Land Data Assimilation & the Global Water Cycle

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George Mason University

Water Cycle Research Making a Difference

Acknowledging:
Adam Schlosser, Jeff Walker, Brian Cosgrove, Rolf Reichle, Jared Entin

http://crew.iges.org

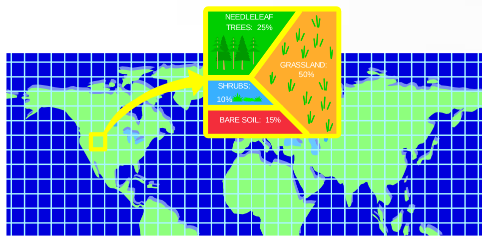
Background: Land Surface Modeling

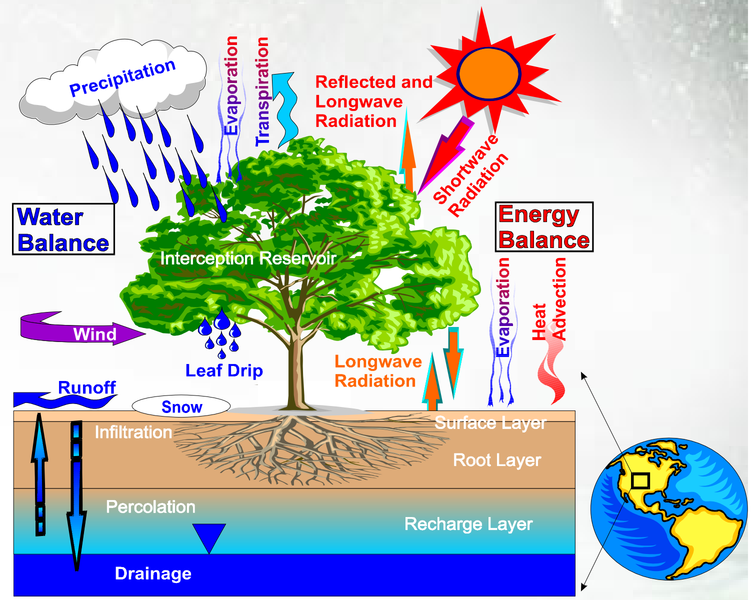
Land Surface Prediction: Accurate land model prediction is essential to enable data assimilation methods to propagate or extend scarce observations in time and space. Based on *water and energy balance*.

Input - Output = Storage Change

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S$$

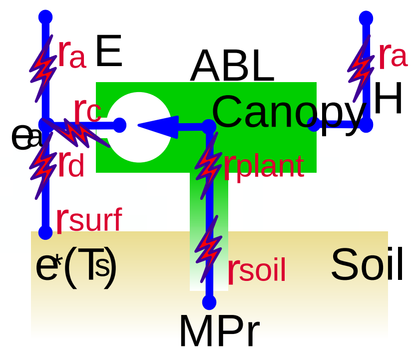
$$R_n - G = L_e + H$$

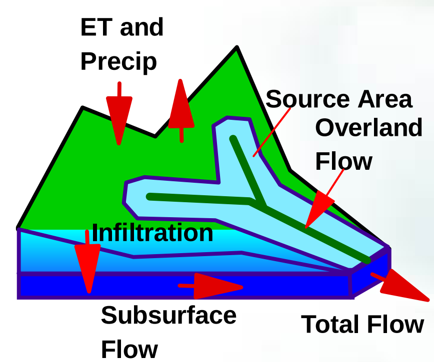




Mosaic (Koster, 1996):
- Based on simple SiB physics.
- Subgrid scale "mosaic"

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

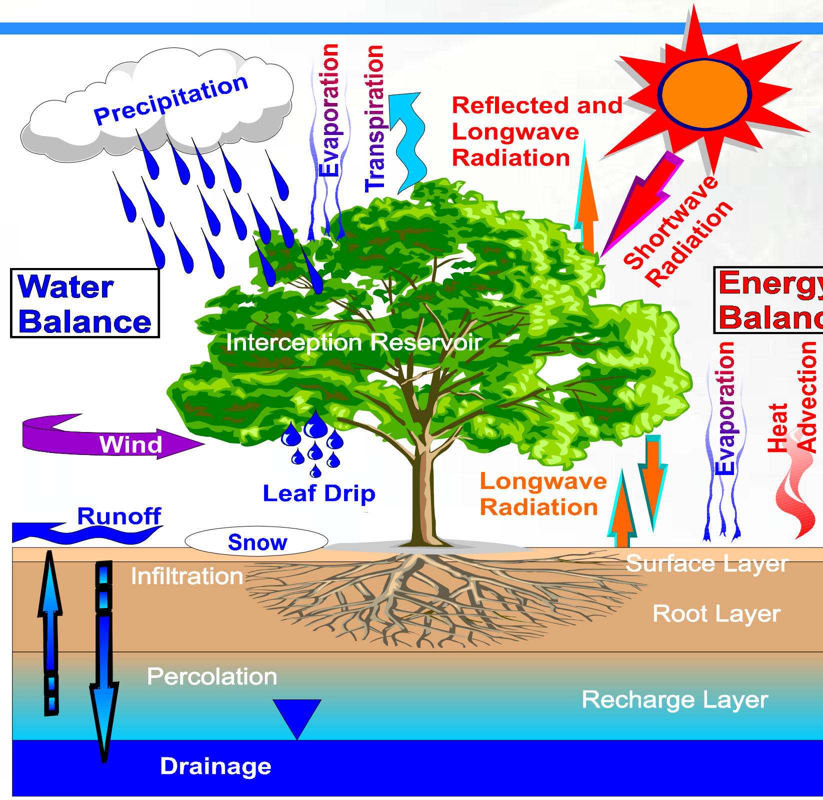
Forcing

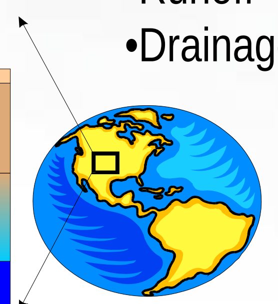
- Precipitation
- Wind
- Humidity
- Radiation
- Air Temperature

Calibration

Parameters

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

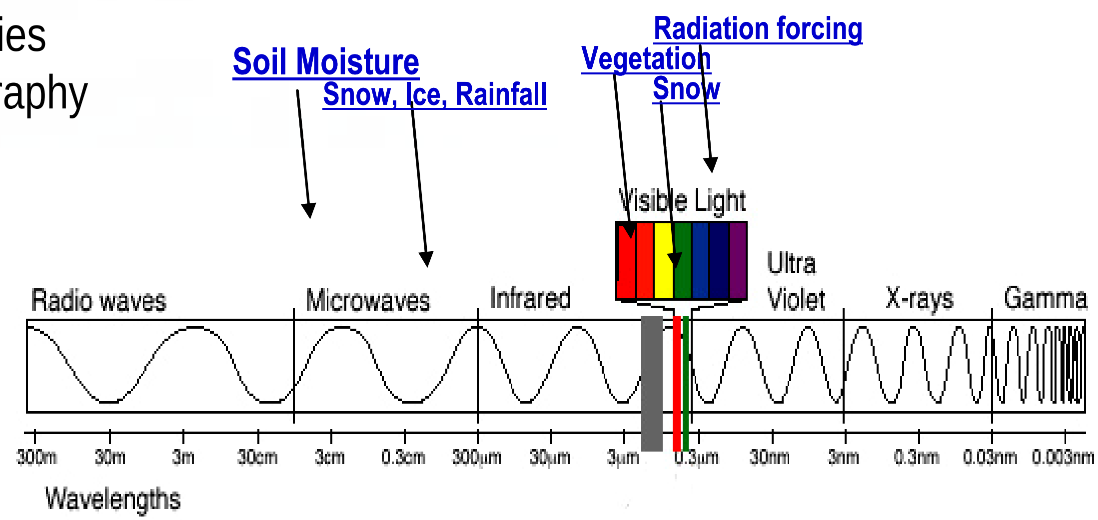




Validation

Fluxes

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



Assimilation

States

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

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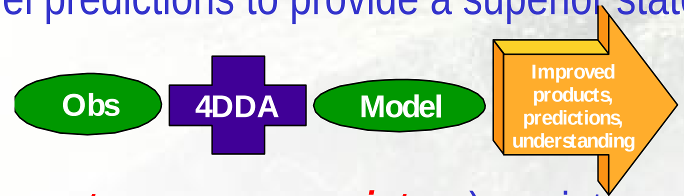
Hydrologic *Data Assimilation*

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

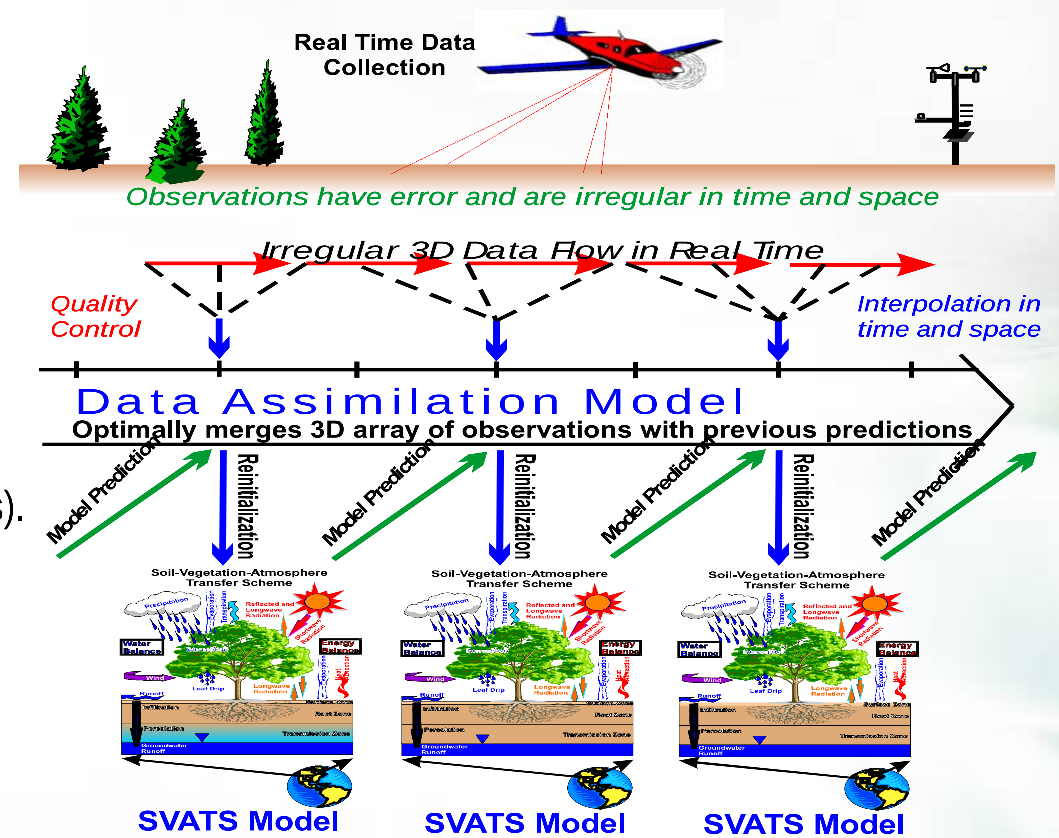
$$\partial x / \partial t = dynamics + physics + \Delta x$$



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 Data Assimilation: Overview

Ultimate Goal: ***Operationally*** **obtain high quality land surface conditions and fluxes.**

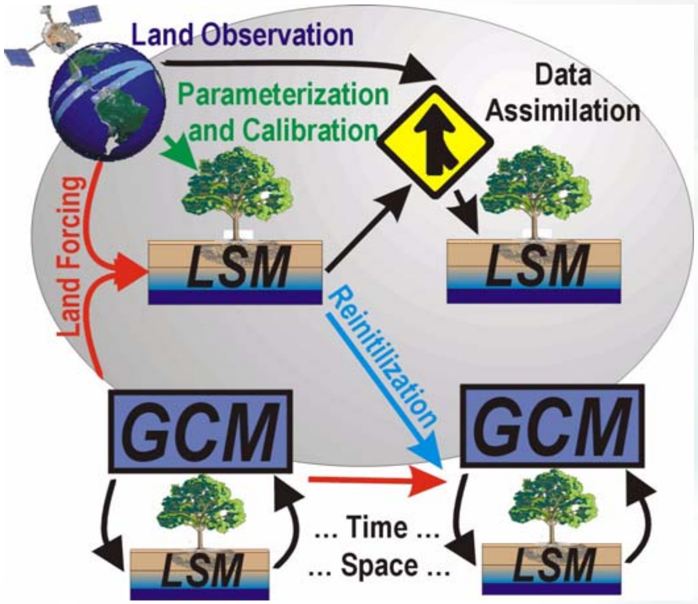
- Optimal integration of land surface observations and predictions.
- Continuous in time & space; local to global scales; retrospective, real-time, and forecasts.

Contributions:

- 4DDA Fields: 4DDA process and new merged data fields useful for research (**process understanding**), applications (**floods/agriculture/drought**), and **weather/climate prediction**.
- Model refinement: Constant confrontation with observations will force model improvements.
- Forecast improvement: Better initial conditions and improved models, predictions of weather, climate, and hydrologic phenomena on various timescales will improve.
- Observation needs: Define characteristics of most important observations, establish observation error criteria.

Components:

- **Observation**: Land surface forcing, storages(states), fluxes, and parameters (**calibration**).
- **Simulation:** Land system process models (Hydrology, Biogeochemistry, etc.).
- **Assimilation:** Short-term state constraints=Energy and Water Storage (Temperature, Snow, Soil Moisture).

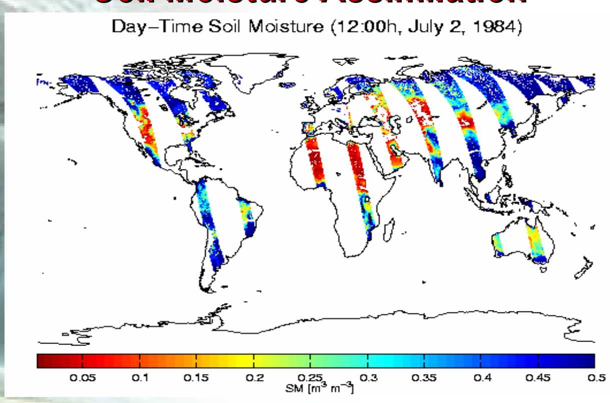


Land Surface Data Assimilation Summary

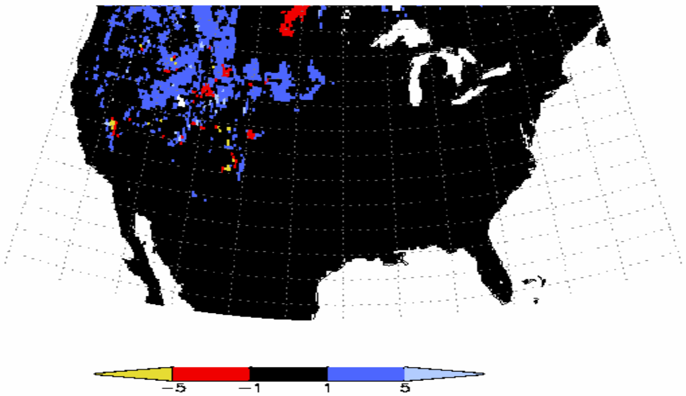
Data Assimilation merges observations & model predictions to provide a superior state estimate.

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.

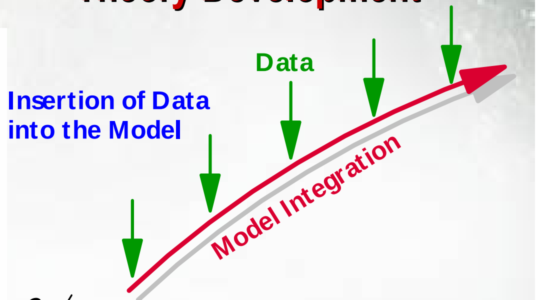
Soil Moisture Assimilation



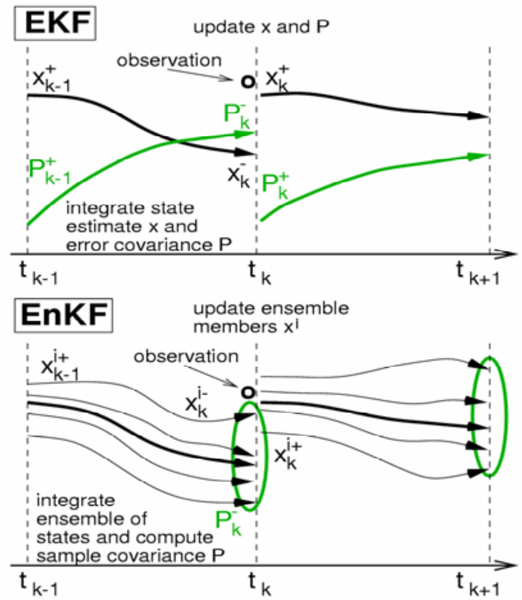
Snow Cover Assimilation



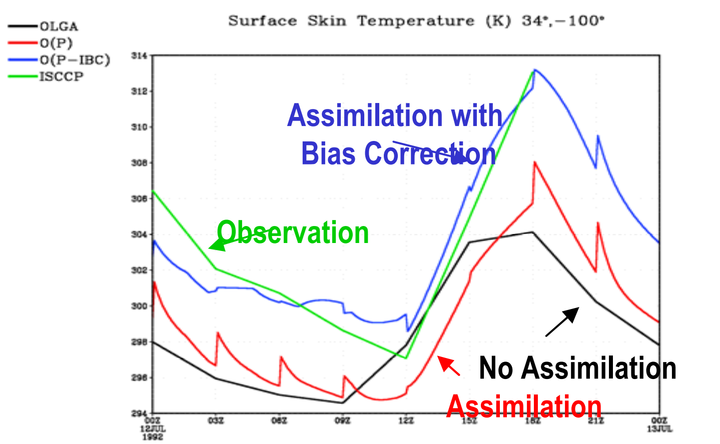
Theory Development



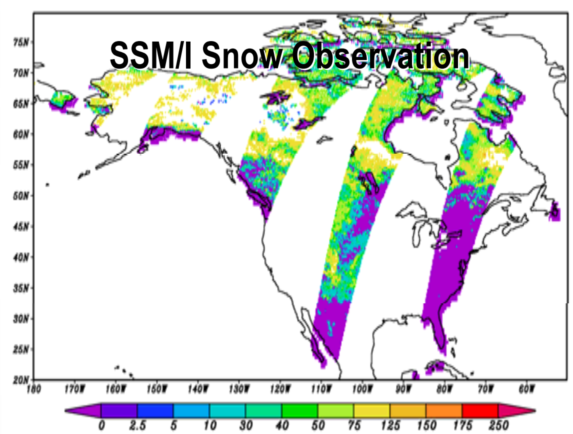
$$\partial x / \partial t = dynamics + physics + \Delta x$$



Skin Temperature Assimilation



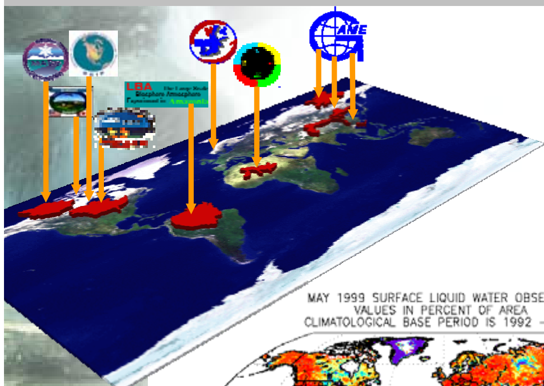
Snow Water Assimilation

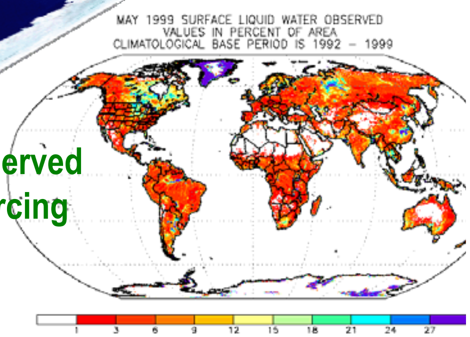


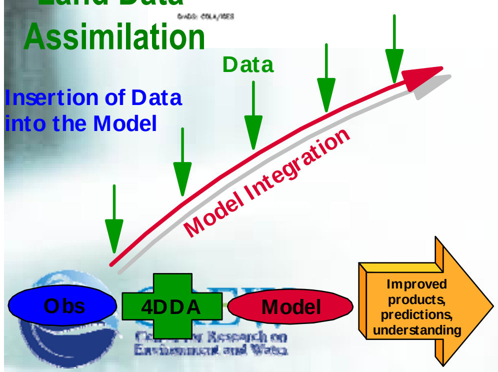
Global Land Data Assimilation System

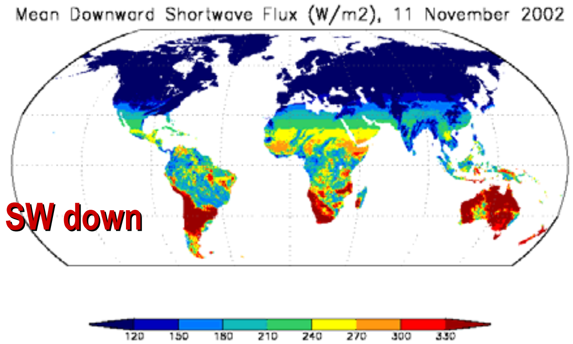
Objective: A 1/4 degree (and other) global land modeling and assimilation system that uses all relevant observed forcing, storages, and validation. Expand the current N. American LDAS to the globe. 1km global resolution goal

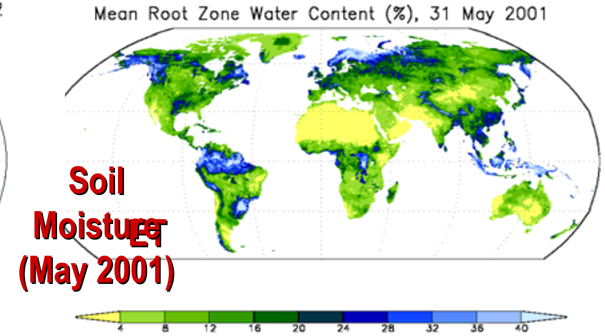
Consistent Global Intercomparison

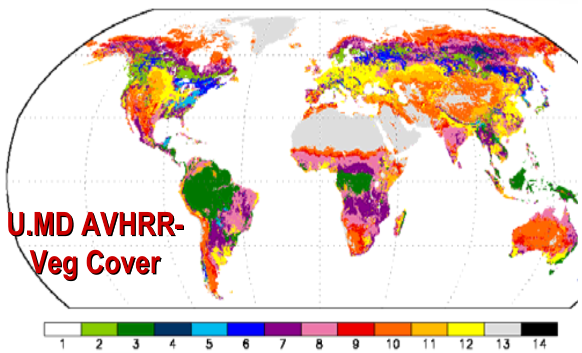


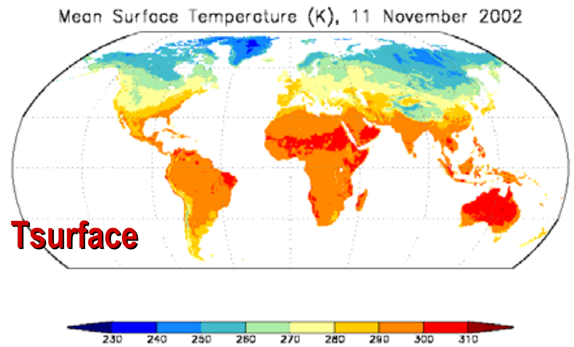


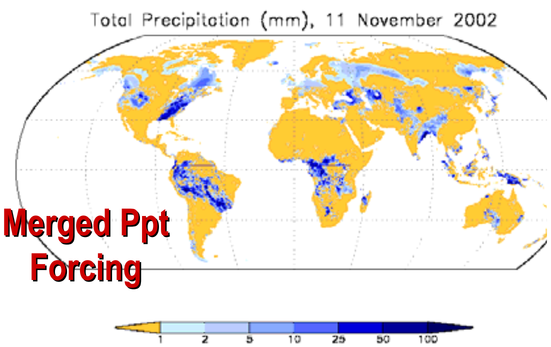


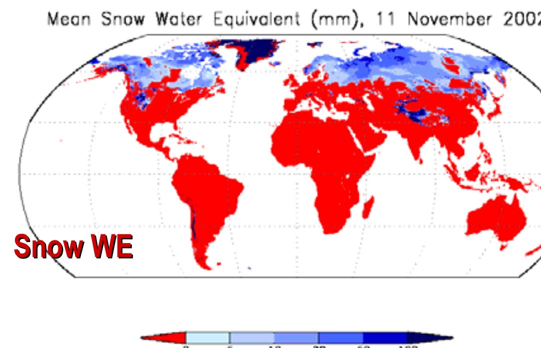










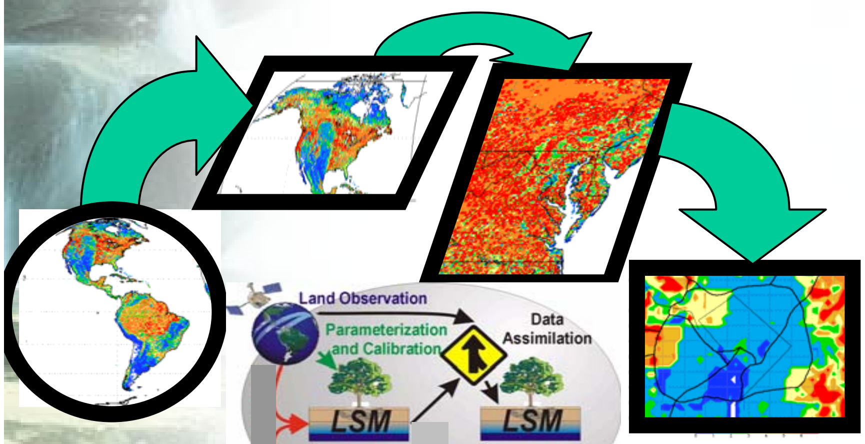


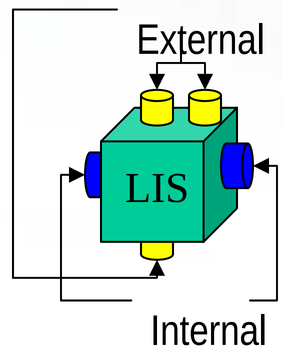
Land Information System http://lis.gsfc.nasa.gov

Co-PIs: P. Houser, C. Peters-Lidard

Summary: LIS is a high performance set of land surface modeling (LSM) assimilation tools.

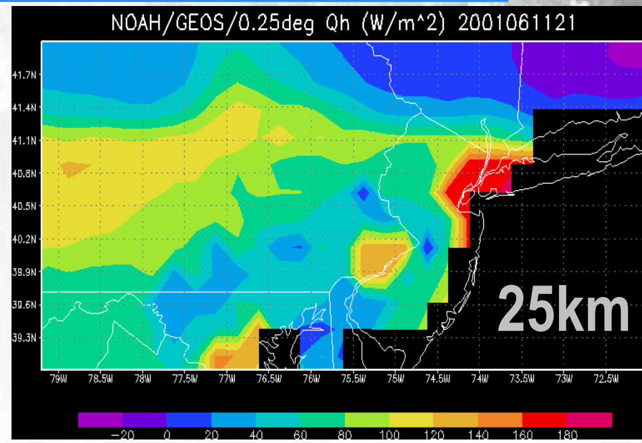
Applications: Weather and climate model initialization and coupled modeling, Flood and water resources, precision agriculture, Mobility assessment …

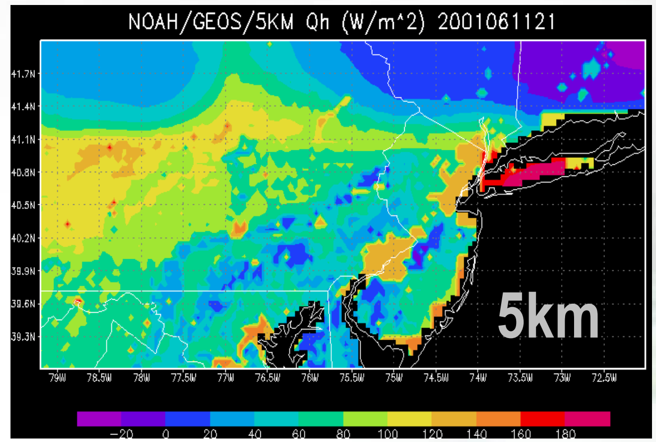


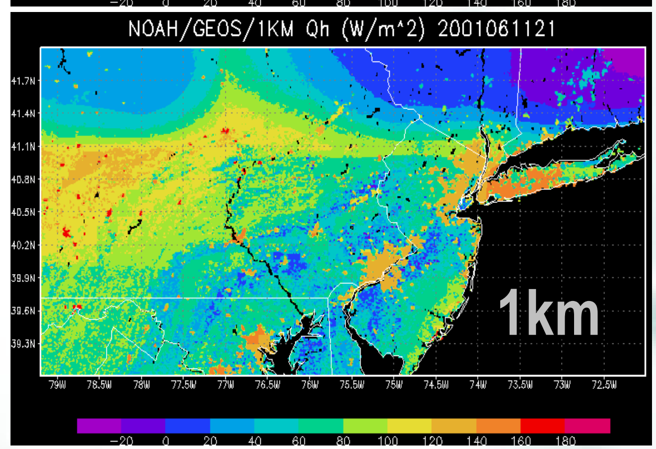


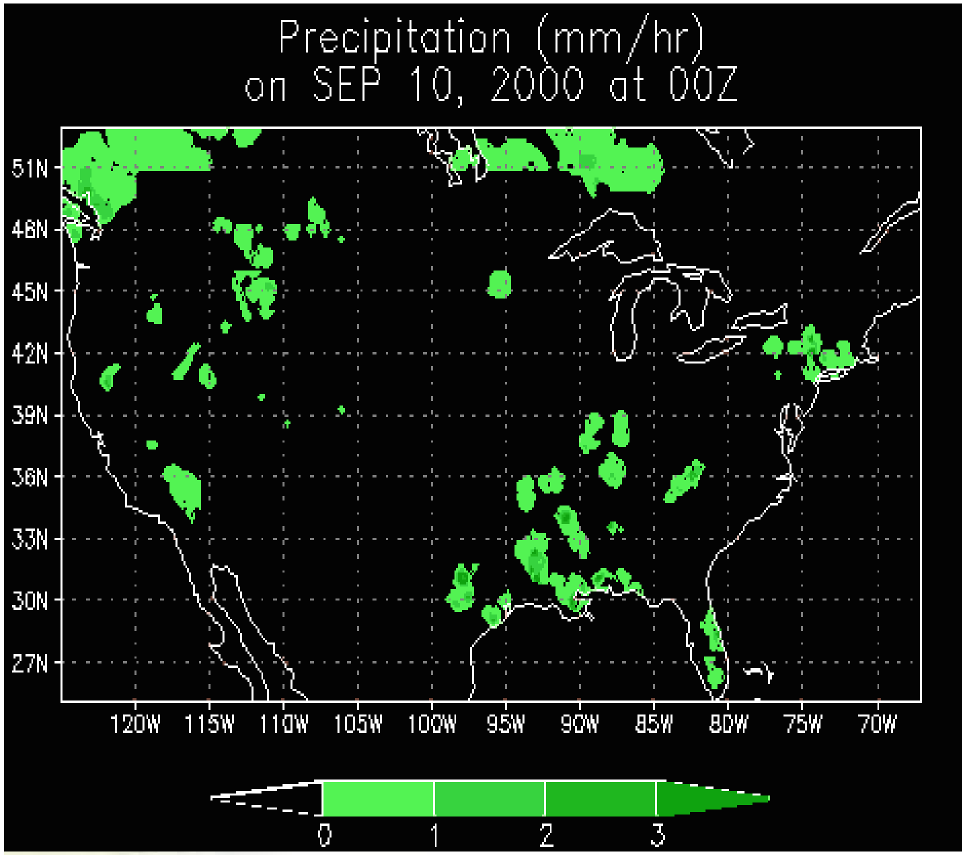
	Memory (MB)	Wallclock time (minutes)	CPU time (minutes)
LDAS	3169	116.7	115.8
LIS	313	22	21.8
reduction factor	10.12	5.3	5.3

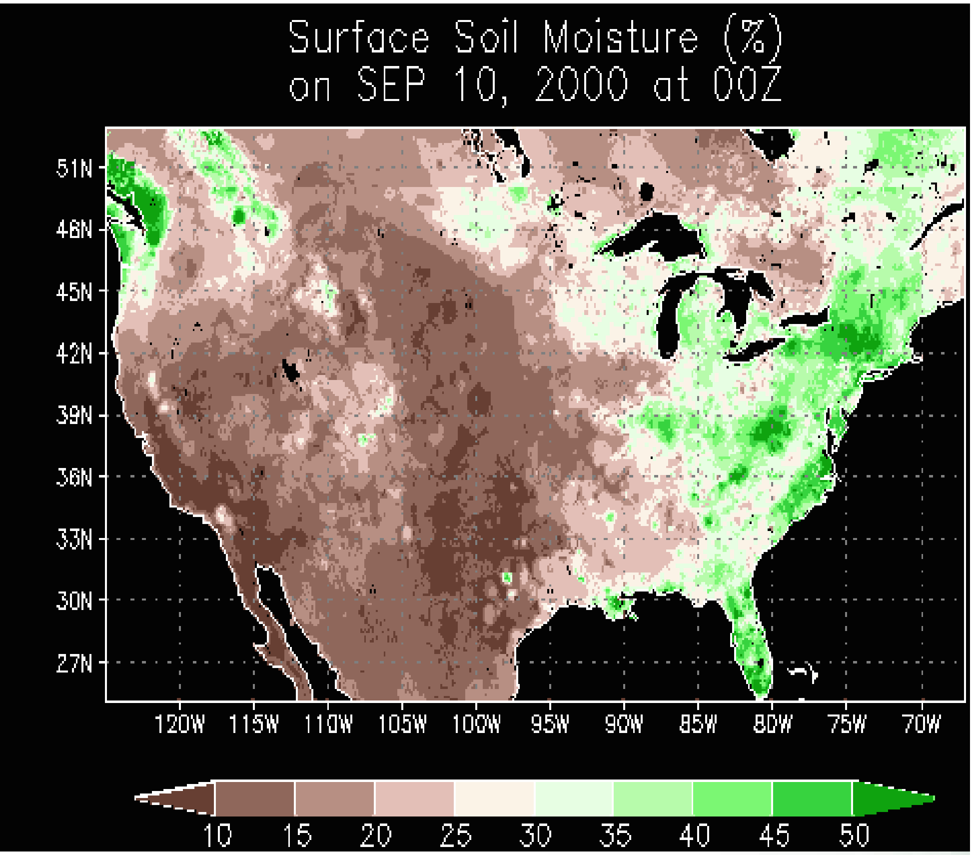
200 Node "LIS" Cluster
Optimized I/O, GDS Servers











LDAS Predictions: Hourly Sept. 2000 Precipitation and Soil Moisture

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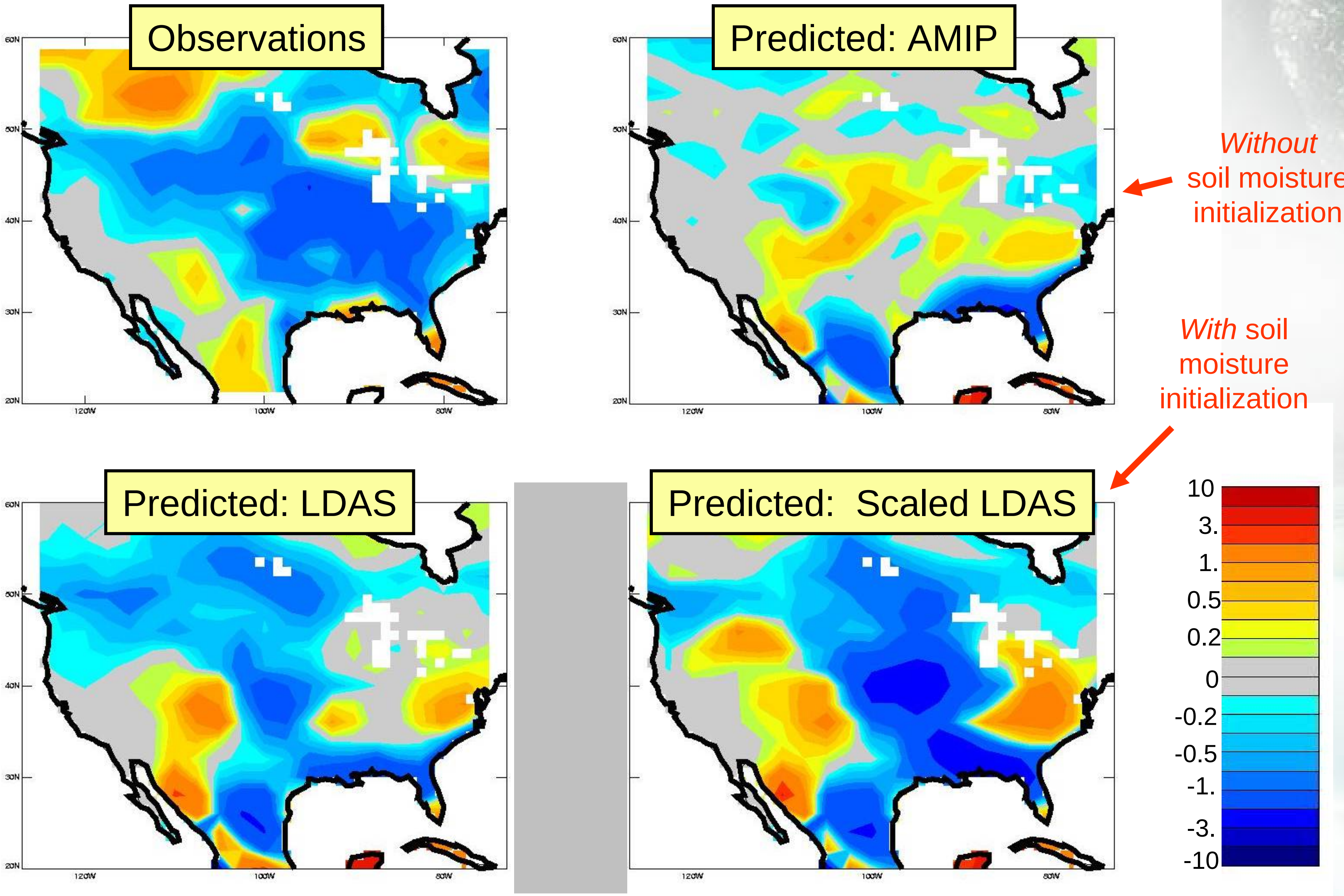
Coupled Model Forecast: 1988 Midwestern U.S. Drought

(JJA precipitation anomalies, in mm/day)

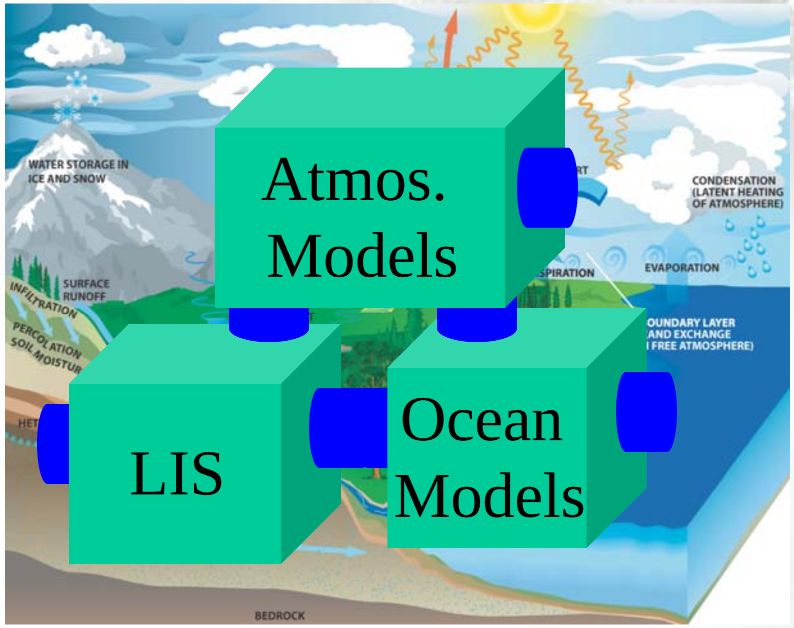


Koster et al., 2004

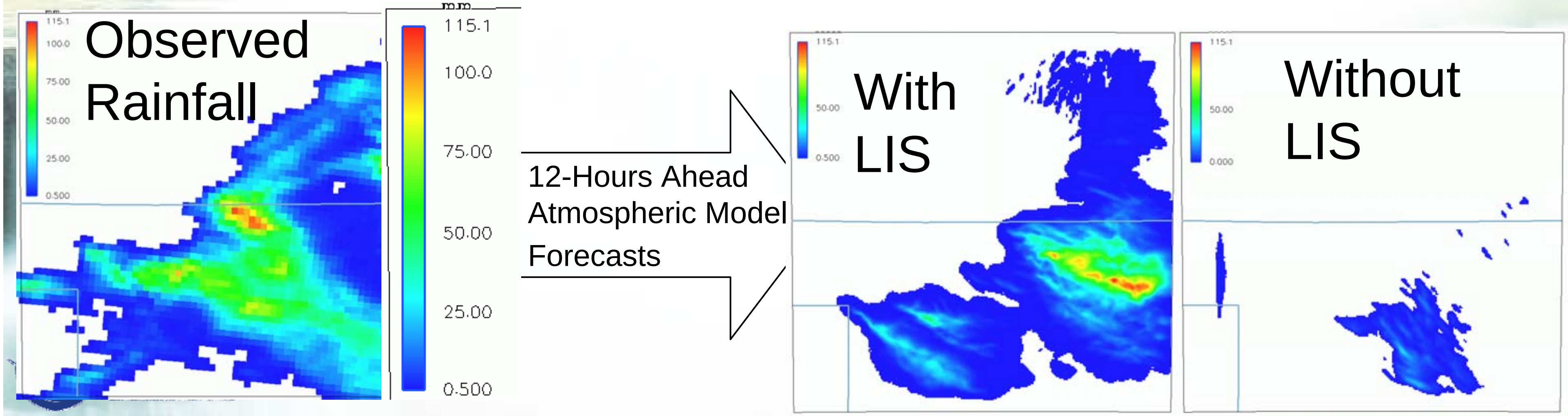
Impact: Coupled Earth System Modeling

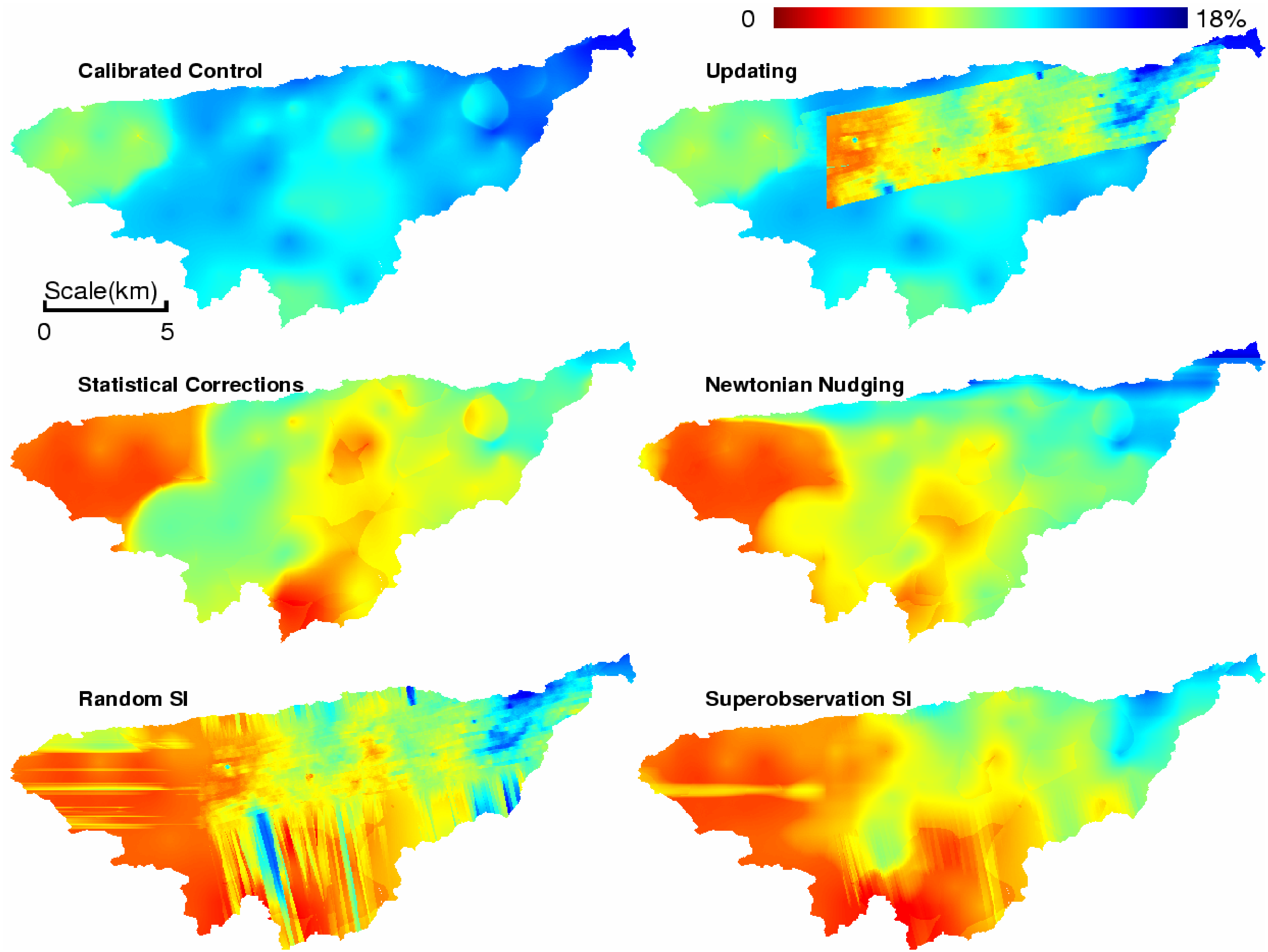
Interoperability with standards:

- The Earth System Modeling Framework (ESMF)
- Assistance for Land Modeling Activities (ALMA)



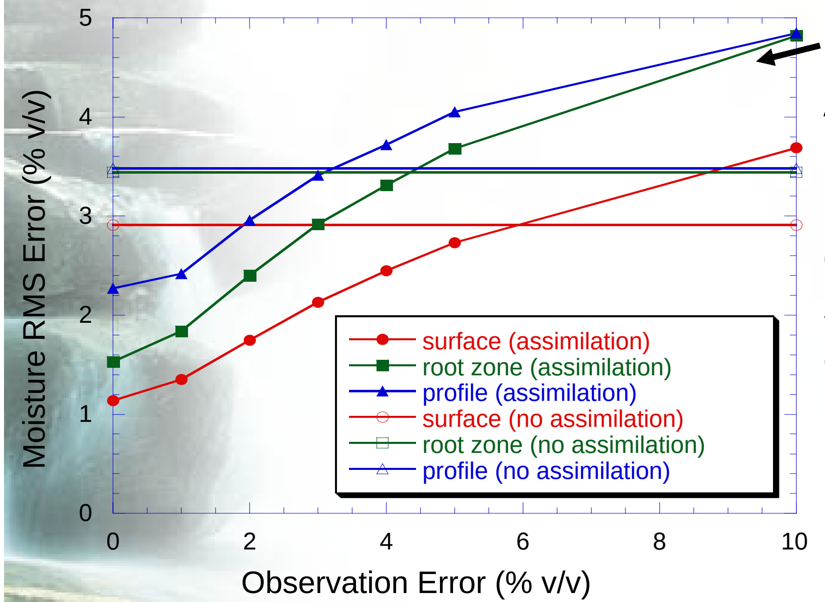
LIS Impact Example: Coupling to a Weather Model



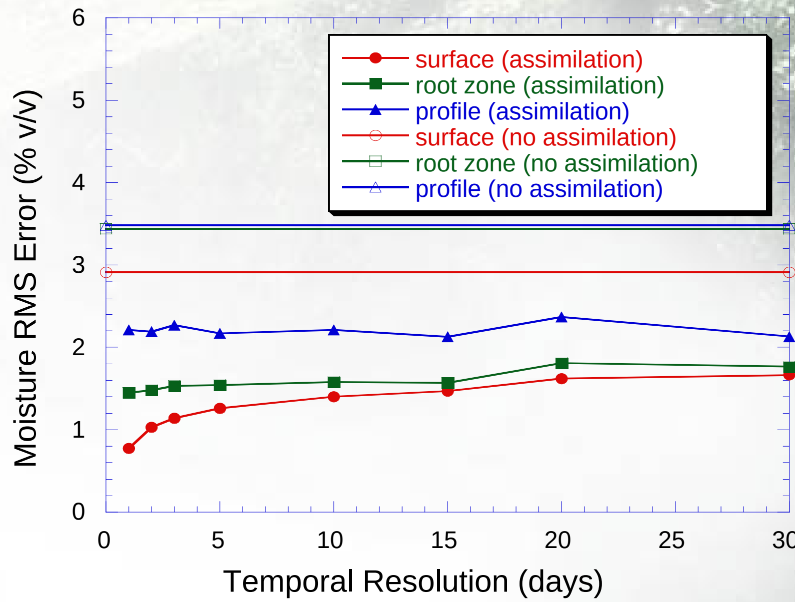


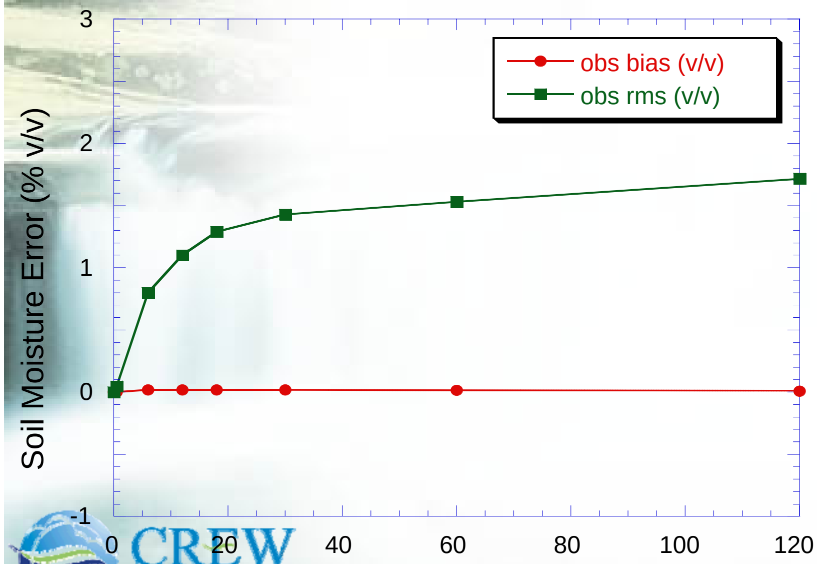
0
18%
Calibrated Control
Updating
Scale(km)
0
5
Statistical Corrections
Newtonian Nudging
Random SI
Superobservation SI

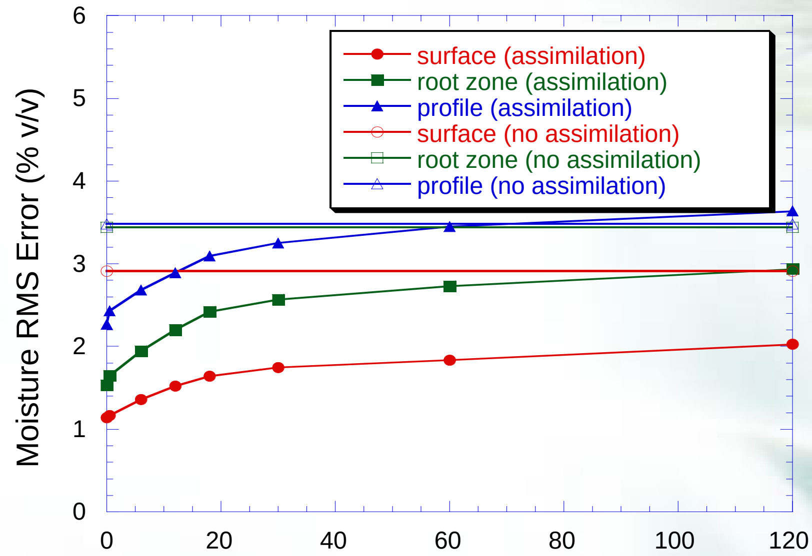
Soil Moisture Observation Error and Resolution Sensitivity:



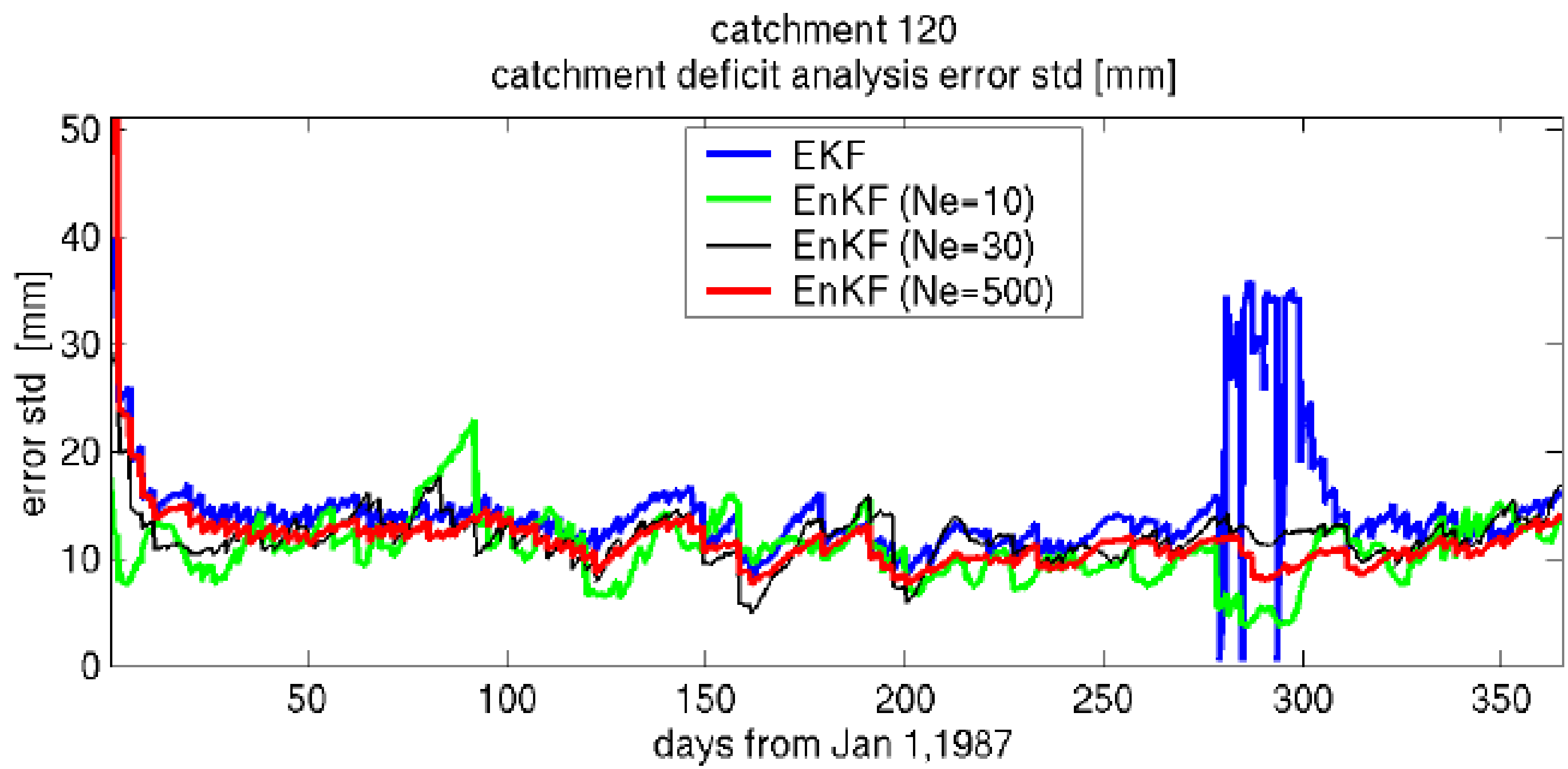
NOTE:
Assimilation of near-surface soil moisture can degrade profile soil moisture if errors are not known perfectly







Non-linear model issues

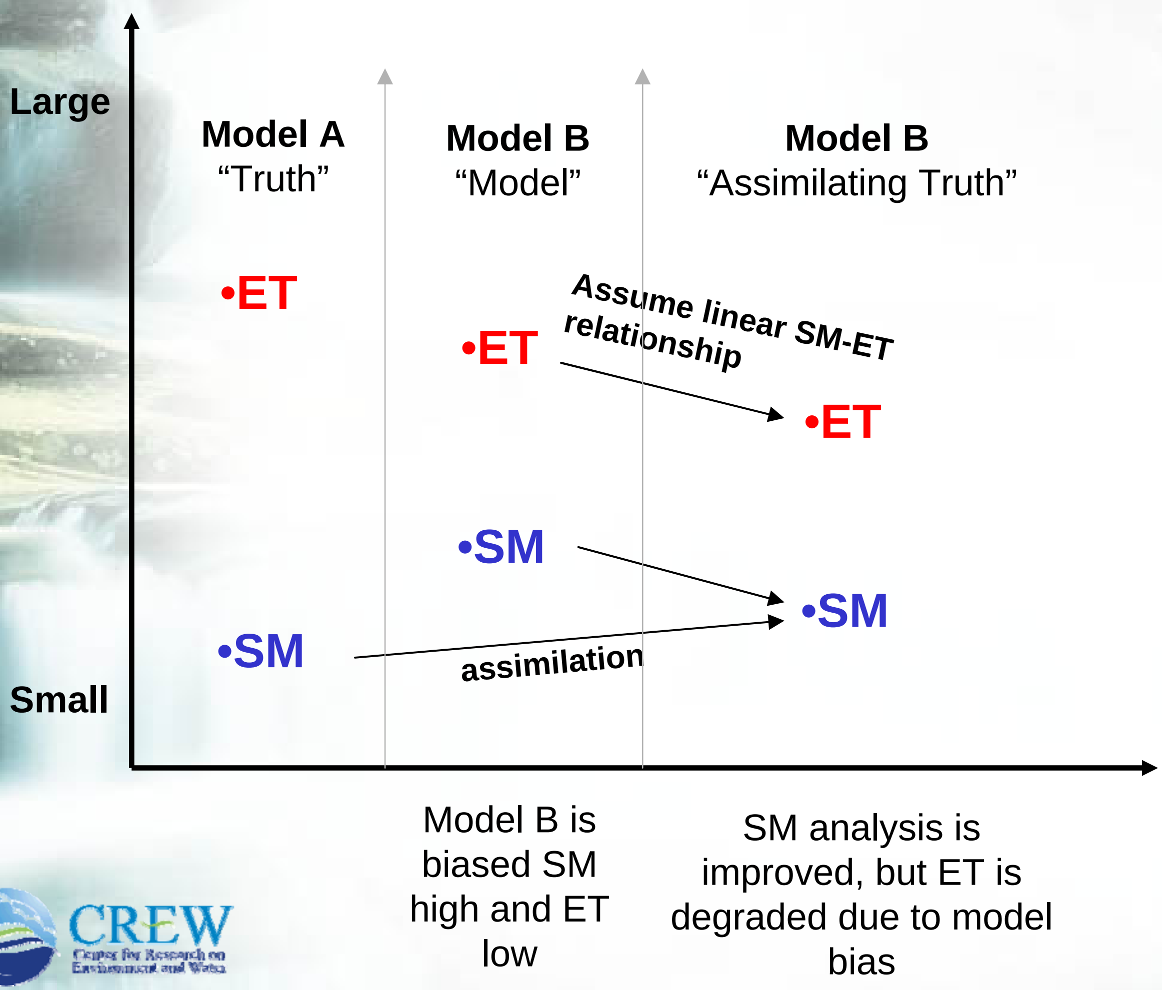


EKF error estimates diverge occasionally.

EnKF error estimates noisy for small ensemble (Ne=10).

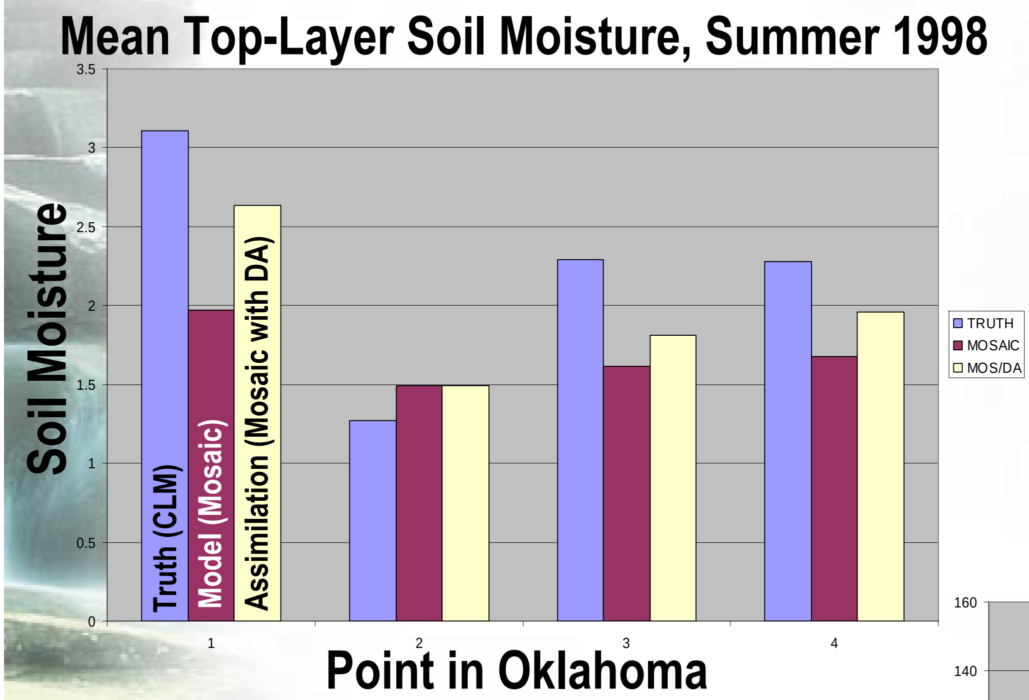
Fraternal Twin Studies

- "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.



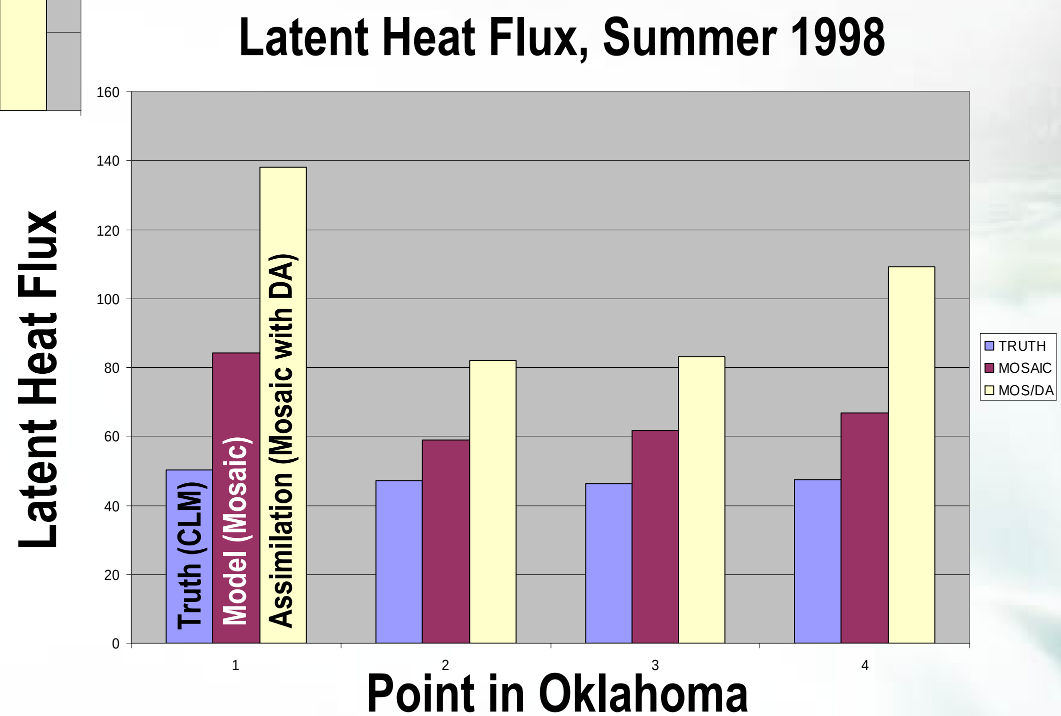
We must not only worry about obtaining an optimal model constraint, but also understand the implications of that constraint.

Fraternal Twin Demonstration



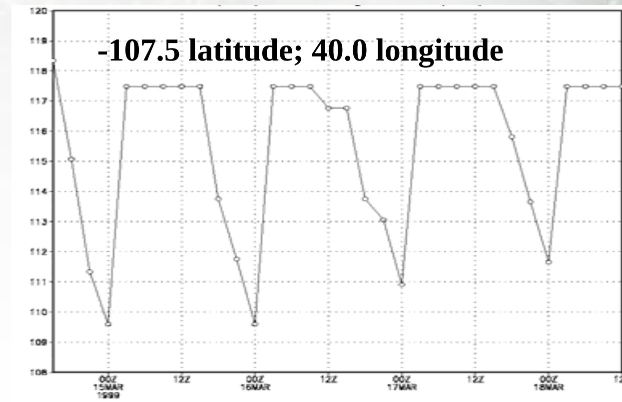
CLM=Truth

Mosaic=Faulty



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:

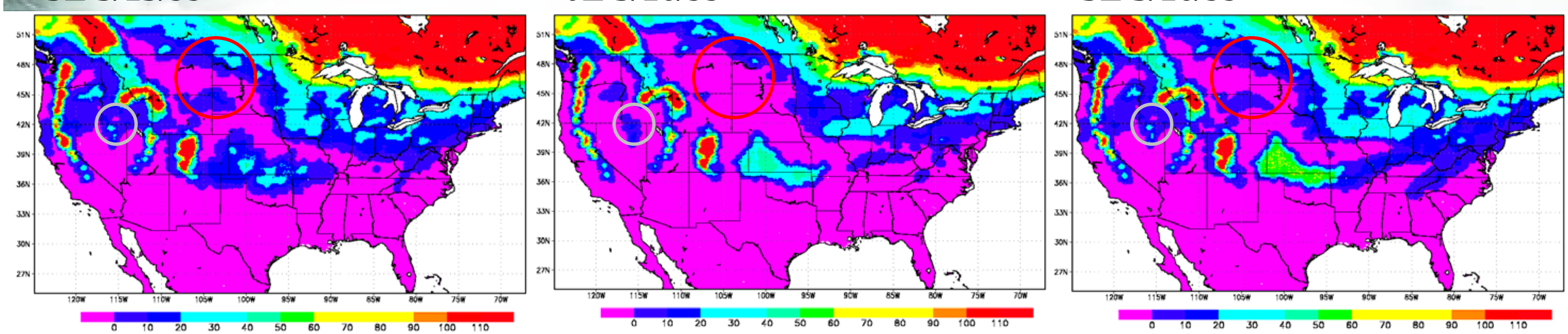
- “Dissappearing” layers and states
- Arbitrary redistribution of mass between layers
- Lack of information in SWE about snow density or depth
- Lack of information in snow cover about snow mass & depth
- Biased forcing causing divergence between analysis steps
- **OBSERVATIONS:** Snow Cover, Snow Water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

Update Time

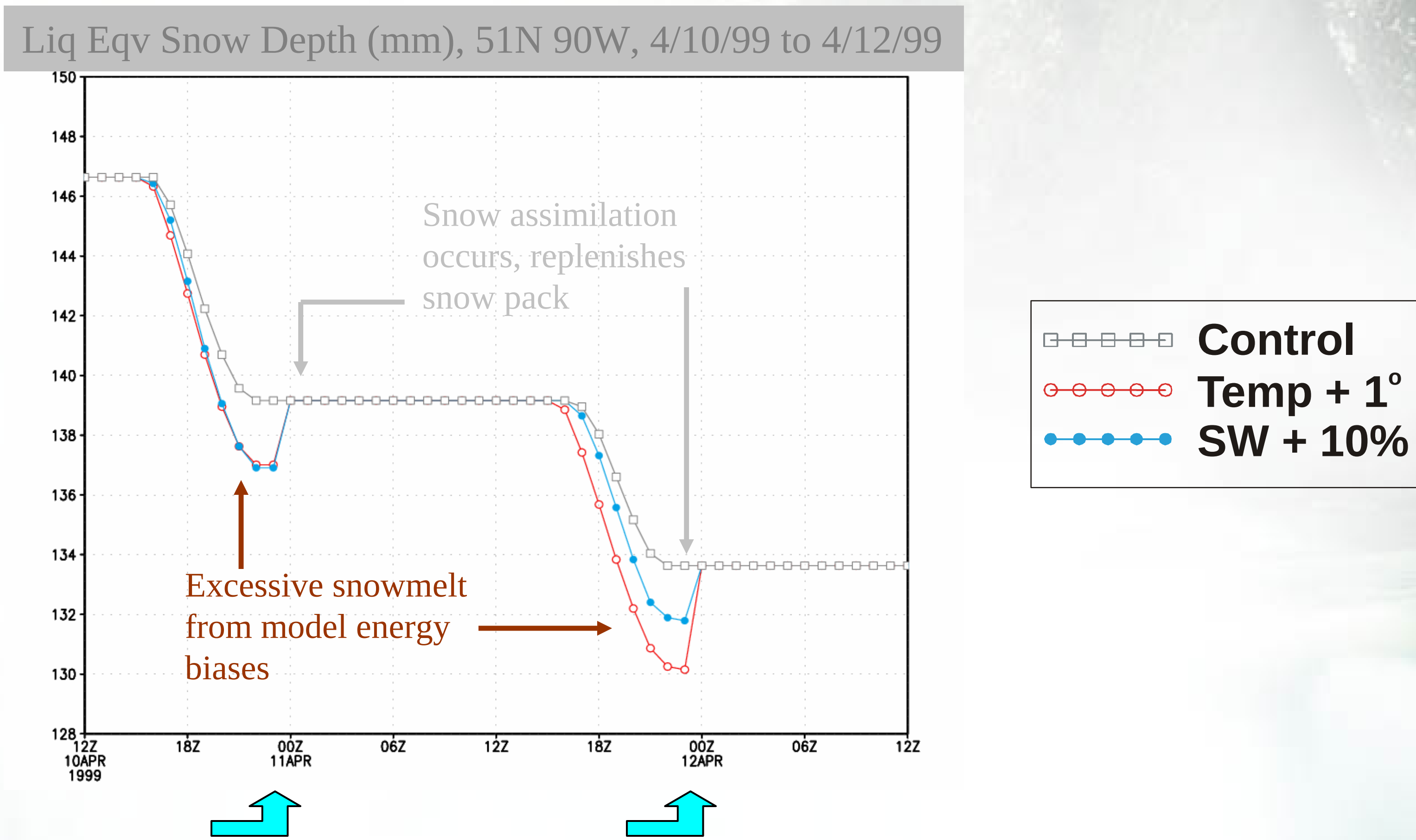
Melt

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

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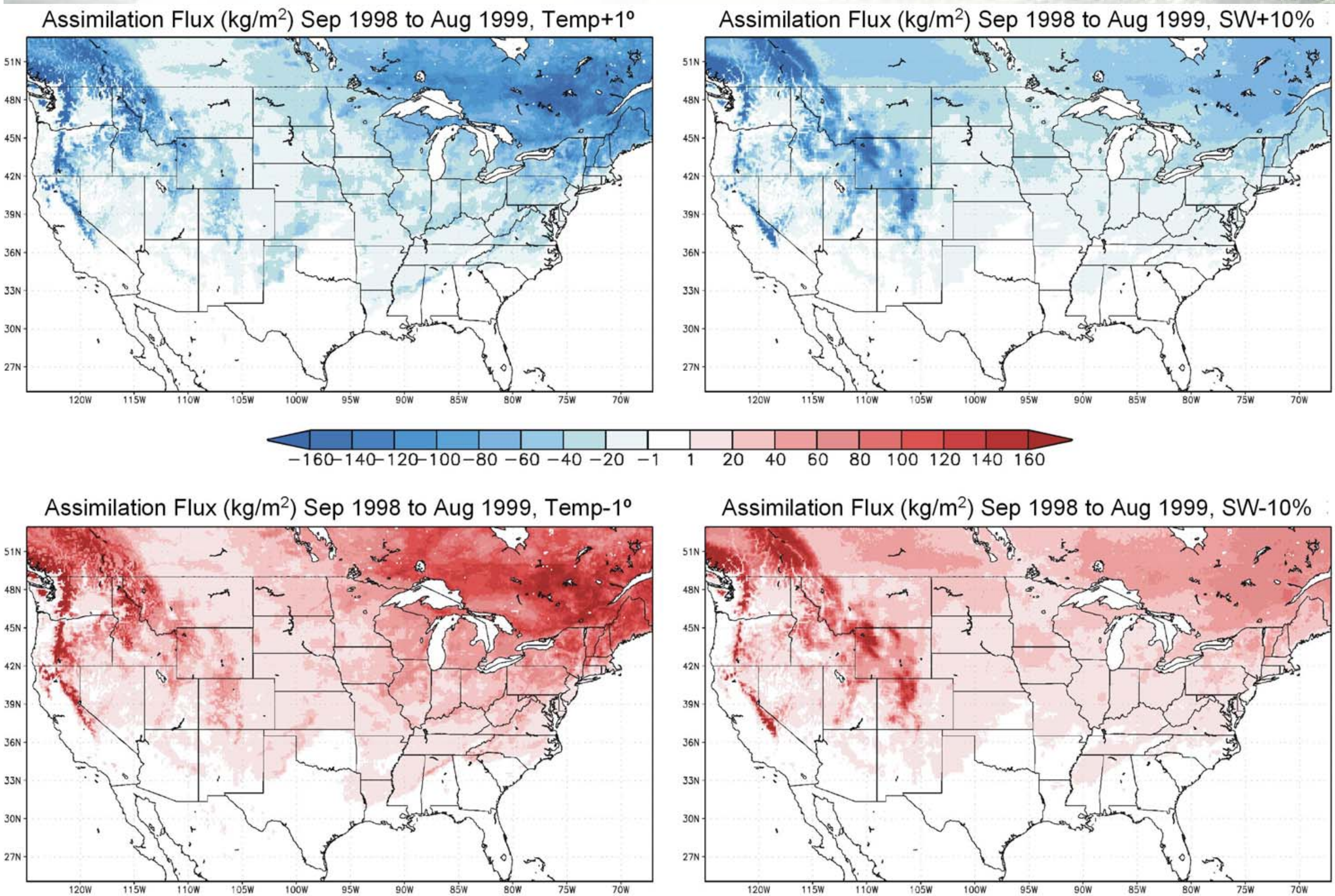
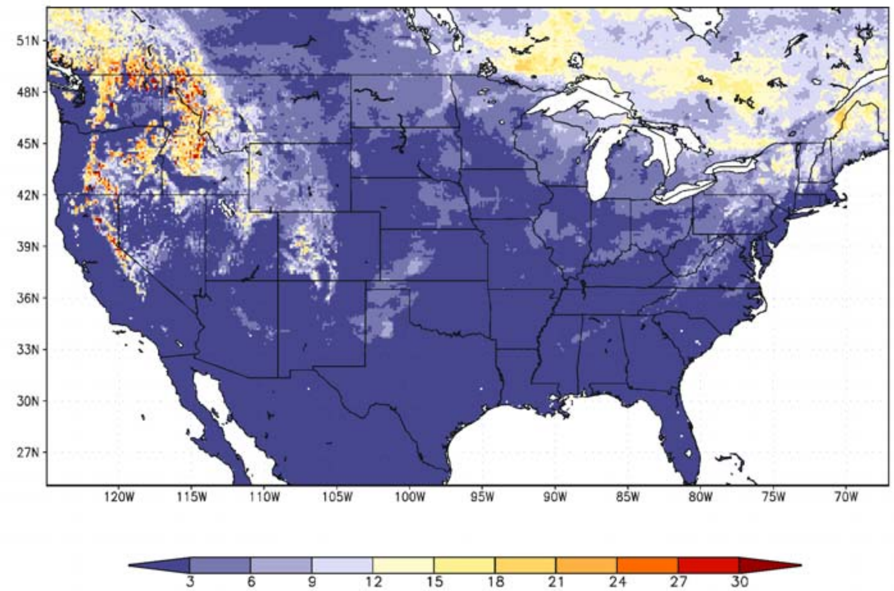
Snow Data Assimilation: Impact of bias



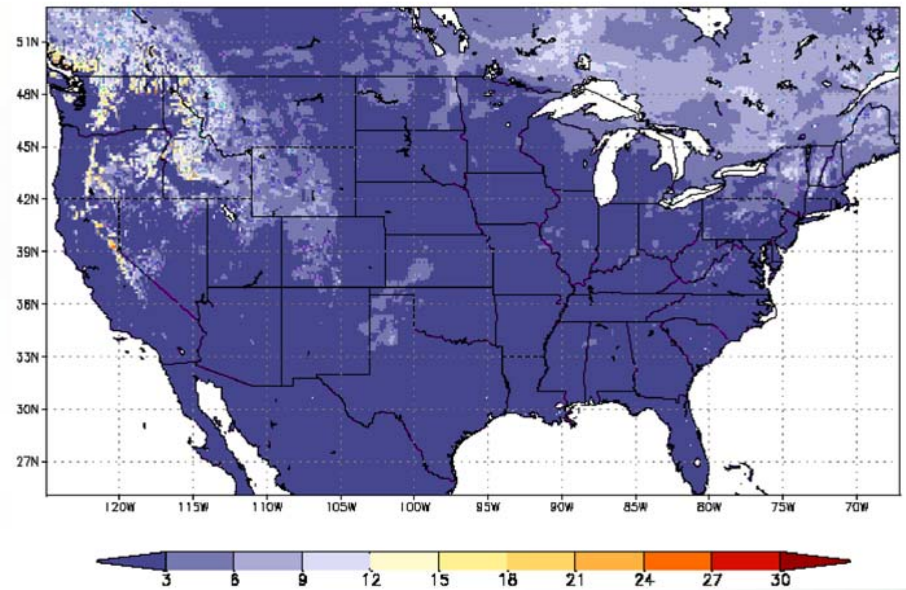
Snow Data Assimilation: Correcting Impact of bias

Snowmelt adjustment (SMA) uses observed depth change to limit melt or accumulation

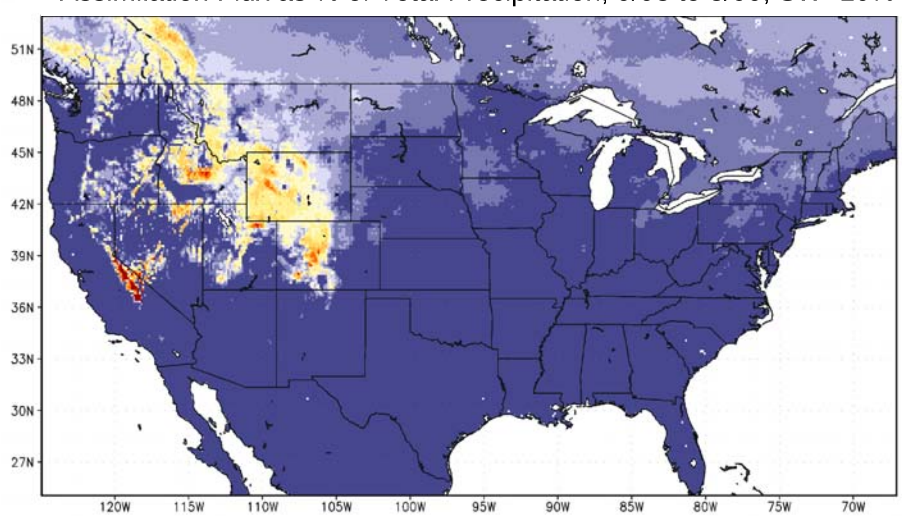
Assimilation Flux as % of Total Precipitation, 9/98 to 8/99, Tmp+1º



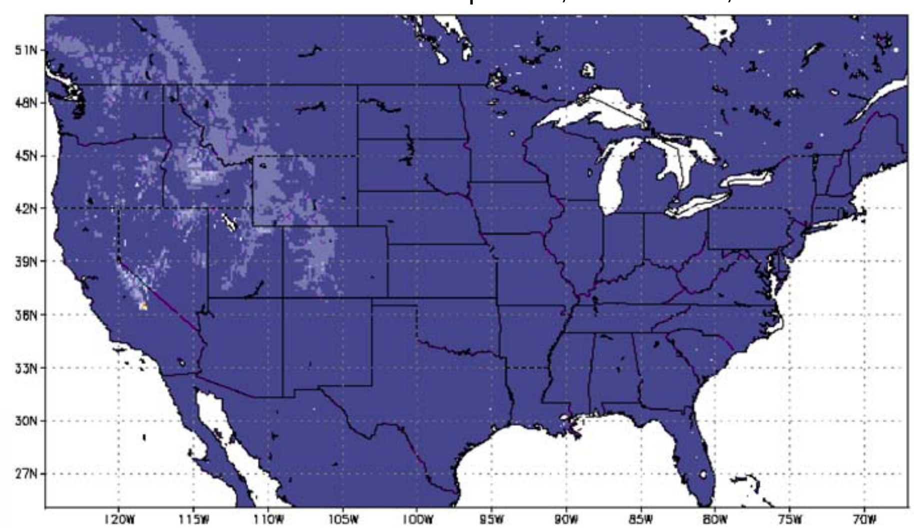
Assimilation Flux as % of Total Precipitation, 9/98 to 8/99, Tmp+1º SMA



Assimilation Flux as % of Total Precipitation, 9/98 to 8/99, SW+10%

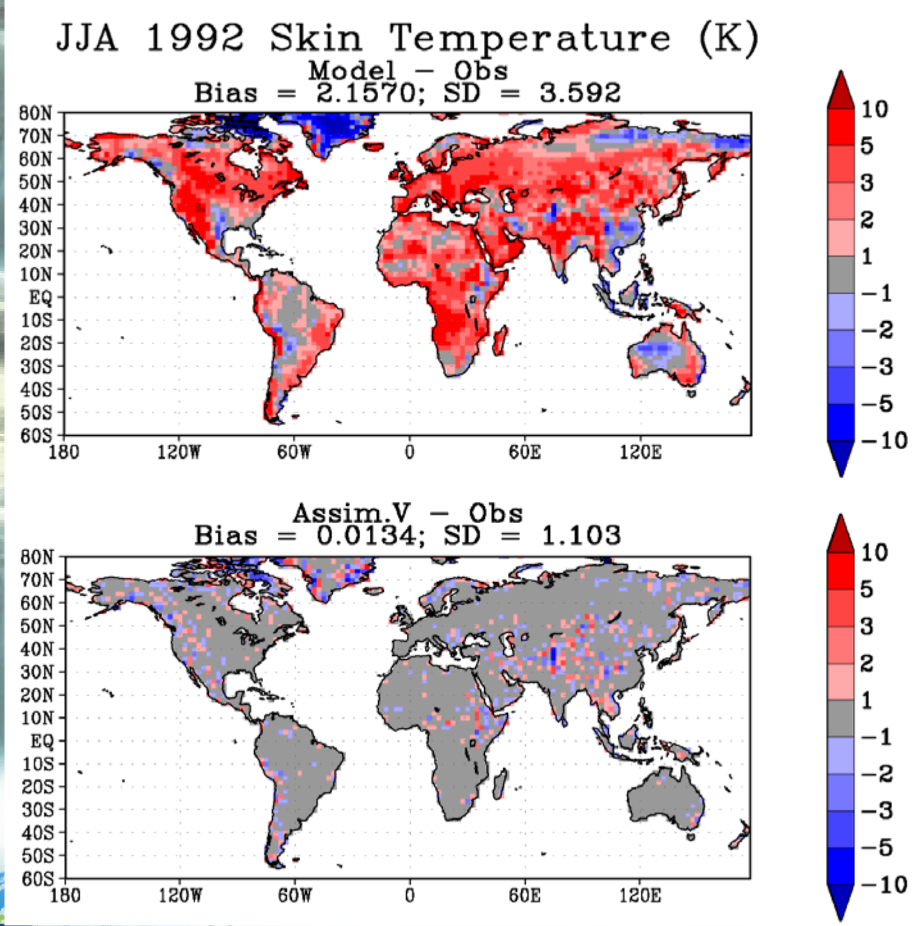


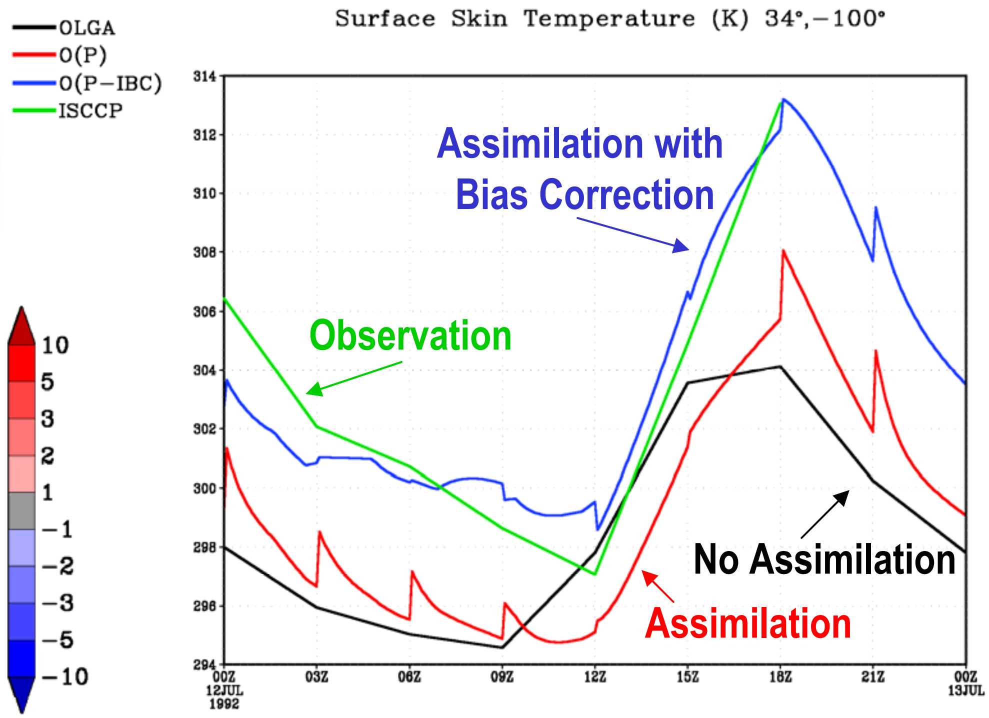
Assimilation Flux as % of Total Precipitation, 9/98 to 8/99, SW+10% SMA



Data Assimilation: T_s Assimilation Results

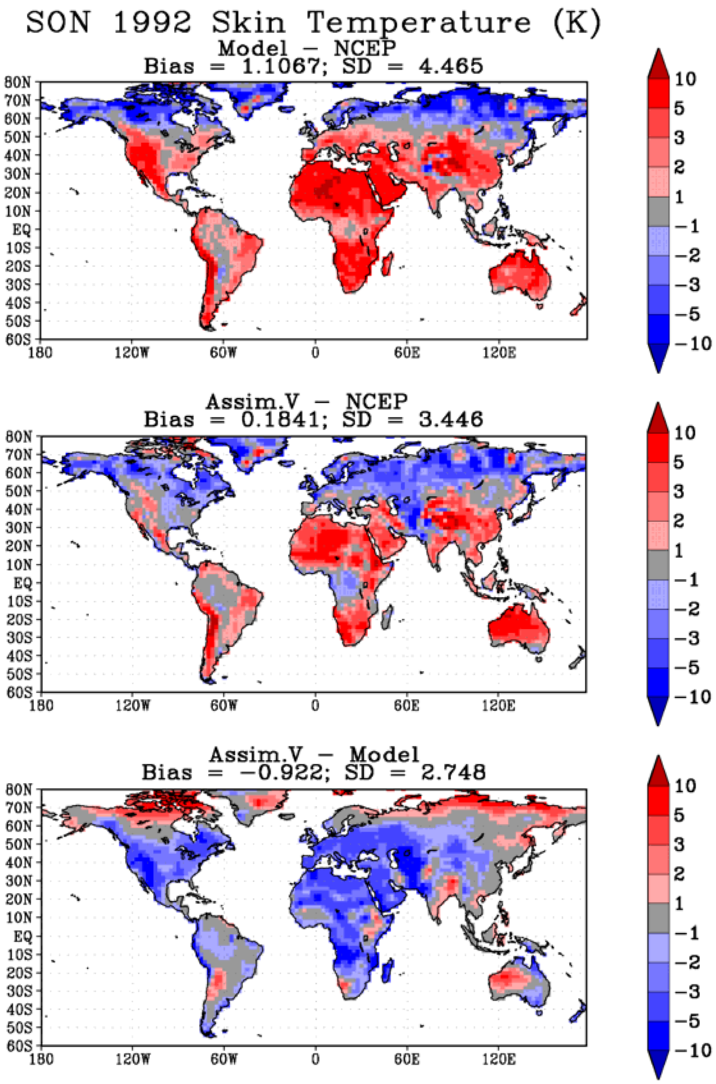
DAO-PSAS **Assimilation** of **ISCCP (IR based) Surface Skin Temperature** into a global 2 degree uncoupled land model.





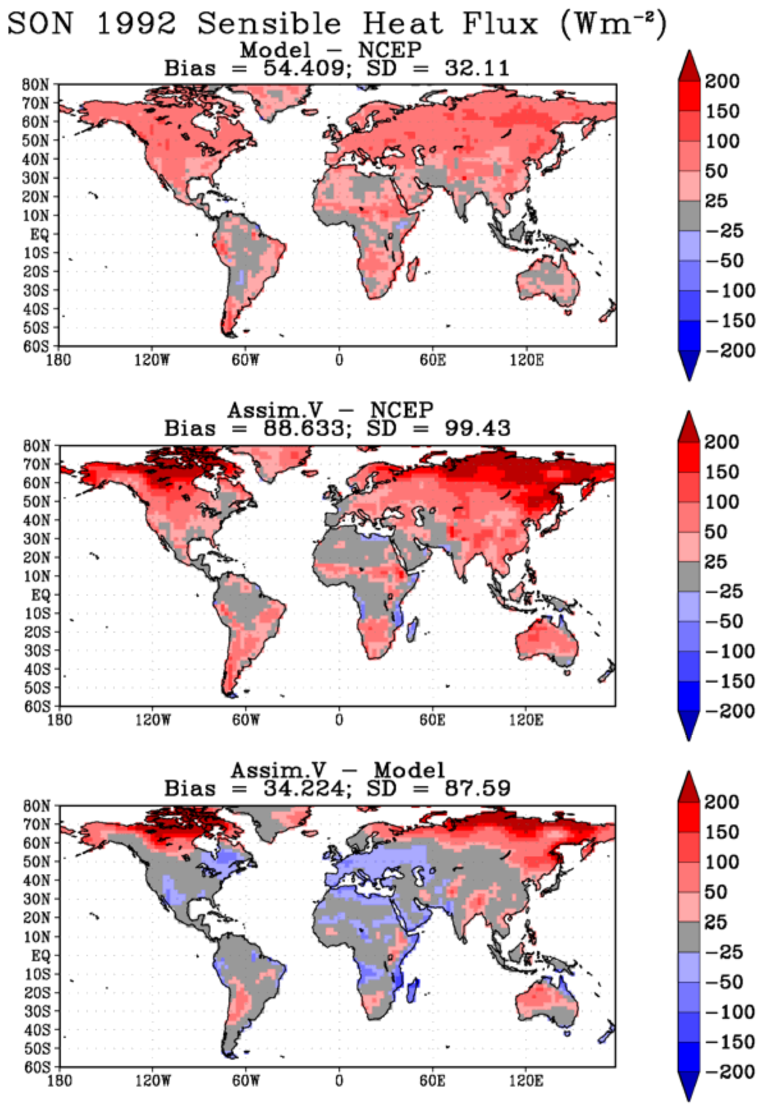
Surface temperature has **very little memory** or inertia, so without a continuous correction, it tends drift toward the control case very quickly.

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:

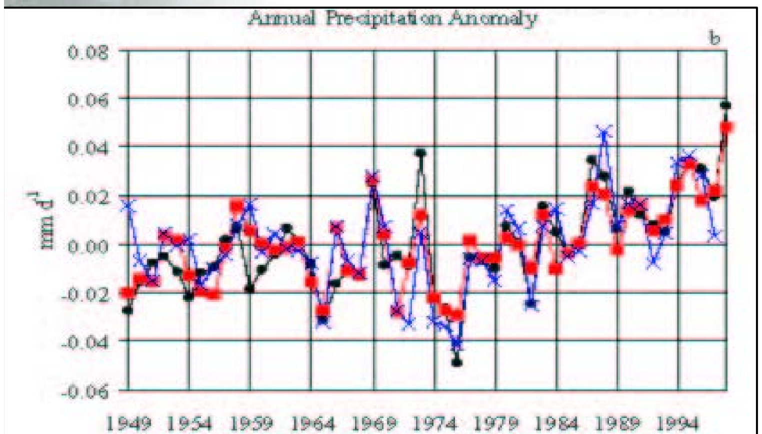
- Tradeoff between using **complex data assimilation techniques,** the **ability to use all the available data** and **operational needs and realities** due to the large computational burdens.
- Tradeoff in dimensionality of data assimilation methods –need may depend on scale.
- Tradeoff between fine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

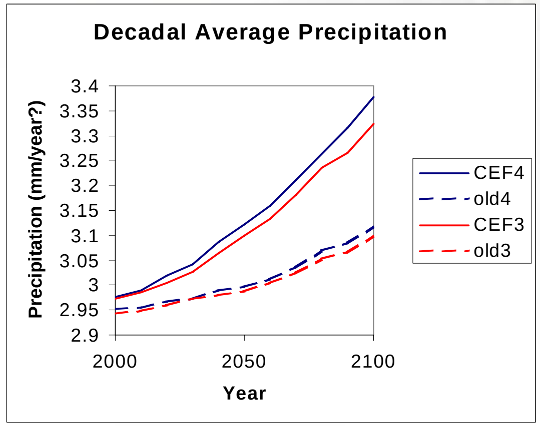
Land Surface Data Assimilation Realities

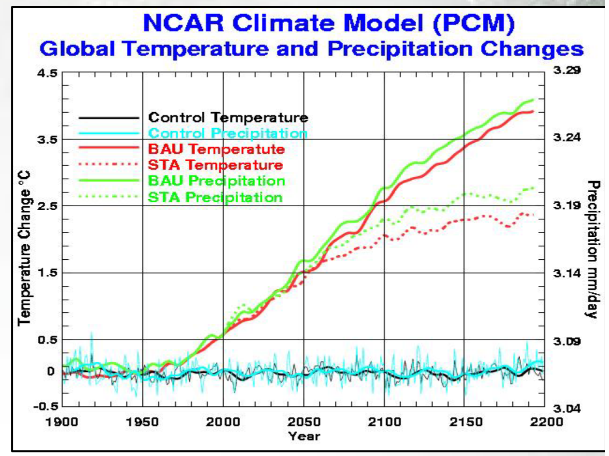
- Large-scale land data assimilation is severely limited by a lack of observations.
- Observation and model *errors are not known* – educated guesses must be used.
- We need to pay attention to the *consequences of assimilation*, not just the optimum assimilation technique. i.e. does the model do silly 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.

Global Water Balance: Motivation and Methodology

- **Assess capability/consistency of “rate” changes in global water cycle detection.**
- **Assess our global-scale capabilities for providing an observed climatology and evaluation tool.**



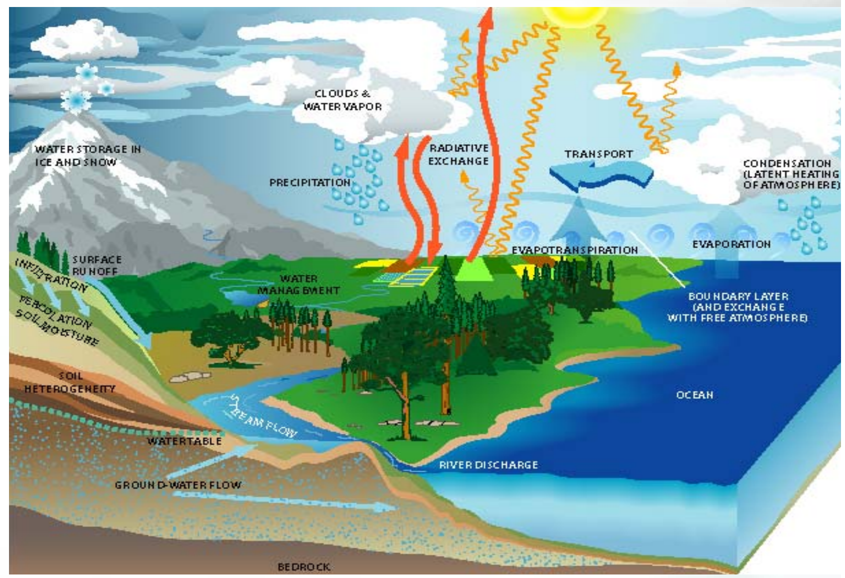




- Check for global balance/consistency:

$$\frac{dQ}{dt} = \langle E \rangle_{land+ocean} - \langle P \rangle_{land+ocean}$$

- Use optimal amount of satellite-based information from disparate data sets which comprise the major global water cycle components (i.e. atmos, ocean and land)



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Global Water Budget Synthesis Products

Precipitation (1979-1999):

- Global Precipitation Climatology Project (GPCP): Adler et al., (2003)
- CPC Merged Analysis of Precipitation (CMAP): Xie and Arkin (1997)

Ocean Evaporation (1987-1999):

- Goddard Satellite-based Surface Turbulent Fluxes Version 2
  - GSSTF2: Chou et al., (2003)
- Hamburg Ocean Atmosphere Parameters and Fluxes from Satellites
  - HOAPS-G: Bentamy et al. (2003) and Fairall et al. (1996)

Land Evaporation:

- Global Offline Land Dataset (GOLD) Versions 1 (1979-1999) and Version 2 (1959-2002): Dirmeyer et al., (2005):
- ***Global Soil Wetness Project Phase 2 (GSWP2): 1986-1995***
  - ***13 Global land models forced with ISLSCP II data at 1° resolution***

Precipitable Water (1988-present): NASA Global Water Vapor Project (NVAP)

Model Output: IPCC Climate of 20th Century Runs

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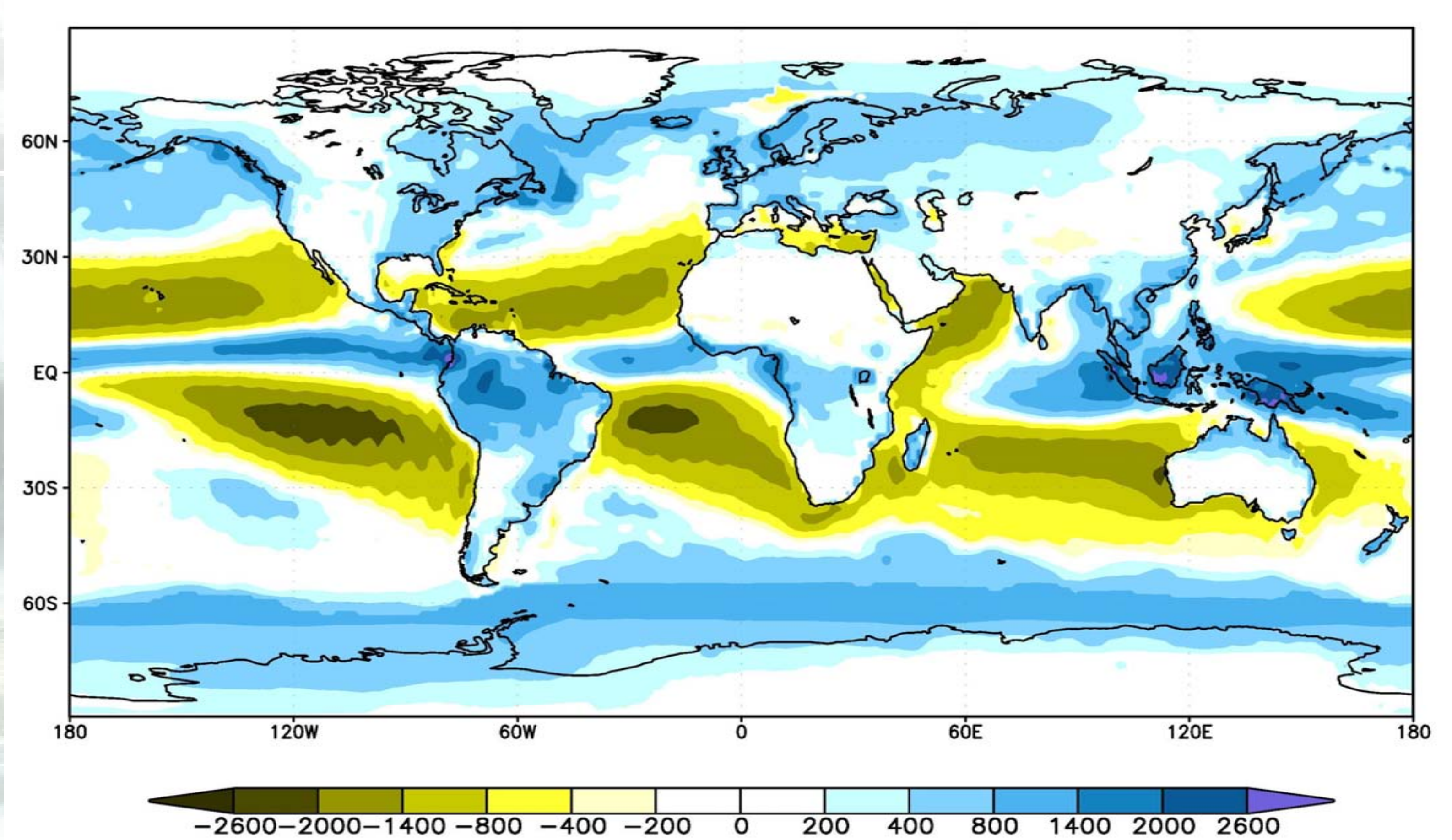
Geographic Distribution of Annual P-E (mm)



- Evaporation excess nearly ubiquitous over sub-tropical oceans, with a sharp contrast at coastal regions.
- Equatorial ocean evaporation minimum consistent with other findings (e.g. Seager *et al.*, 2003).
- Tropical land areas show richest excess in precipitation.
- Major desert regions, tundra, and mountainous regions all indicate deficit to marginally-balanced conditions.
- Mid-latitude and boreal coastal/maritime environments exhibit adequate precipitation supply over evaporation.

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Annual Mean Statistics

Units in kg/yr	Precipitation	Evaporation	| P-E |
Land	1.05E+17 ± 0.02E+17	GOLD1: 0.64E+17	~4.0E+16
	1.02E+17 ± 0.02E+17	GOLD2: 0.62E+17	~4.2E+16
Ocean	3.80E+17 ± 0.06E+17	4.41E+17	6.5E+16
	3.72E+17 ± 0.04E+17	3.93E+17	1.7E+16
Global	GPCP 4.85E+17 ± 0.06E+17	GSSTF2+GOLD 5.03E+17	~ 2.4E+16
	CMAP 4.74E+17 ± 0.04E+17	HOAPS+GOLD 4.56E+17	

Note: Total atmospheric water storage ~ 10^{16} kg

- **Global annual mean precipitation and evaporation balance to ~5%.**
- **Imbalance exceeds global estimate of annual precipitation error.**

Adapted from Schlosser and Houser (2006, submitted)

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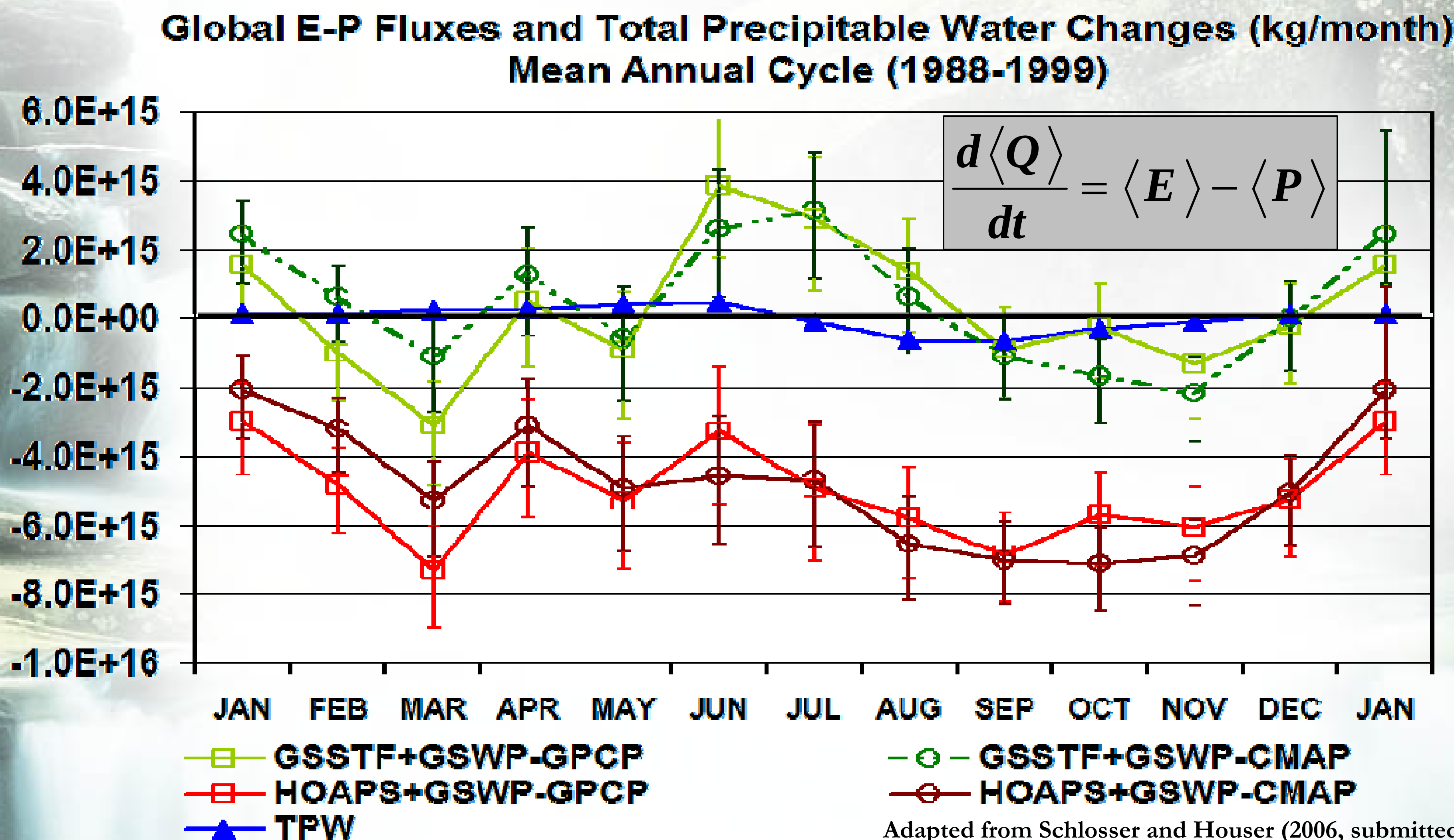
Averaged Annual Cycles of Global Evap and Precip



$$\frac{d\langle Q\rangle}{dt} = \langle E\rangle - \langle P\rangle$$

Adapted from Schlosser and Houser (2006, submitted)

- Uncertainties in global precipitation, land evapotranspiration, and/or changes in TPW cannot account for discrepancies in NH warm-season months.

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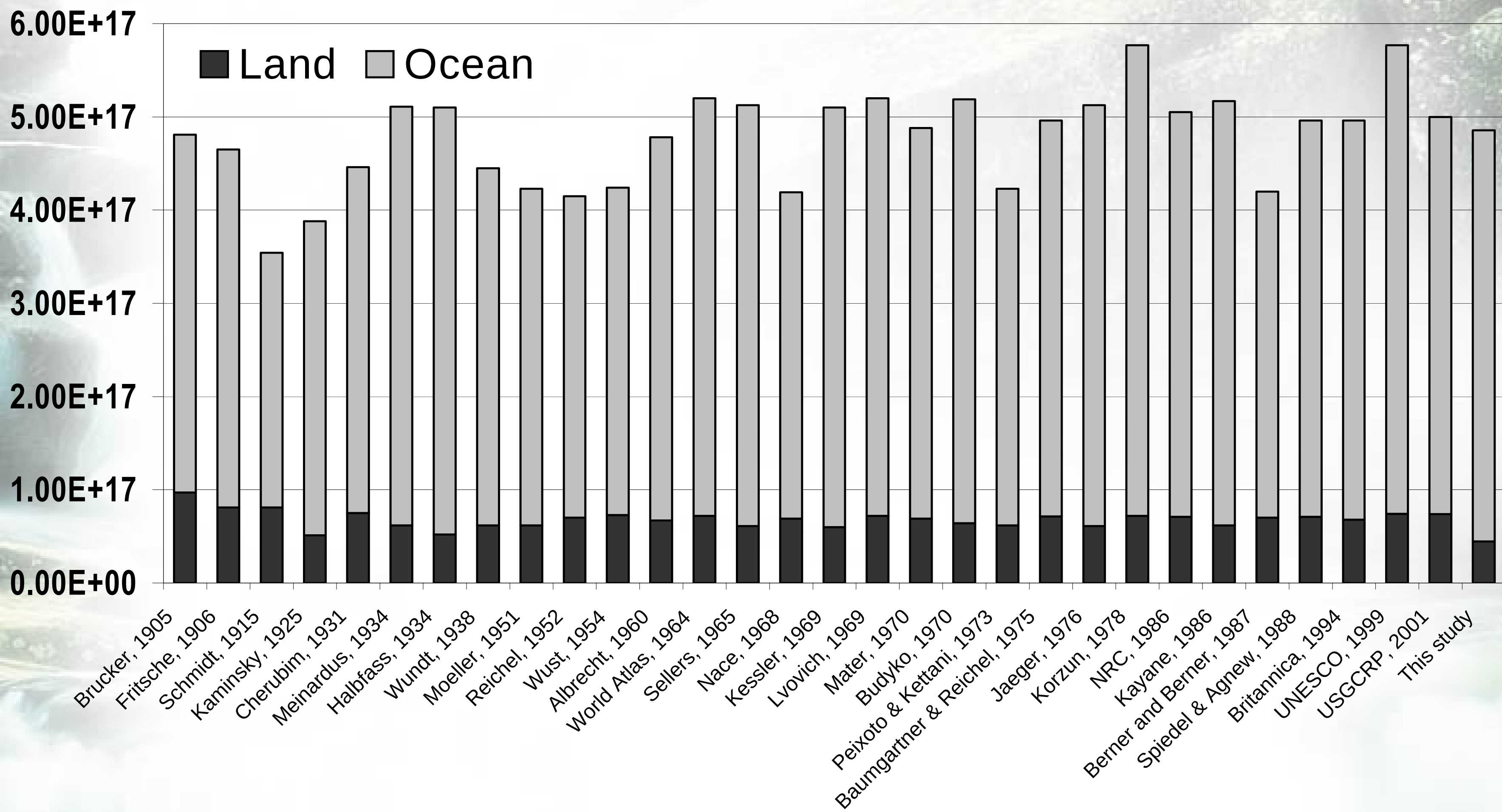
Comparison of Global Fluxes to Previous Estimates



- Global fluxes of precipitation and evaporation are comparable to previous century of estimates.
- No discernable trend is seen in both compilations of the flux estimates.
- The notable disparity with this study is the lower values of both precipitation (not shown) and evaporation flux estimates over land.

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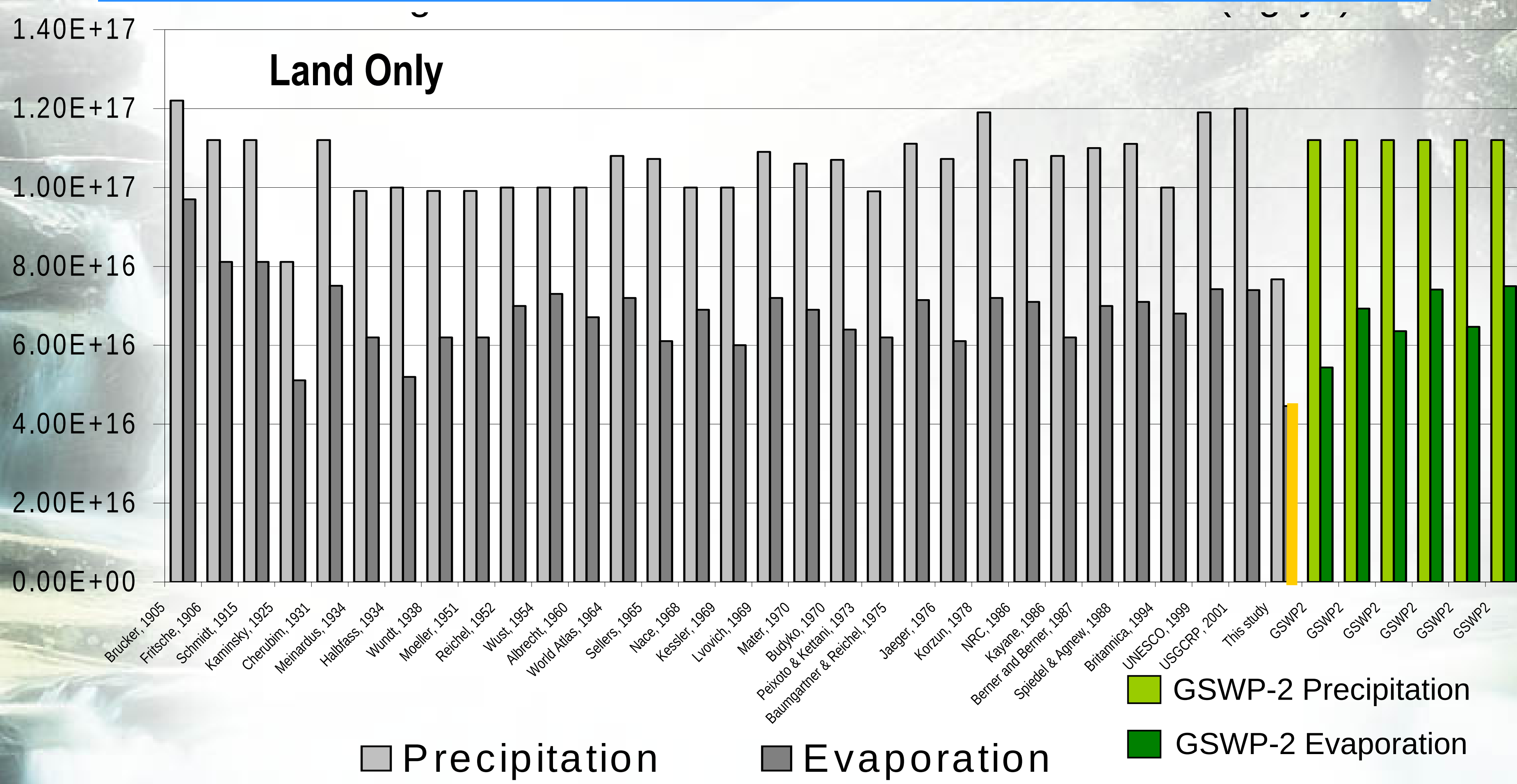
Assessing Historical Land-Flux Estimates



- Global fluxes of precipitation and evaporation are comparable to previous century of estimates.
- No discernable trend is seen in both compilations of the flux estimates.
- The notable disparity with the GOLD study is the lower values over land.
- Scatter of GSWP2 estimates comparable to previous century's estimates.

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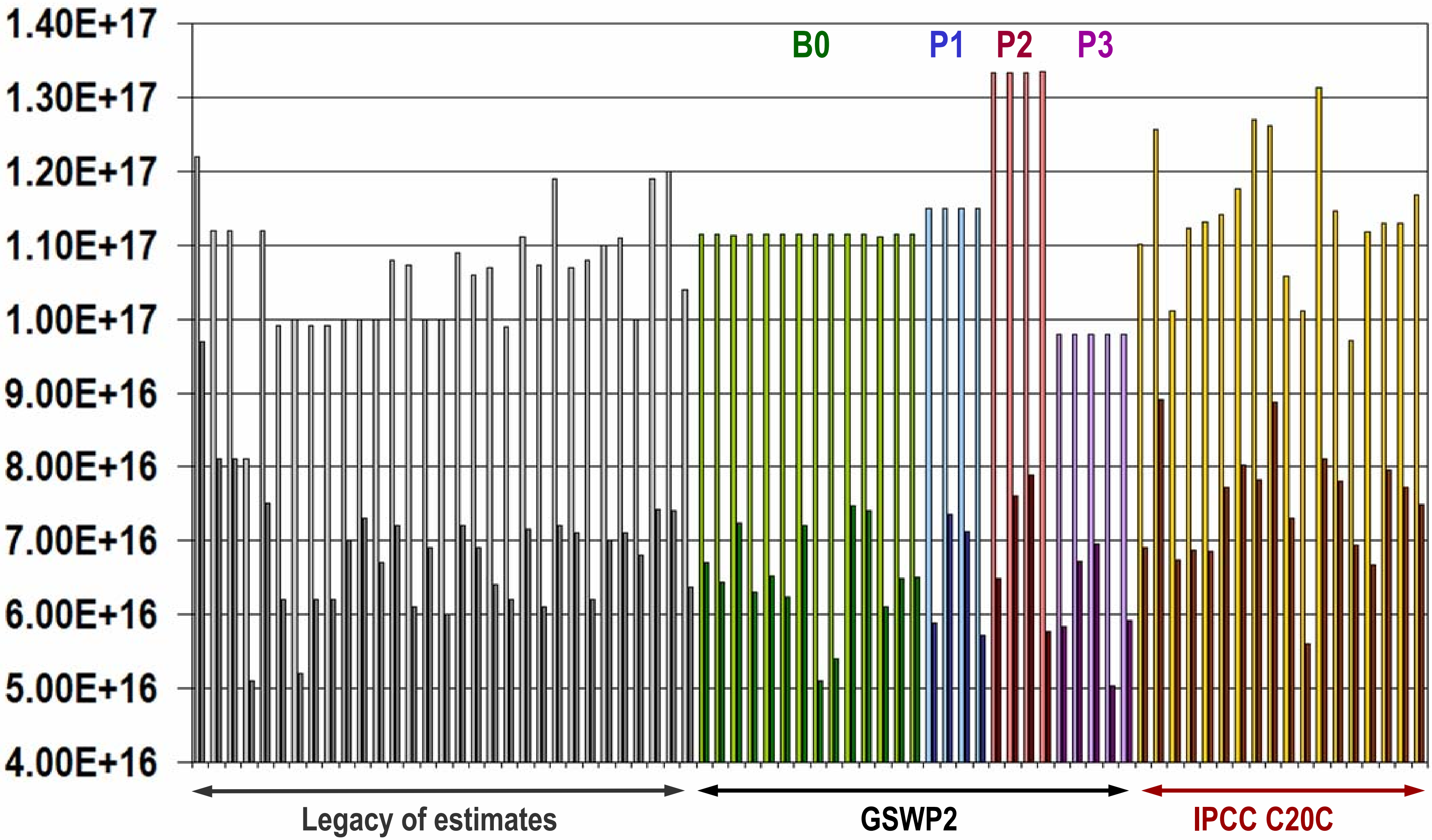
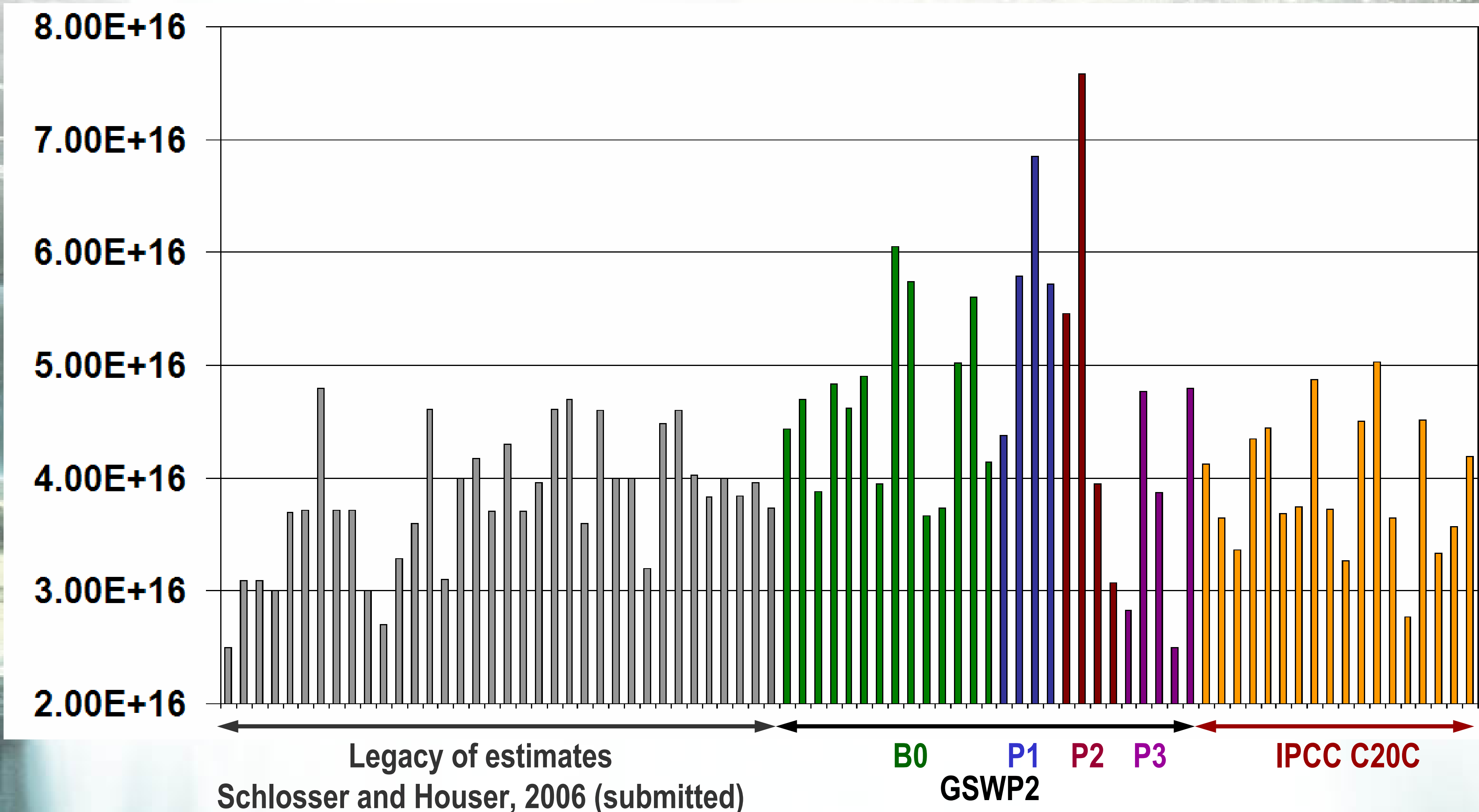
Mean Annual Global Land Precipitation and Evaporation (kg/yr)



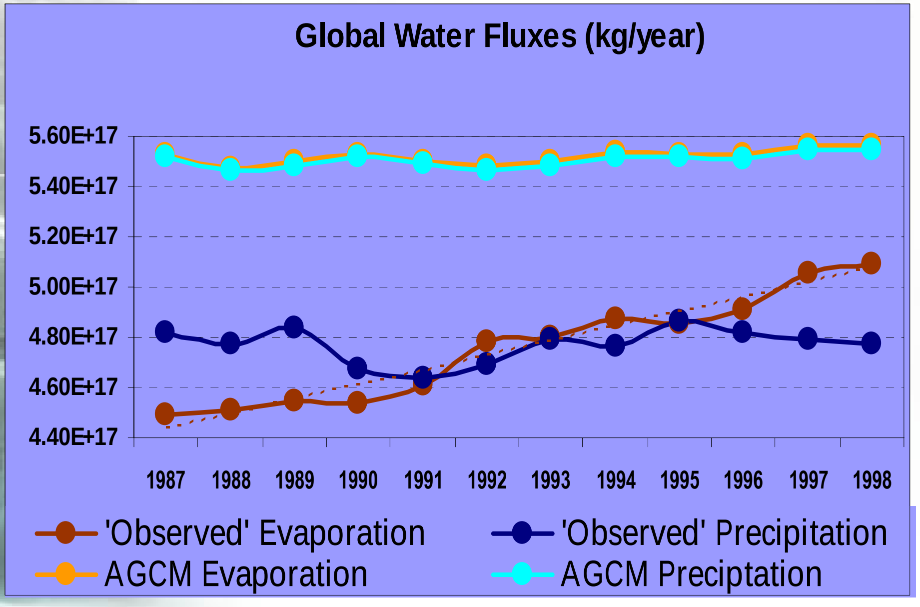
- **Model-based (offline and coupled) scatter of estimates marginally higher than compilation of "modern" observationally-based estimates.**

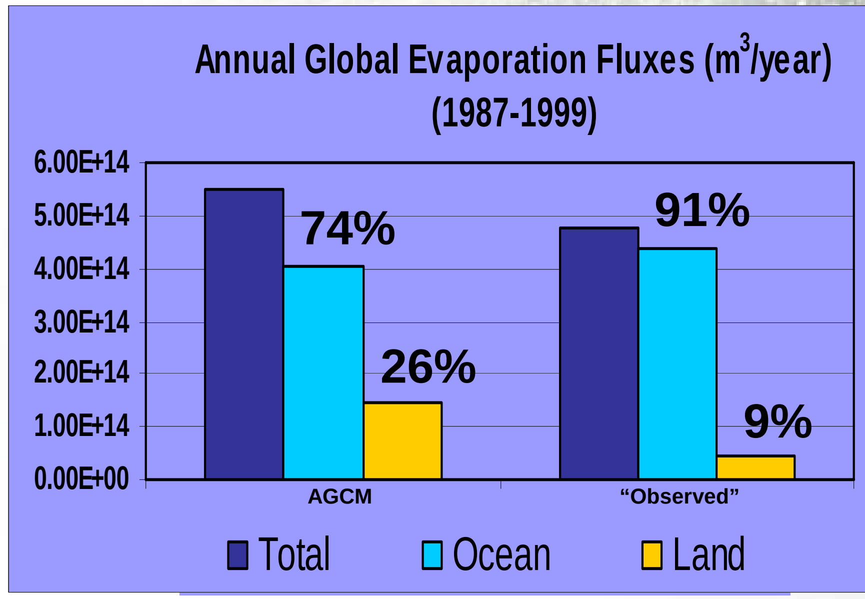
(Implied) Global Annual River Discharge



- Global fluxes comparable among the more recent estimates.
- Early 20th century fluxes highly variable and exhibit marginal trend.

AGCM Precipitation and Evaporation Evaluation





Schlosser

- Observed averaged annual evaporation and precipitation mass flux balance to within 1%.
  - However, interannual global variations considerably uncorrelated.

- AGCM mean "rate" of annual global water cycle exceeds observed (~15%).
- AGCM interannual variability of annual global precip/evap ~50%/35% lower than observed.
- Relative contributions of land and ocean fluxes differ considerably.
  - What are the sources of these discrepancies (both in the models and "observations")?

- Trend in "observed" global evaporation (~1 %/year), but no trend in precipitation.
- Trend in AGCM global water-cycle rate during 1987-1999 and order of magnitude smaller.
  - Source of modeled trend from prescribed SSTs, is the response accurate?
  - Observations insufficient to detect AGCM trend (e.g. Ziegler et al., 2002).

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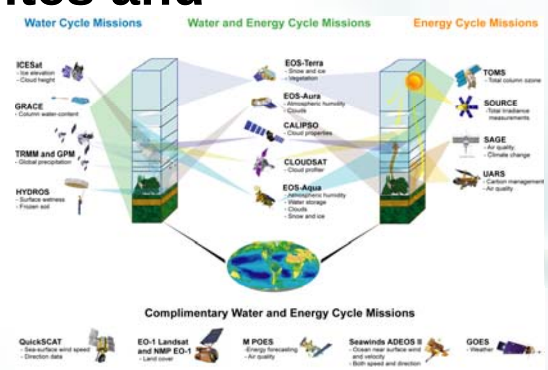
Summary

- **Observationally-based estimates of global water fluxes balance, on an annual basis, to within 10% (~10^{16} kg/yr or ~50 teratons/yr) and fall within the range of previous estimates.**
  - Avg. U.S. yearly consumption ~10^{14} kg **(USDA)**
  - Total amount of water stored in atmosphere ~10^{16} kg
- **AGCM results imply more than a 0.1%/yr precision required for global trend detection, and consistency between precipitation and evaporation (e.g. Bosilovich *et al*., 2004).**
- **Ocean evaporation estimates require further attention, trend validation.**
- **For the forseeable future, global land evaporation estimates will primarily rely on model simulations/assimilation**
  - Veracity and quality of models and (forcing) data
  - Further analysis of GSWP 2 (1986-1995) land simulations
- **Extend/merge synthesis to current/pending satellites and complementary/blended data**
  - TRMM+constellation, GPM, EOS-Aqua/Terra and QuickScat
  - Clouds: e.g. ISCCP, CloudSat, CALIPSO
  - Other precipitation datasets – e.g. CMAP, GHCN, CRU
  - GRACE, IceSat, Aquarius, SMOS, etc…



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