Land Surface in Weather and Climate Models "WorkEta 2016"

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NOAA Center for Weather and Climate Prediction *(NCWCP), College Park, Maryland, USA*

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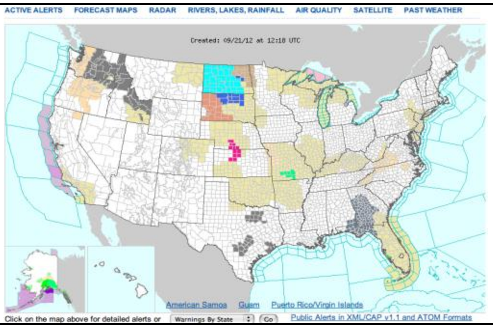

National Weather Service

National Centers for Environmental Prediction

The Office of the Director at the National Centers for Environmental Prediction gives overarching management to the nine centers, which include the:

Aviation Weather Center provides aviation warnings and forecasts of hazardous flight conditions at all levels within domestic and international air space.

Climate Prediction Center monitors and forecasts short-term climate fluctuations and provides information on the effects climate patterns can have on the nation.

Environmental Modeling Center develops and improves numerical weather, climate, hydrological and ocean prediction through a broad program in partnership with the research community.

Hydrometeorological Prediction Center provides nationwide analysis and forecast guidance products out through seven days.

NCEP Central Operations sustains and executes the operational suite of numerical analyses and forecast models and prepares NCEP products for dissemination.

National Hurricane Center provides forecasts of the movement and strength of tropical weather systems and issues watches and warnings for the U.S. and surrounding areas.

Ocean Prediction Center issues weather warnings and forecasts out to five days for the Atlantic and Pacific Oceans north of 30 degrees North.

Space Weather Prediction Center provides space weather alerts and warnings for disturbances that can affect people and equipment working in space and on earth.

St... provide... weather watches for the contiguous United States along with ... weather forecasts.

www.ncep.noaa.gov

NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION NCEP

Environmental Modeling Center

Development, upgrade, transition, maintain models

www.emc.ncep.noaa.gov

World Meteorological Organization
Working together in weather, climate and water

www.wmo.int

World Weather Research Programme

"www.wmo.int "WWRP"

WWRP World Weather Research Programme

"...improve accuracy, lead time and utilization of weather prediction."

WCRP World Climate Research Programme

World Climate Research Programme

www.wcrp-climate.org

WMO IOC ICSU

"Determine the predictability of climate and effect of human activities on climate."

GEWEX

Global Energy and Water Cycle Exchanges Project

"Weather, Water, Climate"

www.gewex.org

Outline

- Role of Land Surface Models (LSMs)
- Model requirements: physics & parameters, atmospheric forcing, land data sets, initial land states
- Land Data Assimilation
- Applications for Weather & Climate
- Testing and Validation
- Improving LSMs and the Expanding role of Land Modeling as part of an integrated Earth System
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- Partners
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Role of Land Models

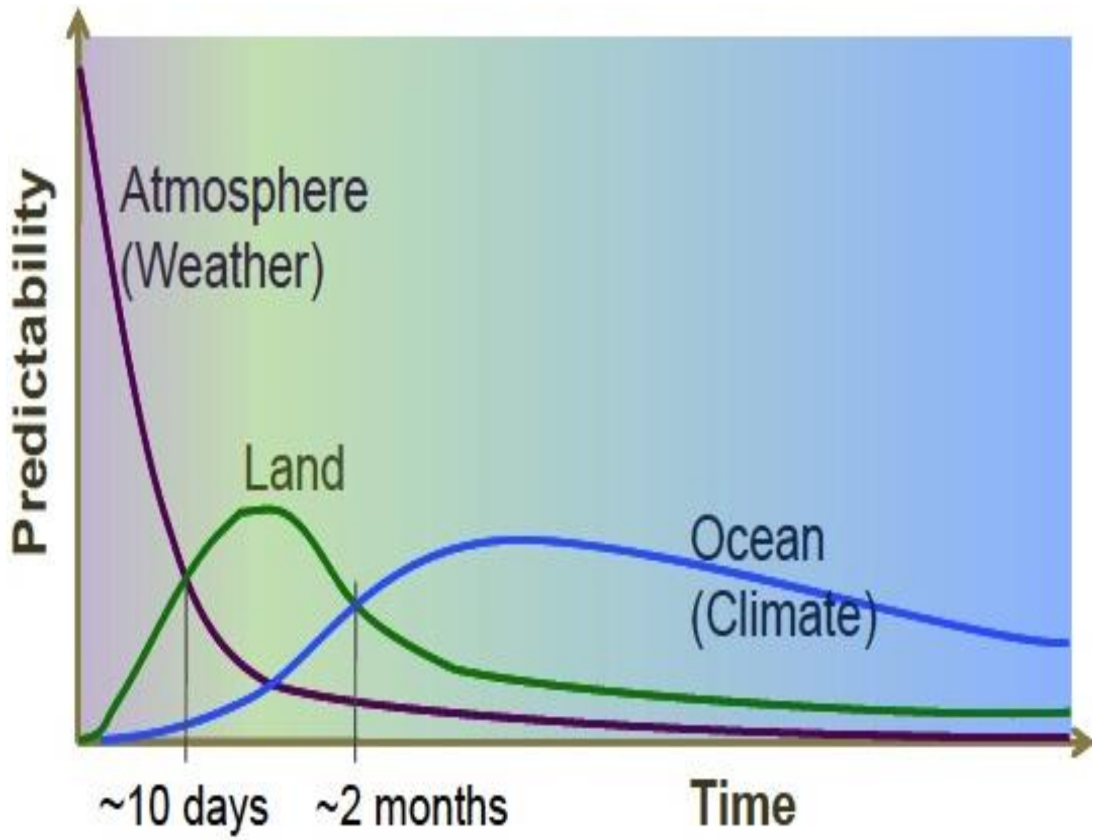
- Traditionally, from a *coupled (atmosphere-ocean-land-ice)* **Numerical Weather Prediction (NWP) and climate modeling perspective**, a land-surface model provides quantities as boundary conditions:
  - Surface **sensible heat flux**,
  - Surface **latent heat flux** (evapotranspiration)
  - Upward **longwave radiation** (or skin temperature and surface emissivity),
  - Upward (**reflected**) **shortwave radiation** (or surface albedo, including snow effects),
  - Surface **momentum exchange**.

Predictability and Prediction

- Land states (namely soil moisture*) can provide predictability in the window between deterministic (weather) and climate (O-A) time scales.

- To have an effect, must have:

1. Memory of initial land states.
2. Sensitivity of fluxes to land states, atmosphere to fluxes.
3. Sufficient variability

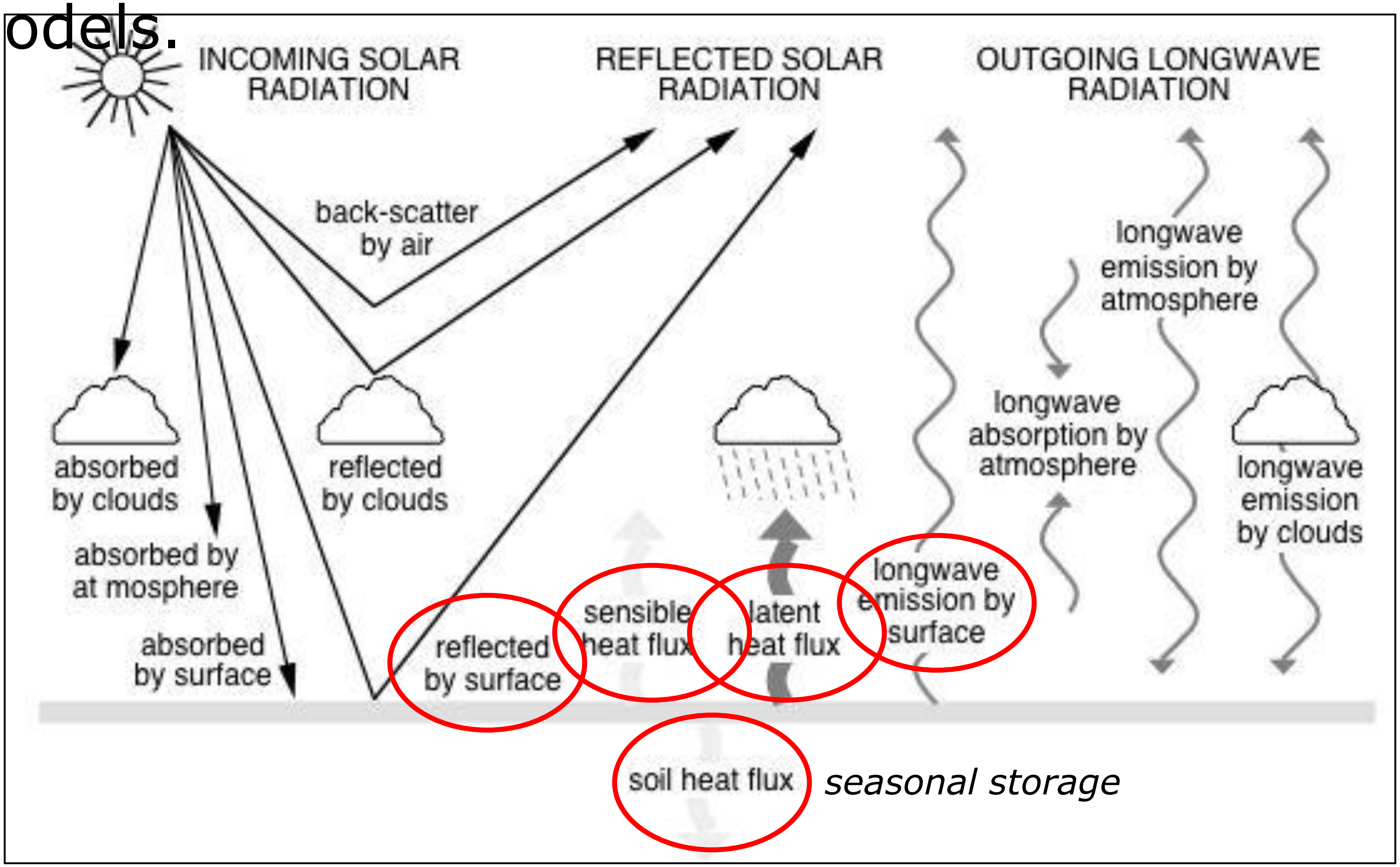


*Snow, too!

Paul Dirmeyer, George Mason Univ.

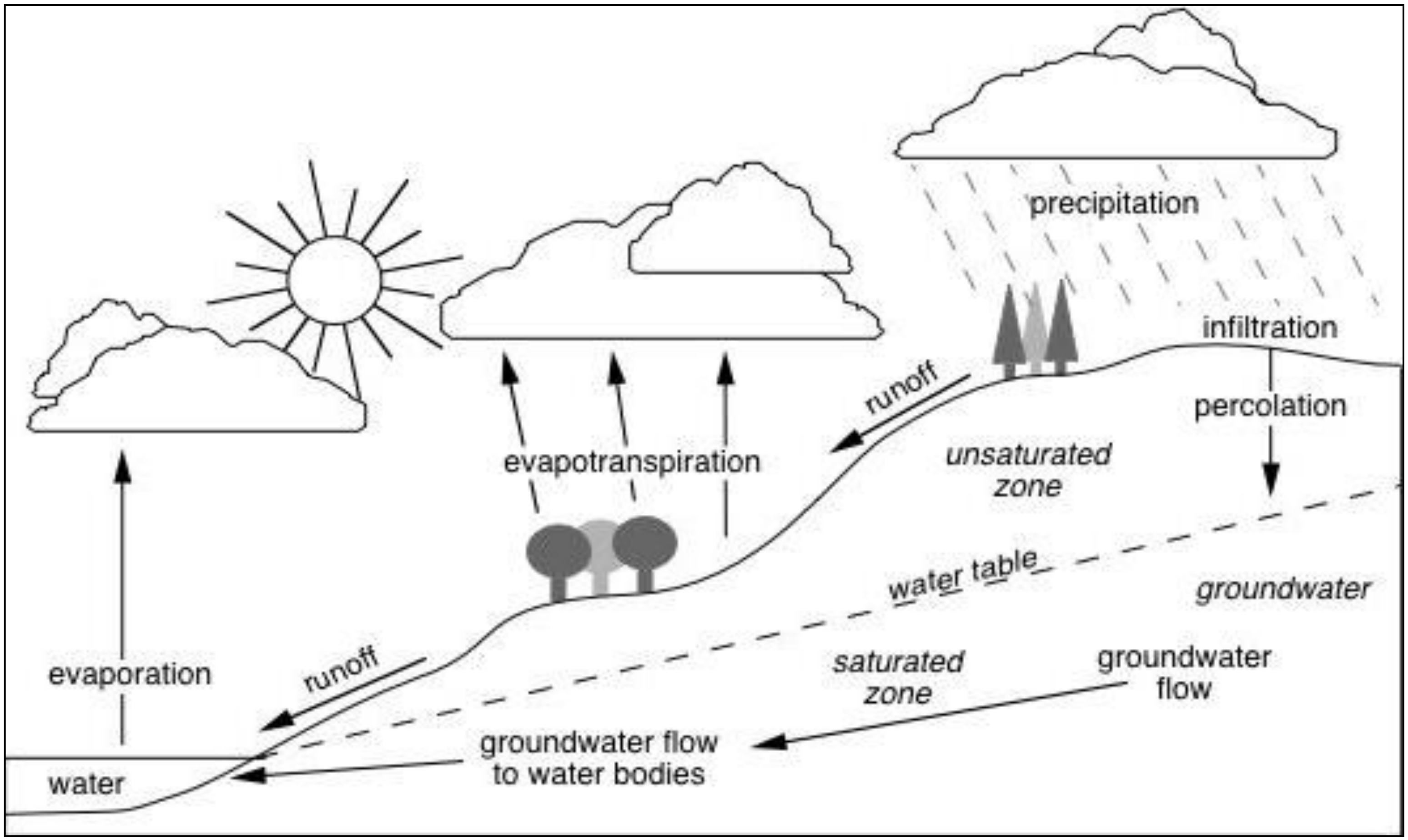
Atmospheric & Surface Energy Budget

- Close the surface energy budget, and provide surface boundary conditions to NWP and climate models.



Water Budget (Hydrological Cycle)

- Close the surface water budget, and provide surface boundary conditions to models.



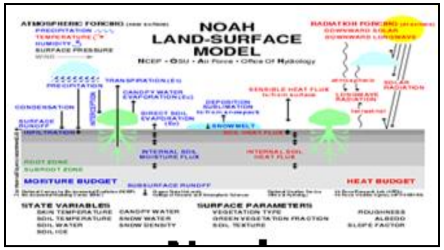
Land Models for Weather and Climate

Weather versus Climate (change) considerations:

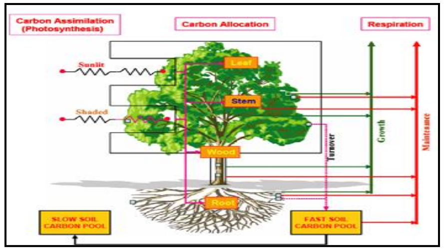
- Static vegetation, vs dynamic vegetation (growth), vs dynamic ecosystems (plant succession), and biogeochemical cycles with CO2-based photo-synthesis, different crops, C3, C4, CAM vegetation.
- Longer time-scales spin-up for deeper soils and groundwater, regions with “slow” hydrological cycle (arid, cold), carbon stores.
- Land-use change (observed/assimilated vs modelled), e.g. harvest, fires, urban areas.
- Human influences, e.g. irrigation/reservoirs, urban.
- Careful bookkeeping of energy, water, other budgets, e.g. even heat transported by rivers for climate!
- Seamless connection between weather and climate.

Land Models for Weather and Climate

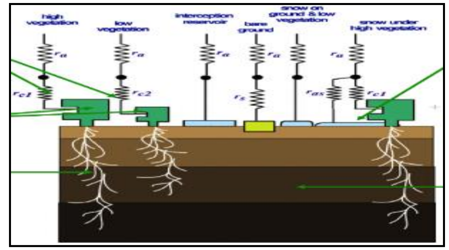
Weather ⟷ **Seasonal Prediction** ⟷ **Climate Change**



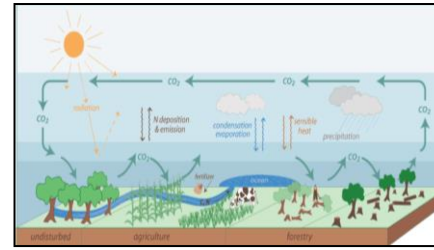
NCEP-NCAR Noah



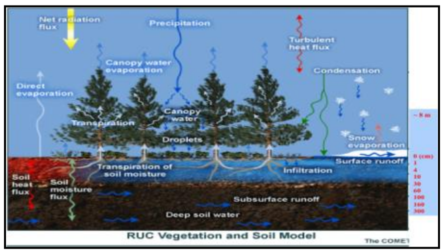
Noah-MP



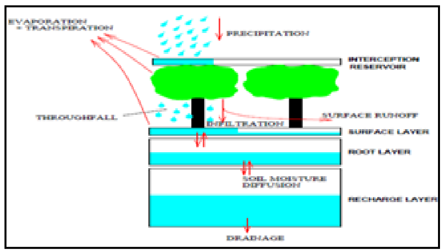
ECMWF TESSEL



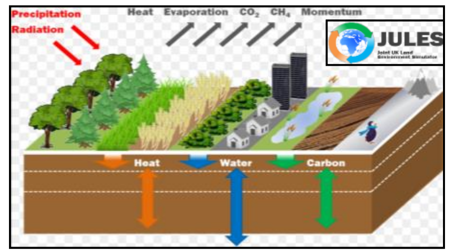
GFDL LM3



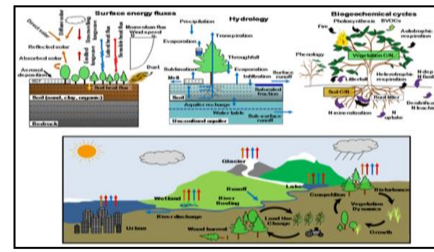
NOAA/ESRL RUC



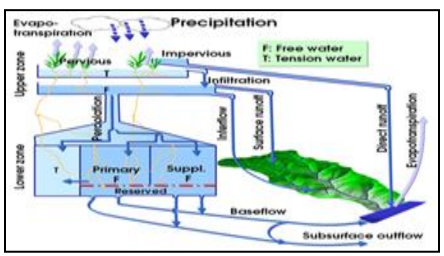
NASA Catchment



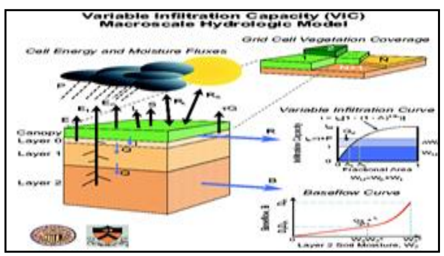
UKMO JULES



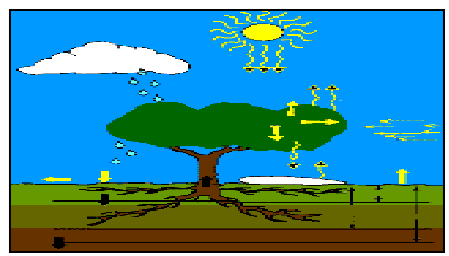
NCAR CLM



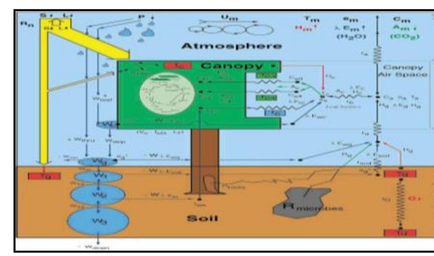
NWS SAC



UW/Princeton VIC



BATS



SiB

- A sampling –use dicates processes simulated and complexity.

Land Modeling History (NCEP/NWP prespective)

- 1960s (6-Layer PE model): land surface ignored, aside from terrain height and surface friction effects.
- 1970s (LFM): land surface ignored.
- Late 1980s (NGM): first land surface model (LSM) introduced:
  - Single layer soil slab (Deardorff “force-restore” soil model).
  - No explicit vegetation treatment.
  - Temporally fixed surface wetness factor.
  - Diurnal cycle treated (and diurnal ABL) with diurnal surface radiation.
  - Surface albedo, surface skin temperature, surface energy balance.
  - Snow cover (but not depth).
- Early1990s (Global MRF): OSU LSM:
  - Multi-layer soil column (2-layers).
  - Explicit annual cycle of vegetation effects.
  - Snow pack physics (snowdepth, SWE).
- Mid 1990s (Meso Eta model): Noah LSM replaces force-restore.
- Mid 2000s (Global Model: GFS): Noah LSM replaces OSU LSM.
- Mid 2000s (Meso Model: WRF): Unified Noah LSM with NCAR.
- 2010s: Noah-MP with NCAR & Noah model development group.

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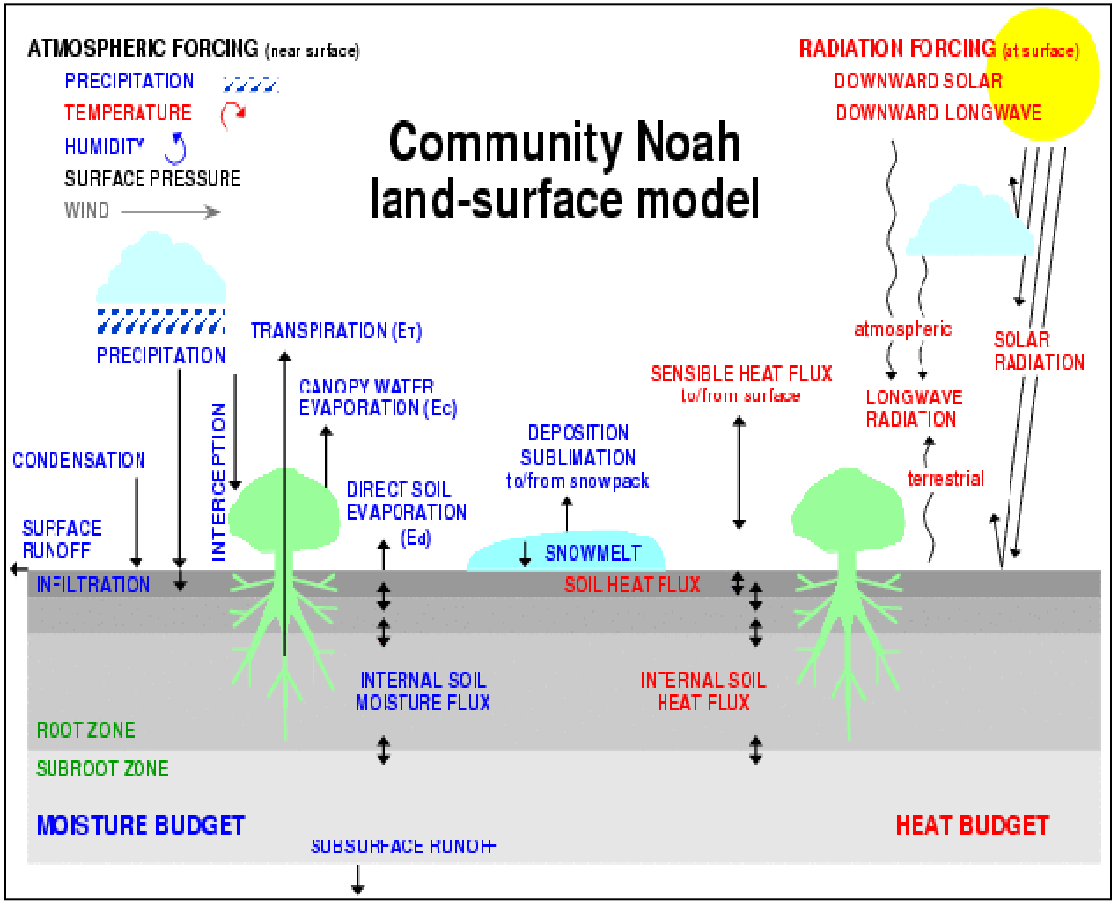
Land Model Requirements

- To provide proper boundary conditions, land model must have:
  - Appropriate **physics** to represent land-surface processes (for relevant time/spatial scales) and associated LSM model parameters.
  - Required **atmospheric forcing** to drive LSM.
  - Corresponding **land data sets**, e.g. land use/land cover (vegetation type), soil type, surface albedo, snow cover, surface roughness, etc.
  - Proper **initial land states**, analogous to initial atmospheric conditions, though land states may carry more “memory” (e.g. especially in deep soil moisture), similar to ocean SSTs.

Unified NCEP-NCAR Noah Land Model

- Four soil layers (shallower near-surface).
- Numerically efficient surface energy budget.
- Jarvis-Stewart "big-leaf" canopy conductance with associated veg parameters.
- Canopy interception.
- Direct soil evaporation.
- Soil hydraulics and soil parameters.
- Vegetation-reduced soil thermal conductivity.
- Patchy/fractional snow cover effect on sfc fluxes.
- Snowpack density and snow water equivalent.
- Freeze/thaw soil physics.



- **Noah for NWP & seasonal prediction.**
- Coupled with NCEP short-range NAM, medium-range GFS, seasonal CFS, HWRF, uncoupled NLDAS and GLDAS.

Land Physics: Basic Prognostic Equations

Soil Moisture (Θ):

$$\frac{\partial \Theta}{\partial t} = \frac{\partial K_\Theta}{\partial z} + \frac{\partial}{\partial z}\left(D_\Theta \frac{\partial \Theta}{\partial z}\right) + F_\Theta$$

•"Richard's Equation"; **DΘ** (soil water diffusivity) and **KΘ** (hydraulic conductivity), are nonlinear functions of soil moisture and soil type (*Cosby et al 1984*); **FΘ** is a source/sink term for precipitation/evapotranspiration.

Soil Temperature (T):

$$C_T \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right)$$

•**CT** (thermal heat capacity) and **KT** (soil thermal conductivity; *Johansen 1975*), non-linear functions of soil/type; soil ice = fct(soil type/temp./moisture).

Canopy water (Cw):

$$\frac{\partial C_w}{\partial t} = P - E_c$$

•**P** (precipitation) increases **Cw**, while **Ec** (canopy water evaporation) decreases **Cw**.

Surface Energy Budget

$$R_n = H + LE + G + SPC$$

Rn = Net radiation = **S↓** - **S↑** + **L↓** - **L↑**

S↓ = incoming shortwave (provided by atmos. model)

S↑ = reflected shortwave (snow-free albedo (〈) provided by atmos. model; 〈 modified by Noah model over snow)

L↓ = downward longwave (provided by atmos. model)

L↑ = emitted longwave = ∑⌠T_s^4 (∑=surface emissivity, ⌠=Stefan-Boltzmann const., T_s=surface skin temp.)

H = sensible heat flux

LE = latent heat flux (surface evapotranspiration)

G = ground heat flux (subsurface soil heat flux)

SPC = snow phase-change heat flux (melting snow)

Land model provides: α, L↑, H, LE, G and SPC.

Surface Water Budget

$$\Delta S = P - R - E$$

⊗S = change in land-surface water
P = precipitation
R = runoff
E = evapotranspiration
P-R = infiltration of moisture into the soil

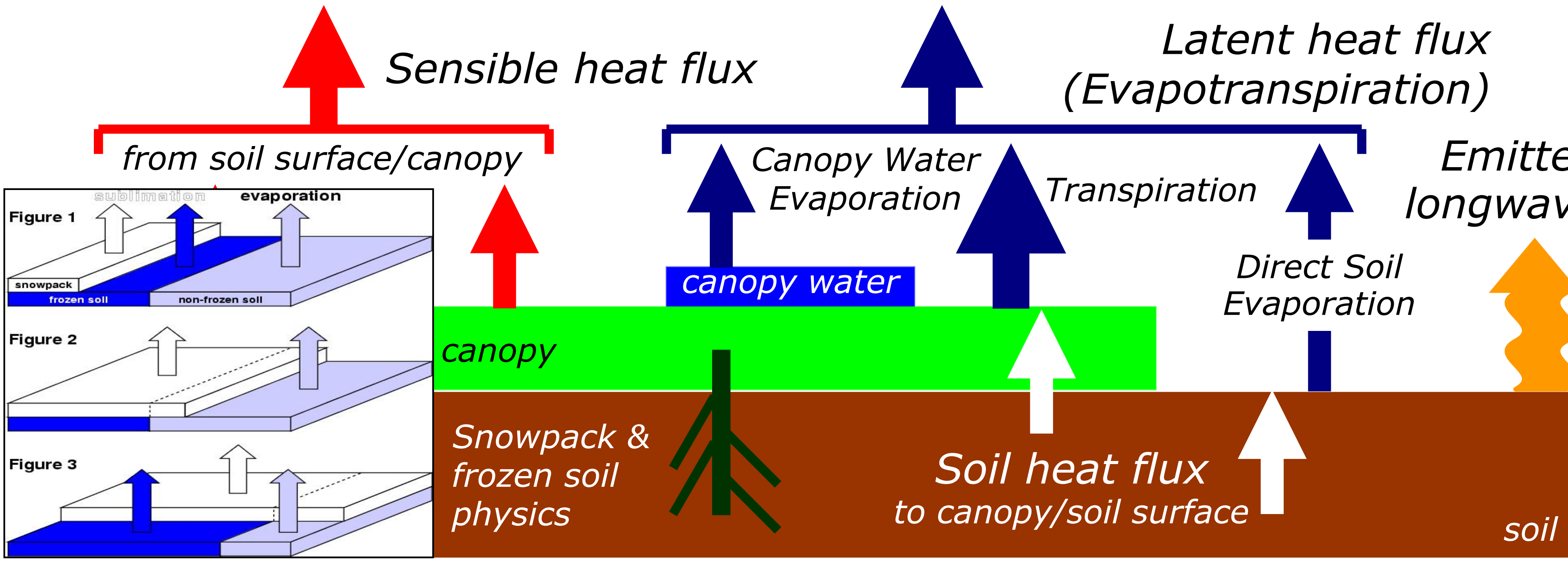
⊗S includes changes in soil moisture, snowpack (cold season), canopy water (dewfall/frostfall & intercepted precipitation, which are small).
E (Evapotranspiration) is a function of surface, soil and vegetation characteristics: canopy water, snow cover/depth, vegetation type/cover/density & rooting depth/ density, soil type, soil water & ice, surface roughness.

Land model provides: ⊗S, R and E.

Land Physics: Flux Boundary Conditions

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

$$LE = LE_c + LE_t + LE_d$$



- **Surface fluxes balanced by net radiation (Rn), = sum of incoming and outgoing solar and terrestrial radiation, with vegetation important for energy partition between H, LE, G, i.e. surface roughness & near-surface turbulence (H), plant & soil processes (LE), and heat transport thru soil/canopy (G), affecting evolving boundary-layer, clouds/convection, and precipitation.**

$$G = \left(\frac{K_T}{\Delta z}\right)(T_{sfc} - T_{soil})$$

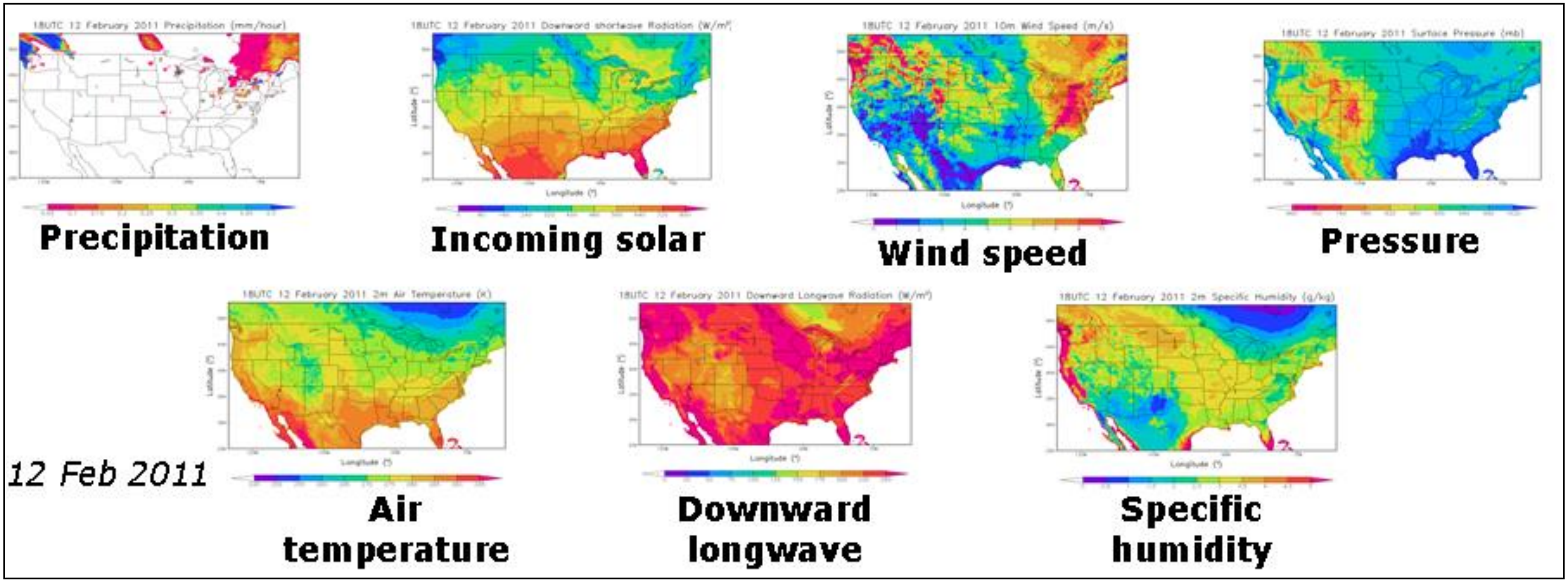
$$R_n = H + LE + G$$

Land Physics: Model Parameters

- Surface **momentum roughness dependent on vegetation**/land-use type and vegetation fraction.
- **Stomatal control dependent on vegetation type**, direct effect on transpiration.
- Depth of snow (snow water equivalent) for deep snow and assumption of **maximum snow albedo is a function of vegetation type**.
- **Heat transfer through vegetation** and into the soil a **function of green vegetation fraction** (coverage) and **leaf area index** (density).
- **Soil thermal and hydraulic processes** highly **dependent on soil type** (vary by orders of magnitude).

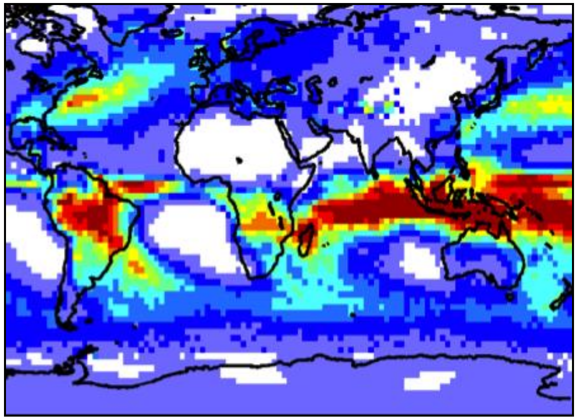
Atmospheric Forcing to Land Model

- Atmospheric forcing from parent atmospheric model (e.g. GFS), or analysis/reanalysis (e.g. CFSR) or Regional Climate Data Assimilation System (real time extension of the North American Regional Reanalysis, NARR), or from observations.
- Precipitation is quite important for land models with observed precip input to the land model in the assimilation cycle, e.g. CPC gauge-based observed precip., temporally disaggregated with radar data (stage IV), satellite data (CMORPH), bias-corrected with "PRISM".

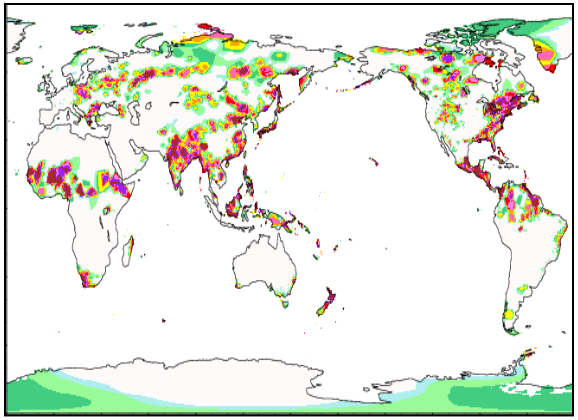


Atmospheric Forcing: Precipitation

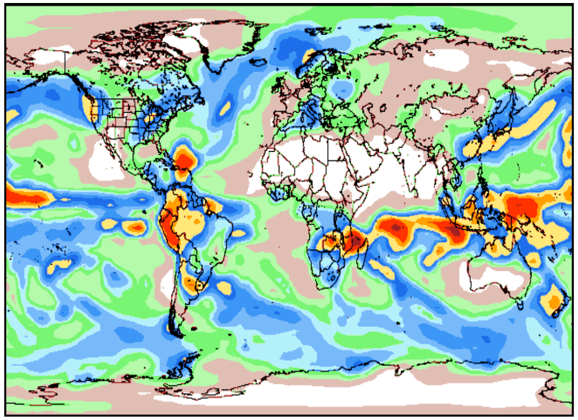
- Global Land Data Assimilation System (GLDAS) used in NCEP Climate Forecast System (CFS) relies on "blended" precipitation product, function of:
- **Satellite-estimated precipitation** (CMAP), heaviest weight in tropics where gauges sparse.
- Surface gauge network, heaviest in mid-latitudes.
- High-latitudes: Model-estimated precipitation based on Global Data Assimililation System (GDAS).



CMAP (satellite)



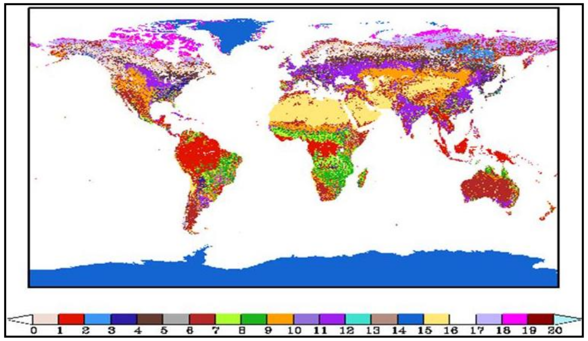
Surface gauge



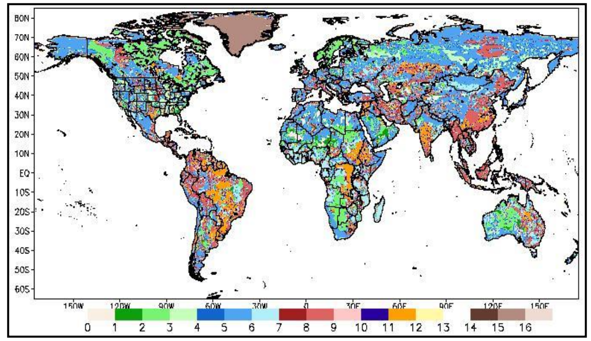
GDAS (model)

Jesse Meng NCEP/EMC, Pingping Xie, NCEP/CPC

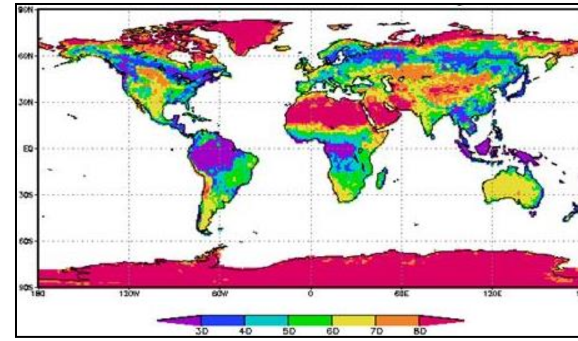
Land Data Sets



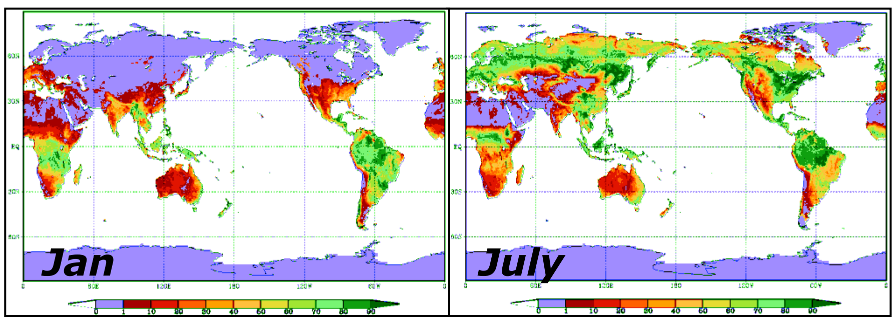
Vegetation Type
(1-km, IGBP-MODIS)



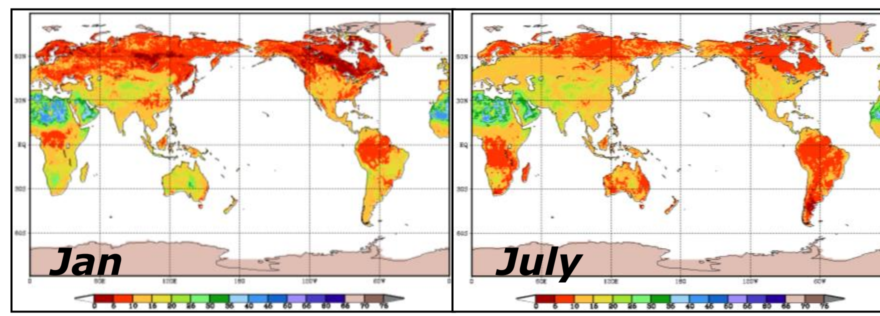
Soil Type
(1-km, STATSGO-FAO)



Max.-Snow Albedo
(1-km, UAz-MODIS)



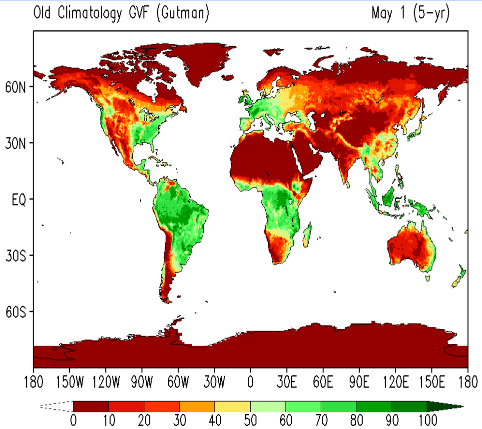
Green Vegetation Fraction
(monthly, 1/8-deg, NESDIS/AVHRR)



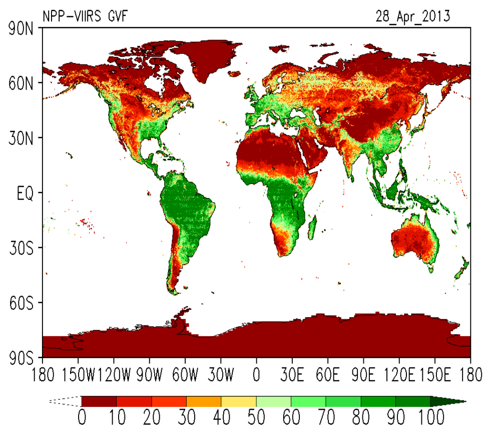
Snow-Free Albedo
(monthly, 1-km, Boston Univ.-MODIS)

- Fixed annual/monthly/weekly climatologies, or near real-time observations; some quantities may be assimilated into Noah, e.g. soil moisture, snow, greenness as initial land states.

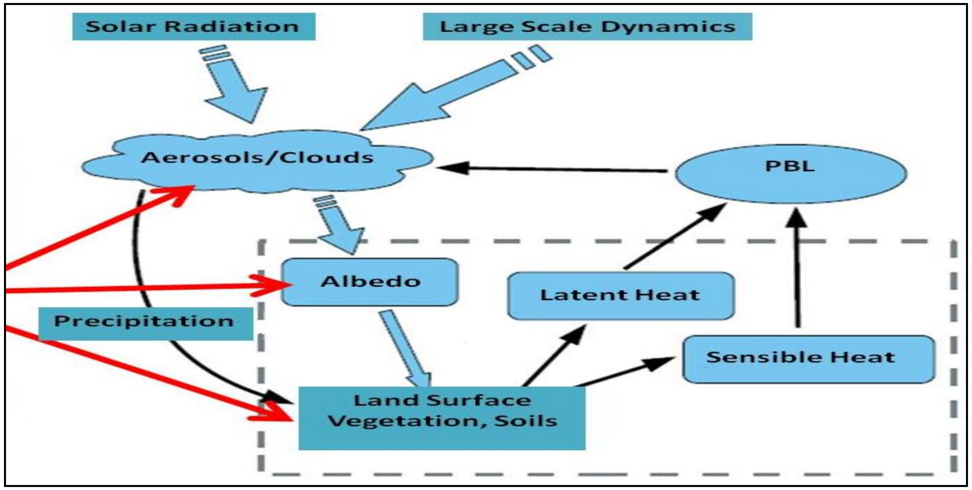
Land Data Sets: Green Vegetation Fraction (GVF) and Wildfire Effects



AVHRR 5-YR Climatology



VIIRS near-realtime

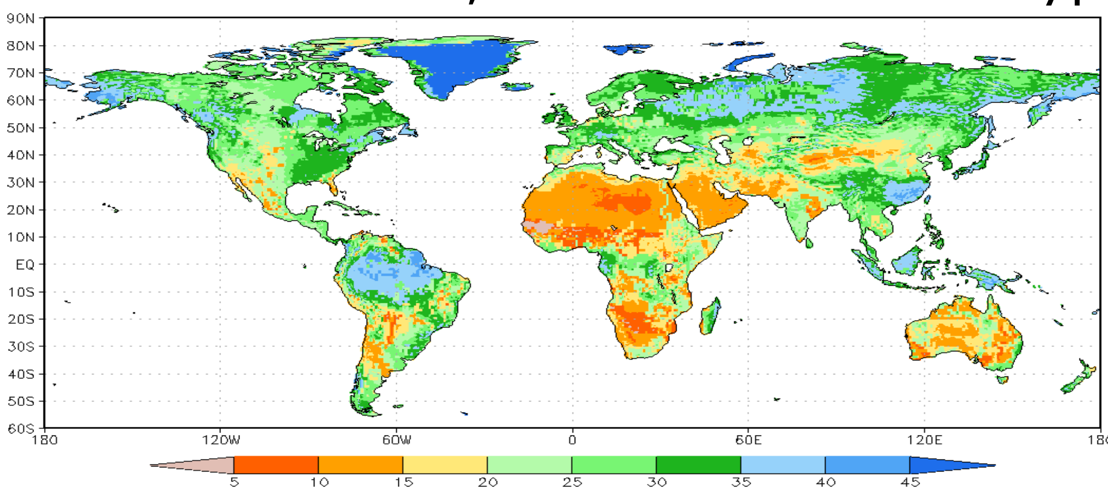


- Use of near real-time (remotely-sensed) GVF leads to better partition between surface heating & evaporation --> impacts surface energy budget, ABL evolution, clouds/convection.
- **Wildfires** affect weather and climate systems: (1) atmos-pheric circulations, (2) aero-sols/clouds, (3) land surface states (GVF, albedo & surface temperature, etc.) → impact on sfc energy budget, etc. Consistency with "burned" & other products, e.g GVF.

Weizhong Zheng and Yihua Wu, NCEP/EMC, Marco Vargas et al, NESDIS/STAR

Initial Land States

- **Land state initial conditions** are necessary for NWP & climate models, and must be consistent with land model used in a given weather or climate model, i.e. from same **cycling** land model.
- Land states spun up in a given NWP or climate model ***cannot*** be used directly to **initialize** another model without **rescaling** because of differing land model soil moisture climatology.
- In seasonal (and longer) climate simulations, land states are cycled, and some land data set quantities may be simulated (and therefore assimilated), e.g. green vegetation fraction & leaf area index, and even land-use type (evolving ecosystems).

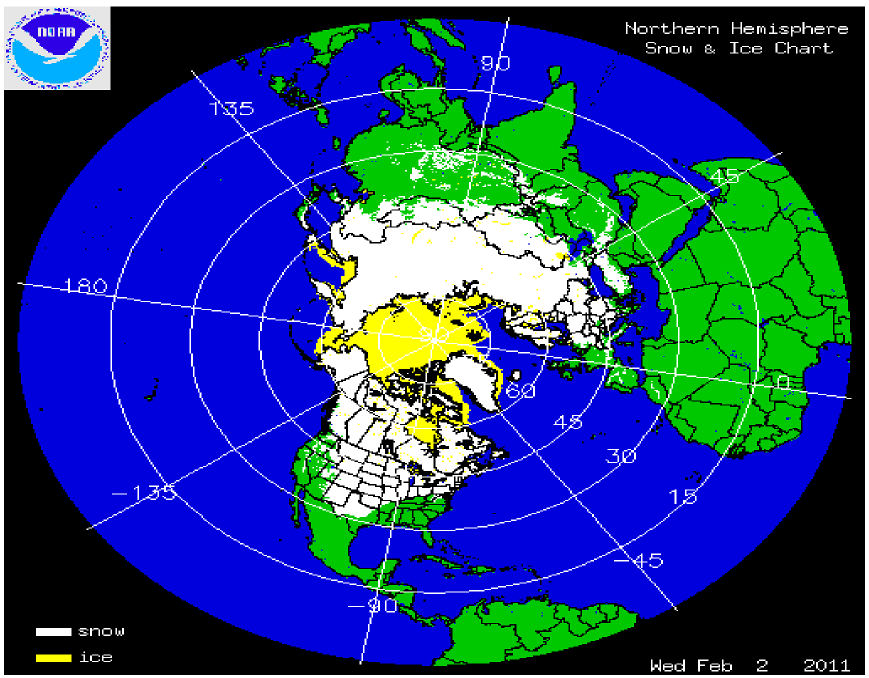


May Soil Moisture Climatology *from 30-year NCEP Climate Forecast System Reanalysis (CFSR), spun up from Noah land model coupled with CFS.*

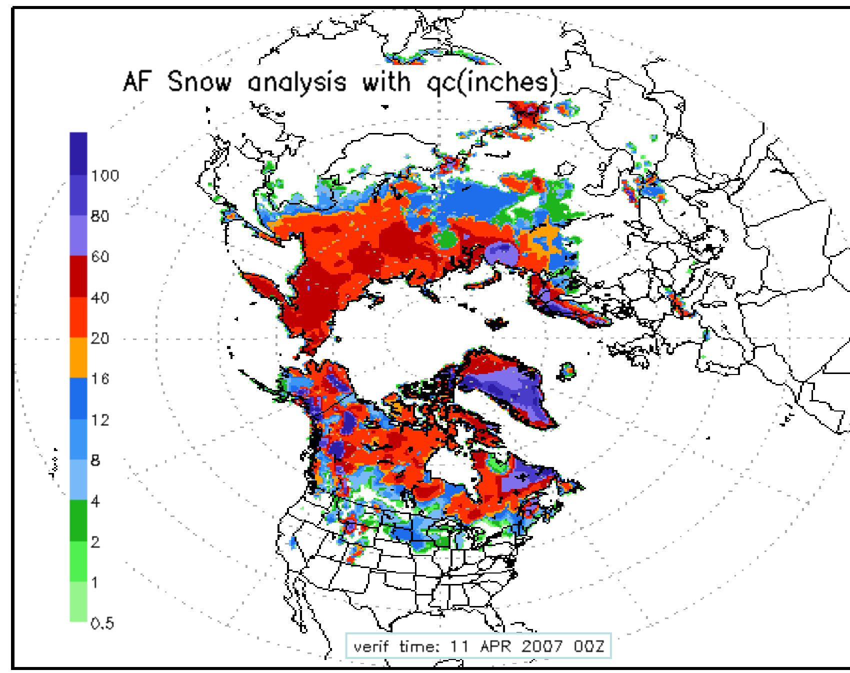
Jesse Meng NCEP/EMC

Initial Land States (cont.)

- In addition to *soil moisture*: the land model provides *surface skin temperature*, *soil temperature*, *soil ice*, *canopy water*, and *snow depth* & *snow water equivalent*.



National Ice Center snow cover



Air Force Weather Agency snow cover & depth