Data Assimilation and Modeling

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Acknowledging:
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GEORGE MASON UNIVERSITY

Water Cycle Research Making a Difference

http://crew.iges.org

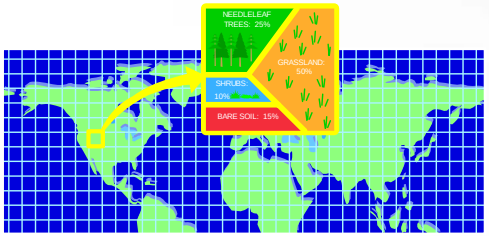
Background: Land Surface Modeling

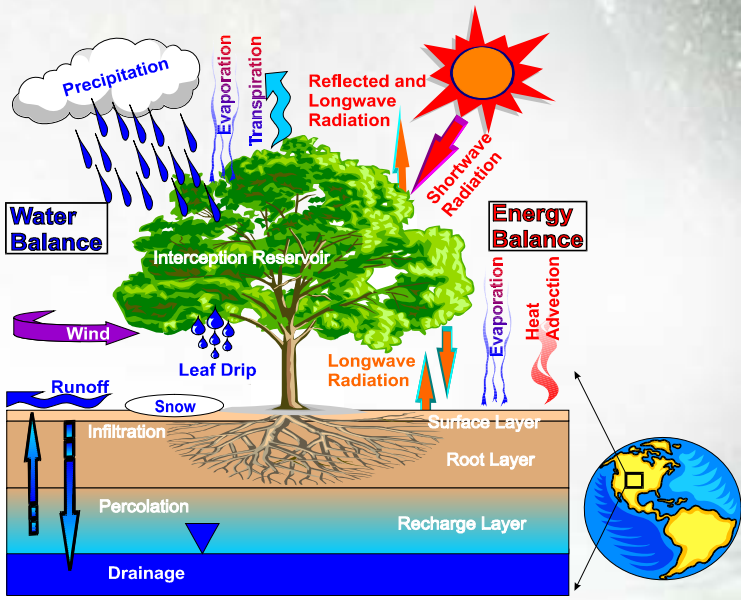
Land Surface Prediction: Accurate land model prediction is essential to enable data assimilation methods to propagate or extend scarce observations in time and space. Based on *water and energy balance*.

Input - Output = Storage Change

P + Gin –(Q + ET + Gout) = ΔS

Rn - G = Le + H



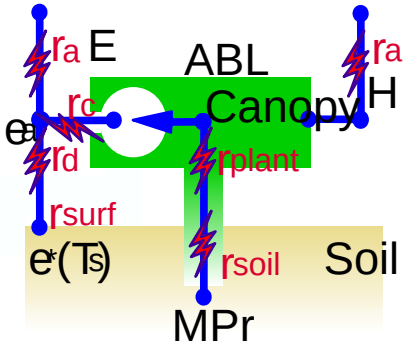


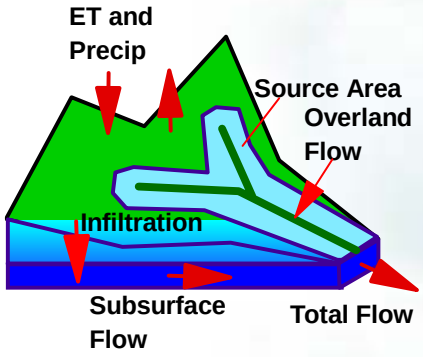
Mosaic (Koster, 1996):
- Based on simple SiB physics.
- Subgrid scale "mosaic"

CLM (Community Land Model, ~2003):
- Community developed "open-source" model.
- 10 soil layers, 5 layer snow scheme.

Catchment Model (Koster et al., 2003):
- Models in catchment space rather than on grids.
- Uses Topmodel concepts to model groundwater

NOAA-NCEP-Noah Model (NCEP, ~2004):
- Operational Land Surface model.





Also: vic, bucket, SiB, etc.

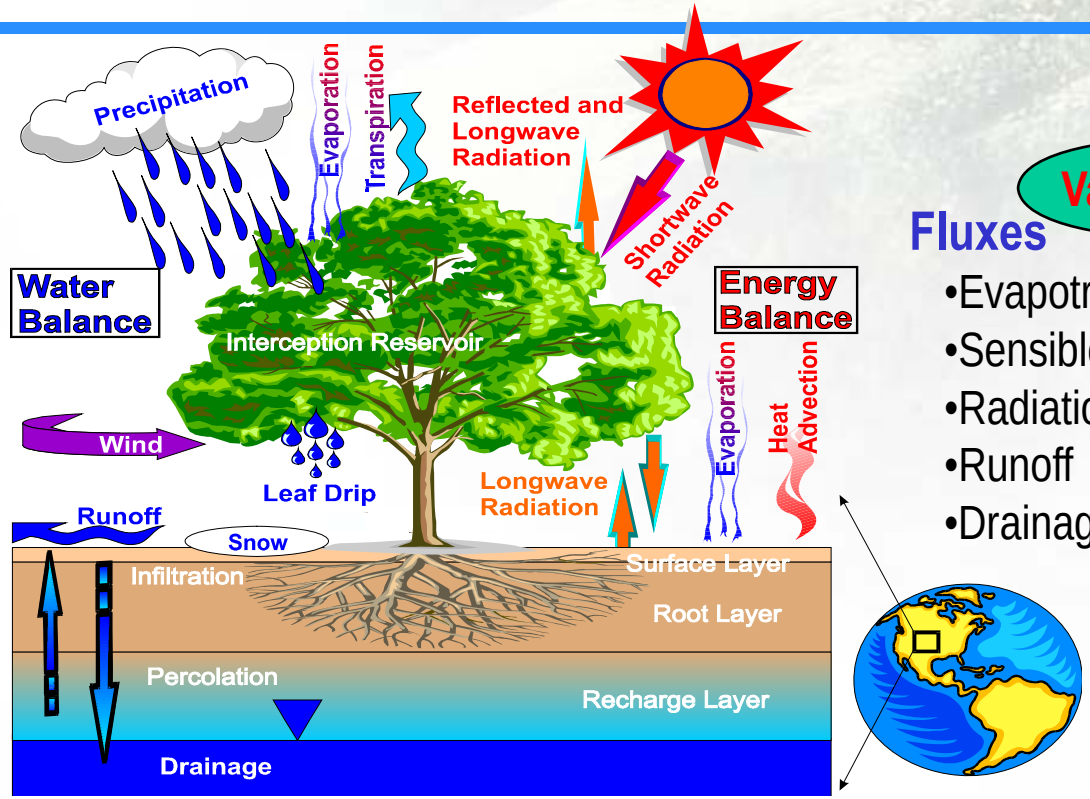
Land Surface Observation

Off-line LDAS

Forcing
- Precipitation
- Wind
- Humidity
- Radiation
- Air Temperature

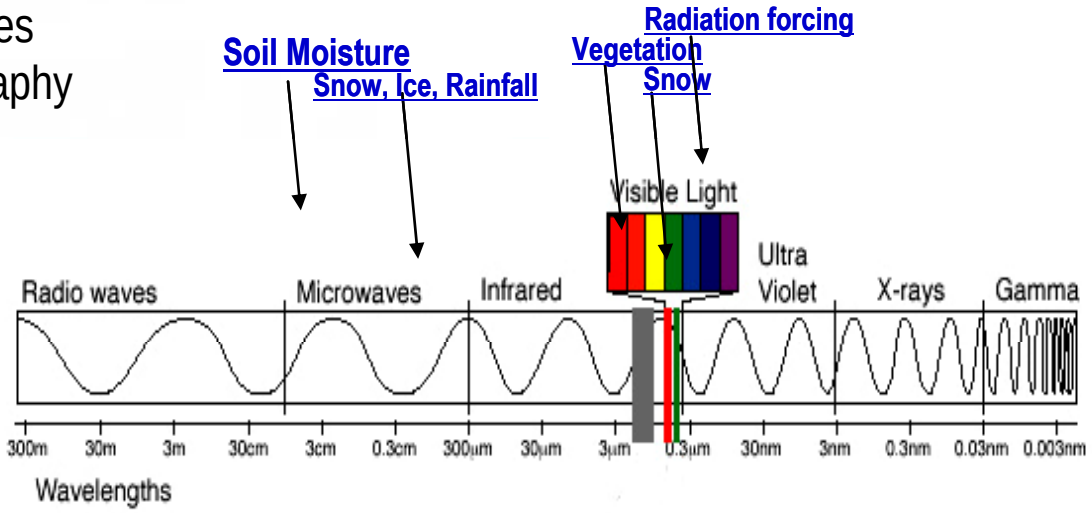
Calibration

Parameters
- Soil Properties
- Vegetation Properties
- Elevation & Topography
- Subgrid Variation
- Catchment Deline
- River Connectivity



Validation

Fluxes
- Evapotranspiration
- Sensible Heat Flux
- Radiation
- Runoff
- Drainage



Assimilation

States
- Soil Moisture
- Temperature
- Snow
- Carbon
- Nitrogen
- Biomass

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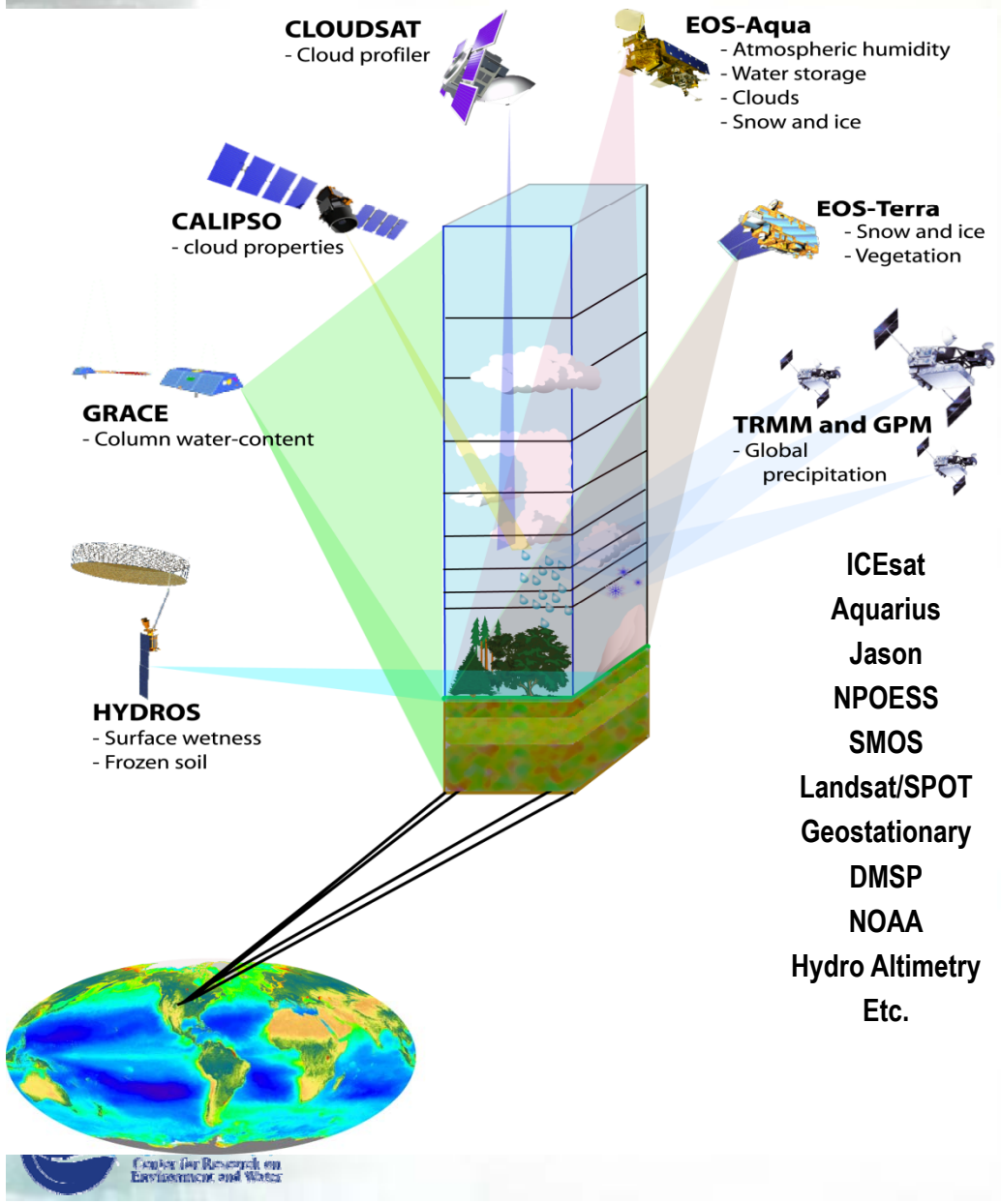
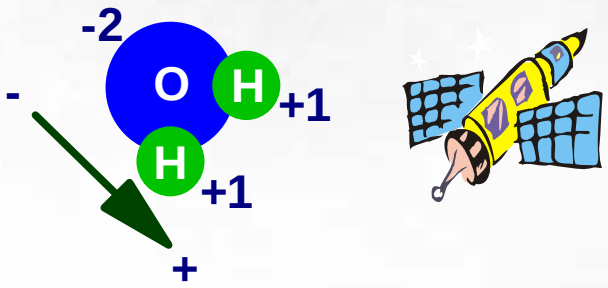
Global Water-Cycle: Observation Strategy



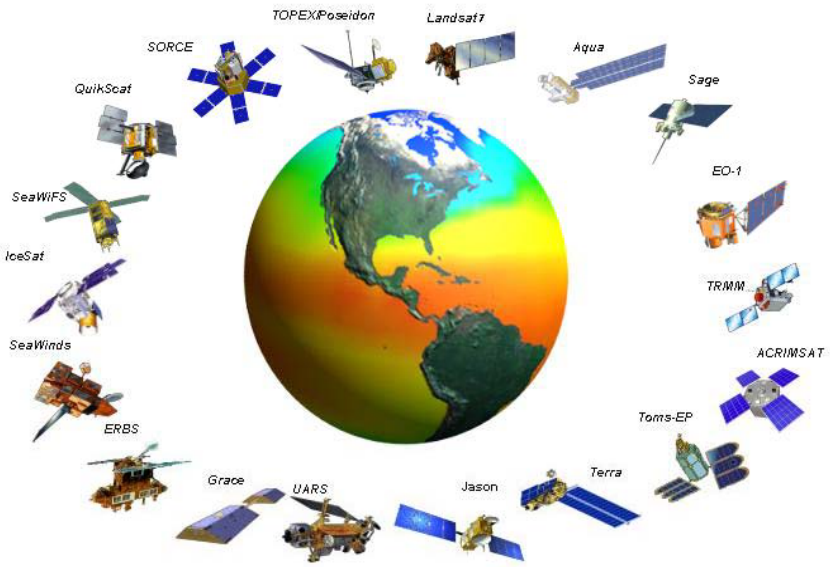
Future: *Water Cycle Mission*

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

Current Observation Capabilities



	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13+
Precipitation	TRMM + constellation					GPM						
Evaporation	EOS Terra EOS Aqua QuickSCAT				ADEOS II		NPP/NPOESS					
P-E	GRACE											
Clouds	Calipso Cloudsat EOS Aqua EOS Terra						NPP/NPOESS					
Water Vapor	EOS Aqua			EOS Aura			NPP/NPOESS					
Land State	EOS Aqua GRACE Icesat						Soil Moisture Mission					

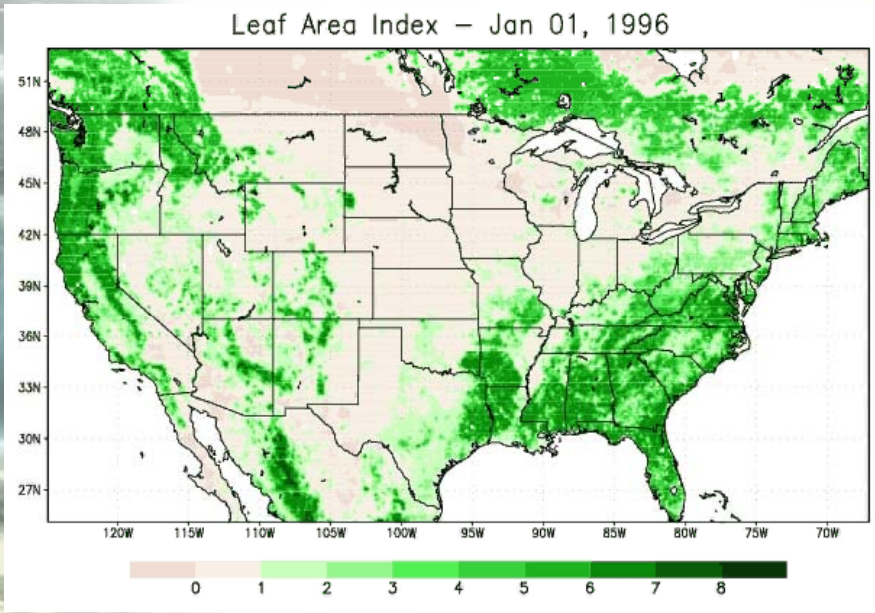
Water-Cycle Mission

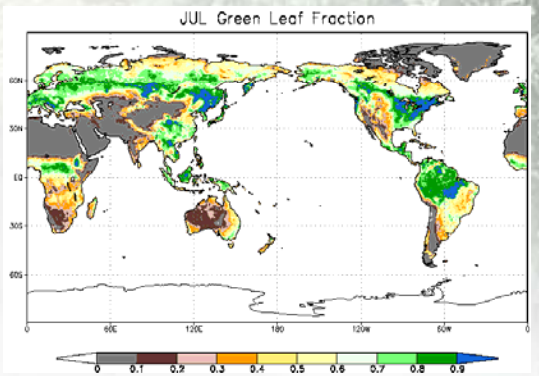
TRMM Precipitation Observations

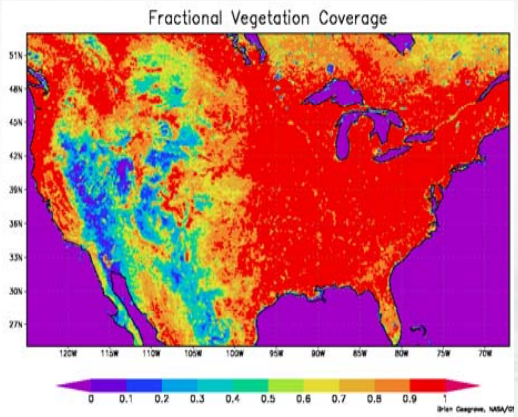
MODIS Snow Observations

Land Parameter Observations

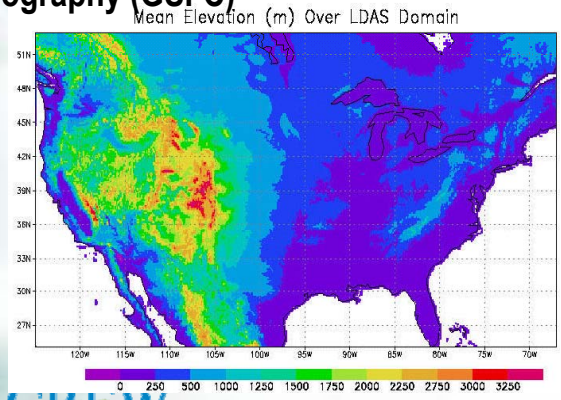
AVHRR/MODIS 1 km LAI -- July



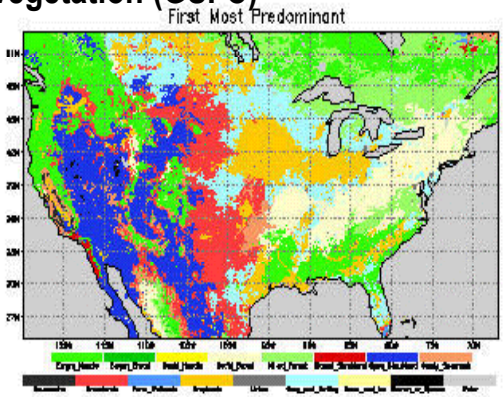




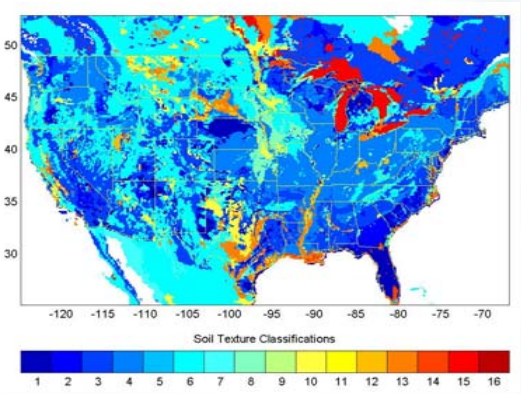
Topography (GSFC)



Vegetation (GSFC)



Soils (NWS-OH)



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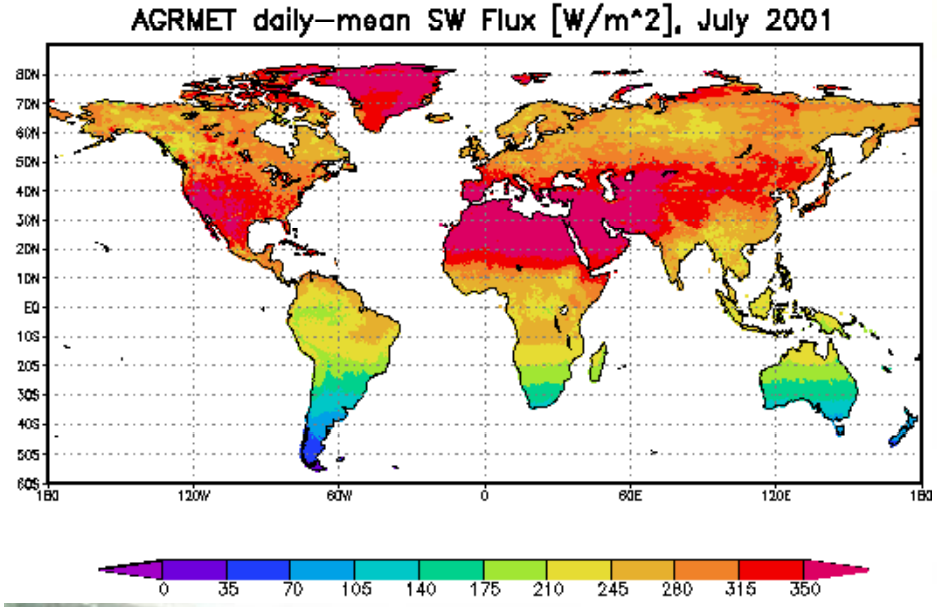
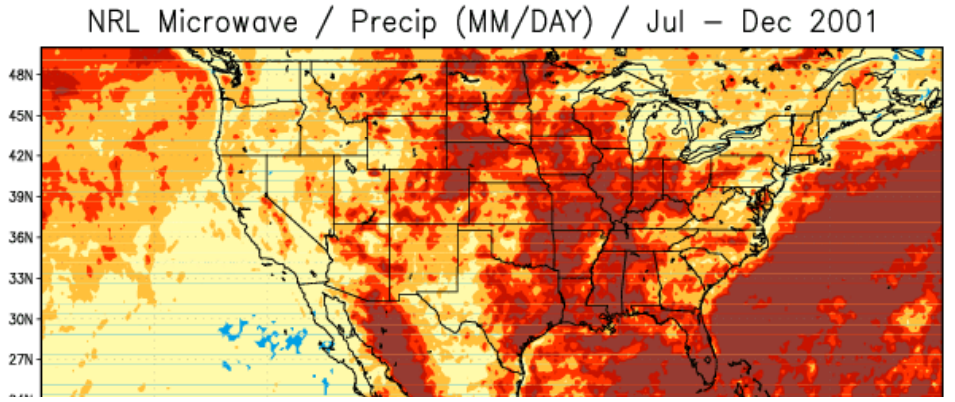
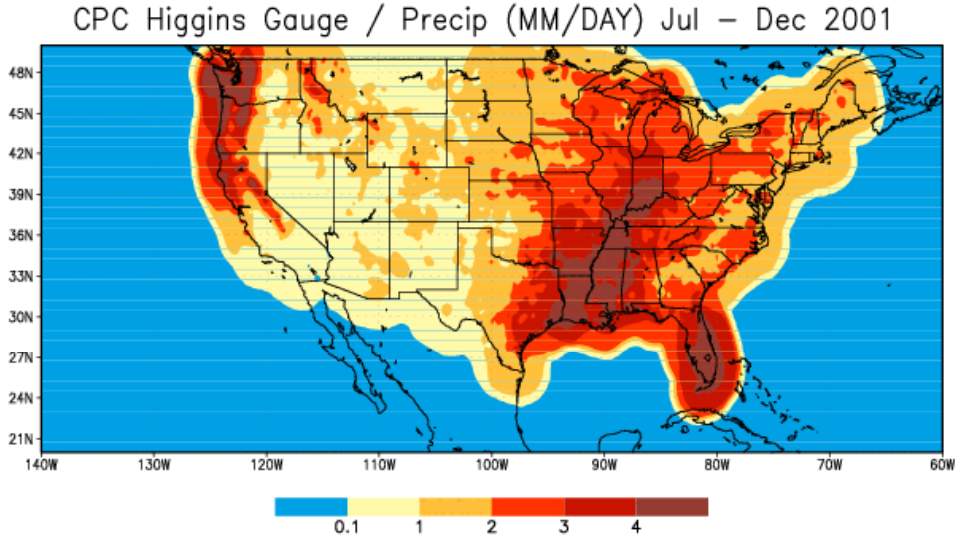
Land Forcing Observations



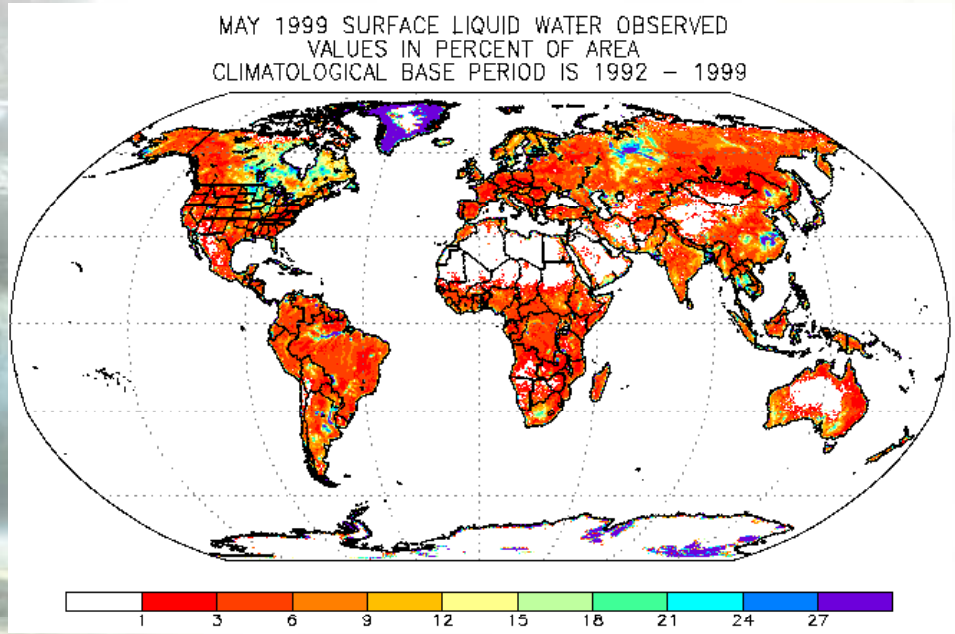


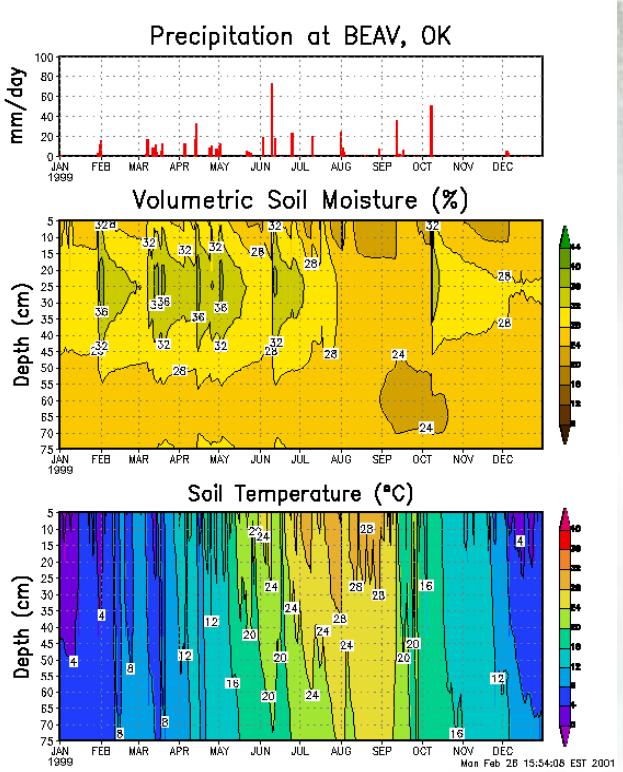


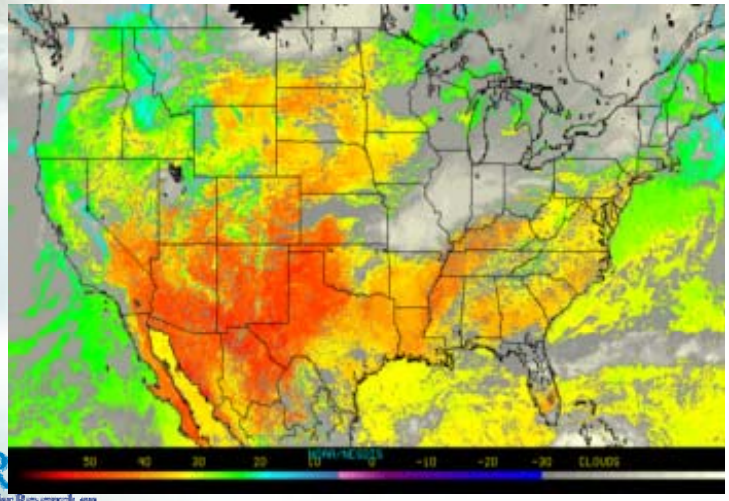
TRMM Precipitation

Land State Observations

Soil Moisture

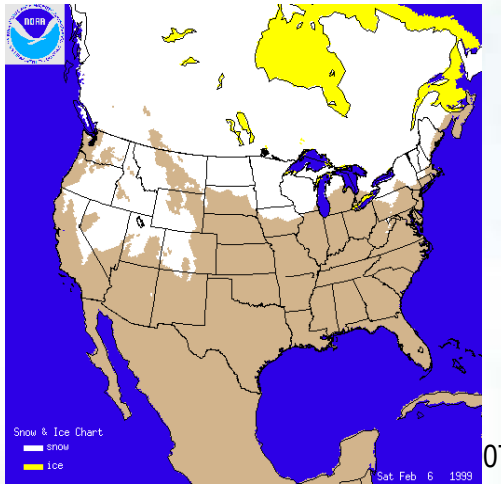






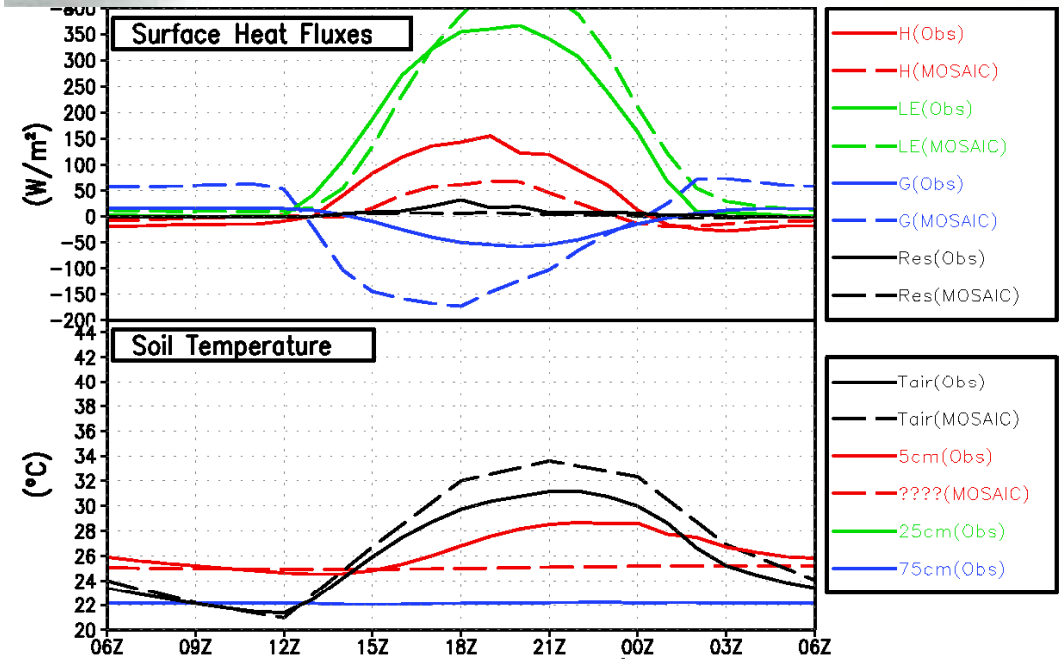
Skin temperature derived from NOAA/NESDIS GOES.

Snow Cover/Depth



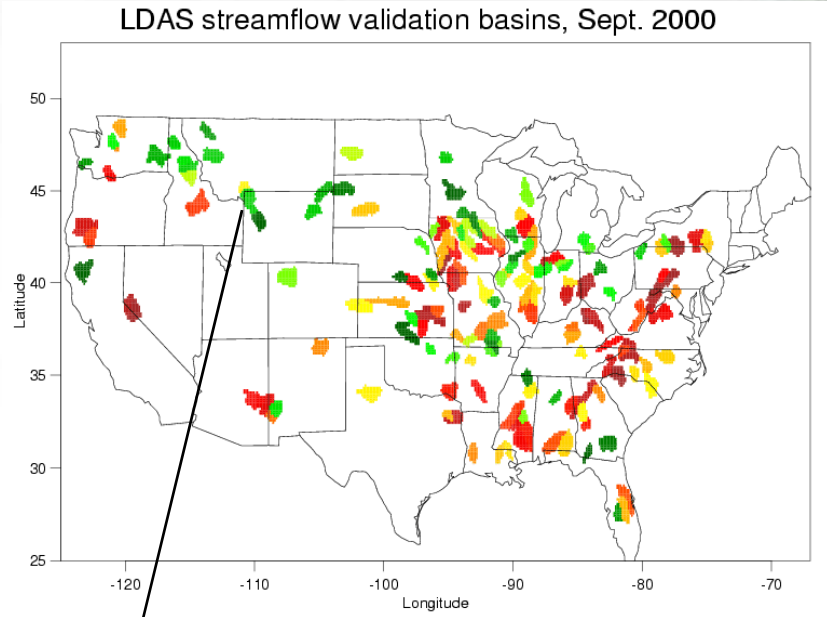
Land Flux Observations

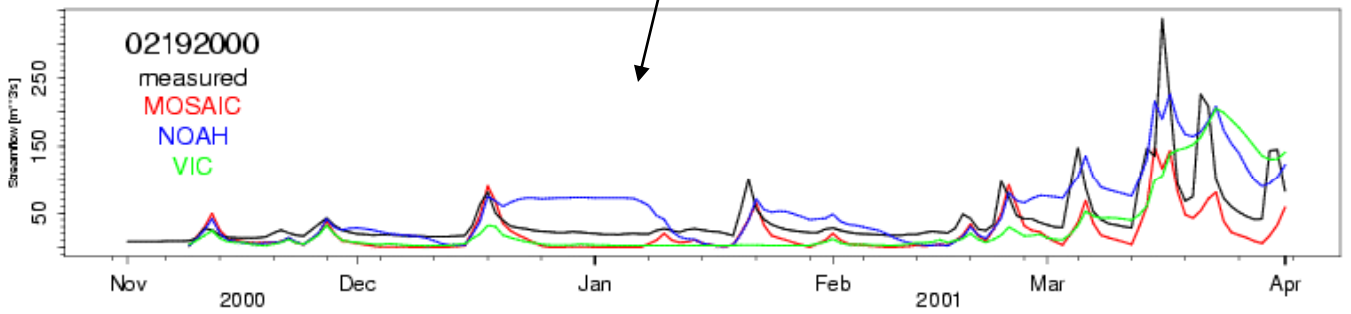
Surface Fluxes



Oklahoma ARM Site

Streamflow

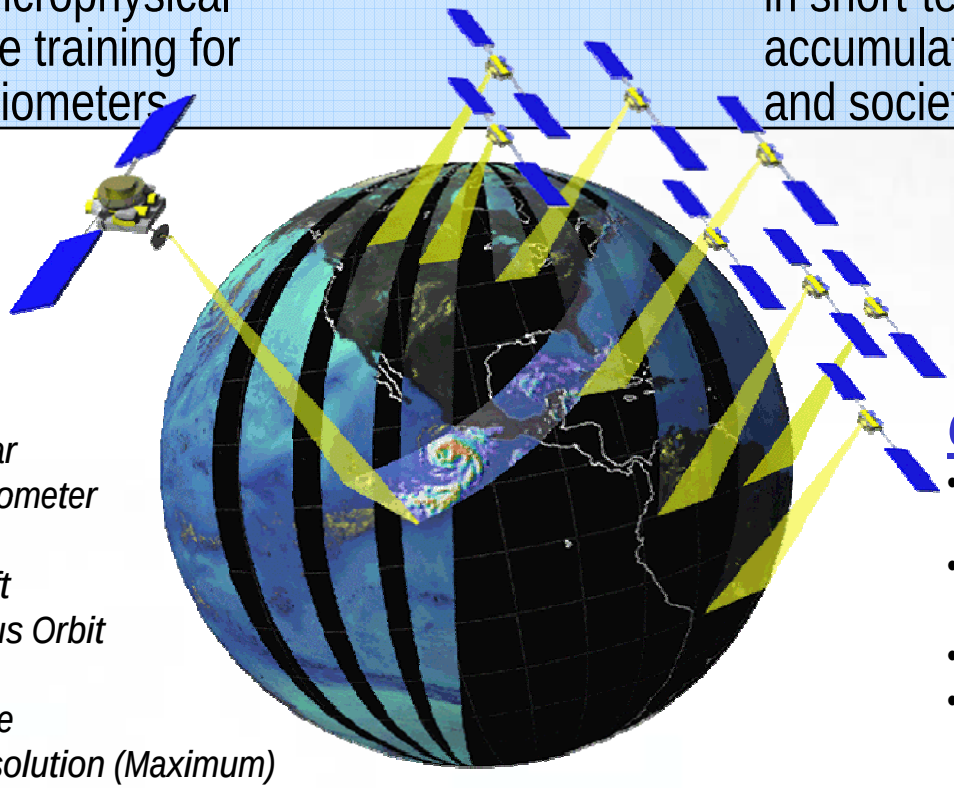




GPM Reference Concept

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*

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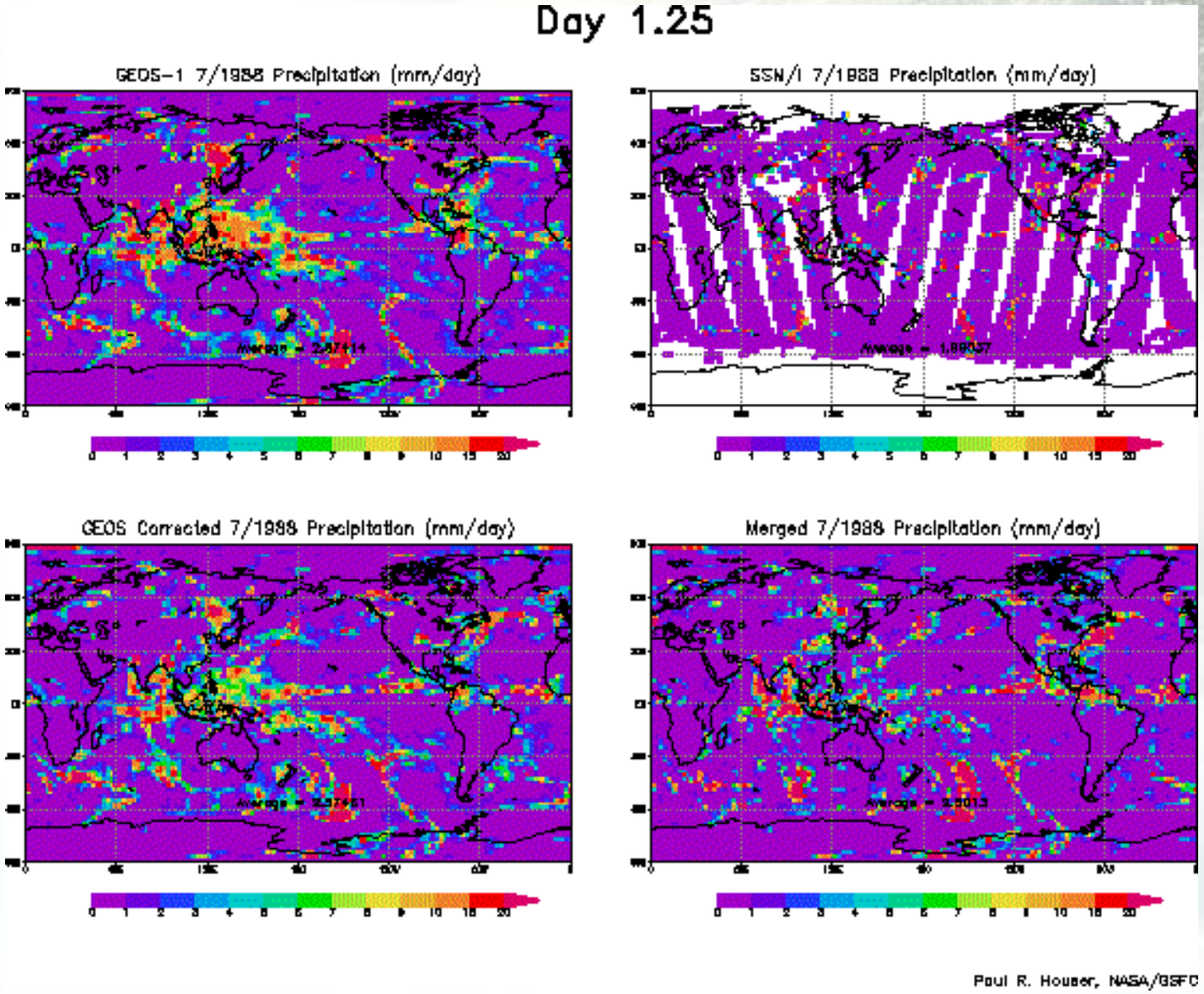
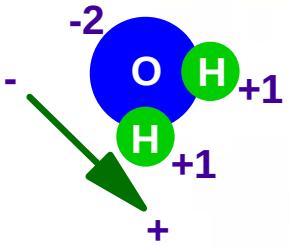
Example 3hr Merged Precipitation Field:

GEOS1 model and SSMI observed precipitation corrected to GPCP and merged using PSAS.

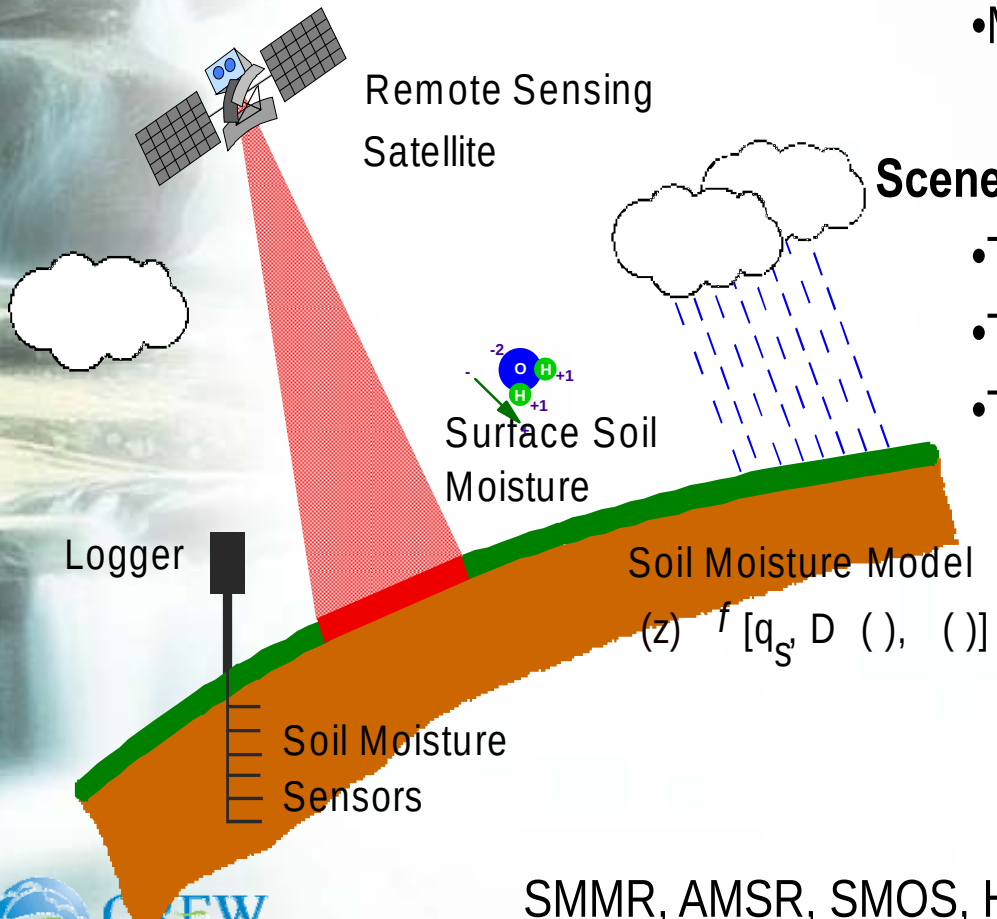


Soil Moisture Remote Sensing



Dielectric constant: Dry soil~3.5, Water ~80

- Water molecule aligns itself to the microwave field
- Penetration depth: ~10 cm
- Measurement depth: ~5 cm



Scene brightness: A combination of:

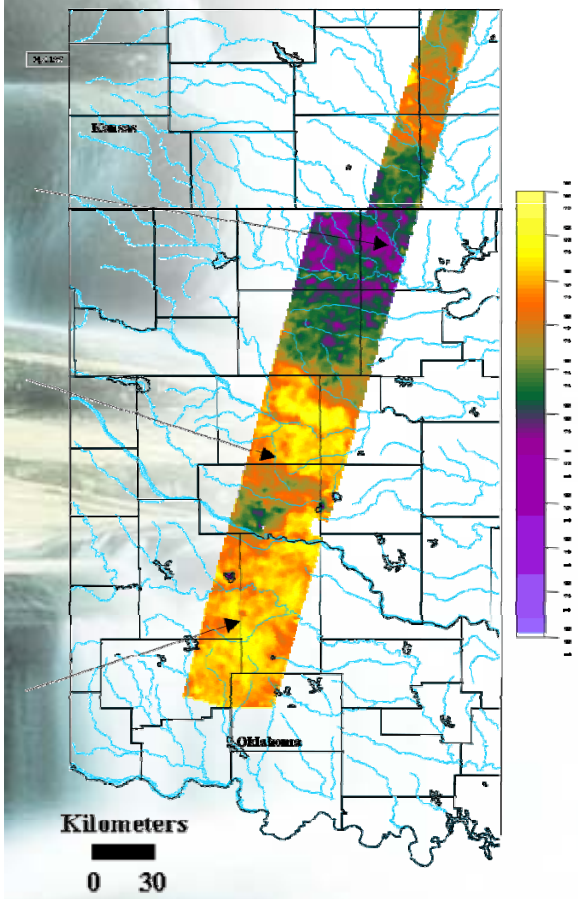
- Tb_c: Canopy brightness (10's K)
- Tb_{sky}: Sky brightness (~2-3 K)
- Tb_g: Soil brightness (~100 K)

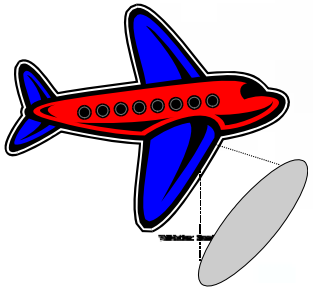
Qualitative Comparison of Active to Passive Microwave Systems.

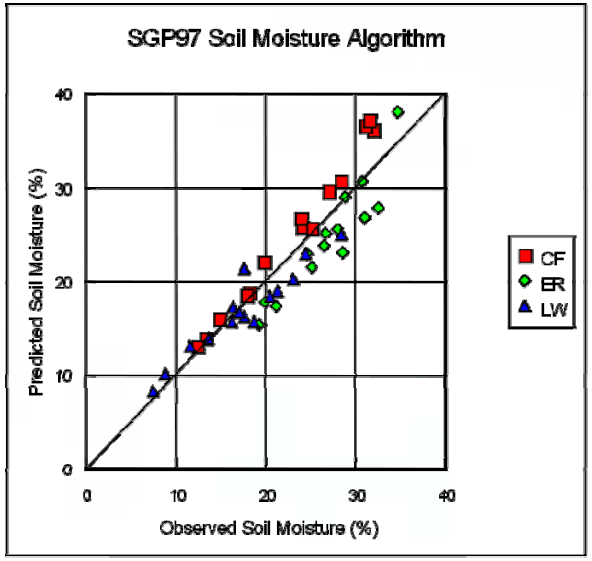
Measurement Characteristic	Passive Microwave	Active Microwave
Sensitivity (StoN)	Very Good	Fair to Good
Data Rates	Low	Very High
Spatial Resolution	10-100 km	10's m
Swath Width	Wide	Moderate
Vegetation Effect	Moderate	Serious
Roughness Effect	Slight	Serious
Topography Effect	Slight	Serious
Revisit Time	Good	Moderate
Algorithm	Good	Moderate

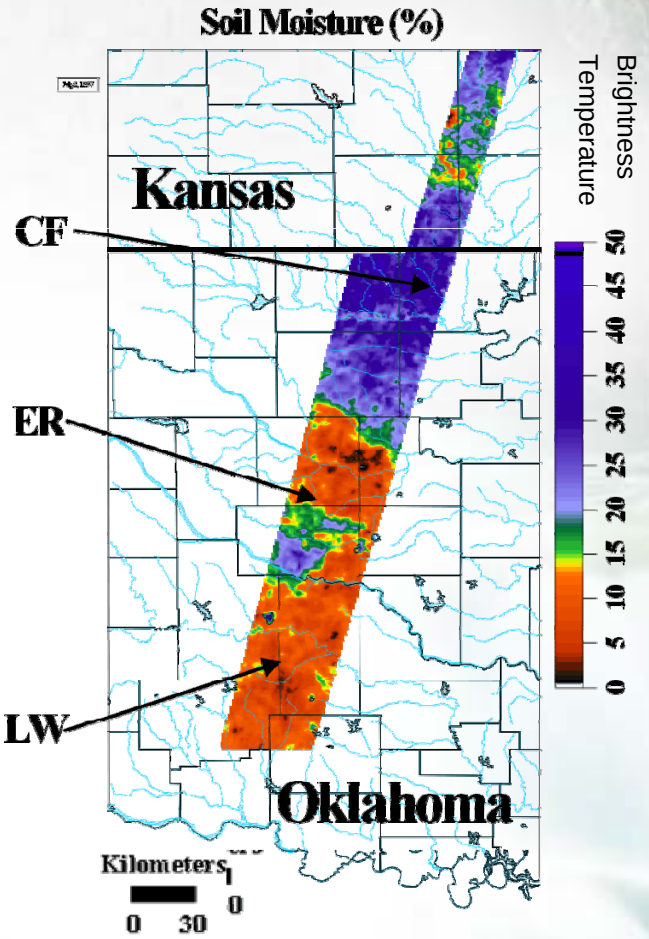
SMMR, AMSR, SMOS, HYDROS (cancelled)

Soil Moisture: Field and Aircraft Validation









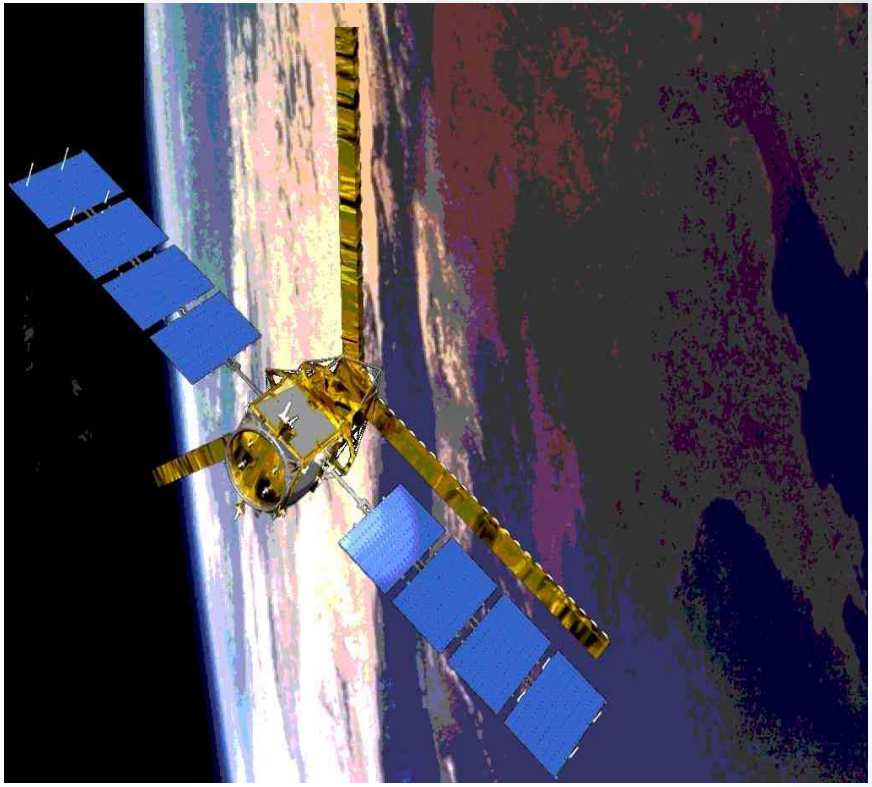
SMOS: ESA Soil Moisture and Ocean Salinity Mission

Soil Moisture and Ocean Salinity (SMOS) mission

2-dimensional interferometric radiometer (50-km resolution).

Multiple-incidence-angle

Target launch 2008



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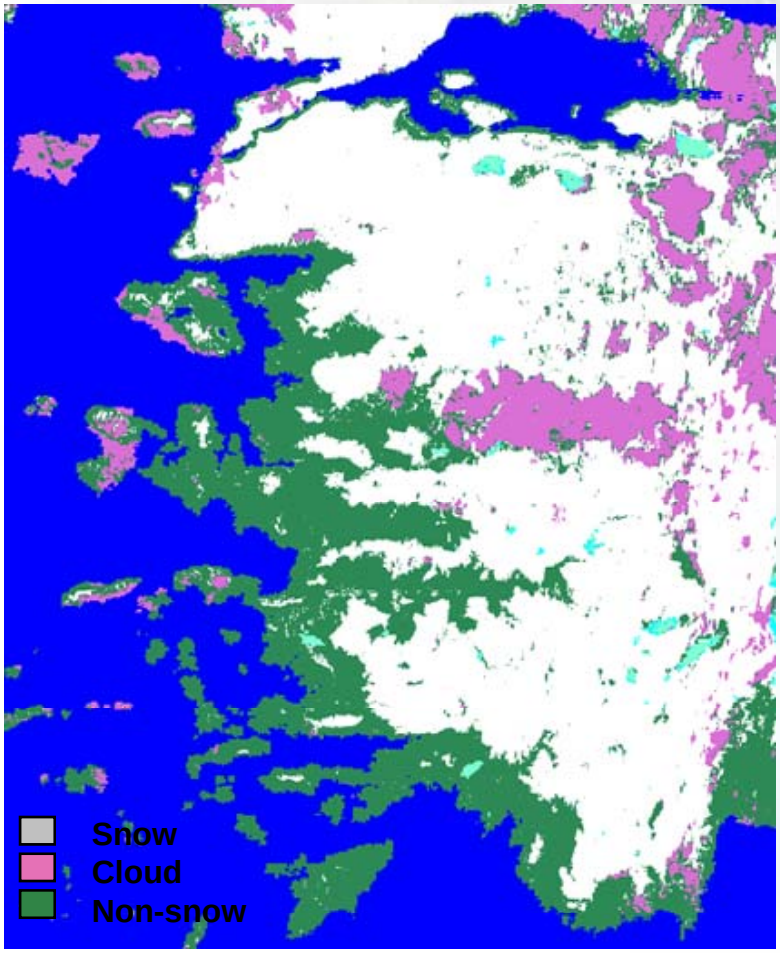
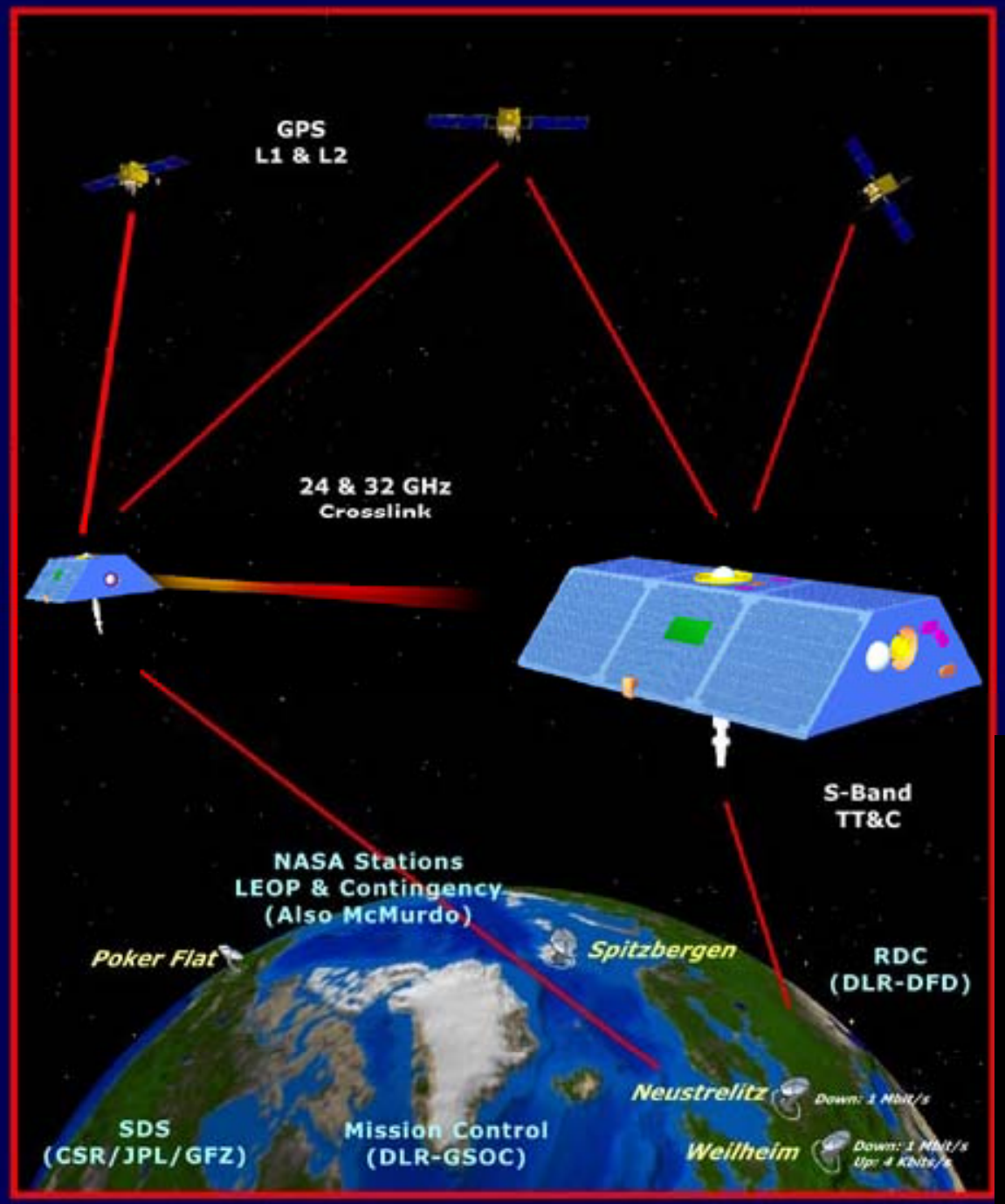
MODIS Snow Cover

MODIS true color image and corresponding MOD10_L2 snow map of Western Turkey on January 27, 2004



Large winter storms and sub-zero temperatures moved through the eastern Mediterranean during the last week of January 2004. The storms brought heavy snows to western Turkey.

GRACE Mission



Science Goals

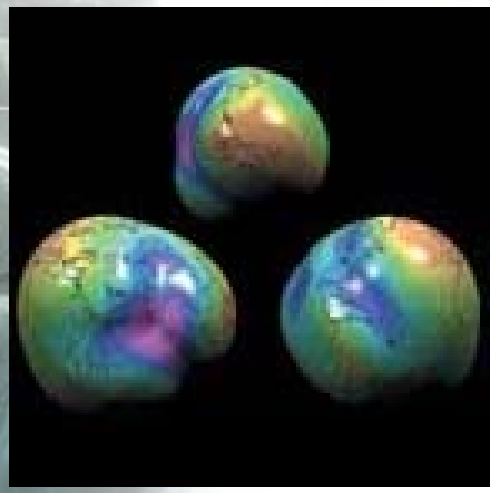
High resolution, mean & time variable gravity field mapping for Earth System Science applications.

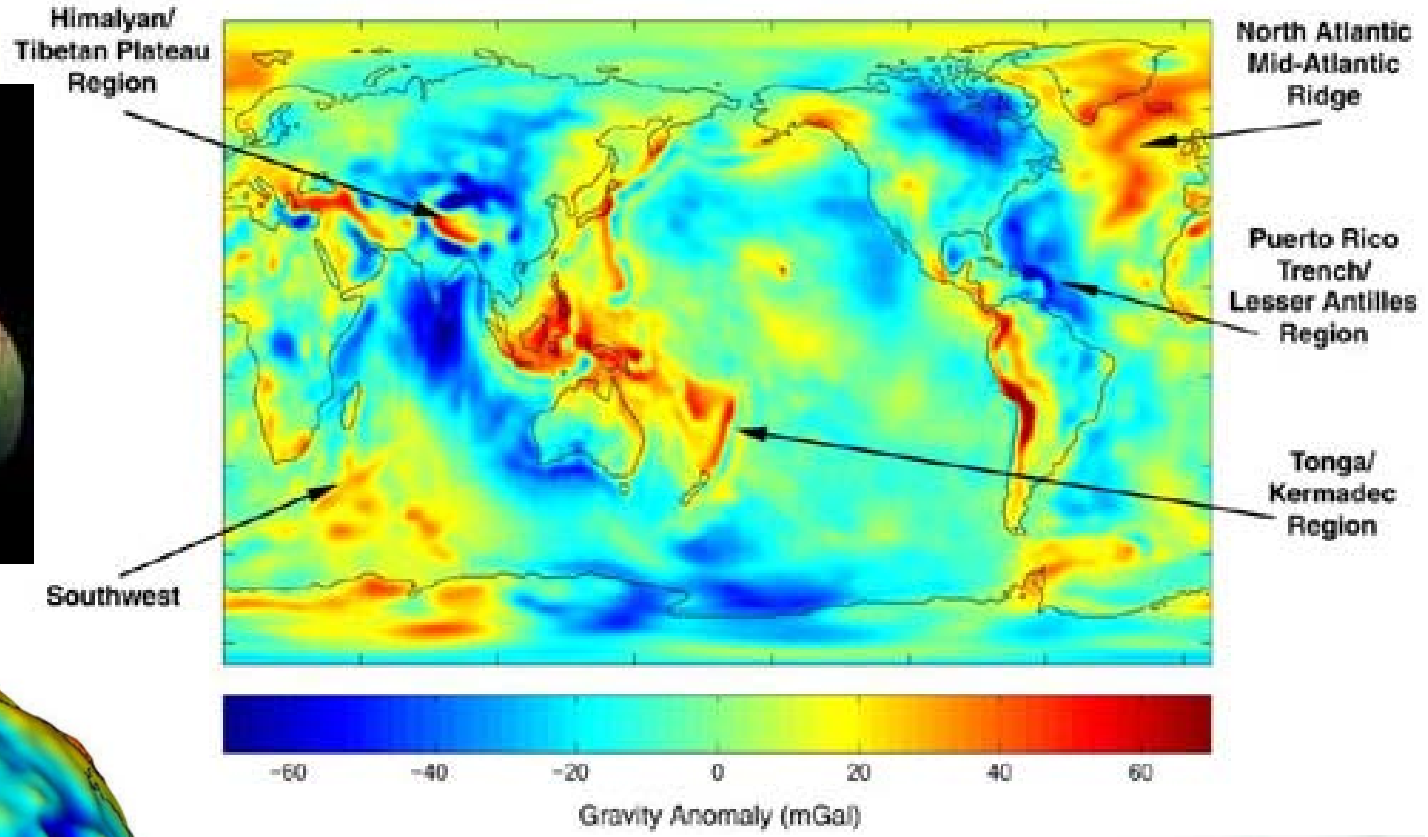
Mission Systems

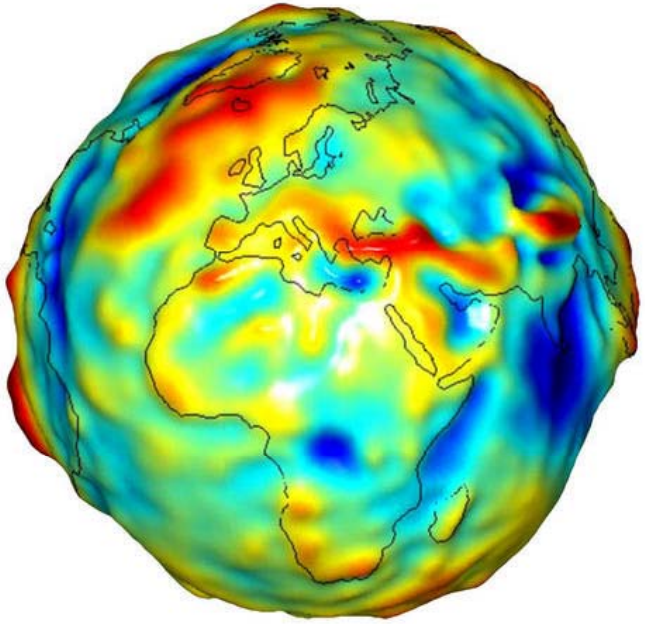
Instruments

- KBR (JPL/SSL)
- ACC (ONERA)
- SCA (DTU)
- GPS (JPL)

Satellite (JPL/DSS)
Launcher (DLR/Eurockot)
Operations (DLR/GSOC)



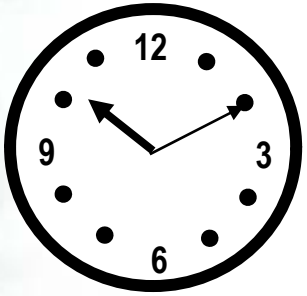

Himalyan/
Tibetan Plateau
Region
North Atlantic
Mid-Atlantic
Ridge
Puerto Rico
Trench/
Lesser Antilles
Region
Tonga/
Kermadec
Region
Southwest
-60
-40
-20
0
20
40
60
Gravity Anomaly (mGal)

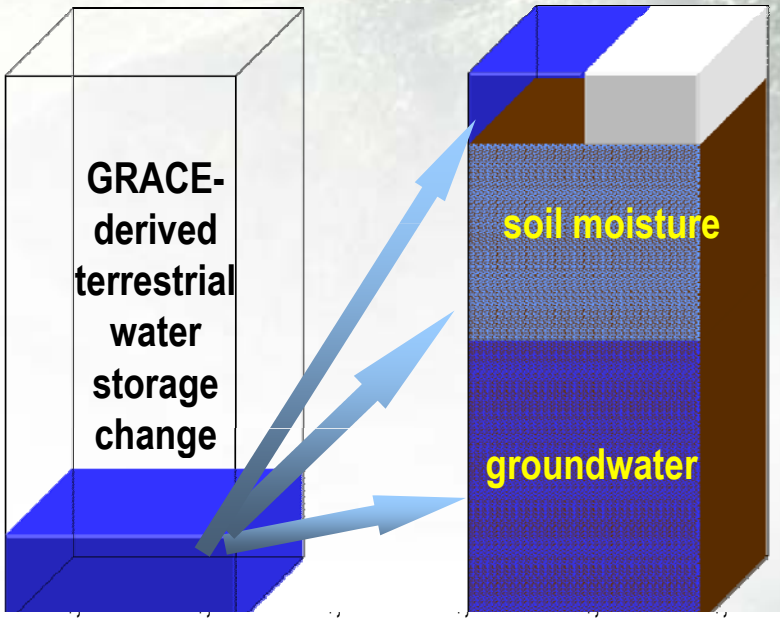


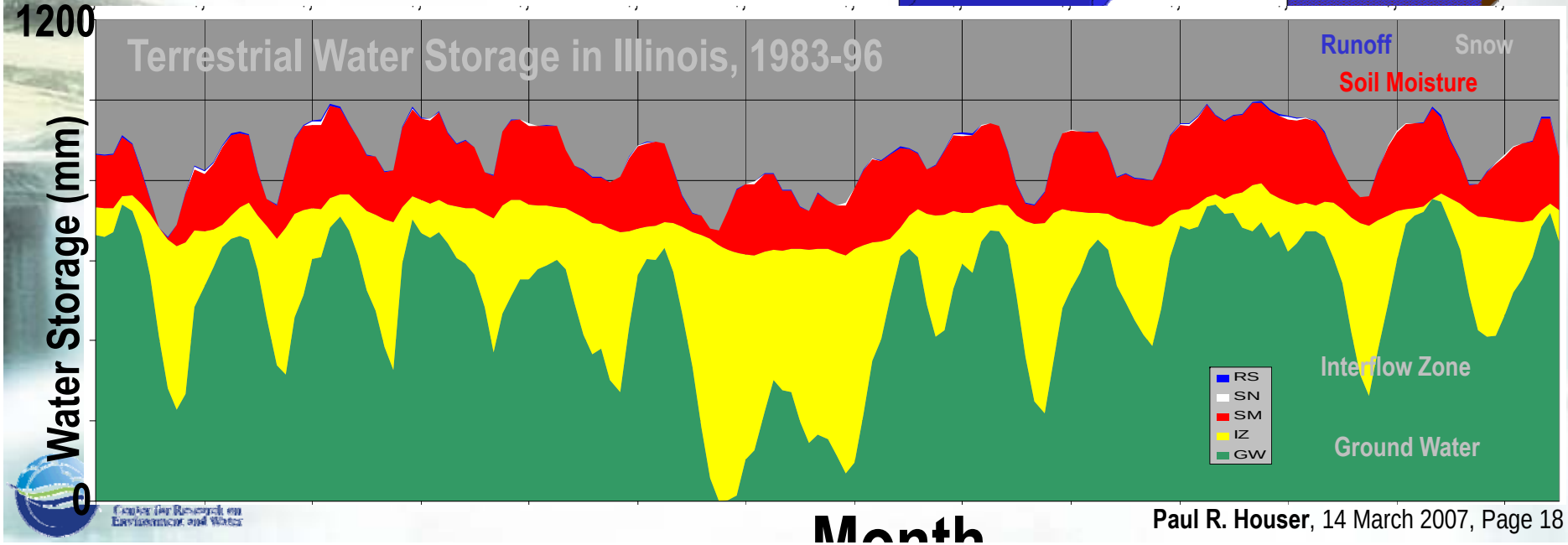
GRACE – Total Water Chcnges

Temporal and Vertical Disaggregation

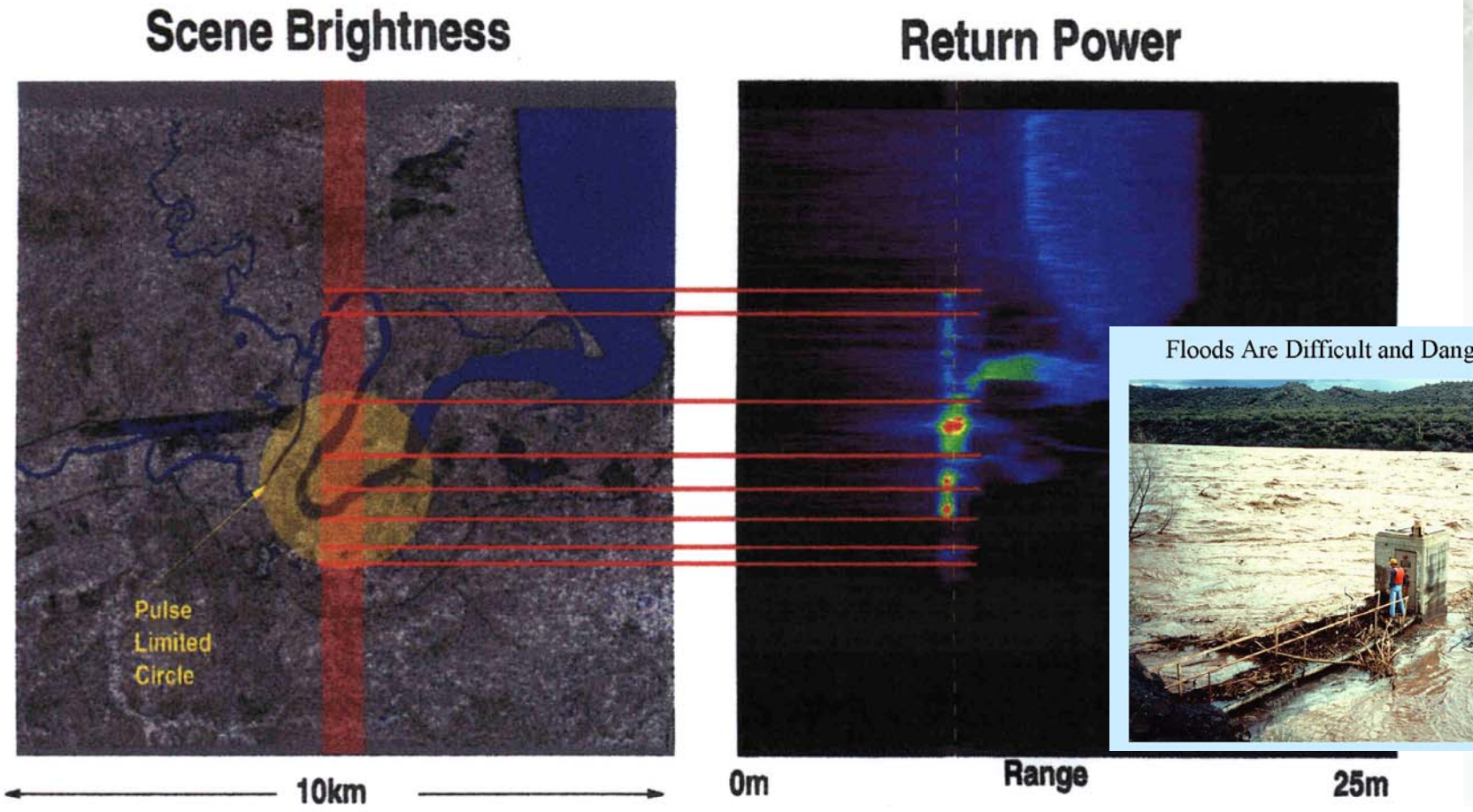
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					







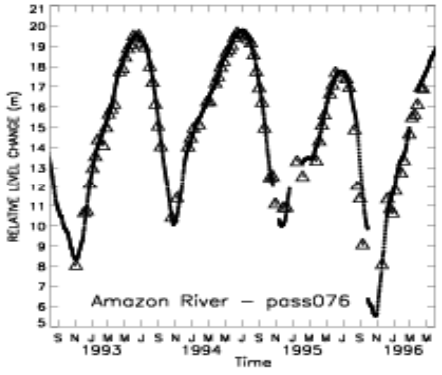
Hydrologic Altimetry *"Streamflow and inundation from space"*

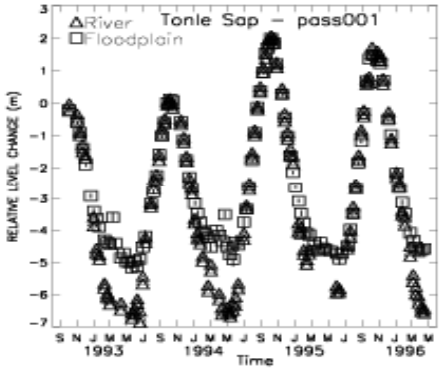


Floodplain, delta, braded, and ice flow streams are impossible to gage – perhaps remote sensing can help?

Surface Water Mission: measure surface water height, velocity, and extent

Potentially laser and/or radar altimetry

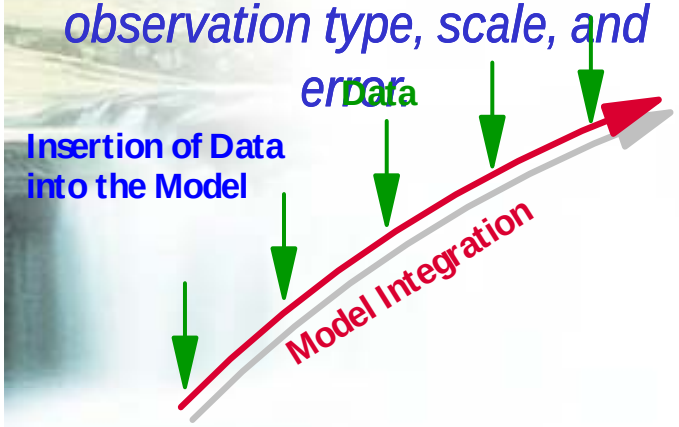




Problem of Observation Integration

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

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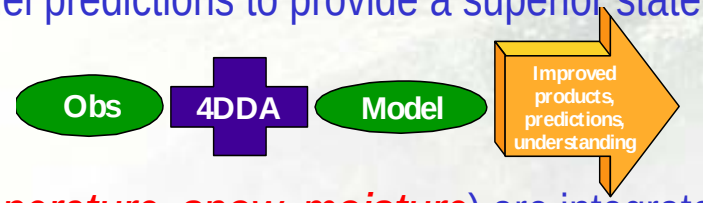
Hydrologic *Data Assimilation*

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

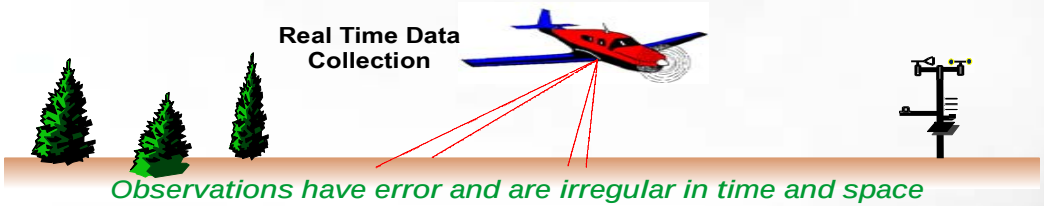
$$\partial x/a = dynamics + physics + \Delta x$$

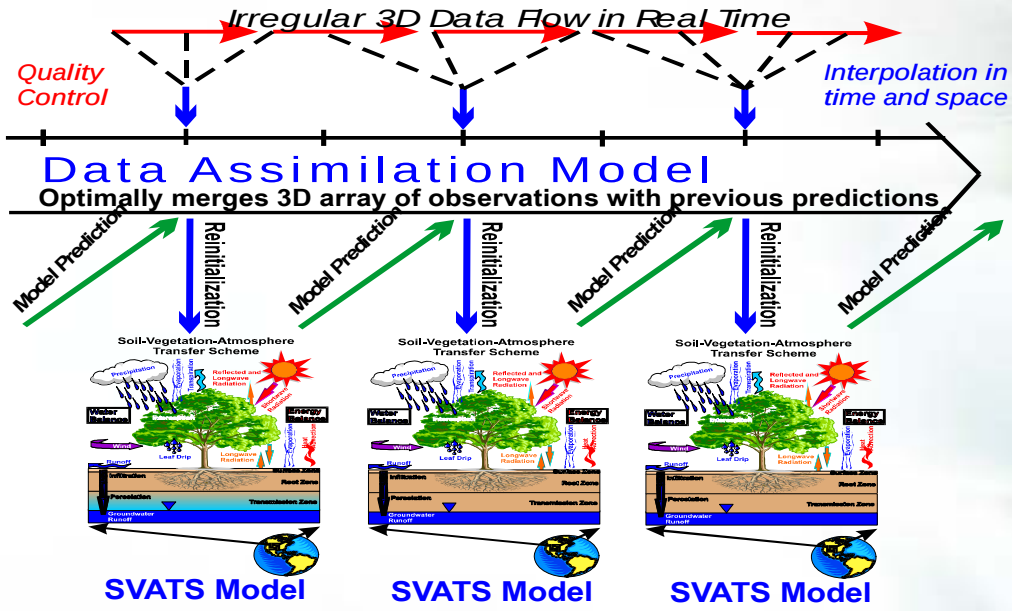


Hydrologic State or storage observations (*temperature, snow, moisture*) are integrated with models.

Data Assimilation Methods: Numerical tools to combine disparate information.

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





Model errors 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).

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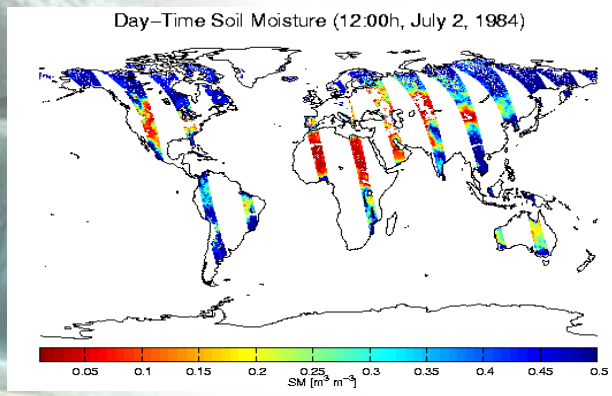
Land Surface Data Assimilation Summary

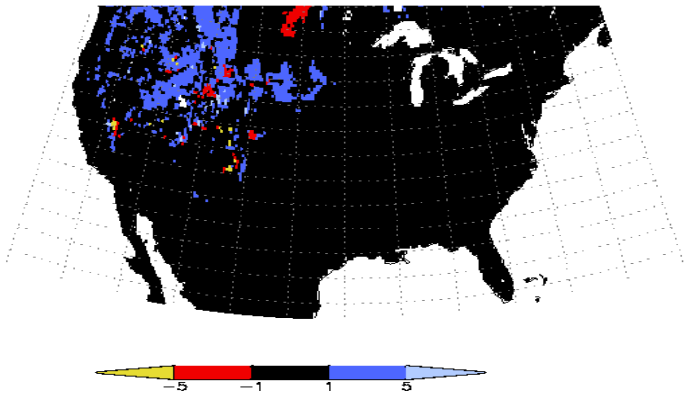
Data Assimilation merges observations & model predictions to provide a superior state estimate.

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.

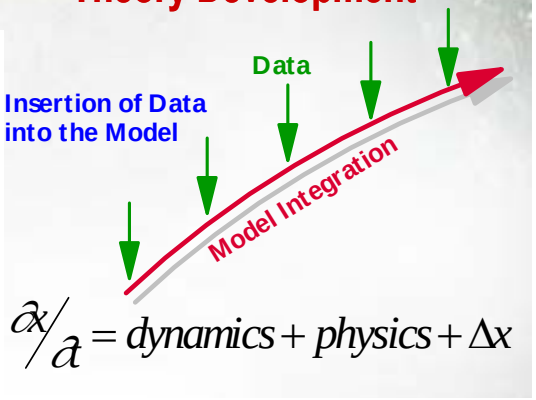
Soil Moisture Assimilation



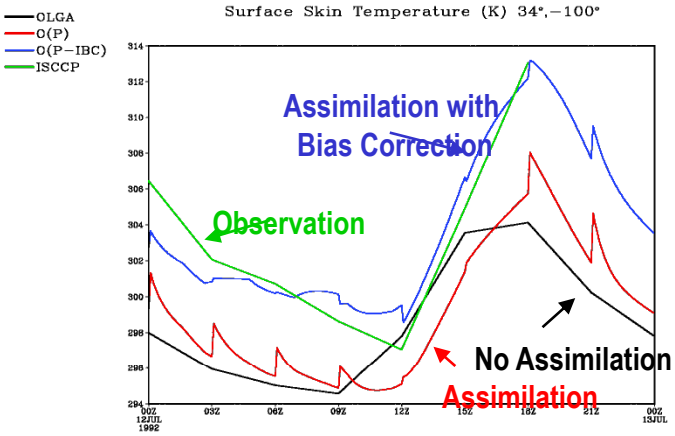
Snow Cover Assimilation



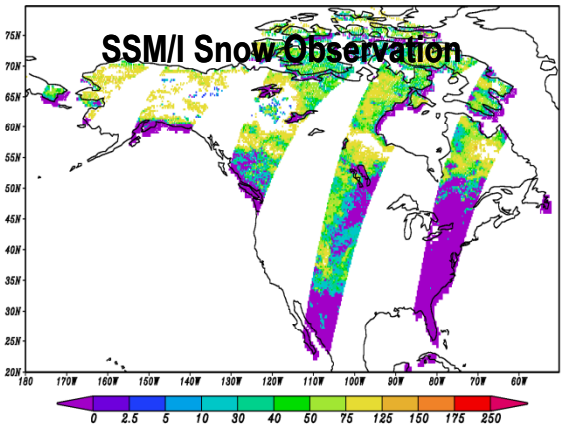
Theory Development

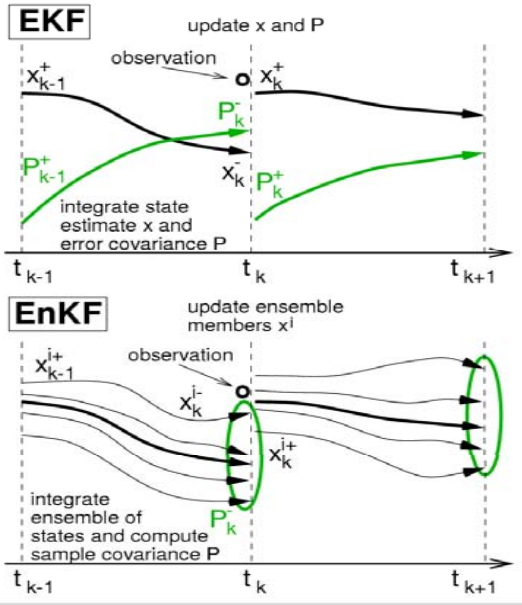


Skin Temperature Assimilation

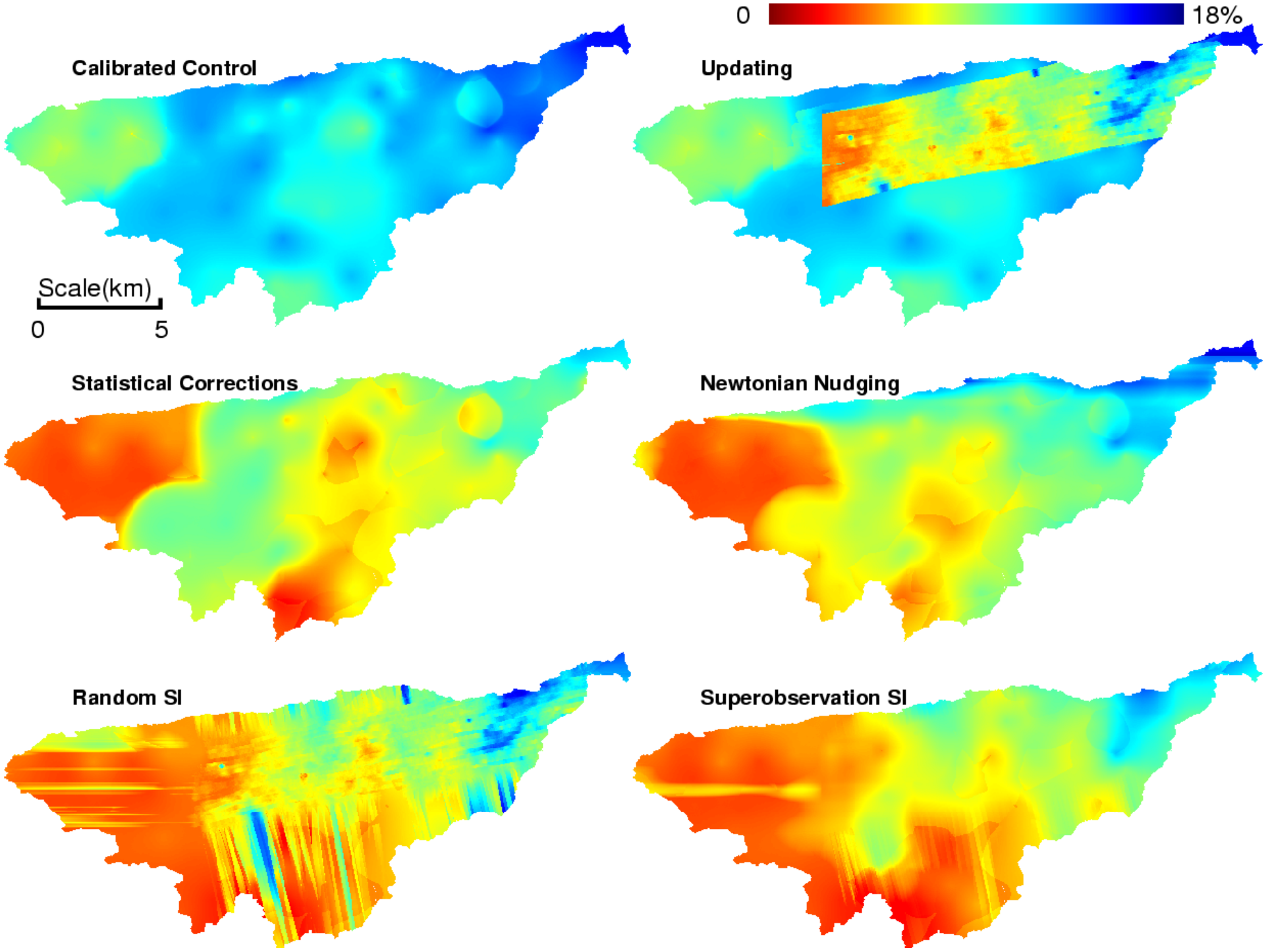


Snow Water Assimilation

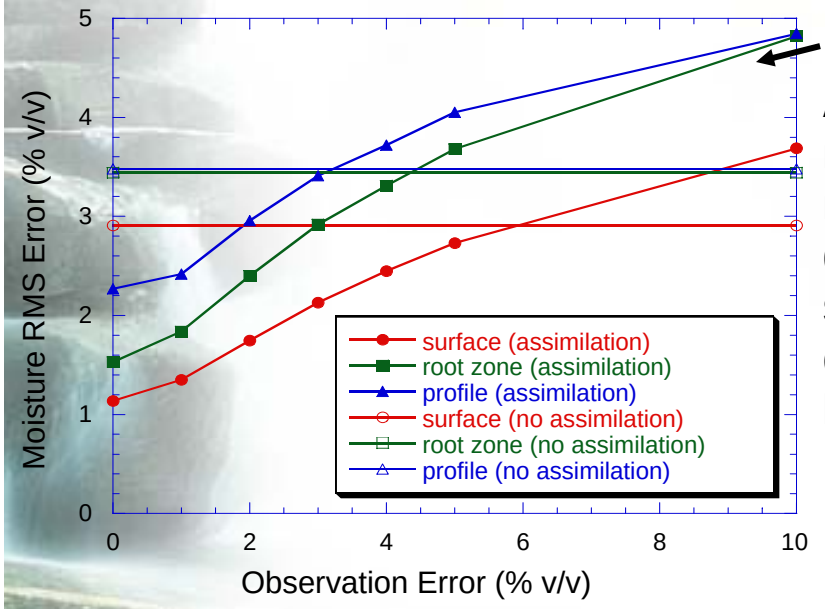




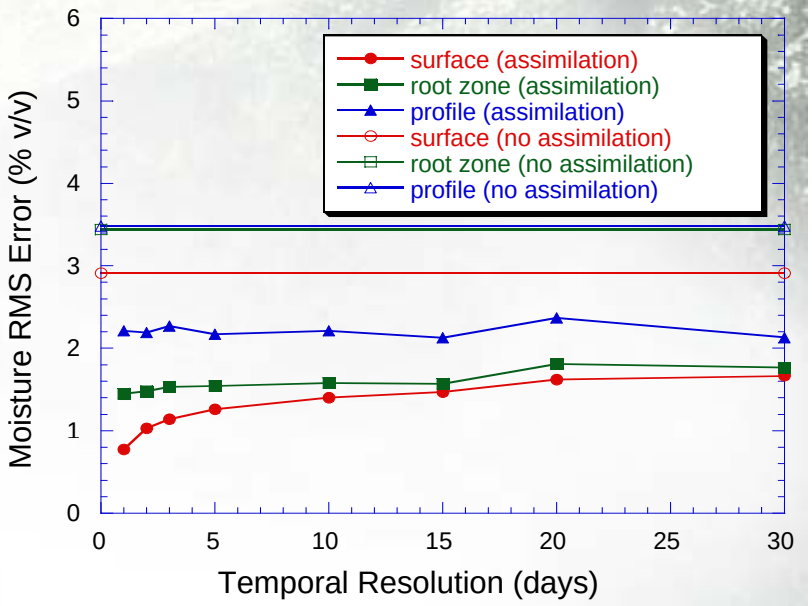
Also: Runoff, Evapotranspiration, groundwater (gravity), and Carbon Assimilation

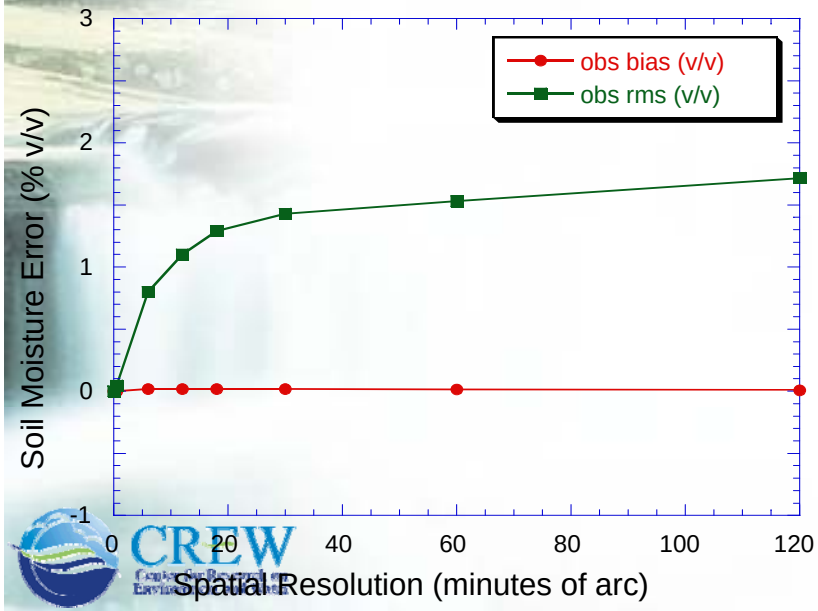

0
18%
Calibrated Control
Updating
Scale(km)
0
5
Statistical Corrections
Newtonian Nudging
Random SI
Superobservation SI

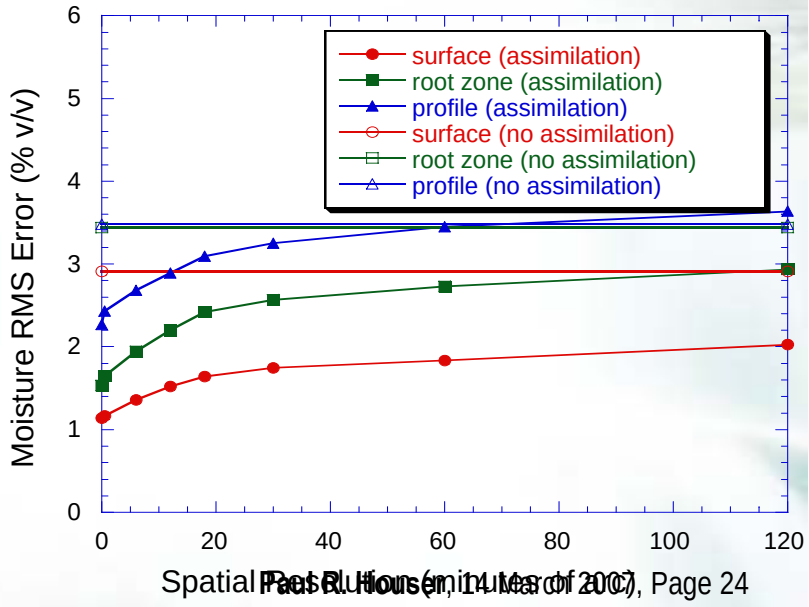
Soil Moisture Observation Error and Resolution Sensitivity:



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

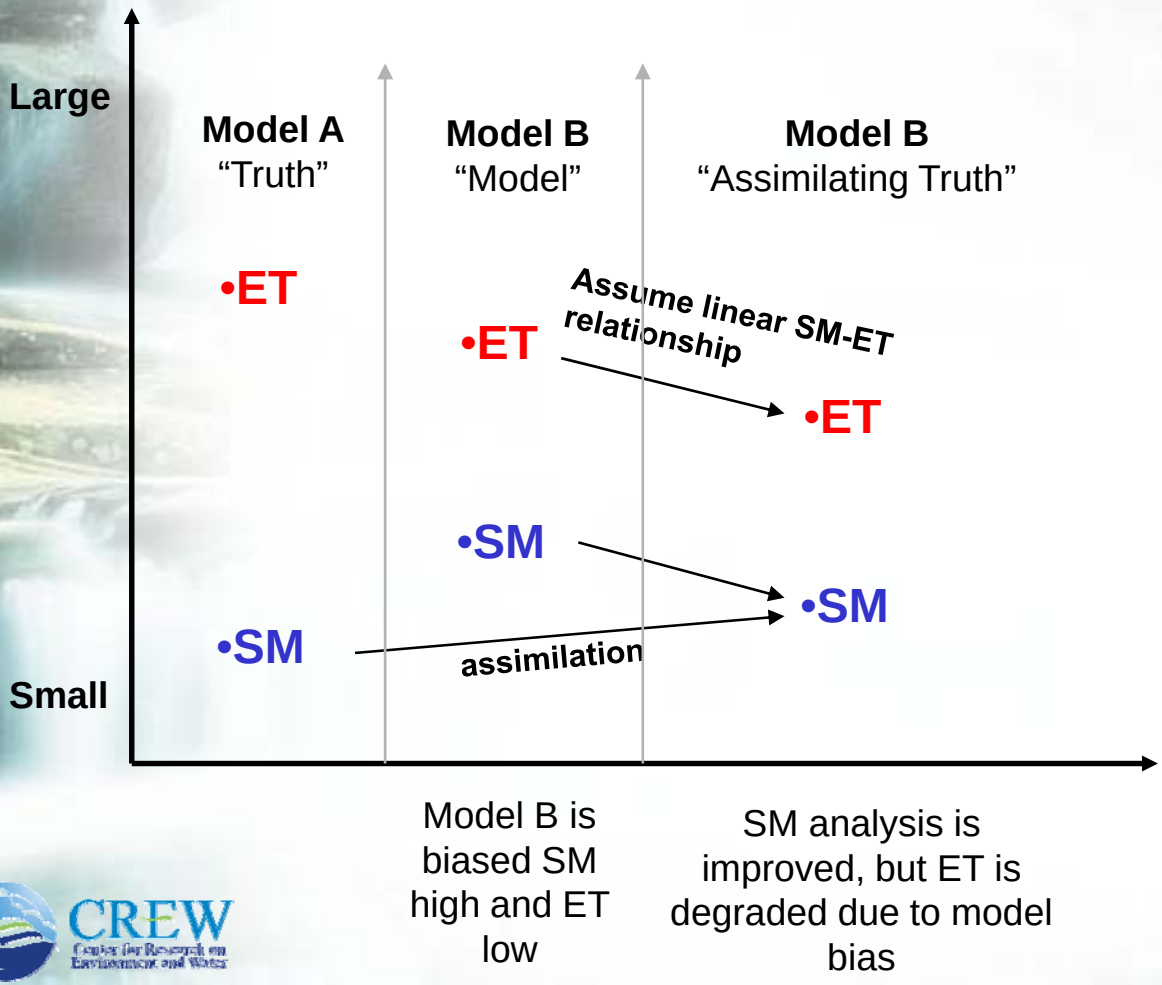






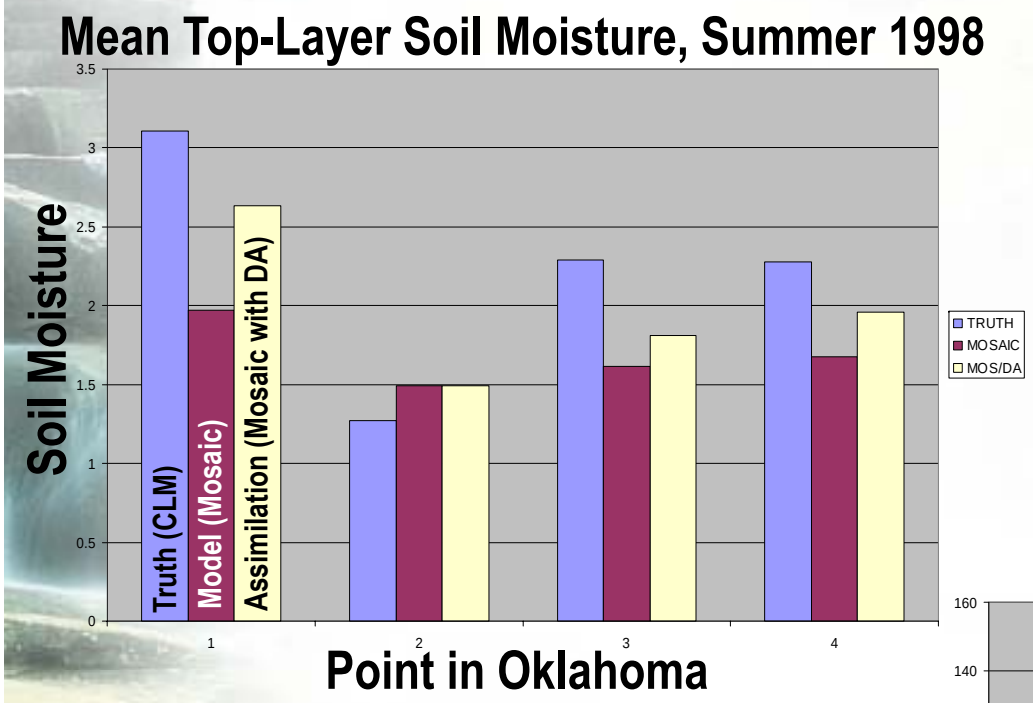
Fraternal Twin Studies

- "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.

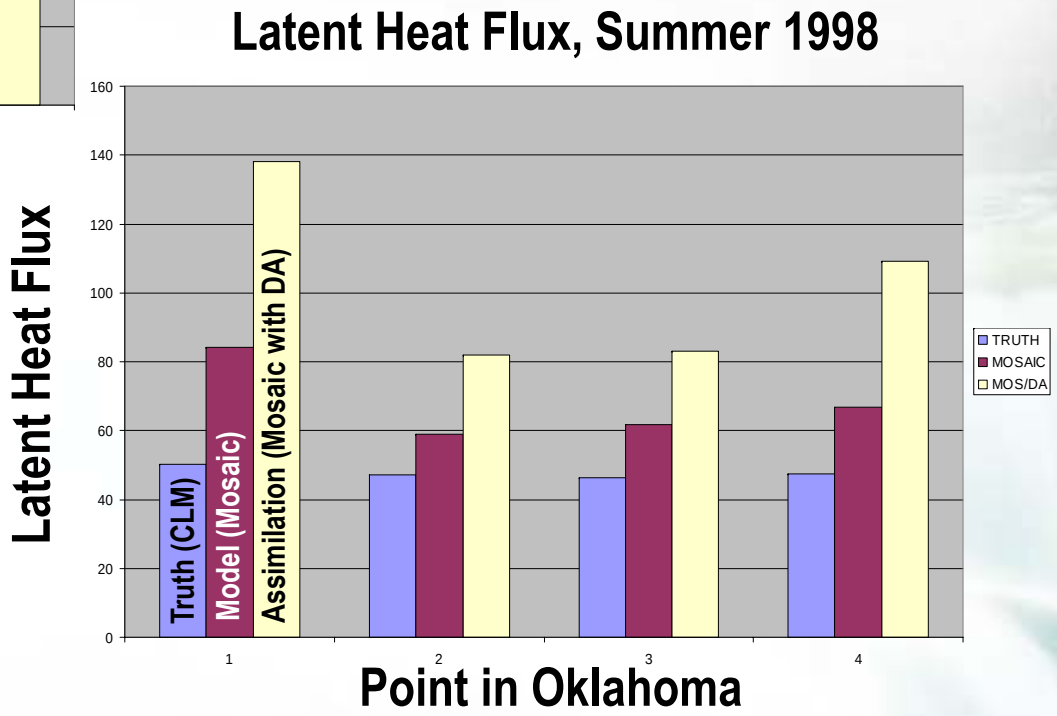


We must not only worry about obtaining an optimal model constraint, but also understand the implications of that constraint.

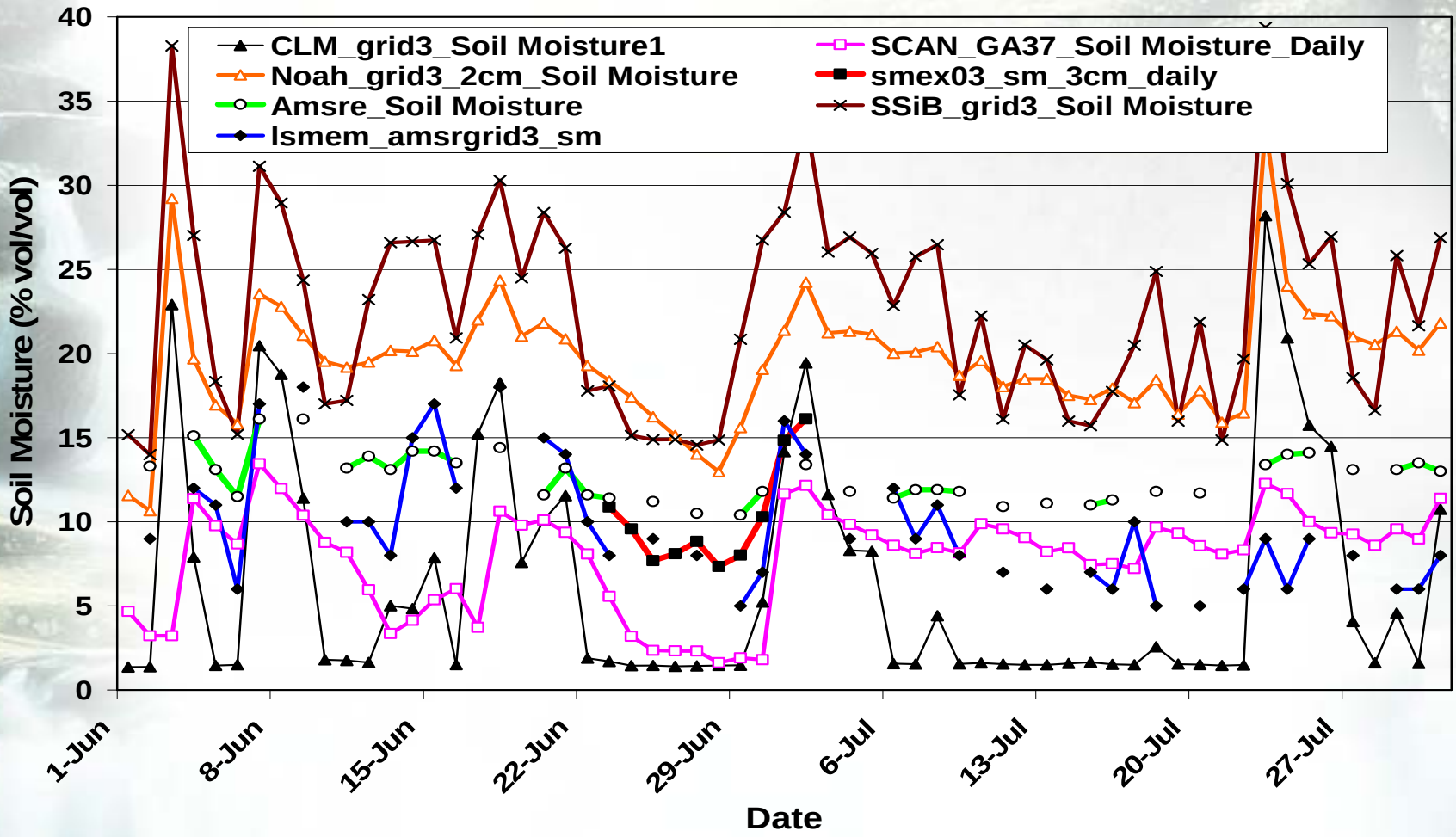
Fraternal Twin Demonstration



CLM=Truth
Mosaic=Faulty



Evaluation of SMMR Soil Moisture



Averaged soil moisture plot over AMSR-E 1/4 degree grid at SMEX03. Noah (2 cm layer SM), CLM (2 cm layer, layer 1), SSiB (2 cm top layer), SCAN (just one station, 5 cm), AMSR-E (2 cm layer), SMEX03 (3 cm layer), LSMEM (2 cm layer).

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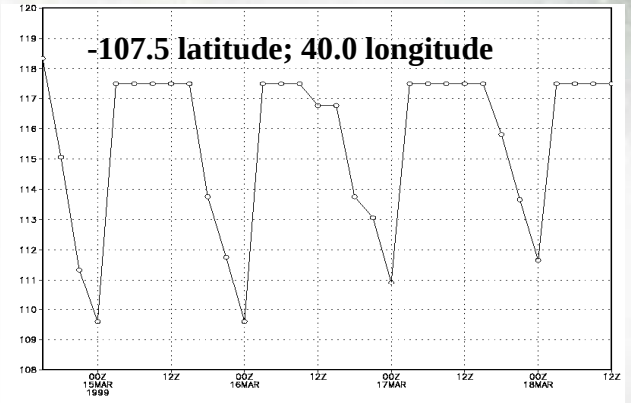
Snow Assimilation: Background & Motivation

- 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.



Unique Snow Data Assimilation Considerations:

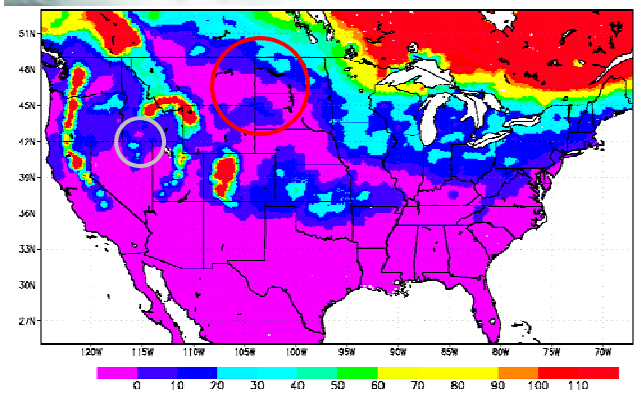
- "Dissappearing" layers and states
- Arbitrary redistribution of mass between layers
- Lack of information in SWE about snow density or depth
- Lack of information in snow cover about snow mass & depth
- Biased forcing causing divergence between analysis steps
- **OBSERVATIONS:** Snow Cover, Snow Water Equiv., Tskin, Snow Fraction

Update Time

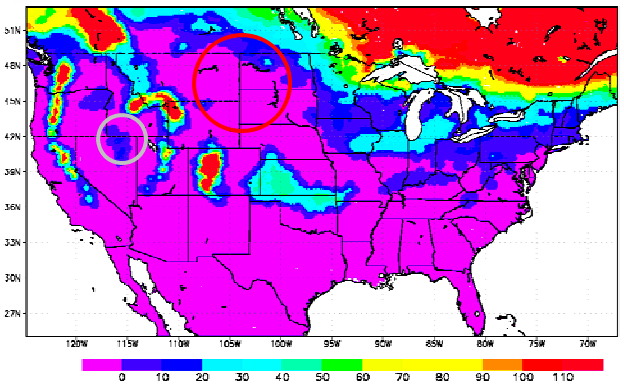
Melt

Update Time

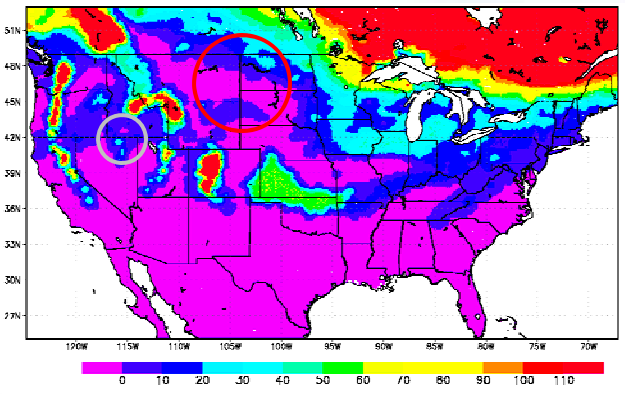
3Z 3/15/99



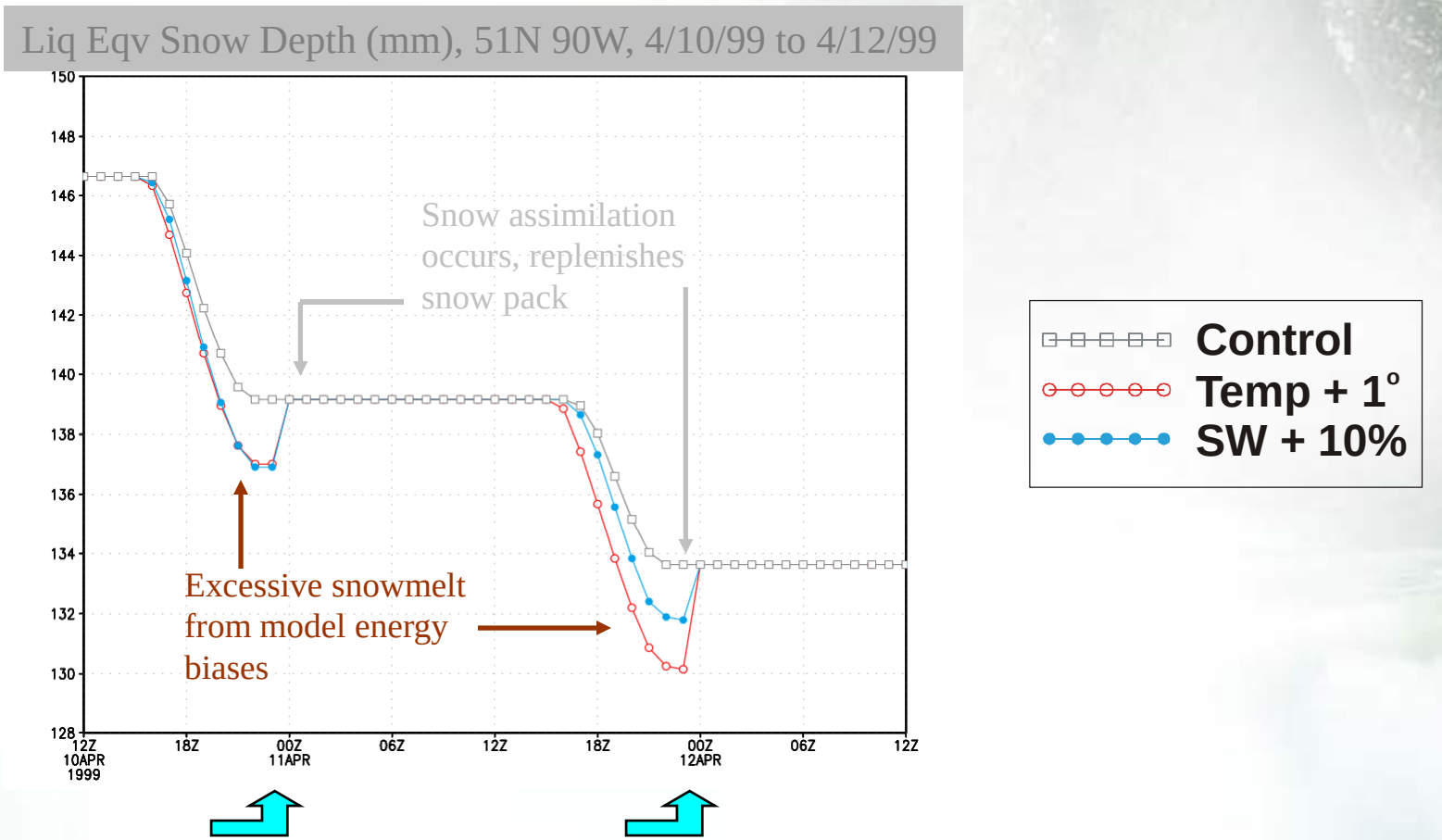
0Z 3/16/99



3Z 3/16/99

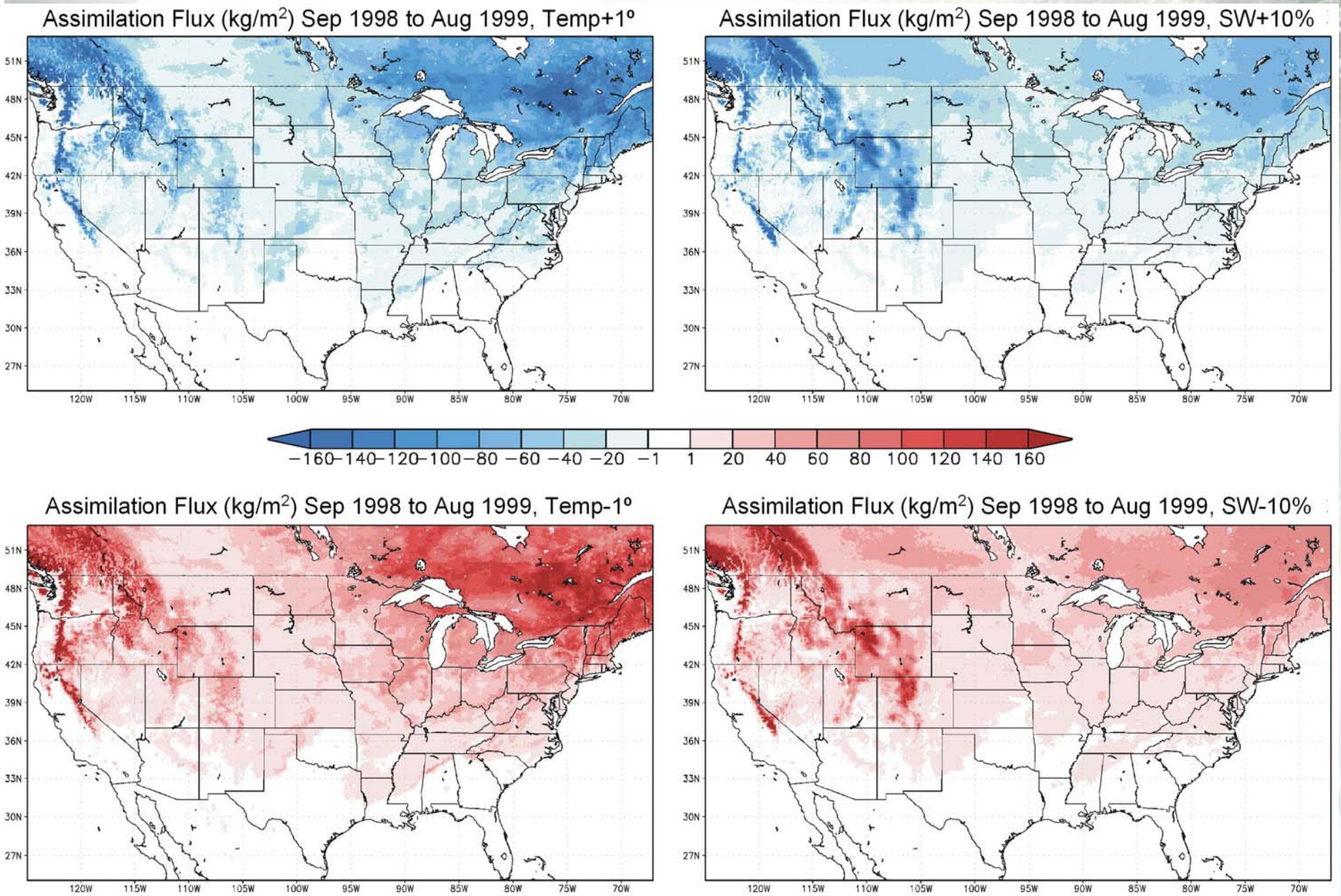


Mosaic LSM Experiments

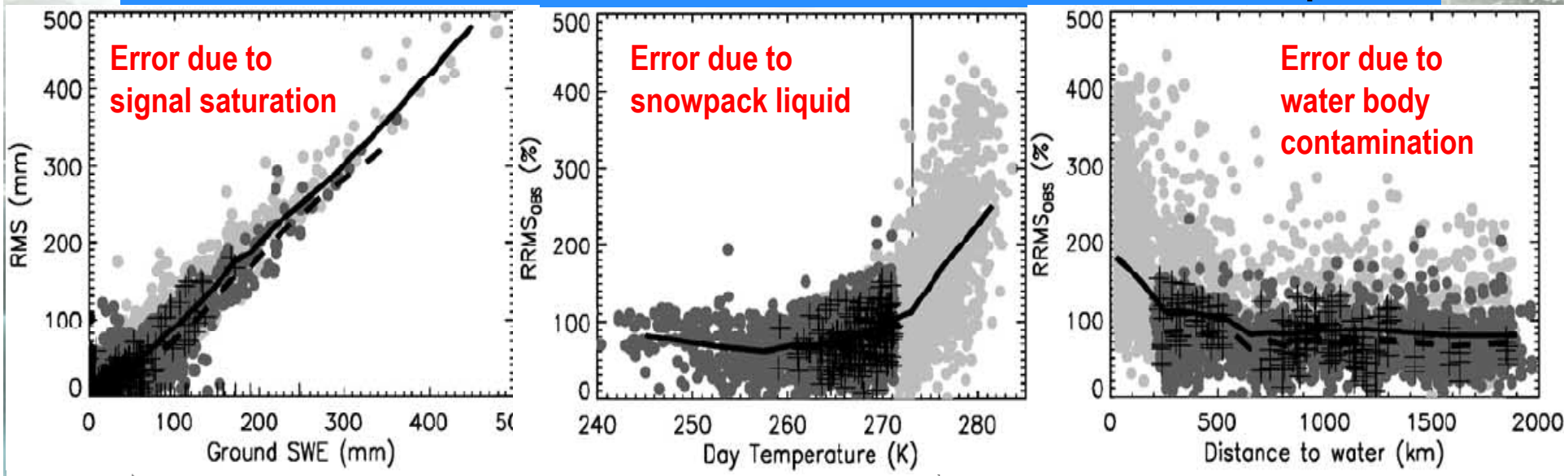


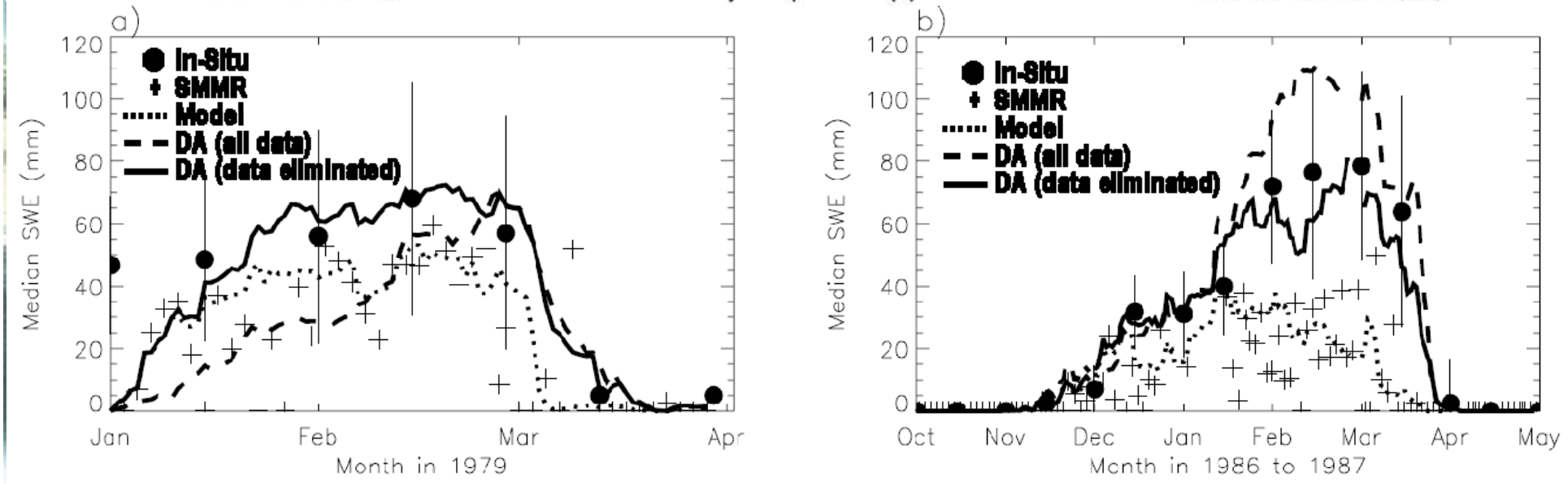
- Excessive melting and replenishment of snow in experimental runs similar to that in the EDAS data

Snow Data Assimilation: Impact of bias



SMMR Snow Retrieval Error & Assimilation Impact

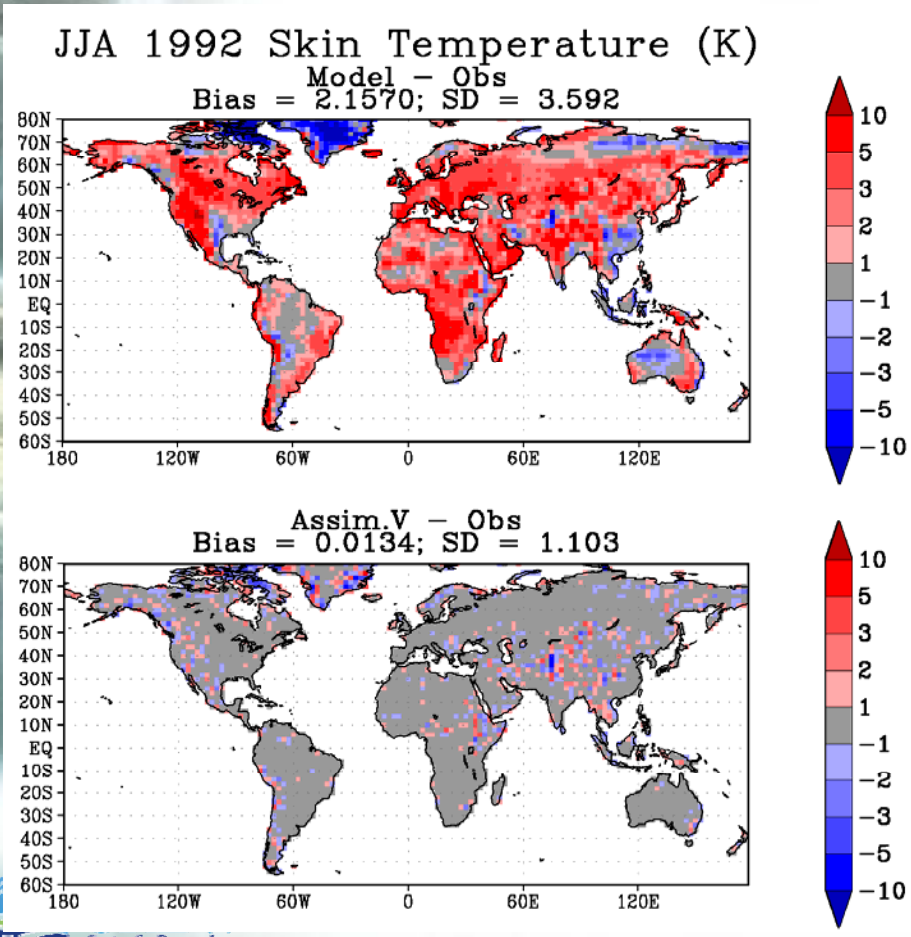


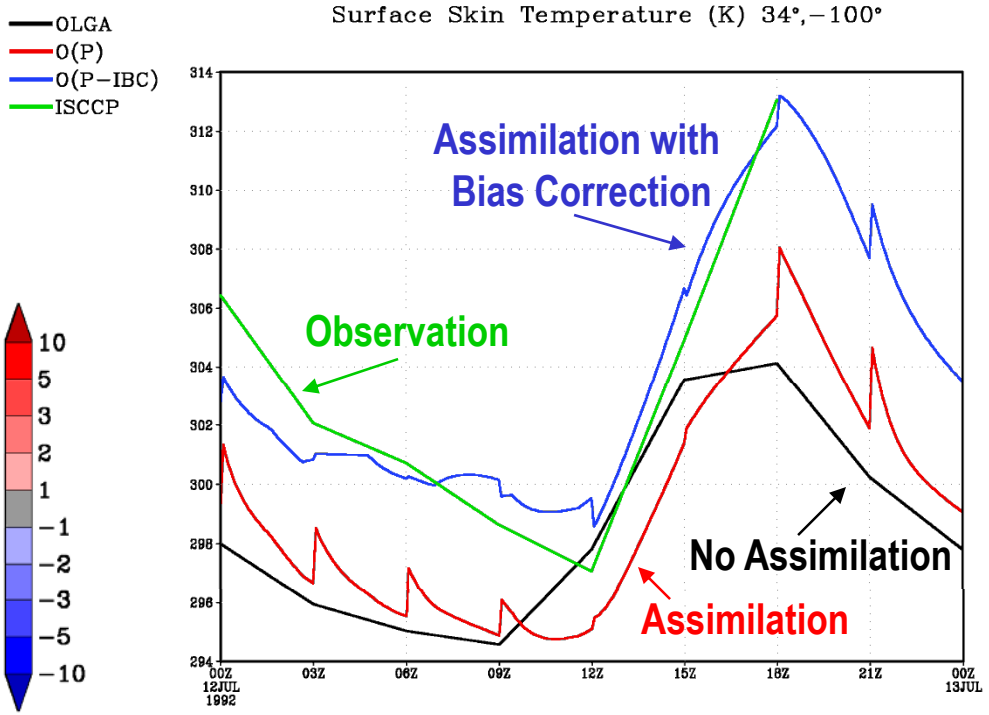


Dong et al., 2005, 2006

Data Assimilation: T_s Assimilation Results

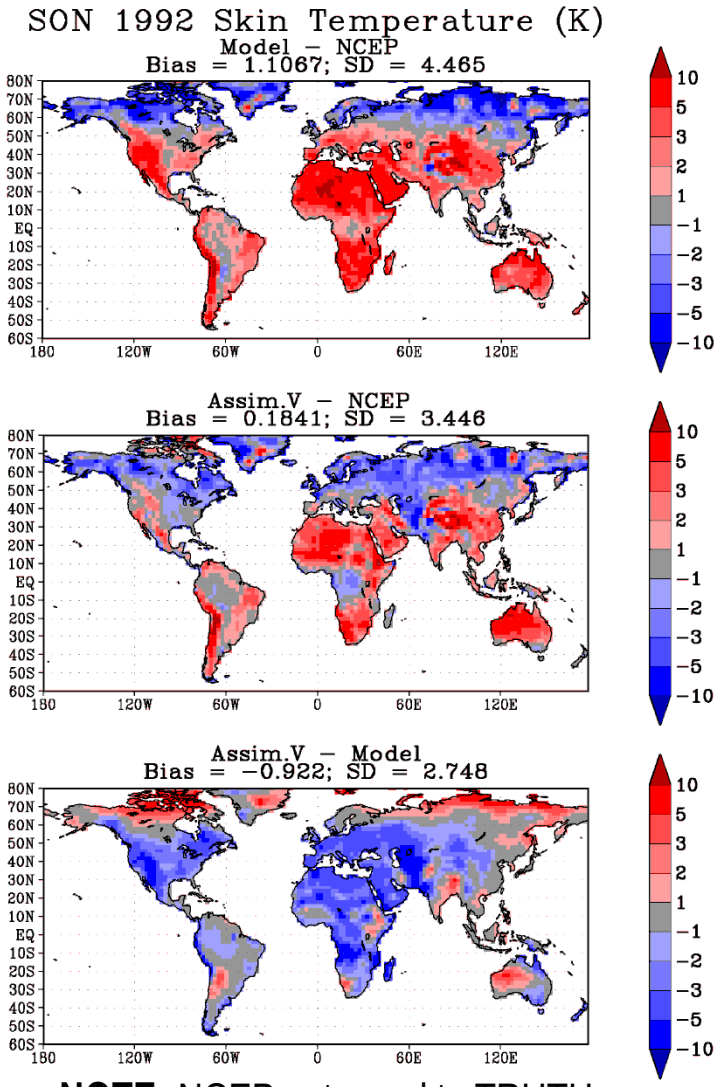
DAO-PSAS **Assimilation** of **ISCCP (IR based) Surface Skin Temperature** into a global 2 degree uncoupled land model.





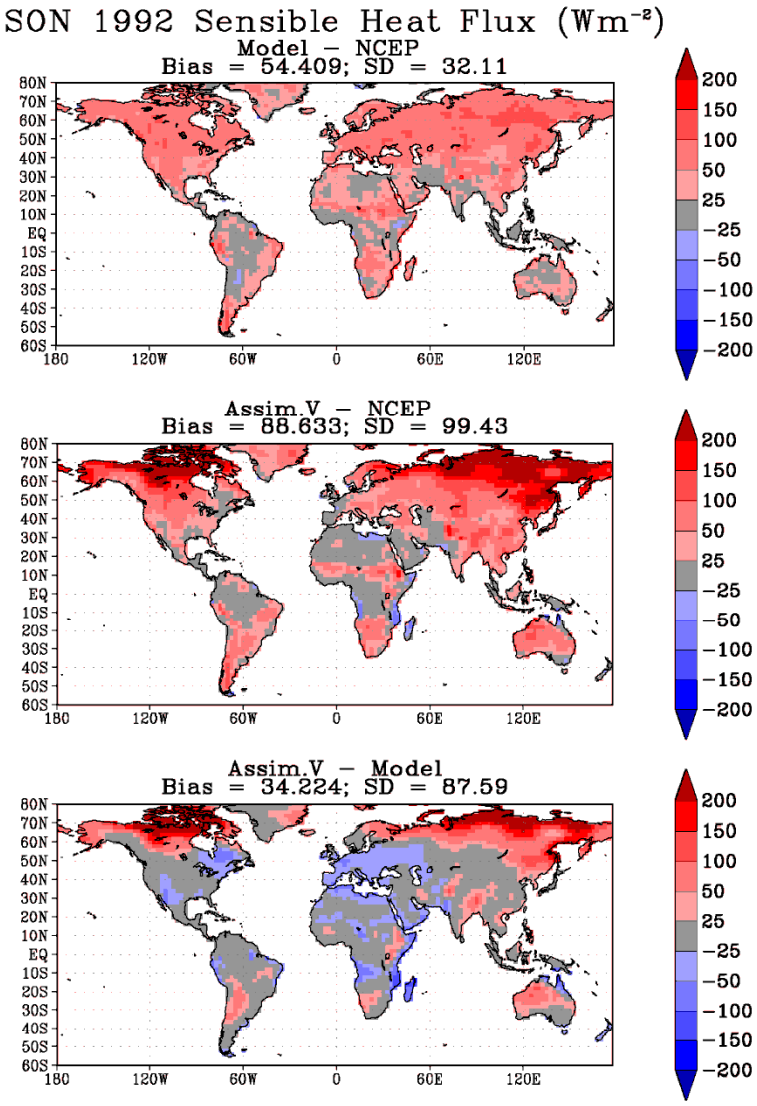
Surface temperature has **very little memory** or inertia, so without a continuous correction, it tends drift toward the control case very quickly.

Data Assimilation: T_s Assimilation Results



Comparison with NCEP Reanalysis

- Skin temperature improves significantly
- Sensible heat flux degrades due to modified near-atmosphere temperature gradient



NOTE: NCEP not equal to TRUTH

Land Surface Data Assimilation: Progress and Realities

Current Status:

- Soil moisture, skin temperature, and snow assimilation have been demonstrated.
- Evapotranspiration, runoff, groundwater (gravity), and carbon assimilation are underway

Data Assimilation Tradeoffs:

- Tradeoff between using **complex data assimilation techniques,** the **ability to use all the available data** and **operational needs and realities** due to the large computational burdens.
- Tradeoff in dimensionality of data assimilation methods –need may depend on scale.
- Tradeoff between fine resolution and large area implementation.

Land Surface Data Assimilation Realities

- Large-scale land data assimilation is severely limited by a lack of observations.
- Observation and model *errors are not known* – educated guesses must be used.
- We need to pay attention to the *consequences of assimilation*, not just the optimum assimilation technique. i.e. does the model do silly things as a result of assimilation, as in snow assimilation example.
- Land model physics can be biased, leading to incorrect fluxes, given correct states.
- Most land observations are only available at the surface, meaning that biased differences in surface observations and predictions can be improperly propagated to depth.
- Assimilation does not always make everything in the model better. In the case of skin temperature assimilation into an uncoupled model, biased air temperatures caused unreasonable near surface gradients to occur using assimilation that lead to questionable surface fluxes.

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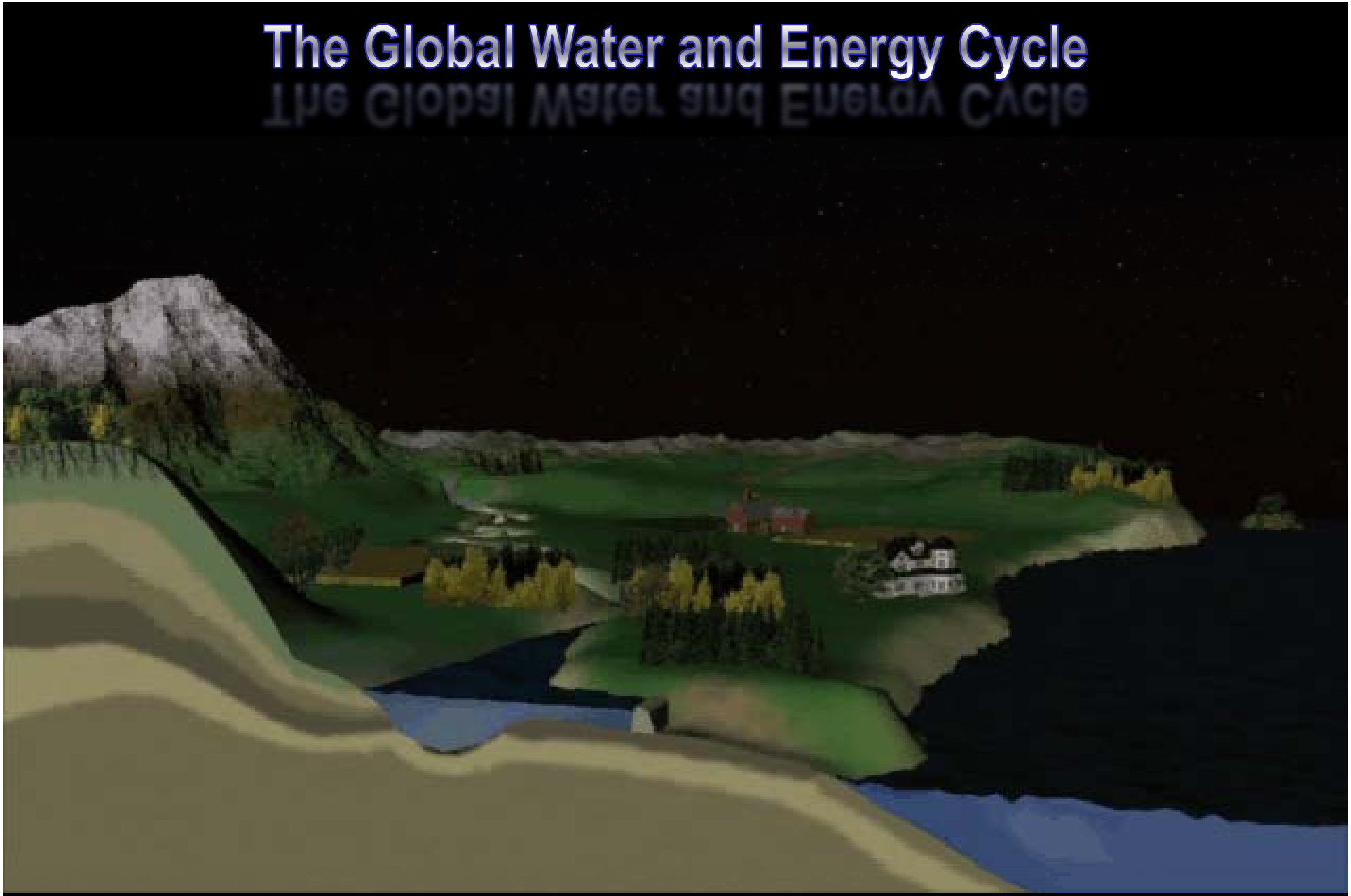
The Global Water and Energy Cycle



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