Land Surface Processes and Land Modelling in Earth System Modeling

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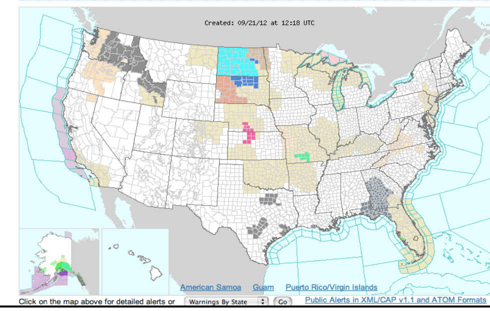

National Weather Service
National Centers for Environmental Prediction

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.

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NCEP

Environmental Modeling Center

Development, upgrade, transition, maintain models

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Outline

- Role of Land Surface Models (LSMs)
- Review of Land Surface Processes
- Land requirements: physics & parameters, atmospheric forcing, land data sets, initial land states, and land data assimilation

- Land Applications for Weather & Climate
- Testing and Validation
- Land Models in a fully-coupled Earth System
- Land-Atmosphere Interactions
- Partners
- Summary

- Why land modeling is needed?

ESM for weather and climate

Weather **Climate**

- Time sc
  - Hour … ond (more
    week
- Spatial
  - Local … bal
- Main C
  - Atmo … n, Land…
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- Predicti
  - Dete … ation from
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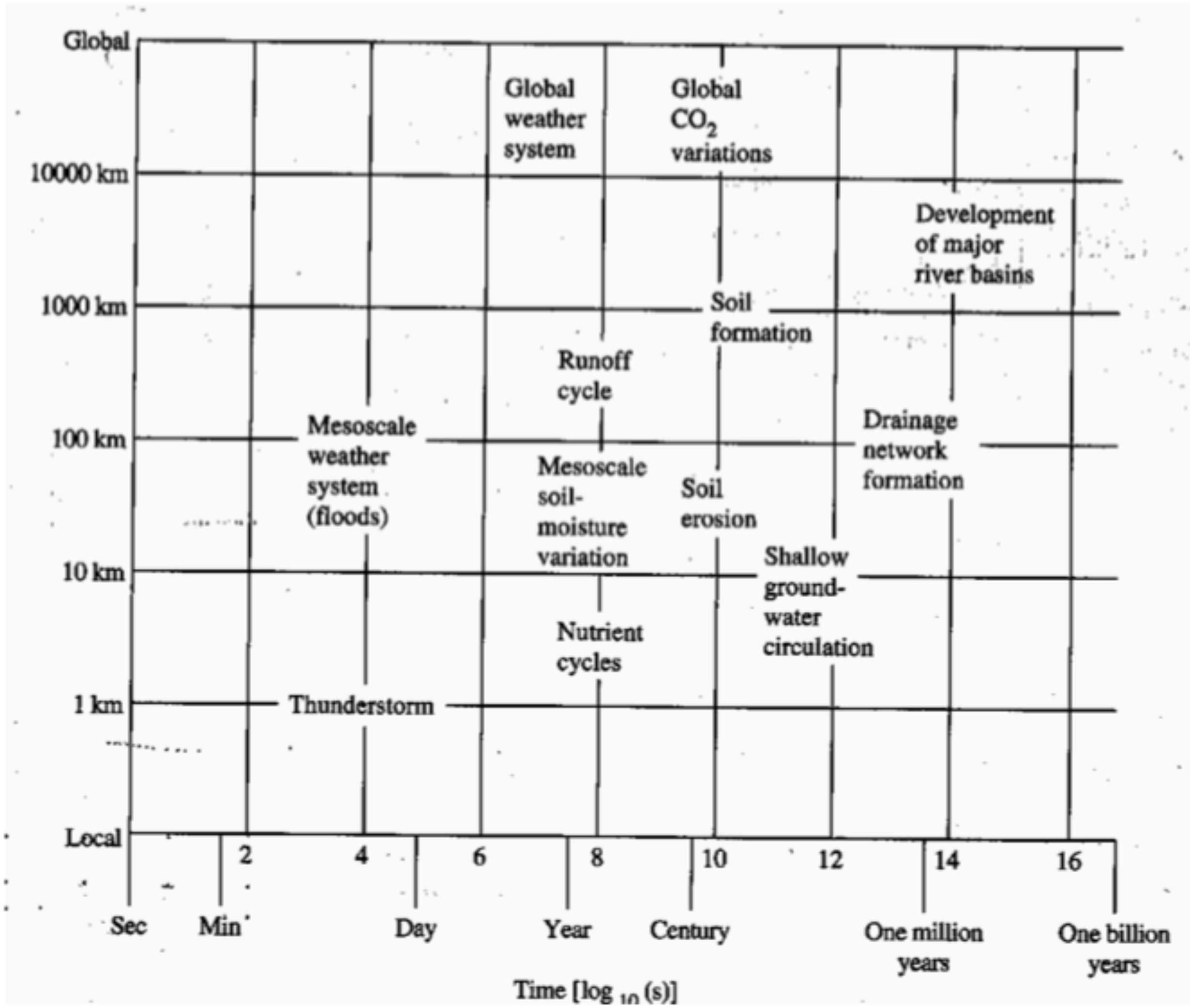
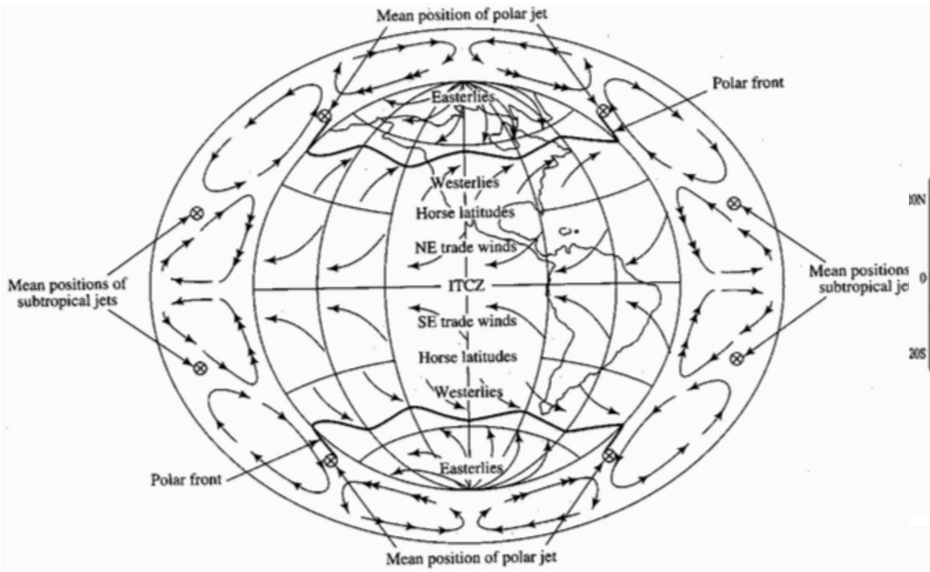
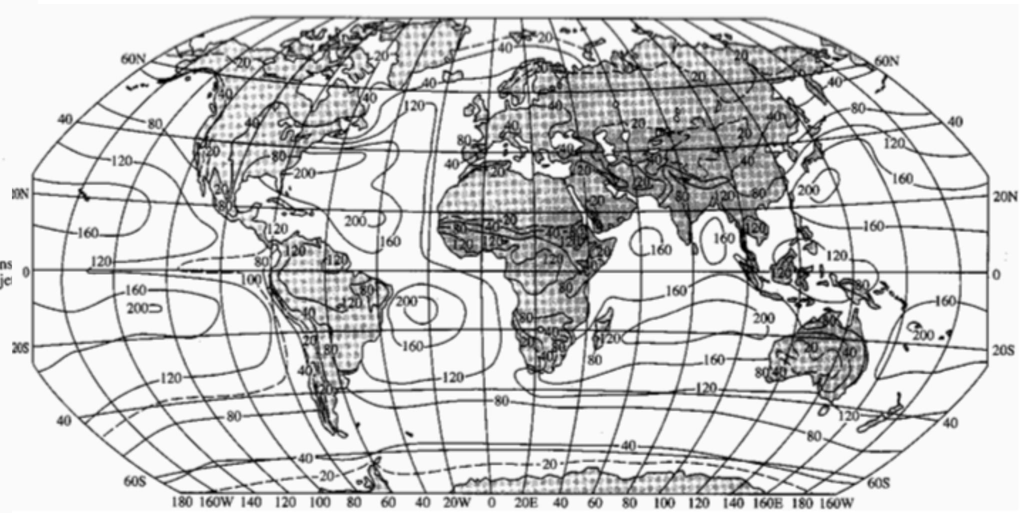
    over … *oblem*
    Prob

Climat … time



Global circulations and evaporation





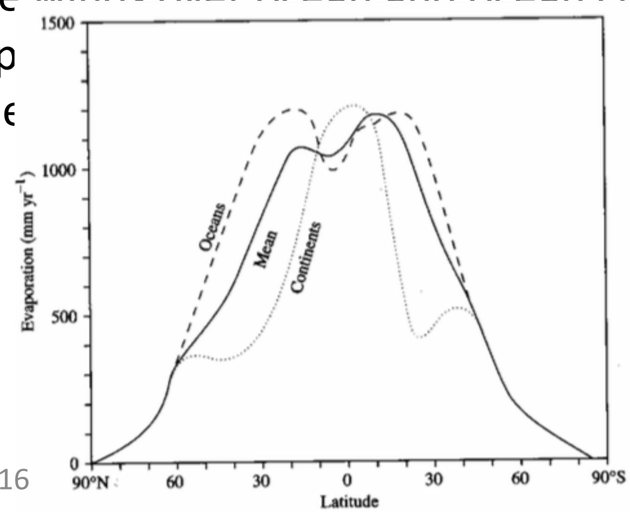
0-30 poleward movement in upper atm
rising air in equator, descend at 30

30-60 poleward moement in lower atm
descending air along 30, rising at 60

60-90 poleward movement in upper atm
ascending air at 60 descending at 90

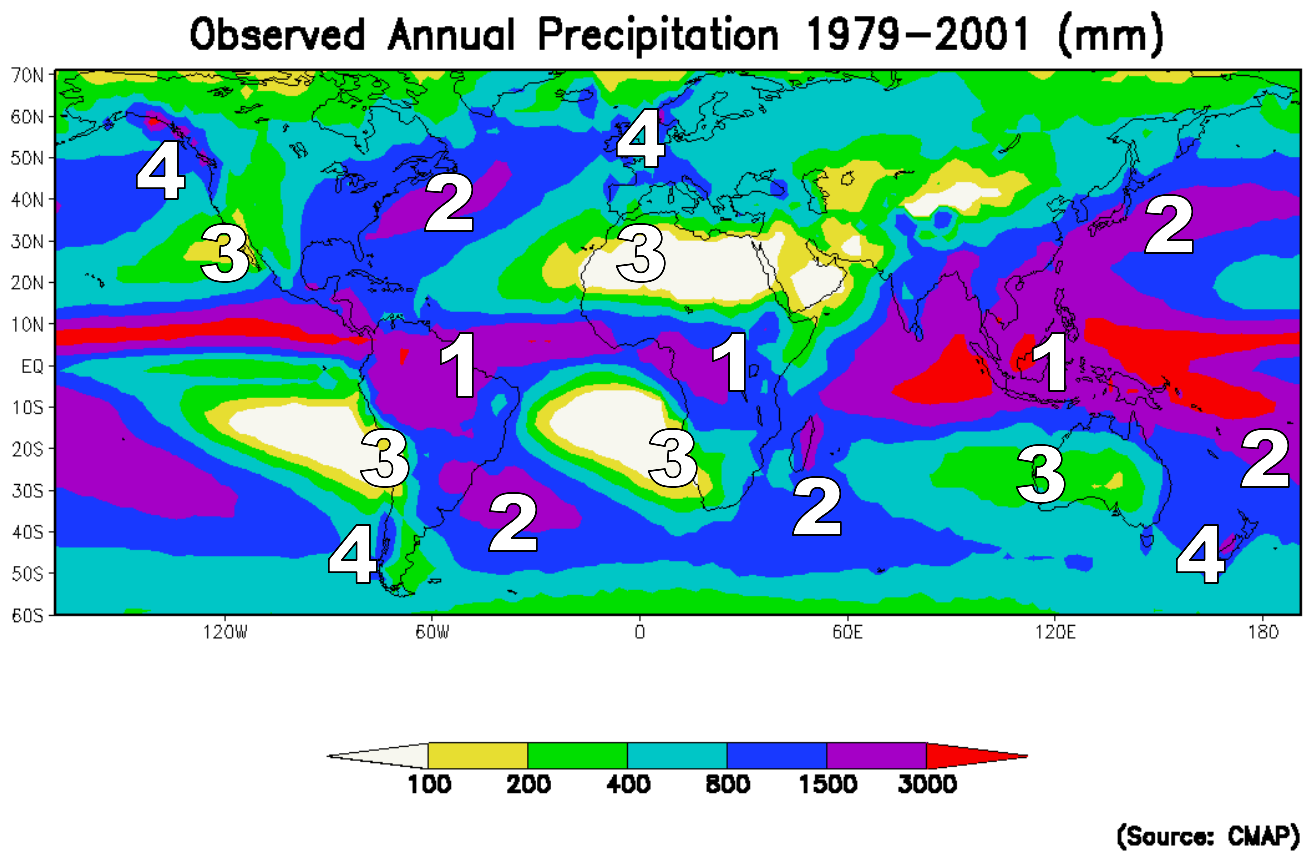
Surface pressure, winds and rainfall are strongly related

Global pattern of E is controlled by radiation balance at the surface (energy-limited), surface winds over ocean and ocean currents (transp … n contine…



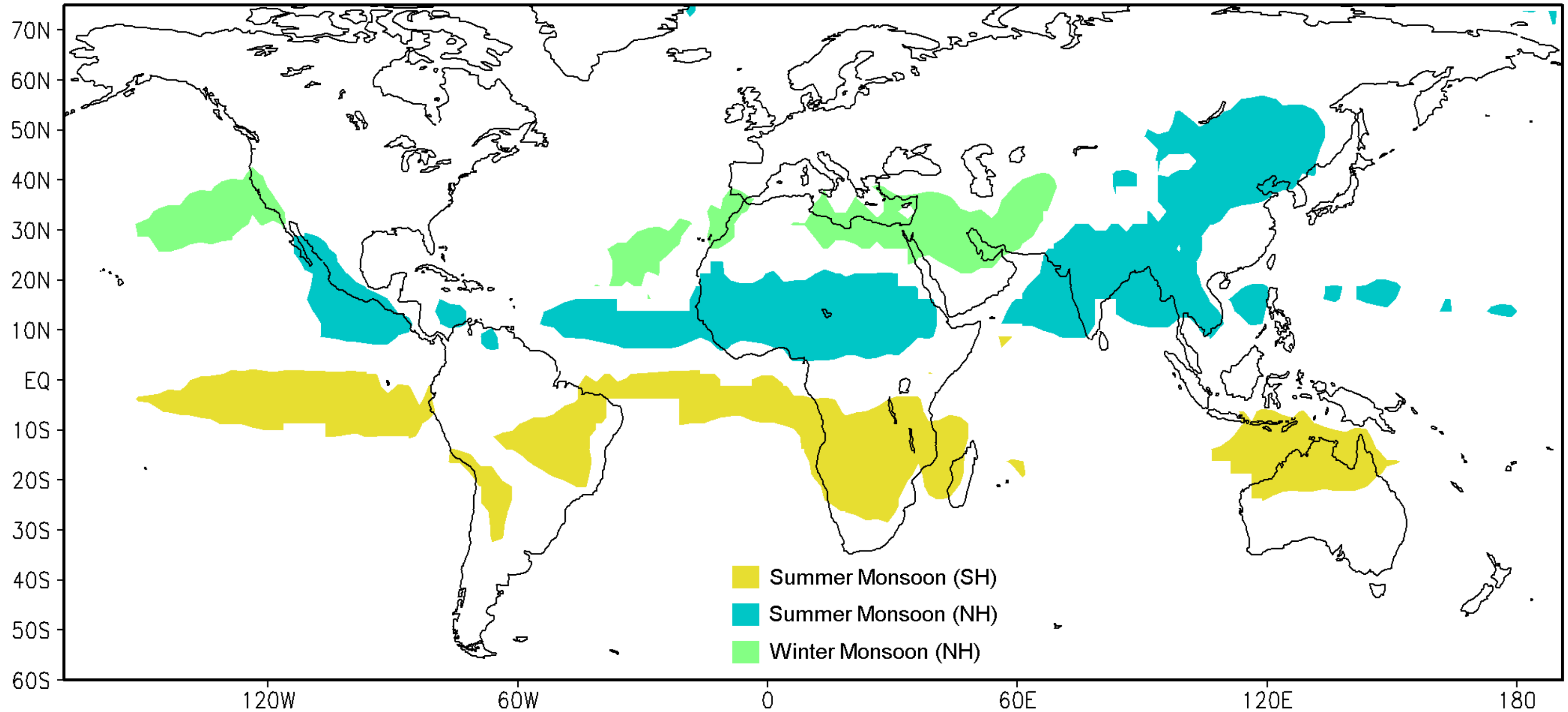
Global pattern of precipitation

1. Tropical convection clusters at 60W (Amazon), 30E (Africa), and 120E (Indonesia).
2. Mid-latitude storm tracks form on the eastern margins of continents.
3. Deserts form in the subtropics on the western sides of continents.
4. Mid-latitude rain forests form where oceanic westerlies hit the coast.



Land determines the location of precipitation

Monsoons



- Over land, monsoons characterized by rainy/dry seasons
  - Summer wet / winter dry monsoons exist primarily in the subtropical regions, but can extend into mid-latitudes.
  - Winter monsoons (a.k.a. Mediterranean climates) exist in the Northern Hemisphere (California, North Africa, Middle East)

Impact of High Terrain

- Himalayas affect the entire depth of the troposphere
  - Temperatures at 500mb (about halfway up through the atmosphere) are considerably warmer because of the presence of the mountain range.
  - This “elevated heat source” is the main engine driving the Asian monsoon.
  - Impacts are even seen in the opposite hemisphere.

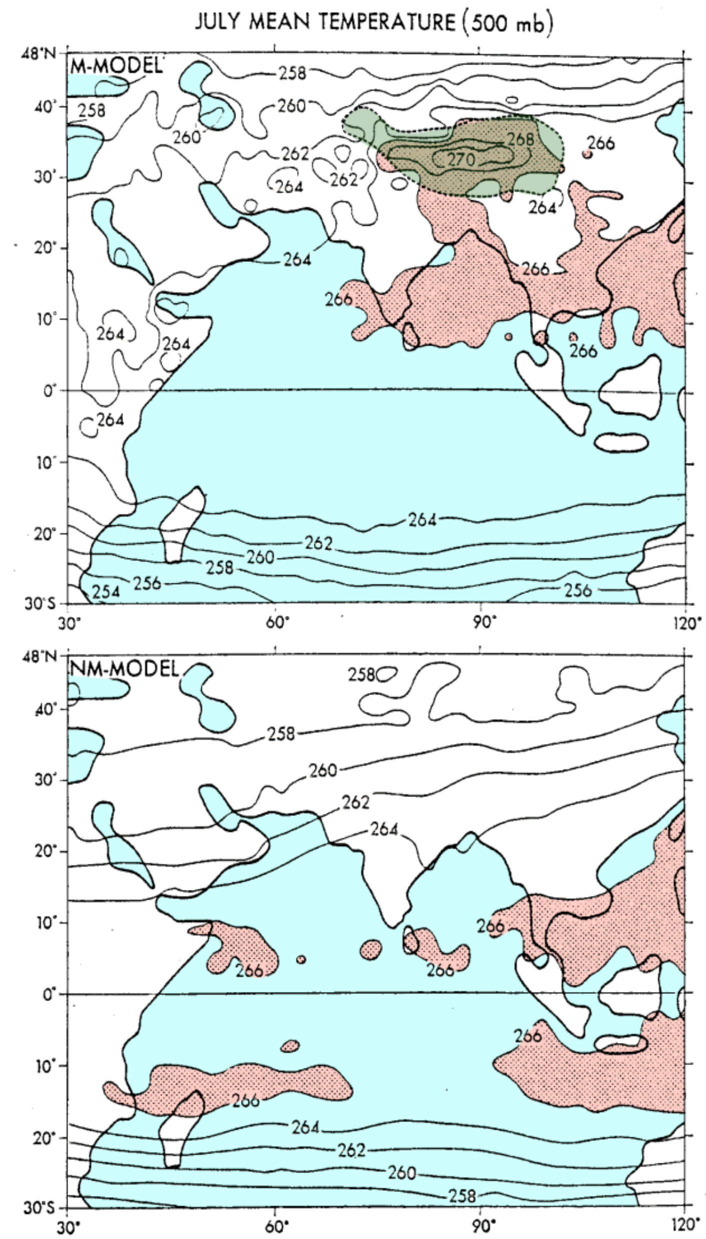
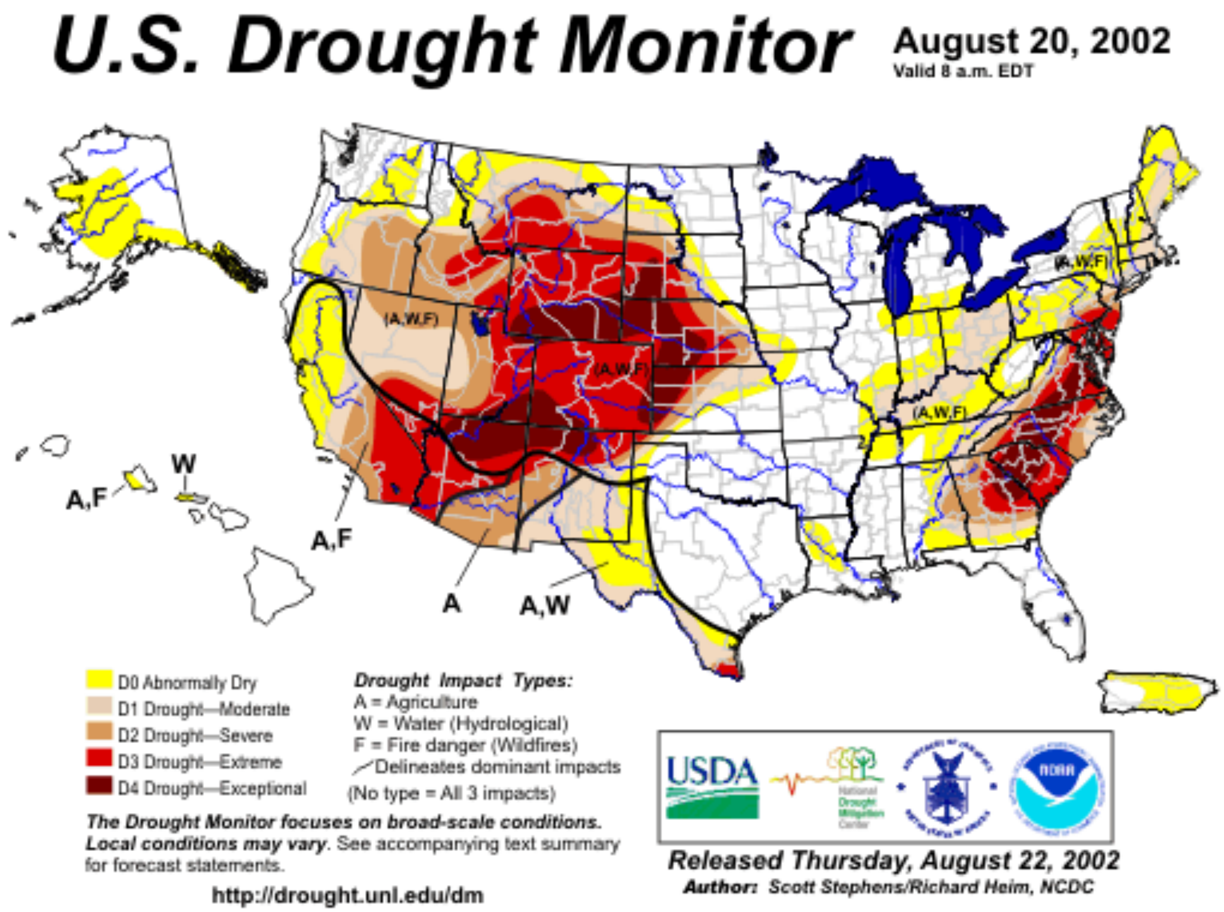


FIG. 4.4. Horizontal distribution of July mean 500 mb temperatures (K) of the M-model (top) and the NM-model (bottom).

Hahn & Manabe (1975)

Precipitation and Soil Moisture

- Lack of precipitation leads to dry soil (drought).
- Does dry soil lead to lack of precipitation?
- Feedback between land and atmosphere.



Tropical land and teleconnections

- Heating of the atmosphere over the tropical convective areas can induce “wavetrains” that arc into the mid-latitudes. These wavetrains may provide a teleconnective link between changes to the land surface in the tropics, and climate in the mid-latitudes

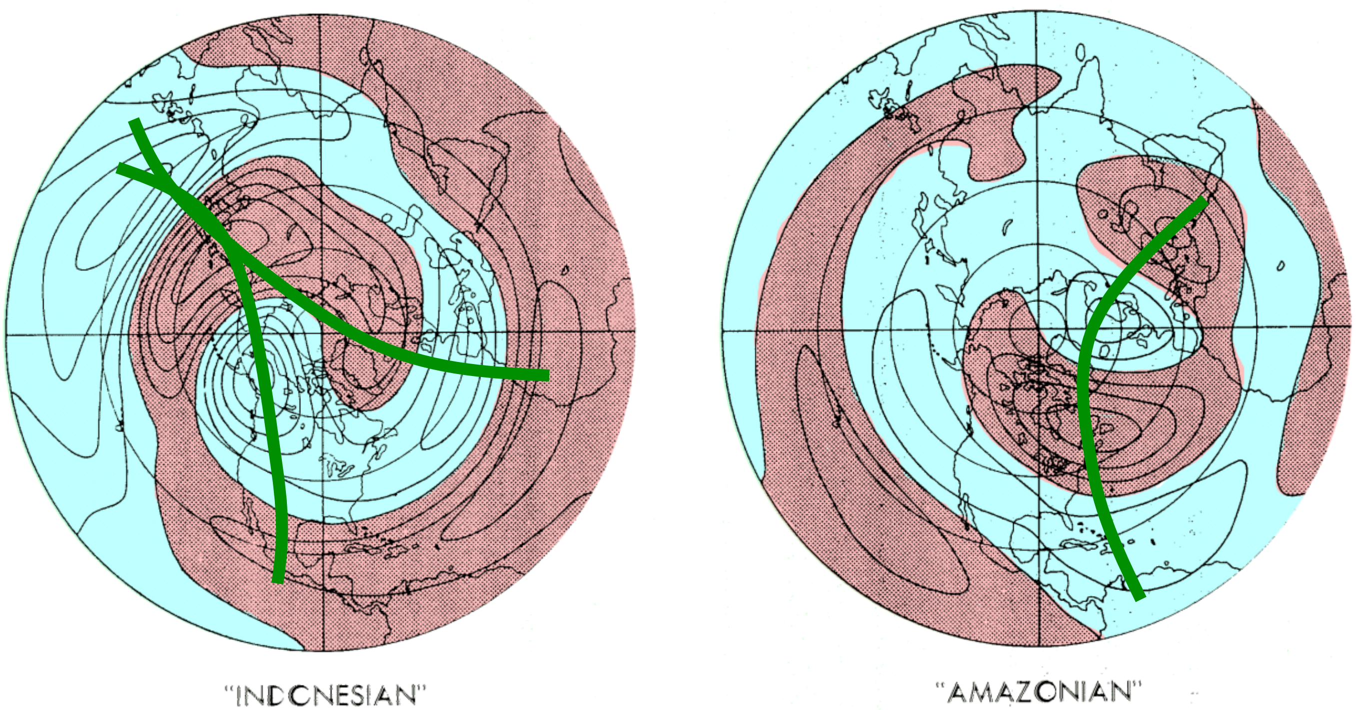


FIG. 9. The tropically forced 300 mb geopotential (of Fig. 8) is split up into parts forced by the 'Indonesian' sector (shown in the left hand panel) and the Amazonian sector (for definition, see the text); the fields are shown in the Northern Hemisphere using a contour interval of 10 gpm which is half of that used in contouring the geopotential in Fig. 8.

Nigam (1988)

Ocean versus Land

1. Ocean has a much higher heat capacity than land.

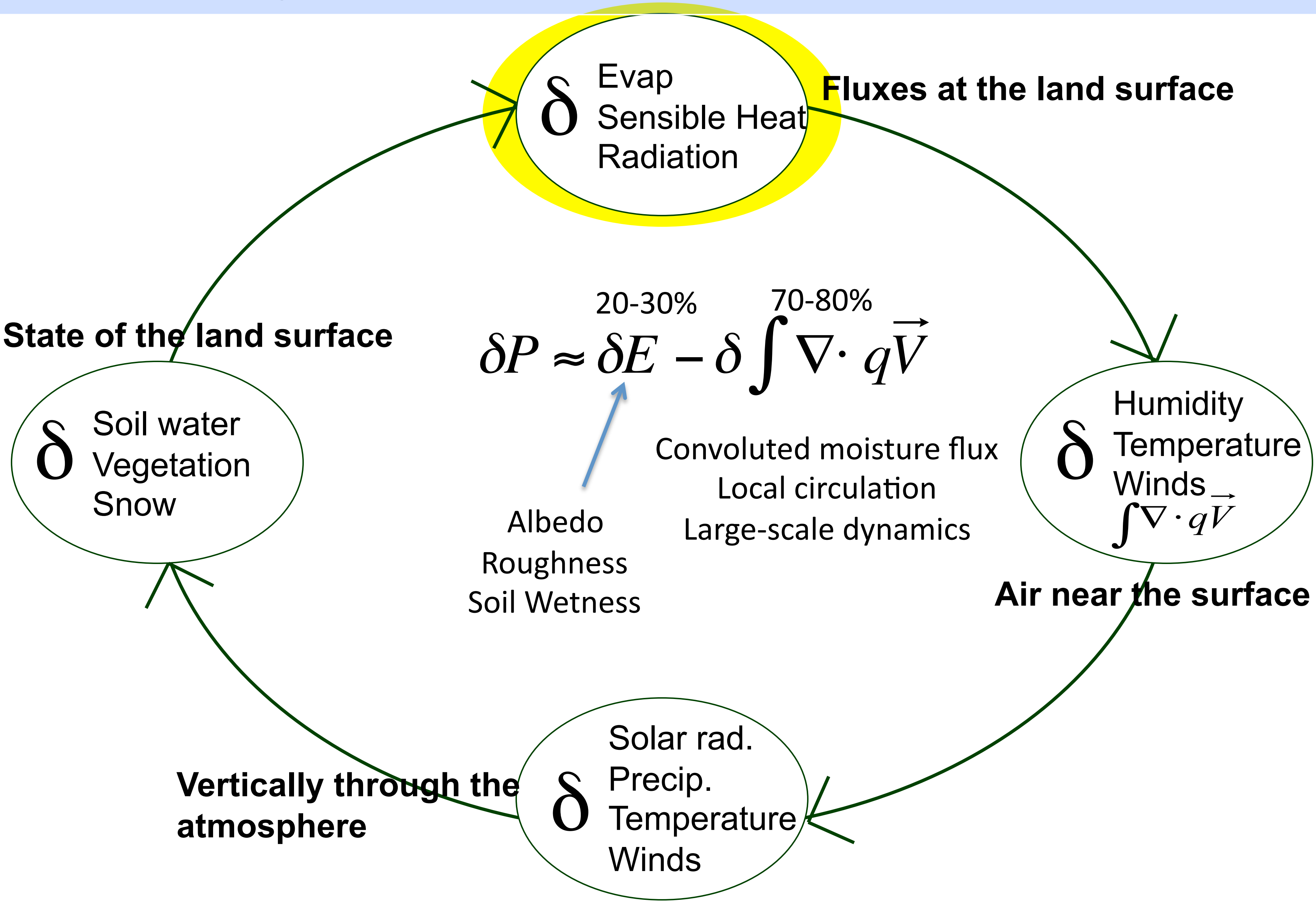
2. Water "flows" while the land surface is fixed. Ocean can transport much heat laterally, land cannot.

3. Ocean, obviously, is wet (evaporation is not limited by lack of moisture). Land can be wet, dry, or somewhere in between (moisture limitations can impede evaporation).

4. The upper layer of the ocean is well mixed, so the surface characteristics are sufficient to define its interaction with the atmosphere, but soil has vertical structure and overlying vegetation. Heat conduction and moisture transport below the surface become important.

These facts have a bearing on the physical interactions between the surface and the atmosphere and on the manner in which drag coefficients are specified.

Simple Land-Climate Interaction



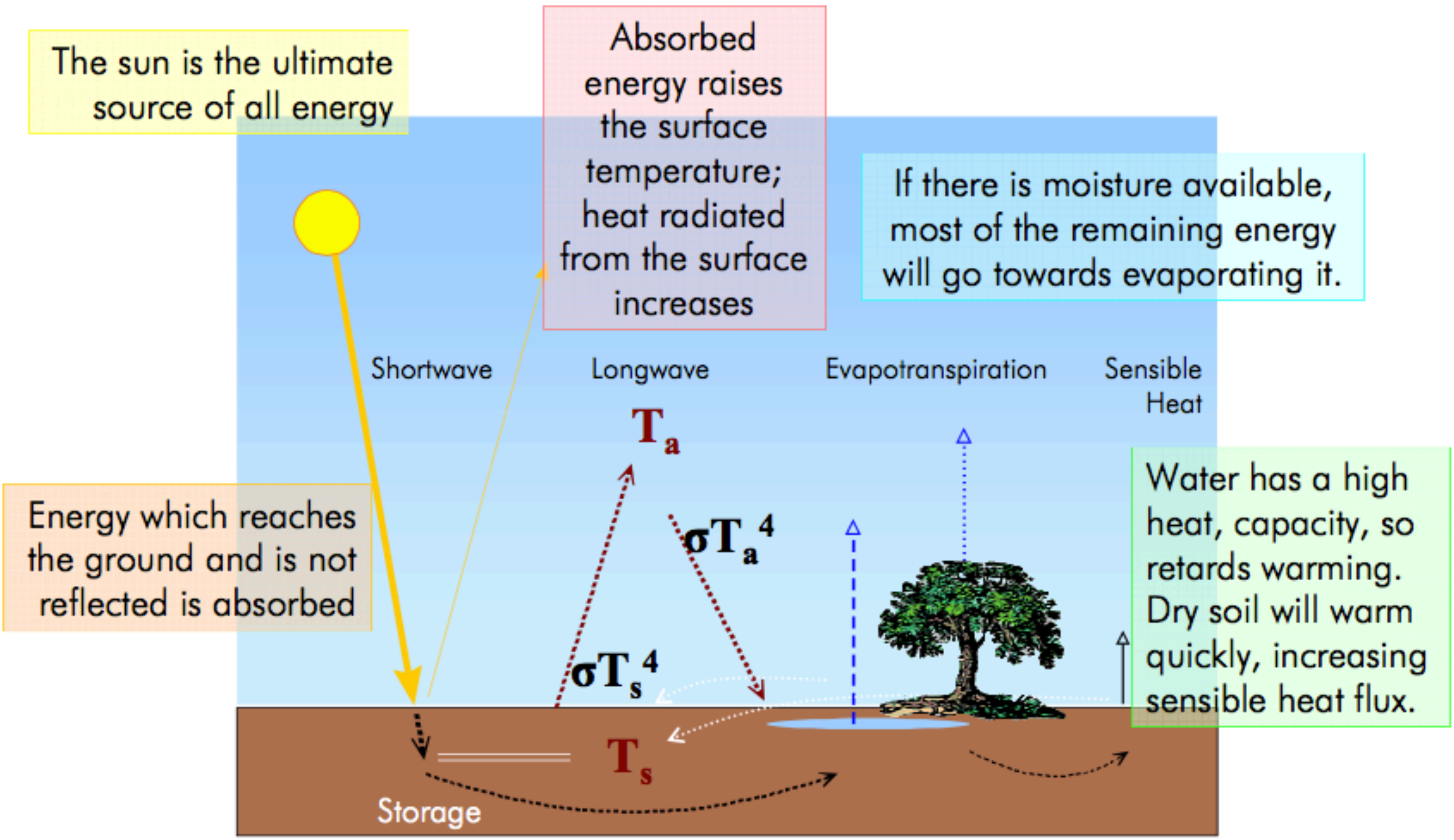
The fluxes

Basic notions of the land's effects on global circulation and climate (mean, diurnal cycle, seasonal cycle)

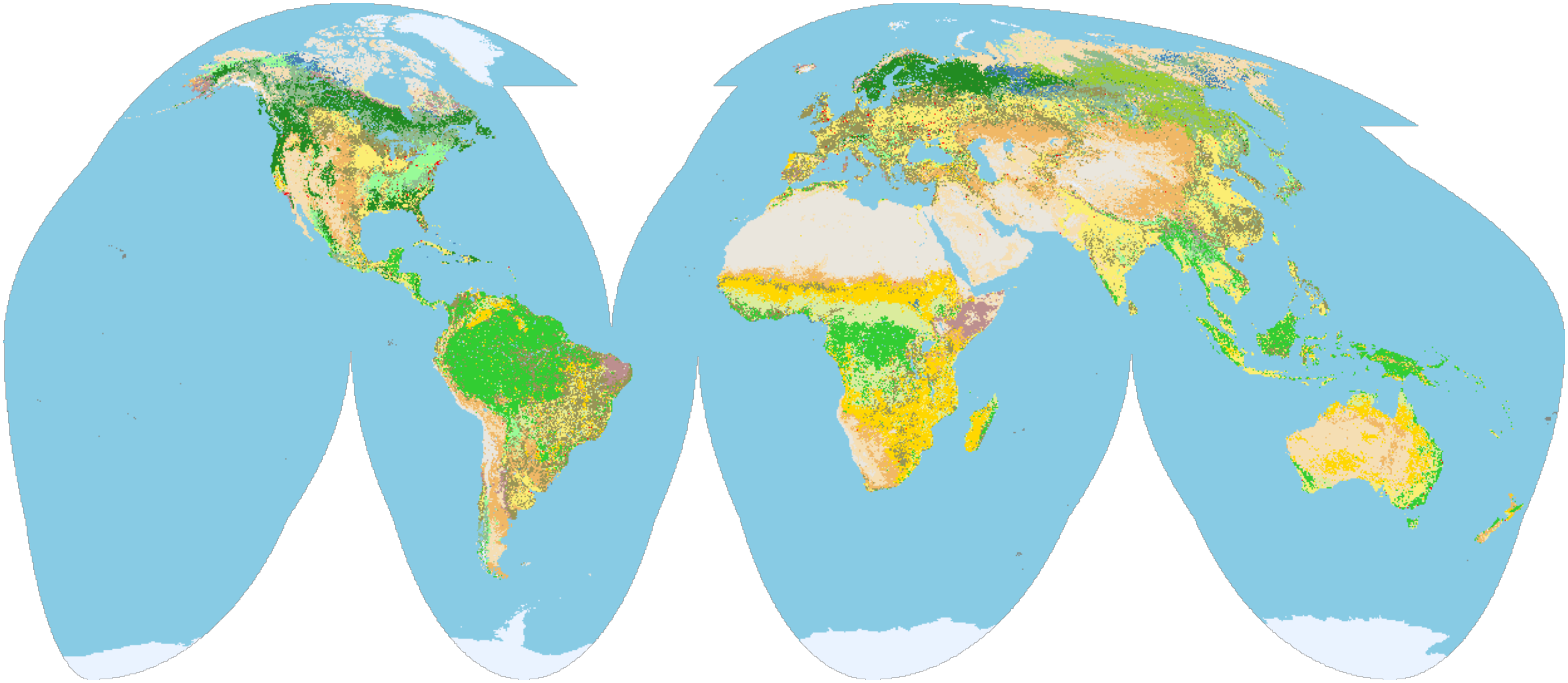
- Momentum
  - Orographic drag, surface roughness, turbulence
- Radiation
  - Solar radiation absorbed, reflected (albedo); longwave radiation
- Heat
  - Sensible heat (conduction), Latent heat (evaporation), Heat storage
- Moisture
  - Precipitation, evaporation, transpiration
- Aerosols
- Trace Gases

These fluxes are the means of communication between land and atmosphere

Energy Balance Over Land



Vegetation distribution



- Much of the variety at the land surface is in the vegetation. The distributions of major types are determined by: climate, soils, and human activity.

So, how simple is this land?

Understanding the role of land in the global circulation and the impact of land-climate interaction in the weather and climate
is certainly not simple.

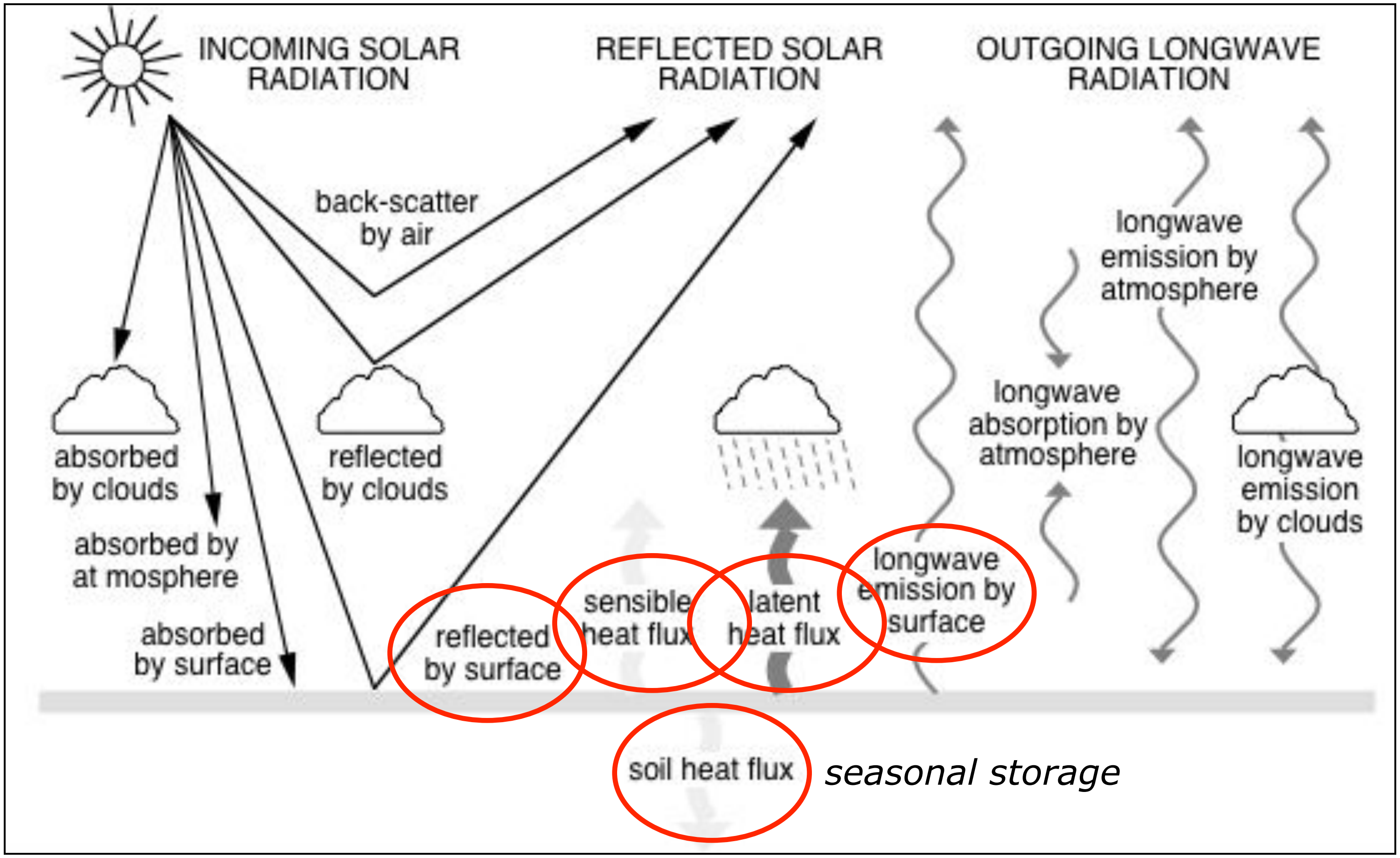
- We cannot do controlled sensitivity studies with the “real world”
- To understand it better, we construct and use land surface models
  - To account how terrestrial water and energy fluxes are being partitioned
- The LSMs are imperfect
  - Assumptions, Simplifications, Parameterizations, Errors
- And, the climate system is non-linear
  - Utterly sensitive to initial conditions
  - Instabilities exist that make prediction difficult
- However, coupling of land surface models are helpful
  - To provide proper boundary conditions for global models

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**.

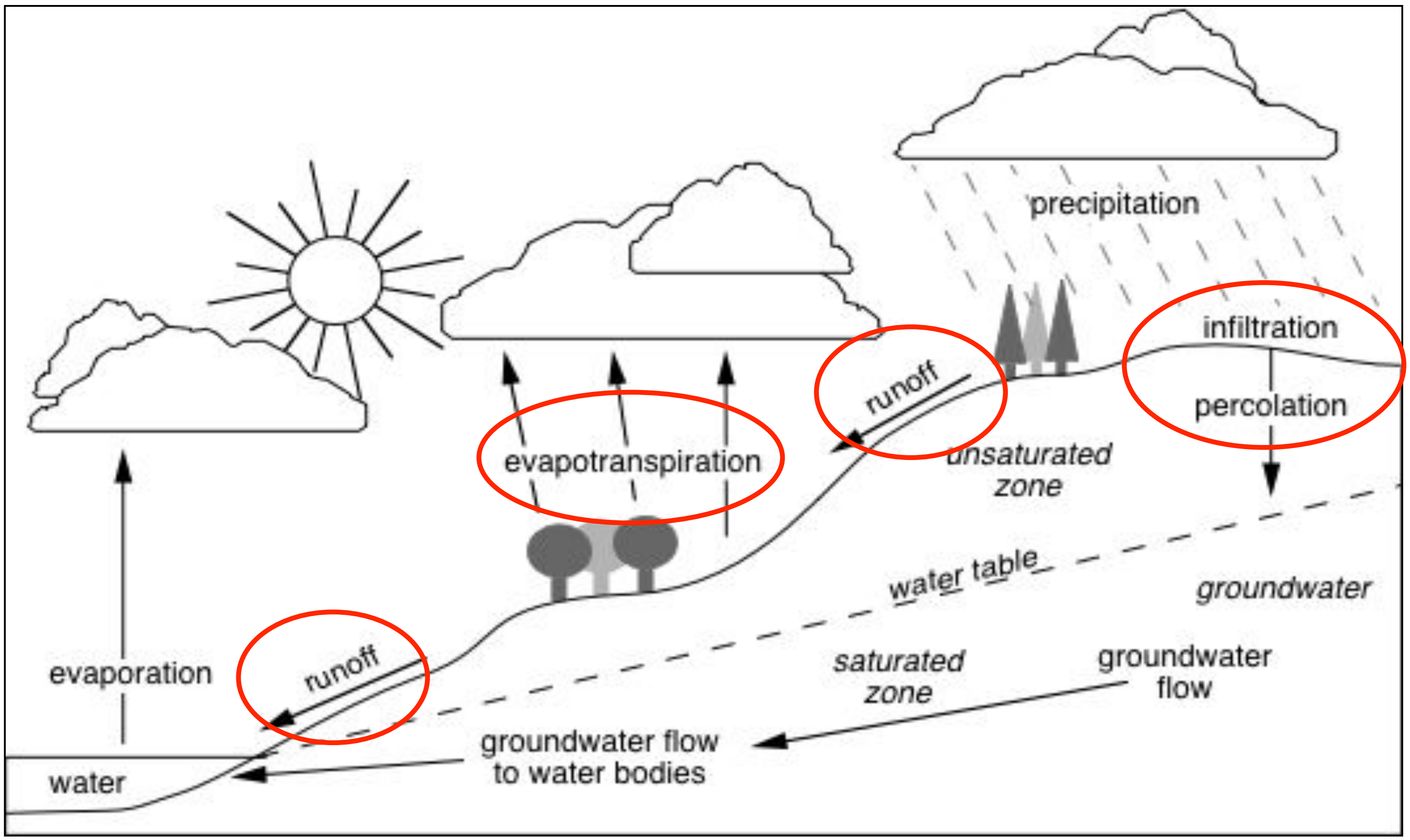
Atmospheric & Surface Energy Budget

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

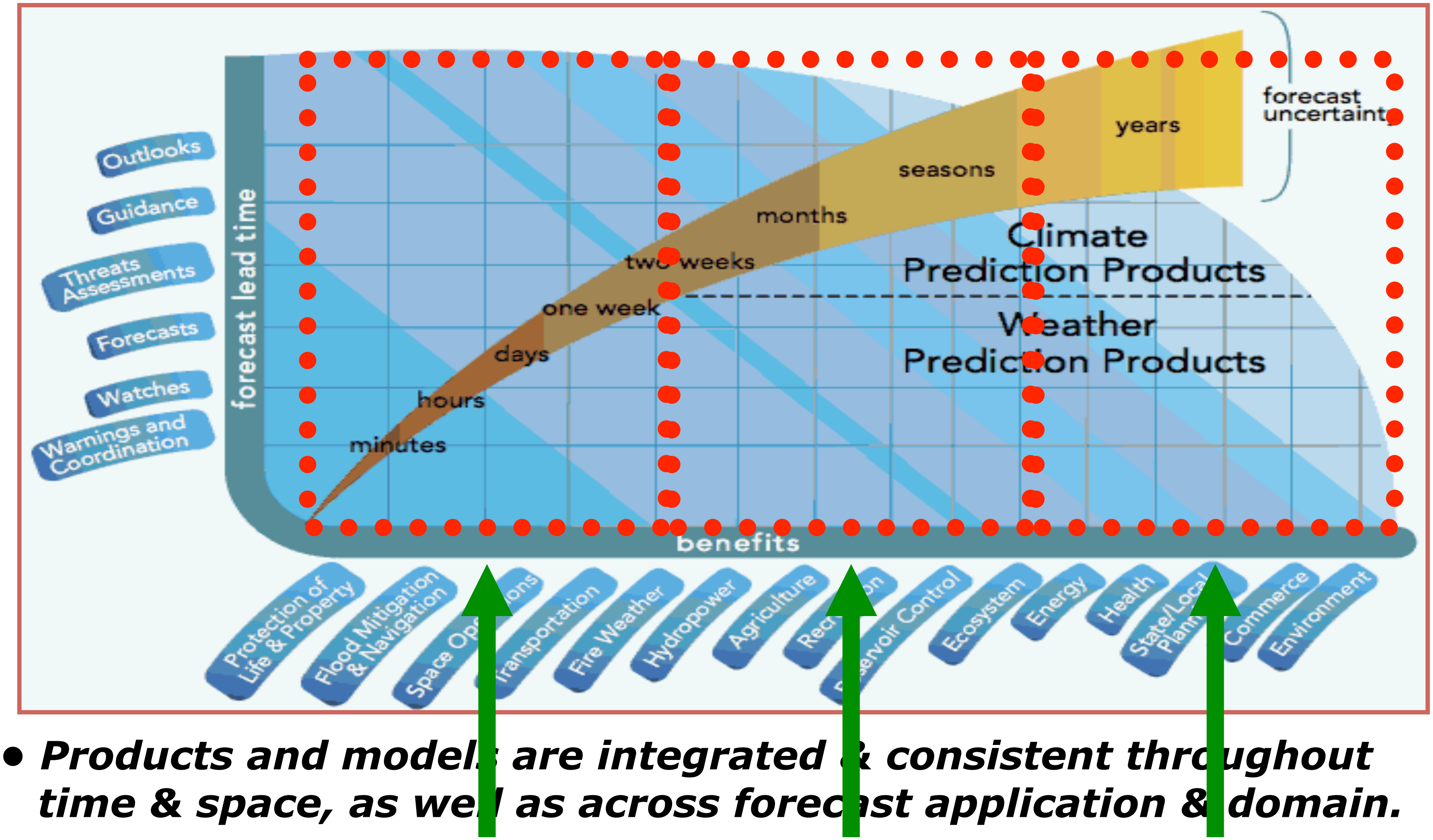


Water Budget (Hydrological Cycle)

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



Weather & Climate: a "Seamless Suite"



- ***Products and models are integrated & consistent throughout time & space, as well as across forecast application & domain.***

Land modeling example:

Static vegetation, e.g. climatology or realtime observations

Dynamic vegetation, e.g. plant growth

Dynamic ecosystems, e.g. changing land cover

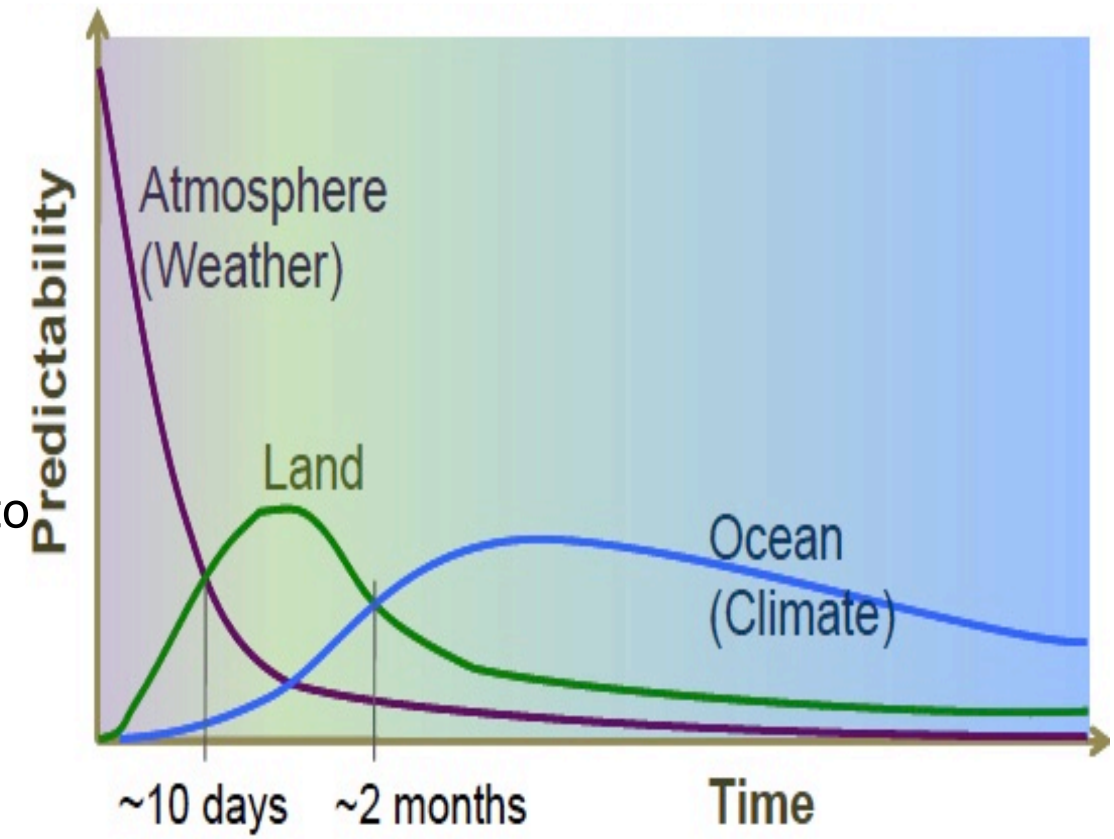
Predictability and Prediction

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

- To have an effect, it 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.

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.

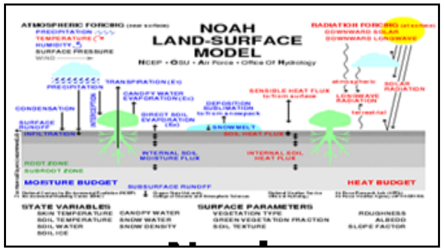
Land Models for Weather and Climate

Weather versus Climate (change) considerations:

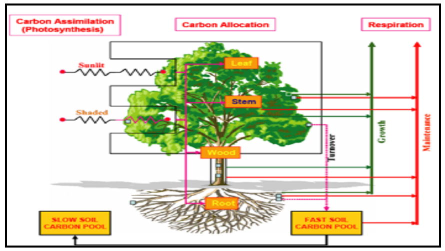
- Vegetation (Static vs dynamic : growth), vs dynamic ecosystems (plant succession), and biogeochemical cycles with CO2-based photo-synthesis, different crops, C3, C4, CAM vegetation.
- Longer time-scales spin-up for deeper soils and groundwater, regions with "slow" hydrological cycle (arid, cold), carbon 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. heat content transported by rivers for climate.
- Seamless connection between weather and climate.

Land Models for Weather and Climate

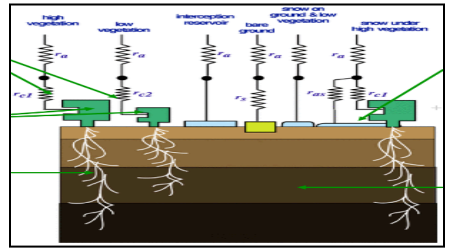
Weather — **Seasonal Prediction** — **Climate Change**



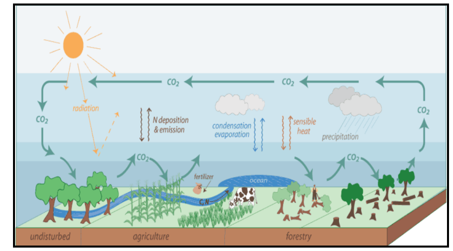
NCEP-NCAR Noah



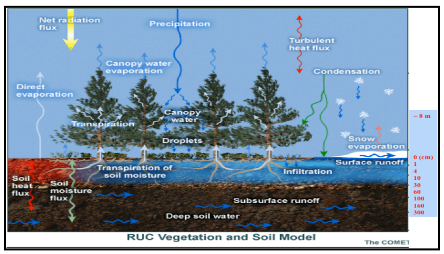
Noah-MP



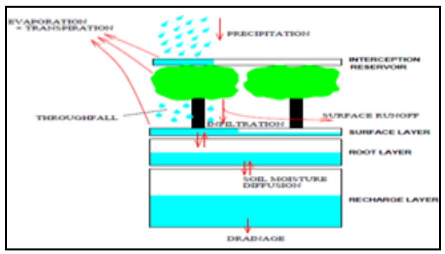
ECMWF TESSEL



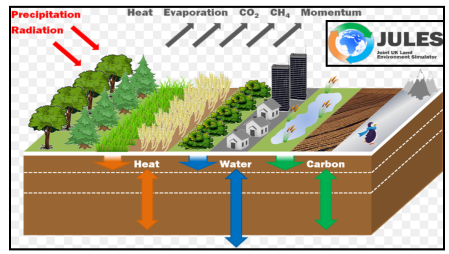
GFDL LM3



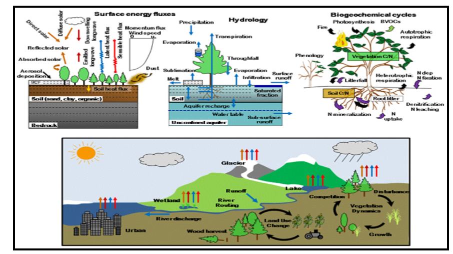
NOAA/ESRL RUC



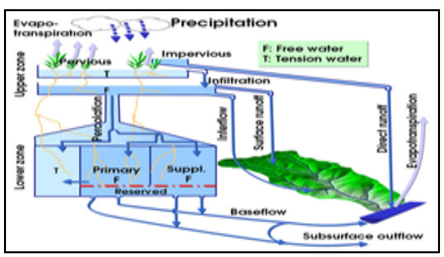
NASA Catchment



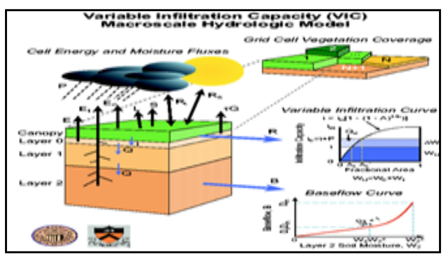
UKMO JULES



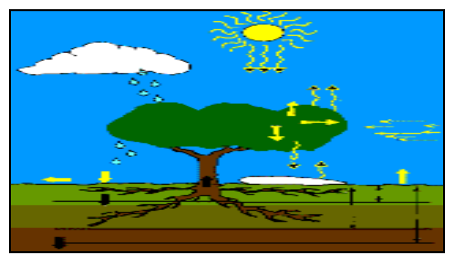
NCAR CLM



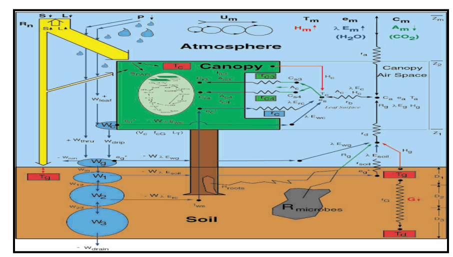
NWS SAC



UW/Princeton VIC



BATS



SiB

- A sampling –use dicates processes simulated and complexity.

- Land surface processes

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.

Two critical roles for a land surface model:

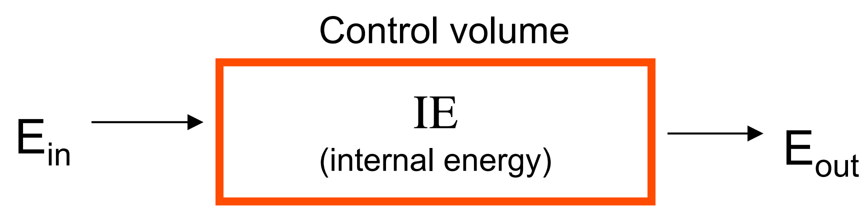
→ Partition incoming radiative energy into latent heat, sensible heat, heat storage, and outgoing radiative energy

→ Partition precipitation into evaporation, runoff, and water storage.

Energy Balance at the Land Surface

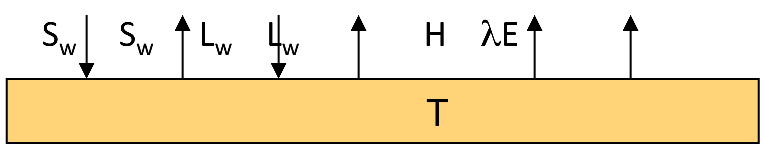
Basic energy balance equation:

$$E_{in}\Delta t = \Delta IE + E_{out}\Delta t$$



for a Single Land Surface Slab, Without Snow

Terms on LHS come from the climate model. Strongly dependent on cloudiness, water vapor, etc.



Terms on RHS are determined by the land surface model.

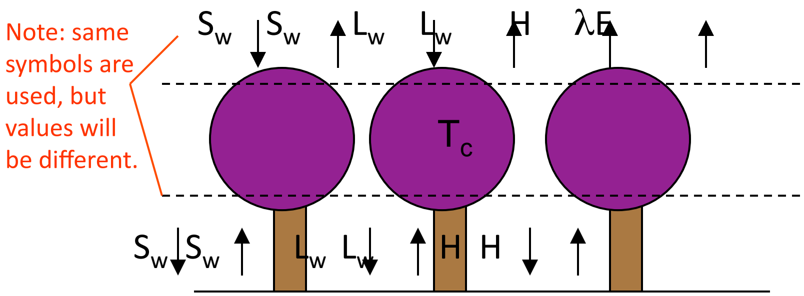
$$S_w^{\downarrow} + L_w^{\downarrow} = S_w^{\uparrow} + L_w^{\uparrow} + H + \lambda E + C_p\Delta T + \text{miscellaneous}$$

where

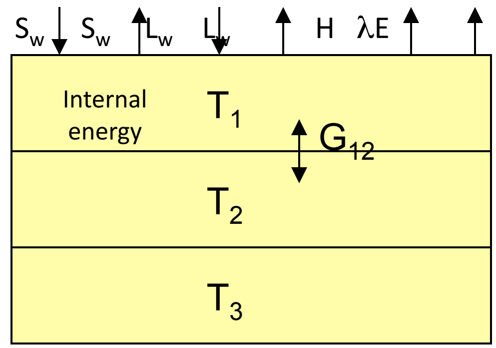
- $S_w^{\downarrow}$ = Incoming shortwave radiation
- $L_w^{\downarrow}$ = Downward longwave radiation
- $S_w^{\uparrow}$ = Reflected shortwave radiation
- $L_w^{\uparrow}$ = Upward longwave radiation
- H = Sensible heat flux
- λ = latent heat of vaporization
- E = Evaporation rate
- C_p = Heat capacity of surface slab
- ΔT = Change in slab's temperature, over the time step
- miscellaneous = energy associated with soil water freezing, plant chemical energy, heat content of precipitation, etc.

Energy balances considering additional layers

Energy balance of a vegetation canopy

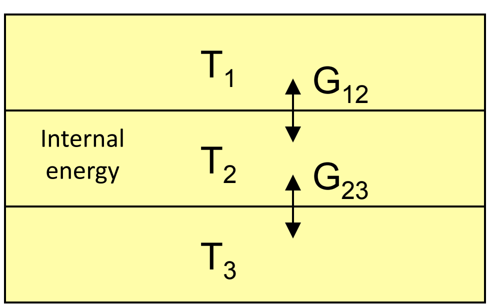


Energy balance in a surface layer

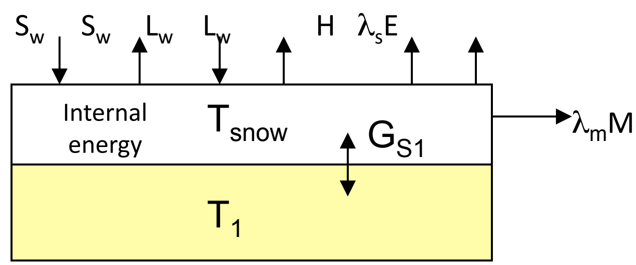


G_{12} = heat flux between soil layers 1 and 2

Energy balance in a subsurface layer



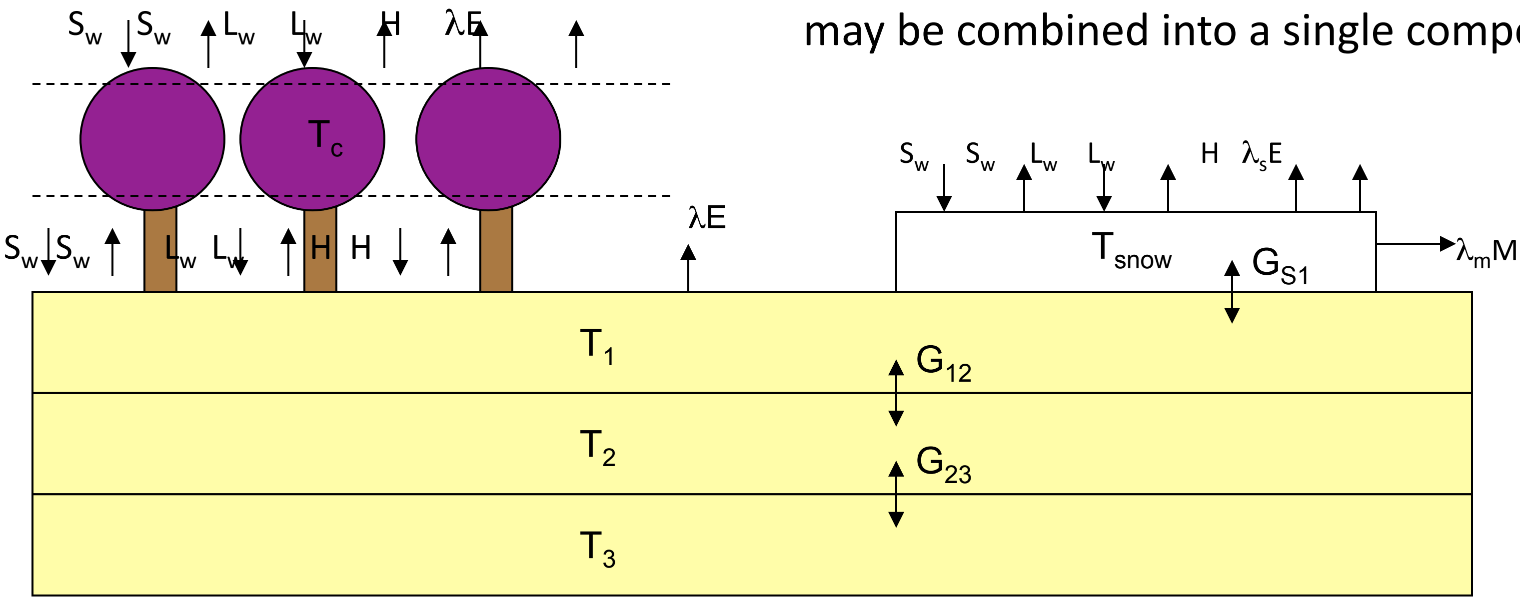
Energy balance in snowpack



λ_m = latent heat of melting
λ_s = latent heat of sublimation
M = snowmelt rate
G_{S1} = heat flux between bottom of pack and soil layer 1

Combinations

In practice, several energy balance calculations may be combined into a single component



Fluxes are usually kept consistent between the "control volumes". If the energy balance calculation for the snowpack includes a flux G_{S1} from the bottom of the pack to the ground, then the energy balance for the top soil layer must include an input flux of G_{S1}.

In this example, a total of five energy balances are included: canopy, snowpack, and three soil layers. Note that LSMs may include additional soil layers or may divide the snowpack itself into more layers, each with its own energy balance.

Radiation

$$S_w^{\downarrow} = \sum_{b=1}^{\#bands} S^{\downarrow}_{w,direct,band:b} + \sum_{b=1}^{\#bands} S^{\downarrow}_{w,diffuse,band:b}$$

reflectance for spectral band

$$S_w^{\uparrow} = \sum_{b=1}^{\#bands} S^{\downarrow}_{w,direct,band:b} * \alpha_{direct,band:b} + \sum_{b=1}^{\#bands} S^{\downarrow}_{w,diffuse,band:b} * \alpha_{diffuse,band:b}$$

Simplest description: without differentiating between diffuse and direct components:

$$Sw\uparrow = Sw\downarrow \, a$$

albedo

Typical albedo values :

sand	.18-.28
grassland	.16-.20
green crops	.15-.25
forests	.14-.20
dense forest	.05-.10
fresh snow	.75-.95
old snow	.40-.60
urban	.14-.18

Stefan-Boltzmann law: $L_w\uparrow = \varepsilon \, \sigma \, T^4$

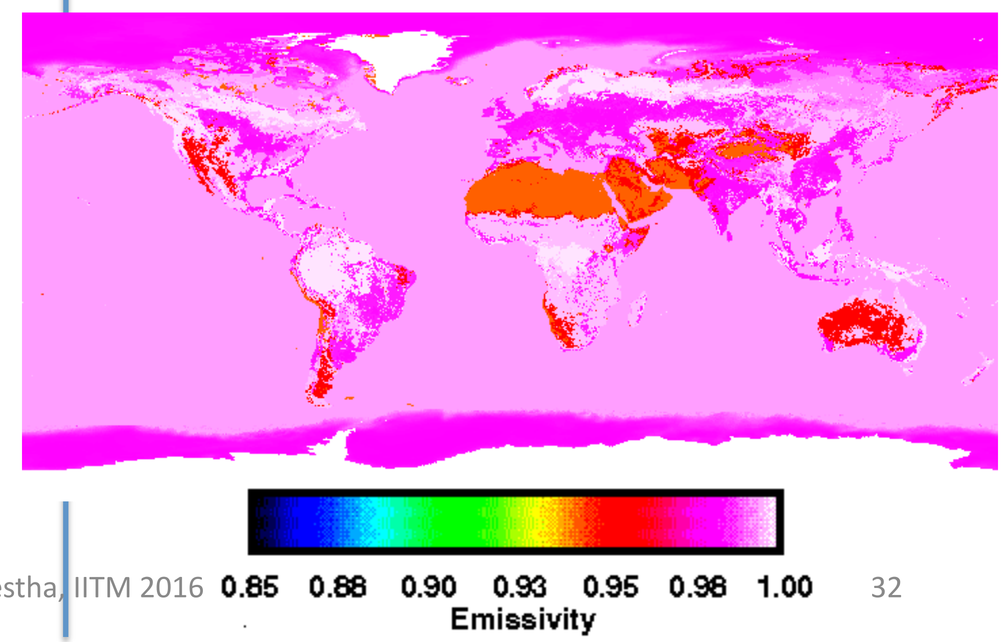
where ε = surface emissivity

σ = Stefan-Boltzmann constant

= 5.67×10^{-8} W/(m^{2}K^4)

T = surface temperature (K)

Emissivities of natural surfaces tend to be slightly less than 1, and they vary with water content. For simplicity, many models assume $\varepsilon = 1$ exactly.



Heat Fluxes

Sensible heat flux (H)

Spatial transfer of the "jiggly-ness" of molecules, as represented by temperature

Equation commonly used in climate models:

$H = \rho\, c_p\, C_H\, |V|\, (T_s - T_r)$,

where

ρ = mean air density

c_p = specific heat of air, constant pressure

C_H = exchange coefficient for heat

$|V|$ = wind speed at reference level

T_s = surface temperature

T_r = air temperature at reference level (e.g., lowest GCM grid box)

For convenience, we can write this in terms of the aerodynamic resistance, r_a:

$$H = \frac{\rho\, c_p\, (T_s - T_r)}{r_a}$$

where $r_a = 1/(C_H\, |V|)$

Latent Heat Flux (LE):

The energy used to transform liquid (or solid) water into water vapor

Latent heat flux from a liquid surface: $\lambda_v E$

where

E = evaporation rate (flux of water molecules away from surface)

λ_v = latent heat of vaporization $= (2.501 - .002361T) \times 10^6$ J/kg (approx)

Latent heat flux from an ice surface: $\lambda_s E$

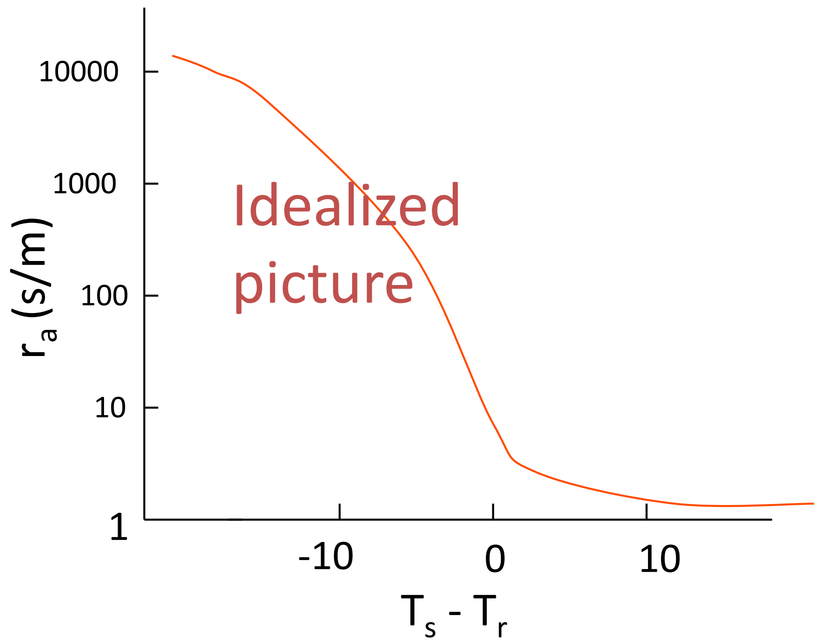
where

λ_s = latent heat of sublimation $= \lambda_v + \lambda_m$

λ_m = latent heat of melting $= 3.34 \times 10^5$ J/kg (approx)

For simplicity, λ_v and λ_s shall be assumed constant. Thus the latent heat flux estimation shall be discussed in terms of the evaporation calculation.

r_a : the aerodynamic resistance represents the difficulty with which heat (jiggliness of molecules) can be transferred through the near surface air. This difference is strongly dependent on wind speed, roughness length, and buoyancy, which itself varies with temperature difference:



$e_s(T)$ = saturation vapor pressure: the vapor pressure at which the condensation vapor onto a surface is equal to the upward flux of vapor from the surface.

$e_s(T)$ varies as $\exp(-0.622 \frac{\lambda}{R_d T})$

$$e_s(T) = \exp(21.18123 - 5418/T)/0.622$$

Mass of vapor per mass of air

Specific humidity, q:

$$q_r = 0.622\ e_r/p$$

(p = surface pressure, e_r = vapor pressure)

Four evaporation components

Transpiration: The flux of moisture drawn out of the soil and then released into the atmosphere by plants.

Bare soil evaporation: Evaporation of soil moisture without help from plants.

Interception loss: Evaporation of rainwater that sits on leaves and ground litter without ever entering the soil

Snow evaporation: sublimation from the surface of the snowpack

Evaporation from a fully wetted surface ($=E_p$)

Here's the famous Penman equation:

"equilibrium evaporation for a saturated air mass passing over a wet surface"

contribution due to subsaturated air

Contains terms that are relatively easy to measure

$$E_{penman} = \frac{(R_{net} - G)\Delta + (\rho c_p / r_a)(e_s(T_r) - e_r)}{\Delta + \gamma}$$

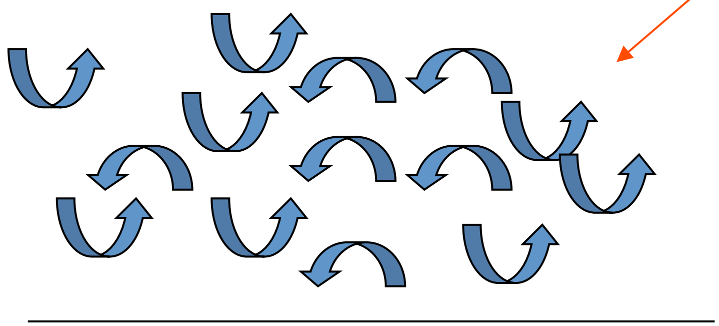
$\Delta = d(e_s)/dT$ $\gamma = c_p p/(0.622\lambda)$ G = heat flux into ground R_{net} = net radiation

The Penman equation can be shown to be equivalent to the following equation, which lies at the heart of the potential evaporation calculation used in many climate models:

$$E_p = \frac{0.622\rho}{p} \frac{e_s(T_s) - e_r}{r_a}$$

A simple rationale:

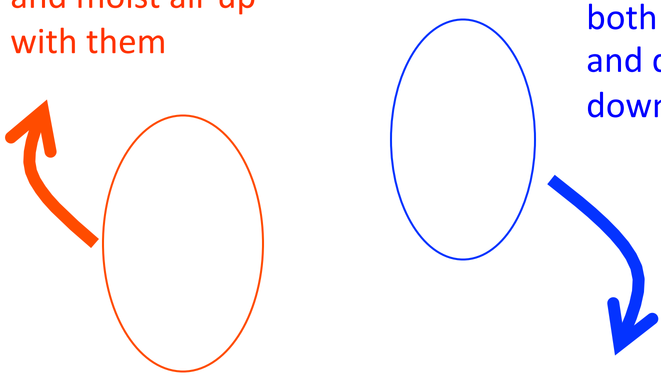
The air is full of eddies. Buoyancy tends to make warm pockets of air rise and cool ones sink.



Land surface

Rising warm pockets bring both warm air and moist air up with them

Descending cool pockets bring both cool air and dry air down with them

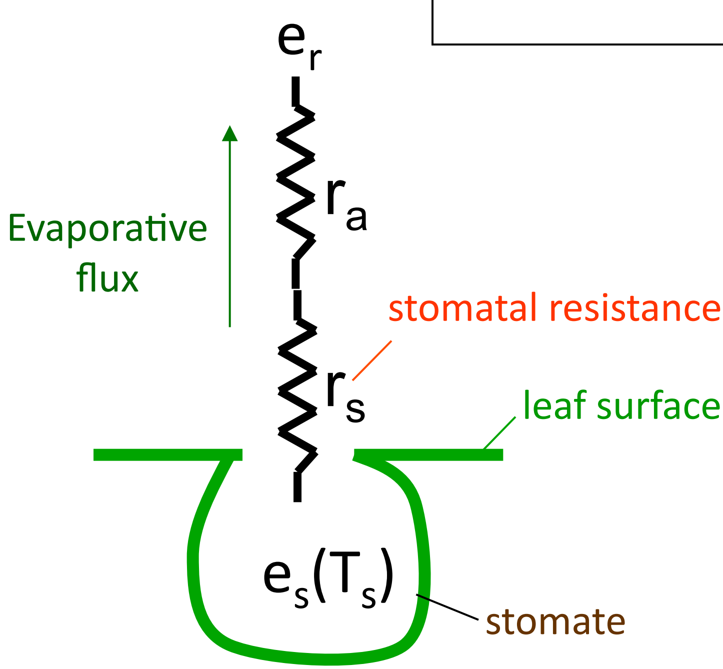


In other words, the same process contributes to both sensible heat flux and evaporation flux. Thus, the same “resistance” applies.

Simplest model for transpiration:

Equation that lies at the heart of standard land surface models!

$$E = \frac{0.622\rho}{p} \frac{e_s(T_s) - e_r}{r_a + r_s}$$



- -- Assumes saturated conditions within plant stomata
- -- Assumes the plant/soil system determines r_s, the stomatal resistance.
- -- Employs "Ohm's Law" analogy, placing stomatal and aerodynamic resistances in series.

Note: above equation is equivalent to the famous Penman-Monteith evaporation equation

$$E_{penman\text{-}monteith} = \frac{(R_{net} - G)\,\Delta + (\rho c_p / r_a)\,(e_s(T_r) - e_r)}{\Delta + \gamma\,(1 + r_s/r_a)}$$

Stomatal resistance is not easy to quantify.

r_s varies with:

- -- plant type and age
- -- photosynthetically active radiation (PAR)
- -- soil moisture (w)
- -- ambient temperature (T_a)
- -- vapor pressure deficit (VPD)
- -- ambient carbon dioxide concentrations

Effective r_s for a full cano
leaf distribution, etc. r

Modeling stomata

"Jarvis-type" models
Many newer models

Key point: Because plant
environmental stress, r_s i
times of environmental s

Minimum Stomatal Resistance [sec m-1}] (from BATS and CLSM, via LDAS)		**Optimal temperature range (K)** From SiB, as used in Mosaic	**Wilting point matric potential (m)** From SiB, as used in Mosaic
1. Evergreen Needleleaf Forest	175	268-313	-250.
2. Evergreen Broadleaf Forest	150	273-318	-500
3. Deciduous Needleleaf Forest	175		
4. Deciduous Broadleaf Forest	175	273-318	-250.
5. Mixed Cover	175		
6. Woodland	173.		
7. Wooded Grassland	169.		
8. Closed Shrubland	175	283-323	-400
9. Open Shrubland	178.		
10. Grassland	165	283-328	-230.
11. Cropland	117		
12. Bare Ground	175		
13. Urban and Built-Up	154.		

Typical approaches to modeling latent heat flux (summary)

Transpiration

$$\lambda_v E = \frac{0.622\lambda_v\rho}{p}\frac{e_s(T_s) - e_r}{r_a + r_s}$$

Evaporation from bare soil

$$\lambda_v E = \frac{0.622\lambda_v\rho}{p}\frac{e_s(T_s) - e_r}{r_a + r_{surface}}$$

Resistance to evaporation imposed by soil

Interception loss

$$\lambda_v E = \frac{0.622\lambda_v\rho}{p}\frac{e_s(T_s) - e_r}{r_a}$$

Note: more complicated forms are possible, e.g., inclusion (in series) of a subcanopy aerodynamic resistance.

Snow evaporation

$$\lambda_s E = \frac{0.622\lambda_s\rho}{p}\frac{e_s(T_s) - e_r}{r_a}$$

HEAT FLUX INTO THE SOIL

One layer soil model: Let G be the residual energy flux at the land surface, i.e.,

$$G = S_w\downarrow + L_w\downarrow - S_w\uparrow - L_w\uparrow - H - \lambda E$$

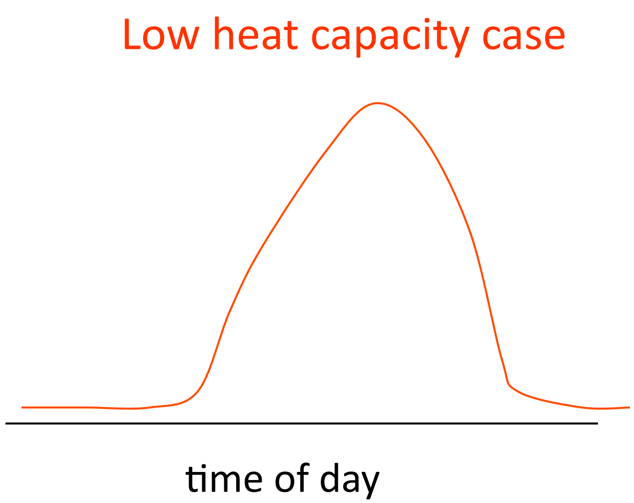
Then the temperature of the soil, T_s, must change by ΔT_s so that

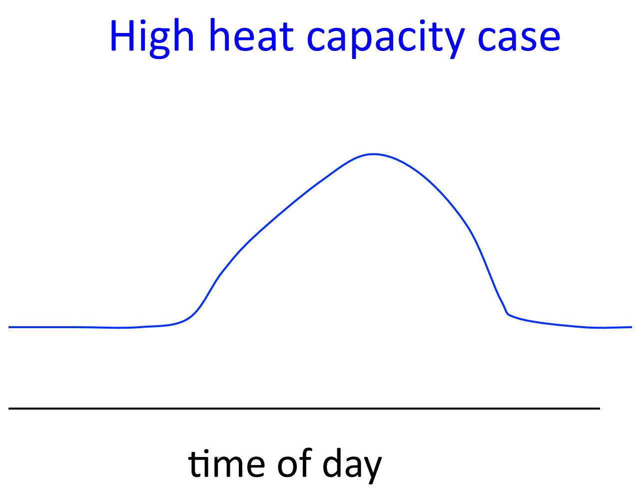
$$G = C_p \Delta T_s / \delta t$$

where

C_p is the heat capacity
δt is the time step length (s)

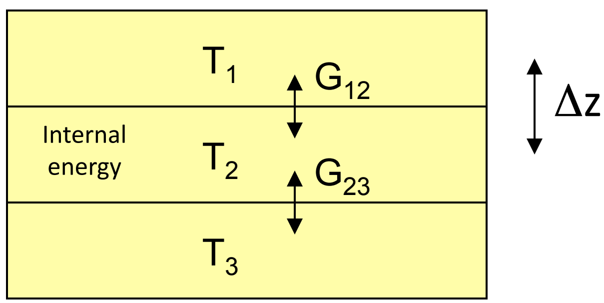
The choice of the heat capacity can have a major impact on the surface energy balance.





-- Heat capacity might, for example, be chosen so that it represents the depth to which the diurnal temperature wave is felt in the soil.
-- Note that heat capacity increases with water content. Incorporating this effect correctly can complicate energy balance calculations.

Heat Flux Between Soil Layers

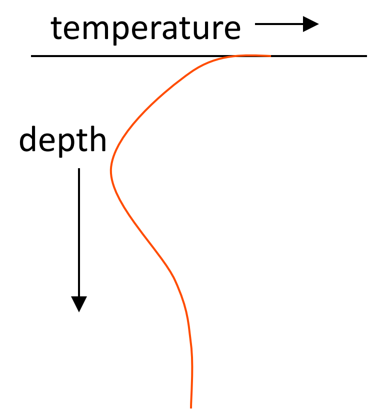


One simple approach:

$$G_{12} = \Lambda\,(T_1 - T_2) / \Delta z$$

where

Λ = thermal conductivity
Δz = distance between centers of soil layers.



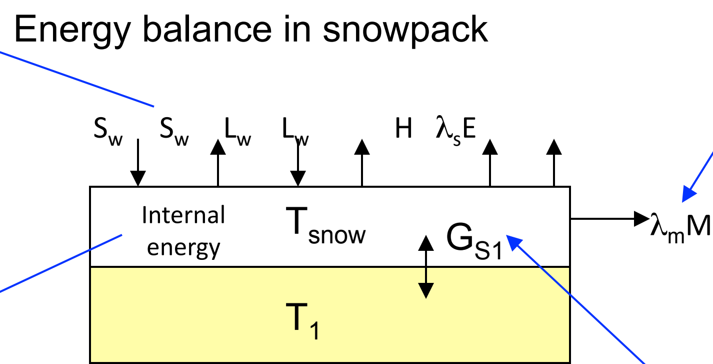
-- Using multiple layers rather than a single layer allows the temperature of the surface layer (which controls fluxes) to be more accurate.

-- Like heat capacity, thermal conductivity increases with water content. Accounting for this is comparatively easy.

Snow modeling

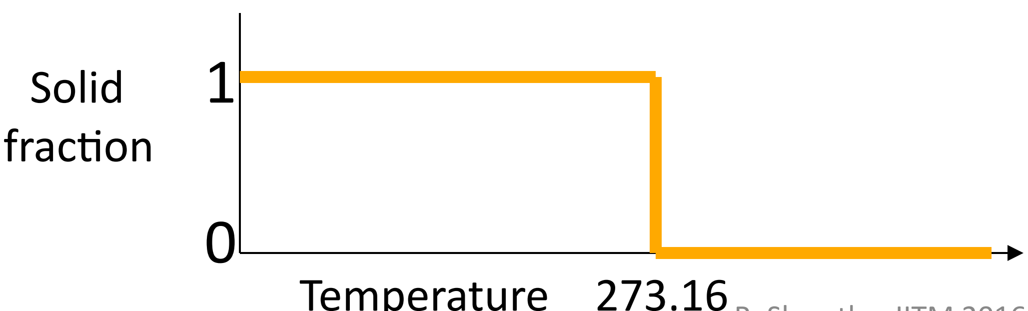
Albedo is high when the snow is fresh, but it decreases as the snow ages.

Internal energy a function of snow amount, snow temperature, and liquid water retention



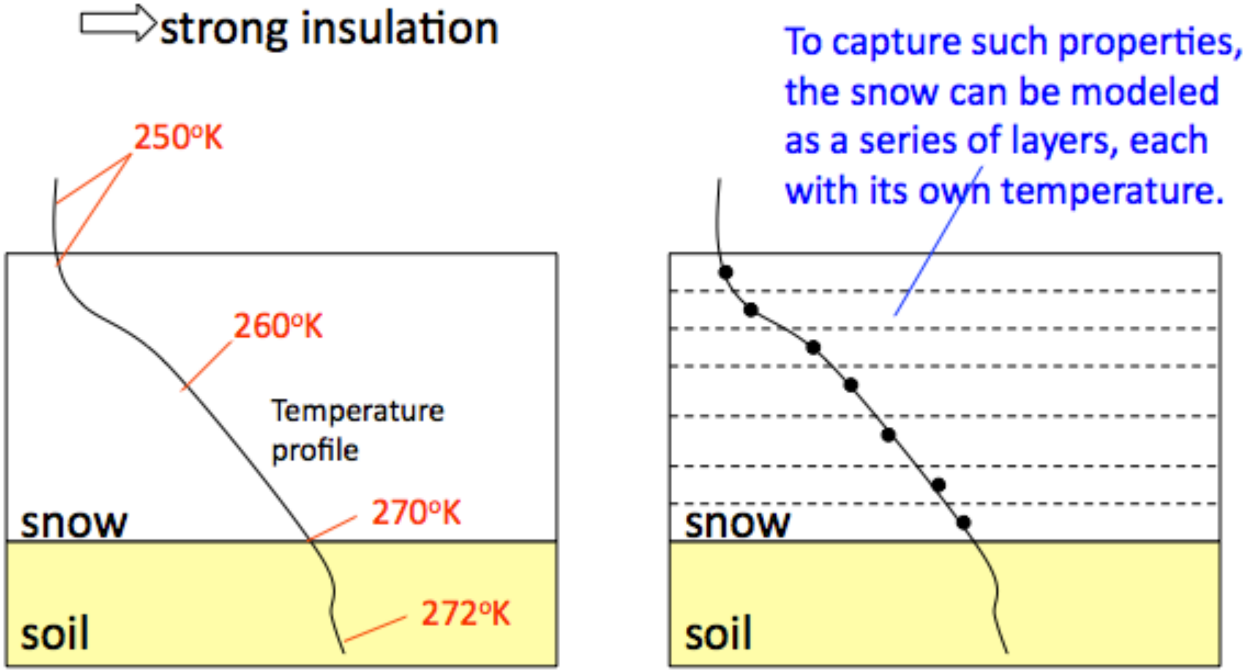
Snowmelt occurs only when snow temperature reaches 273.16°K.

Thermal conductivity within snow pack varies with snow age. It increases with snow density (compaction over time) and with liquid water retention.



Snow profile Temperature

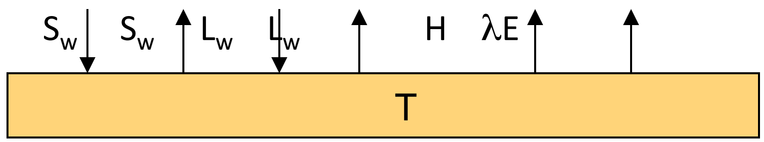
Critical property of snow: Low thermal conductivity
⇨strong insulation



One way:

1. Solve the energy balance for a layer, and determine the updated temperature.
2. If the new temperature is less than or equal to 273.16ºK, then we're done.
3. If the new temperature is greater than 273.16ºK, then recompute the energy balance assuming the new temperature is exactly 273.16ºK.

SOLVING THE ENERGY BALANCE EQUATION



$$S_w^{\downarrow} + L_w^{\downarrow} = S_w^{\uparrow} + L_w^{\uparrow} + H^{\uparrow} + \lambda E + C_p \Delta T/\delta t$$

The key to solving the energy balance equation is to notice that all fluxes on the right hand side of the equation (except $S_w^{\uparrow}$) are functions of the temperature, T_s.

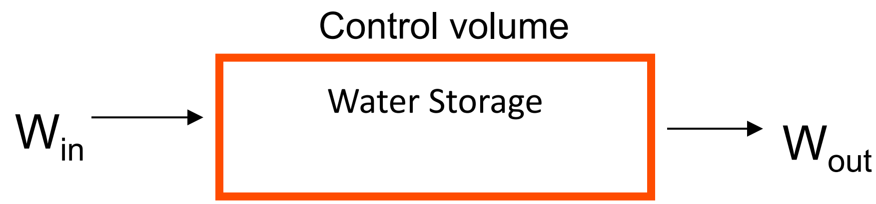
Simplest calculation: Assume heat capacity of surface is zero.

$$S_w^{\downarrow} + L_w^{\downarrow} = S_w^{\uparrow} + f(T_s) \quad \Rightarrow \quad \text{Solve for } T_s$$

Water Balance at the Land Surface

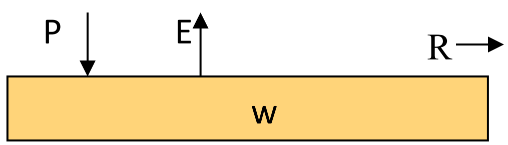
Basic water balance equation:

$$W_{in}\Delta t \; = \; \Delta storage \; + \; W_{out}\Delta t$$



Water Balance for a Single Land Surface Slab, Without Snow
(e.g., standard bucket model)

Terms on LHS come from the climate model. Strongly dependent on cloudiness, water vapor, etc.



Terms on RHS come are determined by the land surface model.

$$P \quad = E + R + C_w \Delta w/\Delta t + \text{miscellaneous}$$

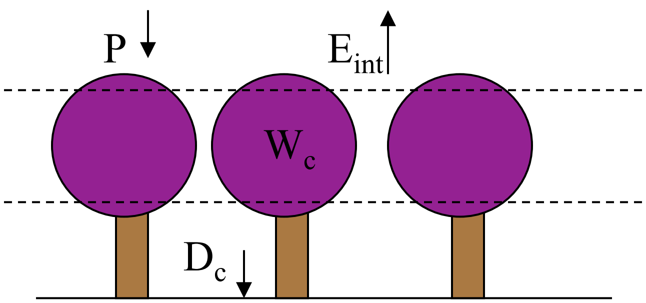
where
- P = Precipitation
- E = Evaporation
- R = Runoff (effectively consisting of surface runoff *and* baseflow)
- C_w = Water holding capacity of surface slab
- Δw = Change in the degree of saturation of the surface slab
- Δt = time step length

miscellaneous = conversion to plant sugars, human consumption, etc.

Simplified water balance

A combination of water balances :

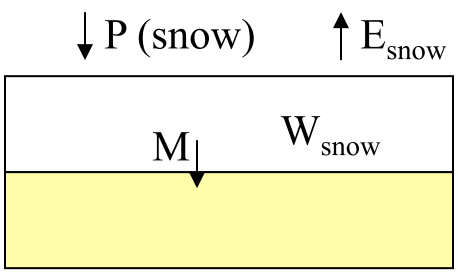
Water balance associated with canopy interception reservoir



$$P = E_{int} + D_c + \frac{\Delta W_c}{\Delta t}$$

E_{int} = interception loss
D_c = drainage through canopy ("throughfall")
ΔW_c = change in canopy interception storage

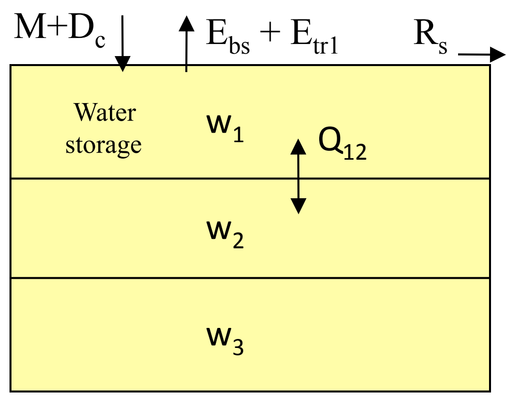
Water balance in a snowpack



$$P = E_{snow} + M + \frac{\Delta W_{snow}}{\Delta t}$$

E_{snow} = sublimation rate
M = snowmelt
ΔW_{snow} = change in snow amount ("infinite" capacity possible)

Water balance in a surface layer

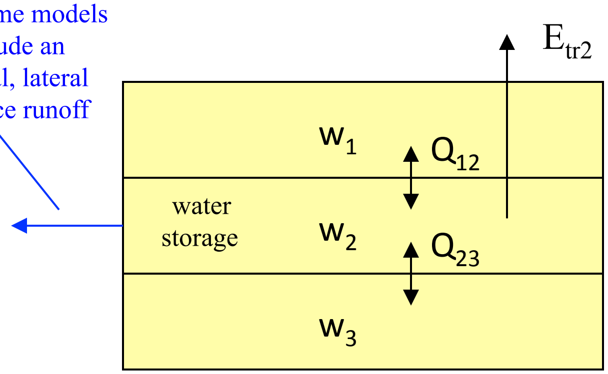


$$M + D_c = E_{bs} + E_{tr1} + R_s + Q_{12} + C_{W1}\Delta W_1/\Delta t$$

E_{bs} = evaporation from bare soil
E_{tr1} = evapotranspiration from layer 1
Q_{12} = water transport from layer 1 to layer 2
C_{W1} = water holding capacity of layer 1
ΔW_1 = change in degree of saturation of layer 1

Water balance in a subsurface layer (e.g., 2nd layer down)

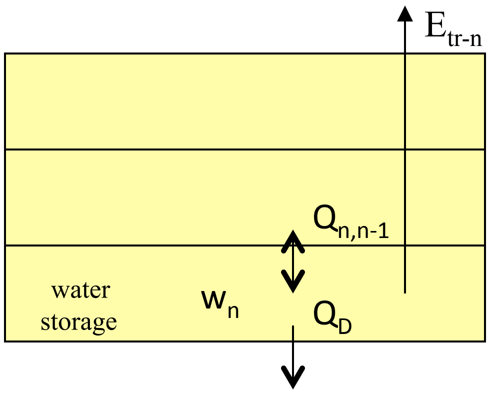
Note: some models may include an additional, lateral subsurface runoff term



$$Q_{12} = Q_{23} + E_{tr2} + C_{W2}\Delta W_2/\Delta t$$

E_{tr2} = evapotranspiration from layer 2
Q_{23} = water transport from layer 2 to layer 3
C_{W2} = water holding capacity of layer 2
ΔW_2 = change in degree of saturation of layer 2

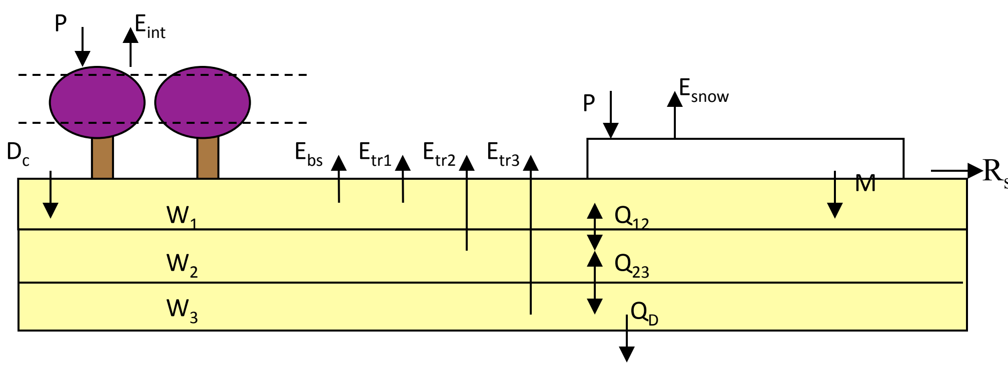
Water balance in the lowest layer



$$Q_{n,n-1} = Q_D + E_{tr-n} + C_{Wn}\Delta W_n/\Delta t$$

E_{tr-n} = evapotranspiration from layer n, if allowed
Q_D = Drainage out of the soil column (baseflow)

A model may compute all of these water balances, taking care to ensure consistency between connecting fluxes (in analogy with the energy balance calculation).



Precipitation, P

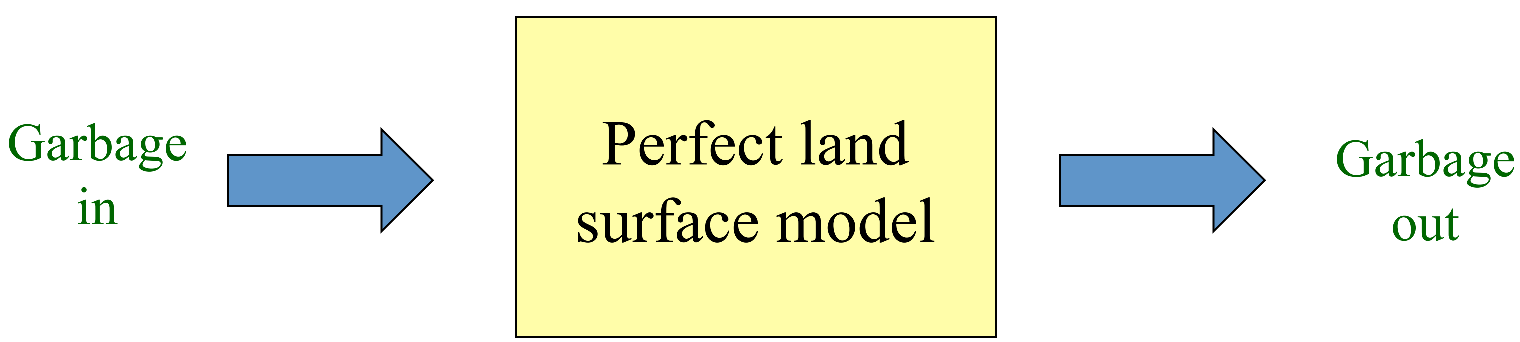
Getting the land surface hydrology right in a climate model is difficult largely because of the precipitation term. At least three aspects of precipitation must be handled accurately:

a. Spatially-averaged precipitation amounts (along with annual means and seasonal totals)

b. Subgrid distribution.

c. Temporal variability and temporal correlations.

Otherwise, even with a perfect land surface model,



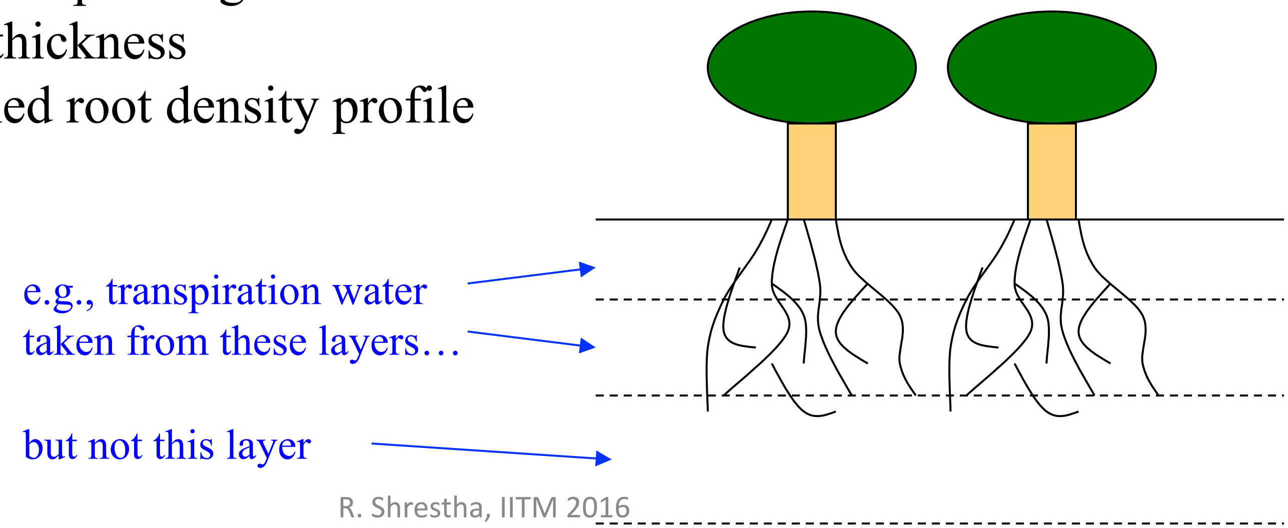
Evaporation

Evaporation is important in water balance as it was in energy balance. Note, though, locations of moisture sinks for bare soil evaporation and transpiration:

Bare soil evaporation water is usually taken from the top soil layer.

Transpiration water is usually taken from the soil layers that comprise the root zone. Different amounts may be taken from different layers depending on:

-- layer thickness
-- assumed root density profile



Runoff

a. Overland flow:

(i) flow generated over permanently saturated zones near a river channel system: "Dunne" runoff

(ii) flow generated because precipitation rate exceeds the infiltration capacity of the soil (a function of soil permeability, soil water content, etc.): "Hortonian" runoff

b. Interflow (rapid lateral subsurface flow through macropores and seepage zones in the soil

c. Baseflow (return flow to stream system from groundwater)

Runoff (streamflow) is affected by such things as:

-- Spatial and temporal distributions of precipitation
-- Evaporation sinks
-- Infiltration characteristics of the soil
-- Watershed topography
-- Presence of lakes and reservoirs

Energy balance versus water balance

Energy balance:
Implicit solution usually necessary
Results in updated temperature prognostics

Water balance:
Implicit solution usually not necessary
Results in updated water storage prognostics

How are the energy and water budgets connected?

1. Evaporation appears in both.
2. Albedo varies with soil moisture content.
3. Thermal conductivity varies with soil moisture content.
4. Thermal emissivity varies with soil moisture content.

Question: Can we address how the energy and water budgets *together* control evaporation rates?

Budyko's analysis of energy and water controls over evaporation

Let P = annual precipitation (mm/day)

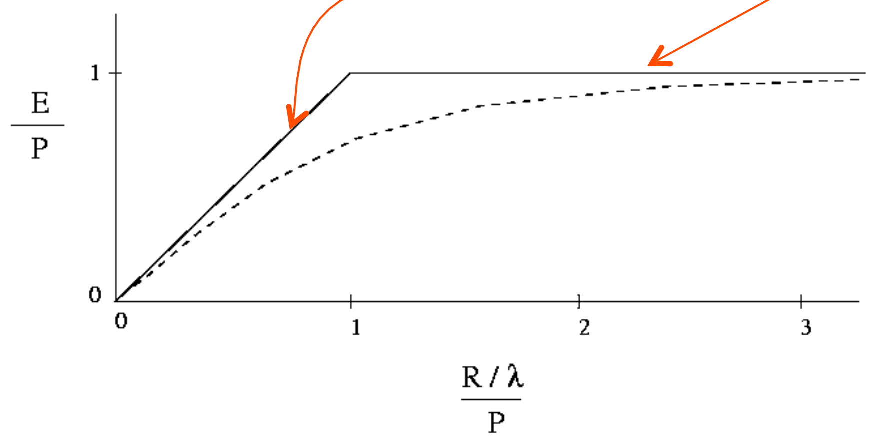
R/λ = annual net radiation (scaled to units of mm/day)

E = annual evaporation (mm/day)

Budyko (1974) first assumed that:

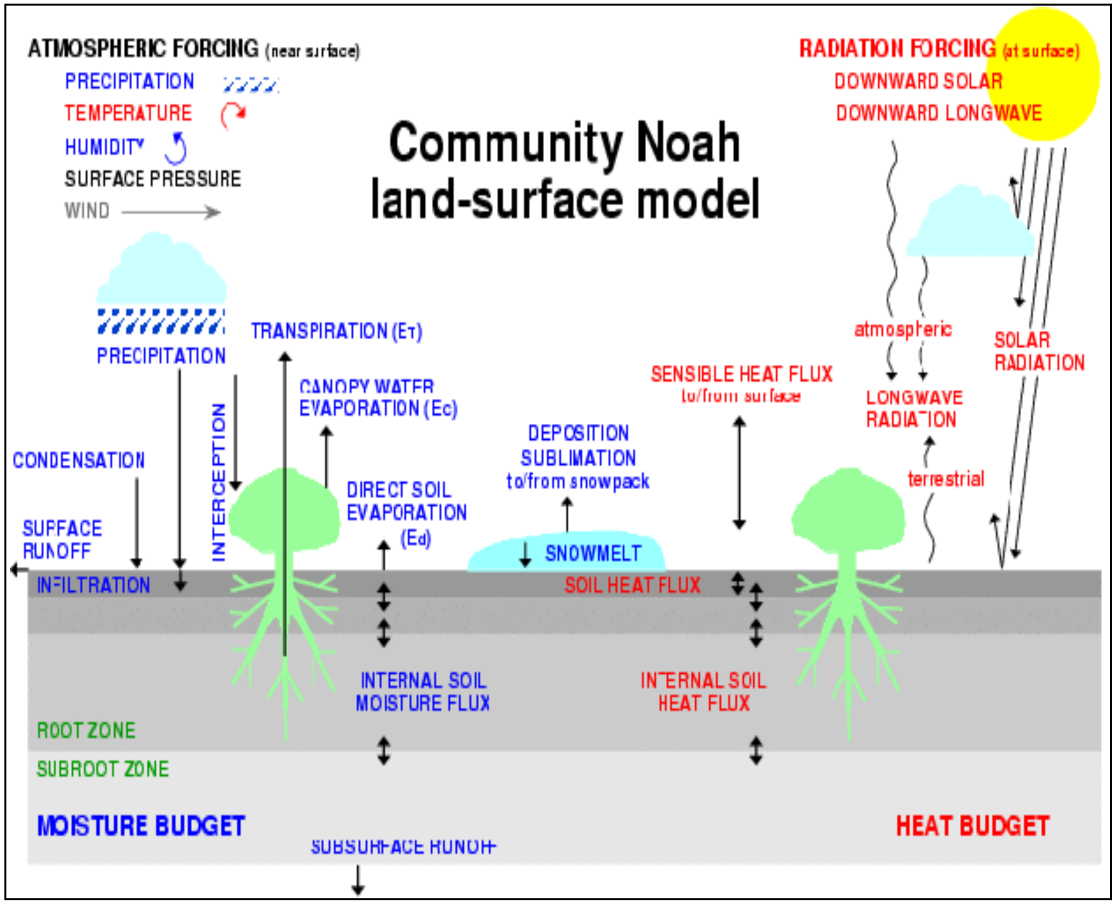
1. E can be no greater than P and R/λ (in the absence of year-to-year storage changes).
2. For $\frac{R}{\lambda} \gg P$, $E \longrightarrow P$
3. For $\frac{R}{\lambda} \ll P$, $E \longrightarrow \frac{R}{\lambda}$

These assymptotes act as barriers to evaporation.



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, etc.

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 (C_w):

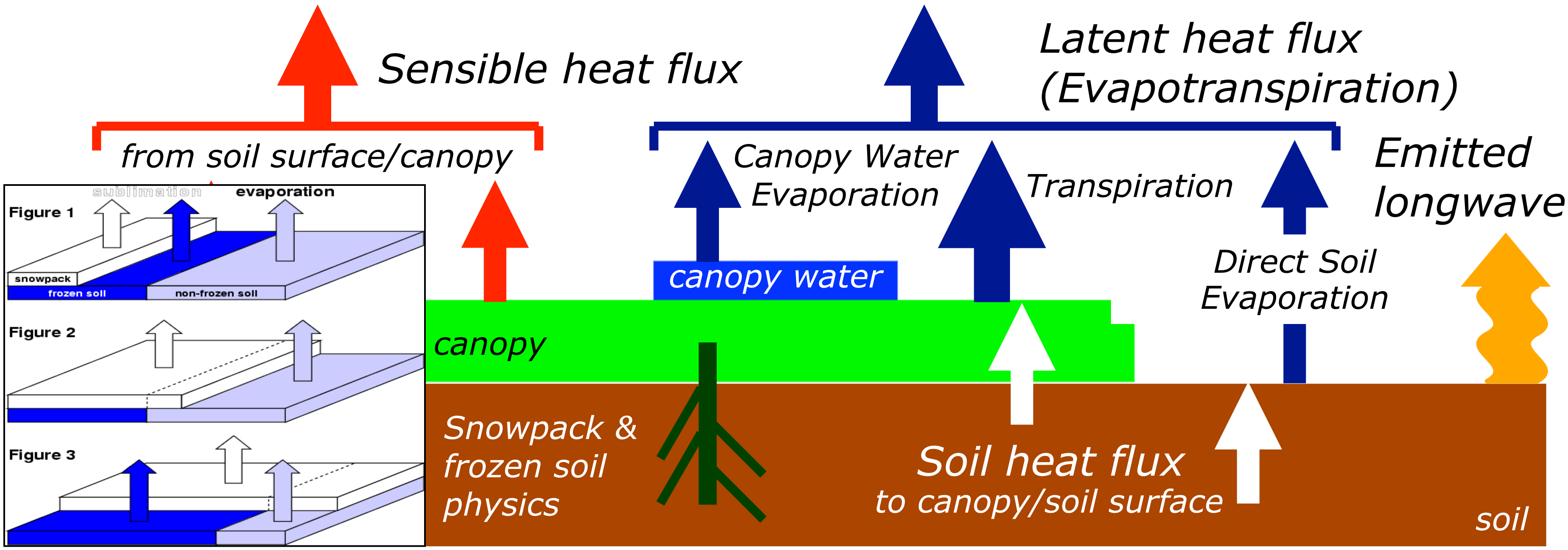
$$\frac{\partial C_w}{\partial t} = P - E_c$$

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

Land Physics: Flux Boundary Conditions

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

$$\mathrm{LE} = \mathrm{LE_c} + \mathrm{LE_t} + \mathrm{LE_d}$$



- **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,**

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

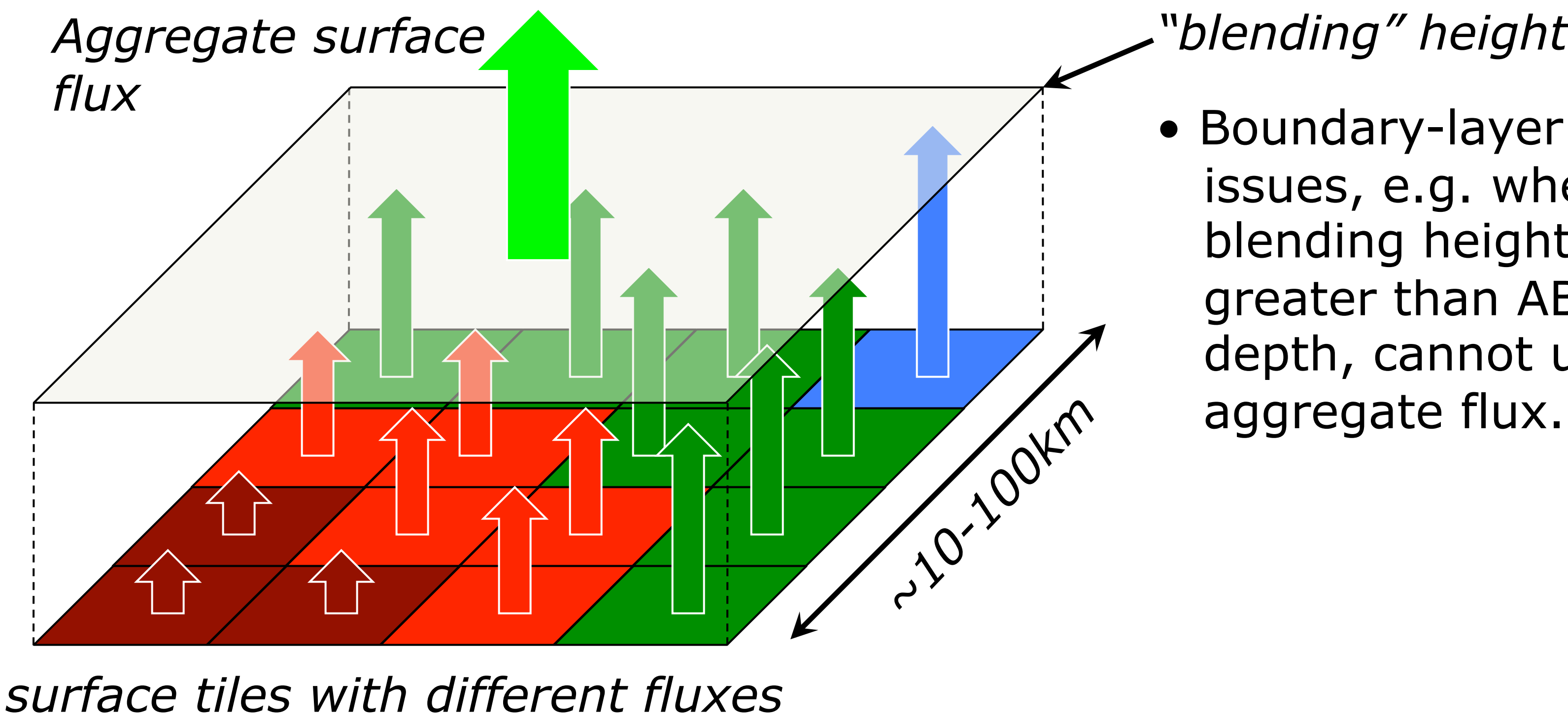
$$R_n = \mathrm{H} + \mathrm{LE} + \mathrm{G}$$

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.

- Land surface modeling

Land Physics: Tiled Land Grid

- A land model grid may comprise sub-atmospheric-grid-scale "tiles", e.g. forest, shrubland, grass, crop, water, etc, O(1-4km).
- Coarser-resolution atmospheric forcing to land.
- Aggregate flux to "parent" atmospheric model.



- Boundary-layer issues, e.g. when blending height is greater than ABL depth, cannot use aggregate flux.

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.

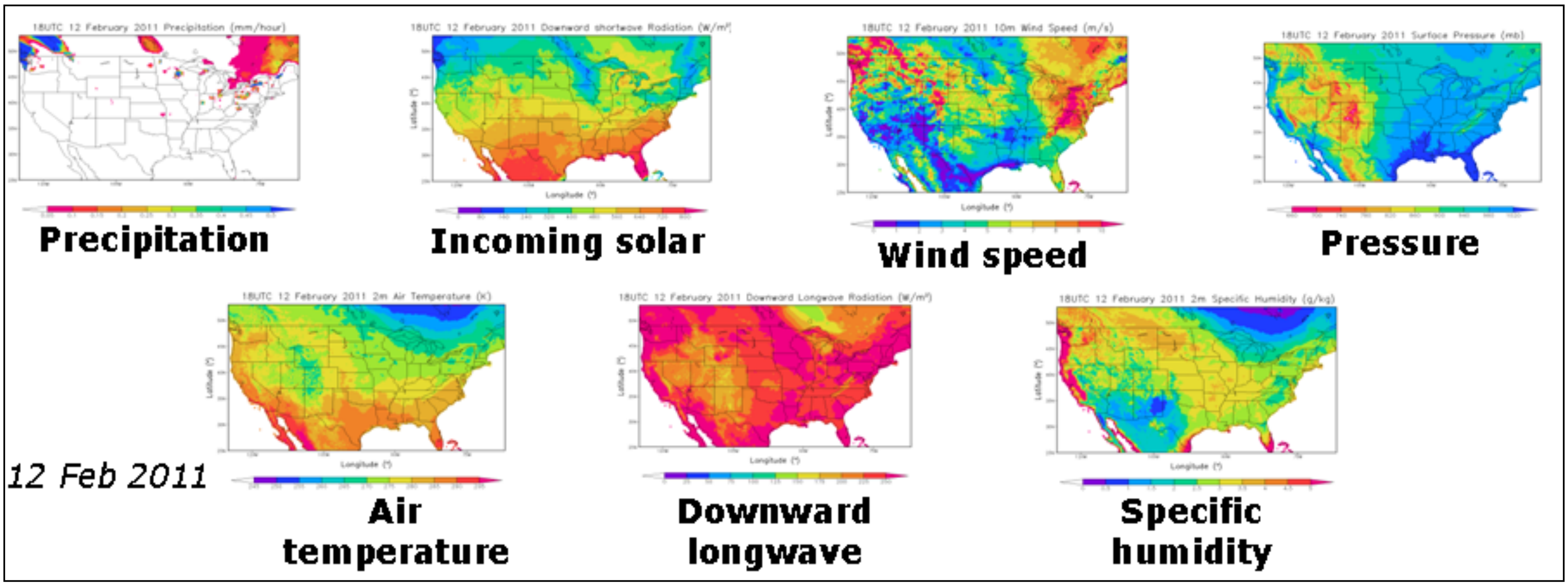
- Depth of snow (snow water equivalent) for deep snow and assumption of **maximum snow albedo**
  is a function of **vegetation type**.

- **Heat transfer through vegetation** and into the soil
  is 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).

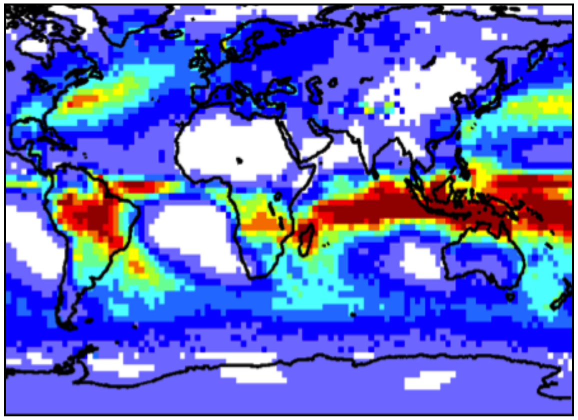
Atmospheric Forcing to Land Model

- 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 precipitation 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".

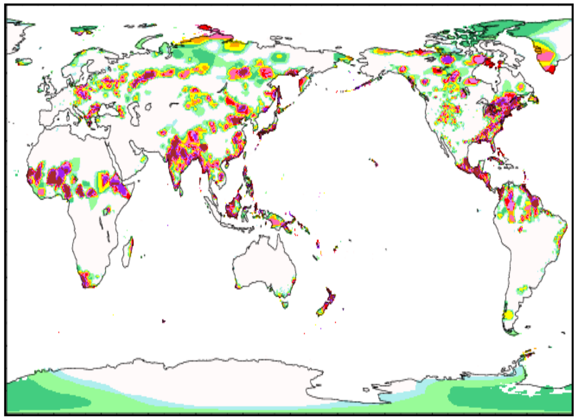


Atmospheric Forcing: Precipitation

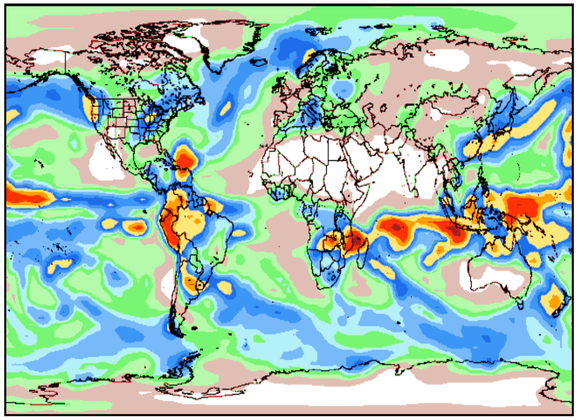
- Global Land Data Assimilation System (GLDAS) used in NCEP Climate Forecast System (CFS) relies on "blended" precipitation product, function of:
- **Satellite-estimated precipitation** (CMAP), heaviest weight in tropics where gauges sparse.
- Surface gauge network, heaviest in mid-latitudes.
- High-latitudes: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



CMAP



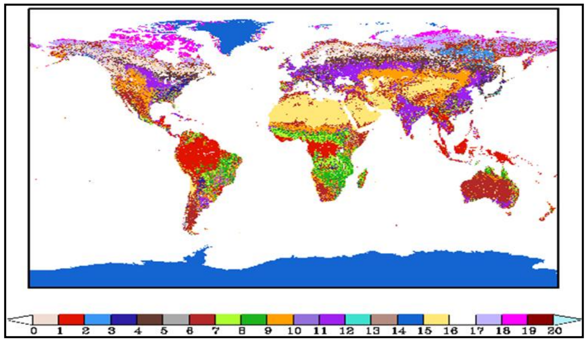
Surface gauge



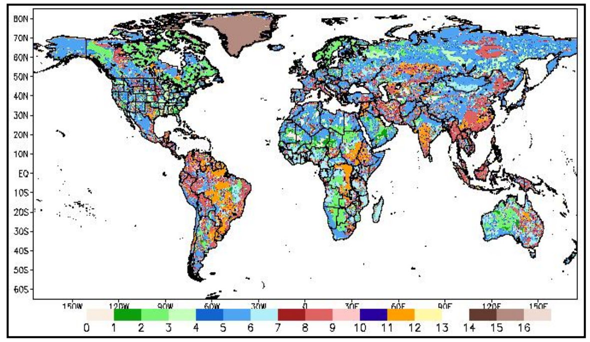
GDAS (model)

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

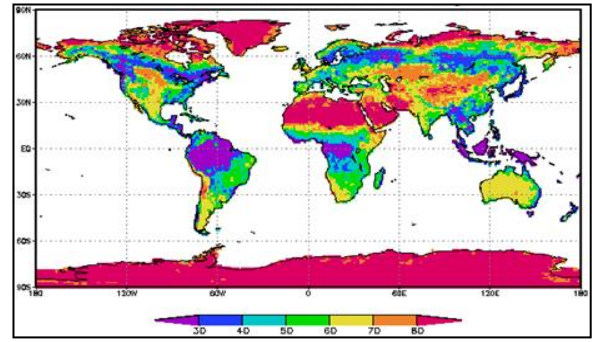
Land Data Sets



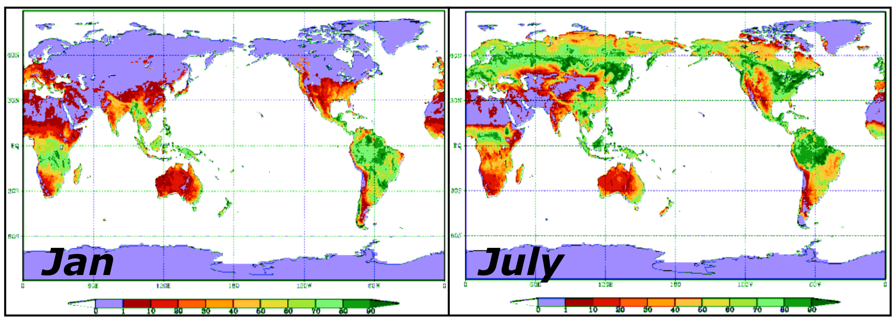
Vegetation Type
(1-km, IGBP-MODIS)



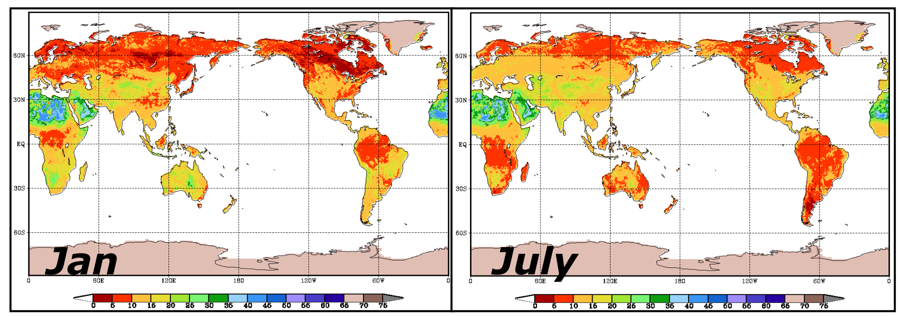
Soil Type
(1-km, STATSGO-FAO)



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



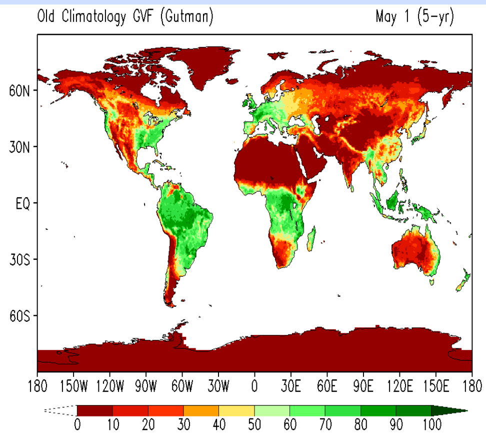
Green Vegetation Fraction
(monthly, 1/8-deg, NESDIS/AVHRR)



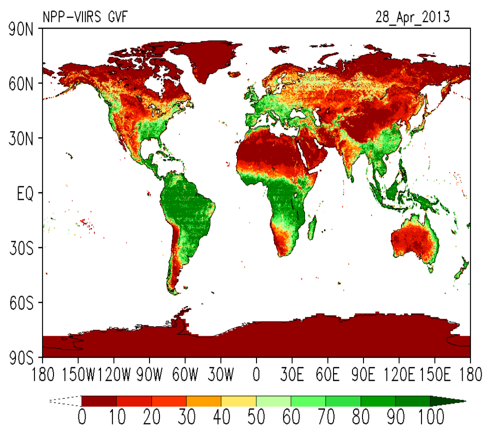
Snow-Free Albedo
(monthly, 1-km, Boston Univ.-MODIS)

- 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.

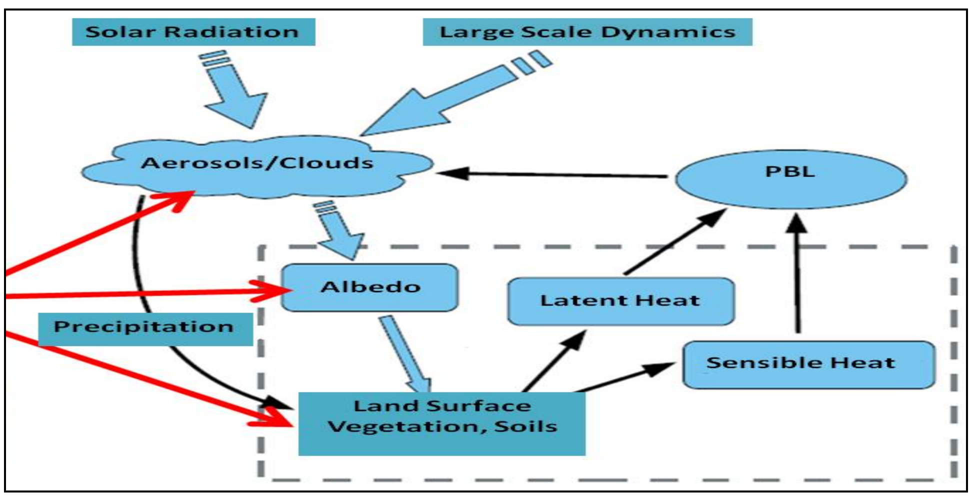
Land Data Sets: Green Vegetation Fraction (GVF) and Wildfire Effects



AVHRR 5-YR Climatology



VIIRS near-realtime

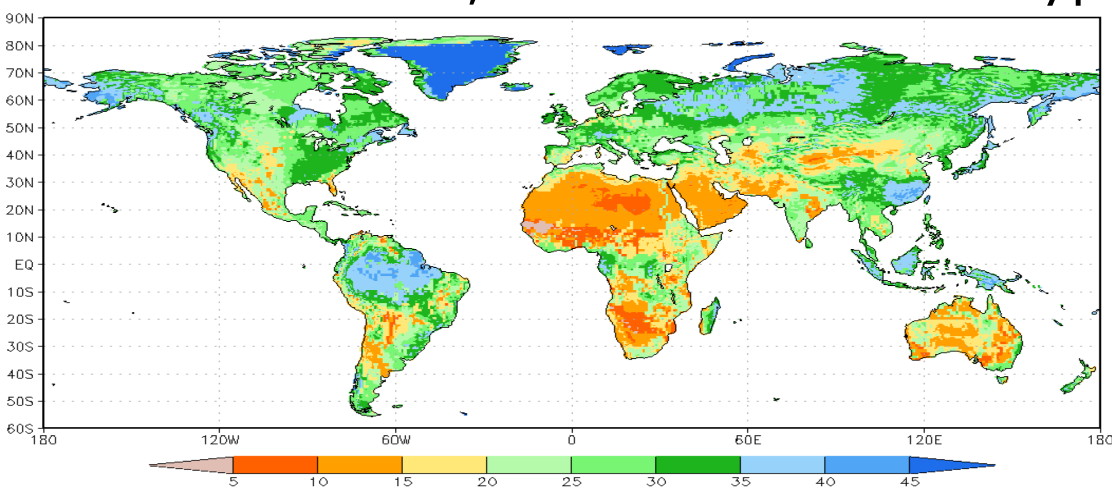


- Use of near realtime GVF leads to better partition between surface heating & evaporation --> impacts surface energy budget, ABL evolution, clouds/convection.
- **Wildfires** affect weather and climate systems: (1) atmos-pheric circulations, (2) aero-sols/clouds, (3) land surface states (GVF, albedo & 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).

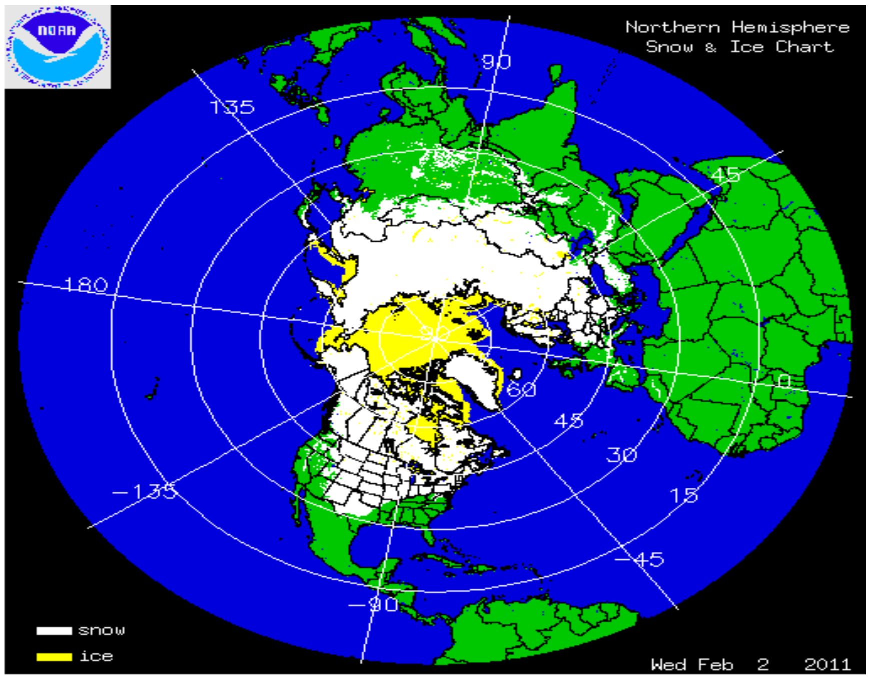


***May Soil Moisture Climatology** from 30-year NCEP Climate Forecast System Reanalysis (CFSR), spun up from Noah land model coupled with CFS.*

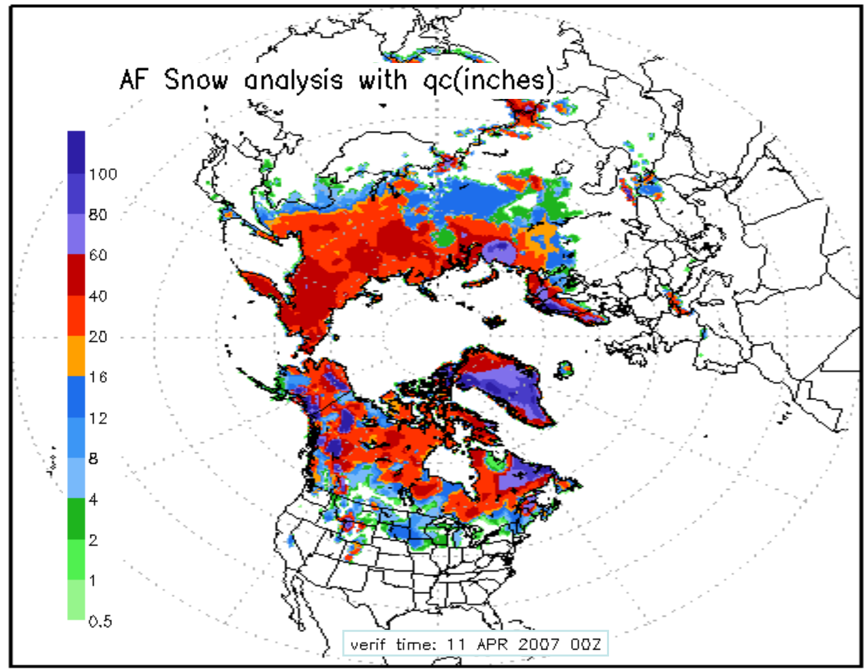
Jesse Meng NCEP/EMC

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*.

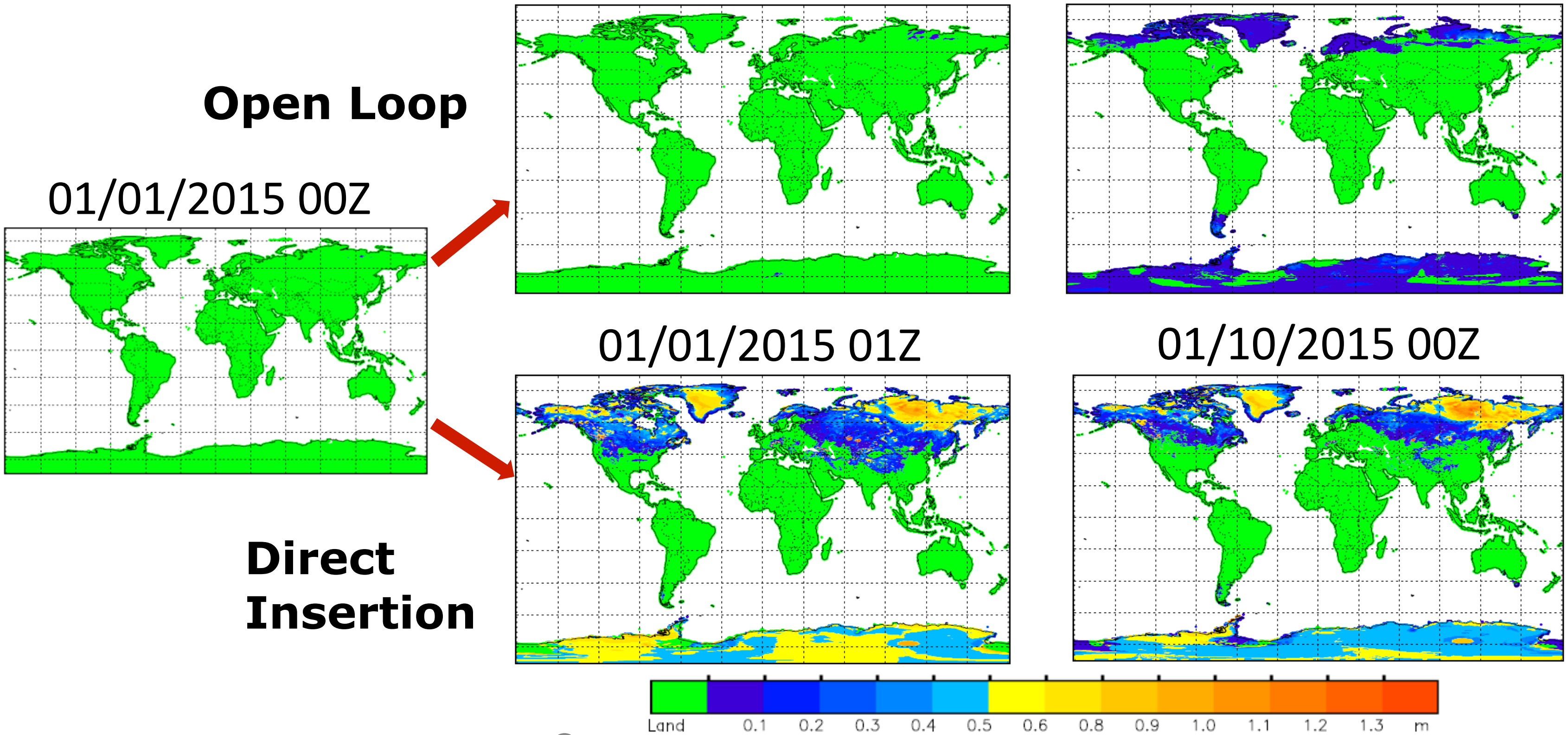


National Ice Center snow cover



Air Force Weather Agency snow cover & depth

Land data assimilation: Snow Depth

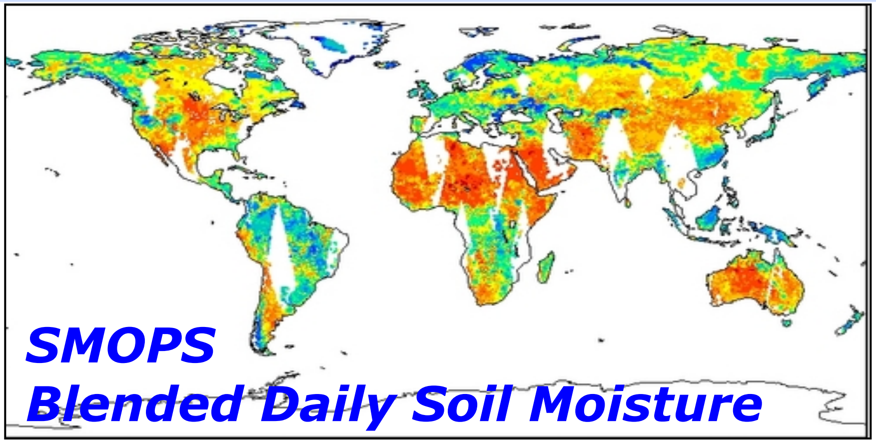


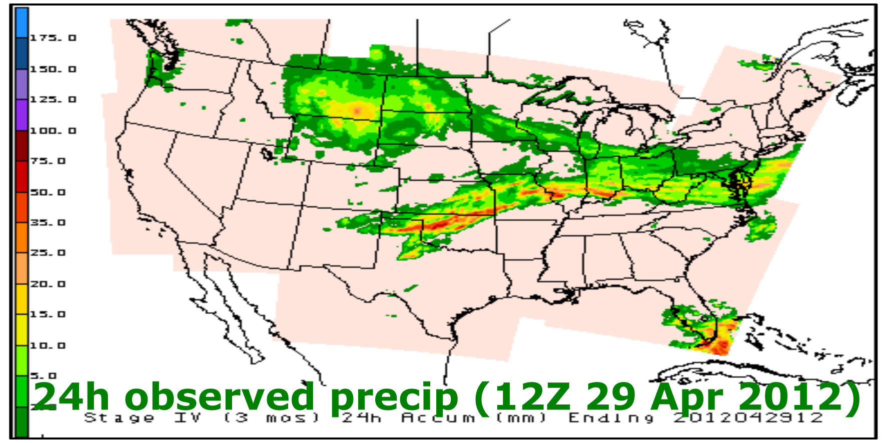
EnKF

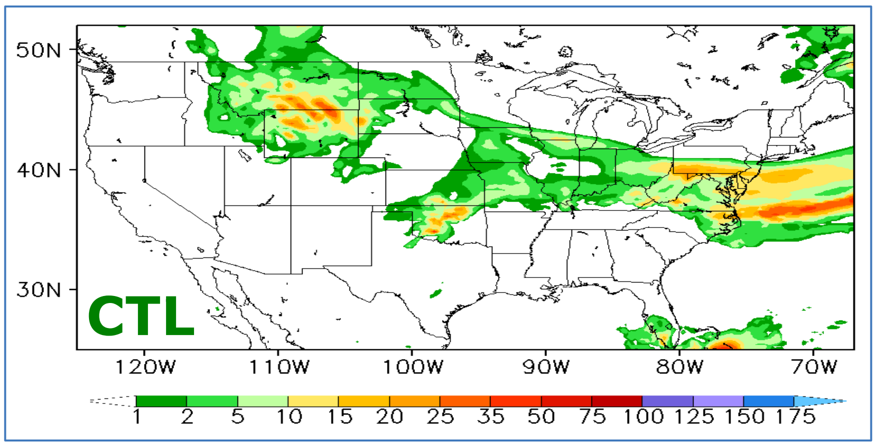
NCEP/EMC land group testing use of NASA LIS EnKF to assimilate AFWA snow depth. Successful EnKF applications require accurate error estimates both from satellite observations and from the land model.

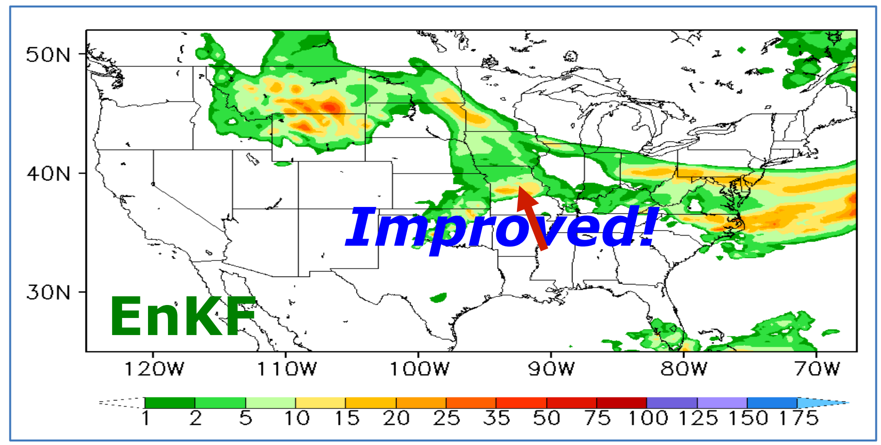
Jiarui Dong, NCEP/EMC

Land data assimilation: Soil Moisture







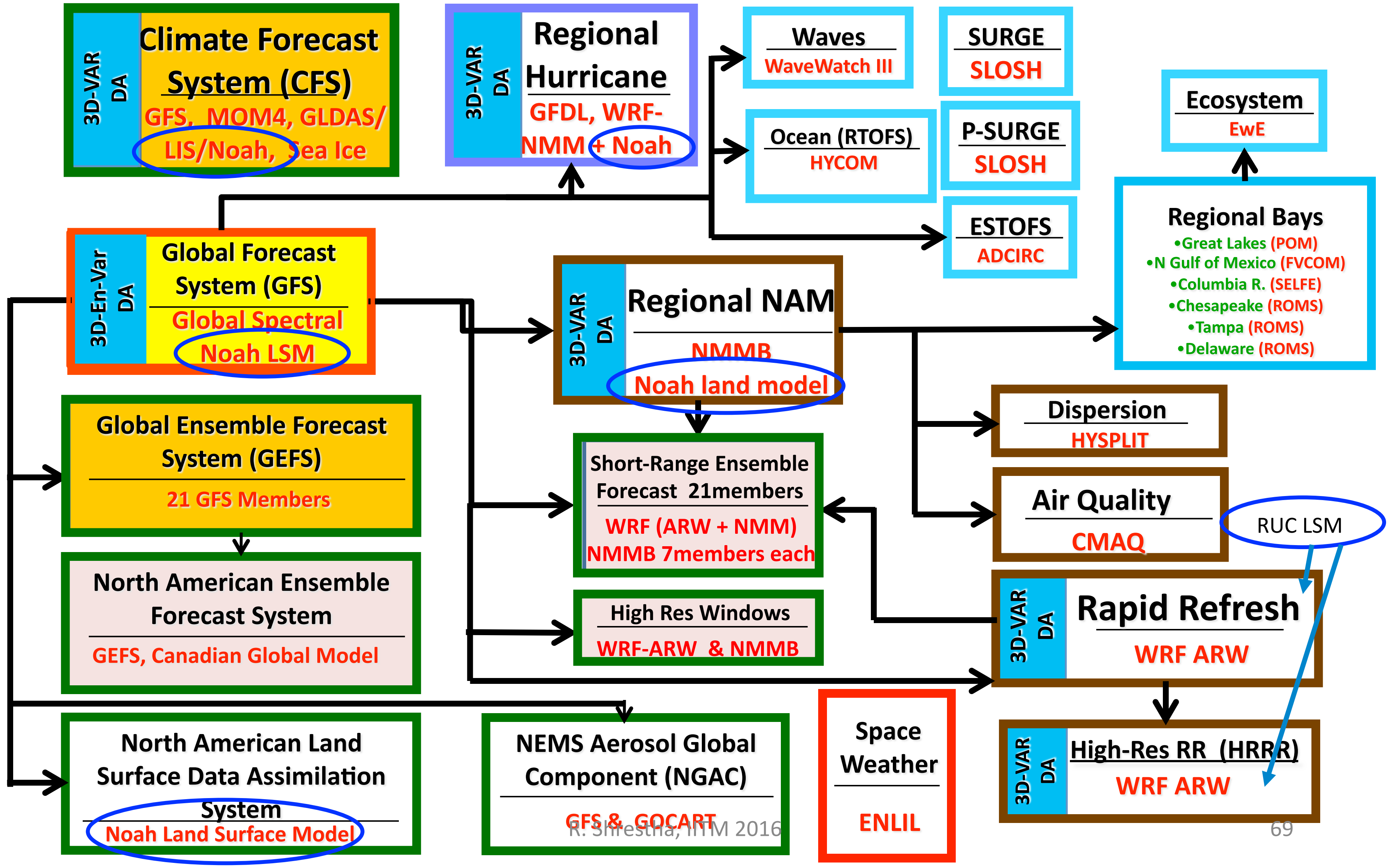


Forecast hour 60-84, precipitation forecast 24h accum (mm) ending at 12Z 29 Apr 2012

- Noah land model multiple-year grid-wise means & std devs used to scale surface layer soil moisture retrievals before assimilation.
- Testing assimilation of SMOPS in GFS; positive impact on precip.

Weizhong Zheng, NCEP/EMC and Xiwu Zhan, NESDIS/STAR

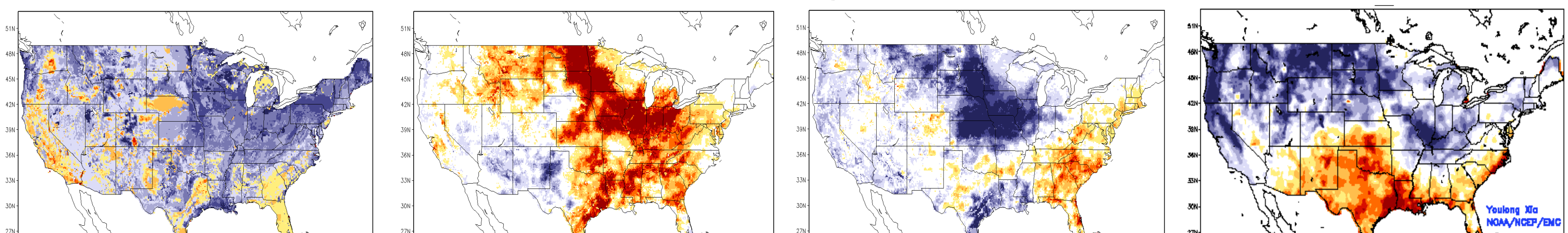
Land Applications for Weather & Climate:
NOAA's Operational Numerical Guidance Suite



North American Land Data Assimilation System (NLDAS)

- <u>August 2014: North American LDAS (NLDAS) operational.</u>
- <u>NLDAS</u>: 4 land models run uncoupled, driven by CPC observed precipitation & NCEP NARR/R-CDAS atmospheric forcing.
- <u>Output</u>: 1/8-deg. **land** & **soil states**, **surface fluxes**, **runoff** & **streamflow**; anomalies from 30-yr climatology for drought.
- <u>Future</u>: higher res. (~3-4km), extend to full North American/ global domains, improved land data sets/data assimil. (soil moisture, snow), physics upgrades including hydrology, initial land states for weather/climate models; global drought info.

www.emc.ncep.noaa.gov/mmb/nldas



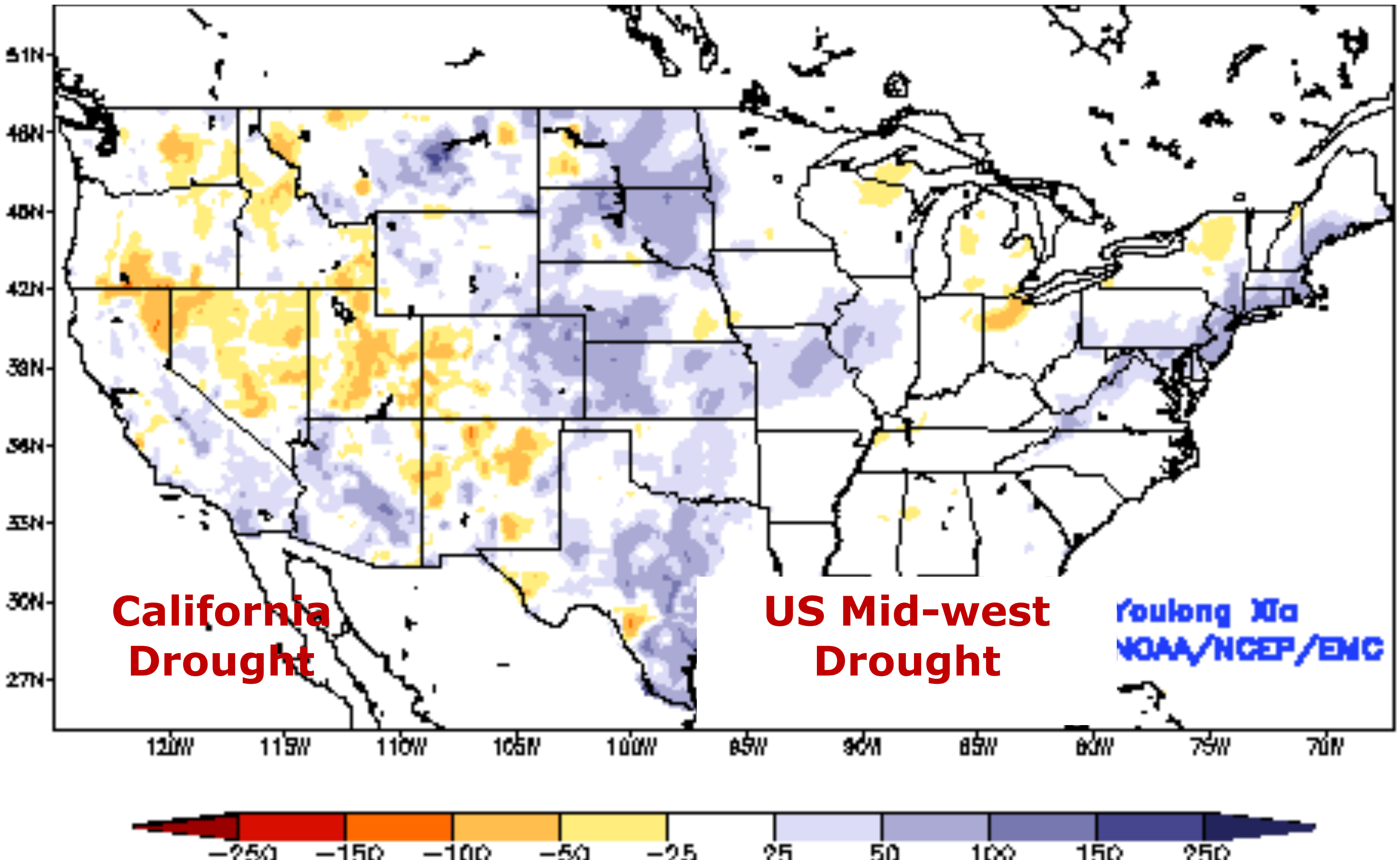
July 30-yr climate | *July 1988 (drought)* | *July 1993 (flood)* | *July 2011 (TX drought)*

NLDAS four-model ensemble soil moisture monthly anomalies

Youlong Xia, NCEP/EMC

NLDAS Soil Moisture Monitoring

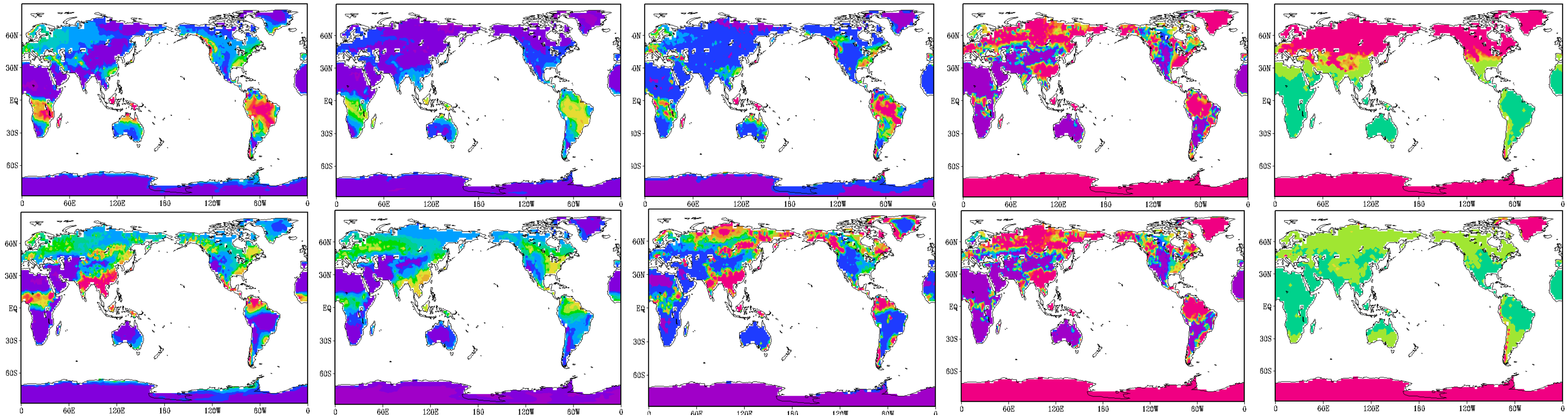
Ensemble mean total column soil moisture anomaly
March 2012 – December 2013



Youlong Xia

Global Land Data Assimilation System (GLDAS)

- Uses **Noah land model** running under NASA Land Information System forced with **Climate Forecast System** (CFS) atmos. data assimil. cycle output, & **"blended" precipitation** (gauge, satellite & model), "semi-coupled" –daily updated land states.
- **Snow** cycled or assimilated (IMS snow cover, AFWA depth).
- GLDAS land "re-runs", with updated forcing, physics, etc.
- 30-year land climatology: energy/water budgets:



Precipitation *Evaporation* *Runoff* *Soil Moisture* Snow

Jan (top), July (bottom) Climatology from 30-year NCEP CFS Reanalysis

(Precip, Evap, Runoff [mm/day]; Soil Moisture, Snow [mm])

Rongqian Yang, Jesse Meng NCEP/EMC

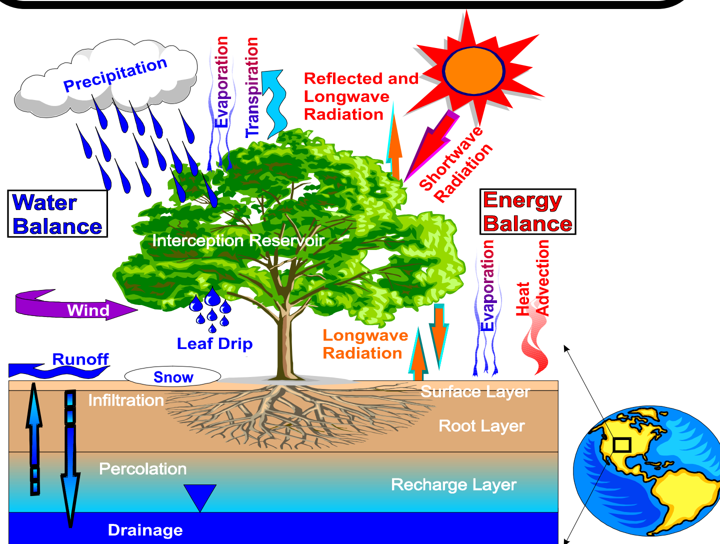
NASA Land Information System (LIS)

Inputs

- Topography, Soils (Static)
- Land Cover, Leaf Area Index (MODIS, AMSR, TRMM, SRTM)
- Meteorology: Modeled & Observed (NLDAS, DMIP II, GFS,GLDAS,TRMM GOES, Station)
- Observed States (Snow Soil Moisture Temperature)

Physics

Land Surface Models
SAC-HT/SNOW17
Noah, CLM, VIC, Catchment



Data Assimilation Modules
(DI, EKF, EnKF)

Outputs

- Surface Energy Fluxes (Q_h,Q_{le})
- Soil Moisture Evaporation
- Surface Water Fluxes (e.g., Runoff)
- Surface States (Snowpack)

Applications

- Water Supply & Demand
- Agriculture Hydro-Electric Power, Water Quality
- Improved Short Term & Long Term Predictions

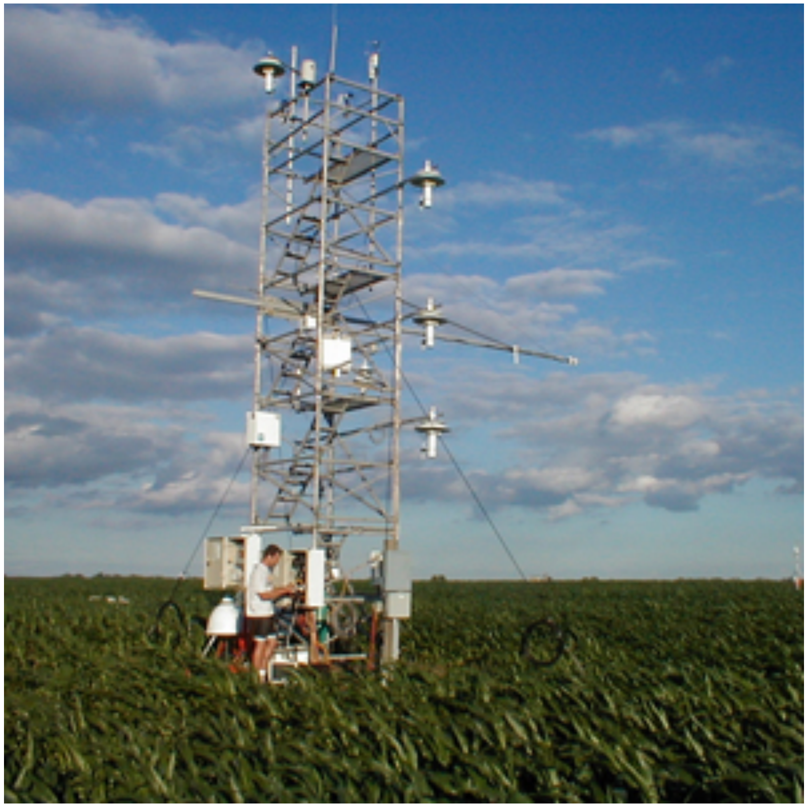
Christa Peters-Lidard et al., NASA/GSFC/HSB

- Land model Testing and Validation

Land Model Testing and Validation

- **Validation** uses near-**surface** observations, e.g. routine weather observations of air temperature, dew point and relative humidity, 10-meter wind, along with upper-air validation, precipitation scores, etc.

- To more fully validate land models, **surface fluxes** and soil states (soil moisture, etc) are also used.

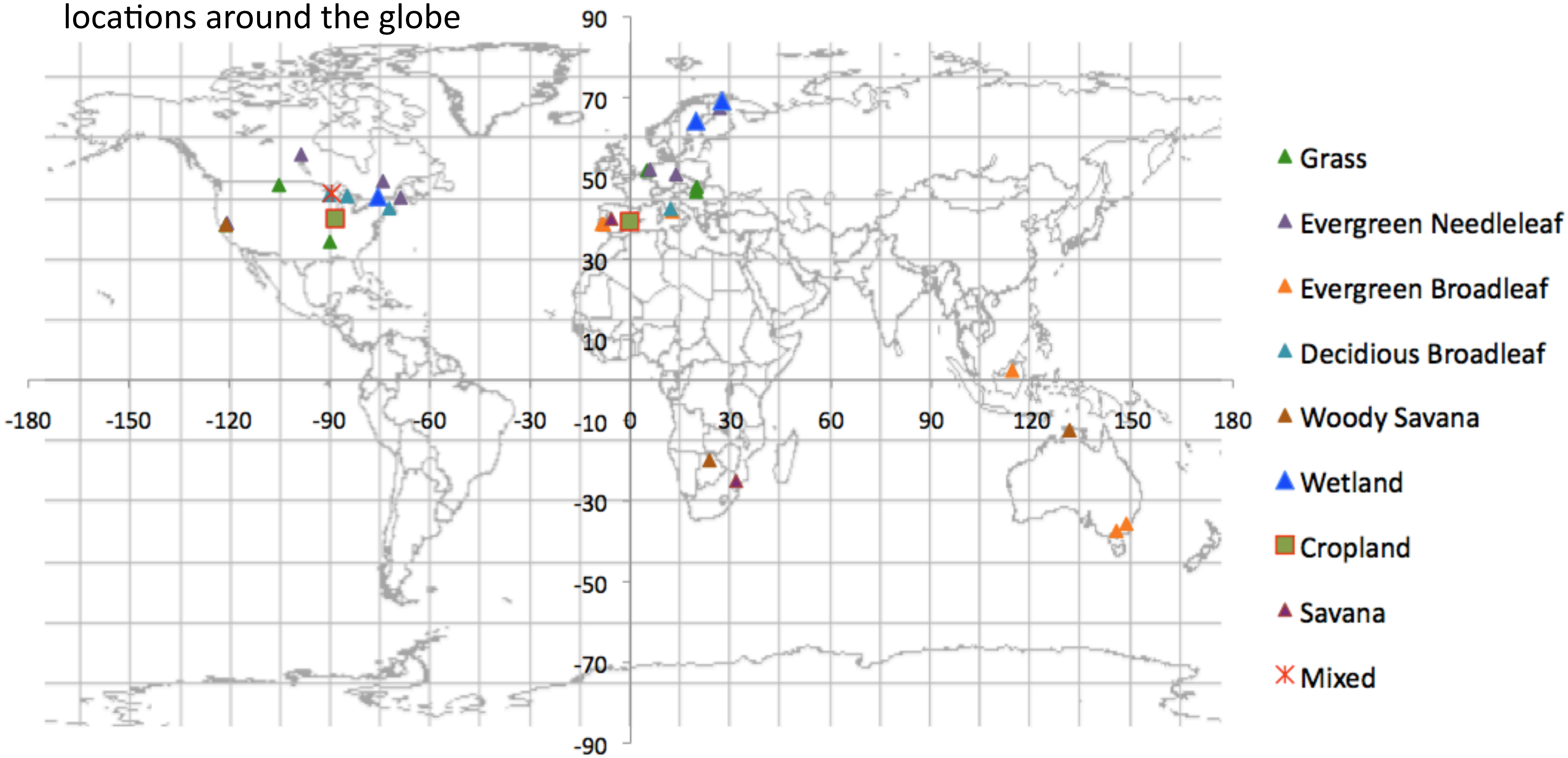


- Monthly diurnal composites to **assess systematic model biases** (averaging out transient atmospheric conditions), and suggest land physics upgrades.

Compare monthly diurnal composites of model output versus observations from flux sites to assess systematic model biases.

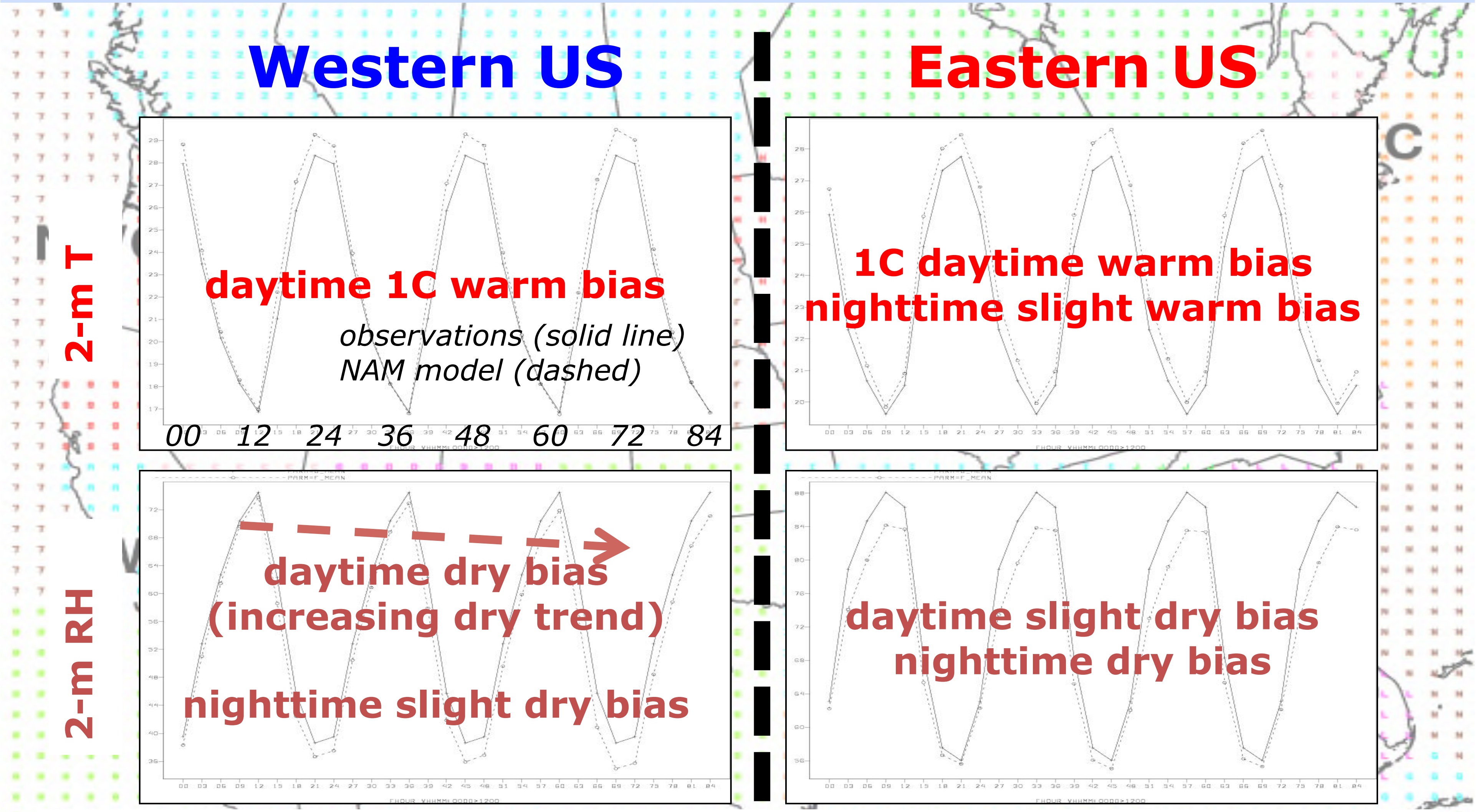
PALS – The Protocol for the Analysis of Land Surface Models

- to evaluate and benchmark the performance of different land models at various locations around the globe



Testing & Validation: NWP model

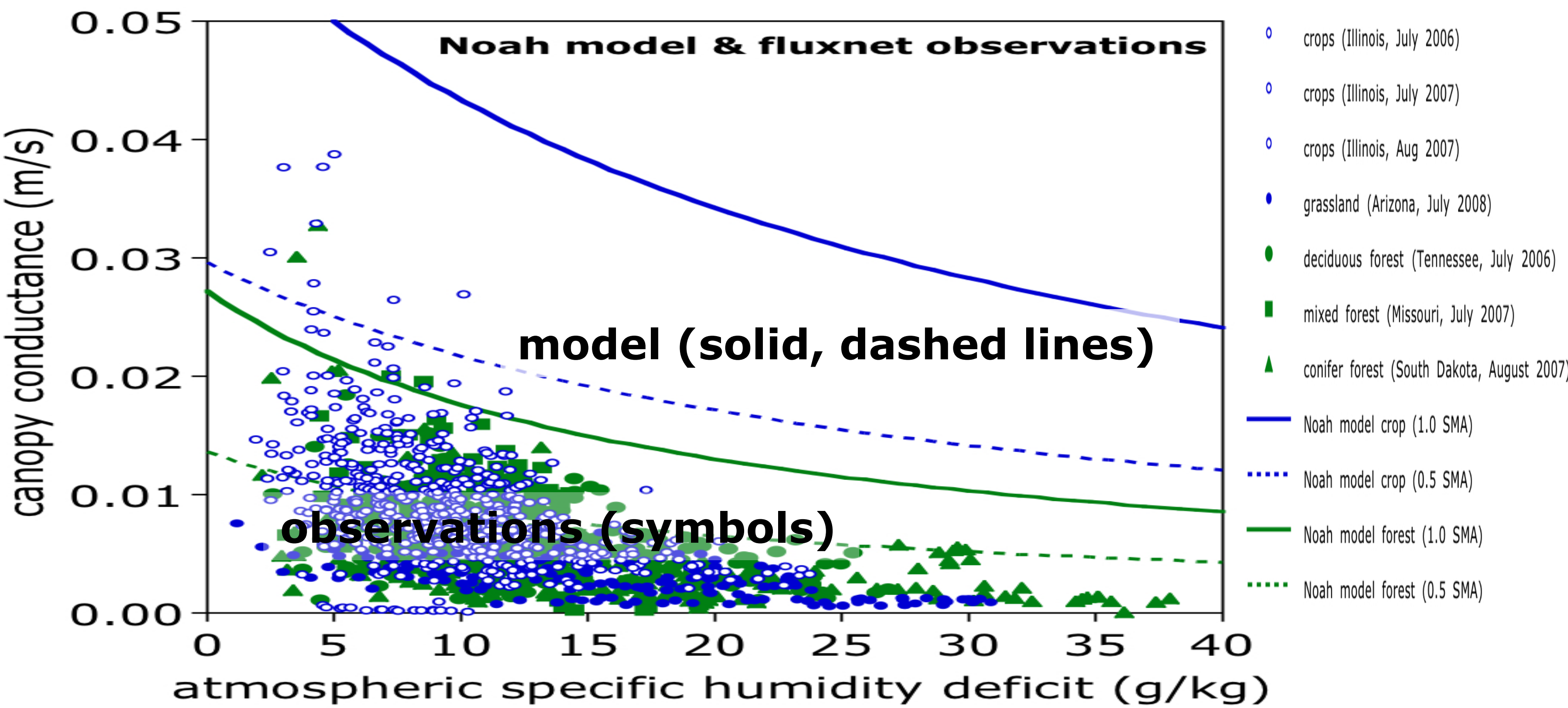
NCEP North American Mesoscale model, 0-84hr forecast



- **Assess systematic biases using diurnal monthly means.**

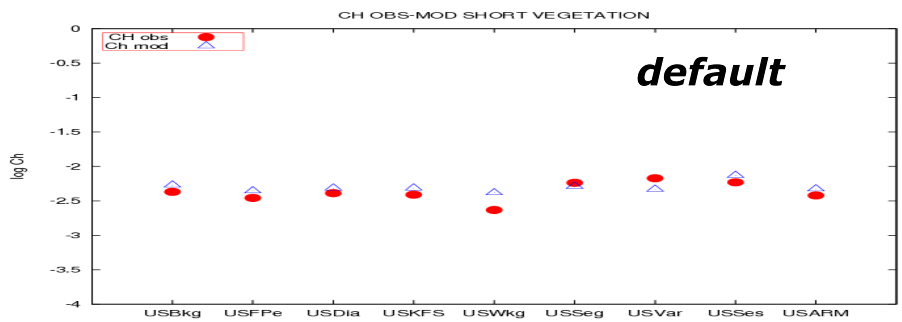
Testing & Validation: Model components

- Use surface fluxes (e.g. latent and sensible) to evaluate land-surface physics formulations and parameters, e.g. invert transpiration formulation to infer canopy conductance (below).

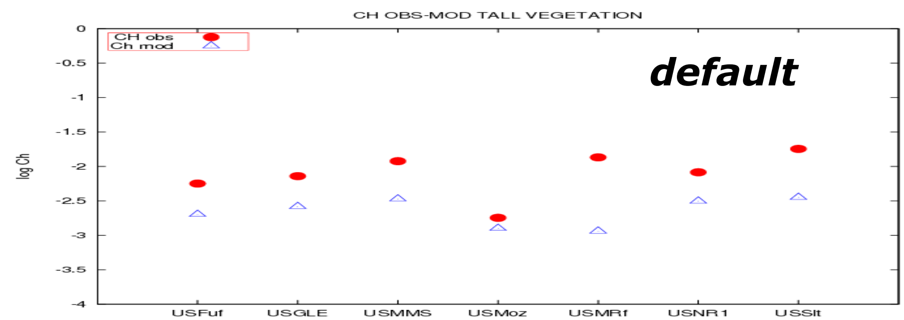


Testing and Validation: Surface-layer Simulator

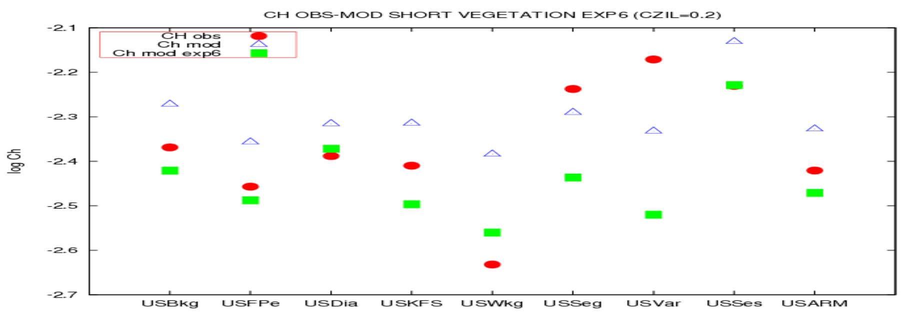
- GOAL: Improve surface turbulence exchange coefficients.
- Surface-layer simulation (“SLS”) code simulates surface-layer and schemes from meso-NAM and medium-range GFS.
- Use observations to drive SLS (U,T,q and Tsfc) and compare with inferred Ch, Cd from independent “fluxnet” obs (H, LE, τ).
- Bias in surface exchange coefficient for heat dependent on vegetation height. Action: adjust thermal roughness parameter.



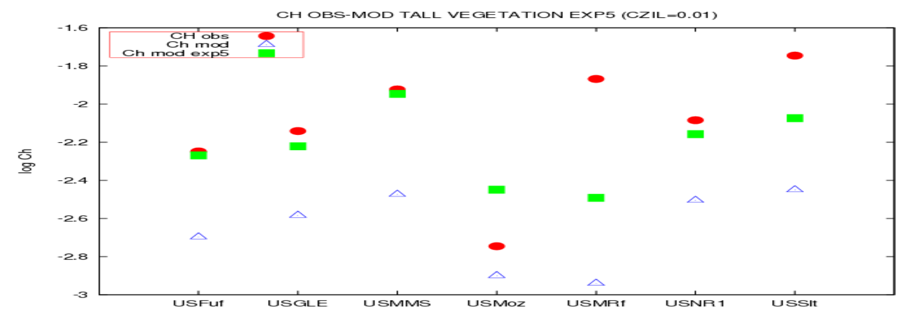
short vegetation, czil=0.1



tall vegetation, czil=0.1



short vegetation, czil=0.2

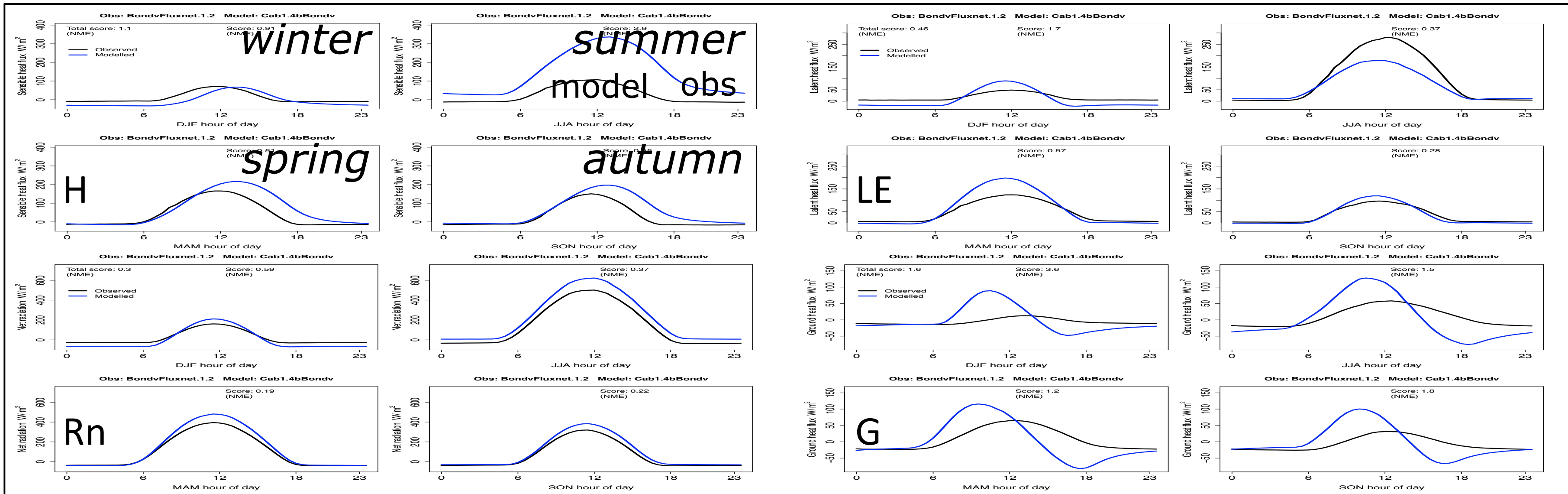


tall vegetation, czil=0.01

Caterina Tassone, NCEP/EMC

Testing & Validation: Land Model Benchmarking

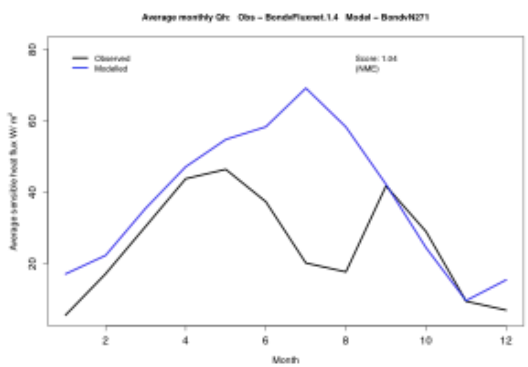
- Benchmarking: Decide how good model needs to be, then run model and ask: *Does model reach the level required?*
- ***P****rotocol for the* ***A****nalysis of* ***L****and* ***S****urface models (****PALS****)*: www.pals.unsw.edu.au. ***GEWEX/GLASS project.***
- Compare models with empirical/statistical approaches, previous model versions, other land models. Different plots/tables of model validation and benchmarking metrics.
- Identify systematic biases for model development/validation.

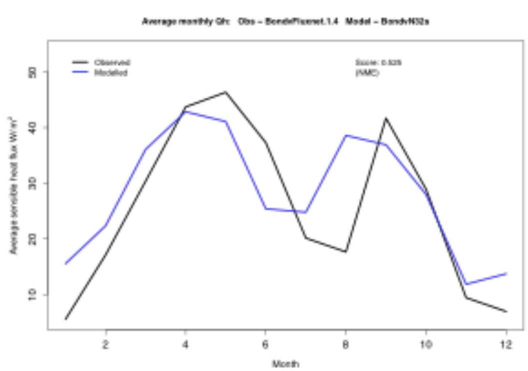


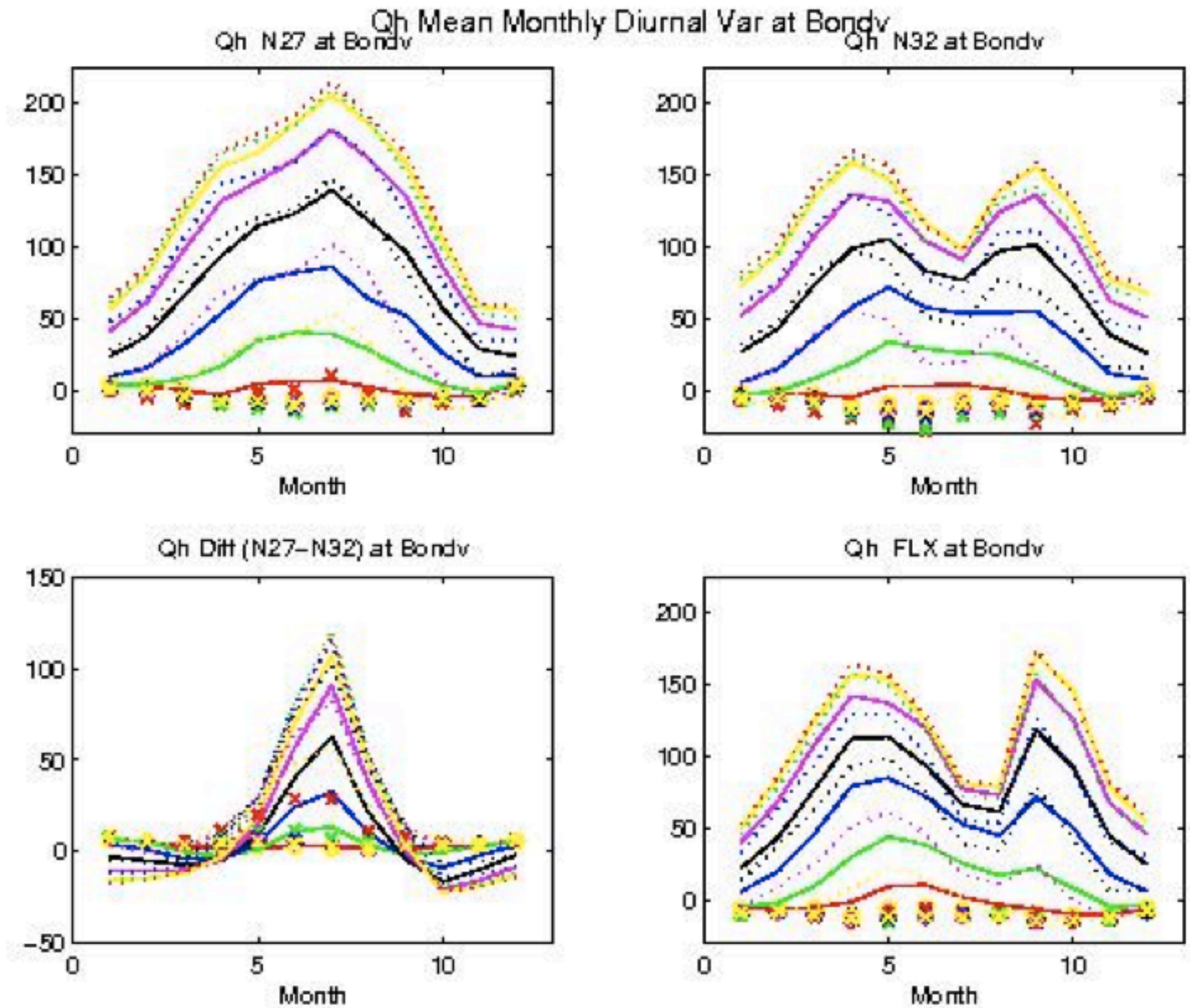
PALS example: CABLE (BOM/Aust.) land model, Bondville, IL, USA (cropland), 1997-2006, avg diurnal cycles.

Martin Best (UKMO), Gab Abramowitz (UNSW) et al.

Diurnal partition of Qh annual cycle

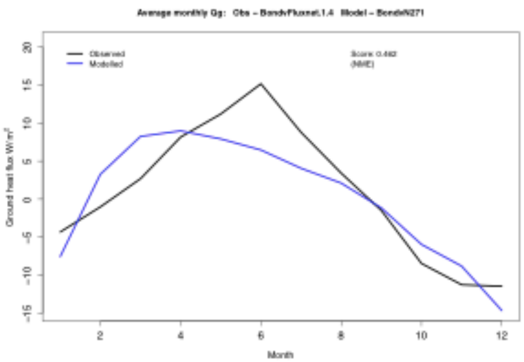


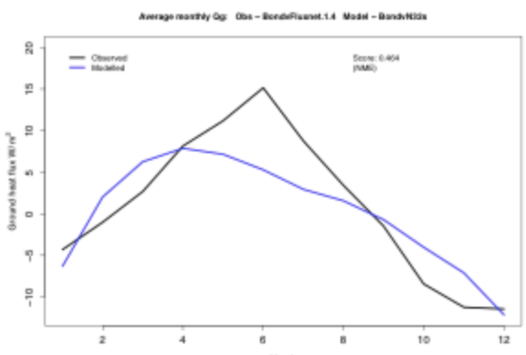


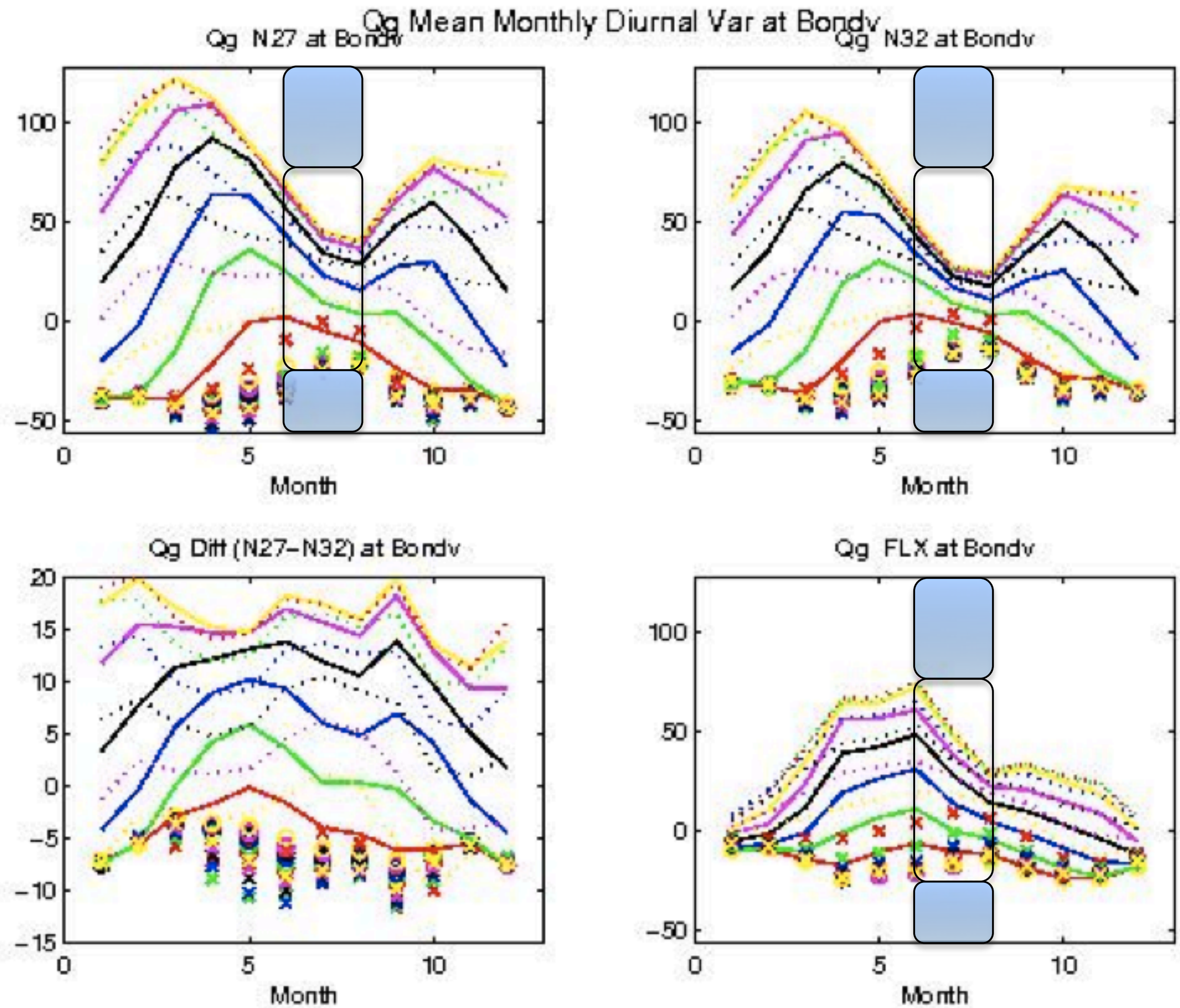


Noah 3.3 has produced double peak, but the recession of first peak still has issues, particularly for the 'before noon' segment of the daytime fluxes.

Diurnal partition of Qg annual cycle







Both Noah2.7 and Noah3.3 have serious issues except for summer season

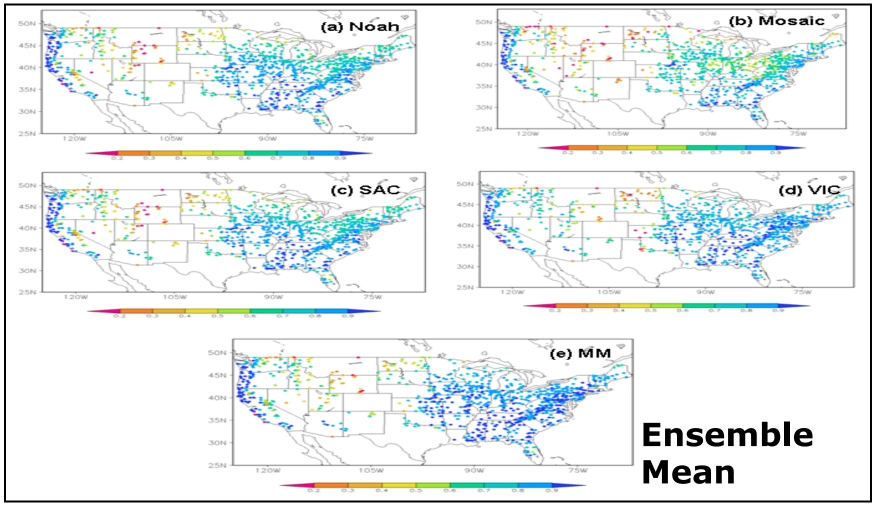
Testing & Validation: "uncoupled" NLDAS

Comprehensive evaluation against *in situ* observations and/or remotely sensed data sets.

Energy flux validation from tower: net radiation, sensible, latent & ground heat fluxes.

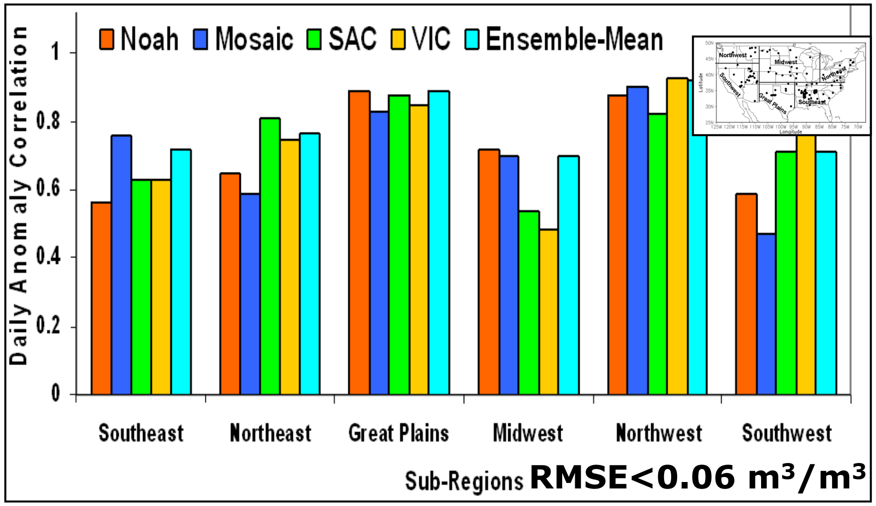
Water budget: evaporation, total runoff/streamflow.

State variables: soil moist., soil/skin temp., snow depth/cover.



Xia et al., JGR-atmosphere (2012)

Monthly streamflow anomaly correlation (1979-2007 USGS measured streamflow)



Xia et al., J. Hydrol. (2014)

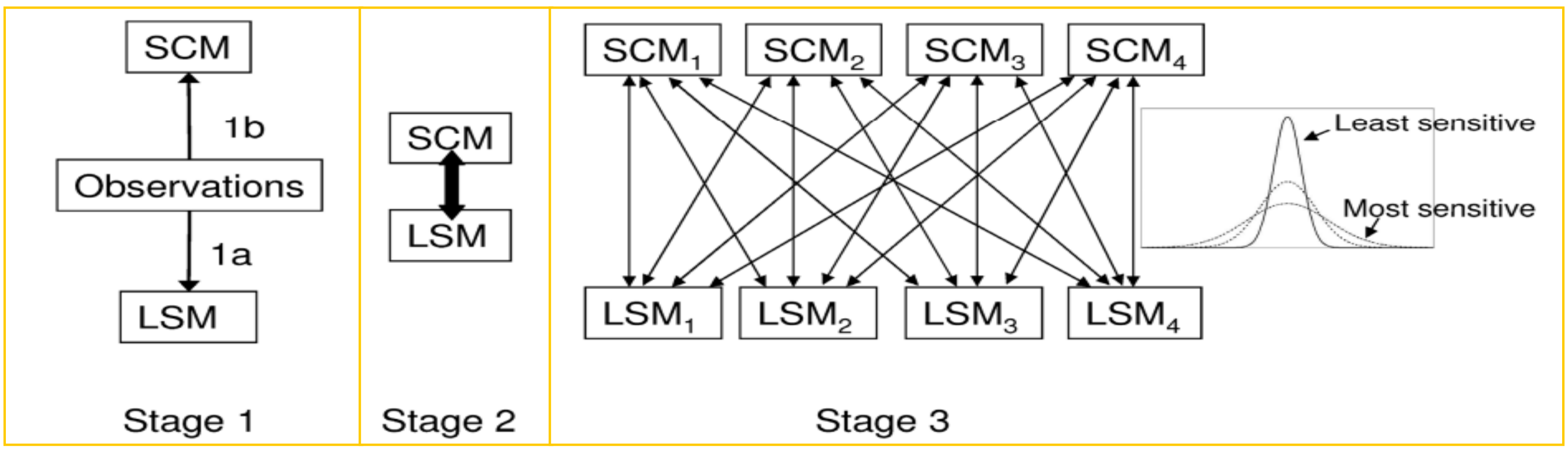
Daily top 1m soil moisture anomaly corr. (2002-2009 US SCAN Network)

Diurnal land-atmosphere coupling experiment (DICE)

Objective: Assess impact of land-atmosphere feedbacks.
Stage 1: stand alone land, and single column model (SCM) alone.
Stage 2: Coupled land-SCM.
Stage 3: Sensitivity of LSMs & SCMs to variations in forcing.

Data Set: CASES-99 field experiment in Kansas, using 3 days: 23-26 Oct 1999, 19UTC-19UTC.

Joint GEWEX GLASS-GASS project –outgrowth of GABLS2 (boundary-layer project) where *land-atmosphere coupling was identified as a important mechanism*. ~10 models participating.



Martin Best and Adrian Lock (UKMO) et al.

Testing & Validation: Land and related issues

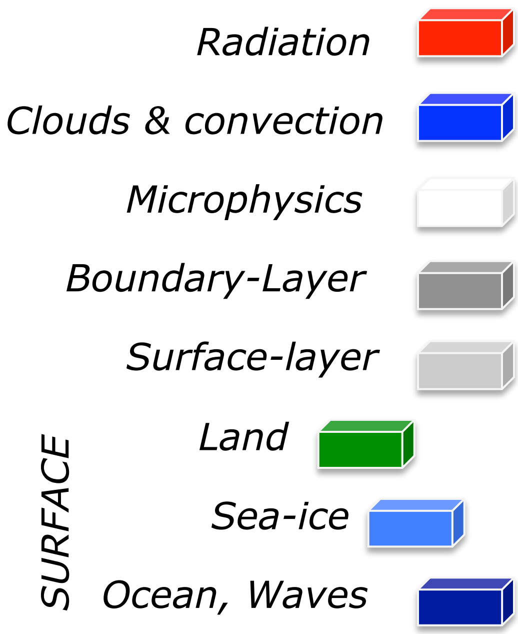
Low-level biases in winds, temperature, and humidity are influenced in part by the land surface via biases in surface fluxes exchanged with the atmospheric model (& effect on precipitation).

Improving the proper partition of surface energy budget between sensible, latent, soil heat flux and outgoing longwave radiation, and effect on water budget, requires:

- Improved vegetation physics/parameters to calculate ET.
- Better soil physics/properties to address surface heterogeneity.
- Improved snow physics (melt/freeze, densification).
- Surface-layer physics, especially nighttime/stable conditions, and interaction with the surface & atmospheric boundary layer.
- Remote sensing of many different initial land states, e.g. near-realtime vegetation; corresponding data assimilation of these land states, e.g. snow, soil moisture, GVF.
- Improved forcing for the land model, especially precipitation and downward radiation; requires enhanced downscaling techniques.

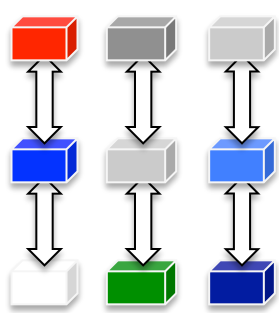
Testing & Validation: Simple-to-More Complex Hierarchy of Model Parameterization Development

Simulators

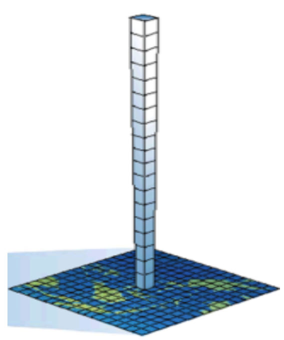


- Simulators: test submodel parameterizations at process level, e.g. radiation-only, land-only, etc.
- Testbed data sets to develop, drive & validate submodels: observations, models, idealized, *with "benchmarks" before adopting changes*.
- Submodel interactions, *with benchmarks*.
- Full columns, *with benchmarks*.
- Limited-area/3-D (convection) *with benchmarks*.
- Regional & global NWP & seasonal climate, *with benchmarks.*
- **More efficient** model development, community engagement, R2O/O2R & computer usage.

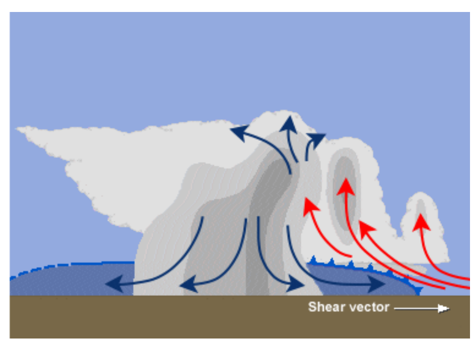
Interaction tests



Column tests

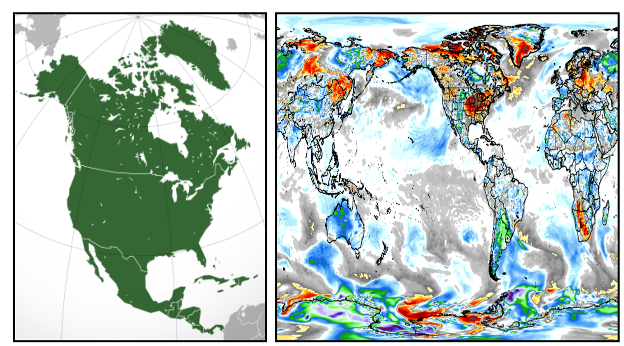


Limited-area



R. Shrestha, IITM 2016

Regional & Global



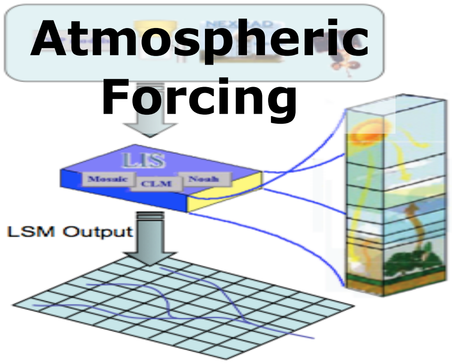
Land Models in Earth Systems

In a more fully-coupled ***Earth System***, this role involves ***Weather & Climate*** connections to:

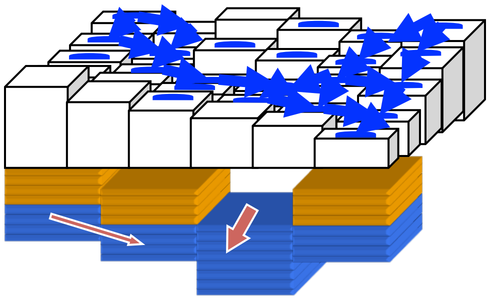
- ***Hydrology***: soil moisture & ground water/water tables, irrigation and groundwater extraction, water quality, streamflow and river discharge to oceans, drought/flood, lakes, and reservoirs/human mgmt.
- ***Biogeochemical cycles***: application to ecosystems, both terrestrial & marine, dynamic vegetation and biomass, carbon budgets, etc.
- ***Air Quality***: interaction with boundary-layer, biogenic emissions, VOC, dust/aerosols, etc.

More constraints, i.e. must close energy and water budgets, and those related to air quality and BGC cycles. *Get the right answers for the right reasons!*

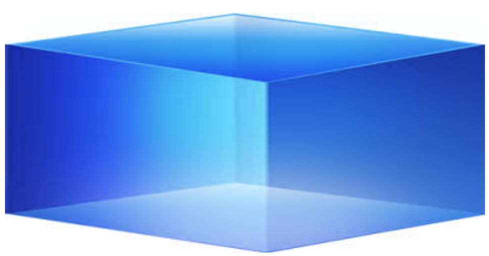
Hydrology: River-routing, Groundwater



Surface flow

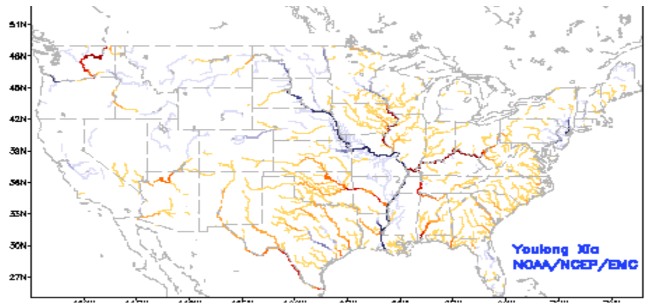


Saturated subsurface flow

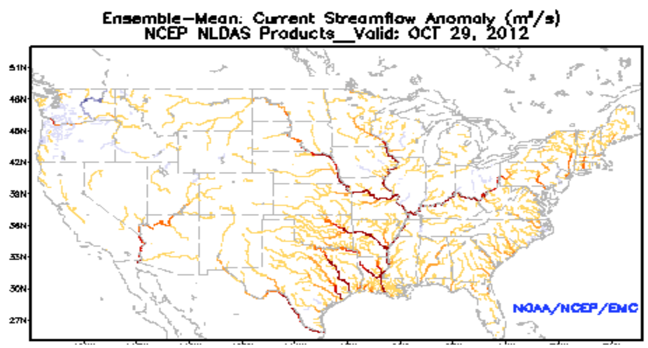


Groundwater

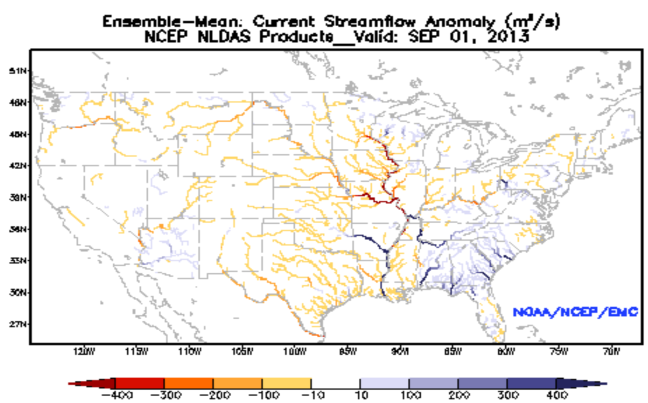
Ensemble mean daily streamflow anomaly



Hurricane Irene and Tropical Storm Lee, 20 August – 17 September 2011



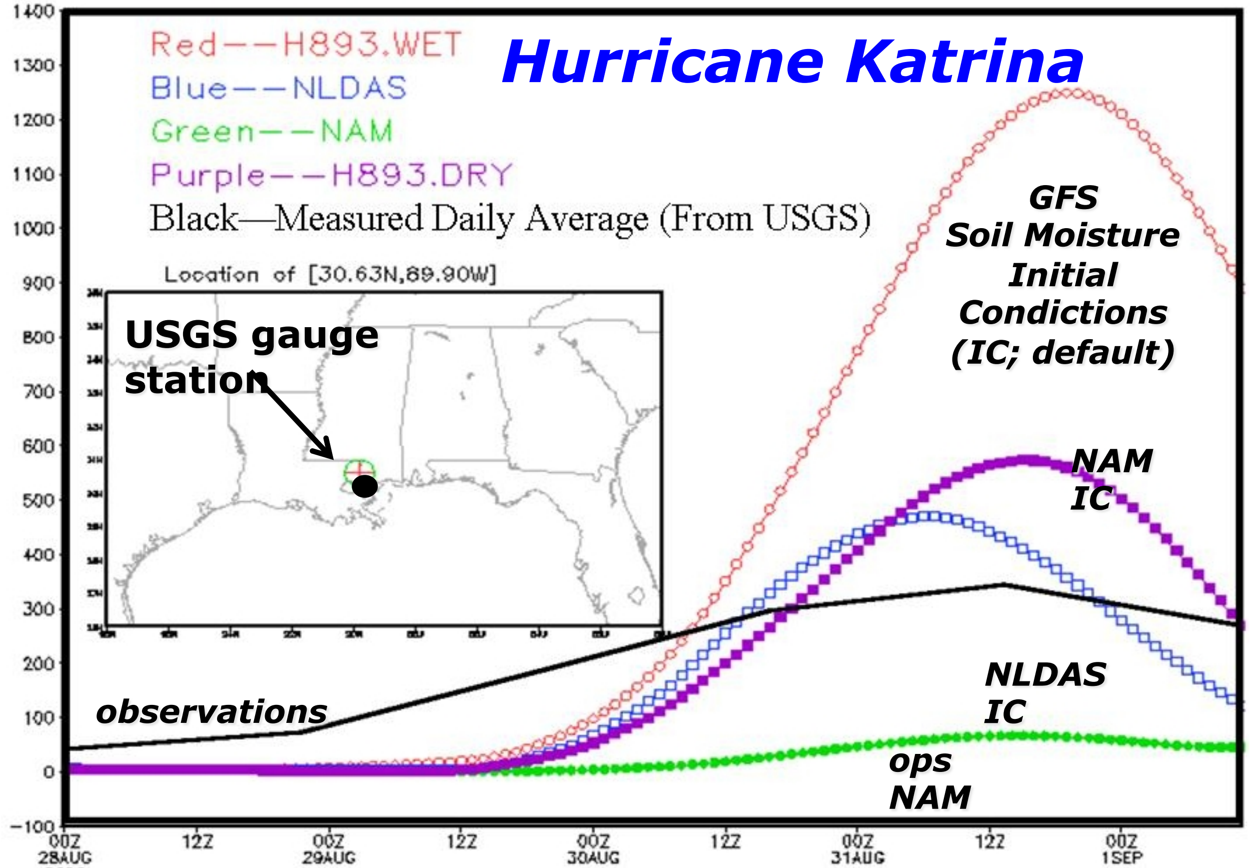
Superstorm Sandy, 29 October – 04 November 2012



Colorado Front Range Flooding, September 2013

- Physical-based Noah model included in (mesoscale) Hurricane Weather Research & Forecasting model, with little degradation in track & intensity & precip.

- **Inland flood forecasting** (right) using Noah runoff & streamflow model.
- Extend to global/ climate models: **river discharge to oceans**.

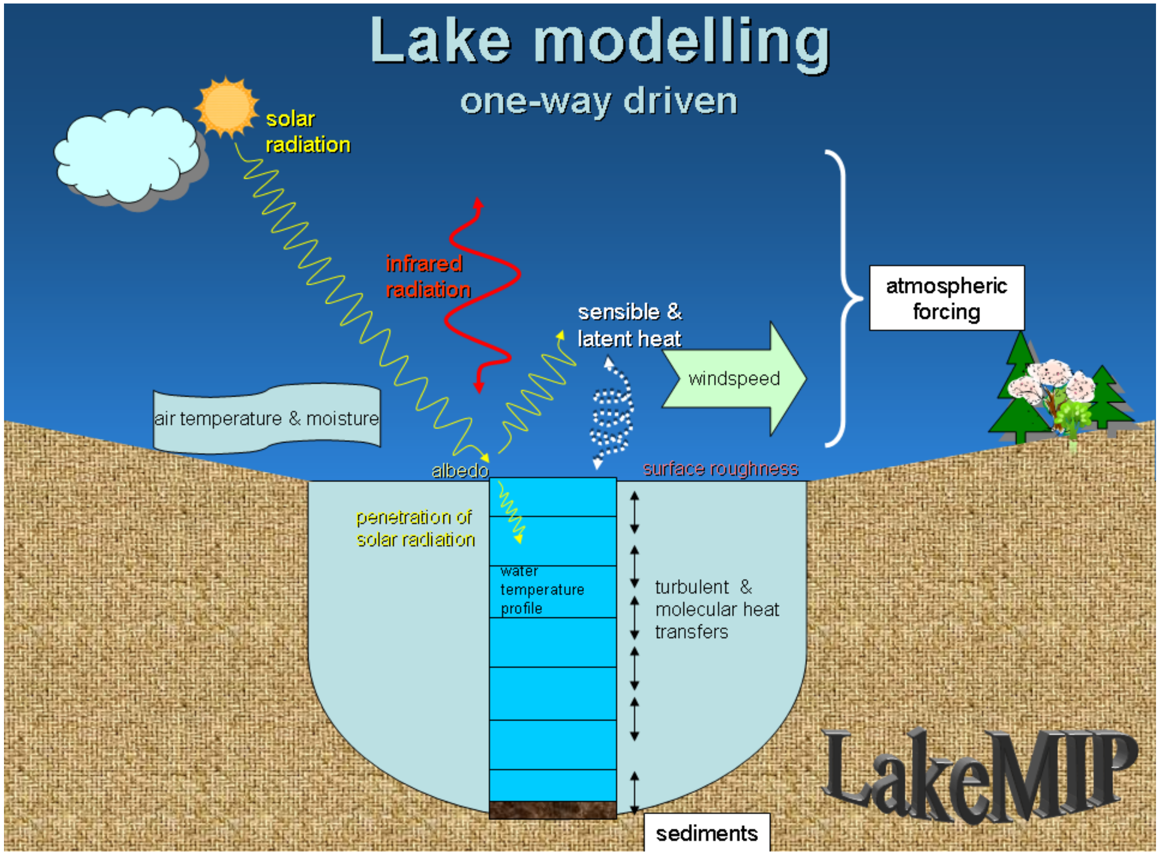


Yihua Wu (NCEP/EMC land team)

Lakes

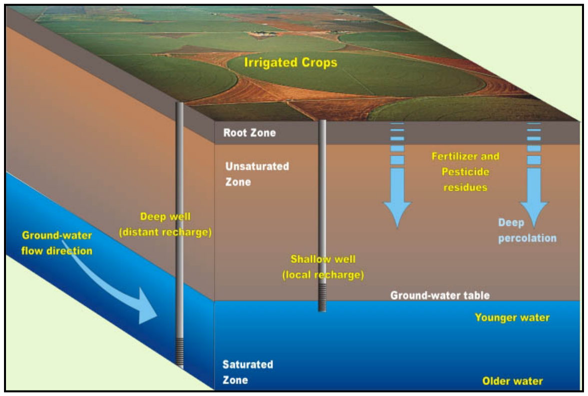
- ***Thousands*** of lakes on scale of 1-4km not resolved by SST analysis -> greatly influence surface fluxes; explicit vs subgrid.
- Freshwater lake "***FLake***" model *(Dmitrii Mironov, DWD).*

- Two-layer.
- Atmospheric forcing inputs.
- Temperature & energy budget.
- Mixed-layer and thermocline.
- Snow-ice module
- Specified depth/ turbidity.
- Used in COSMO, HIRLAM, NAM (regional), and global ECMWF, CMC, UKMO.



Yihua Wu, NCEP/EMC

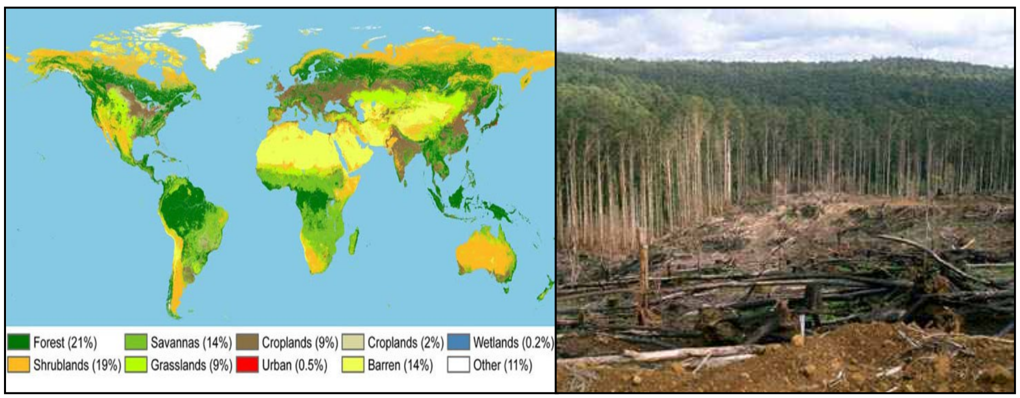
Human Influences/Management



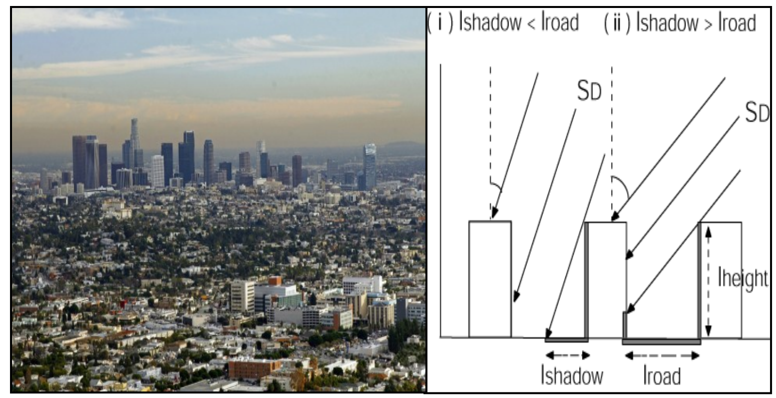
Groundwater Extraction

Irrigation

Reservoirs



Land-cover change/deforestation



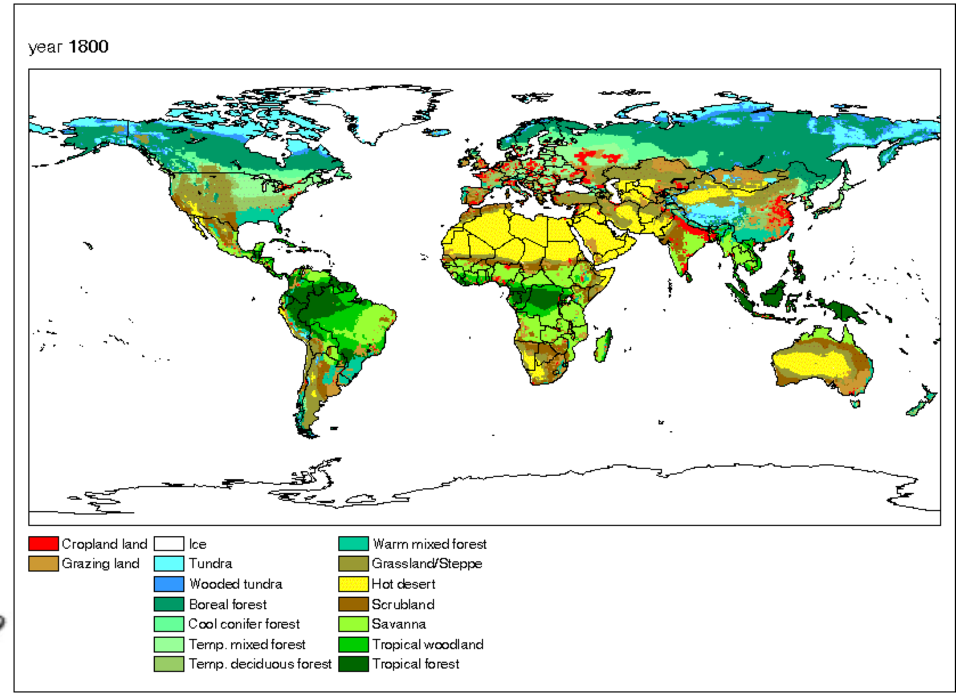
Urban areas/model

- Proper initial conditions (e.g. via remote sensing), and improved land model physics parameterizations.

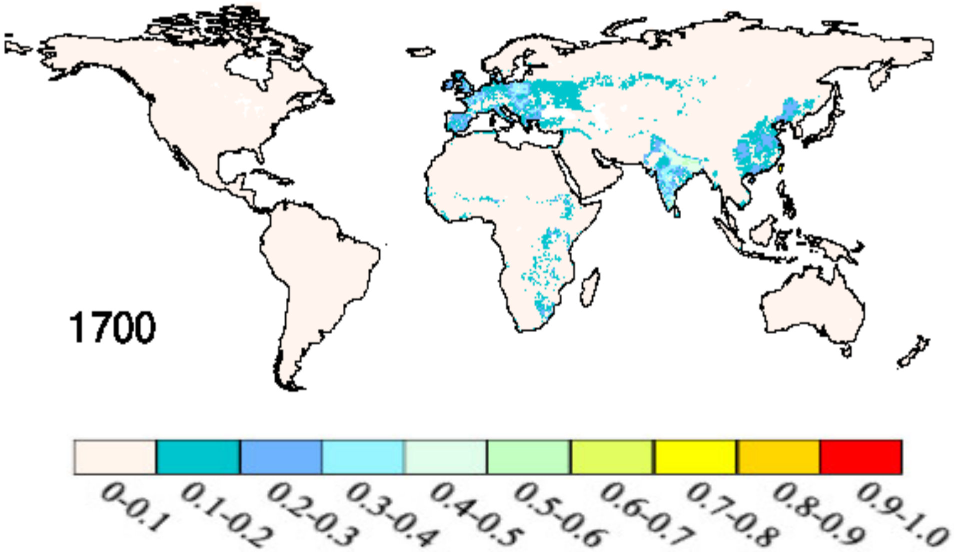
- Challenges of changing land use

Historical Changes

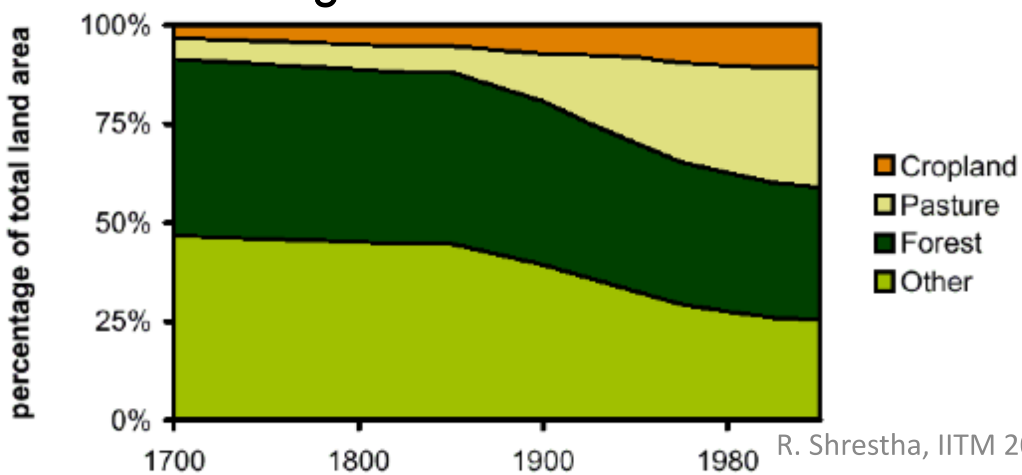
300 Years of Land Use Change



The Spread of Agriculture



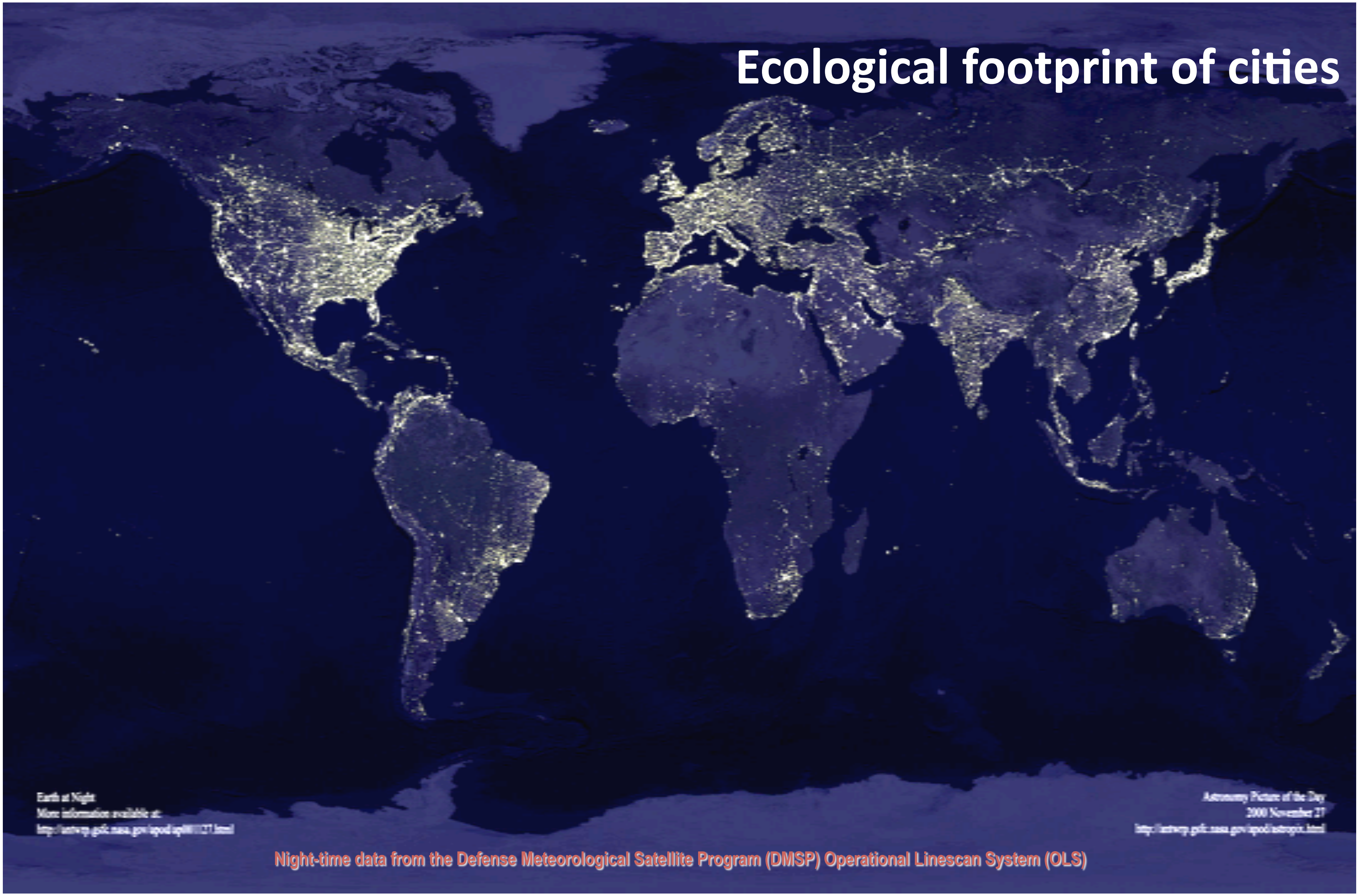
Change in Land use



Center for Sustainability and the Global Environment
Institute for Environmental Studies
University of Wisconsin-Madison

Goldewijk K and Battjes J.J., 1997

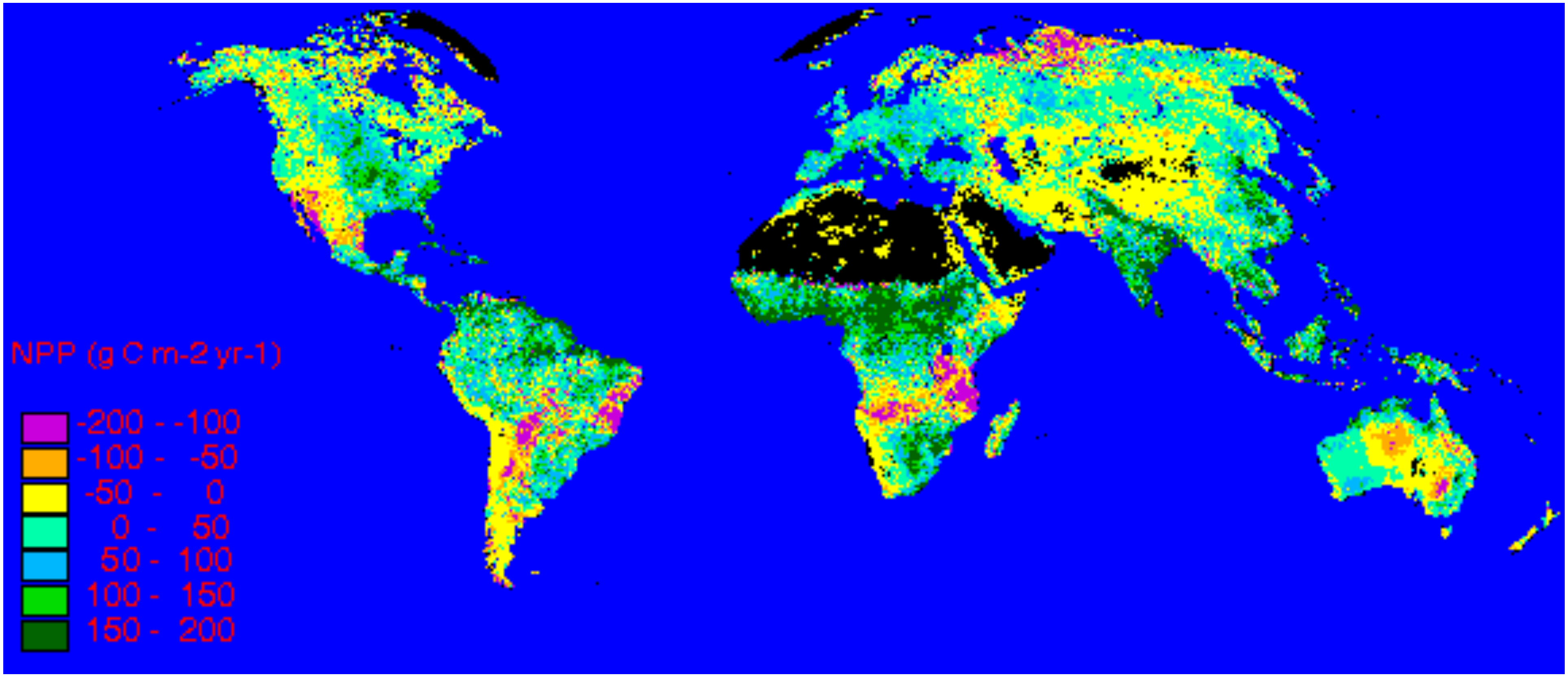
Ecological footprint of cities



Elvidge et al., 1997

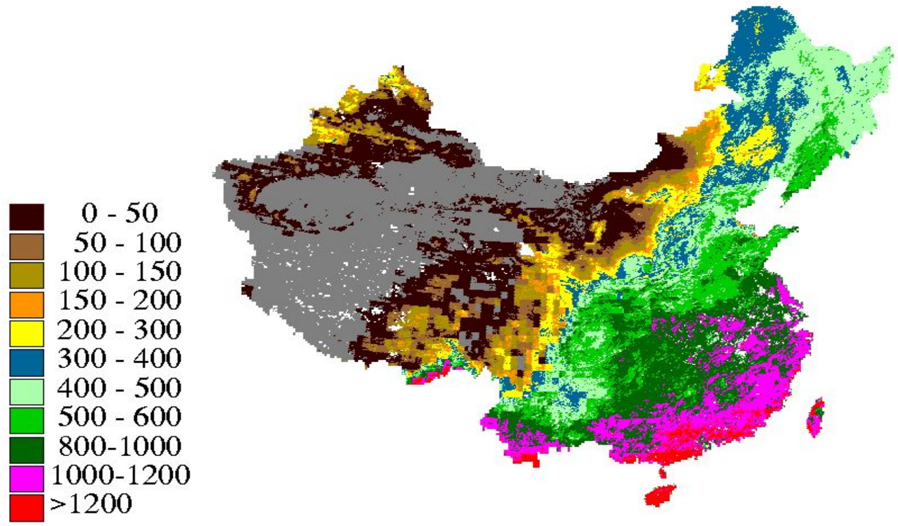
Point: Area of urban-industrial infrastructure remains small relative to other land-use/cover changes, but its "footprint" has significant land implications.

Estimate of changes in annual NPP 1982-2000

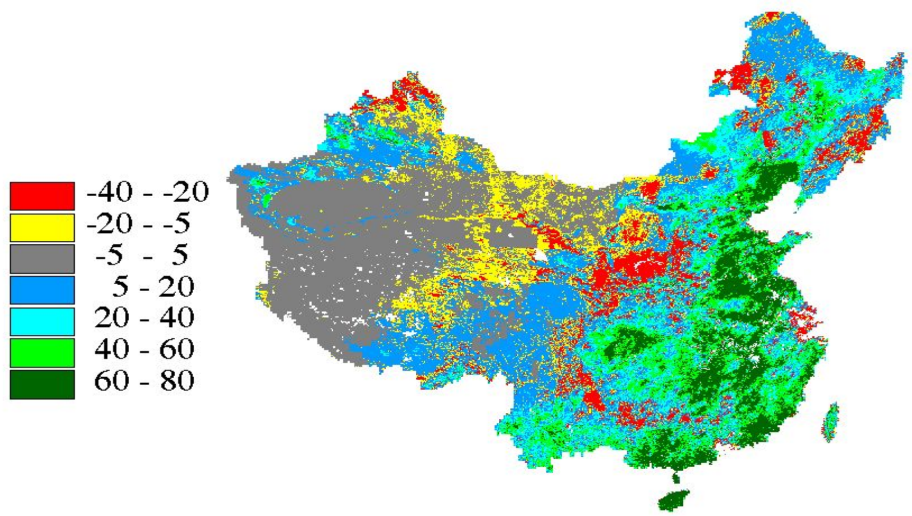


Global monitoring can be performed by satellite, if great care is taken to calibrate and validate retrievals.

Changes in agriculture reflected as NPP changes evident from satellite

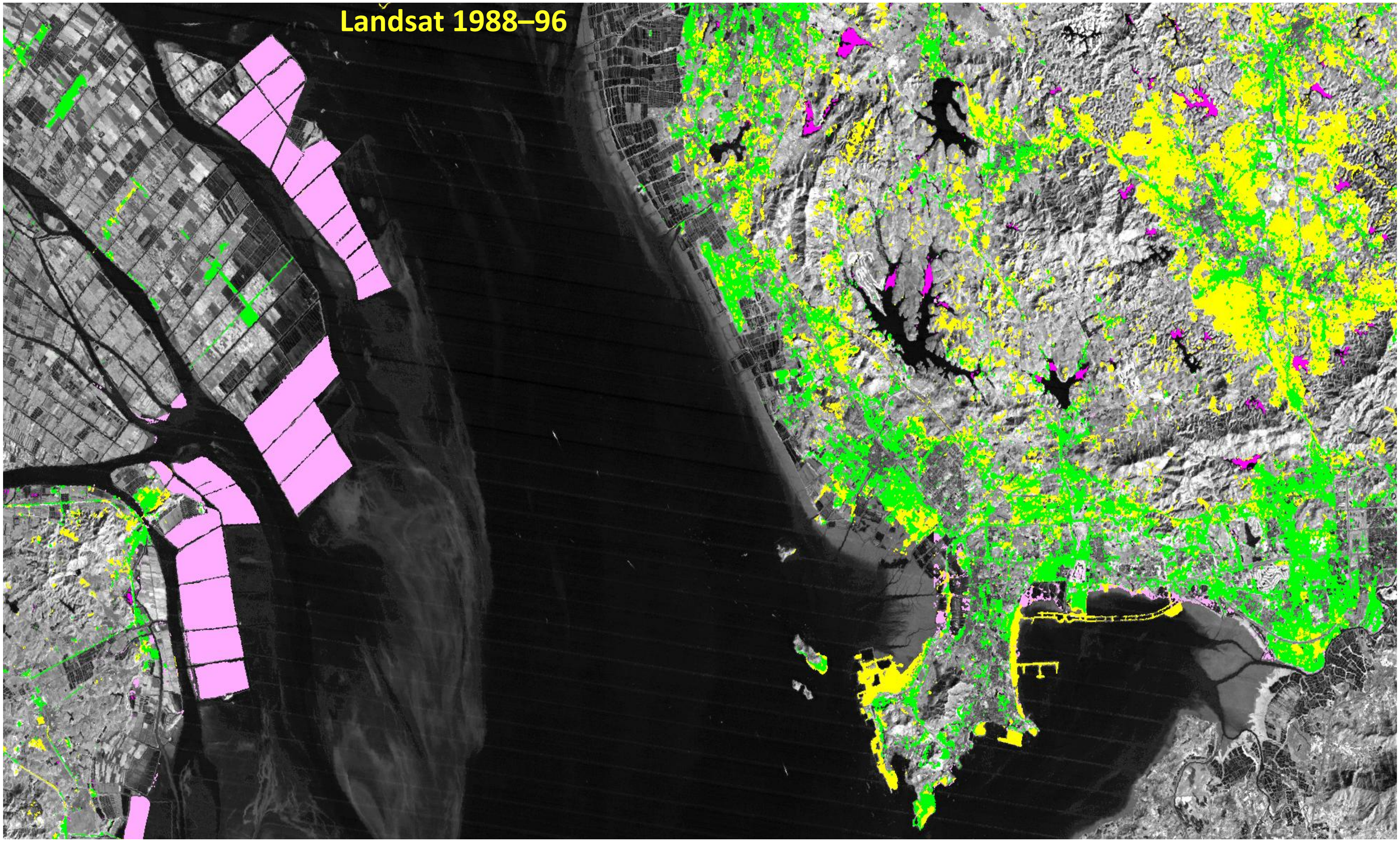


Annual net primary productivity in 1981-2000 (g C m-2)



Changes in net primary productivity between 1981 and 2000 (g C m-2)

Urban expansion into “prime” agricultural land



Agriculture to urban

Natural vegetation/water to urban

Agriculture/natural vegetation to water

Water to agriculture

(K. Seto, Boston U.)

Aral Sea Background Info Cont.

Climate Changes:

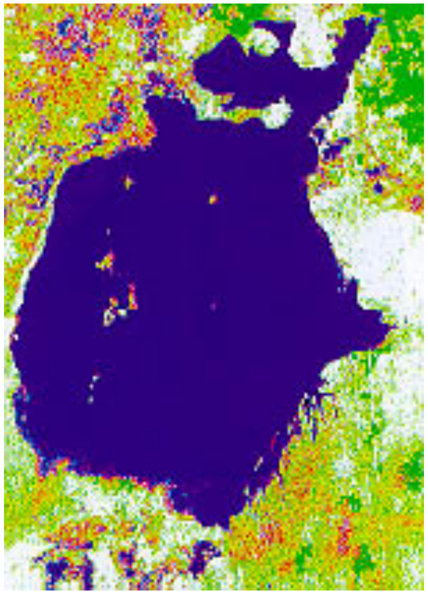
- Longer, colder winters
- Shorter, drier summers
- Growing season shortened to 170 days
- Precipitation decreased 10x along shore regions
- Salt rain

Effects of Salt:

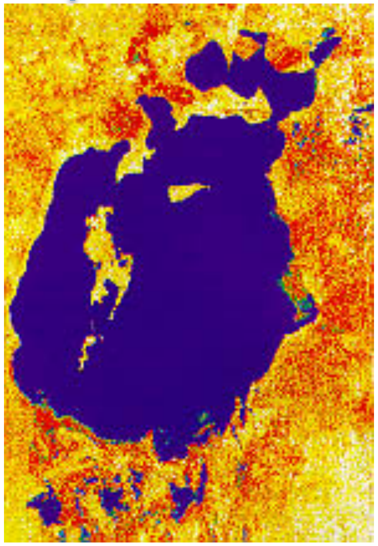
- Kills crops, trees, and wildlife
- Destroys pasture lands
- Cotton and crop yields have declined dramatically
- Fishing industry devastated (twenty of twenty-four native species extinct)
- Roughly ½ of area's bird and mammal species gone

Complicating Factors:

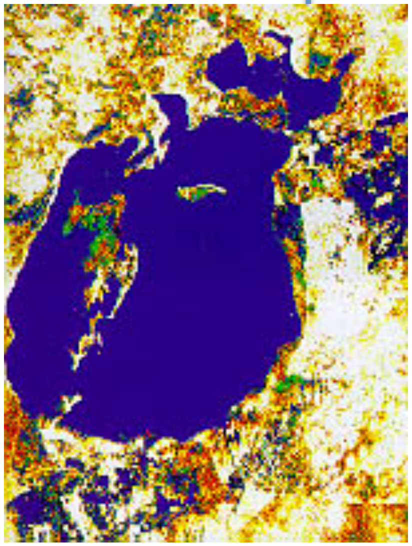
- To raise yields, farmers increase use of herbicides, insecticides, fertilizers
- Many of the chemicals have accumulated in the ground water
- Low flows have concentrated salts, pesticides, toxic chemicals.
- Surface water unfit to drink



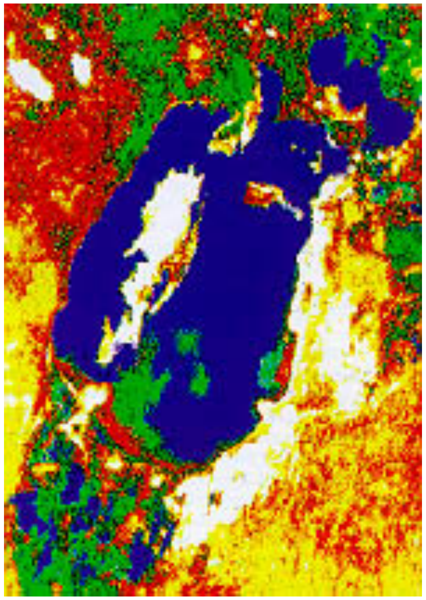
1977



1984



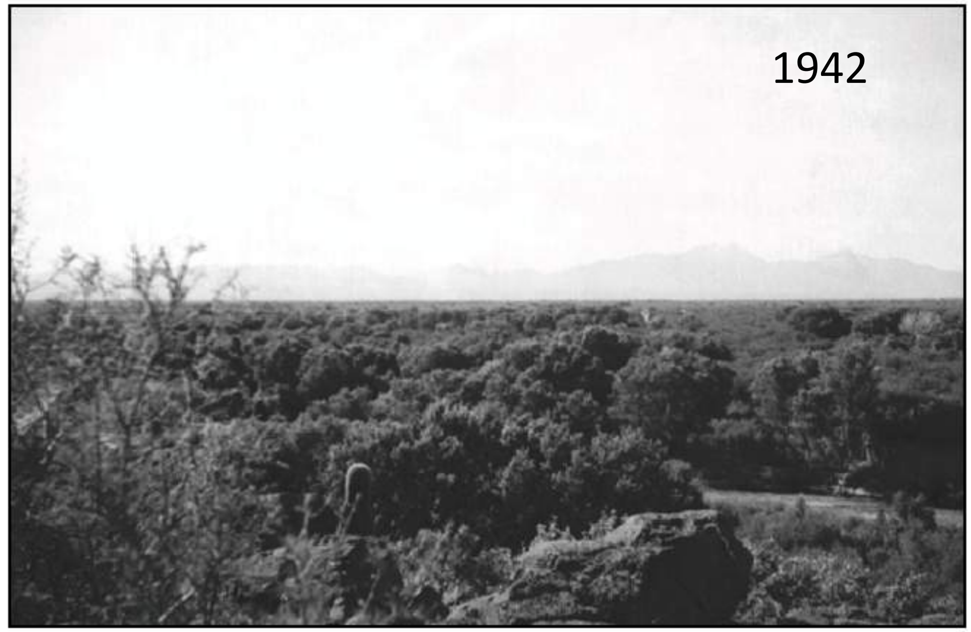
1989

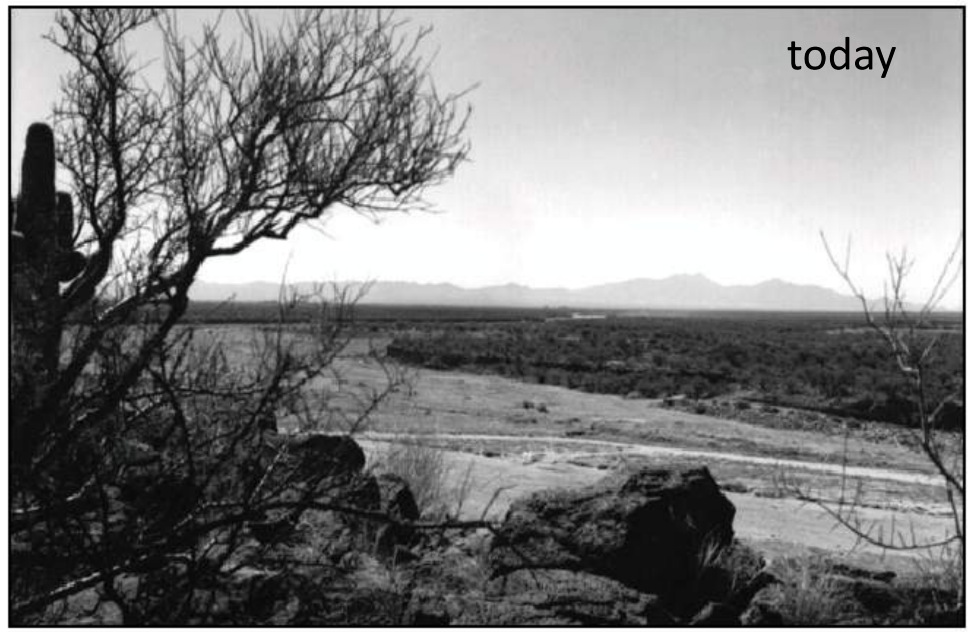


1995

Groundwater Pumping

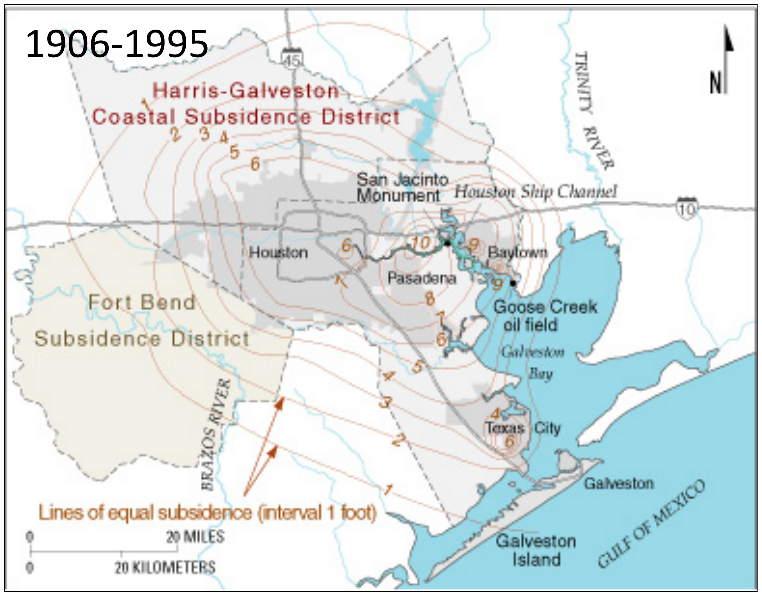
Not only surface water diversion leads to desertification. Pumping of groundwater to supply the city of Tucson, Arizona has lowered the water table over 60m in some locations, causing creeks to run dry, and riparian vegetation to die out, greatly reducing local evapotranspiration.

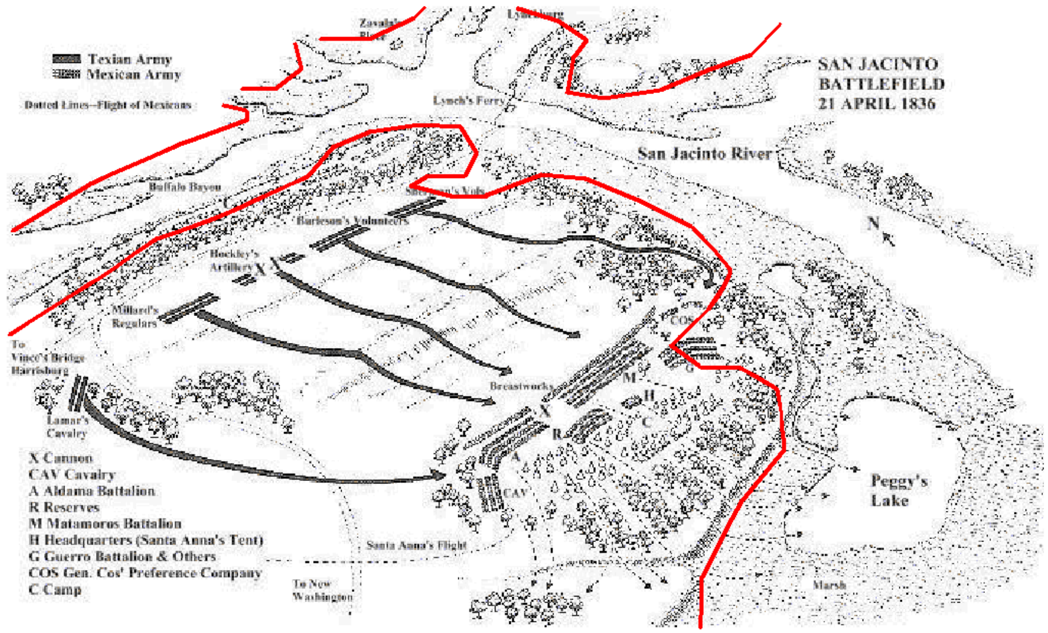




Subsidence

Venice is not the only city sinking into the sea. Houston is subsiding due to groundwater, gas and oil pumping.

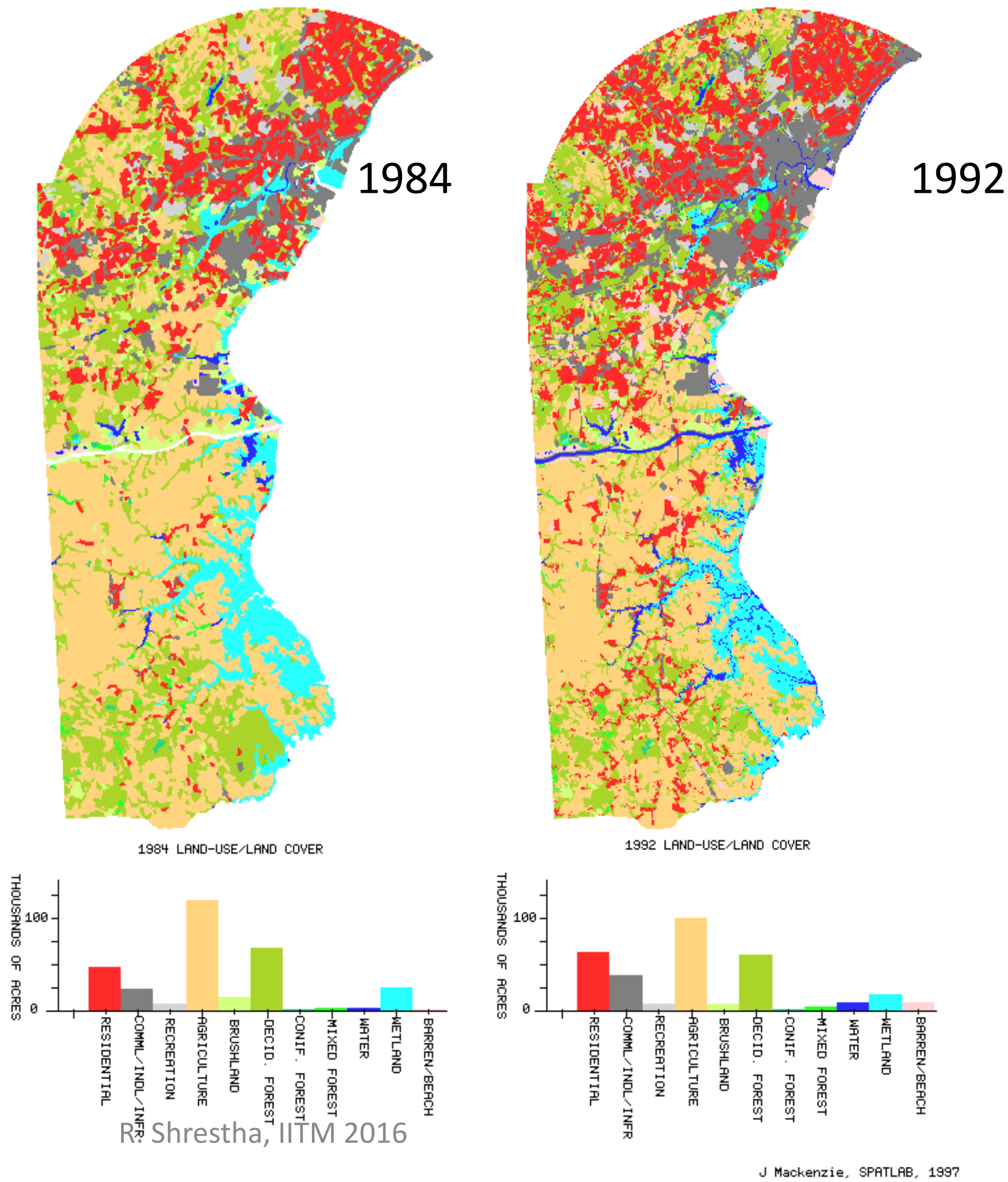


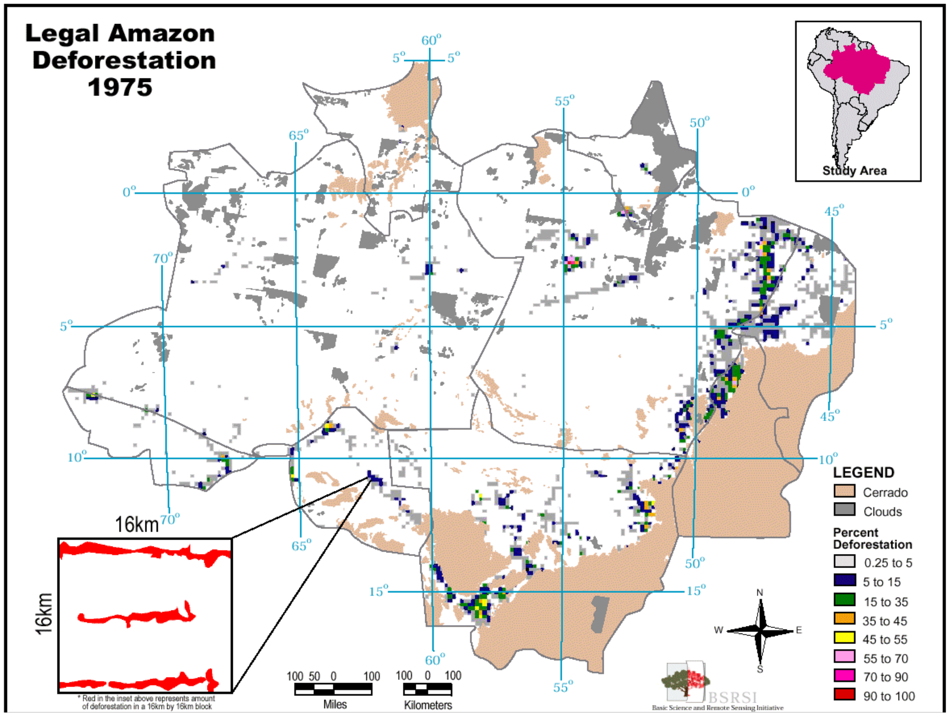


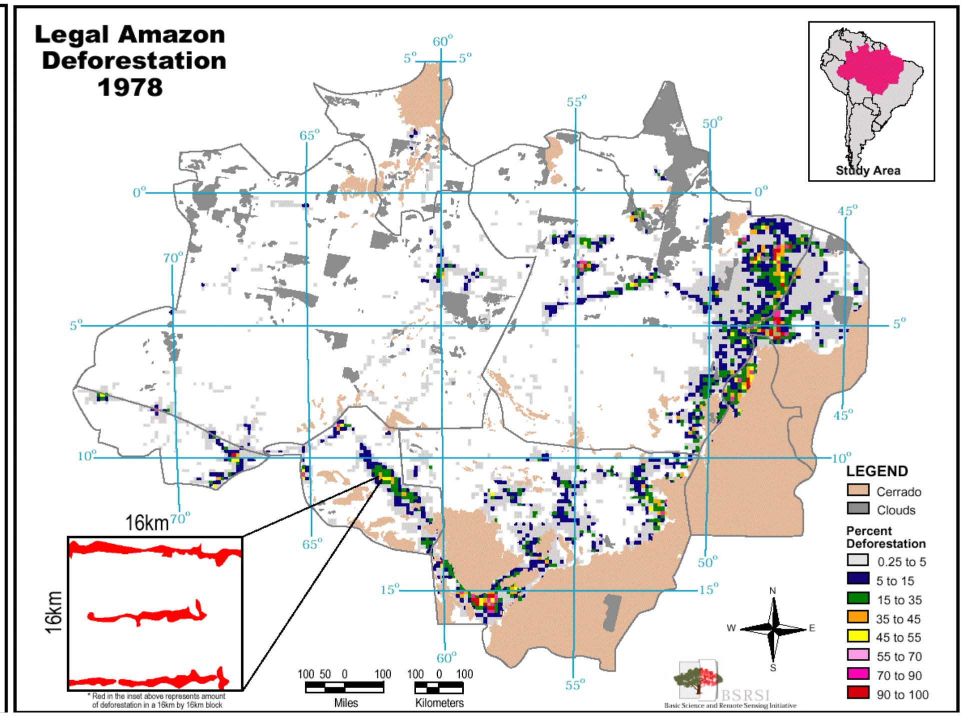
From *The Battle of SanJacinto and the San Jacinto Campaign;* L. W. Kemp and Ed Kalman; at www.tamu.edu/ccbn/dewitt/batsanjacinto.htm
This is an excellent web source for the battle with a number of period drawings and biographies of the commanders. The San Jacinto Monument would be located about ½ way between the two lines of combatants. The Battleship Texas is moored around where it says "Buffalo Bayou", and Lynch's Ferry is now known as the Lynchburg Ferry.

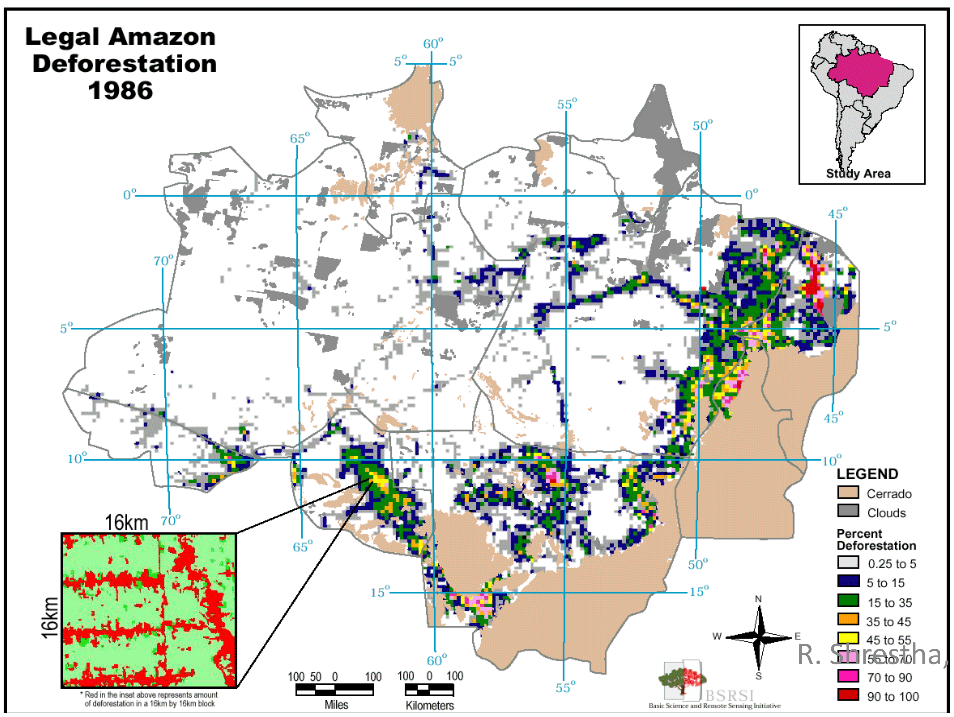
Land use change in northern Delaware

Notice not only the spread of urbanization, but also the loss of wetlands, and the shift of agriculture to consume forest areas as cities spread into farmland.









LEGEND

Cerrado

Clouds

Percent Deforestation

0.25 to 5

5 to 15

15 to 35

35 to 45

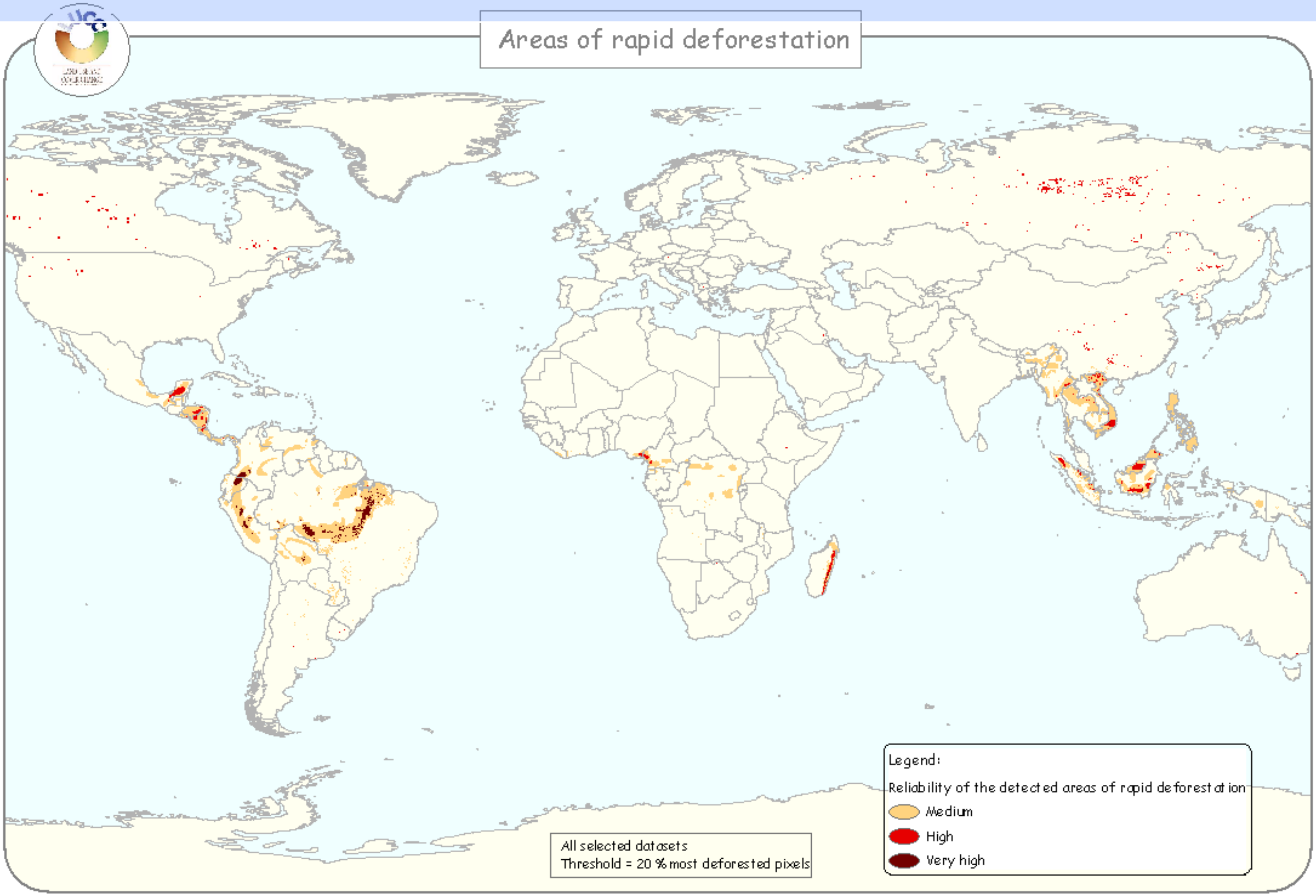
45 to 55

55 to 70

70 to 90

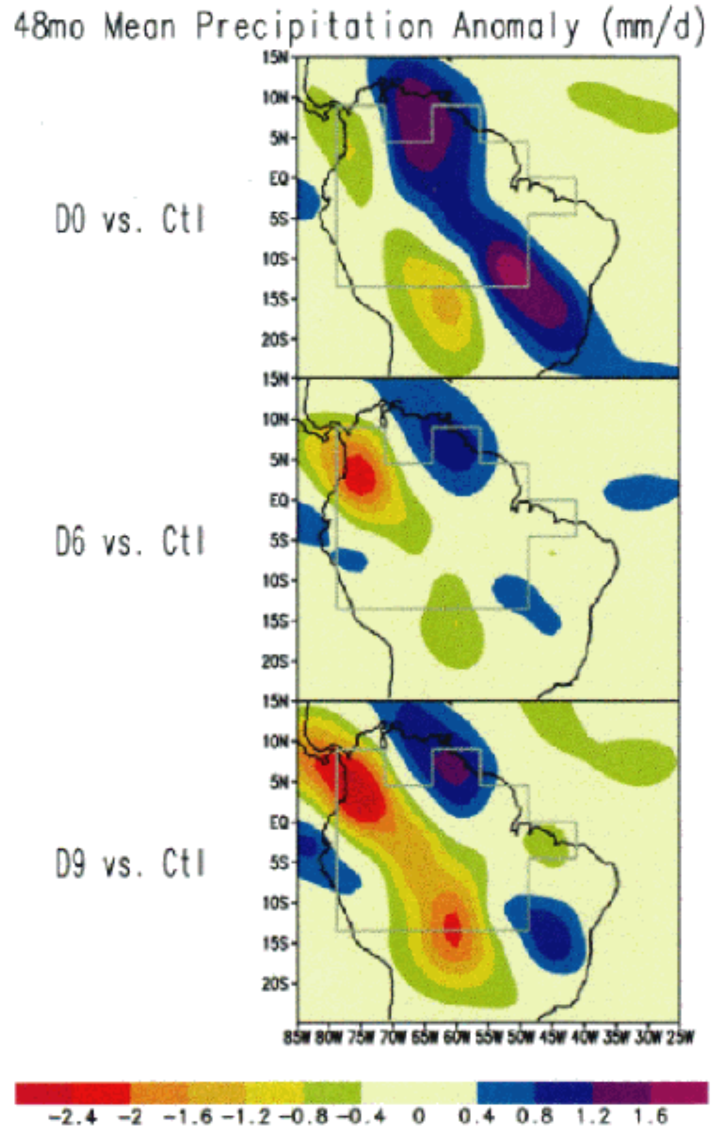
90 to 100

Deforestation



Albedo & Deforestation

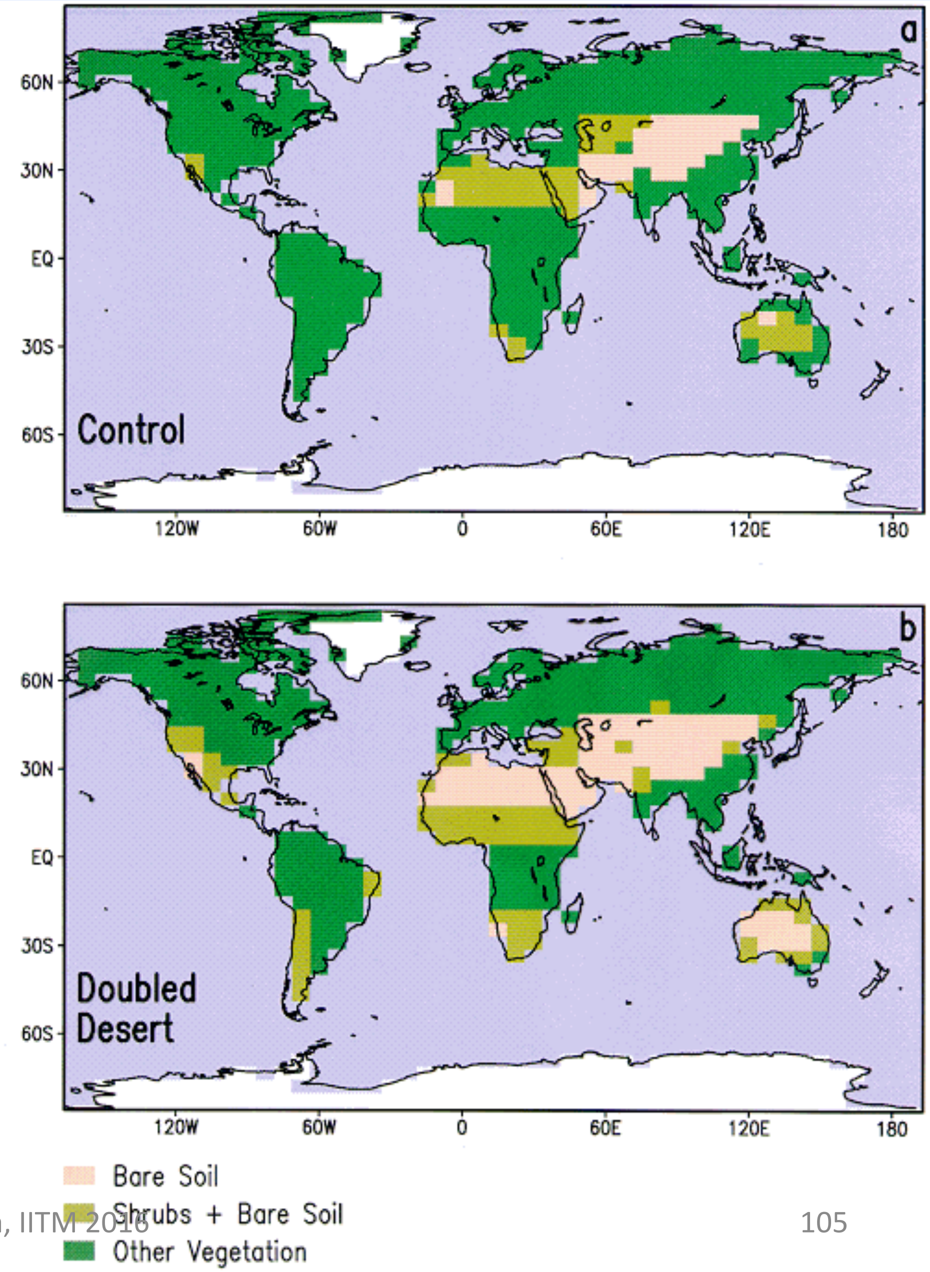
- Deforestation with an albedo = rainforest (D0); 6% lighter (D6); and 9% lighter (D9).
- Dark grassland → net increase in rainfall.
- Light grassland → net decrease.
- Pattern of rainfall change is consistent.



Dirmeyer & Shukla (1994 *JGR*)

Monsoon region sensitivity

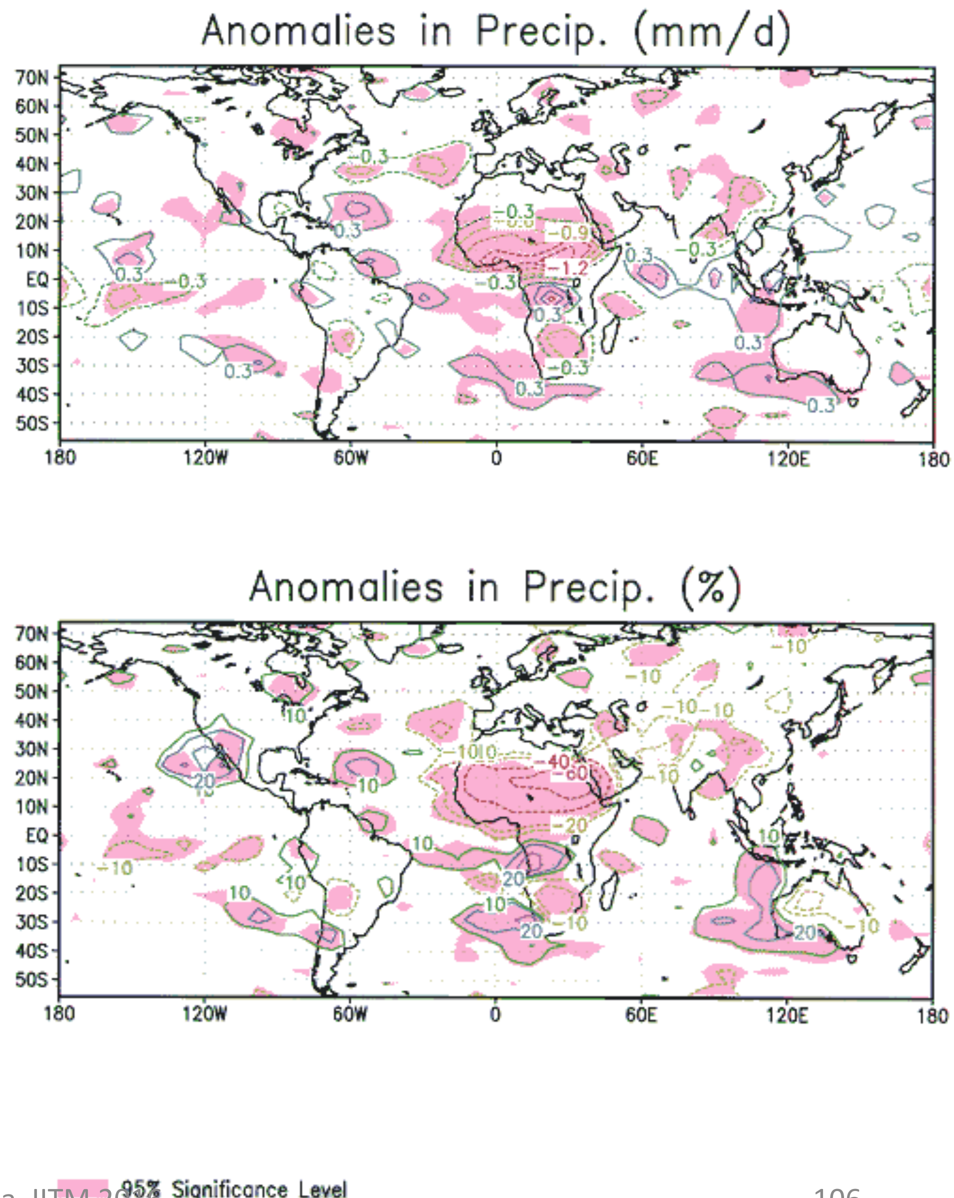
• Sensitivity experiments of desertification show that monsoon regions are most sensitive to impacts of land use/cover change…



Dirmeyer & Shukla (1996 *QJRMS*)

Rainfall Impacts

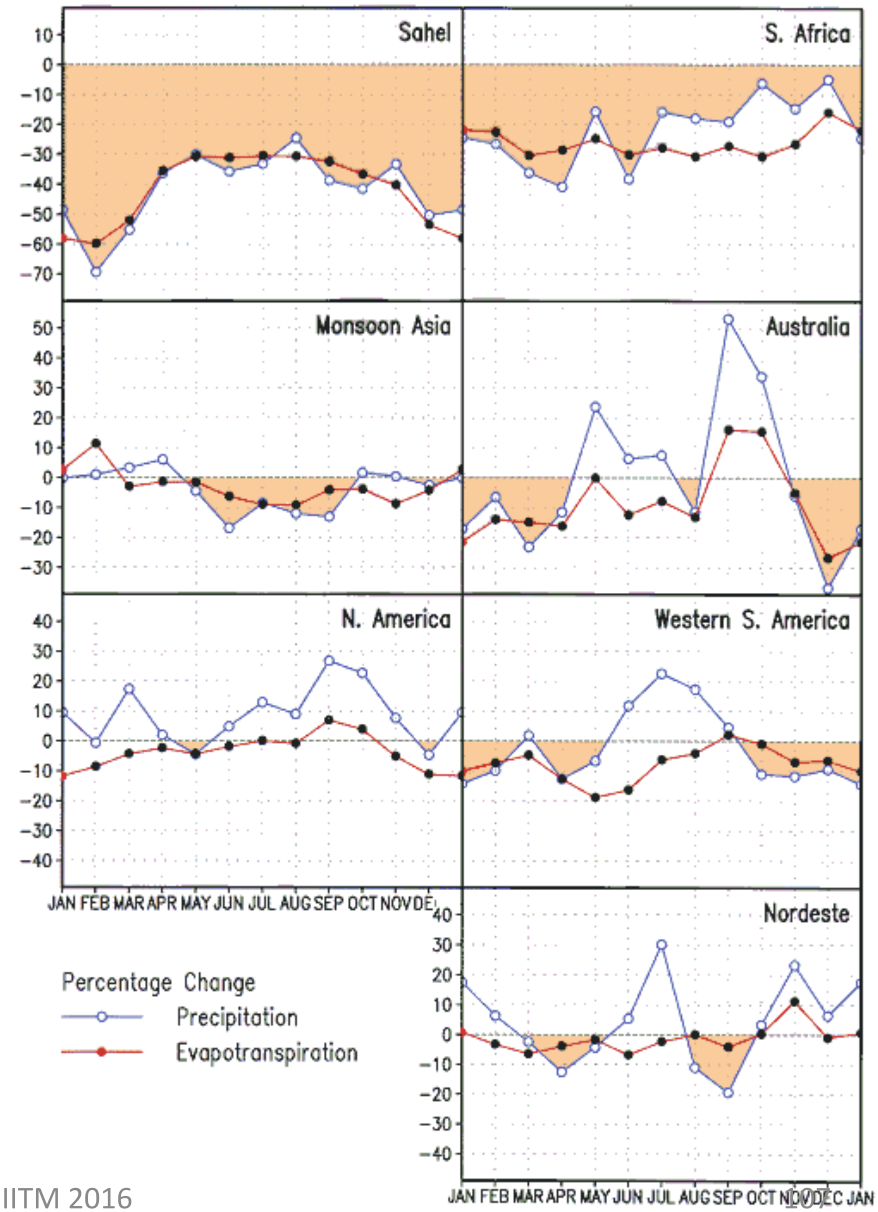
- The largest impacts are in the monsoon regions of Africa (Sahel and South Africa).
- Second are the land-sea monsoons of South Asia, Australia and North America.
- Tropical rainfall intensifies to offset the loss in the subtropics.



Dirmeyer & Shukla (1996 *QJRMS*)

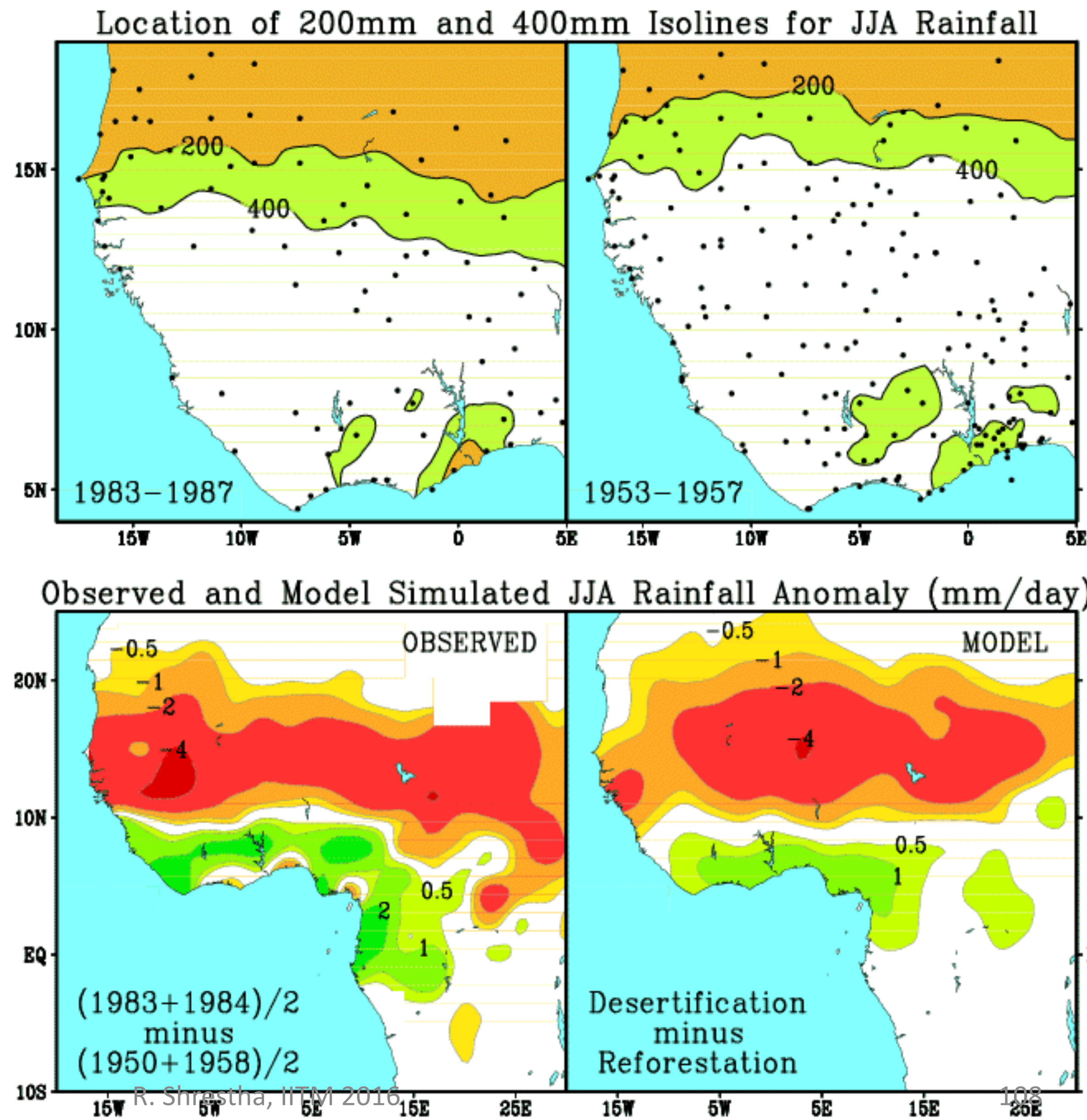
Rainfall Impacts 2

- Impacts over Africa are year-round.
- Asia, Australia, S. America have rainfall decreases during summer only.
- North America shows an increase in rainfall.

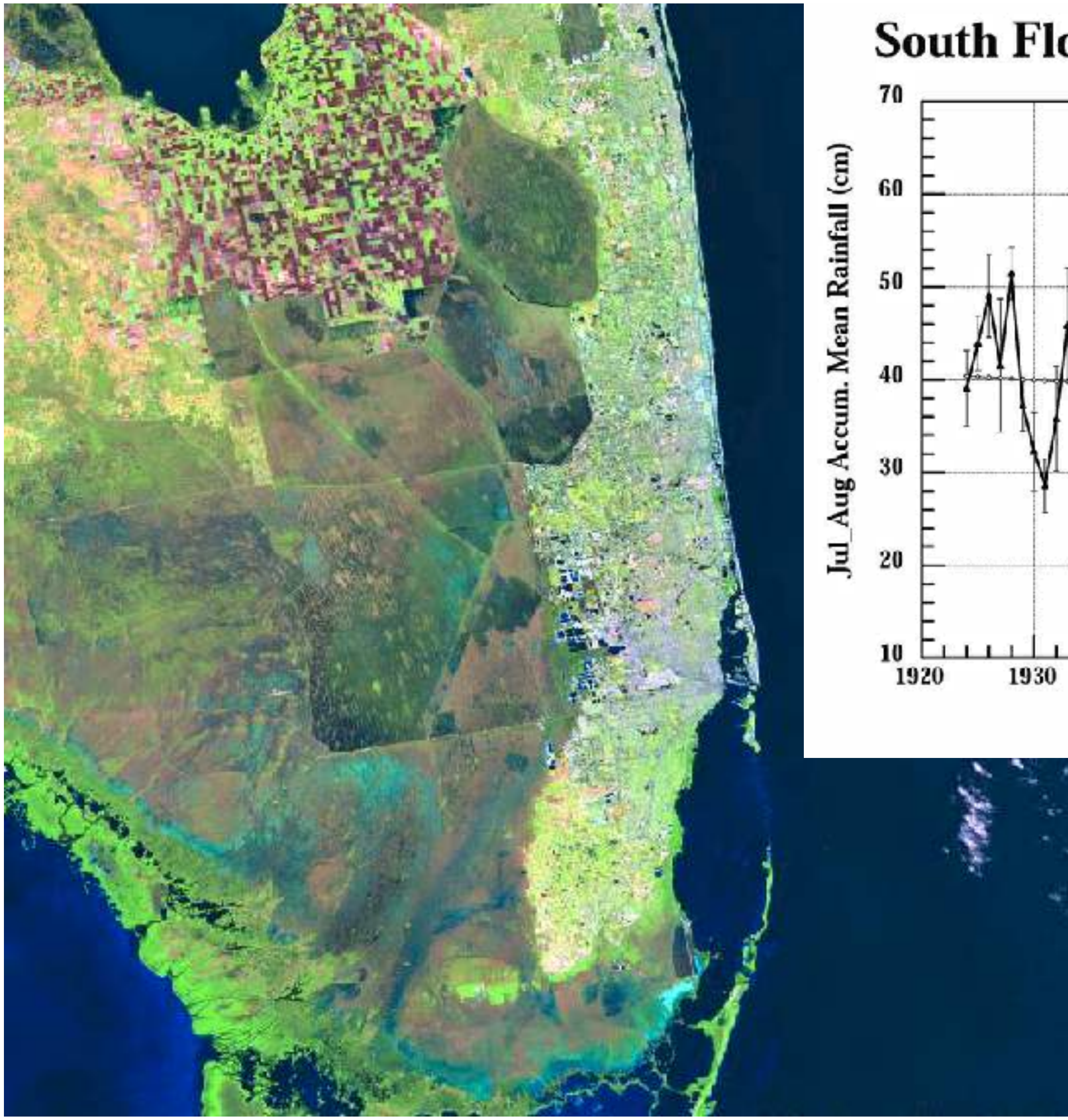


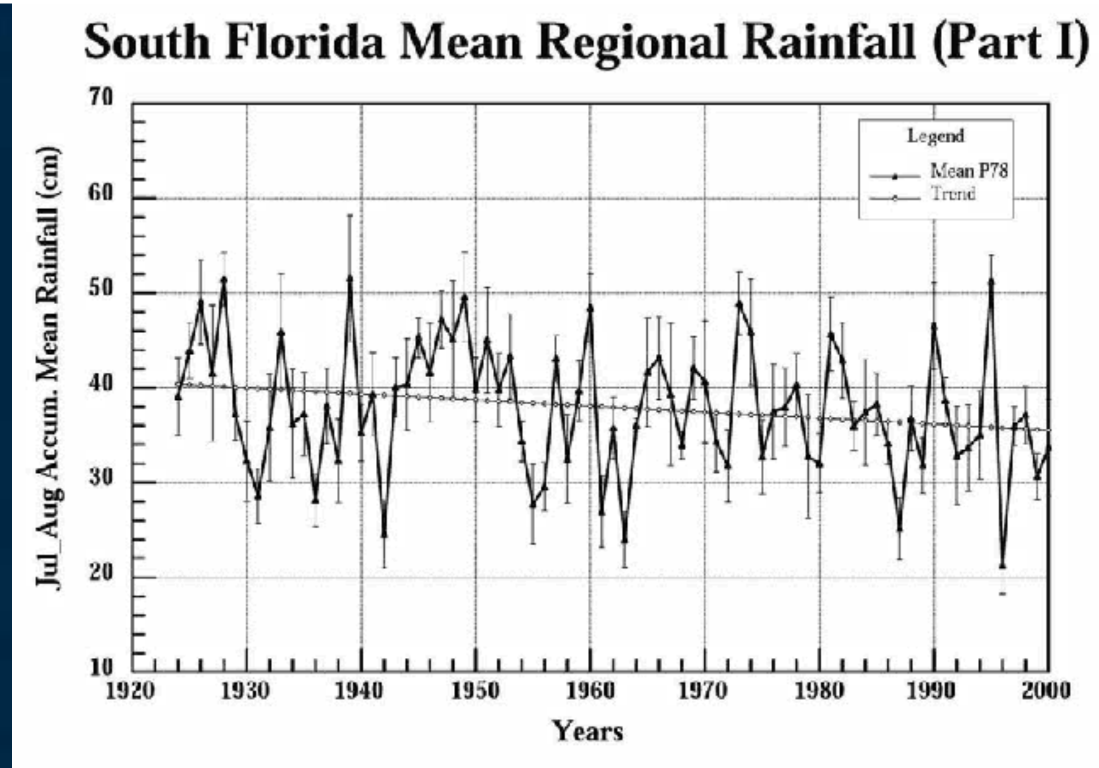
Sahel Desertification

- Observed patterns of precipitation change were modeled in a GCM by changing regional vegetation to reflect desertification (Xue and Shukla, 1993 *J. Climate*).
- Did overgrazing cause climate change? Did climate variability cause desertification? Feedbacks???



Land Cover Change and Subtropical Climate

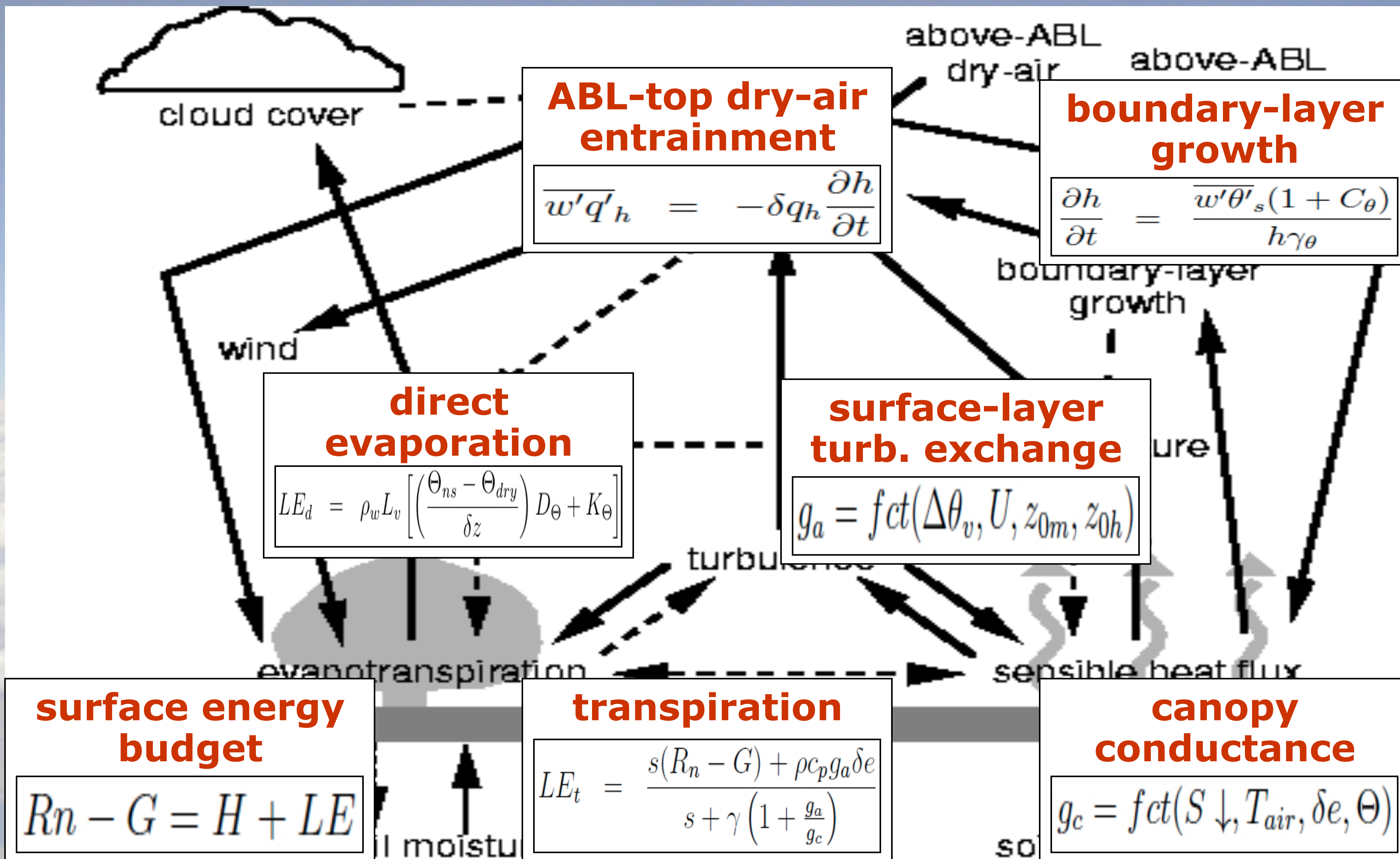




- Are observed rainfall trends (~10% in 80 years) due to large-scale land use change? (Pielke et al 1999; Marshall et al. 2004)

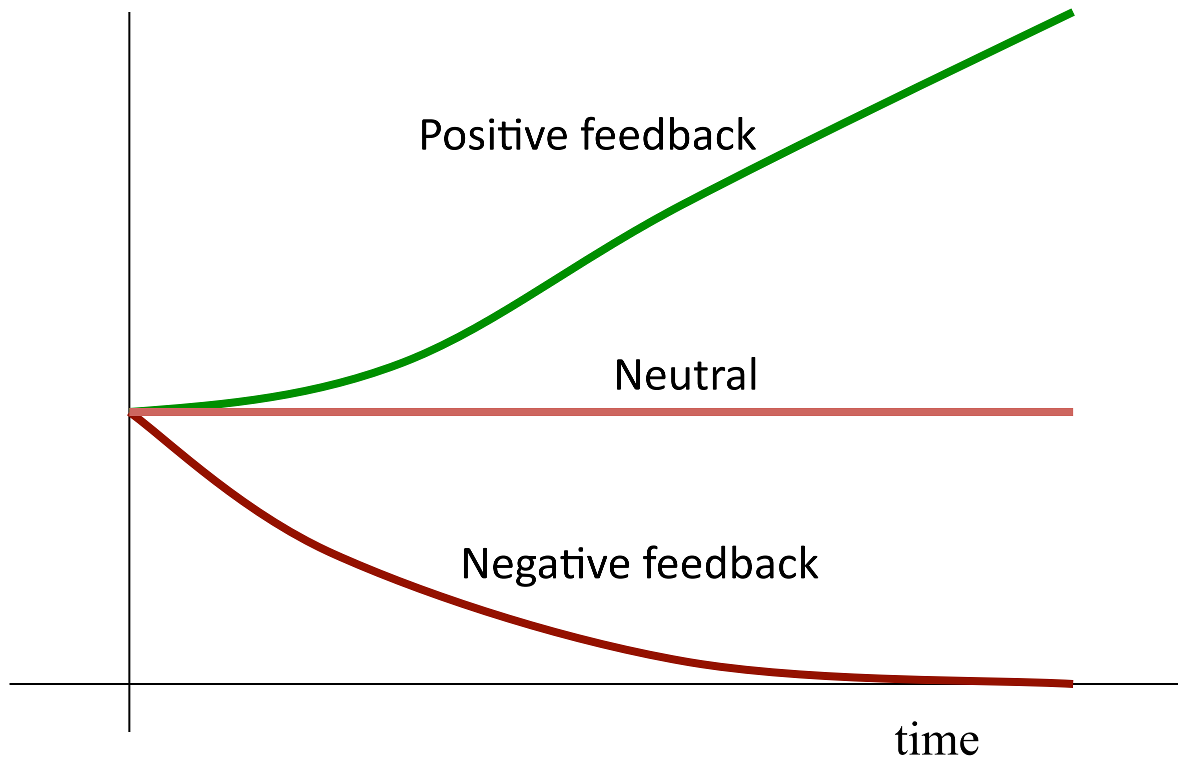
- Land Climate Interaction

Land-Atmosphere Interactions

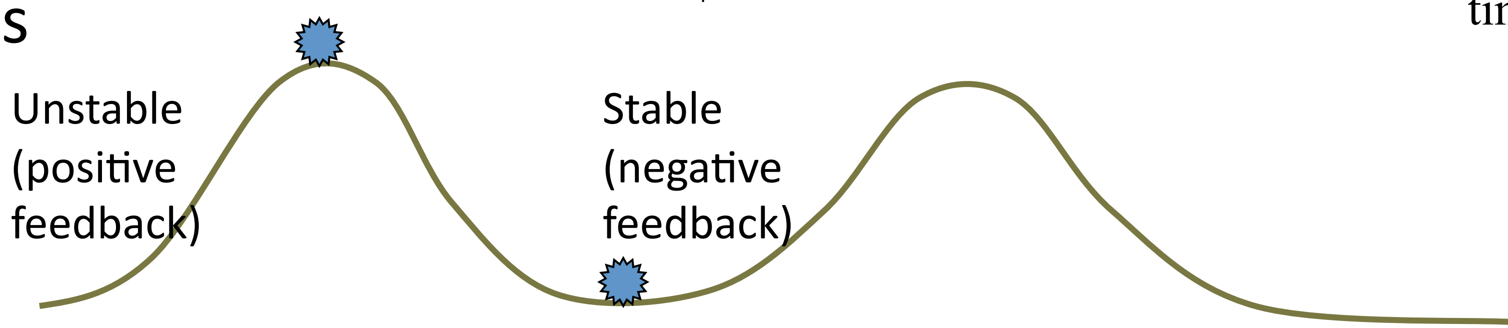


Feedback of land

- Does the cycle between land and atmosphere lead to amplification or damping of climate anomalies?



- Climate attractors (potential) can be a useful way to visualize this



What is land-atmosphere feedback on precipitation?

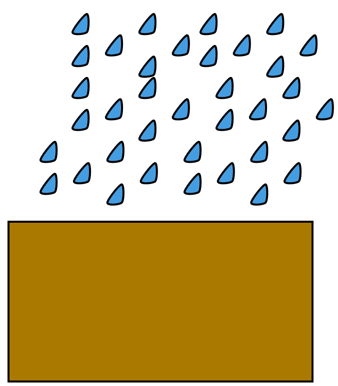
Precipitation wets the surface...

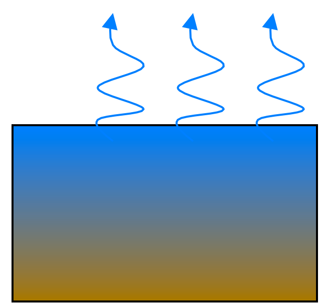
...causing soil moisture to increase...

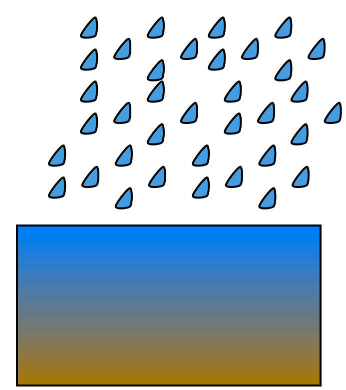
...which causes evaporation to increase during subsequent days and weeks...

...which affects the overlying atmosphere (the boundary layer structure, humidity, etc.)...

...thereby (maybe) inducing additional precipitation







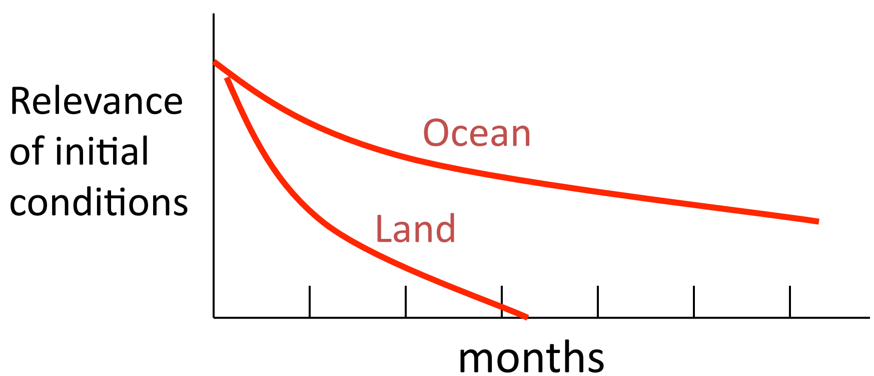
Perhaps such feedback contributes to predictability.

Short-term weather predictions are limited by chaos in the atmosphere.

Establish atmospheric state → Initialize model with that state; integrate into future → Short-term (~several days) weather prediction

Longer term predictions rely on slower moving components of the Earth's system, such as ocean heat content and soil moisture.

Establish ocean state, land moisture state → Initialize model with those states; integrate into future → Long-term (~weeks to years) prediction of ocean and/or land states → Associated prediction of weather, if weather responds to these states



For soil moisture to contribute to precipitation predictability, two things must happen:

1. A soil moisture anomaly must be "remembered" into the forecast period.
2. The atmosphere must respond in a predictable way to the remembered soil moisture anomalies

Soil Moisture Memory

Observational soil moisture measurements give some indication of soil moisture memory.

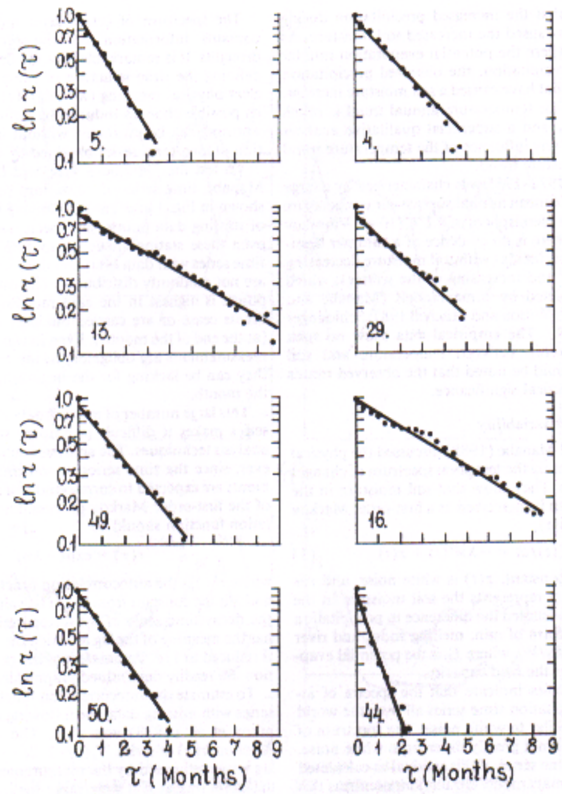


FIG. 6. Examples of empirical estimates of autocorrelation functions of time series of soil moisture in 1-m deep soil layer. τ is the lag in months. The lines correspond to the approximation used, figures in the lower left corner are the same as the station numbers. Stations 4 and 5 are in the forest zone, station 29 is in the forest-steppe zone, stations 13 and 16 are in the steppe zone, station 49, semiarid zone, stations 44 and 50 are in the desert.

Vinnikov and Yeserkepova, 1991

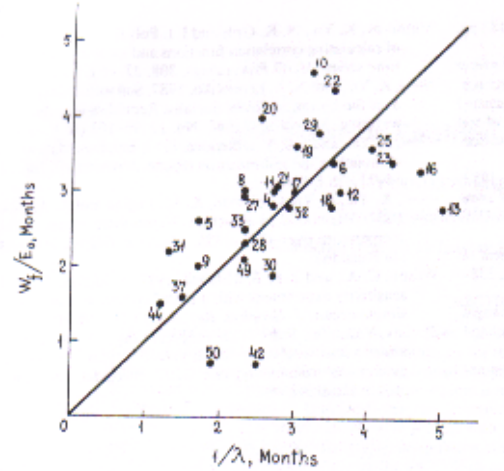
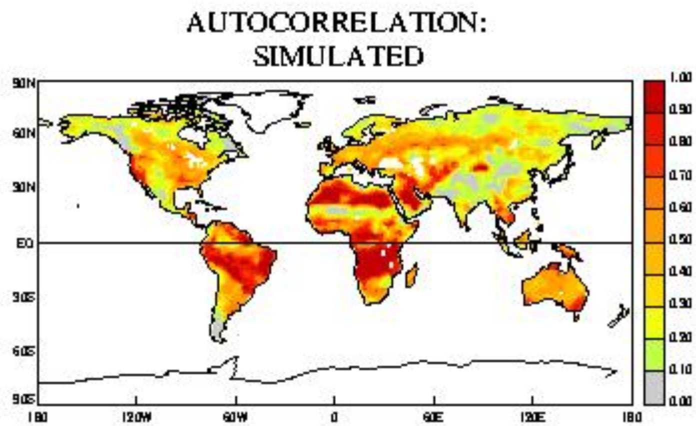
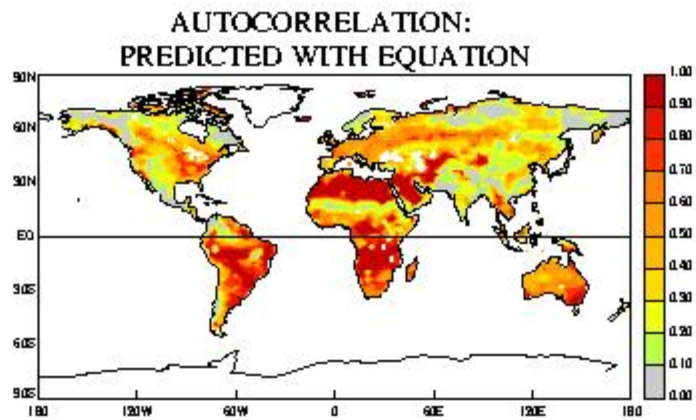


FIG. 7. Comparison of empirical and theoretical estimates of the decay time scale of soil wetness (in months).

Vinnikov and Yeserkepova, 1991

Soil moisture timescales of several months are possible. "The most important part of upper layer (up to 1 m) soil moisture variability in the middle latitudes of the northern hemisphere has … a temporal correlation scale equal to about 3 months." (Vinnikov et al., JGR, 101, 7163-7174, 1996.)





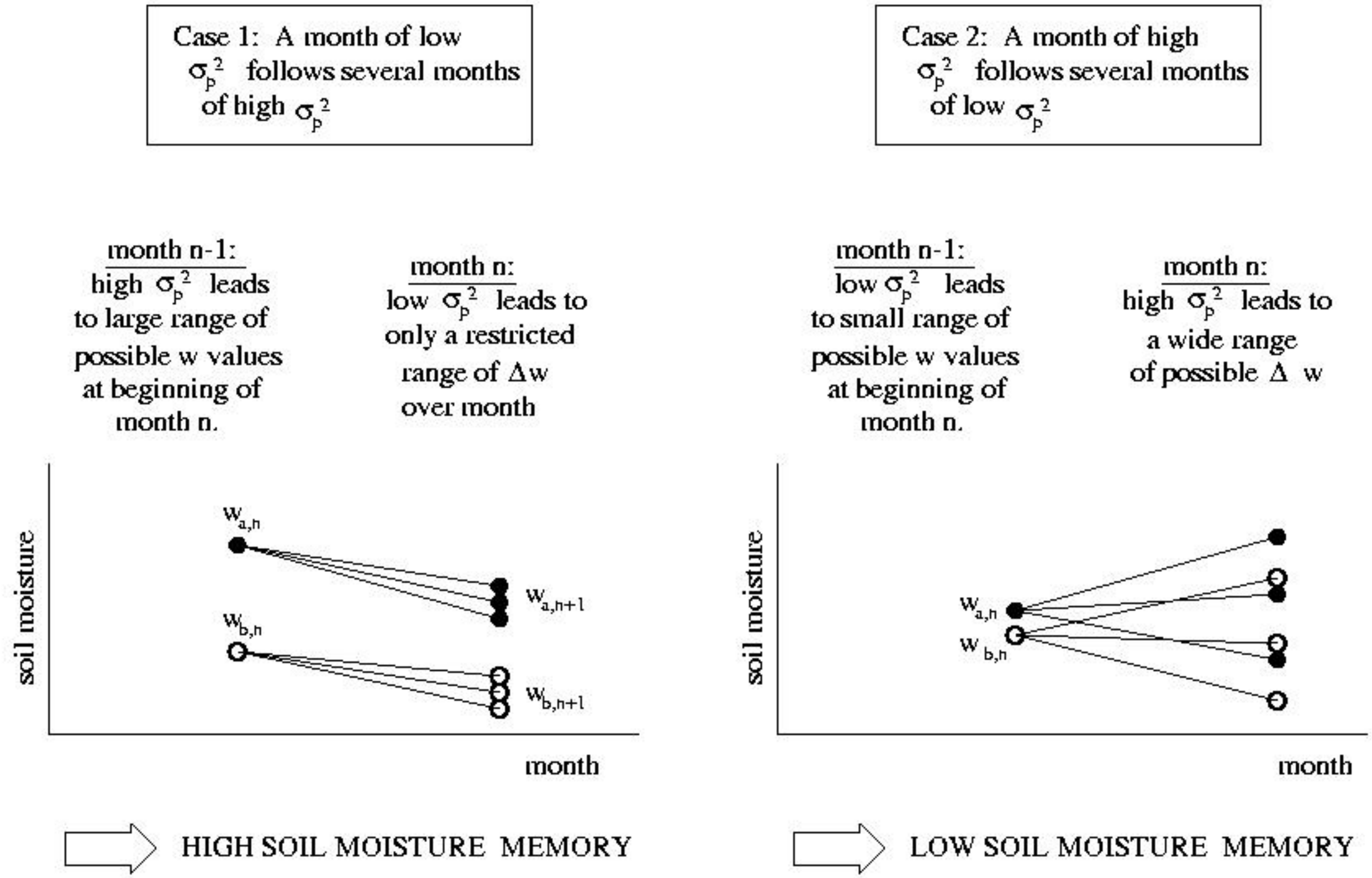
Memory equation:

$$\rho = \frac{\mathrm{cov}(w_n, w_{n+1})}{\sigma_{w_n}\sigma_{w_{n+1}}} = \frac{\sigma_{w_n}}{\sigma_{w_{n+1}}}\left[\frac{2 - \left(\frac{c\bar{R}_n}{C_s}\right) - \left(\frac{a\bar{P}_n}{C_s}\right)}{2 + \left(\frac{c\bar{R}_n}{C_s}\right) + \left(\frac{a\bar{P}_n}{C_s}\right)}\right] + \frac{\mathrm{cov}(w_n, F_n)}{\sigma_{w_n}^2}$$

The autocorrelation equation effectively relates soil moisture memory to four separate controls:

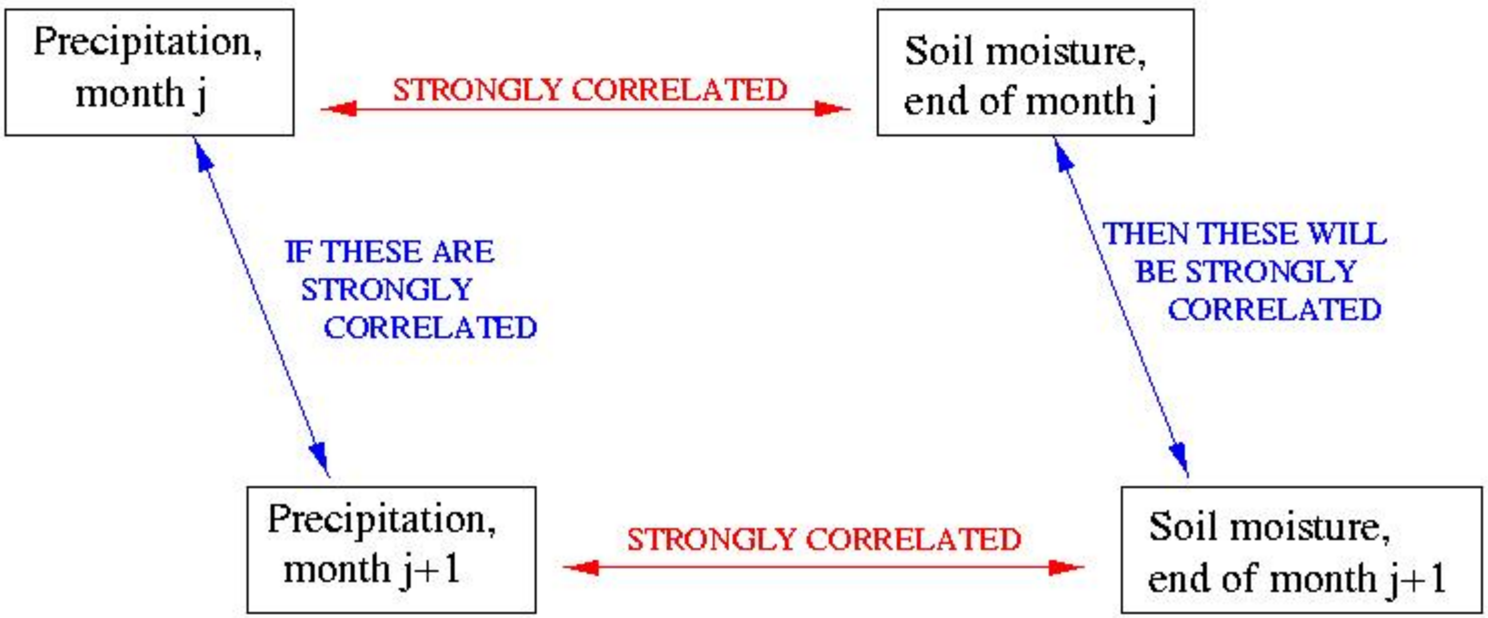
1. seasonality in the statistics of the atmospheric forcings,
2. the variation of evaporation with soil moisture,
3. the variation of runoff with soil moisture,
4. correlation between the atmospheric forcings and antecedent soil moisture.

Seasonality term: $\sigma_{wn}/\sigma_{wn+1}$



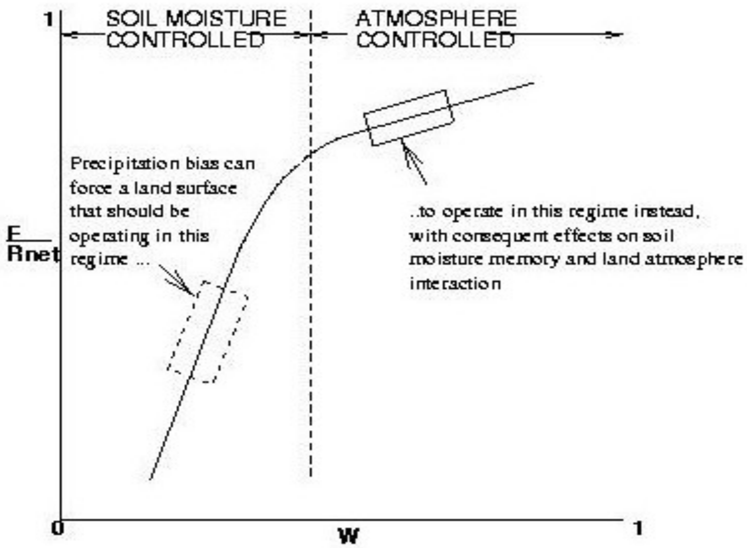
Persistence in forcing

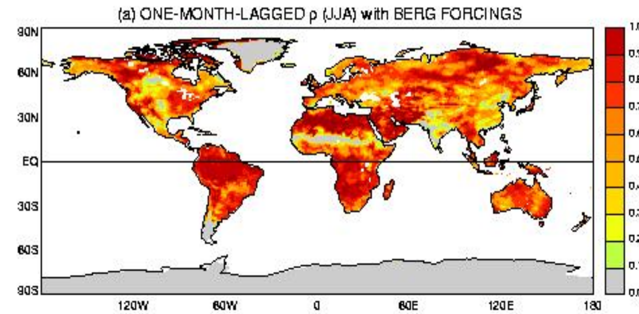
(the covariance term)

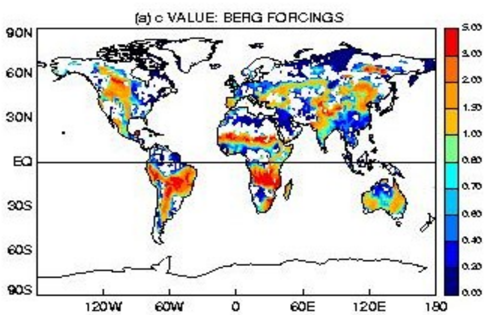


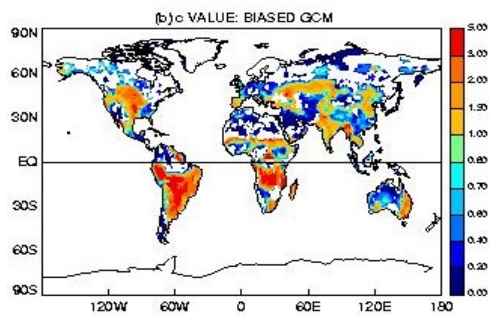
Note: persistence in forcing may result from land-atmosphere feedback.

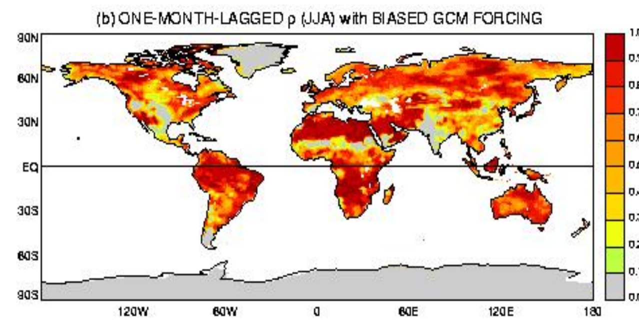
Effect of Climate Bias on Evaporative Regime

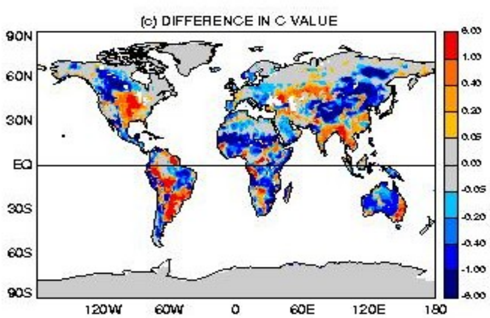




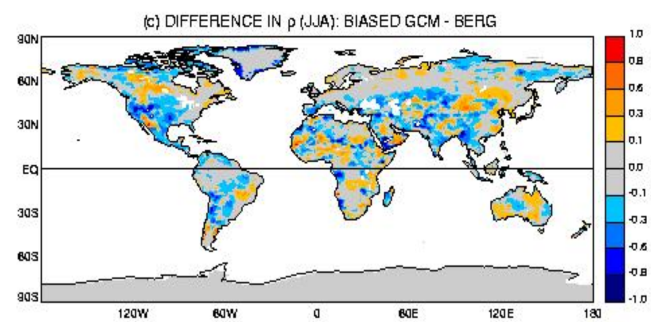








Different sensitivities of evaporation to soil moisture result from different climatologies of forcing.



Errors in memory due to GCM biases in forcing

Atmosphere's Response to Soil Moisture Anomalies

Three ways of looking for evidence of atmospheric response:

1. Examine observational data.

→ Very difficult.

2. Simple analytical models.

→ Advantage: feedbacks can be quantified and easily understood. Disadvantage: ignores some nonlinearities and complexities of system.

Examples:
Rodriguez-Iturbe et al., WRR, 27, 1899-1906, 1991.
Brubaker and Entekhabi, WRR, 32, 1343-1357, 1996.
Liu and Avissar, J. Clim, 12, 2154-2168, 1999.

3. GCM studies.

→ Useful for several reasons: (a) full set of diagnostic out-puts, (b) inclusion of nonlinearities, and (c) ability to do sensitivity studies.

GCM evidence goes way back...

Shukla and Mintz (1982) provide one of the first AGCM studies demonstrating the impact of land moisture anomalies on precipitation:

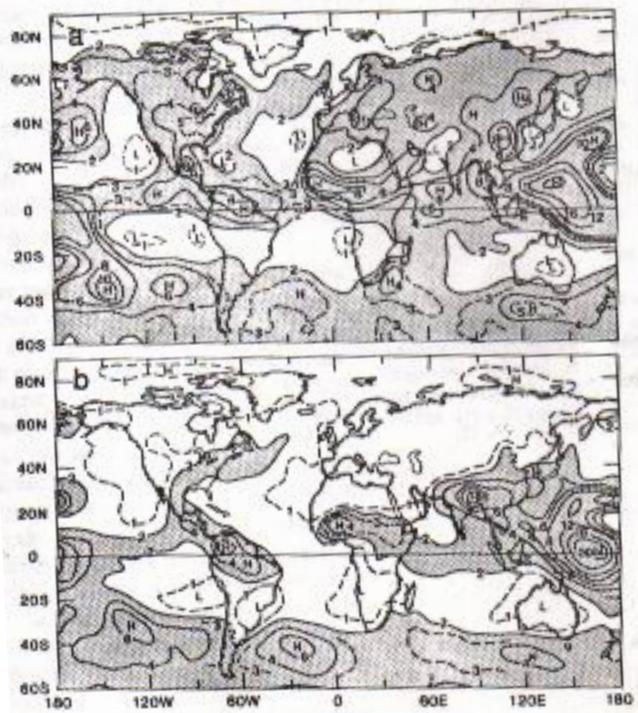


Fig. 1. Simulated July precipitation (millimeters per day) in (a) the wet-soil and (b) the dry-soil case.

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Questions that can be addressed with an GCM: How large is the impact of a land anomaly on the atmosphere? What are the relative roles of ocean variability, land variability, and chaotic atmospheric dynamics in determining precipitation over continents?

Studies examining the impact of "perfectly forecasted" soil moisture on the simulation of non-extreme interannual variations. Some examples:

Delworth and Manabe, J. Climate, 1, 523-547, 1988.

Dirmeyer, J. Climate, 13, 2900-2922, 2000.

Douville et al., J. Climate, 14, 2381-2403, 2001.

Simulated precipitation variability can be described in terms of a simple linear system:

Total precipitation variance

Precipitation variance in the absence of land feedback

$$\sigma^2_{ALO} = \sigma^2_{AO} \left[X_o + (1 - X_o) \right] \qquad \frac{\sigma^2_{ALO}}{\sigma^2_{AO}}$$

Exp.	# of simulations	Length	Total years	Description
A	4	200 yr	800	Prescribed, climatological land; climato-logical ocean
AL	4	200 yr	800	Interactive land, climato-logical ocean
AO	16	45 yr	720	Prescribed, climatological land, interan-nually varying ocean
ALO	16	45 yr	720	Interactive land, interan-nually varying ocean

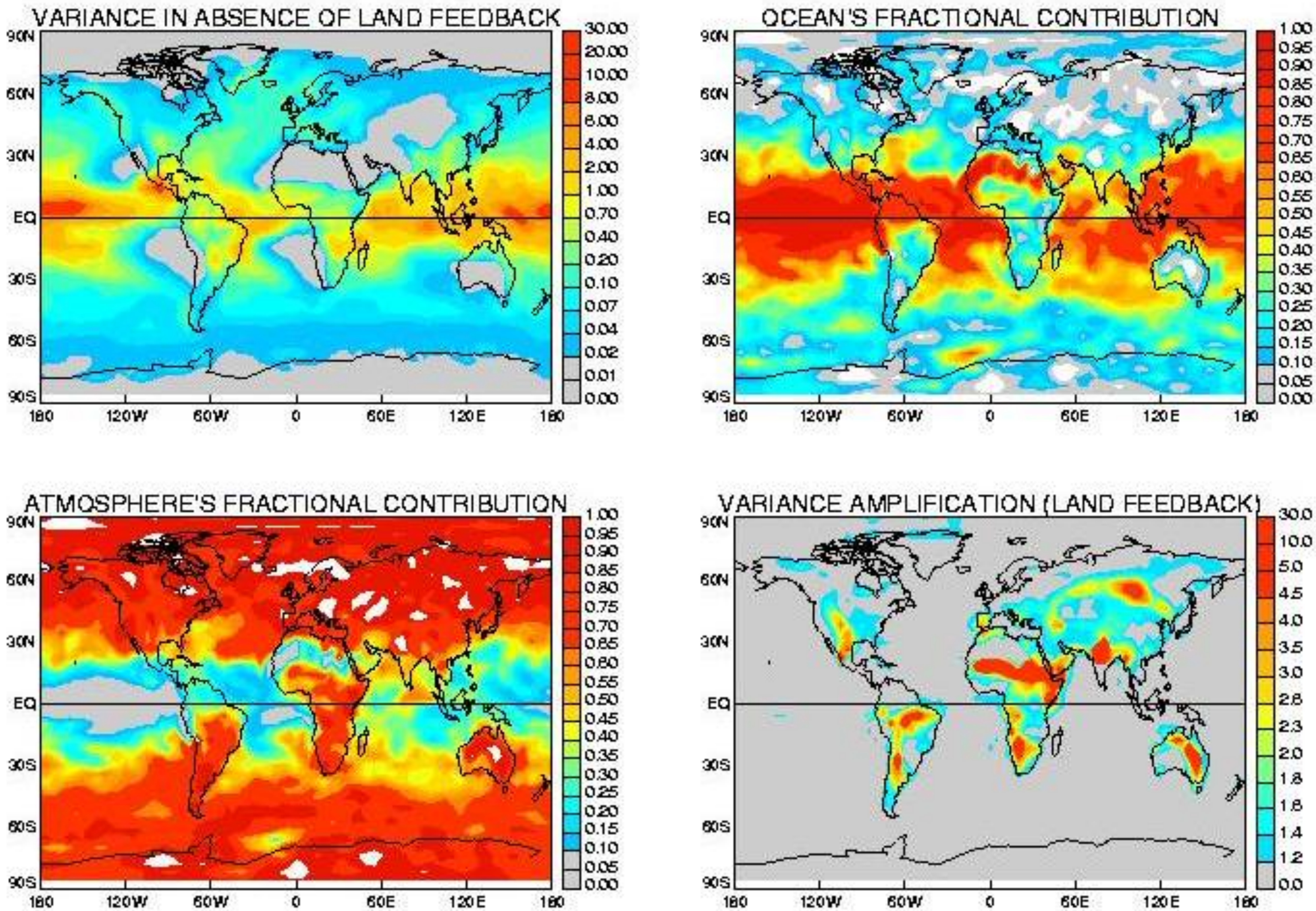
Evaporation efficiency (ratio of evaporation to potential evaporation) prescribed at every time step to seasonally-varying climatological means

SSTs set to seasonally-varying climatological means (from obs)

SSTs set to interannually-varying values (from obs)

LSM in model allowed to run freely

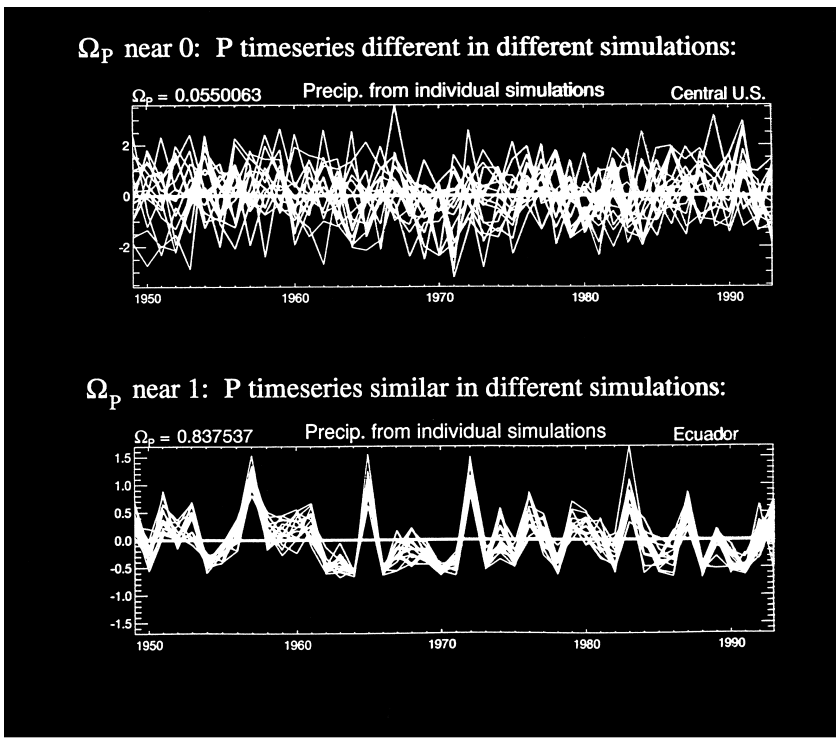
Contributions to Precipitation Variability



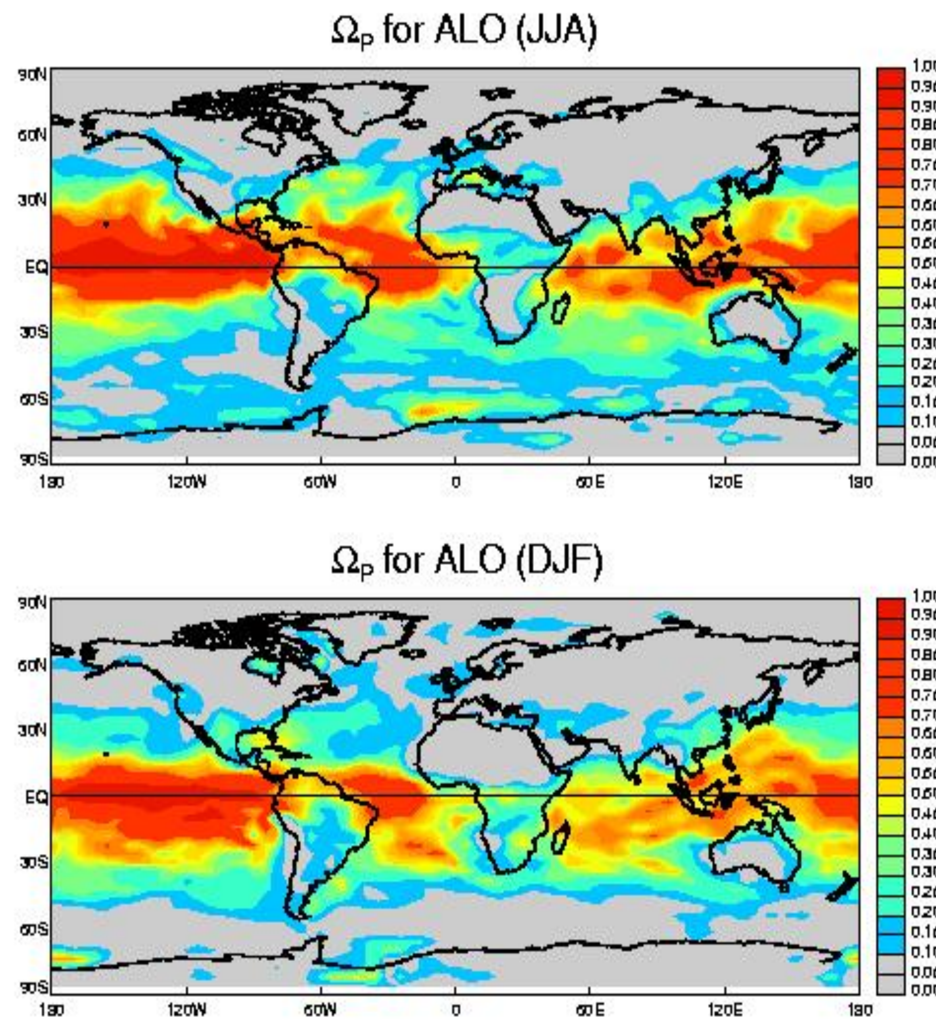
Randy Koster, GSFC, NASA

In an additional ensemble, every member of the ensemble is subject to the same time series of evaporation efficiency. Does the precipitation respond coherently to this signal?

A variable Ω is defined that describes the coherence between the different precipitation time series.



Results for SST control over precipitation coherence:



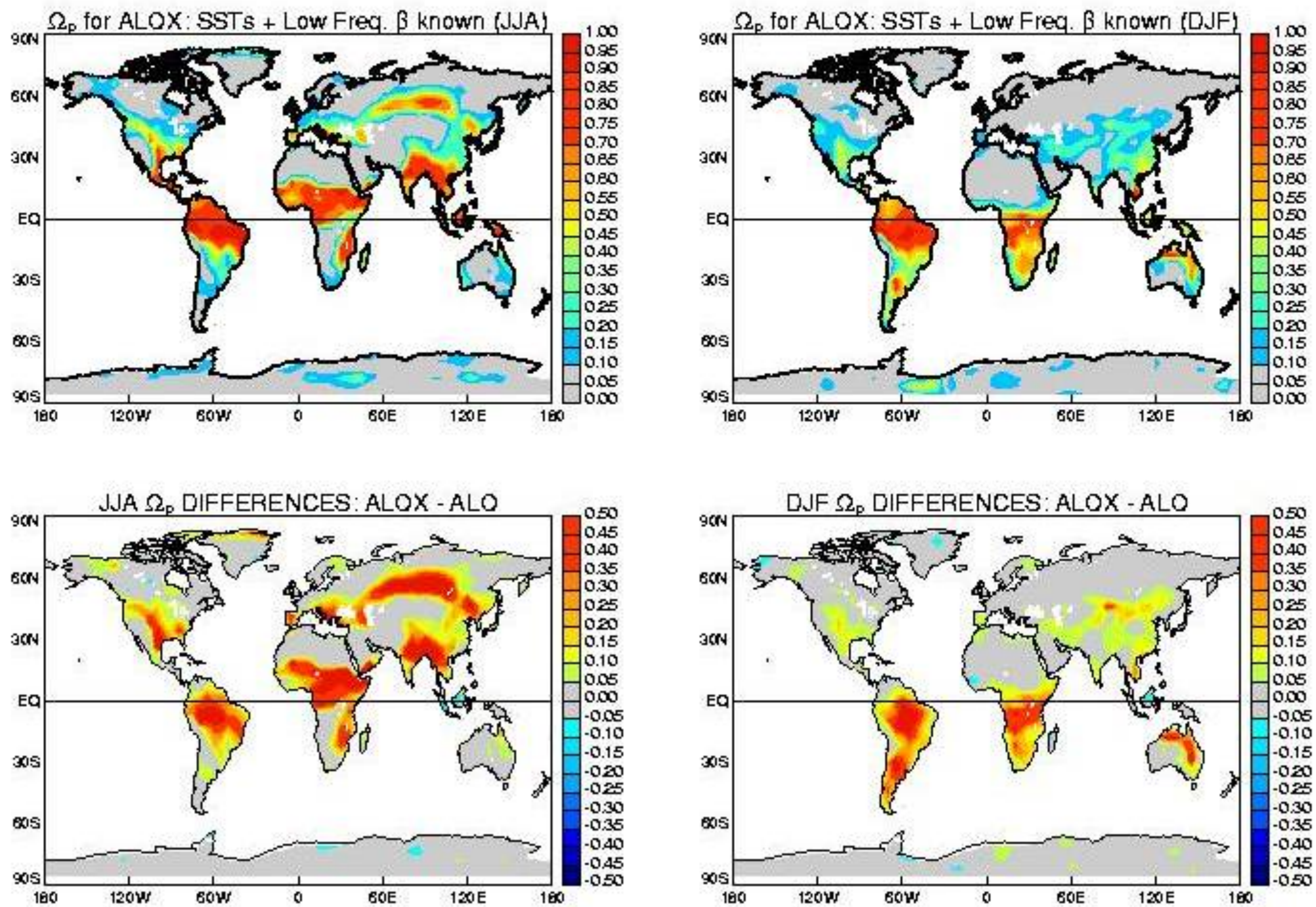
Koster et al. (2001)

Summer

Winter

Results for SST and soil moisture control over precipitation coherence →

Differences: an indication of the impacts of soil moisture control alone →



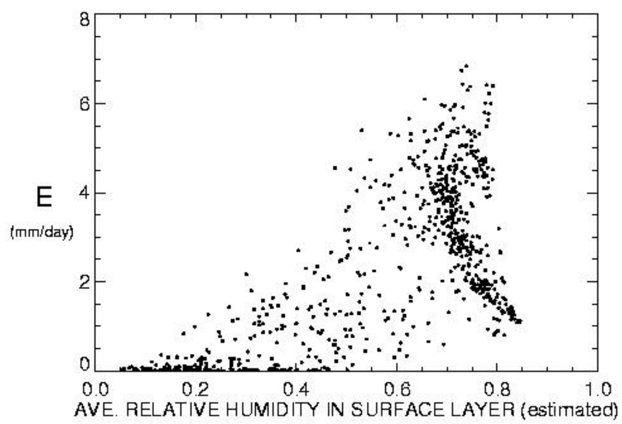
Koster et al. (2001)

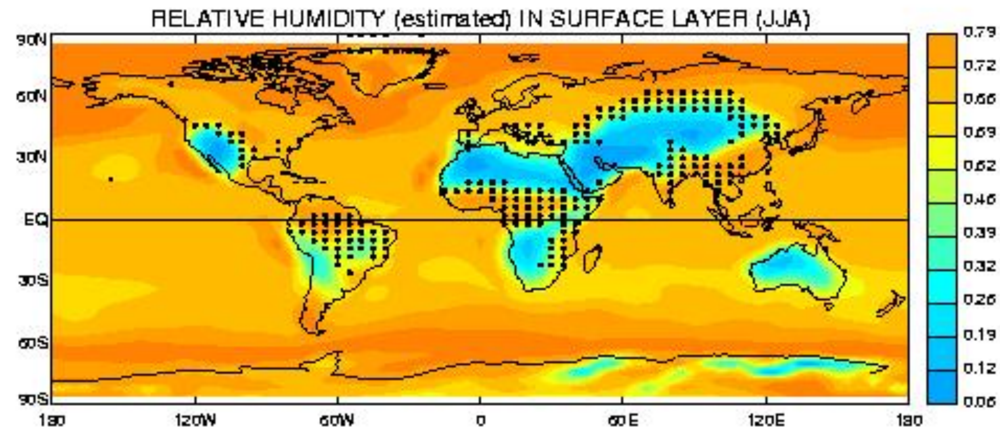
Why does land moisture have an effect where it does? For a large effect, two things are needed:

- a large enough evaporation signal
- a coherent evaporation signal – for a given soil moisture anomaly, the resulting evaporation anomaly must be predictable.

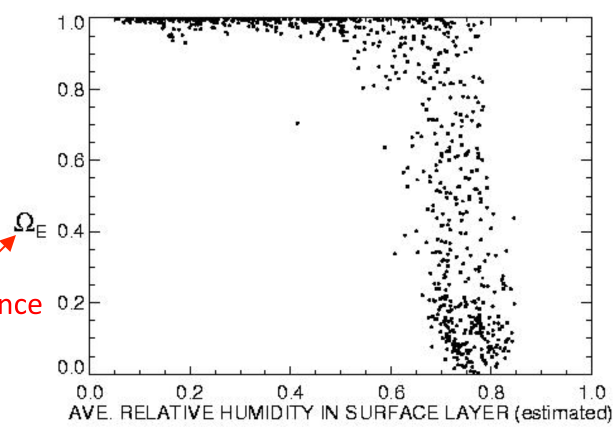
Both conditions can be related to relative humidity:

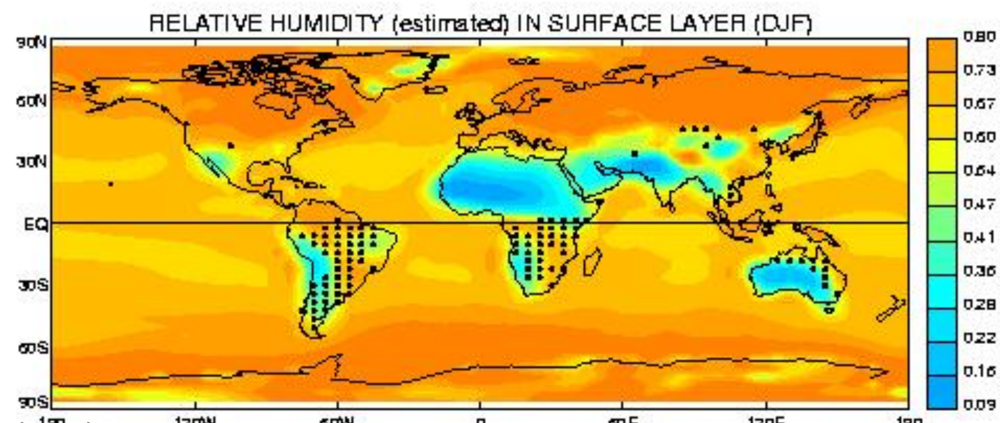
The dots show where the land's signal is strong. From the map, we see a strong signal in the transition zones between wet and dry climates.





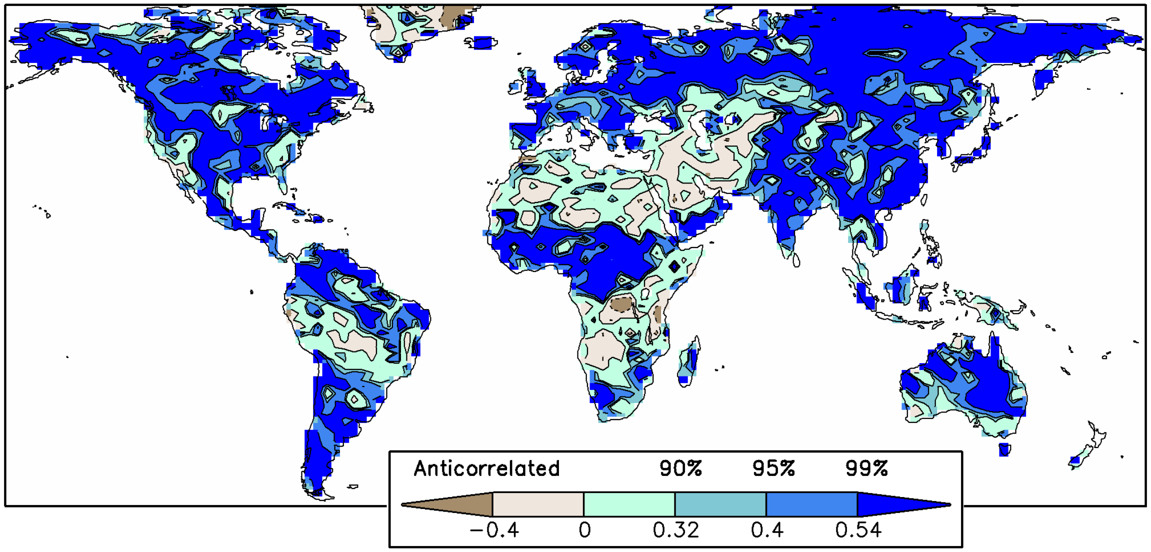
Evap. coherence





Koster et al. (2001)

results from the COLA GCM:



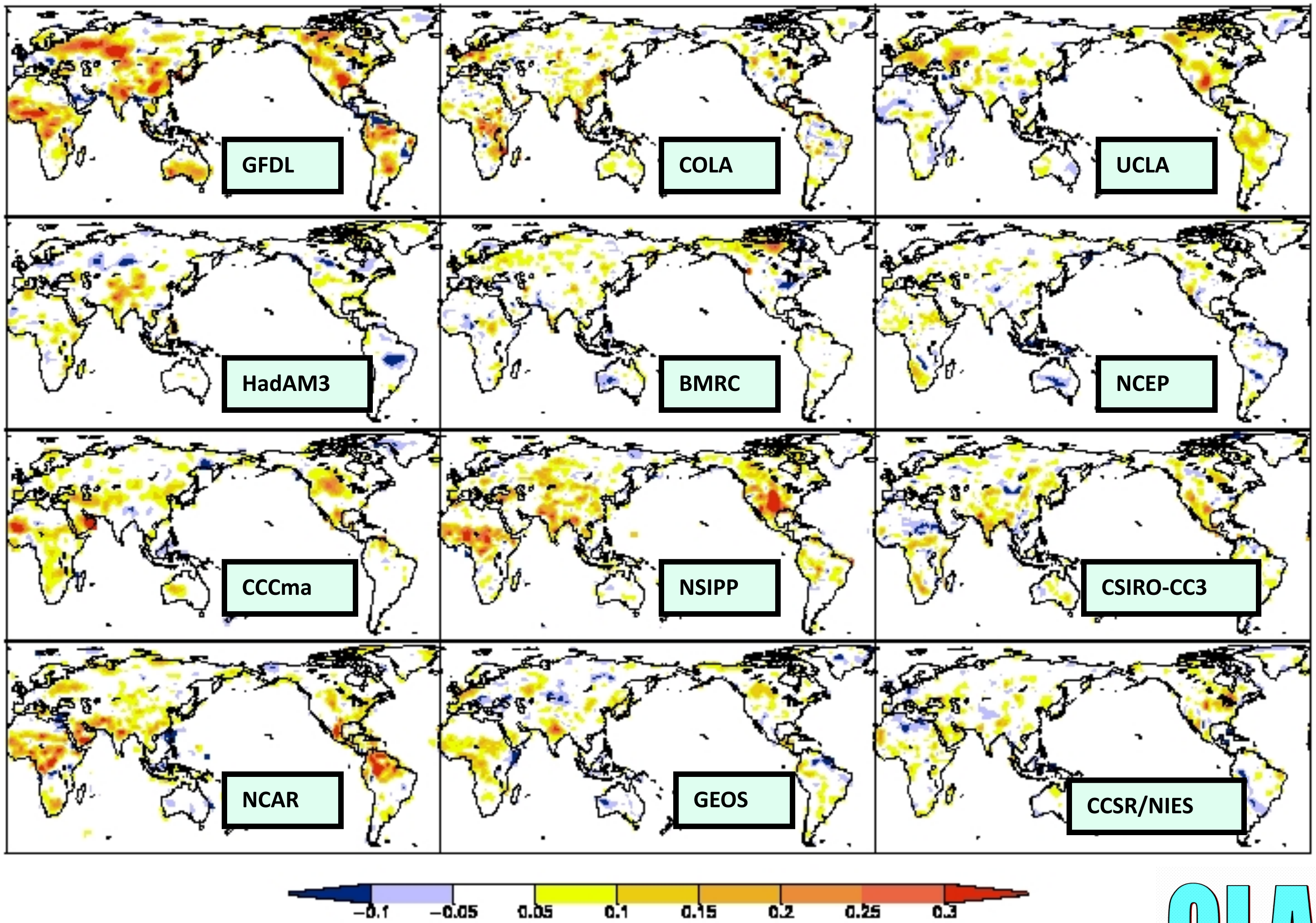
Blue shading indicates regions where a continually prescribed soil wetness has a direct impact, through evaporation, on precipitation simulated during boreal summer in a climate model. Percentages indicate the likelihood that simulated impacts are not the product of chance.

Some critical questions:

1. How does the atmosphere's response to soil moisture anomalies vary with GCM?
2. Can we define an objective way of comparing this response?

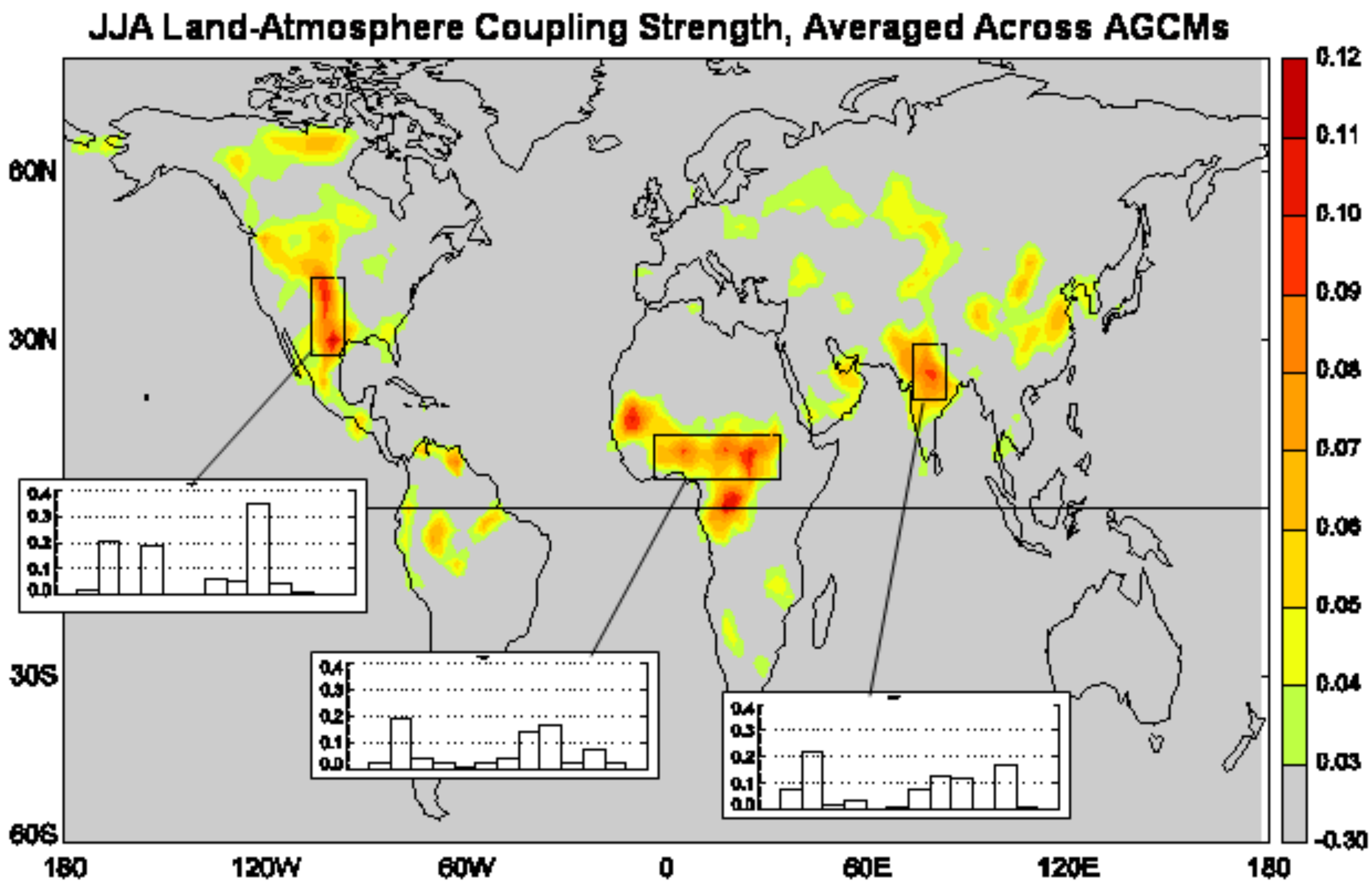
Paul Dirmeyer, Zichang Guo, COLA GMU

Ω_p (S - W): Impact of sub-surface soil moisture on precipitation



Paul Dirmeyer, Zichang Guo, COLA GMU

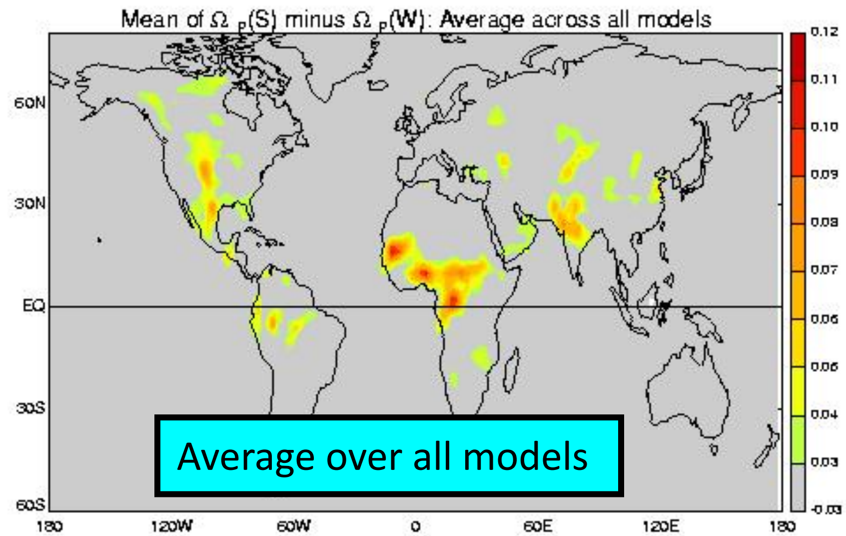
The GLACE project showed that while the 12 participating models differ in their land-atmosphere coupling strengths, certain features of the coupling patterns are common to many of the models. These features are brought out by averaging over all of the model results:

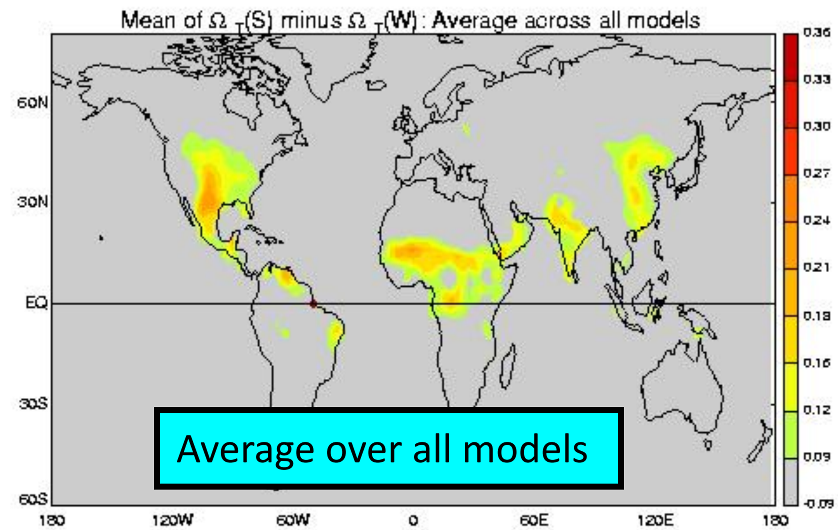


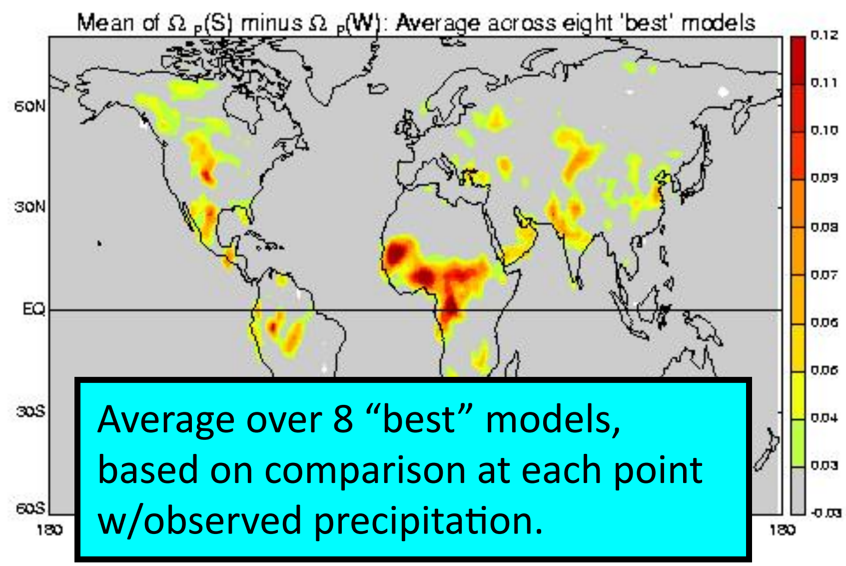
Paul Dirmeyer, Zichang Guo, COLA GMU

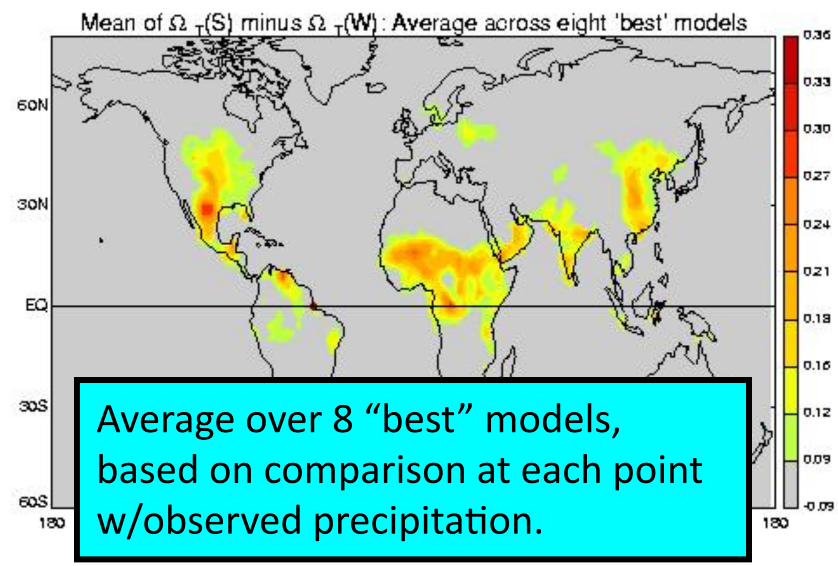
Precipitation hotspots

Air temperature hotspots



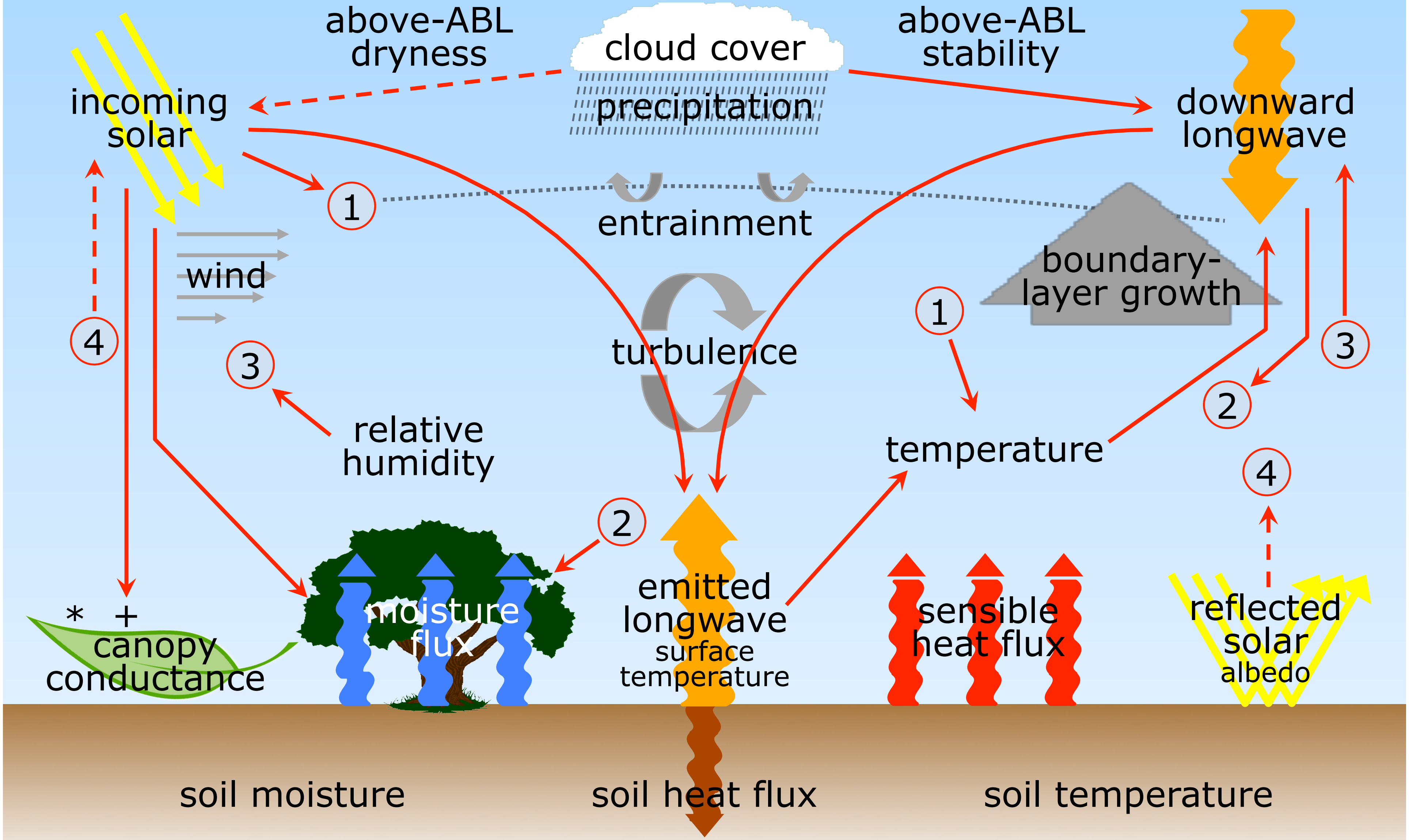






Paul Dirmeyer, Zichang Guo, COLA GMU

Local Land-Atmosphere Interactions

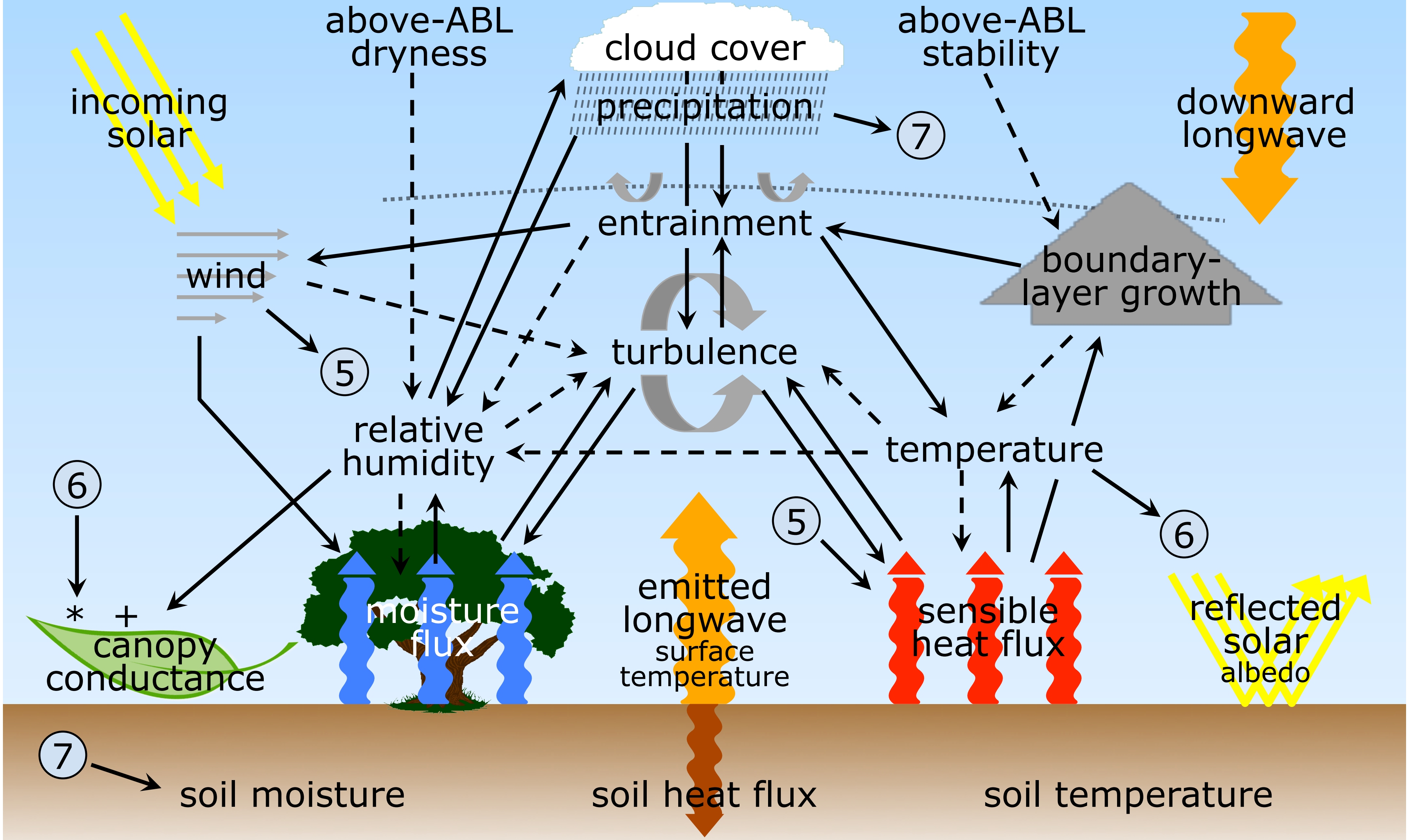


radiation

+positive feedback for C3 & C4 plants, negative feedback for CAM plants

feedbacks:
positive
negative

Local Land-Atmosphere Interactions



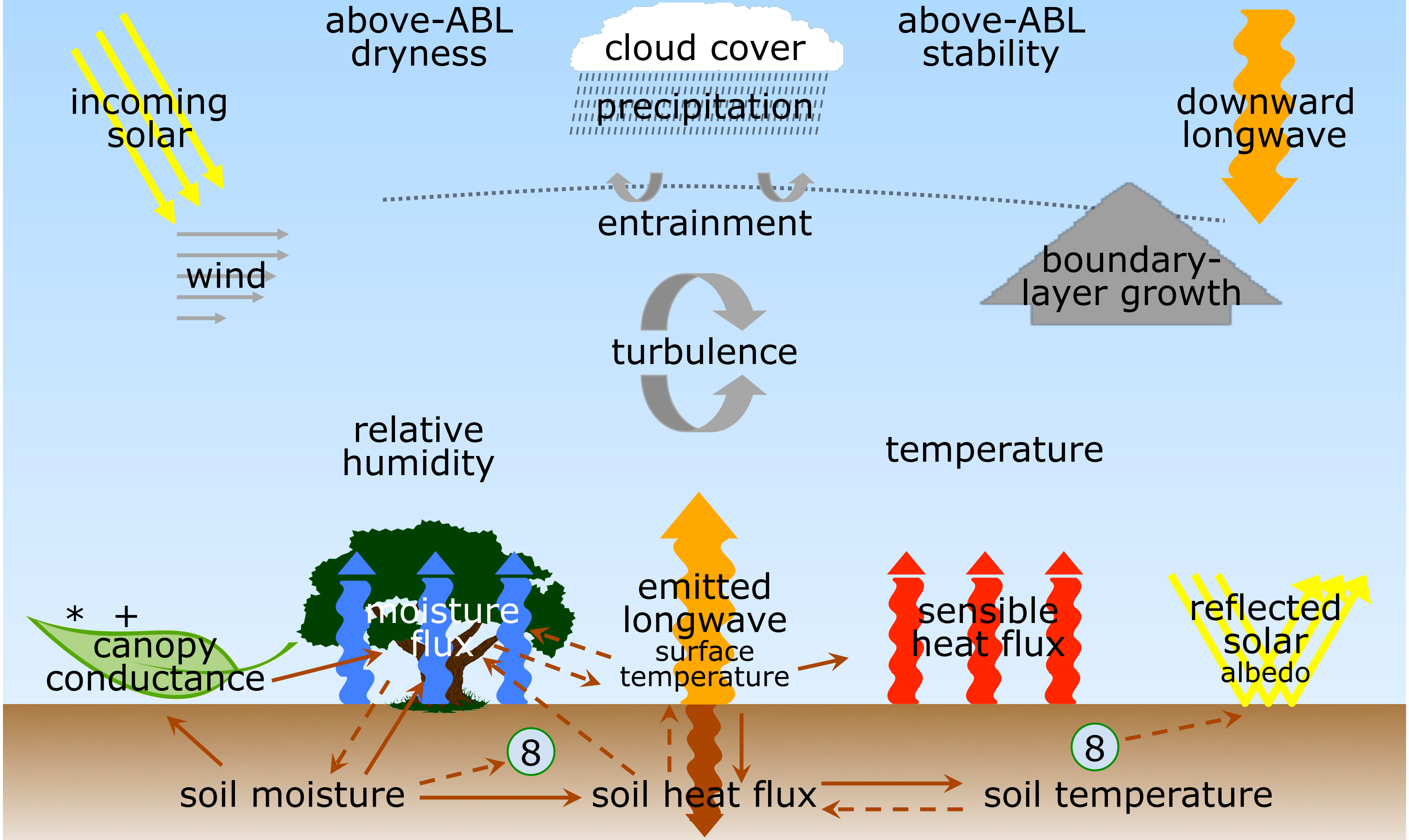
surface layer & ABL

negative feedback above optimal temperature

feedbacks:
positive
negative

R. Shrestha, IITM 2016

Local Land-Atmosphere Interactions



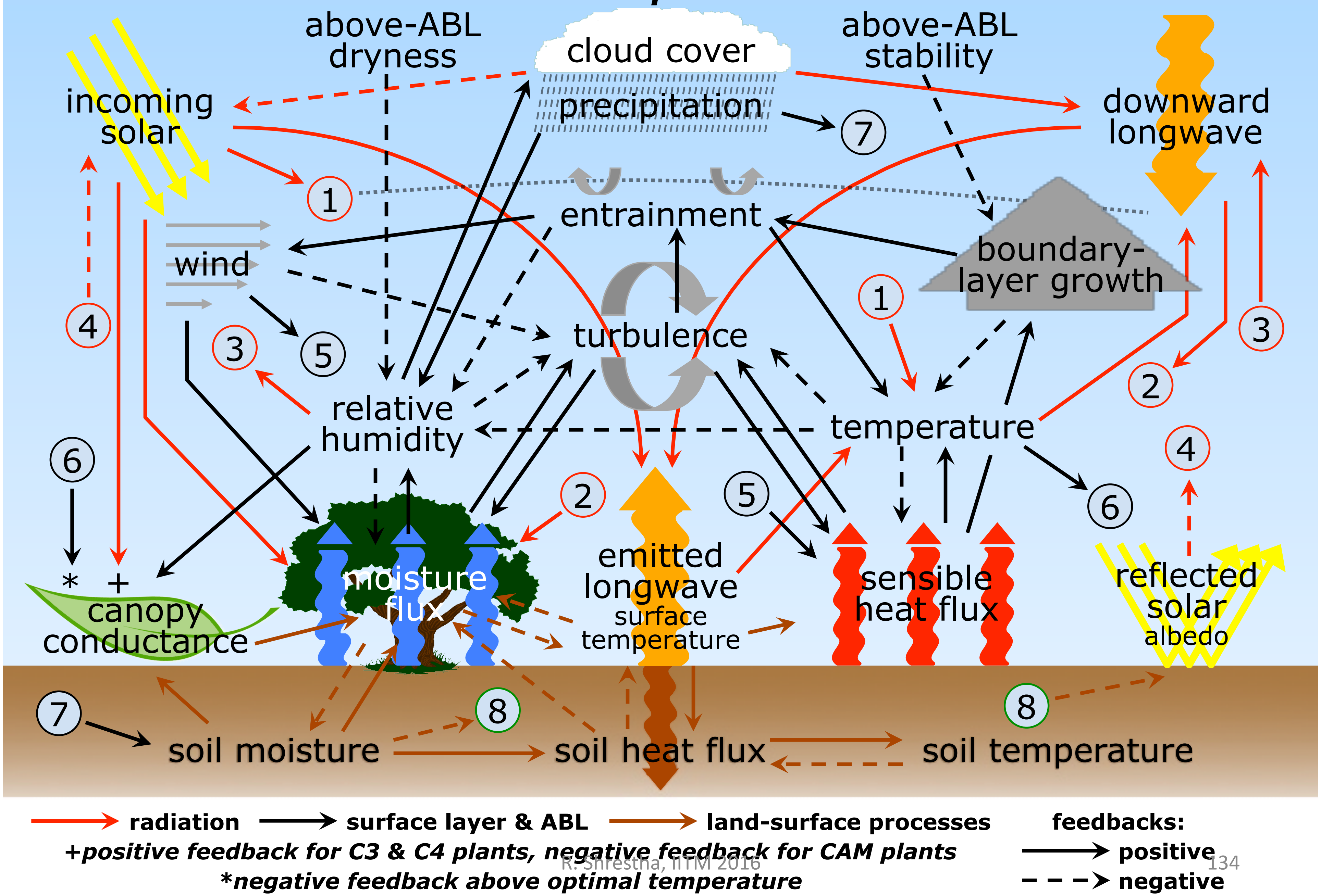
land-surface processes

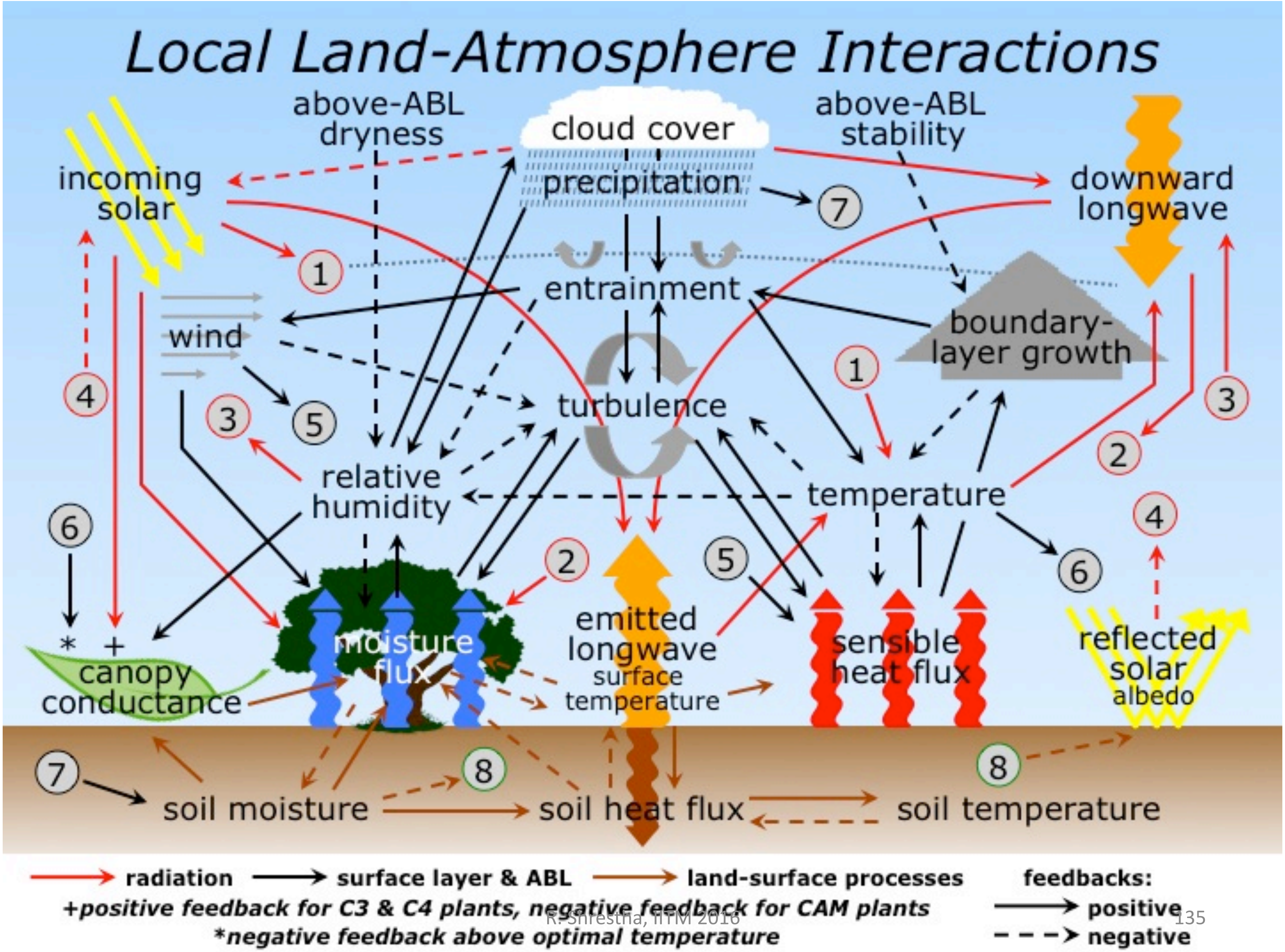
feedbacks:

positive

negative

Local Land-Atmosphere Interactions




Local Land-Atmosphere Interactions
above-ABL dryness
cloud cover
precipitation
above-ABL stability
incoming solar
downward longwave
entrainment
boundary-layer growth
wind
turbulence
relative humidity
temperature
canopy conductance
moisture flux
emitted longwave
surface temperature
sensible heat flux
reflected solar
albedo
soil moisture
soil heat flux
soil temperature
radiation
surface layer & ABL
land-surface processes
feedbacks:
positive
negative
+positive feedback for C3 & C4 plants, negative feedback for CAM plants
*negative feedback above optimal temperature

Land-Atmosphere Interactions

Betts et al (1996)

Considered diurnal, seasonal, century time scales

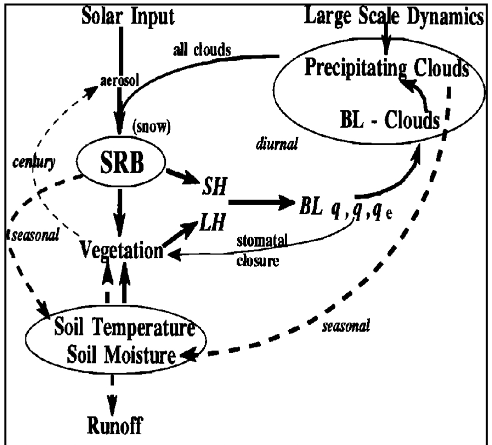


Figure 1. Schematic showing some important land surface-atmosphere interactions on different timescales.

Beljaars (2005)

"We discussed including this in a recent document, but dropped it because it was too confusing."

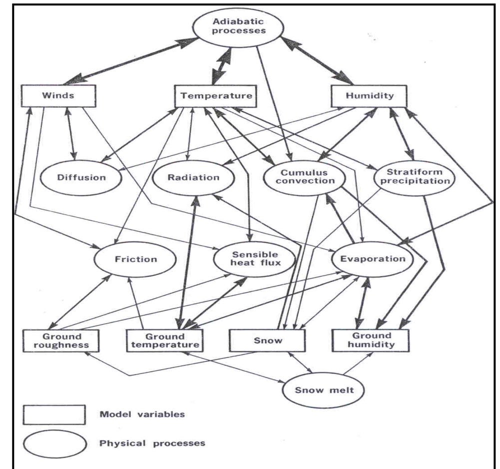
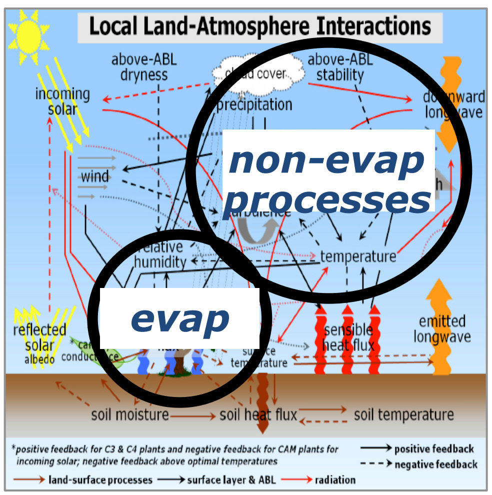


Fig. 1.1 Schematic representation of the processes included in the ECMWF model.

Adapted from *Ek & Holtslag (2004)*

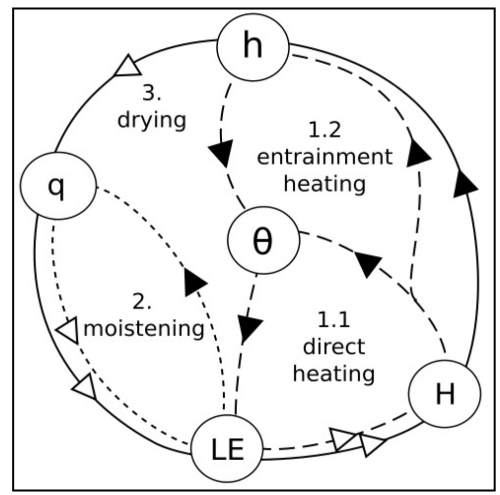
Characterized land and atmospheric processes and feedbacks for typical daytime with focus on soil moisture vs other processes.



v.Heerwaarden et al (2009)

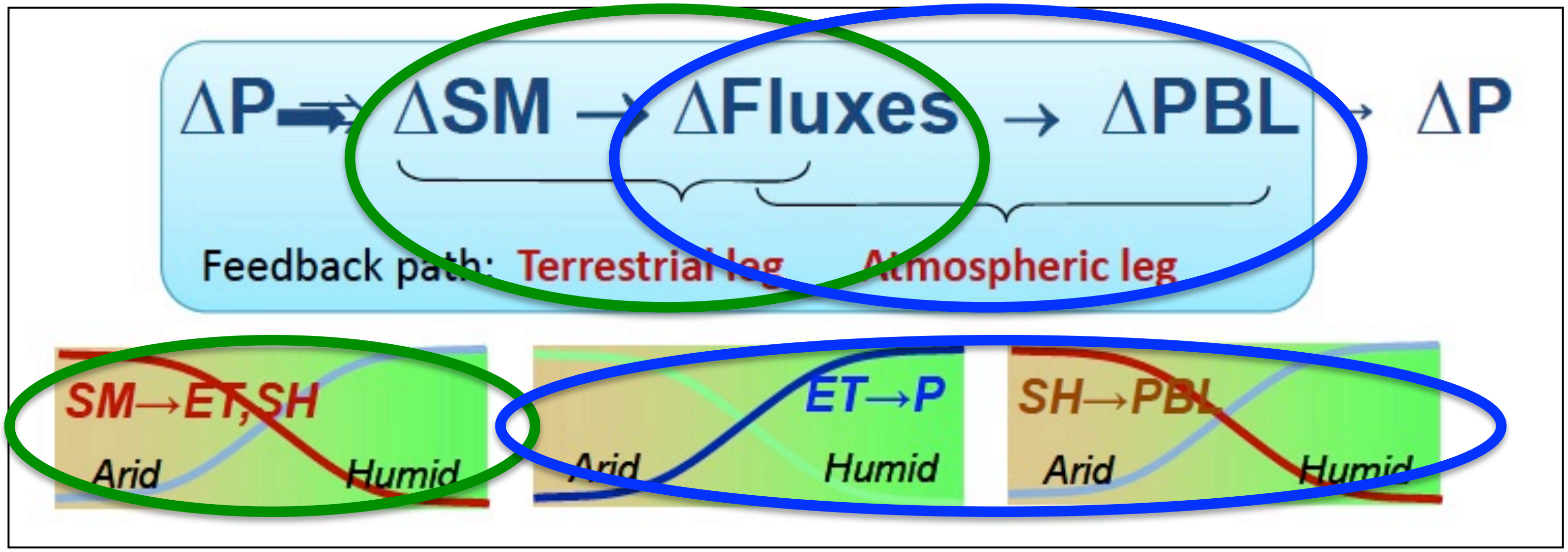
"Ek & Holtslag is too complicated"

Negative feedback mechanisms and the relationships among variables that regulate evaporation.



Land-Atmosphere Interactions

Land-Atmosphere Feedbacks stand on 2 legs



- **Terrestrial** – When/where does soil moisture (vegetation, soil, snow, etc.) control the partitioning of net radiation into sensible and latent heat flux (and soil heat flux)?
- **Atmosphere** – When/where do surface fluxes significantly affect boundary-layer growth, clouds and precipitation?

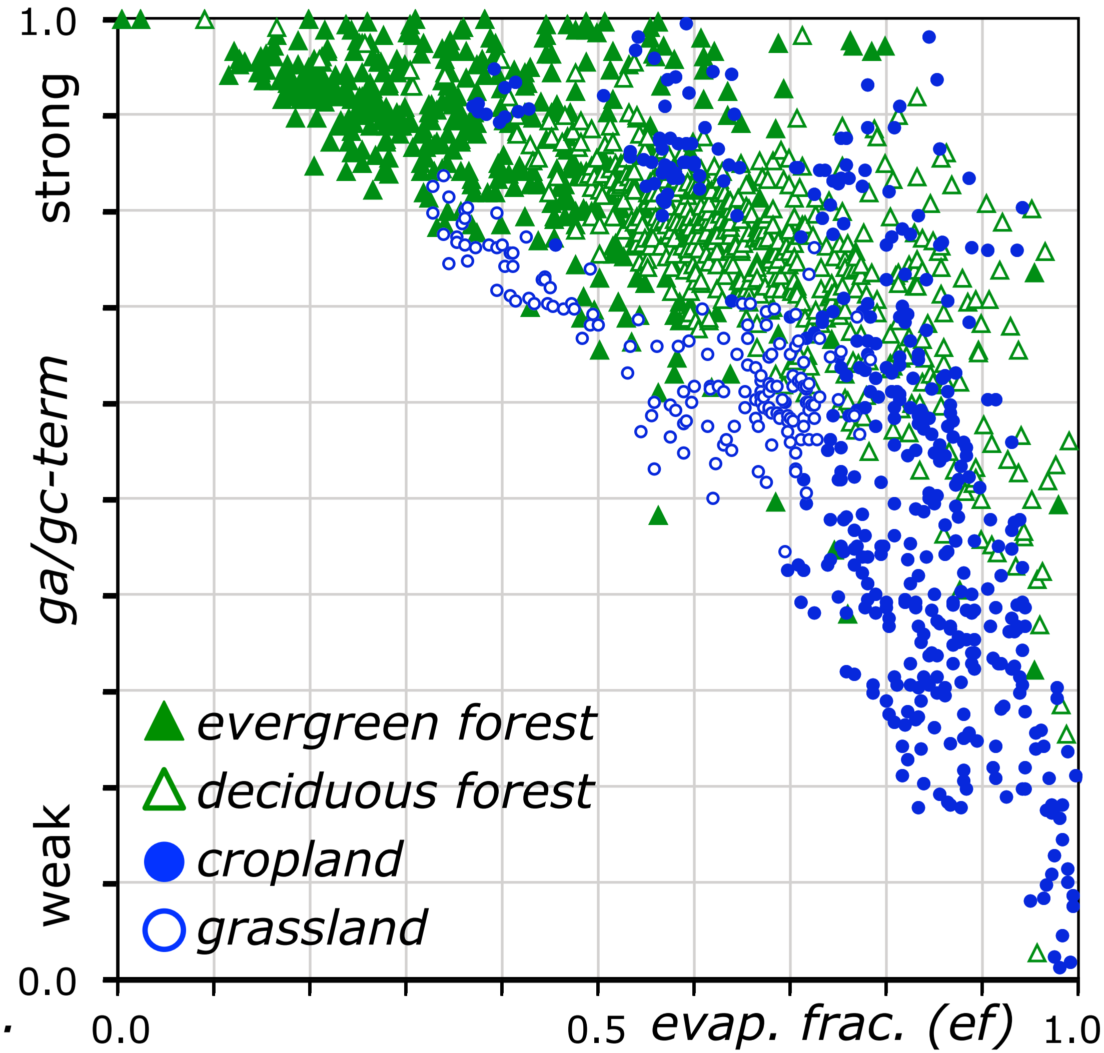
Paul Dirmeyer, George Mason Univ., Joe Santanello, NASA/GSFC

Near-Surface Interactions:

Soil moisture – evapotranspiration relationships

Evaporative fraction (ef) vs. *ga/gc-term* ("coupling strength") from surface flux site observations (Fluxnet):

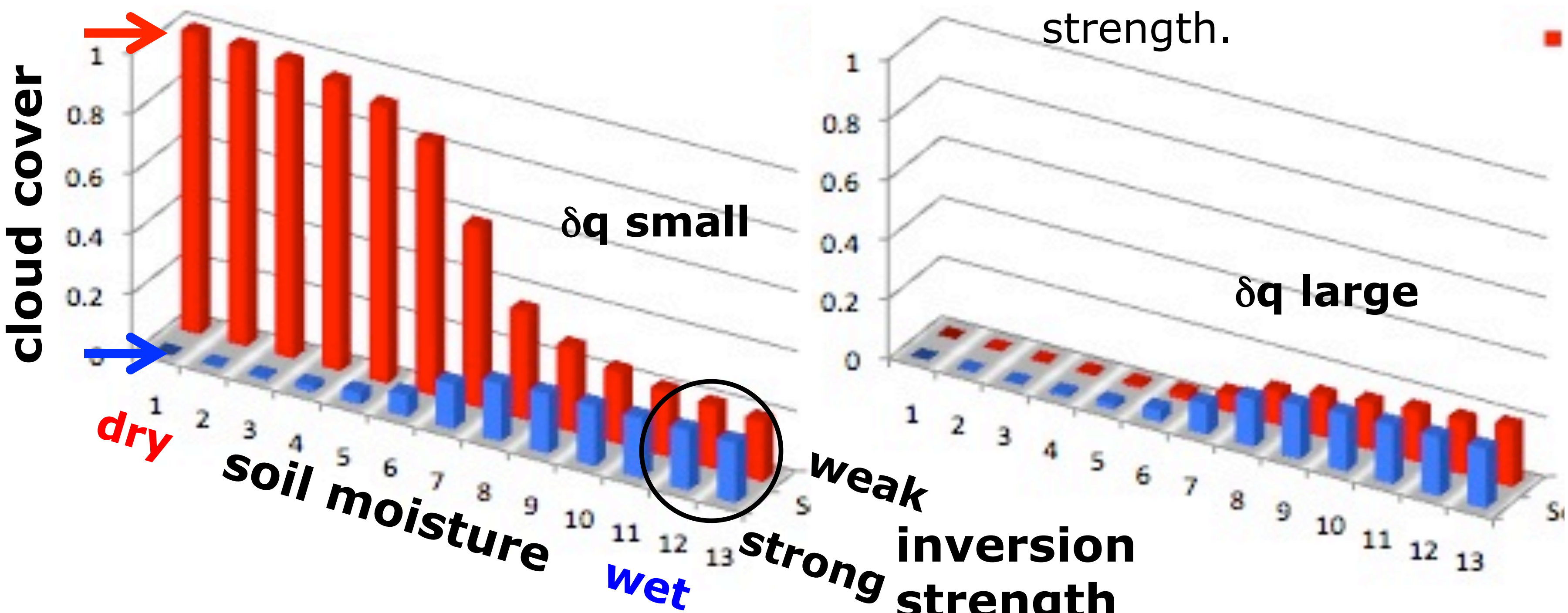
- higher ef:
- stronger land-atmosphere coupling for forests.
- weaker land-atmosphere coupling for cropland and grassland.
- lower ef: strong coupling regardless of vegetation type: due to stronger surface heating and turbulence (larger ga, smaller gc).
- *need to include G-related terms & direct evaporation.*



Land-Atmosphere Interactions:

Soil moisture/ET role in ABL & cloud development

- dry soil/strong inversion -> shallow ABL, no clouds.
- dry soil/weak inversion -> deeper ABL, more clouds.
- moist soil -> shallow ABL, cloud cover similar.
- dry aloft (δq large) -> fewer clouds regardless of inversion strength.



- Sensitivity tests with many single column model runs.

Summary

- Land models provide surface **boundary conditions** for weather and climate models, and then **proper representation of interactions** with atmosphere.
- For weather and climate modeling, land models must have **valid** (scale-aware) **physics** and associated parameters, representative **land data sets** (in some cases **near-realtime)**, proper **atmospheric forcing**, and **initial and *cycled* land states**. Longer time scales require more processes (physics).
- Land model **validation** using (near-) **surface observations**, e.g. air temperature, relative humidity, wind, soil moisture, surface fluxes, etc… suggests model **physics improvements**.
- The role of land models is expanding for weather and climate in increasingly more fully-coupled Earth-System Models (atmosphere-ocean-land-sea ice-waves-aerosols) with **connections** between **Weather & Climate** and **Hydrology**, **Ecosystems & Biogeochemical** cycles (e.g. **carbon**), and **Air Quality** communities & models on local as well as large scales.

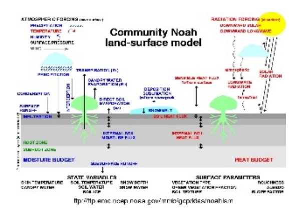
NCEP/EMC Land Team Partners

NCEP/EMC Land Team: *Michael Ek, Jiarui* Dong, Weizhong Zheng, Helin Wei, Jesse Meng, Youlong Xia, Rongqian Yang, Yihua Wu, Caterina Tassone, Roshan Shresth, working with:

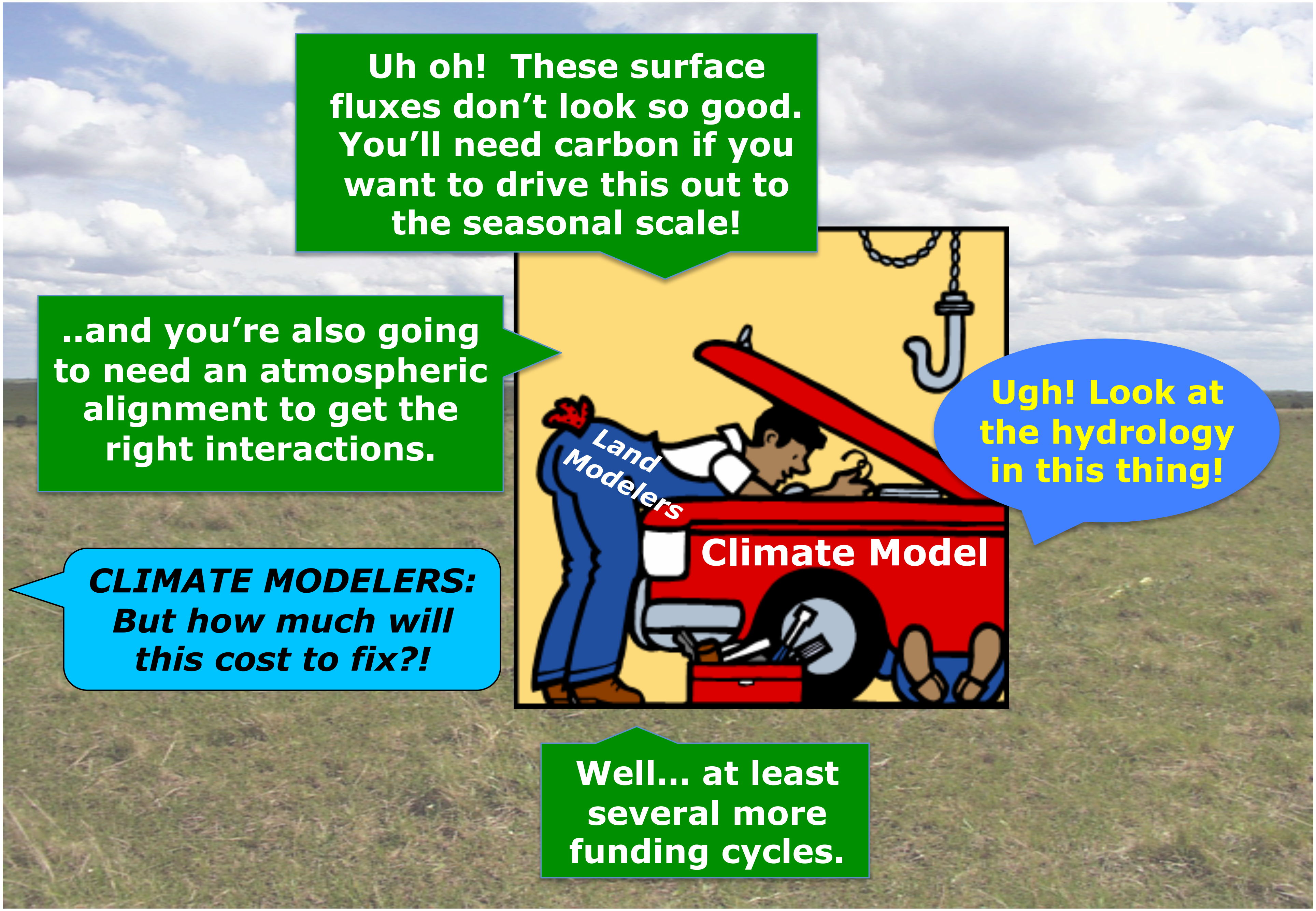
Land Data Assimilation (LDA), LDA Systems (e.g. “NLDAS”):
- NASA/GSFC: Christa Peters-Lidard, David Mocko et al.
- NCEP/Climate Prediction Center: Kingtse Mo et al.
- Princeton University: Eric Wood, Justin Sheffield et al.
- Univ. Washington: Dennis Lettenmaier (now UCLA) et al.
- Michigan State Univ./formerly Princeton: Lifeng Luo .

Remotely-sensed Land Data Sets:
- NESDIS/STAR land group: Ivan Csiszar, Xiwu Zhan (soil moisture), Bob Yu (Tskin), Marco Vargas (vegetation) et al.

Land Model (Physics) Development:
- NCAR/RAL: Fei Chen, Mike Barlage, Mukul Tewari, et al.
- NWS National Water Center: Brian Cosgrove et al.
- Univ. Ariz.: Xubin Zeng et al.
- UT-Austin: Zong-Liang Yang et al.
- WRF land working group and NOAA/ESRL land model development: Tanya Smirnova/NOAA/ESRL.



GEWEX/GLASS, GASS projects: Land model benchmarking, land-atmosphere interaction experiments with many international partners.


Uh oh! These surface fluxes don't look so good. You'll need carbon if you want to drive this out to the seasonal scale!
..and you're also going to need an atmospheric alignment to get the right interactions.
Ugh! Look at the hydrology in this thing!
Land Modelers
Climate Model
CLIMATE MODELERS: But how much will this cost to fix?!
Well... at least several more funding cycles.


Thank you!