A Description and Example Output of the WRF-NMM land surface and radiation packages used at NCEP

Ken Mitchell and Michael Ek
NCEP/EMC
NOAA/NWS

WRF-NMM Tutorial
8-11 August 2006
Boulder, CO

Noah Land Surface Model

- **WRF-NMM**
  - ♦ sf_surface_physics = 99
  - ♦ NCEP Noah LSM (aka NMM-LSM)
    - o 99 percent similarity with NCAR Noah LSM

- **WRF-ARW**
  - ♦ sf_surface_physics = 2
  - ♦ NCAR Noah LSM

- <u>Near future goal</u> (6-12 months)
  - ♦ NCEP-NCAR “Unified Noah LSM”
  - ♦ **Only** sf_surface_physics = 2
  - ♦ For both WRF-NMM and WRF-ARW

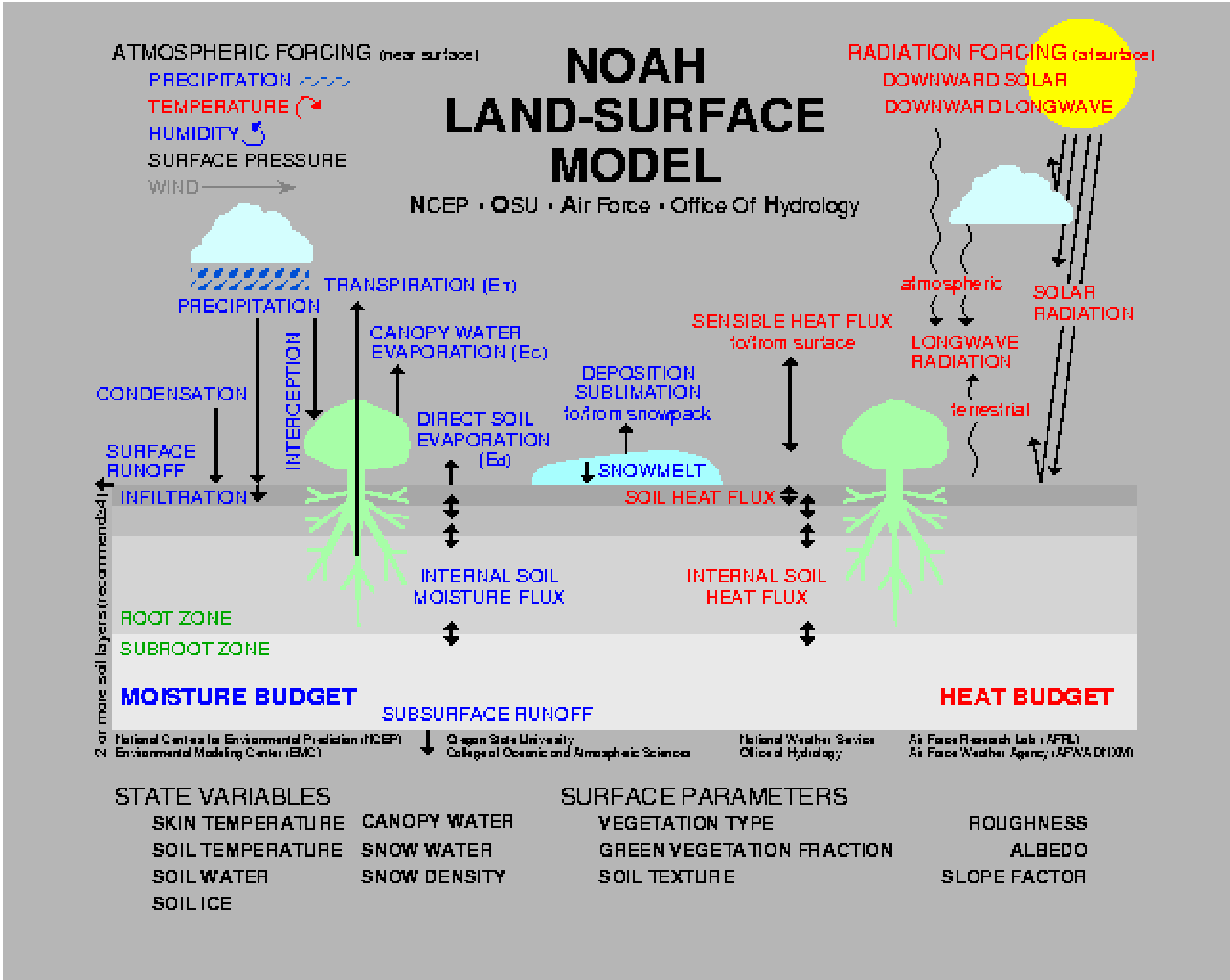
Recommended physics options for WRF-NMM (as used at NCEP)

- sf_sfclay_physics = 2
- sf_surface_physics = 99
  - NCEP Noah LSM (aka NMM-LSM)
- bl_pbl_physics = 2
- cu_physics = 2
- mp_physics = 5
- ra_sw_physics = 99
- ra_lw_physics = 99

Recommended WRF SI options for WRF-NMM (as used at NCEP)

- **Horizontal Interpolations**
  - HINTERP_METHOD 1 (4-point linear)
  - LSM_HINTERP_METHOD 0 (nearest neighbor)

- **Source of initial conditions**
  - USE ETA GRIB for <u>atmospheric initial conditions</u>
    - Unless domain outside N. America, then use GFS
  - USE ETA GRIB for <u>land initial conditions</u>
    - Unless domain outside N. America, then use GFS
      - AFWA global AGRMET also suitable
    - Use NCEP Regional Reanalysis for old cases
      - Use NCEP-NCAR Global Reanalysis only as last resort
- **Source of lateral boundary conditions**
  - USE GFS GRIB for lateral boundary conditions



NOAH LAND-SURFACE MODEL
NCEP • OSU • Air Force • Office Of Hydrology
ATMOSPHERIC FORCING (near surface)
PRECIPITATION
TEMPERATURE
HUMIDITY
SURFACE PRESSURE
WIND
RADIATION FORCING (at surface)
DOWNWARD SOLAR
DOWNWARD LONGWAVE
PRECIPITATION
TRANSPIRATION (Et)
INTERCEPTION
CANOPY WATER EVAPORATION (Ec)
CONDENSATION
SURFACE RUNOFF
INFILTRATION
DIRECT SOIL EVAPORATION (Ed)
DEPOSITION SUBLIMATION to/from snowpack
SNOWMELT
SENSIBLE HEAT FLUX to/from surface
atmospheric
LONGWAVE RADIATION
terrestrial
SOLAR RADIATION
SOIL HEAT FLUX
INTERNAL SOIL MOISTURE FLUX
INTERNAL SOIL HEAT FLUX
ROOT ZONE
SUBROOT ZONE
MOISTURE BUDGET
SUBSURFACE RUNOFF
HEAT BUDGET
2 or more soil layers (recommend≥4)
National Centers for Environmental Prediction (NCEP)
Environmental Modeling Center (EMC)
Oregon State University
College of Oceanic and Atmospheric Sciences
National Weather Service
Office of Hydrology
Air Force Research Lab (AFRL)
Air Force Weather Agency (AFWA DNXM)
STATE VARIABLES
SKIN TEMPERATURE
SOIL TEMPERATURE
SOIL WATER
SOIL ICE
CANOPY WATER
SNOW WATER
SNOW DENSITY
SURFACE PARAMETERS
VEGETATION TYPE
GREEN VEGETATION FRACTION
SOIL TEXTURE
ROUGHNESS
ALBEDO
SLOPE FACTOR

History of the Noah LSM

- **Oregon State University: 1980's**
  - OSU/CAPS LSM (PI L. Mahrt, co-Is H.-L. Pan and M. Ek)
  - Significant funding from Air Force Geophysics Lab (AFGL)
  - Tested in AFGL MM5 and AFGL Global Spectral Model
- **Transitioned to AFWA late 1980's**
  - Implemented operationally in AFWA AGRMET in 1990
- **Transitioned to NCEP NWP models in 1990's**
  - K. Mitchell, F. Chen, M. Ek, H.-L. Pan
  - Renamed "NOAH" LSM <u>after many NCEP and OHD upgrades</u>
    - N (<u>N</u>CEP)
    - O (<u>O</u>regon State University)
    - A (<u>A</u>ir Force)
    - H (<u>H</u>ydrological Development Office of National Weather Service)
  - Renamed "Noah" LSM after many additional key collaborators
    - NCAR, NASA
- **Transitioned to NCAR in late 1990's**
  - F. Chen: MM5
- **Transitioned to WRF**: NCAR, NCEP, AFWA, NRL

Noah LSM Upgrades via NCEP

- **<u>cold season processes</u>**(*Koren et al 1999*)
  - -- patchy snow cover (snow sublimation)
  - -- frozen soil (new state variable)
  - -- snow density (new state variable)

- **<u>bare soil evaporation refinements</u>**
  - -- parameterize upper sfc crust cap on evap

- **<u>soil heat flux</u>**
  - -- new soil thermal conductivity (*Peters-Lidard et al 1998*)
  - -- refinements under snowpack
  - -- refinements under vegetation (*Peters-Lidard et al 1997*)

- **<u>surface characterization</u>**
  - -- revised snow albedo algorithm

- **<u>vegetation</u>**
  - -- deeper rooting depth in forests
  - -- canopy resistance refinements

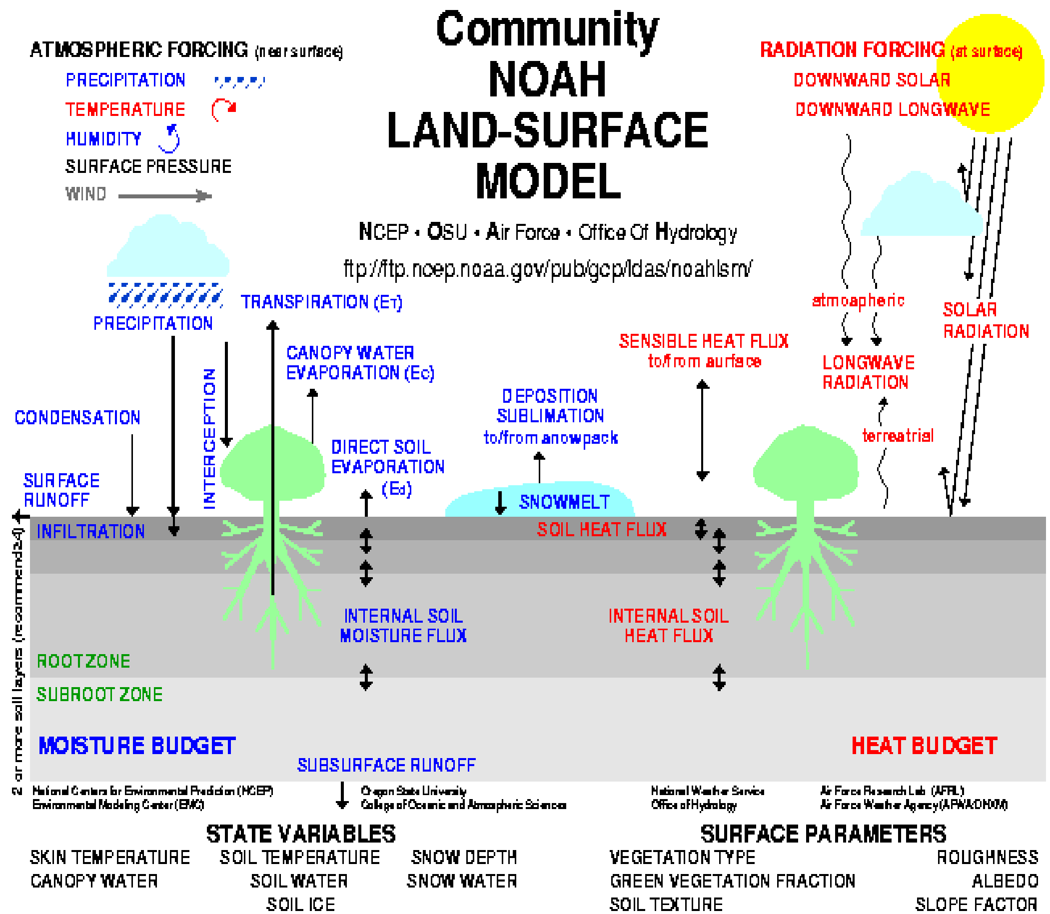


Figure 1. Schematic of the NCEP community NOAH land-surface model of multi-layer soil, vegetation, and snowpack.

NOAH LSM tested in various land-model intercomparison projects, e.g., GSWP 1 & 2, PILPS 2a, 2c, 2d, 2e, Rhone, DMIP, GLACE.

Noah LSM Upgrades at NCAR

- **Allow for surface emissivity of less than 1**
  - Land-use type dependent

- **Modify surface roughness length over snow**
  - decrease for increasing snow depth

- **Add treatment for urban landuse class**

- **High resolution land-use and soil type maps**
  - global 1-km USGS land-use map (30 sec)
    - 24 classes
    - NCAR added 3 more classes (27 total)
  - global 1-km STATSGO/FAO soil type map (30 sec)
    - 16 classes

Key References for Noah LSM

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

Noah Implementations at NCEP

- Eta mesoscale model: Jan 1996
- EDAS: Eta Data Assimilation System: Jun 1998
  - fully continuous cycling
- NCEP 25-year Regional Reanalysis: Apr 2004
  - EDAS based
  - Daily realtime extension now operational
- Global Forecast System: 31 May 2005
- Global Data Assimilation System: 31 May 2005

- **Associated Uncoupled Testing of Noah LSM at NCEP**
  - **1D site-specific testing: e.g. for various PILPS phases (2a, 2d, 2g)**
  - **3D regional testing:**
    - **NLDAS**
    - **for PILPS-3C, PILPS-2e, PILPS-Rhone**
  - **3D global testing:**
    - **GLDAS/LIS (with NASA/GSFC/HSB)**
    - **GSWP 1 (1-year) and 2 (10-years)**

Noah LSM implementations at NCAR

- **In MM5**
  - ~ year 2000
- **In WRF-ARW**
  - ~ year 2003

Noah LSM Physics

- <u>Four soil layers</u> (10, 30, 60, 100 cm thick)
- <u>Prognostic Land States</u>
  - Surface skin temperature
  - Total soil moisture each layer (volumetric)
    - total of liquid and frozen
    - bounded by saturation value (soil type dependent)
  - Liquid soil moisture each layer (volumetric)
    - can be supercooled
  - Soil temperature each layer
  - Canopy water content
    - dew/frost, intercepted precipitation
  - Snowpack water equivalent (SWE) content
  - Snowpack depth (physical snow depth)
- <u>Above prognostic states require initial conditions</u>
  - Provided by WRF SI and REAL

Noah LSM physics

- **An LSM must provide 4 quantities to parent atmospheric model**
  - surface sensible heat flux
  - surface latent heat flux
  - upward longwave radiation
    - Alternatively: <u>skin temperature</u> and sfc emissivity
  - upward (reflected) shortwave radiation
    - Alternatively: <u>surface albedo</u>, including snow effect

Attributes of Noah Land-Surface Physics

- 4 soil layers (10, 30, 60, 100 cm thick)
  - predict soil moisture/temperature
- Explicit vegetation physics
  - 27 vegetation classes over Eta domain
  - annual cycle of fraction of green vegetation cover
- Explicit snowpack physics
  - prognostic treatment of snowpack
- Explicit frozen soil physics:
  - frozen ground (soil ice) treatment
  - Latent heat sink/source (freeze/thaw)
  - Reduces infiltration of precipitation
  - Reduces vertical movement of soil water, including uptake by roots

Noah LSM Physics:
Surface energy balance:

Rnet = SH + LH + GH + SPGH

Rnet = Net radiation (downward/upward longwave/shortwave)

SH = sensible heat flux

LH = latent heat flux (surface evaporation)

GH = ground heat flux (subsurface heat flux)

SPGH = snow phase-change heat flux (heat sink of melting snow

Noah LSM Physics: Land Surface Water Balance (Exp: monthly, summer, central U.S.)

$$dS = P - R - E$$

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 <u>vegetation</u> type, rooting depth/density, fractional cover, greenness.

All terms in units of mm.

Noah LSM Physics: Soil Prognostic Equations

- Soil Moisture:
  - "Richard's Equation" for soil water movement
  - D, K functions (soil texture)
  - F_θ represents sources (rainfall) and sinks (evaporation)
- Soil Temperature
  - C, Kt functions (soil texture, soil moisture)
  - Soil temperature information used to compute ground heat flux

Noah LSM Physics: Surface Evaporation

$$\mathbf{E = Edir + Et + Ec + Esnow}$$

WHERE:

E = total surface evaporation from combined soil/vegetation

E_{dir} = direct evaporation from soil

E_t = transpiration through plant canopy

E_c = evaporation from canopy-intercepted rainfall

E_{snow} = sublimation from snowpack

Noah LSM Physics: Et = transpiration

- Et represent a flux of moisture from the vegetation canopy via root uptake, that can be parameterized in terms of “resistances” to the “potential” flux.

FLUX = POTENTIAL/RESISTANCE

- Potential ET can roughly be thought of as the rate of ET from an open pan of water. In the soil/vegetation medium, what are some resistances to this?
  - Available amount of soil moisture
  - Canopy (stomatal) resistance: function of vegetation type and amount of green vegetation

Noah LSM Physics: Canopy Resistance

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

$$E_t/E_{dir} \approx f(\sigma_f)$$

  - Green vegetation in Eta based on 5 year NDVI climatology of monthly values
  - Not only the amount, but the TYPE of vegetation determines canopy resistance (R_c):

Canopy Resistance (continued)

- Where:

Rcmin ≈ f(vegetation type)

F1 ≈ f(amount of PAR:solar insolation)

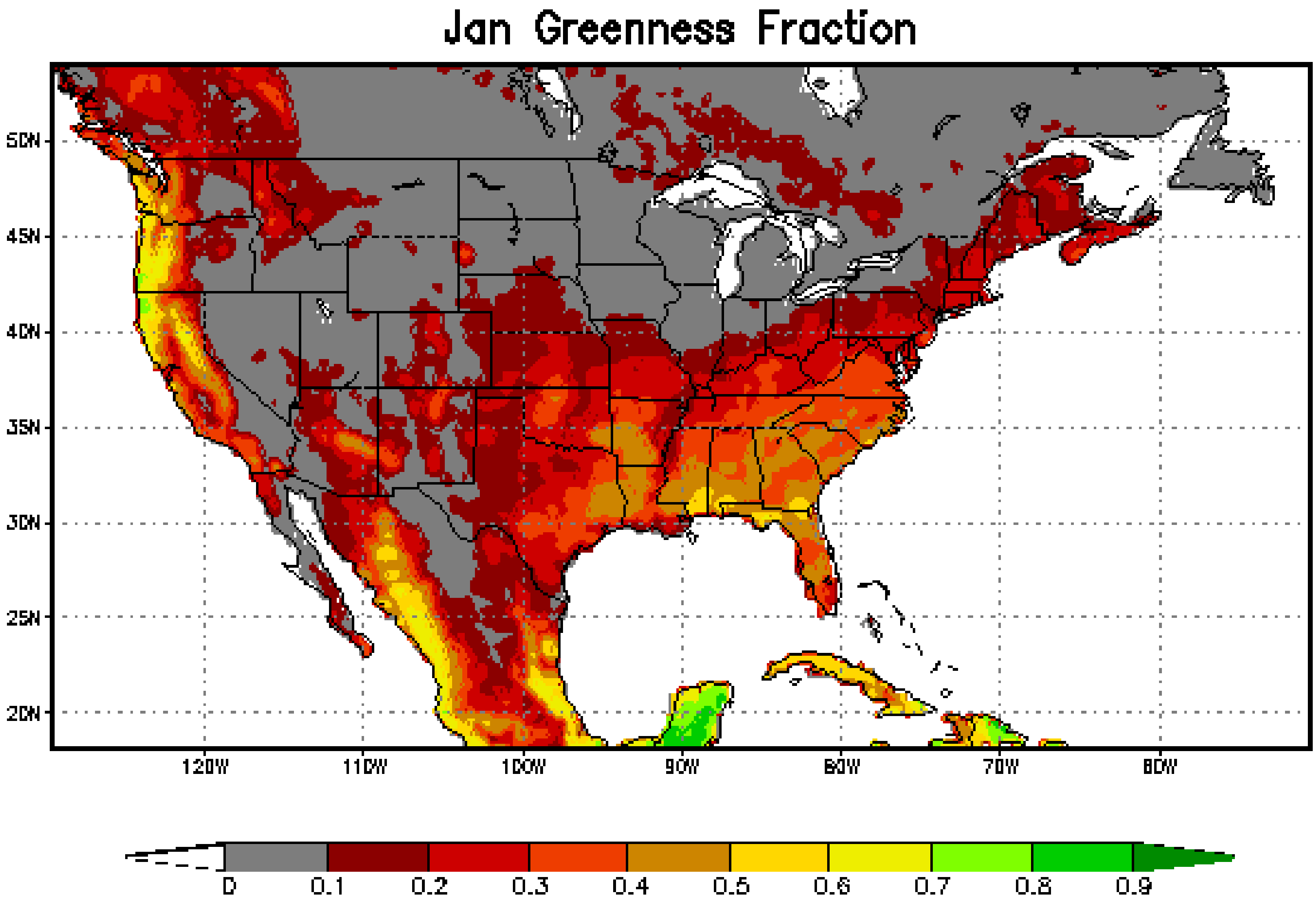
F2 ≈ f(air temperature: heat stress)

F3 ≈ f(air humidity: dry air stress)

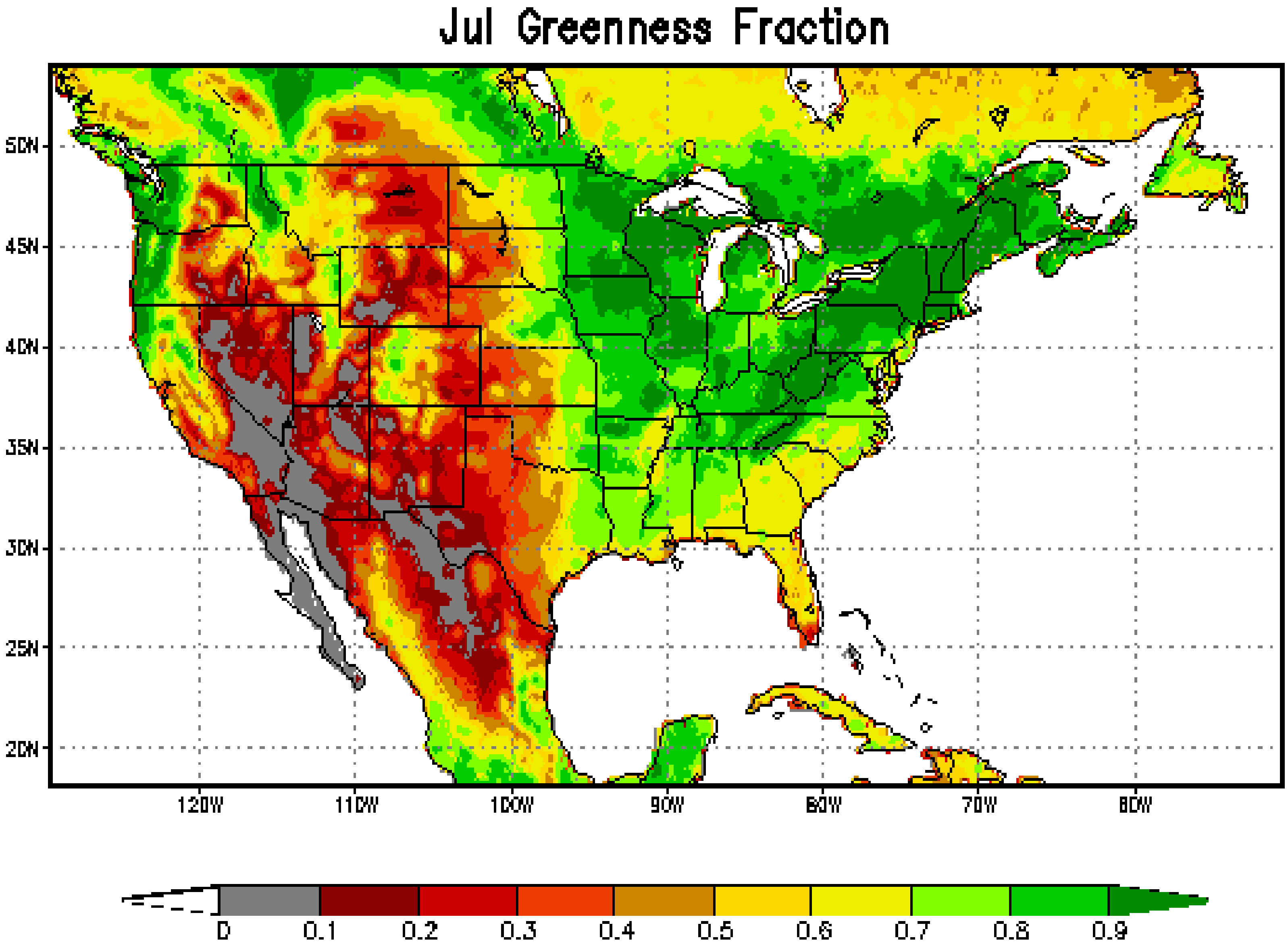
F4 ≈ f(soil moisture: dry soil stress)

- Thus: hot air, dry air, dry soil lead to stressed vegetation and reduced transpiration

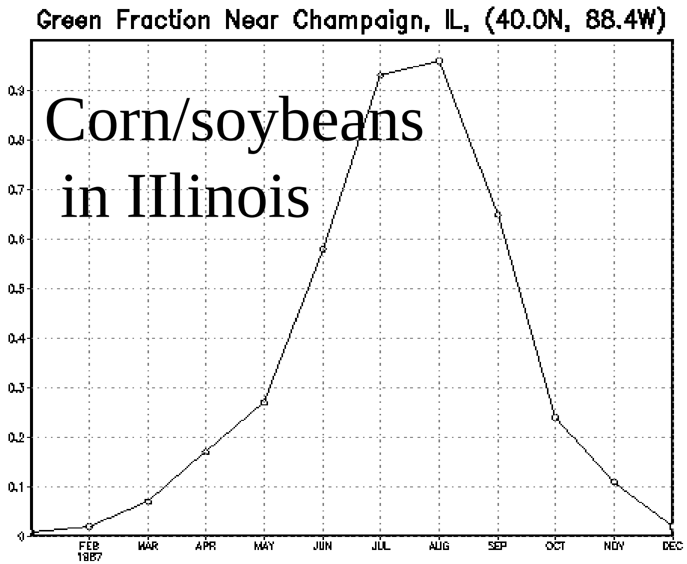
January Green Vegetation Fraction in Noah LSM

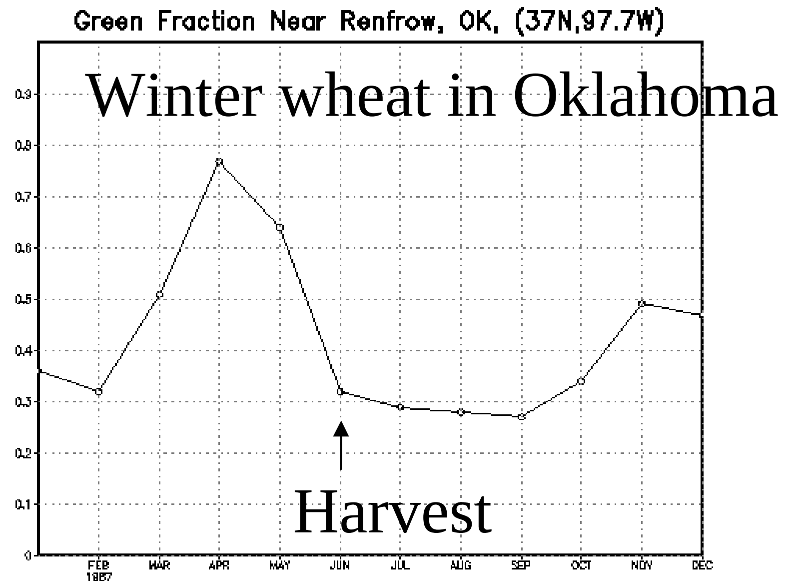


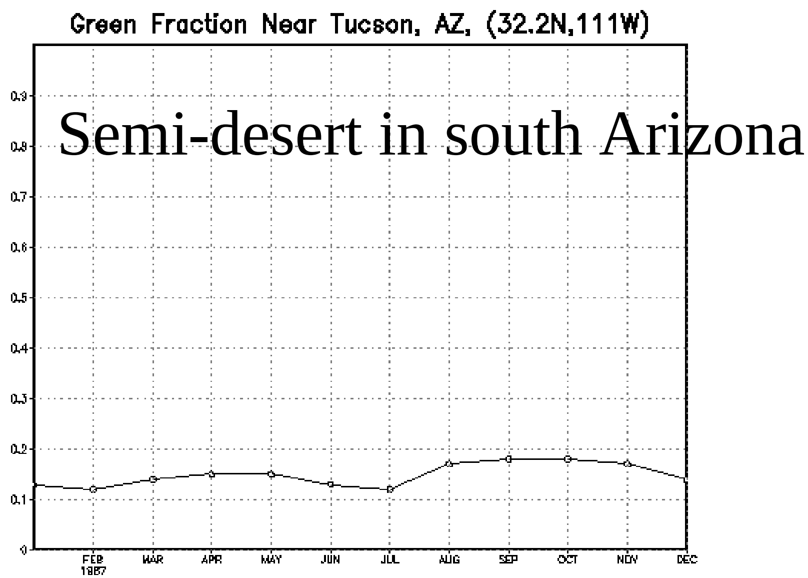
July Green Vegetation Fraction in Noah LSM

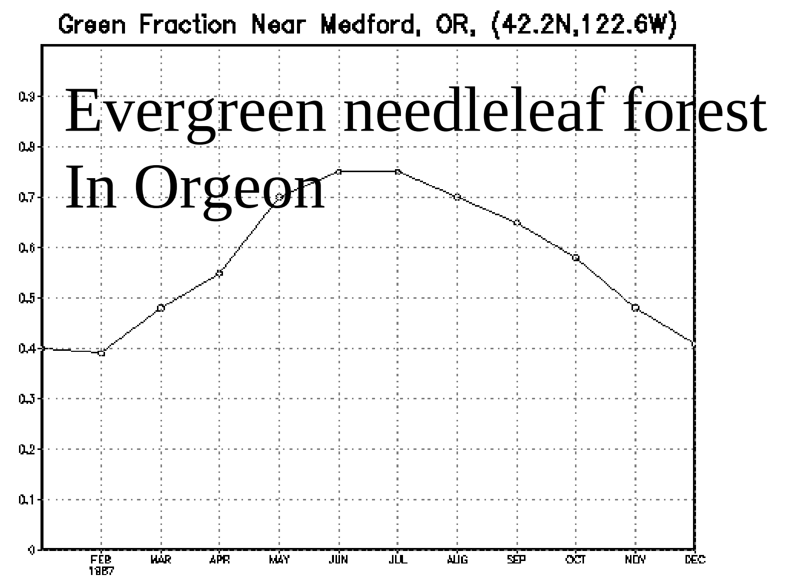


Example Annual Time Series of Green Vegetation Fraction in No



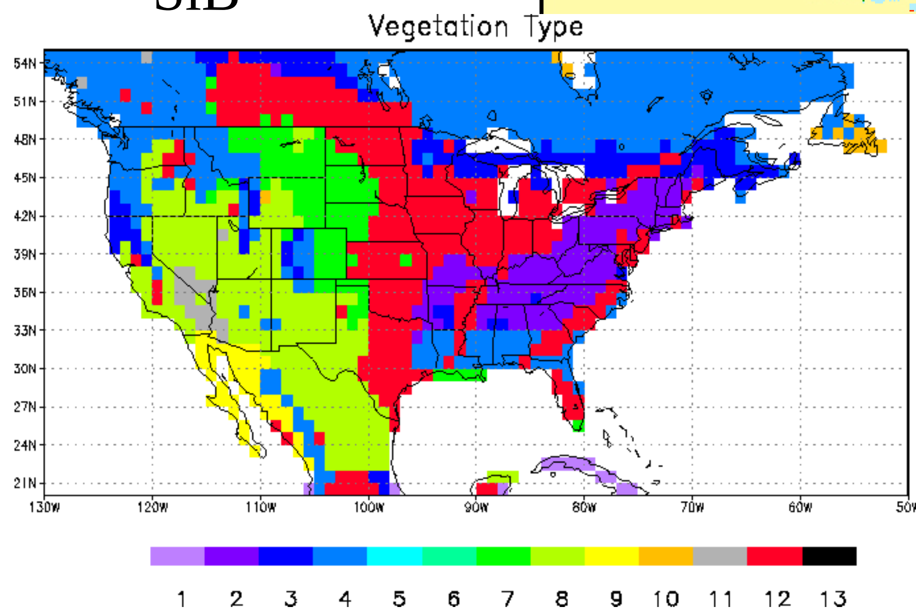


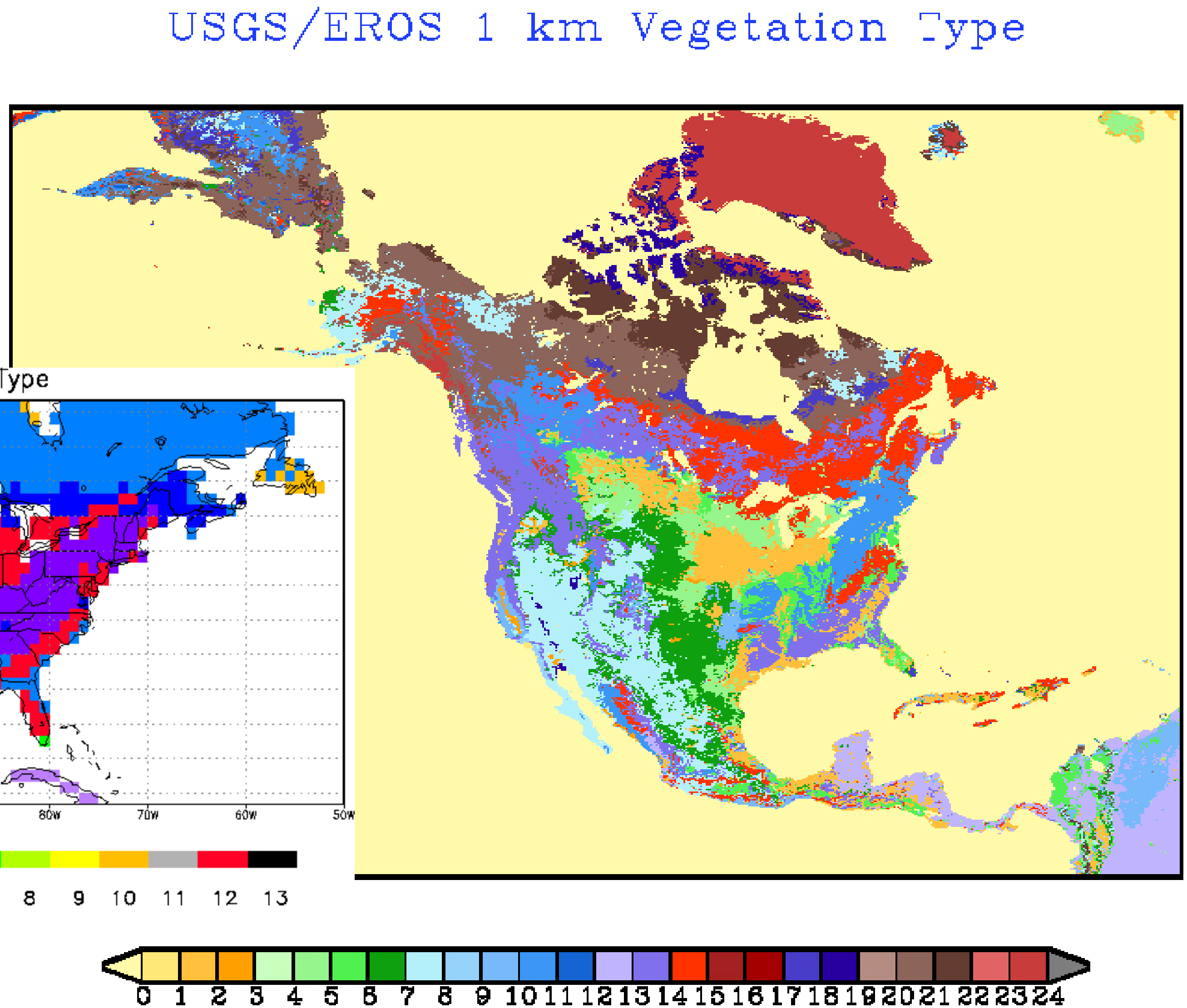




New USGS 24-class high-resolution (1-km) vegetation data set replaces old SiB 13-class 1-degree data set

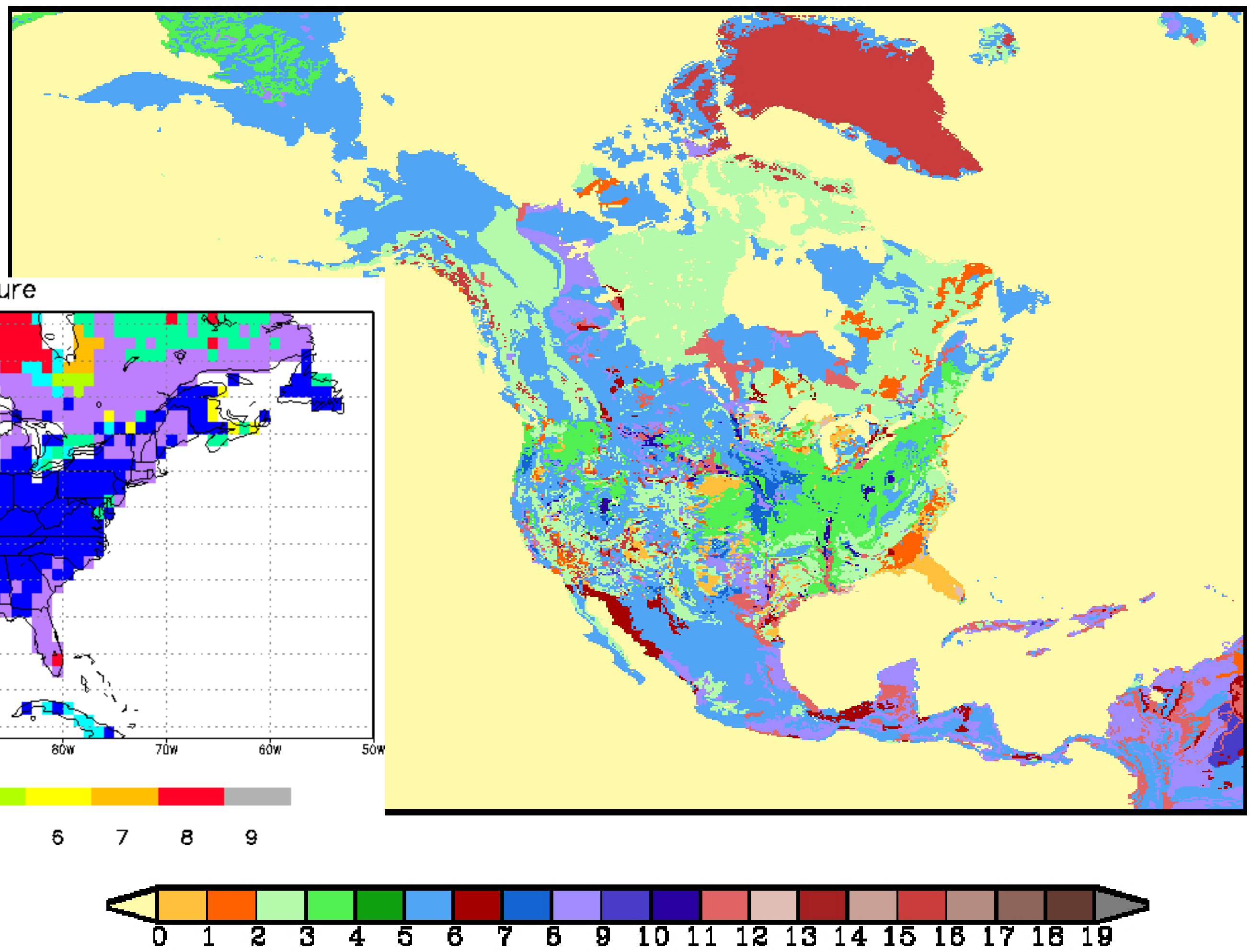
SiB



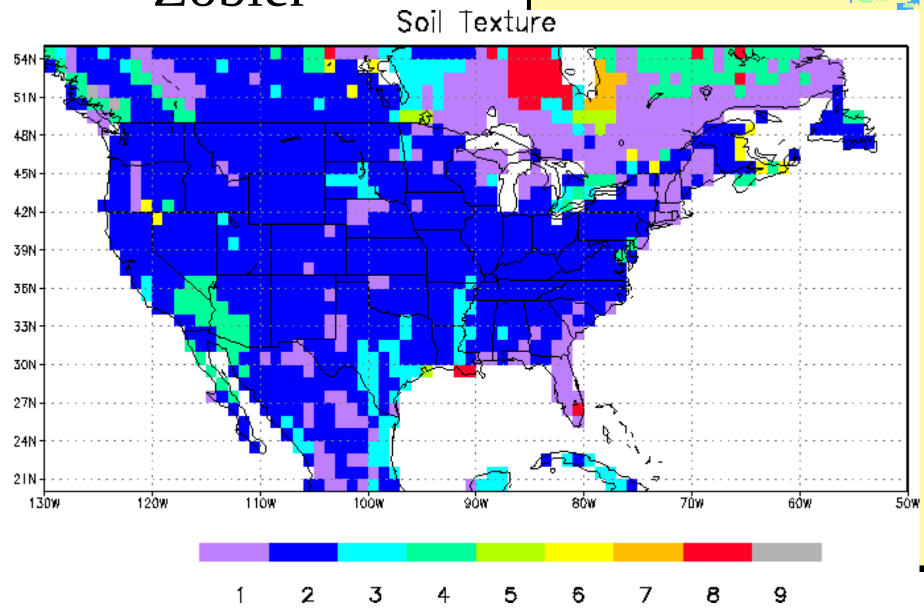


New STATSGO 16-class high-resolution (1-km) soils data base replaces old Zobler 9-class 1-degree data set

FAO/STATSCO Soil Type



Zobler

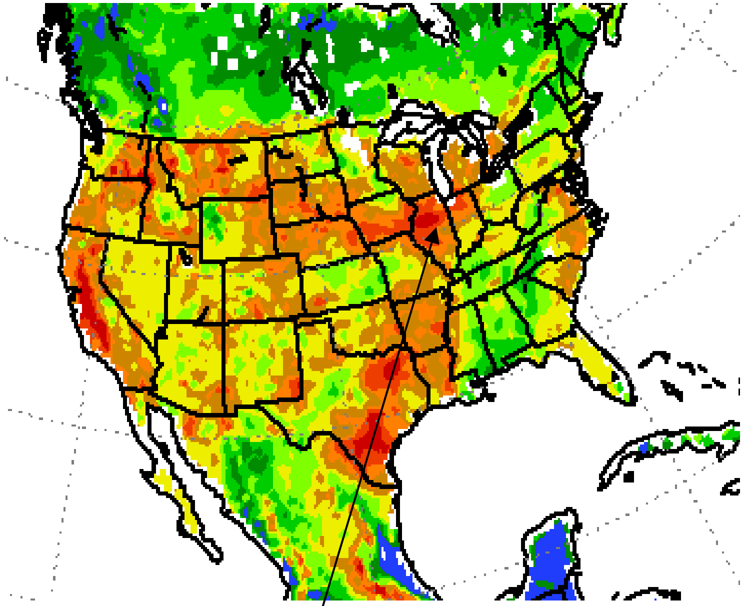


Example of Noah LSM performance in NCEP ops Eta/Noah (NAM)

Ops Eta/Noah (NAM) Soil Moisture

0–100cm MOIST AVAIL NAM 00H FCST

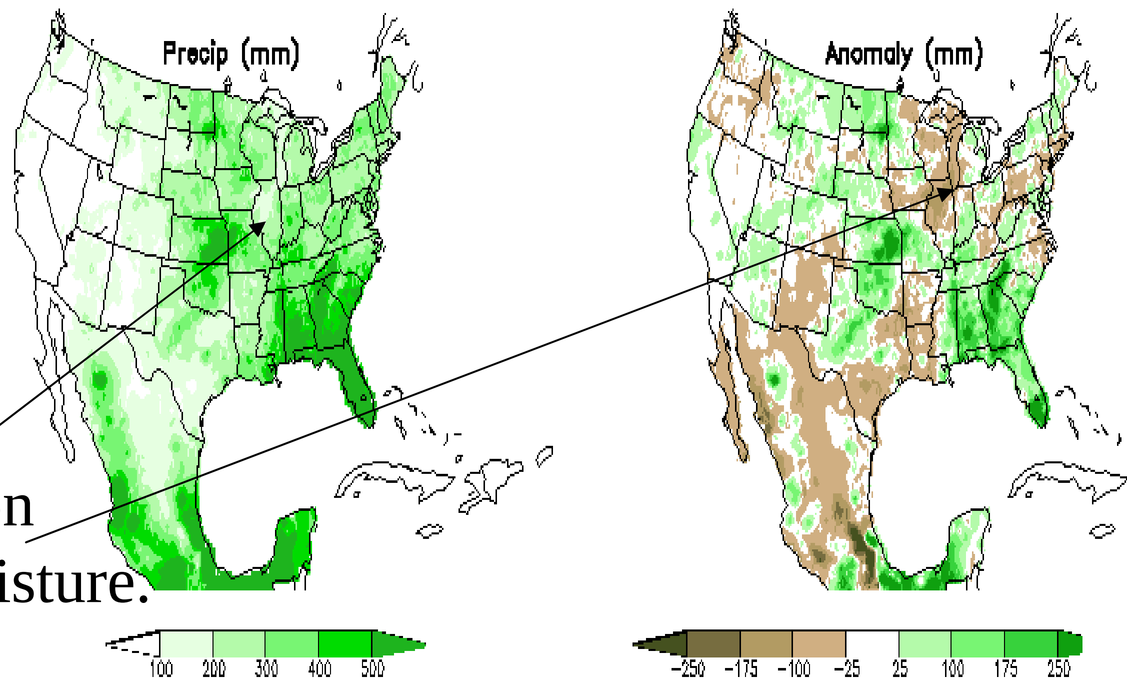
VALID 12Z 06 SEP 2005



Soil moisture availability: Fraction of soil saturation in top 1-meter of soil column (soil layers 1-3)

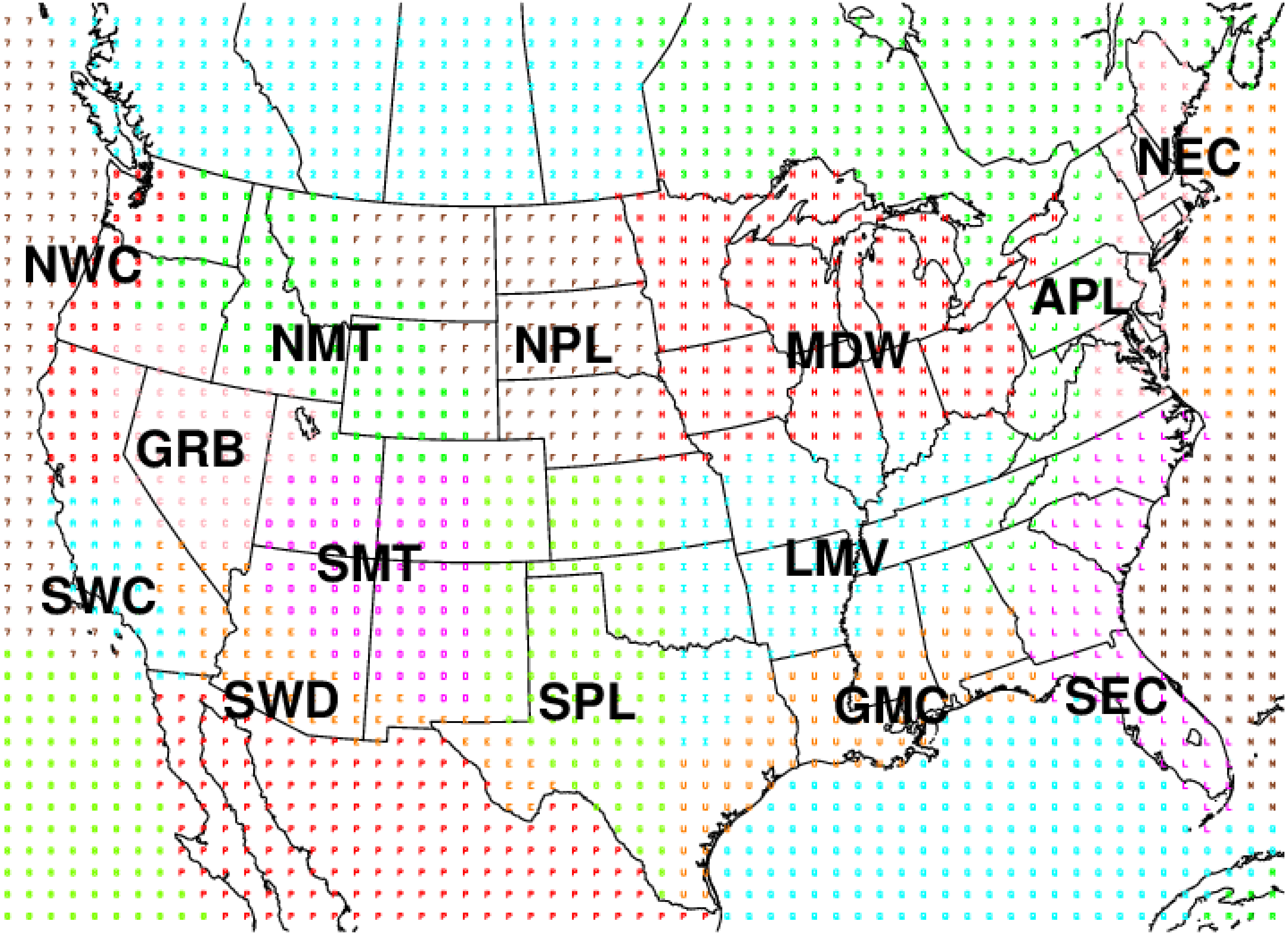
Precipitation Analysis

90–day accumulation ending 20050831



Note: Midwest is one region of anomalously dry soil moisture.

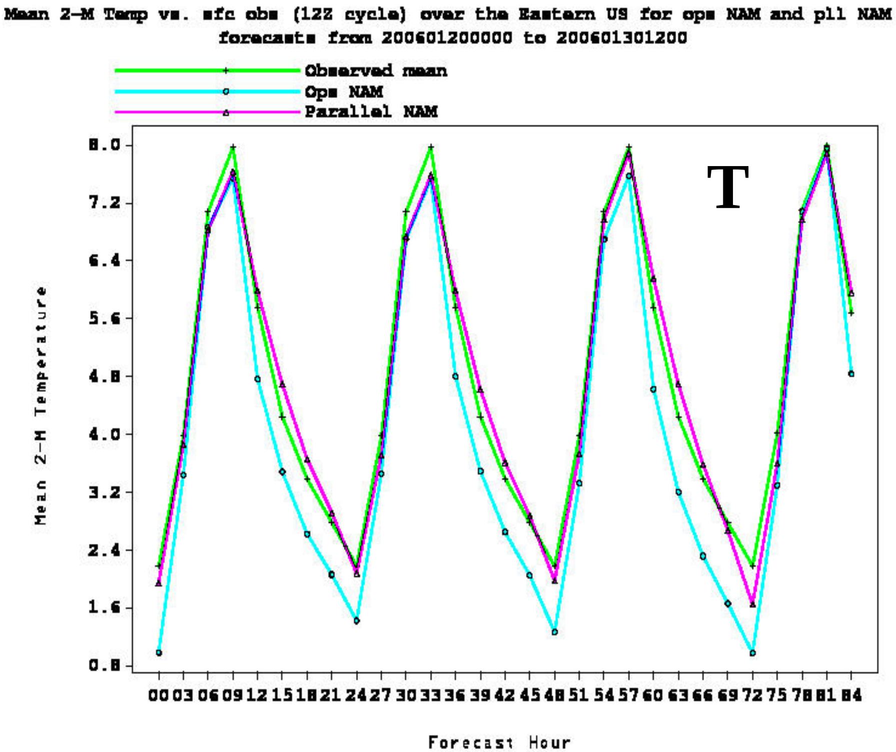
Routine NCEP verication regions for ops Eta/Noah NAM and para WRF-NMM/Noah

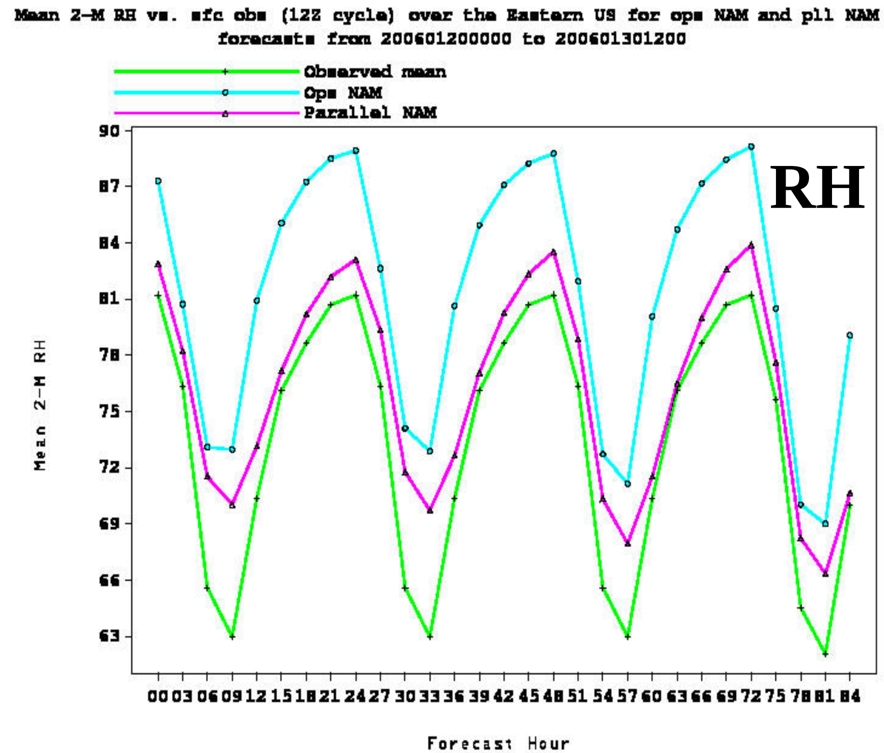


Verification of 2-meter air temperature and relative humidity in NCEP ops Eta/Noah (NAM) and realtime parallel WRF-NMM/Noah 84-hour forecasts from 12Z

EASTERN US: 20-30 JANUARY 2006

Yellow line: from station obs, Light blue line: from ops Eta/Noah (NAM) Dark blue line: from parallel WRF-NMM/Noah (NAMX)

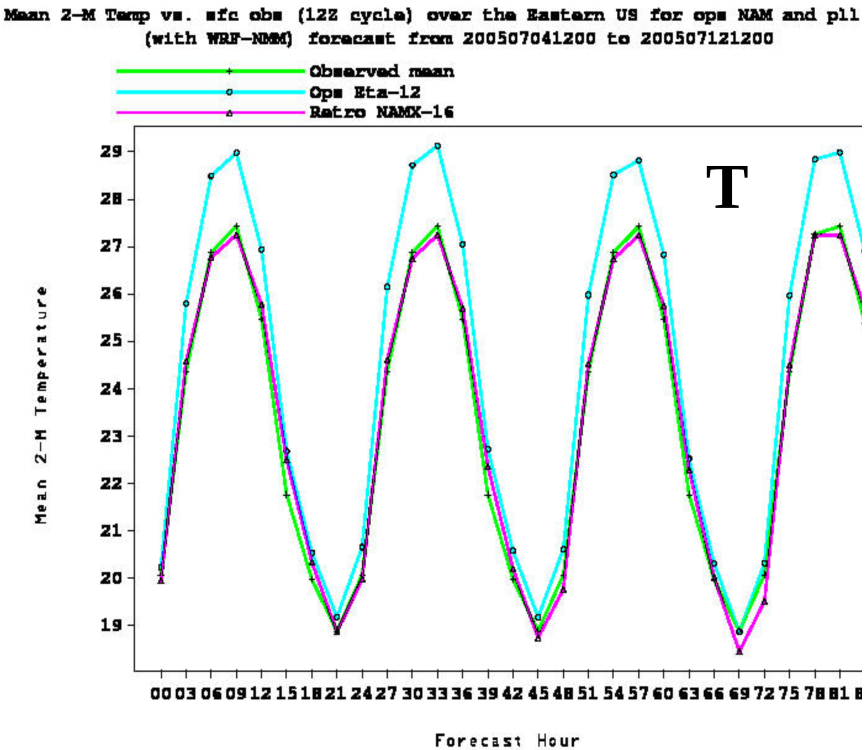


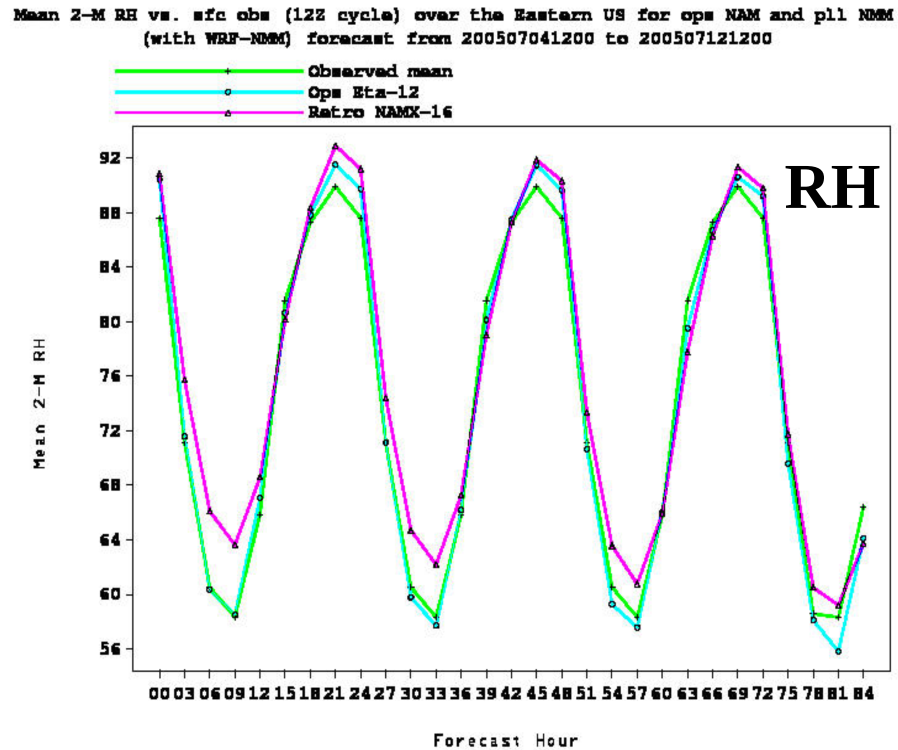


Verification of 2-meter air temperature and relative humidity in NCEP ops Eta/Noah (NAM) and retrospective WRF-NMM/Noah 84-hour forecasts from 12Z

EASTERN US: 04-12 JULY 2005

Yellow line: from station obs, Light blue line: from ops Eta/Noah (NAM) Dark blue line: from retrospective WRF-NMM/Noah (NAMX)





Radiation Physics used by NCEP in WRF-NMM

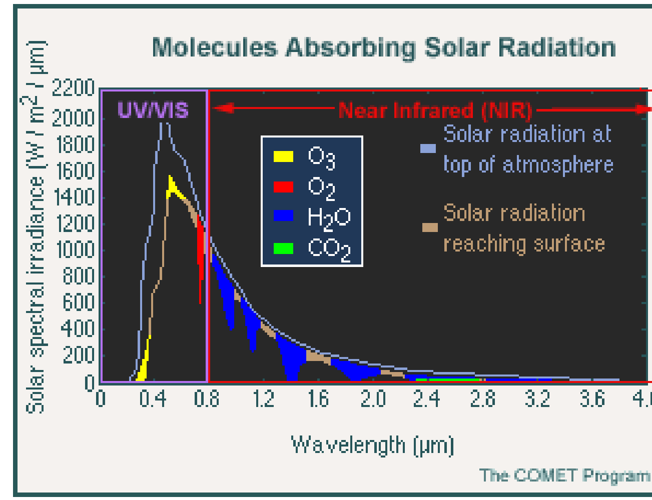
Material provided by B. Ferrier

ra_sw_physics = 99   (from GFDL)

ra_lw_physics = 99   (from GFDL)

Shortwave Radiation (clear sky)

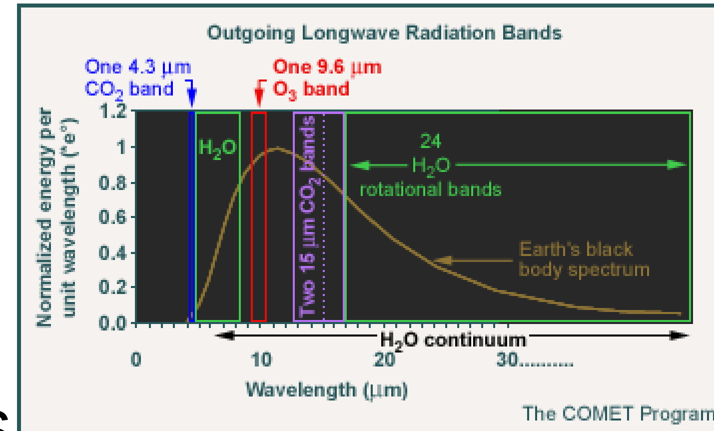
- Lacis-Hansen (1974) - atmospheric scattering, reflection, absorption over UV/visible and near infrared (NIR extends out to 10 μm)



- Reflection & scattering done separately for UV/vis and NIR
- Done layer by layer
- Clear-sky absorbers
  - Zonally averaged observed ozone (O_3) for four seasons, interpolated with time (season) & latitude
  - 330 ppm carbon dioxide (CO_2) at all layers
  - Water vapor mixing ratios (predicted)
- More information at this COMET page
  - http://meted.ucar.edu/nwp/pcu2/etarad3.htm

Longwave Radiation (clear sky)

- Fels and Schwarzkopf at GFDL ('75, '85, '91)
  - O_3 at 9.6 µm (9.35-10.10 µm)
  - CO_2 at 15 µm (12.5-14.93 µm & 14.93-17.86 µm)
  - CO_2 at 4.3 µm (4.2-4.4 µm) as source of emitted radiation only; absorption is not calculated
  - H_2O at 6.3 µm (100 sub-bands from 4.55-8.33 µm)
  - H_2O "rotational " bands at >12 µm
  - Weak continuous H_2O absorption in the 8-12 µm range (8.33-9.35 µm, 9.35-10.10 µm, & 10.10-12.5 µm)



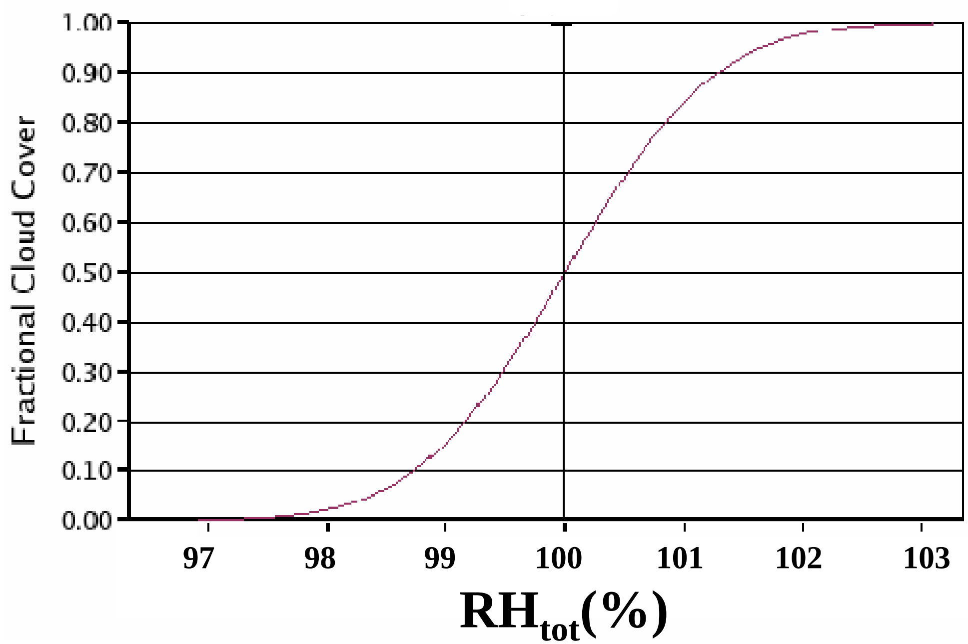
Cloud inputs to radiation (1 of 2)

- Stratiform clouds
  - Cloud optical depths functions of cloud water (q_w) and ice mixing (q_i) ratios (cloud ice & “snow”; ignores effects from rain)
  - Crude partial cloudiness scheme
    - o RH_{tot} is assumed to be Gaussian distributed

$RH_{tot}=(q_v + q_w + q_i)/q_{vs}$,

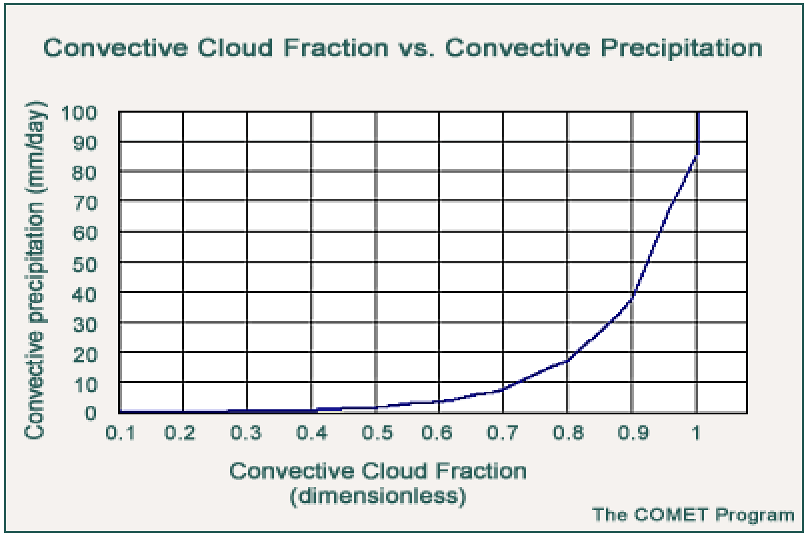
where q’s are mixing ratios:

q_v = water vapor,
q_w = cloud water,
q_i = ice,
q_{vs} = saturation vapor



Cloud inputs to radiation (2 of 2)

- Convective clouds
  - Cloud fractions vary w/ hourly convective precip rates (Slingo, 1987)
  - Cloud fraction assumed to be 10% for shallow (nonprecipitating) convection.



  - Cloud optical depths for convective clouds assume a cloud mixing ratio of 0.1 g kg^{-1} for water or ice, but applied only when convective cloud fraction exceeds that for grid-scale clouds within a grid box
- Random overlap for separate cloud layers, maximum overlap for adjacent cloud layers

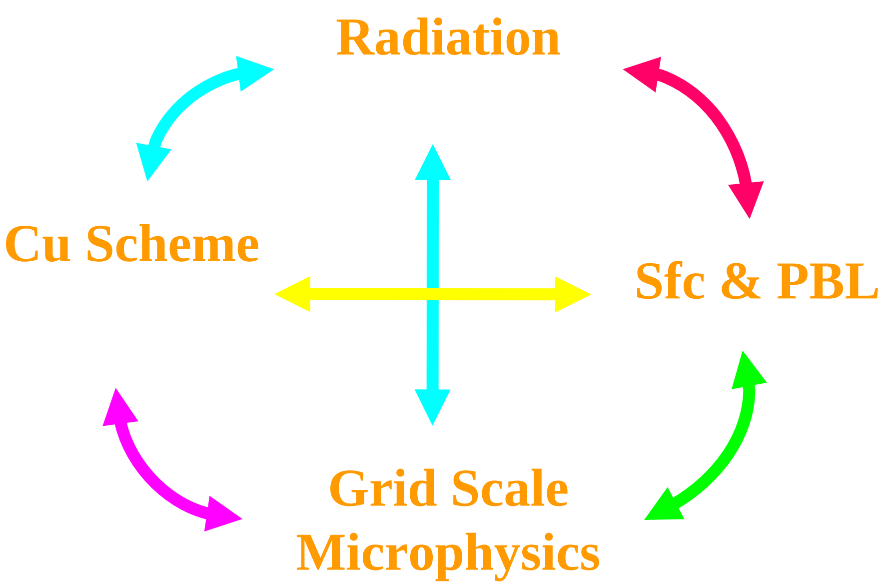
Cloud-Radiation Challenges

- Sensitivities to:
  - Cloud optical properties (cloud fractions, cloud & ice water paths, effective radius of water & ice, single scattering albedos for water, overlap assumptions)
  - Cloud microphysics (glaciation temperature, ice nucleation rates, autoconversion cloud to rain, etc.)
  - Aerosol effects
  - Surface albedos (including diurnal variations of direct beam component)
  - Treatment of parameterized convection
  - Model domain top – how much of ozone layer is missing?

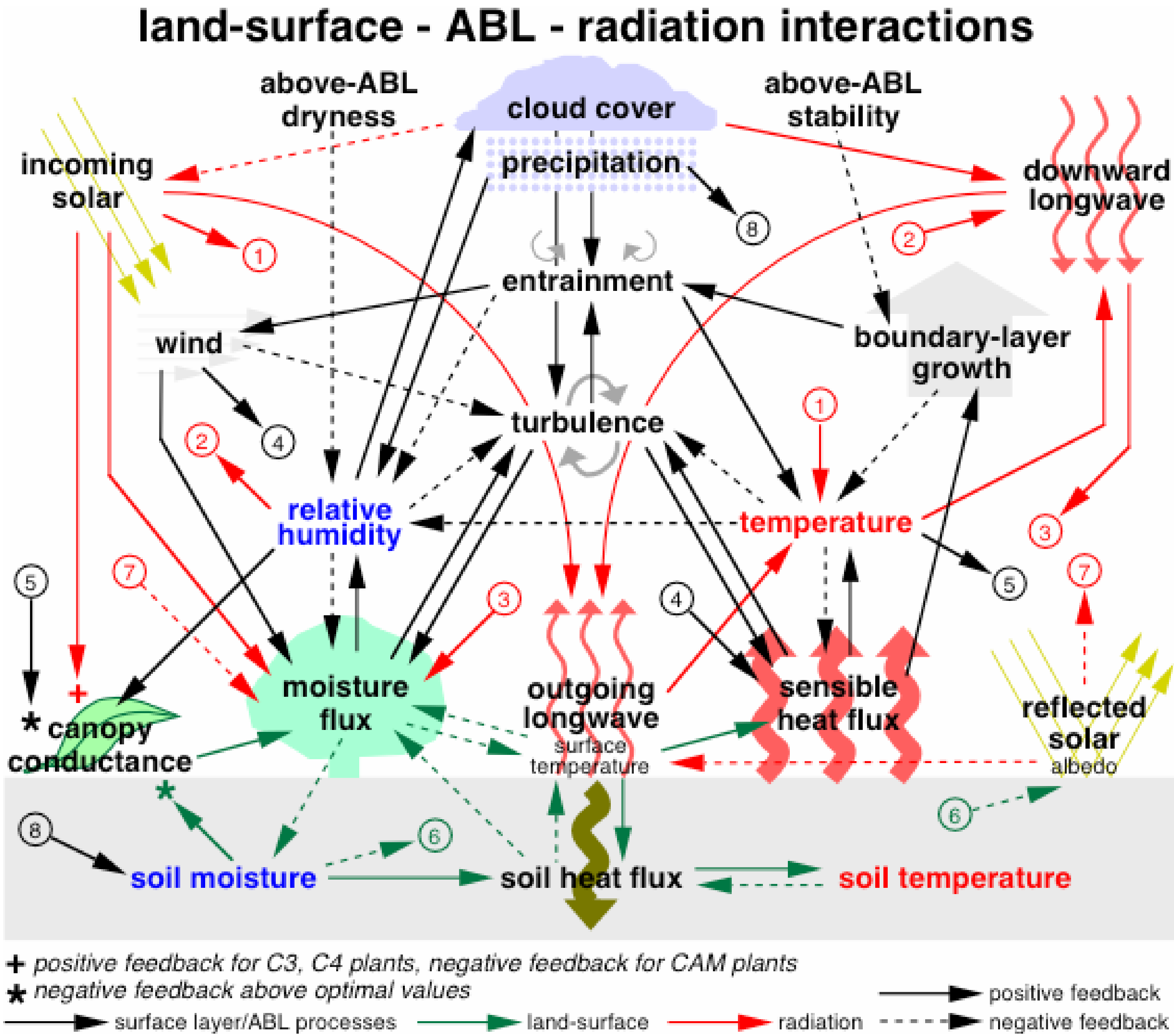
Contact Brad Ferrier for more information

“THE PHYSICS WHEEL OF PAIN”

Direct Physical Interaction of Clouds



1. **Hydrometeor phase, cloud optical properties, cloud overlap assumptions, & cloud fractions**
2. **Precipitation (incl. phase) and clouds**
3. **Subgrid transports, stabilization, detrainment**
4. **Sfc energy fluxes, land & ocean surface models**
5. **Convection (deep & shallow), PBL evolution, precipitation**


land-surface - ABL - radiation interactions
above-ABL dryness
cloud cover
above-ABL stability
incoming solar
precipitation
downward longwave
entrainment
wind
boundary-layer growth
turbulence
relative humidity
temperature
moisture flux
outgoing longwave
surface temperature
sensible heat flux
reflected solar
albedo
canopy conductance
soil moisture
soil heat flux
soil temperature
+ positive feedback for C3, C4 plants, negative feedback for CAM plants
* negative feedback above optimal values
surface layer/ABL processes
land-surface
radiation
positive feedback
negative feedback