A mission simulation and evaluation platform for terrestrial hydrology using the NASA Land Information System (LIS)

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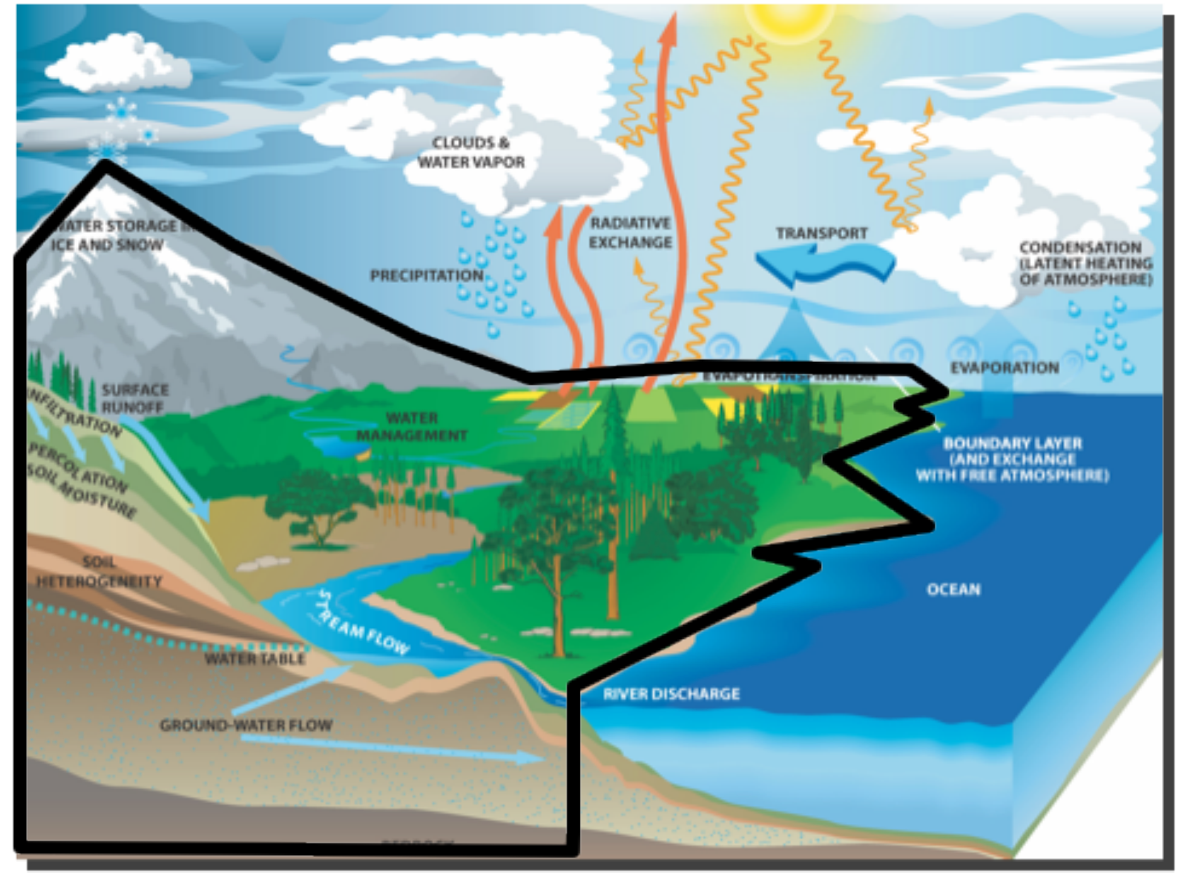
Motivation

- Extend the state-of-the-art in OSSEs in terrestrial hydrology
  - Broader range of computational methods: Employ the computational subsystems of optimization and uncertainty estimation in addition to the data assimilation subsystem to conduct OSSEs that go beyond the "classic" assimilation OSSEs.
  - End-to-end, applications-focused OSSEs: Demonstrate "end-to-end" OSSEs that quantify the impact of raw remote-sensing observations (in the radiance space) for improving both hydrologic science and societal applications (e.g. droughts, landslides, weather forecasting)
  - Systematic, standardized evaluation : Using LVT, demonstrate the systematic evaluation of OSSE results using a wide range of metrics that quantify measures such as accuracy, uncertainty, sensitivity and information content.
- Demonstrate the above OSSE capabilities for both current and planned missions

Land Information System (LIS)

- A system to study land surface processes and land-atmosphere interactions
  - Integrates satellite- and ground-based observational data products with land surface modeling techniques
  - Capable of modeling at different spatial scales
- A comprehensive, sequential data assimilation subsystem based on NASA Global Modeling and Assimilation Office (GMAO) infrastructure for improved state estimation using remote sensing observations
- Coupled land-atmosphere systems that employ LIS as the land surface component (earlier Advanced Information Systems Technology (AIST) funded work)
- Comprehensive optimization and uncertainty estimation subsystems that employ remote sensing observations for parameter estimation (previous AIST project)



- NASA's 2005 software of the year award
- Used by the Air Force Weather Agency (AFWA) as the operational land surface modeling system

http://lis.gsfc.nasa.gov

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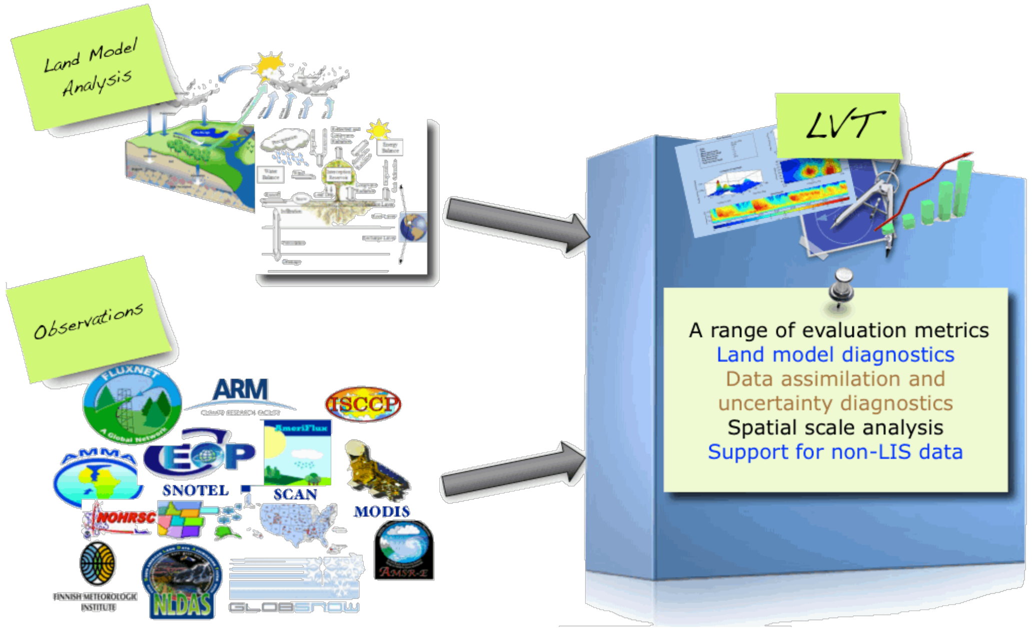
Land surface Verification Toolkit (LVT)



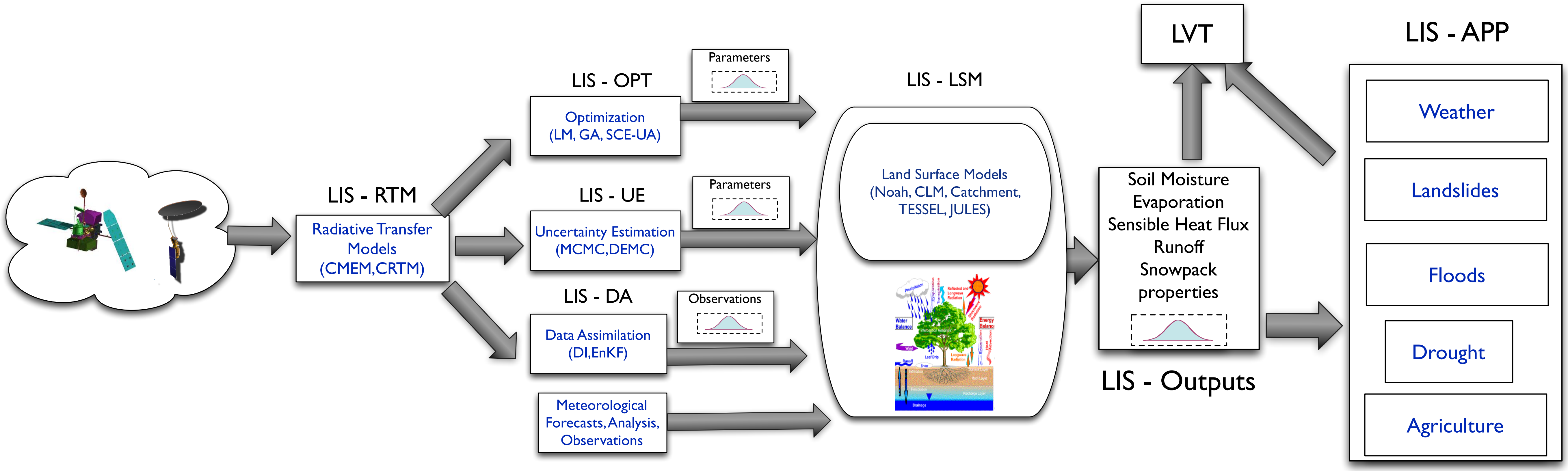
Metric Class	Examples
Accuracy metrics	RMSE, Bias, Correlation
Ensemble metrics	Mean, Standard deviation, Likelihood
Uncertainty metrics	Uncertainty importance
Information theory metrics	Entropy, Complexity
Data assimilation metrics	Mean, variance, lag correlations of innovation distributions
Spatial similarity metrics	Hausdorff distance
Scale decomposition metrics	Discrete wavelet transforms

- A framework developed to provide an automated, consolidated environment for systematic land surface model evaluation
- A large suite of analysis metrics, including accuracy-based metrics, ensemble and uncertainty measures, information theory metrics and similarity measures has been built into LVT

The capabilities of LVT enable an environment for performing systematic evaluation of the OSSEs using various metrics including end-use oriented measures.

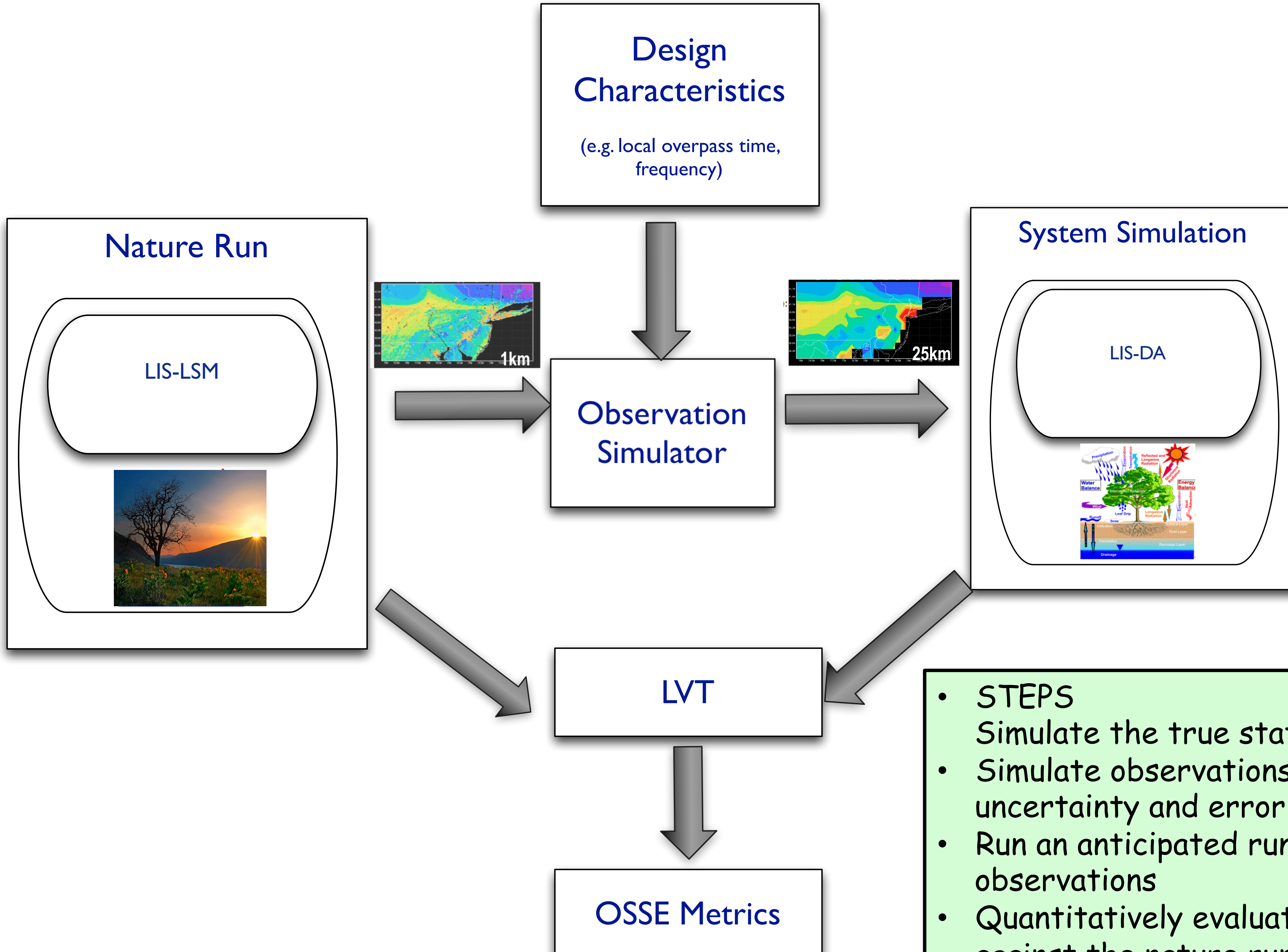
Kumar et al. (2012), Land surface Verification Toolkit (LVT) – A generalized framework for land surface model evaluation, Geosci. Model. Dev.

Schematic of the proposed OSSE platform



- End-to-end OSSE platform for terrestrial hydrology that links raw observations, radiative transfer models, data assimilation, uncertainty estimation, physical models, end-use applications and evaluation and verification techniques within a single integrated framework.

"Classic"/ Traditional OSSE setup



- STEPS
  Simulate the true state with a nature run
- Simulate observations accounting for uncertainty and error
- Run an anticipated run using simulated observations
- Quantitatively evaluate the anticipated run against the nature run

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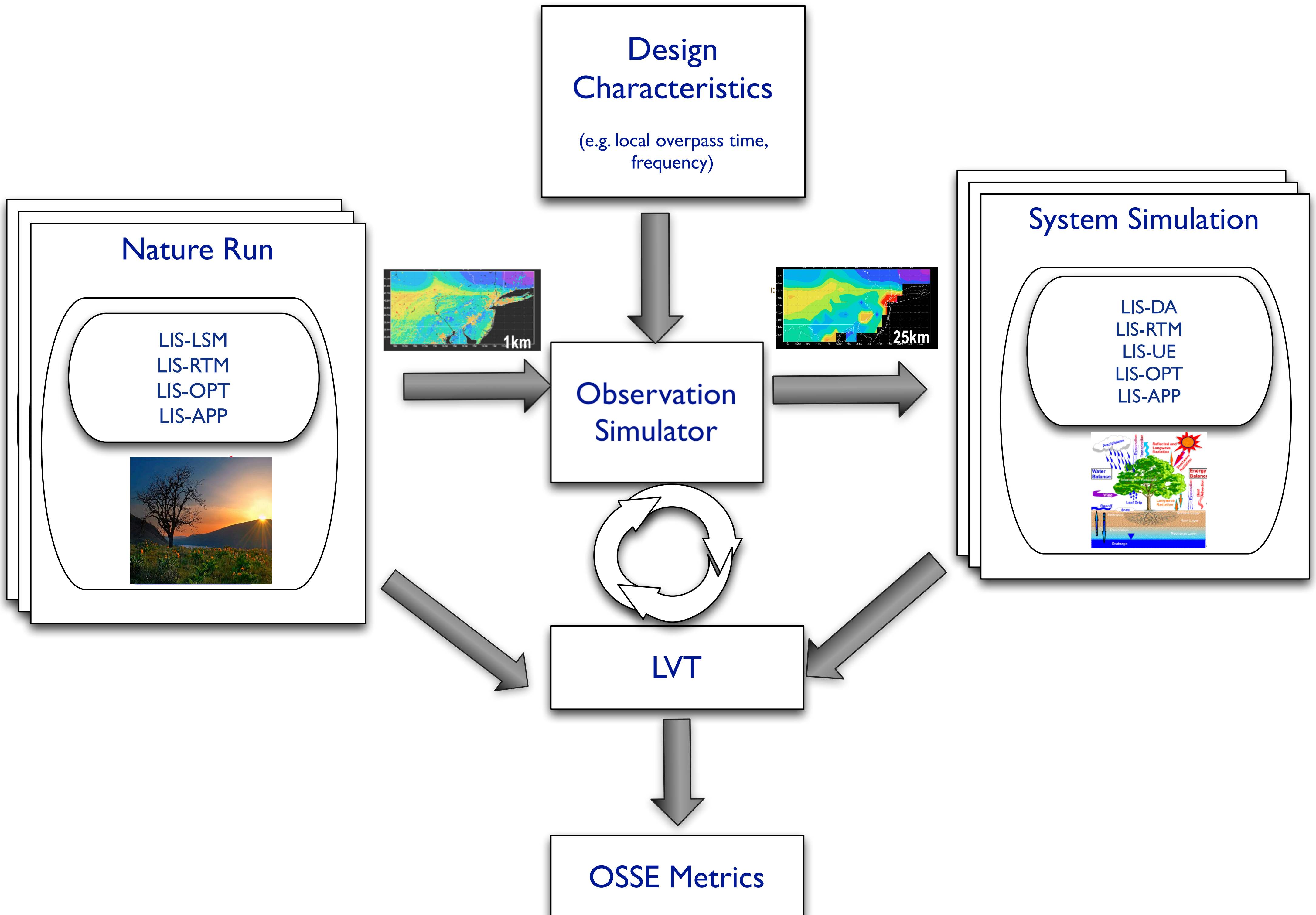
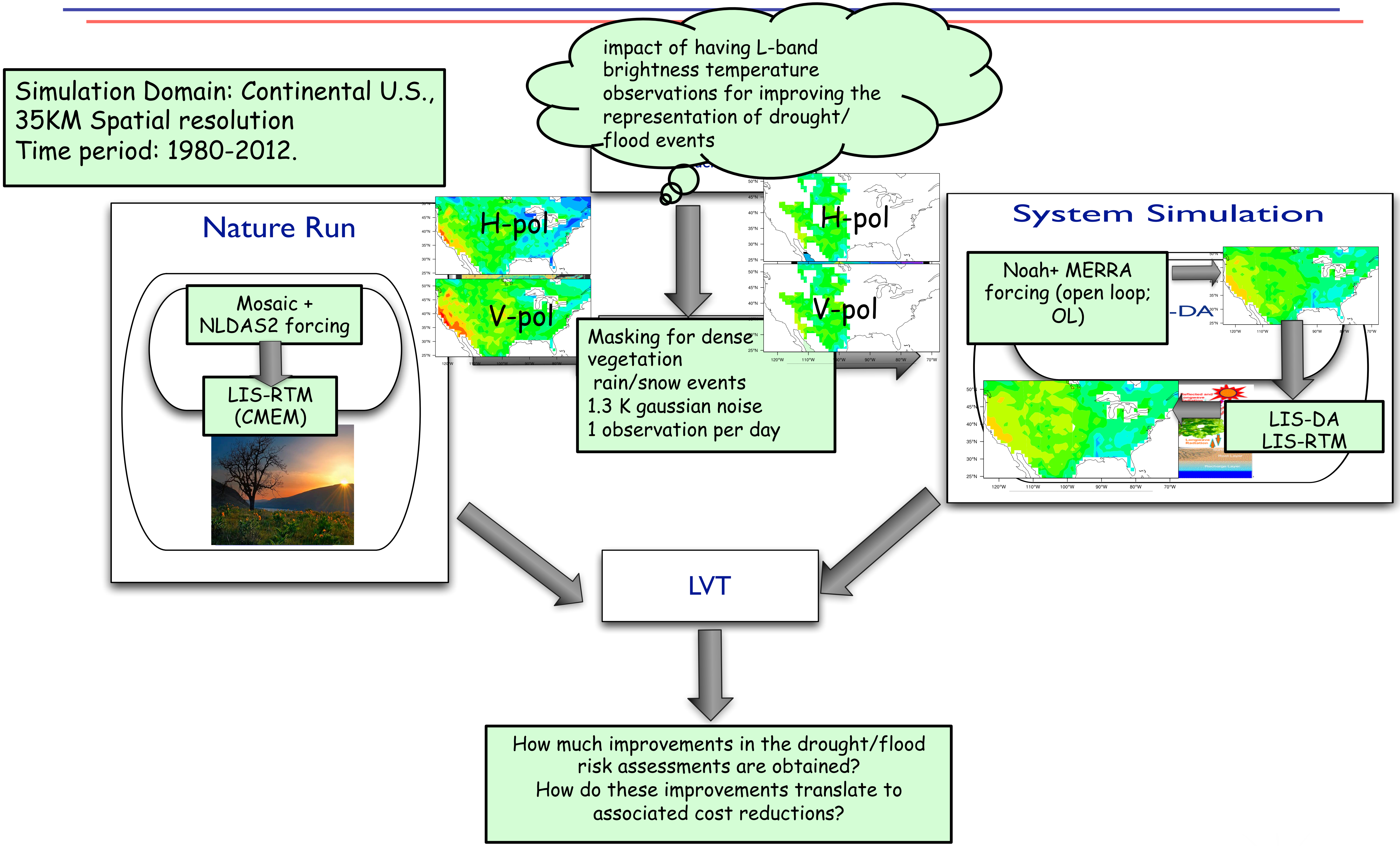
Target OSSE setup



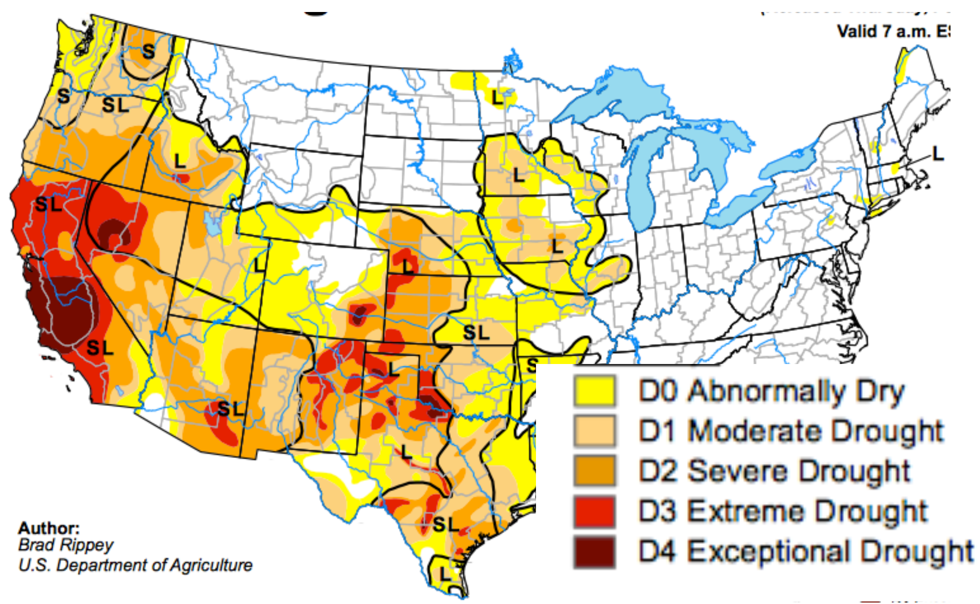
OSSE to examine the impact of soil moisture observations on drought/flood risk estimation



Kumar et al. (2014), "Assessing the impact of L-band observations on drought and flood risk estimation: A decision theoretic approach in an OSSE environment, Journal of Hydrometeorology, Special collection on SMAP applications, in revisions.

Quantifying drought/flood-risk

- Droughts are typically quantified through normalized indices that capture deficits of the water cycle variable (precipitation, soil moisture, streamflow) from average conditions
- A common approach is to use root zone soil moisture percentile-based drought indices
- The U.S. Drought Monitor (USDM) defines drought into 5 categories: D0 – abnormally dry < 30 %tile; D1-extreme drought; <20%, D2 –severe drought<10%, D3-extreme drought<5% and D4-exceptional drought < 2%



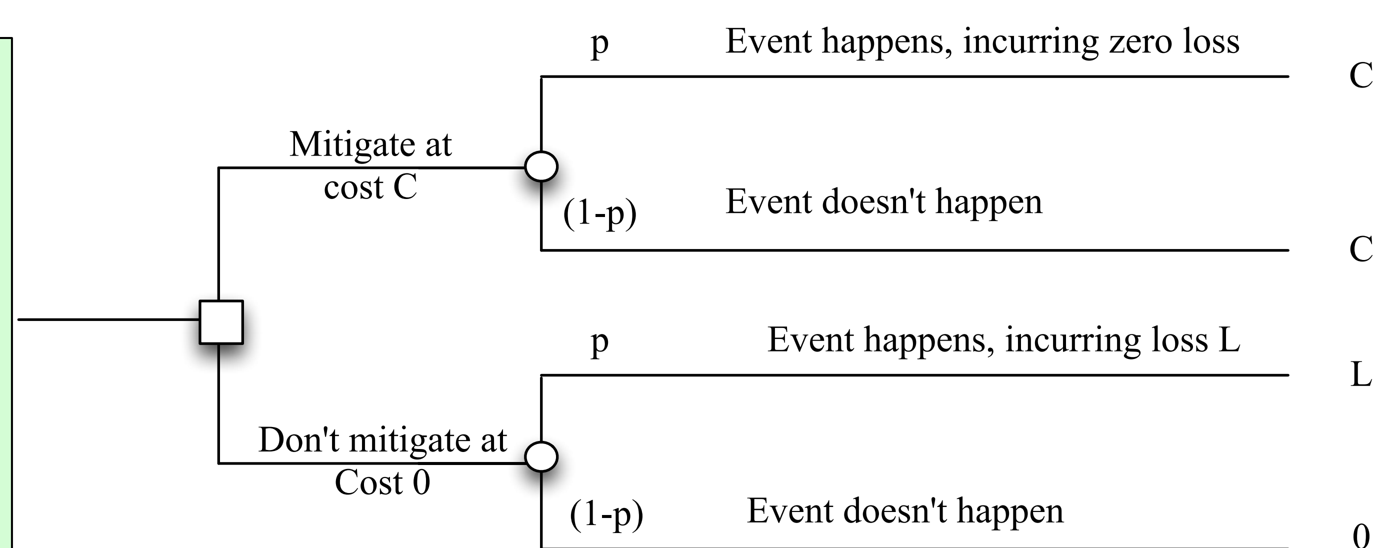
- These normalized indices can also be used to quantify wetter than normal conditions (flood risk conditions). F0 (>70%), F1 (>80%), F2(>90%), F3(>95%) and F4 (> 98%)
- Essentially the OSSE examines the contribution of the soil moisture retrievals towards improving the extremes of the soil moisture distribution

Decision theory model for an economic assessment of the SMAP OSSE

- Statistical decision theory has lots to say about making OSSEs relevant. E.g. : "Commercial decisions are often made, not on the basis of events which are likely to occur, but on the basis of events that are unlikely to occur, but which if they occur, would involve serious financial loss (Palmer, 2002)
- A simple approach:
    - C – cost of taking action to mitigate event (e.g. drought) regardless of whether event happens or not
    - L – loss if event happens and no-mitigation was taken ($C/L < 1$)
    - p – probability of the event as assessed by the ensemble

The total cost is computed by summing across the cost/loss incurred for each flood/drought event

The costs can be computed both from a "deterministic" approach that uses the ensemble mean values in the decision tree or a "probabilistic" approach that diagnoses the probability of the event from the ensemble

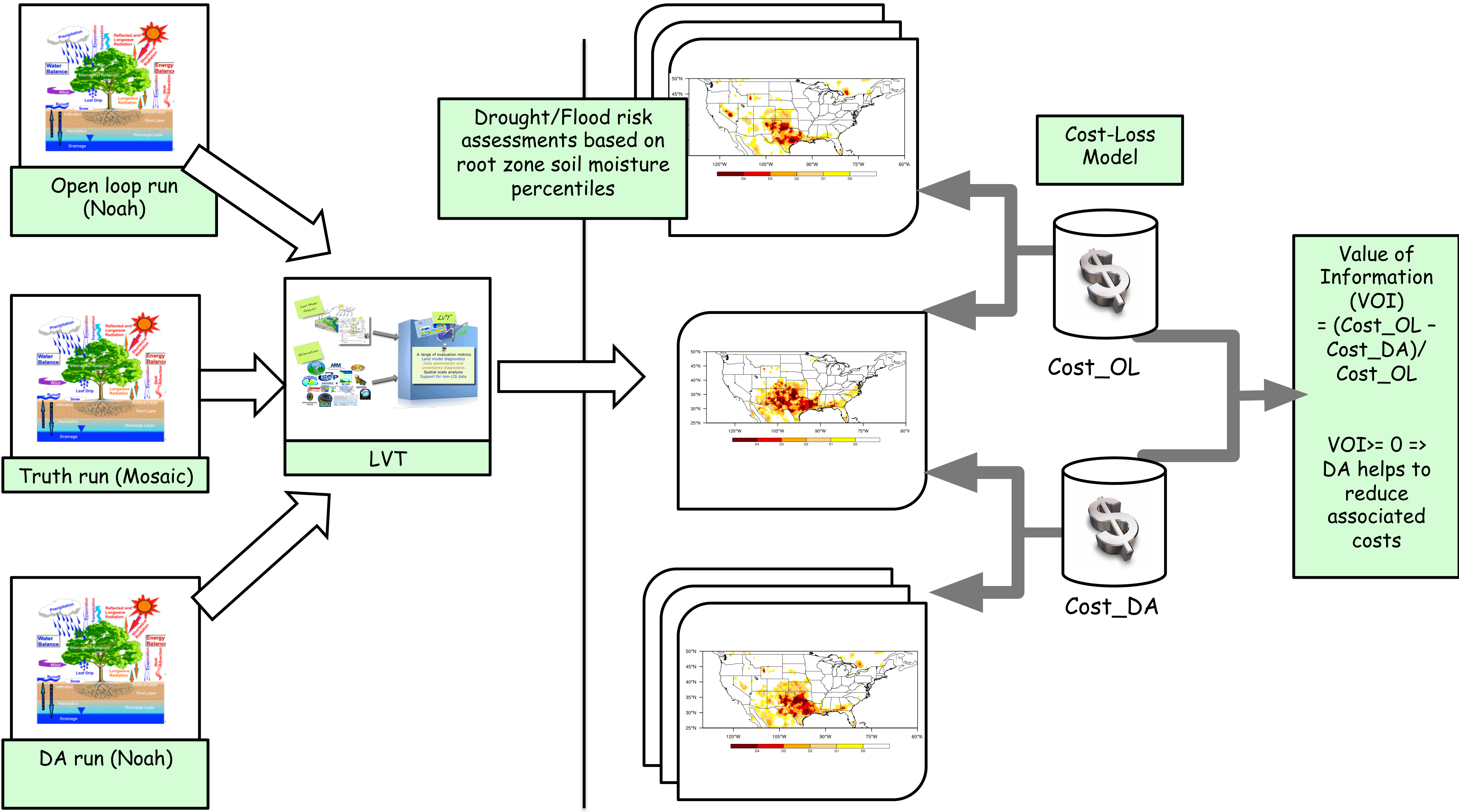


Mitigate if $C < pL$

Or

$P > C/L$

Sequence of decision theory analysis in the SMAP OSSE

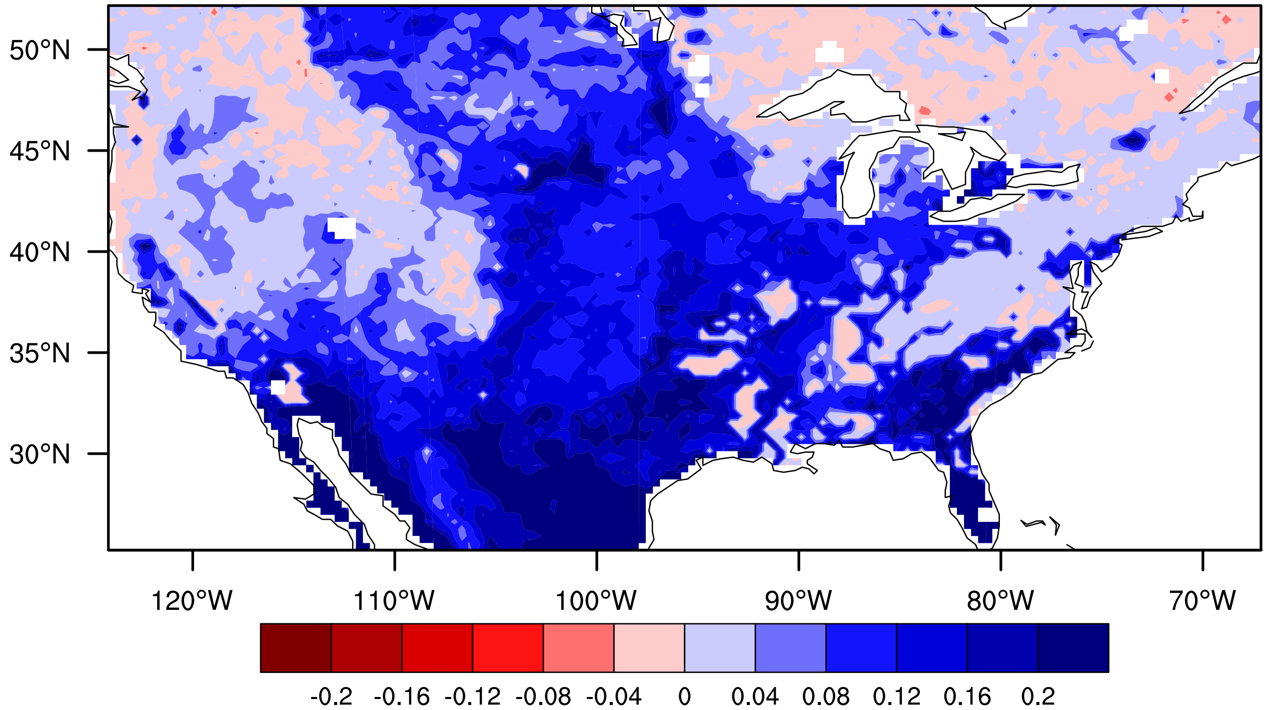


Improvements in soil moisture fields from DA

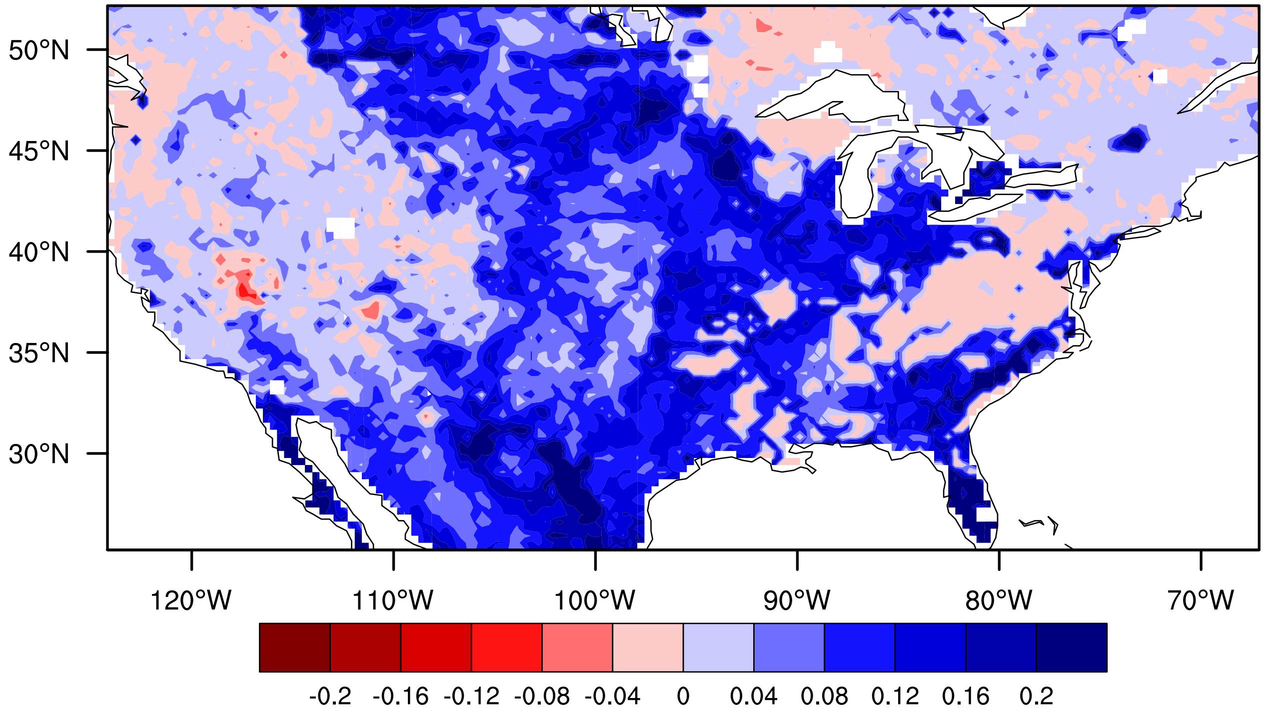
Maps present Anomaly R (DA) – Anomaly R (OL) of surface and root zone soil moisture.

Blue (positive values) indicate improvements
Red (negative values) indicate degradations

Assimilation of L-band Tb provides improvements to both surface and root zone soil moisture fields.

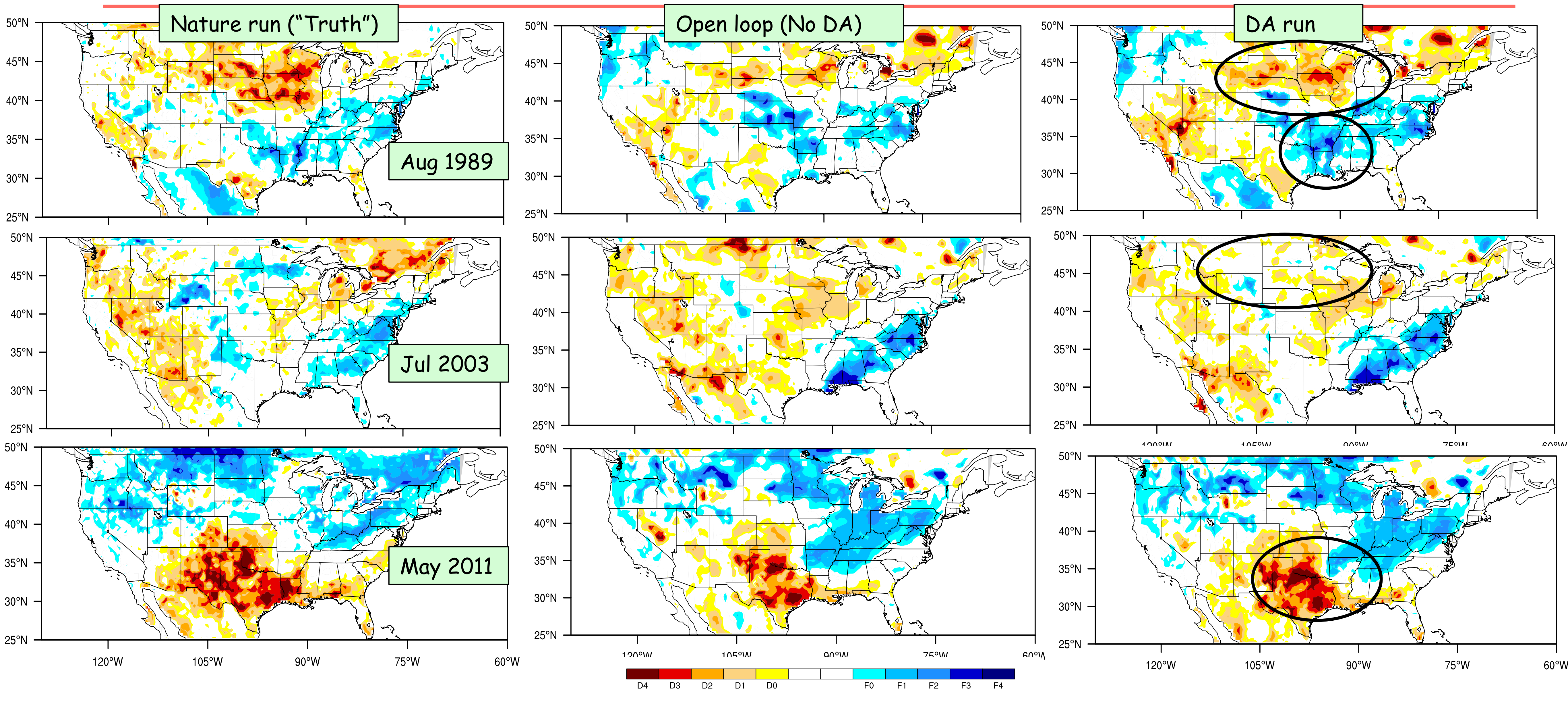


Surface soil moisture



Root zone soil moisture

Comparison of percentile maps

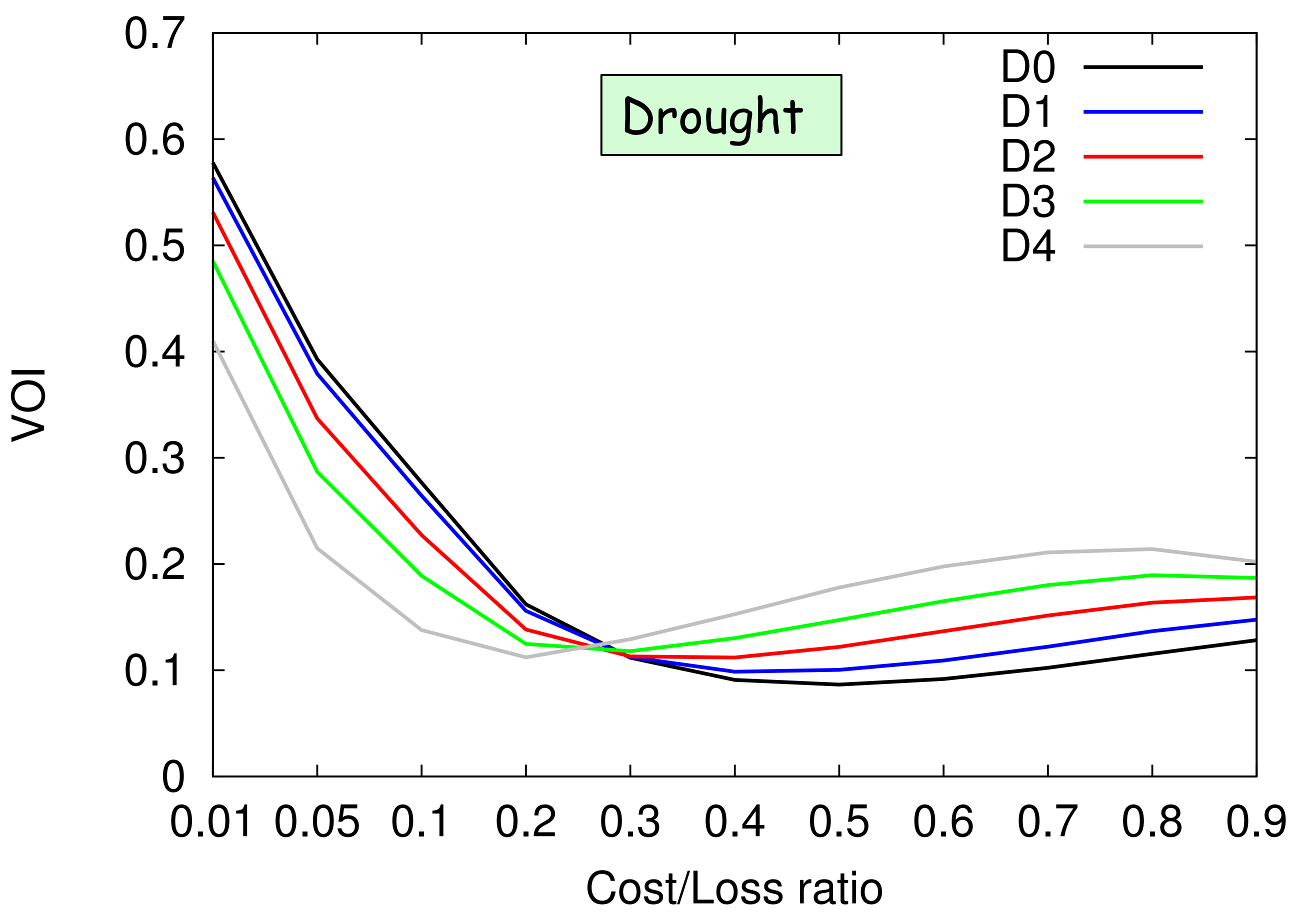


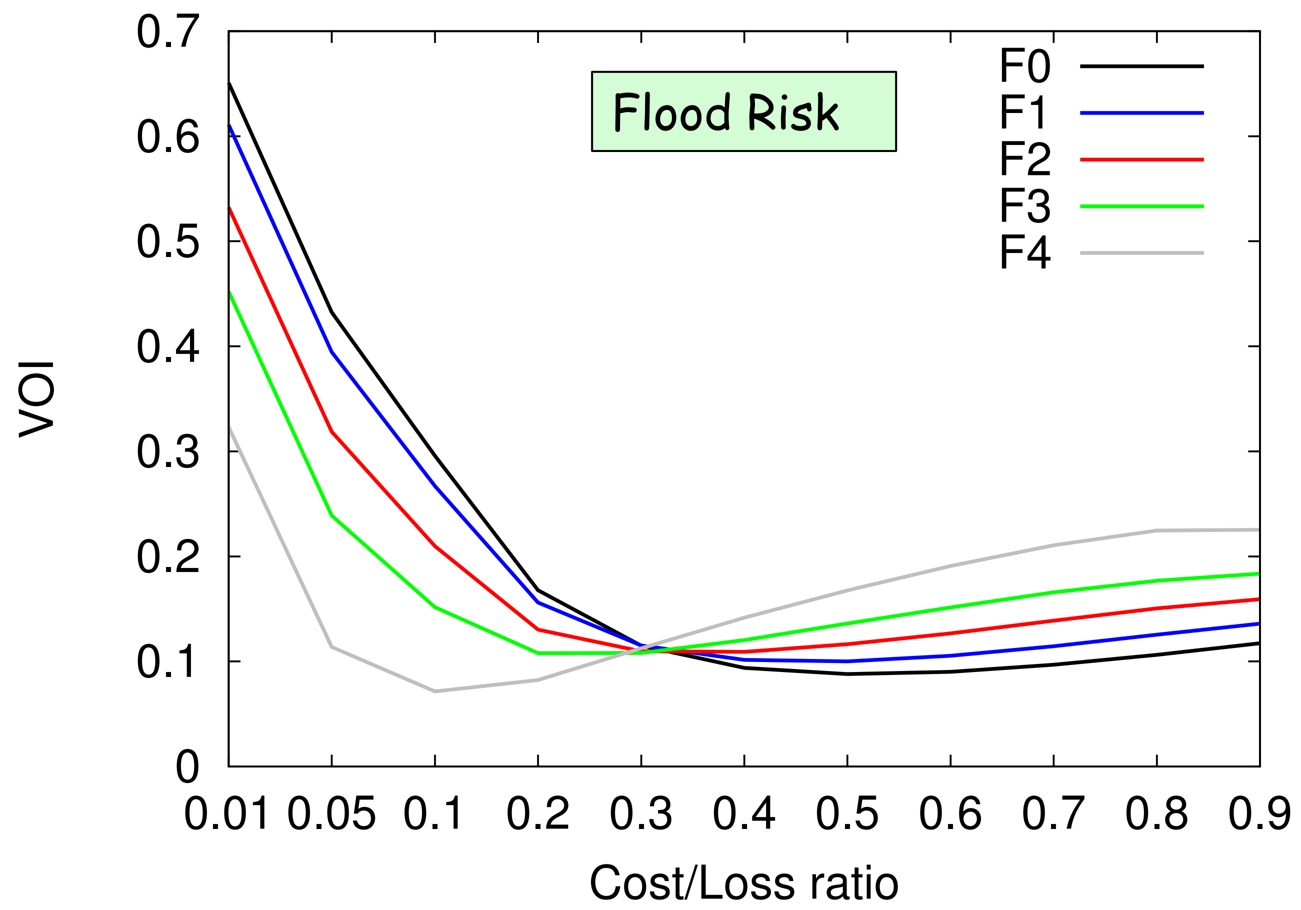
The assimilation of L-band Tb observations aid in improving the representation of drought/flood risk estimates

- Aug 1989 case: DA correctly intensifies the drought over the Midwest, improves flood risk estimation over lower Mississippi
- July 2003 case: DA reduces the severity of drought over the Highplains (that was incorrectly specified in the open loop run)
- May 2011 : DA correctly intensifies the drought over Texas

Value of information from "probabilistic" estimates

VOI = (Cost_OL – Cost_DA)/Cost_OL





The value of information is calculated for 5 different drought and flood categories (based on the percentile thresholds)

- The value of information from the probabilistic estimates are generally greater than those obtained from the deterministic estimates, as information is lost when summarizing the value of observations based on ensemble mean (used in the deterministic estimate)
- The contribution to the value of information metric for low C/L ratios are from the improving the probability of detection of drought events through DA and for high C/L ratios are from reducing the false alarm ratio of drought events in the open loop run

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OSSE to examine the impact of precip observations on landslide prediction

- Landslides are one of the most pervasive hazards in the world, resulting in more fatalities and economic damage than is generally recognized. An estimated 98% of all landslides are triggered by rainfall.
- Remote sensing information is poised to provide significant inputs to physical landslide modeling approaches in order to estimate these processes over larger areas
- Current physically-based slope-stability models are conducted at very high spatial resolution with in-situ gauge data and few/no studies use satellite-based rain for local models
- This work considers how satellite-based products from Tropical Rainfall Measuring Mission (TRMM) and simulated data from the GPM mission may prove useful in applying a landslide model over broader regions

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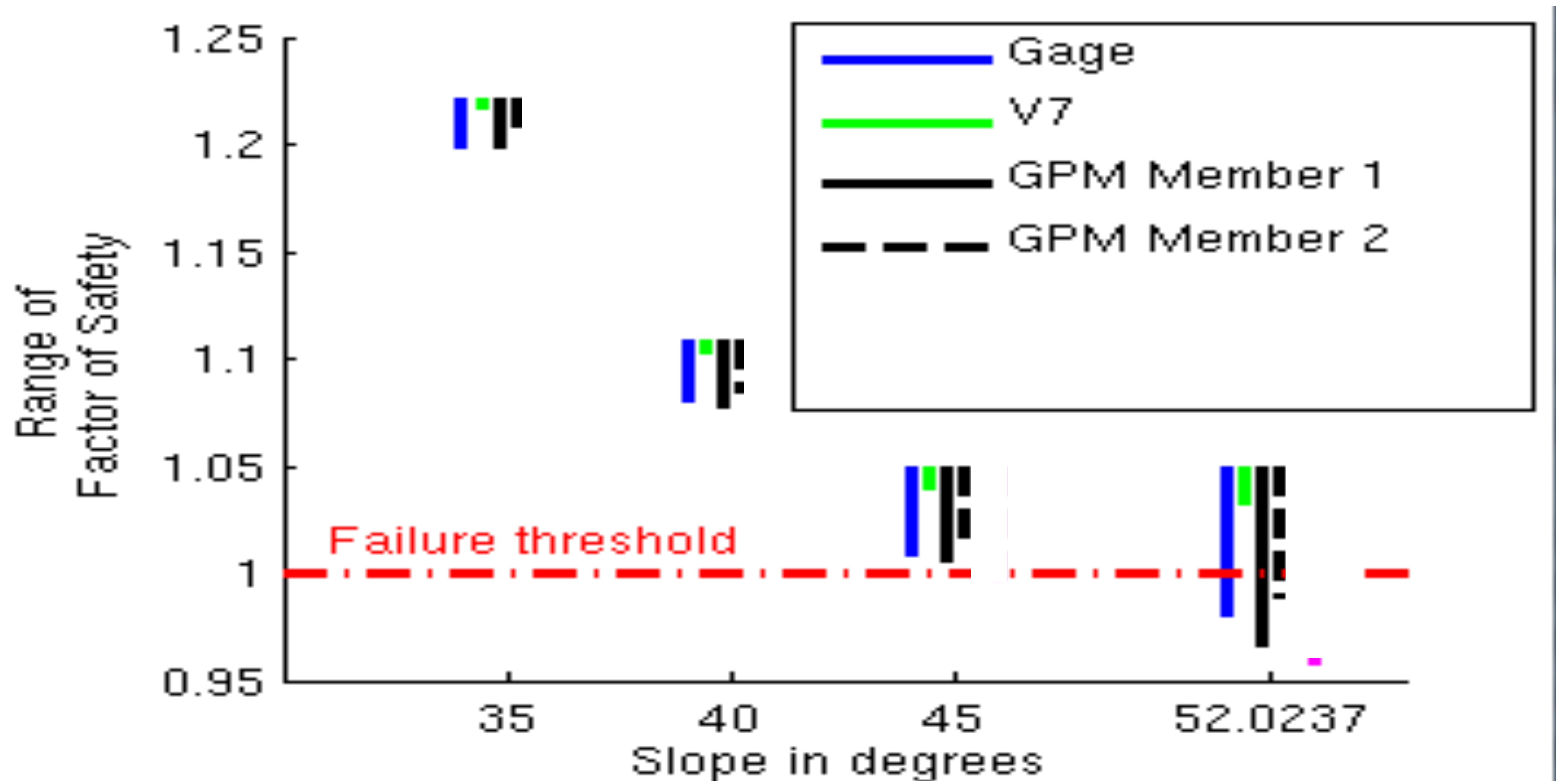
TRMM vs. GPM Landslide Forecasts

Range of FoS from Start of simulation to minimum



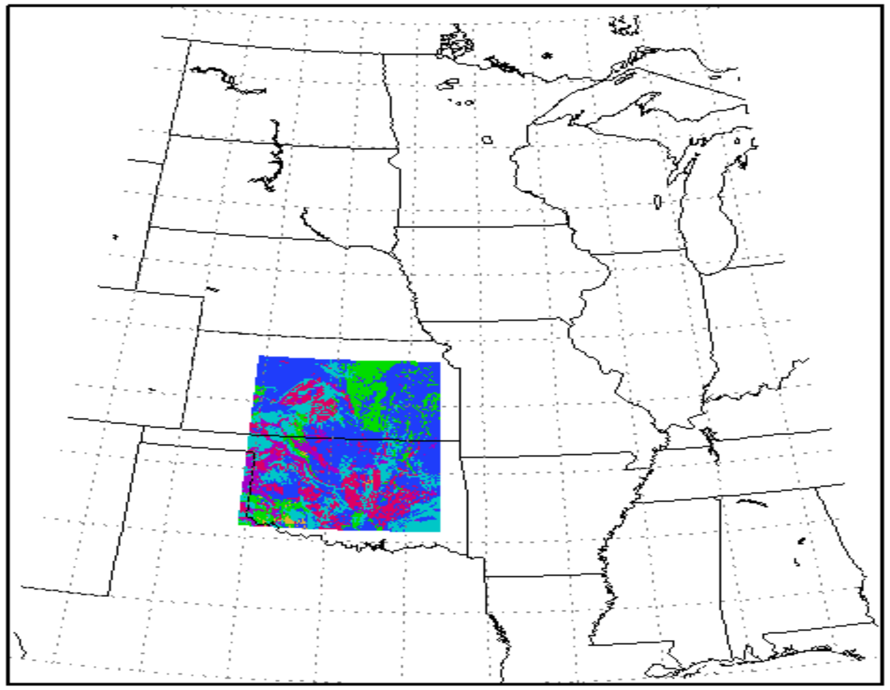
- GPM Ensemble members show improvement for determining decreases FoS over the observed landslide failure region but upper ensemble values overestimate failure

Yatheendradas et al. (2014), ""Evaluation of satellite rainfall for physically-based landslide modeling applications: examples over the Washington State region" J. Hydrometeorology, in prep.

OSSE to examine the impact of soil moisture observations on weather forecasting

- Objective: Quantify the impact of soil moisture observations on an end-use application – How much do the observations impact short-term hydrometeorological prediction?

- Perform soil moisture assimilation during an offline LSM spinup (using LIS-DA) and use it to initialize short term forecasts (using LIS-WRF)



- Case study:
  - Domain : U.S. Southern Great Plains (500x500 @1km resolution) (using the Noah v3.3 LSM + YSU PBL scheme)
  - Time period: **Dry (2006)** vs. **Wet (2007)** regimes over U.S. SGP
    - **14 July 2006** (dry; LIS-WRF test case)
    - **26-28 July 2007** (wet; scattered precip)
  - DA integrations are conducted using 1-d EnKF assimilating LPRM soil moisture retrievals from AMSR-E; Model runs forced with NLDAS-2 data

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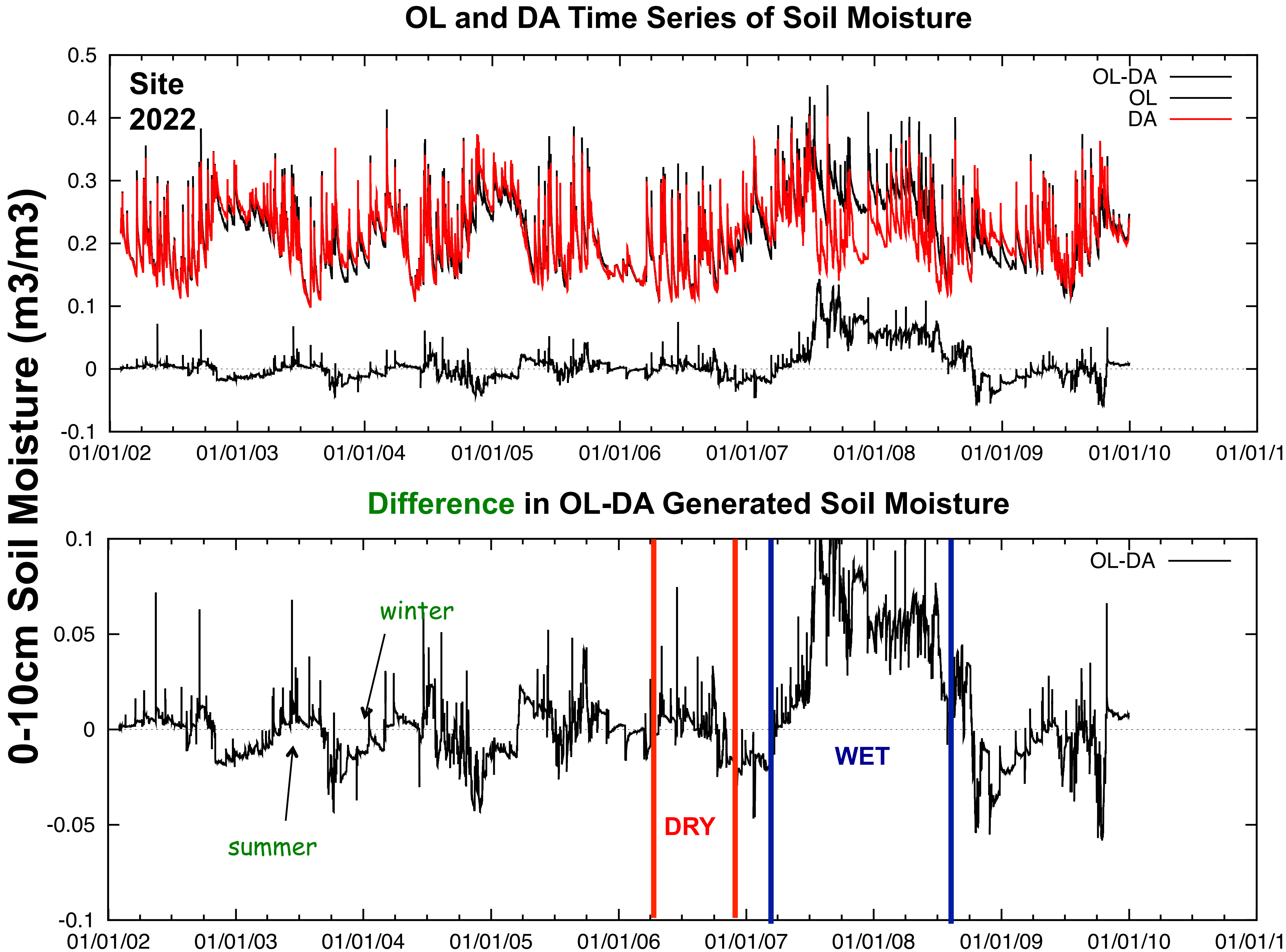
Impact of DA on Soil Moisture – 2002-2010



The time series plots show the seasonal impact of DA

During the summer months, the impact of DA is to produce drier soils, which gets amplified during the wet extremes

During the winter months the impact of DA is to produce wetter soils

Similar patterns seen at other two Soil Climate Analysis Network (SCAN) network sites

Land-Atmosphere Coupling

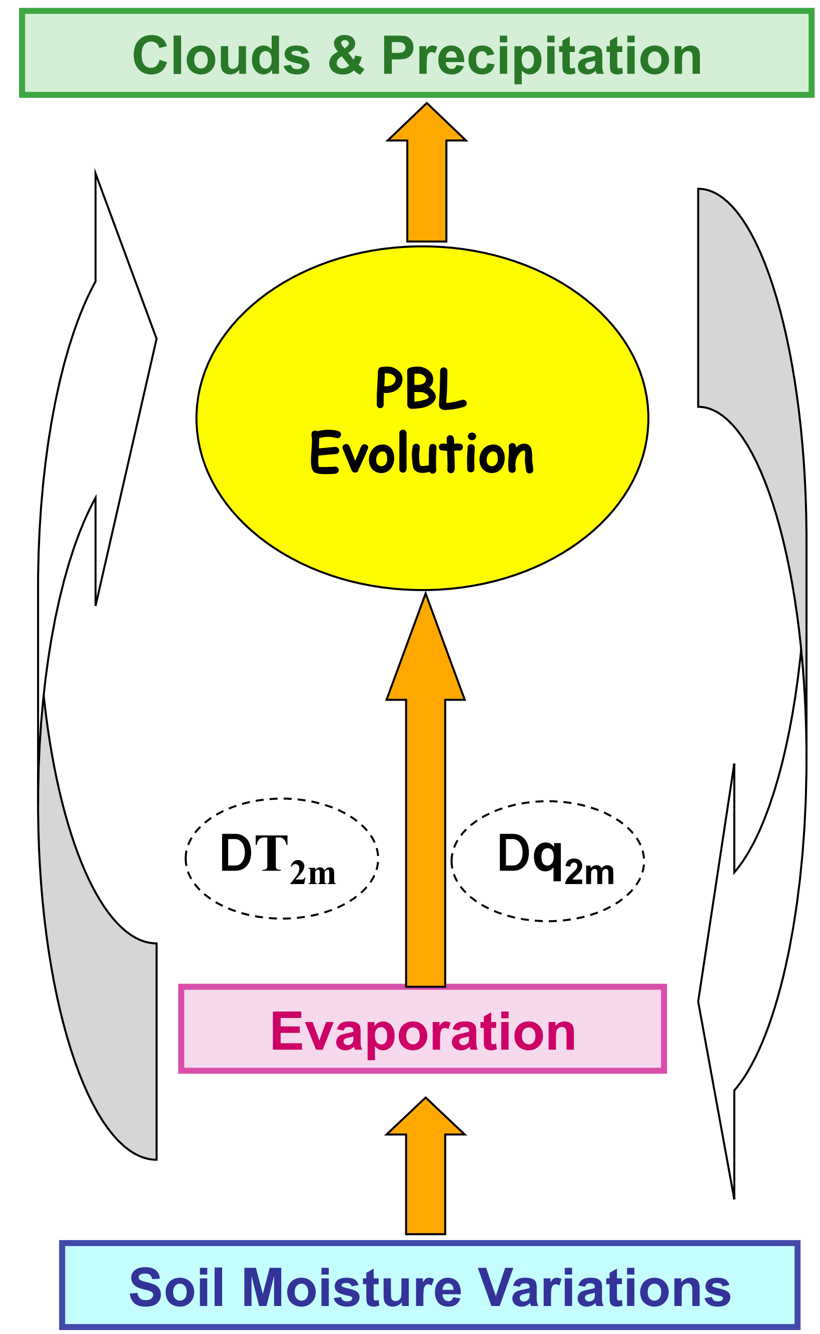
- **Land-atmosphere (L-A) interactions** play a critical role in supporting and modulating extreme dry and wet regimes, and must therefore be quantified and simulated correctly in coupled models.

- Recent efforts to quantify the strength of Local L-A Coupling ('LoCo') in prediction models have produced diagnostics that integrate across both the land and PBL components of the system.

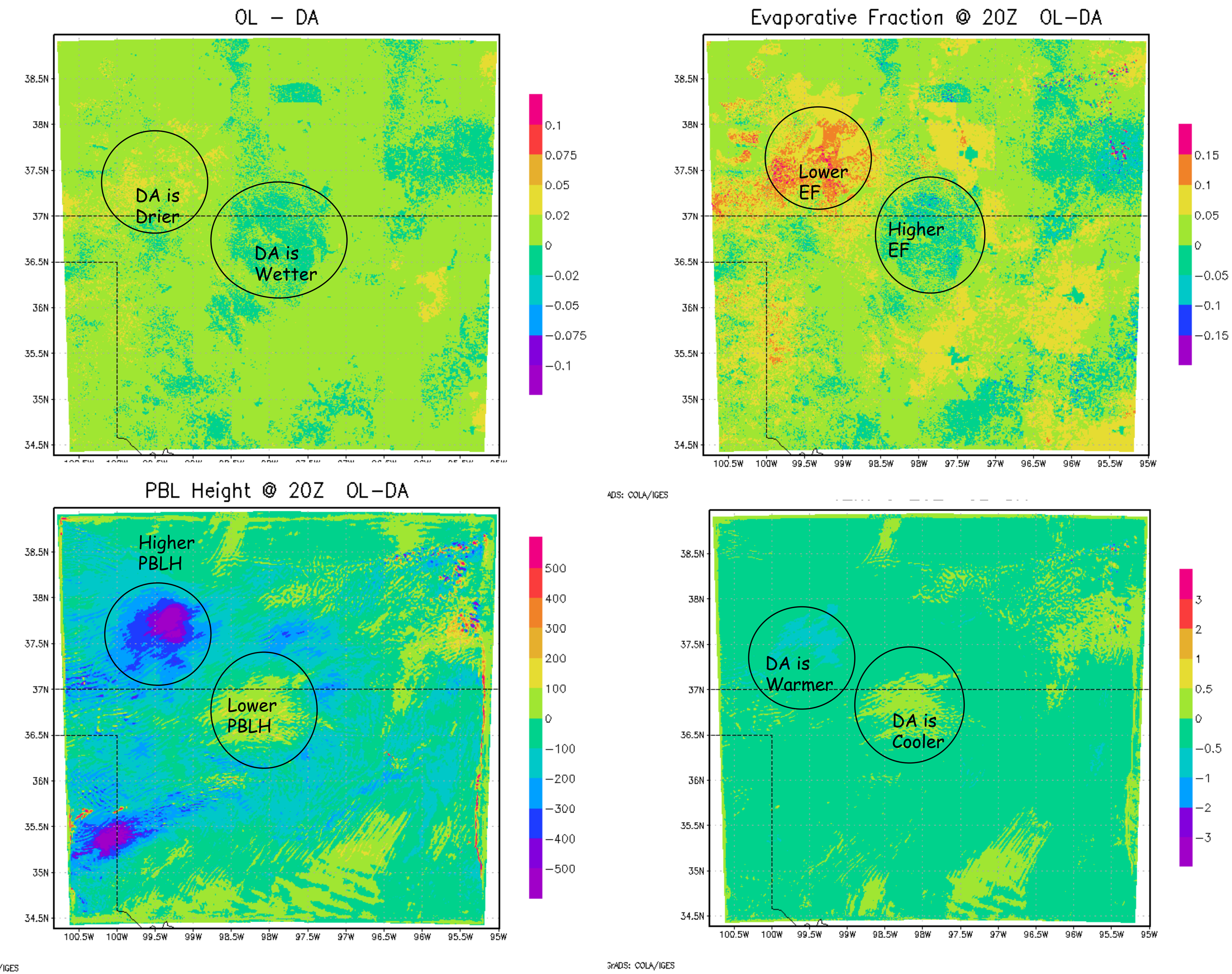
DSM → DEF → DPBL → DENT → DEF ► DPrecip/Clouds
(a) (b) (c) (d)

SM: Soil Moisture PBL: Planetary Boundary Layer (Mixed-layer quantities)
ENT: Entrainment fluxes EF: Evaporative Fraction P/Cloud: Moist processes

- LoCo diagnostics provide simultaneous assessment of the land-PBL states, fluxes, and interactions, highlighting the accuracies and potential deficiencies in components of the modeling system.



Impact of DA on Land-Atmosphere Coupling
14 July 2006



-Soil moisture initial condition (OL-DA) impacted across the domain.

-Primarily drying due to DA with patches of wetting

-Impacts translate directly to midday (20Z) EF, PBLH, T2m.

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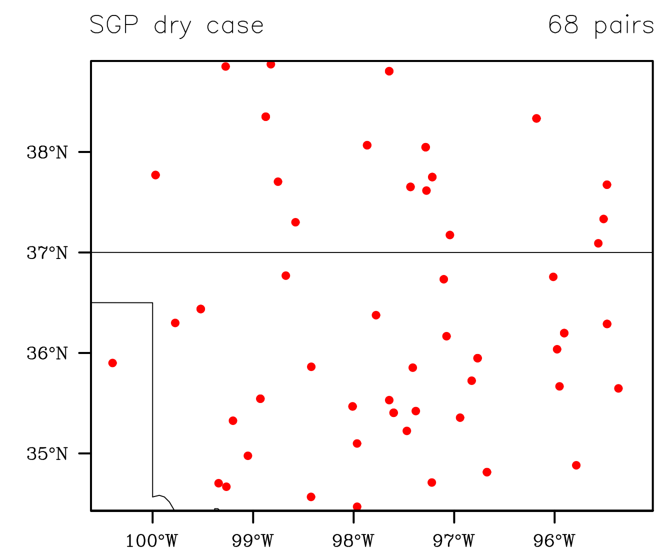
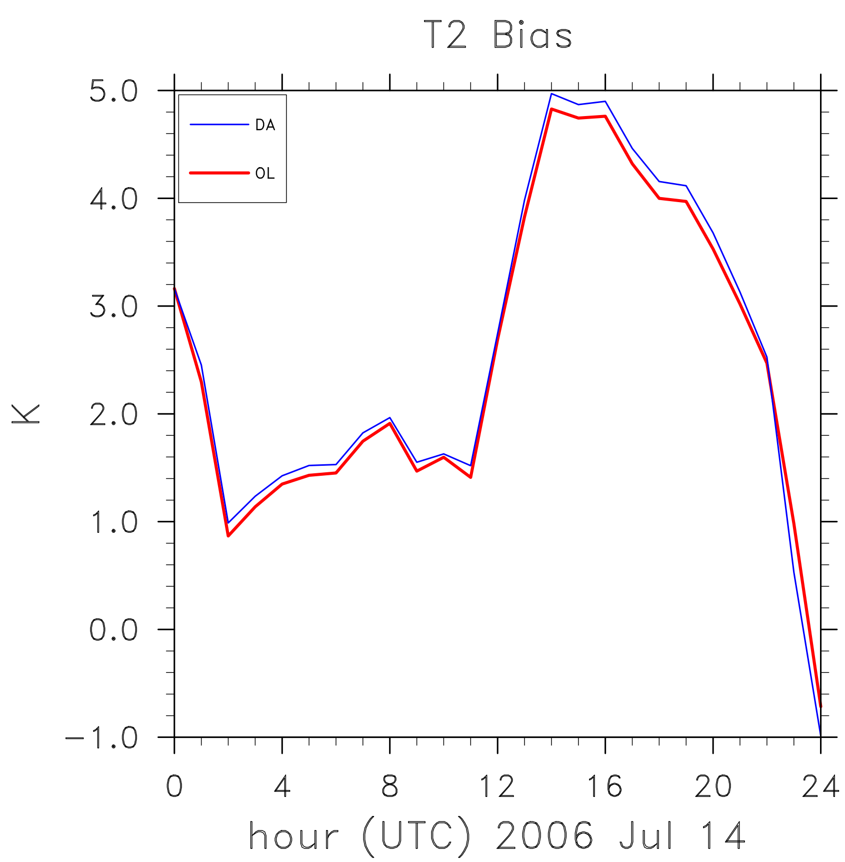
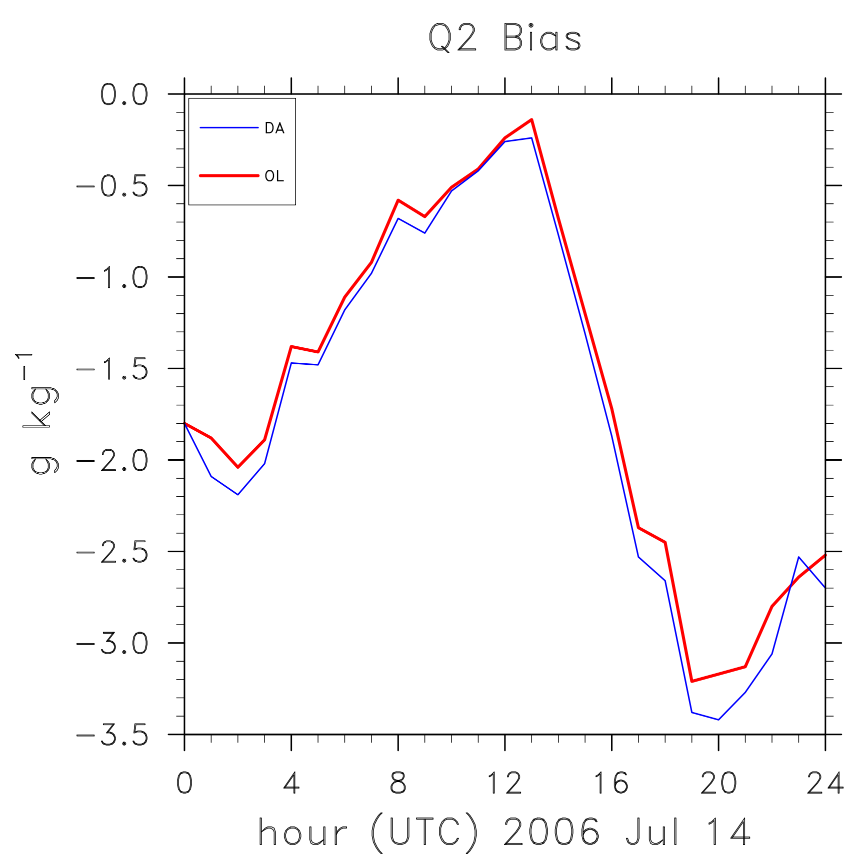
WRF Forecast Evaluation – 14 July 2006

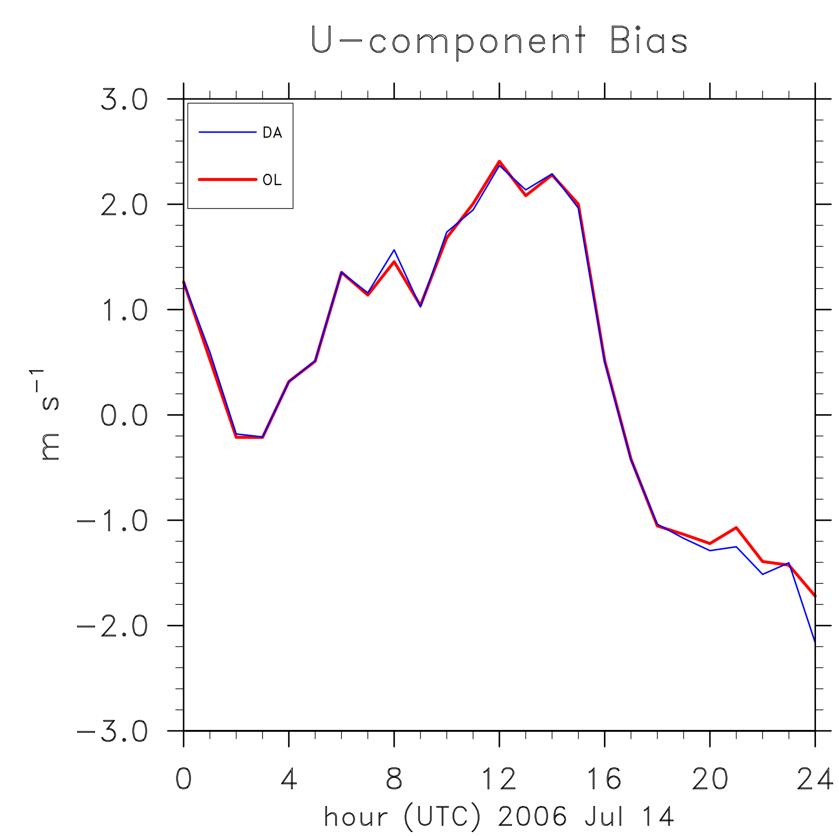


- 2-meter Air Temperature and Humidity show slight decrease in skill (increased bias) due to soil moisture assimilation

- DA produces warmer temperatures and lower humidity due to drier overall surface conditions







Weather forecasting OSSE Summary

- Impacts of LIS-DA on WRF initial conditions (soil moisture & temperature) are felt **throughout 24-48 hour forecasts** in terms of surface fluxes, PBL evolution, and ambient temperature and humidity.

- LoCo analyses reveal that large impacts on **land-PBL coupling** can be introduced by DA.

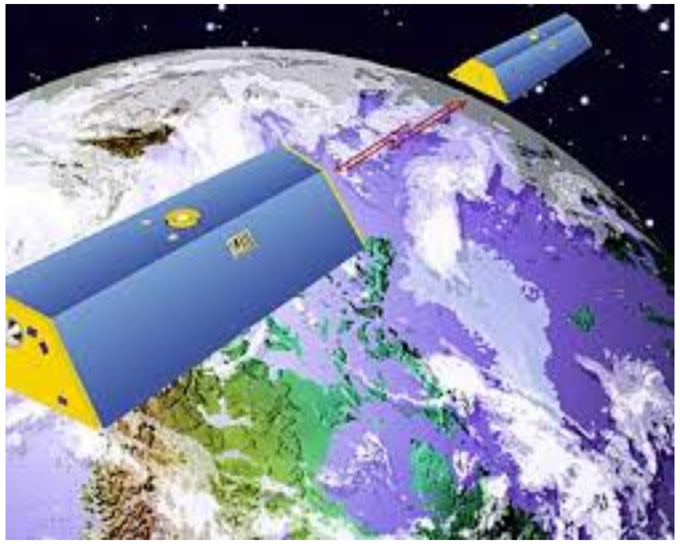
- Impacts during the dry regime (2006) are more marginal and variable across the domain, but **are larger and more widespread during the wet regime (2007)** due to bigger DA increments.

- Overall tendency of DA to produce **drier soils tends to degrade forecast skill** (fluxes, 2/10m variables), as the LSM was too dry already.

- Coarse resolution DA in an well-forced offline LSM does not necessarily improve results.

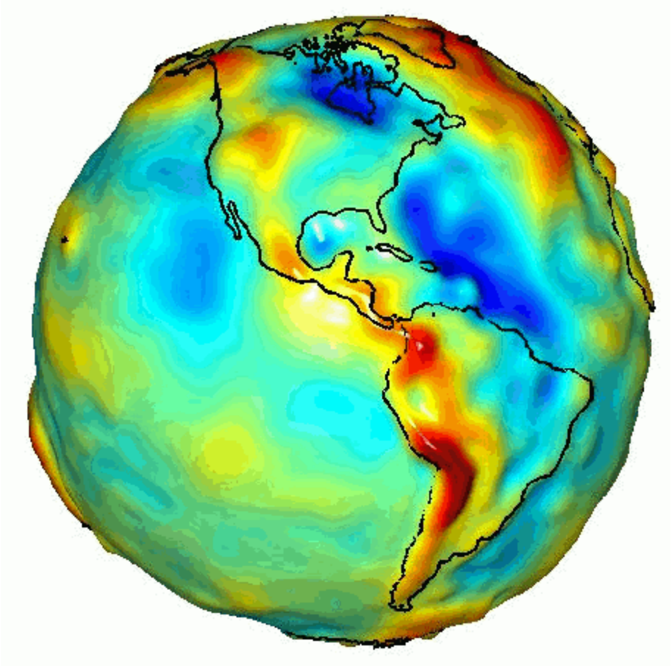
OSSEs for the development of future GRACE missions

- GRACE – Gravity Recovery and Climate Experiment (launched in 2002) satellite provides measurements of Earth's gravity field anomalies



- Measurements are NOT derived from electromagnetic waves; GRACE uses a microwave ranging system to measure changes in the speed and distance between two identical spacecrafts ("Tom" and "Jerry") flying in a polar orbit at about 220 km apart, 500 km above earth

- The twin satellites sense minute variations in Earth's gravitational pull. By combining the data of distance between the satellites and GPS measurements of the position of satellites, a detailed map of Gravity anomalies can be constructed (at a spatial resolution of about 660 km)



- Through the gravity field measurements, GRACE shows how mass is distributed around the planet and varies over time.

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GRACE OSSE

- A global 10-yr nature run (at 25 km resolution) using the Catchment LSM has been completed. The TWS fields from the simulation has been provided to the GRACE SDT.
- The GRACE SDT has identified the year 2008 as the target for simulation experiments.
- The planned SDT products will be at 500 km and 350 km (gaussian averaging radius employed in deriving the mass anomalies from the raw gravimetric data) with the following parameters varied:
  - Altitude (300 km, 350 km, 400 km)
  - Accuracy error
  - Solution time span (13-day, 30-day) with orbits adjusted for optimal repeat periods
- Smaller radius implies more spatial detail, but larger uncertainty
- Time permitting, the experiments will be extended for other years (2006 and 2007)

Summary

- A comprehensive environment for conducting end-to-end and applications focused OSSEs for terrestrial hydrology has been developed
- The environment has been demonstrated for a number of OSSEs for current and future missions (e.g. SMAP, GPM)
- The GRACE science definition team is employing this environment for the development of future GRACE missions.