Validation of a simplified land surface model and its application to the case of shallow cumulus convection development

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January 2013
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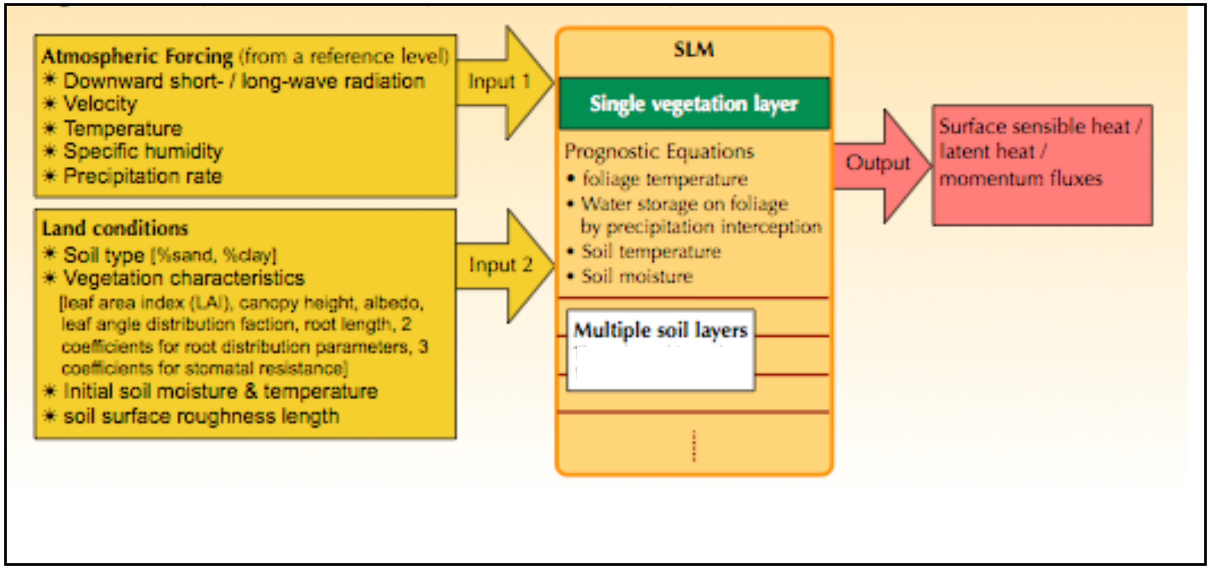
Simplified Land Model (SLM)

- Design Goal
  - Going back to first generation of land models
  - Use minimal set of parameters characterizing land surface conditions
  - Incorporate only the processes necessary to simulate diurnal convection over land
    - diurnal variations of radiative fluxes / turbulent fluxes of heat, moisture and momentum

- SLM structure
  - 1 vegetation layer + multiple soil layers
  - Vegetation layer : single type of vegetation, 100% coverage
  - Soil layers : soil type invariable with depth



Simplified Land Model (SLM)

Prognostic Equation

1. Foliage Temperature (T_c)

$$c_{p\,vege}\frac{dT_c}{dt} = R_{nc} - H_c - LE_c$$

R_{nc} : Net radiation on canopy $[W/m^2]$

H_c : Sensible heat flux from canopy $[W/m^2]$

LE_c : Latent heat flux from canopy $[W/m^2]$

$c_{p\,vege}$: Heat capacity of canopy $[W/m^2]$

2. Moisture storage on canopy (M_c)

$$\frac{dM_c}{dt} = P_c - D_c - \frac{LE_{wc}}{L_v}$$

P_c : Precipitation interception rate $[mm/s]$

D_c : Drainage rate from canopy $[mm/s]$

LE_{wc} : Evaporation rate from water held on leaves $[mm/s]$

L_v : Latent heat of vaporization $[J/kg]$

- Precipitation on Canopy
  - Precipitation direct fall-through (P_D)
    - Exponentially decaying light attenuation method for radiative fluxes is applied
      : Solar zenith angle for exponential decay coefficient (k_a) is assumed to be 90° for precipitation

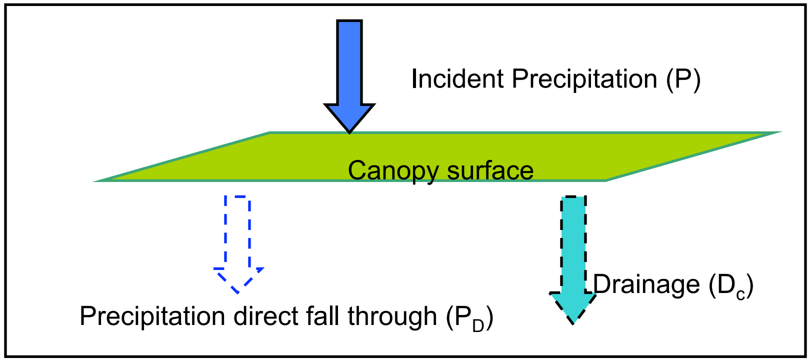
$$P_D = P\exp(-k_a LAI)$$

  - Precipitation interception on canopy (P_c)

$$P_C = P - P_D$$

  - Drainage from canopy (D_C)
    - When water held on canopy exceeds its limit (S_C)
      : no interception & water excess dripping

$$D_C = \begin{cases} P_c + \dfrac{(S_c - M_c)}{\Delta t} & M_c \geq S_c \\ 0 & otherwise \end{cases}$$



Simplified Land Model (SLM)

- **Soil Model**
  - Diffusion method is applied for soil heat and moisture transport
  - Soil texture (%SAND, %CLAY) determines soil characteristics
    - Following Cosby et al. (1984)
      - Hydraulic conductivity at saturation
      - Volumetric water content at saturation (porosity)
      - Soil matric potential at saturation
    - Following de Vries (1963), soil solids heat capacity
  - Soil thermal conductivity is determined by weighing dry soil and saturated soil heat conductivity (Johansen, 1975)

❖ Soil surface albedo

:Dependent upon first soil layer wetness.

Following Idso et al. (1975)

$$\alpha_s = \begin{cases} 0.31 - 0.34 W_1 & W_1 \le 0.5 \\ 0.14 & otherwise \end{cases}$$

- **Prognostic Equation for soil**

3. <u>Soil Temperature</u>

$$c\frac{\partial T}{\partial t} = -\frac{\partial G}{\partial z} = -\frac{\partial}{\partial z}\left(-\lambda_h \frac{\partial T}{\partial z}\right)$$

c : volumetric soil heat capacity $[\mathrm{J/m^3}K]$

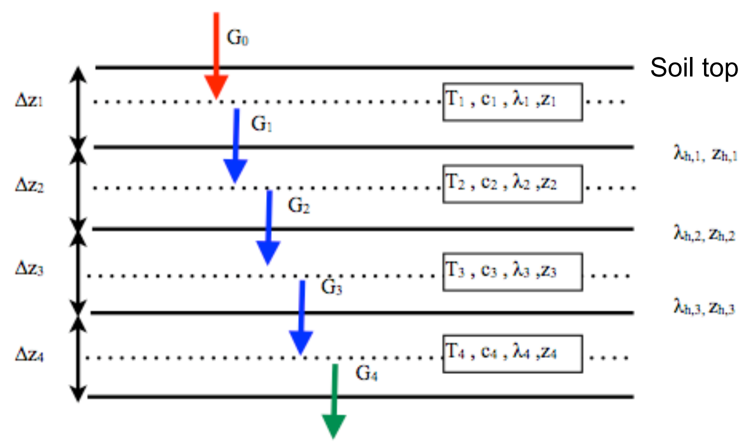
G : heat flux across interfacial layer (between adjactent soil layers)

λ_h : soil heat conductivity at interfacial layer

depth - weighed between adjacent layers' heat conductivity

$$G_i = -\lambda_{h\,i}\frac{T_{i+1} - T_i}{z_{i+1} - z_i} \quad downward\;\; for\; G > 0$$

$$c_i\frac{\Delta T_i}{\Delta t} = -\frac{G_{i+1} - G_i}{z_{i+1} - z_i}$$



Simplified Land Model (SLM)

- **Prognostic Equation for soil**

4. <u>Soil Wetness</u> (W)

First layer :

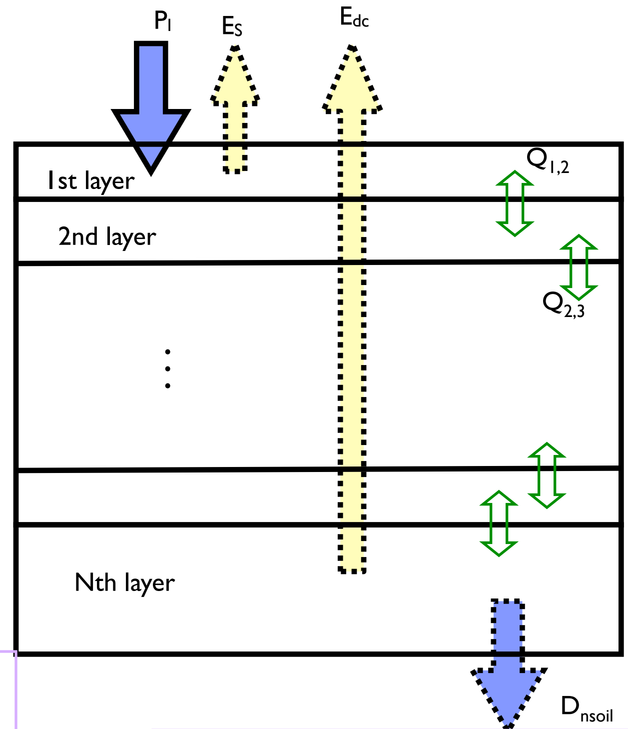
$$\frac{\partial W_1}{\partial t} = \frac{1}{\theta_s d_1}\left(P_I - Q_{1,2} - E_s - F_{root,1}E_{dc}\right)$$

Second $-(N-1)_{th}$ *layer :*

$$\frac{\partial W_i}{\partial t} = \frac{1}{\theta_s d_i}\left(Q_{i-1,i} - Q_{i,i+1} - F_{root,i}E_{dc}\right)$$

Bottom layer :

$$\frac{\partial W_{nsoil}}{\partial t} = \frac{1}{\theta_s d_{nsoil}}\left(Q_{nsoil-1,nsoil} - F_{root,nsoil}E_{dc} - D_{nsoil}\right)$$



- **Water transport between layers (Q)**
  - Diffusion method is applied

$$Q = -K\frac{\partial(\Psi + z)}{\partial z} = -K\left(\frac{\partial \Psi}{\partial z} + 1\right)$$

$$Q_{i,i+1} = -K_{h,i}\left(\frac{\Psi_{i+1} - \Psi_i}{z_{i+1} - z_i}\right) \quad \textit{downward flux for } Q > 0$$

- **Root density Fraction (F_{root}) [Zeng (2001)]**

Cumulative root density fraction(Y) is written as

$$Y_i = 1 - \frac{1}{2}\left(e^{-add_i} + e^{-bdd_i}\right)$$

where dd_i is the depth of soil layer i from soil top,

a and b are vegetation depedent parameter.

Thus, for fraction of root densitiy in each soil layer

$$F_{root,i} = Y_i - Y_{i-1}$$

θ_s : soil porosity

d_i : depth of soil layer [m]

$Q_{i,i+1}$: water transport between i & $(i+1)_{th}$ layer $[m/s]$

$F_{root,i}$: fraction of root density in each soil layer

E_s : direct evaporation at soil surface $[m/s]$

E_{dc} : transpiration rate $[m/s]$

P_I : precipitation infiltration rate $[m/s]$

D_{nsoil} : bottom layer drainage

Ψ_i : soil matric moisture potentail [m]

K_i : soil hydraulic conductivity $[m/s]$

$K_{h,i}$: soil hydraulic conductivity at interfacial layer depth - averaged between adjacent layers' K_i

Simplified Land Model (SLM)

- **Turbulent fluxes for heat and moisture**

: Bulk aerodynamic resistance method

- Sensible Heat flux

$$For\ soil: H_{soil} = \rho c_p \frac{(T_{soil1} - T_a)}{r_d}$$

$$For\ canopy: H_{canopy} = \rho c_p \frac{(T_c - T_a)}{r_b}$$

$$Total: H_{total} = H_{soil} + H_{canopy}$$

- Latent Heat Flux

$$For\ soil: \quad LE_{soil} = \rho L_v \frac{\beta(f_h q_*(T_{soil1}) - q_a)}{r_d}$$

$$For\ canopy: LE_{canopy} = LE_{wc} + LE_{dc}$$

$$LE_{wc} = \rho L_v \frac{W_c(q_*(T_c) - q_a)}{2r_b}$$

$$LE_{dc} = \rho L_v \frac{(1 - W_c)(q_*(T_c) - q_a)}{(2r_b + r_c)}$$

$$Total: LE_{total} = LE_{soil} + LE_{canopy}$$

For soil direct evaporation (LE_{soil}), molecular diffusion factor (ß) reduces evaporation when soil moisture (1st layer) is under its field capacity (Lee and Pielke ,1992).

- W_c : fraction of leaves that hold water upon it.

- **Bulk aerodynamic resistances**

Leaf boundary layer resistance (Dickinson et al., 1993)

$$r_b = \frac{1}{LAI\ C_v}\left(\frac{U_*}{d_{leaf}}\right)^{-0.5}$$

,where C_v is 0.01ms$^{-0.5}$

d_{leaf} (characteristic leaf length scale) is set to 4cm.

Under canopy aerodynamic resistance (Sakaguchi and Zeng, 2009)

$$r_d = \frac{1}{U_* C_{uv}}$$

C_{uv} is the turbulent transfer coeffeicient interpolated between the values for baresoil and dense canopy and written as

$$C_{uv} = C_{bare} e^{-LAI} + C_{dense}(1 - e^{-LAI})$$

C_{dense} (turbulent transfer coefficient under dense canopy) accounts for the undercanopy stability.

- **Stomatal resistance (Jacquemin and Noilhan, 1990)**

: function of air temperature (F1), water vapor pressure deficit (F2),solar radiation(F3) and soil moisture (F4).

$$r_c = \frac{r_{c\,min}}{LAIF_1F_2F_3F_4}$$

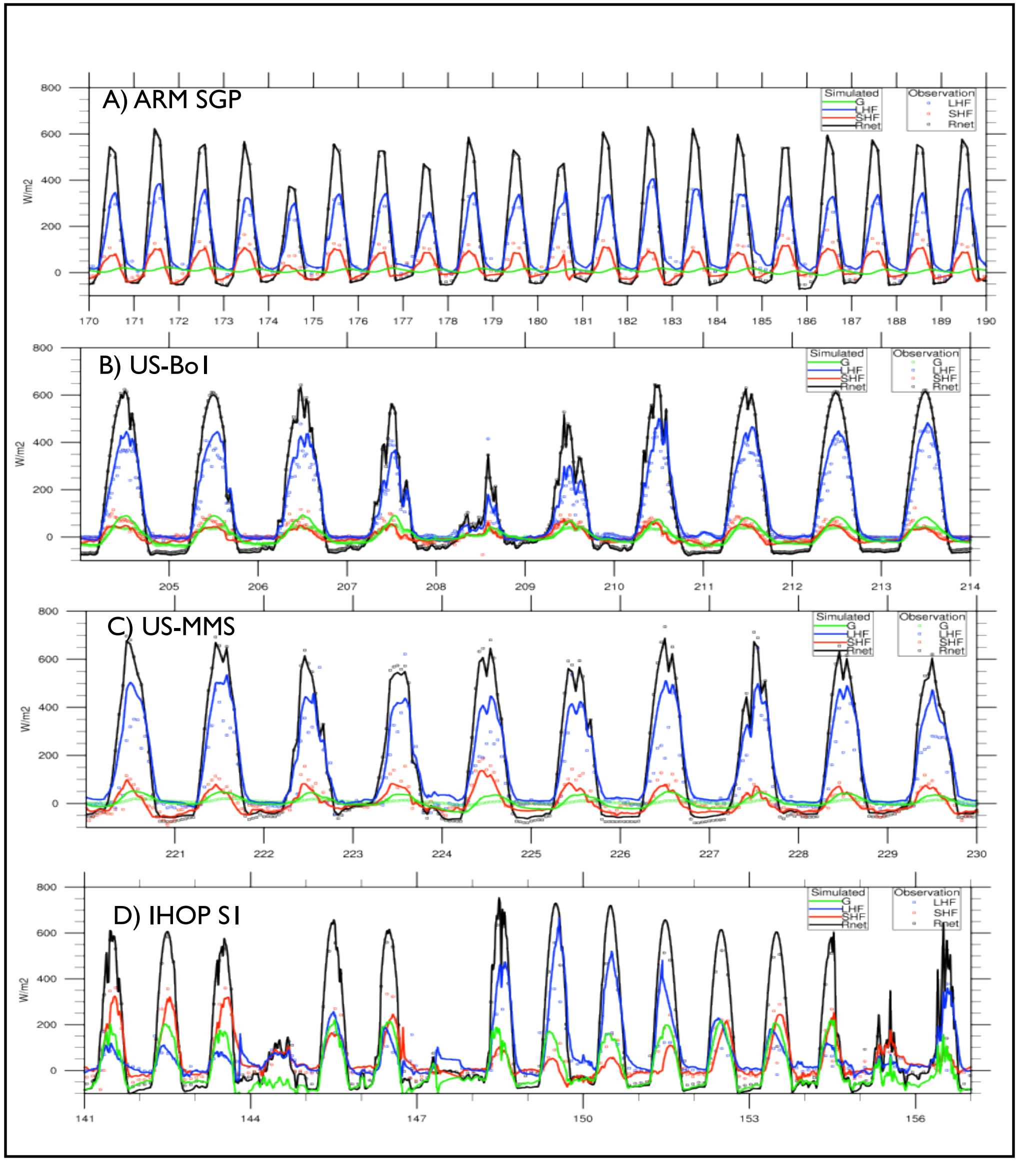
Validation of SLM

- Performance of SLM is tested over 4 sites
  - Atmospheric forcing for SLM is provided for every 30min-1hr from observation

Site	IHOP S1	US Bo1	ARM SGP	US MMS
Location	Booker, Texas	Bondvill, Illinois	SGP, Oklahoma	Morgan Monroe State Park, Indiana
Data source	International H20 project (IHOP)	AmeriFlux	ARM IHOP 1997	AmeriFlux
Simulation period	May 20 - Jun. 6, 2002	Jul. 23 - Aug. 2, 2007	Jun. 19 - Jul.9, 1997	Aug. 8 - Aug. 18, 2009
Vegetation type	Baresoil	Corn Field	Grassland	Deciduous-Broadleaf forest
Vegetation and soil properties				
LAI	0	4	2	5.5
Canopy height [m]		0.5	0.5	27
Surface roughness length	0.0024	0.06	0.06	1.485
Displacement length		0.34	0.34	18.36
Leaf angle distribution factor		-0.3	-0.3	0.25
Vegetation albedo		0.16	0.16	0.15
Root length		1	1	2
Coefficient set (a,b) for root density fraction		(5.558, 2.614)	(10.74,2.608)	(5.99,1.955)
Soil type (%SAND,%CLAY)	Silty clay loam (10,34)	Silty loam (17,13)	Silty clay loam (10,34)	Clay loam (34,40)

Validation of SLM

- Surface energy budget



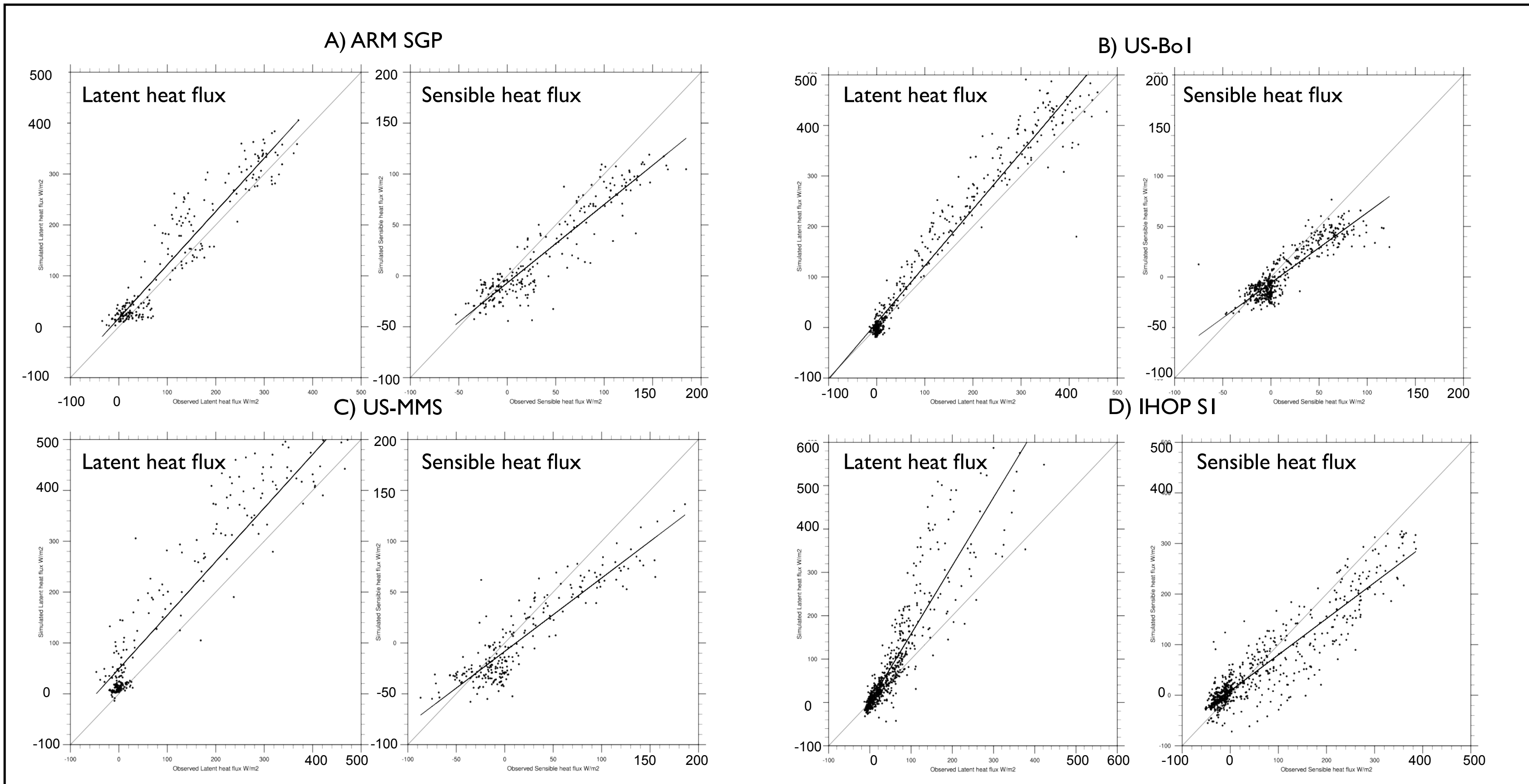
- Simulated surface energy budget is compared with observation over 4 test sites

- Figure legend
  - G (soil heat flux, green)
  - SHF (sensible heat flux, red)
  - LHF (latent heat flux, blue)
  - Rnet (net radiation, blaci)
  - Lines are simulated results/ dots are observation

- Model computed diurnal cycle of surface energy budget is in reasonable agreement with observation

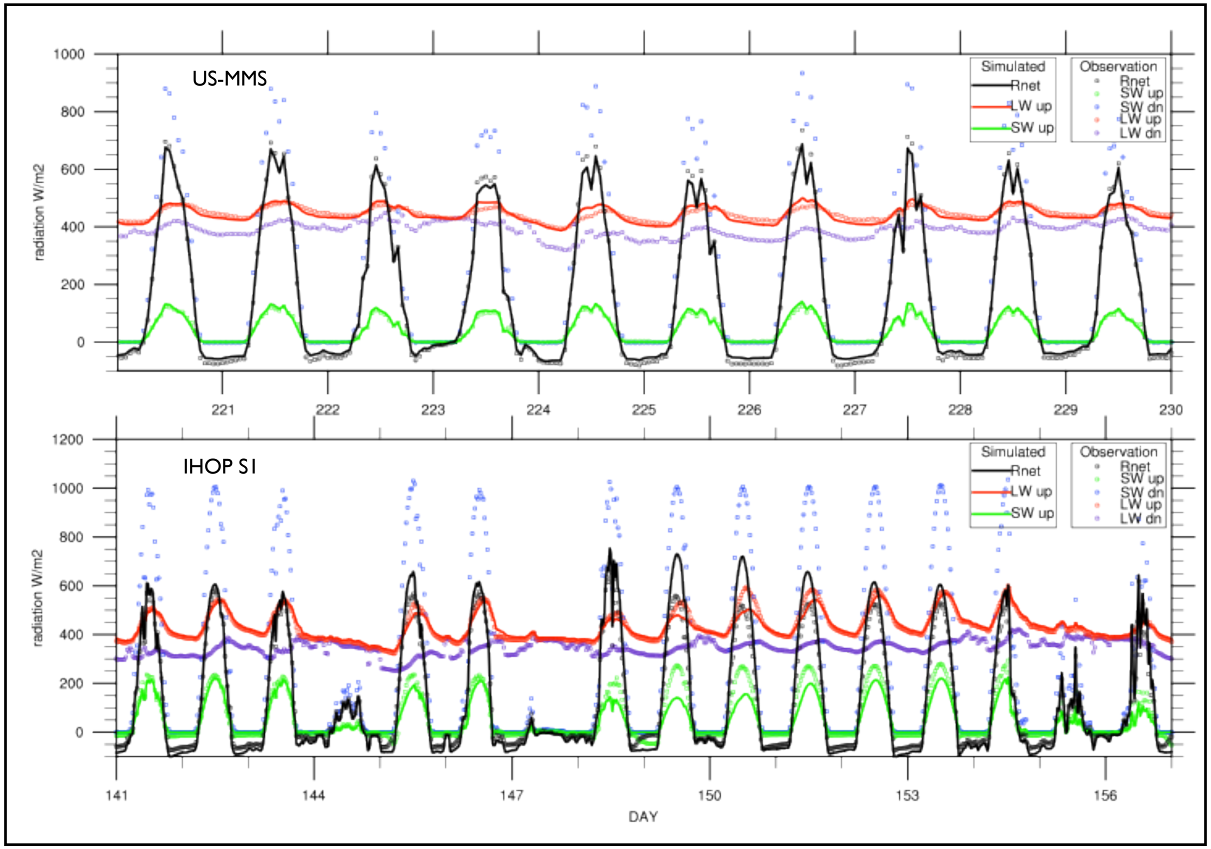
Validation of SLM

- Surface sensible and latent heat flux
  - Observed (x-axis) vs. Simulated (y-axis) sensible and latent heat fluxes
  - Light-grey line is 1:1 line / black line is a regression line
  - Slight overestimation in latent heat flux and underestimation in sensible heat flux over all test sites
    - Discrepancy in diurnal cycle amplitudes



Validation of SLM

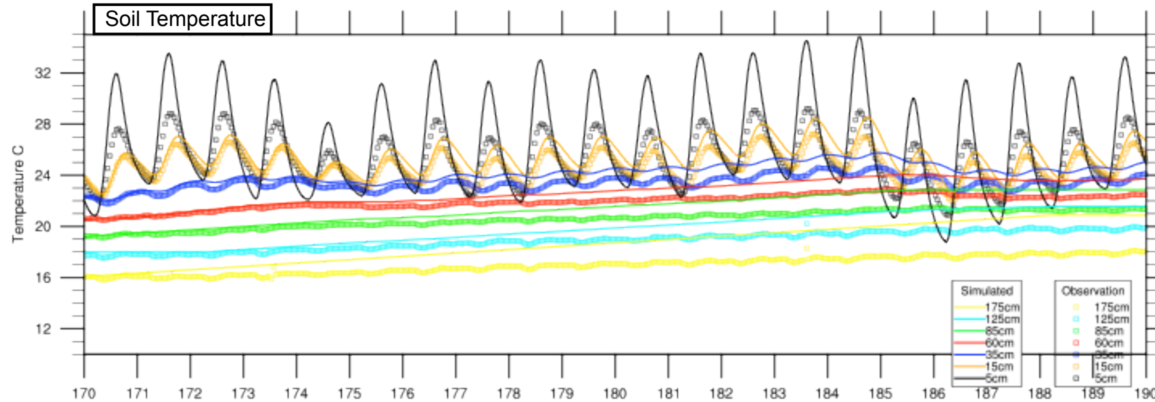
- Surface radiation budget
  - SLM requires downward solar and longwave radiation input
  - Computed upward solar radiation, longwave radiation and net radiation at surface are compared with observation over US MMS (forest) and IHOP S1 (baresoil) sites.
  - Diurnal cycle of surface radiation computed from the SLM compares to the observation well.
    - Vegetation type specific albedo and soil moisture dependent soil albedo
      - Predicted reflected solar radiation at surface generally follows the observations

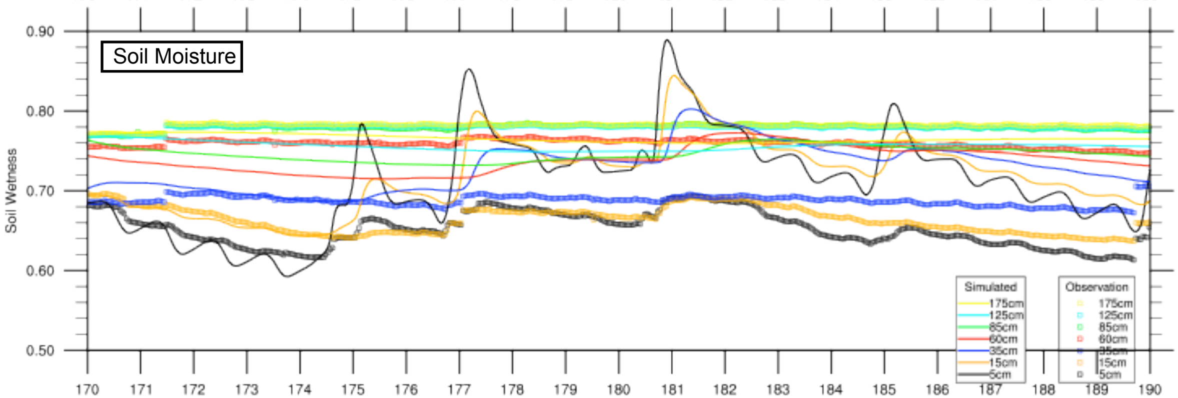


- Figure legend
  - SW dn (blue) : downward solar radiation
  - LW dn(purple):downward longwave radiation
  - SW up (green) : upward solar radiation
  - LW up (red) : upward solar radiation
  - Rnet (black) : net radiation
  - Lines are simulated results and dots are from observation

Validation of SLM

- Soil wetness & temperature over ARM SGP site
  - Phase of soil temperature diurnal cycle agrees well with observation
  - Overestimation in diurnal amplitude of temperature and wetness near surface
    - Rain over-moistens near surface soil layers compared to the observation
  - Discrepancy may suggests following
    - Vertical transport alone is not sufficient to redistribute soil heat and moisture within soil column
    - Uncertainty in soil properties parameterized based on soil texture
    - Assigning soil model with single soil type is unrealistic





- Figure Legend
  - Lines are simulated results and markers are from the observation
  - Each color represents different depths
    - 5 cm : black
    - 15 cm : orange
    - 35 cm : blue
    - 60 cm : red
    - 85 cm : green
    - 125 cm : cyan
    - 175 cm : yellow

Integration of SLM into SAM cloud resolving model

: application to the case of shallow cumulus cloud development over land

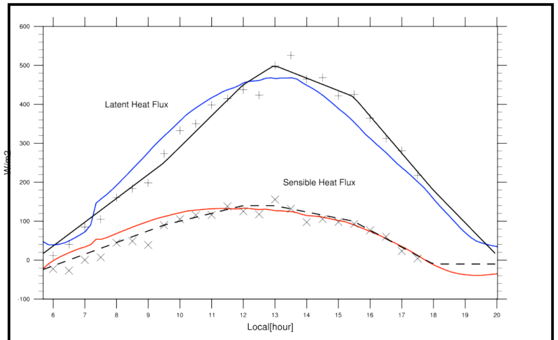
- For SLM-SAM coupled system
  - Atmospheric conditions for SLM is provided from the lowest model level of SAM
  - Computed surface fluxes are returned to SAM as atmospheric lower boundary condition

- We benchmark LES model study in the diurnal cycle of shallow cumulus convection over land studied by Brown et al. (2002)
  - Case setup
    - Case 1 (LAND OFF)
      - SAM is run alone with prescribed sensible and latent heat fluxes as in Brown et al. (2002)
    - Case 2 (LAND ON)
      - SLM-SAM is used
      - Land conditions are provided from the SLM validation site, SGP ARM
      - Surface fluxes are calculated
    - Common set-ups
      - Initial temperature and specific humidity : Observed at SGP site of ARM program on June 21 (1997)
        - Temperature profile is modified from observation as diagnosed large-scale forcing do not explain a cooling at 500-2000m from 1130UTC to 1430 UTC
      - Domain size : 6400 x 6400m^2 with dx=66.7m
      - Run starts on 1130 UTC

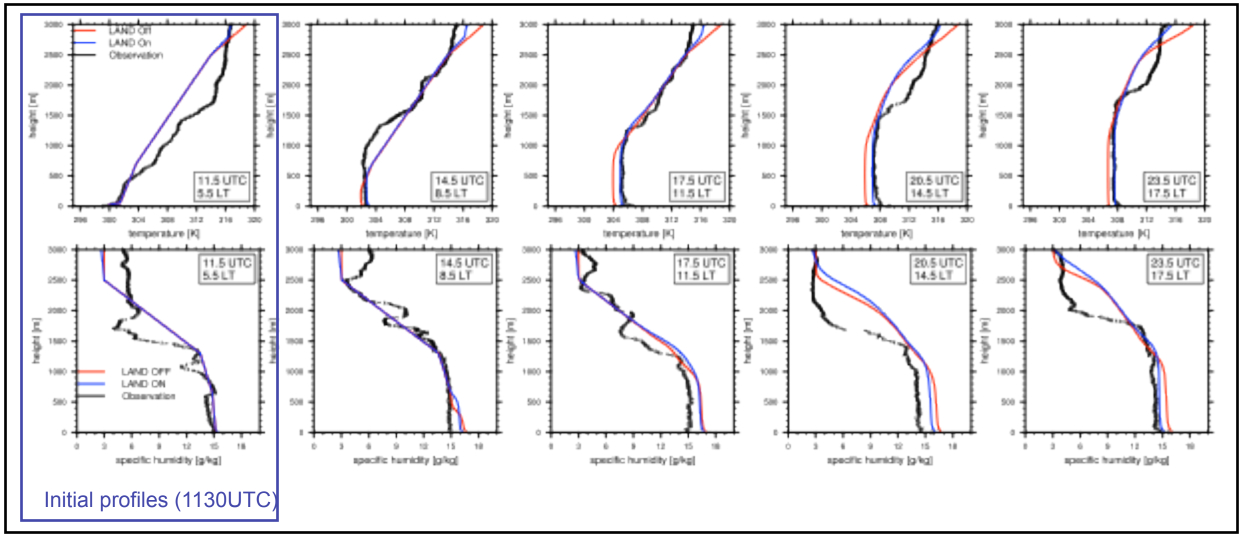
Integration of SLM into SAM cloud resolving model

: application to the case of shallow cumulus cloud development over land

- Surface fluxes
  - Computed sensible and latent heat fluxes agree well with observation



Crosses are from observation, black lines are fitted to the observation and colored lines are computed from SLM

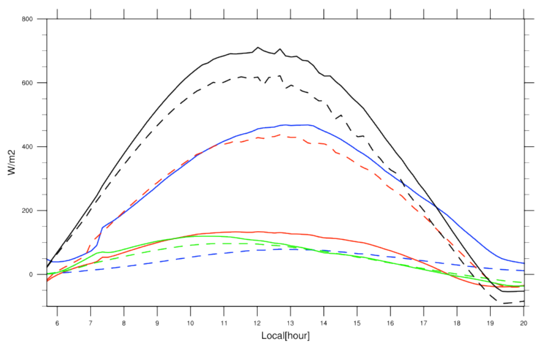


- Profiles in T and q
  - For LAND ON case (blue lines)
    - T profile (top) in mixed layer follows the observation well from 1730UTC
    - q profile (bottom) in mixed layer is about 1g/kg overestimated as shown in other LES results in Brown et al. (2002)
  - Discrepancies above mixed layer may be due to the uncertainties in large-scale forcing and modified initial profiles.

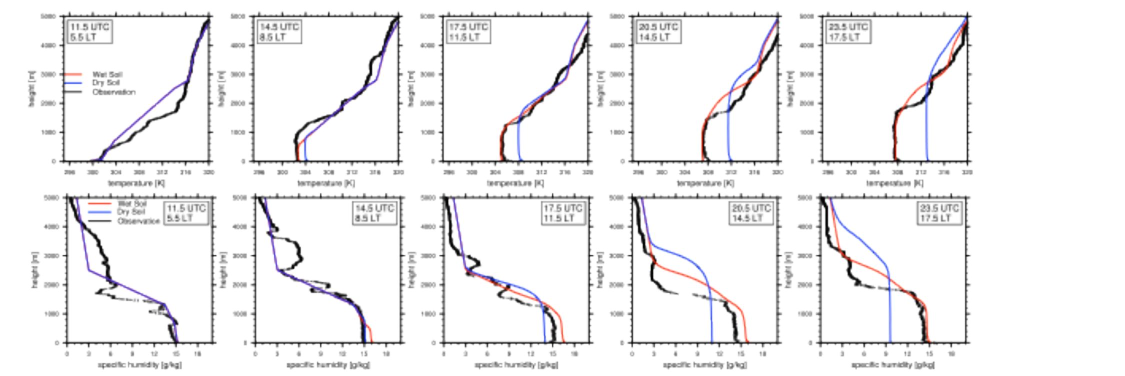
Integration of SLM into SAM cloud resolving model

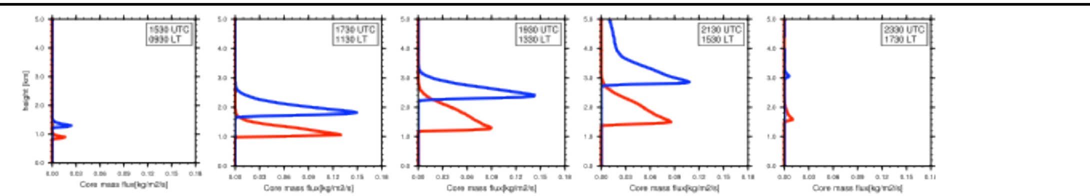
: Sensitivity of PBL development over land upon soil moisture

- Simulation set up
  - Control (Wet run) : we follow shallow cumulus convection over land (Brown et al. 2002)
    - Initial soil moisture varies between 0.6-0.68 from observation made at SGP ARM sites
  - Sensitivity run (Dry run) : we use drier initial soil moisture profile (0.1-0.3, linearly increasing with depth)
  - Other setup remains the same with Brown et al. (2002) benchmark case.
- Over dry soil
  - Bowen ratio increases
  - Mixed layer develops deeper with warmer and drier profiles
  - Cloud base is higher



Time series of surface energy budget for 'wet soil' run (soil line) and 'dry soil' run (dashed line). Net radiation (black), sensible heat flux (red), latent heat flux (blue), soil heat flux (green)

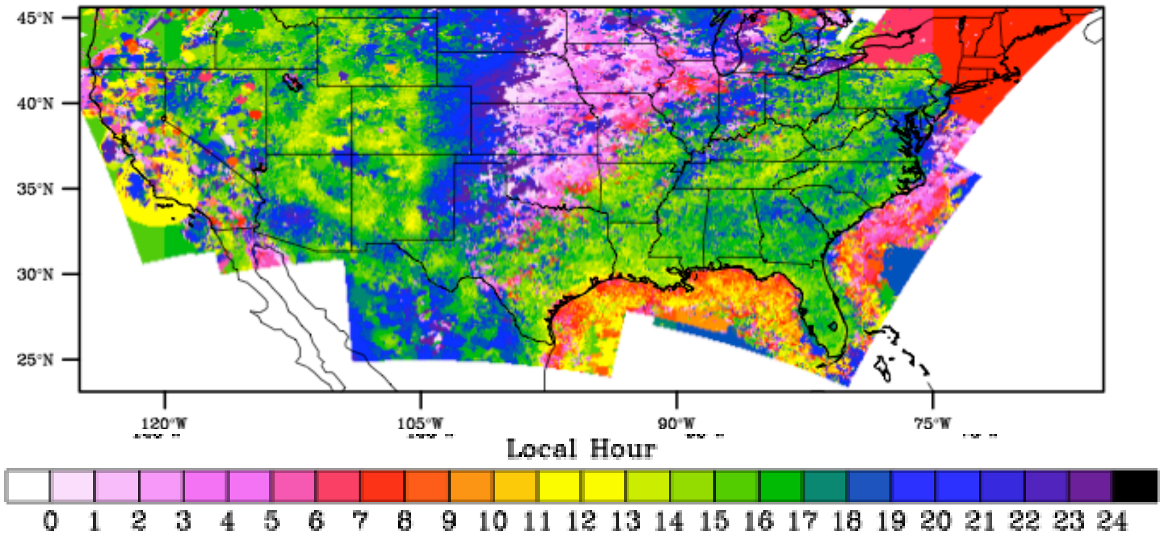




Timeseries of core mass flux profile starting from 1530 UTC to 2130 UTC. Red line is from ‘wet’ soil run and blue line is the result from ‘dry’ soil run.

Diurnal cycle of convection over land

- Most inland regions exhibit late afternoon - early evening precipitation maximum.

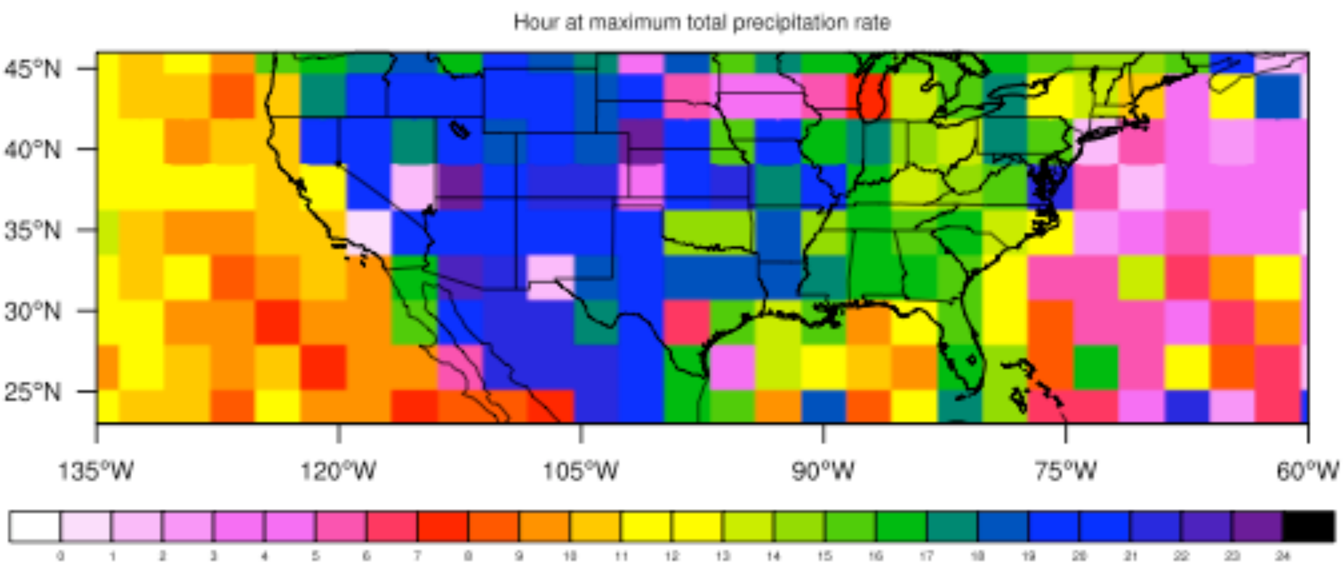


Map of maximum precipitation hour over US from gridded Radar stage IV data averaged from 2002-2011 (year 2003 data is not included)

- Is diurnal cycle of precipitation purely based on local physics? Or associated with large scale dynamics?

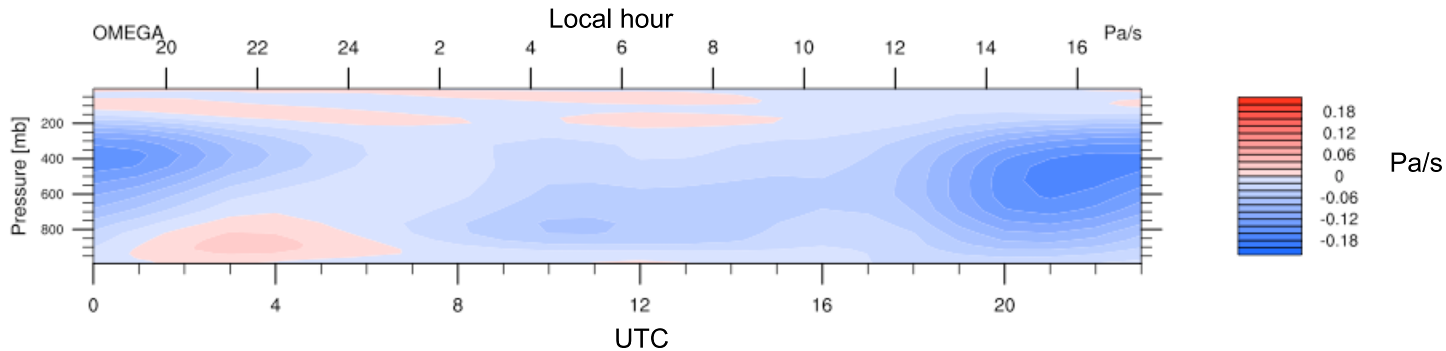
Diurnal cycle of convection over land

- SPCAM is run for 2 years with hourly output
  - JJA average shows that SPCAM reproduces observed diurnal cycle of precipitation over Eastern US.

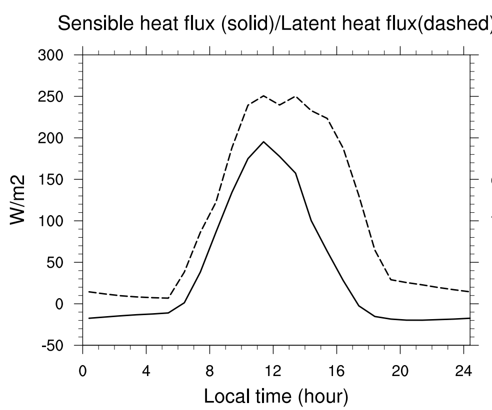


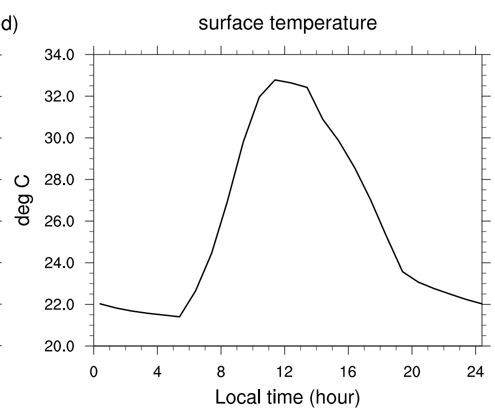
Diurnal cycle of convection over land

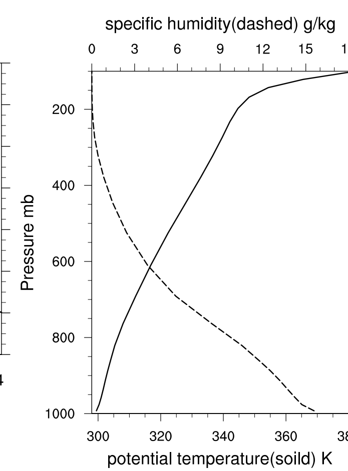
- Forcings are extracted from JJA averaged SPCAM Year01 result at 32N 84W location
  - Hourly surface heat flux, latent heat flux, surface temperature, omega
  - JJA mean sounding

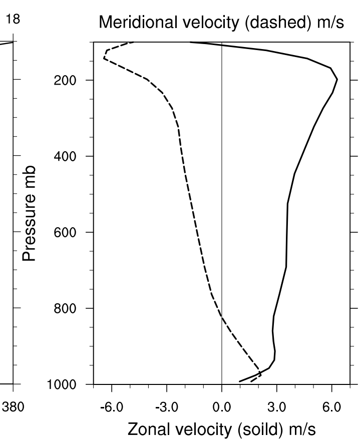


Omega field shows subsidence from 8pm to 2am below 700mb



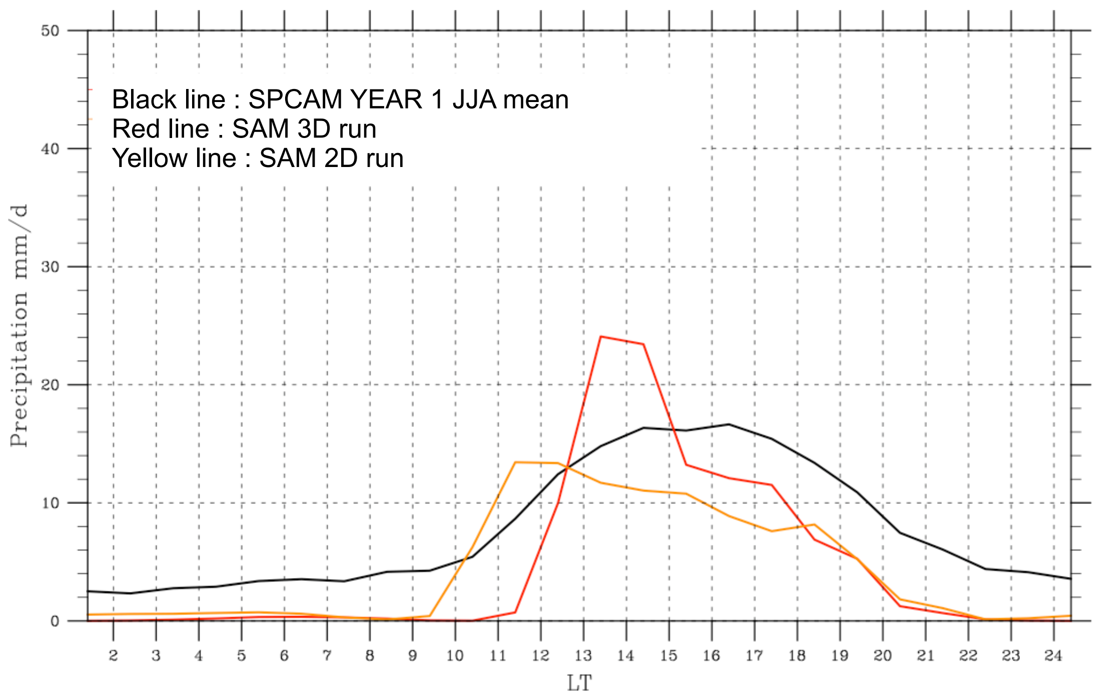






Diurnal cycle of convection over land

- SAM is run to reproduce the SPCAM result
  - Hourly omega, surface fluxes, and surface temperatures are prescribed from SPCAM 1year JJA mean
  - SPCAM JJA mean sounding is applied
  - Nudging t,q,u,v at all levels with 1day relaxation time
  - 2D run (32x28 with dx=4km)
  - 3D run (1024x1024x64, dx = 100m)
  - Precipitation both from 2D and 3D runs show earlier maximum compared to SPCAM result



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