ARC CENTRE OF EXCELLENCE FOR CLIMATE SYSTEM SCIENCE

Australian Government
Australian Research Council

Introduction to Land Surface Modeling
Hydrology

Mark Decker
(m.decker@unsw.edu.au)

THE AUSTRALIAN NATIONAL UNIVERSITY ANU
MONASH University
THE UNIVERSITY OF MELBOURNE
UNSW THE UNIVERSITY OF NEW SOUTH WALES
UNIVERSITY OF TASMANIA

Outline

1) **Overview & definitions**

2) **LSM Overview**
   1D model with independent columns

3) **Soil Moisture**
   Soil properties
   Vertical Redistribution
   Infiltration and Drainage

4) **Horizontal Surface/Subsurface fluxes**
   Parameterizations

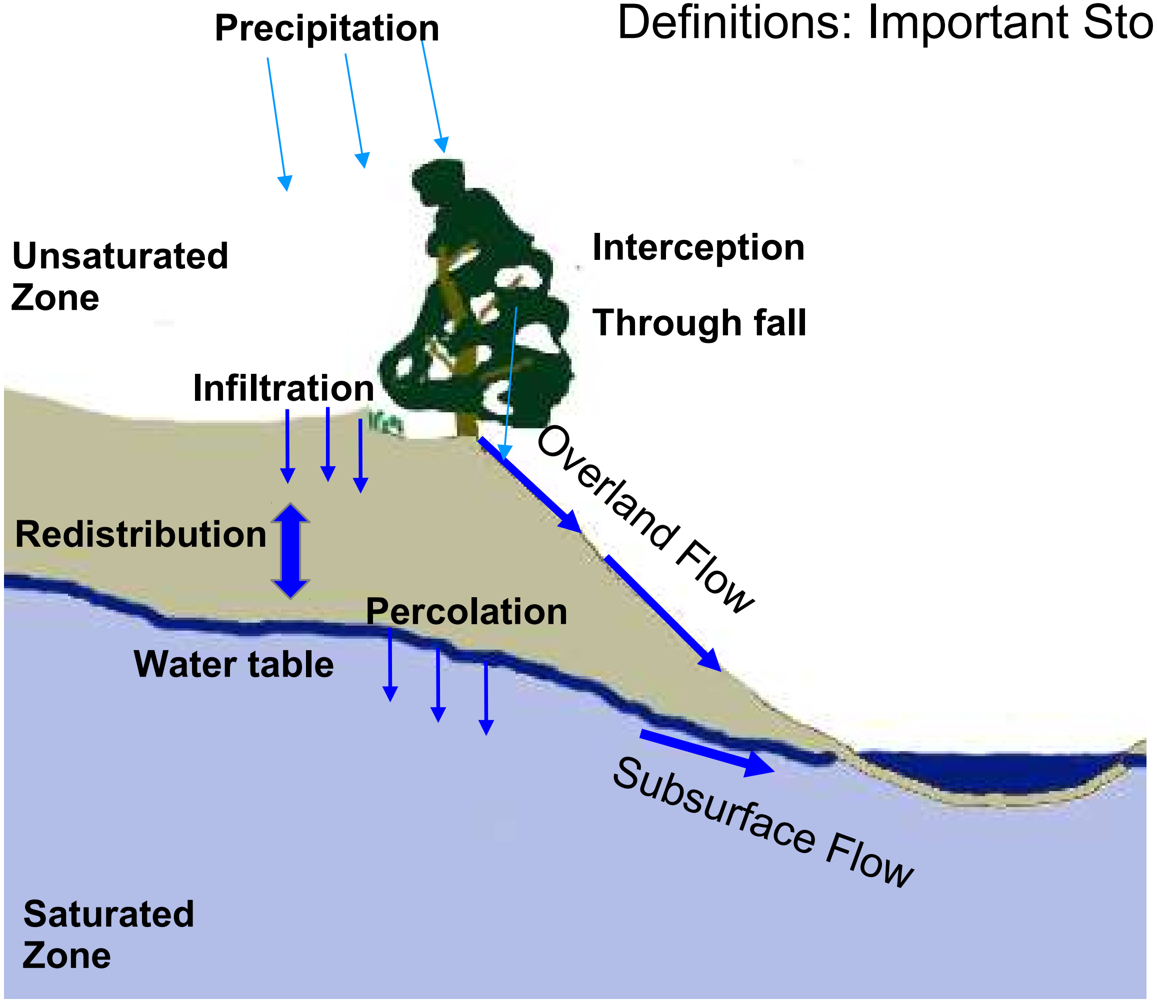
5) **Groundwater (aquifer)**
   1D conceptual
   Explicit representation

6) **River Routing**
   Governing Equations
   Land surface model simplifications

7) **Snow**
   Horizontal extent
   Compaction, melting, freezing

For Each topic
Describe physical processes
Summarize LSM implementations

Definitions: Important Stores and Fluxes



Interception
Precipitation that adheres to vegetation

Through fall
Intercepted water that falls to the surface

Infiltration
Flux of water into the soil at the surface

Overland Flow
Water unable to infiltration that flows horizontally along the surface

Unsaturated Zone
Water content of soil is less than maximum capacity

Redistribution
Vertical fluxes of water (both directions)

Saturated Zone
Soil pores entirely filled with water

Water table
Boundary separating saturated and unsaturated zones

Percolation
Flux from the unsaturated to the saturated zones

Subsurface flow
Horizontal flux primarily in the saturated zone

Climate/Weather models are generally 1D

Simulate area mean hydrology

Divide soil column into n layers

Explicitly simulate vertical movement of water

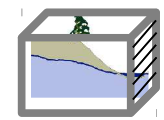
- **Changes in water for each layer**
- **Fluxes between layers (q)**

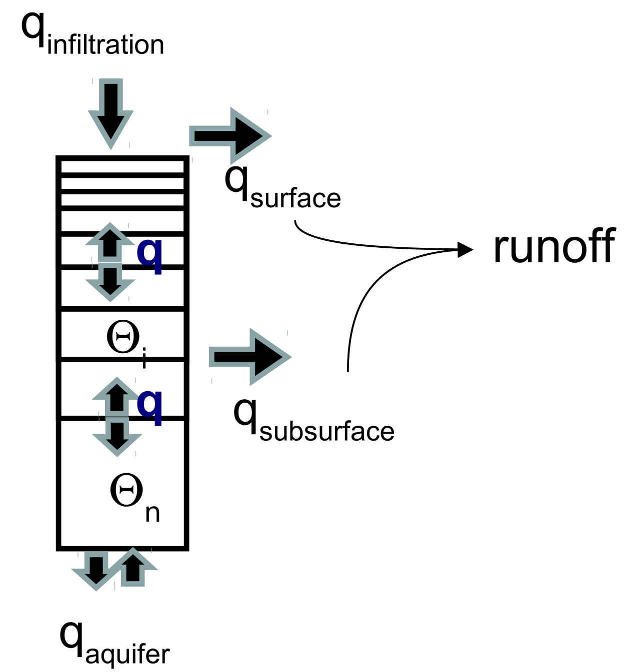
Sometimes include a groundwater

- $q_{aquifer}$

Parameterize horizontal fluxes

- $q_{surface}$, $q_{subsurface}$





What governs soil moisture fluxes?

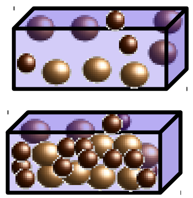
Fluxes of Water in soil

Porosity: The ratio of the vacant volume to the total volume

Function of soil type

Silt: 0.3-0.5
Clay: 0.4-0.7
Sand: 0.2-0.5

$$p_o = \frac{V_v}{V_t}$$



Hydraulic Conductivity: Describes ability of water to travel through pores

Changes with soil type
Empirically related to liquid water content. Decreases with water content.
Greatly reduced when soil liquid freezes
Macro-pores (large voids from decaying roots, soil movement, etc.) can be significant

Soil Potential: Potential energy relative to a reference, drives moisture fluxes

Unsaturated Soils:

Matric: Result of adhesive forces forming a meniscus of water around soil particles. Negative.
Gravimetric: Due to gravity, equal to depth. Positive.
Osmotic: Heterogeneous solute concentrations. Negative, usually neglected in LSMs.

Saturated Soils:

Pressure: Heterogeneous distribution of water.
Gravimetric: Due to gravity. Positive.
Osmotic: Heterogeneous solute concentrations. Negative, usually neglected

Soil Moisture Fluxes

Darcy's Law: Flux proportional to gradient in soil potential

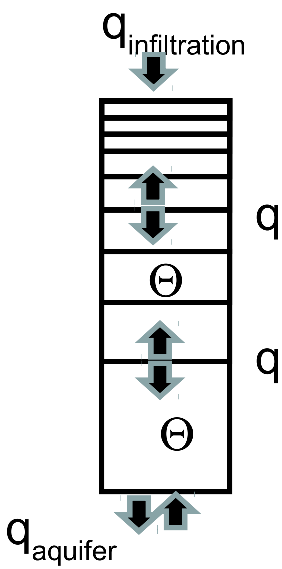
3D: $q = -k \nabla (\psi_h)$ $\psi_h = \sum \psi_i$

Climate Models (almost) universally 1D (vertical)

$$q = -k \frac{\partial \psi_h}{\partial z} \qquad \psi_h = \psi_m + z \qquad q = -k \frac{\partial (\psi_m + z)}{\partial z}$$

Flux in soil proportional to the conductivity times gradient in potential

LSM soil layers



Richards Equation: Conservation of mass applied to Darcy's Law.

Determines soil water content.

Θ is the volumetric water content of the soil ($mm^3\ mm^{-3}$)

1D Equation in climate models

$$\frac{\partial \Theta}{\partial t} = \frac{\partial q}{\partial z} \qquad \frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left[-k \frac{\partial (\psi_m + z)}{\partial z}\right]$$

ψ_m :Soil matric potential (mm)

Θ : Volumetric water content ($mm^3\ mm^{-3}$)

Changes soil moisture content result from gradients in moisture fluxes

Highly non-linear due to dependence of k and ψ_m on Θ

Analytic solutions to Richards Equation are limited

Numerous numerical solutions to Richards Equation.

Interception and Infiltration

Interception

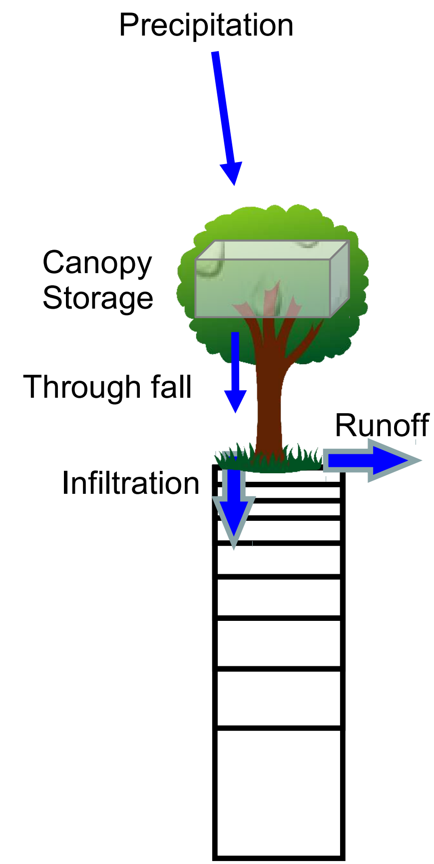
Precipitation collides with vegetation and canopy can store water
Depends on vegetation amount, type, rate and type of precipitation

$$q_{int} = q_{precip} F_{int}[LAI].$$

F_{int} commonly an exponential function
LAI: leaf are index (area of leaves per srf area)

$$\frac{dW_{can}}{dt} = q_{int} - q_{thru} - E.$$

Water balance governs canopy water
W_{can}: Canopy water content
E: Evaporation/sublimation



Infiltration

Limit flux into soil based on state of soil
Depends on surface layer moisture, ice, soil properties
For through fall over unsaturated soils:

$$q_{infl,max} = K_{sat,srf} F_{infl}\left[\theta, \theta_{sat}, \frac{\partial \psi}{\partial \theta}\right].$$

F_{infl} can be one of many functions
$q_{infl,max}$ is the maximum infiltration

Infiltration limited by

1) K_{sat}
2) θ relative to θ_{sat}
3) ψ (soil potential) changes

Through fall that cannot infiltrate the soil becomes surface runoff

Surface and Subsurface Runoff

Surface Runoff (Overland Flow): q_{srf}

Two processes:

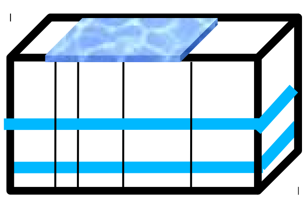
1) Dunne mechanism: runoff due to water falling on saturated areas
2) Horton mechanism: runoff from a water flux being larger than the infiltration capacity

Grid cells typically much larger than hill slopes (subgrid scale process)

Dependencies:

Saturated area, Θ, topography, vegetation, soil properties, soil ice

Saturated Fraction
Imagine a grid cell with $\Theta < \Theta_{max}$



Saturated fraction is parameterized using Θ

Low elevations
- Saturated
  - precipitation immediately runs off (Dunne)

Higher Elevations
- Unsaturated
  - Precipitation infiltrates and/or runs off

Common Parameterizarion

$$q_{srf} = F_{sat}\, q_{thr} + (1 - F_{sat})(q_{thr} - q_{infl}^{max})$$

Saturated: Dunne

Unsaturated: Horton

F_{sat}: Saturated fraction of grid cell
q_{thr}: Through fall reaching soil
q^{max}_{infl}: Maximum infiltration rate

Surface and Subsurface Runoff

Surface Runoff (Overland Flow): q_{srf}

Grid cells typically much larger than hill slopes (subgrid scale process)
Parameterize the dependence on
Surface layer soil moisture, topography, vegetation, soil properties

$$q_{\mathrm{srf}} = F_{sat}\, q_{\mathrm{thr}} + \left(1 - F_{\mathrm{sat}}\right)\left(q_{\mathrm{thr}} - q_{\mathrm{infl}}^{\mathrm{max}}\right)$$

F_{sat}: Saturated fraction of grid cell
q_{thr}: Through fall reaching soil
q^{max}_{infl}: Maximum infiltration rate

Saturated->Dunne->Runoff
Unsaturated->Horton->Runoff+Infiltration

Subsurface Fluxes (runoff): q_{sub}

Subgrid scale (topography governing fluxes not typically resolved)
Parameterize the dependence on soil moisture, topography, soil properties

Common Parameterizarion

$$q_{\mathrm{sub}} = G\left[z_{elv}\right]\Gamma\left[Z_{\nabla}\right]$$

Z_{elv}: Elevation in some manner
Z_{∇} : Water Table Depth
G and Γ: Functions that prescribe q_{sub} behavior

How can we define F_{sat}, G and Γ using physical mechanisms?
Common Approach: TOPMODEL

Surface Runoff

$$q_{srf} = F_{sat} q_{thr} + (1 - F_{sat})(q_{thr} - q_{infl}^{max})$$

Subsurface Runoff

$$q_{sub} = G[z_{elv}] \Gamma [Z_{\nabla}]$$

TOPMODEL based runoff

Conceptually based on hydrologically similar areas

Subgrid scale topographic statistics governs subgrid storage, Z_{∇} and F_{sat}

Assumes: 1) uniform runoff (per area) drains through a point 2) horizontal hydraulic gradient given by topography

Subsurface runoff varies exponentially with water storage

Topographic Index: Larger area -> large λ

$$\lambda = \ln\left[\frac{a}{\tan(B)}\right]$$

a: Catchment Area (region that drains to a given point)

B: Local slope of the surface

Saturated Fraction:

$$F_{sat} = \int_{\lambda > \lambda_m + f z_{\nabla}} pdf(\lambda)\, d\lambda$$

pdf(λ): Probability distribution of λ from the grid cell

λ_m: Grid cell mean λ

Z_{∇} : Grid cell mean water table depth

f: Tunable parameter

F_{sat} is equal to the area where the subgrid λ is greater than $\lambda_m + fZ_{\nabla}$ (mean λ and Z_{∇})

Subgrid topographic statistics give subgrid soil water and water table depth
Provide a statistical alternative to explicitly simulating these fine scales
Assumptions are not always valid

Surface Runoff

$$q_{\mathrm{srf}} = F_{sat}\, q_{\mathrm{thr}} + (1 - F_{\mathrm{sat}})(q_{\mathrm{thr}} - q_{\mathrm{infl}}^{\max})$$

Subsurface Runoff

$$q_{\mathrm{sub}} = G[z_{elv}]\, \Gamma[Z_{\nabla}]$$

TOPMODEL based runoff

Subsurface Runoff

$$q_{\mathrm{sub}} = T_i \tan[B]$$

Topographic gradients drive subsurface fluxes

Horizontal transmissivity (i.e. conductivity) declines exponentially with Z_{∇}

Climate Models frequently adopt this functional form

$$q_{\mathrm{sub}} = \frac{K_{\mathrm{sat}}}{f} e^{-\lambda_m} e^{-fZ_{\nabla}}$$

λ_m: Grid cell mean λ
Z_{∇} : Grid cell mean water table depth
f: Tunable parameter

$$q_{\mathrm{sub}} = q_{max}\, e^{-fZ_{\nabla}}$$

Alternative that combines the topographic index and K_{sat} into q_{max}

TOPMODEL concepts are widely used in the parameterization of surface and subsurface runoff in climate and weather land surface models

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Subsurface fluxes from above generally applied to both the saturated or unsaturated zone depending on the soil moisture state

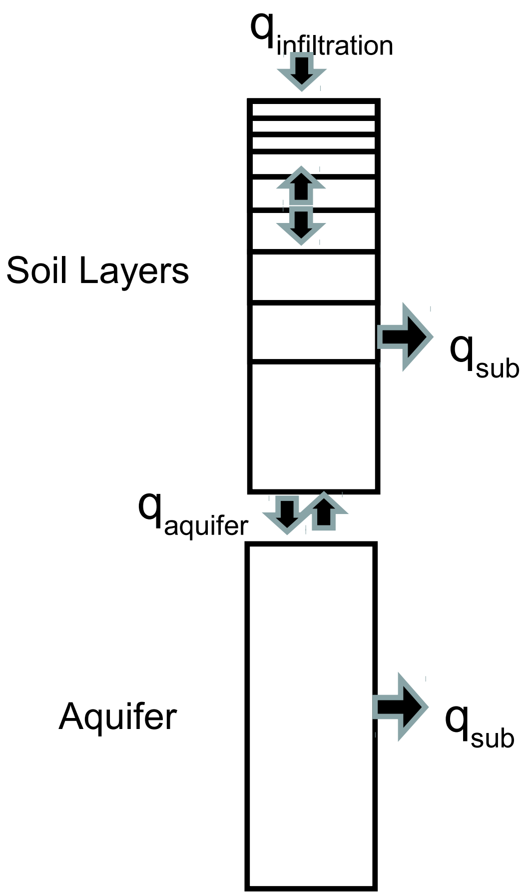
1D Conceptual groundwater

Increasingly included in LSMs
Dominant LSM formulation
Simple bucket model

$$\frac{d\Theta_{gw}}{dt} = q_{aquifer} - q_{sub}$$

Vertical, horizontal fluxes and drainage parameterized

No transfer between grid cells
Neglects groundwater coupling with
- Stream flow
- Flood plains
- Anthropogenic removal



Explicit horizontal fluxes and Z_∇ dynamics: 2D groundwater model

Model resolution resolves the topography that governs fluxes

- Increasingly computationally viable
- Unknown aquifer and soil properties remain problematic

Common among hydrologists, used by at least 1 LSM

Simplifying Assumptions (Dupuit-Forchheimer)

- Z_∇ is relatively flat with a hydrostatic saturated zone
- Horizontal fluxes & K invariant with respect to z

Solves for the thickness of the saturated layer:

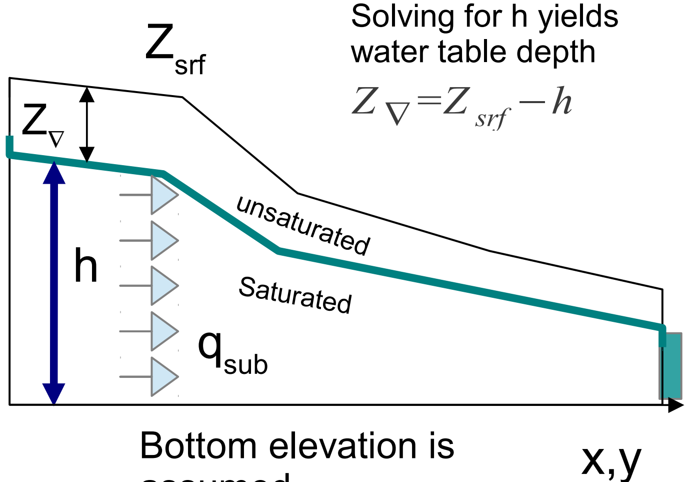
Darcy's Law: $q_{sub} = -kh \nabla_{xy}[h]$

h: thickness of saturated zone
xy: horizontal direction

Conservation of mass: $$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[-kh\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[-kh\frac{\partial h}{\partial y}\right]$$

Solving for h yields water table depth

$$Z_\nabla = Z_{srf} - h$$



Bottom elevation is assumed

Simplified 2D simplified equation for groundwater dynamics (i.e.Z_∇)

Explicit horizontal transport between grid cells

Computationally expensive compared to 1D models

River Routing

Transport subsurface and surface runoff to ocean
Dependent on Gravity, slope, friction, channel geometry, runoff

Saint-Venant Equation

1D Shallow water equation that approximates river flow

Mass Conservation

$$\frac{\partial y}{\partial t} + D_h \frac{\partial V}{\partial x} + V \frac{\partial y}{\partial x} = R_{sub} + R_{srf}$$

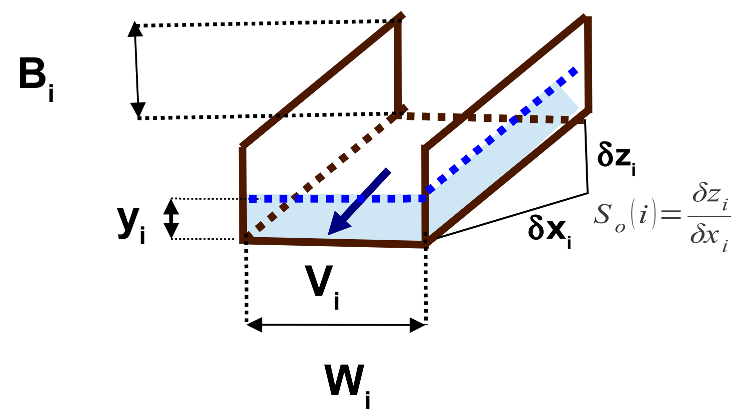
Momentum Conservation

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial y}{\partial x} = g\left(S_o - S_f\right)$$

y: river height
V: velocity
D: channel geom.
R: runoff

S_o: river bed slope
S_f: friction term
x:distance
g: gravity

Rectangle Channel



Climate models generally used a simplified equation set although some now use the above

Simplified River Routing in Global Models

Flow direction specified for each cell using topography
Right: Each cell has one downstream cell
Can have multiple downstream cells

At grid cell i, the mass of river water is given by

$$\frac{dW_i}{dt} = \sum q_i^{\text{in}} - \sum q_i^{\text{out}} + R_i$$

W: river water mass
R: source/sink

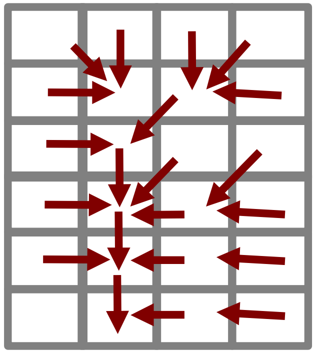
Source/SInk: $R_i = \left(q_{\text{srf}} + q_{subsrf}\right)\Delta t$

Surface and subsurface runoff

Discharge proportional to river storage

Fluxes (in and out) $q_i^{\text{in}} = \sum_{n=1}^{N} \mu W_{i-n}$ $\quad q_i^{\text{out}} = \mu W_i$

Flow direction predetermined using topography

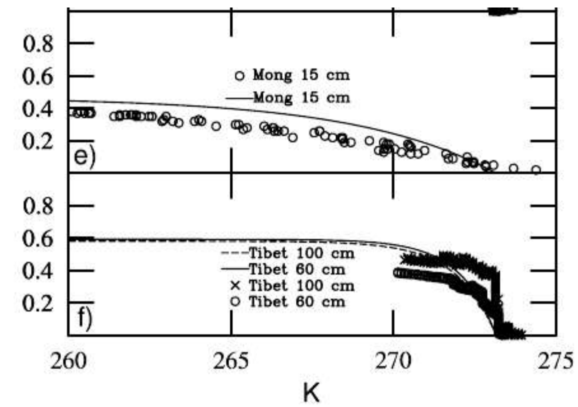


Above: Downstream cell is one of eight neighboring cells

Alternatively downstream cells can be defined beyond neighbors

Soil Ice in LSMs

Frozen soil
- Reduces hydraulic conductivity
- Limits all fluxes
- Liquid and Ice coexist below T < 0°C
  - Adhesion forces ensure some liquid



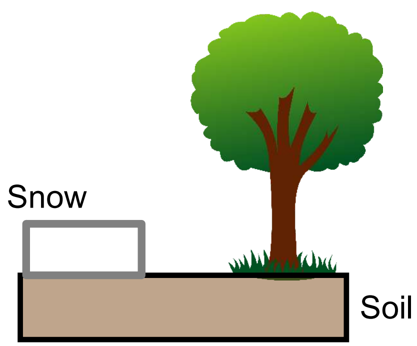
Snow Parameterizations

Single (mufti-layer) liquid/ice and energy balance

$$\frac{dM_{sno}}{dt} = q_{input} - q_{\mathrm{melt}} + q_{frz} - E_{\mathrm{sublimation}}$$

$$\frac{dM_{liq}}{dt} = q_{melt} - q_{\mathrm{frz}} - q_{\mathrm{drain}}$$

Processes
- Accumulation, melting, refreezing, sublimation
- Compaction
  - Snow density increases with time



Subgrid scale heterogeneity & vegetation burial
- Fraction coverage parameterized
- Vegetation buried if snow depth > vegetation height

Summary

LSM Hydrology Overview
- 1D model with independent columns
- Focus on vertical fluxes

Soil Moisture
- Vertical redistribution from Richards equation and Darcy's law

Horizontal Surface/Subsurface fluxes
- parameterized using topography

Groundwater
- 1D conceptual

River Routing
- Only horizontal process
- Coupling neglected

Snow processes