Land Surface Processes and their Modeling in WRF

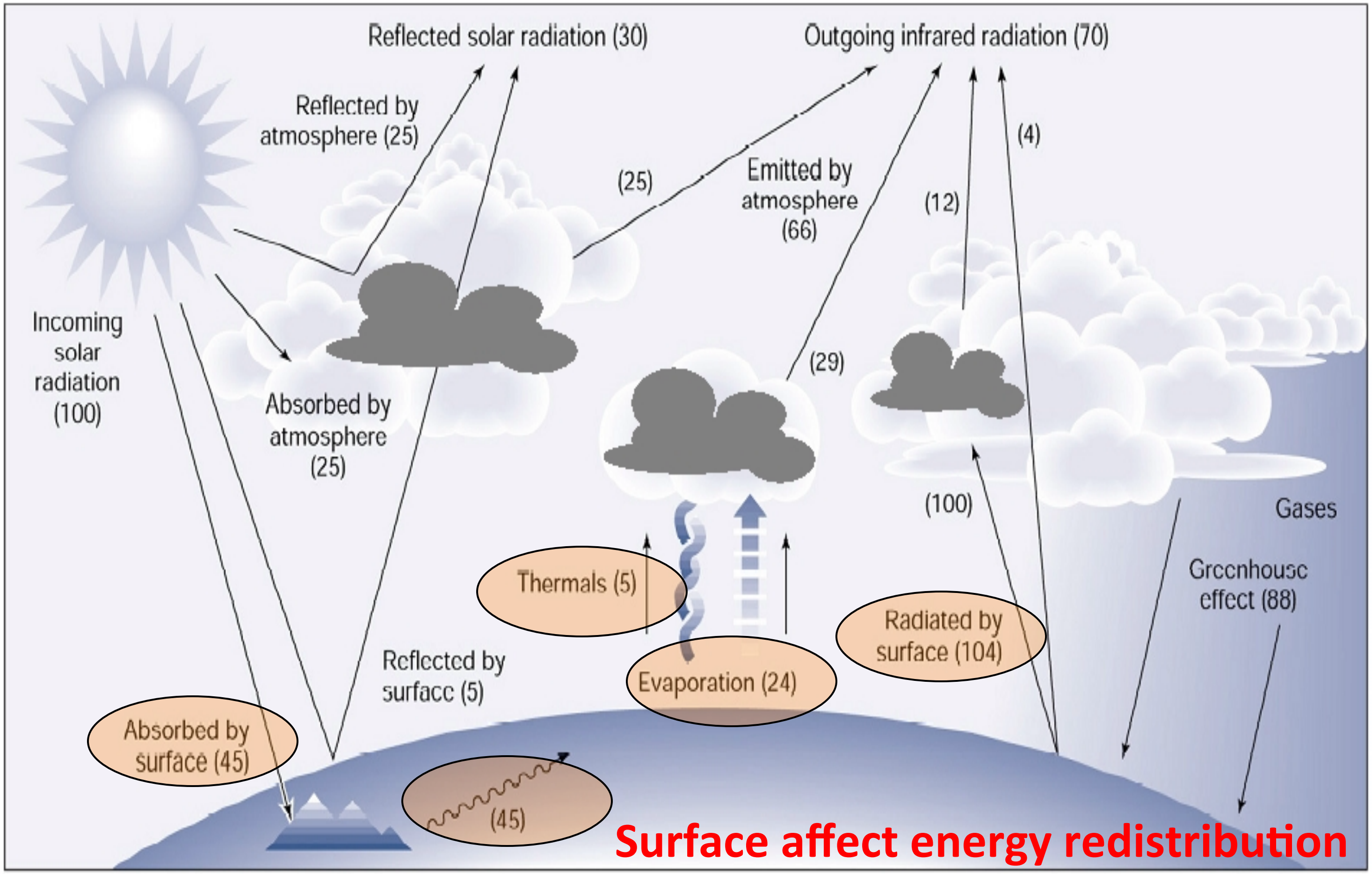
Fei Chen
Research Applications Laboratory (RAL)
National Center for Atmospheric Research
Boulder, Colorado, USA.

With contributing materials from Mike Ek (EMC/NOAA), Jonathan Pleim (NERL/EPA) and Tanya Smirnova (ESRL/NOAA)

Outline

- **Why do we need land surface models (LSM) in numerical weather and climate models?**
- **What are the LSMs and their functions in WRF?**
- **How to initialize land state variables?**
- **What else do we need to know?**

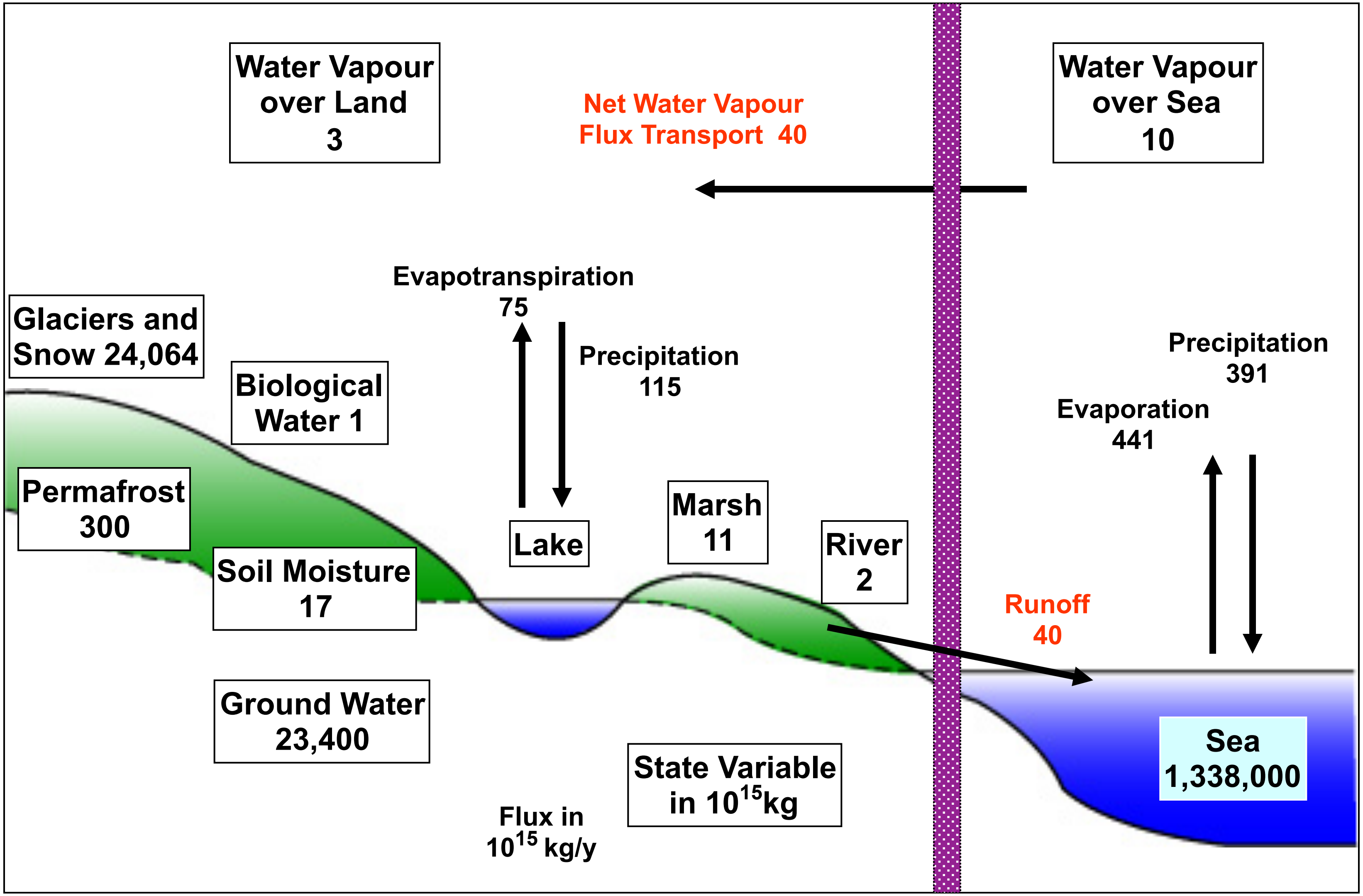
Earth's Global Energy Budget



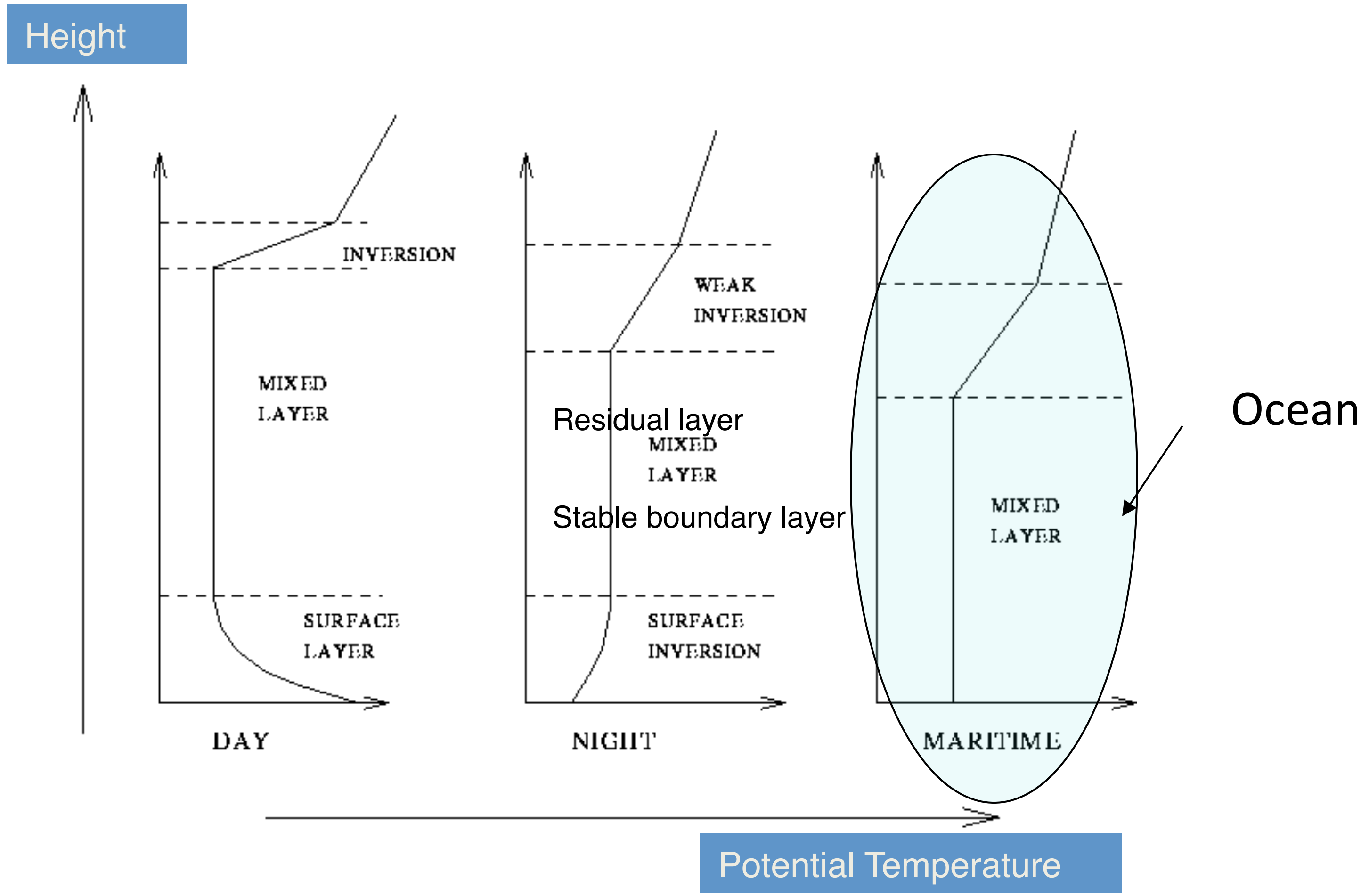
- Incident solar flux normalized to "100 units"
- Albedo ~ .30: (25 from clouds and 5 from ground)
- 70 units still left to be absorbed and re-emitted
  - 45 units absorbed by the surface, 25 units by the atmosphere
  - Change of state of water takes a lot of energy: 24 of the 45 units absorbed by the surface used for evaporation

Global Water Cycle

Surface (ocean and land): source of water vapor to the atmosphere



Classic Forms of ***Boundary Layer*** Evolution



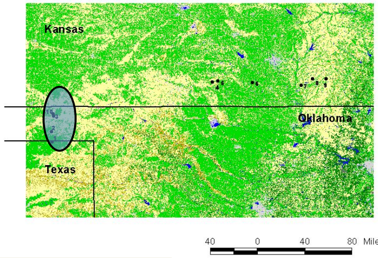
The BL over land has strong diurnal cycle

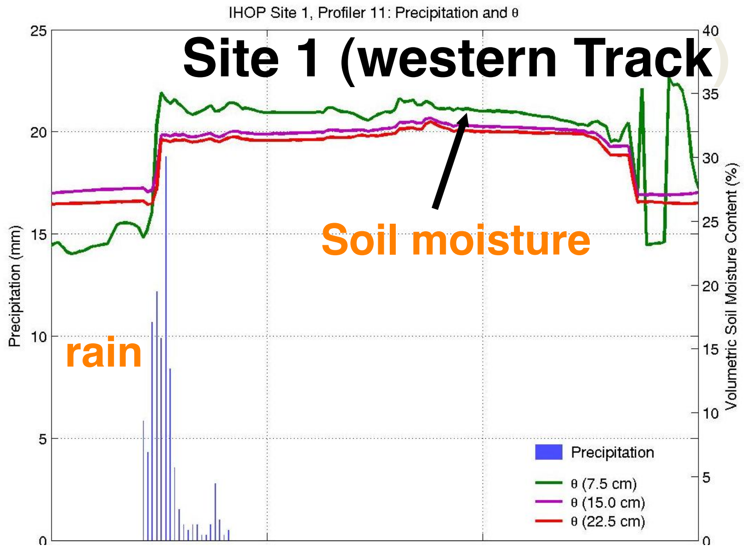
The Atmospheric Boundary Layer (ABL) growth is driven primarily by

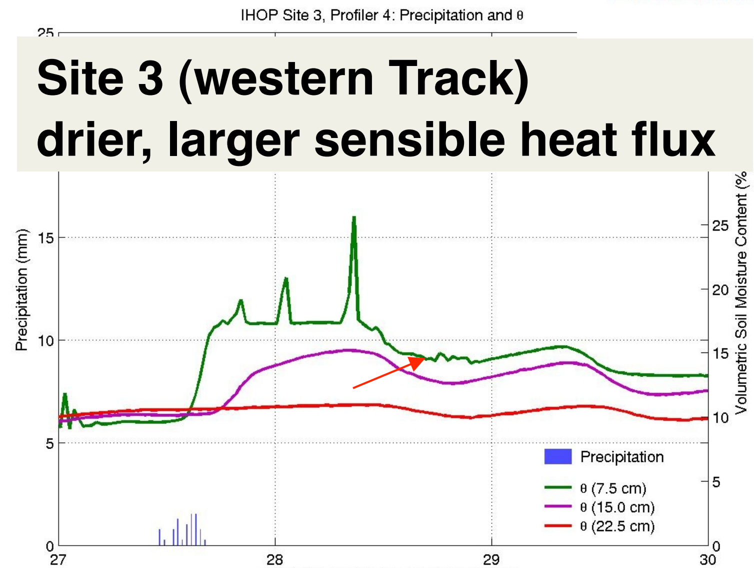
- Entrainment of warmer air from the free troposphere.
- Surface sensible and latent fluxes.
- Also be influenced by the presence of mesoscale phenomena such as the sea-breeze or the mountain valley circulation, due to surface differential heating.

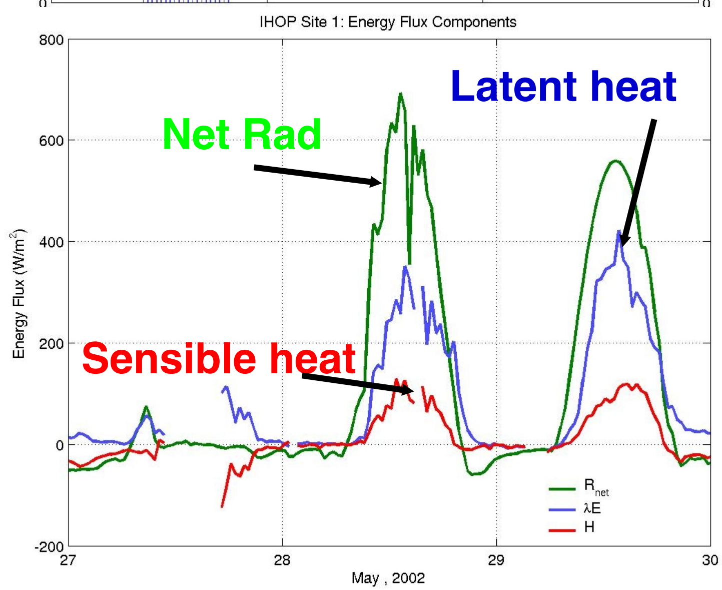
Surface Heterogeneity on 29 May 2002

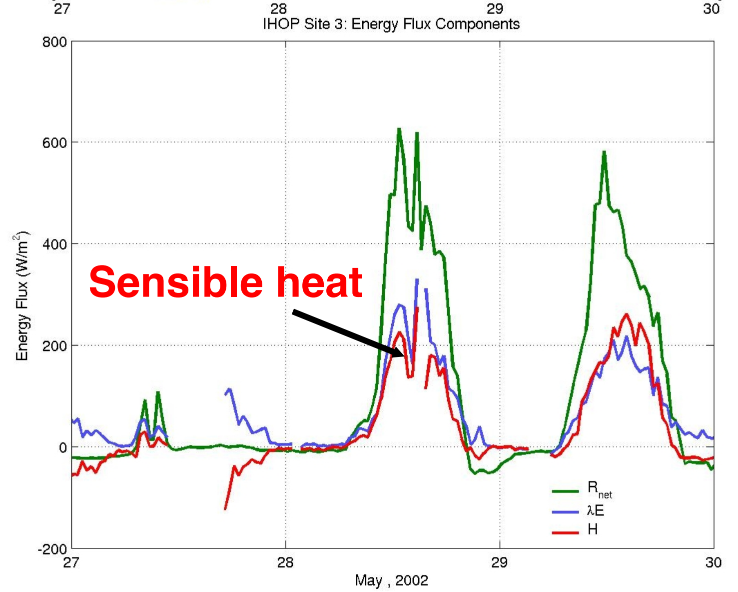
Contrast between two IHOP-02 western Sites ~50 km apart





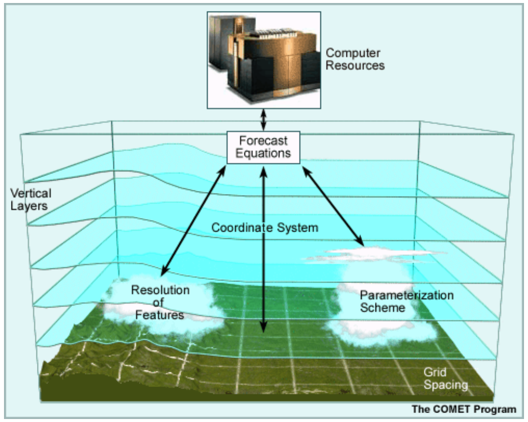


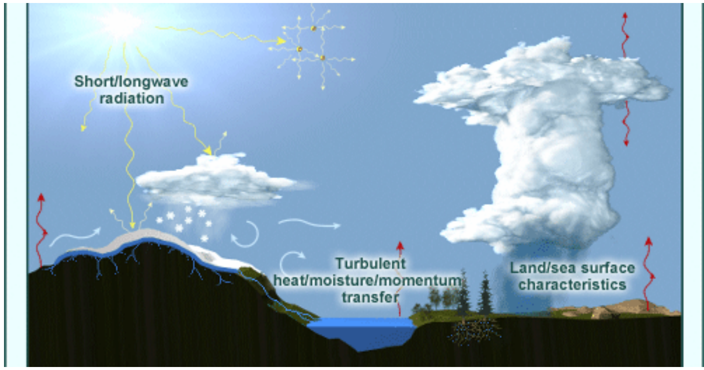




Physics parameterization in atmospheric models

- Dynamics
- Physics
  - Computers are not yet powerful enough to directly treat them
  - Processes are not understood well to be represented by an equation
  - Method of counting for subgrid-scale processes is called parameterization
    - modeling the *effects* of a process (emulation) rather than modeling the process itself (simulation).





Why Do We Need Land Surface Models?

- Need to account for subgrid-scale sensible and latent fluxes
- The lower boundary is the only physical boundary for atmospheric models
- LSM becomes increasingly important:
  - More complex PBL schemes are sensitive to surface fluxes and cloud/cumulus schemes are sensitive to the PBL structures
  - NWP models increase their grid-spacing (1-km and sub 1-km). Need to capture mesoscale circulations forced by surface variability in albedo, soil moisture/temperature, landuse, and snow
- Not a simple task: tremendous land surface variability and complex land surface/hydrology processes
- Initialization of soil moisture/temperature is a challenge

Outline

- **Why do we need land surface models (LSM) in numerical weather and climate models?**
- **What are the LSMs and their functions in WRF?**
- **How to initialize land state variables?**
- **What else do we need to know?**

Five LSMs in WRF

sf_surface_physics=1: 5-layer thermal diffusion model, no prediction of soil moisture, snow, and vegetation.

sf_surface_physics=2: Noah LSM (Unified ARW/NMM version in Version 3)

- Vegetation effects
- Predeicts soil temperature and soil moisture in four layers and diagnoses skin temperature, predicts snow cover and canopy moisture, handles fractional snow cover and frozen soil
- New time-varying snow albedo (in V3.1)
- Noah is coupled with two Urban Canopy Model (UCM) options (sf_urban_physics, ARW only)
  - sf_urban_physics=1: single-layer UCM (SLUCM)
  - sf_urban_physics=2: Building Environment Parameterization (BEP), a multi-layer urban model)
    - Can be used with MYJ PBL or BouLac PBL to represent buildings higher than lowest model levels
  - sf_urban_physics=3: Building Energy Model (BEM). Work with BEP.

Five LSMs in WRF(Conti.)

sf_surface_physics=3: RUC LSM

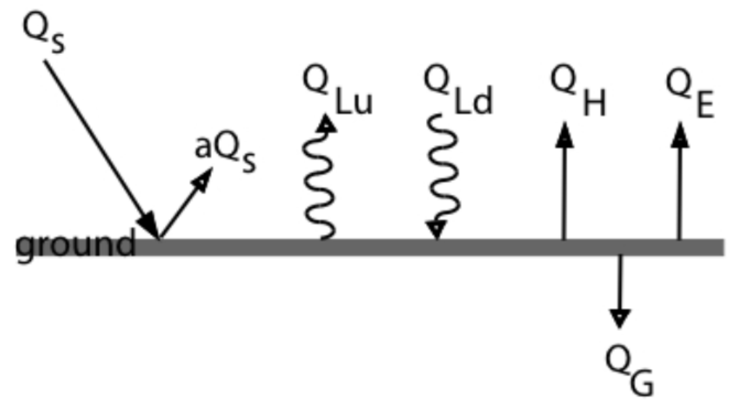
- Vegetation effects included
- Predicts soil temperature and soil moisture in six layers
- Multi-layer snow model

sf_surface_physics=7: Pleim-Xiu LSM (EPA)

- New in Version 3
- Vegetation effects included
- Predicts soil temperature and soil moisture in two layers
- Simple snow-cover model

sf_surface_physics=88: GFDL slab model. Simple land treatment for HWRF physics, force-restore 1-layer model with constant substrate

Essentials: An LSM must provide 4 quantities to parent atmospheric models



- surface sensible heat flux Q_H
- surface latent heat flux Q_E
- upward longwave radiation Q_{Lu}
  - Alternatively: skin temperature and sfc emissivity
- upward (reflected) shortwave radiation aQ_S
  - Alternatively: surface albedo, including snow effect

Pleim-Xiu (PX) LSM

- Simple LSM designed particularly for retrospective simulations
  - indirect data assimilation for dynamic adjustment of soil moisture and temperature
- Soil Moisture and Temp in two Layers
  - Surface (1 cm), Root Zone (1 m)
- Three pathways for evaporation
  - Ground evaporation - f(sfc soil moisture)
  - Wet canopies - f(cwc)
  - Evapotranspiration - f(stomatal resistance)
- Seasonal Vegetation Growth Model
- Can use high resolution LU data from NLCD (30 m resolution) combined with MODIS LU outside CONUS
- Uses subgrid fractional LU and soil type data to compute grid cell aggregate parameters.

Running WRF with PX scheme

- Namelist switch:
  - sf_surface_physics=7
- Designed for use with Pleim surface scheme and ACM PBL scheme:
  - sf_sfclay_physics=7
  - bl_pbl_physics=7
- Other namelist variables:
  - num_soil_layers = 2
    - number of soil layers in land surface model
  - pxlsm_smois_init (max_dom) = 0 or 1
    - Soil moisture initialization option:
    - 0 - From analysis, 1 - From MAVAIL
- IPXWRF: utility program to recycle soil moisture and temperature from previous run for initialization (pxlsm_smois_init=0)
  - Available from USEPA (gilliam.robert@epa.gov)
- Need to create SFCFDDA file using *Obsgrid* for soil moisture and temperature nudging

Obsgrid → http://www.mmm.ucar.edu/wrf/src/OBSGRID.tar.gz

Aspects of RUC LSM that differ from Noah LSM:

- Surface layer

- layer approach to energy and moisture budget
- implicit solution of energy and moisture budgets
- bare soil evaporation based on actual moisture gradient

- Soil model

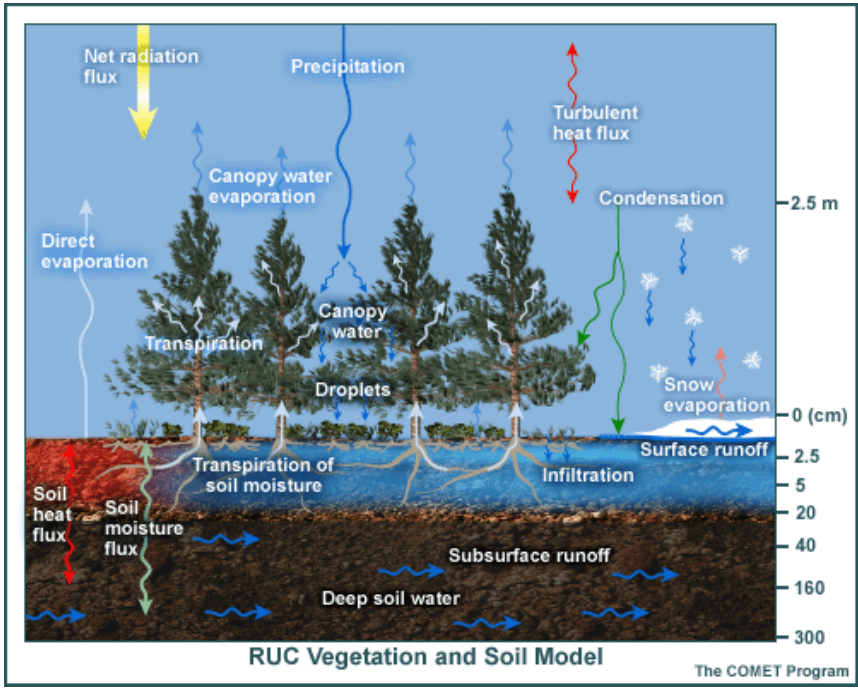
- soil moisture variable - $(\theta - \theta_r)$
- 2nd order numerical approximation

  for hydraulic conductivity
- larger number of levels, thinner top layers

- 2-layer Snow model versus bulk layer

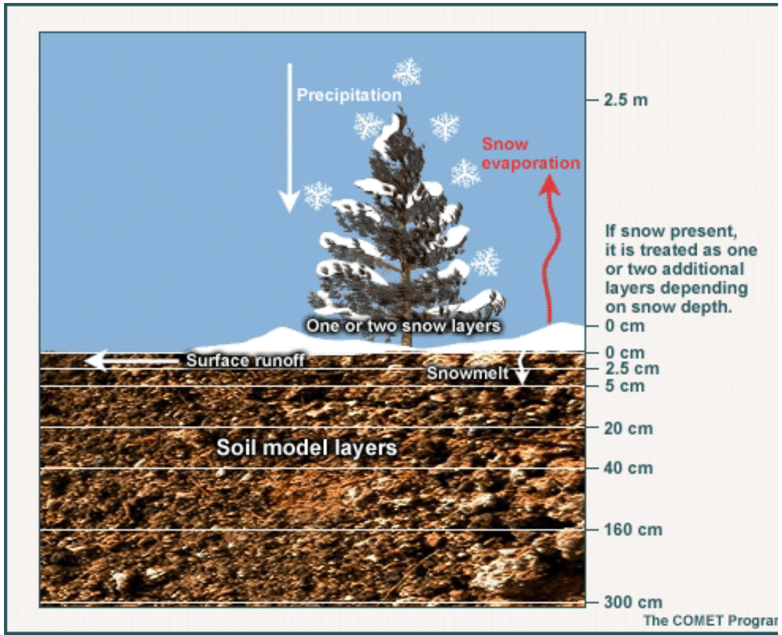
- treatment of mixed phase precipitation

- Frozen soil physics algorithm



Snow model in RUC-LSM

1. One- or two-layer snow model (threshold – 7.5 cm)
2. Changing snow density depending on snow depth, temperature, compaction parameter
3. Snow can be melted from the top and bottom of snow pack
4. Prescribed amount of liquid water (13%) from melting can stay inside the snow pack
5. Melted water infiltrates into soil and forms surface runoff



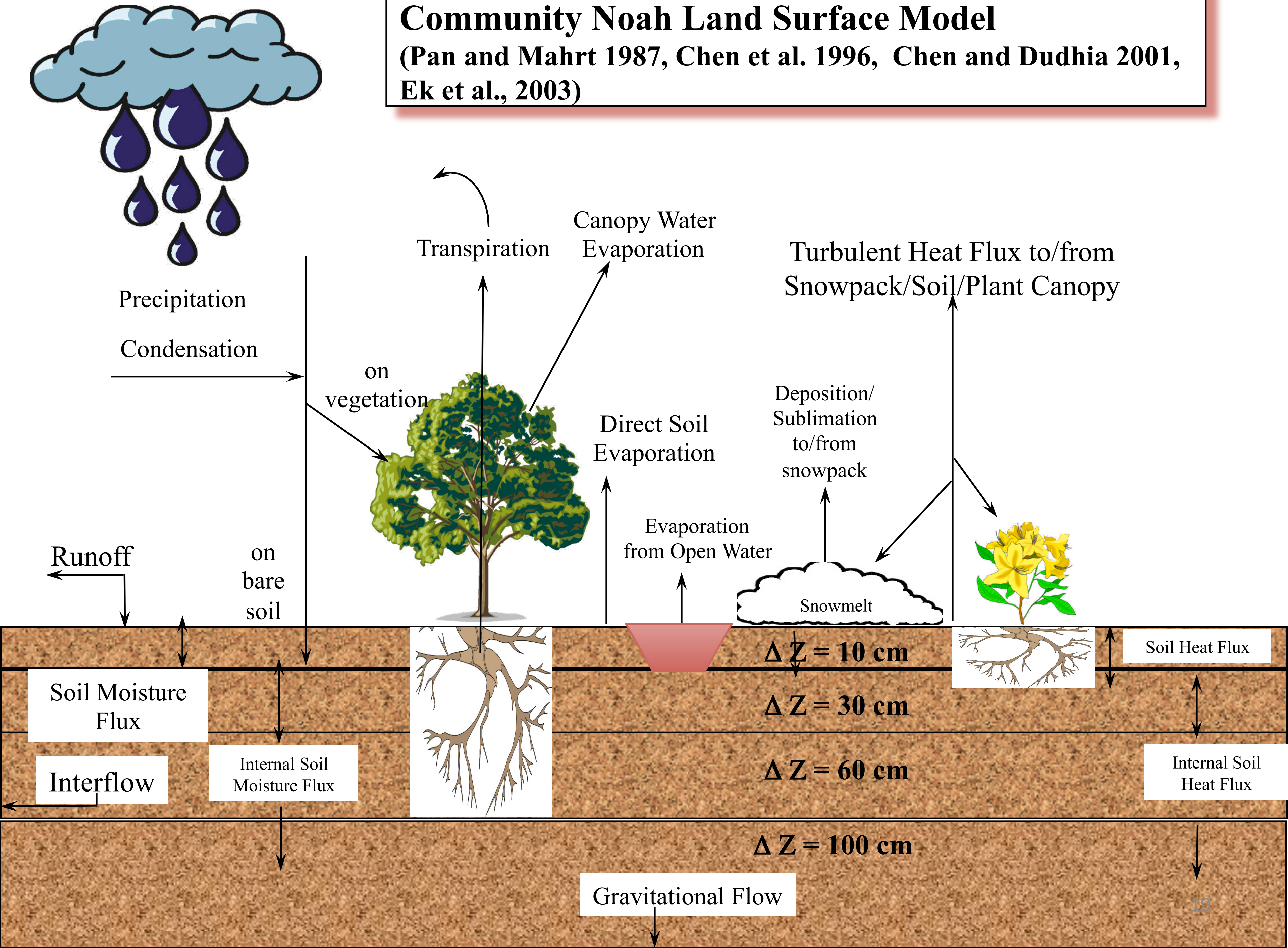
Falling snow can be intercepted by the vegetation canopy until the holding capacity is exceeded

Two Important Transport Mechanisms

- Molecular conduction of heat, diffusion of tracers, and viscous transfer of momentum cause transport between the surface and the lowest millimeters of air diffusion
  - Diffusivity for heat, and water vapor: ~ 10^{-5} m^2s^{-1}
  - Require large gradient (e.g., 10^4 Km^{-1})
  - Can be neglected above the lowest few centimeter
- Turbulent fluxes:
  - Diffusion coefficient depend on height, wind speed, friction, instability: ~ 10^0 m^2s^{-1}, about 10^4-10^5 larger than molecular diffusivity
  - Caused by small and large eddies: very efficient

Community Noah Land Surface Model

(Pan and Mahrt 1987, Chen et al. 1996, Chen and Dudhia 2001, Ek et al., 2003)



Develop the Advanced Noah Land Surface Modeling System for WRF

- Multi-institutional collaborative effort among NCEP, NCAR, U.S. Air Force Weather Agency, NASA, and university community for NWP community
- Designed for high-resolution realtime weather forecast, air pollution, local and regional hydrologic applications
  - Relatively simple, robust, efficient
- Noah implemented/tested in
  - Operational NCEP models:
    - NAM (12-km, 60-layer) regional model and data assimilation system
    - GFS global forecast model
    - GFDL hurricane model
  - 25-year Regional Reanalysis system (32-km, 60-layer)
  - AFWA: global land data assimilation system (AGRMET)
  - NCAR community mesoscale models
    - MM5 mesoscale model
    - WRF mesoscale model
- Coupled WRF/Noah operational:
  - AFWA: WRF-ARW for operations July 2006
  - NCEP: WRF-NMM for operations June 2006

Key References for the Noah LSM

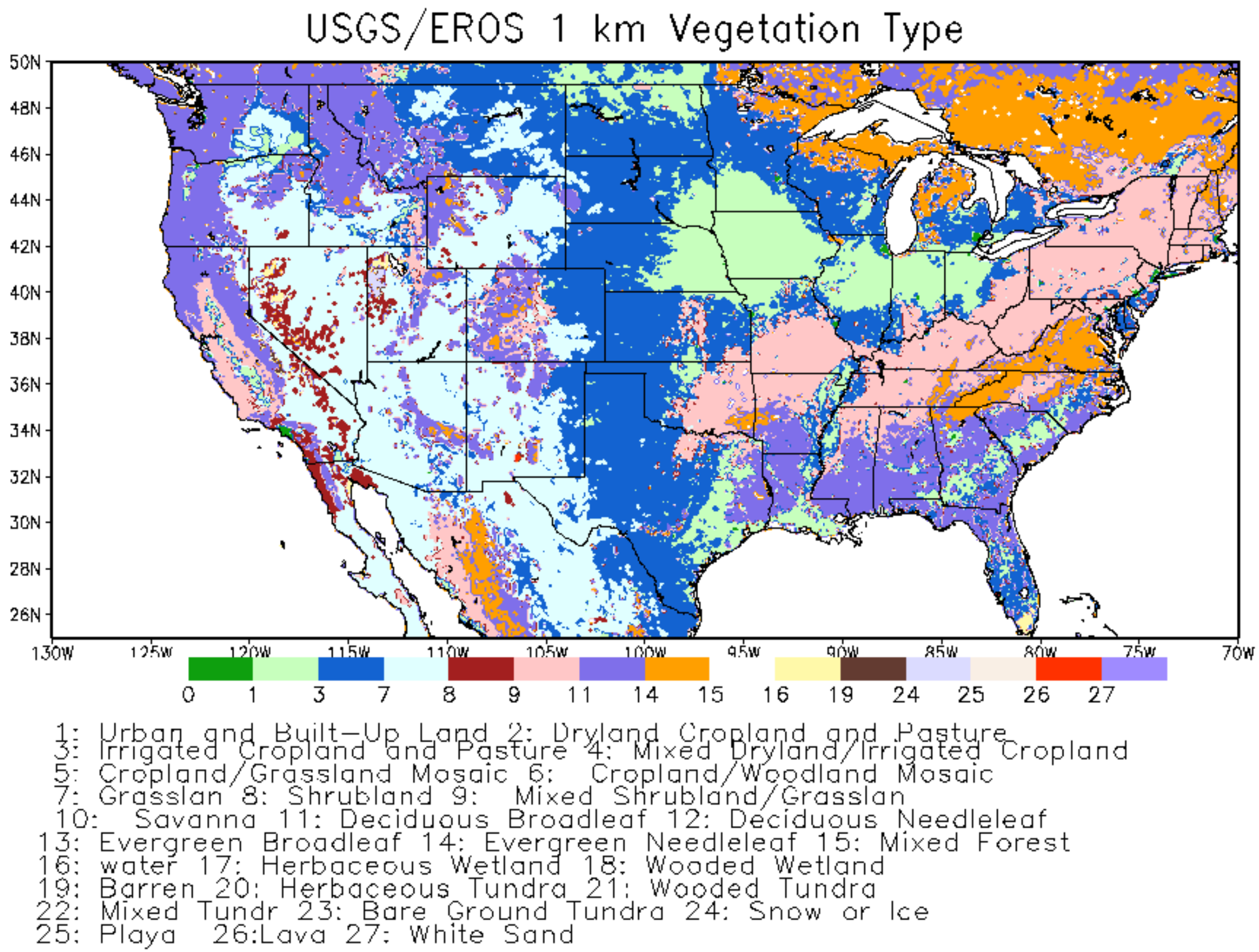
- Physics (1-d column model)
  - Warm season
    - Chen et al. (1996, JGR, 101)
  - Cold season (snowpack and frozen soil)
    - Koren et al. (1999, JGR, 104)
- In Mesoscale models
  - NCEP Eta model
    - Chen et al. (1997, BLM, 85)
    - Ek et al. (2003, JGR, 108)
  - NCAR MM5 and WRF models
    - Chen & Dudhia (2001, MWR, 129)
    - Chen et al., (2011, Int. J. Climatology), WRF-Noah-Urban

Noah LSM Physics in WRF: Overview

- Four soil layers (10, 30, 60, 100 cm thick)
- Prognostic Land States
  - Surface skin temperature
  - Total soil moisture at each layer (volumetric)
    - total of liquid and frozen (bounded by saturation value depending on soil type)
  - Liquid soil moisture each layer (volumetric)
    - can be supercooled
  - Soil temperature at each layer
  - Canopy water content
    - dew/frost, intercepted precipitation
  - Snowpack water equivalent (SWE) content
    - Patchy snow cover is diagnosed
    - Snowpack depth (physical snow depth)
- Above prognostic states require initial conditions
  - from atmospheric model prediction/analyses
  - from high-resolution land data assimilation system (HRLDAS)

Key Input to the Noah LSM

- Land-use land-cover (vegetation) type
- Soil texture
- Secondary parameters can be specified as function of the above three primary parameters



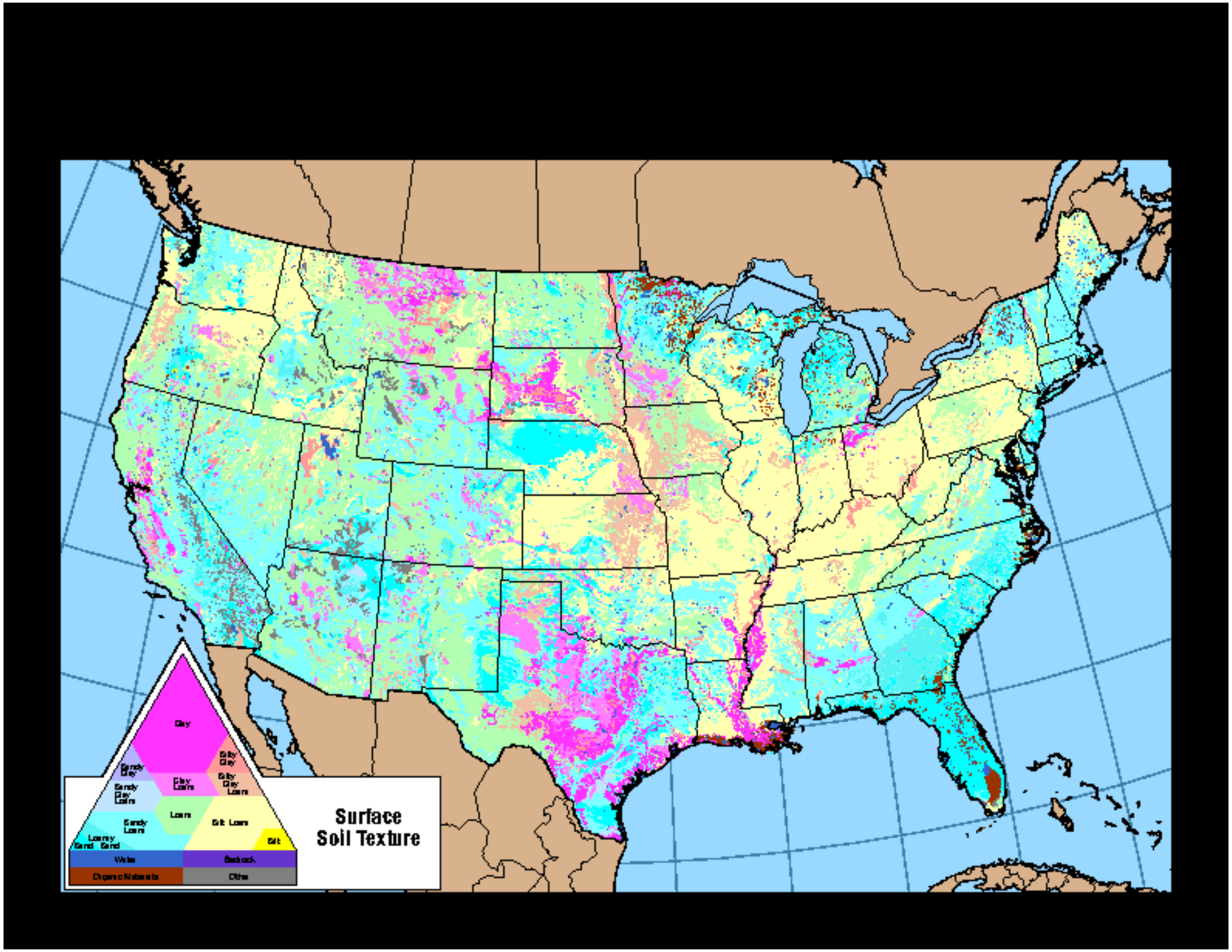
→ determine Rc_min, and other vegetation parameters

Albedo - SFC albedo (in percentage)	RGL - Parameter used in radiation stress function
Z0 – Roughness Length (m)	HS - Parameter used in vapor pressure deficit
SHDFAC - Green vegetation fraction	SNUP - Threshold depth for 100% snow cover
NROOT - Number of root layers	LAI - Leaf area index (dimensionless)
RS - stomatal resistance (s m-1)	MAXALB - Upper bound on max albedo snow

Vegetation Parameters (VEGPARM.TBL)

Category	Class	Albedo	Z0	SHDFAC	NROOT	RS	RGL	HS	SNUP	LAI	MAXALB
Urban and Built-Up Land	1	0.15	1.00	0.10	1	200.	999.	999.0	0.04	4	40
Dryland Cropland and Pasture	2	0.19	0.07	0.80	3	40.	100.	36.25	0.04	4	64
Irrigated Cropland and Pasture	3	0.15	0.07	0.80	3	40.	100.	36.25	0.04	4	64
Mixed Dryland/Irrigated Cropland and Pasture	4	0.17	0.07	0.80	3	40.	100.	36.25	0.04	4	64
Cropland/Grassland Mosaic	5	0.19	0.07	0.80	3	40.	100.	36.25	0.04	4	64
Cropland/Woodland Mosaic	6	0.19	0.15	0.80	3	70.	65.	44.14	0.04	4	60
Grassland	7	0.19	0.08	0.80	3	40.	100.	36.35	0.04	4	64
Shrubland	8	0.25	0.03	0.70	3	300.	100.	42.00	0.03	4	69
Mixed Shrubland/Grassland	9	0.23	0.05	0.70	3	170.	100.	39.18	0.035	4	67
Savanna	10	0.20	0.86	0.50	3	70.	65.	54.53	0.04	4	45
Deciduous Broadleaf Forest	11	0.12	0.80	0.80	4	100.	30.	54.53	0.08	4	58
Deciduous Needleleaf Forest	12	0.11	0.85	0.70	4	150.	30.	47.35	0.08	4	54
Evergreen Broadleaf Forest	13	0.11	2.65	0.95	4	150.	30.	41.69	0.08	4	32
Evergreen Needleleaf Forest	14	0.10	1.09	0.70	4	125.	30.	47.35	0.08	4	52
Mixed Forest	15	0.12	0.80	0.80	4	125.	30.	51.93	0.08	4	53
Water Bodies	16	0.19	0.001	0.00	0	100.	30.	51.75	0.01	4	70
Herbaceous Wetland	17	0.12	0.04	0.60	2	40.	100	60.00	0.01	4	35
Wooded Wetland	18	0.12	0.05	0.60	2	100.	30.	51.93	0.02	4	30
Barren and Sparsely Vegetated	19	0.12	0.01	0.01	1	999.	999.	999.0	0.02	4	69
Herbaceous Tundra	20	0.16	0.04	0.60	3	150.	100.	42.00	0.025	4	58
Wooded Tundra	21	0.16	0.06	0.60	3	150.	100.	42.00	0.025	4	55
Mixed Tundra	22	0.16	0.05	0.60	3	150.	100.	42.00	0.025	4	55
Bare Ground Tundra	23	0.17	0.03	0.30	2	200.	100.	42.00	0.02	4	65
Snow or Ice	24	0.70	0.001	0.00	1	999.	999.	999.0	0.02	4	75

Global Soil Texture Map



→ determine Kt, and other soil parameters

BB – Function of Soil type	SATPSI - SAT (saturation) soil potential
DRYSMC- dry soil moisture threshold (volumetric)	SATDK - SAT soil conductivity
F11 - Soil thermal diffusivity/conductivity coef.	SATDW - SAT soil diffusivity
MAXSMC - MAX soil moisture content (porosity), Volumetric	WLTSMC - Wilting point soil moisture(Volumetric)
REFSMC - Reference soil moisture (field capacity), Volumetric	QTZ - Soil quartz content

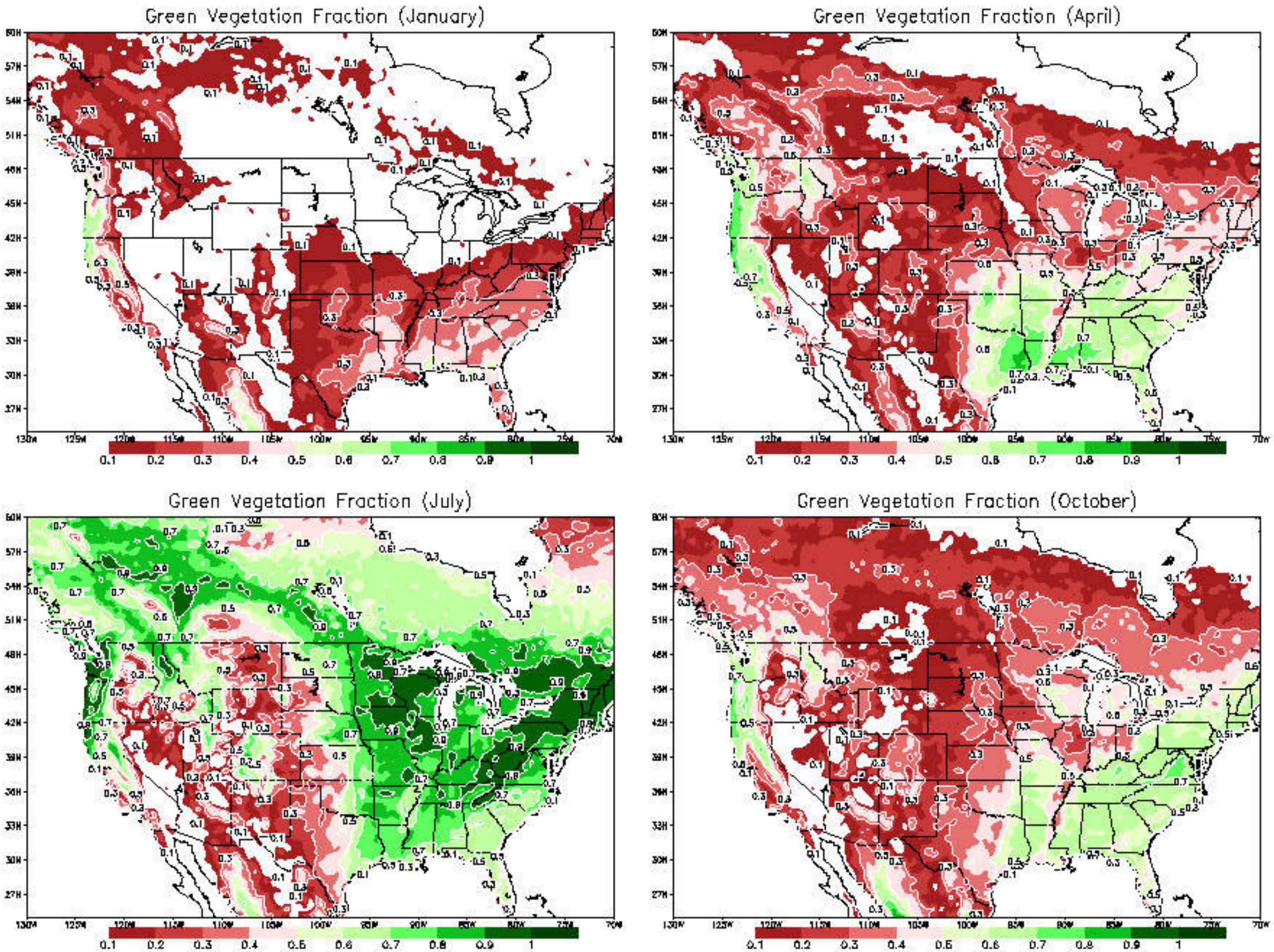
Soil Parameters (SOILPARM.TBL)

Category Type	Class	BB	DRYSMC	F11	MAXSMC	REFSMC	SATPSI	SATDK	SATDW	WLTSMC	QTZ
Sand	1	2.79	0.010	-0.472	0.339	0.236	0.069	1.07E-6	0.608E-6	0.010	0.92
Loamy Sand	2	4.26	0.028	-1.044	0.421	0.383	0.036	1.41E-5	0.514E-5	0.028	0.82
Sandy Loam	3	4.74	0.047	-0.569	0.434	0.383	0.141	5.23E-6	0.805E-5	0.047	0.60
Silt Loam	4	5.33	0.084	0.162	0.476	0.360	0.759	2.81E-6	0.239E-4	0.084	0.25
Silt	5	5.33	0.084	0.162	0.476	0.383	0.759	2.81E-6	0.239E-4	0.084	0.10
Loam	6	5.25	0.066	-0.327	0.439	0.329	0.355	3.38E-6	0.143E-4	0.066	0.40
Sandy Clay Loam	7	6.66	0.067	-1.491	0.404	0.314	0.135	4.45E-6	0.990E-5	0.067	0.60
Silty Clay Loam	8	8.72	0.120	-1.118	0.464	0.387	0.617	2.04E-6	0.237E-4	0.120	0.10
Clay Loam	9	8.17	0.103	-1.297	0.465	0.382	0.263	2.45E-6	0.113E-4	0.103	0.35
Sandy Clay	10	10.73	0.100	-3.209	0.406	0.338	0.098	7.22E-6	0.187E-4	0.100	0.52
Silty Clay	11	10.39	0.126	-1.916	0.468	0.404	0.324	1.34E-6	0.964E-5	0.126	0.10
Clay	12	11.55	0.138	-2.138	0.468	0.412	0.468	9.74E-7	0.112E-4	0.138	0.25
Organic Material	13	5.25	0.066	-0.327	0.439	0.329	0.355	3.38E-6	0.143E-4	0.066	0.05
Bedrock	15	2.79	0.006	-1.111	0.20	0.17	0.069	1.41E-4	0.136E-3	0.006	0.07
Land ice	16	4.26	0.028	-1.044	0.421	0.283	0.036	1.41E-5	0.514E-5	0.028	0.25

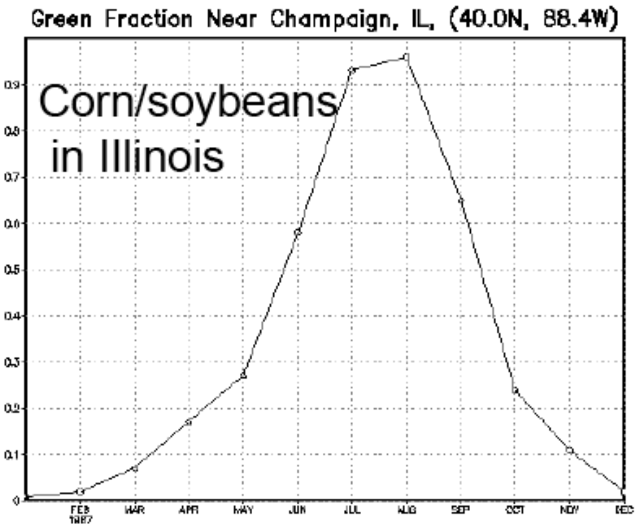
Key Input to the Noah LSM

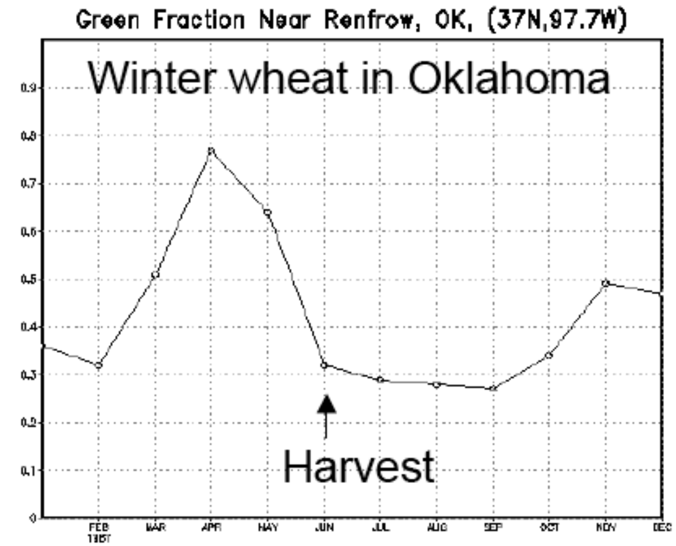
- However, some secondary parameters can be specified as spatial 2-D fields (i.e., like gridded primary fields)
- The following parameters can be specified either from the table or from 2-d data
  - Albedo
  - Green vegetation fraction
  - Leaf area index
  - Maximum snow albedo

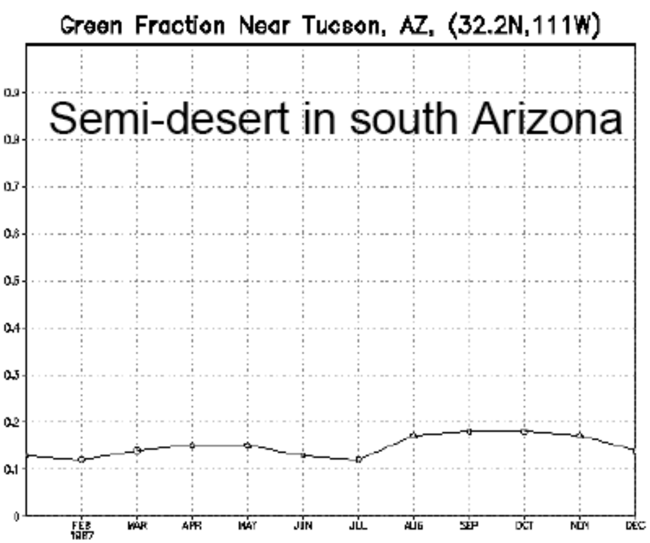
Seasonality of vegetation
Based on monthly NDVI

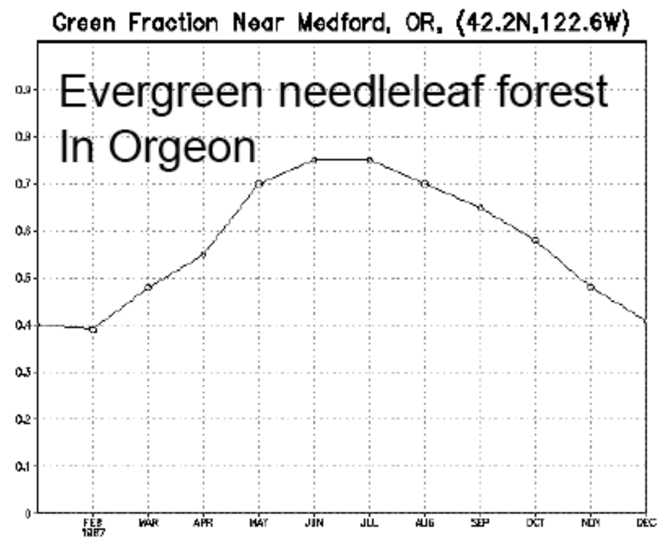


Example Annual Time Series of Green Vegetation Fraction in Noah LSM









Noah LSM Physics : Soil Prognostic Equation

Vertical water transport within the substrate

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

-"Richard's Equation for soil water movement
- D (soil-water diffusivity), K (hydraulic conductivity) depend on soil texture, soil moisture
- F_{θ} represents sources (rainfall) and sinks (evaporation)

Vertical heat transport within the substrate

$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_t(\theta)\frac{\partial T}{\partial z}\right)$$

- C (heat capacity), K_t (thermal conductivity) depend on soil texture, soil moisture
- Soil temperature information used to compute ground heat flux

Noah LSM Physics: Surface Water Budget

(Exp: monthly, summer, central U.S.)

$$dS = P - R - E$$

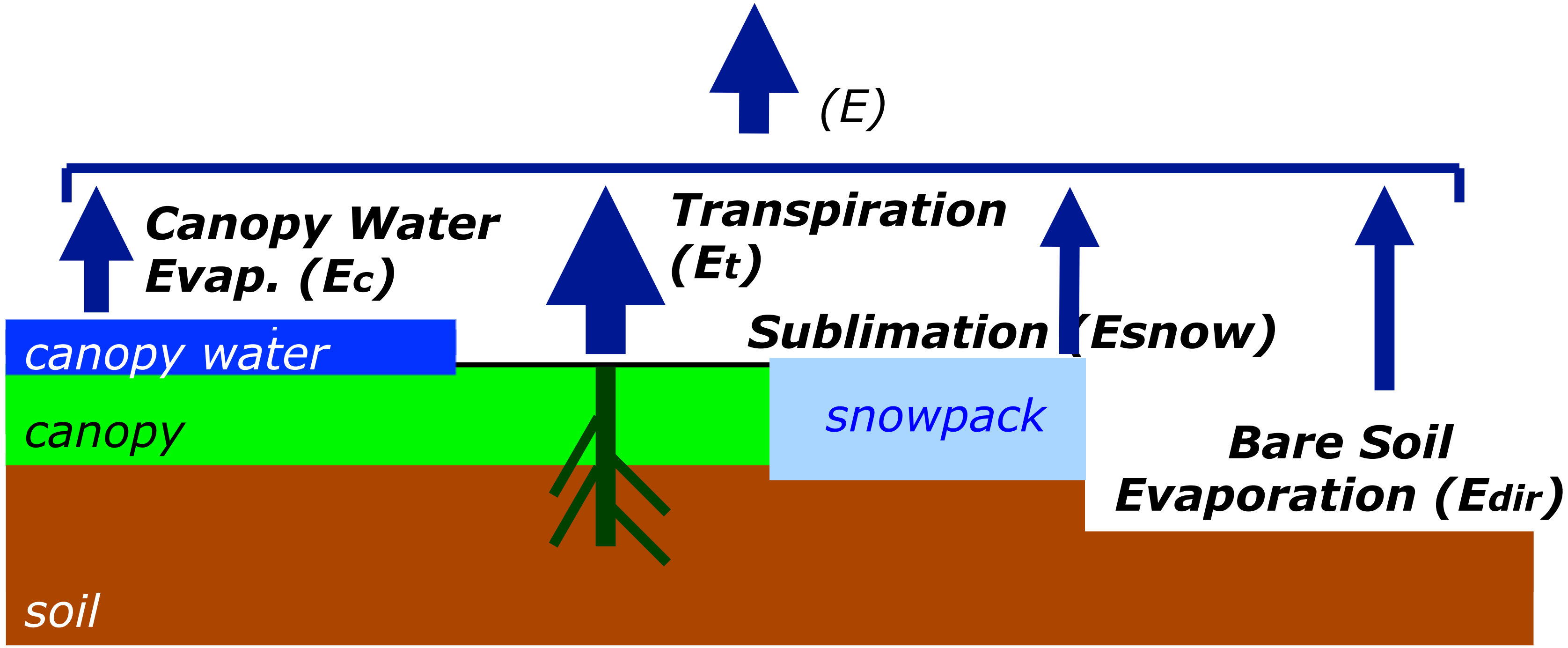
Where:

dS	= change in soil moisture content	- 75 mm
P	= precipitation	75
R	= runoff	25
E	= evaporation	125

Evaporation is a function of soil moisture and vegetation type, rooting depth/density, green vegetation cover

Noah LSM Physics: Surface Evaporation

$$E = Edir + Et + Ec + Esnow$$



- E: total surface evaporation from combined soil/vegetation
- Edir: direct evaporation from soil
- Et: transpiration through plant canopy
- Ec: evaporation from canopy-intercepted rainfall
- Esnow: sublimation from snowpack

Noah LSM Physics: Vegetation Transpiration (Et)

- Et represents evaporation of water from plant canopy via uptake from roots in the soil, which can be parameterized in terms of "resistances" to the "potential" flux

  Flux = Potential/Resistance

- Potential evaporation: amount of evaporation that would occur if a sufficient water source were available. Surface and air temperatures, insolation, and wind all affect this

Noah LSM Physics: Canopy Resistance

- Canopy transpiration determined by:

  - Amount of photosynthetically active (green) vegetation.
  - Green vegetation fraction (Fg, GVF) partitions direct (bare soil) evaporation from canopy transpiration:

    Et/Edir ≈ f(Fg)

- Not only the amount, but the TYPE of vegetation determines canopy resistance (Rc):

$$Rc = \frac{Rc\_\min}{LAI\; F_1\, F_2\, F_3\, F_4}$$

Canopy Resistance (continued)

$$Rc = \frac{Rc\_\min}{LAI\, F_1 F_2 F_3 F_4}$$

- Where:
  - LAI: leaf area index
  - Rc_min ≈ f(vegetation type)
  - F1 ≈ f(amount of PAR:solar insolation)
  - F2 ≈ f(air temperature: heat stress)
  - F3 ≈ f(air humidity: dry air stress)
  - F4 ≈ f(soil moisture: dry soil stress)
- Thus: hot and dry air, dry soil lead to stressed vegetation and reduced transpiration

Rc formulations: Jarvis vs Ball-Berry

Jarvis scheme

$$R_c = \frac{R_c\_\min}{LAI \times F1 \times F2 \times F3 \times F4}$$

LAI – Leaf Area Index,
F1 ~ f (amount of PAR)
F2 ~ f(air temperature: heat stress)
F3 ~ f(air humidity: dry air stress)
F4 ~ f(soil moisture: dry soil stress)

Fundamental difference: evapotranspiration as an 'inevitable cost' the foliage incurs during photosynthesis or carbon assimilation

A_n: three potentially limiting factors:

1. efficiency of the photosynthetic enzyme system
2. amount of PAR absorbed by leaf chlorophyll
3. capacity of the C3 and C4 vegetation to utilize the photosynthesis products

Ball-Berry scheme in GEM (Gas Exchange Model)

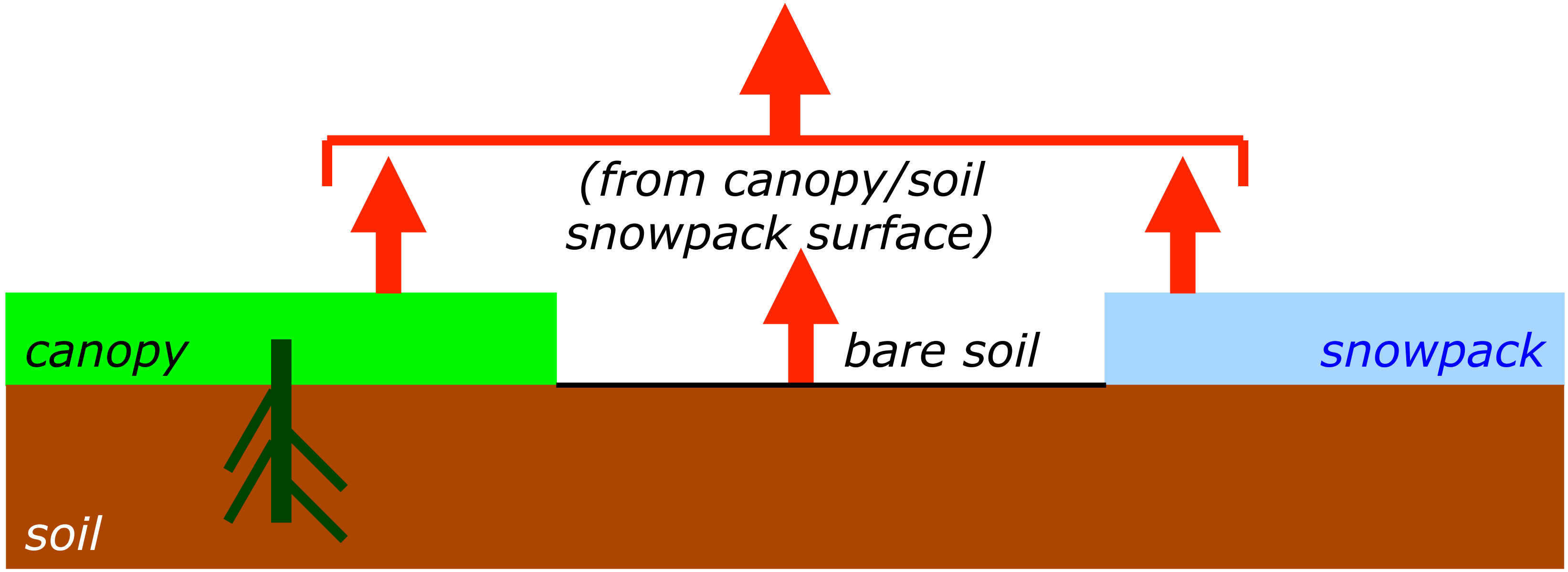
$$g_s = m\frac{A_n}{C_s}h_s p_s + b \qquad R_c = \frac{1}{g_s}$$

hs – relative humidity at leaf surface
ps – Surface atmospheric pressure
An – net CO2 assimilation or photosynthesis rate
Cs – CO2 concentration at leaf surface
m and b are linear coeff based on gas exchange consideration

GEM model reference: Niyogi, Alapaty, Raman, Chen, 2009: *J. Appli. Meteorol. Climat.*

Noah Surface Sensible Heat Flux

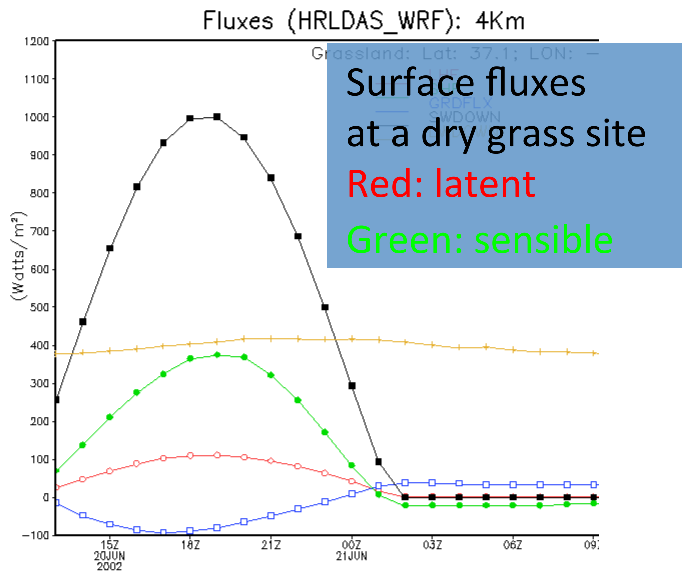
$$\mathbf{H = \rho c_p C_h U(T_{sfc} - T_{air})}$$



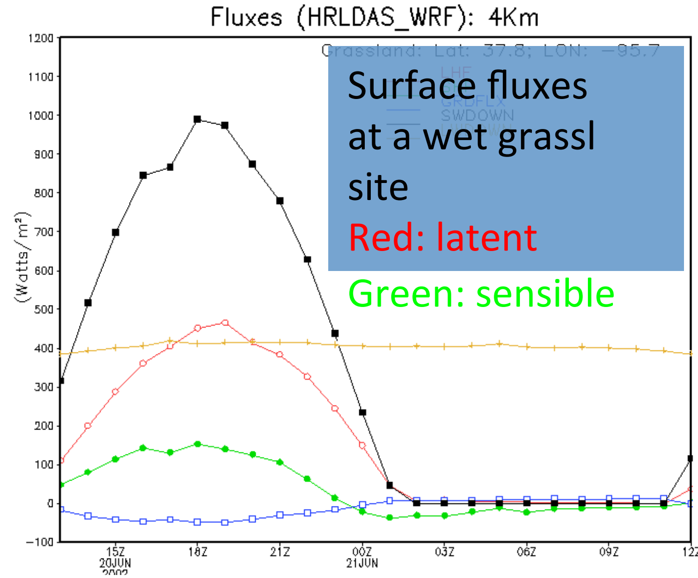
ρ, $\mathbf{c_p}$ = air density, specific heat
$\mathbf{C_h}$ = surface-layer turbulent exchange coeff.
$\mathbf{U}$ = wind speed
$\mathbf{T_{sfc}-T_{air}}$ = surface-air temperature difference

- "effective" $\mathbf{T_{sfc}}$ for canopy, bare soil, snowpack.

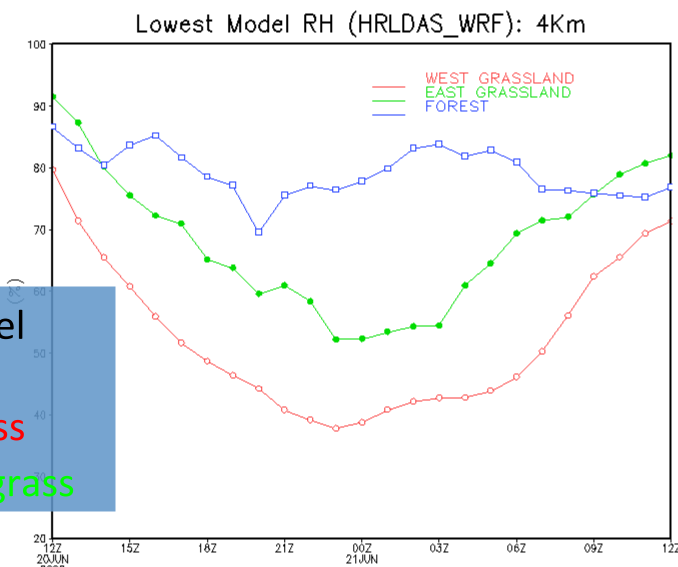
WRF/Noah simulated typical summer surface fluxes and PBL depth



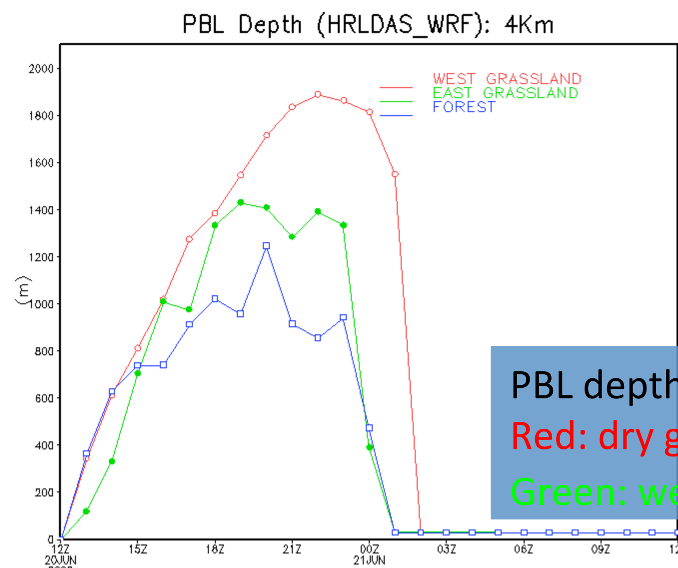
Surface fluxes at a dry grass site
Red: latent
Green: sensible



Surface fluxes at a wet grassl site
Red: latent
Green: sensible



Lowest model level RH
Red: dry grass
Green: wet grass



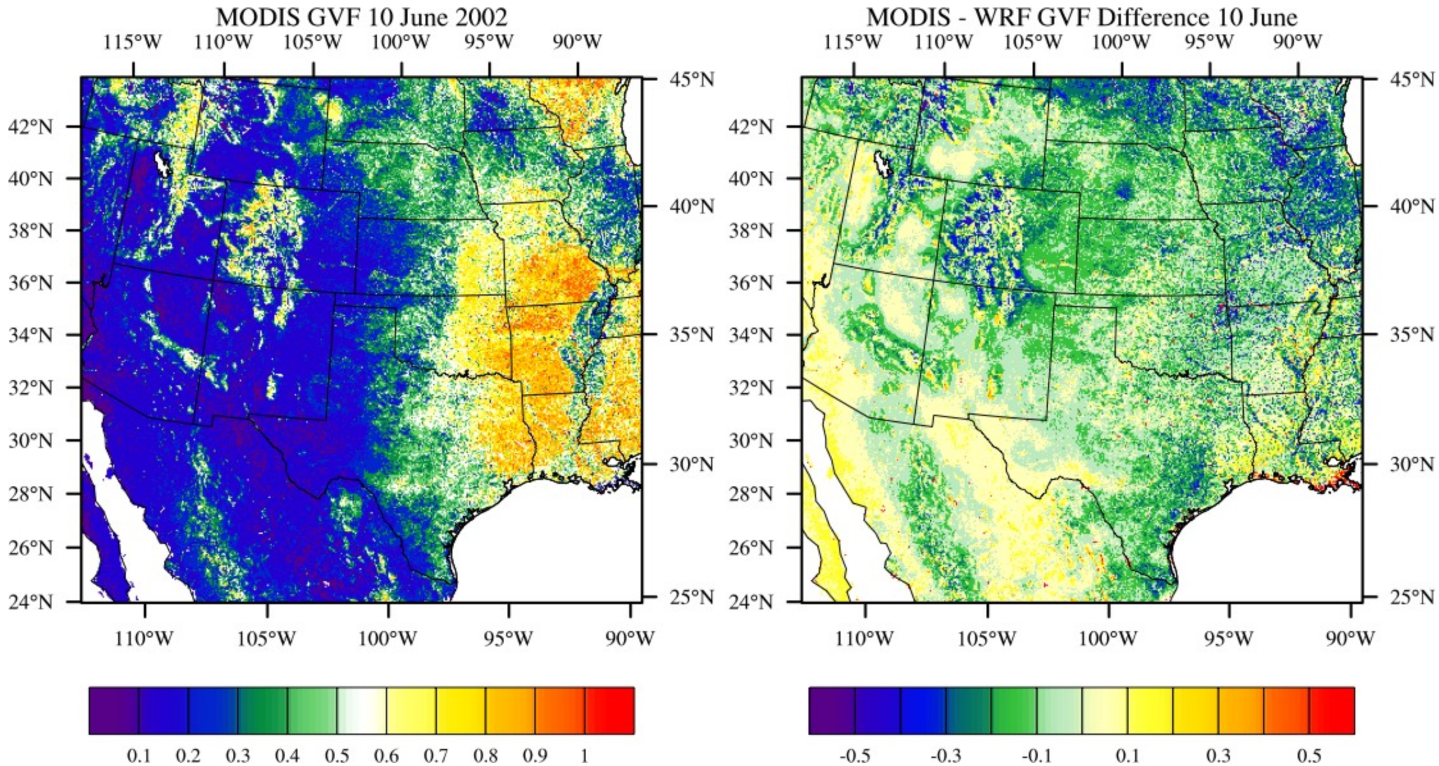
PBL depth
Red: dry grass
Green: wet grass

Noah V 3.1 released in WRF 3.1 April 2009

Largest modifications in Noah since 2004

1. New global 1-km MODIS based land-use and land-cover data
2. New vegetation and soil parameter tables to accommodate both USGS and MODIS LULC data
3. New capabilities for treating time-varying vegetation phenology
   a) Directly import MODIS/AVHRR leaf area index, green vegetation fraction
   b) Scaled LAI, albedo, emissivity, and roughness length between its minimum and maximum values using time-varying GVF
4. Updated maximum snow albedo based on MODIS data
5. A new multi-layer urban canopy model (Centro de Investigaciones Energeticas, Spain; and Arizona State U.)
6. Improved the parameterization of time-varying snow albedo (U. Washington, NCEP)

Comparison of MODIS 12 June 2002 realtime data and WRF June climatology



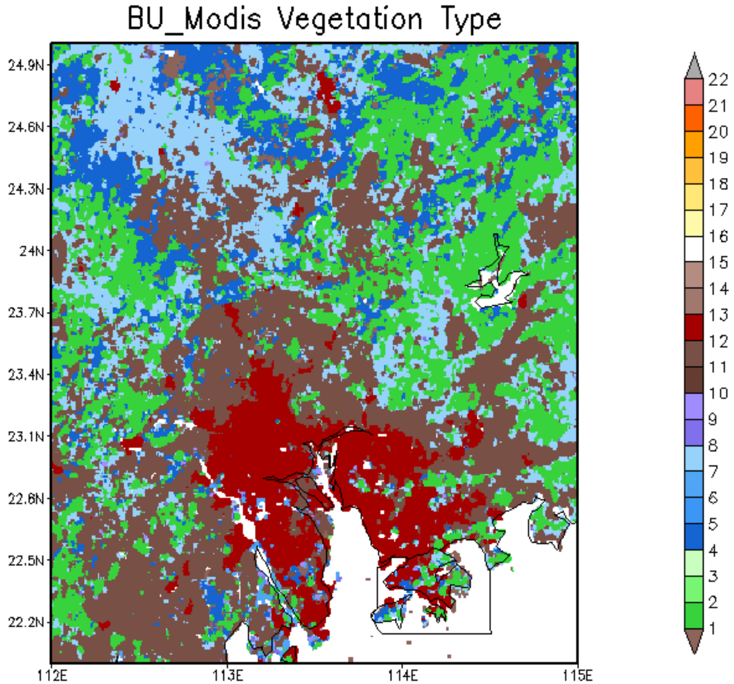
- MODIS green vegetation fraction lower over most of the domain

AVHRR vs MODIS land-use data set

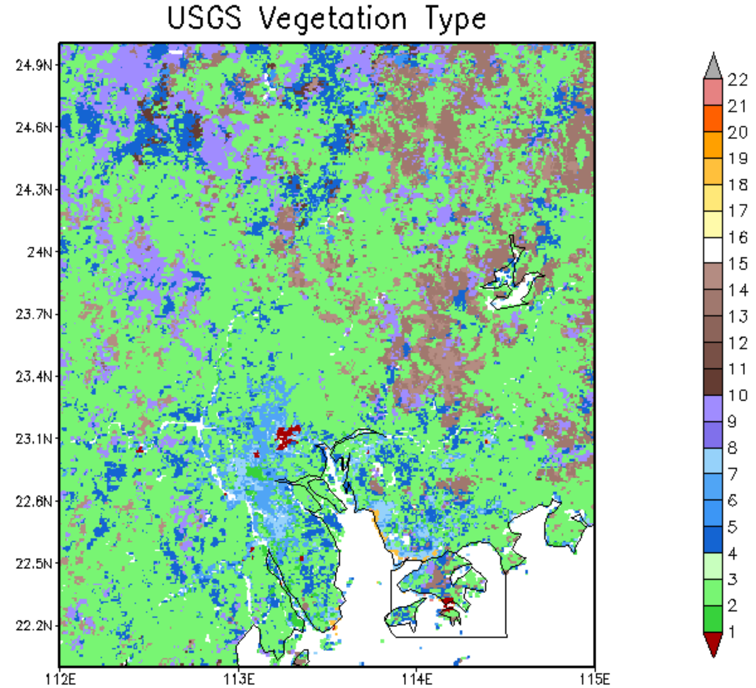
	AVHRR	MODIS
Data Collection Instrument	AVHRR (Advanced Very High Resolution Radiometer)	MODIS (MODerate resolution Imaging Spectroradiometer)
Channels	5 channels	15 land surface/vegetation dedicated channels
Data Collection Dates	April 1992 – March 1993	January 2001 – December 2001 Reflecting recent land-use change
Data Provider	USGS/ORNL	Boston University
Classification Scheme	Modified USGS	Modified IGBP IGBP used in NPOESS and next-generation NWP models
# of Categories	24*	19*

MODIS vs AVHRR

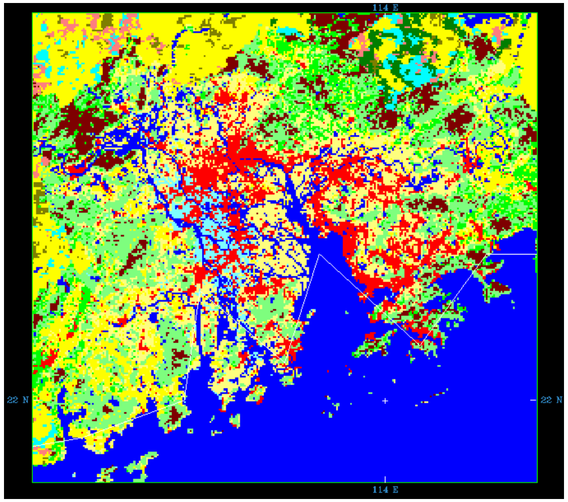
Red: urban areas in the Pearl River Delta, China



2001 MODIS data

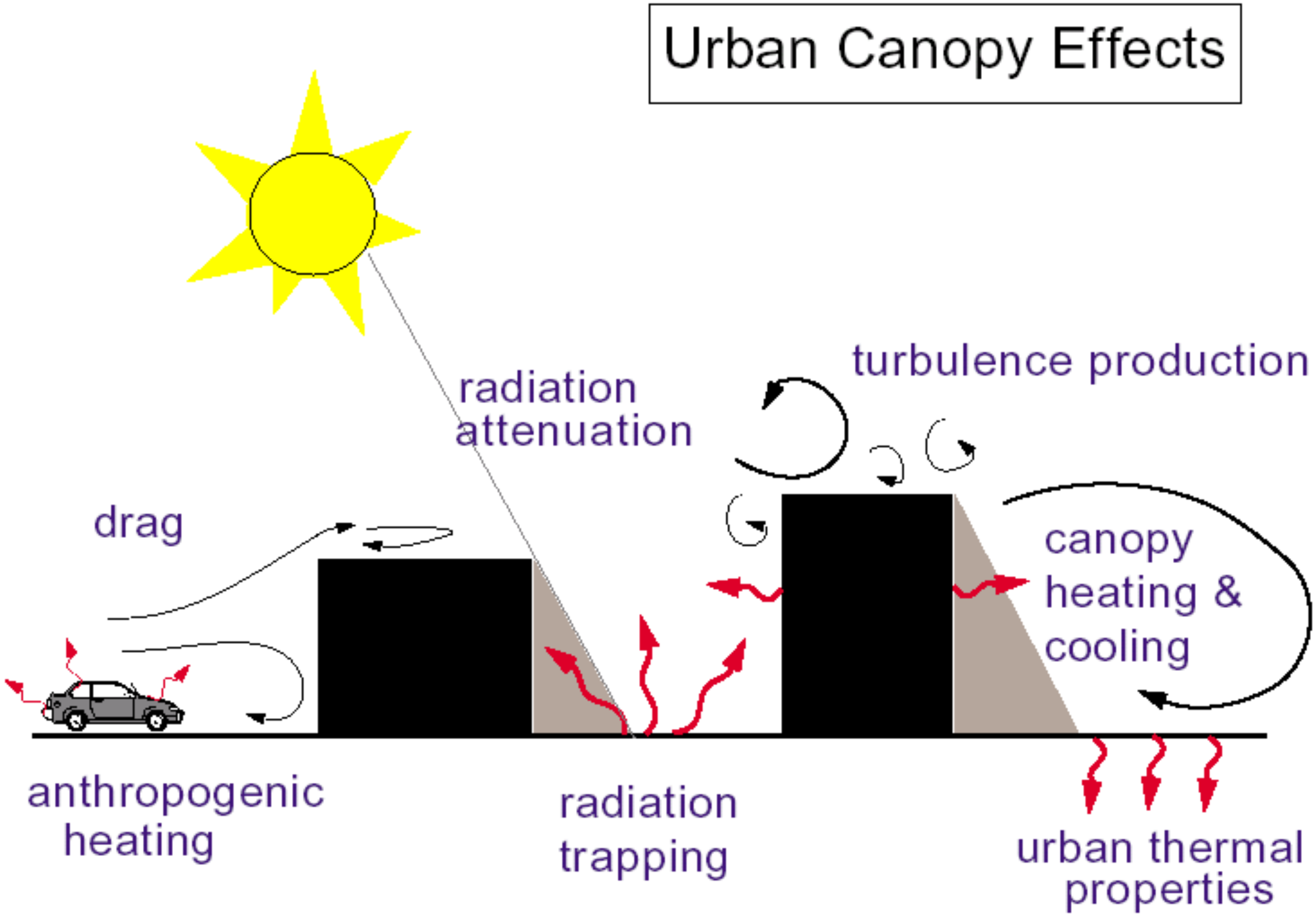


1993 USGS data



Data from HK urban planning office

Urban Modeling in WRF-Noah



Urban Modeling in WRF-Noah: Three parameterization schemes

1. Bulk parameterization

- Large roughness length: from 0.5 m to 0.8 m (<1.0m)
  - turbulence generated by roughness elements
- Small albedo: from 0.18 to 0.15
  - radiation trapping
- Large volumetric heat capacity and thermal conductivity: $3.0 10^6$ J m^{-3} K^{-1} and 3.24 W m^{-1} K^{-1}
  - heat storage in buildings
- Low evaporation: the green vegetation fraction was reduced to 0.05, and the available urban soil water capacity was decreased.
- Available since WRF V2.0

  sf_surface_physics = 2 (Noah), sf_urban_physics = 0

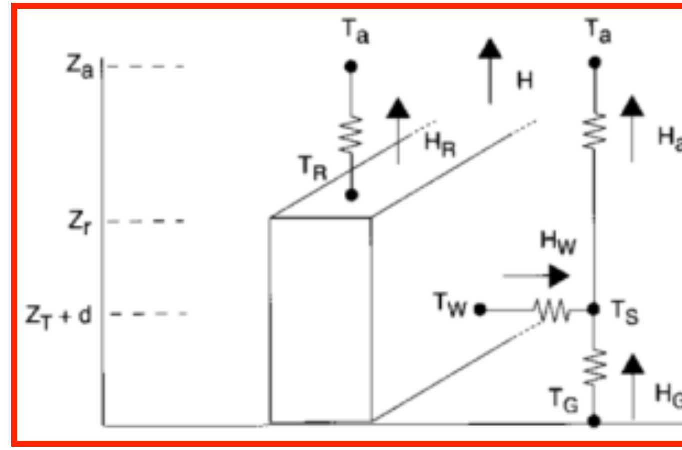
- Reference: Liu et al., 2006: *Journal of Applied Meteorology and Climatology,* 45:7, 912-929

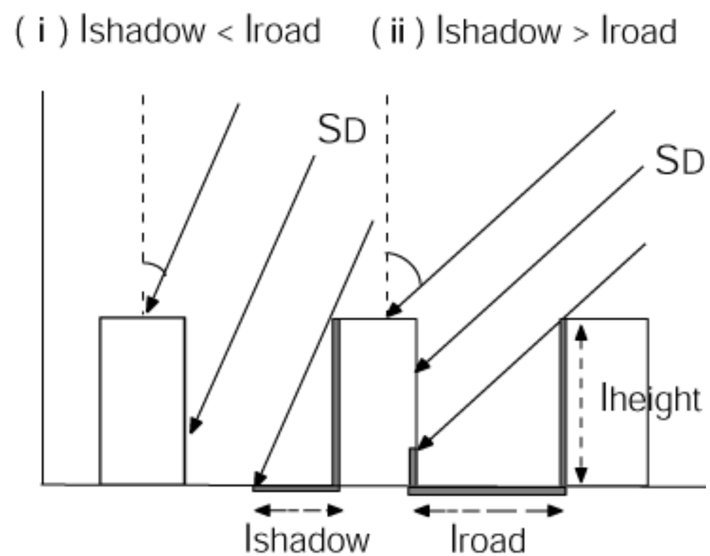
Urban Modeling in WRF-Noah: Three parameterization schemes

2. Single-layer Urban Canopy Model (SLUCM)

- 2-D urban geometry
- Street canyons
- Shadowing from buildings and reflection of radiation
- Multi-layer roof, wall and road models
- Available since WRF V2.2

  sf_surface_physics = 2 (Noah)
  sf_urban_physics = 1

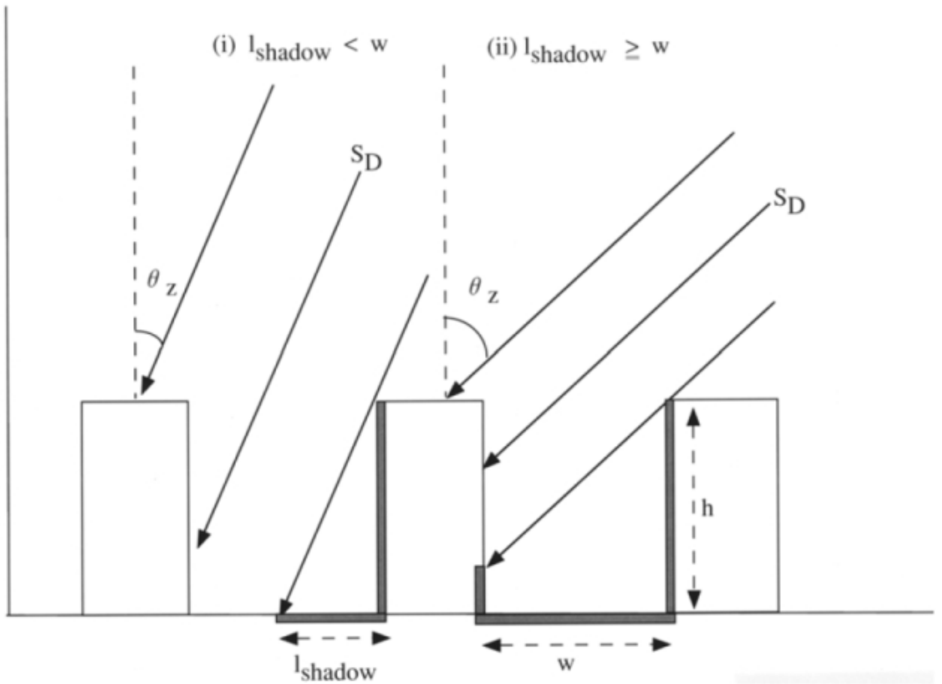




- References:
  - Kusaka et al., Bound.-Layer Meteor., 2001, 329-358.
  - Miao et al., J. Appl. Meteor. Climatol., 2009, 484-501

Short-wave radiation in SLUCM

$$l_{\text{shadow}} = \begin{cases} h \tan\theta_z \sin\theta_n & (l_{\text{shadow}} < w) \\ w & (l_{\text{shadow}} \geq w) \end{cases}$$



$$S_{W,1} = S_D \frac{l_{\text{shadow}}}{2h}(1-\alpha_W) + S_Q F_{W\to S}(1-\alpha_W),$$

$$S_{W,2} = S_D \frac{(w - l_{\text{shadow}})}{w}\alpha_G F_{W\to G}(1-\alpha_W) + S_Q F_{W\to G}(1-\alpha_W)$$
$$+ S_D \frac{l_{\text{shadow}}}{2h}\alpha_W F_{W\to W}(1-\alpha_W) + S_Q F_{W\to S}\alpha_W F_{W\to W}(1-\alpha_W),$$

$$S_{G,1} = S_D \frac{(w - l_{\text{shadow}})}{w}(1-\alpha_G) + S_Q F_{G\to S}(1-\alpha_G),$$

$$S_{G,2} = S_D \frac{l_{\text{shadow}}}{2h}\alpha_W F_{G\to W}(1-\alpha_G) + S_Q F_{W\to S}\alpha_W F_{G\to W}(1-\alpha_G).$$

Sensible heat fluxes from SLUCM

$$H_W = C_W(T_W - T_S),$$

$$H_G = C_G(T_G - T_S),$$

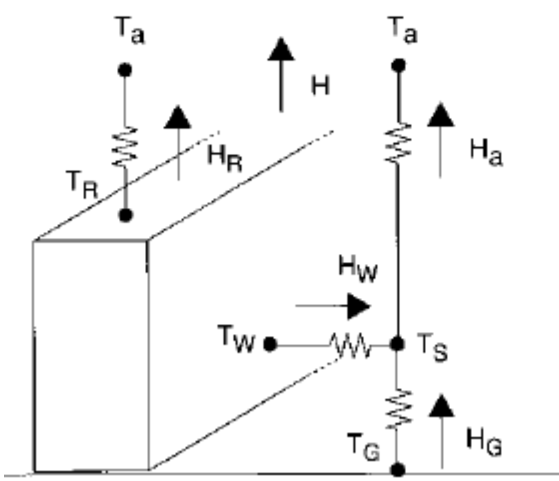
$$C_W = C_G = \begin{cases} 7.51U_S^{0.78} & (U_S > 5\,\mathrm{m\,s^{-1}}) \\ 6.15 + 4.18U_S & (U_S \leq 5\,\mathrm{m\,s^{-1}}). \end{cases}$$

$$H_a = \rho c_p \frac{k u_*}{\Psi_h}(T_S - T_a).$$

The air within the urban canopy-layer has a negligible heat capacity and so sensible heat flux from the building wall H_W and from the road H_G must be balanced by the sensible heat flux to the atmosphere from the canyon space, i.e.,

$$w H_a = 2h H_W + w H_G.$$

$$H = A_u[r H_R + w H_a] + A_v H_v,$$
$$+ AH$$

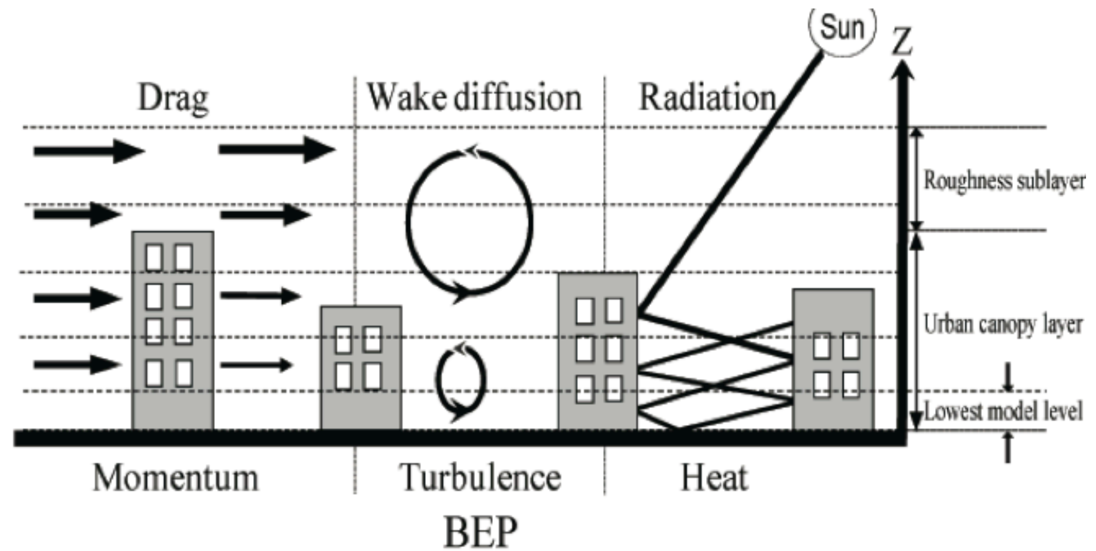


Urban Modeling in WRF-Noah:
Three parameterization schemes

3. Multi-layer Urban Canopy Model: Building Effect Parameterization (BEP) scheme

- Direct interactions with WRF PBL scheme at multiple vertical layers
- Calculate effects of buildings on momentum and heat fluxes
- Modify TKE scheme and turbulent length scales
- Available since WRF3. 1
  sf_surface_physics = 2 (Noah)
  sf_urban_physics = 2
- works with WRF

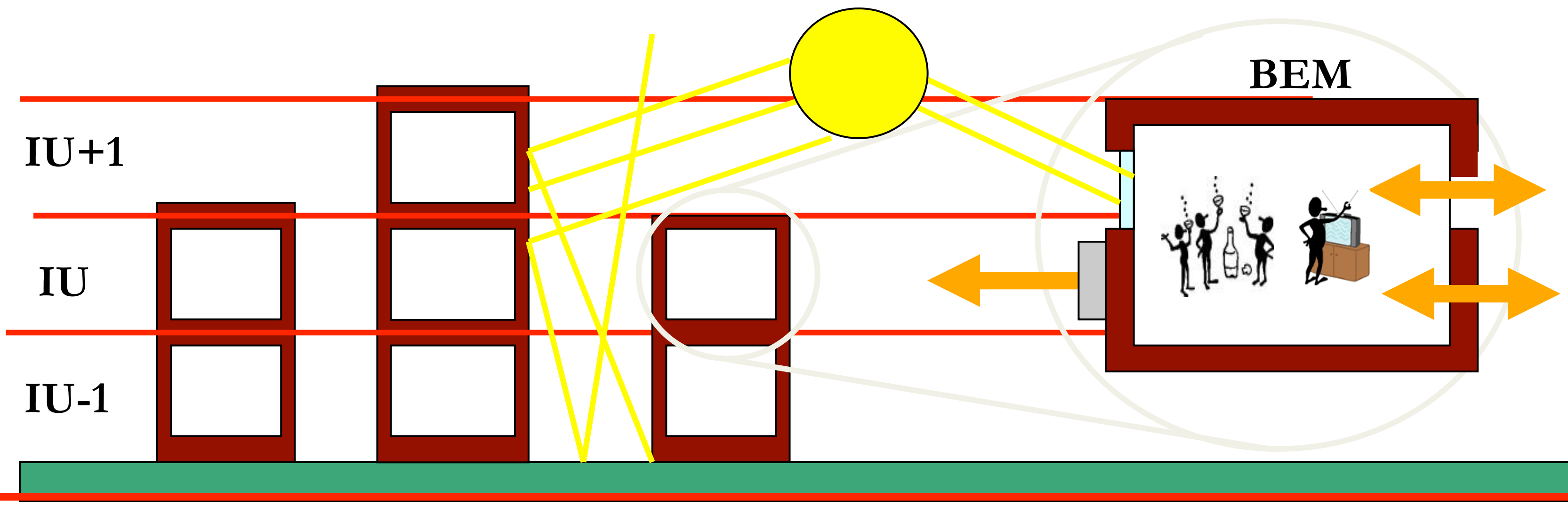
BouLac and MYJ PBL only



Reference: Martilli et al., 2002, *Boundary Layer Meteorology.*

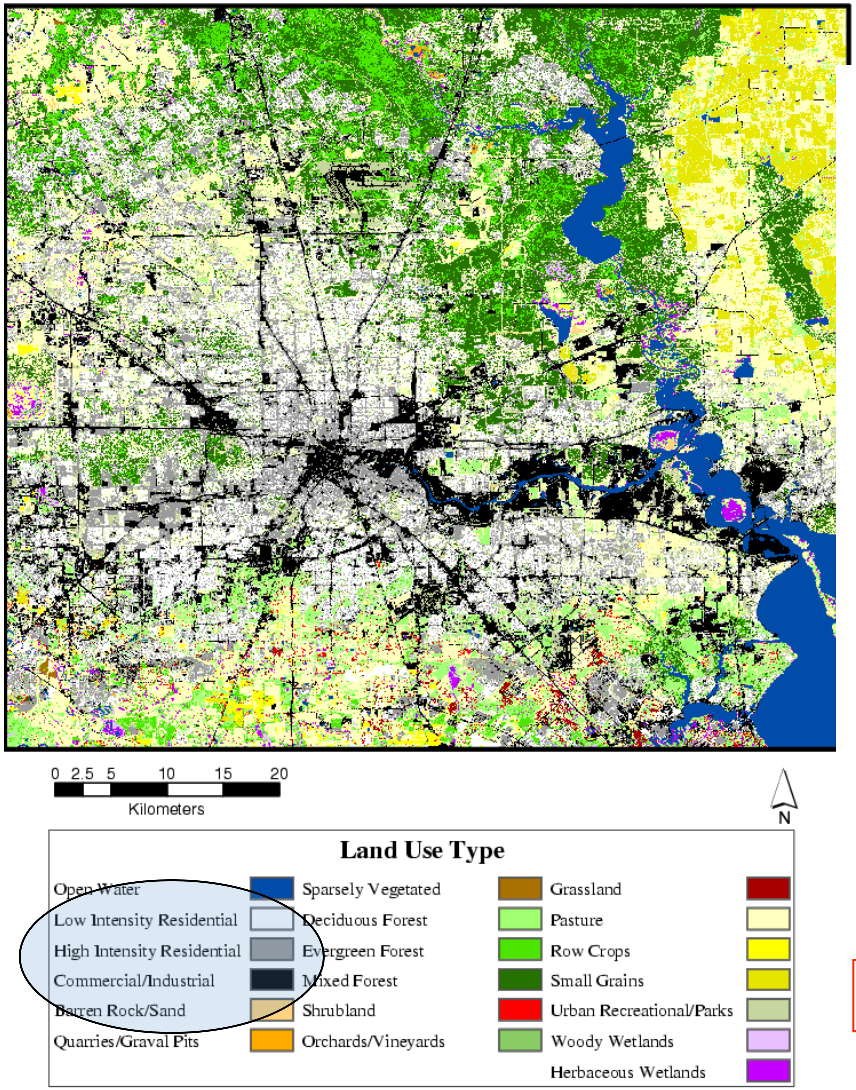
Building Energy Model (BEM):
Representing indoor-outdoor exchange

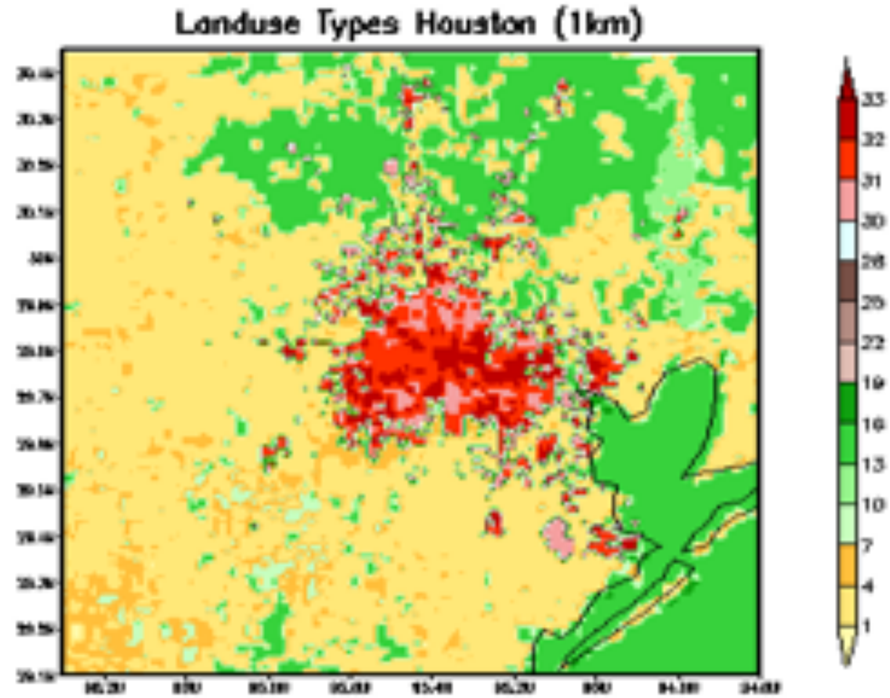
- Time-varying floor air temperature and air humidity are estimated
- Natural ventilation, heat generated by equipment and occupants, heat transfer through the walls, and the radiation through the windows
- Heat generated from cooling(Air conditioning)/heating the indoor air temperature
- Available since WRF3. 2
  sf_surface_physics = 2 (Noah), sf_urban_physics = 3
- works with BEP and BouLac and MYJ PBL only



!! We do not attempt to simulate a specific building, rather an average behaviour over the grid cell!!
Salamanca and Martilli (2009, *Theoreti. Appli. Climatol.)*

Urban Model Input: urban land-use





NLCD 30-m Landsat land-cover for Houston

UCM parameters (look-up table: urbparm.tbl)

Parameters shared by SLUCM and BEP

Parameter	Unit	Specific Values for			SLUCM	BEP
		Low intensity residential	High intensity residential	Industrial, commercial		
h (Building Height)	m	5	7.5	10	Yes	No
l_{roof} (Roof Width)	m	8.3	9.4	10	Yes	No
l_{road} (Road Width)	m	8.3	9.4	10	Yes	No
AH (Anthropogenic Heat)	W m^{-2}	20	50	90	Yes	No
F_{urb} (Urban fraction)	Fraction	0.5	0.9	0.95	Yes	Yes
C_R (Heat capacity of roof)	J m^{-3} K^{-1}	1.0E6	1.0E6	1.0E6	Yes	Yes
C_W (Heat capacity of building wall)	J m^{-3} K^{-1}	1.0E6	1.0E6	1.0E6	Yes	Yes
C_G (Heat capacity of road)	J m^{-3} K^{-1}	1.4E6	1.4E6	1.4E6	Yes	Yes
λ_R (Thermal Conductivity of roof)	J $m^{-1}s^{-1}K^{-1}$	0.67	0.67	0.67	Yes	Yes
λ_W (Thermal Conductivity of building wall)	J $m^{-1}s^{-1}K^{-1}$	0.67	0.67	0.67	Yes	Yes
λ_G (Thermal Conductivity of road)	J $m^{-1}s^{-1}K^{-1}$	0.4004	0.4004	0.4004	Yes	Yes
α_R (Surface Albedo of roof)	Fraction	0.20	0.20	0.20	Yes	Yes
α_W (Surface Albedo of building wall)	Fraction	0.20	0.20	0.20	Yes	Yes
α_G (Surface Albedo of road)	Fraction	0.20	0.20	0.20	Yes	Yes
ε_R (Surface emissivity of roof)	-	0.90	0.90	0.90	Yes	Yes
ε_W (Surface emissivity of building wall)	-	0.90	0.90	0.90	Yes	Yes
ε_G (Surface emissivity of road)	-	0.95	0.95	0.95	Yes	Yes
Z_{0R} (Roughness length for momentum over	m	0.01	0.01	0.01	Yes*	Yes

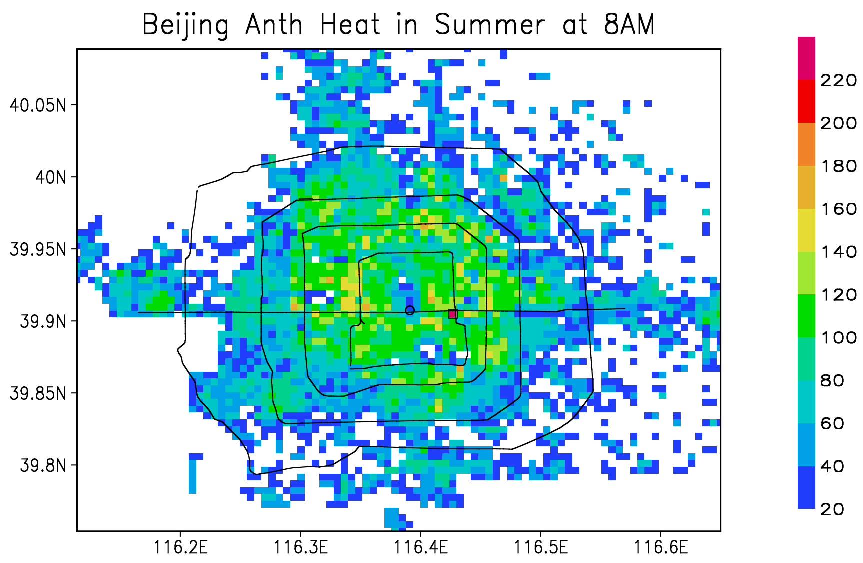
Parameters used in BEP only

b) Parameters used only in BEP

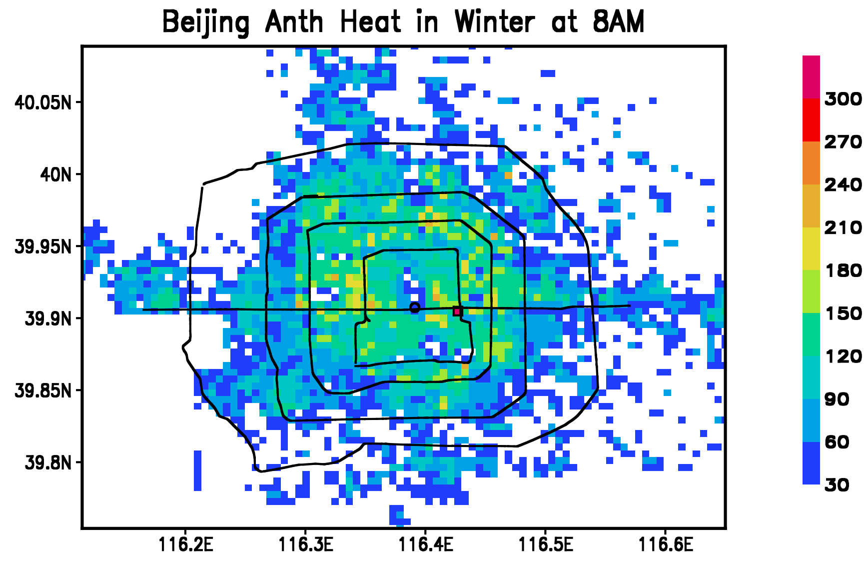
Street Parameters		Directions from North (degrees)		Directions from North (degrees)		Directions from north (degrees)		No	Yes
		0	90	0	90	0	90		
W (Street Width)	m	15	15	15	15	15	15		
B (Building Width)	m	15	15	15	15	15	15		
h (Building Heights)	m	Height	%	Height	%	Height	%		
		5	50	10	3	5	30		
		10	50	15	7	10	40		
				20	12	15	50		
				25	18				
				30	20				
				35	18				
				40	12				
				45	7				
				50	3				

Anthropogenic heating (AH)

0800 LST Summer



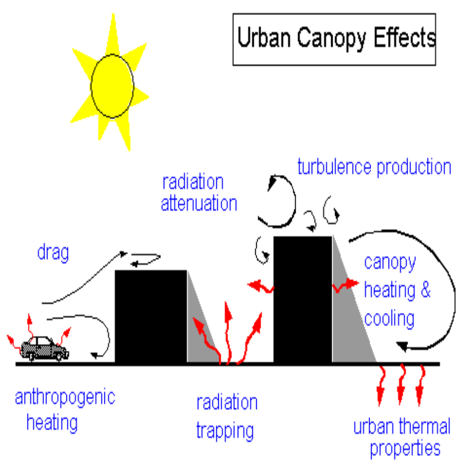
0800 LST Winter

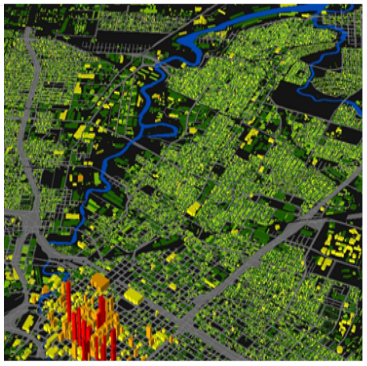


NUDAPT: gridded UCM parameters

National Urban Database and Access Portal Tool

METHODOLOGY: Meso-urban scale modeling



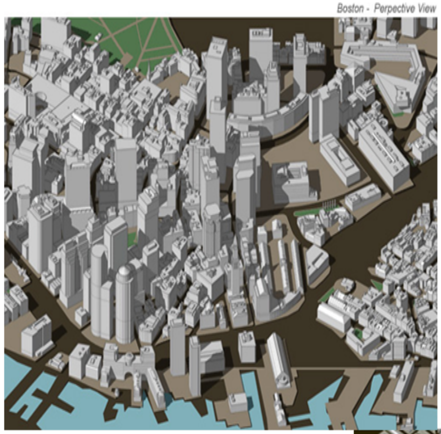


Salt Lake City, UT (Don Green Photography)

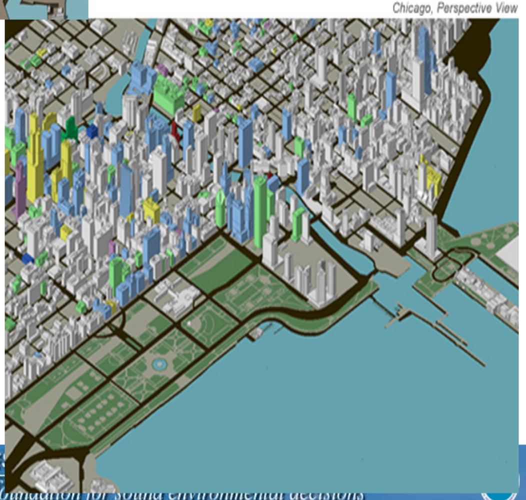
Modeler Needs:
To capture the grid average effect of detailed urban features in mesoscale atmospheric models

Solution:
Modelers have defined and implemented urban canopy parameterizations into their models (e.g., MM5, WRF, HOTMAC, RAMS, COAMPS...)

Urban building data



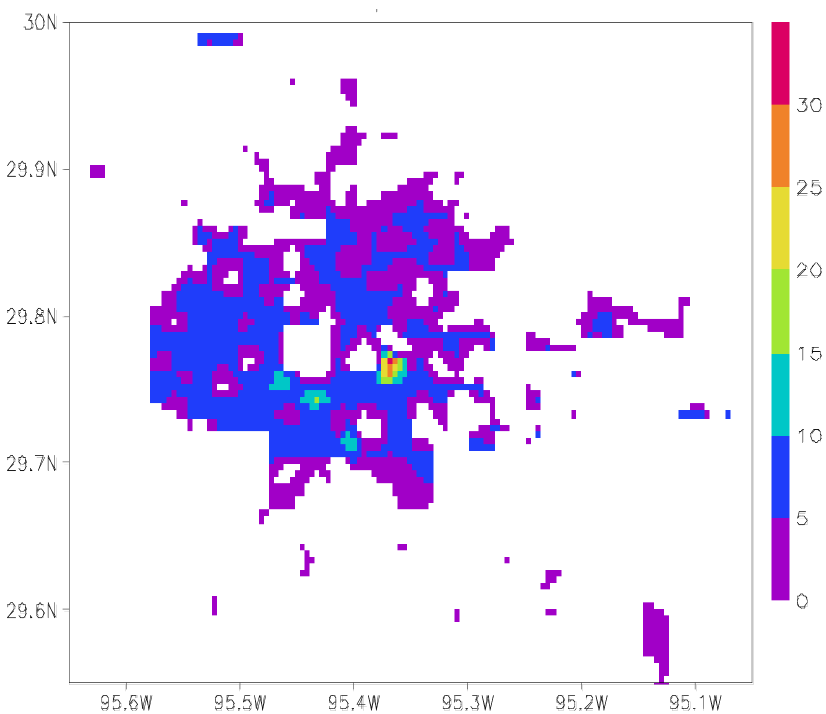
We have the technology and means for obtaining building data at high resolution; such data and ancillary data are becoming increasingly more available for our major cities



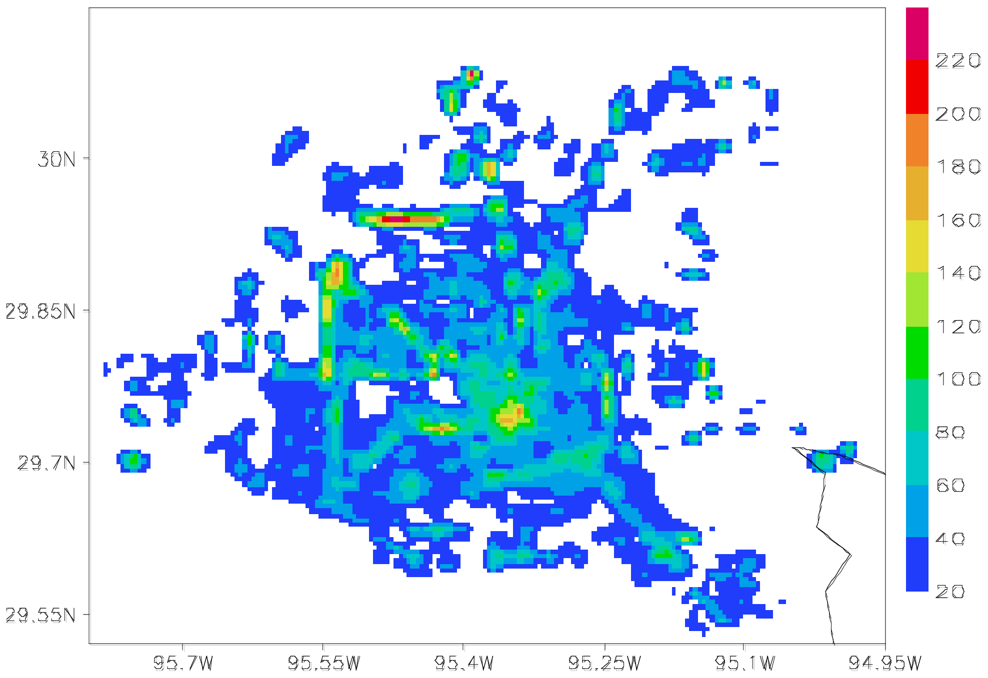
High resolution urban morphological data can be derived from lidar mapping and photogrammetric techniques

Examples of NUDAPT data used in WRF/UCM For Houston

Plan area weighted mean building height (Max: 33 m)



Anthropogenic heating at 1700LST for August (Max: 268.5 W/m2)



Outline

- **Why do we need land surface models (LSM) in numerical weather and climate models?**
- **What are the LSMs and their functions in WRF?**
- **How to initialize land state variables?**
- **What else do we need to know?**

Motivation for land state assimilation

- Mesoscale models need to capture atmospheric motions resulted from surface forcing.
- No routine high-resolution soil observation network.

Indirect Soil Moisture and Temperature Nudging

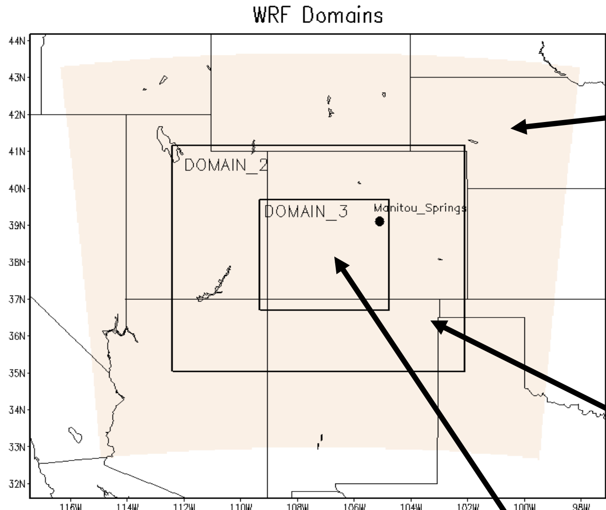
- Soil moisture nudging = Func(T_{2m}-bias, RH_{2m}-bias)
  - Uses forecast bias in T_{2m}, RH_{2m} compared to analyses from *Obsgrid*
  - Dynamically adjusts soil moisture → stomatal conductance →Evapotranspiration → Bowen ratio → T_{2m}, RH_{2m}
  - Nudging coefficients are functions of surface flux related parameters:
    - stomatal conductance, aerodynamic resistance, solar radiation, etc
  - Reduces dependence on initial soil moisture
- Deep soil temperature nudging only at night
  - Optimizes soil heat flux in simple 2-layer force-restore model
  - Deep soil temperature time scale is set to 10 days so the nudging can have some lasting effect
  - *Greatly improves air temperature simulation, especially in winter*

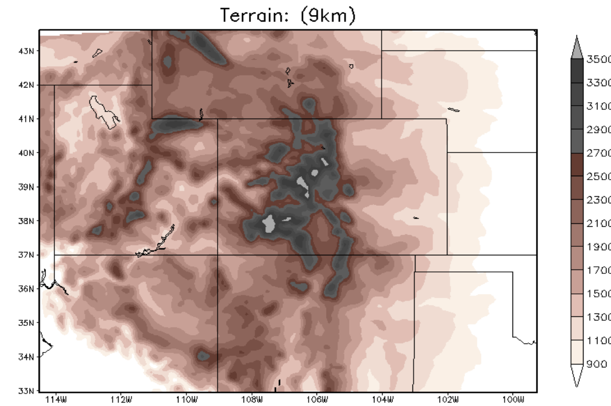
Offline land data assimilation system (LDAS)

- LDAS approach: using observed rainfall, analyzed downward solar radiation, and atmospheric analysis to drive LSMs in uncoupled mode
  - NCEP NLDAS: North America, 1/8 degree.
  - AFWA AGRMET: global, 47-km, long-term archive.
  - GLDAS, NASA-LIS.
  - NCAR High-resolution land data assimilation System (HRLDAS).
- HRLDAS (code, user's guide) is available:

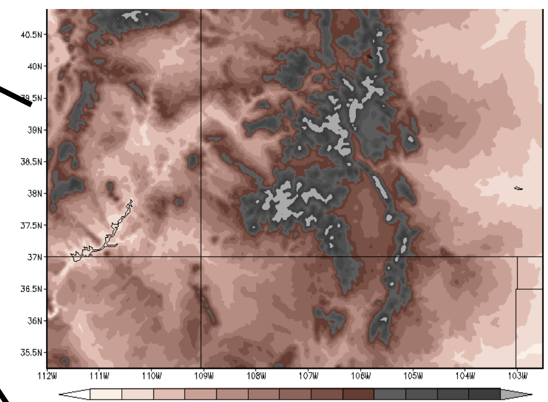
http://www.ral.ucar.edu/research/land/technology/lsm.php

Challenge: Initialize land state variables in nested WRF domains

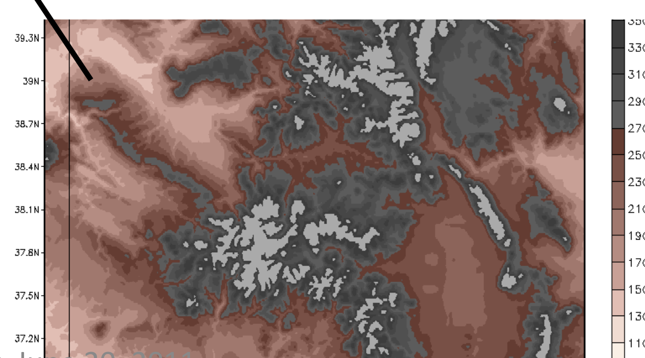




9-km domain 1
Terrain height



3-km domain 2
Terrain height

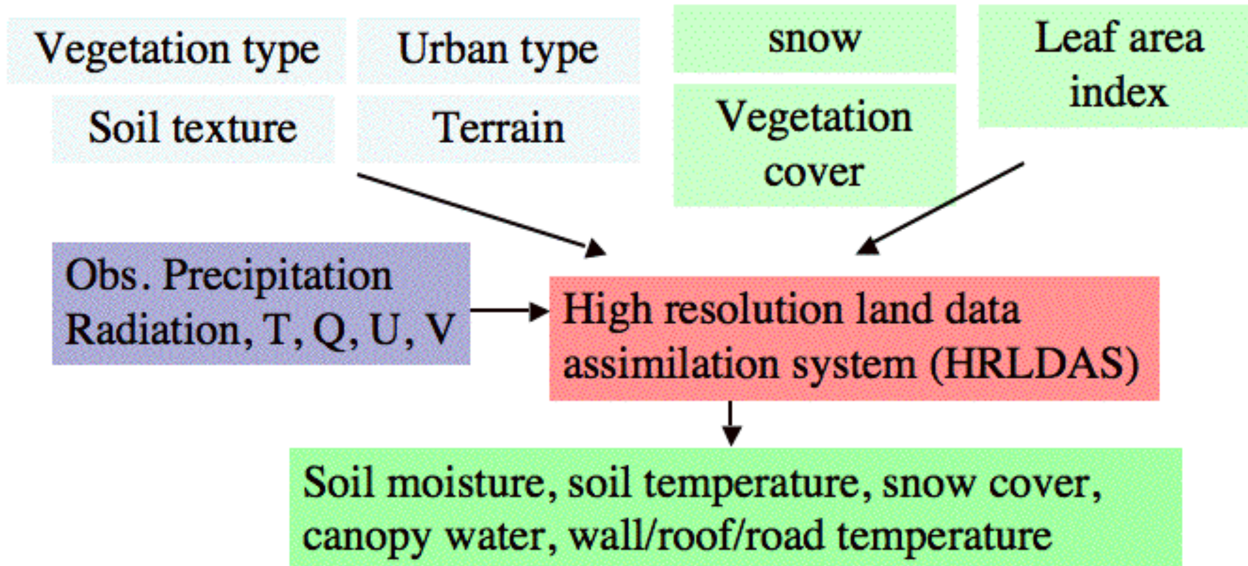


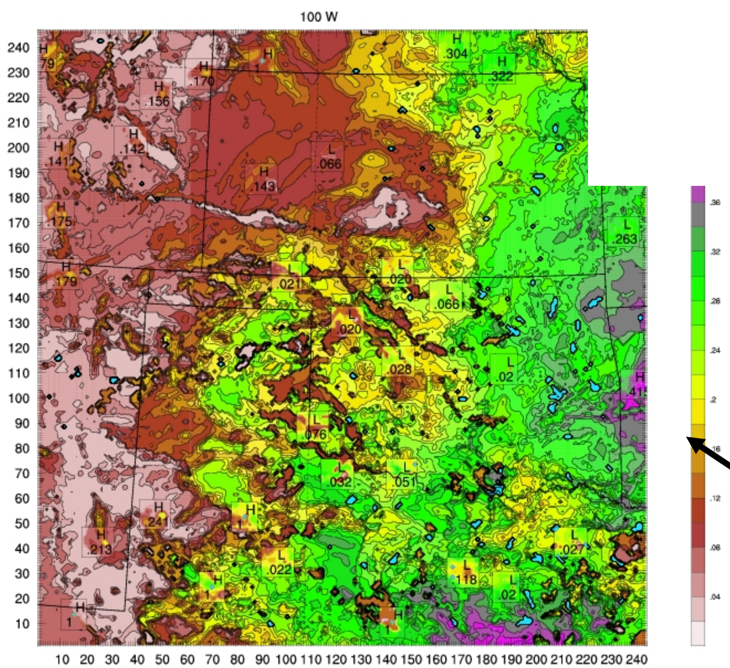
1-km domain 3
Terrain height

HRLDAS executed on the same Grids as mesoscale NWP models

- Using the same LSM
- No mismatch of terrain, land use type, soil texture, physical parameters
- No interpolation and soil moisture conversion.

High-Resolution Land Dada Assimilation System (HRLDAS): Capturing Small-Scale Variability





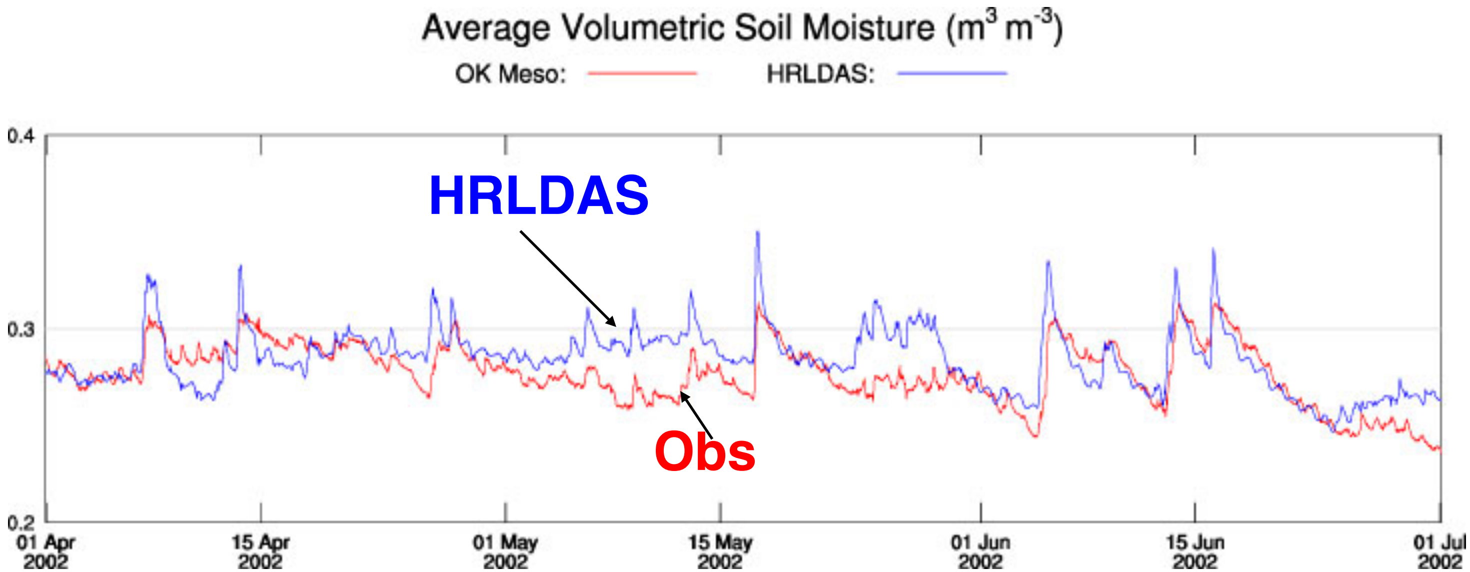
4-km HRLDAS surface soil moisture in IHOP domain 12Z May 29, 2002

HRLDAS Verification

4-month (2002) HRLDAS Soil Moisture vs Oklahoma Mesonet Observation

After 18-month spin-up

Surface (0-10 cm) volumetric soil moisture averaged for Mesonet 62 stations



Chen et al. 2007, *J. Appl. Meteorol. and Clim*.

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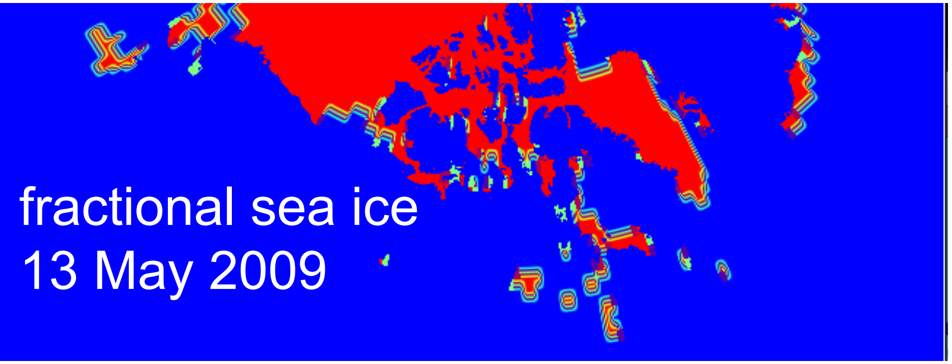
- **What else do we need to know?**

Yes, LSMs do treat sec-ice

Sea Ice is initialized from NESDIS snow/ ice data



New sea ice treatment in RUC LSM

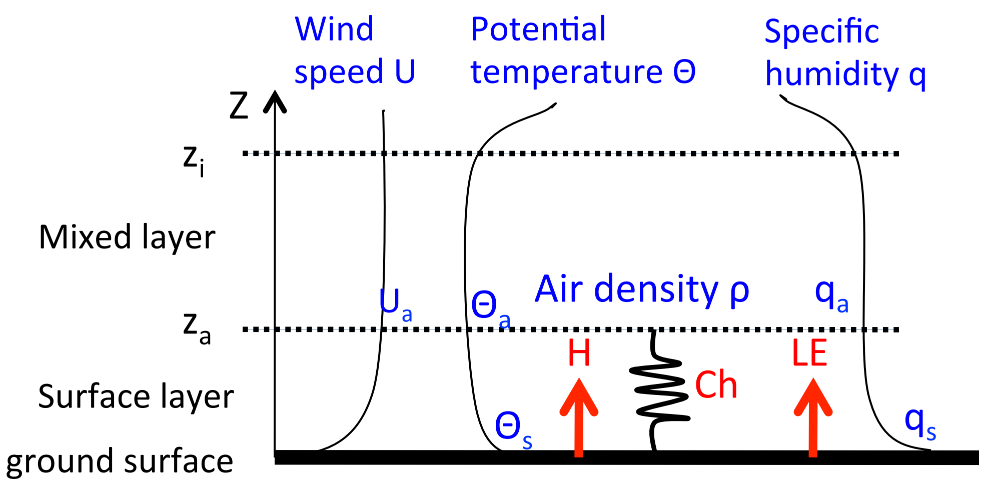
- Solution of surface energy budget and heat diffusion equation in ice
- Snow accumulation/melting on the sea ice surface
- Snow/Ice Albedo - function of snow/ice surface temperature
- Option of fractional sea ice
- No melting, drifting or building new sea ice

Old sea ice in RUC LSM

- Skin temperature is prescribed to be equal to temperature at the 1st atmospheric level
- No snow on sea ice

Important role of the atmospheric surface layer parameterization

- Lowest model level
- Provide Surface exchange coefficient (Ch): control the total heat flux transported into atmosphere.



$$H = \rho C_p C_h |U_a| (\theta_s - \theta_a)$$

$$LE = \rho C_h |U_a| (q_s - q_a)$$

Atmospheric surface-layer parameterization

- Compute Ch based on Monin-Obukhov similarity theory:

$$C_h = \frac{k^2/R}{\left[\ln\left(\frac{z}{z_{om}}\right) - \Psi_m\left(\frac{z}{L}\right) + \Psi_m\left(\frac{z_{om}}{L}\right)\right]\left[\ln\left(\frac{z}{z_{ot}}\right) - \Psi_h\left(\frac{z}{L}\right) + \Psi_h\left(\frac{z_{ot}}{L}\right)\right]}$$

k : von Karman constant; L : Obukhov length; R : Prandtl number;

Ψ_m and Ψ_h : stability functions; based on 1960s Kansas experiment;

z_{om} : roughness length for momentum; z_{ot} : roughness length for moisture/heat

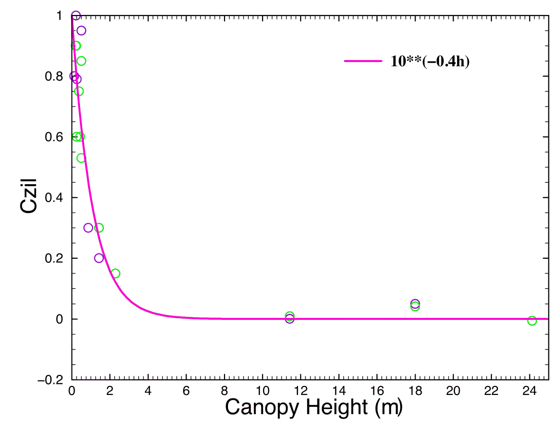
- Chen et al. 1997 (BLM): surface fluxes less sensitive to treatment M-O based stability functions.
- Rather, they are sensitive to z_{ot} $z_{ot} \neq z_{om}$

Parameterizing z_{ot} in WRF

- Some models assume a constant ration z_{ot} / z_{om}
- Noah LSM uses Zilitinkevich scheme: $z_{ot} / z_{om} = \exp(-kC_{zil}\sqrt{R_e^*})$

- Czil is a tuning parameter that modulates z_{ot} / z_{om}
- Smaller values of Czil =>larger Zot => rougher surface for heat and moisture => stronger turbulence => larger C_h

=>strong surface coupling



For two surface-layer schemes in WRF

- sf_sfclay_physics=1: Monin-Obukhov similarity theory
- sf_sfclay_physics=2: MOST (MYJ)
- iz0tlnd thermal roughness length options for land point:

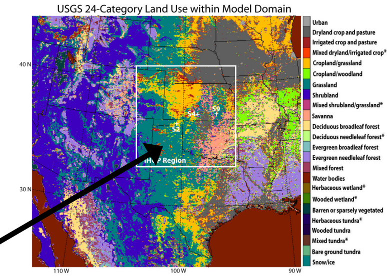
  0: Original Zilitinkevich, Czil=0.1

  1: based on Chen-Zhang (2009), Czil depend on vegetation canopy height

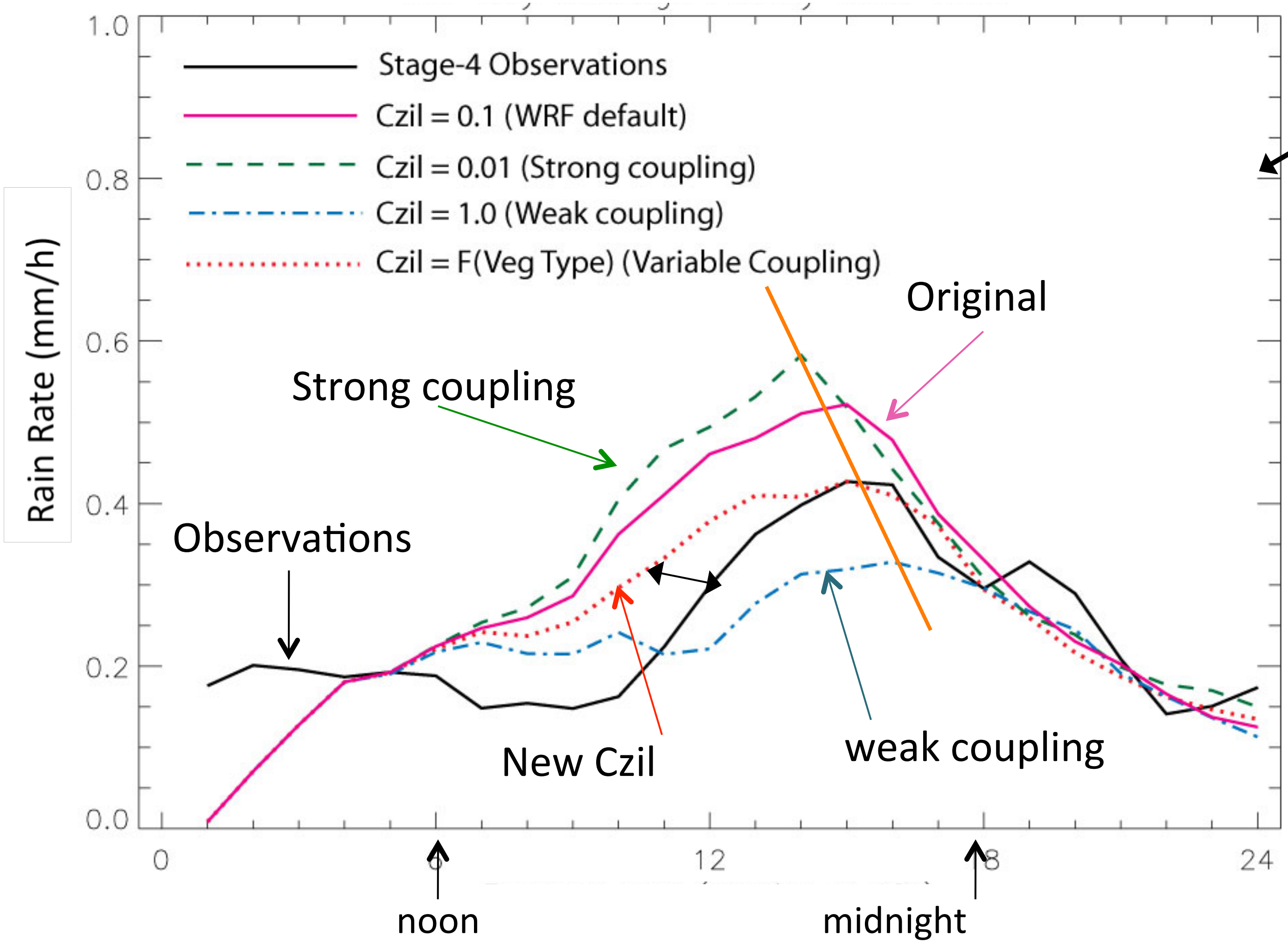
Surface coupling strength can

a) modify timing of peak-rain by 2-3 hours

b) change rainfall amount by twice as much



Six-Day Average Diurnal Cycle of Forecasted Hourly Rain (mm/h)



Using new C&Z2009 formulation still overestimate precipitation

Trier et al., 2011, *Wea Forecasting*

Further Reading

- Noah Land surface modeling, urban modeling, and data assimilation

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