NASA and Land Surface Data Assimilation
or
NASA Contributions to GCIP Objectives in Remote Sensing and Land Surface Modeling

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And the NLDAS, GLDAS, NSIPP, CLM, DAO, LIS teams

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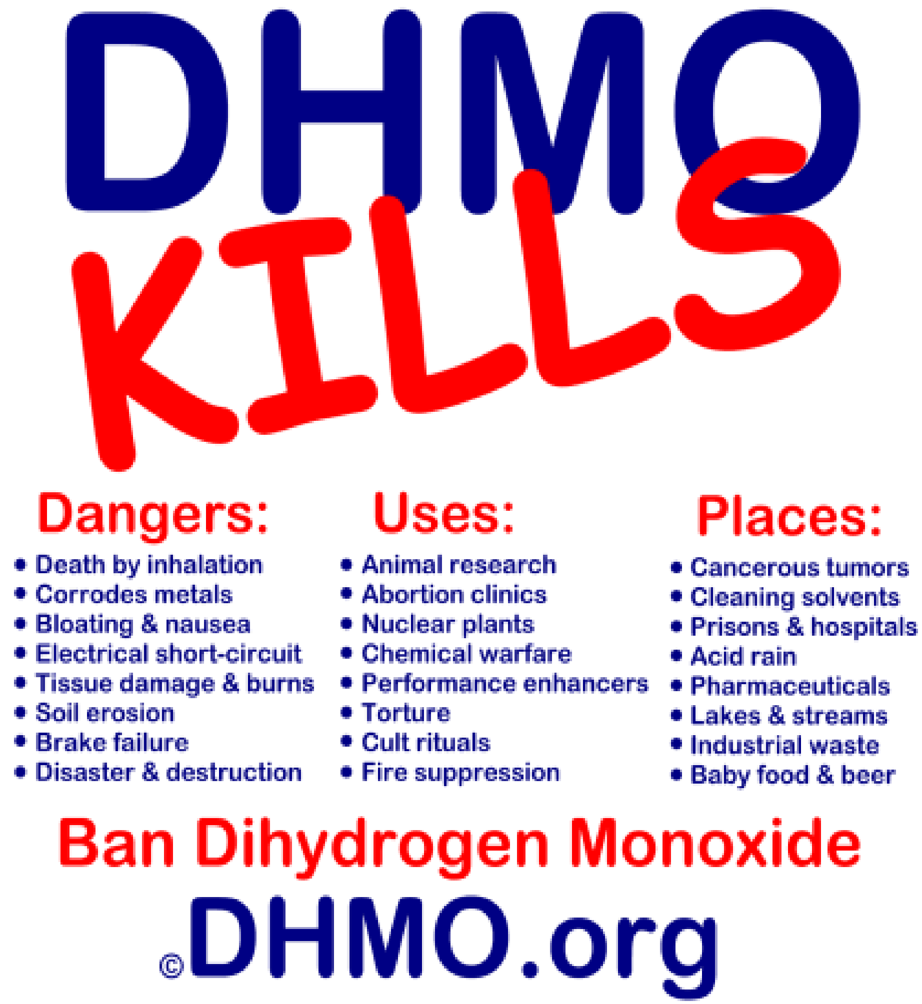
The Truth about DIHYDROGEN MONOXIDE

Dihydrogen Monoxide (DHMO) is perhaps the single most prevalent of all chemicals that can be dangerous to human life. Despite this truth, most people are not unduly concerned about the dangers of Dihydrogen Monoxide. Governments, civic leaders, corporations, military organizations, and citizens in every walk of life seem to either be ignorant of or shrug off the truth about Dihydrogen Monoxide as not being applicable to them.

•also known as **hydric acid**, and is the major component of acid rain.
•contributes to the **greenhouse effect**.
•may cause **severe burns.**
•contributes to the **erosion** of our natural landscape.
•accelerates **corrosion and rusting**.
•may cause **electrical failures** and decreased effectiveness of automobile brakes.
•has been found in excised **tumors**.

Write your Congressman!
Get the T-Shirt, Only $18.95!

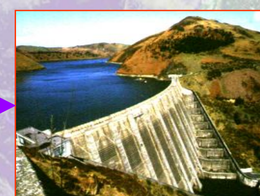


Why study the water cycle?... Earth is a water planet! *Water is Life…*

Water in Climate

Fluxes and Feedbacks

Water in the environment



Water supply and quality

Water for consumption

Variations in greenhouse gases, aerosols, and solar activity force changes in climate…

*…but, consequences of climate change are **realized through the water cycle**.*

Thus, we must ***characterize***, ***understand***, and ***predict*** *variations in the global water cycle and assess potential abrupt climate changes.*

NASA Water and Energy Cycle Research Program

We aim to *characterize*, *understand*, and *predict* variability in the global water cycle, which involves complex interactions between atmospheric, physical, biogeochemical processes, and human activities.

- NASA Global Water and Energy Cycle Research Program: Determine water-cycle variability, fluxes and feedbacks, and the predictable hydrologic consequences of climate change.
- Current predictions of precipitation and hydrologic phenomena lack skill.
- Hydrologic research is well poised to pull together our water-cycle expertise and make *real progress* toward answering grand-challenge water cycle questions

We need an overarching vision for water cycle research that we can agree on and organize around.

Improve water cycle prediction

This vision encompasses the essential elements of the GEWEX, NASA-ESE and USGCRP science plans, while maintaining clear deliverables, metrics and applications.

This will require critical center, national, and international science and technology partnerships.

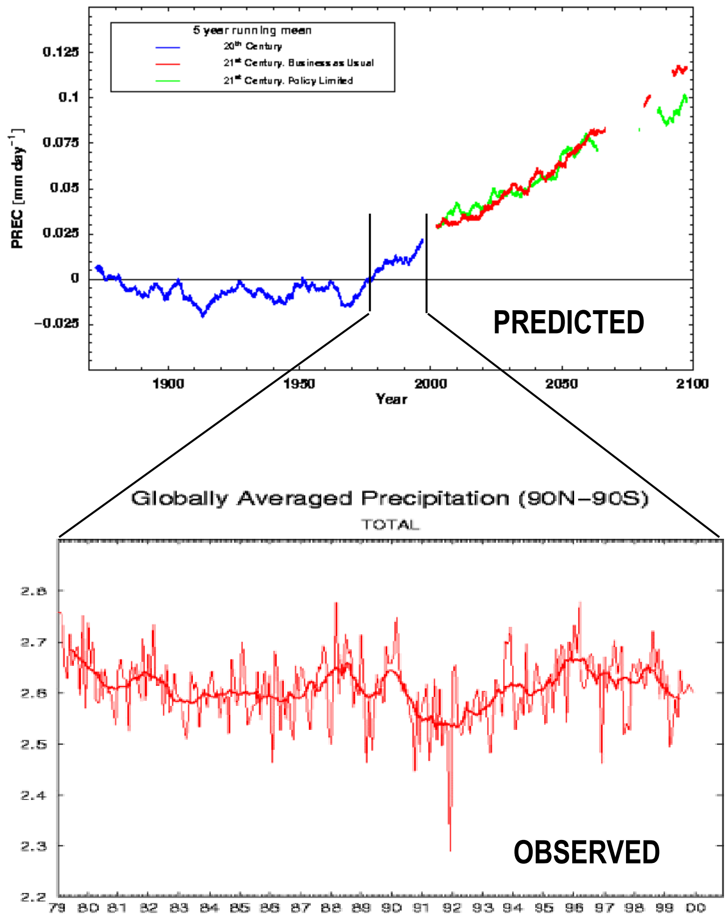
GAPP aims to address role of land surface in climate prediction based on:

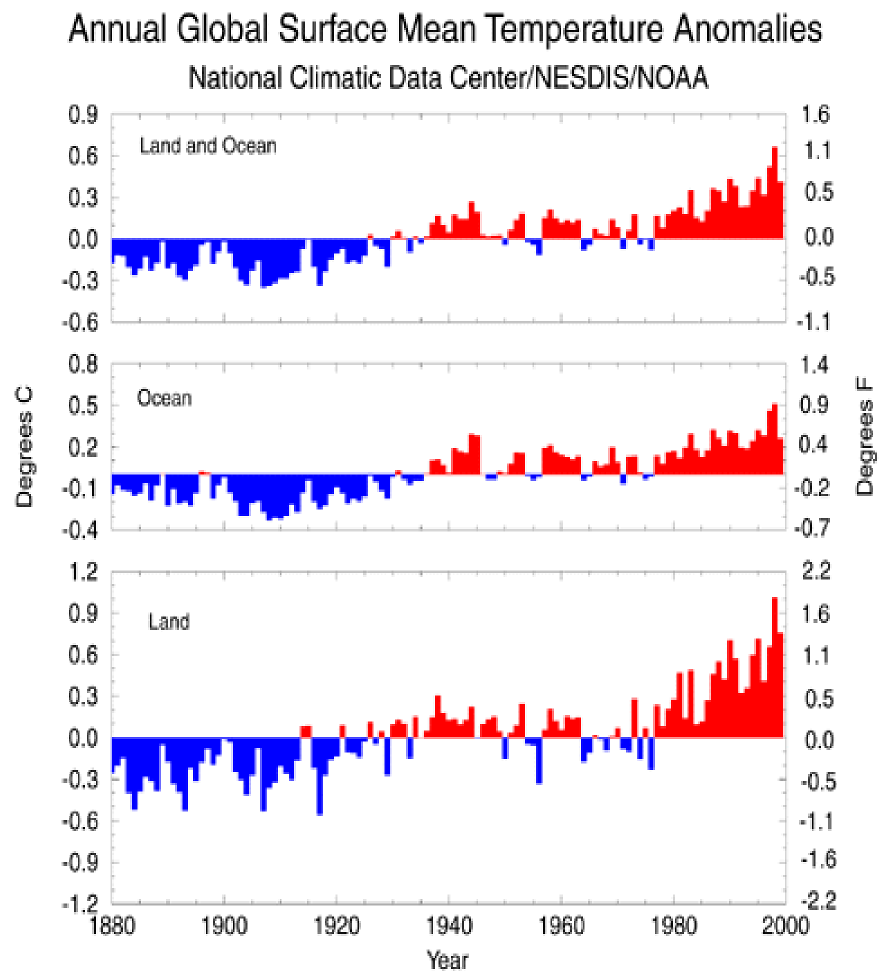
- **New understanding**
- **New observations**
- **New models**

And use improved predictions for better water resource applications

Current state of climate-change science

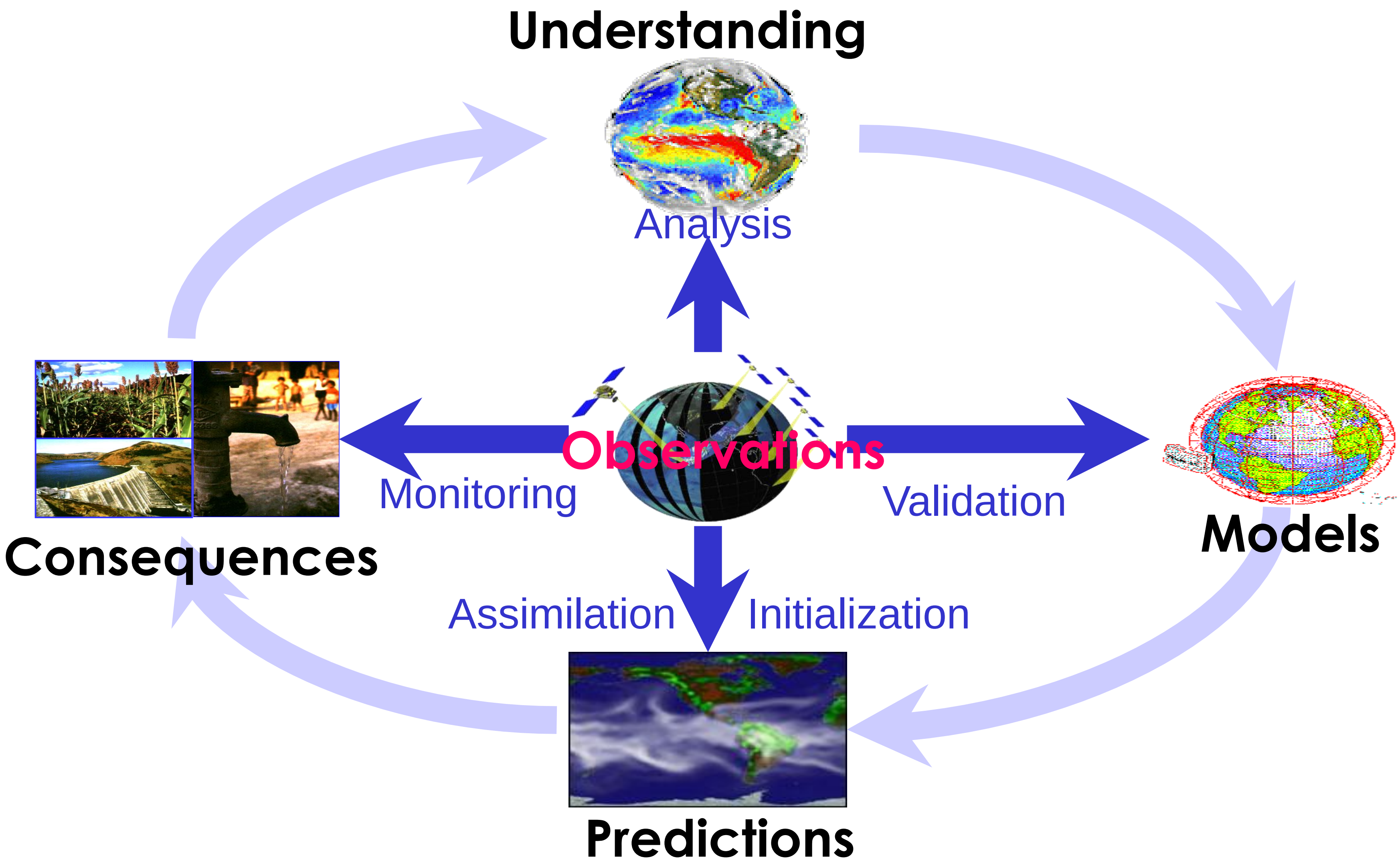
Global Precipitation





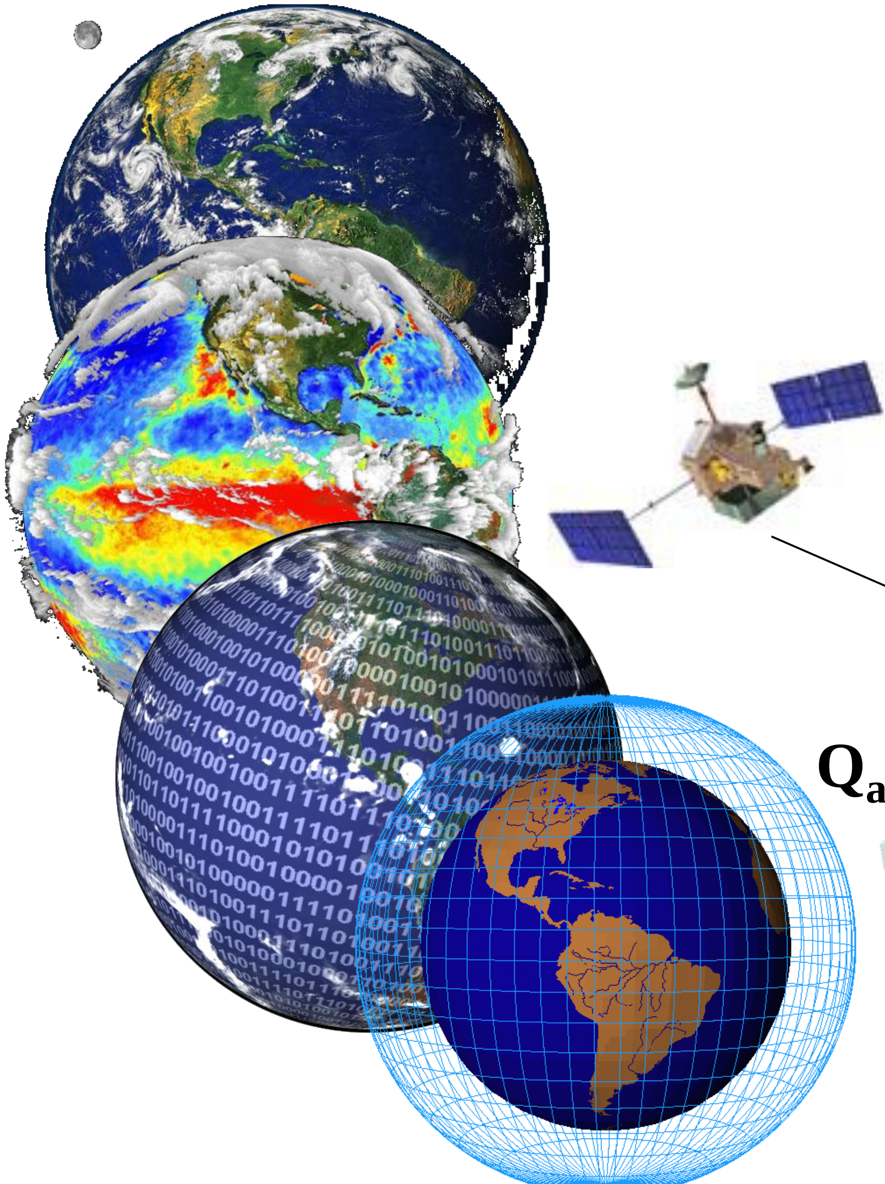
We've observed global warming in the last century and our models can "match" this warming, but our ability to quantify significant trends or simulate hydrologic (i.e. precipitation) variations is inadequate.

Water Cycle Research: From Observations to Consequences



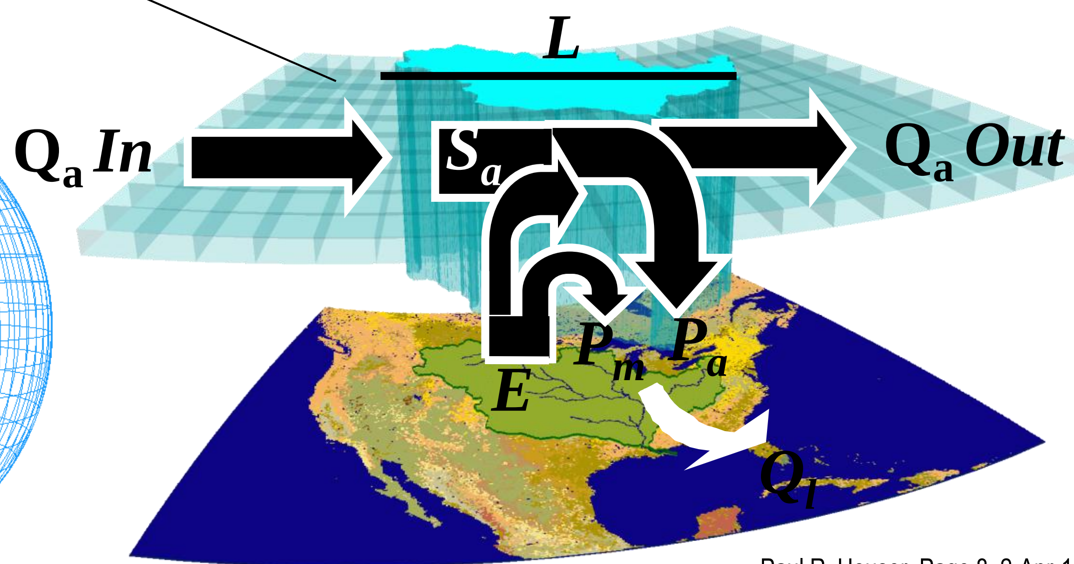
NASA is *the U.S. space agency* and should exploit its unique capabilities for space-based observations to promote scientific understanding

Observation Strategy



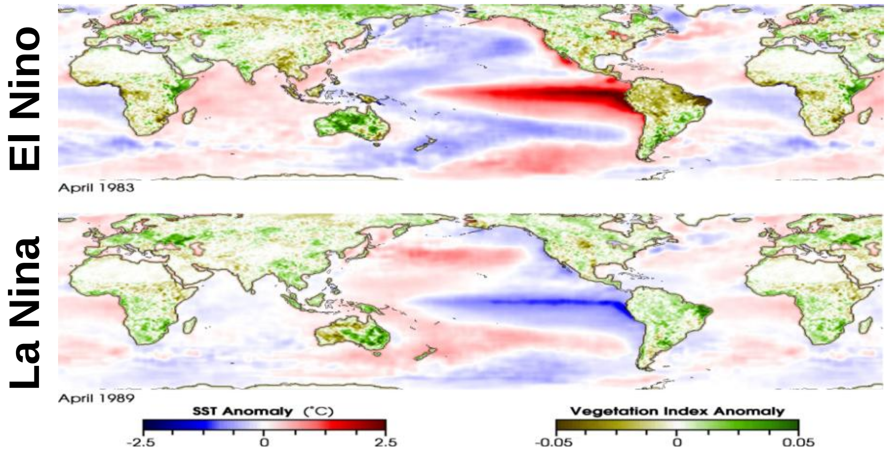
Input - Output = Storage Change

Transport + Evaporation - Precipitation – Runoff - P
= ΔLand Storage + ΔWater Vapor

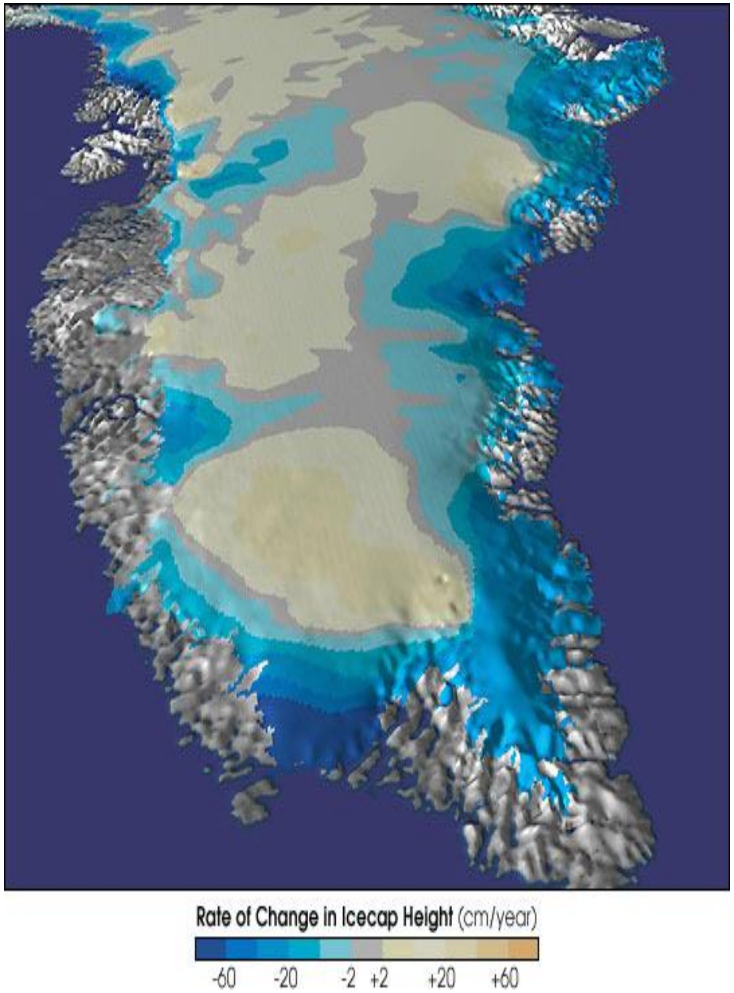


Global Water Cycle: Diagnose and Identify Predictable Changes **Current Capabilities**

Ocean temperatures and vegetation



Measuring Changes in Ice Cover

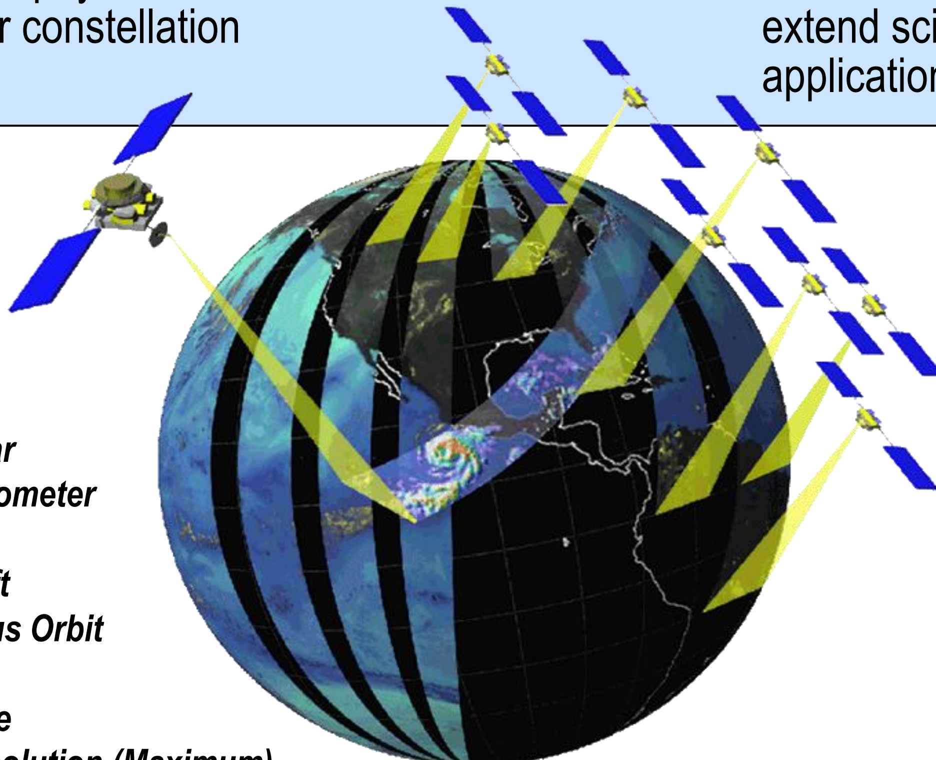


TRMM Precipitation Observations

GPM Reference Concept

OBJECTIVE: Understand the horizontal and vertical structure of rainfall and Its microphysical element. Provide training for constellation radiometers.

OBJECTIVE: Provide enough sampling to reduce uncertainty in short-term rainfall accumulations. extend scientific and societal applications.



Core Satellite

- *Dual Frequency Radar*
- *Multi-frequency Radiometer*
- *H2-A Launch*
- *TRMM-like Spacecraft*
- *Non-Sun Synchronous Orbit*
- *~65° Inclination*
- *~400 - 500 km Altitude*
- *~4 km Horizontal Resolution (Maximum)*
- *250 m Vertical Resolution*

Constellation Satellites

- *Multiple Satellites with Microwave Radiometers*
- *Aggregate Revisit Time, 3 Hour goal*
- *Sun-Synchronous Polar Orbits*
- *~600 km Altitude*

Precipitation Validation Sites

- *Global Ground Based Rain Measurement*

Global Precipitation Processing Center

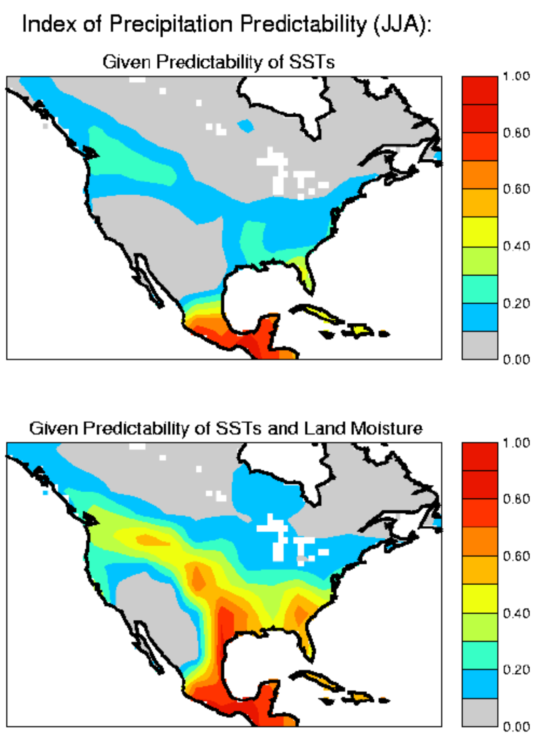
- *Capable of Producing Global Precip Data Products as Defined by GPM Partners*

What we propose to do

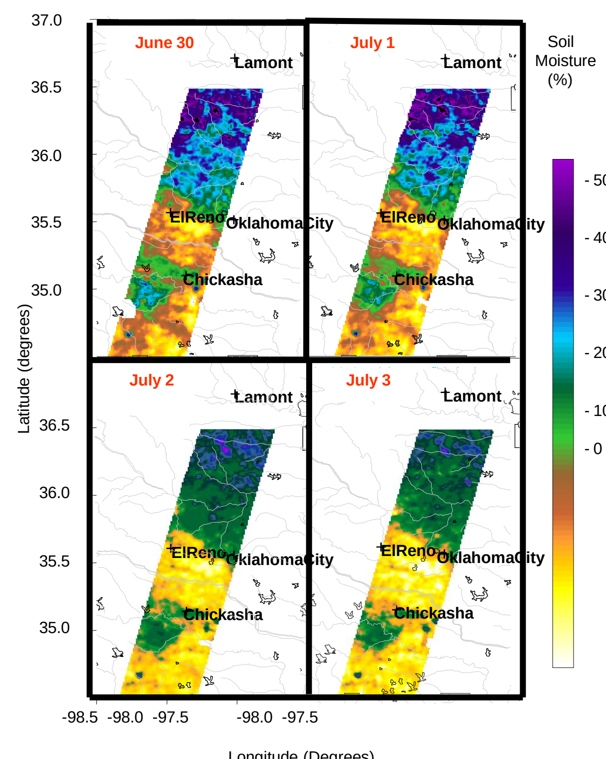
Exploratory Observations

Soil Moisture Mission

Understand the impact of soil moisture and on flood/drought prediction, weather forecasting, and agriculture.

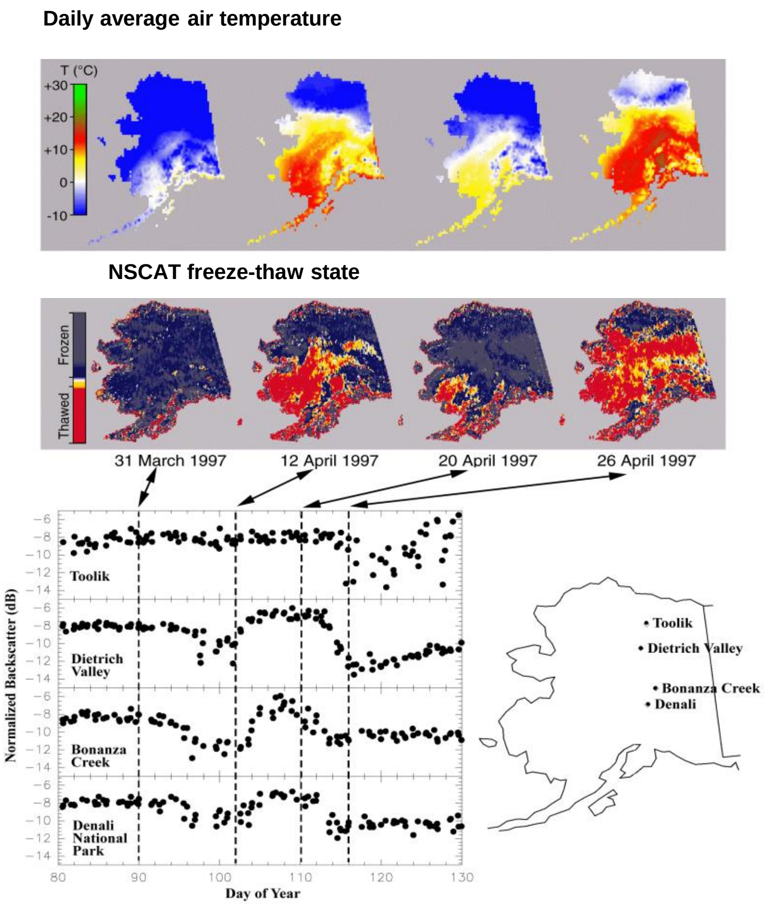


Global soil moisture observation using microwave observations



Cold Seasons Experiment/Mission

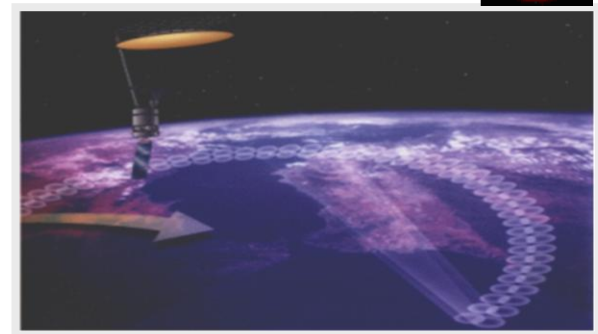
Cold-Seasons Hydrology Mission:



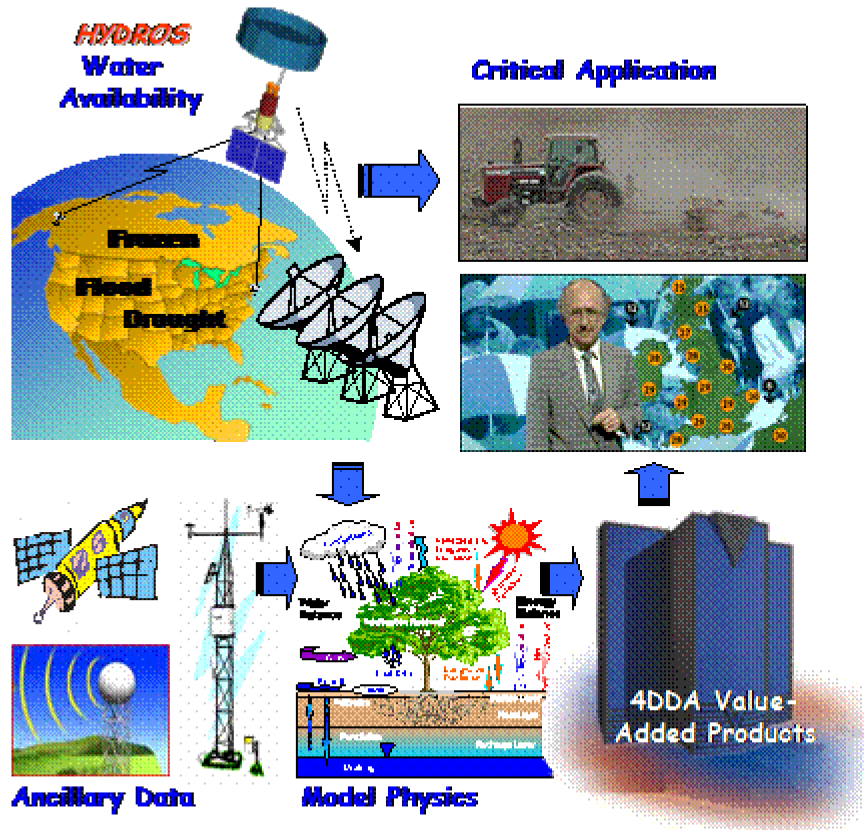
Cold Seasons Hydrology Experiment
Colorado, 2002-2005

Don Cline, National Operational Hydrologic Remote Sensing Center

HYDROS: HYDROspheric States mission



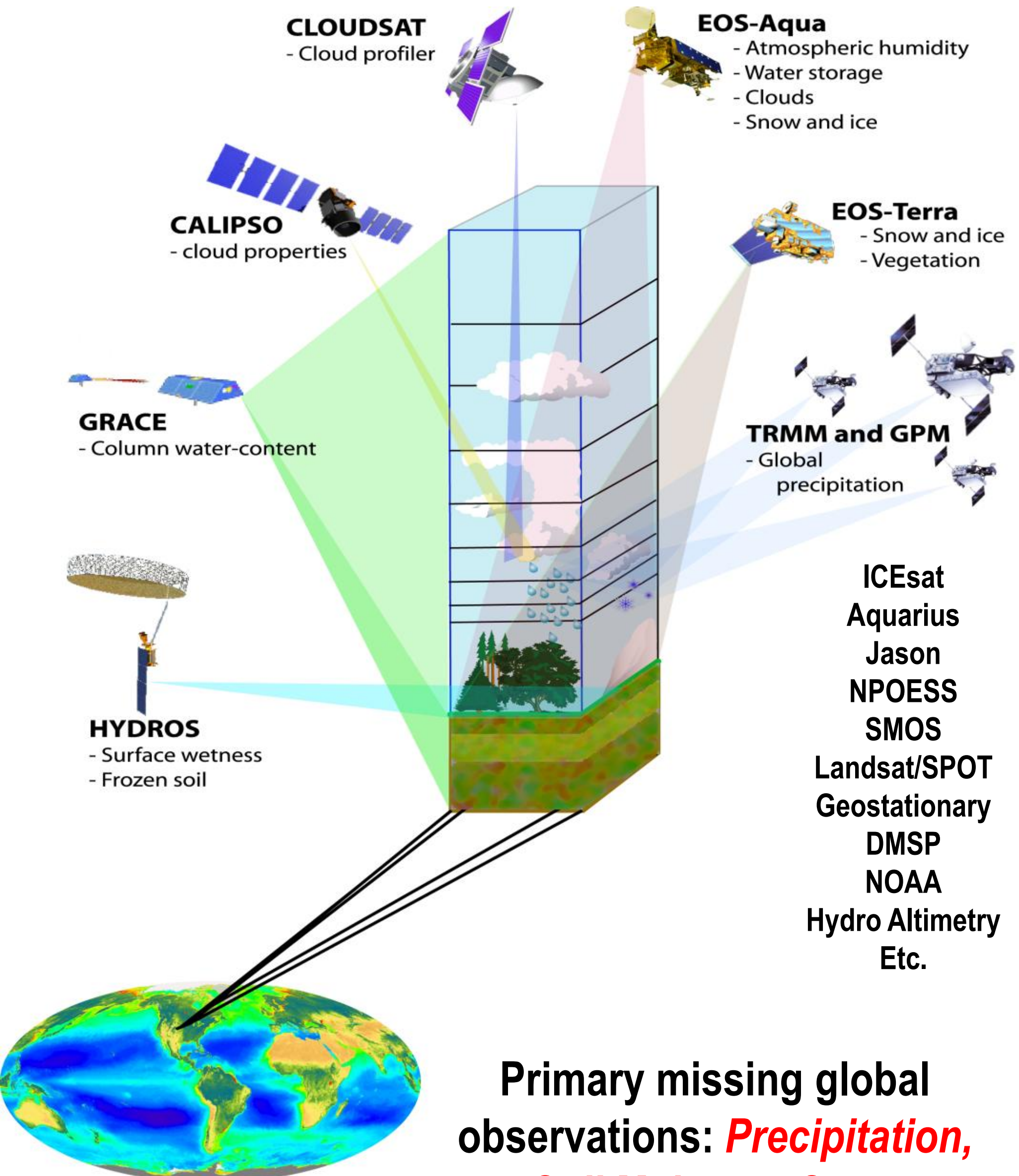
HYDROS is a proposed NASA ESSP mission to make the first spaceborne observations of global soil water availability (moisture and freeze/thaw) that enable new scientific investigations of atmospheric predictability and global change processes.



Dara Entekhabi	(MIT PI)
Paul R. Houser	(GSFC Project Scientist)
Eni Njoku	(JPL Project Scientist)

In response to the 2001 NASA ESSP-3 Proposal Solicitation:
Target Launch: 2006

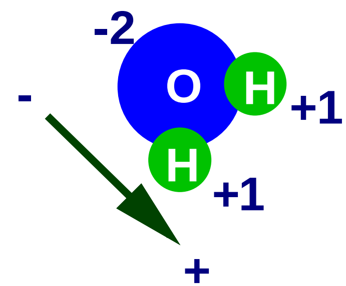
Global Water-Cycle: Observation Strategy

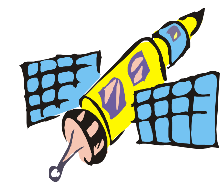


Primary missing global observations: *Precipitation, Soil Moisture, Snow*

Future: *Water Cycle Mission*

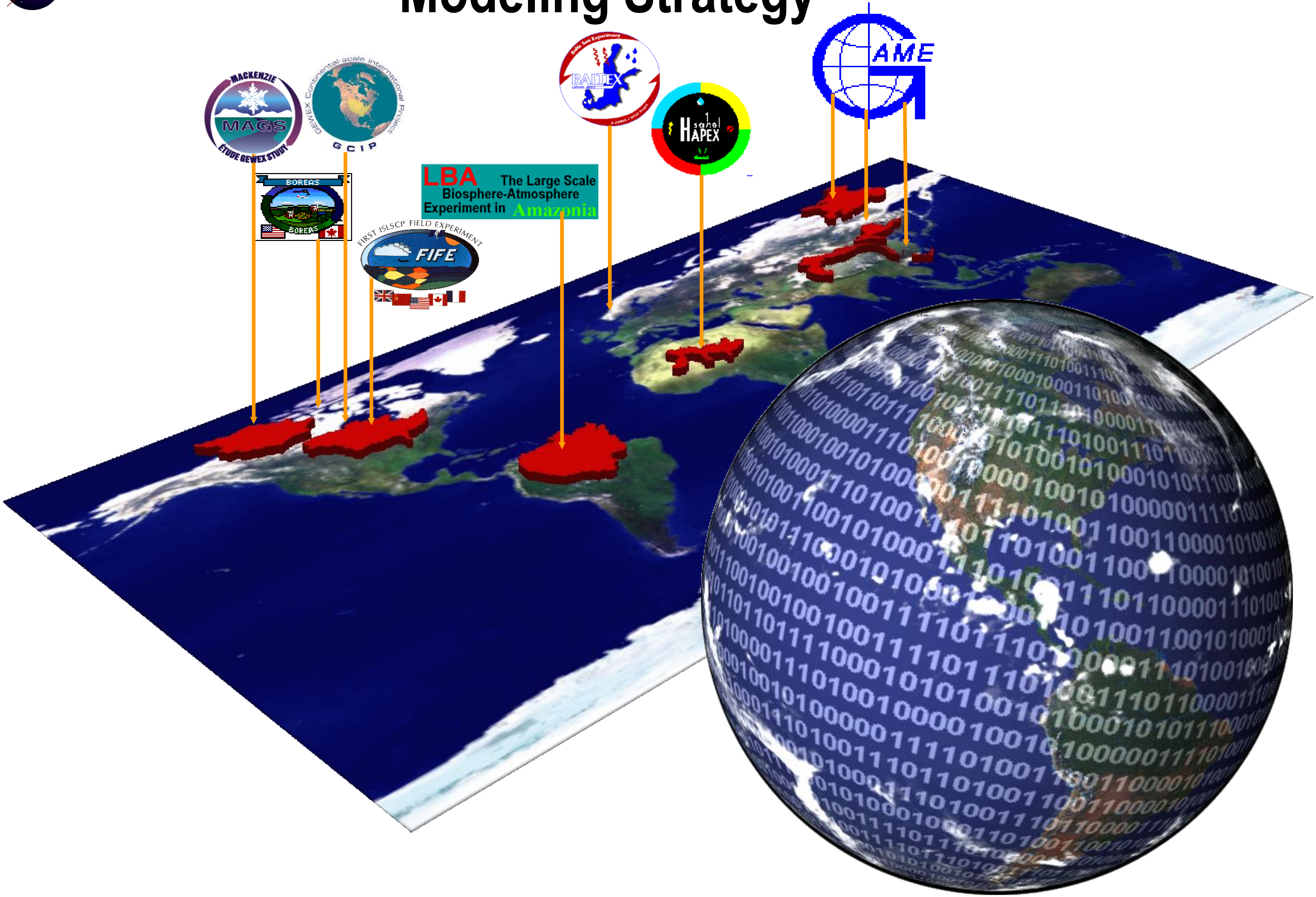
Observation of water molecules through the atmosphere and land surface using an ***active/passive hyperspectral*** microwave instrument.



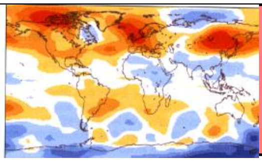


Quantity	Spatial Resolution	Temporal Resolution	Frequency
Groundwater	50 km	2 weeks	100 MHz?
Soil Moisture	10 km	3 days	1.4 GHz
Salinity	50 km	2 weeks	1.4 GH
Freeze/thaw	1 km	1 day	1.2 GHz
Rain	5 km	3 hour	10-90 GHz
Falling Snow	5 km	3 hour	150 GHz
Snow	1-5 km	1 day	10-90 GHz
TPW	10 km		
	(sea)	3 hour	6-37 GHz
	(land)	3 hour	183 GHz
Temperature	10 km		
	(sea)	3 hour	6-37 GHz
	(land)	3 hour	6-37 GHz
ET (4DDA)	5 km	3 hour	1.4-90 GHz

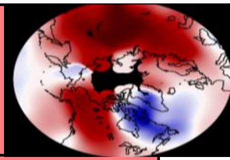
Modeling Strategy

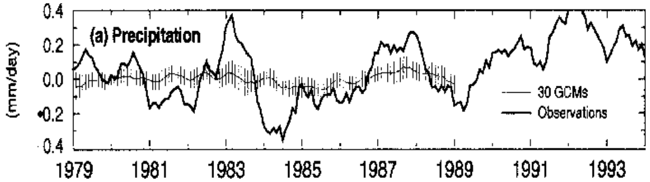


Water-Cycle Prediction Strategy



Global Warming Scenarios





Existing Climate Models

Integrated Water-Cycle Observation System: *In-Situ and Space-Based Observing Programs*

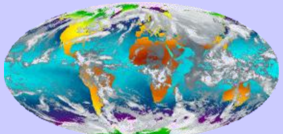
Advance Understanding and Model Physics

Improve Initialization & Assimilation

Diagnose and Identify Predictable Changes

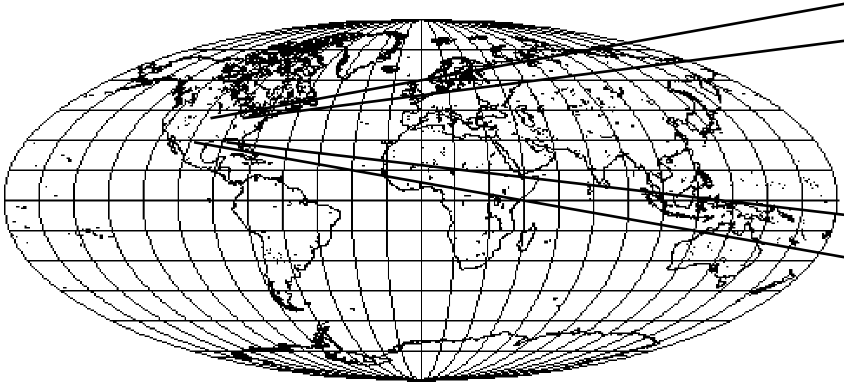
Next-generation Global Water-Cycle Prediction System

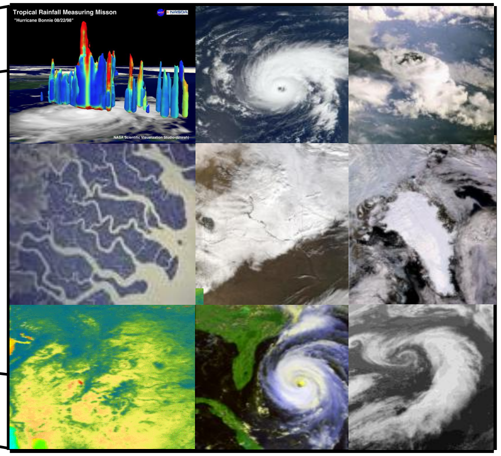
Water-cycle Prediction



Global Water Cycle: Advance Understanding and Model Physics

Climate models' grid-box representation of Earth's processes...





Each grid-box can only represent the "average" conditions of its area.

However, controlling processes of the water cycle (e.g. precipitation) vary over much smaller areas.

How can climate models effectively represent the controlling processes of the global water cycle?

"Conventional" approach: make the model grid-boxes smaller (increase resolution)

- **Slow progress: may take ~50 years to be computationally feasible**

Breakthrough approach: ***Simulate a sample*** of the small-scale physics and dynamics using high resolution ***process-resolving models*** within each climate model grid-box

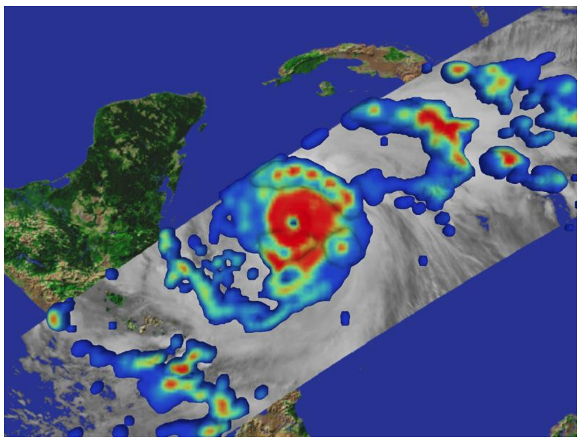
- **"Short-cut" the conventional approach (~10 years to implement)**

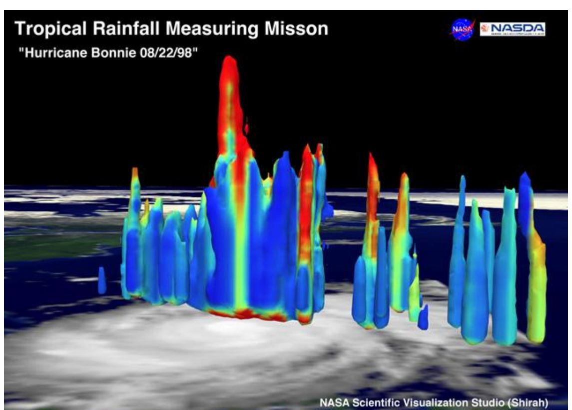
Global Water Cycle: Using Observations with Models to Improve Predictions

•DAO (A. Hao) has demonstrated significant model improvement by assimilating TRMM precipitation data.

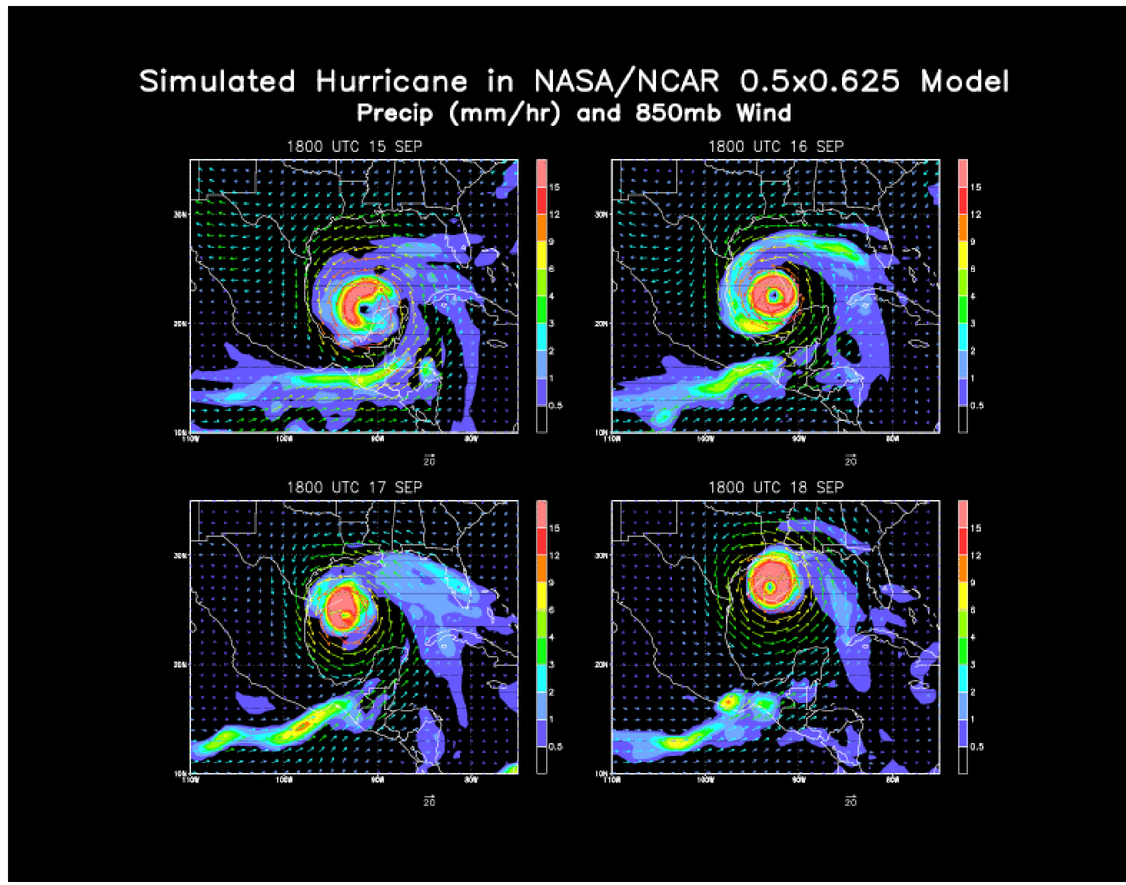
•Transfer to NOAA through ***Joint NOAA-NASA Center for Data Assimilation***

TRMM Precipitation



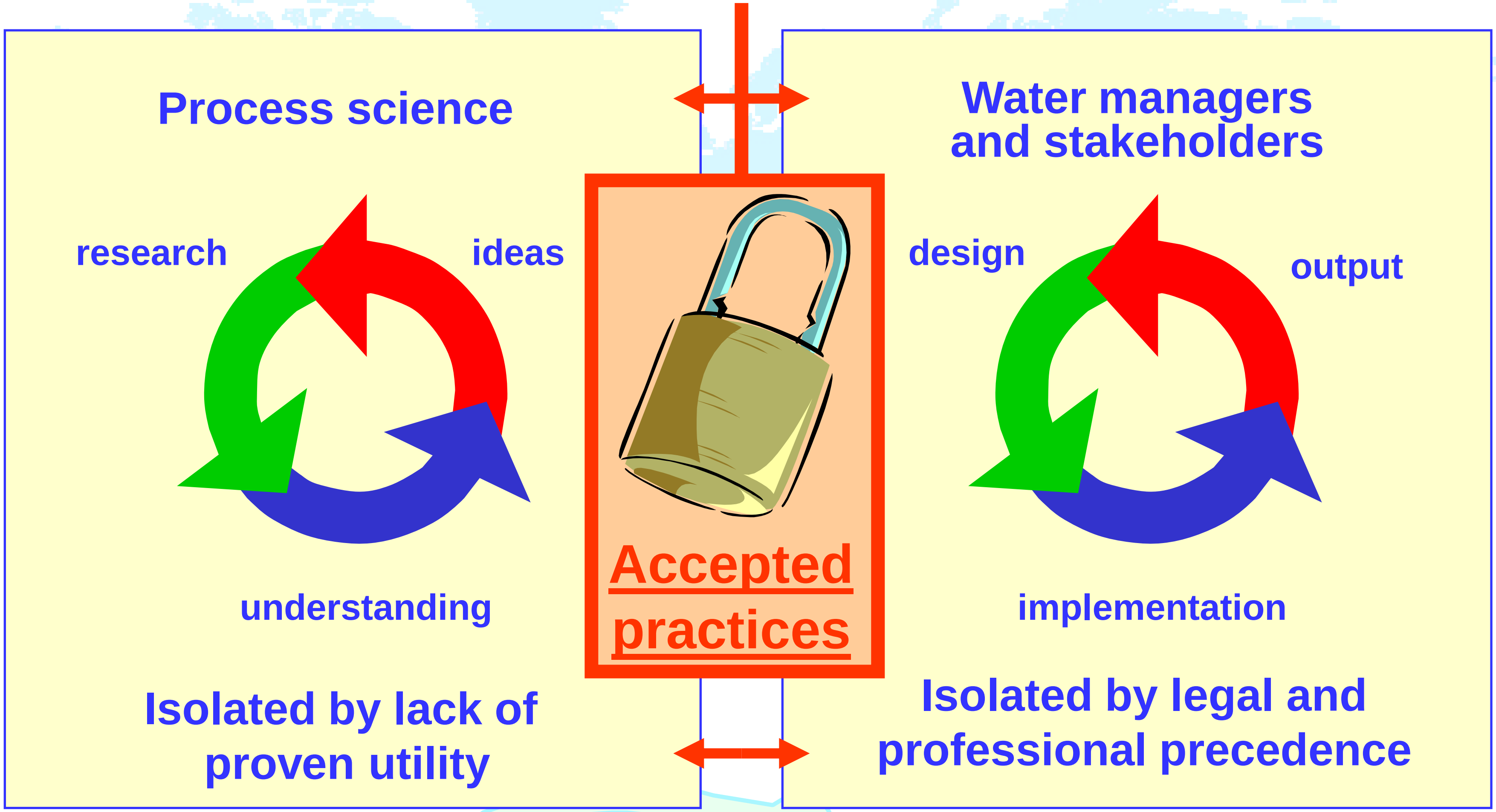


DAO Hurricane Simulation



Hydrologic Applications: The Paradigm Lock

……based on outdated knowledge and technology



Do we need better water resource management?

- We are experiencing dramatic population increases.
- We must find a sustainable balance between water resources for humans and ecosystems.
- Current management is complicated by uncertain global change, strong heterogeneity in ecology and topography, and rapid land use change.
- Ultimately, there is a limited supply of water that will meet limited needs.

Science and technology can help to maximize the use of limited resources, through:

- ***Characterization*** of current conditions, limits, and hazards.
- Enabling basic process ***understanding*** (complex groundwater, snow, riparian, runoff, infiltration, and atmospheric water interactions).
- Developing reliable short to long term ***prediction*** capabilities.

We must also have links between the science/technology and stakeholders.

- Science and technology must be ***defined by*** application needs.
- We must understand ***management and policy*** (i.e. understand and predict human behavior, water banking, management, and operations)
- Must have aggressive ***education*** of the public, stakeholders, policymakers, and ***scientists***.
- We must develop science/technology that is ***useful*** to water resource managers.

We know Earth science and technology has the potential to broadly improve water application….

So, why isn't improved research and technology always resulting in improved applications?

- Inadequate ***understanding of application needs*** results in less useful science and technology investments.
- Inadequate availability of ***technology*** (we currently lack useful water resource observations).
- Inadequate ***integration of information*** (we currently lack informative predictions).

So, what can we do about this?

Improved prediction of consequences is the key.

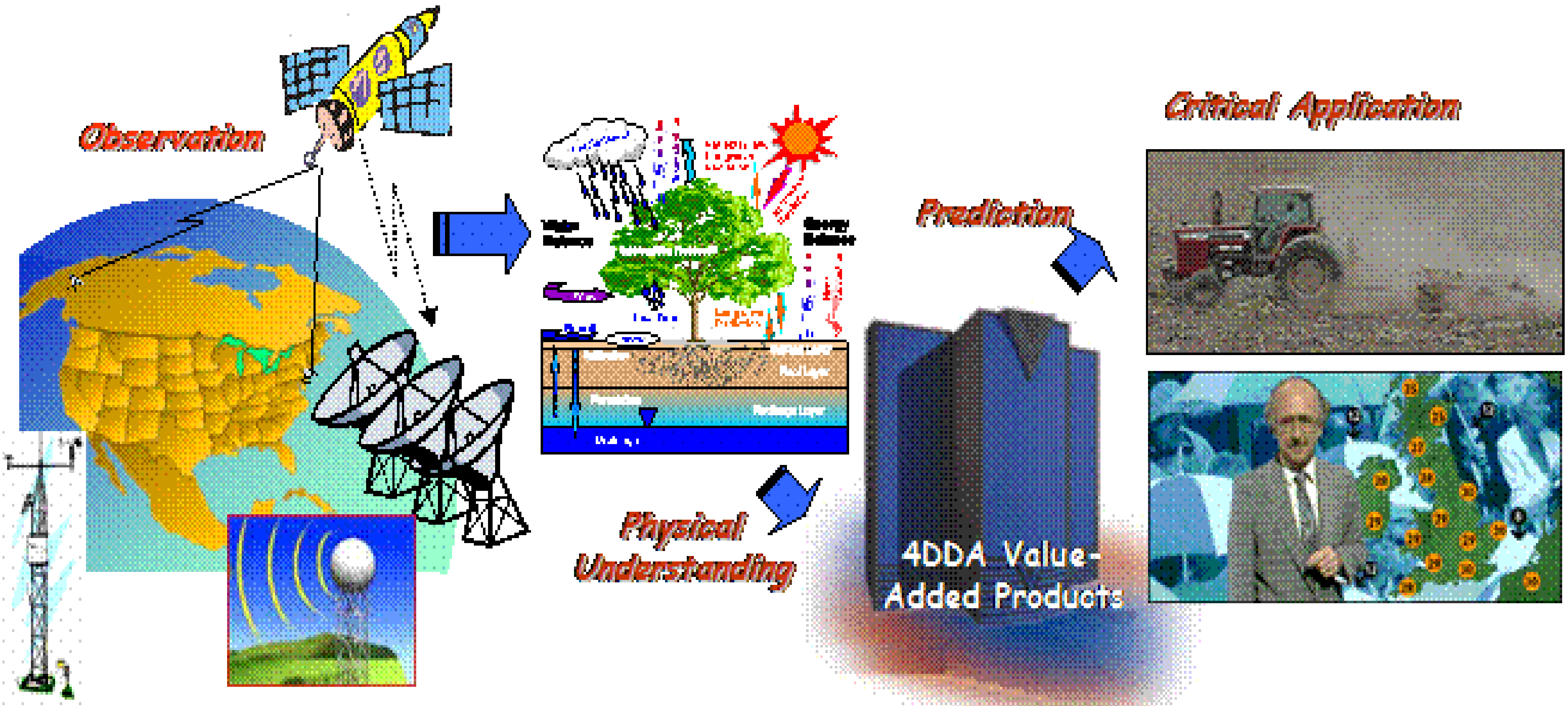
Homeland Security

- A critical homeland security issue is the vitality of our environment - primarily defined by availability and quality of air and water resources.
- Homeland security efforts must therefore include:
  - Advances to understand, assess, and predict natural and human-induced variations in our environment that can enable retooled policies and planning, allocation of resources, and partnership strategies.
  - Scientists and stakeholders have become isolated: scientists by the lack of proven utility of their findings and stakeholders by legal and professional precedence and disaggregated institutions.
  - Communication must be established to get information to users fast, to evaluate various response options in a prediction system, enable planning, and to ultimately take decisive mitigation action.

Global Water Cycle: Linking Science to Consequences

End-to-end coordination enabling understanding and prediction of the Earth's water cycle system:

Research driven by the needs of society



To deliver social, economic and environmental benefit to stakeholders through sustainable and appropriate use of water by directing water cycle science towards improved integrated water system management

Water Cycle Science-Application Link: UNESCO-*HELP*

HELP

Hydrology for the Environment, Life and Policy

HELP

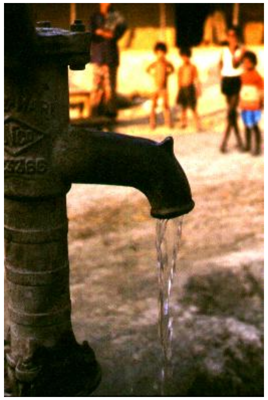
Real people
Real catchments
Real answers

To deliver social, economic and environmental benefit to stakeholders through sustainable and appropriate use of water by directing hydrological science towards improved integrated catchment management

- **WHAT IS THE REQUIRED PRODUCT?** **hydrological research which is directly responsive** to water-related policy and development issues.

- **WHAT IS THE NATURE OF THE INITIATIVE?** **a global network of experimental hydrological catchments** in a range of bio-climatic zones and socio-economic conditions freely exchanging data and understanding

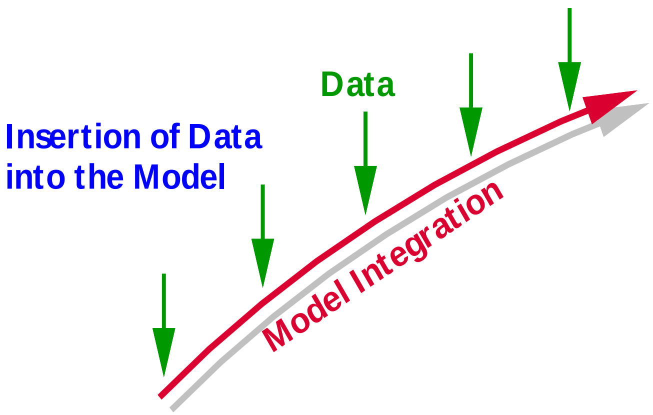
- **HOW WILL IT OPERATE?**
  - **multi-disciplinary**, involving mangers, policy makers and scientists
  - **“bottom up” selection** of the science to be undertaken
  - **use existing networks** where possible
  - **complementary** to other water-related international programmes
  - **new data and knowledge, and capacity building, if required**



Problem of Observation Integration

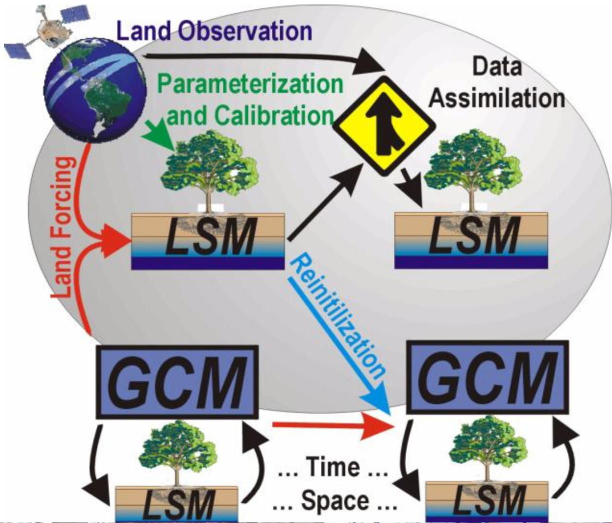
Due to its importance, hydrologic data availability will increase.

Complete quantification of hydrologic variability requires innovative organization, comprehension, and integration of diverse hydrologic information due to disparity in observation type, scale, and error.



Hydrologic Quantity	Remote-Sensing Technique	Time Scale	Space Scale	Accuracy Considerations
Precipitation	Infrared	1hr	4km	Tropical convective clouds only
	Passive microwave	3hr	10km	Land calibration problems
	Active Microwave	10day	10m	Land calibration problems
Surface Soil Moisture	C or L-band radar	10day	10m	Significant noise from vegetation and roughness
	C- or L- band radiometer	1-3day	10km	limited to sparse vegetation, low topographic relief
Surface Skin Temperature	infrared	1hr	10m	soil/vegetation average, cloud contamination
Snow Cover	visible/infrared	1hr	10m	Cloud contamination, vegetation masking, bright soil problems
Snow Water Equivalent	passive microwave	1-3day	10km	Limited depth penetration
	active microwave	10day	10m	
Water level/velocity	laser	10day		Cloud penetration problems
	radar	10day		
Total water storage changes	gravity changes	30day	1000km	Bulk water storage change
Evaporation	IR and Models	1hour	4km	Significant assumptions

Land Data Assimilation Systems: Motivation



Quantification and prediction of hydrologic variability

- Critical for initialization and improvement of weather/climate forecasts
- Critical for applications such as floods, agriculture, military operations, etc.

Maturing of hydrologic observation and prediction tools:

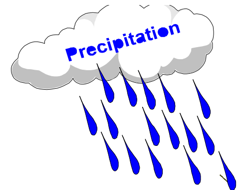
- Observation: Forcing, storages(states), fluxes, and parameters.
- Simulation: Land process models (Hydrology, Biogeochemistry, etc.).
- Assimilation: Short-term state constraints.

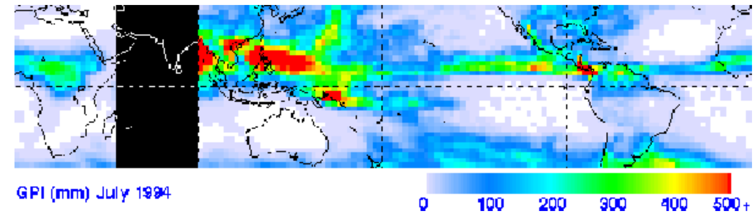
The "GSFC-Land Working Group" – DAO, NSIPP, LDAS

Background: Land Surface Observations

Precipitation: ***Remote-Sensing:*** SSM/I, TRMM, AMSR, GOES, AVHRR

In-Situ: Surface Gages and Doppler Radar



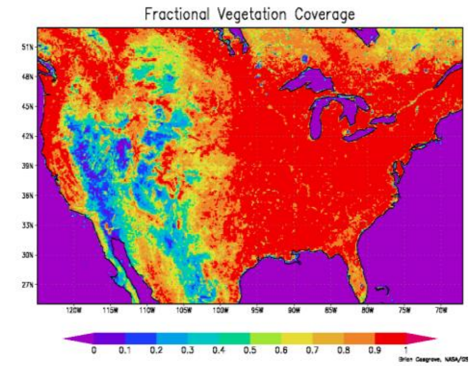


Radiation: ***Remote-Sensing:*** MODIS, GOES, AVHRR

In-Situ: DOE-ARM, Mesonets, USDA-ARS

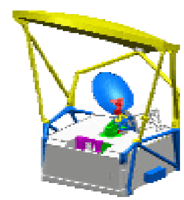
Surface Temperature: ***Remote-Sensing:*** AVHRR, MODIS, SSM/I, GOES

In-Situ: DOE-ARM, Mesonets, NWS-ASOS, USDA-ARS



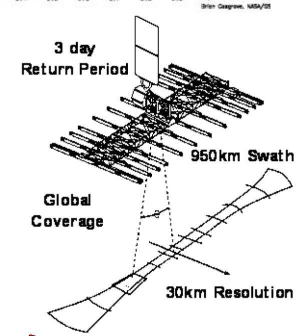
Soil Moisture: ***Remote-Sensing:*** TRMM, SSM/I, AMSR, **HYDROS**, ESTAR, NOHRSC, SMOS

In-Situ: DOE-ARM, Mesonets, Global Soil Moisture Data Bank, USDA-ARS



Groundwater: ***Remote-Sensing:*** GRACE

In-Situ: Well Observations



Snow Cover, Depth & Water: ***Remote-Sensing:*** AVHRR, MODIS, SSM/I, AMSR, GOES, NWCC, NOHRSC

In-Situ: SNOTEL

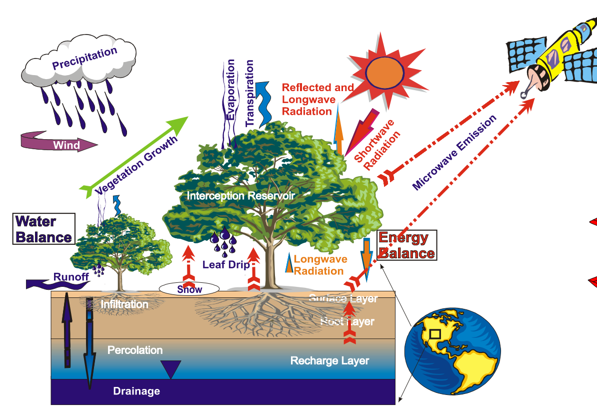
Streamflow: ***Remote-Sensing:*** Laser/Radar Altimiter

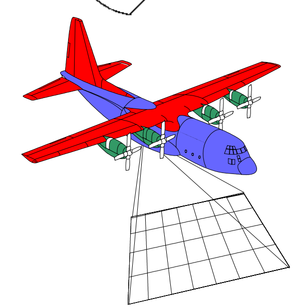
In-Situ: Real-Time USGS, USDA-ARS

Vegetation: ***Remote-Sensing:*** AVHRR, TM, VCL, MODIS, GOES

In-Situ: Field Experiments

Others: Soils, Latent & Sensible heat fluxes, etc.





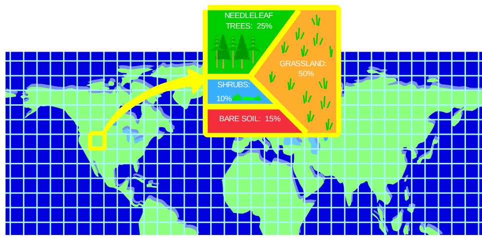
Background: Land Surface Modeling

Land Surface Prediction: Accurate land model prediction is essential to enable data assimilation methods to propagate or extend scarce observations in time and space. Based on ***water and energy balance***.

Input - Output = Storage Change

P + Gin –(Q + ET + Gout) = ΔS

Rn - G = Le + H

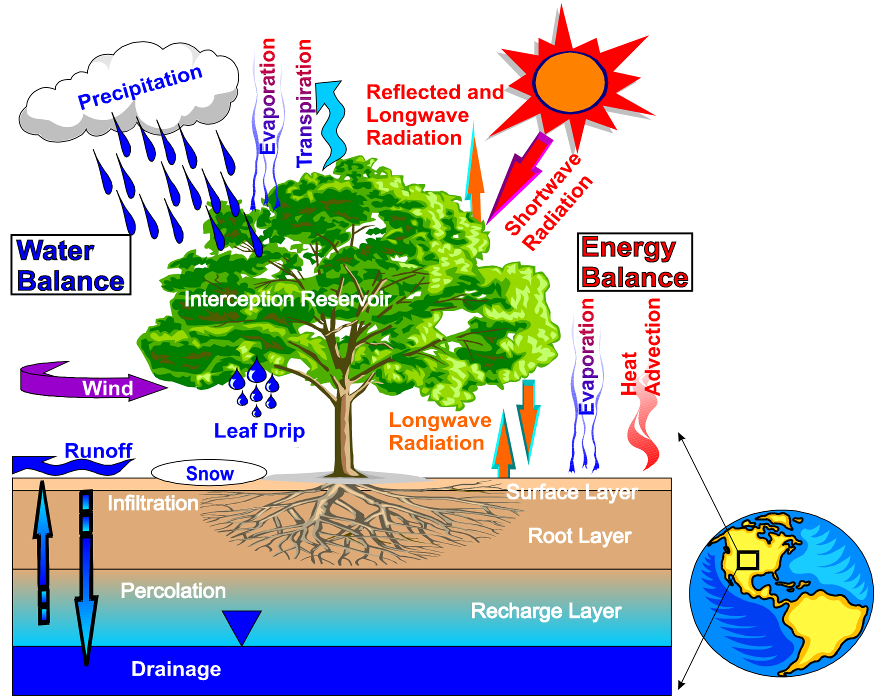


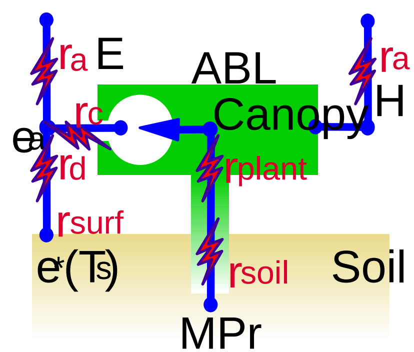
Mosaic (Koster, 1996):
- Based on simple SiB physics.
- Subgrid scale "mosaic"

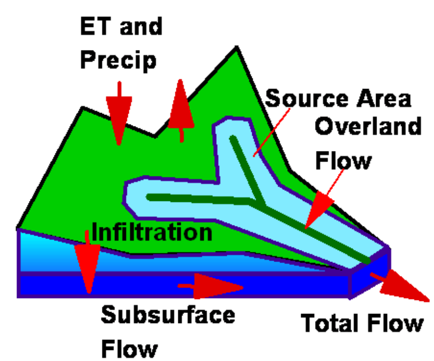
CLM (Community Land Model, ~2001):
- Community developed “open-source” model.
- 10 soil layers, 5 layer snow scheme.

Catchment Model (Koster et al., 2000):
- Models in catchment space rather than on grids.
- Uses Topmodel concepts to model groundwater

NOAA-NCEP-NOAH Model (NCEP, ~2001):
- Operational Land Surface model.





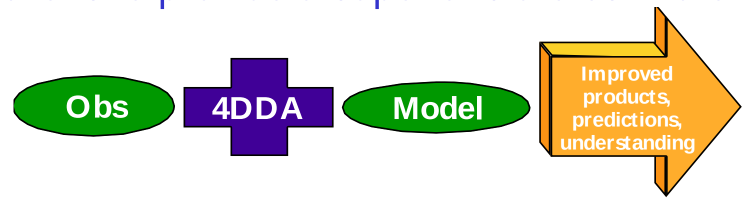


Also: vic, bucket, SiB, etc.

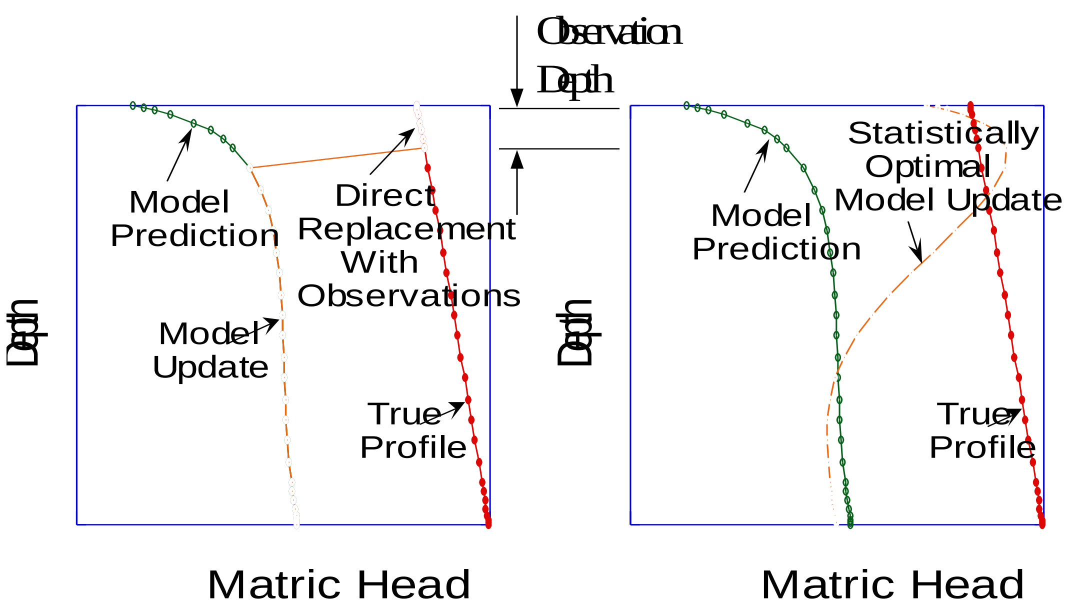
Background: Data Assimilation

Data Assimilation merges observations & model predictions to provide a superior state estimate.

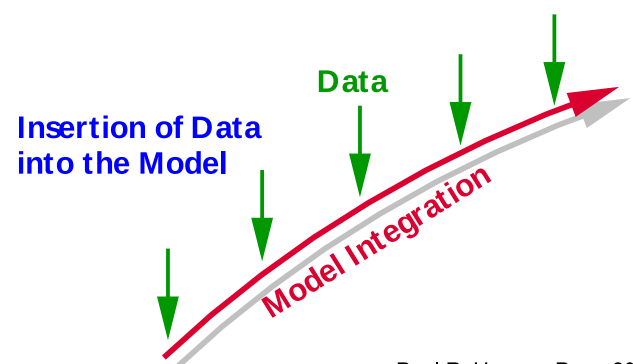
$$\partial x / \partial t = dynamics + physics + \Delta x$$



Remotely-sensed hydrologic **state** or storage observations (***temperature, snow, soil moisture***) are integrated with a land surface model prediction.



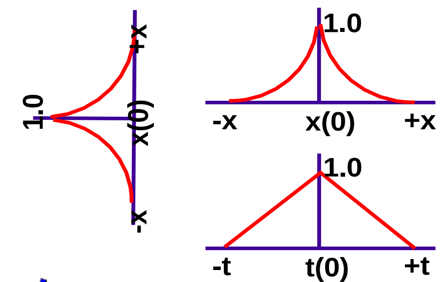
- Errors in land model prediction result from:
  - Initialization error.
  - Errors in atmospheric forcing data.
  - Errors in LSM physics (model not perfect).
  - Errors in representation (sub-grid processes).
  - Errors in parameters (soil and vegetation).



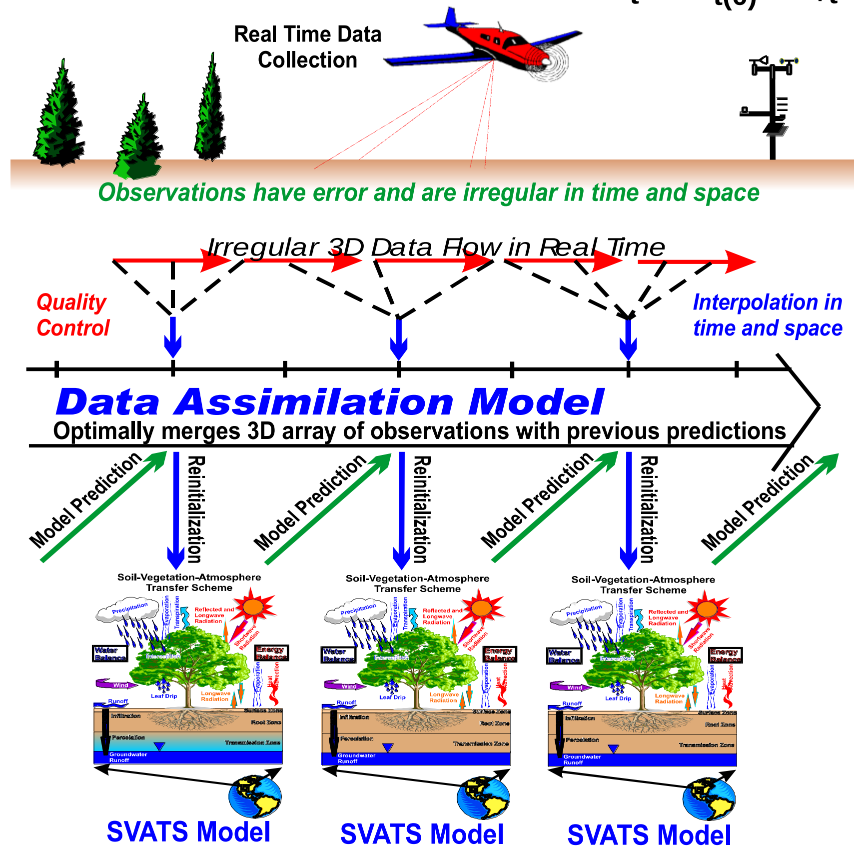
Background: Data Assimilation

Data Assimilation Methods: Numerical tools to combine disparate information.

$$A = B + \sum_{k=1}^{K} W_{ik}[O_k - B_k]$$



1. **Direct Insertion, Updating, or Dynamic Initialization:**
2. **Newtonian Nudging:**
3. **Optimal or Statistical Interpolation:**
4. **Kalman Filtering: EKF & EnKF**
5. **Variational Approaches - Adjoint:**

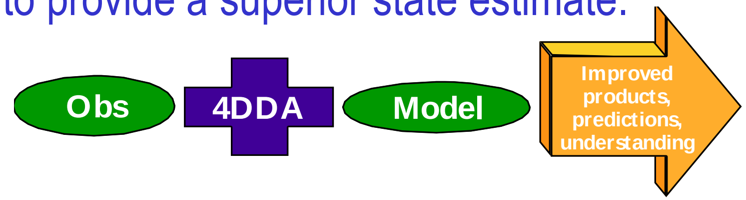


GOAL: Understand algorithm differences to use the most appropriate method for the problem to be addressed

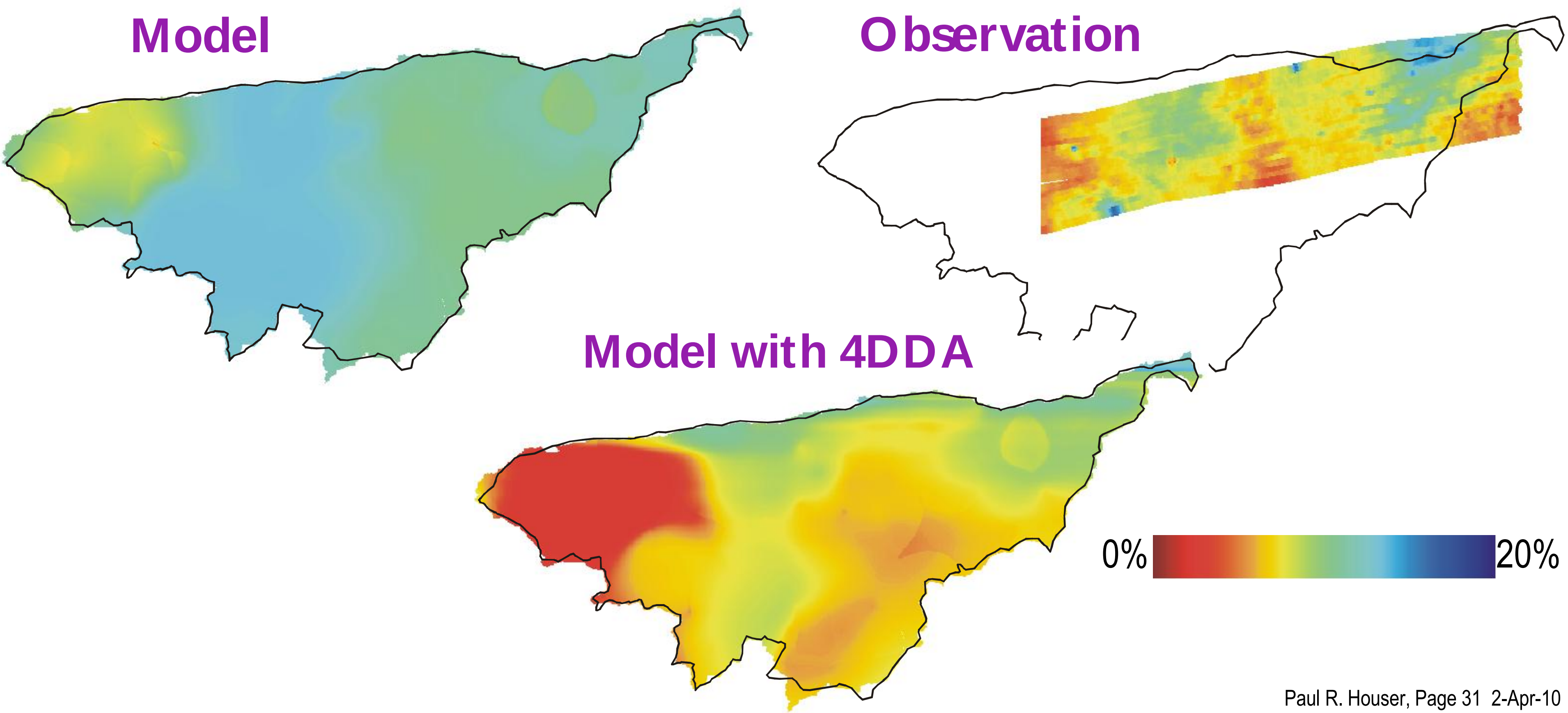
Land Data Assimilation

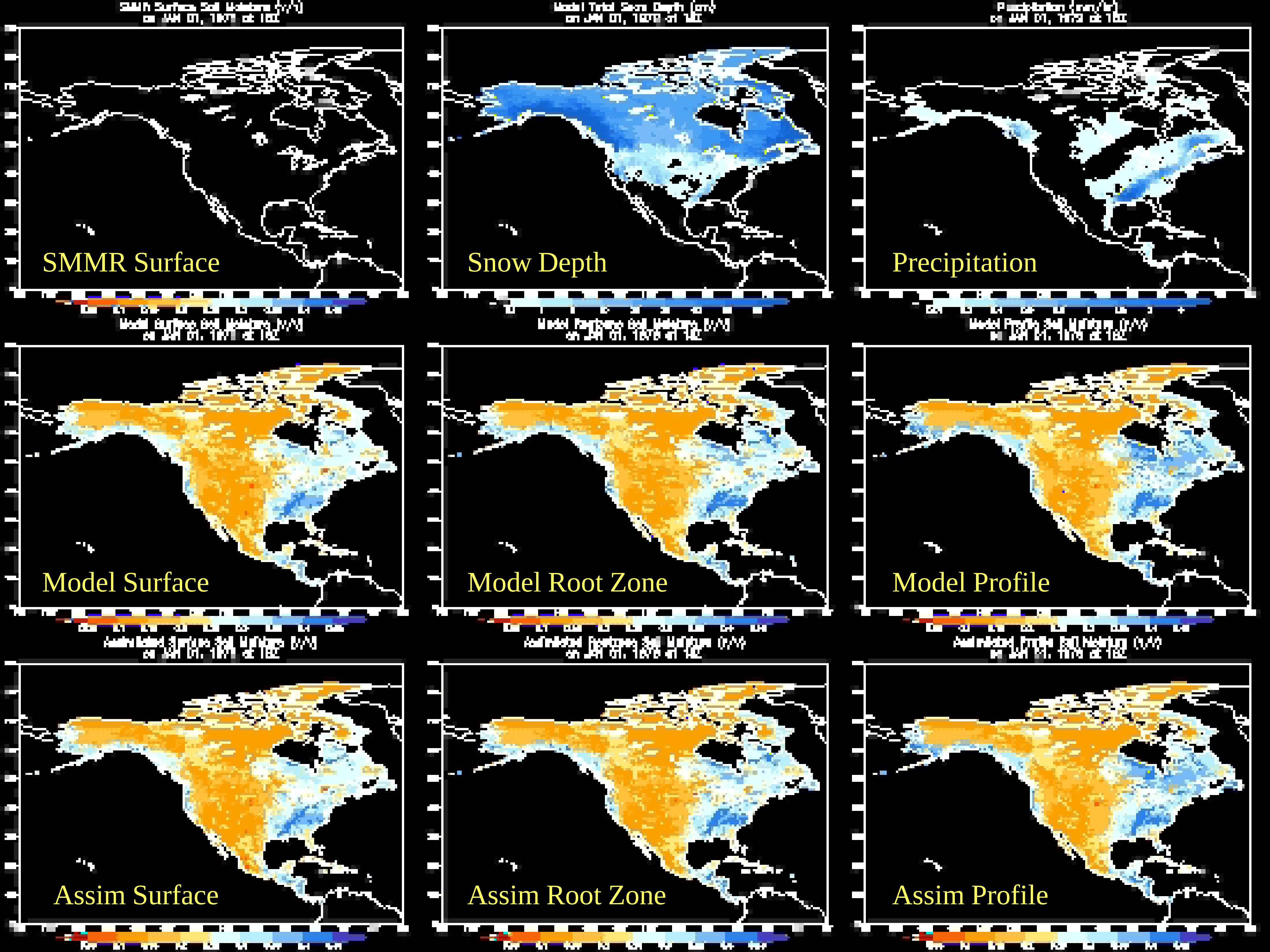
Data Assimilation merges observations & model predictions to provide a superior state estimate.

$$\partial x / \partial t = dynamics + physics + \Delta x$$

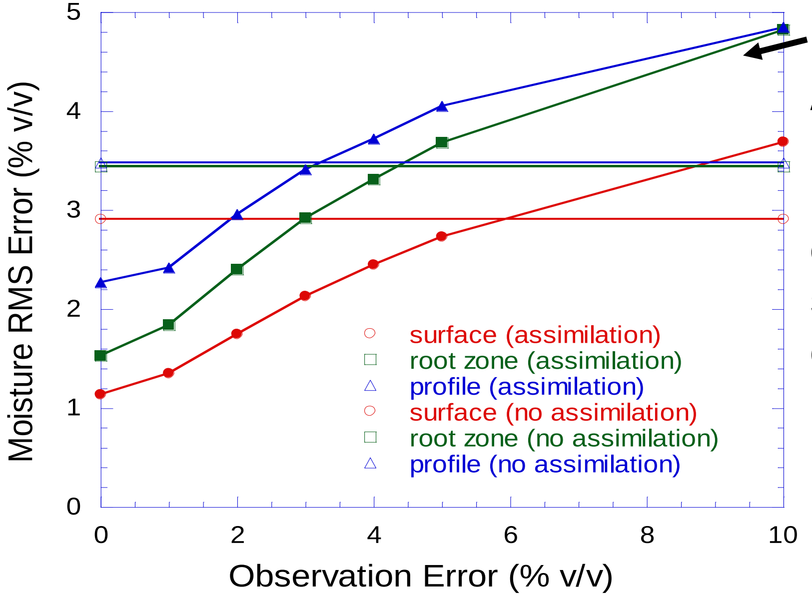


Remotely-sensed hydrologic **state** or storage observations (**temperature, snow, soil moisture**) are integrated into a hydrologic model to improve prediction, produce research-quality data sets, and to enhance understanding of complex hydrologic phenomenon.

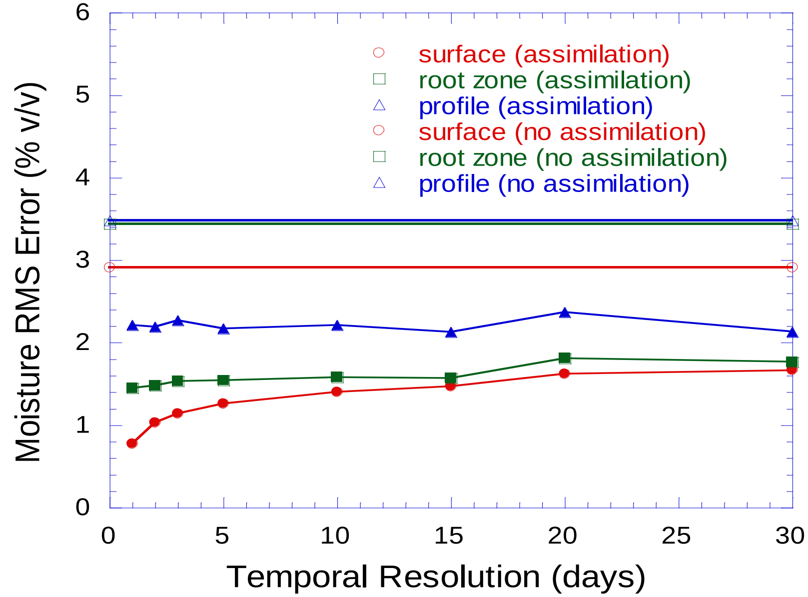


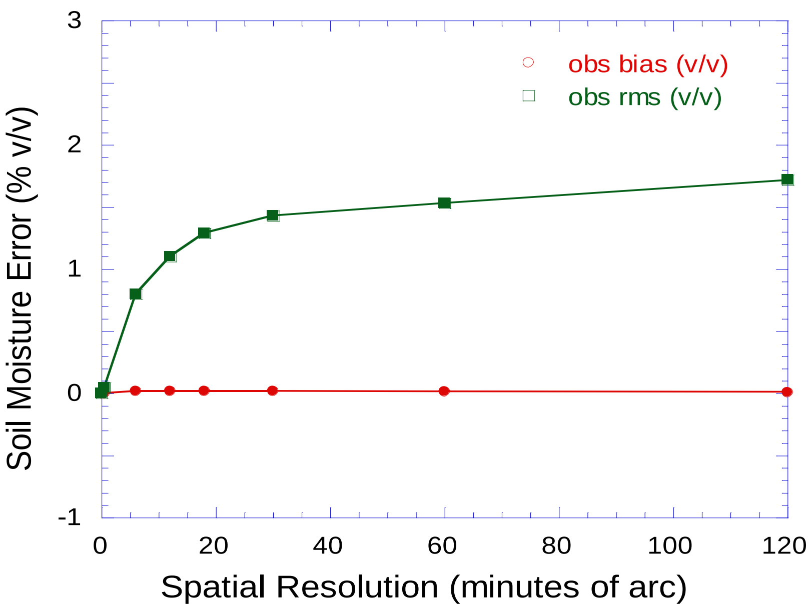

SMMR Surface
Snow Depth
Precipitation
Model Surface
Model Root Zone
Model Profile
Assim Surface
Assim Root Zone
Assim Profile

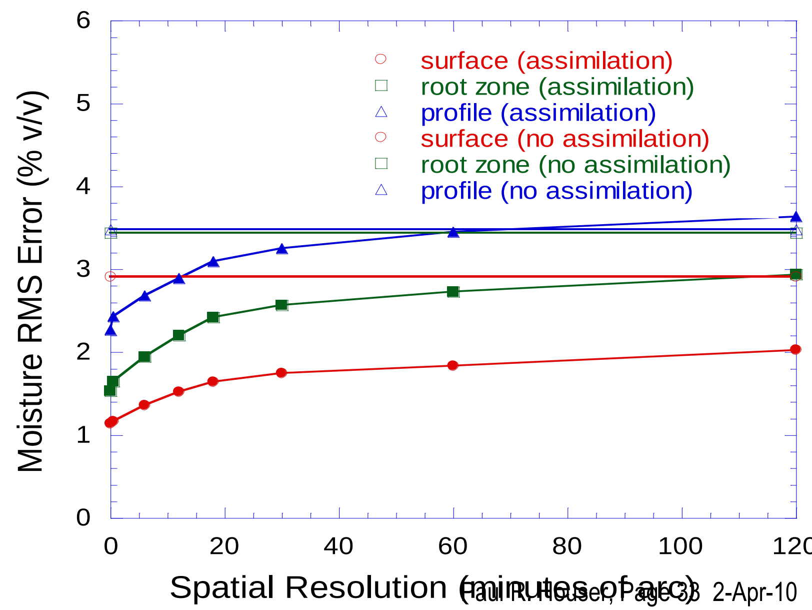
Soil Moisture Observation Error and Resolution Sensitivity:



NOTE:
Assimilation of near-surface soil moisture can degrade profile soil moisture if errors are not known perfectly

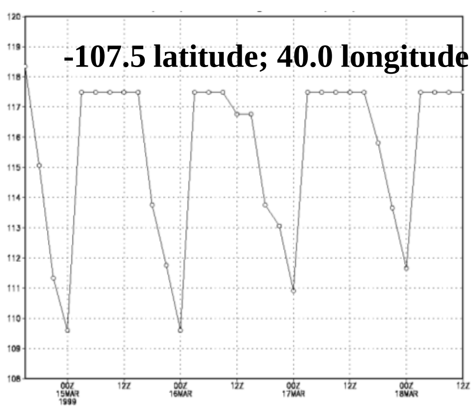






Snow Assimilation:

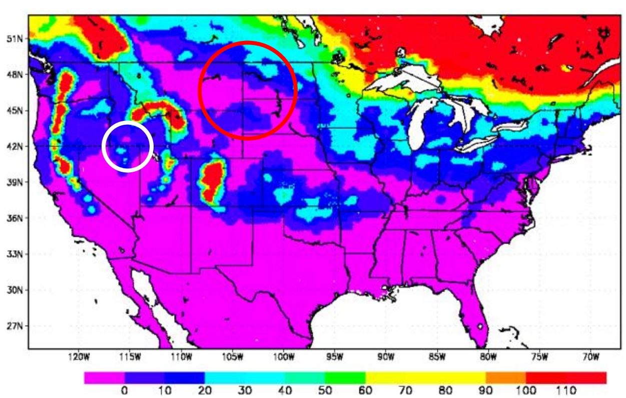
- In the northern hemisphere the snow cover ranges from 7% to 40% during the annual cycle.
- The high albedo, low thermal conductivity and large spatial/temporal variability impact energy/water budgets.
- Sno/bare soil interfaces cause wind circulations.
- Direct replacement does not account for model bias.



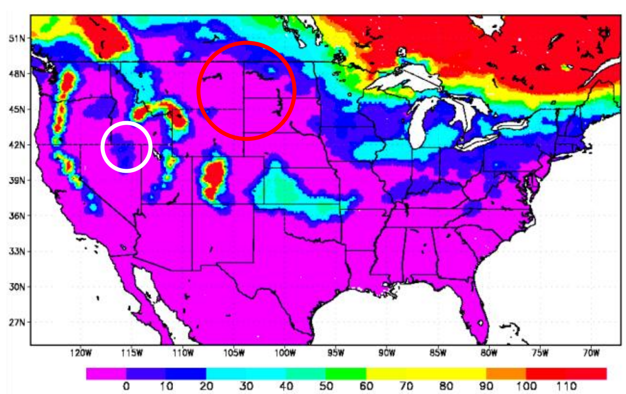
Update Time

Melt

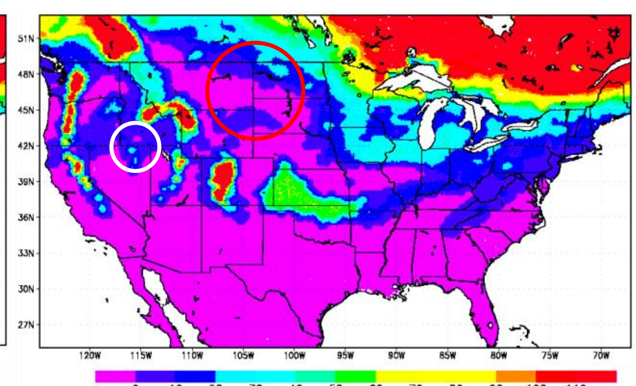
3Z 3/15/99



0Z 3/16/99



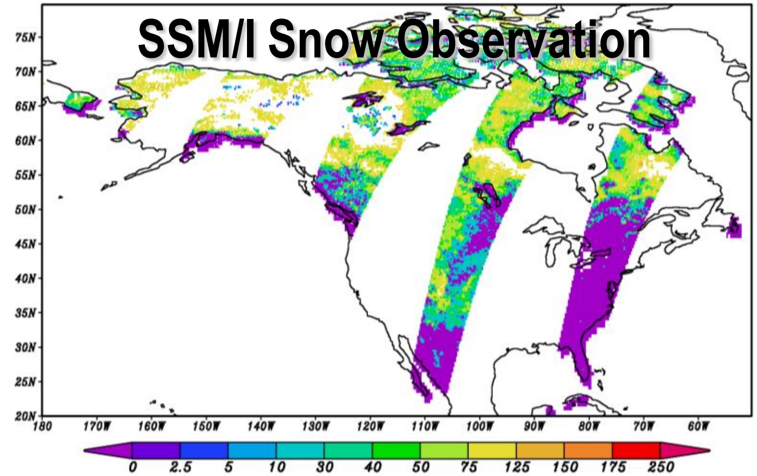
3Z 3/16/99



Snow Data Assimilation

Develop a Kalman filter snow assimilation to overcome current limitations with assimilation of snow water equivalent, snow depth, and snow cover.

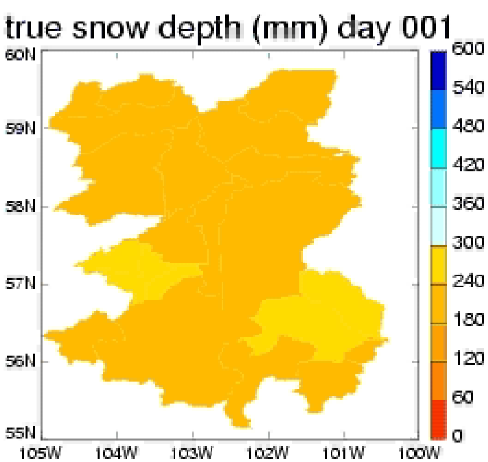
- Investigate novel snow observation products such as snow melt signature and fractional snow cover.
- Provide a basis for global implementation.



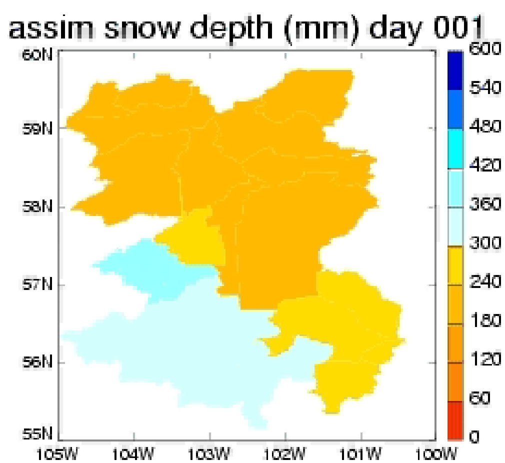
Unique Snow Data Assimilation Considerations:

- “Dissappearing” layers and states
- Arbitrary redistribution of mass between layers
- Lack of information in SWE about snow density or depth
- Lack of information in snow cover about snow mass & depth
- Biased forcing causing divergence between analysis steps

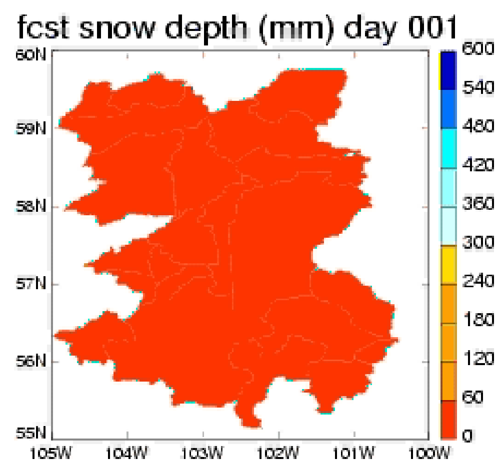
Truth run

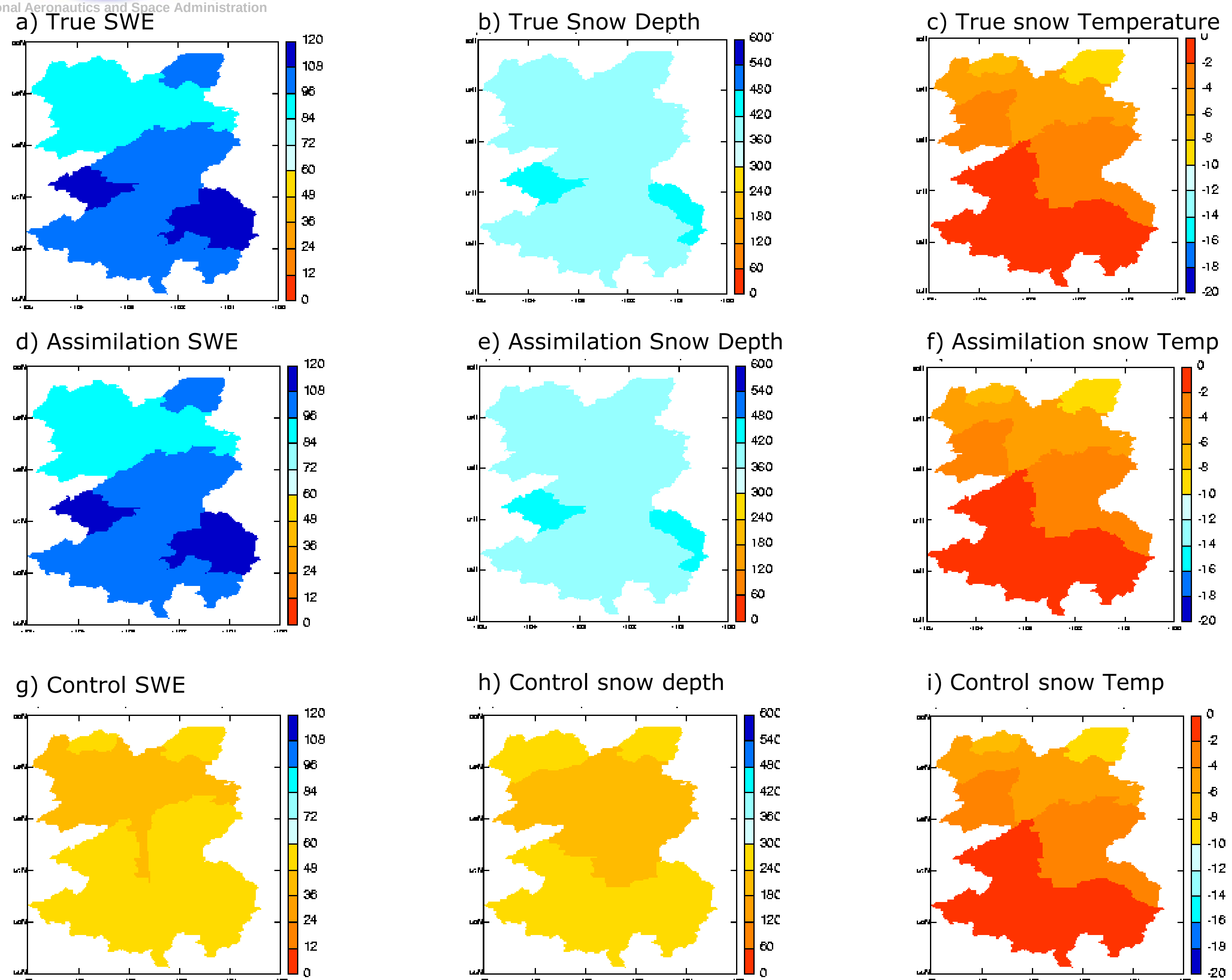


Assimilation run



Control run

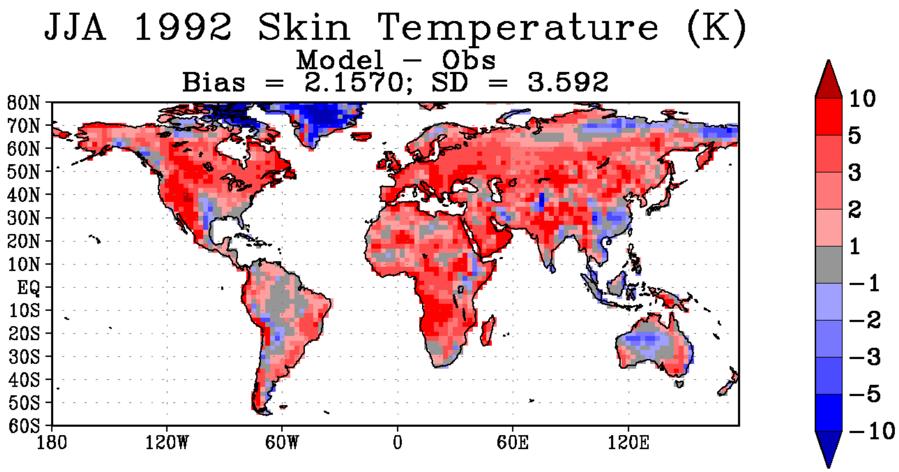


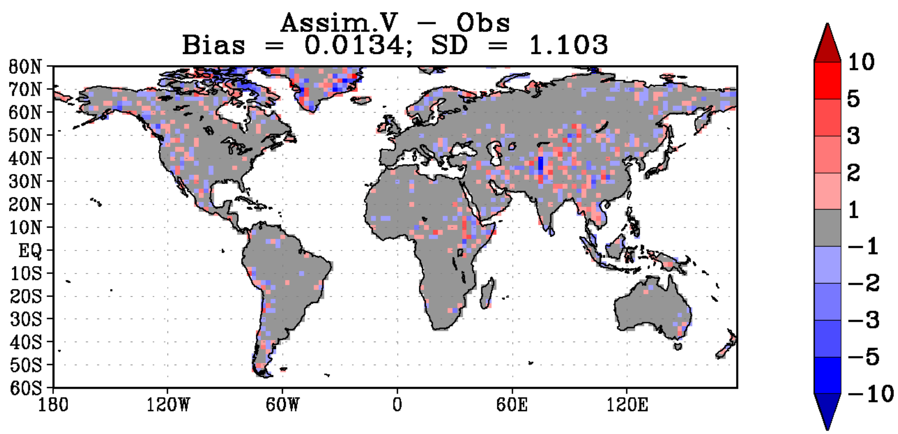


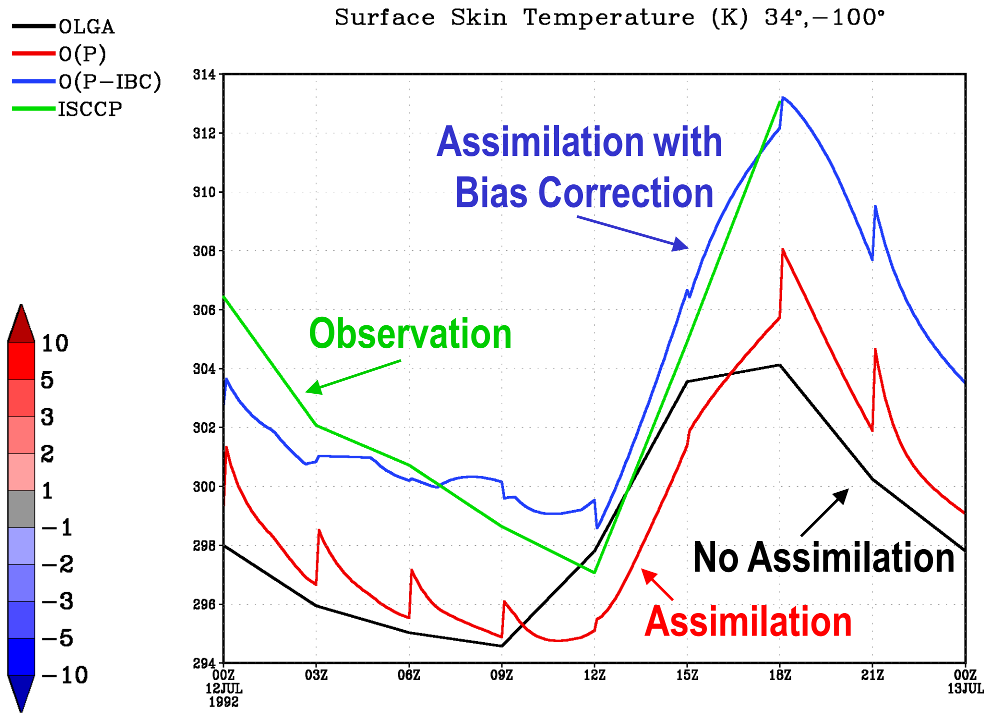
Snapshots on 3/16/1987 from truth, assimilation and control runs. The assimilation and control runs start from the same poor initial condition on 1/1/1987. Here, a), d), g) Snow water equivalent (SWE, in mm); b), e) h) snow depth (in mm), and c), f), i) snow temperature (in C). There results are plotted over 24 continuous catchments.

Surface skin temperature data assimilation

DAO-PSAS **Assimilation** of **ISCCP (IR based) Surface Skin Temperature** into a global 2 degree uncoupled land model.



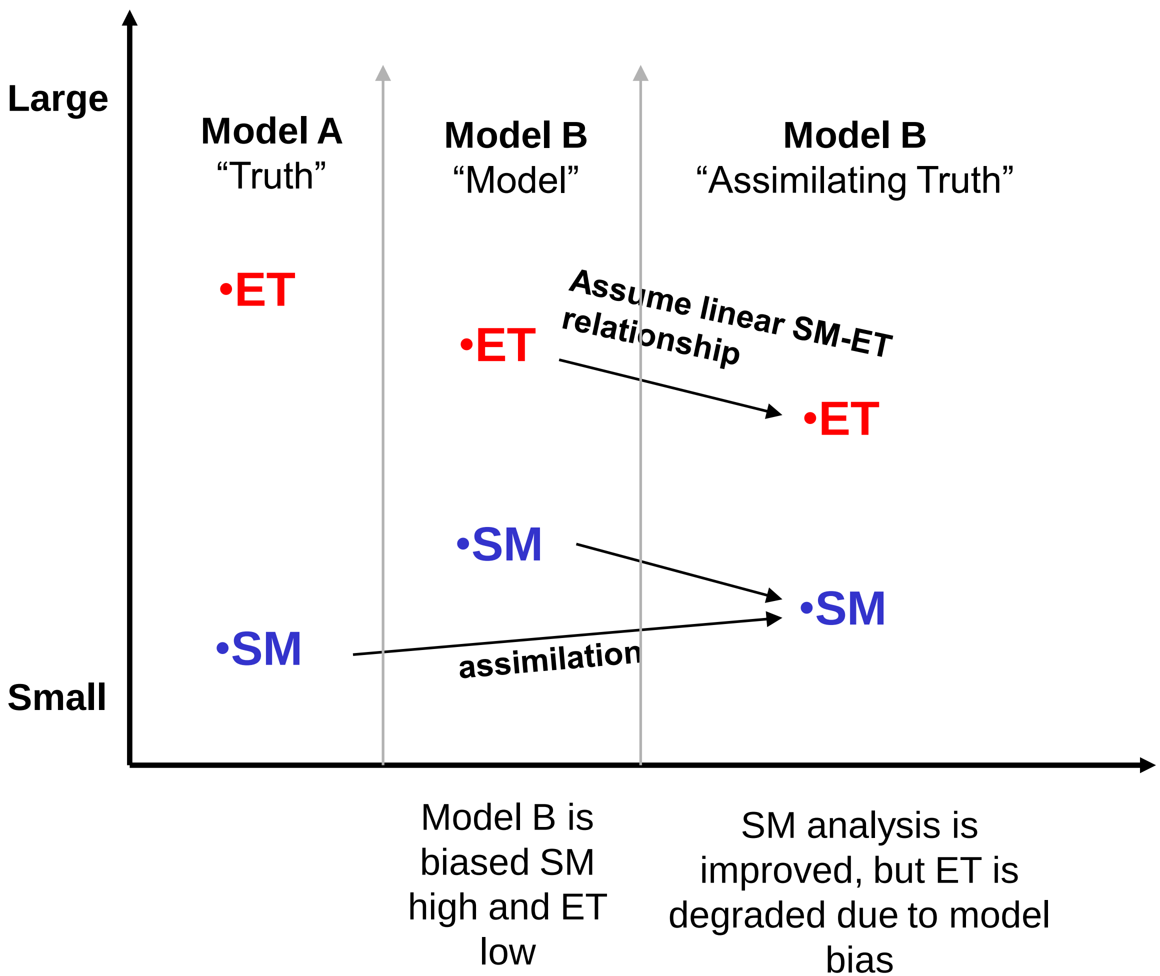




Surface temperature has **very little memory** or inertia, so without a continuous correction, it tends drift toward the control case very quickly.

Fraternal Twin Studies

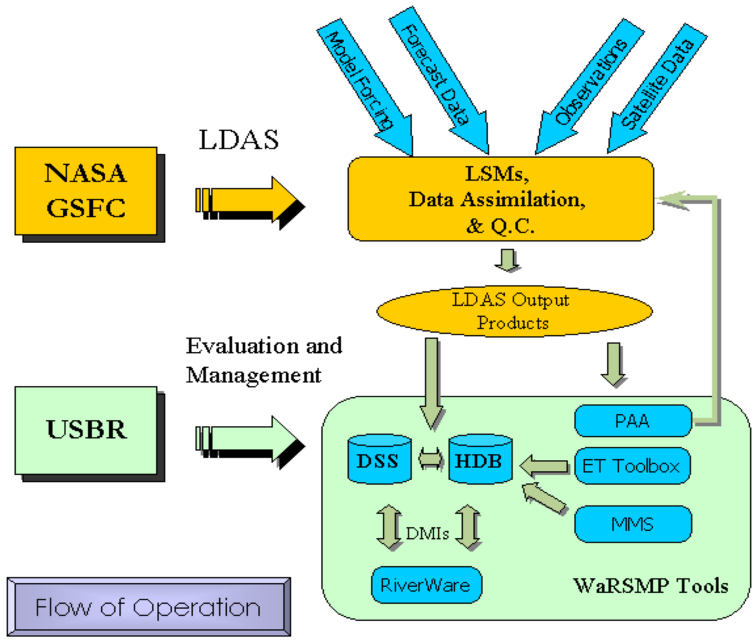
- "Truth" from one model is assimilated into a second model with a biased parameterization
- The "truth" twin can be treated as a perfect observation to help illustrate conceptual problems beyond the assimilation procedure.



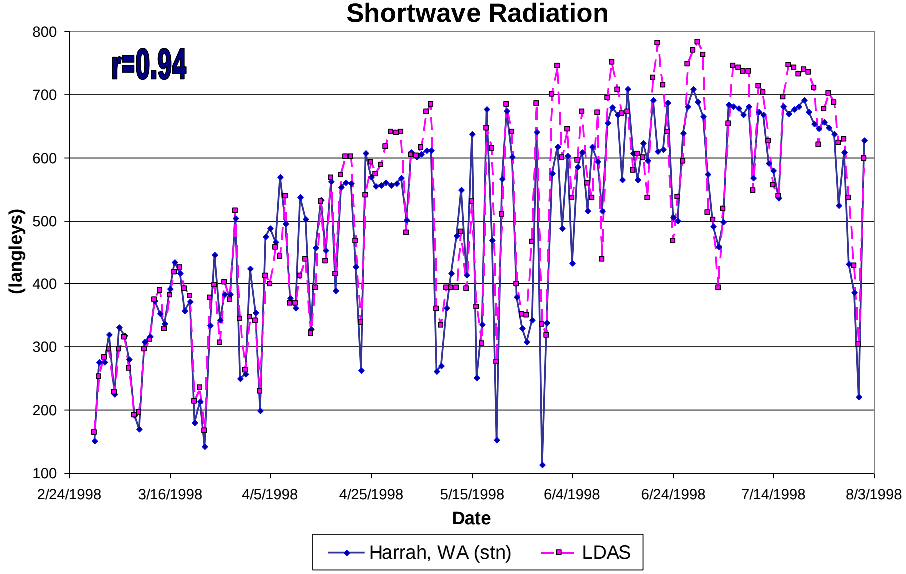
We must not only worry about obtaining an optimal model constraint, but also understand the implications of that constraint.

Water Resource Applications

- Collaborating with other agencies, e.g., the U.S. Bureau of Reclamation, to integrate the use of LDAS products in water resource management issues
- Developing retrospective studies and working to maintain land surface model simulations in both near real-time and forecast settings to be used by water resourc managers and policy/decision makers



Harrah, WA. Station Compared to LDAS: 1998 Downward Shortwave Radiation

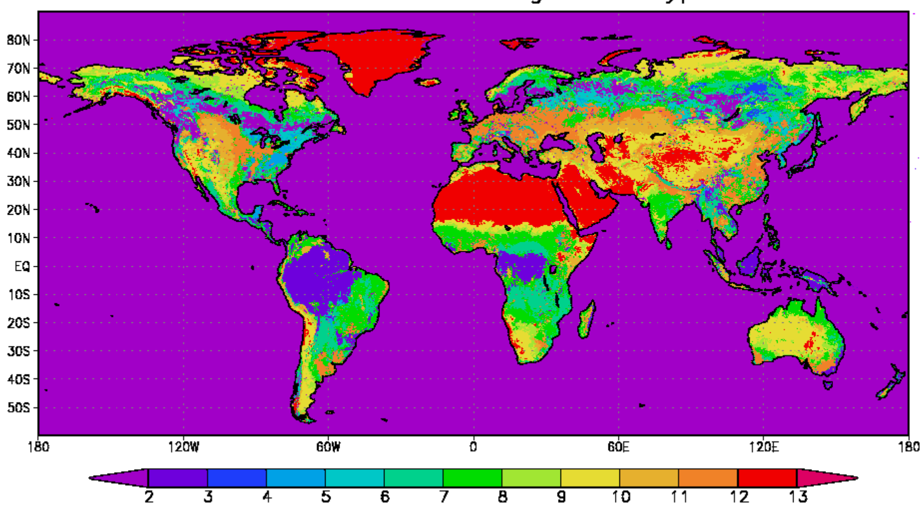


- Evaluation of NLDAS in on-going case investigations to monitor and forecast extreme flooding and drought events
- Produce successful demonstration of these applications-based studies and begin applying to other countries facing water resource-related issues

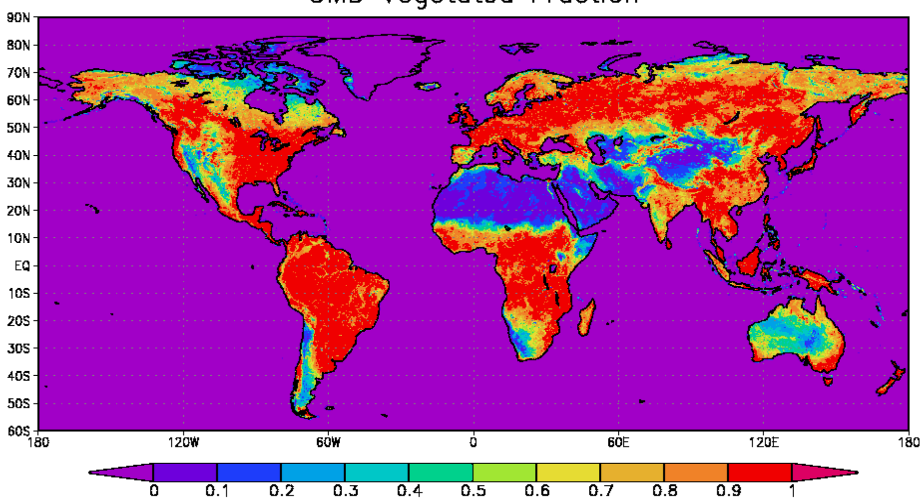
Paul R. Houser, NASA/GSFC Hydrological Sciences
Paul.Houser@gsfc.nasa.gov

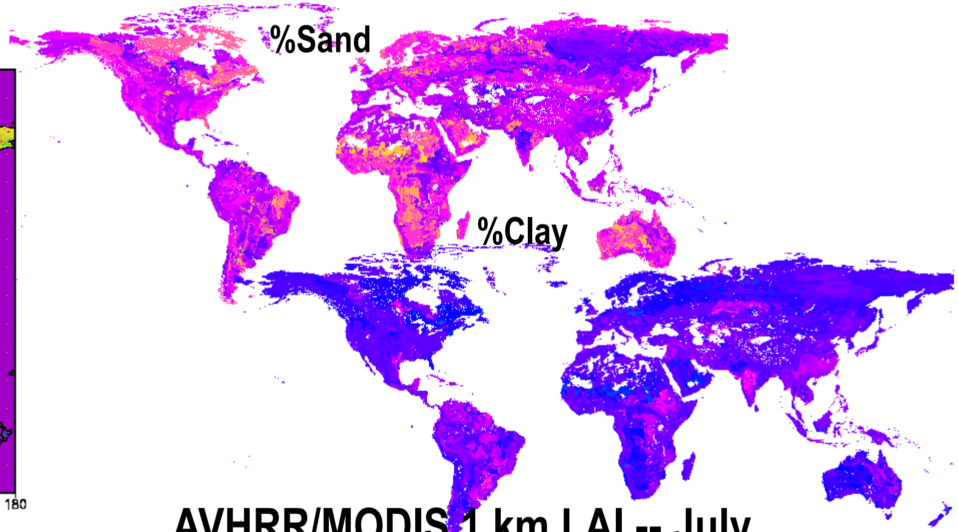
Global Land Data Assimilation System

UMD Predominant Vegetation Type



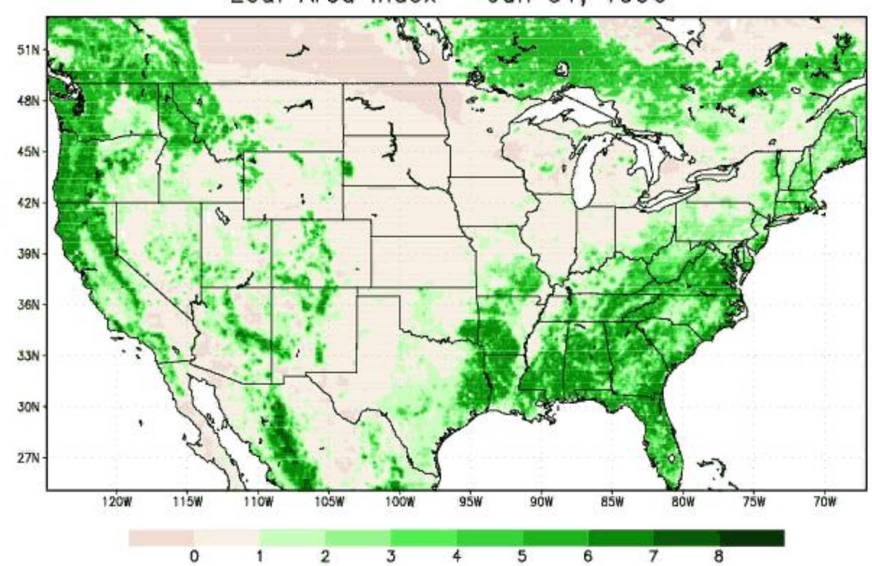
UMD Vegetated Fraction



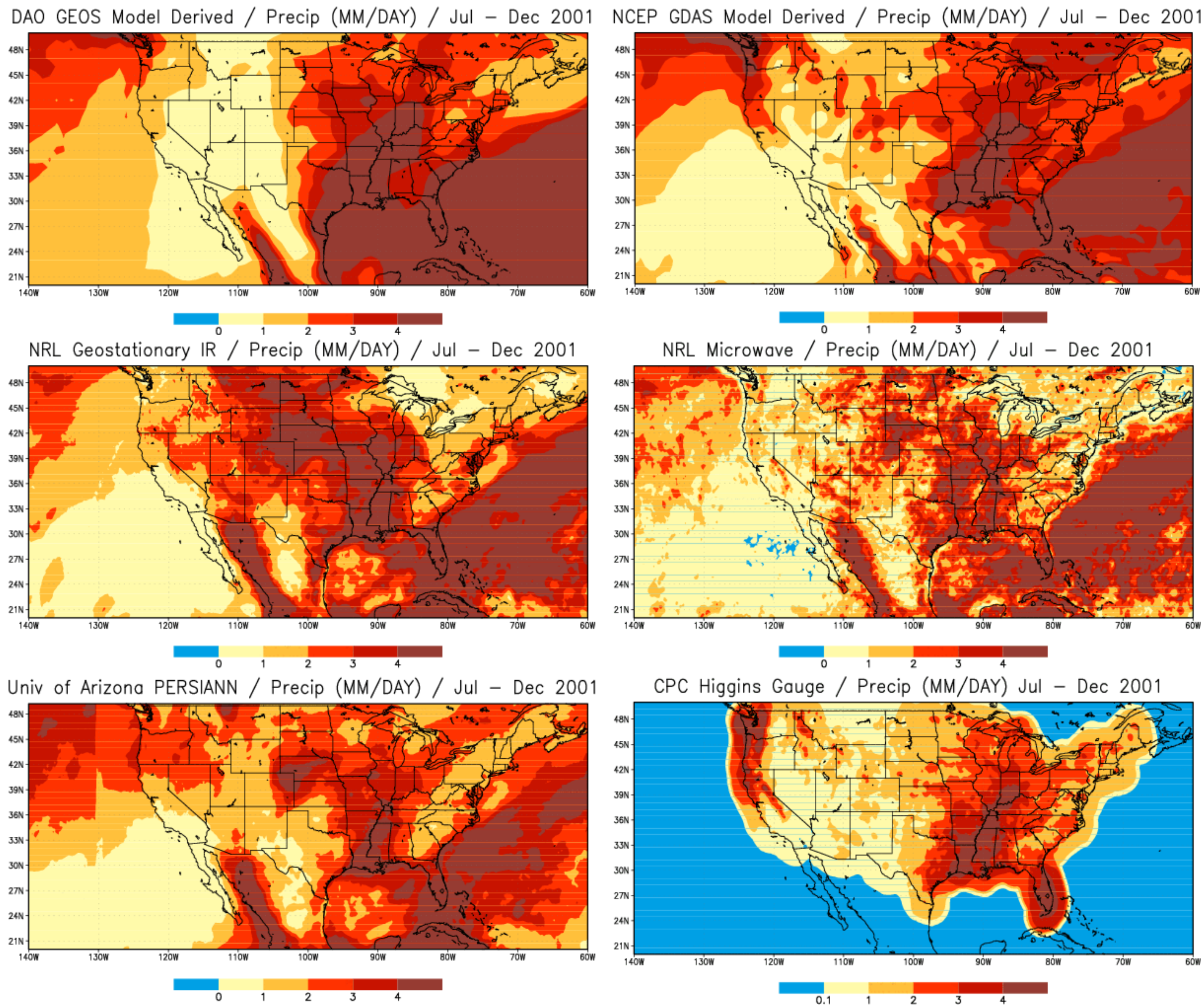


AVHRR/MODIS 1 km LAI -- July

Leaf Area Index – Jan 01, 1996

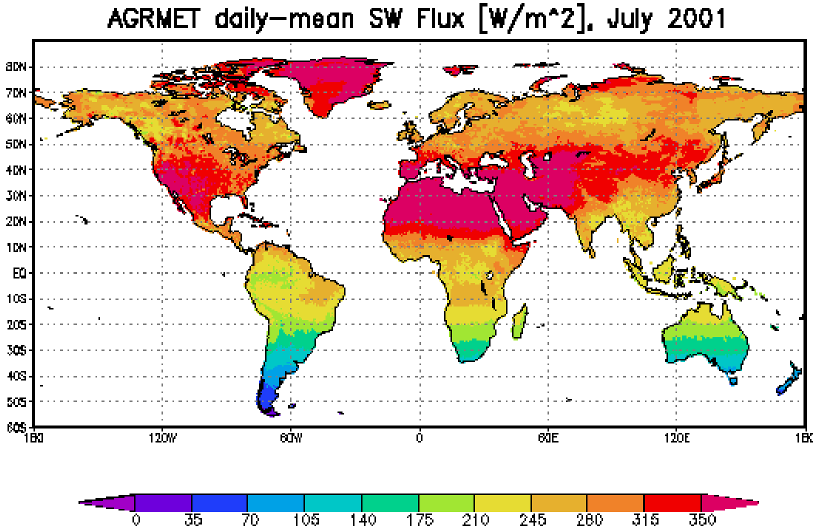


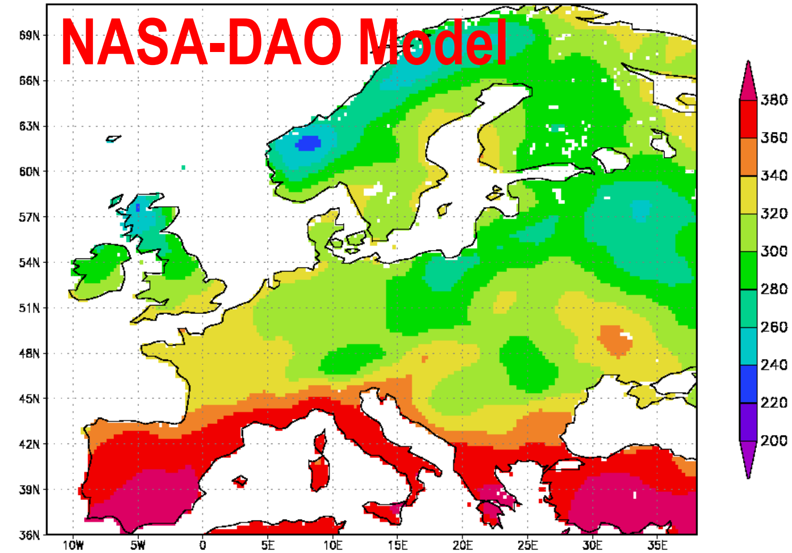
Precipitation evaluation

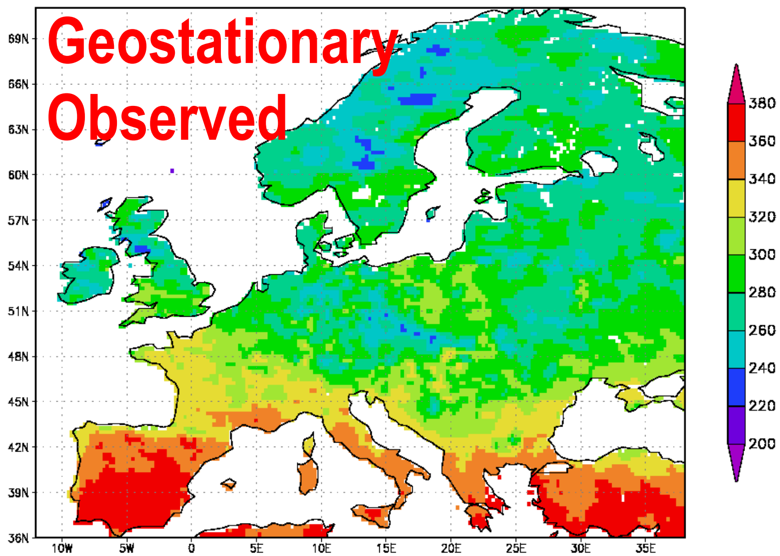


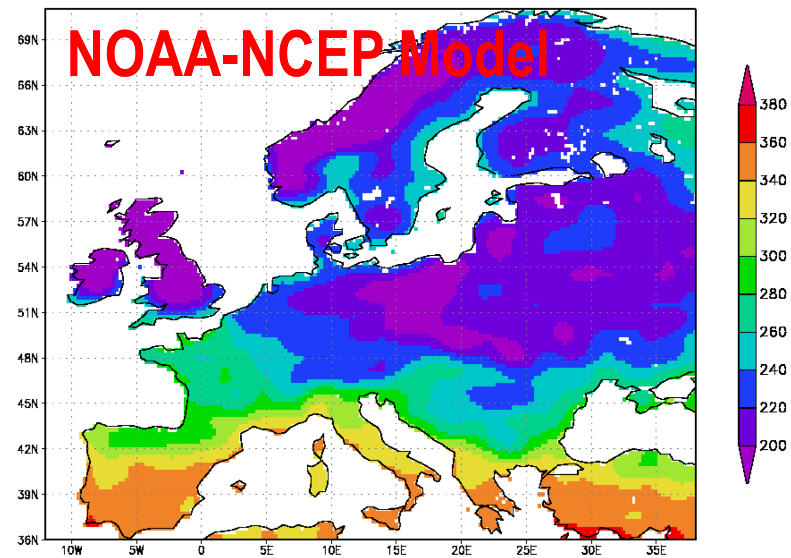
Surface SWdown flux evaluation; June 2001

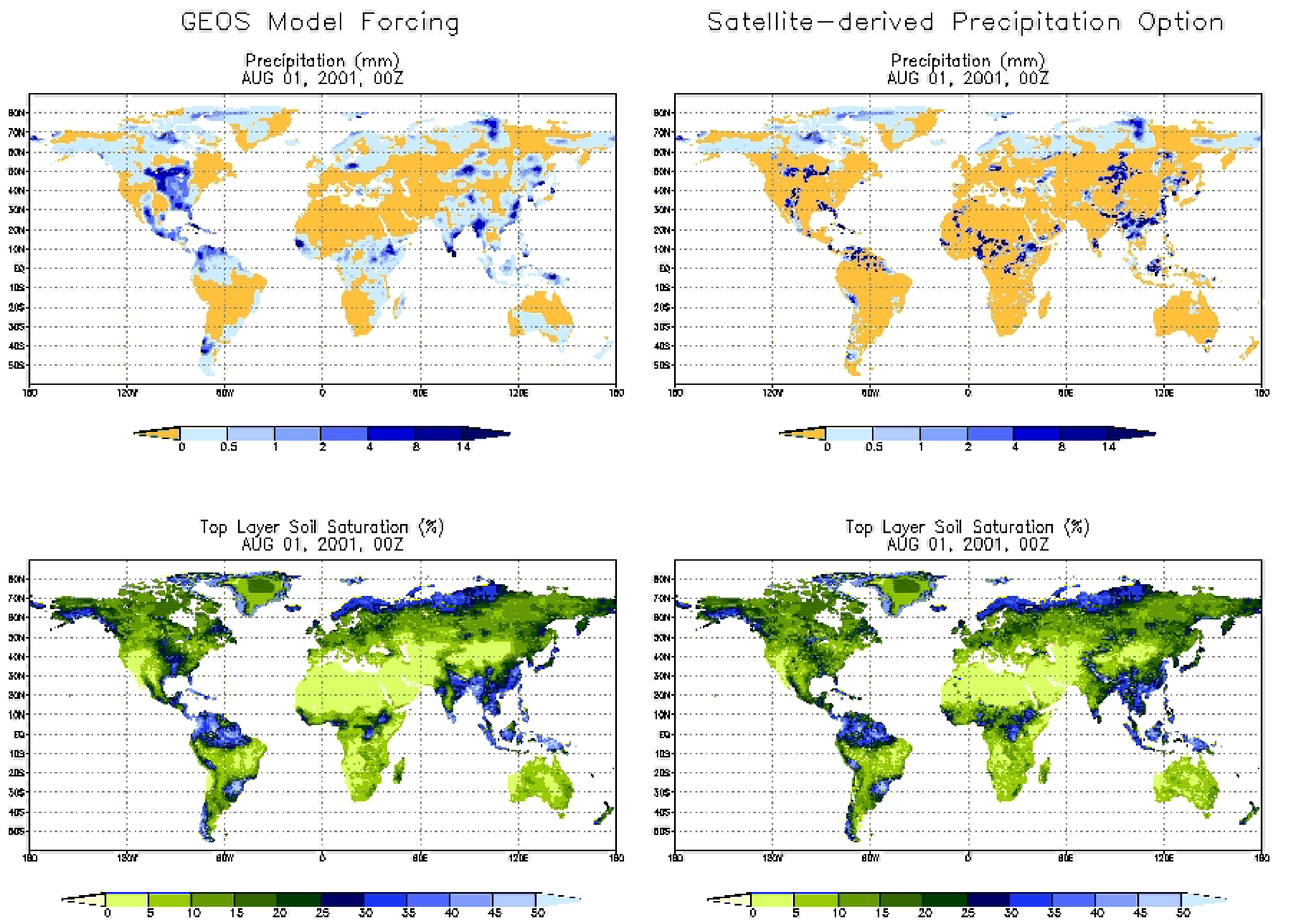
Geostationary Observed



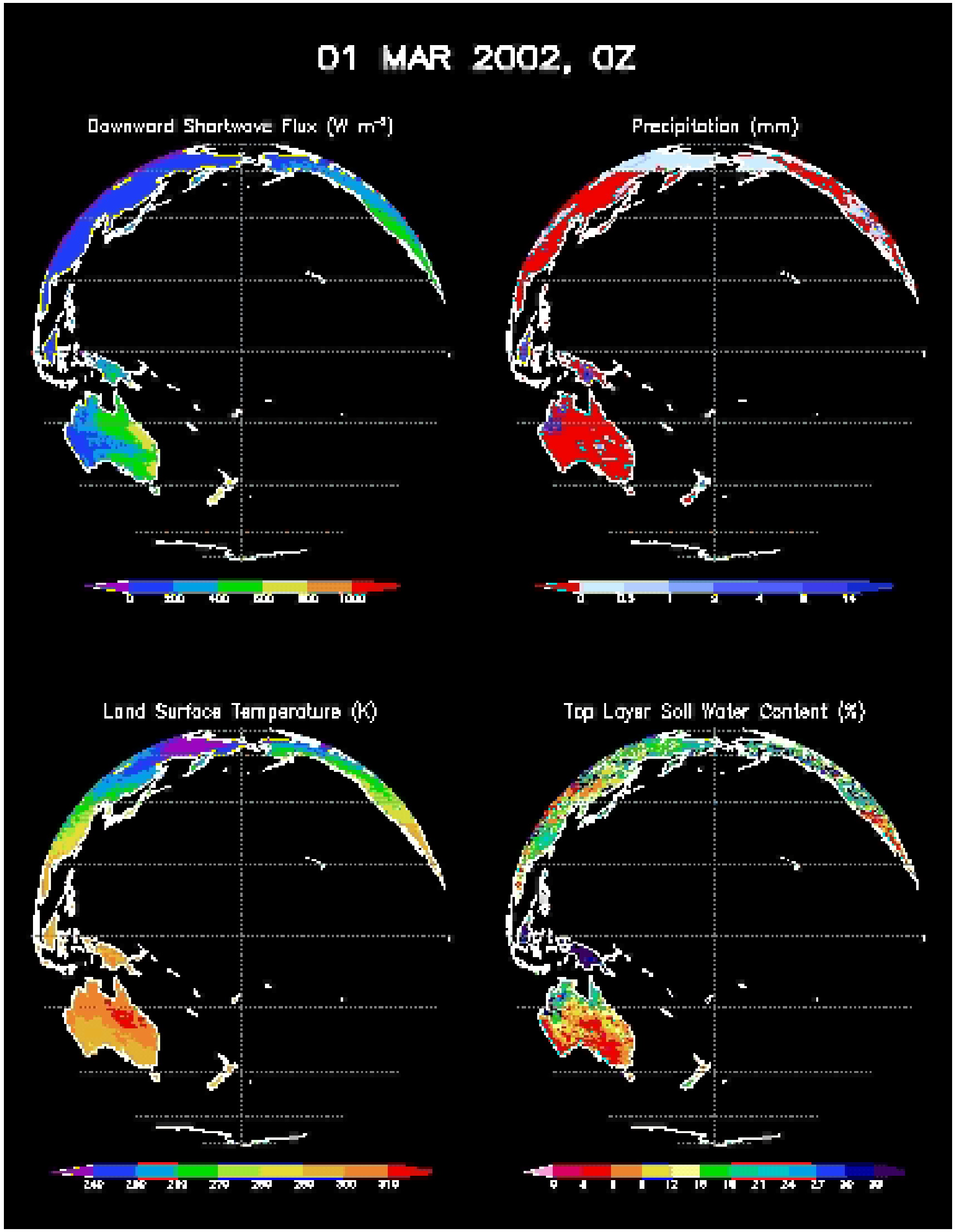







GEOS Model Forcing
Satellite-derived Precipitation Option
Precipitation (mm)
AUG 01, 2001, 00Z
0 0.5 1 2 4 8 14
Top Layer Soil Saturation (%)
AUG 01, 2001, 00Z
0 5 10 15 20 25 30 35 40 45 50

GLDAS Results



Geostationary observations are critical to GLDAS because of their high temporal repeat

Land Information System: *A high-performance extension of GLDAS*

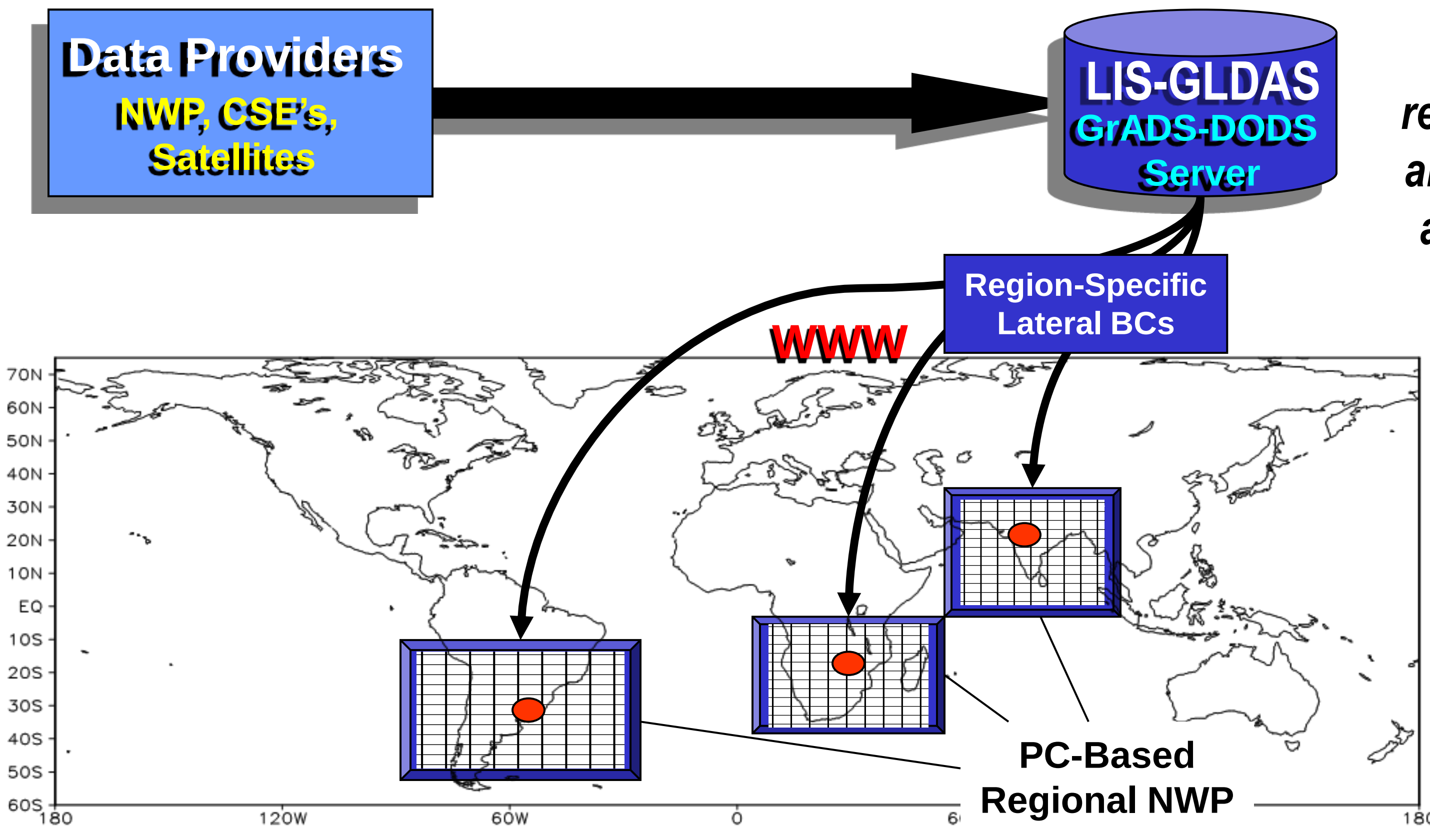
LIS components:

(1) A high-resolution (1km) Global Land Data Assimilation System running several land surface models, land surface data assimilation, and integrated database operations.

(2) A web-based user interface for data mining, modeling, and visualization.

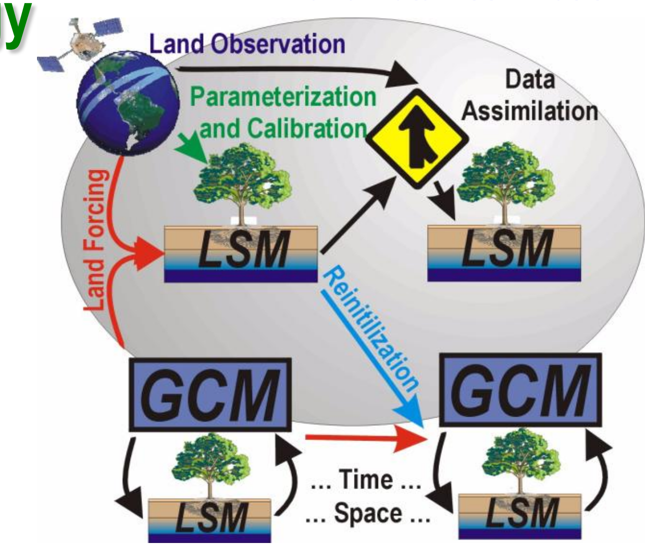
(3) A portable platform-independent, web-database system.

(4) Explicit integration to the Earth System Modeling Framework (ESMF).



Data can be remotely accessed and analyzed from a GUI, web page, or model code

GLDAS: CEOP Synergy



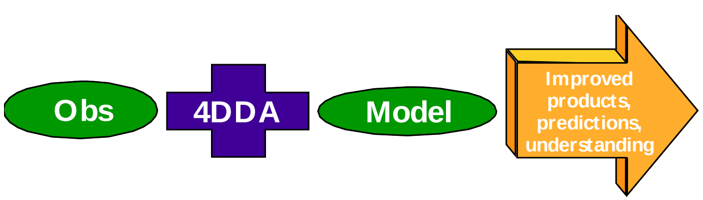
CEOP and GLDAS have value-added synergy:

- ***Test and evaluate multiple land surface hydrologic models***
- ***Long term*** land model baseline experiments and intercomparisons
- ***Linking of reference sites*** with globally consistent observation and modeling to enable GEWEX-CSE land transferability studies.
- ***Initialize land*** surface states for seasonal-to-interannual coupled ***predictions***.
- Use GLDAS to **evaluate** NWP and climate predictions for land.
- **Integrate remote sensing** land observations in land/atmospheric modeling for use in CEOP and higher level understanding.
- GLDAS may serve as a CEOP ***data integration center***.
- Data assimilation and modeling may serve as a ***quality control check*** on observations.
- 4DDA "value-added" GLDAS-CEOP datasets

"LDAS" concept:

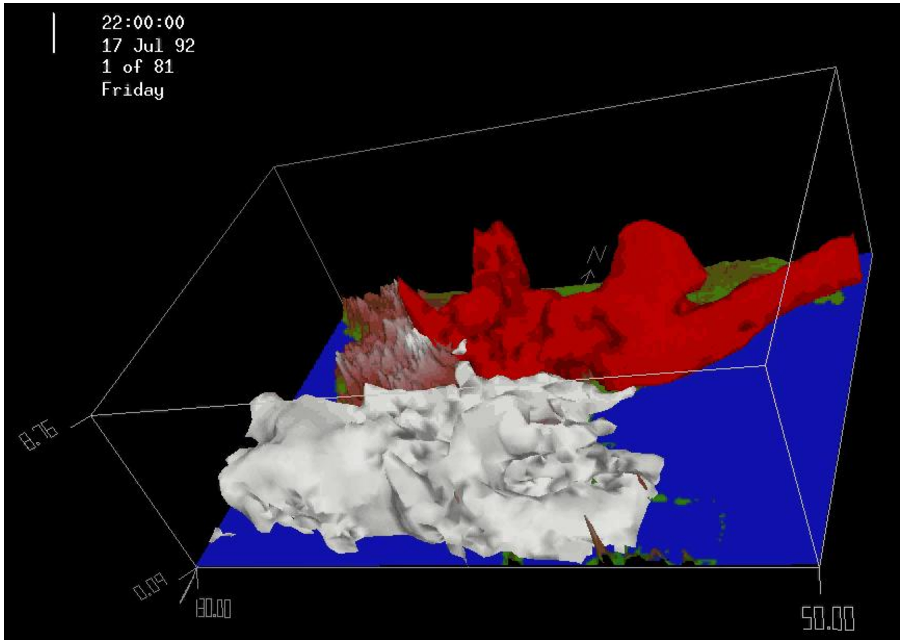
Optimal integration of observation, simulation, and assimilation tools to *operationally* obtain high quality land surface conditions and fluxes continuous in time&space; multiple scales; retrospective, realtime, forecast

GLDAS views CEOP as an opportunity for increased community involvement and coordinated validation through data set development and continuity.



Water Cycling Research: coupling LDAS results

- Objective: To better understand the water cycle by quantifying geographic sources (local and remote) of precipitating waterSoil water anomalies likely affect the local continental source of water for precipitation in the monsoon (e.g. Atlas et al. 1993)
- Controlled sensitivity experiments can be performed, using GLDAS initial conditions for the FVGCM
- Using realistic perturbations, what is the impact of wet and dry anomalies on the monsoon precipitation, and the relative sources of water



North America: Water evaporates from the Caribbean Sea moving westward (white isosurface) as the circulation changes this water is transported northward into the US. (The red isosurface shows water that has evaporated from the central US)

Bosilovich and Schubert, 2002; Bosilovich 2002

Land Data Assimilation: Selected Future Challenges

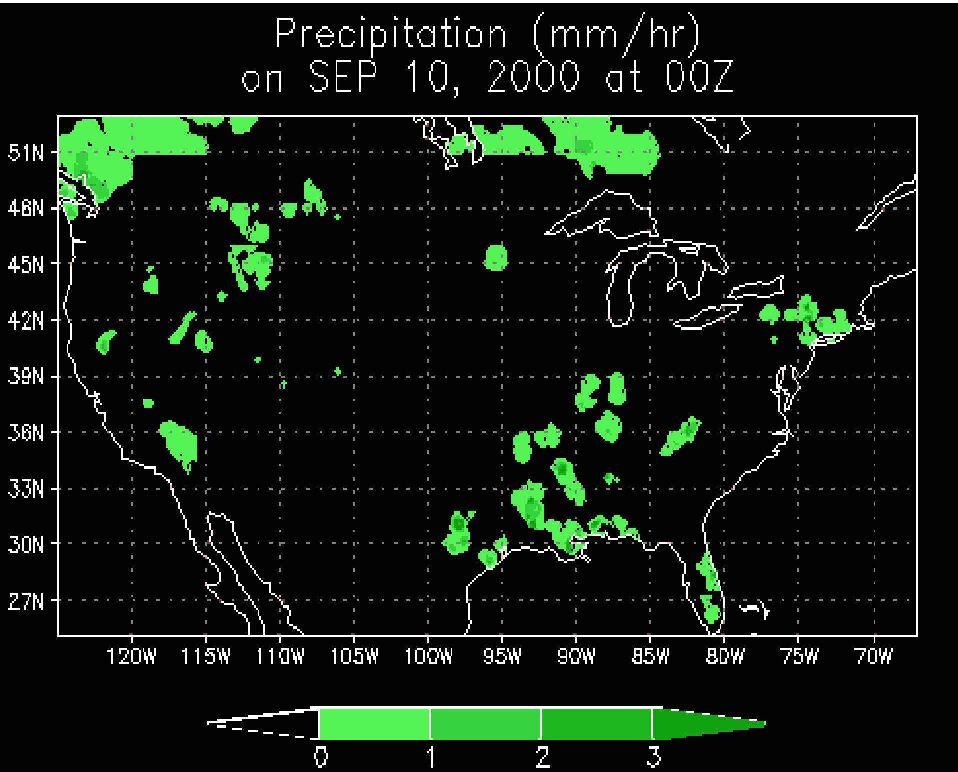
Data Assimilation Algorithm Development: *Link calibration and assimilation* in a logical and mutually beneficial way and move towards *multivariate assimilation* of data with complementary information

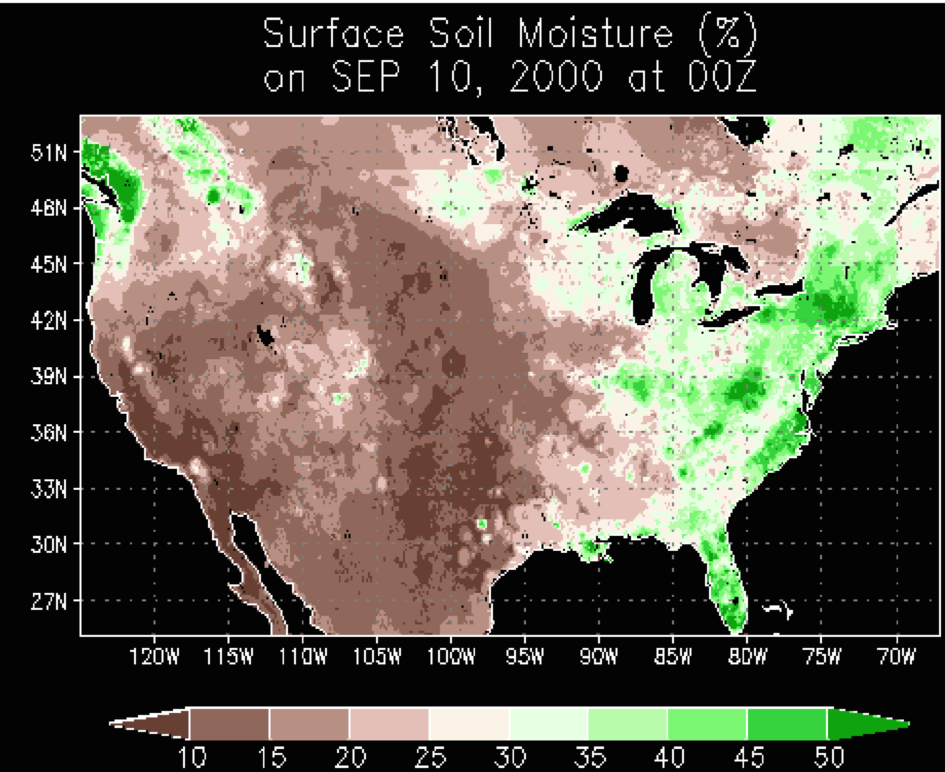
Land Observation Systems: Regular provision of *snow, soil moisture*, and *surface temperature* with knowledge of *observation errors*

Land Modeling: Better *correlation* of land model states with observations, and knowledge of *prediction errors* and Advanced processes: *River runoff/routing*, *vegetation and carbon dynamics, groundwater interaction*

Assimilate new types of data: Streamflow, vegetation dynamics, groundwater/total water storage (Gravity), evapotranspiration

Coupled feedbacks: Understand the impact of land assimilation feedbacks on coupled system predictions.





A Vision for the Water Cycle Research?

Improve Water Cycle Prediction