Land Surface Physics:
Representing Land Processes and Land-Atmosphere Interaction in Earth System Models for Weather and Climate

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and many collaborators worldwide!

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Representing Land Processes and Land-Atmosphere Interaction in Earth System Models
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Outline

- Why land?
- Role of Land Models.
- Land Model requirements.
- Testing and Validation.
- Land Models in a fully-coupled Earth System
- Land-Atmosphere Interaction.
- Summary.

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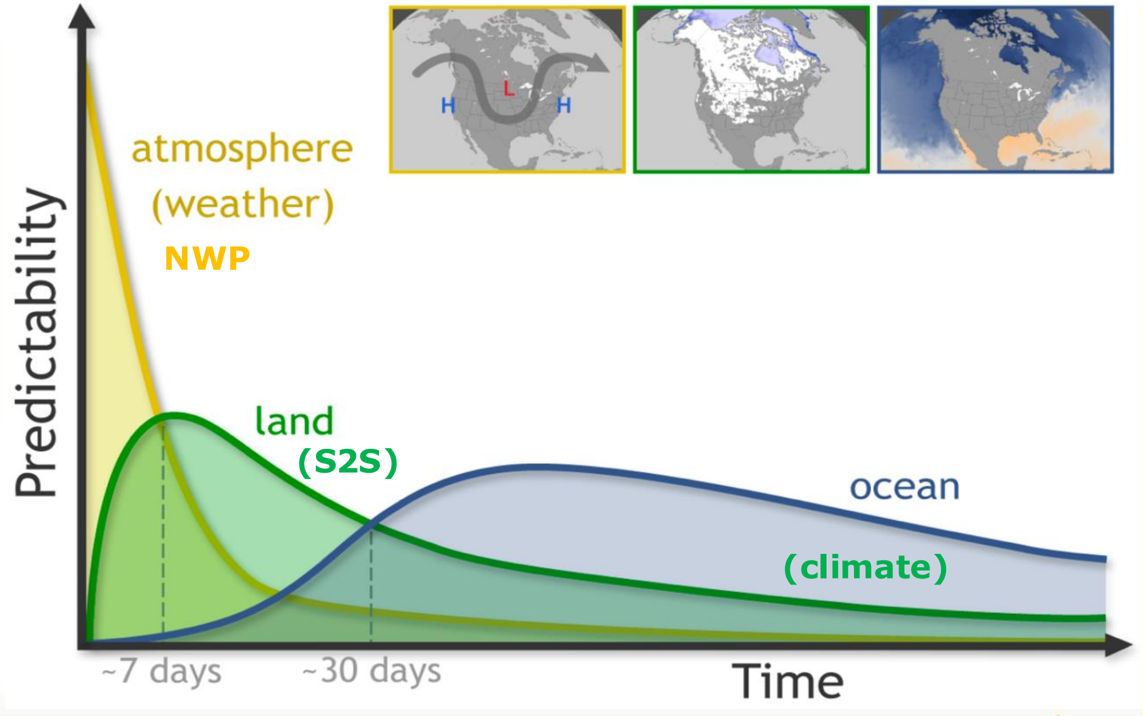
Why Land? Predictability and Prediction

- Land states, i.e. **Soil Moisture**, **Snow** and **Soil Temperature (and ice)**, can provide predictability from deterministic Weather (from day "zero" using Numerical Weather Prediction (NWP) models) to Climate (Ocean-Atmosphere), with land nominally peaking at subseasonal-seasonal (S2S) time scales.
- **Vegetation** states, related to soil moisture anomalies and optimal plant growth conditions, also give predict-ability at and beyond S2S time scales.
- Land-Atmosphere coupling is active where there is ***sensitivity***, ***variability*** and ***memory***.
- ***Good models*** and ***analyses*** of land, atmosphere and ocean states are needed to exploit this source of skill.



from Paul Dirmeyer

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Role of Land Models

Traditionally, from the perspective of **Numerical Weather Prediction (NWP)** or **Climate Models** (*coupled atmosphere-ocean-land-ice)*, a land model provides quantities as boundary conditions for heat and moisture (energy and water budgets) and momentum, i.e. ”Source/Sink terms”.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Global Atmospheric Models: The Equations

The momentum equations are

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + V\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta} - fV + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{dry}T_v\frac{\partial}{\partial \lambda}(\ln p)\right\} = P_U + K_U$$

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2+V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} + fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{dry}T_v\frac{\partial}{\partial \theta}(\ln p)\right\} = P_V + K_V$$

The thermodynamic equation is

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_v \omega}{(1+(\delta-1)q)p} = P_T + K_T$$

The moisture equation is

$$\frac{\partial q}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} + \dot{\eta}\frac{\partial q}{\partial \eta} = P_q + K_q$$

The continuity equation is

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla\cdot\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

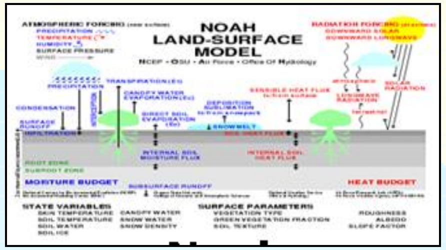
The geopotential ϕ which appears in (2.1) and (2.2) is defined by the hydrostatic equation

$$\frac{\partial \phi}{\partial \eta} = -\frac{R_{dry}T_v}{p}\frac{\partial p}{\partial \eta}$$

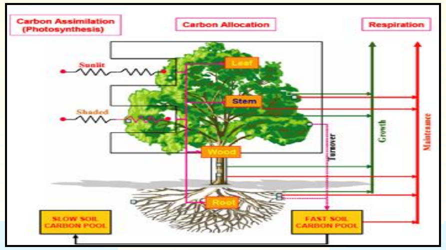
There you are! Land: the Source/Sink Terms

Land Models for Weather and Climate

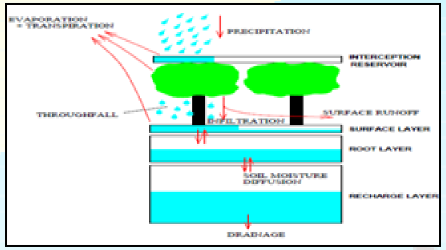
Weather ⟷ **Seasonal Prediction** ⟷ **Climate Change**



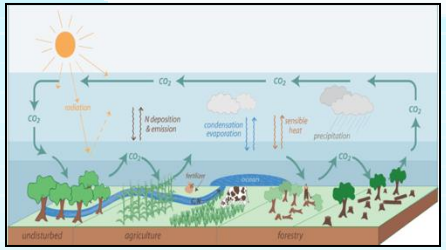
NCEP-NCAR Noah



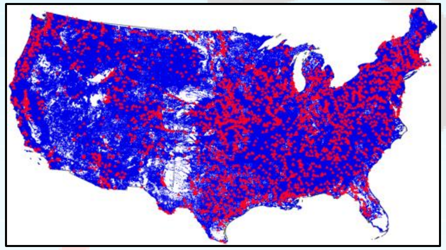
Noah-MP



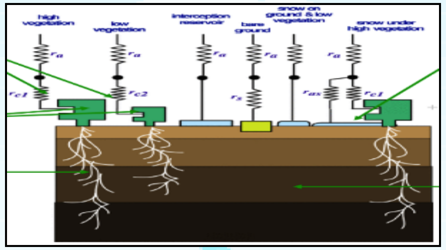
NASA Catchment



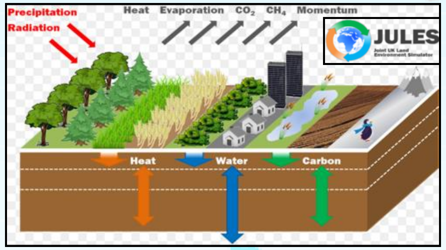
GFDL LM



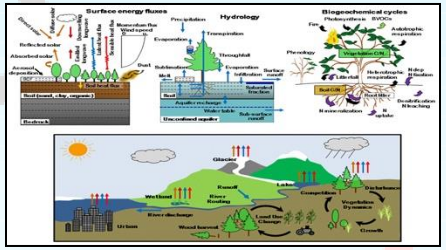
NWS Nat'l Water



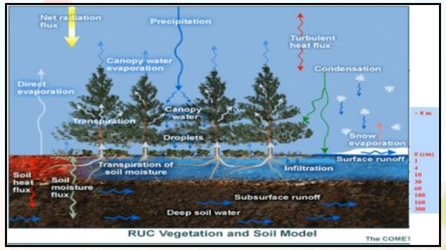
ECMWF ECLand



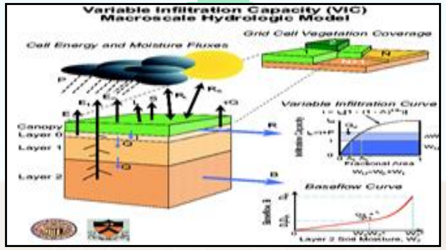
UKMO JULES



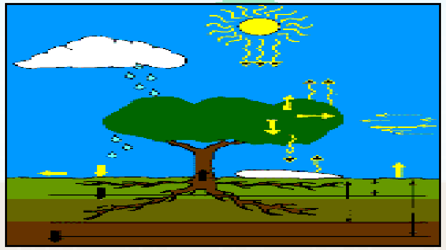
NCAR CLM



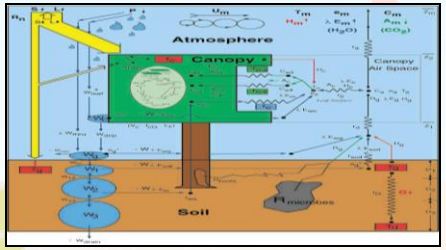
NOAA/ESRL RUC



UW/Princeton VIC



BATS



SiB

A sampling: use dictates complexity and processes simulated.

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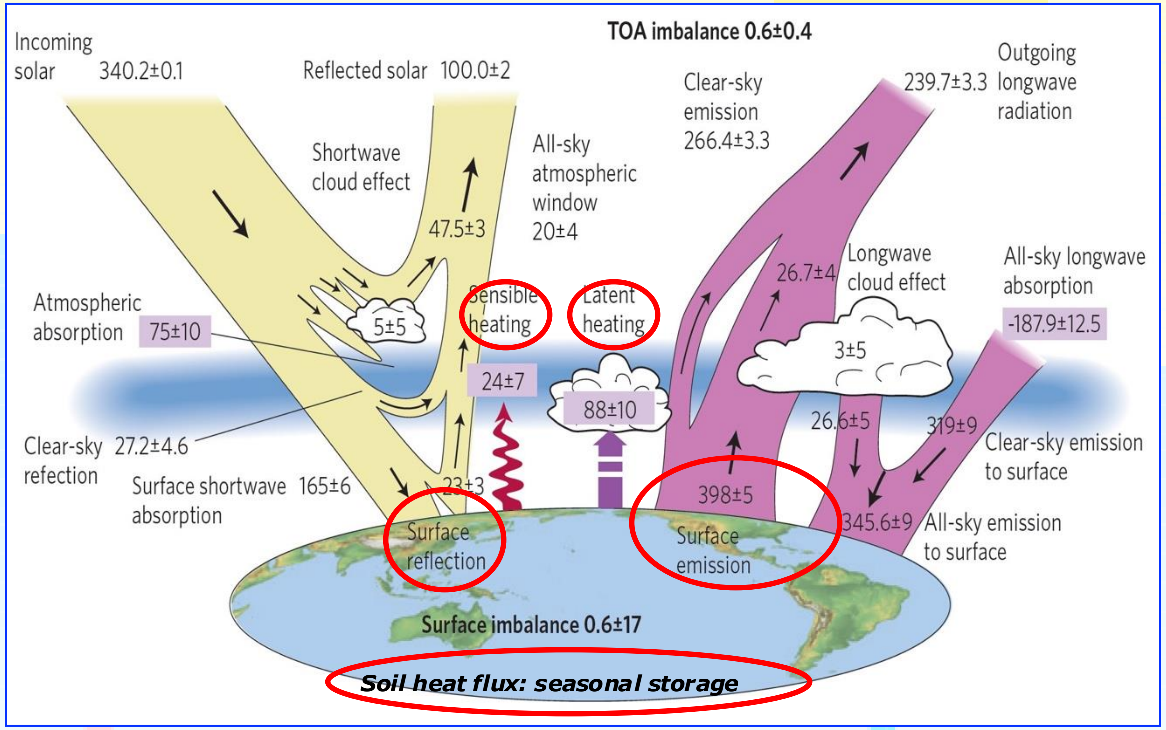
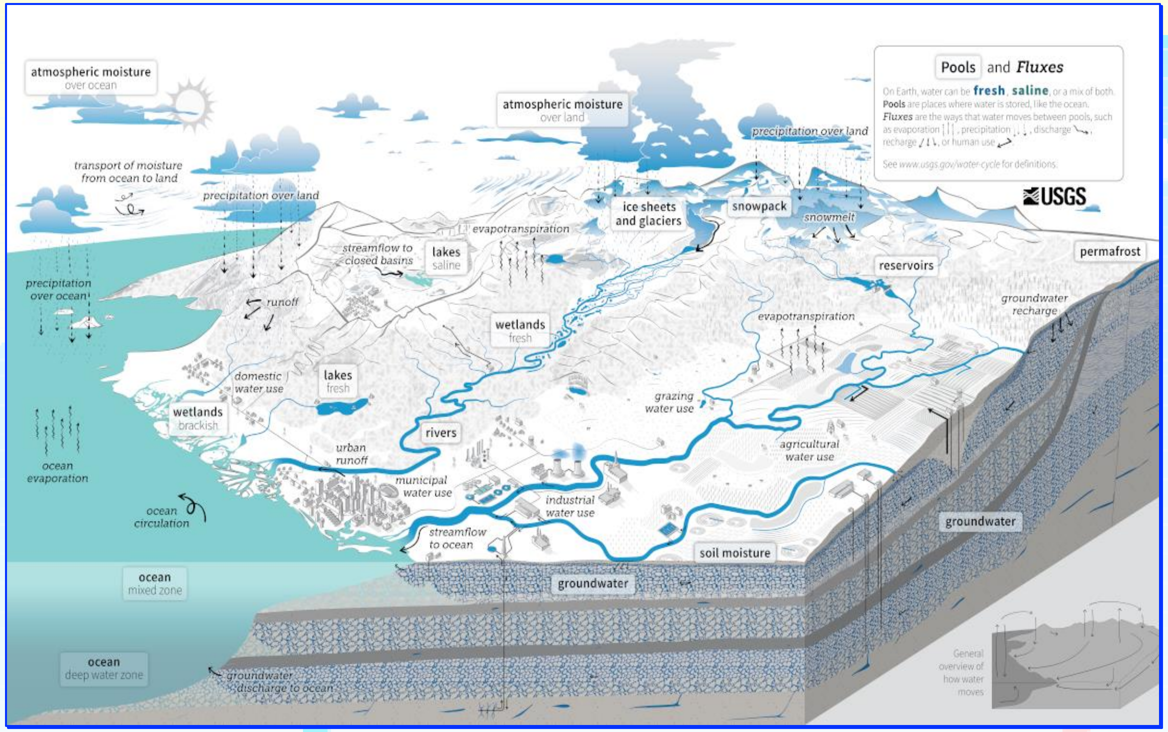
Land Model Requirements

- To provide proper **boundary conditions for atmosphere**, land model must have:
  - Appropriate **land physics** to represent land processes (land states and surface fluxes) for relevant time/spatial scales, and associated **land model parameters**.
  - Required **atmospheric forcing** to drive land model, i.e. observed or idealized data sets or interactive with atmosphere.
  - Corresponding **land data sets**, e.g. land use/land cover (vegetation type), soil type, surface albedo, snow cover, surface roughness, etc. *Some of these may be modelled.*
  - Proper **initial land states**, analogous to initial atmospheric conditions, though land states may carry more "memory" (e.g. especially in deeper soil moisture), similar to ocean SSTs and ocean heat content.
- Land data sets & initial land states may "overlap", that is, some land data sets (assumed) static while others "evolve", with use of many **remotely-sensed data sets/products**, also for atmospheric forcing, and for land model validation, and making use of **land data assimilation**.

Land Models: Energy and Water Budgets



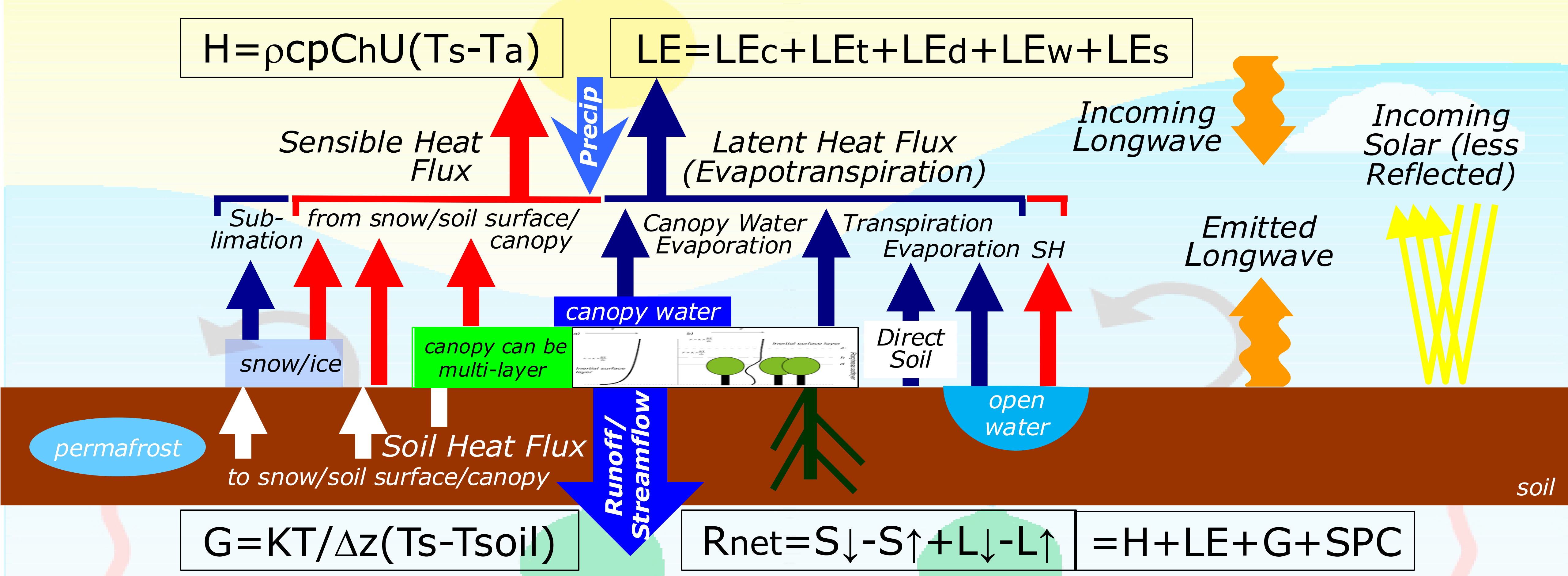
Stephens et al 2012



USGS 2022

- We must more properly represent and close the (surface) **energy budget** and **water budget (hydrological cycle)** to provide surface boundary conditions in weather and climate models.
- As mentioned above, “bookkeeping” for **energy** & **water**, as well as **BGCs** is ***particularly important for climate models.***

Surface Energy and Water Budgets: Flux Boundary Conditions



- **Surface Energy Budget: Land model provides L↑, H, LE, G & SPC (melting snow phase change), and affects the surface albedo and surface emissivity.**
- **Surface Water Budget: Land model provides change in terrestrial water states (ΔS: soil moisture, snow/ice, canopy water), Runoff & LE, where ΔS=P-R-LE.**

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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 highly nonlinear functions of soil moisture & soil type (e.g. *Cosby et al 1984, van Genuchten, 1980*); **FΘ** 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; e.g. *Johansen 1975*), non-linear functions of soil moisture/type; soil ice = fct(soil type, temperature, moisture).

Canopy water (Cw):

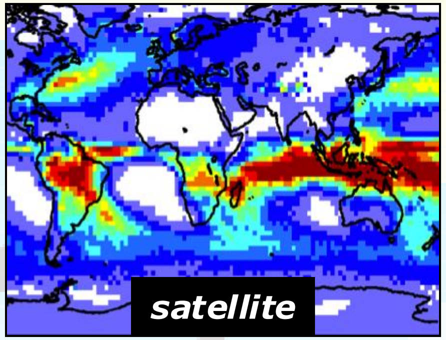
$$\frac{\partial C_w}{\partial t} = P - E_c$$

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

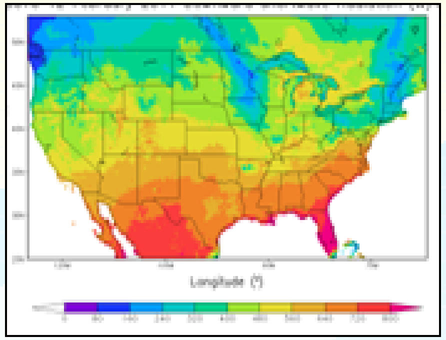
Dynamic vegetation*: plant growth, other BGC processes.*

Atmospheric Forcing to Land Model

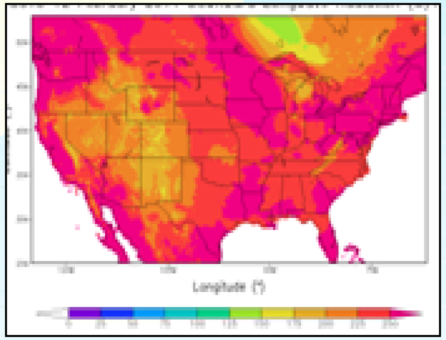
- Atmospheric forcing from a parent atmospheric model (analysis or reanalysis) and/or from in situ or remotely-sensed observations, where precipitation is generally the most important for land models.



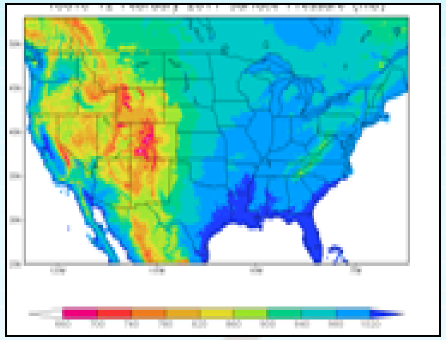
Precipitation



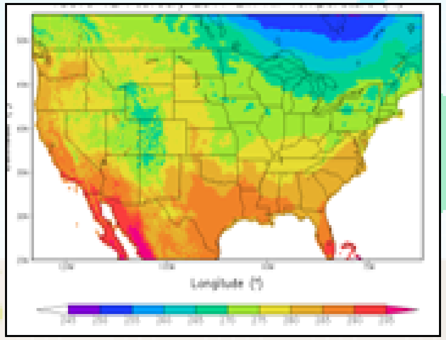
Incoming Solar



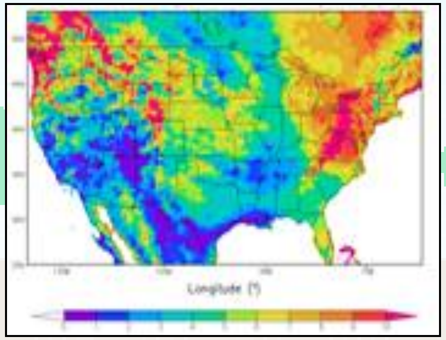
Downward Longwave



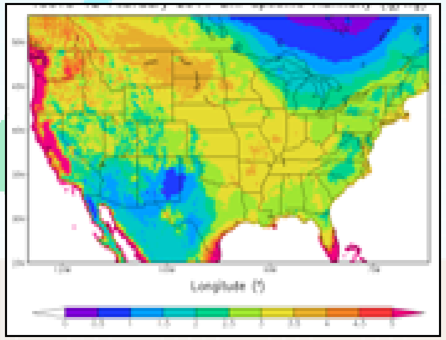
Air Pressure



Air Temperature

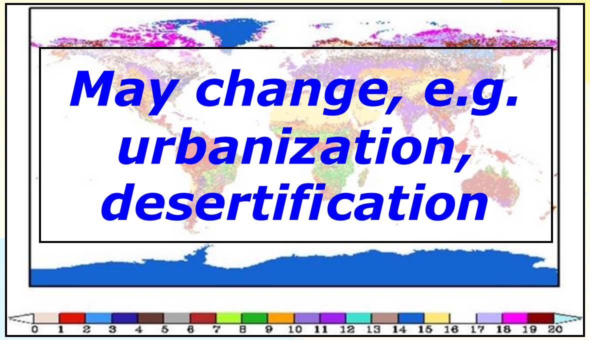


Wind Speed

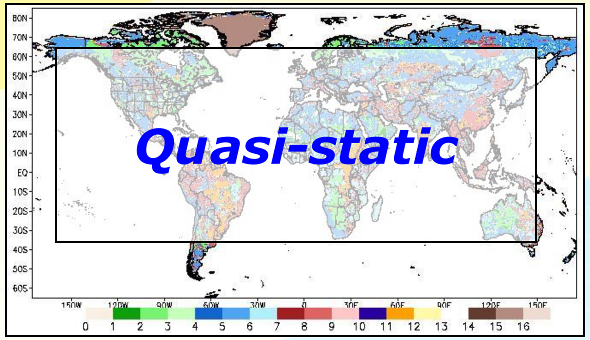


Specific Humidity

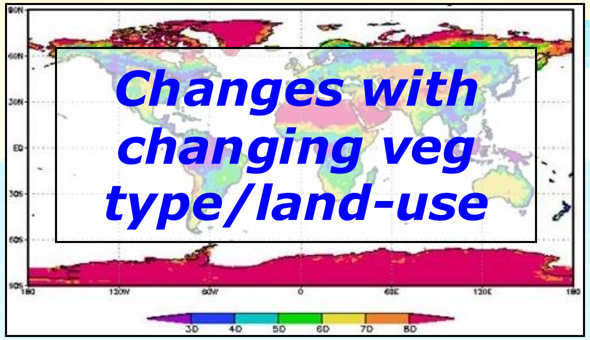
Land Data Sets



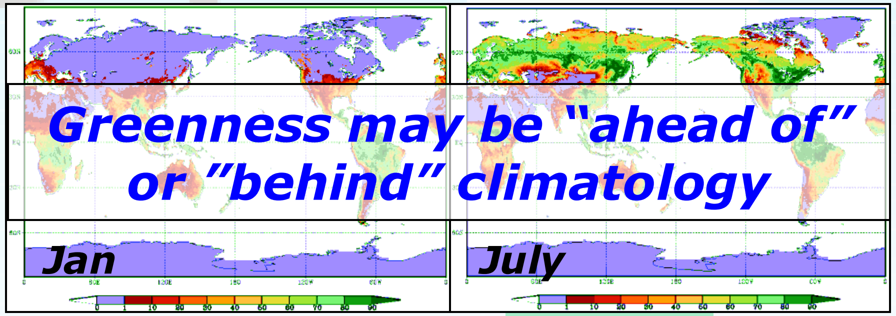
Land-Use/Vegetation
(1-km, IGBP-MODIS)



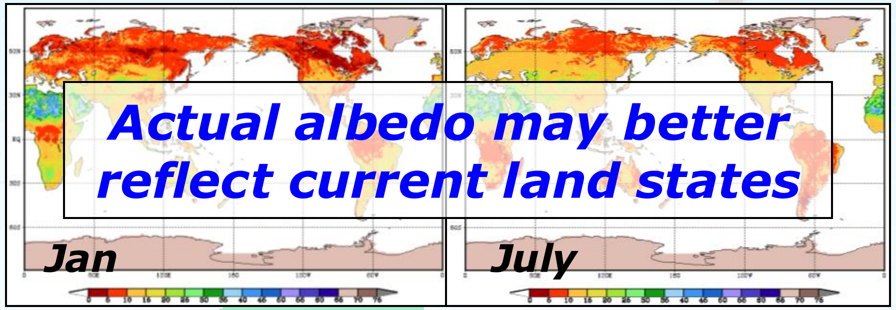
Soil Type
(1-km, STATSGO-FAO)



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



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

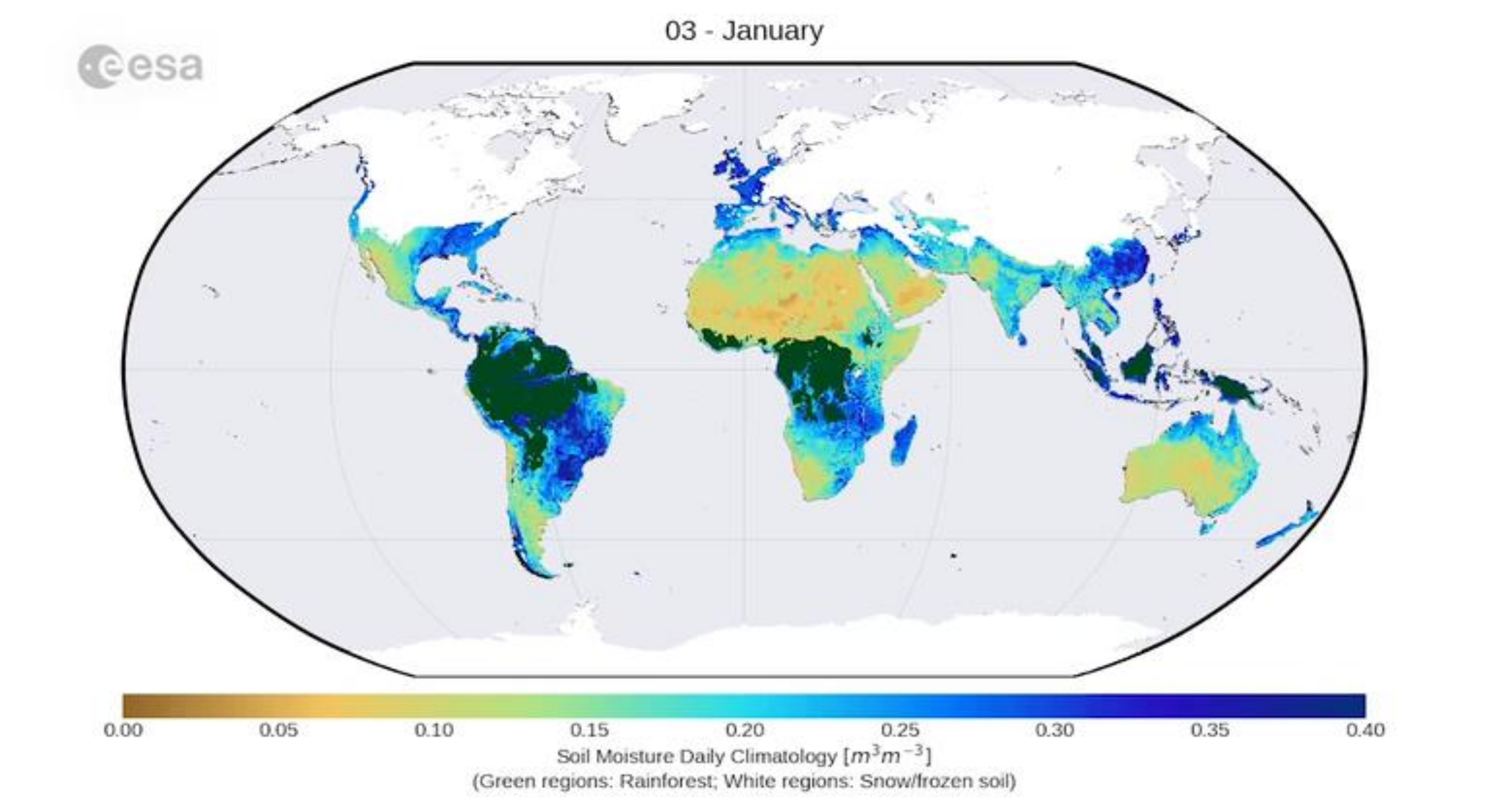


Snow-Free Albedo
(monthly, 1-km, Boston Univ.-MODIS)

- Fixed annual/monthly/weekly climatologies, or near real-time observations, or modelled; some quantities may be assimilated into land models, e.g. "nudging" soil moisture, vegetation, snow initial land states.

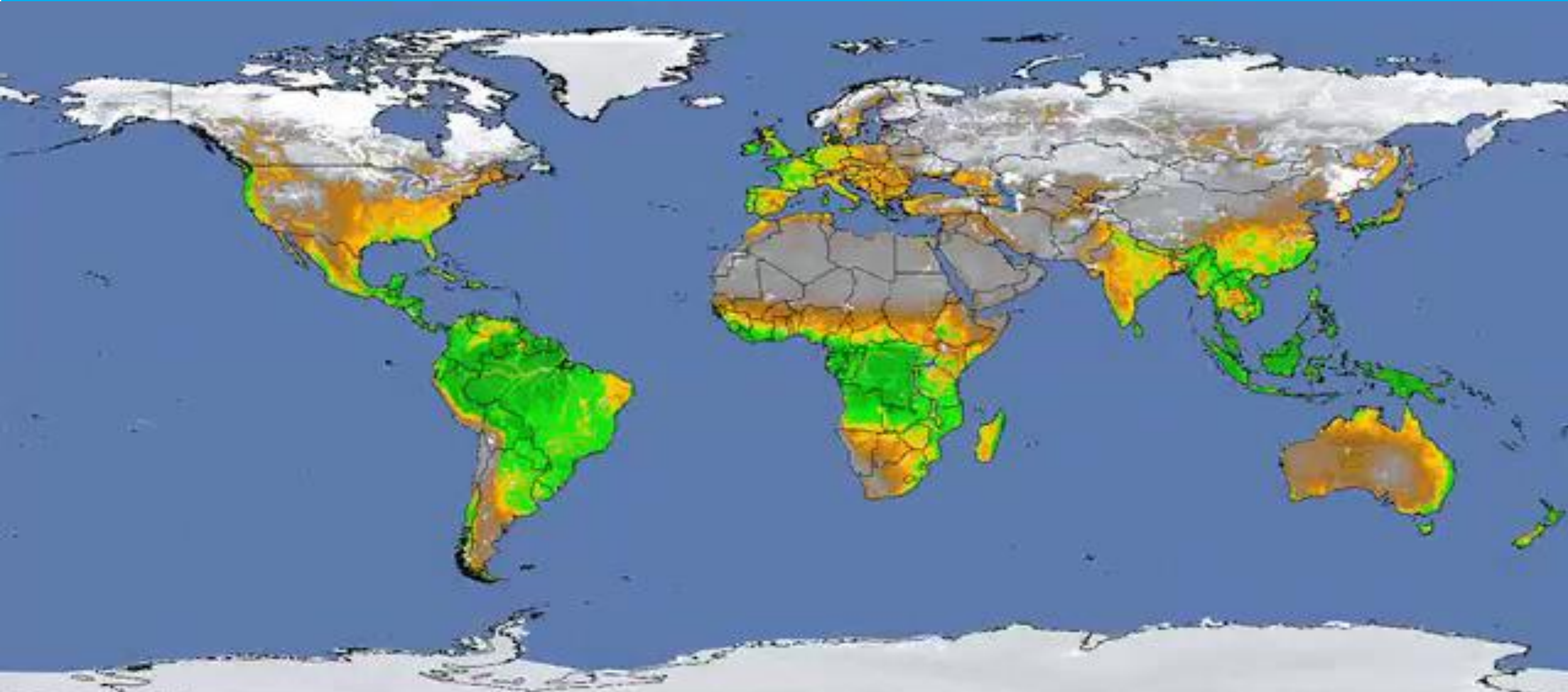
Land States: Soil Moisture

- **Land state initial conditions**: necessary for Earth System Models (ESMs) for weather and climate, and must be consistent with a **cycling** land model used in a given ESM.
- Land states spun up in one ESM ***cannot*** be simply used directly to **initialize** another ESM, where some kind of soil moisture "**rescaling**" is required because of different soil moisture climatologies in models.
- 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 and leaf area index, and even land-use type (evolving land-use and ecosystems).



Global annual cycle based on nearly 40 years of data from multiple satellite sensors. Blue (brown) is high (low) soil moisture, rainforests green, frozen soil white.

Land Data Sets: Vegetation Cover and Density



MODIS satellite data: Multi-year Leaf Area Index (Weizhong Zheng and Yihua Wu, NCEP/EMC, Marco Vargas et al, NESDIS/STAR)

Land States: Snow Cover

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

Snow cover: one year example from MODIS satellite data (Jiarui Dong et al, NCEP/EMC; Peter Romanov et al, NESDIS/STAR)

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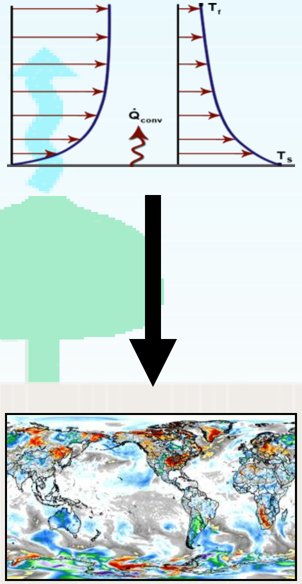
Land Model Testing and Validation

- **Standard validation** of NWP & climate models uses **near-surface** observations, e.g. routine weather observations of air temperature, humidity, and 10-m wind, along with upper-air, precipitation measurements, MJO for subseasonal, ENSO index for climate, etc.
- More comprehensive validation *at the process level*: use **surface fluxes** and **soil states** (soil moisture, soil ice, soil temperature, and vegetation characteristics), **hydrologic** information (streamflow/river discharge).
- **ML/AI** (Machine Learning / Artificial Intelligence): an important/rapidly-evolving topic. Utilize large data sets to better inform us about improving model physics at the process level, e.g. plant processes, surface-layer turbulence.

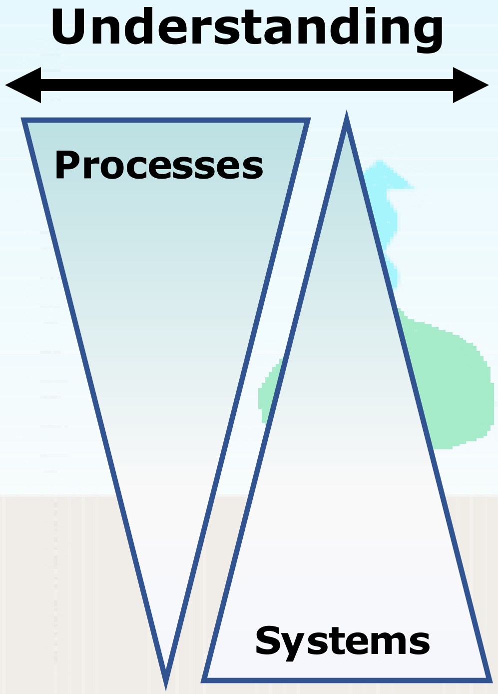
Testing: Hierarchical System Development

- **Hierarchical System Development (HSD)** is a "systems engineering" approach for model development that **helps to better identify and address systematic biases**.
- **Simple-to-complex** testing for different HSD steps. Drive models with: (1) observations, (2) model output, (3) idealized data sets.
- **Comes from the climate world**, e.g. Tim Palmer, Julia Slingo, Christian Jakob, and others.
- **End-to-end system** includes data ingest and quality control, data assimilation, modeling, post-processing, verification.
- **Infrastructure**: software required to connect different HSD steps efficiently.
- **Verification**: necessary to assess model performance, using "cumulative" metrics/benchmarks, many at process level.

Single Processes



Complex Systems

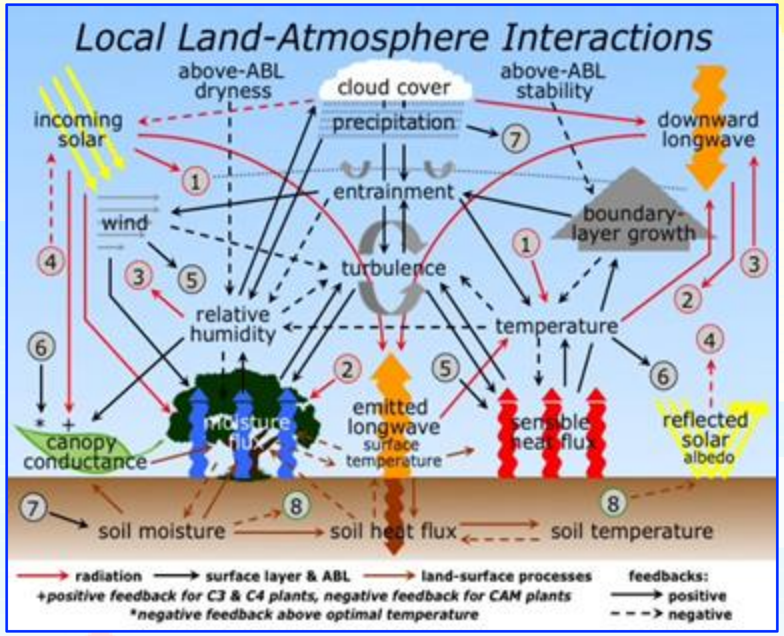


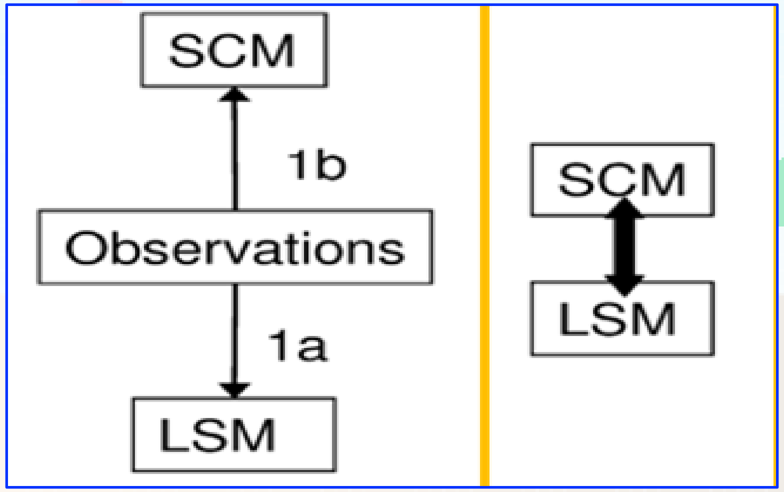
HSD Testing Steps

Process-Level Assessments

- Process Simulator
- Single Column Model
- 2D Model
- Small Domain Model
- Regional Model
- Global Model
- Fully Coupled Model

HSD Example: evaluation of interacting land+PBL physics using SCM





Single column model study: Focus on surface fluxes, PBL characteristics and land-atmosphere interaction, noting systematic biases.

<u>Finding</u>: review/refine land model sub-components used for surface flux calculations.

New phase of **GEWEX Atmospheric Boundary Layer Study** (GABLS) will rely on **GLAFO*** data sets to study interacting land+PBL.

*GLAFO: The GEWEX Land-Atmosphere Feedback Observatory.

HSD Testing

- Process Simulator
- Single Column Model
- 2D Model
- Small Domain Model
- Regional Model
- Global Model
- Fully Coupled Model

GABLS2 used CASES 1999 (US Southern Great Plains) data sets; extended to the DIurnal land-atmosphere Coupling Experiment (DICE) project, i.e. Best, Lock et al 2025: *"Rolling DICE to advance knowledge of land-atmosphere interactions".*

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, with effect on boundary-layer evolution, and downstread influence on clouds/convection/precipitation.*

Improving diurnal/seasonal partition of surface energy budget *between sensible, latent, soil heat flux, outgoing longwave radiation, and effect on water budget & BGCs, requires:*

- **Improved vegetation physics**/parameters to calculate ET.
- **Better soil physics**/properties address surface heterogeneity (hydraulics & thermodynamics).
- **Improved snow physics** (melt/freeze, densification).
- **Surface-layer physics** (turbulence), especially nighttime/**stable** conditions, and **interaction/coupling** between the surface and the atmosphere (atmospheric boundary layer).
- **Remote sensing of different initial land states**, e.g. near-real-time vegetation; corresponding data assimilation of these land states, e.g. snow, soil moisture, surface water, green vegetation fraction & veg density. *Future: PBL-from-space (NASA incubator program).*
- **Improved atmospheric forcing** for land models, especially precipitation and downward radiation; requires enhanced downscaling techniques.

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Land Models in Earth Systems

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

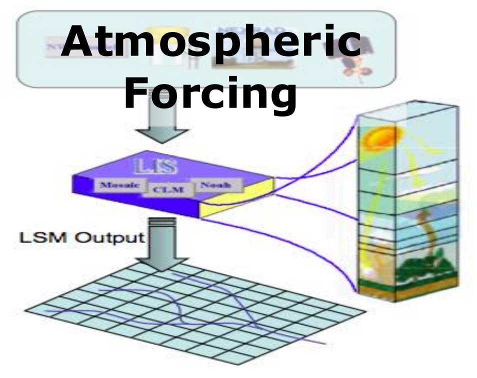
- ***Hydrology***: soil moisture & ground water/water tables, irrigation and groundwater extraction, water quality, streamflow and river discharge to oceans, drought/flood, lakes, and reservoirs/human mgmt.
- ***Biogeochemical cycles***: application to ecosystems, both terrestrial & marine, dynamic vegetation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

Must connect Earth system components across temporal and spatial scales.

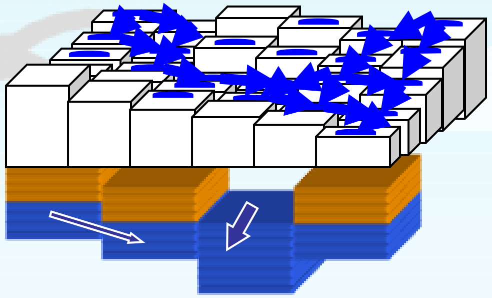
More constraints, i.e. must close energy & water budgets, and those related to BGC cycles and air/water quality/ecosystems.

Less degrees of freedom so we can't simply calibrate or "tune" our way out of model biases.

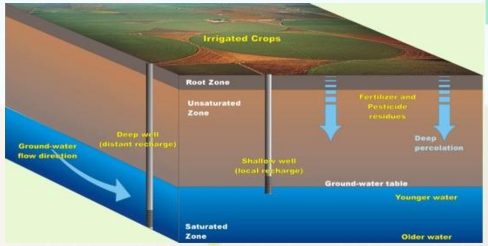
Hydrology: River-routing, Groundwater, River Discharge (to ocean)



Surface flow

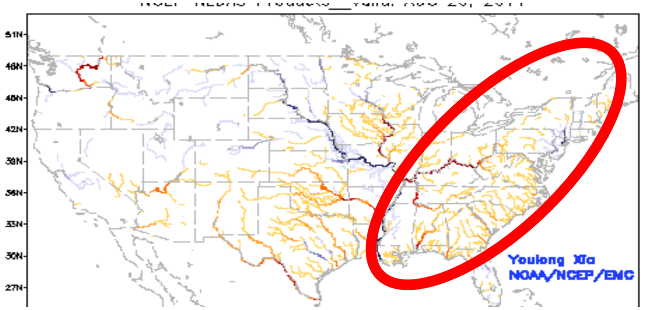


Saturated subsurface flow

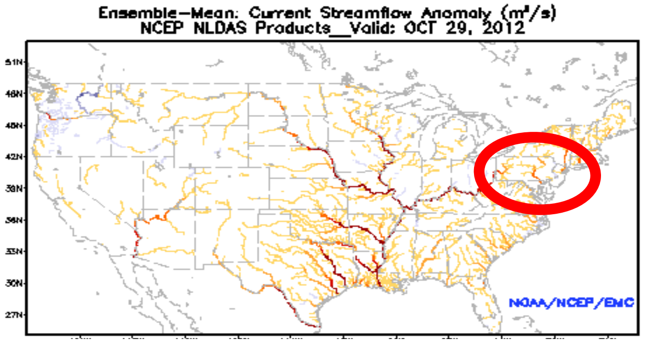


Groundwater

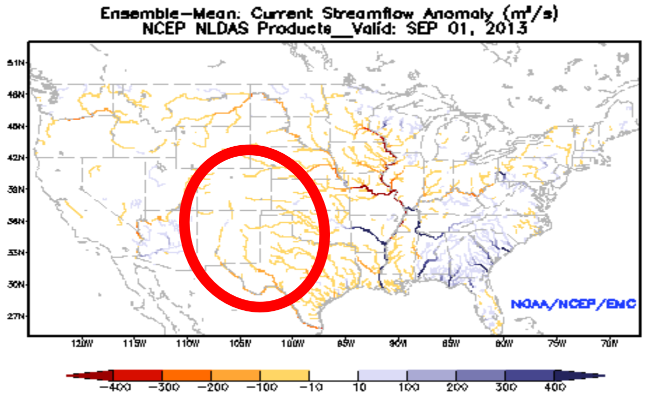
"NLDAS" 14-km daily streamflow anomaly (30-yr climo.)



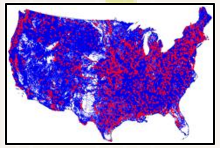
Hurricane Irene and Tropical Storm Lee, 20 August – 17 September 2011



Superstorm Sandy, 29 October – 04 November 2012



Colorado Front Range Flooding, September 2013

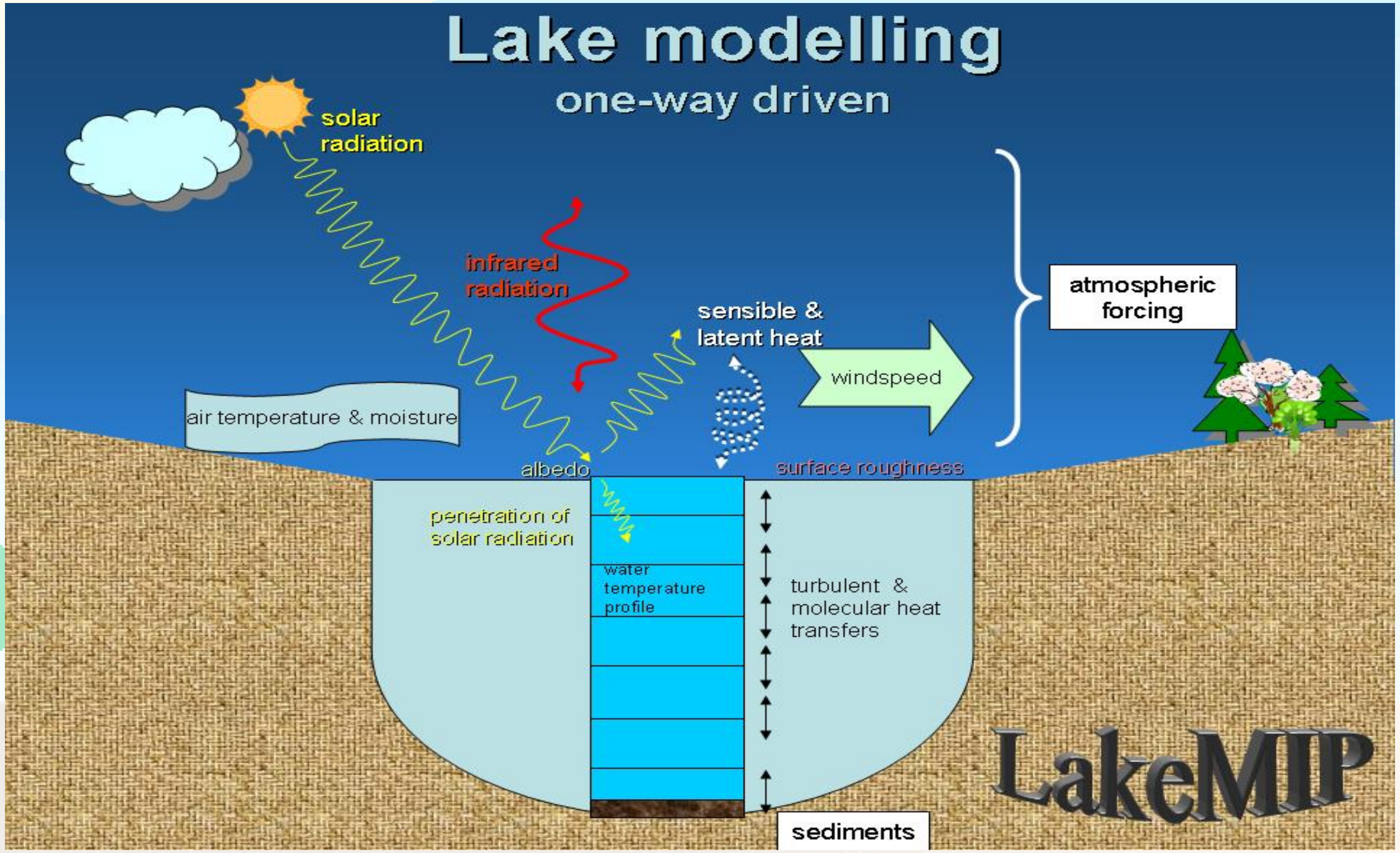


NWS high-resolution National Water Model 1-km land, 250m hydro

Lakes: *"It's not ocean, so let the land modelers deal with lakes!"*

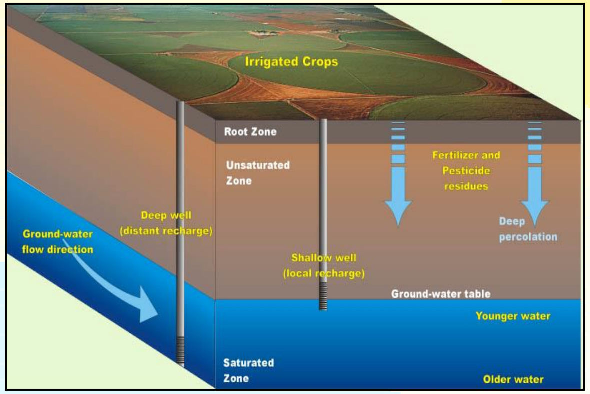
- ***Thousands*** of lakes on scale of 1-km to 4-km not resolved by SST analysis -> greatly influence surface fluxes; explicitly represented in models vs subgrid.
- One example is the simple freshwater lake "***FLake***" model *(Dmitrii Mironov, DWD).*

- Two-layer.
- Atmospheric forcing inputs.
- Lake temperatures and energy budget.
- Mixed-layer and thermocline.
- Snow-ice module.
- Specified depth/turbidity.
- Used in regional models: ICON, COSMO, HIRLAM, NAM. Global models: ECMWF, CMC, UKMO, GFS.
- More sophisticated lake models, e.g. multi-layer NCAR CLM (w/10).



Yihua Wu (NCEP/EMC)

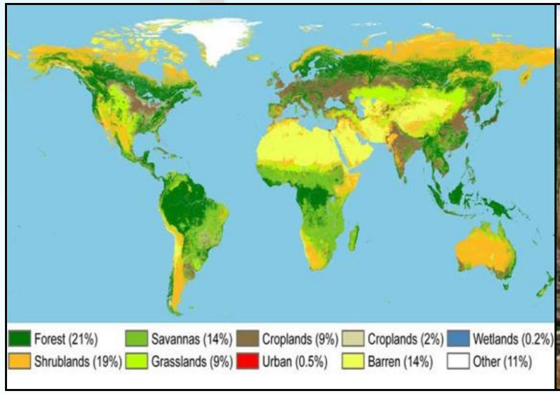
Human Influences/Water Management



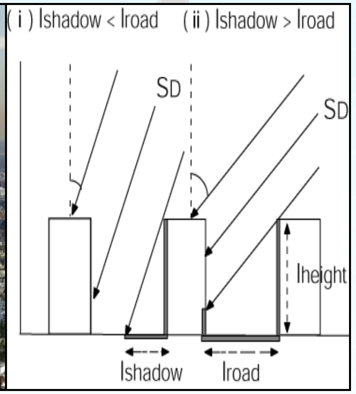
Groundwater Extraction

Crop models and Irrigation

Reservoirs



Land-cover change/deforestation



Urban regions/modeling

- Proper initial conditions (e.g. via remote sensing), and improved and higher-resolution land physics parameterizations must account for these factors. Again, use of land data assiilation.

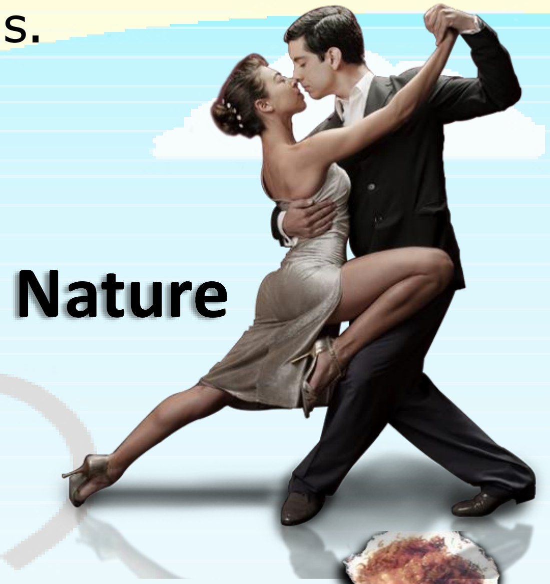
Outline

- Why land?
- Role of Land Models.
- Land Model requirements.
- Testing and Validation.
- Land Models in a fully-coupled Earth System.
- Land-Atmosphere Interaction.
- Summary.

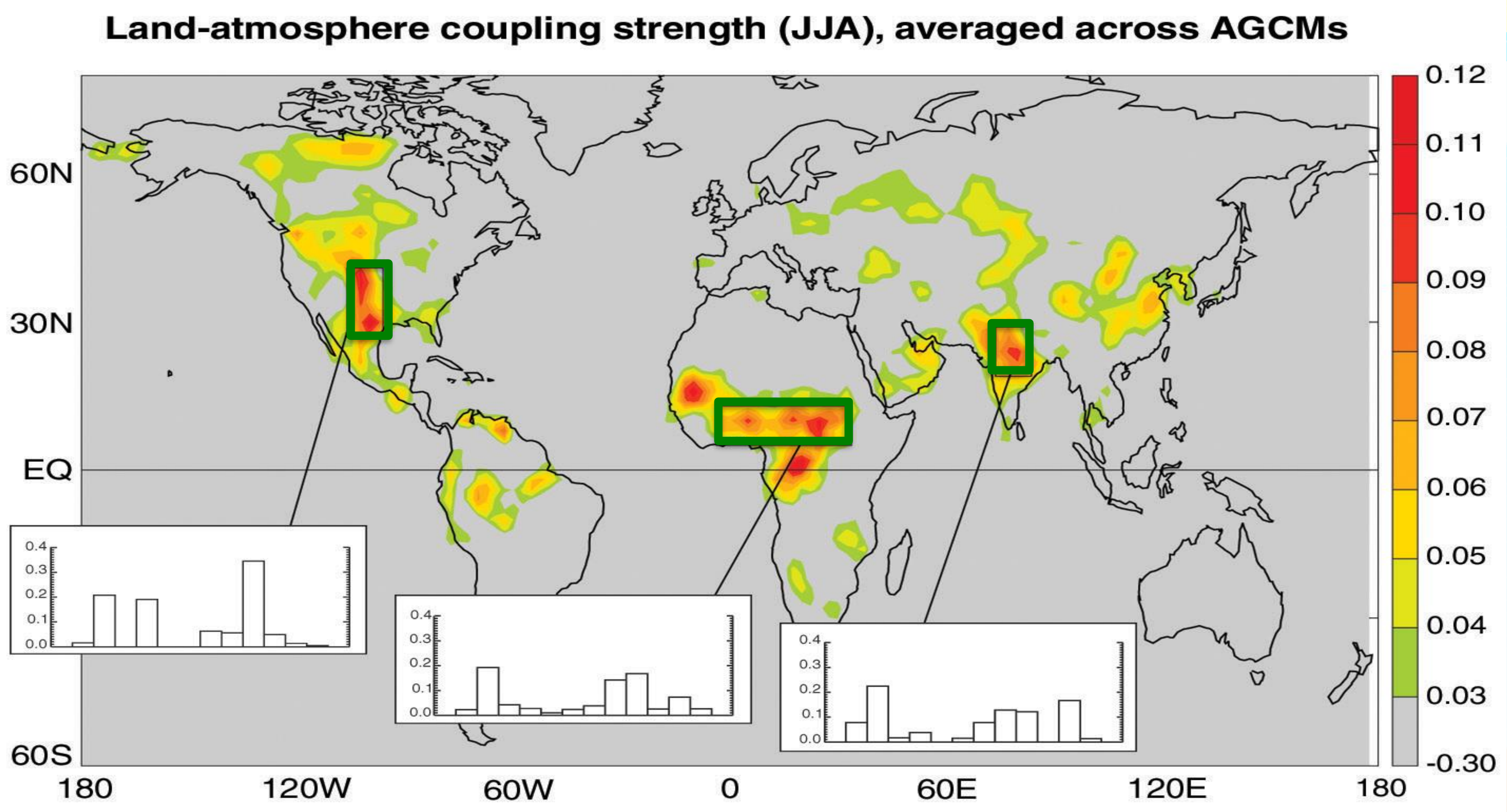
Land-Atmosphere Interaction

- **Land & atmosphere are intimately coupled**: short to long time scales.
- However, historically land models and atmospheric models have been **developed separately**, and then plugged together. Not so good for simulating coupled land-atmosphere processes…
- **Land-atmosphere interaction** remains a weak link in Earth system prediction models for Numerical Weather Prediction (NWP) & Climate.
- **Coupling strength** affects surface fluxes and boundary-layer evolution (with downstream influences), so important for weather and climate; develop/use land-atmosphere coupling metrics: *Is the coupling correct?*
- Need to understand **many land & atmospheric processes and interactions**, with proper representation in weather/climate models...
- ...e.g. soil moisture/evaporative flux to the atmosphere (boundary-layer development, clouds/convection), hydrology/river-flow & connection to oceans, dust/suspension and surface chemistry interactions, plants, etc.

Coupling begins locally!



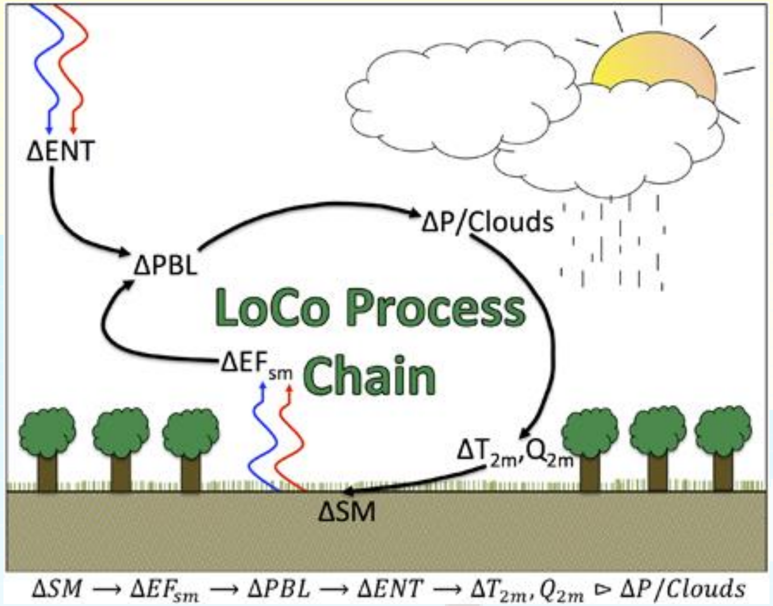
Large-scale Land-Atmosphere Interactions: Soil Moisture-Precipitation "Hot spots"



- **Modeling study: Areas with largest soil moisture gradients have greatest affect on rainfall.**

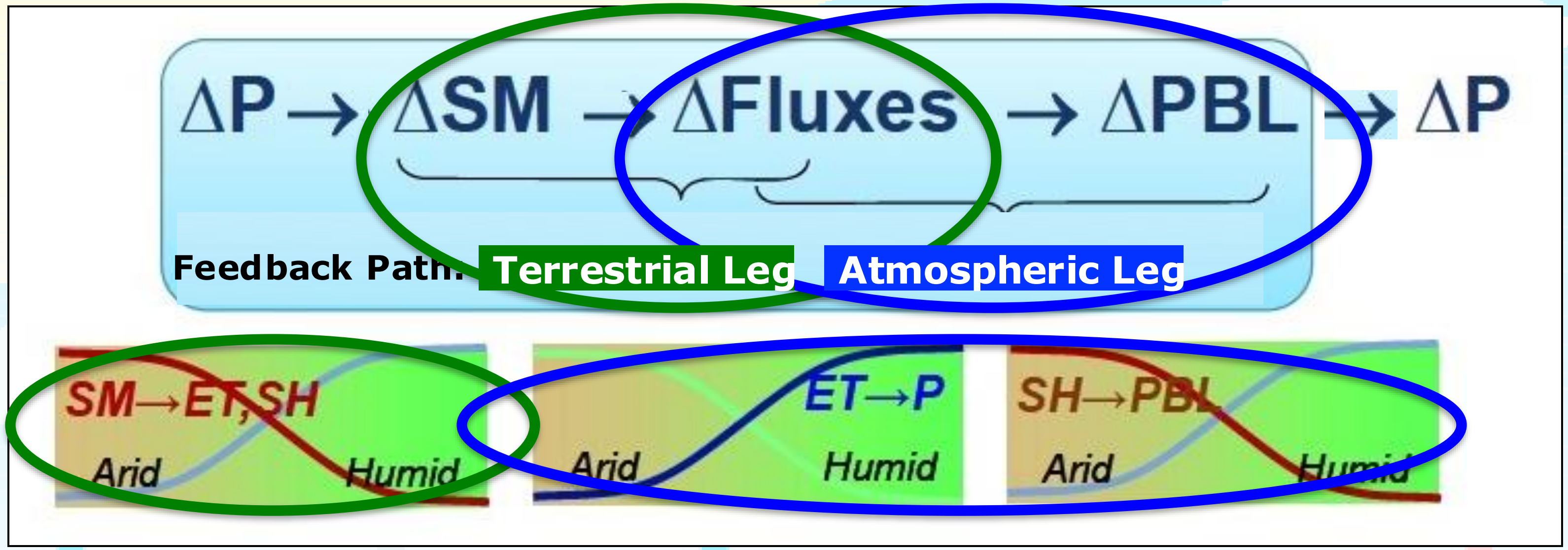
  R. Koster* et al (2004), NASA/GSFC. *author of *The Swenson Code*

Local Land-Atmosphere Interaction and Coupling



GEWEX Local Land-Atmosphere Coupling (LoCo) project

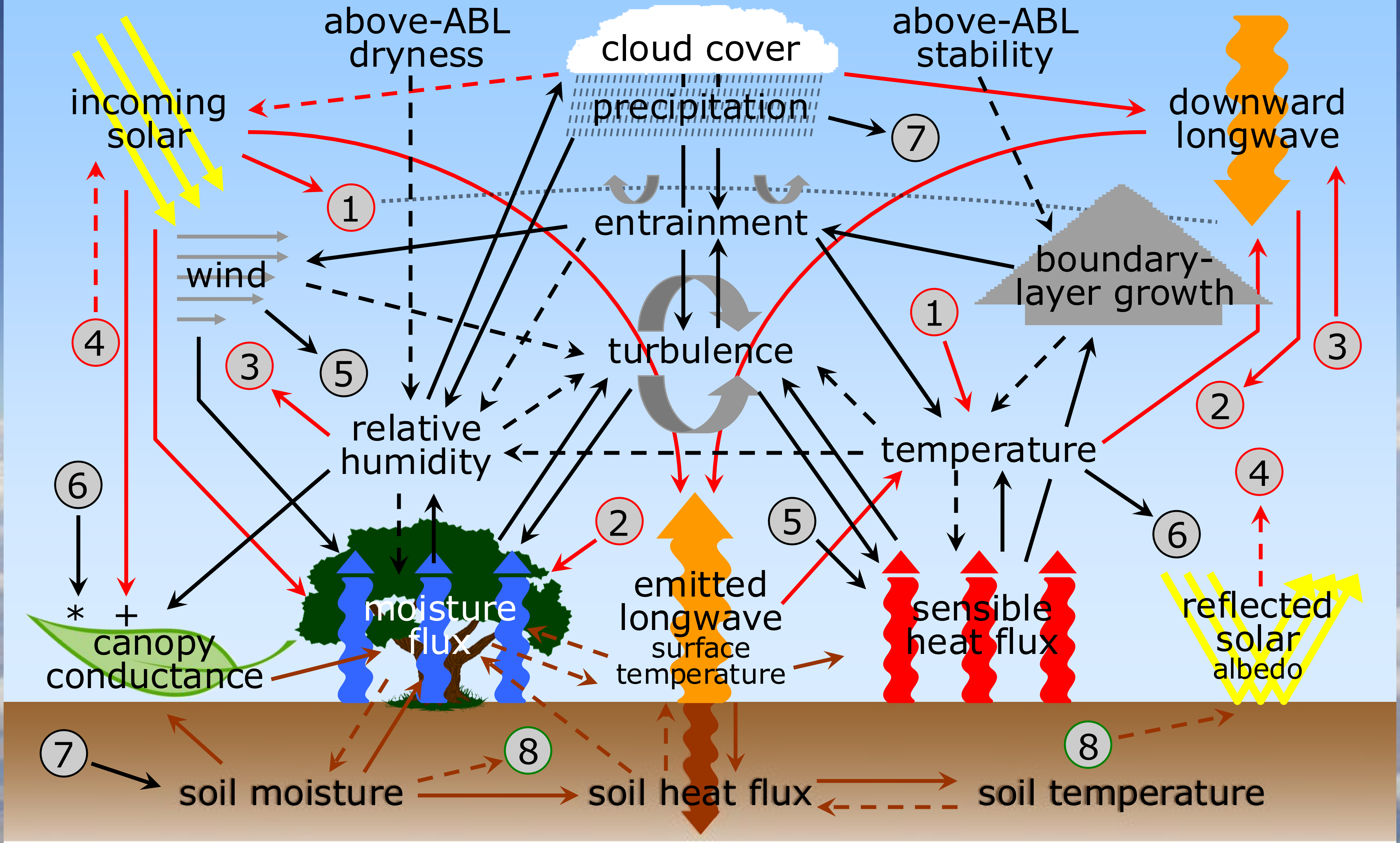
Land-Atmosphere Coupling & Feedbacks "Stand on 2 Legs"



- **Terrestrial Leg** – 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 Leg** – When/where do surface fluxes significantly affect boundary-layer growth, clouds and precipitation?

Figures from Paul Dirmeyer (George Mason Univ.), Joe Santanello (NASA/GSFC)

Local Land-Atmosphere Interactions

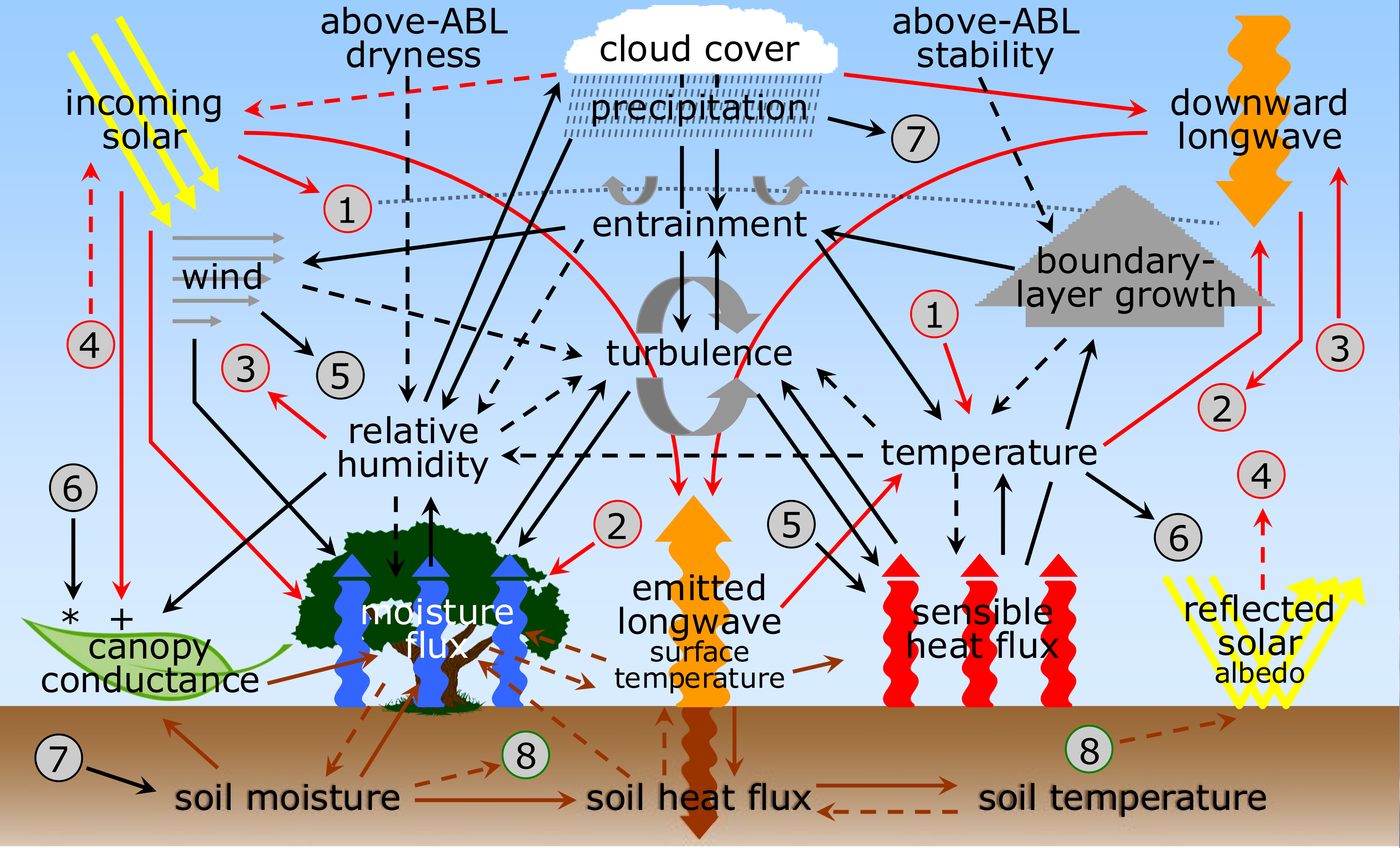


radiation **surface layer & ABL** **land-surface processes** **feedbacks:**

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

****negative feedback above optimal temperature*** **negative**

Local Land-Atmosphere Interactions



radiation **surface layer & ABL** **land-surface processes** **feedbacks:**

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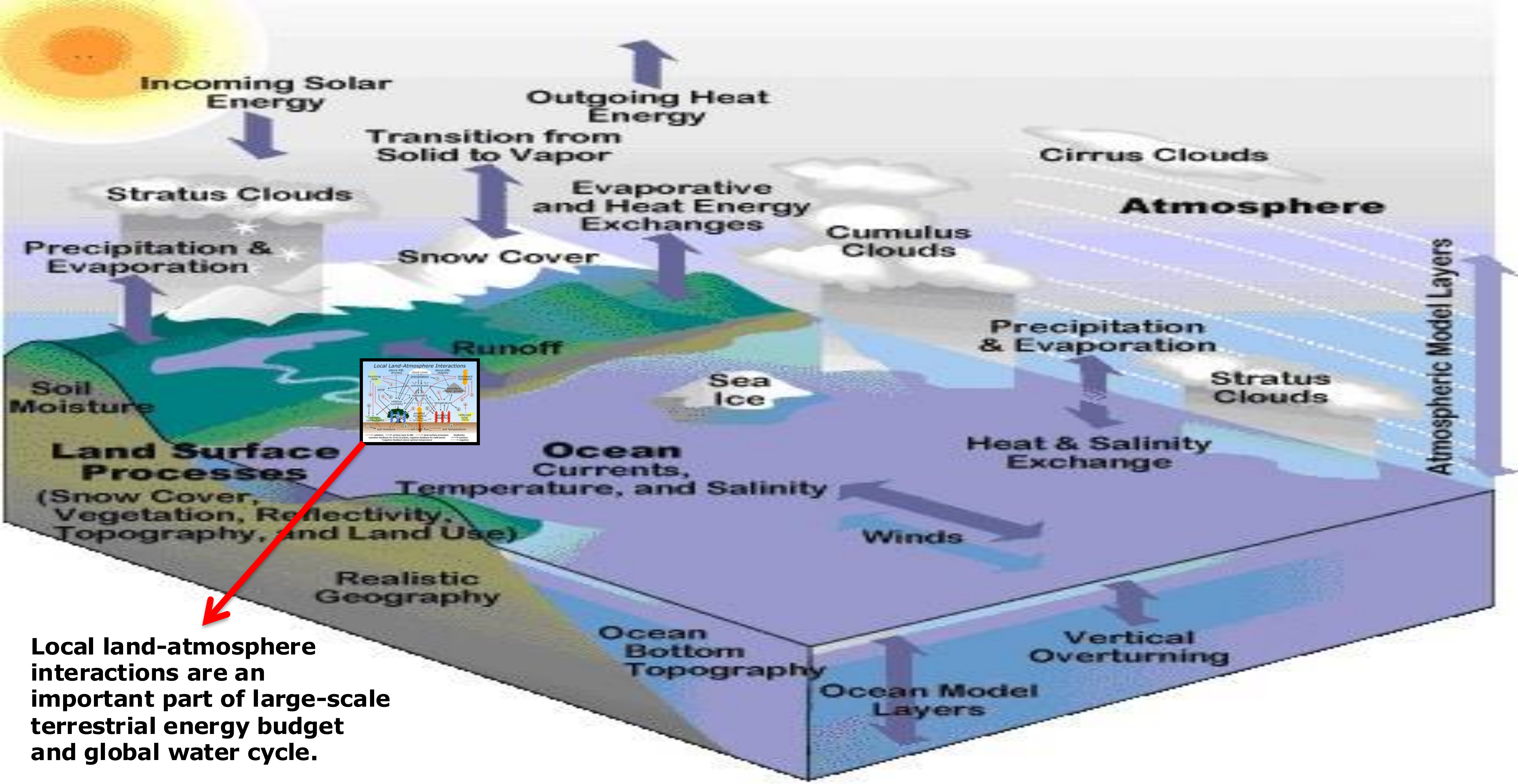

Local land-atmosphere interactions are an important part of large-scale terrestrial energy budget and global water cycle.

Outline

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Summary

- **Predictability** from **soil moisture/temperature/ice, vegetation,** and **snow cover.** Important for short/NWP time scales (<10-14 days), out to Subseasonal-to-seasonal, and on longer climate time scales.
- Land models provide surface **boundary conditions** for weather and climate models; requires proper representation of **land-atmosphere interaction**. *Also provides upper boundary for hydrological models.*
- For earth system modeling, land models must have **valid** (and scale-aware) **physics** and associated parameters, proper **atmospheric forcing**, representative **land data sets** (in some cases near real-time and possibly assimilated), and **initial** & **cycled land states**.
- Land model **validation** using (near-) **surface & ABL observations** of temperature, humidity and winds, as well as upper air profiles, plus specialized data sets from surface/ABL networks & field programs. Extensive **data "mining"** required for processes-level studies & validation.
- Role of land models critical in Earth System Models, with **connections** between **Weather & Climate** and **Hydrology**, **Ecosystems and Biogeochemical** cycles (e.g. **carbon**), and **Air and Water Quality**. ***So less degrees of freedom to tune our way out of model biases!***

"Get the right answers for the right reasons."

International Collaborations

www.wmo.int

World Meteorological Organization
Working together in weather, climate and water

World Weather Research Programme
"www.wmo.int "WWRP"

WWRP WORLD WEATHER RESEARCH PROGRAMME

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

WCRP World Climate Research Programme

World Climate Research Programme

www.wcrp-climate.org

WMO IOC ICSU

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

GEWEX

Global Energy and Water Cycle Exchanges Project

"Weather, Water, Climate"

GLASS

GEWEX Global Land-Atmosphere System Studies (GLASS) panel focuses on model development and evaluation, concentrating on the next generation of land models, and land-atmosphere interaction.

www.gewex.org

NSF NCAR

NCAR Advanced Study Program & Other Opportunities!

Next-Generation Workforce

Our scientists collaborate with K-12 schools, universities and research institutions to inspire and train future generations in the atmospheric and Earth system sciences.

Advanced Study Program

The Advanced Study Program provides an opportunity to conduct independent research at NSF NCAR. ASP postdoctoral fellows and graduate visitors are part of a collaborative cohort, are mentored by leading NSF NCAR scientists and engineers, and benefit from the breadth of science and training taking place at NSF NCAR.

Being an Intern at NSF NCAR

Learn more about being an intern at NSF NCAR and explore professional development workshop topics.

Postdoctoral Programs

Build your professional path through a postdoctoral fellowship opportunity at NSF NCAR.

EXPLORE MORE

Early-Career

Discover opportunities for professional development and training of early-career staff at NSF NCAR and UCAR.

2025 Early Career Leadership Program

The Early Career Leadership Program or ECLP is a seven week opportunity for early-career scientists and technical staff at NSF NCAR and UCP to develop leadership skills and a sense of cohort with peers across the organization, while learning about the organization. Potential topics include: effective communication, self-awareness, listening as a leader, emotional intelligence, networking, mentoring, scientific and technical communication, and more. This program is sponsored by NSF NCAR EdEC.

Early Career Scientist Assembly

The ECSA represents the interests of early-career scientists, voicing concerns, solutions, and successes from early-career scientists to NSF NCAR and UCAR management to guide institutional policies.

Career Development for Postdocs

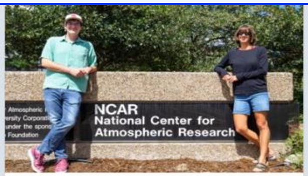
Postdoctoral fellows can participate in regular professional development workshops and events throughout the year, which are led by NSF NCAR scientists and staff, and faculty from our university community.

EXPLORE MORE

Feel free to send me an email with your CV and a few sentences or a short paragraph or two about what you do or are interested in. We can see how to connect with a relevant NCAR project/ researcher.

ASP Postdoctoral Fellowship Program

The postdoctoral fellowship program provides an opportunity for recent Ph.D. scientists to continue to pursue their research interests in atmospheric and related science. The program also invites postdoctorates from a variety of disciplines to apply their training to research in the atmospheric sciences.



Graduate Visitor Program

The ASP Graduate Visitor Program is designed to provide NSF NCAR staff opportunities to bring graduate students to NSF NCAR for 3 to 12-month collaborative visits with the endorsement of their thesis advisors and in pursuit of their thesis research.

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Early Career Scientist Assembly

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ASP Colloquia

ASP hosts an annual colloquium exploring subjects that represent new or rapidly developing areas of research. The colloquium brings together lecturers and graduate students to NSF NCAR for two weeks for classroom presentations, instruction and interaction.

Re: "Other": There are often many other post-doc research opportunities at NCAR.

www.asp.ucar.edu

ncar.ucar.edu

NCAR/UCAR Current job openings: https://ucar.wd5.myworkdayjobs.com/UCAR_Careers


THANK YOU!
OBRIGADO!