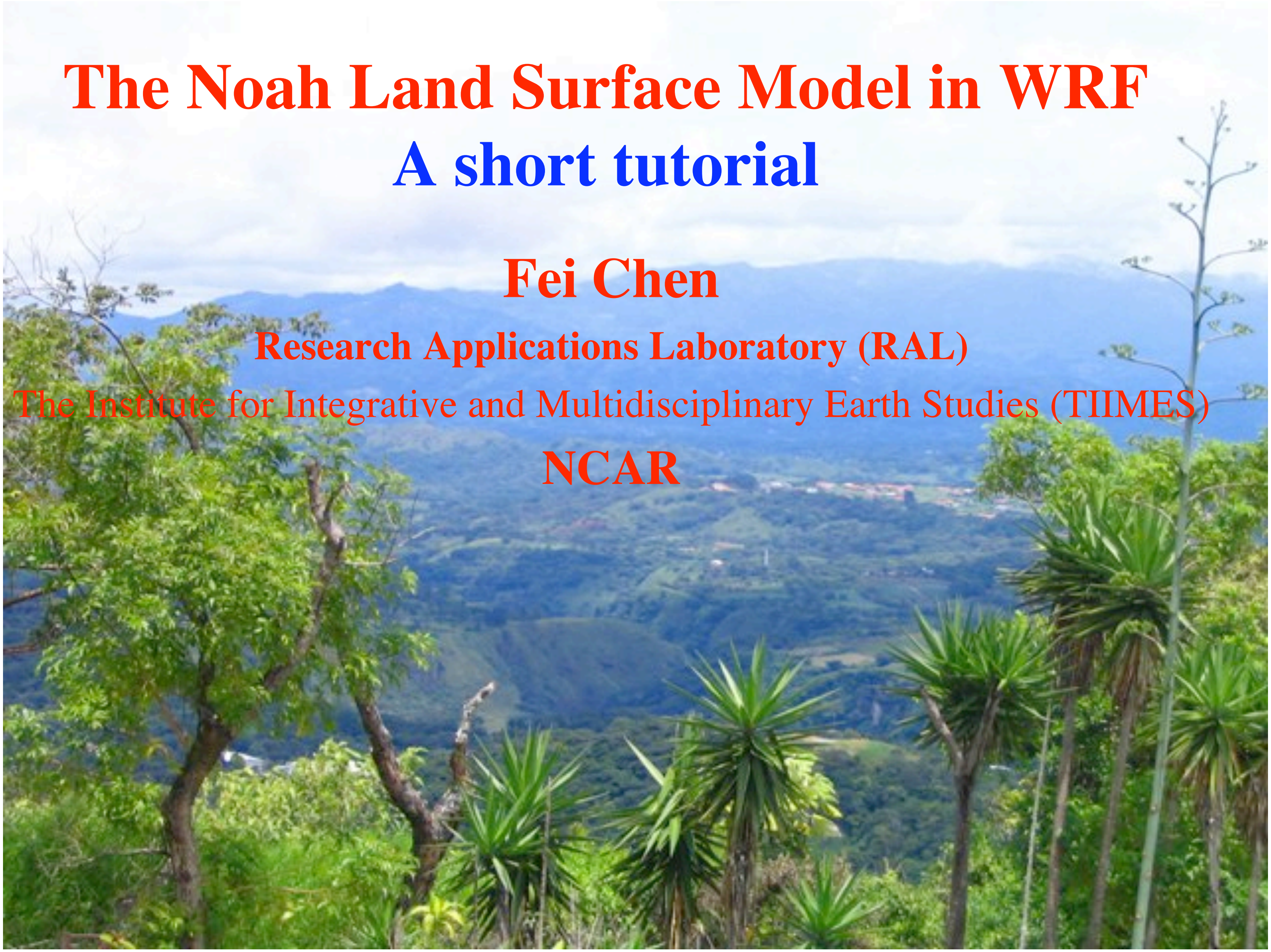

The Noah Land Surface Model in WRF

A short tutorial

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NCAR

LSM group meeting, 17 April 2007.

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Outline

- Overview of land surface processes
- The Noah LSM in WRF
- Surface layer parameterization

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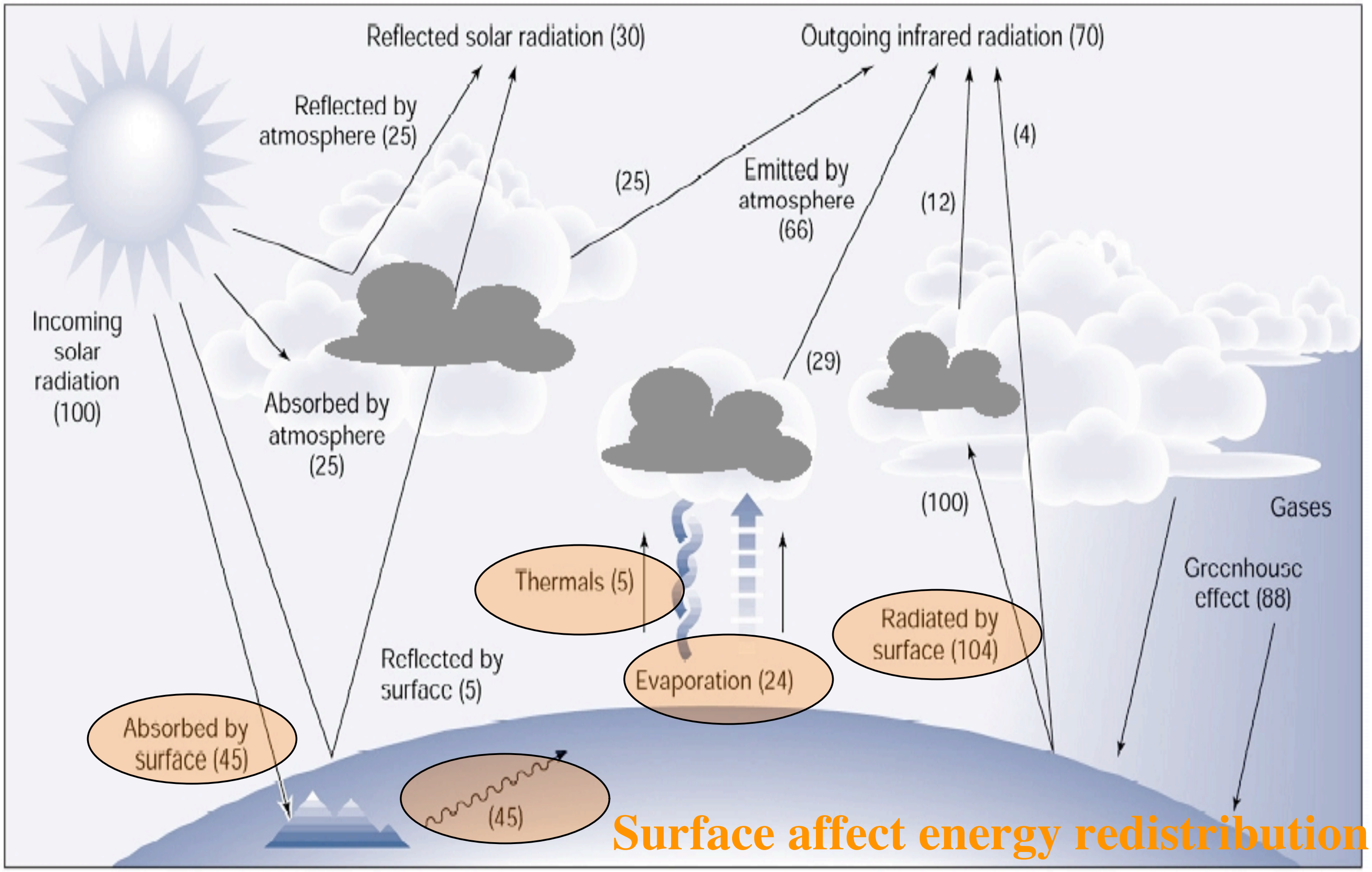
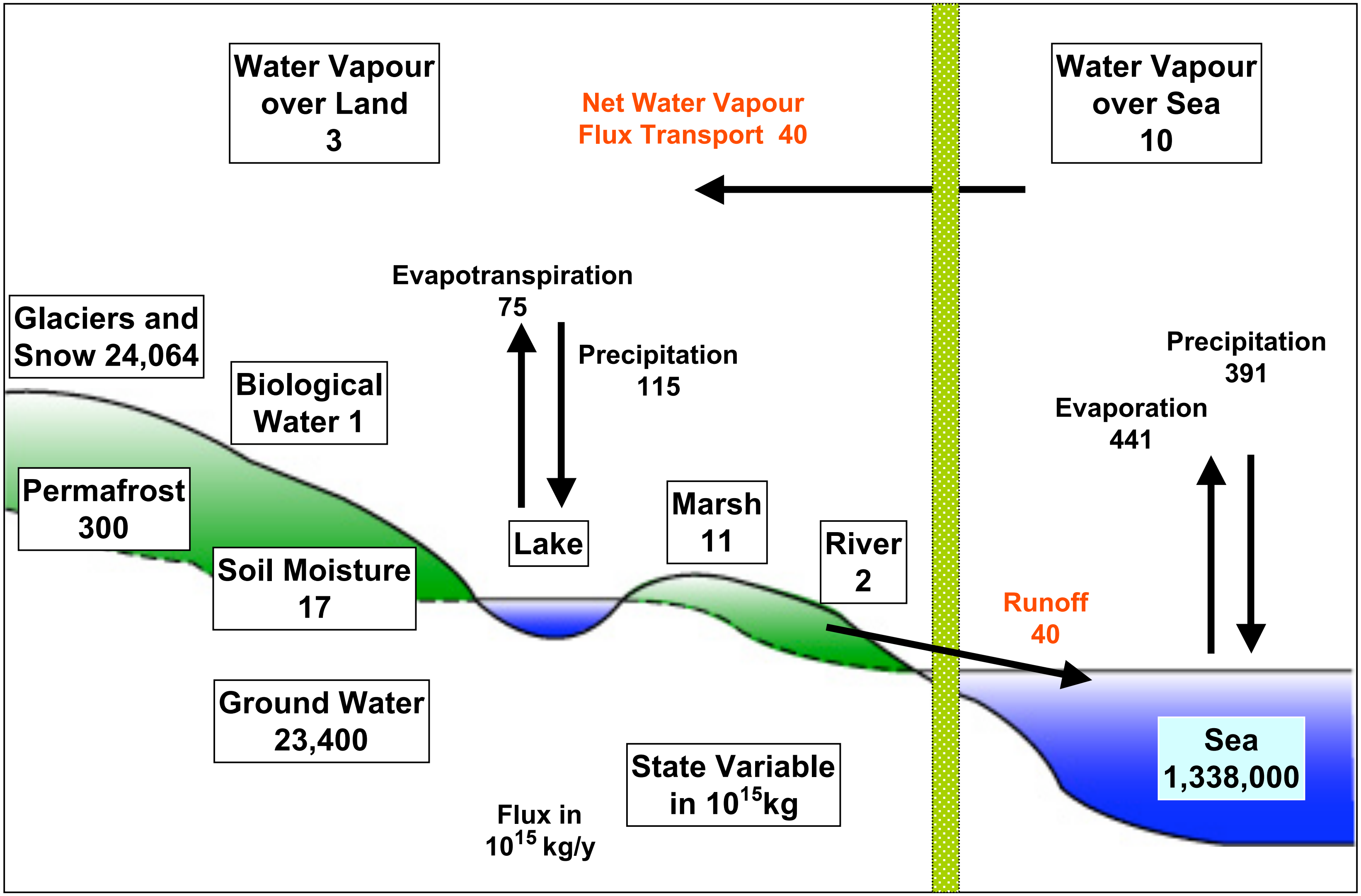
Earth's Global Energy Budget



- 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 ground, 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



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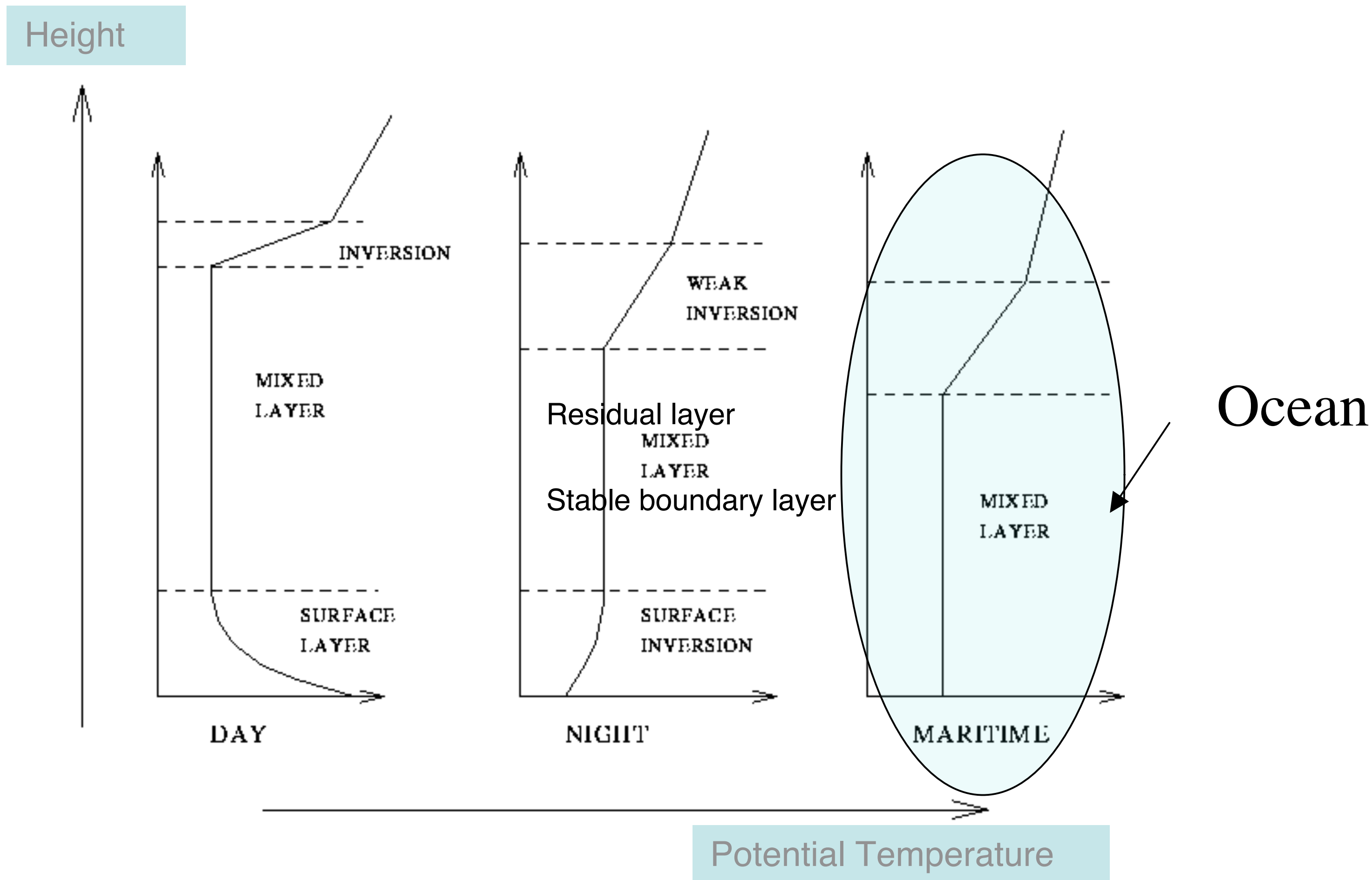
Classic Forms of ***Boundary Layer*** Evolution



Why and how BL over land is different from that over water?

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

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

Outline

- **Overview of land surface processes**
- **The Noah LSM in WRF**
- **Surface layer parameterization**

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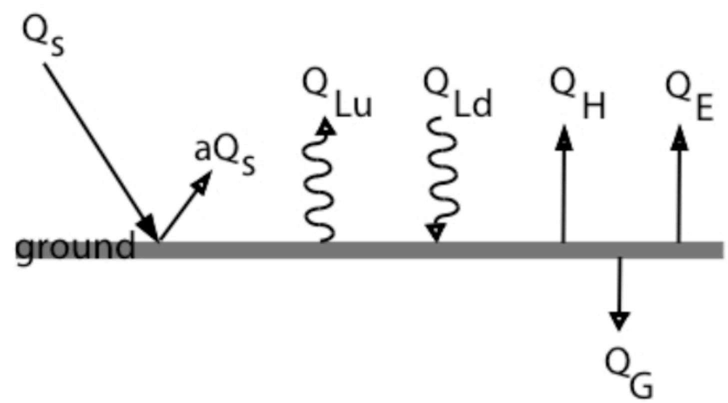
Why Do We Need Land Surface Models?

- Need to account for subgrid-scale 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

Land-surface model (LSM) development chronology

- Gen-0 (prior to 60s): lack of land-surface processes (prescribed diurnal cycle of surface temperature)
- Gen-1a (mid 60s): surface model with time-fixed soil moisture
- Gen-1b (late 60s): Bucket Model (Manabe 1969): time- and space-varying soil moisture
- Gen-2 (70s): Big-leaf model (Deardorff 1978): explicit vegetation treatment; a major milestone
- Gen-3 (late 80s): development of more sophisticated models including hydrological, biophysical, biochemical, ecological processes (e.g., BATS, SiB, NCARLSM, Century)
- mid 90s: implementation of advanced LSMs at major operational numerical weather prediction (NWP) centers

An LSM must provide 4 quantities to parent atmospheric model



- 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

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 momentum, 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

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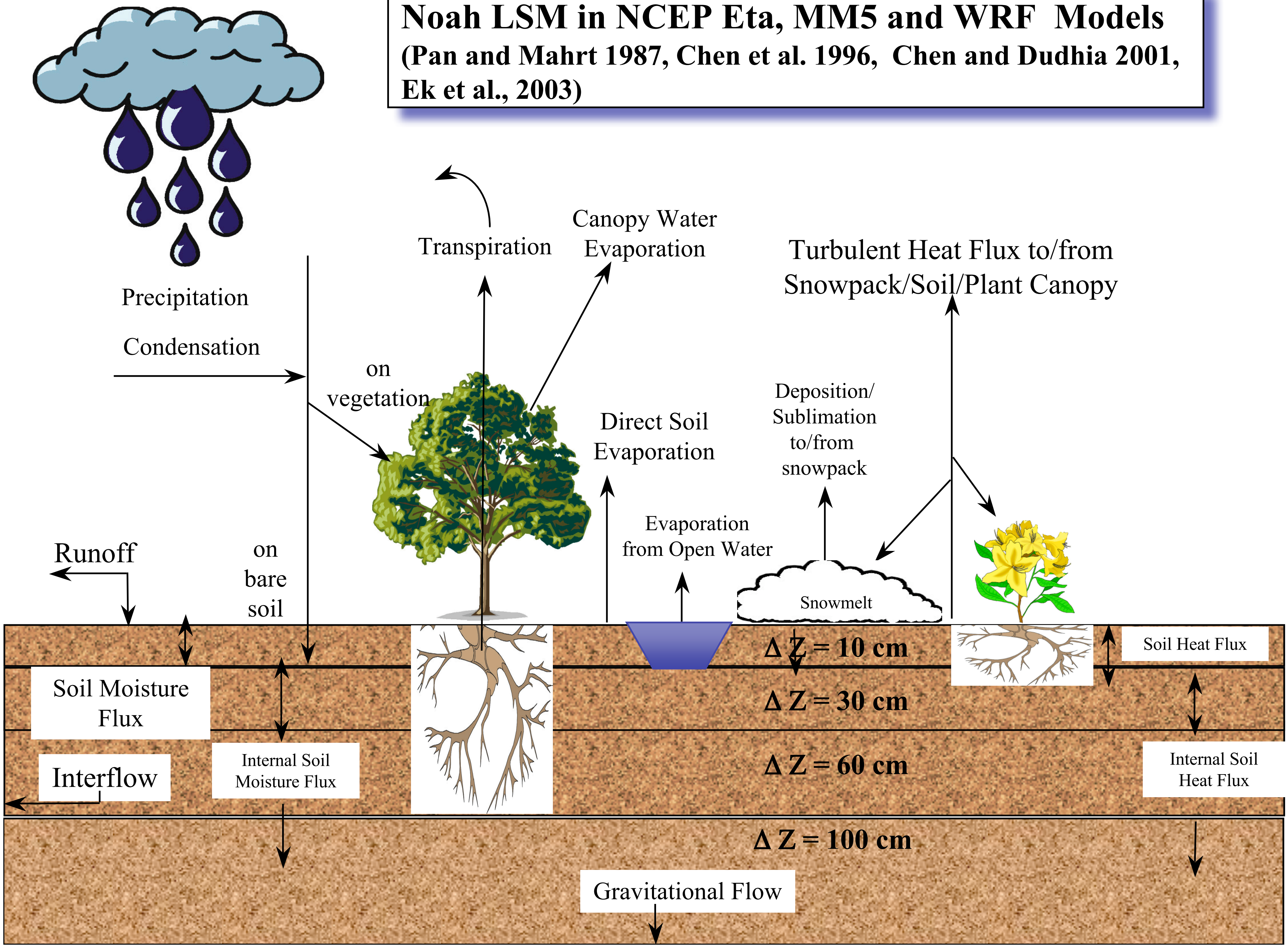
Noah LSM in NCEP Eta, MM5 and WRF Models
(Pan and Mahrt 1987, Chen et al. 1996, Chen and Dudhia 2001, Ek et al., 2003)



Noah LSM in WRF V2.2 (Dec 2006)

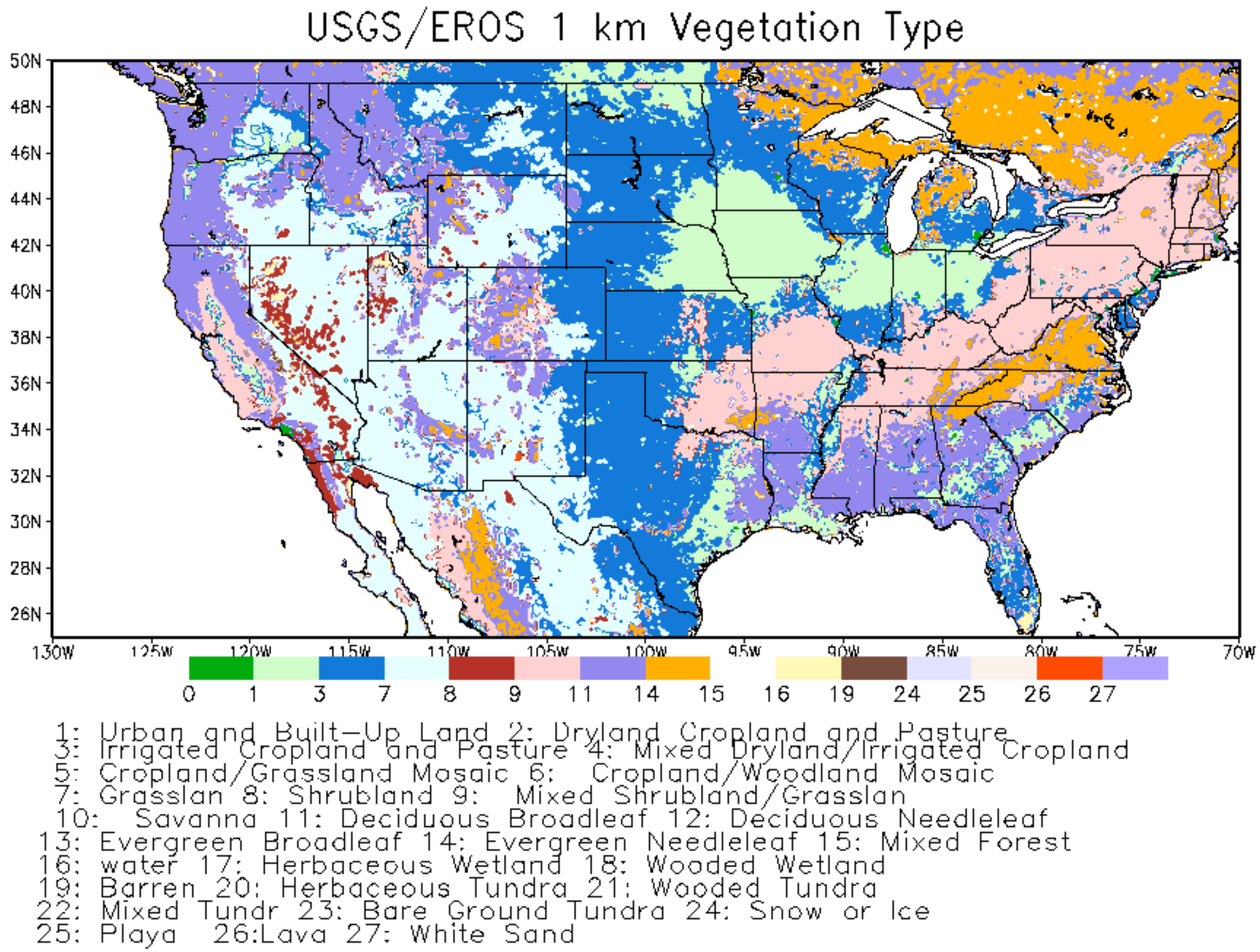
- Improved Physics
  - Frozen-ground physics
  - Patchy snow cover, time-varying snow density and snow roughness length
  - Soil heat flux treatment under snow pack
  - Modified soil thermal conductivity
  - Seasonal surface emissivity
  - Simple treatment of urban landuse
- Additional background fields
  - Monthly global climatology albedo (0.15 degree)
  - Global maximum snow albedo database
- Import various sources of soil data
  - NCEP Eta/EDAS (40-km): 4-layer soil moisture and temperature
  - NCEP AVN/GFS/Reanalysis: 2-layer soil data
  - AFWA AGRMET: global land data assimilation system (47-km)
  - NCEP NLDAS: North-American land data assimilation system (1/8 degree); 4-layer soil data
  - NCAR HRLDAS 4-layer soil data
- WRF/Noah coupled to a single-layer urban canopy mode

Key References for the Noah LSM

- Physics (1-d column model)
  - Warm season
    - F. Chen et al. (1996, JGR, 101)
  - Cold season (snowpack and frozen soil)
    - V. Koren et al. (1999, JGR, 104)
- In Mesoscale models
  - NCEP Eta model
    - M. Ek et al. (2003, JGR, 108)
  - NCAR MM5 model
    - F. Chen & J. Dudhia (2001,MWR, 129)

Key Input to the Noah LSM

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



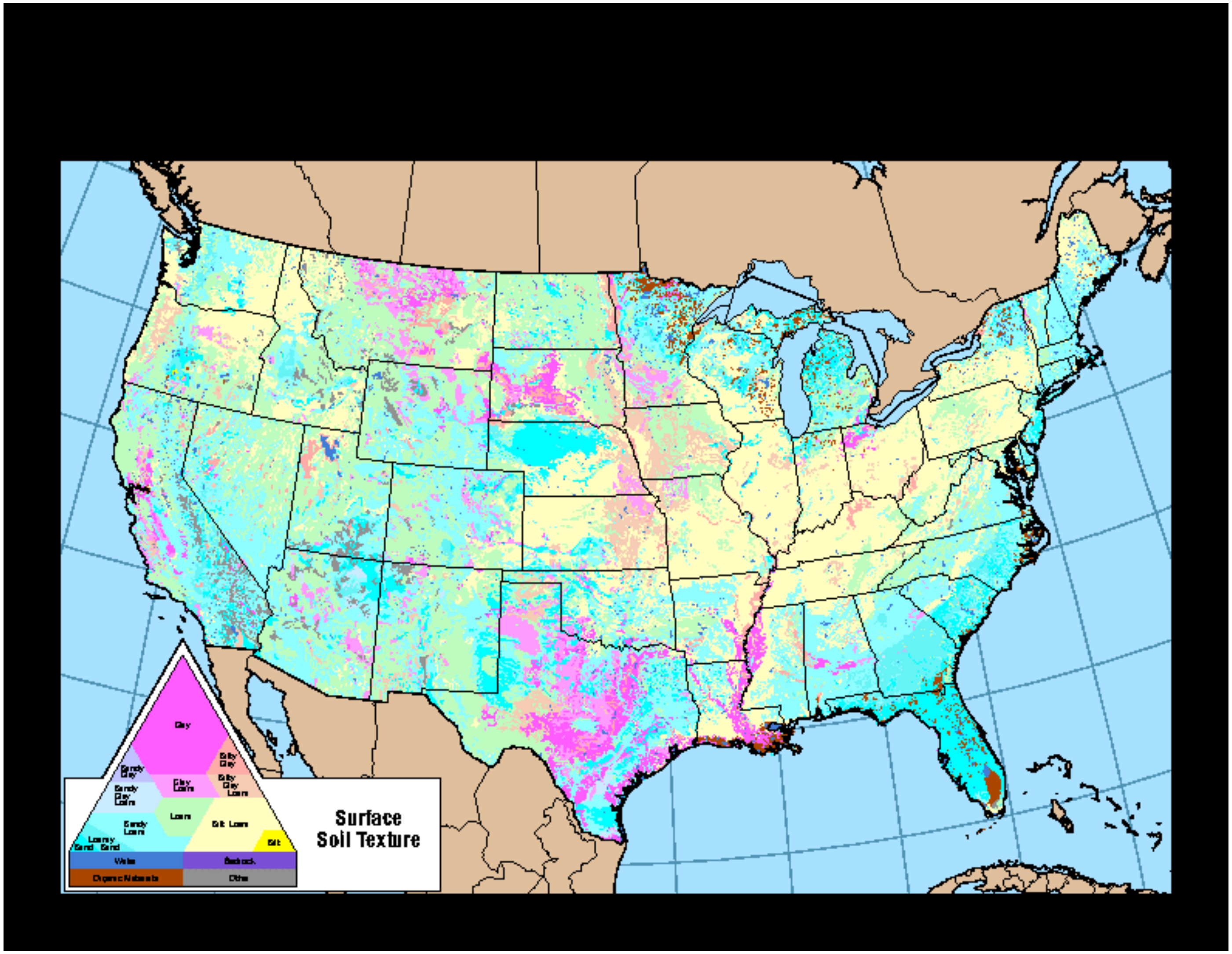
→ determine Rc_min, and other vegetation parameters

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

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

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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

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
  - Maximum snow albedo

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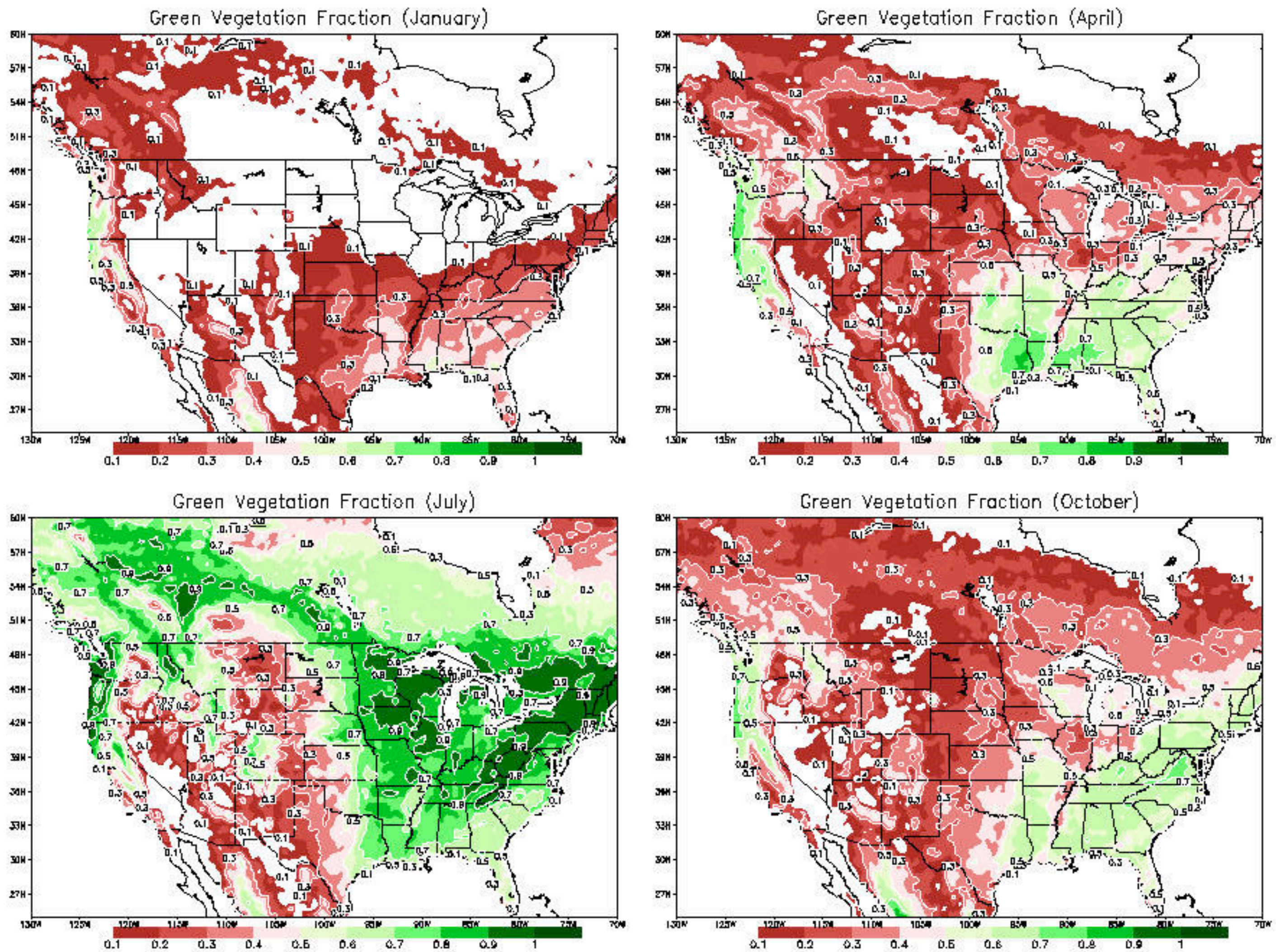
Seasonality of vegetation

Based on monthly NDVI



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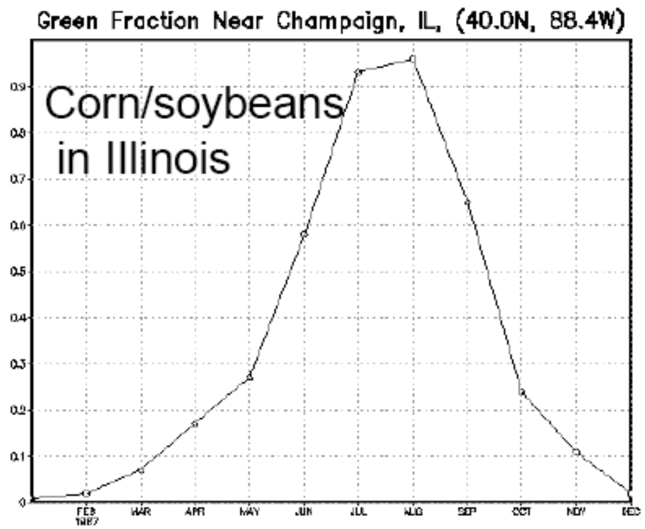
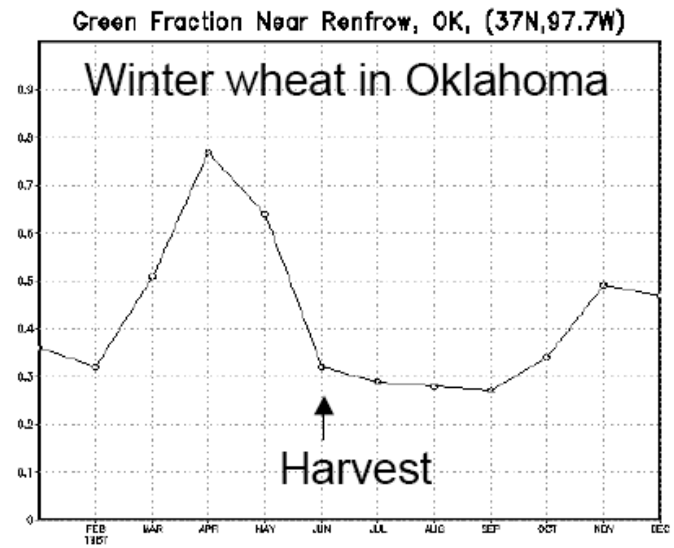
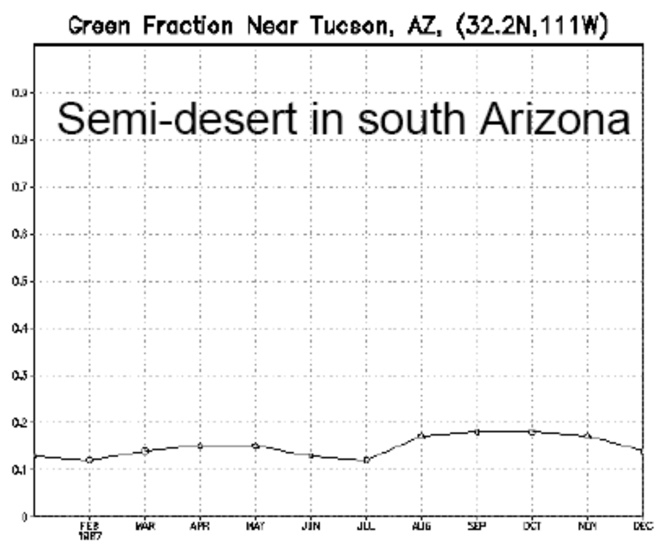
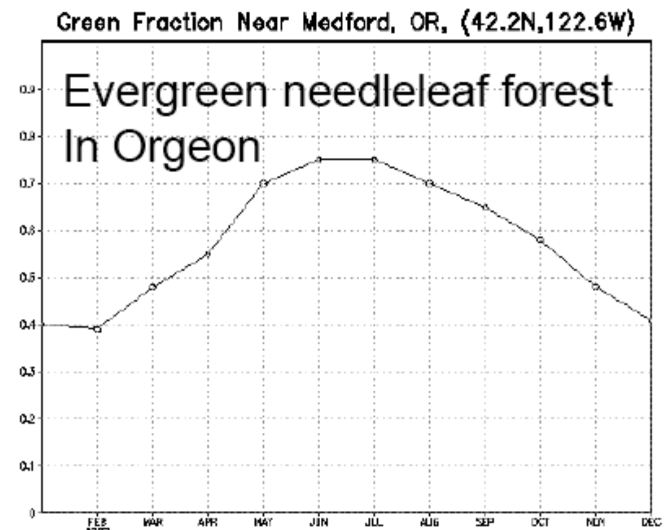
Example Annual Time Series of Green Vegetation Fraction in Noah LSM









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LSM group meeting, 17 April 2007.

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***

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
  - Snowpack depth (physical snow depth)
- Above prognostic states require initial conditions
  - Provided by WRF Preprocessing System (WPS) (former SI and REAL)

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Noah LSM Physics : Soil Prognostic Equation

Soil Moisture

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

-"Richard's Equation for soil water movement
- D, K functions (soil texture, soil moisture)
- F_θ represents sources (rainfall) and sinks (evaporation)

Soil Temperature

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

- C, K_t functions (soil texture, soil moisture)
- Soil temperature information used to compute ground heat flux

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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

(P-R) = infiltration

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

Noah LSM Physics: Surface Evaporation

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

Where:

- 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

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Noah LSM Physics: Canopy Resistance

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

$$Et/Edir \approx f(Fg)$$

- Fg in WRF based on 5-year NDVI climatology of monthly values
- 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

Canopy Resistance (continued)

Jarvis Scheme vs Ball-Berry Scheme

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

↓

Ball-Berry scheme in GEM (Gas Exchange Model)

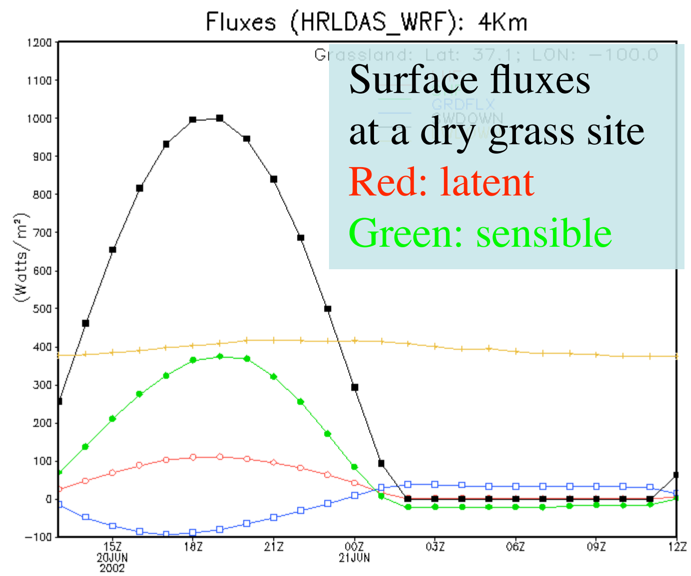
$$g_s = m\frac{A_n}{C_s}h_s p_s + b \qquad R_c = \frac{1}{g_s}$$

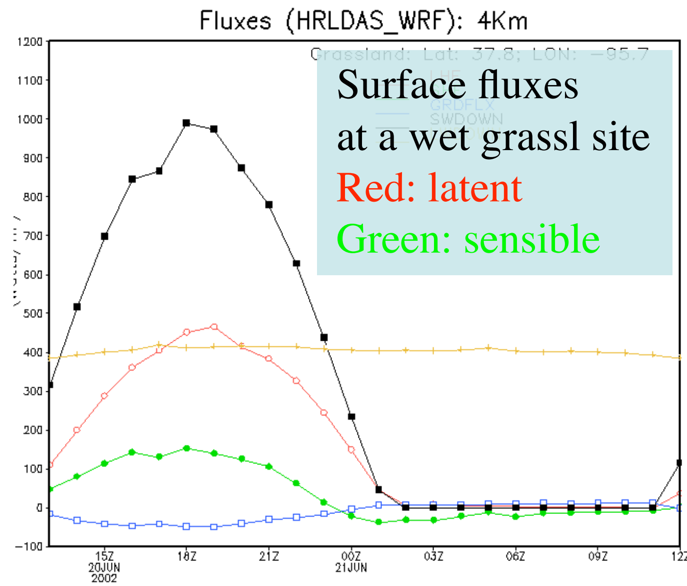
hs – relative humidity at leaf surface
ps – Surface atmospheric pressure
An – net CO2 assimilation or photosynthesis rate
Cs – CO2 concentration at leaf surface
m and b are linear coeff based on gas exchange consideration

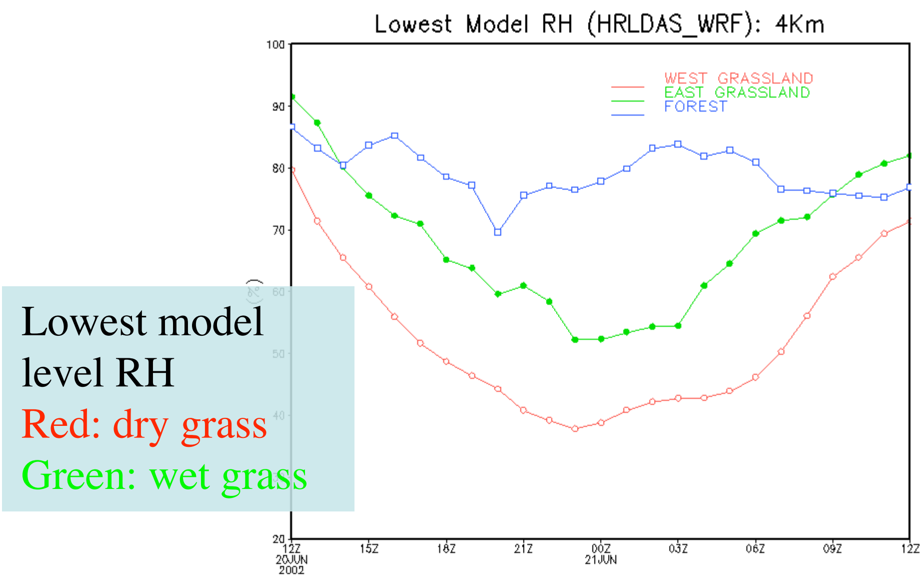
A_n: three potentially limiting factors:

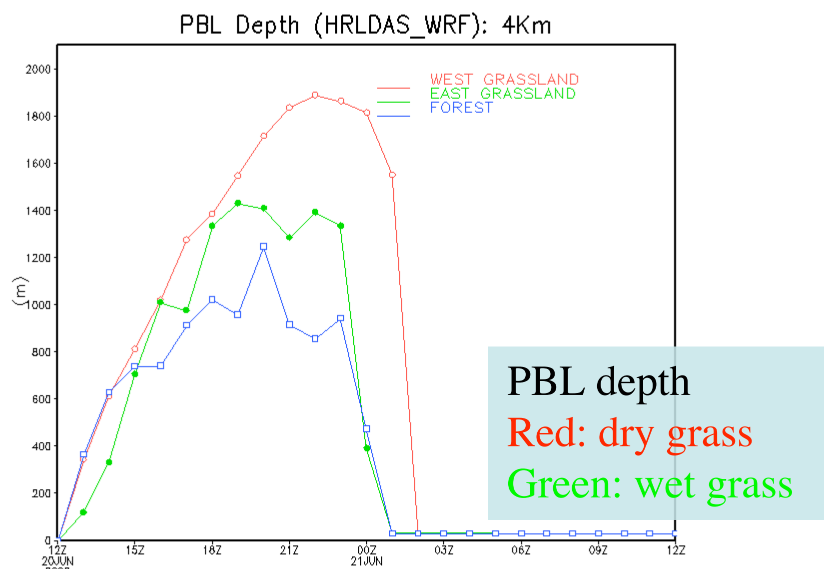
1. efficiency of the photosynthetic enzyme system
2. amount of PAR absorbed by leaf chlorophyll
3. capacity of the C3 and C4 vegetation to utilize the photosynthesis products

WRF/Noah simulated
typical summer surface fluxes and PBL depth



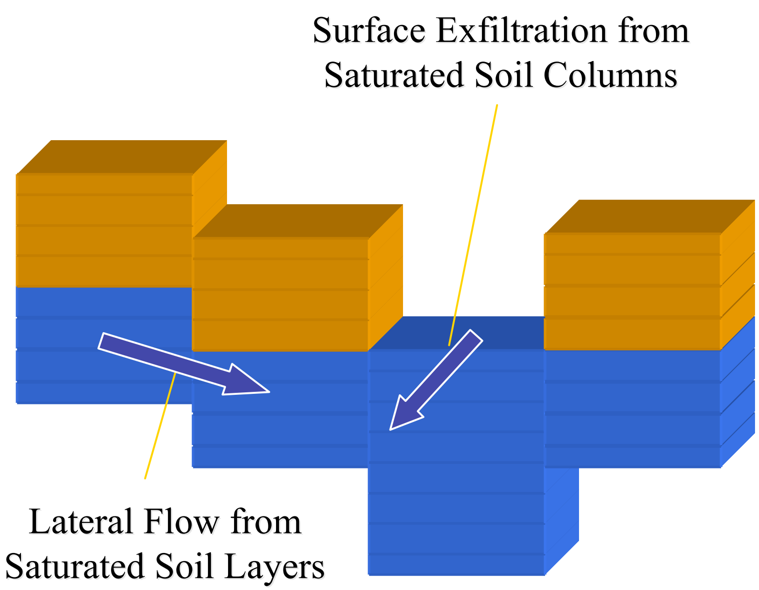






Subsurface Flow Routing Noah-Router

(NCAR Tech Note: Gochis and Chen, 2003)



Saturated Subsurface Routing
Wigmosta et. al, 1994

- New Parameters: Lateral K_{sat}, n – exponential decay coefficient
- Critical initialization value: water table depth
- 8-layer soil model (2m – depth)
- Quasi steady-state saturated flow model, 2-d (x-,y-configuration)
- Exfiltration from fully-saturated soil columns

$$\beta = SOX_{i,j} - dzdx + 1E - 30$$

$$hh = \left(1 - \frac{z}{SOLDEP}\right)^n$$

$$\gamma = \frac{(gsize \times LKSAT \times SOLDEP)}{n} \tan\beta$$

$$qsub_x = \gamma * hh$$

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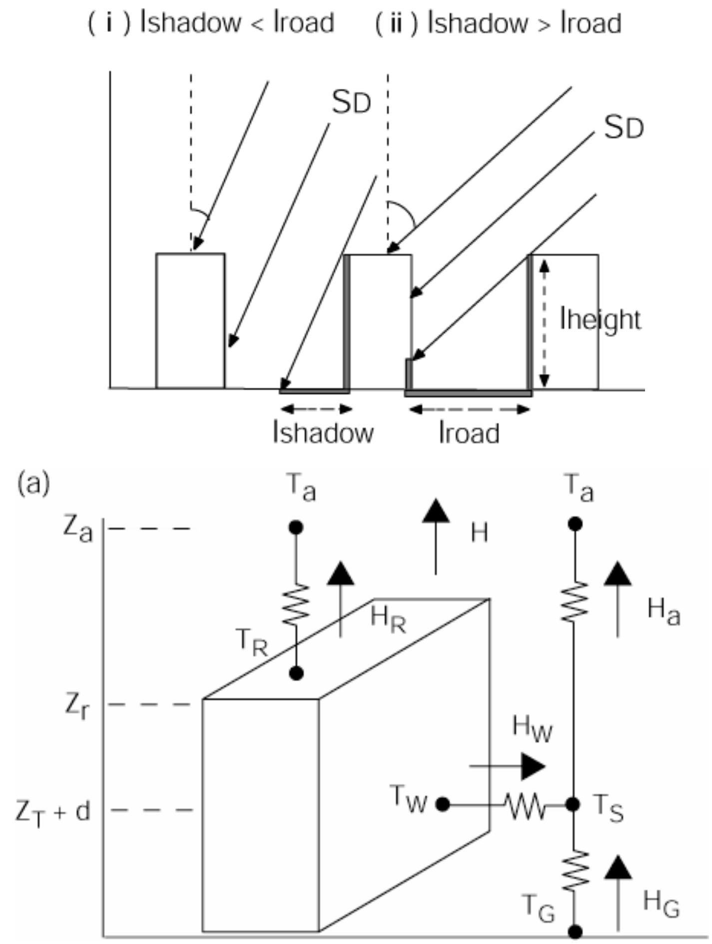
WRF/Noah LSM/Urban-Canopy Coupled Model

- Single layer urban-canopy model (UCM, Kusaka et al., 2004)
- Noah handle natural surfaces, UCM treats man-made surfaces
  - 2-D urban geometry (orientation, diurnal cycle of solar azimuth), symmetrical street canyons with infinite length
  - Shadowing from buildings and reflection of radiation
  - Multi-layer roof, wall and road models



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Outline

- **Overview of land surface processes**
- **The Noah LSM in WRF**
- **Surface layer parameterization**

Surface layer parameterization

- Coupling between skin layer and first model level (depends on roughness lengths and wind speed)

Surface sensible heat flux $H = \rho c_p C_h |u_a|(\theta_s - \theta_a)$

Surface latent heat flux $E = \rho C_e |u_a|(q_s - q_a)$

Surface exchange coefficient:

$$C_h = \frac{k^2/R}{[\ln(\frac{z}{z_{0m}}) - \Psi_m(\frac{z}{L}) + \Psi_m(\frac{z_{0m}}{L})][\ln(\frac{z}{z_{0t}}) - \Psi_h(\frac{z}{L}) + \Psi_h(\frac{z_{0t}}{L})]}$$

- Surface fluxes are more sensitive to the treatment of roughness length for heat/moisture than to M-O based surface layer schemes themselves (Chen et al. 1997)

Surface layer parameterization

- Treatment of roughness length for heat and moisture

$$\frac{Z_{om}}{Z_{ot}} = \exp(k\ C\ \sqrt{\mathrm{R}_e{}^*})$$

Re: roughness Reynolds number,

C: empirical constant; unknown in Zilitinkevich (1995) formulation,

Chen et al. (1997, BLM) suggested *C*=0.1, but can range from 0.01 to 1.0

Surface layer parameterization

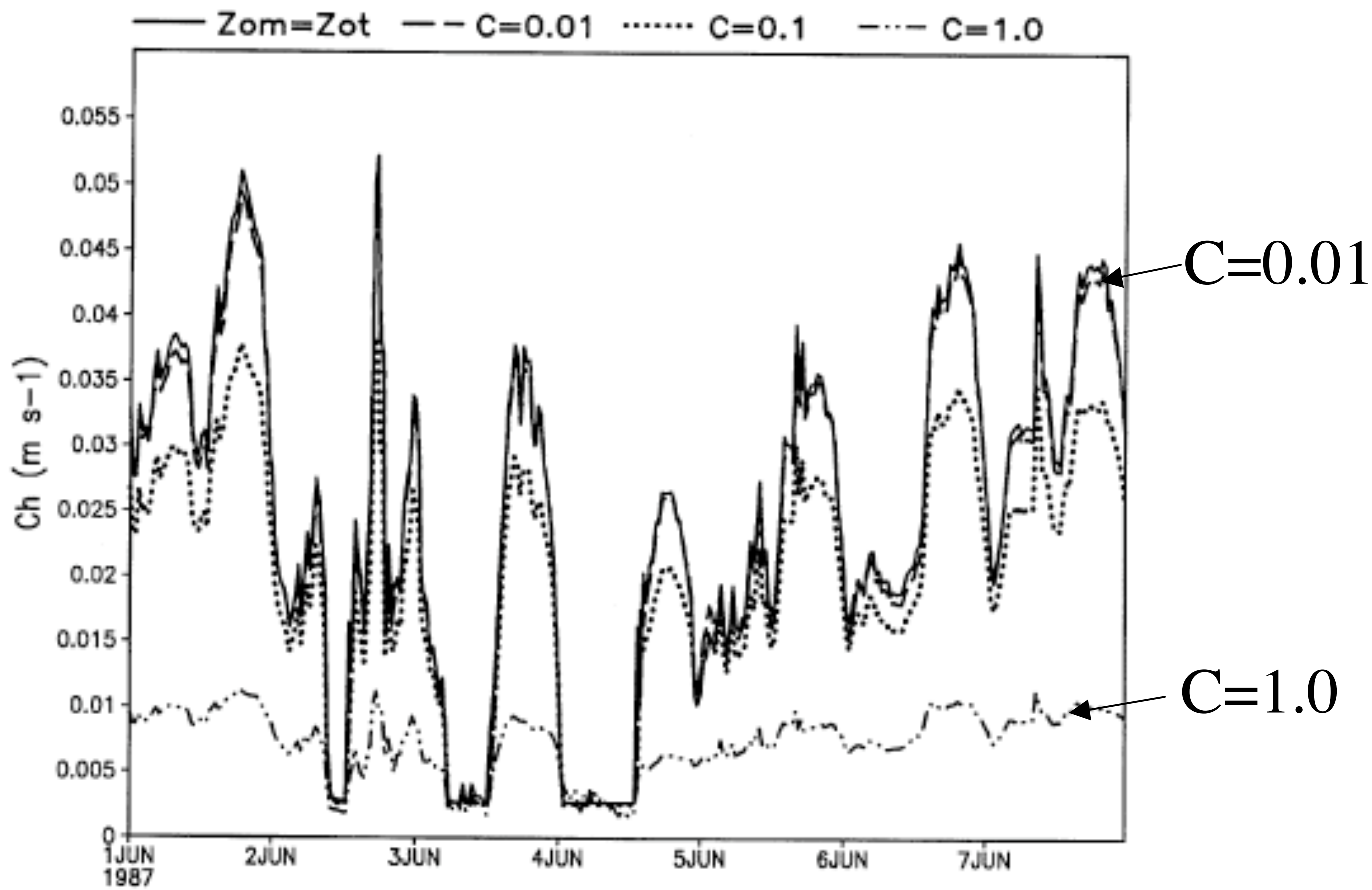


Figure 5. Comparison of diurnal variation of (a) surface exchange coefficient, (b) latent heat flux, (c) sensible heat flux, and (d) surface skin temperature between FIFE observations for 1–7 June 1987 and simulations with the following different z_{0t}: $z_{0m} = z_{0t}$; $C = 0.01$ in Zilitinkevich formulation (refer Equation (1)); $C = 0.1$; and $C = 1.0$. The Paulson scheme is used in these simulations.

Surface layer parameterization

Sensible heat flux

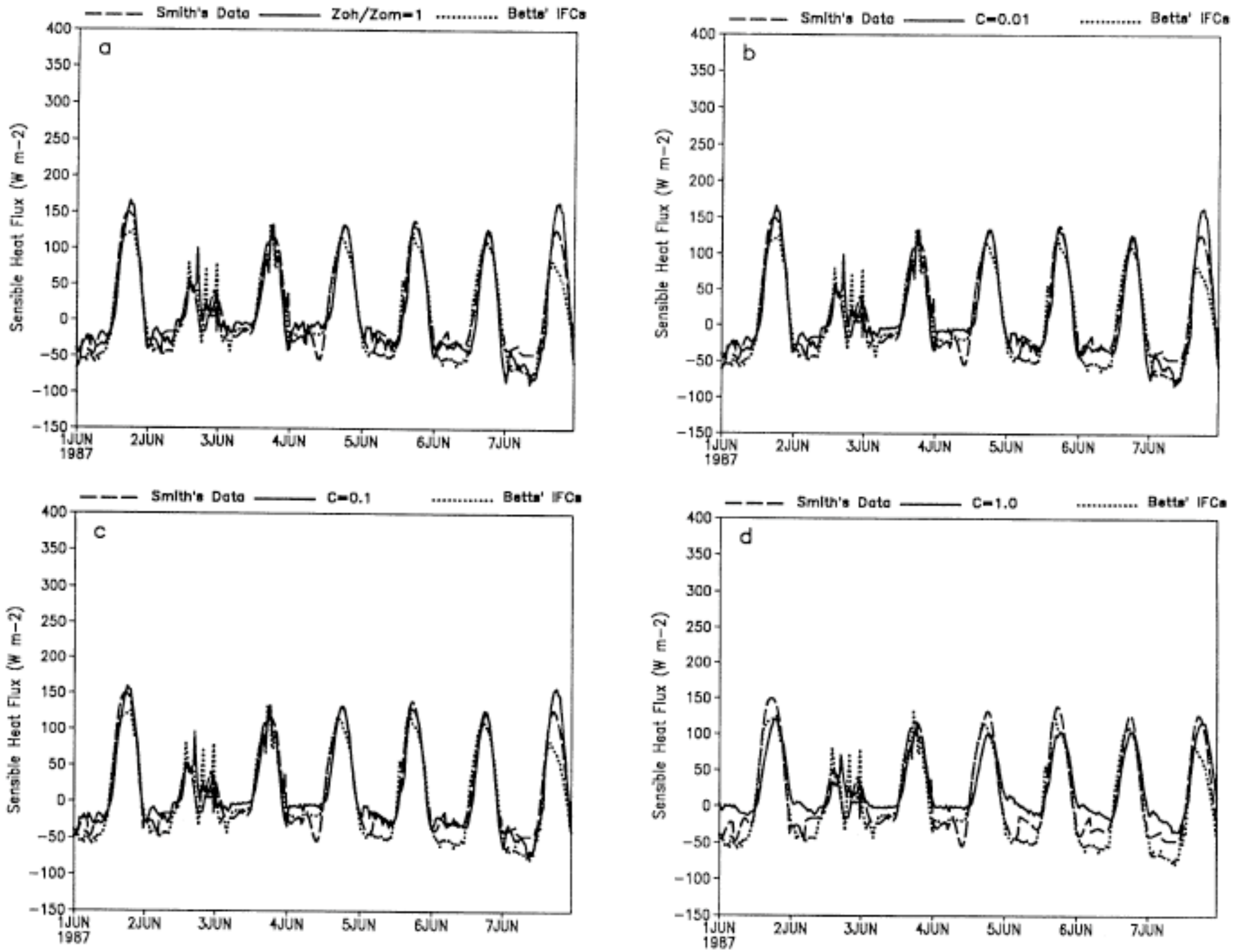


Figure 5c.

Surface layer parameterization

Surface skin temperature

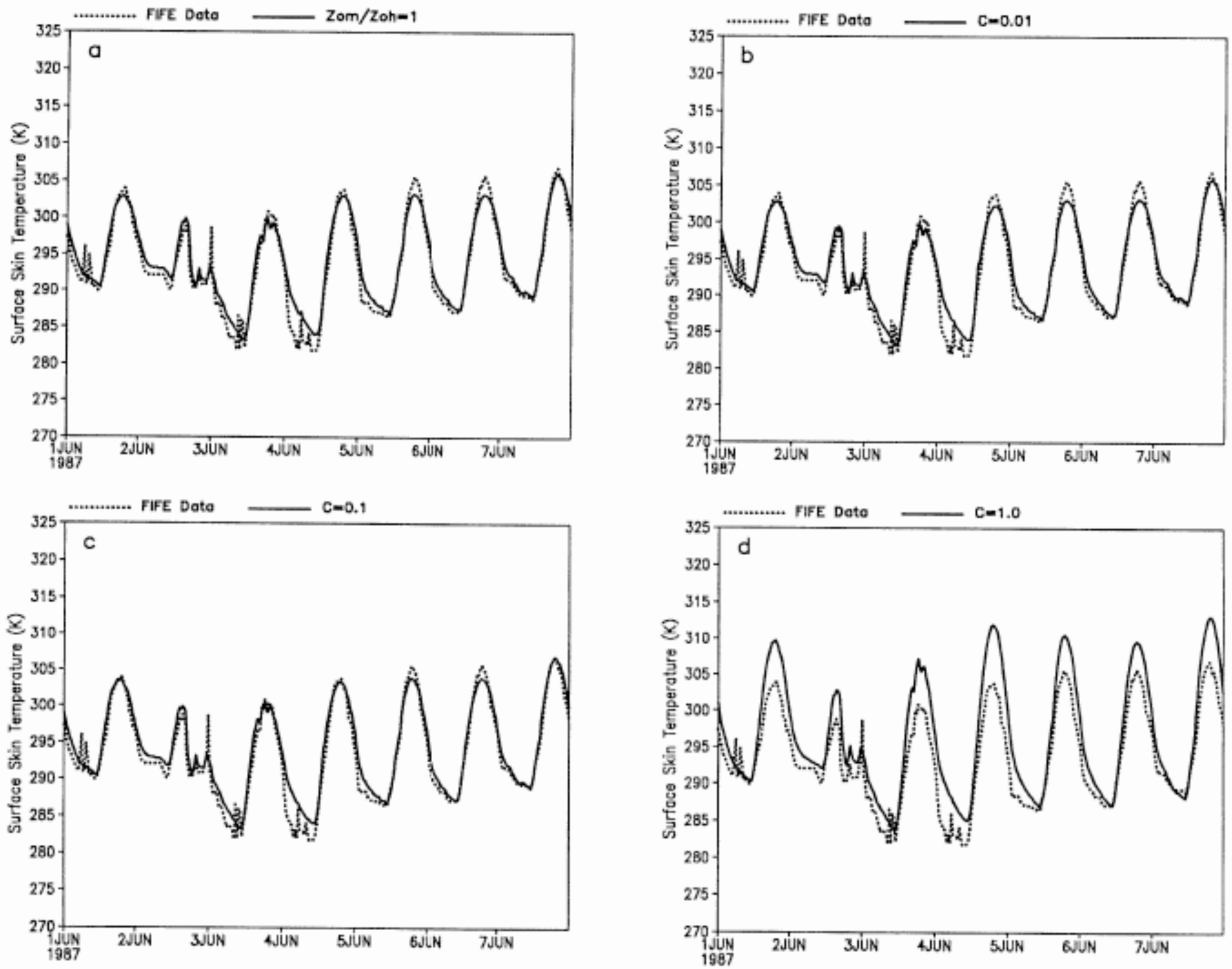


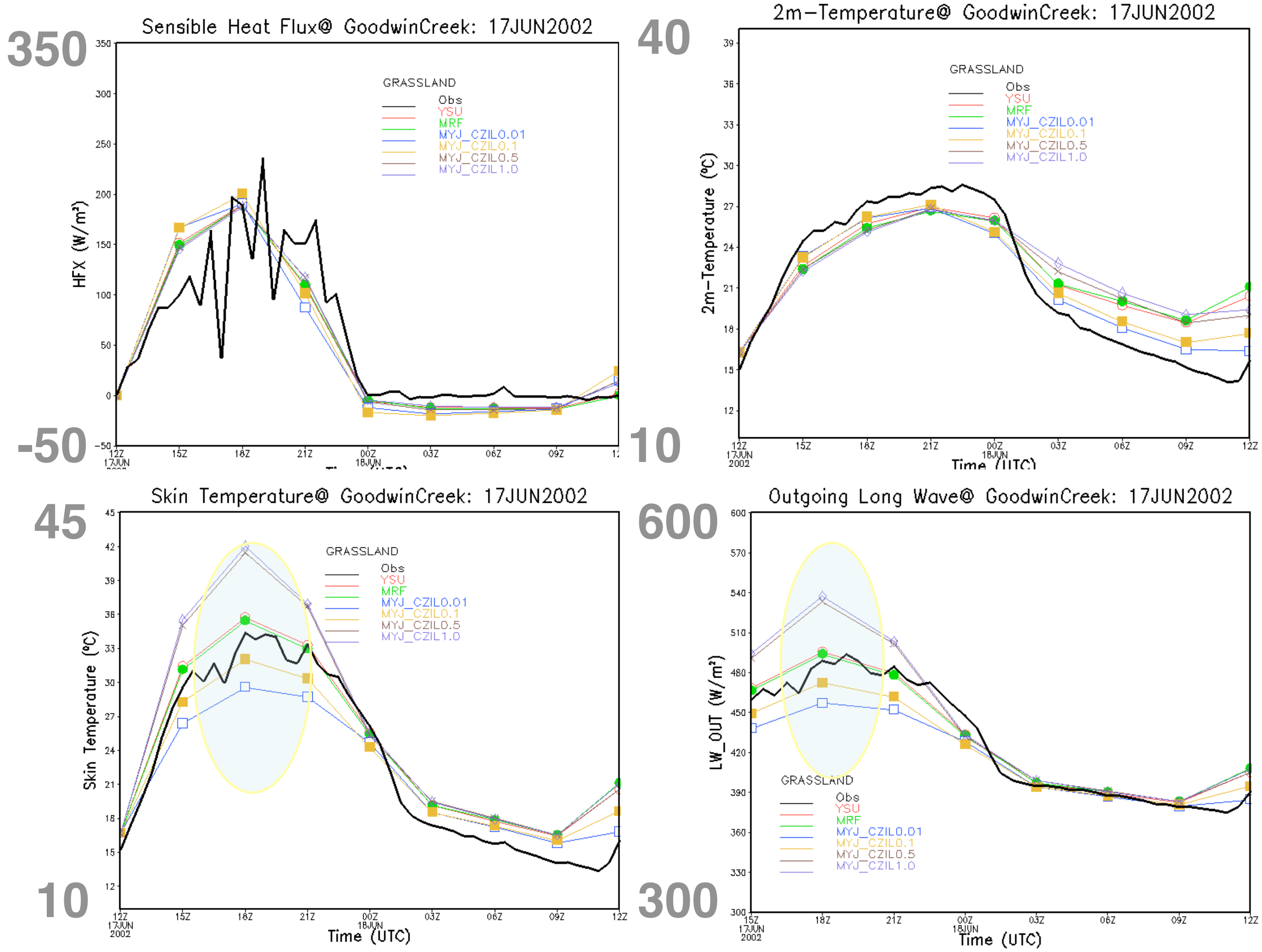
Figure 5d.

Comparison at Goodwin Creek, MS, C4 grass

Different surface and PBL schemes can produce the same sensible heat fluxes and 2-m temperature, but vastly different upward longwave radiation

Differences by surface layer uncertainties are equal to (more than) that caused by different PBL schemes

Smaller *C* values
- more coupling
- lower skin T and LW_{up}



YSU
MRF
MYJ, CZIL=0.01
MYJ, CZIL=0.1
MYJ, CZIL=0.5
MYJ, CZIL=1.0
Observation

NCAR

Further Reading

- Noah Land surface modeling and data assimilation

  - Chen, F., K. Mitchell, J. Schaake, Y. Xue, H. Pan, V. Koren, Y. Duan, M. Ek, and A. Betts, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.,* **101**, 7251-7268.
  - Chen, F., and J. Dudhia, 2001: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Mon. Wea. Rev., 129, 569-585.
  - Chen, F., R. Pielke, Sr., and K. Mitchell, 2001: Development and application of land-surface models for mesoscale atmospheric models: Problems and Promises. *Observation and Modeling of the Land Surface Hydrological Processes*., V. Lakshmi, J. Alberston, and J. Schaake (Editors), American Geophysical Union, 107-135.
  - Ek, et al., 2003: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. J. Geophys. Res.
  - Mitchell, et al., 2004: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. J. Geophys. Res., 109.
  - Chen et al., 2006: 2006: Evaluation of the Characteristics of the NCAR High-Resolution Land Data Assimilation System During IHOP-02. *J. Appli. Meteorol*, in press.

- Interactions among land surface, PBL, and convection

  - Anthes, R. A., Y.-H. Kuo, S. G. Benjamin, and Y.-F. Li, 1982: The evolution of the mesoscale environment of severe local storms: Preliminary modeling esults. *Mon. Wea. Rev.,* **110.**
  - Benjamin, S.G., and T.N. Carlson, 1986: Some effects of surface heating and topography on the regional severe storm environment, Part 1, Three-dimensional simulations. *Mon. Wea. Rev.,* **114,** 307-329.
  - Lanicci, J.M., T.N. Carlson and T.T. Warner, 1987: Sensitivity of the Great Plains severe-storm environment to soil-moisture distribution. *Mon. Wea. Rev*., **115**
  - Chen, F., and R. Avissar, 1994: Impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models. *J. Appl. Meteorol.*, **33.**
  - Segal, M., R.W. Arritt, C. Clark, R. Rabin, and J. Brown, 1995: Scaling evaluation of the effect of surface characteristics on potential for deep convection over uniform terrain. *Mon. Wea. Rev*., **123**
  - Ziegler, C.L., T.J. Lee, and R.A. Pielke, Sr., 1997: Convective initiation at the dryline: a modeling study. *Mon. Wea. Rev*., **125**
  - Chen, F., T. Warner, and K. Manning, 2001: Sensitivity of orographic moist convection to landscape variability: A Study of the Buffalo Creek, Colorado, flash-flood case of 1996. *J. Atmos. Sci.,* **58**.
  - Koster, R.D, and Coauthors, 2004**:** Regions of Strong Coupling Between Soil Moisture and Precipitation. *Science*, 305, Issue 5687, 1138-1140.
  - Trier, S.B., F. Chen, and K. W. Manning, 2004: A study of convection initiation in a mesoscale model using high resolution land surface initial conditions. *Mon. Wea. Rev.*, **132**
  - Holt, T. R., D. Niyogi, F. Chen, K. Manning, M. LeMone, and A. Qureshi, 2006: Effect of land-atmosphere interactions on the IHOP 24-25 May 2002 convection case. *Mon. Wea. Rev.*