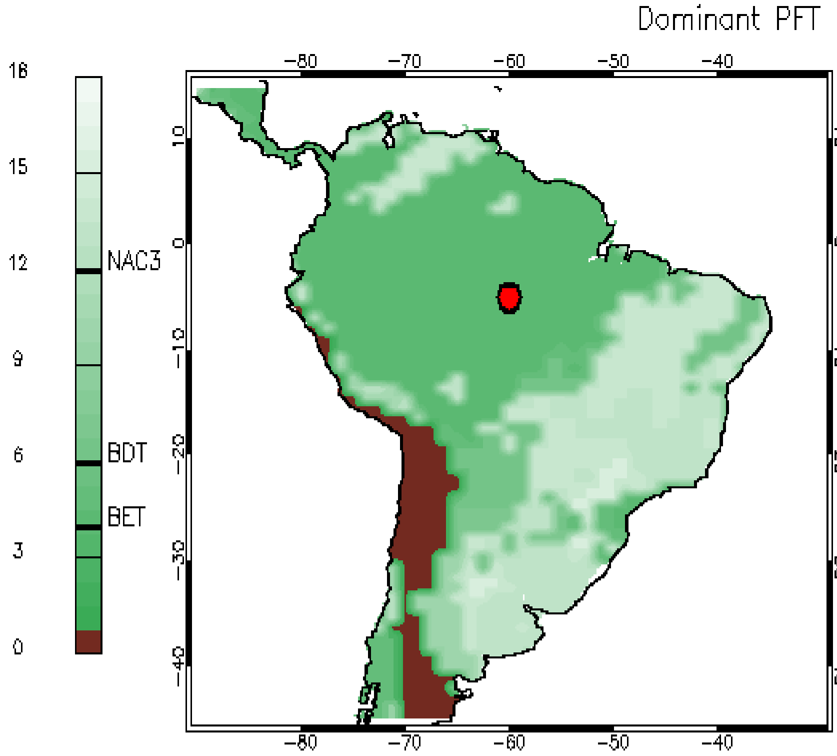


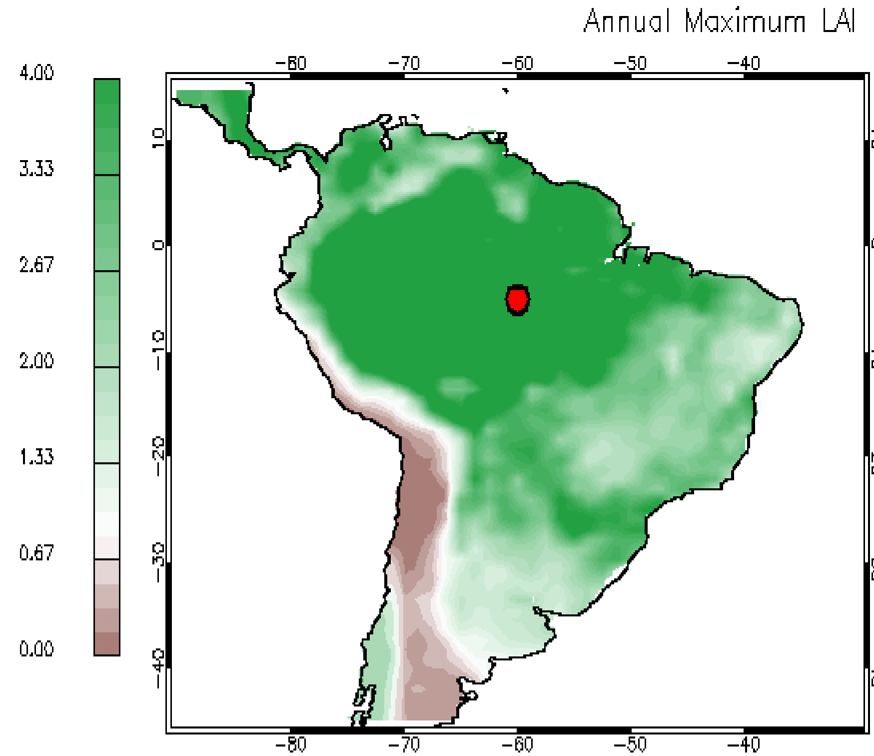
Example I
Effects of Parameter Change



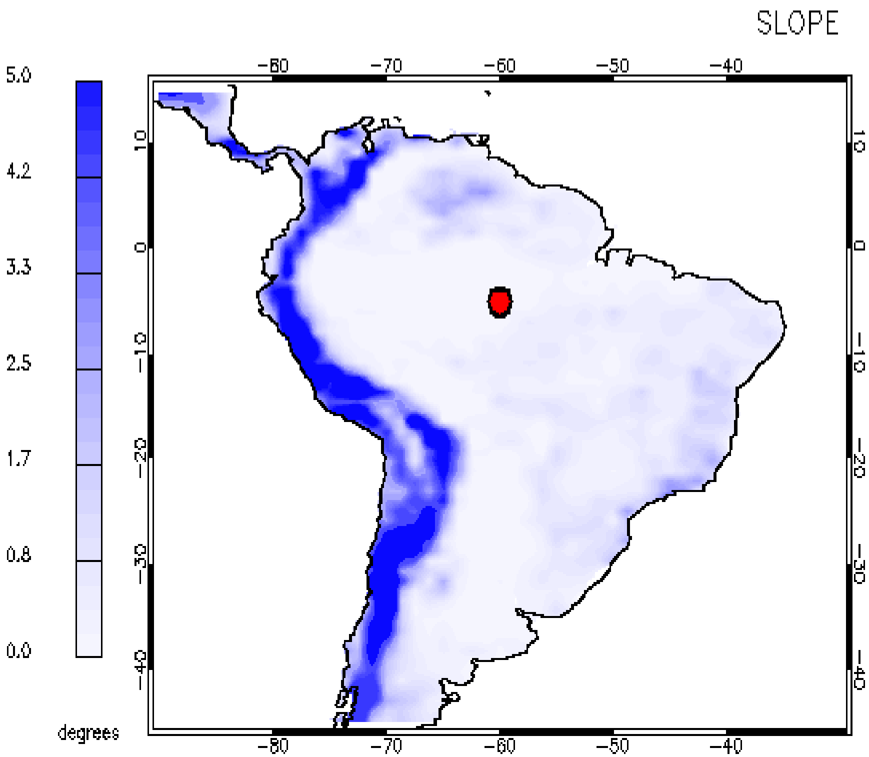
60W / 5S

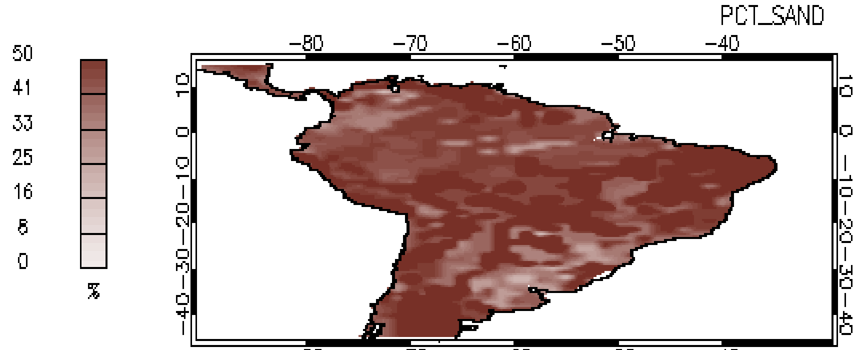
Hydrologically Relevant Surface Data

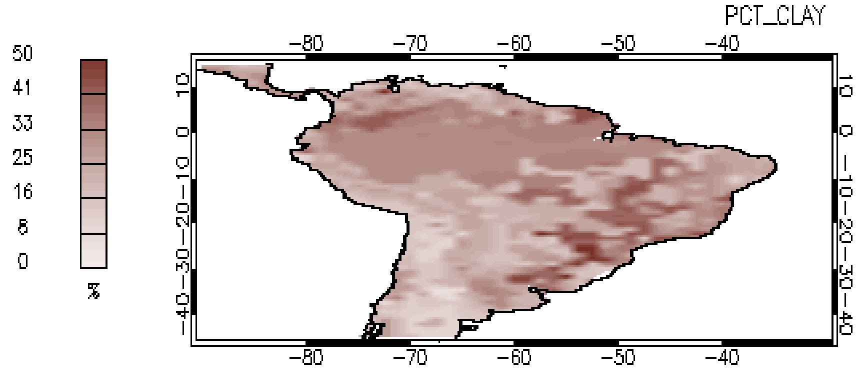




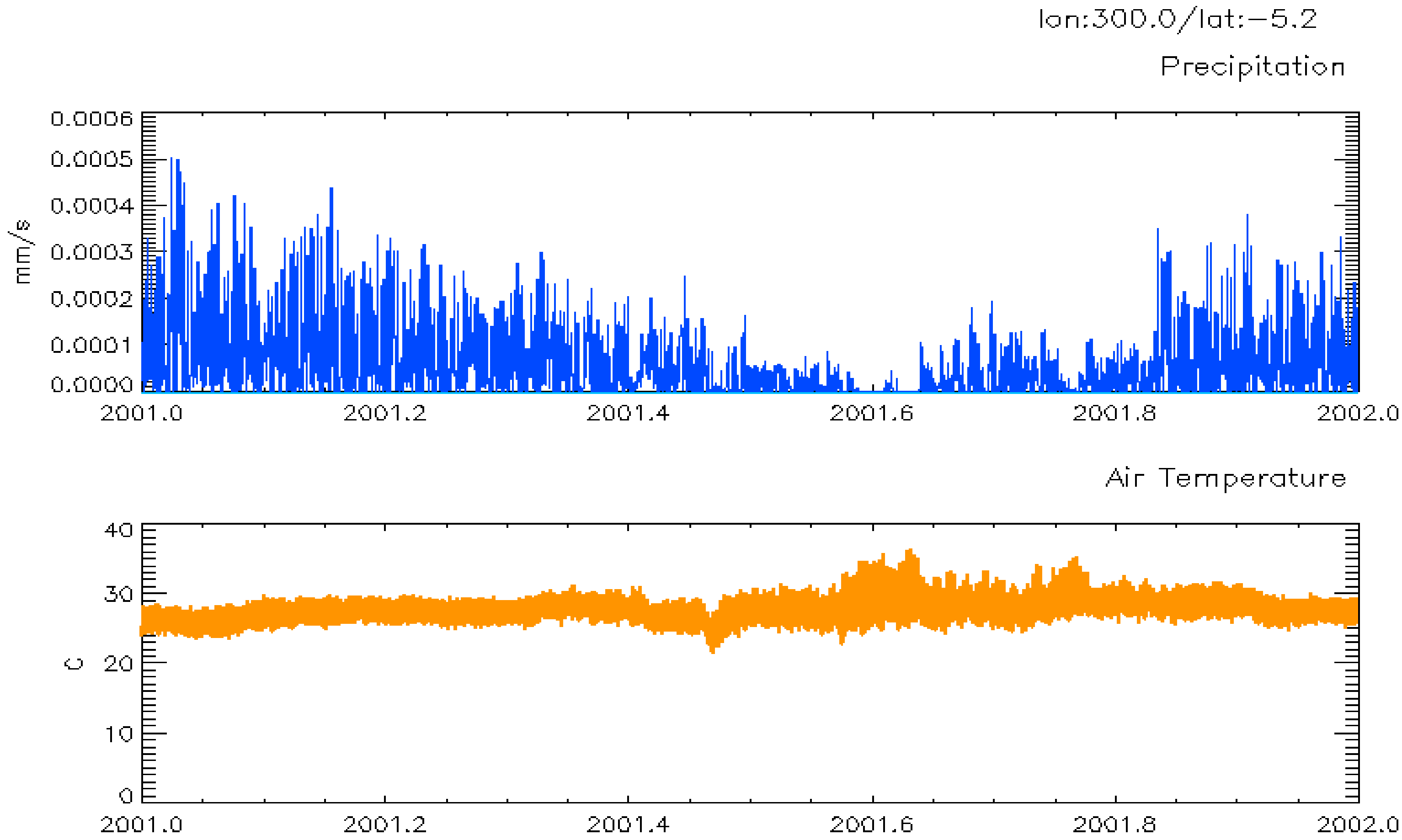
Hydrological Relevant Surface Data



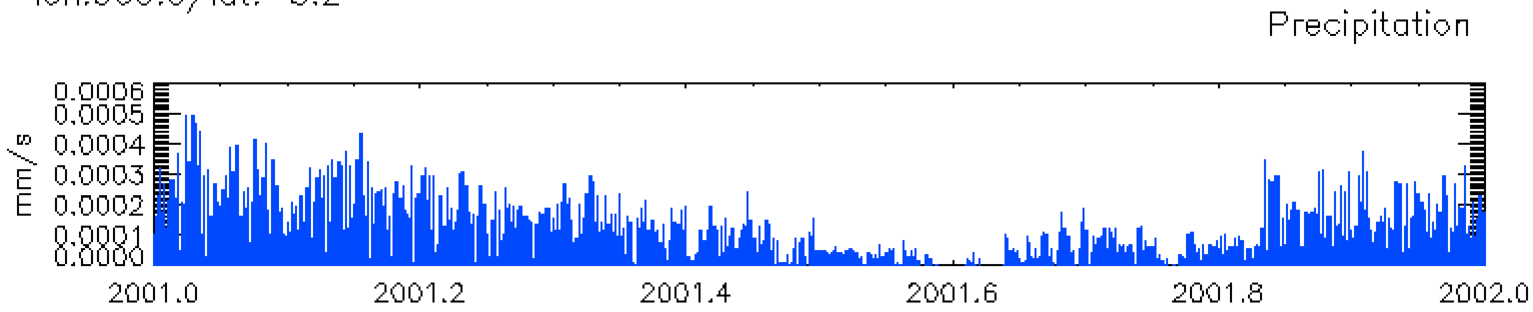


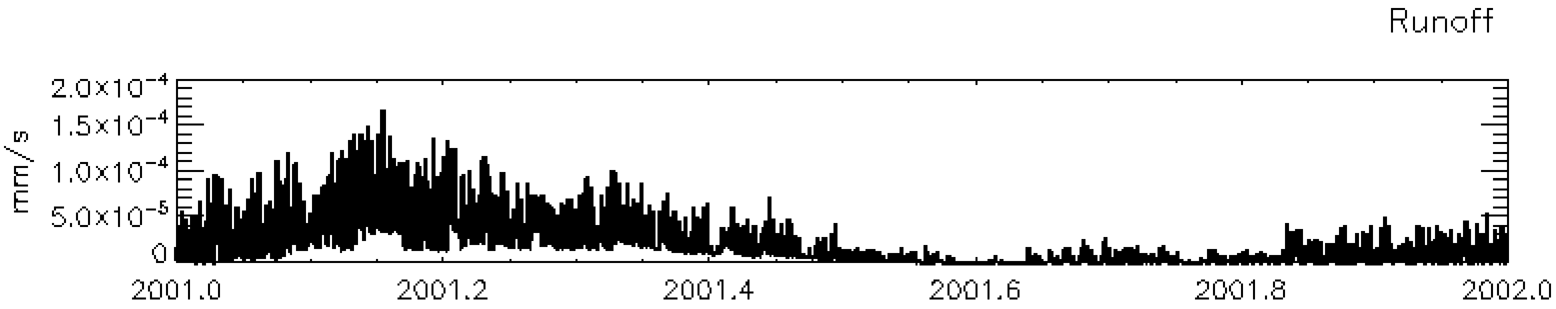


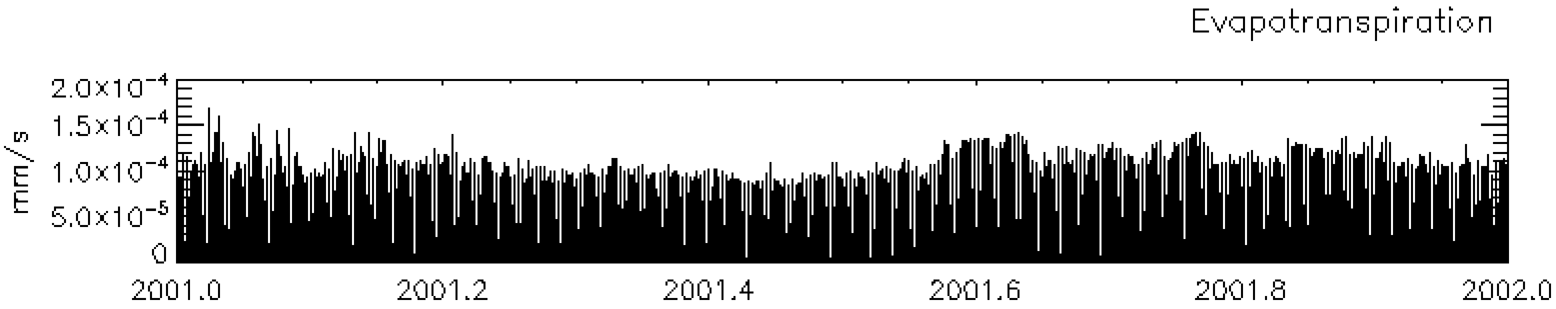
Time Series

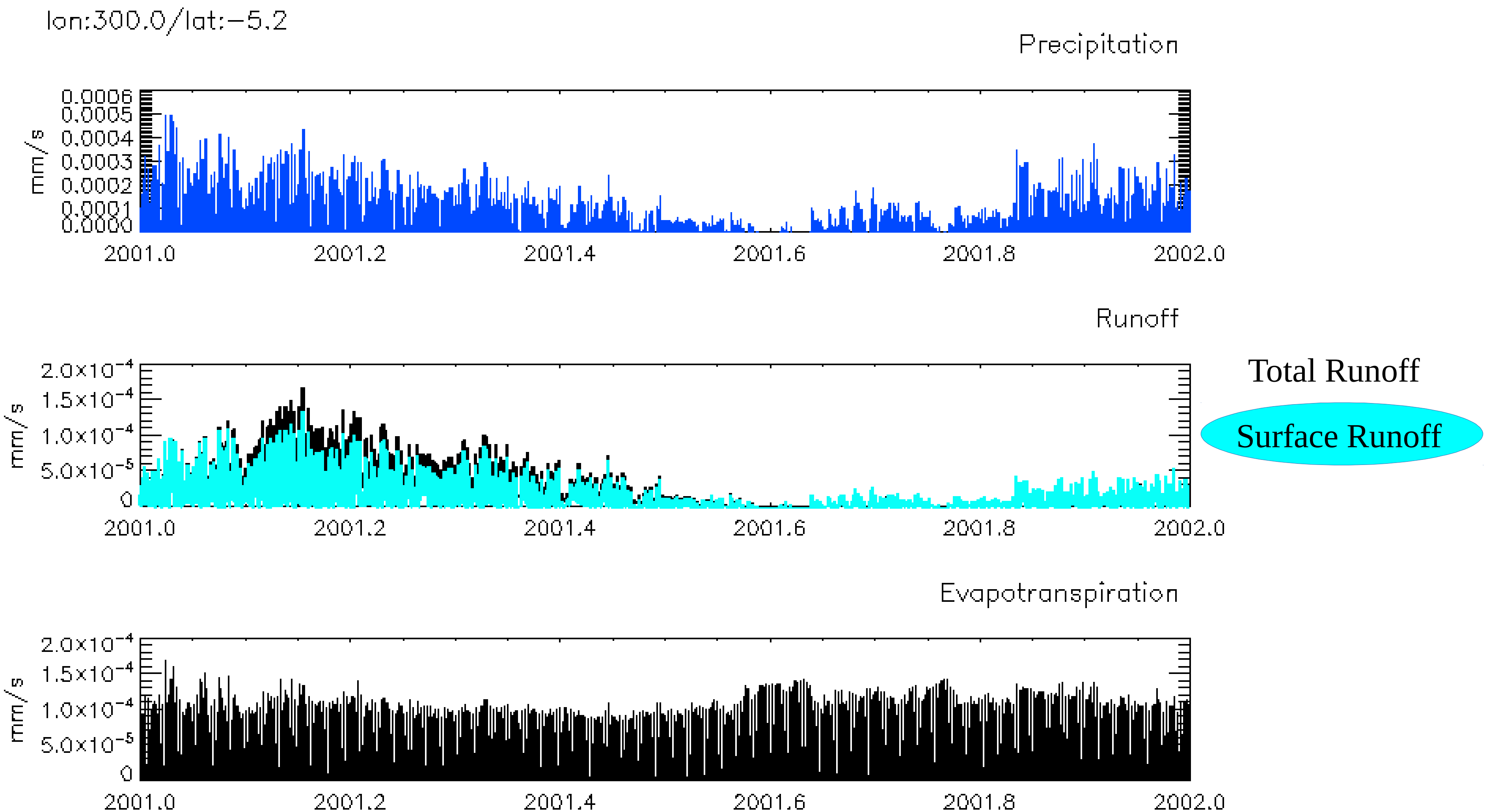

lon:300.0/lat:−5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Air Temperature
C
40
30
20
10
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0

lon:300.0/lat:−5.2

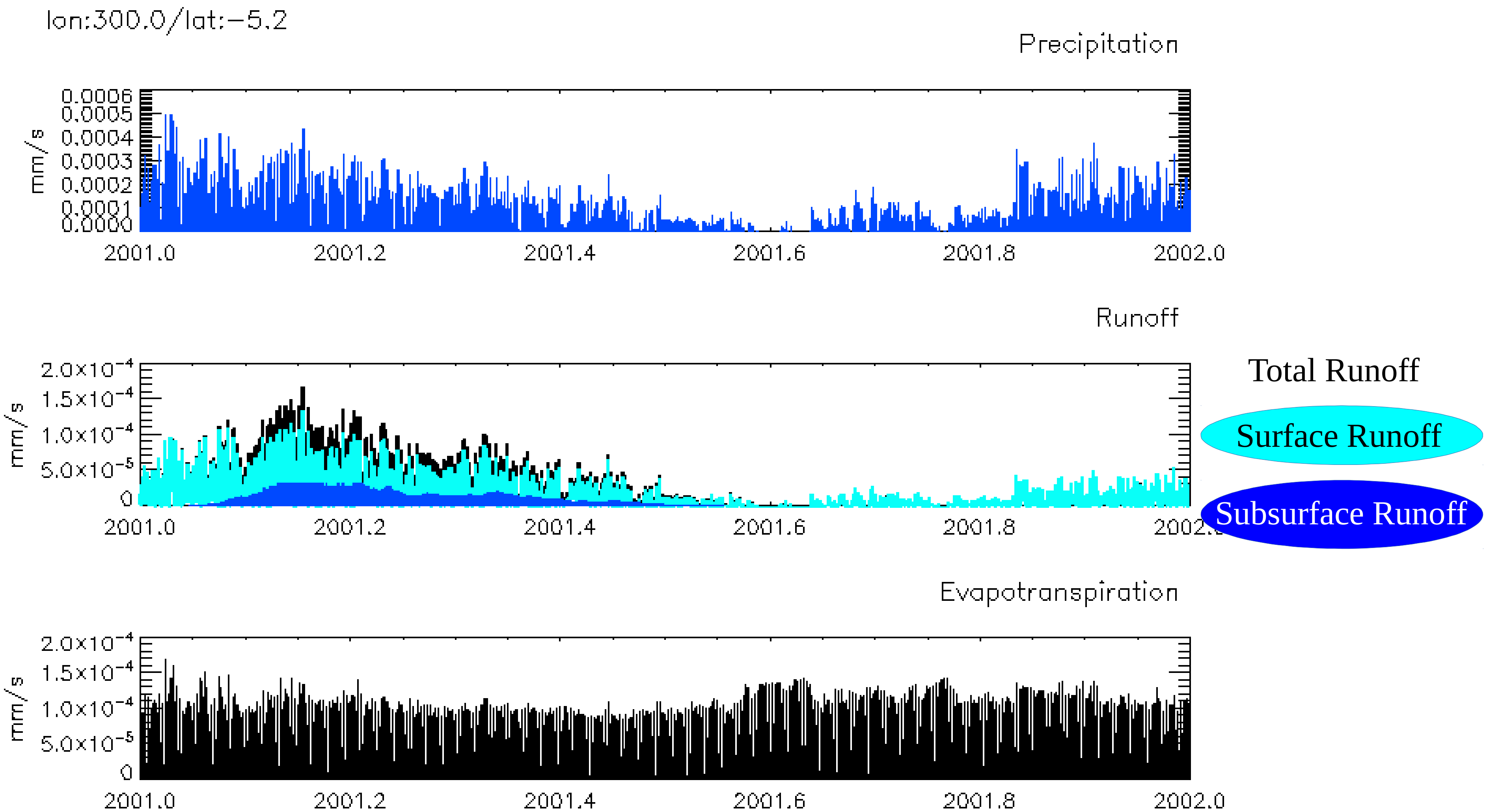




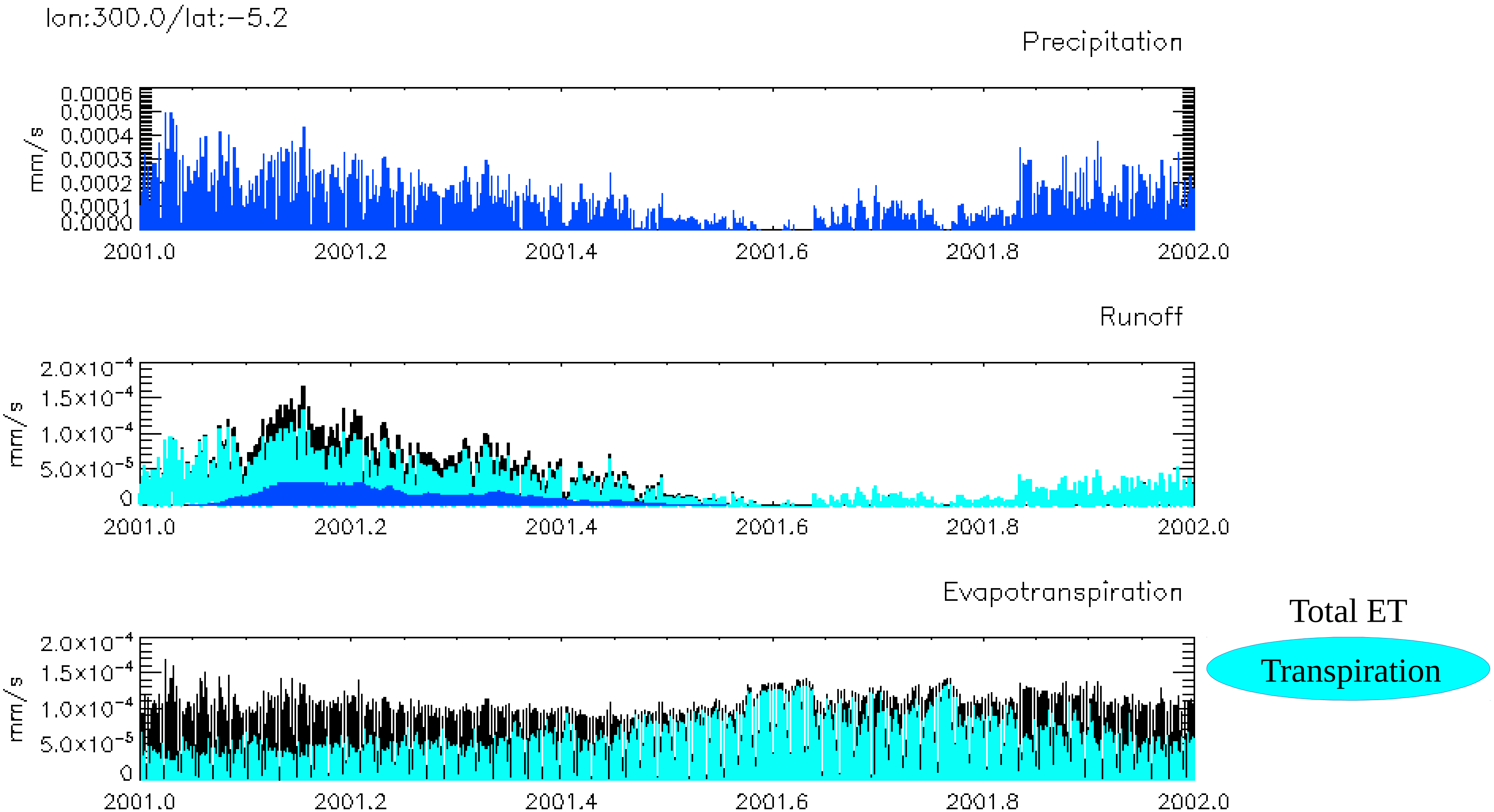


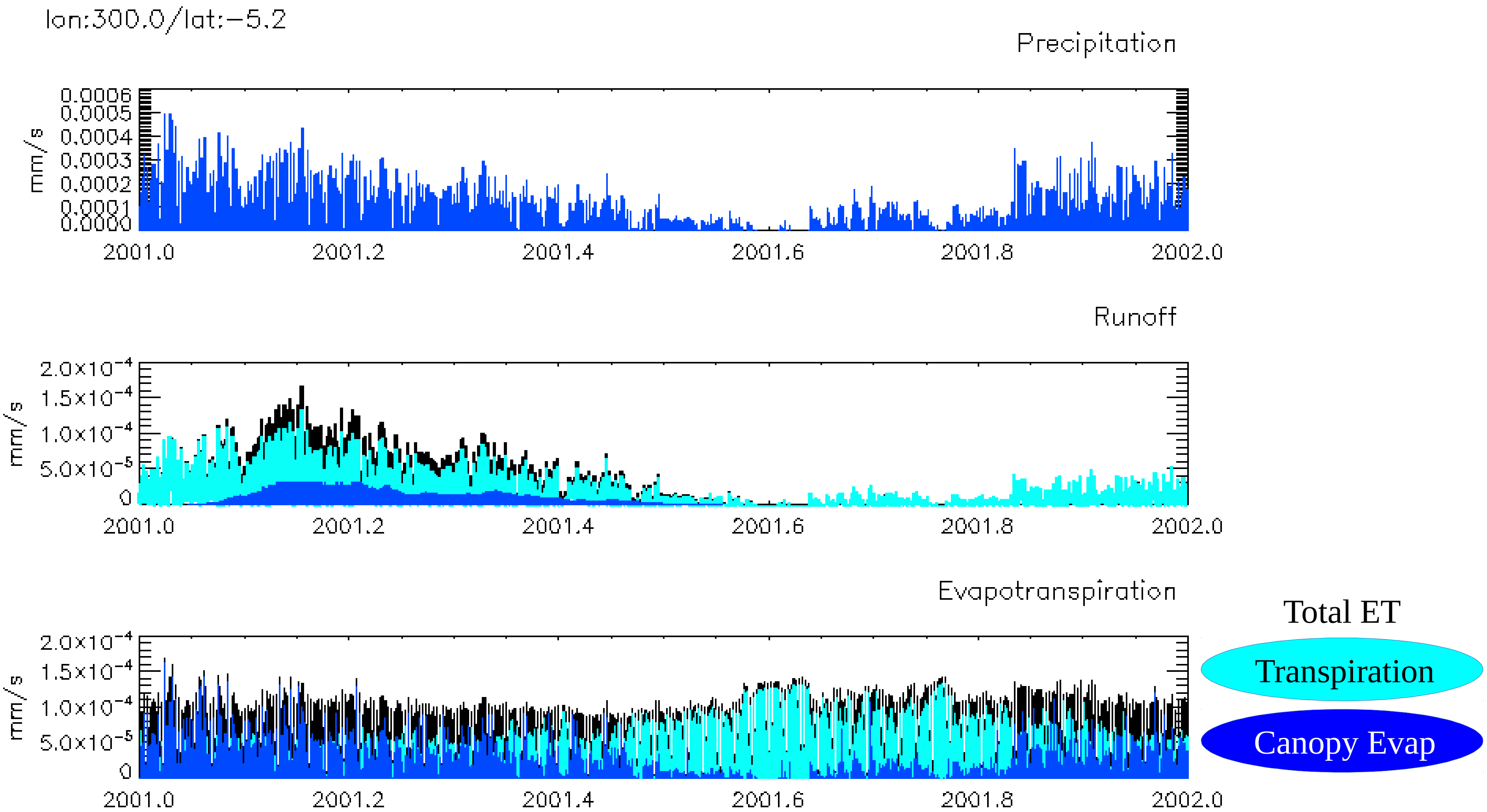


lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
Total Runoff
Surface Runoff
mm/s
2.0x10^-4
1.5x10^-4
1.0x10^-4
5.0x10^-5
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Evapotranspiration
mm/s
2.0x10^-4
1.5x10^-4
1.0x10^-4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

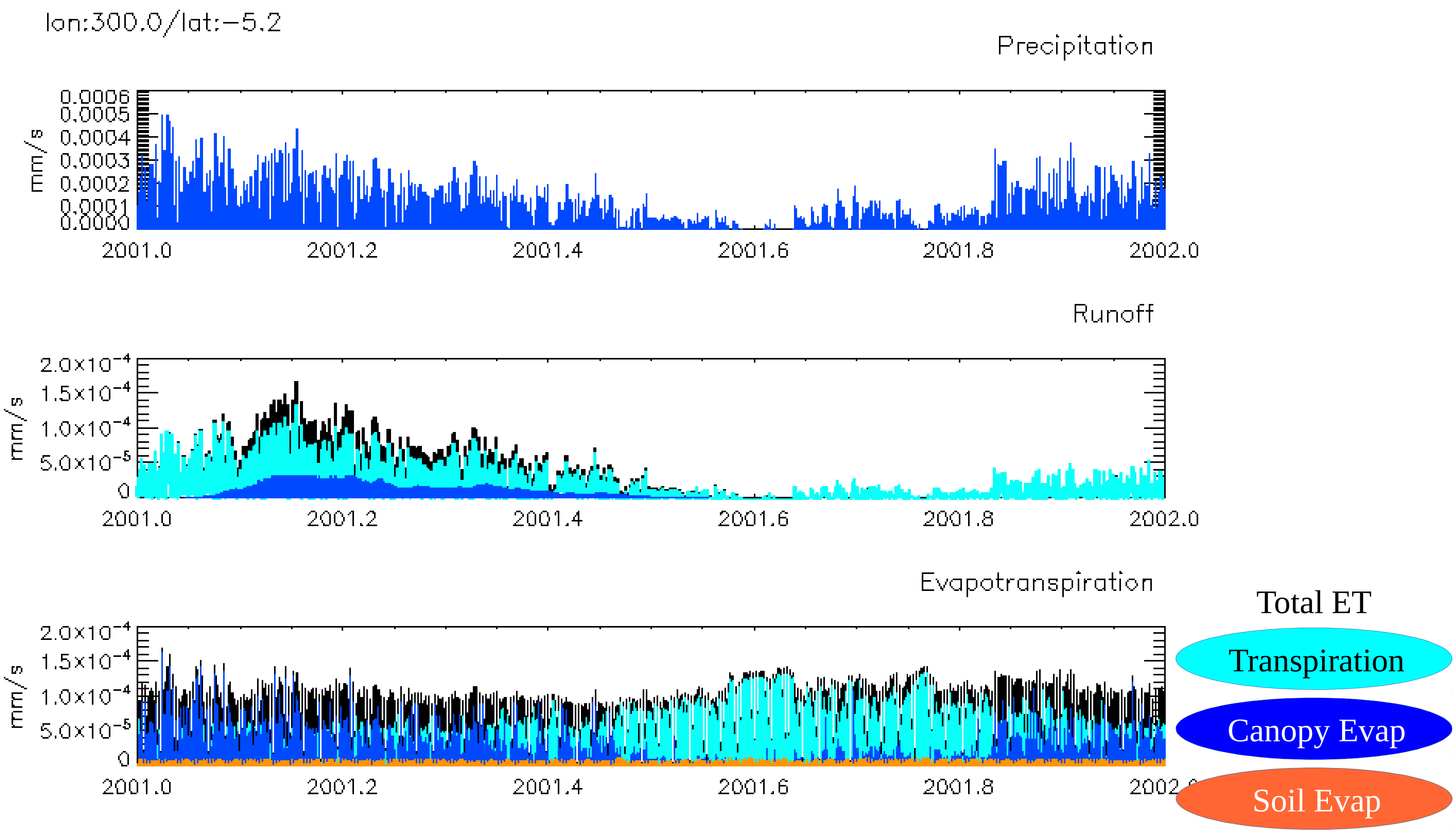


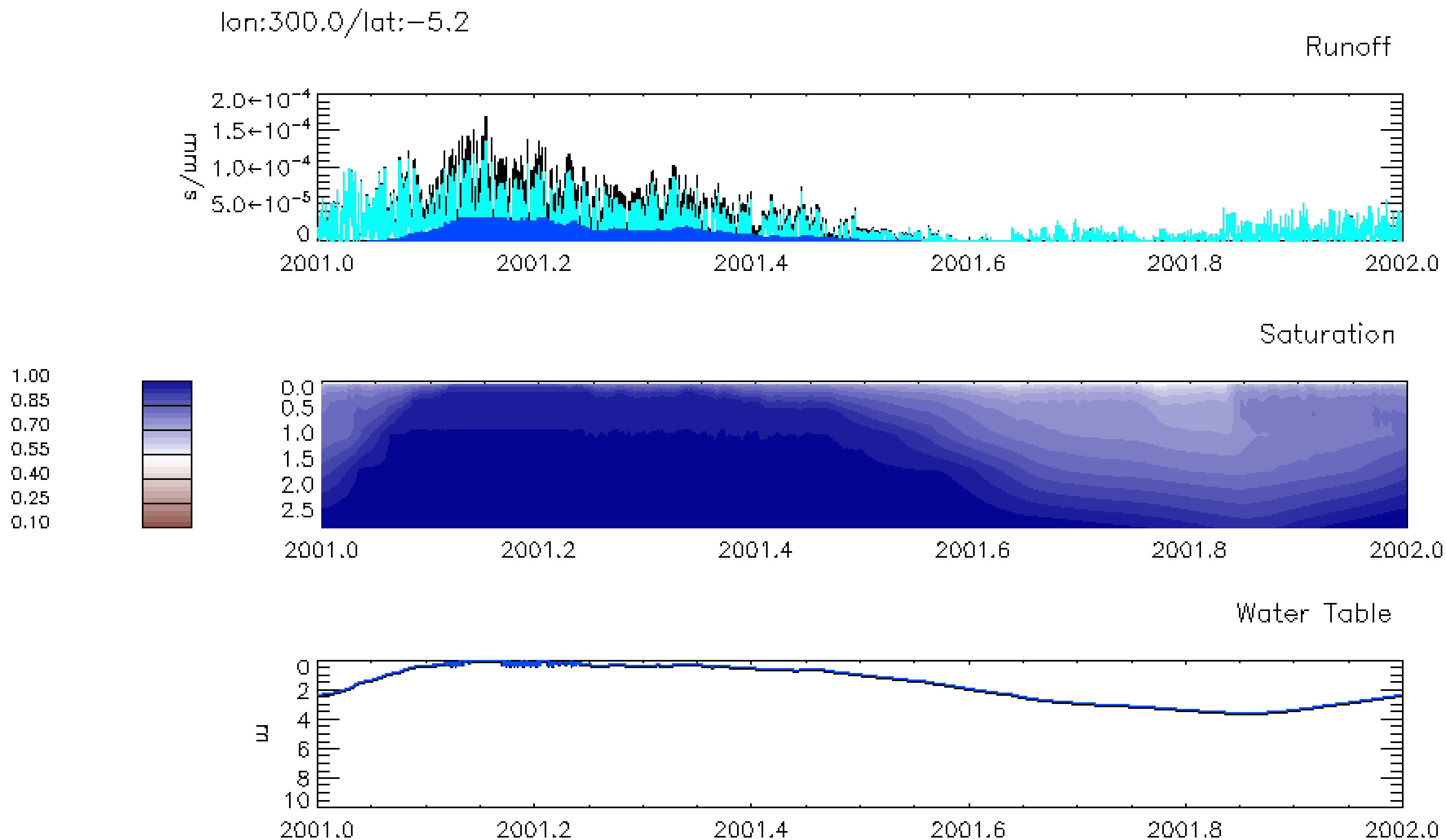
lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0
Total Runoff
Surface Runoff
Subsurface Runoff
Evapotranspiration
mm/s
2.0x10⁻⁴
1.5x10⁻⁴
1.0x10⁻⁴
5.0x10⁻⁵
0


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
Evapotranspiration
mm/s
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
2.0×10^{-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
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
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
2002.0
Total ET
Transpiration
Canopy Evap
Soil Evap



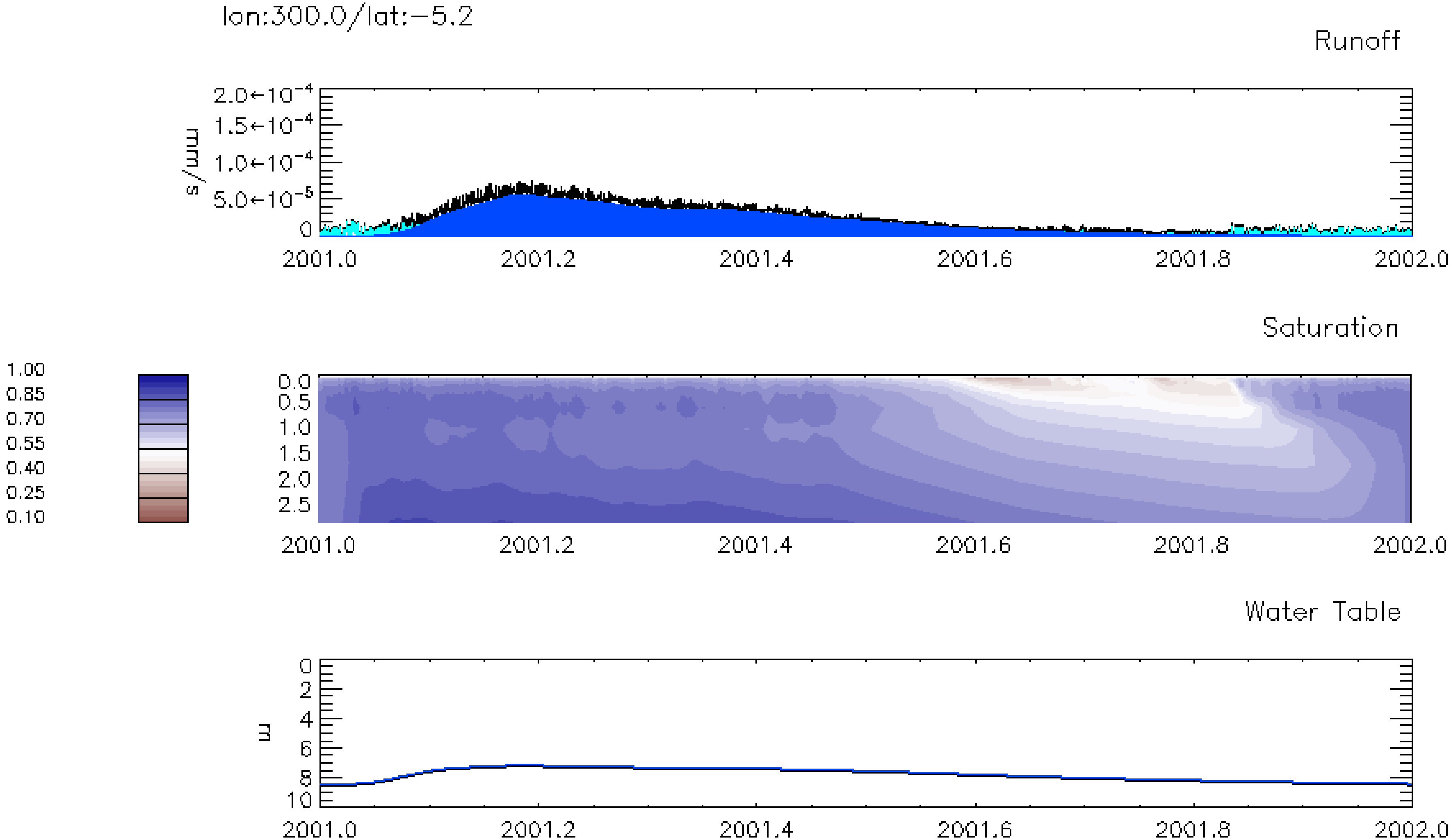
lon:300.0/lat:−5.2
Runoff
mm/s
2.0←10−4
1.5←10−4
1.0←10−4
5.0←10−5
0
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Saturation
1.00
0.85
0.70
0.55
0.40
0.25
0.10
0.0
0.5
1.0
1.5
2.0
2.5
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Water Table
m
0
2
4
6
8
10
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0

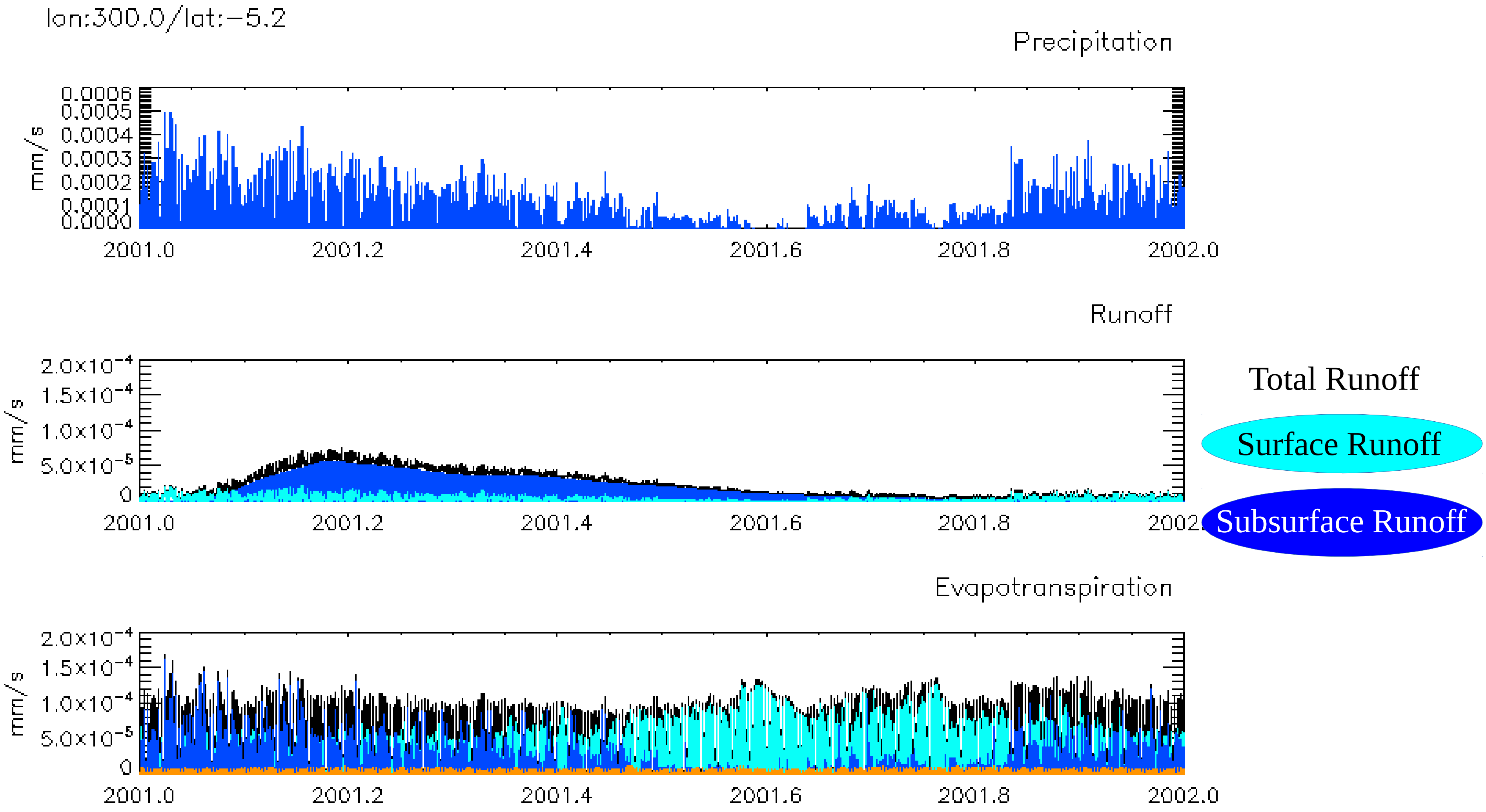
Example: Effects of Modifying the Water Table

$$\Delta ZWT = Qdrainage - Qrecharge$$

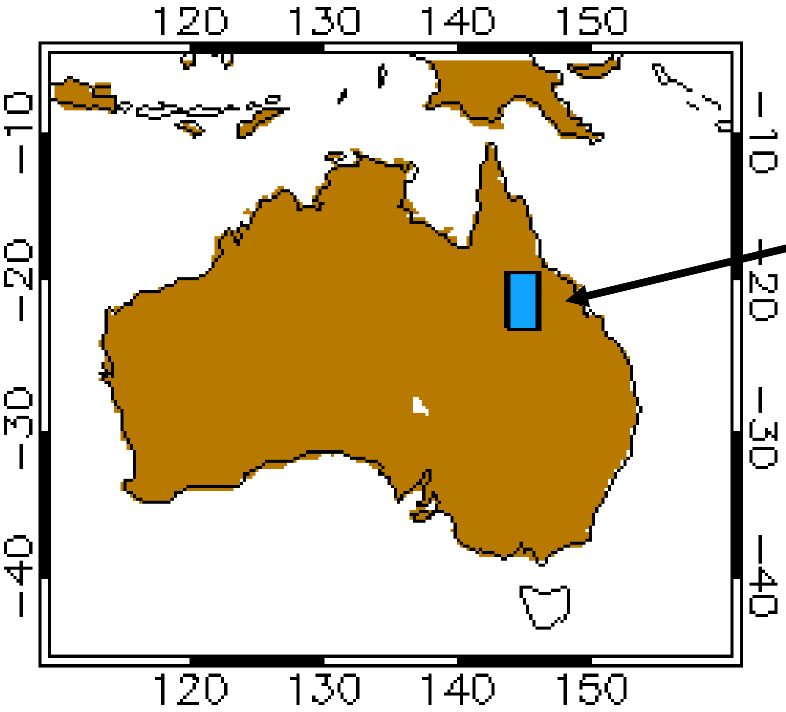
$$Qdrainage = A \exp(-f\ z)$$

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


lon:300.0/lat:-5.2
Runoff
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

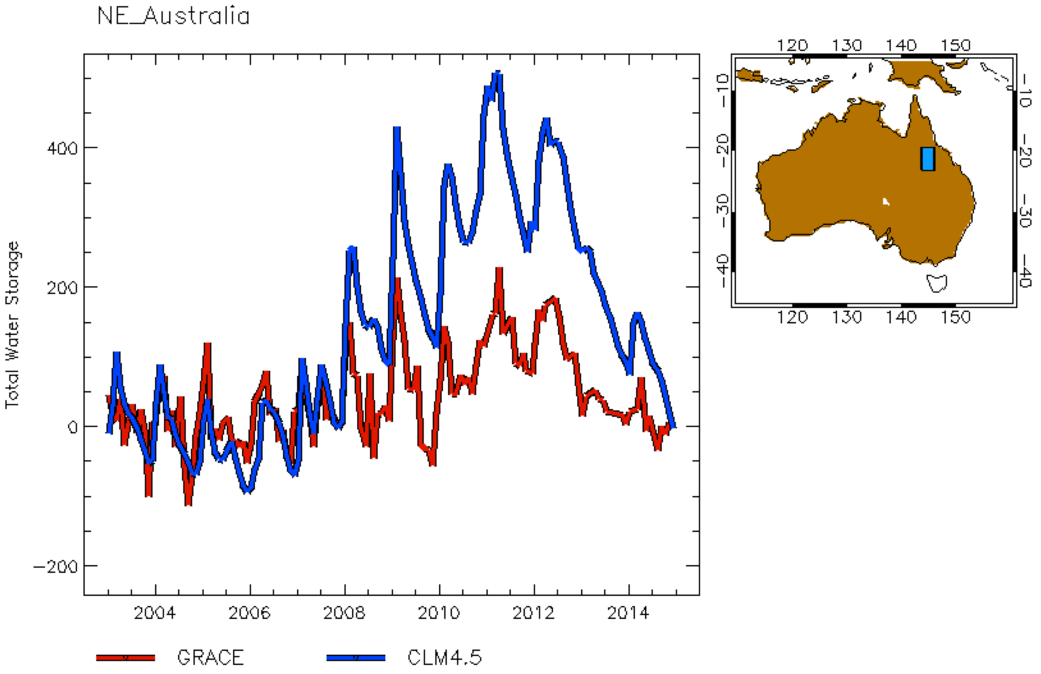

lon:300.0/lat:-5.2
Precipitation
mm/s
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
2001.0
2001.2
2001.4
2001.6
2001.8
2002.0
Runoff
mm/s
2.0×10^{-4}
1.5×10^{-4}
1.0×10^{-4}
5.0×10^{-5}
0
Total Runoff
Surface Runoff
Subsurface Runoff
Evapotranspiration
mm/s
2.0×10^{-4}
1.5×10^{-4}
1.0×10^{-4}
5.0×10^{-5}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

Example II
Model Structural Change

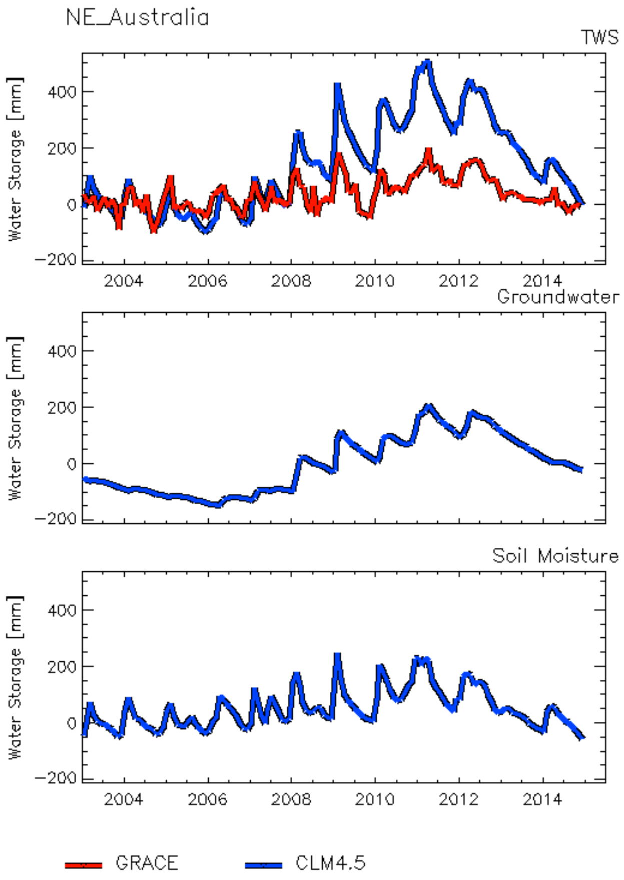


NE Australia

GRACE Water Storage Comparison



GRACE Water Storage Comparison

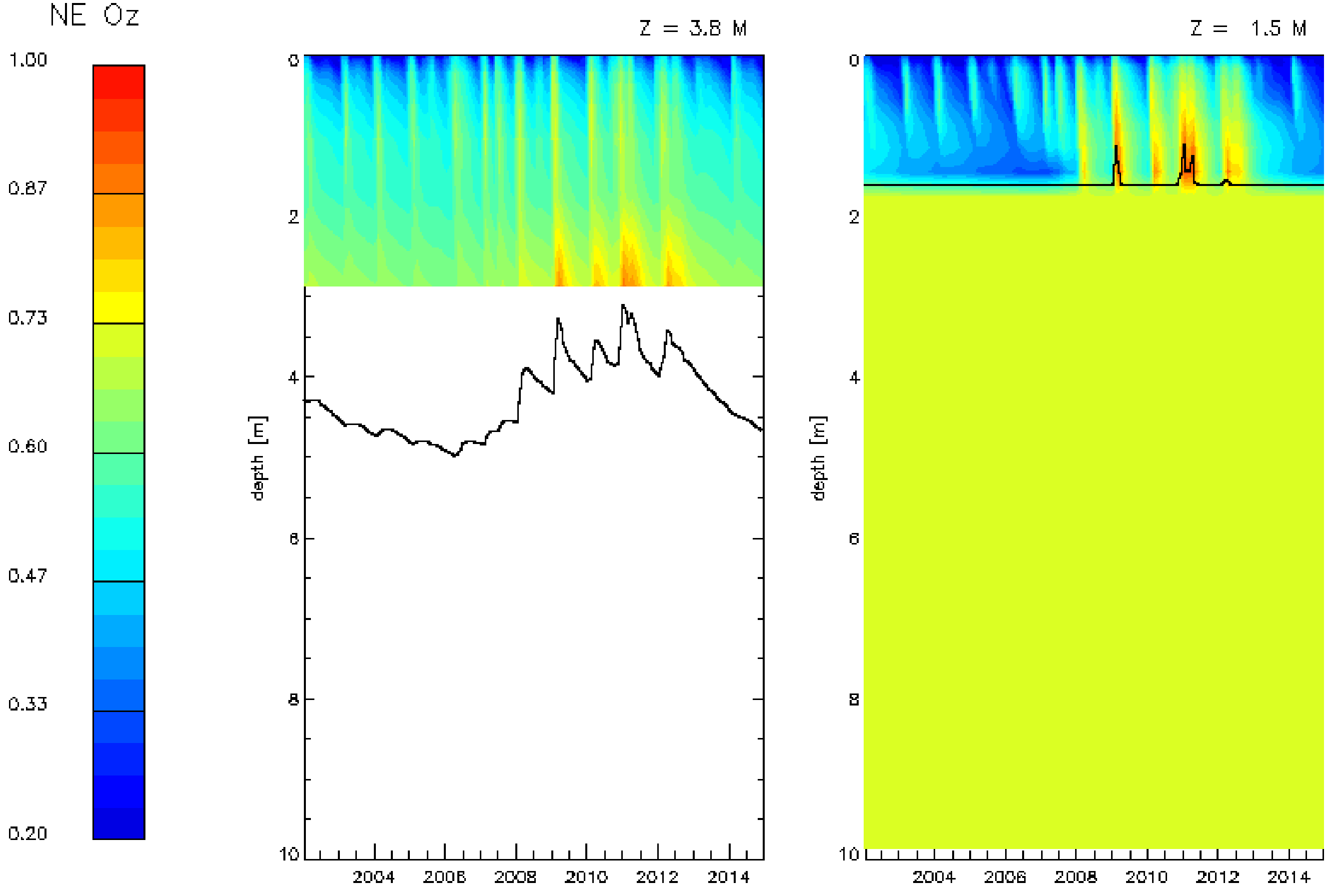


Total Water Storage

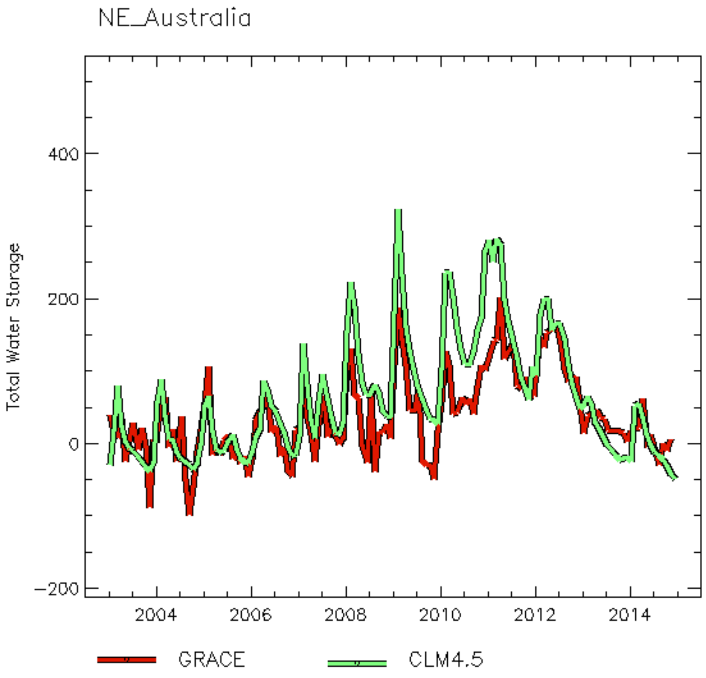
Groundwater Storage

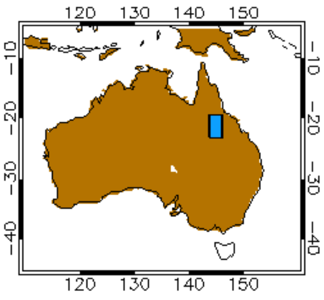
Soil Water Storage

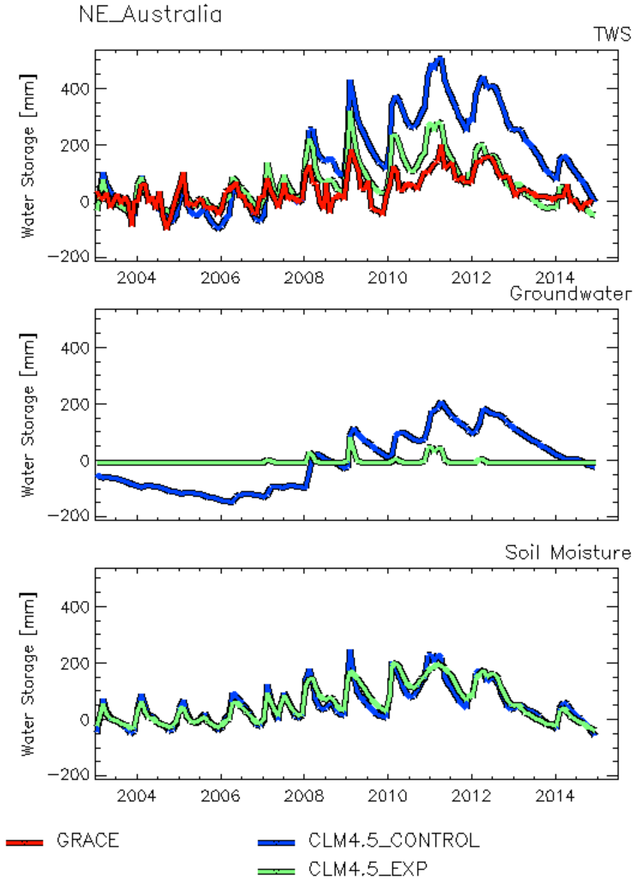
Spatially Variable Soil Depth



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

Questions?