Simulating Soil Moisture Dynamics in NCEP Numerical Weather/Climate Prediction Models

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Outline

- Introduction of LSM in NCEP Model Systems
  - Role of soil water
  - LSM in NOAA Model Production Suite
  - Features of Noah
  - Outputs of Noah
- Soil Physics of Noah
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  - Soil water retention curves & Pedotransfer functions
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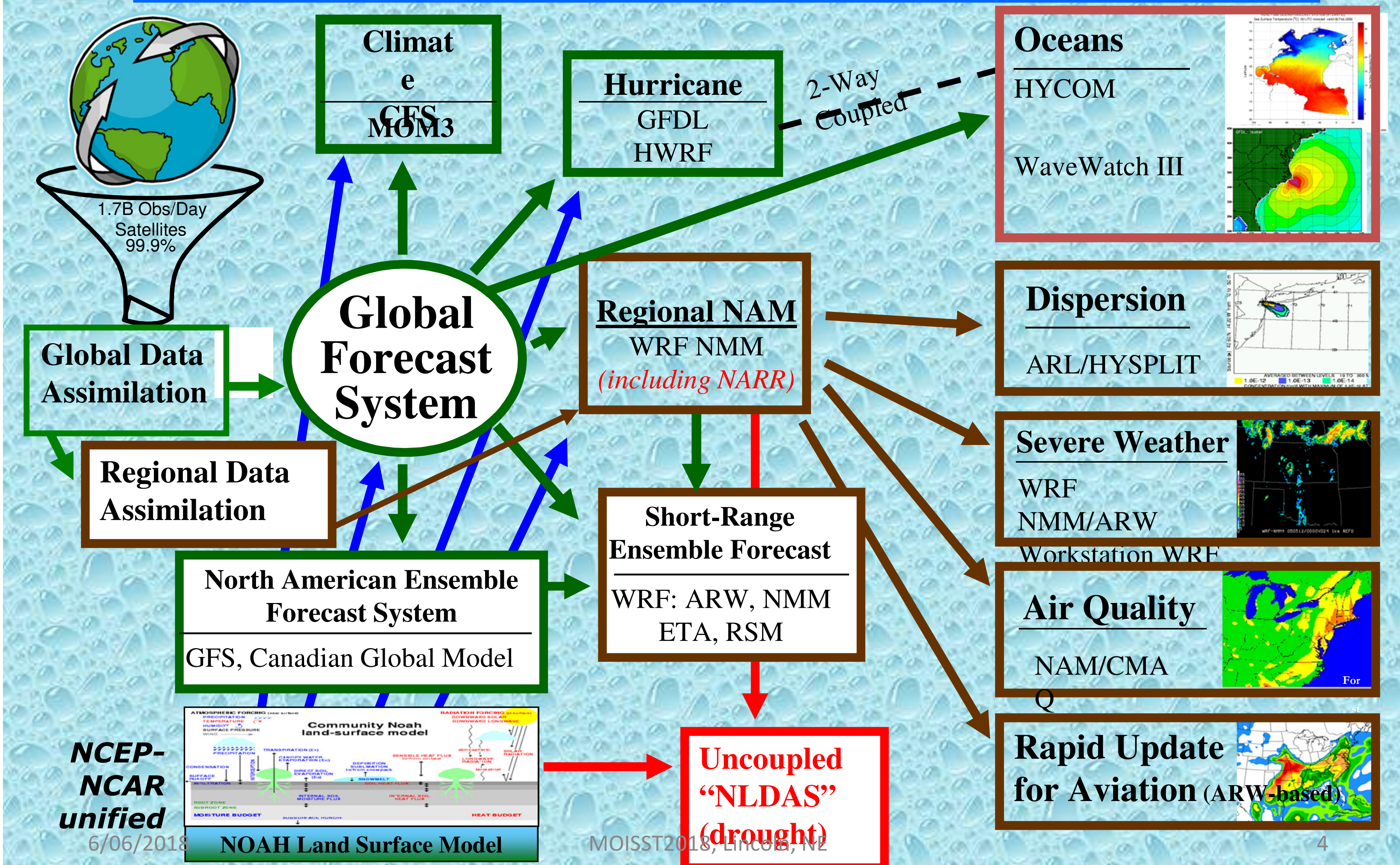
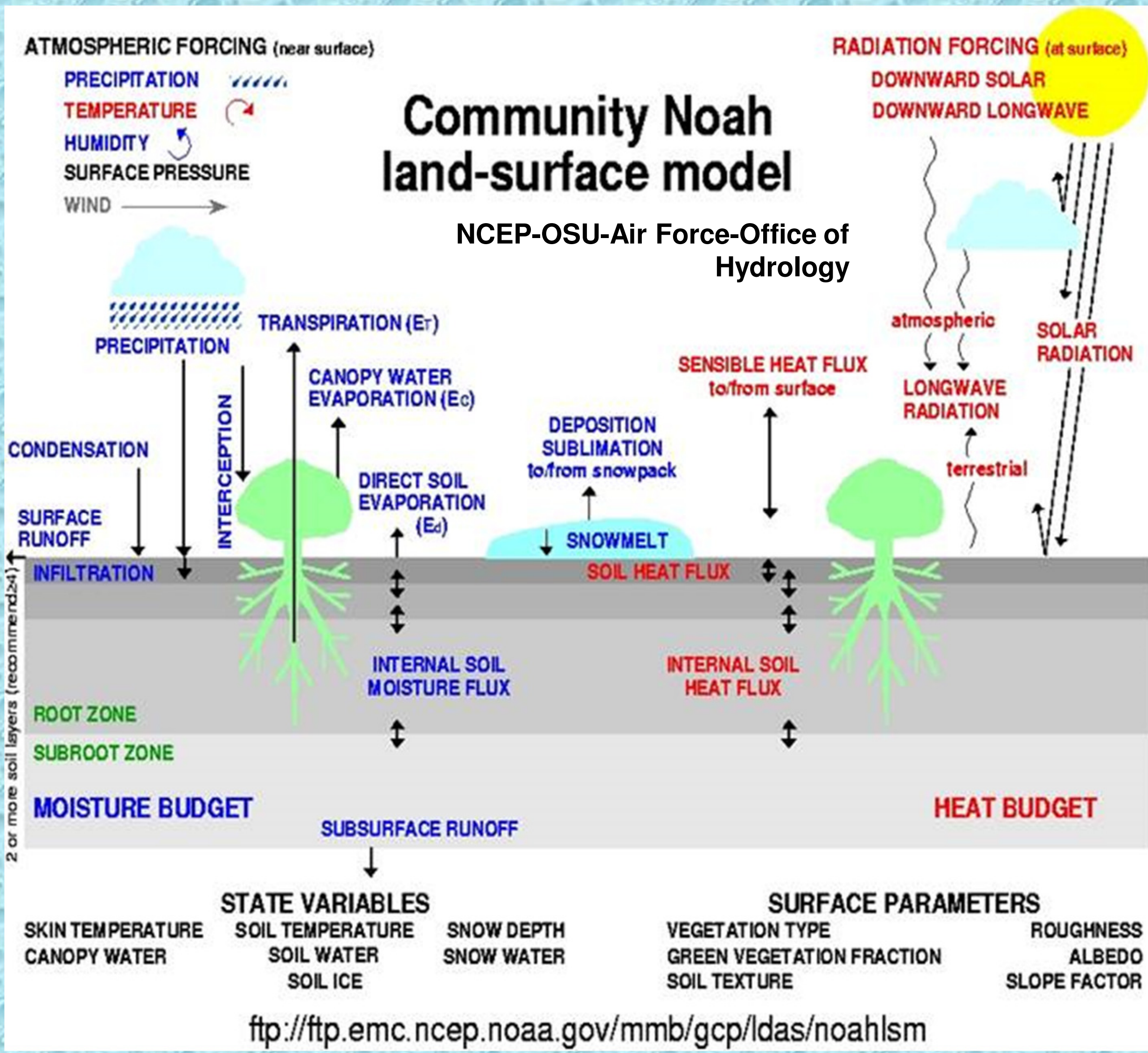
The Role of Soil Moisture in NWP

- Soil moisture plays an important role in the development of weather patterns and the production of precipitation
- Soil moisture strongly affects the amount of precipitation that runs off into nearby streams and rivers.
- Improving the simulation of soil moisture dynamics in numerical weather/climate prediction models can lead to significant forecast skill improvements.

Noah Land Model Connections in NOAA's NWS Model Production Suite

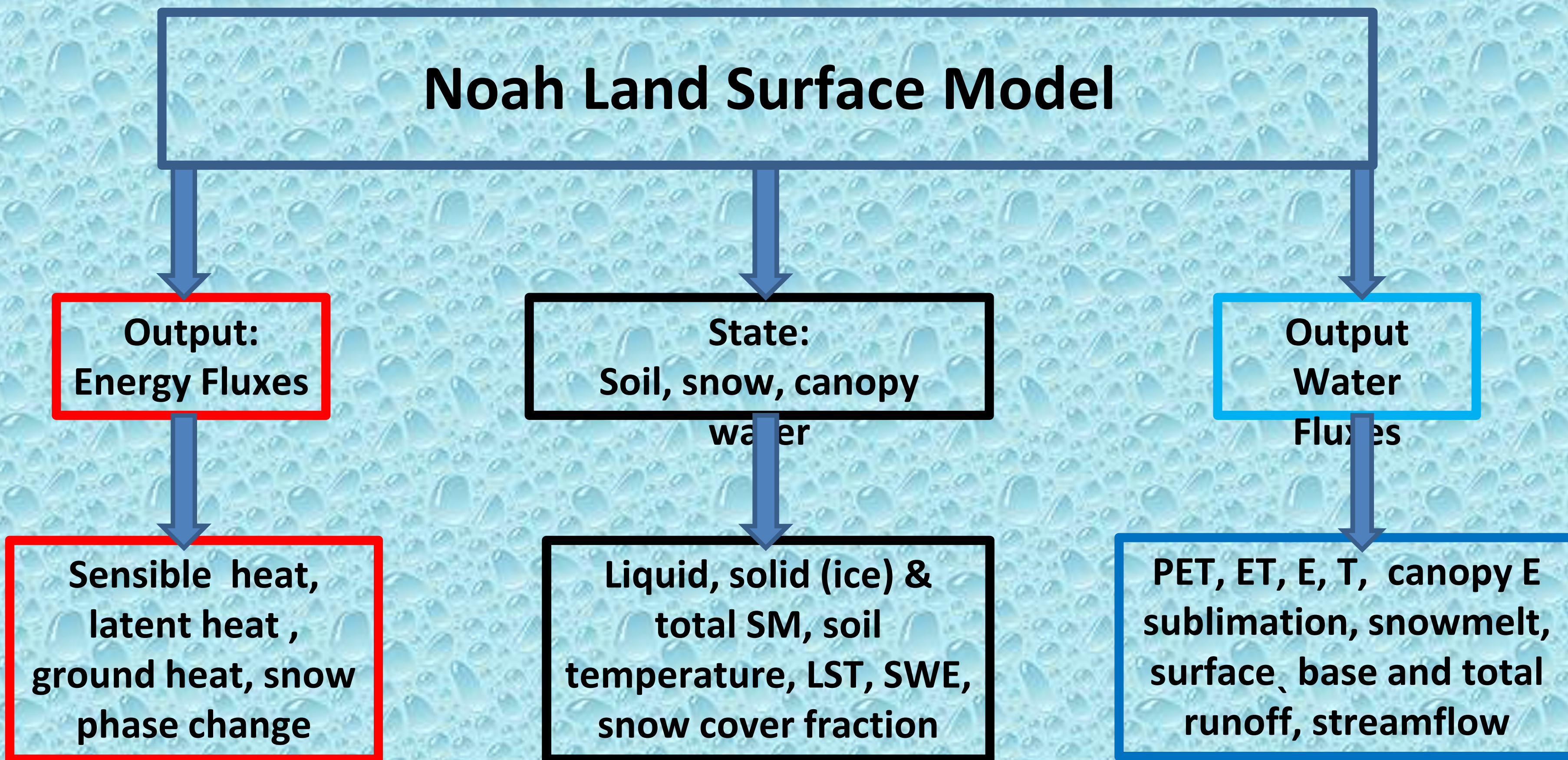


The Features of Noah



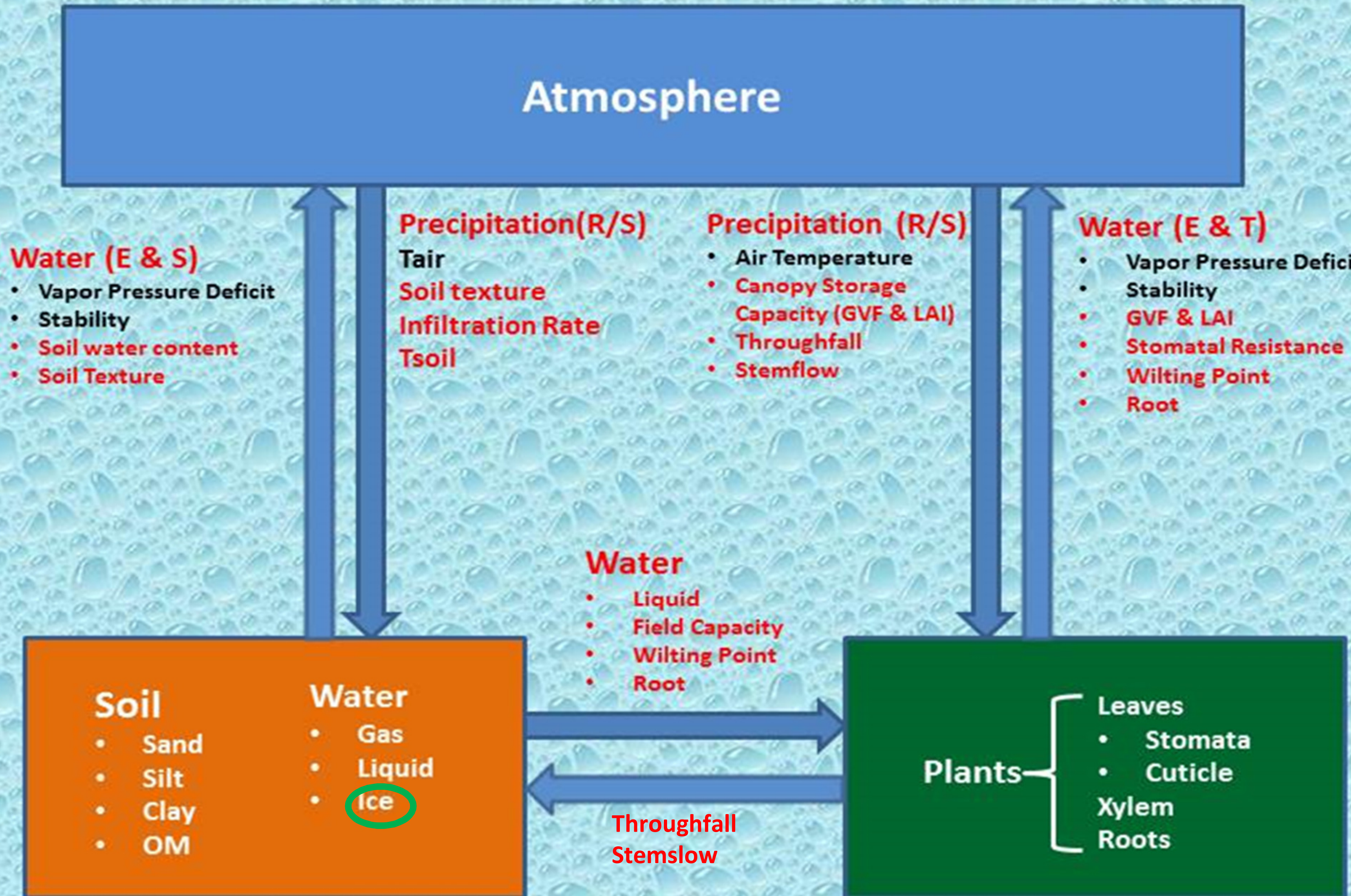
1) Multiple soil layers (usually 4 layers: 0-10,10-40, 40-100 and 100-200 cm depth) with a one-layer vegetation canopy;
2) Spatially varying root depth and seasonal cycle of vegetation cover;
3) Frozen soil physics for cold regions, and improved soil and snowpack thermal conductivity;
4) Predicts total soil moisture, liquid soil moisture and soil ice, soil temperature, land surface skin temperature, land surface evaporation and sensible heat flux, and runoff.

Outputs of Noah



Hourly products

Water in the atmosphere-soil-plants continuum



Infiltration

$$I_{c,t} = D_b[1 - exp(-K_{dt}\Delta t)]$$

$$Db(i) = \mathbf{Dbmax}\ (\mathbf{i})[1 - \frac{\mathbf{SH2O}\ (i) + \mathbf{SIce}(\mathbf{i}) - \mathbf{SMCWLT}(\mathbf{i})}{\mathbf{SMCMAX}(\mathbf{i}) - \mathbf{SMCWLT}(\mathbf{i})}]$$

$$Dbmax(i) = -\mathbf{Z}(\mathbf{i})[\mathbf{SMCMAX}(\mathbf{i}) - \mathbf{SMCWLT}(i)]$$

$$Ir = (\frac{PX * \mathbf{I}_{C,t}}{\mathbf{PX} + \mathbf{I}_{C,t}})/\Delta T$$

Where $I_{c,t}$ the cumulative infiltration capacity at a certain moment in time t, Δt is the model time step, K_{dt} is a constant, and D_b represents the spatially averaged soil water storage, Dbmax(i), SH2O(i), Sice(i), SMCWILT(i) and SMCMAX (i) are the maximum soil water storage, the liquid water, Ice, plant wilting point and soil porocity in soil layer I, Ir the infiltration rate for the whole soil column, PX is the precipitation input into the whole column.

Richard's Equation

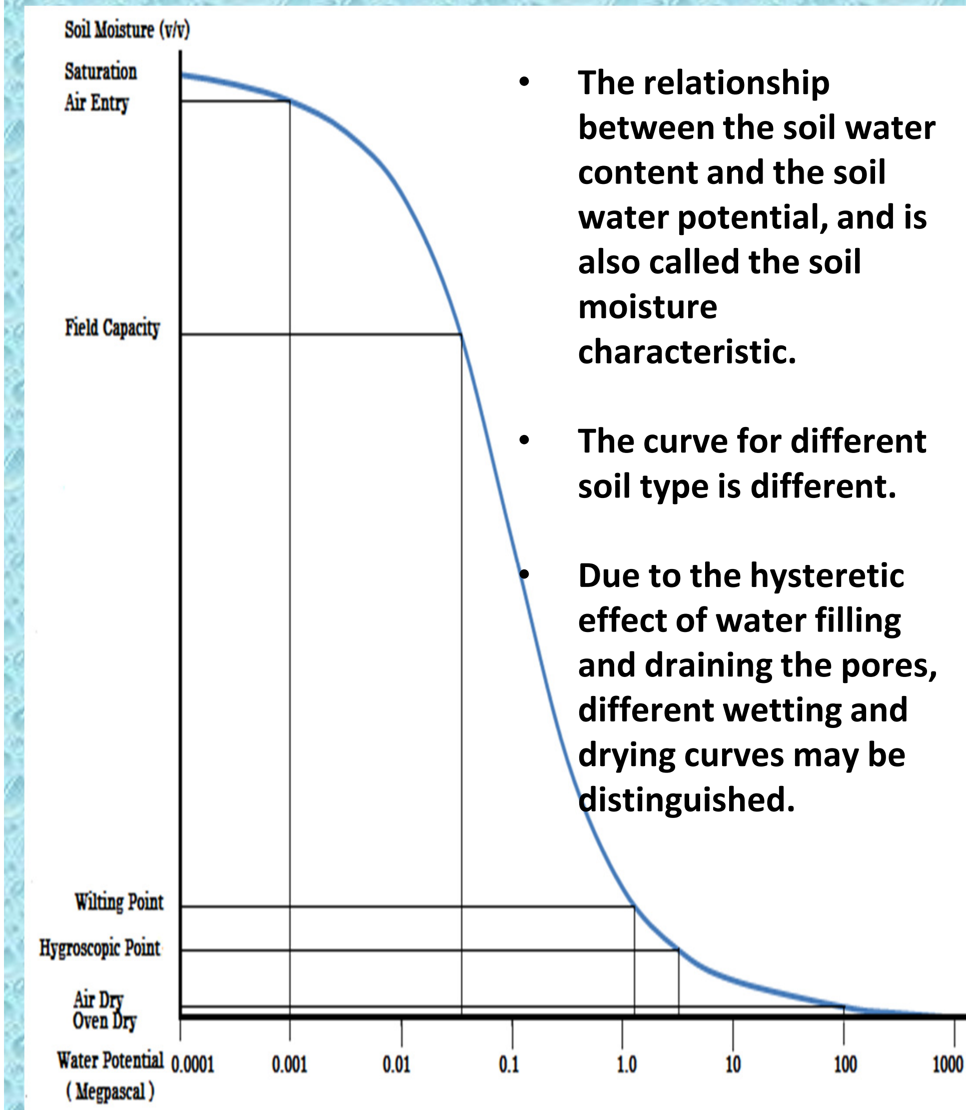
Soil Moisture (θ):

$$\frac{\partial \theta}{\partial t} = \frac{\partial K_\theta}{\partial z} + \frac{\partial}{\partial z}\left(D_\theta \frac{\partial \theta}{\partial z}\right) + F_\theta$$

Crank-Nicholson numerical scheme

- **D_θ is the soil water diffusivity and**
- **K_θ is the hydraulic conductivity,**
- **F_θ is a source/sink term for precipitation & evapotranspiration.**
- **Soil water retention curves & Pedo-Transfer Functions are needed to get D_θ and K_θ.**
- **D_θ and K_θ are nonlinear functions of soil moisture and soil type (*Cosby et al 1984*);**

Soil Water Retention Curve & Pedotransfer functions (PTF)



- The relationship between the soil water content and the soil water potential, and is also called the soil moisture characteristic.
- The curve for different soil type is different.
- Due to the hysteretic effect of water filling and draining the pores, different wetting and drying curves may be distinguished.

1	Gardner (1958) lognormal distribution	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[1+(\alpha\psi)^n\right]^{-1}$	Does not work well for very wet soils
2	Brooks-Corey (1964)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)(\alpha\psi)^{-\lambda}$	Discontinuous, not well for dry soil
3	Farrel and Larson (1972)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[1-\left(\frac{\ln(\psi/\psi_{cr})}{\alpha}\right)\right]$	does not give the sigmoidal curve
4	Campbell (1974)	$\theta(\psi)=\theta_s(\alpha\psi)^{\lambda}$	Does not work well for very dry soils
5	van Genuchten (1980)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[1+(\alpha\psi)^n\right]^{-m}$	Fitting parameters, Not work for dry soils
6	Tani (1982)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[1+(\alpha\psi)e^{-\alpha\psi}\right]$	
7	Williams et al. (1983)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\exp\left[A+B\ln(\psi)\right]$	does not give the sigmoidal curve
8	McKee and Bumb (1984)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)A\exp\left[a_6\psi-B\right]$	does not give the sigmoidal curve
9	McKee and Bumb (1987)	$\theta(\psi)=\theta_r+1/\left[1+A\exp(a_6\psi-B)\right]$	May not work well for very wet soils
10	Russo (1988)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[(1+0.5\alpha\psi)e^{0.5\alpha\psi}\right]^{2/n+2}$	Did not work well
11	Fredlund-Xing (1994)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)/\left\{\ln\left[2.7183+(\alpha\psi)^n\right]\right\}^m$	Complex
12	Assouline (1998)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left\{1-\exp\left[-\delta\left(\psi^{-1}-\psi_L^{-1}\right)^{\beta}\right]\right\}$	No cross validation
13	Kosugi (1999) lognormal distribution	$\theta(\psi)=\theta_r+\frac{1}{2}(\theta_s-\theta_r)erfc\left[\frac{\ln(\psi/\psi_m)}{\sigma\sqrt{2}}\right]$	More complex
14	Durner (1994); Dexter (2008); Omuto, (2009)	$\theta(\psi)=\theta_r+\theta_{s1}e^{-\alpha_1\psi}+\theta_{s2}e^{-\alpha_2\psi}$	Biexponential, Very complex, works for multimodel soil.
15	Buitenwerf (2014) Exponential	$\theta(\psi)=(\theta_s+\theta_r)e^{-\alpha\psi}$	does not give the sigmoidal curve
16	Matlan et al. (2014)	$\theta(\psi)=\theta_r+(\theta_s-\theta_r)/\left[1+e^{(n*\ln(\psi)-b)}\right]$	Modifed Gardner Method, no cross validation

Widely Used Pedotransfer Functions (PTF)

Brook & Corey (1964)
Clapp & Hornberger (1978)

$$\Theta = \left(\frac{\Psi_b}{\Psi}\right)^{\lambda}$$

$$K = K_s \Theta^{2b+3}$$

$$D_\theta = -\left(\frac{bK_s\psi_b}{\theta_s}\right)\left(\frac{\theta}{\theta_s}\right)^{b+3}$$

ψ_b -- air-entry value of suction
ψ -- Suction or soil water potential
λ -- Pore-size distribution index

Van Genuchten (1980)

$$\Theta = \left(\frac{1}{1+(a\psi)^n}\right)^n$$

$$K = K_s \Theta^{1/2}[1-(1-\Theta^{1/m})^n]^2$$

$$D_\theta = K\left(\frac{\partial\theta}{\partial\Psi}\right)$$

a , m and n are three shape parameters;
a is related to the inverse of the air entry suction (cm^{-1})
n is a measure of the pore-size distribution (dimensionless).

$$\Theta = \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

θ_r -- residual volumetric water content

θ_s -- Saturated volumetric water content

Computation of Surface Water & Latent Heat Fluxes

Surface Water Budget

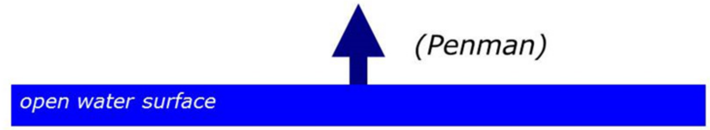
$$\Delta S = P - R - E$$

ΔS = change in land-surface water
P = precipitation
R = runoff
E = evapotranspiration
P-R = infiltration of moisture into the soil

• **ΔS** includes changes in soil moisture, snowpack (cold season), and canopy water (dewfall/frostfall and intercepted precipitation, which are small).
• Evapotranspiration is a function of surface, soil and vegetation characteristics: canopy water, snow cover/depth, vegetation type/cover/density & rooting depth/density, soil type, soil water & ice, surface roughness.
• Noah model provides: **ΔS**, **R** and **E**.

Potential Evaporation

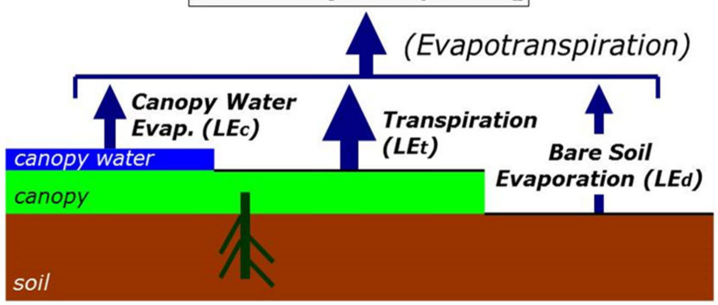
$$LE_p = \frac{\Delta(R_n - G) + \rho c_p C_h U \delta e}{\Delta + \gamma}$$



Δ = slope of saturation vapor pressure curve
Rn-G = available energy
ρ = air density
cp = specific heat
Ch = surface-layer turbulent exchange coefficient
U = wind speed
δe = atmos. vapor pressure deficit (humidity)
γ = psychrometric constant, fct(pressure)

Surface Latent Heat Flux

$$LE = LE_c + LE_t + LE_d$$



• **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**.

Surface Latent Heat Flux (cont.)

Canopy Water Evaporation (LEc): $LE_c = \left(\frac{C_w}{C_s}\right)^{n_c} LE_p$

• **Cw**, **Cs** are canopy water & canopy water saturation, respectively, a function of veg. type; **nc** is a coeff.

Transpiration (LEt): $LE_t = \frac{\Delta(R_n - G) + \rho c_p C_h U \delta e}{\Delta + \gamma(1 + C_h U / g_c)}$

$g_c = g_{Cmax}(g_\downarrow \cdot g_T \cdot g_{\delta e} \cdot g_\Theta)$

• **gc** is canopy conductance, **gcmax** is maximum canopy conductance and **gs⇓**, **gT**, **gδe**, **gΘ** are solar, air temperature, humidity, and soil moisture availability factors, respectively, all functions of vegetation type.

Bare Soil Evaporation (LEd): $LE_d = \left(\frac{\Theta - \Theta_d}{\Theta_s - \Theta_d}\right)^{n_d} LE_p$

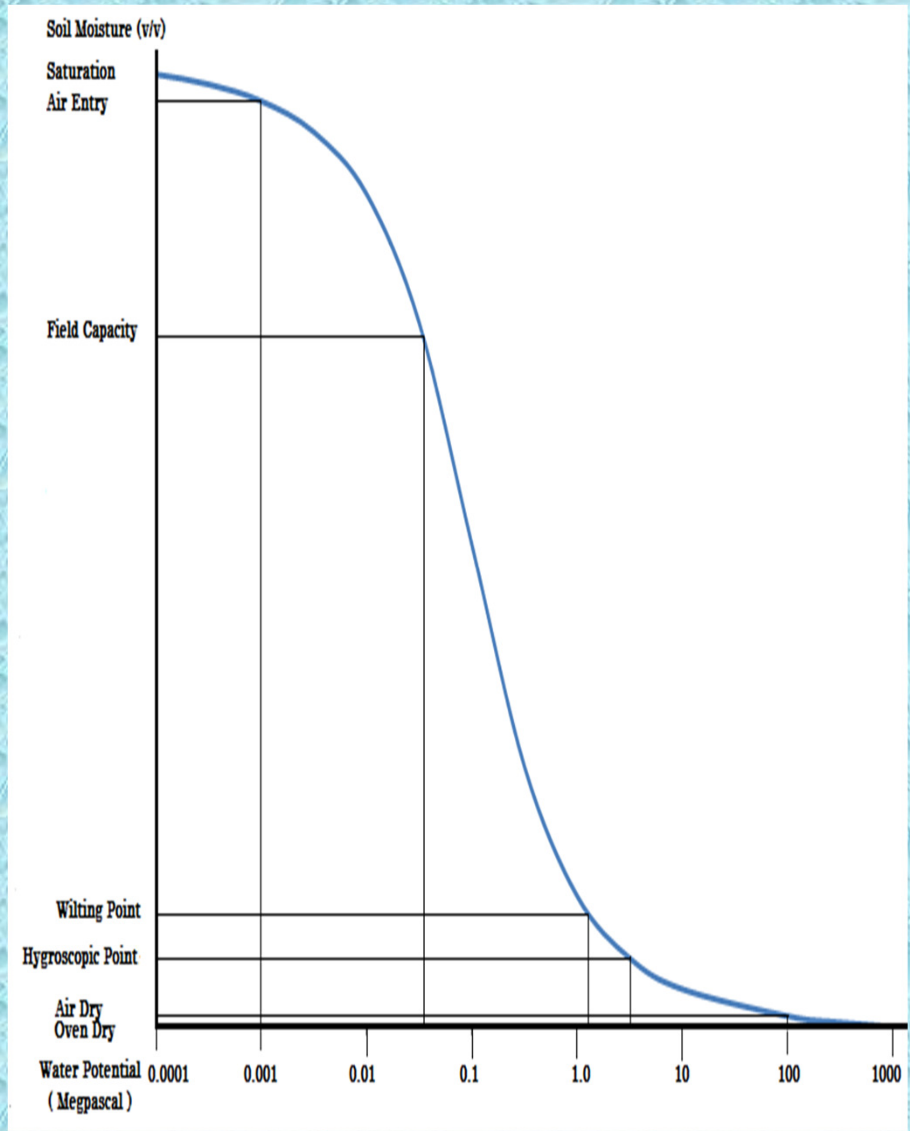
• **Θd**, **Θs** are dry (minimum) & saturated soil moisture contents, respectively, a fct of soil type; **nd** is a coeff.

Current Soil Parameters Used in NOAH Model

- **One value for all layers**
- **Developed by Cosby in 1984 based on limited soil data**
- **1km Resolution for US, 12 km for global**
- **Most parameters are from literature**
- **Go forward:**
  - **More soil layers (9-10)**
  - **Thinner top layers (1-2 cm)**
  - **Deeper depth (3 m)**

Soil Water Potential and Water Condition

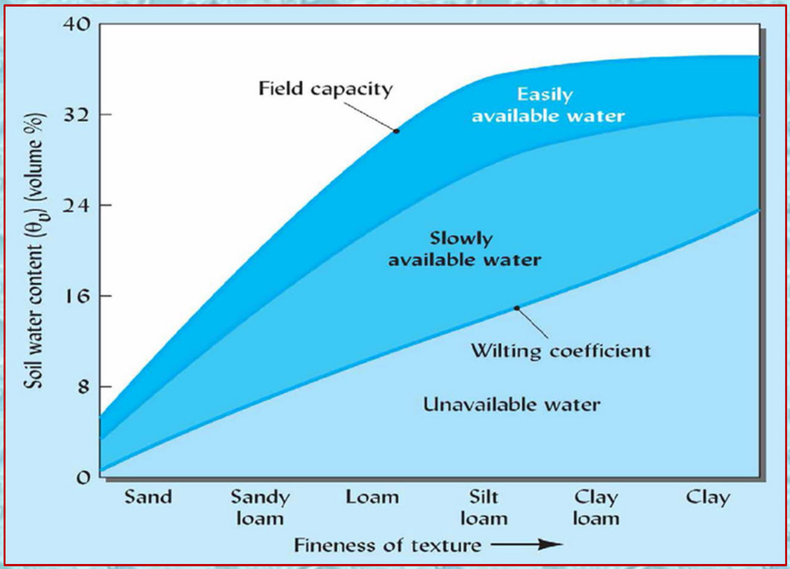
Parameter	Water Content	Water Potential Bar	Water Potential Mpa
Saturation	Porosity	0.001	0.0001
Air Entry	?	0.01	0.001
		0.1	0.01
Field Capacity		0.333	0.0333
Wilting Point		15	1.5
Hygroscopic Point (in humid air)	?	31	3.1
		100	10
Air Dry (in dry air)	?	1000	100
Oven Dry	0	10000	1000

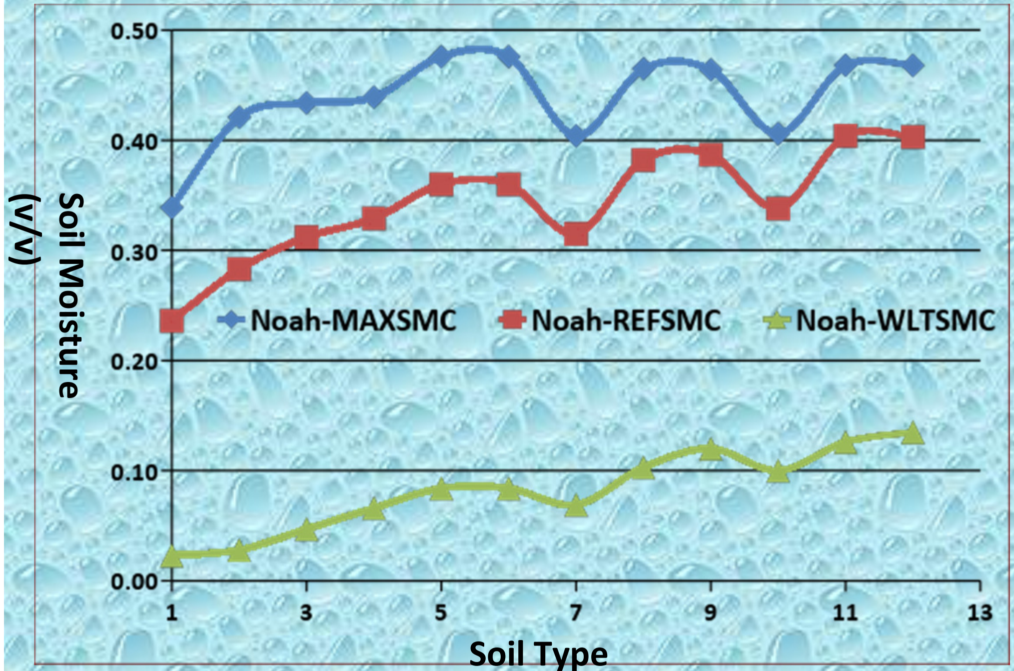


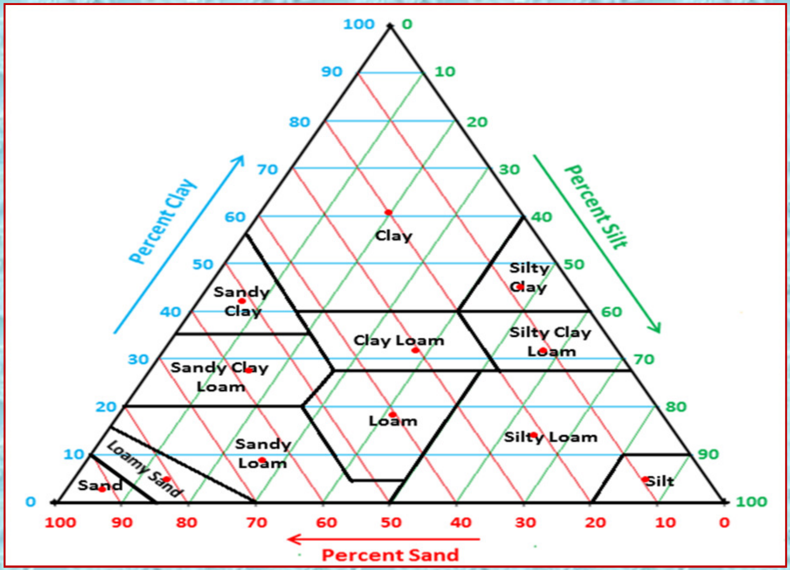
Develop and apply new soil parameters in NCEP model systems

a. **Soil physical parameters affect soil thermal and hydrological processes in LSM.**

b. **12 major soil types based USDA soil classification, and thermal and hydraulic parameters are created for each soil types and are inputted into model as a table .**





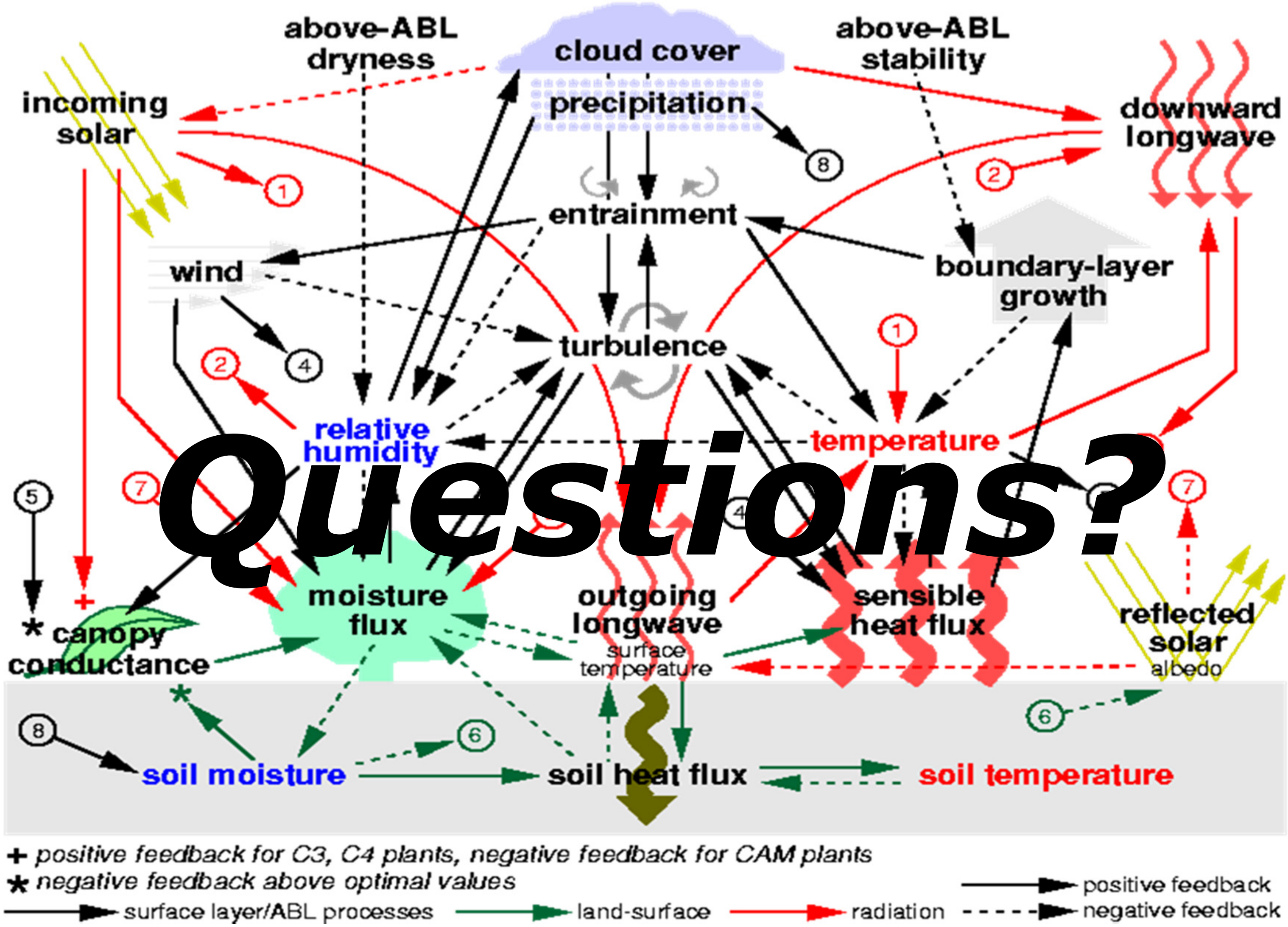


Summary

- The Noah LSM is a physically based model, can be run in offline mode (NLDAS/GLDAS) or a fully coupled mode (CFS/GFS/NAM)
- The LSM produces continuous spatial and temporal soil moisture products, including multi-layer soil moisture, evapotranspiration and total runoff/streamflow. These products are very important for drought and flooding monitoring tasks in operations, practical applications and research
- It is needed to measure liquid water and ice in soil for model validation
- It is needed to measure some important soil parameters to develop and improve models
- We are looking for collaboration from soil community for model validation, model development. We also welcome you to use our products.

Thank You very much

Questions?



Physics "Wheel of Pain"