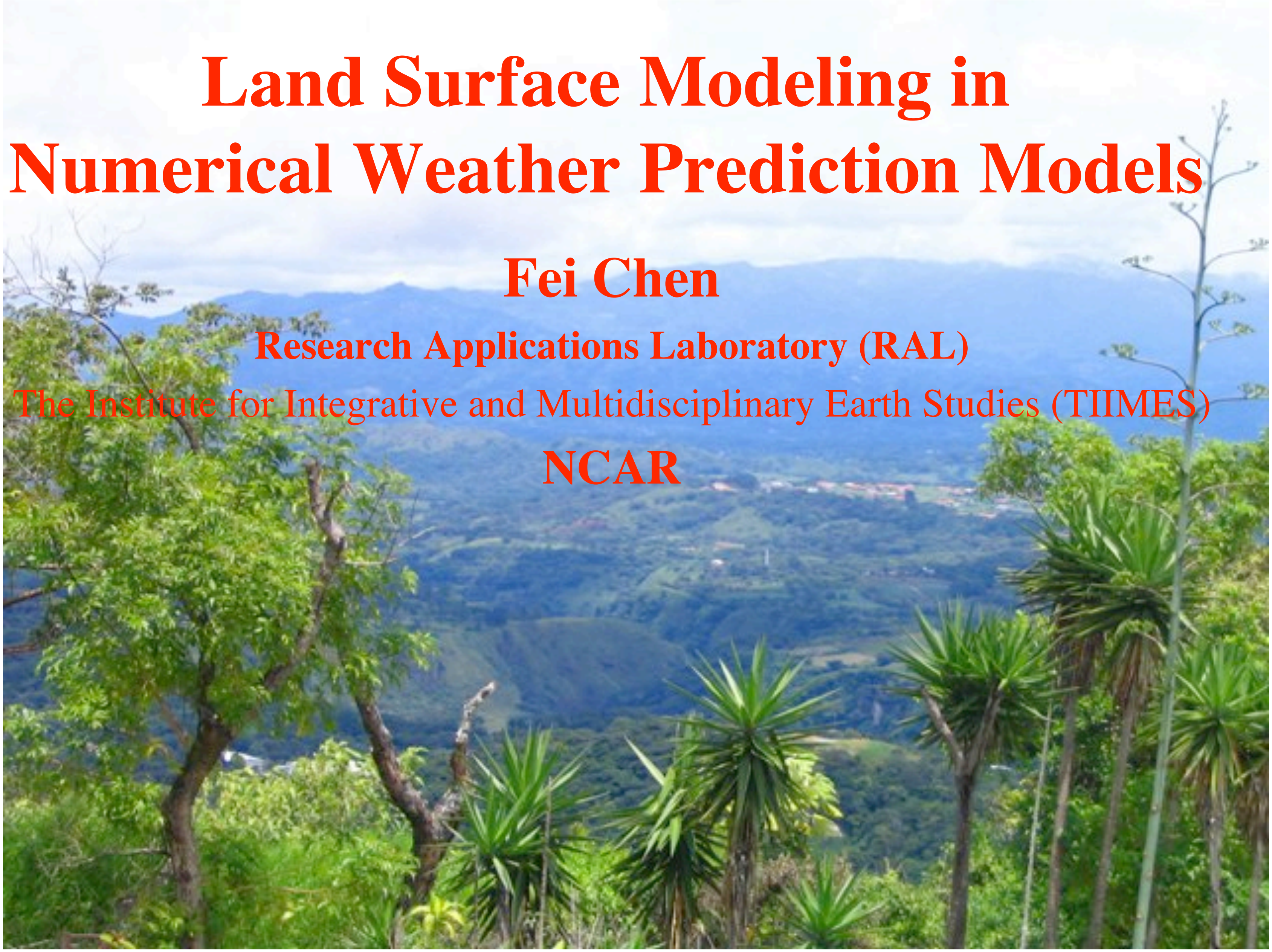


Land Surface Modeling in Numerical Weather Prediction Models

Fei Chen

Research Applications Laboratory (RAL)

The Institute for Integrative and Multidisciplinary Earth Studies (TIIMES)

NCAR

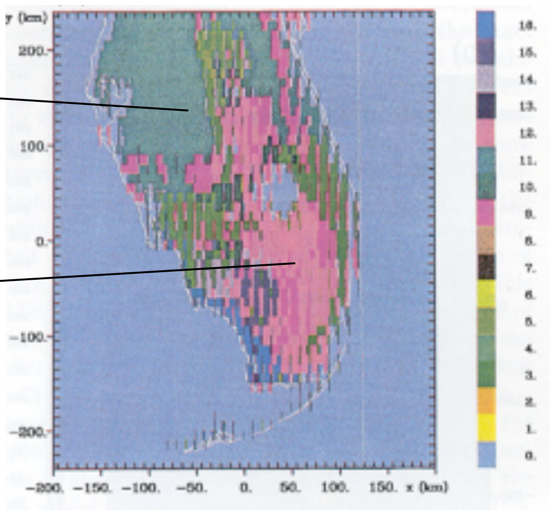
Lecture at the UT-Austin, Austin, 17 October 2006.

Effects of Land-use Change on Rainfall

1900

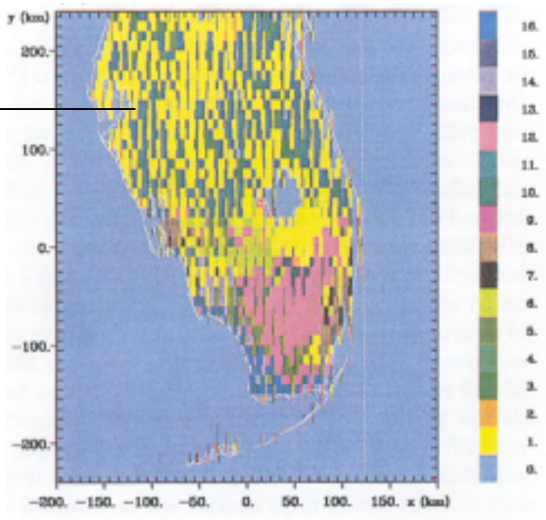
Evergreen Shrub

Marsh

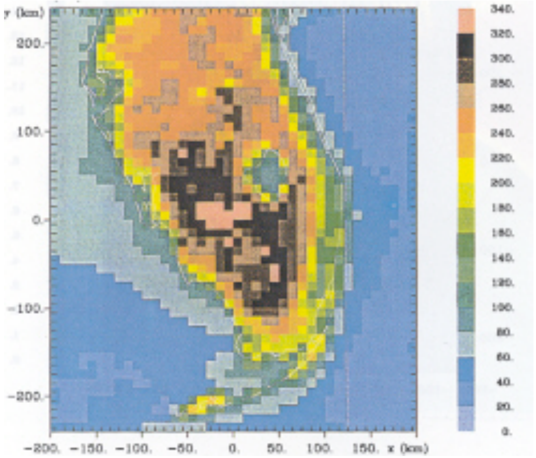


1993

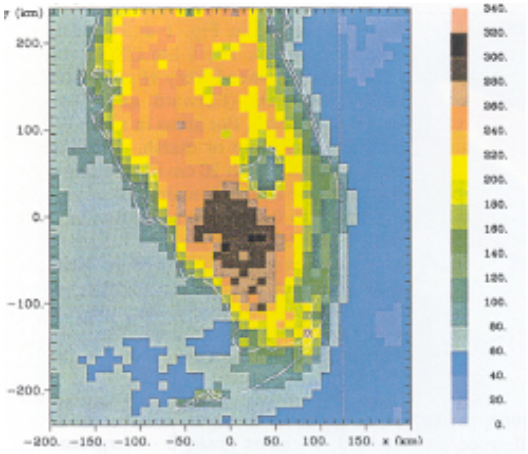
Crops



June – July Rainfall (mm)



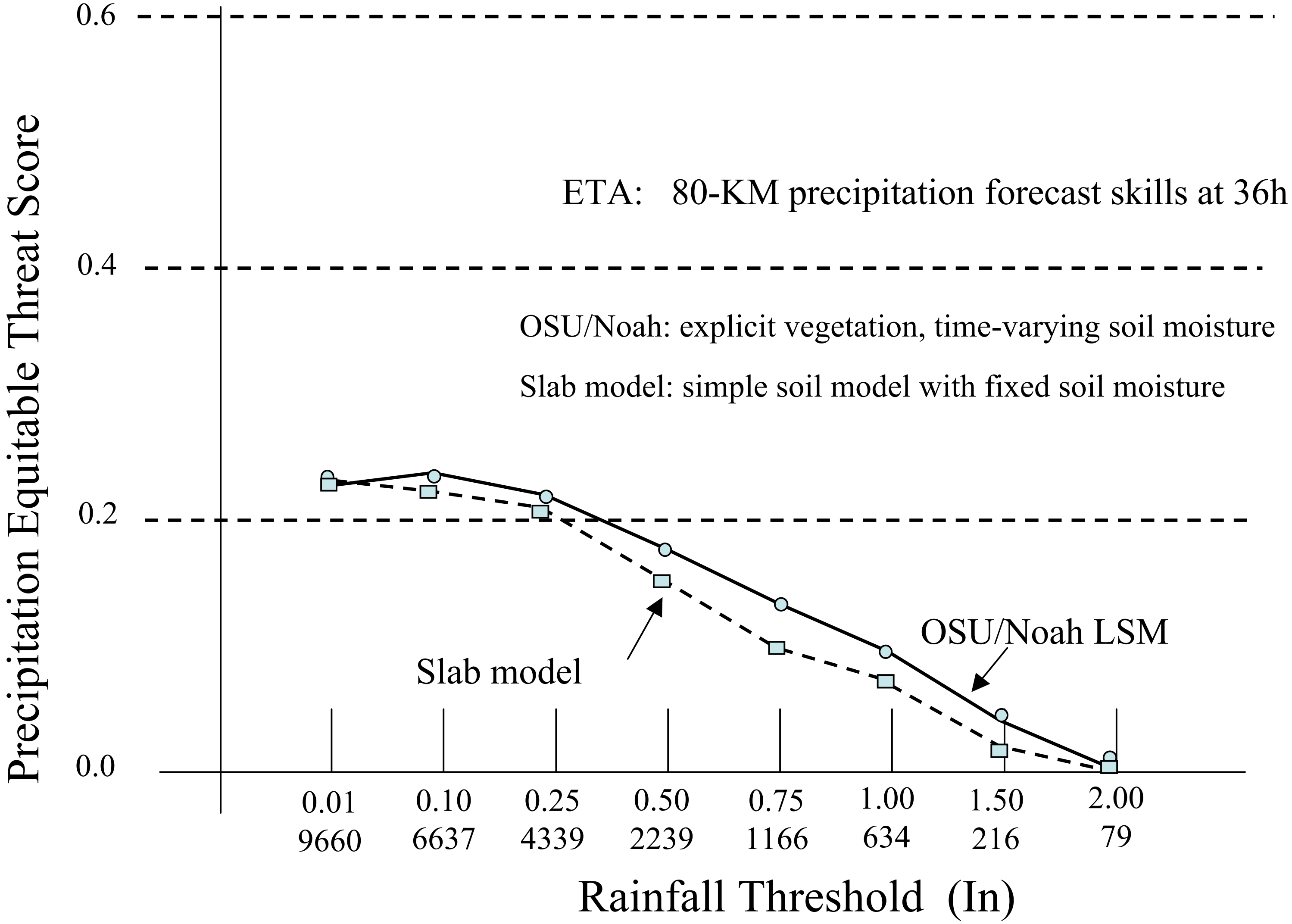
Average rain (238mm)



213mm

Impact of Land Surface Model on NWP Quantitative Precipitation Forecast

Valid 2 June 91 - 29 June 91



ETA: 80-KM precipitation forecast skills at 36h

OSU/Noah: explicit vegetation, time-varying soil moisture

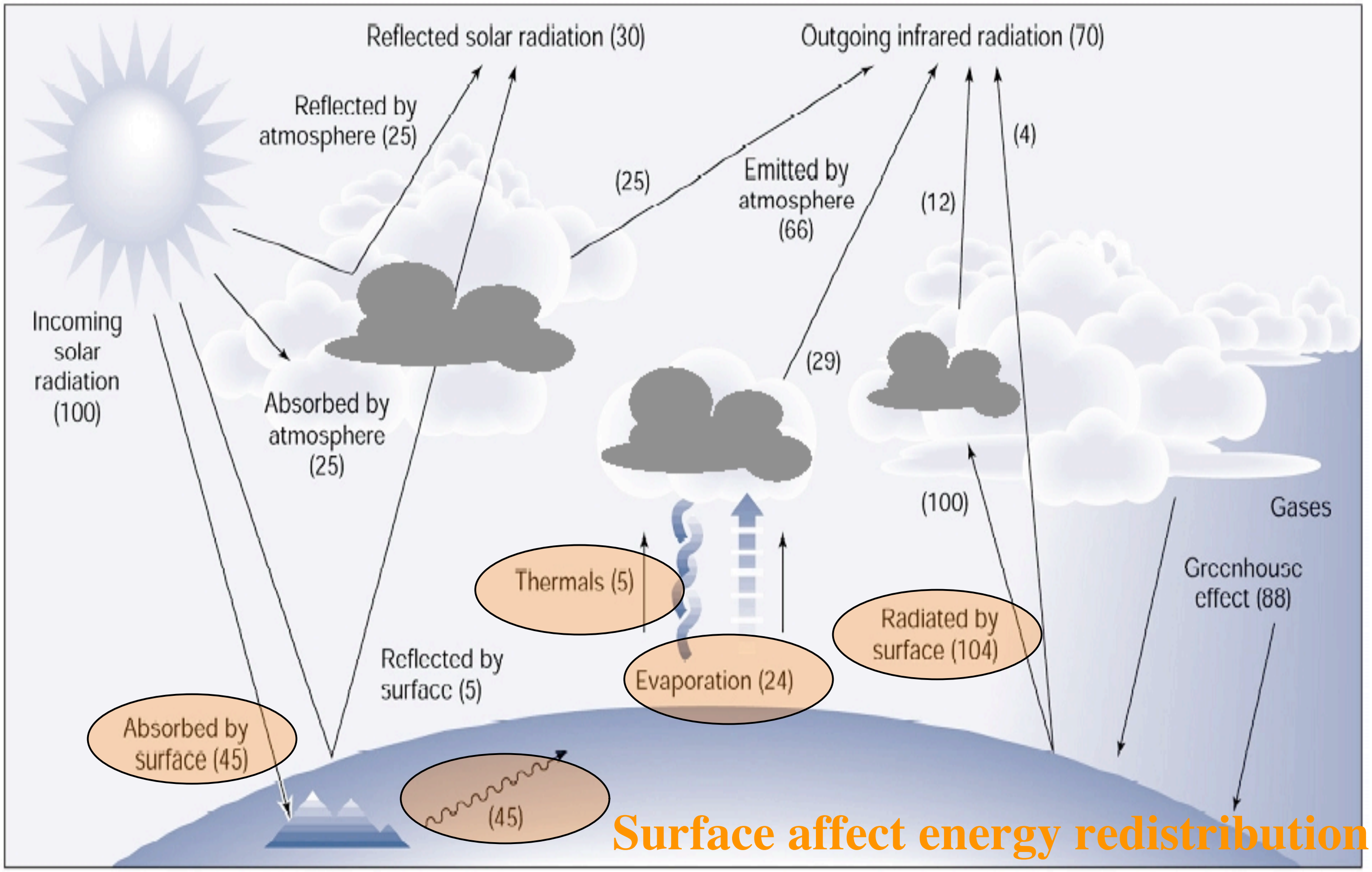
Slab model: simple soil model with fixed soil moisture

Chen, Pielke, and Mitchell, 2001, chapter in “*Observation and Modeling of the Land Surface Hydrological Processes*”

Outline

- Overview of land surface processes
- **Modeling of land surface in mesoscale numerical prediction models**
- **Land data assimilation techniques**

Earth’s Global Energy Budget



Surface affect energy redistribution

- 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

Aristotle (350 BC)

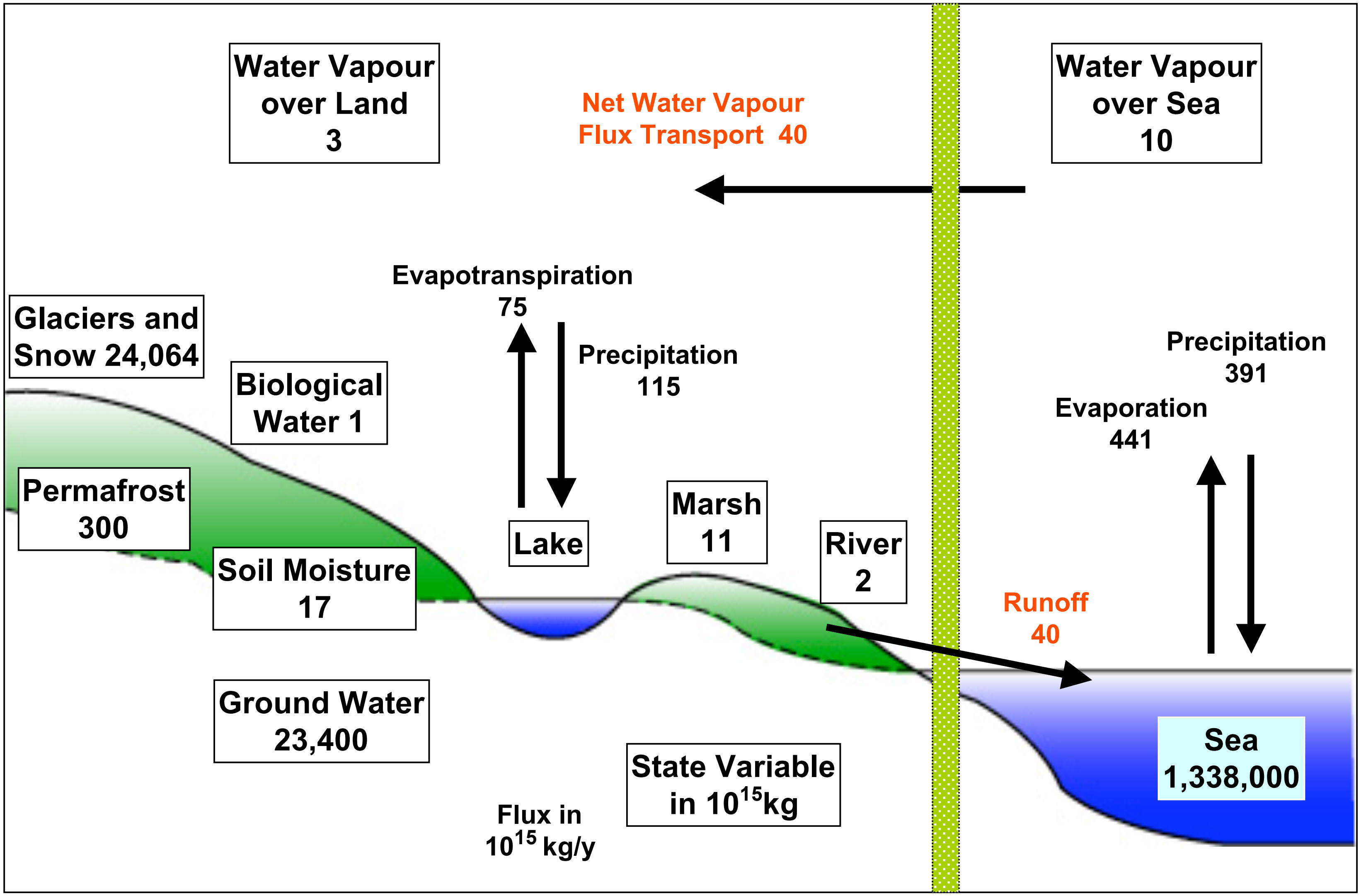
- The term ***meteorology*** comes from Aristotle's book "*Meteorology* (or Meteorological)"
- ***Hydrological cycle***:

  "Now the sun, moving as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried up and is dissolved into vapour and rises to the upper region, where it is condensed again by the cold and so returns to the earth".

NCAR

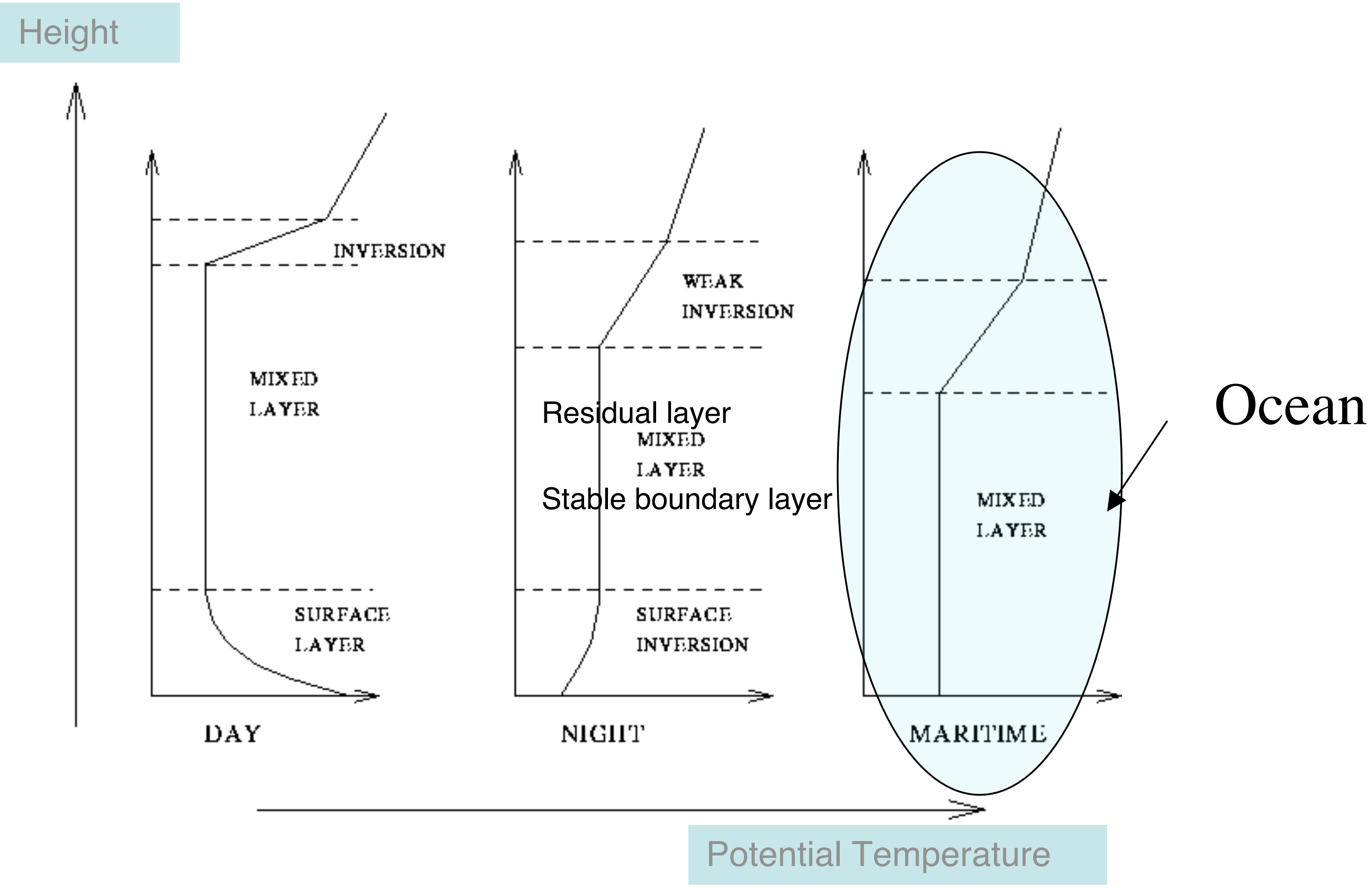
Global Water Cycle

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



Lecture at the UT-Austin, Austin, 17 October 2006.

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



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

The Boundary Layer Over Water

- Surface energy balance of water
  - Low albedo: most shortwave radiation absorbed.
  - Large emissivity: `black bodies'
  - Large heat capacity and rapid conduction/convection: SST relatively constant over daily timescales
  - Large evaporation: source of latent heat for the atmosphere
- Boundary layer
  - Humid and relatively cool
  - Small diurnal cycle
  - cooler by day (warmer at night) than BL over adjacent land
  - Land-sea breeze

The Boundary Layer Over Land

- Surface energy balance of land
  - Complex surface conditions: soil moisture and vegetation for partitioning of latent and sensible heat (Bowen Ratio)
  - Small heat capacity and slow conduction/convection
  - Large diurnal cycle caused by daytime solar heating and nocturnal longwave cooling
- Boundary layer
  - Daytime
    - shortwave radiation heat the ground
    - surface layer becomes warm and a slightly unstable layer in the lowest tens of meters; generation of turbulence
    - heat diffuses higher into the BL by turbulent mixing, and the inversion is eroded

The Boundary Layer Over Land (Cont.)

- Nocturnal
  - Upper levels cool through long-wave radiation
  - Air slightly higher in BL cools by radiation and by conduction downwards (negative sensible heat flux)
  - Low levels become cold and very stable layer near the surface
  - Vertical motion and turbulence *suppressed*
  - Upward ground heat flux determine the rate at which the ground temperature falls

NCAR

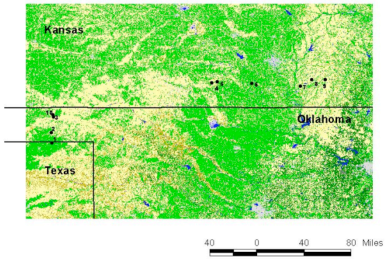
The Atmospheric Boundary Layer (ABL) growth is driven primarily by

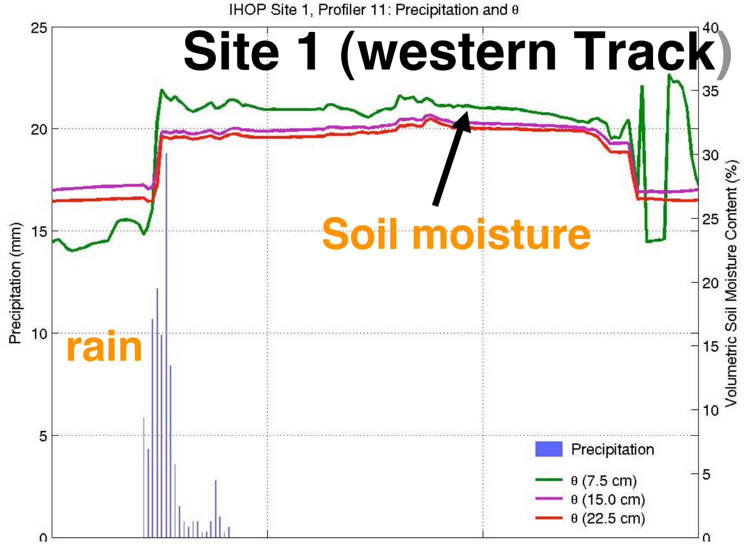
- Entrainment of warmer air from the free troposphere
- Surface sensible and latent fluxes (topic addressing by this lecture).
- Also be influenced by the presence of mesoscale phenomena such as the sea-breeze or the mountain valley circulation, due to surface differential heating.

NCAR

Spatial Variability of PBL on 29 May 02

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

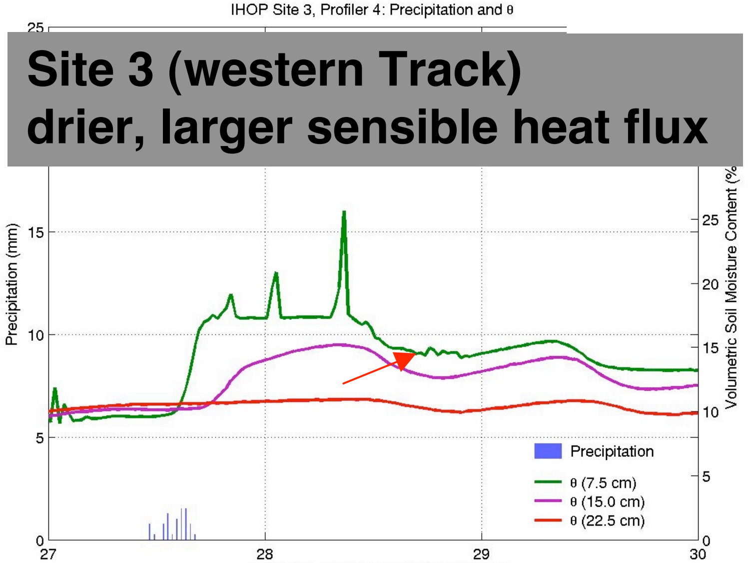




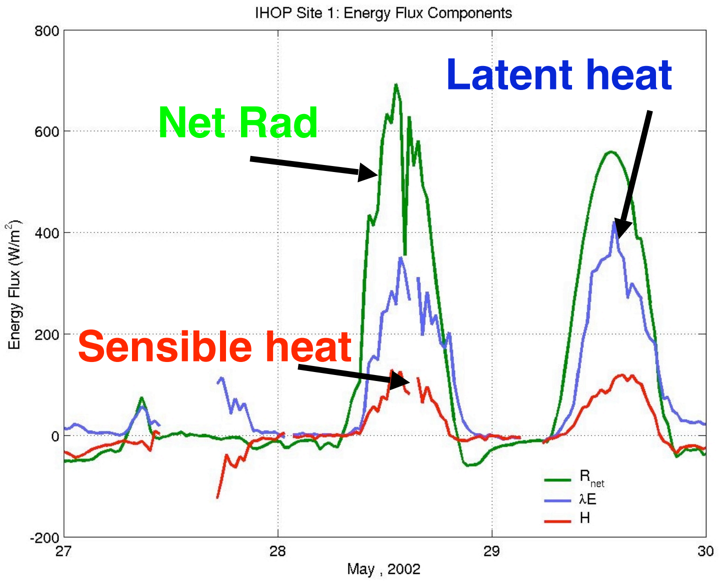
Site 1 (western Track)

Soil moisture

rain



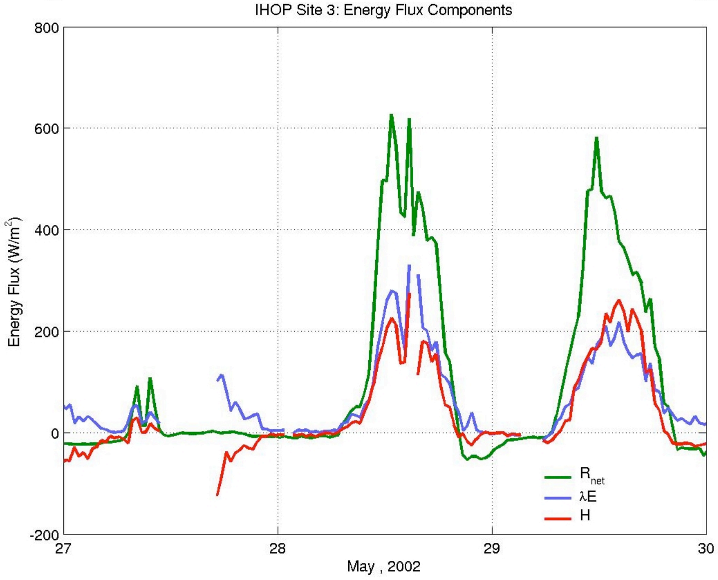
Site 3 (western Track)
drier, larger sensible heat flux



Latent heat

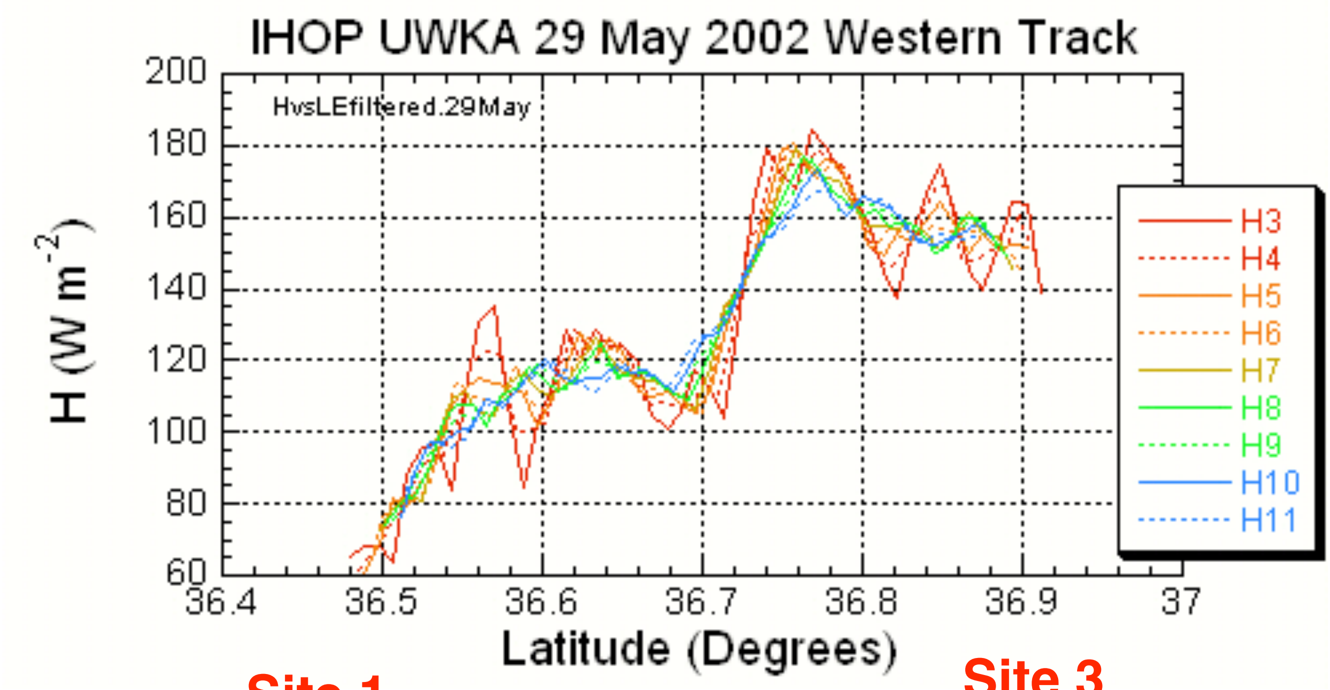
Net Rad

Sensible heat



Spatial Variability of PBL

The differences in surface sensible heating resulted in 200-300 m deeper boundary layer at Site 3



Site 1
Wet soil

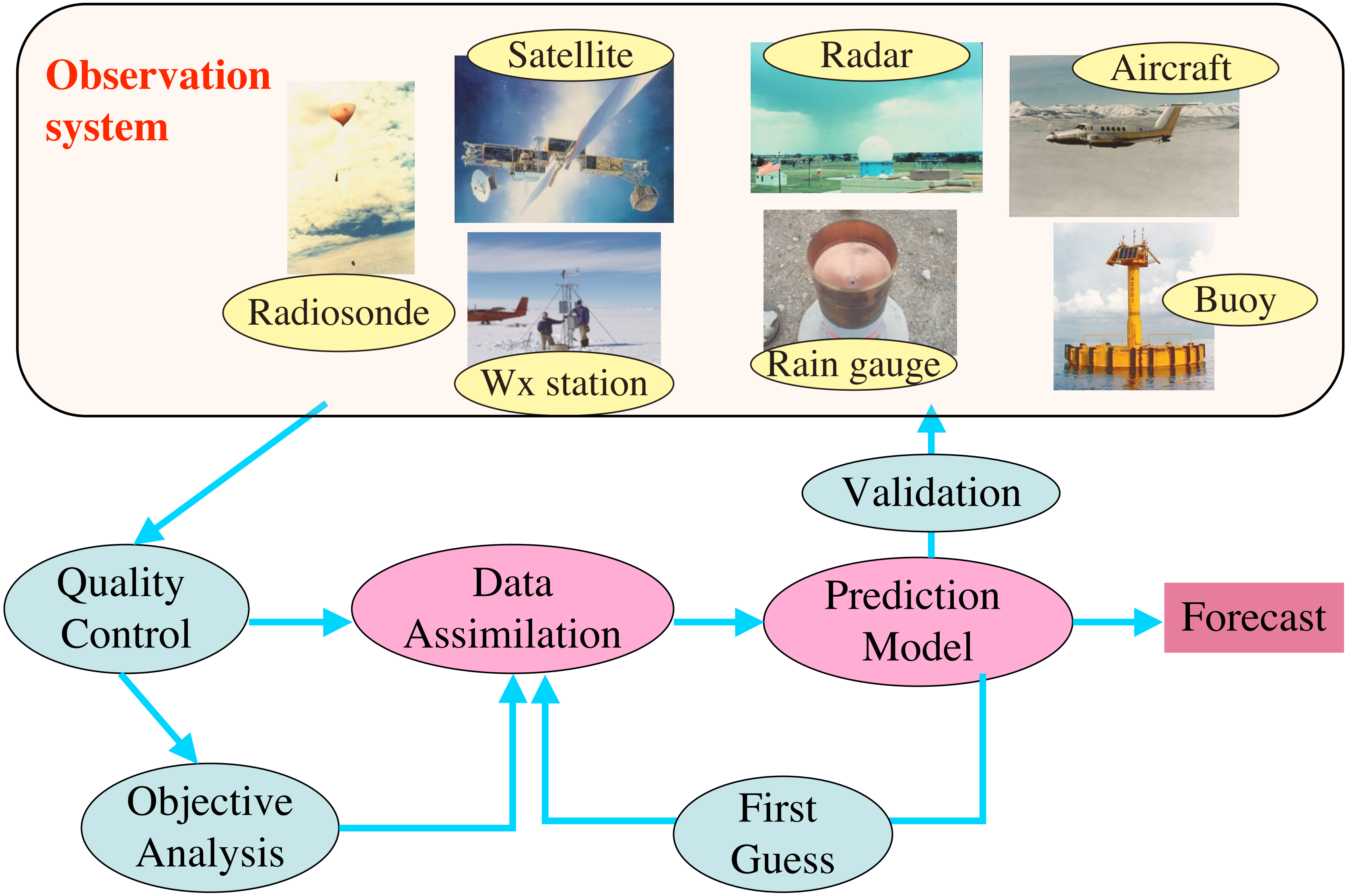
Site 3
dry soil

Outline

- **Overview of land surface processes**
- **Modeling of land surface in mesoscale numerical prediction models**
- **Land data assimilation techniques**

NCAR

General Flow of Numerical Weather Prediction (NWP)



Observation system

Radiosonde

Satellite

Wx station

Radar

Rain gauge

Aircraft

Buoy

Quality Control

Objective Analysis

Data Assimilation

First Guess

Prediction Model

Validation

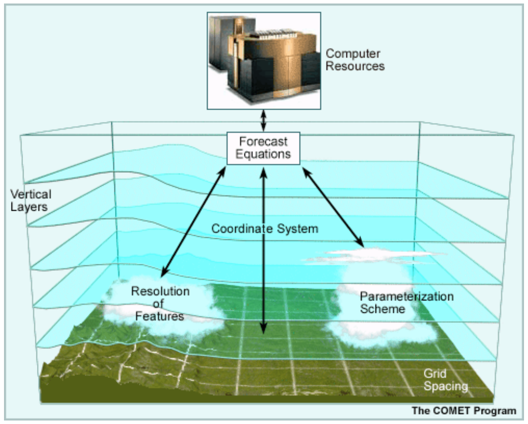
Forecast

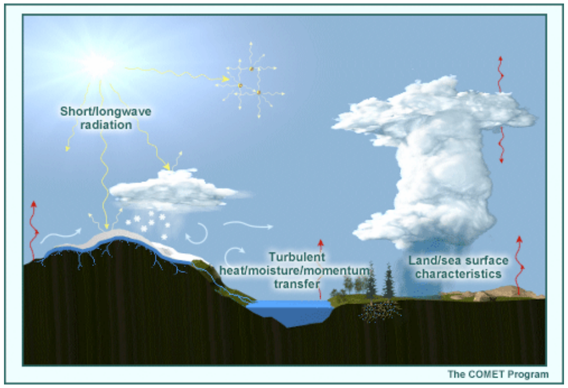
Examples of NWP Models

- **Global models**
  - **GFS,** Global Forecast System (previously AVN), NOAA.
  - **NOGAPS,** US Navy.
  - **GEM,** Global Environmental Multiscale, Meteorological Service of Canada
  - **ECMWF,** model by the European Centre for Medium-Range Weather Forecasts
  - **UKMET,** UK Met Office
  - **GME,** German Weather Service
- **Regional models**
  - **WRF**, Weather Research and Forecasting Model
  - **NAM,** North American Mesoscale (formerly Eta - renamed Jan 2005), NOAA
  - **NMM-WRF,** Weather Research and Forecasting Nonhydrostatic Mesoscale Model became the NAM at NCEP in June 2006.
  - **ARW(RF),** Advanced Research WRF developed primarily at NCAR)
  - **MM5**, Fifth Generation Penn State/NCAR Mesoscale Model, PSU/NCAR
  - **HIRLAM,** High Resolution Limited Area Model

Physics Parameterization in NWP Model

- Dynamics
- Physics
  - Computers are not yet powerful enough to directly treat them (not even the Lonestar!)
  - 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).





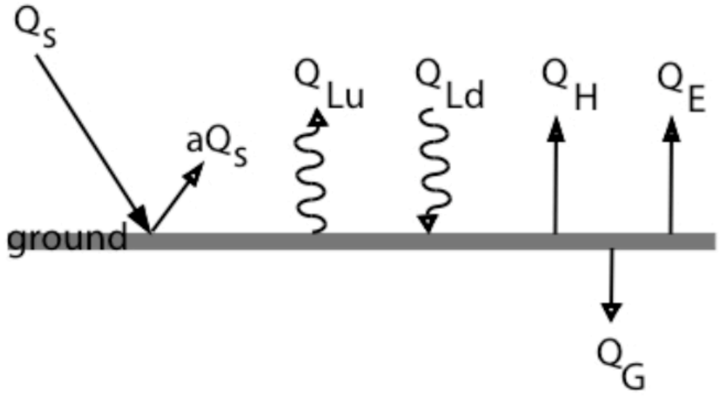
Why Do We Need Land Surface Models?

- Need to account for subgrid-scale 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

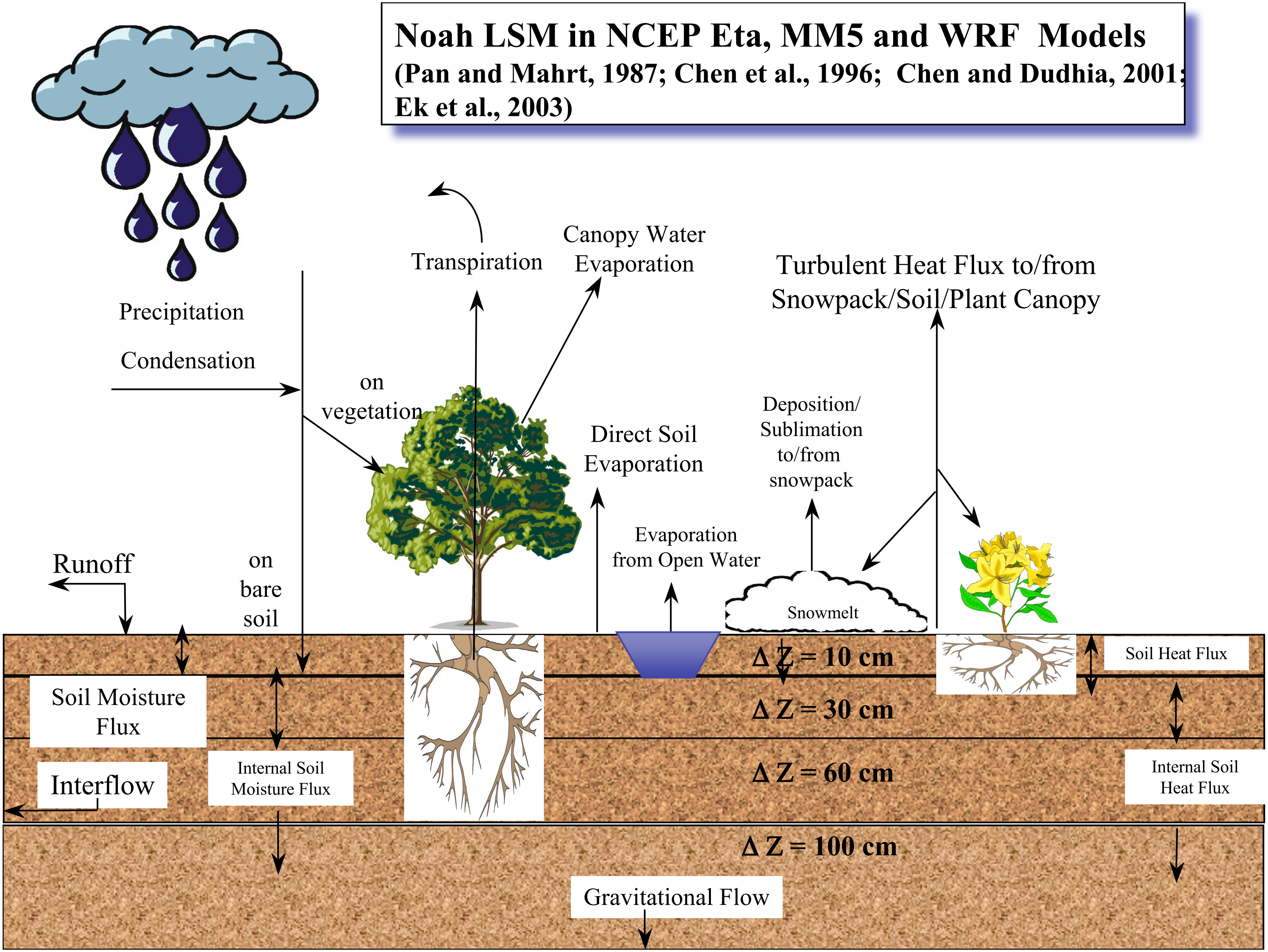
- Molecular conduction of heat, diffusion of tracers, and viscous transfer of momentum cause transport between the surface and the lowest millimeters of air diffusion
  - Diffusivity for momentum, heat, and water vapor: ~ 10^{-5} m^2s^{-1}
  - Require large gradient (e.g., 10^4 Km^{-1})
  - Can be neglected 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

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 to develop the unified Noah LSM for numerical weather prediction 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
  - Navy: operational COAMPS
- Coupled WRF/Noah operational:
  - AFWA: WRF-ARW for operations July 2006
  - NCEP: WRF-NMM for operations June 2006

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)



Precipitation

Condensation

on vegetation

on bare soil

Transpiration

Canopy Water Evaporation

Direct Soil Evaporation

Evaporation from Open Water

Deposition/ Sublimation to/from snowpack

Snowmelt

Turbulent Heat Flux to/from Snowpack/Soil/Plant Canopy

Runoff

Soil Moisture Flux

Interflow

Internal Soil Moisture Flux

Soil Heat Flux

Internal Soil Heat Flux

$\Delta Z = 10$ cm

$\Delta Z = 30$ cm

$\Delta Z = 60$ cm

$\Delta Z = 100$ cm

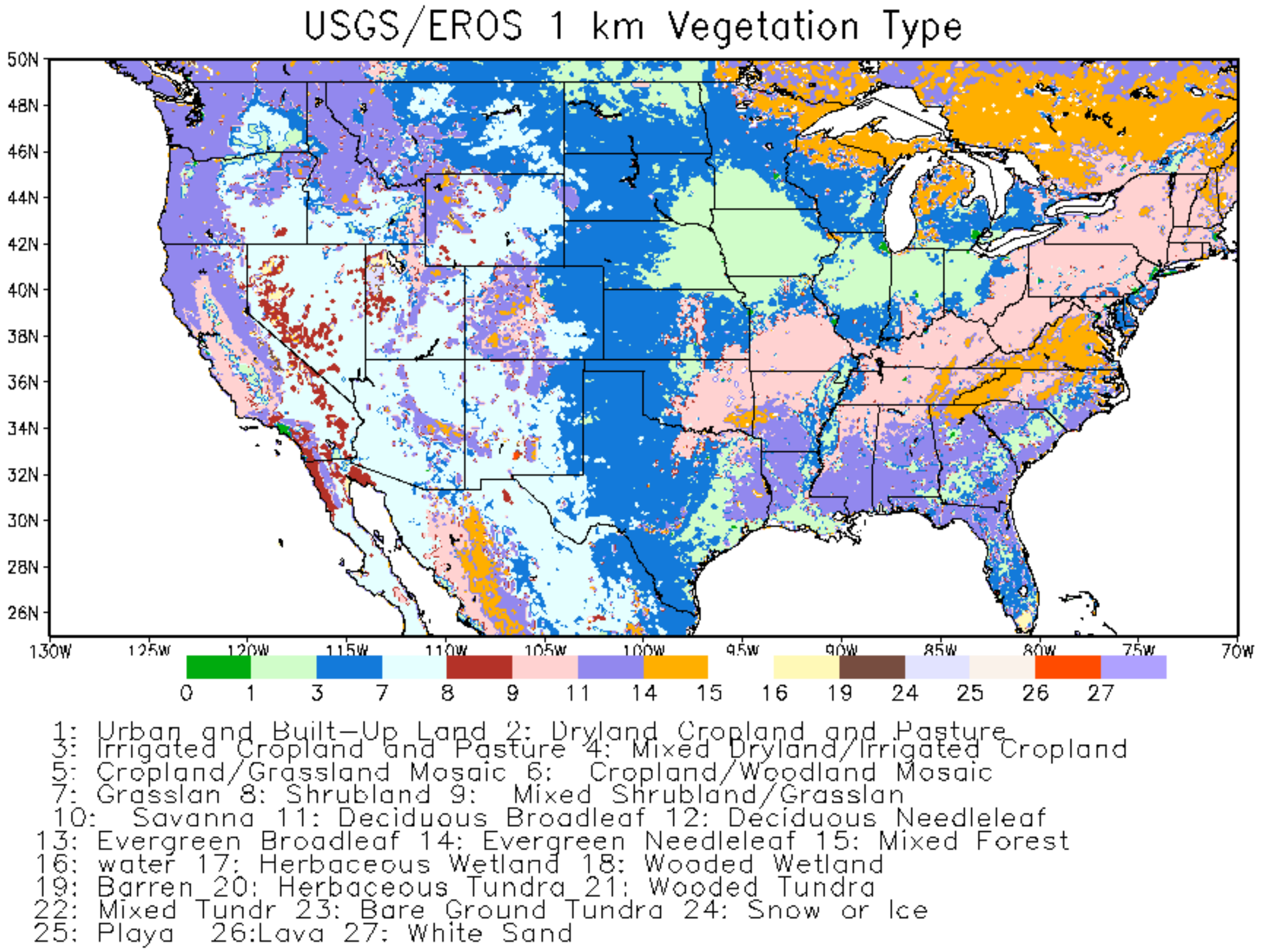
Gravitational Flow

Noah LSM in WRF V2.0 (May 2004)

- 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 urban canopy mode release Nov. 2006

Key References for Noah LSM

- Physics (1-d column model)
  - Warm season
    - F. Chen et al. (1996, JGR, 101, p7251-7268)
  - Cold season (snowpack and frozen soil)
    - V. Koren et al. (1999, JGR, 104, p19569-19585)
- In Mesoscale models
  - NCEP Eta model
    - M. Ek et al. (2003, JGR, 108)
  - NCAR MM5 model
    - F. Chen & J. Dudhia (2001a, 2001b, MWR, 129, p569-604)

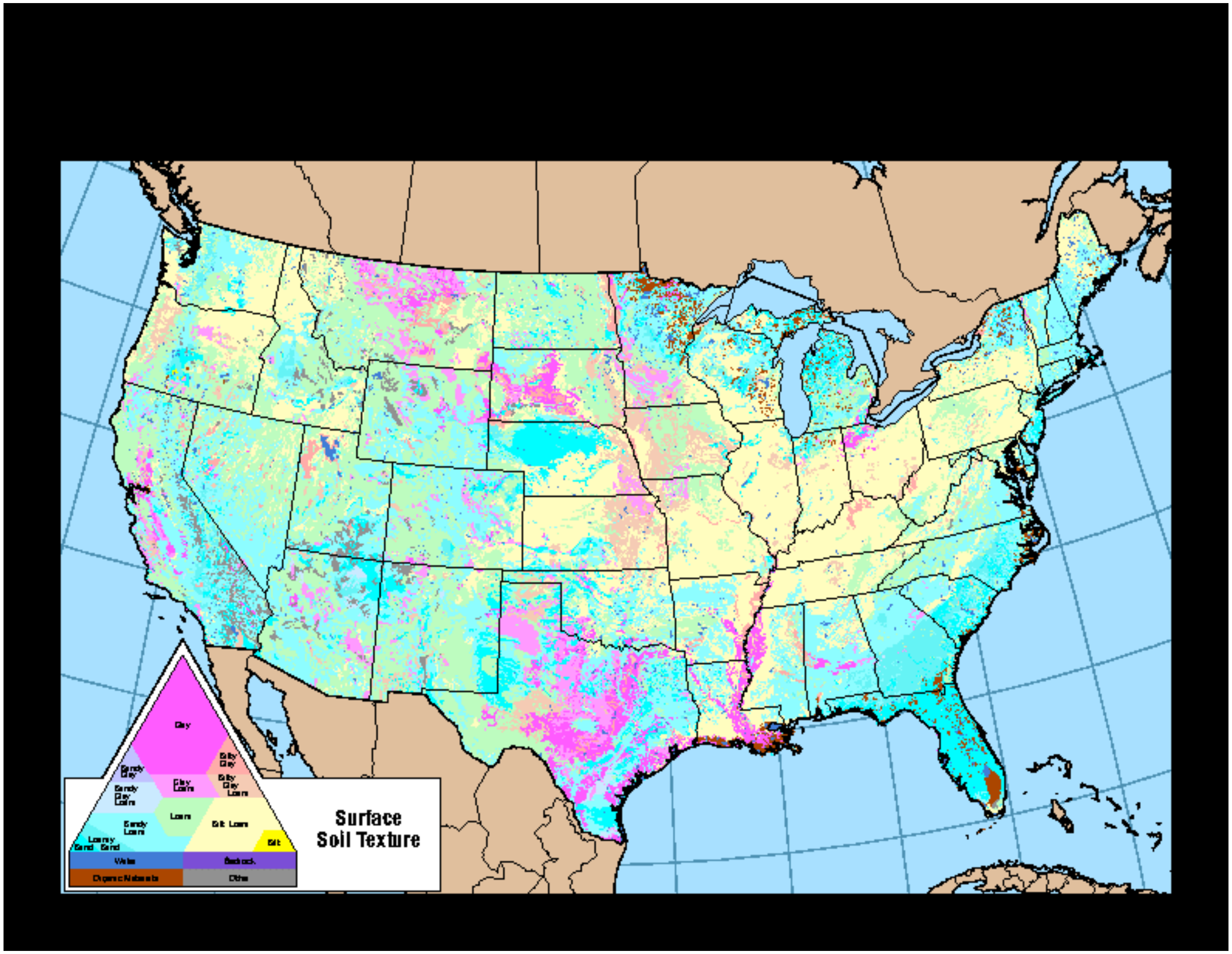


USGS/EROS 1 km Vegetation Type

1: Urban and Built-Up Land 2: Dryland Cropland and Pasture
3: Irrigated Cropland and Pasture 4: Mixed Dryland/Irrigated Cropland
5: Cropland/Grassland Mosaic 6: Cropland/Woodland Mosaic
7: Grasslan 8: Shrubland 9: Mixed Shrubland/Grasslan
10: Savanna 11: Deciduous Broadleaf 12: Deciduous Needleleaf
13: Evergreen Broadleaf 14: Evergreen Needleleaf 15: Mixed Forest
16: water 17: Herbaceous Wetland 18: Wooded Wetland
19: Barren 20: Herbaceous Tundra 21: Wooded Tundra
22: Mixed Tundr 23: Bare Ground Tundra 24: Snow or Ice
25: Playa 26:Lava 27: White Sand

→ determine Rc_min, and other vegetation parameters

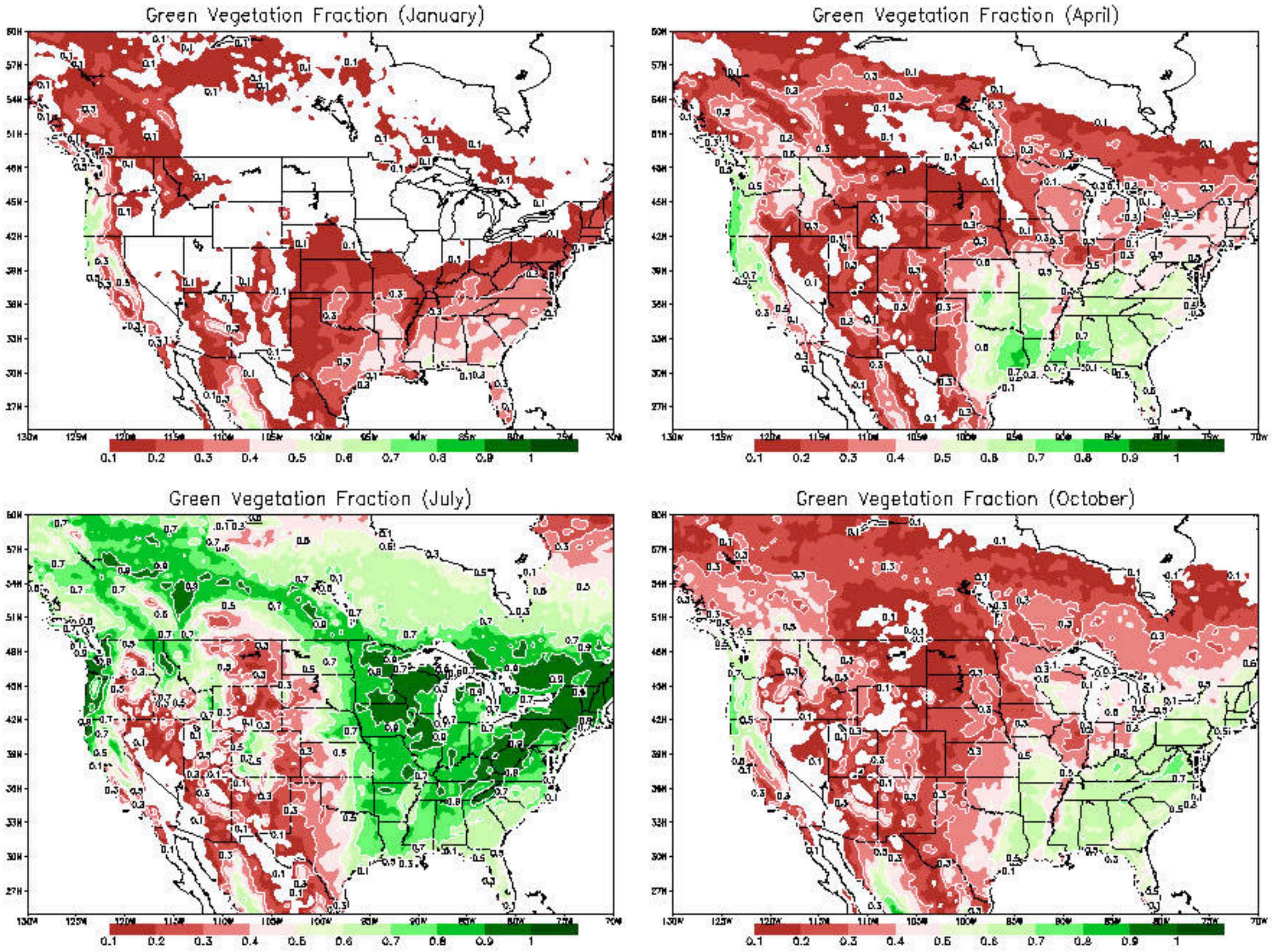
Global Soil Texture Map



→ determine Kt, and other soil parameters

Seasonality of vegetation

Based on monthly NDVI



Green Vegetation Fraction (January)

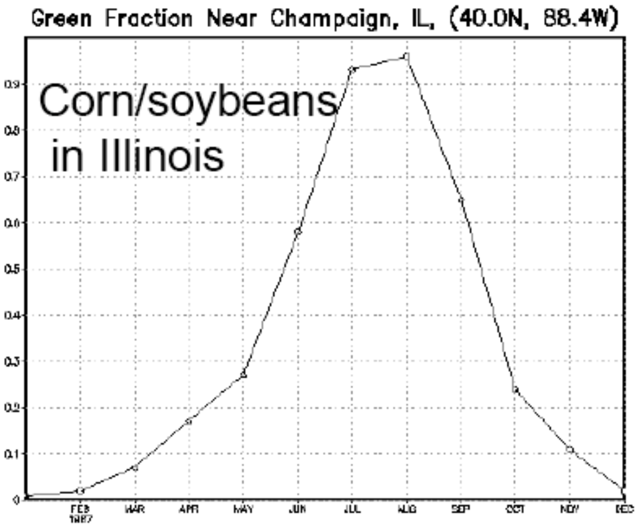
Green Vegetation Fraction (April)

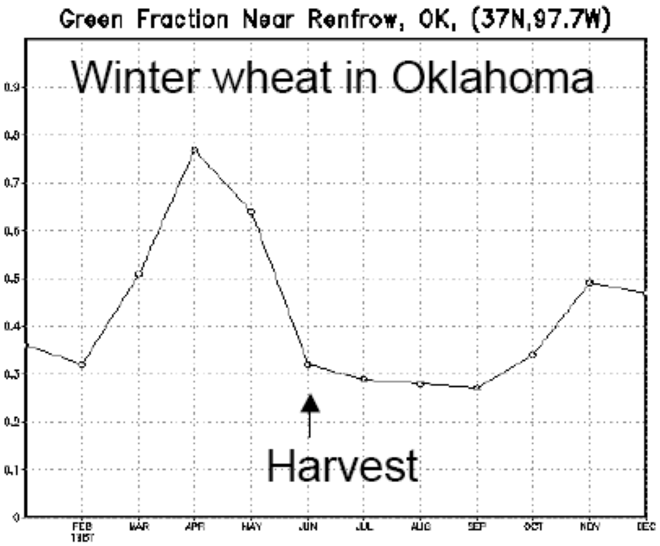
Green Vegetation Fraction (July)

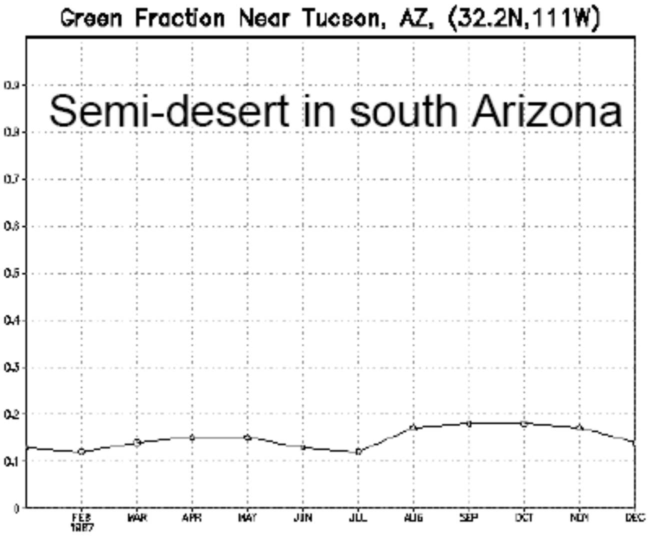
Green Vegetation Fraction (October)

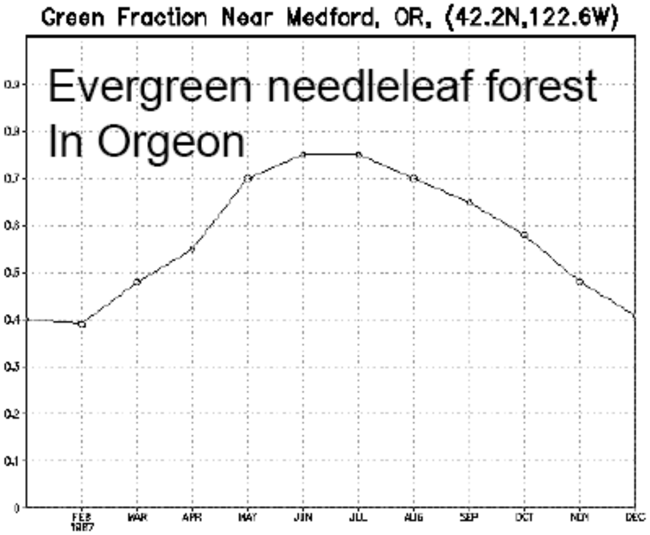
NCAR

Example Annual Time Series of Green Vegetation Fraction in Noah LSM









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)

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

NCAR

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

NCAR

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

NCAR

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):

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

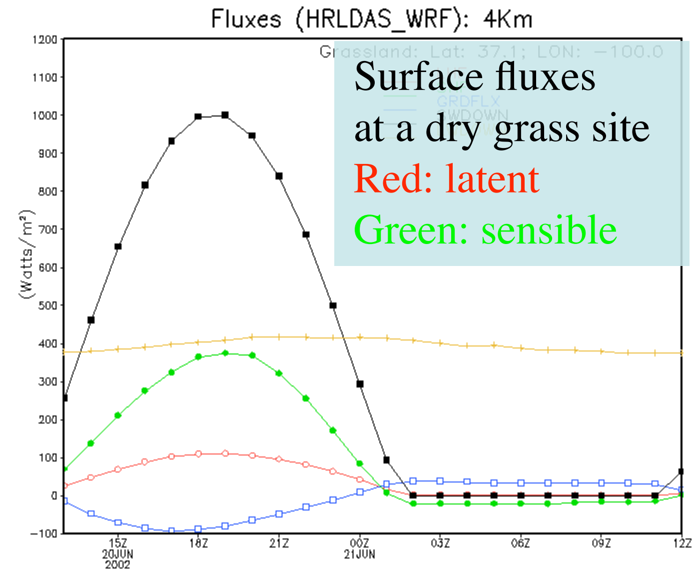
NCAR

Canopy Resistance (continued)

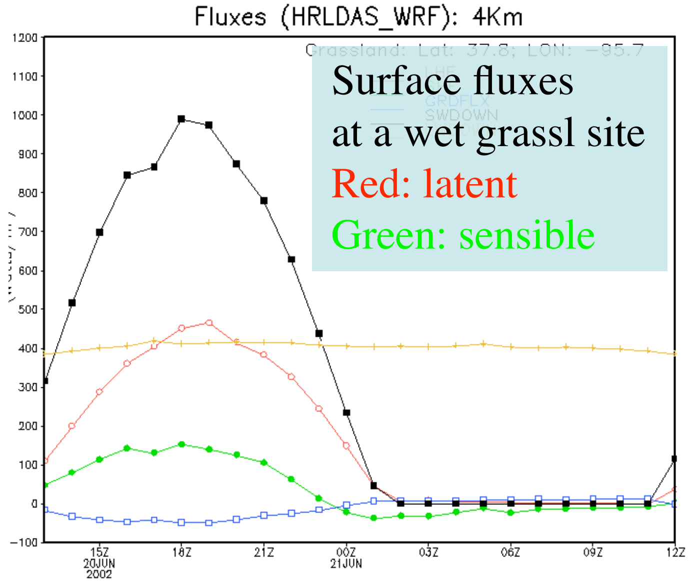
$$Rc = \frac{Rc\_\min}{LAI\, F_1\, F_2\, F_3\, F_4}$$

- 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

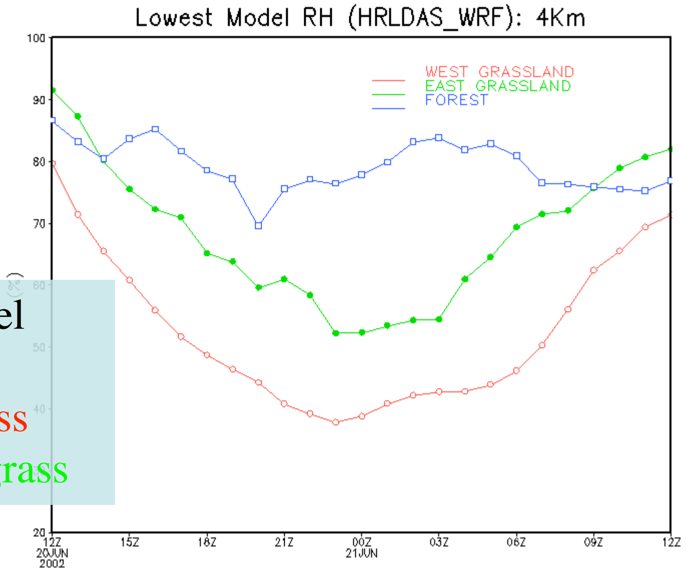
WRF/Noah simulated typical summer surface fluxes and PBL depth



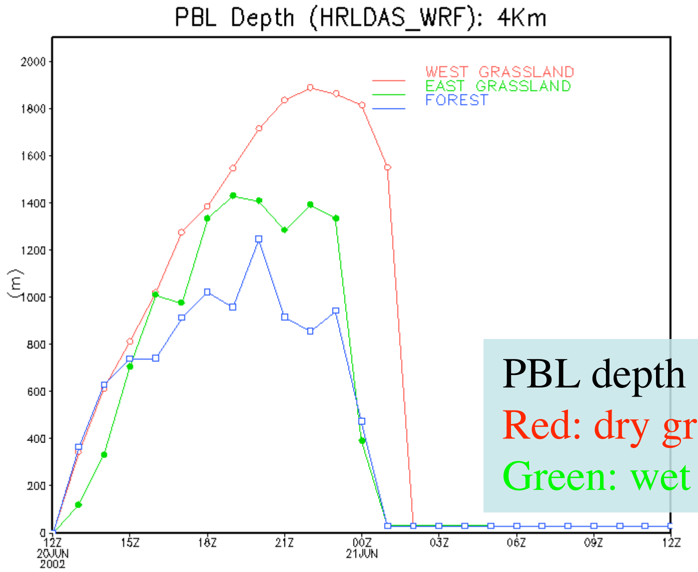
Surface fluxes
at a dry grass site
Red: latent
Green: sensible



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



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

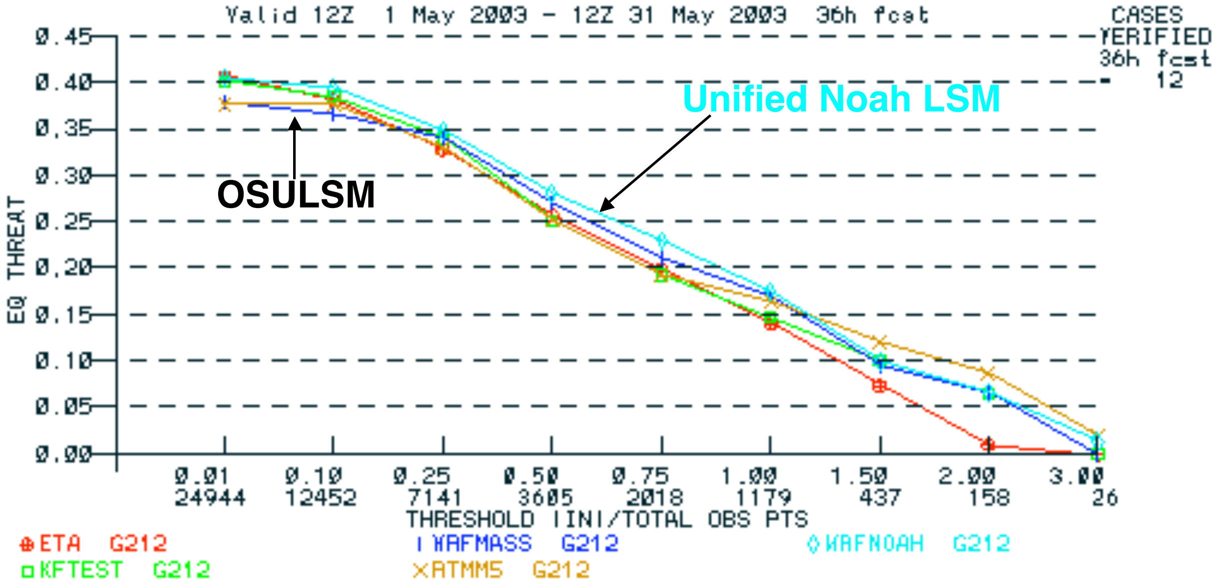


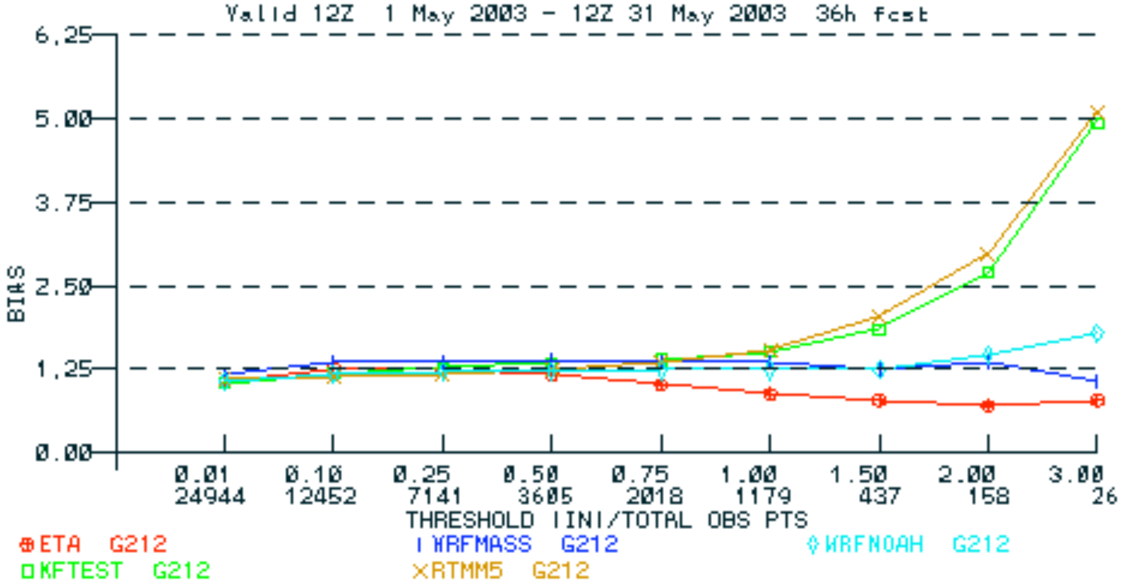
PBL depth
Red: dry grass
Green: wet grass

The unified Noah LSM significantly improved the precipitation score compared to its predecessor OSULSM

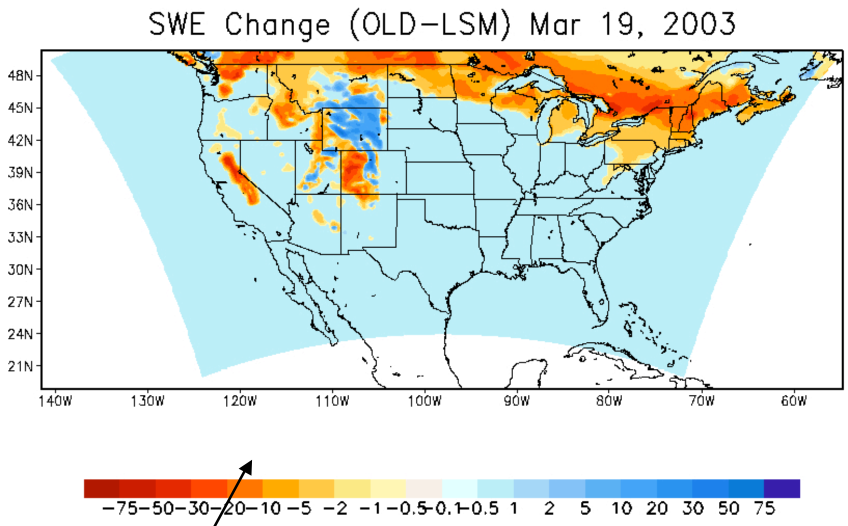
Realtime 22-km CONUS 12Z Cycle initialized from 40-km EDAS

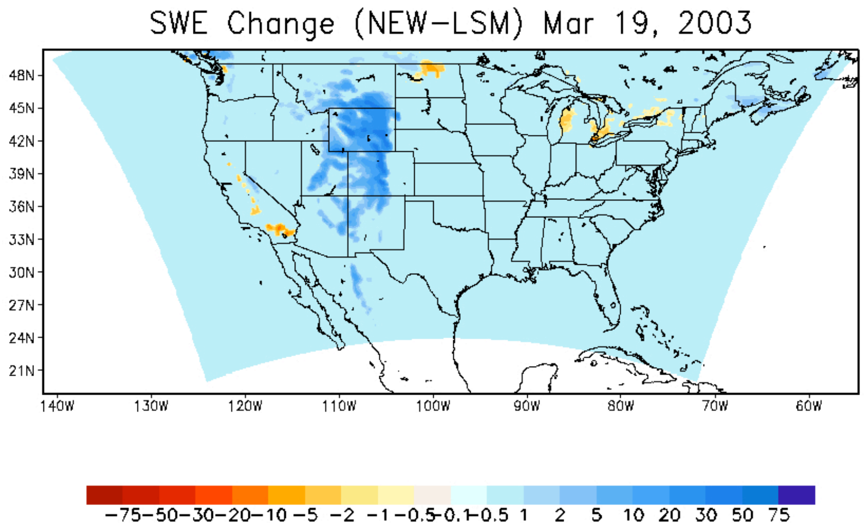
12-36 h forecasted rainfall from 15 to 31 May 2003 verified on #212 grid



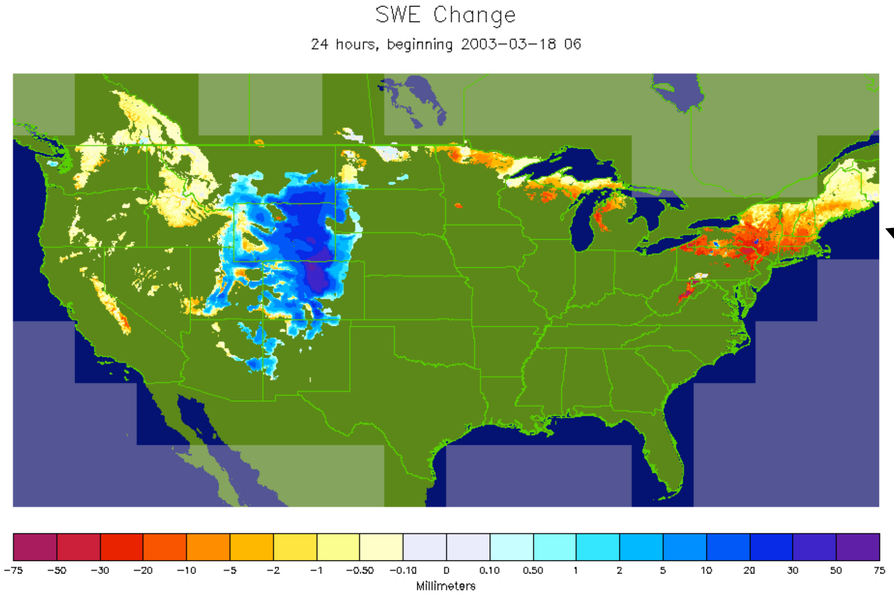


WRF/ Noah Snow Storm Case 18 March 2003
24-h snow water equivalent change valid at 00Z 19 March


SWE Change (OLD-LSM) Mar 19, 2003


SWE Change (NEW-LSM) Mar 19, 2003

Snow melted too quickly in the OSULSM


SWE Change

24 hours, beginning 2003−03−18 06

Obs 24-h SWE change valid at 06Z 19 March

NCAR

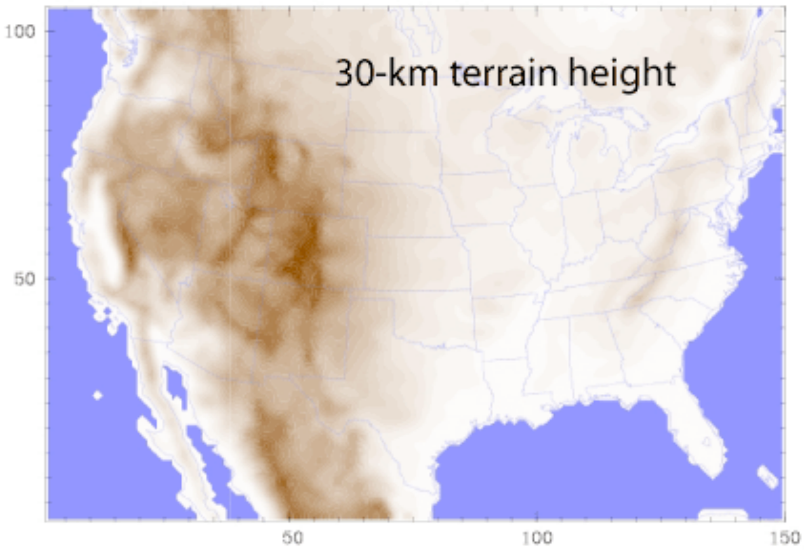
Outline

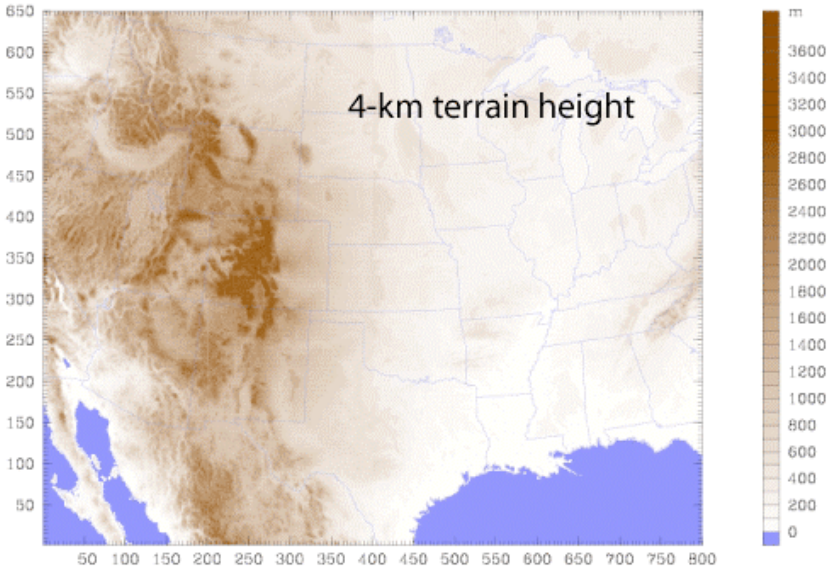
- **Overview of land surface processes**
- **Modeling of land surface in mesoscale numerical prediction models**
- **Land data assimilation techniques**

Motivation

- Mesoscale models need to capture atmospheric boundary layer structures and motions resulted from surface forcing
- No routine high-resolution soil observation network at continental scale available for mesoscale coupled system initialization
- Ultimate approach is to combine observation (including satellite), modeling, and data assimilation
- Alternatives: Using observed rainfall, analyzed downward solar radiation, and atmospheric analysis to drive LSMs in uncoupled mode
  - NCEP NLDAS: North America, 1/8 degree
  - AFWA ARGMET: global, 47-km, long-term archive

Using one source of land state data to initialize a forecast model with different model configurations: *Mis-match of terrain, landuse, soil texture, and physical parameters used in LSMs*





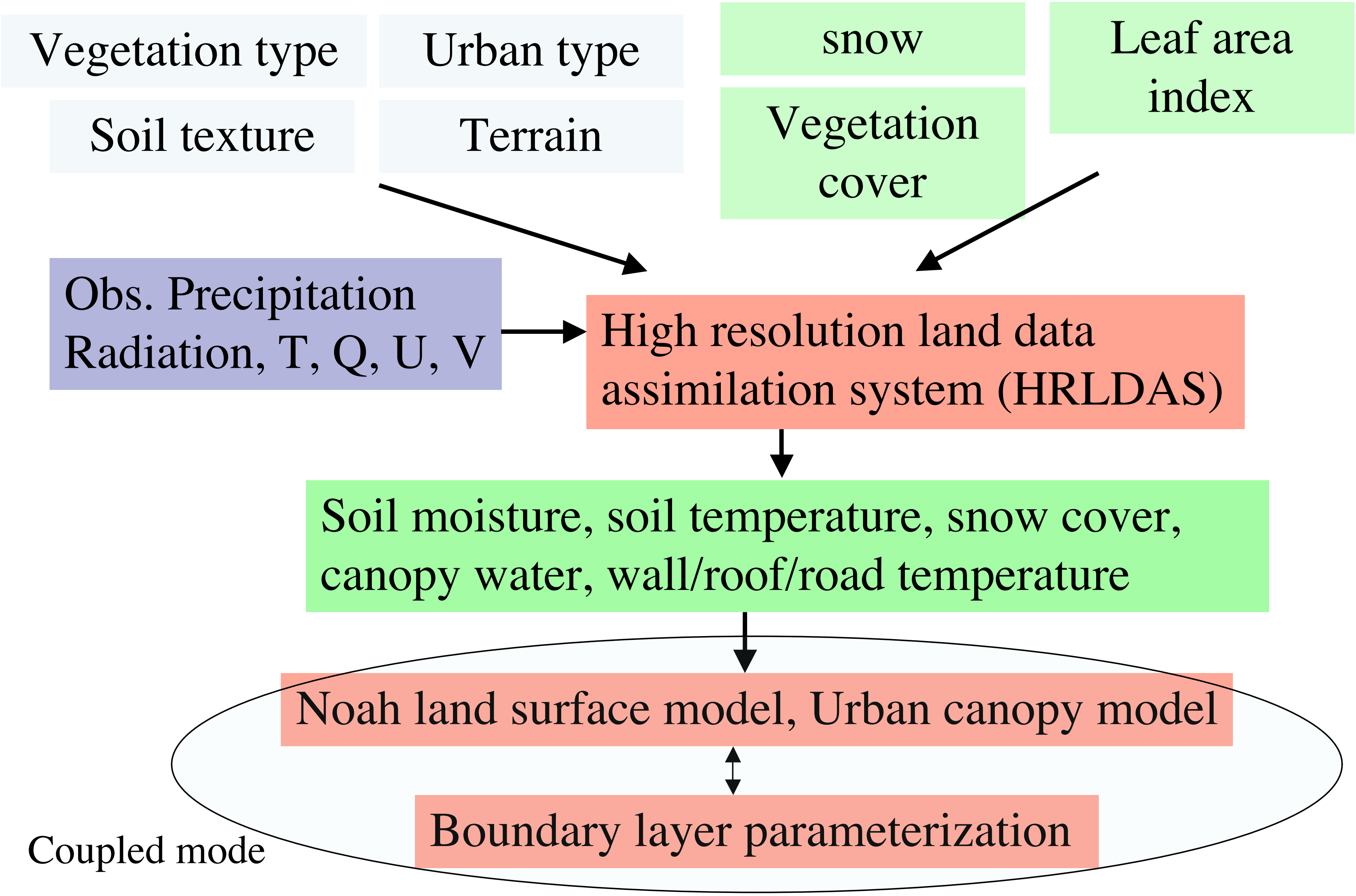
NCAR High-Resolution Land Data Assimilation System (HRLDAS) Concept

Run uncoupled LSM on the same grid as mesoscale NWP models

- Using the same LSM as in coupled NWP model: same soil moisture climatology
- No Mis-match of terrain, land use type, soil texture, physical parameters between sources of soil data and NWP models
- No interpolation and soil moisture conversion

NCAR

High-resolution Land surface and urban modeling and assimilation system (Chen et al. 2006, JAMC)



Vegetation type

Urban type

Soil texture

Terrain

snow

Vegetation cover

Leaf area index

Obs. Precipitation
Radiation, T, Q, U, V

High resolution land data assimilation system (HRLDAS)

Soil moisture, soil temperature, snow cover, canopy water, wall/roof/road temperature

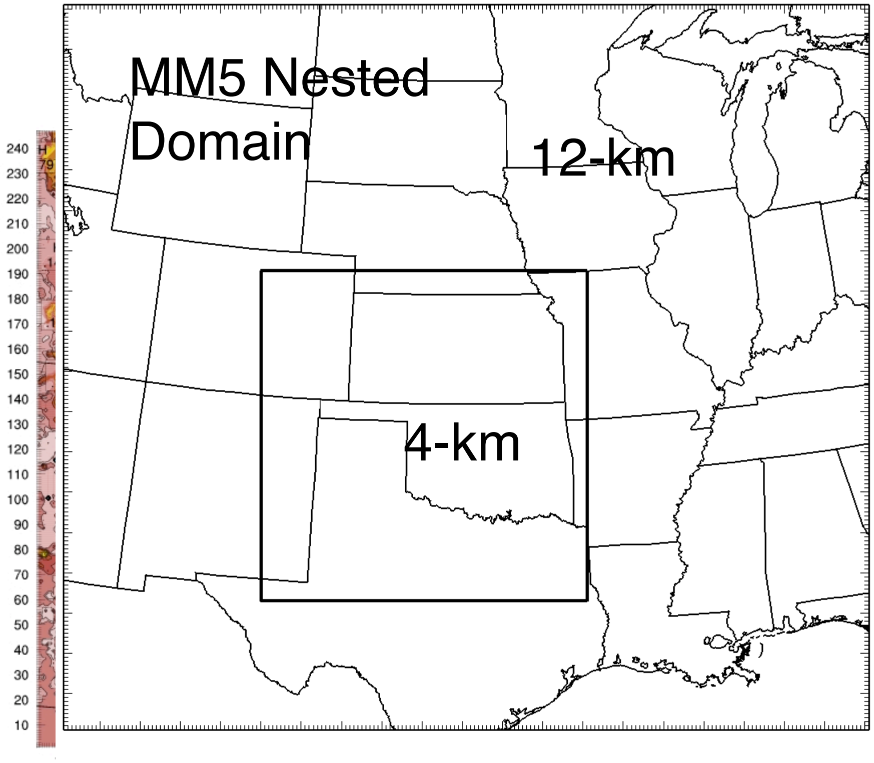
Noah land surface model, Urban canopy model

Boundary layer parameterization

Coupled mode

HRLDAS: Capturing Small-Scale Variability

- Input:
  - 4-km hourly NCEP Stage-II rainfall
  - 1-km landuse type and soil texture maps
  - 0.5 degree hourly GOES downward solar radiation
  - 0.15 degree AVHRR vegetation fraction
  - T,q, u, v, from model based analysis
- Output: **long term evolution of multi-layer soil moisture and temperature, surface fluxes, and runoff**

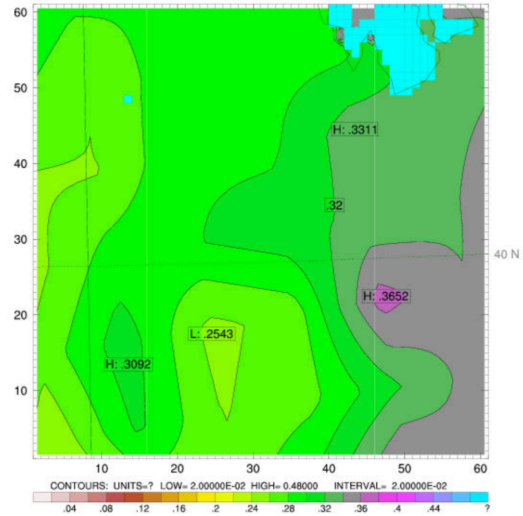


4-km HRLDAS surface soil moisture in IHOP domain 12 Z May 29 2002

HRLDAS Surface layer (top 10 cm soil) volumetric soil moisture

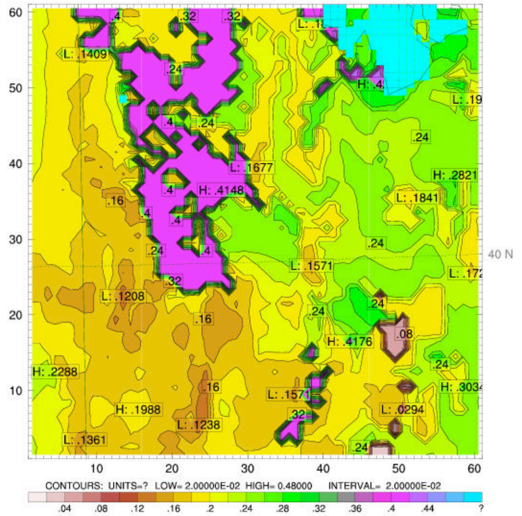
Initial time

From coarse resolution of EDAS field



46 days later

Heterogeneity was developed in the 4-km domain

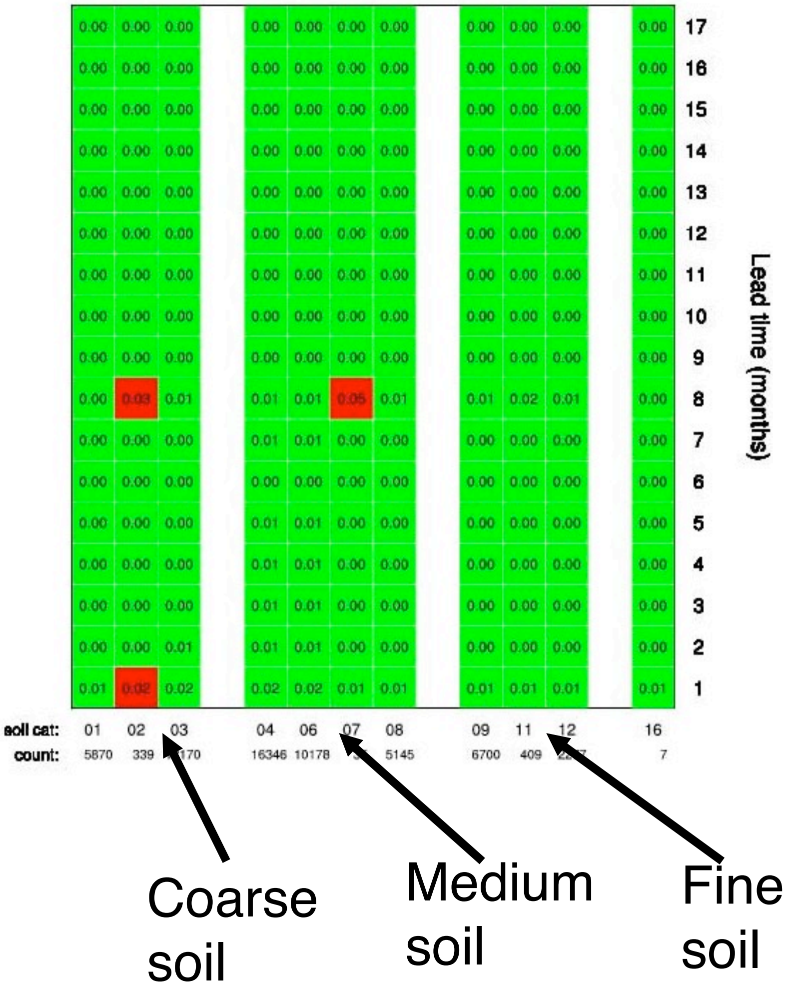


NCAR

HRLDAS Spin-Up

Volumetric soil moisture RMS difference (m^3m^{-3}) 🟩 ≤ 0.02   0.02 < 🟥 ≤0.1   0.1 < 🟦

1^{st} layer soil moisture



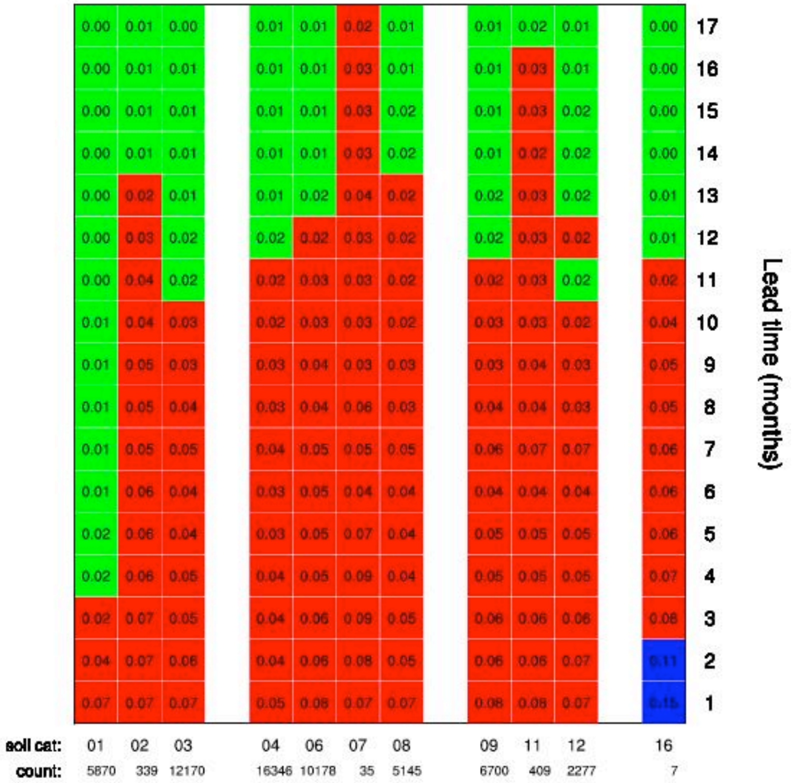
soil cat:	01	02	03	04	06	07	08	09	11	12	16	Lead time (months)
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9
	0.00	0.03	0.01	0.01	0.01	0.05	0.01	0.01	0.02	0.01	0.00	8
	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	7
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6
	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	5
	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	4
	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	3
	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2
	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	1
count:	5870	339	[illegible]170	16346	10178	[illegible]	5145	6700	409	22[illegible]7	7	

Coarse soil

Medium soil

Fine soil

3^{rd} layer soil moisture



soil cat:	01	02	03	04	06	07	08	09	11	12	16	Lead time (months)
	0.00	0.01	0.00	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.00	17
	0.00	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.03	0.01	0.00	16
	0.00	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.03	0.02	0.00	15
	0.00	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.02	0.02	0.00	14
	0.00	0.02	0.01	0.01	0.02	0.04	0.02	0.02	0.03	0.02	0.01	13
	0.00	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.01	12
	0.00	0.04	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.02	0.02	11
	0.01	0.04	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.02	0.04	10
	0.01	0.05	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.05	9
	0.01	0.05	0.04	0.03	0.04	0.06	0.03	0.04	0.04	0.03	0.05	8
	0.01	0.05	0.05	0.04	0.05	0.05	0.05	0.06	0.07	0.07	0.06	7
	0.01	0.06	0.04	0.03	0.05	0.04	0.04	0.04	0.04	0.04	0.06	6
	0.02	0.06	0.04	0.03	0.05	0.07	0.04	0.05	0.05	0.05	0.06	5
	0.02	0.06	0.05	0.04	0.05	0.09	0.04	0.05	0.05	0.05	0.07	4
	0.02	0.07	0.05	0.04	0.06	0.09	0.05	0.06	0.06	0.06	0.08	3
	0.04	0.07	0.06	0.04	0.06	0.08	0.05	0.06	0.06	0.07	0.11	2
	0.07	0.07	0.07	0.05	0.08	0.07	0.07	0.08	0.08	0.07	0.15	1
count:	5870	339	12170	16346	10178	35	5145	6700	409	2277	7	

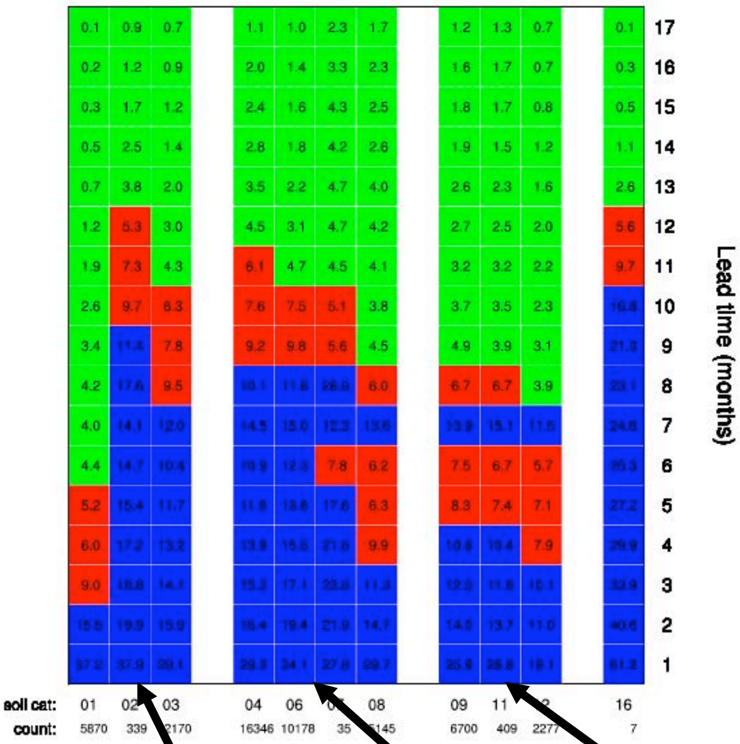
Quick spin-up for coarse soil texture

HRLDAS Spin-Up

Surface heat flux
RMS difference (Wm^{-2})

🟩 ≤ 5   5 < 🟥 ≤ 10   10 < 🟦

Sensible heat flux



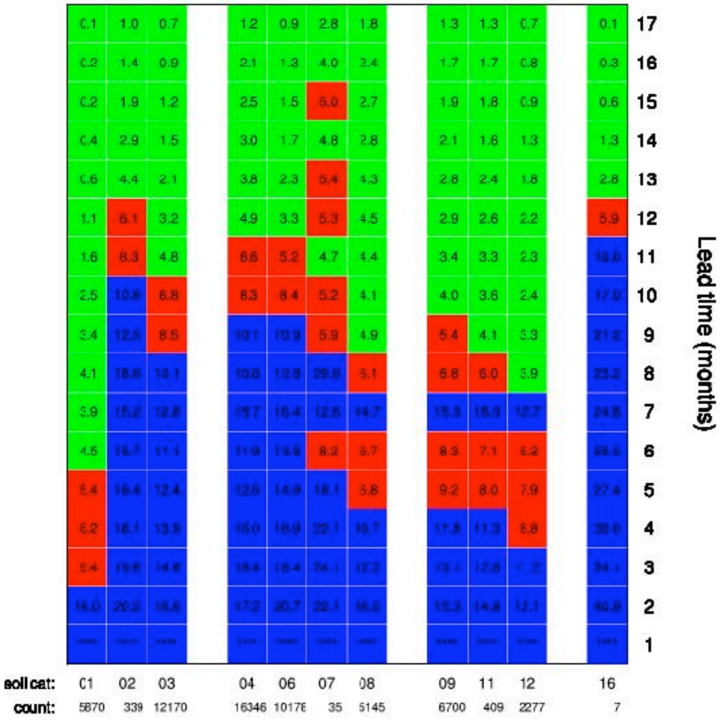
soil cat:	01	02	03	04	06	07	08	09	11	12	16	Lead time (months)
count:	5870	339	12170	16346	10178	35	5145	6700	409	2277	7	
	0.1	0.9	0.7	1.1	1.0	2.3	1.7	1.2	1.3	0.7	0.1	17
	0.2	1.2	0.9	2.0	1.4	3.3	2.3	1.6	1.7	0.7	0.3	16
	0.3	1.7	1.2	2.4	1.6	4.3	2.5	1.8	1.7	0.8	0.5	15
	0.5	2.5	1.4	2.8	1.8	4.2	2.6	1.9	1.5	1.2	1.1	14
	0.7	3.8	2.0	3.5	2.2	4.7	4.0	2.6	2.3	1.6	2.6	13
	1.2	5.3	3.0	4.5	3.1	4.7	4.2	2.7	2.5	2.0	5.6	12
	1.9	7.3	4.3	6.1	4.7	4.5	4.1	3.2	3.2	2.2	9.7	11
	2.6	9.7	6.3	7.6	7.5	5.1	3.8	3.7	3.5	2.3	10.8	10
	3.4	11.4	7.8	9.2	9.8	5.6	4.5	4.9	3.9	3.1	21.8	9
	4.2	17.6	9.5	10.1	11.6	26.9	6.0	6.7	6.7	3.9	23.1	8
	4.0	14.1	12.0	14.5	15.0	12.3	13.6	13.9	15.1	11.5	24.6	7
	4.4	14.7	10.4	10.9	12.3	7.8	6.2	7.5	6.7	5.7	35.3	6
	5.2	15.4	11.7	11.8	13.6	17.6	6.3	8.3	7.4	7.1	27.2	5
	6.0	17.2	13.2	13.8	15.5	21.6	9.9	10.8	10.4	7.9	29.9	4
	9.0	18.8	14.1	15.2	17.1	23.8	11.3	12.0	11.8	10.1	32.9	3
	15.6	19.9	15.9	16.4	19.4	21.9	14.7	14.5	13.7	11.0	40.6	2
	27.2	37.9	29.1	29.3	34.1	27.8	29.7	25.6	28.8	19.1	61.2	1

Coarse soil

Medium soil

Fine soil

Latent heat flux

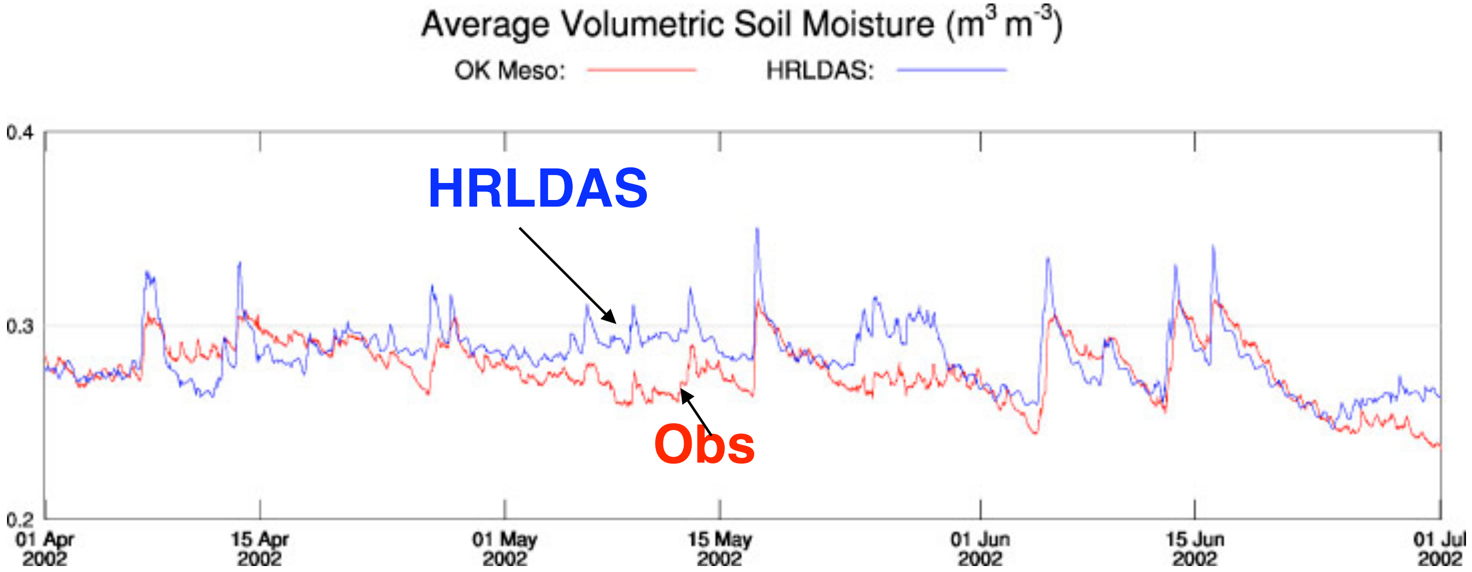


soil cat:	01	02	03	04	06	07	08	09	11	12	16	Lead time (months)
count:	5870	339	12170	16346	10178	35	5145	6700	409	2277	7	
	0.1	1.0	0.7	1.2	0.9	2.8	1.8	1.3	1.3	0.7	0.1	17
	0.2	1.4	0.9	2.1	1.3	4.0	2.4	1.7	1.7	0.8	0.3	16
	0.2	1.9	1.2	2.5	1.5	5.0	2.7	1.9	1.8	0.9	0.6	15
	0.4	2.9	1.5	3.0	1.7	4.8	2.8	2.1	1.6	1.3	1.3	14
	0.6	4.4	2.1	3.8	2.3	5.4	4.3	2.8	2.4	1.8	2.8	13
	1.1	6.1	3.2	4.9	3.3	5.3	4.5	2.9	2.6	2.2	5.9	12
	1.6	8.3	4.8	6.6	5.2	4.7	4.4	3.4	3.3	2.3	12.0	11
	2.5	10.8	6.8	8.3	8.4	5.2	4.1	4.0	3.6	2.4	17.0	10
	3.4	12.6	8.5	10.1	10.9	5.9	4.9	5.4	4.1	3.3	21.2	9
	4.1	18.6	10.1	10.8	12.8	29.6	5.1	6.8	6.0	3.9	23.2	8
	3.9	15.2	12.8	15.7	16.4	12.6	14.7	15.3	16.3	12.7	24.6	7
	4.5	15.7	11.1	11.9	13.9	8.2	6.7	8.3	7.1	6.2	28.6	6
	5.4	16.4	12.4	12.6	14.9	18.1	5.8	9.2	8.0	7.9	27.4	5
	6.2	18.1	13.9	15.0	18.9	22.1	10.7	11.8	11.3	6.8	30.0	4
	5.4	19.6	14.6	16.4	16.4	24.1	12.2	13.1	12.6	[illegible]	34.1	3
	16.0	20.5	18.6	17.2	20.7	22.1	16.0	15.3	14.8	12.1	40.9	2
	****	****	****	****	****	****	****	****	****	****	****	1

HRLDAS Verification

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

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



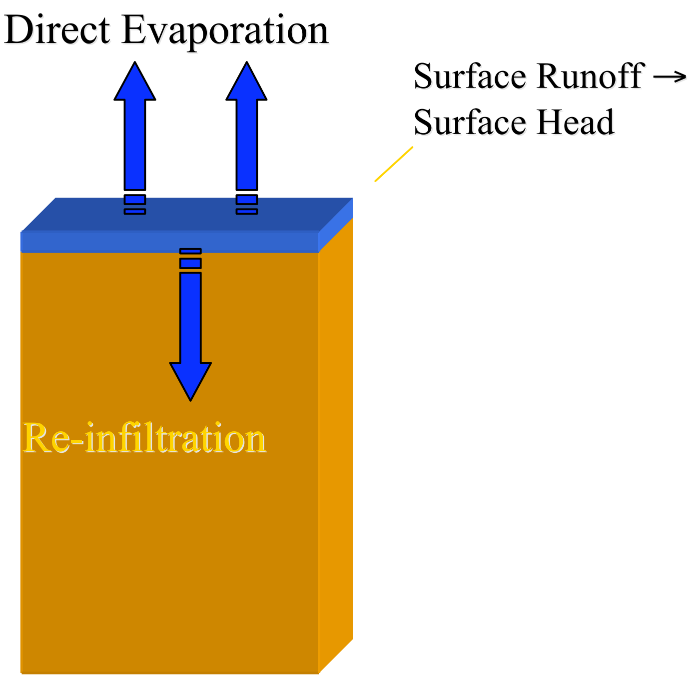
NCAR

Lecture at the UT-Austin, Austin, 17 October 2006.

Dynamic modeling of land-surface hydrology

‘*Noah-Router*’: Ponded Water Processes

(NCAR Tech Note: Gochis and Chen, 2003)

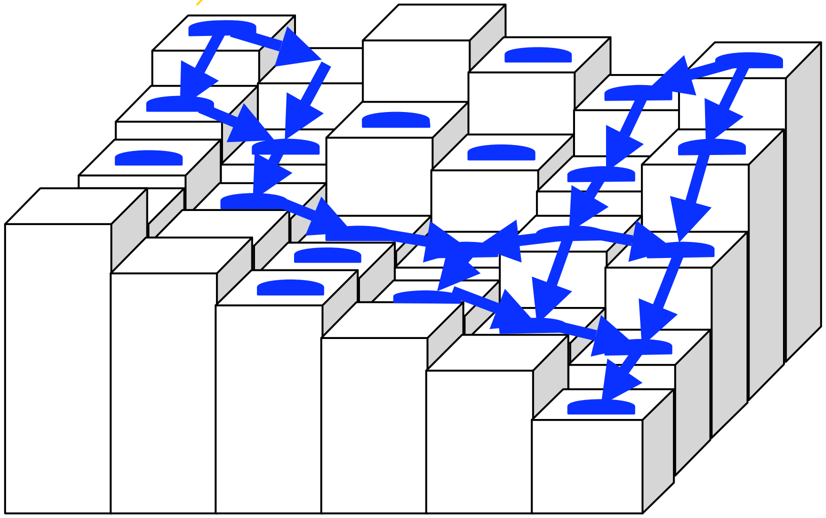


Ponded Water Evaporation and Re-infiltration

- New Parameters: None
- Currently no formulation for partial area coverage
- Ponded water consists of: residual of ‘infiltration excess’ from previous time step and routed surface water
- Direct evaporation of ponded water reduces potential evaporation
- Ponded water not evaporated is subject to infiltration

Overland Flow Processes in Noah-Router

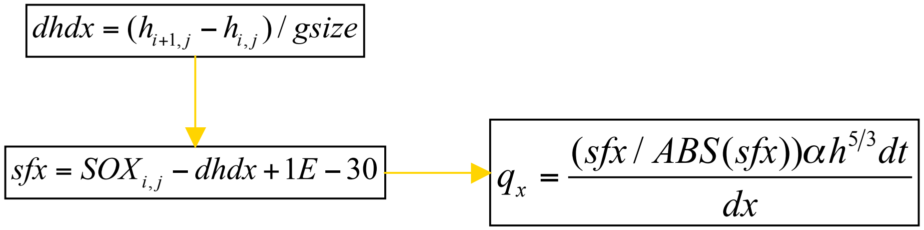
(NCAR Tech Note: Gochis and Chen, 2003)



IF (Surface Head > Retention Depth) →
Route Water as Overland Flow

2-Dimensional
Diffusive Wave
Overland Flow Routing
Ogden, 1997

- New Parameters: retention depth, surface roughness
- Ponded water in excess of retention depth subject to overland flow
- Overland flow: fully-unsteady, explicit, finite-difference, 2-dimensional diffusive wave (generally applicable to length scales < 1km)



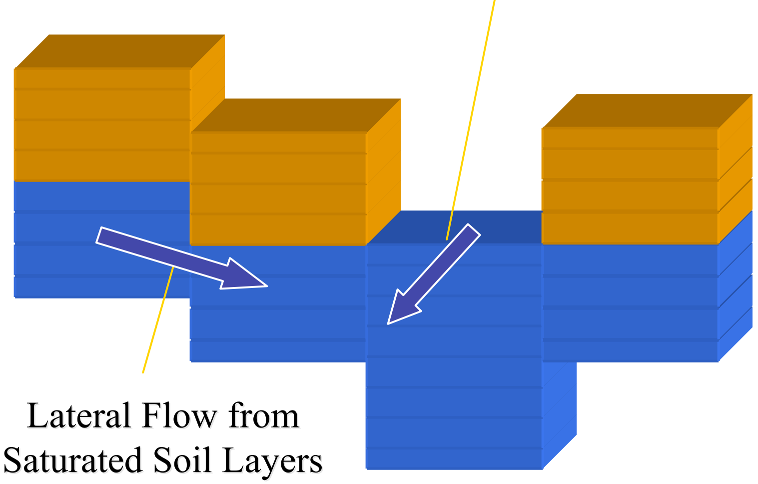
$$dhdx = (h_{i+1,j} - h_{i,j}) / gsize$$

$$sfx = SOX_{i,j} - dhdx + 1E-30$$

$$q_x = \frac{(sfx / ABS(sfx))\alpha h^{5/3} dt}{dx}$$

Subsurface Flow Routing Noah-Router

(NCAR Tech Note: Gochis and Chen, 2003)



Surface Exfiltration from Saturated Soil Columns

Lateral Flow from Saturated Soil Layers

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

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

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

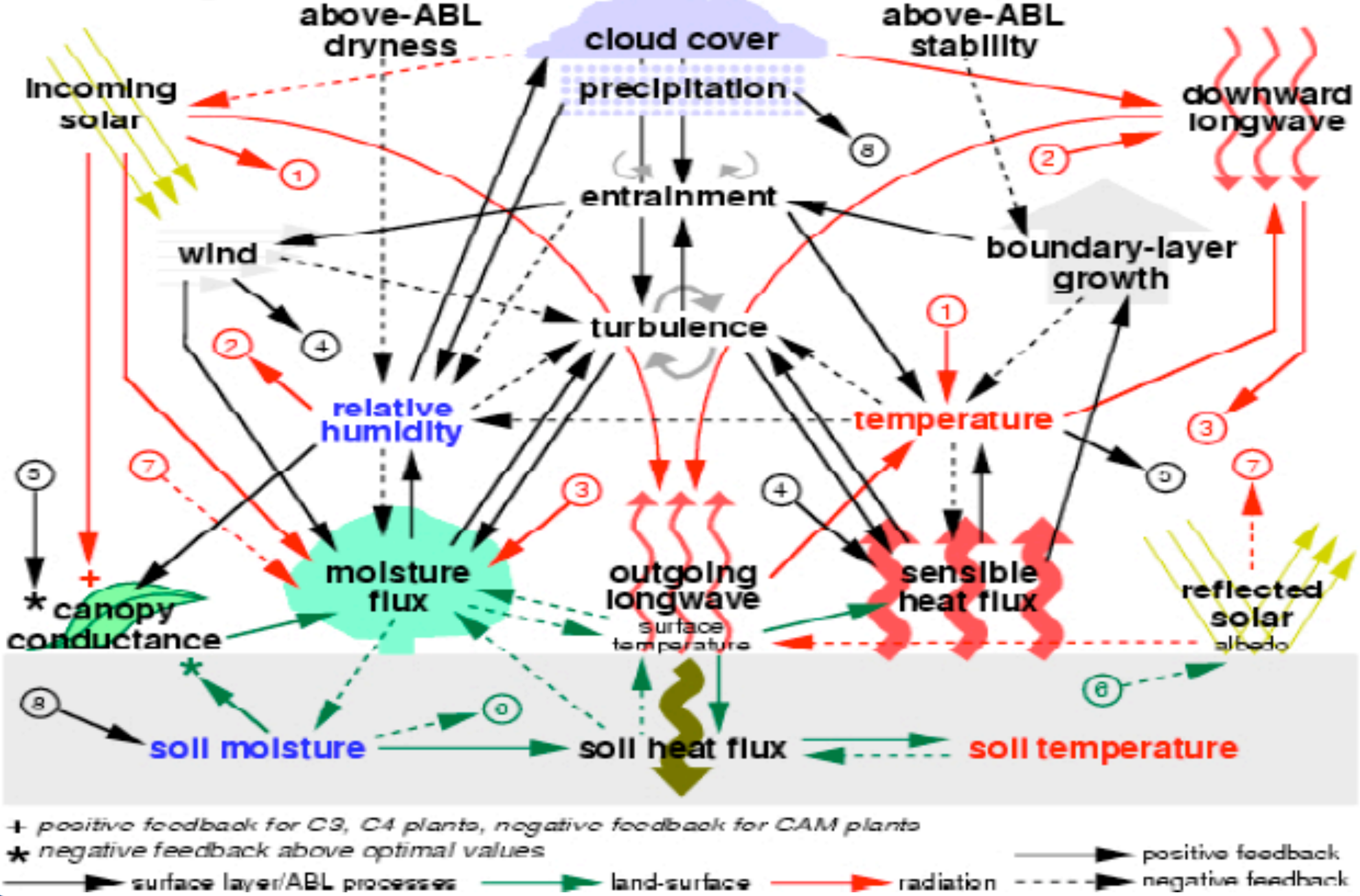
$$hh = \left(1 - \frac{z}{SOLDEP}\right)^{n}$$

$$qsub_x = \gamma * hh$$

Summary

- Land surface is one of the two primary driving force for boundary layer development, so to affect cloud and precipitation
- LSM may be the most complex parameterization scheme in NWP models
  - Diverse physical processes
  - Background vegetation and soil fields
  - Initialization of soil state variables
- Do not underestimate the challenge in land surface modeling

the Physics Wheel of Pain



NCAR

Lecture at the UT-Austin, Austin, 17 October 2006.

Land Surface Modeling is both Science and Art

Questions should be asked:

- Which of surface processes are accounted for in LSM? What is the magnitude of their effects relative to other dynamical processes, such as advection?
- What is the source for the initial surface data (land use, soil texture, LAI, GVF) for LSM? How representative are they?
- How is each characteristic handled as the model forecast evolves? For example, fixed fields or forecasted fields?
- How realistically does the model account for surface processes? LSMs use discrete soil layers and the number and thickness of soil layers impacts its ability to accurately calculate soil moisture and temperature.

Land Surface Modeling is both Science and Art

- Errors in surface energy and/or water balances stem from:
  - Incorrect amounts of short- and longwave radiation reaching the earth
  - Incorrect surface albedo due to unrepresentative surface
  - Incorrect evaporation due to soil moisture errors resulted from precipitation errors
  - Incorrect snow cover and depth not be accurately predicted or prescribed
  - Feedbacks from other errors. Too little or too much evaporation may result in cloudiness errors, which will result in net solar radiation errors, which will amplify existing surface temperature errors

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.*