Introduction to
Land Surface Modelling

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Outline

- Introduction: why, what?
- Evolution of land surface models
- Energy Balance
- Water balance
- Carbon cycle /Chemistry

What is a land surface model?

- Land surface models (LSMs) are the part of earth system models that simulate processes occurring at the Earth's surface.

- LSM uses quantitative methods to simulate the exchange of water and energy fluxes at the Earth surface–atmosphere interface.

Why land surface matter?

- Land-surface fluxes provide the bottom boundary condition for weather and climate models.

- Input of fresh water to the ocean

- Processes important to human and ecology : e.g. modulate extreme

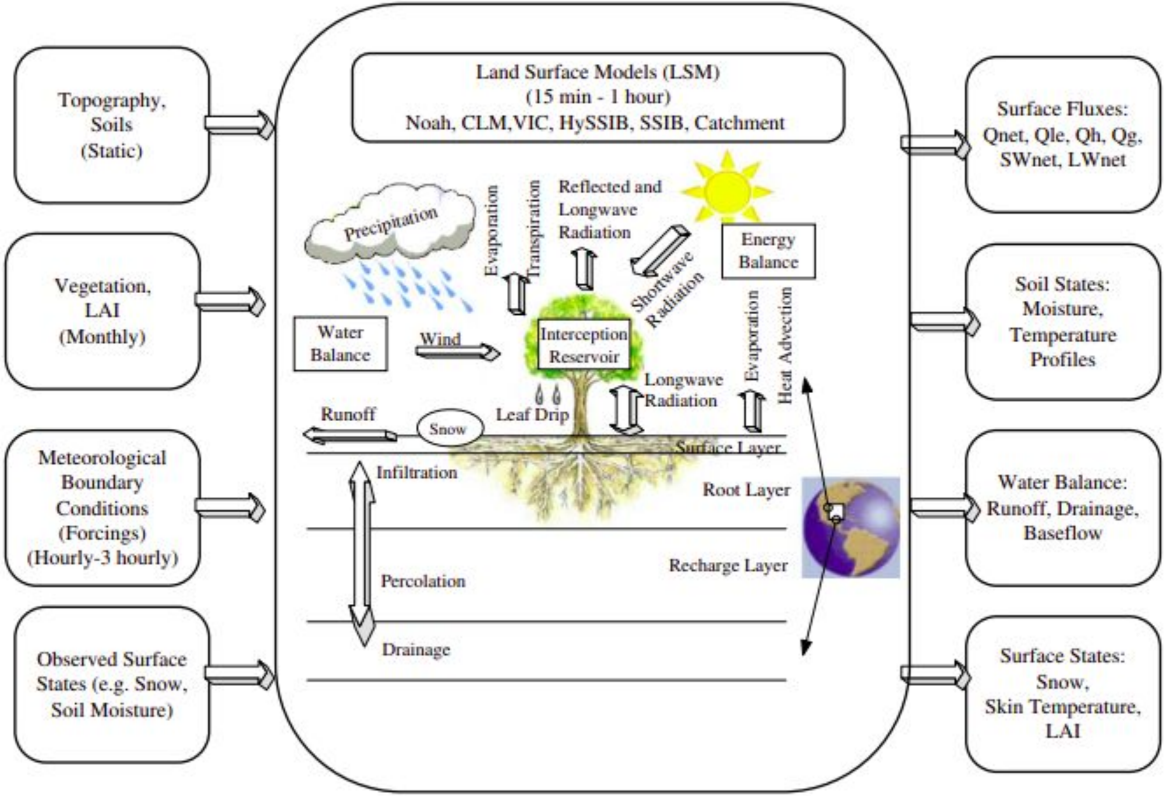
- Land takes about 25% of atmospheric CO_2 emission

- Land has “memory” -important for S2S prediction

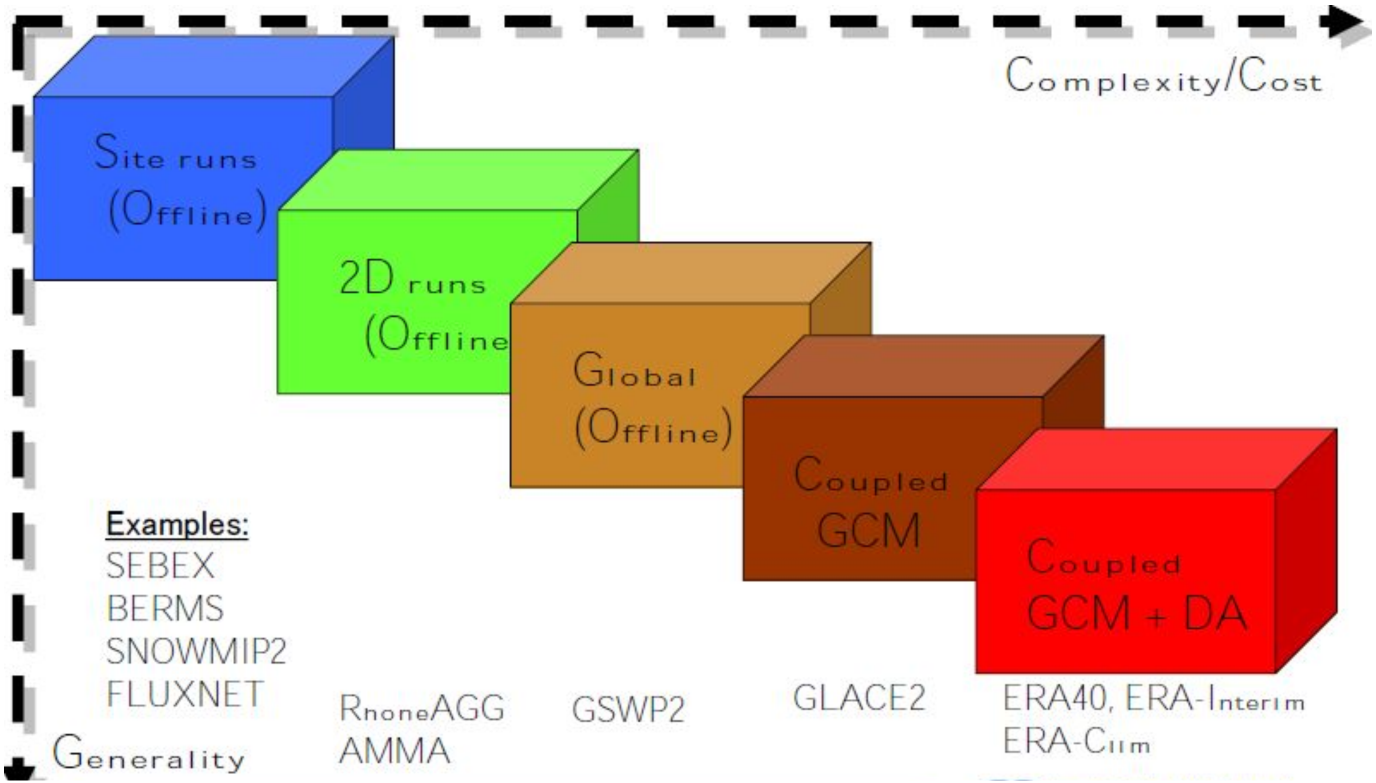
LSM from Hydrology vs Meteorology perspective

Meteorology	Hydrology
- Cover global /regional, grid based , time scale in the order of minute	Basin or sub-basin scale, Conceptual (lumped), distributed (semi-distributed, daily time scale
- Multi-layer soil parametrization and solve waster and temperature numerically diffusive equation	Usually one layer, treat soil heterogeneous
- Less attention to lateral flow of water	Represent lateral flow, less interested in temperature

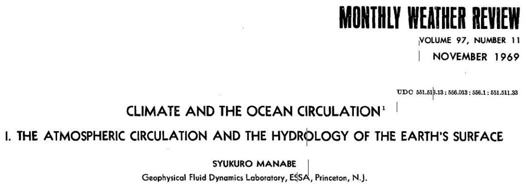
LSM: What do they need and what do we get



Stages of land surface model development



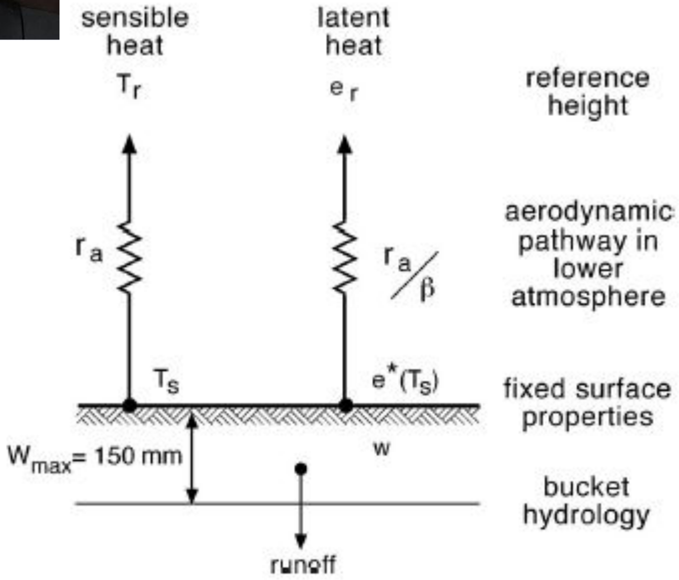
Evolution of Land surface models: First generation


MONTHLY WEATHER REVIEW
VOLUME 97, NUMBER 11
NOVEMBER 1969
UDC 551.513.13 : 556.013 : 556.1 : 551.511.33
CLIMATE AND THE OCEAN CIRCULATION[1]
I. THE ATMOSPHERIC CIRCULATION AND THE HYDROLOGY OF THE EARTH'S SURFACE
SYUKURO MANABE
Geophysical Fluid Dynamics Laboratory, ESSA, Princeton, N.J.

Manabe, 1969 bucket model

- assume homogeneous surface
- Runoff <->When bucket fills
- Constant soil depth
- Fixed soil property
- Same albedo, water holding capacity
- Water content limited AE, 1 layer
- No explicit treatment of vegetation

$$H = \frac{T_s - T_r}{r_a} \rho c_p \qquad \lambda E = \left(\frac{e^*(T_s) - e_r}{r_s + r_a} \right) \frac{\rho c_p}{\gamma}$$



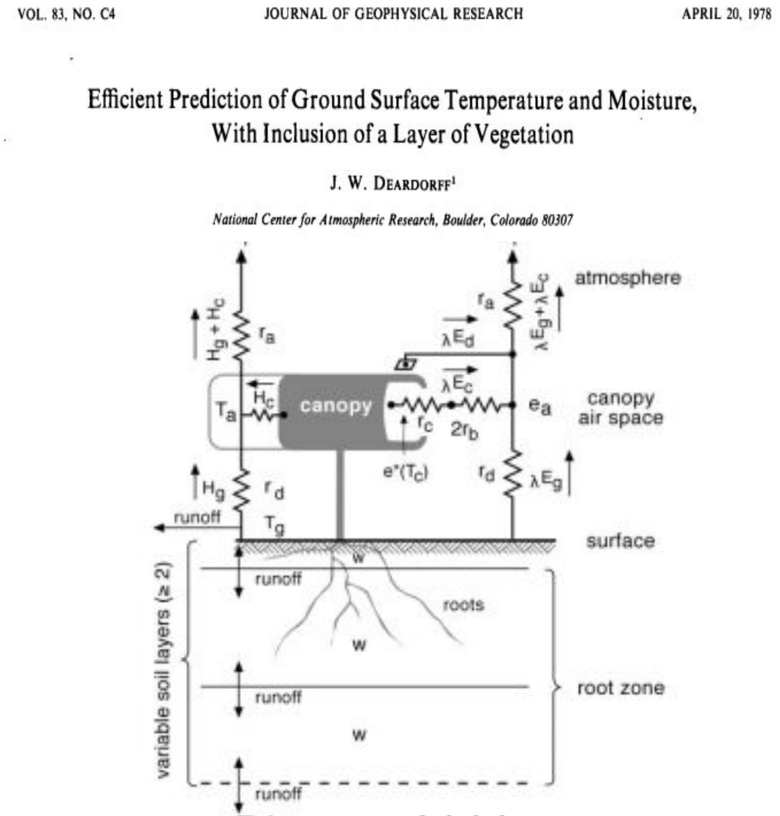
ra is the aerodynamic resistance
rs is the surface resistance to the transfer of water from the surface to the air

$F \sim (X_b - X_a)/r_{ab}$ I ~ V/R (electricity)

Evolution of Land surface models: Second generation

Deardorff, 1978; Dickinson, 1983 (BATS)

- Considered the role of vegetation on energy water budgets, momentum transfer
- multiple soil layers (>=2)
- vertical transfer of water within the soil profile
- Saturation / infiltration excess surface runoff generation


VOL. 83, NO. C4 JOURNAL OF GEOPHYSICAL RESEARCH APRIL 20, 1978

Efficient Prediction of Ground Surface Temperature and Moisture, With Inclusion of a Layer of Vegetation

J. W. DEARDORFF[1]

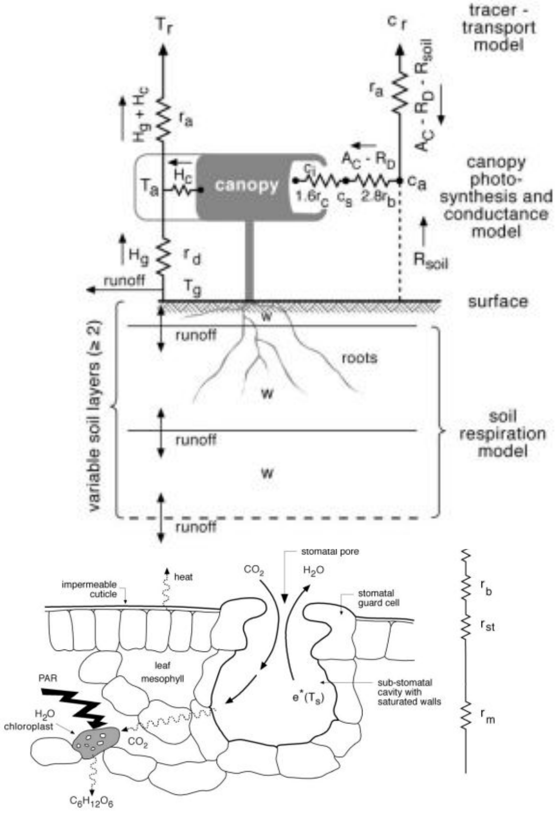
National Center for Atmospheric Research, Boulder, Colorado 80307

Pitman, 2003

Evolution of Land surface models: Third generation

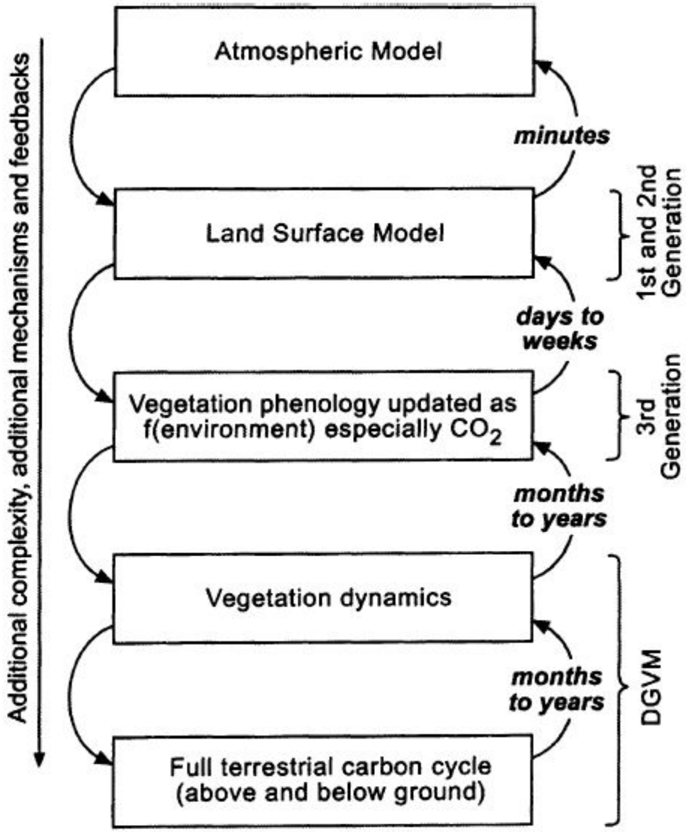
Collatz et al, 1991; Sellers et al, 1992:

- addition of an explicit canopy photosynthesis and conductance
- address the issue of carbon uptake by plants, and soil respiration
- No interactions between model soil columns
- No coupling with groundwater



Pitman, 2003

Evolution of Land surface models: 4th generation

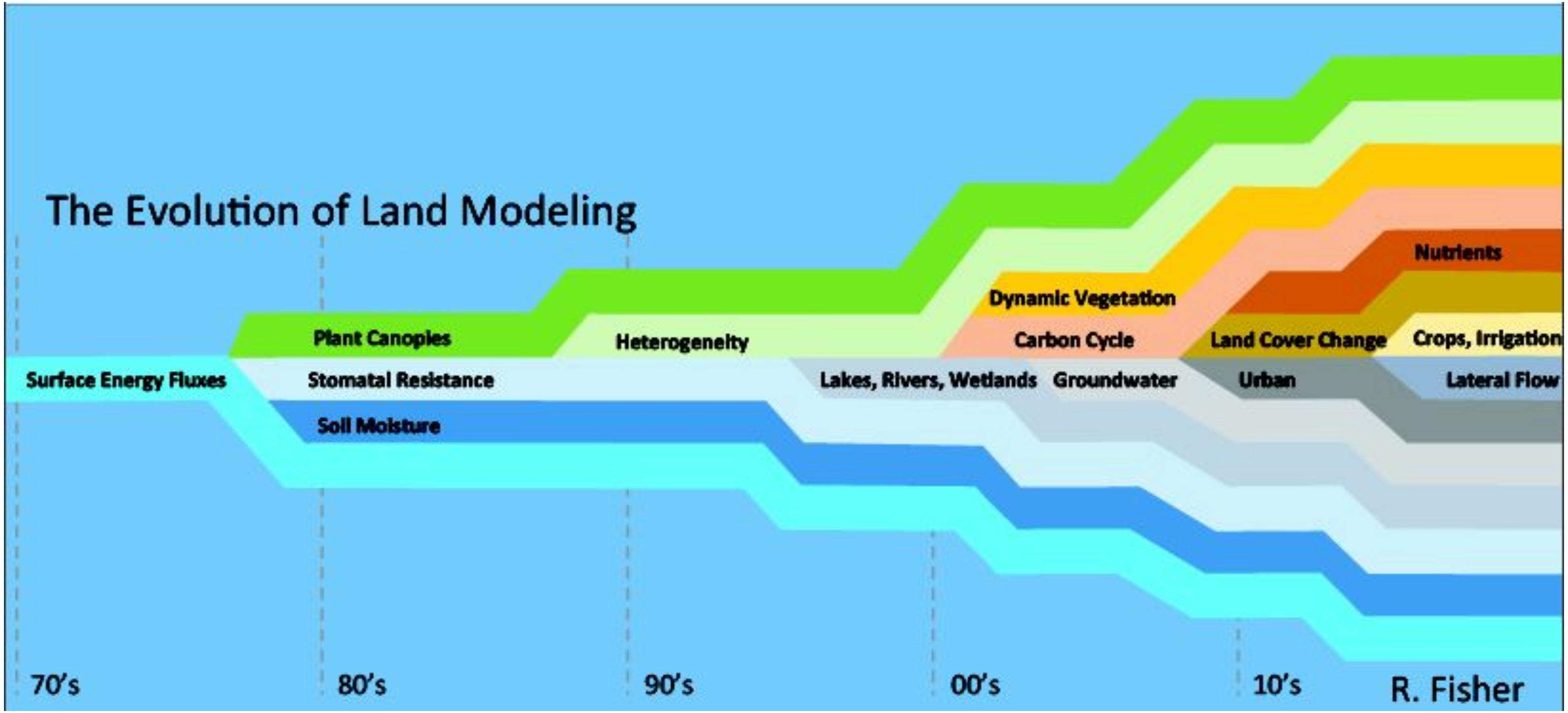


Pitman, 2003

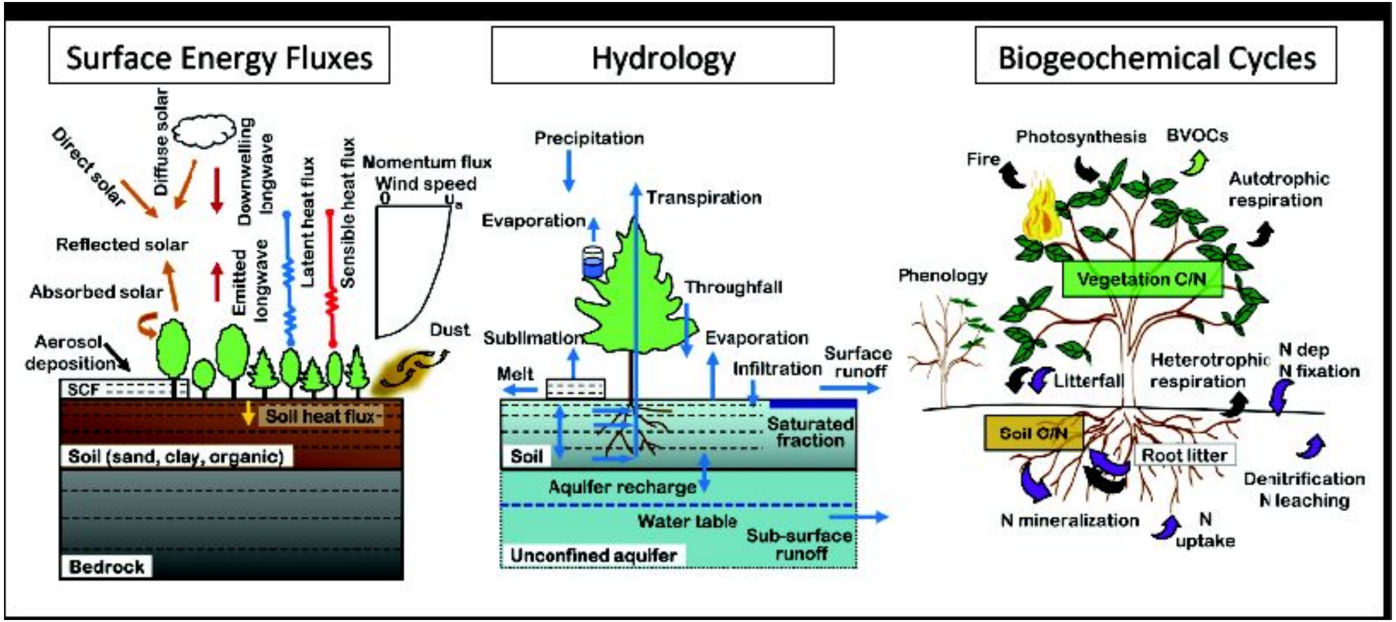
LSM are now inter-disciplinary

Land as lower boundary condition now becomes as integral component of

of atmospheric model to = = = = = = = => Earth System models



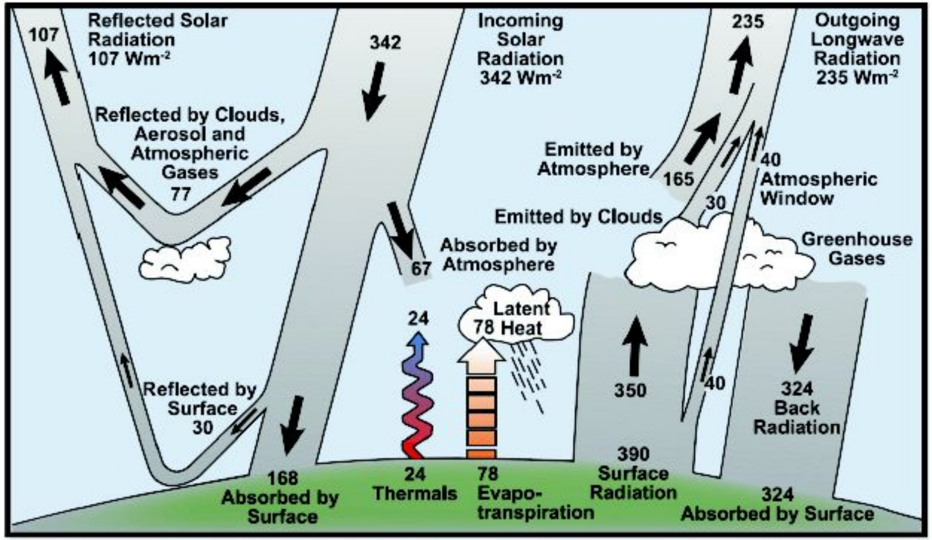
What does land surface models do?



Land surface model solves the following key cycles at each model time step:

- Surface Energy Balance
- Surface Water Balance
- Carbon Balance

Energy balance



$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G$$

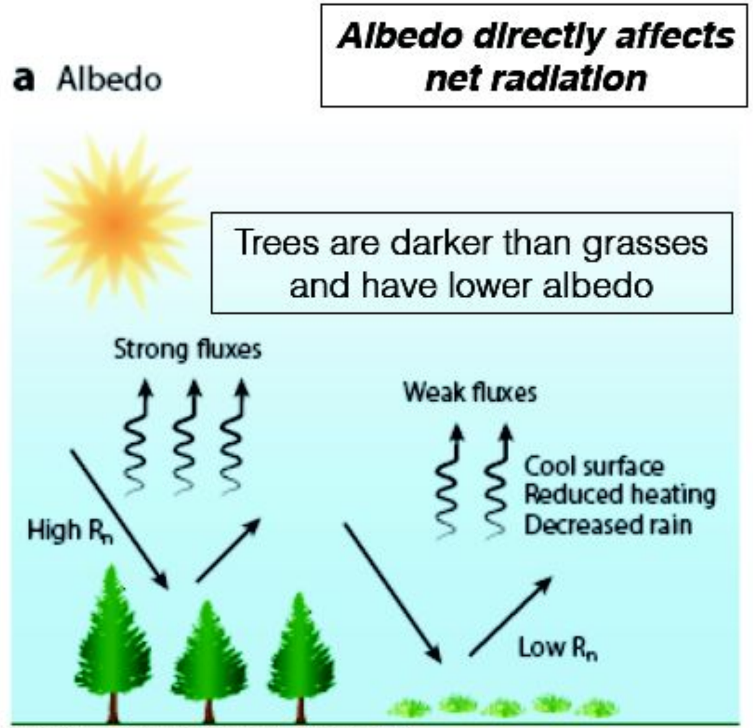
$S^{\downarrow} - S^{\uparrow} + L^{\downarrow} - L^{\uparrow}$ = net radiation

$$R_n = S\downarrow(1-\alpha) + L\downarrow - L\uparrow$$

$$R_n = H + \lambda E + G$$

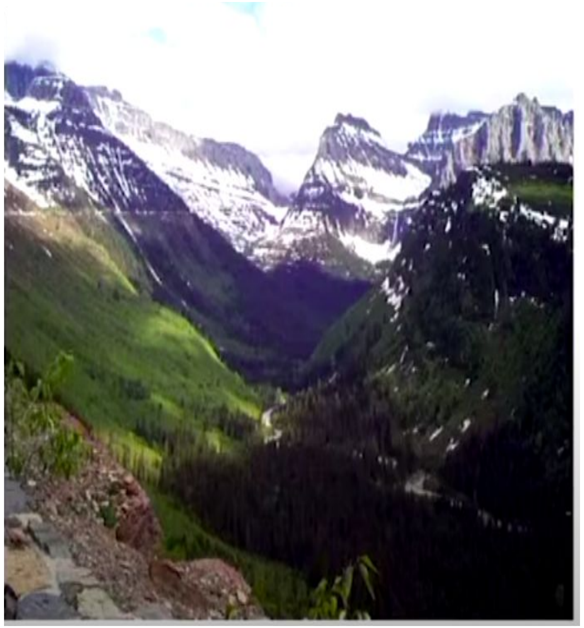
Net radiation is balanced by surface heat fluxes

Surface features affecting Energy balance: (i) Albedo

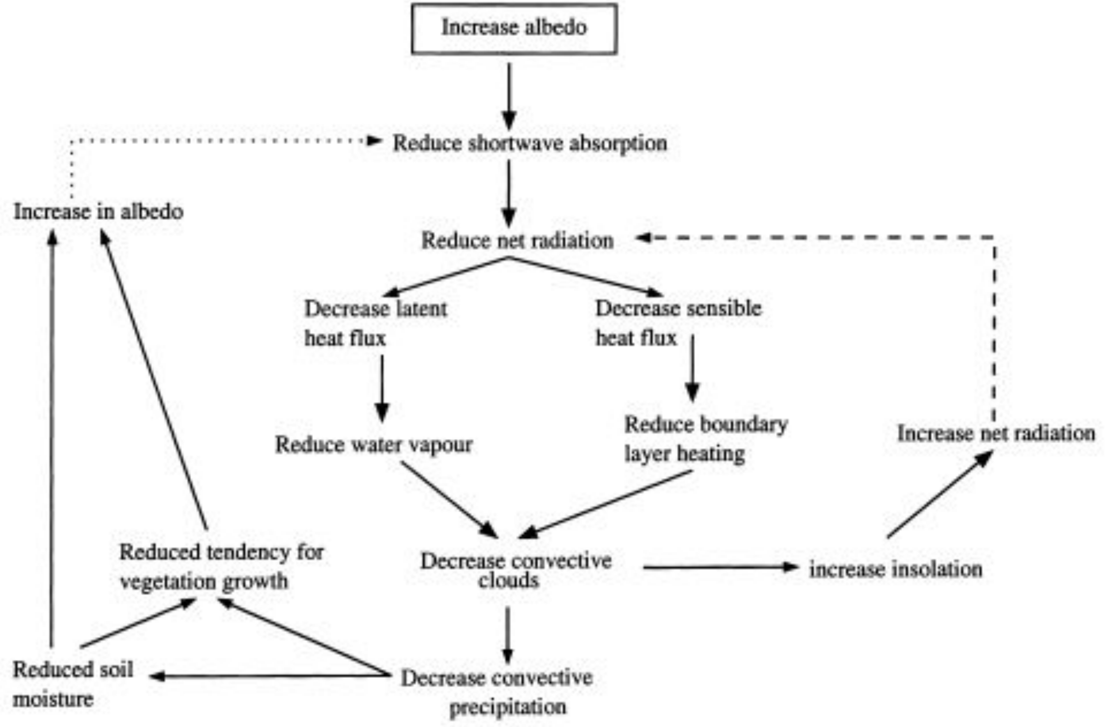


Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

Surface type	Albedo
Ocean and lakes	0.03-0.10[a]
Bare soil	
Wet, dark	0.05
Dry, dark	0.13
Dry, light	0.40
Evergreen conifer	0.08-0.11
Deciduous conifer	0.13-0.15
Evergreen broadleaf	0.11-0.13
Deciduous broadleaf	0.14-0.15
Arctic tundra	0.15-0.20
Grassland	0.18-0.21
Savanna	0.18-0.21
Agricultural crops	0.18-0.19
Desert	0.20-0.45
Sea ice	0.30-0.45
Snow	
Old	0.40-0.70
Fresh	0.75-0.95



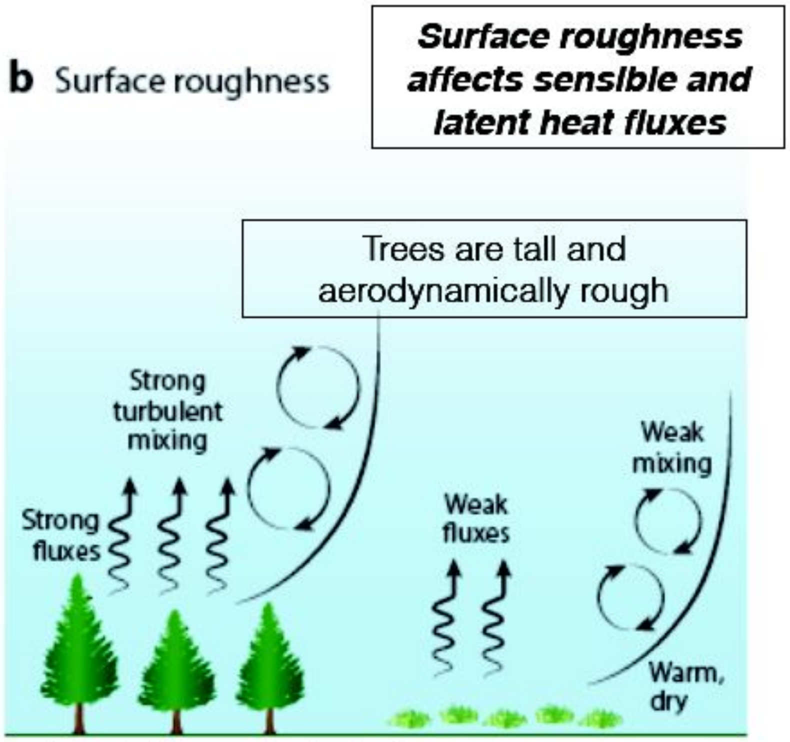
Surface albedo - atmosphere pathways



…… +ve feedback

- - - - - -Ve feedback

Surface features affecting Energy balance: (b) surface roughness



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
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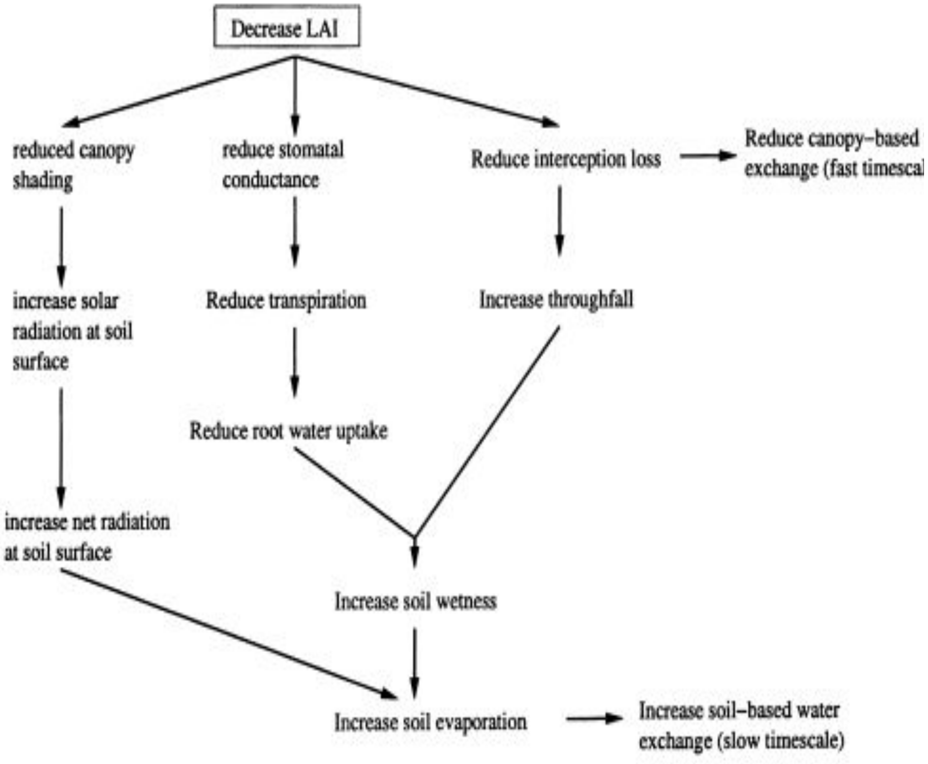
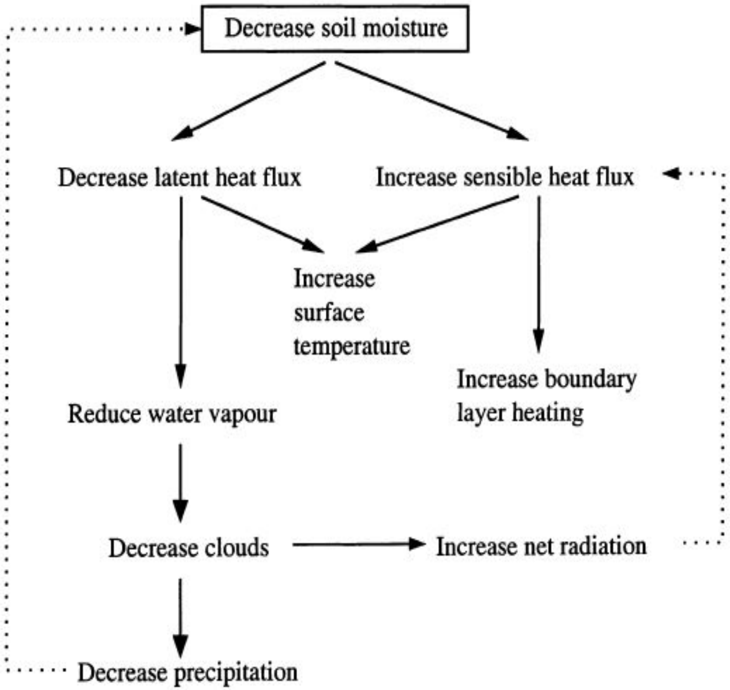
- rough surfaces are more tightly coupled to the atmosphere than a smooth surface.
- A reduction in surface roughness produced an increase in wind speed and increase in moisture convergence (Sud et al., 1988)

Impact of deforestation and soil moisture





Pitman 2003

Sensible heat flux

Equation commonly used in climate models:

$$H = \rho C_p K_H |V| (T_S - T_R)$$

where:

- ρ is mean air density
- C_p is specific heat of air at constant pressure
- K_H is exchange coefficient for heat
- $|V|$ is wind speed at reference level
- T_S is surface temperature
- T_R is air temperature at reference level

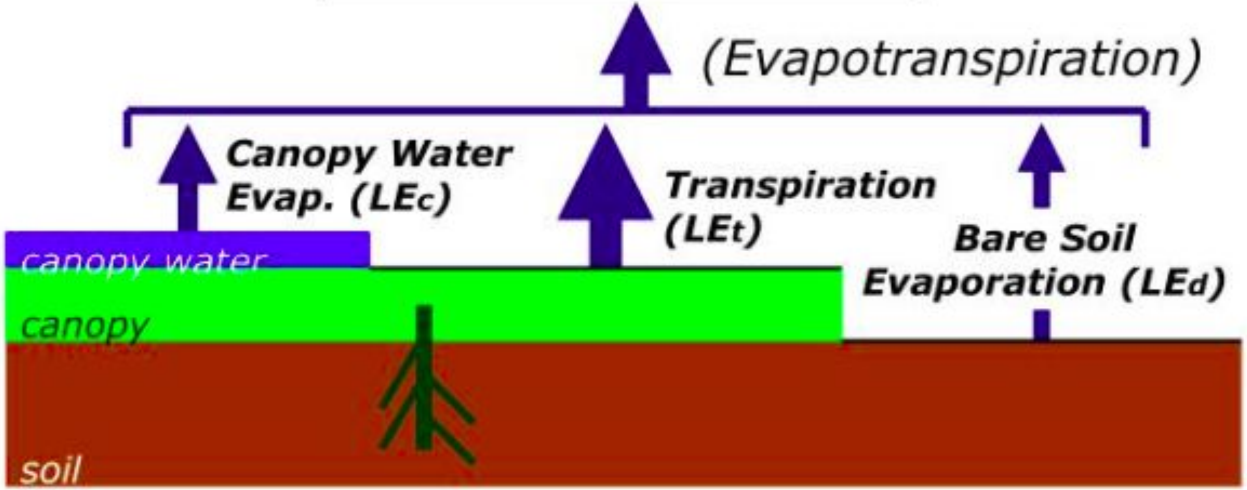
We commonly write this in terms of an aerodynamic resistance r_a:

$$H = \frac{\rho C_p (T_S - T_R)}{r_a} \quad \text{where:} \quad r_a = \frac{1}{K_H |V|}$$

$K_H |V|$ is effectively a conductance of heat between surface and air.

Latent heat flux

$$\boxed{\mathrm{LE} = \mathrm{LE_c} + \mathrm{LE_t} + \mathrm{LE_d}}$$



- **LEc** is a function of canopy water % saturation.
- **LEt** uses *Jarvis (1976)-Stewart (1988)* “big-leaf” canopy conductance.
- **LEd** is a function of near-surface soil % saturation.
- **LEc**, **LEt**, and **LEd** are all a function of **LEp**.

Ground (or Soil) Heat Flux

(to/from the soil to the surface)

$$G = (\lambda T/\Delta z)\ (Tsfc - Tsoil)$$

where:

λT = soil thermal conductivity (function of soil texture, larger for moister soil)

Δz = upper soil layer thickness

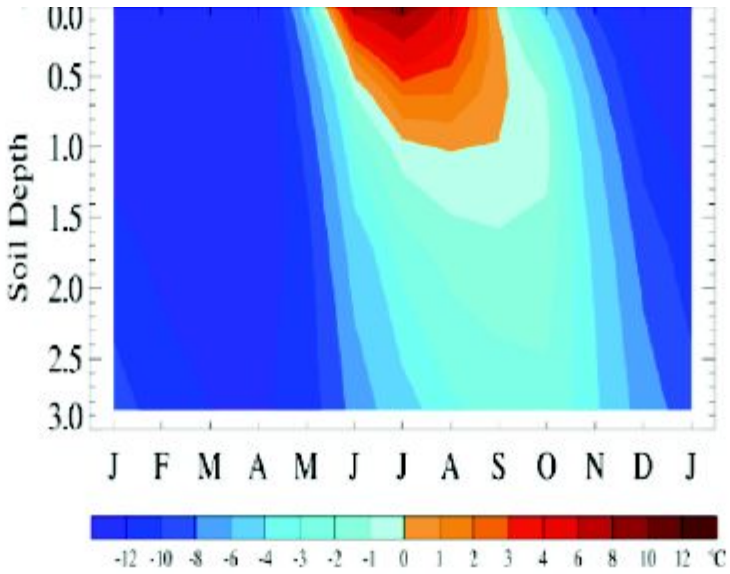
Tsfc - Tsoil = surface-soil temperature gradient

Heat conduction within soil layers

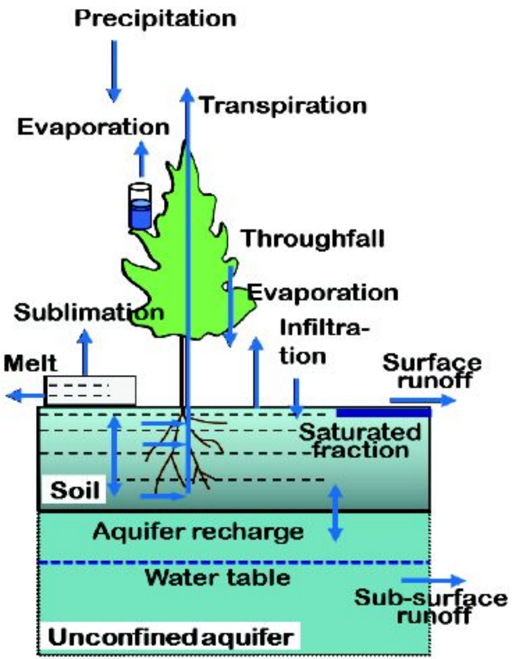
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

where C_p (heat capacity) and K (thermal conductivity) are functions of:

- **temperature**
- **total soil moisture**
- **soil texture**
- **ice/liquid content**



Surface water balance



$$P = (E_s + E_t + E_c) + (R_{surf} + R_{sub\text{-}surf}) + \Delta SM/\Delta t$$

Evaporation (various ways to parameterize)

$$E = E_{dir} + E_t + E_c \quad (7)$$

The direct evaporation from the ground surface is determined by

$$E_{dir} = (1-\sigma_f)\beta^2 E_p,$$

where

$$\beta^2 = \left(\frac{\Theta_1 - \Theta_w}{\Theta_{ref} - \Theta_w}\right)^2$$

The canopy transpiration from the vegetated portion of a model grid cell is

$$E_t = \sigma_f E_p B_c \left[1 - \left(\frac{W_c}{S}\right)^n\right]$$

where B_c embodies canopy resistance, including soil moisture stress. The factor $(W_c/S)^n$ serves as a weighting coefficient to suppress E_t in favor of E_c as the canopy surface becomes increasingly wet.

latent heat flux is therefore the sum of the direct evaporation and canopy transpiration terms. This is a reasonable assumption given the relative insignificance of E_c compared with E_{dir} and E_t.

evaporation is the sum of evaporation from the soil (E_g), wet canopies (E_r), and evapotranspiration (E_{tr}):

$$E_g = \rho_a(1 - \text{veg})\frac{\beta}{R_a + R_{bw}}[q_{sat}(T_s) - q_a], \quad (1)$$

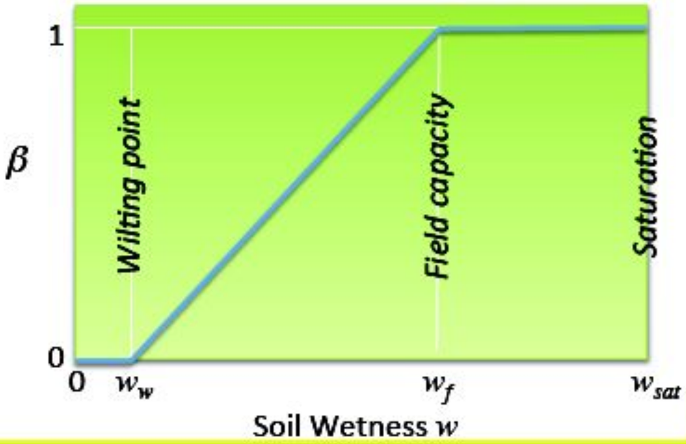
$$E_r = \rho_a \text{veg}\frac{\delta}{R_a + R_{bw}}[q_{sat}(T_s) - q_a], \quad \text{and} \quad (2)$$

$$E_{tr} = \rho_a \text{veg}\frac{1-\delta}{R_a + R_{bw} + R_c}[q_{sat}(T_s) - q_a], \quad (3)$$

where ρ_a is air density, veg is the fractional area covered by vegetation, β is the availability factor of water from wet soil, R_a is the aerodynamic resistance, R_{bw} is the quasi-laminar boundary layer resistance for water vapor, R_c is the canopy resistance, $q_{sat}(T_s)$ is the saturated mixing ratio at the soil surface temperature T_s, q_a is the atmospheric mixing ratio in the lowest model layer, and δ is the fraction of leaf area that is covered with water.

Evaporation from Bare Soil

- Bare soil evaporation draws moisture only from the top layer of soil (that exposed to the air).
- The simplest (and first) formulation of soil in an LSM was a “Bucket model” by S. Manabe*. It used a “beta” formulation for soil evaporation:



$$E = \beta E_P$$

$$\beta = 0, \qquad w \le w_w$$

$$\beta = \frac{w - w_w}{w_f - w_w}, \qquad w_w < w < w_f$$

$$\beta = 1, \qquad w \ge w_f$$

* Manabe, 1969: *Mon. Wea. Rev.*, 739-774.

Evapotranspiration from open water

- Evaporation from open water occurs at the potential rate.
- Priestley-Taylor formulation for wet surfaces:

$$E_P = \alpha \frac{mR_{NET}}{\lambda_v (m+\gamma)} \qquad m = \frac{de_s}{dT}$$

  - m is slope of saturation vapor pressure with temperature at surface temperature T (recall the Clausius-Clapeyron relationship).
  - R_{NET} is net energy available, minus that which warms the water.
  - γ is the psychrometric constant.
  - Empirical observation has shown $\alpha \cong 1.26$.
- E_P is called the potential evaporation. In this formulation, there is only dependence on net radiation and temperature.

Evapotranspiration from open water

- The Priestley-Taylor "fudge factor" α accounts for the aerodynamic aspect of evaporation. The Penman equation is slightly more sophisticated and accounts for it directly:

$$E_P = \frac{mR_{NET} + c_p\rho[e_s(T_S) - e(T_A)]/r_a}{\lambda_v(m+\gamma)}$$

  - Note that the vapor pressure deficit and aerodynamic resistance are expressed directly in this formulation.
  - Forms of this equation are commonly used in models for evaporation from wet surfaces or open water in models.

- Note: Some LSMs neglect possible evaporation from open water entirely, and some leave it to a lake model or parameterization to handle.

Surface and subsurface Runoff

[*Beven and Kirkby*, 1979]. For a rainfall rate P (net of interception), saturation excess surface runoff is calculated as

$$R_s = f_{sat} P.$$

$$f_{sat} = 1 - \left(1 - \frac{S - S_0}{S_{\max} - S_0}\right)^{\frac{b}{b+1}}$$

where S_0 is the minimum storage below which there is no surface saturation, $S_{\max}$ is the maximum possible gridbox storage (at saturation) and b is a shape parameter. The interpretation of the value of b in terms of the shape of the pdf is discussed by *Moore* [1985]. Subsequent precipitation

and *Sivapalan*, 1997; *Niu et al.*, 2005]. Subsurface runoff is calculated as

$$R_b = R_{b\max} e^{-f z_w} \quad (3)$$

where the parameter $R_{b\max}$ is the subsurface runoff when the depth to the water table is zero. *Niu et al.* [2005] considered

Clark and Gidney (2008)

Water movement within soil layer

$$\underbrace{\frac{\partial \theta}{\partial t}}_{\text{Soil moisture change over time}} = \frac{\partial}{\partial z}\left[\underbrace{k\left(\frac{\partial(\psi-\psi_E)}{\partial z}\right)}_{\text{Vertical water flux (Darcy's law)}}\right] - \underbrace{Q}_{\text{Sink term (evapotranspiration, runoff)}}$$

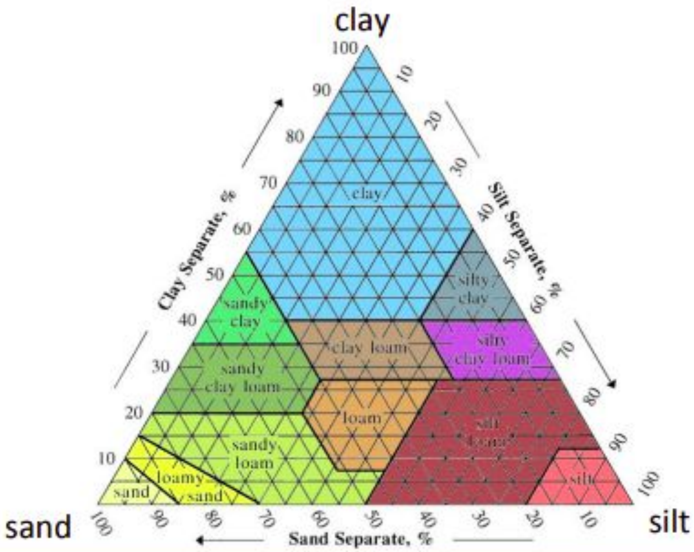
Hydraulic conductivity dependent on water content and soil type

- Mineral and organic properties
- Vertical profile

Texture and Soil Properties

- It is common in land models to define a small number of <u>texture classes</u>, each with a set of parameters defining its ability to conduct or transfer heat and water in the vertical.

- An example is shown on the right



Soil texture and physical properties

Soil texture	Field capacity m^3/m^3	Permanent wilting point m^3/m^3	Bulk density g/cm^3
Sand	0.10-0.20	0.03-0.10	1.55-1.80
Loamy Sand	0.11-0.19	0.03-0.10	1.60
Sandy Loam	0.15-0.27	0.06-0.12	1.40-1.60
Loam	0.20-0.30	0.11-0.17	1.35-1.50
Silt Loam	0.22-0.36	0.09-0.21	1.30
Clay Loam	0.31-0.42	0.15-0.20	1.30-1.40
Silt Clay Loam	0.30-0.37	0.17-0.24	1.35
Silty Clay	0.35-0.46	0.17-0.22	1.25-1.35
Clay	0.33-0.49	0.19-0.24	1.20-1.30

Routing (to account for lateral movement of runoff)

N.B. the runoff values coming from LSM are gridded values and are not connected to form streamflow

The runoff transformation (or river routing) model is based on the water balance equation for a channel, which can be written as

$$\frac{dS_r}{dt} = Y_{in} - Y_{out}, \qquad (1)$$

where S_r is water storage in the channel within a single grid cell, Y_{in} is water inflow into the channel (both from channels in adjacent cells and as a result of lateral inflow in the cell under consideration), Y_{out} is water flow in the channel at the grid cell outlet. The value of Y_{in} is commonly taken to be constant within each time step used to describe runoff transformation in the channel network. The parameterization of Y_{out} is based on the relationship

$$Y_{out} = \frac{u_e}{d_c} S_r, \qquad (2)$$

where d_c is the distance between grid cells, u_e is the effective velocity of water flow in the channel (with accounting for channel meandering). The mean global value of u_e is about 0.35–0.36 m/s [25, 30, 35].

Substituting (2) into (1) and solving the obtained equation, we obtain the recurrent relationship that describes the dynamics of water in the channel and allows us to readily determine the values of water flow in the channel Y_{out} corresponding to the computational time step:

$$S_r(t_{i+1}) = C_{\Delta t} S_r(t_i) + (1 - C_{\Delta t}) \frac{d_c Y_{in}}{u_e},$$
$$C_{\Delta t} = \exp\left(-\frac{u_e}{d_c}\Delta t\right), \quad \Delta t = t_{i+1} - t_i, \qquad (3)$$

where Δt is time step in the calculation of runoff transformation, and $S_r(t_i)$ and $S_r(t_{i+1})$ are water storages in

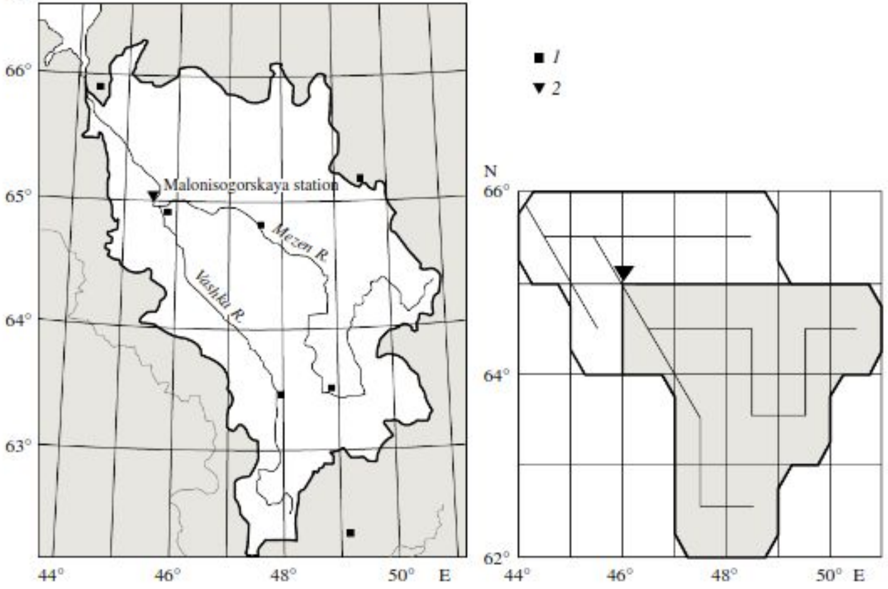


Fig. 1. (a) Mezen River basin and (b) its schematization for streamflow simulations. (*1*) Meteorological, (*2*) streamflow gauging station.

Role of vegetation for Carbon balance

There are two primary purposes of modelling vegetation physiology and soil biogeochemistry in LSMs.

1. the physical structure of vegetation and the process of photosynthesis affect the exchange of momentum, energy, water and CO_2 at the land-atmosphere boundary.
2. the vegetation and soil processes affect allocation of the Earth's carbon to storage in the land.

Carbon balance

$$\underbrace{R_C - E_C}_{\text{Interface}} = \underbrace{\Delta S_C}_{\text{Land}}$$

- R_C is carbon respiration (uptake by plants), silicate weathering
- E_C is carbon emission (microbe respiration, decomposition, wood burning, fossil fuels, wildfires, volcanic eruptions etc.)
- ΔS_C is change in carbon storage in the land (vegetation biomass, soil organic carbon, mineral formation, etc.)