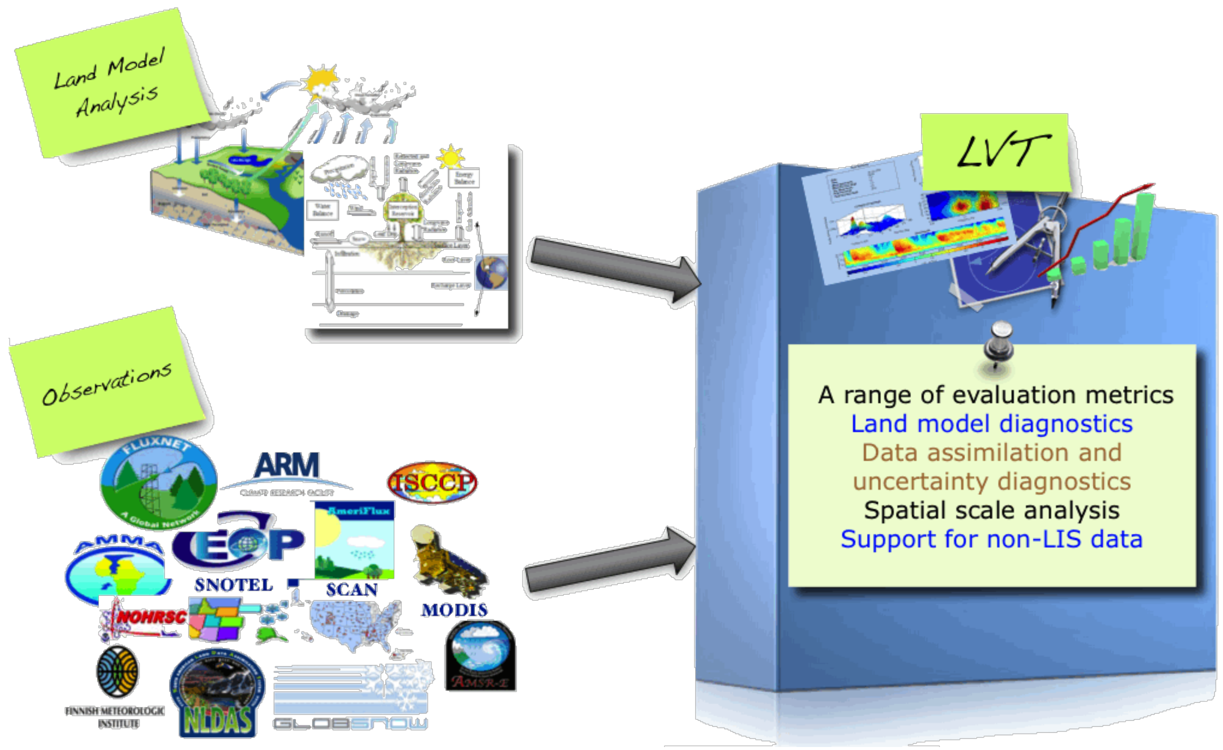
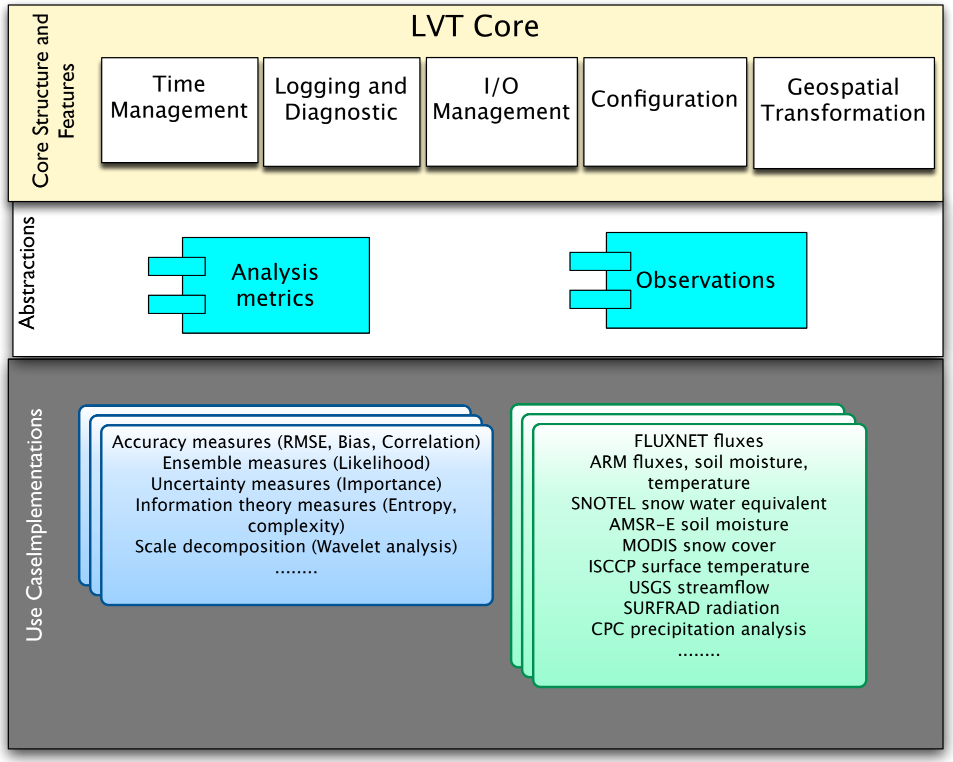
Land surface Verification Toolkit (LVT)



- LVT is a framework developed to provide an automated, consolidated environment for systematic land surface model evaluation
- Includes support for a range of in-situ, remote-sensing and other model and reanalysis products.
- Supports the analysis of outputs from various LIS subsystems, including LIS-DA, LIS-OPT, LIS-UE

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

Design of LVT



- Designed as a stand-alone system; Analysis instances are enabled by specifying a configuration file (much like LIS). No external scripting is required.
- Designed as an object-oriented framework with extensible features enabled for
  - Specifying new metrics
  - Specifying new observational datasets.

Observational data support – A growing list

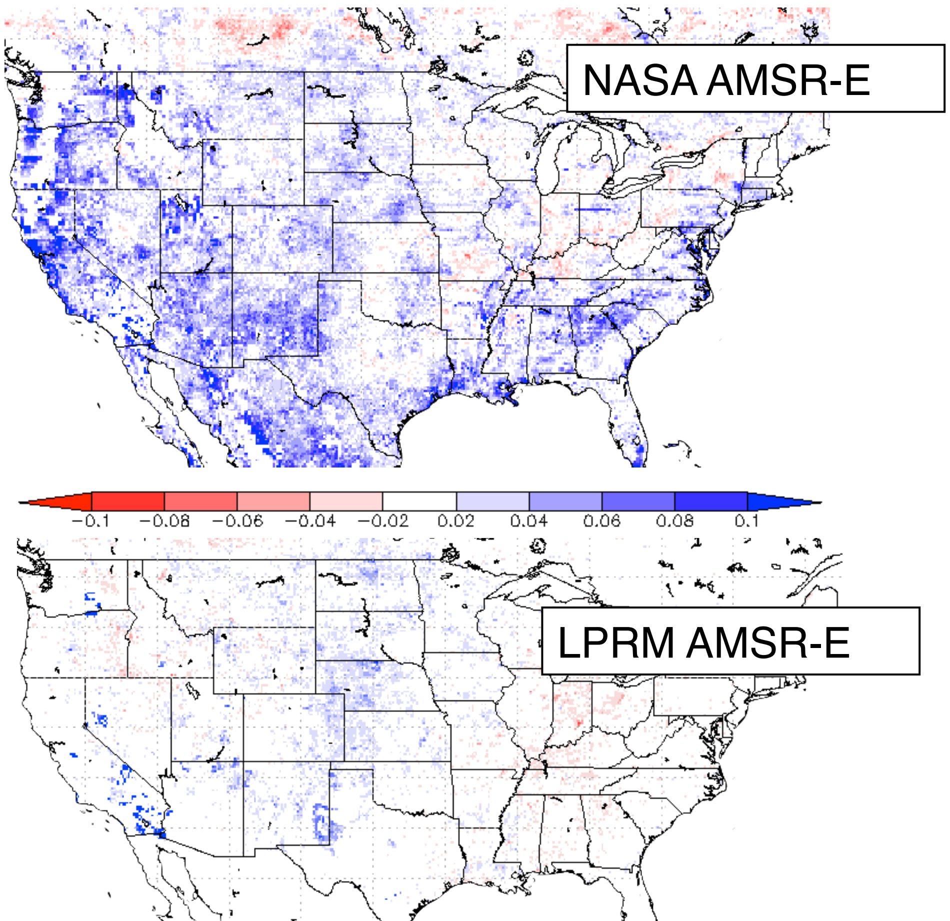
Dataset	Measurement variables
Model/reanalysis outputs	
Agricultural Meteorology Model (AGRMET) from the Air Force Weather Agency (AFWA)	Water and energy fluxes, Soil moisture, soil temperature, Snow conditions, meteorology
NLDAS model outputs Mitchell et al. (2004)	Water and energy fluxes Soil moisture, soil temperature, snow conditions, meteorology
GLDAS model outputs Rodell et al. (2004b)	Water and energy fluxes, Soil moisture, soil temperature, snow conditions, meteorology
Canadian Meteorological Center (CMC) snow depth analysis Brown and Brasnett (2010)	Snow depth
Snow Data Assimilation System SNODAS; Barrett (2003)	Snow depth, snow water equivalent

Satellite and remote sensing data	
AFWA NASA Snow Algorithm ANSA; Foster et al., 2011	Snow cover, snow depth, snow water equivalent
GlobSnow; Pulliainen (2006) (www.globsnow.info/)	Snow cover, snow water equivalent
International Satellite Cloud Climatology Project; ISCCP; Rossow and Schiffer (1991) (isccp.nasa.gov)	Land surface temperature
MODIS/Terra Snow cover 500 m MOD10A1; Hall et al. (2006)	Snow cover
MODIS Evapotranspiration product MOD16; Mu et al. (2007)	Evapotranspiration
NASA Level-3, soil moisture retrieval from AMSR-E (AE_Land3) Njoku et al. (2003)	Soil moisture
Land Parameter Retrieval Model (LPRM) from NASA GSFC and VU Amsterdam Owe et al. (2008)	Soil moisture

In-situ measurements	
AMMA (database.amma-international.org/)	Water and energy fluxes, soil moisture, soil temperature
Atmospheric Radiation Measurement (ARM) (www.arm.gov)	Water and energy fluxes, Soil moisture, soil temperature, meteorology
Ameriflux (public.ornl.gov/ameriflux/)	Water and energy fluxes
Coordinated Energy and water cycle Observations Project (CEOP) (www.ceop.net/)	Water and energy fluxes, soil moisture, soil temperature, meteorology
National Weather Service Cooperative Observer Program (COOP) (www.nws.noaa.gov/om/coop/)	Snow depth, precipitation, land surface temperature
NOAA CPC unified Higgins et al. (1996)	Precipitation
Gridded FLUXNET Jung et al. (2009)	Water and energy fluxes
Finnish Meteorological Institute FMI/SYKE; www.environment.fi/syke	Snow water equivalent
Global Summary of the Day (GSOD)	Snow depth
International Soil Moisture Network (www.ipf.tuwien.ac.at/insitu/)	Soil moisture
Soil Climate Analysis Network (SCAN; www.wcc.nrcs.usda.gov/scan/)	Soil moisture Soil temperature
WMO synoptic observations	Snow depth
NRCS SNOwpack TELemetry network (SNOTEL; www.wcc.nrcs.usda.gov/snow/)	Snow water equivalent
Surface Radiation Network (SURFRAD) (www.srrb.noaa.gov/surfrad/)	Downwelling shortwave, downwelling longwave
Southwest Watershed Research Center (SWRC; www.tucson.ars.ag.gov/dap/)	Soil moisture, soil temperature
USGS water data (waterdata.usgs.gov/nwis)	Streamflow
AMSR-E radiances (mrain.atmos.colostate.edu/LEVEL1C/)	Brightness temperature for different channels

Metrics development in LVT

- 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



Change in Metric entropy as a result of the assimilation of soil moisture retrievals of AMSR-E from NASA and LPRM algorithms

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

Metric entropy provides a measure of the randomness in the soil moisture time series at each grid point. The availability of information theory metrics in LVT provides a way to discriminate model simulations based on their information content.

Capabilities

- LVT reconciles the differences in spatial and temporal resolutions by bringing the model (LIS) and observational datasets to a common (user-specified) space and time domain.
- Support for datasets in their “native” formats; Once the specific plugin to process a particular dataset is built, datasets can be directly employed within LVT. E.g. ARM-CART measurements.
- Supports non-LIS datasets for intercomparisons – (An observational processing mode in LVT enables the conversion of an external dataset to a “LIS like” form.
- Miscellaneous:
  - Confidence intervals on analysis statistics
  - Analysis outputs in ASCII, binary, GriB, NETCDF formats
  - Probability density functions of computed metrics
  - Stratify analysis by external datasets
  - Stratify analysis based on a model variable (e.g. day-night stratification)
  - Land surface diagnostics

lvt.config

```
LVT running mode:              "LIS output processing"
Map projection of the LIS run: "latlon"
LIS nest index:                1
Number of surface model types:  1
Surface model types:           "LSM"
LIS output source:             "LSM"
LIS output format:             "grib1"
LIS output naming style:       "WMO convention"
LIS output methodology:        "2d gridspace"
LVT output format:             "netcdf"
LVT output methodology:        "2d gridspace"
Map projection of parameter data: "latlon"
Observation source:                 "FLUXNET"
```

Running mode supports LSM intercomparisons/added analysis, analysis of DA diagnostics, processing of observational datasets.

Supports the analysis of both LSM and other surface model outputs

Supports all output formats and styles (grid/vector/ensemble) from LIS

The analysis time period is a subset of the LIS output

Allows analysis restarts – for long analysis integrations.

```
Start mode:                                        coldstart
LVT restart output interval:                       "1mo"
LVT restart filename:                              none
Starting year:                                     2008
Starting month:                                    1
Starting day:                                      1
Starting hour:                                     0
Starting minute:                                   0
Starting second:                                   0
Ending year:                                       2008
Ending month:                                      5
Ending day:                                        1
Ending hour:                                       0
Ending minute:                                     0
Ending second:                                     0
LIS output timestep:                               "3hr"
Undefined value:                                  -9999
LVT diagnostic file:                               FLUXNET/lvtlog
LIS output directory:                            ../AGRMET_s4
Number of ensembles per tile:                    1
```

lvt.config

```
#LIS domain
Run domain lower left lat:                    -59.875
Run domain lower left lon:                   -179.875
Run domain upper right lat:                    89.875
Run domain upper right lon:                   179.875
Run domain resolution (dx):                     0.25
Run domain resolution (dy):                     0.25

LIS run domain lower left lat:                -59.875
LIS run domain lower left lon:               -179.875
LIS run domain upper right lat:                89.875
LIS run domain upper right lon:               179.875
LIS run domain resolution (dx):                 0.25
LIS run domain resolution (dy):                 0.25
```

The analysis domain can be a subset of the LIS output domain

LVT supports both upscaling and downscaling of the LIS outputs

```
LIS output attributes file:   './FLUXNET/MODEL_OUTPUT_LIST_LVT.TBL'
```

The attributes file specifies the variables included in the analysis

```
#Energy balance components
Swnet:        0  W/m2    DN   1 0 0 1 111 10     0 # Net Shortwave Radiation (W/m2)
Lwnet:        0  W/m2    DN   1 0 0 1 112 10     0 # Net Longwave Radiation (W/m2)
Qle:          1  W/m2    UP   1 0 0 1 121 10     1 # Latent Heat Flux (W/m2)
Qh:           1  W/m2    UP   1 0 0 1 122 10     1 # Sensible Heat Flux (W/m2)
Qg:           1  W/m2    DN   1 0 0 1 155 10     0 # Ground Heat Flux (W/m2)
Qf:           0  W/m2    S2L  1 0 0 1 229 10     0 # Energy of fusion (W/m2)
Qv:           0  W/m2    S2V  1 0 0 1 134 10     0 # Energy of sublimation (W/m2)
Qa:           0  W/m2    DN   1 0 0 1 136 10     0 # Advective Energy (W/m2)
```

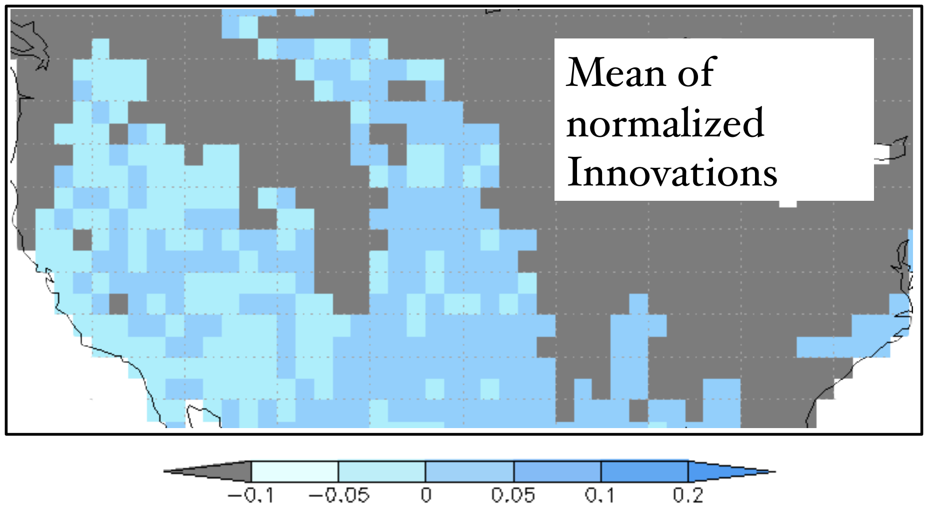
The first column indicates the variables included in the LIS output; the last column indicates the variables that needs to be included in the LVT analysis (LIS output contains Qle, Qh, Qg, LVT output contains Qle and Qh)

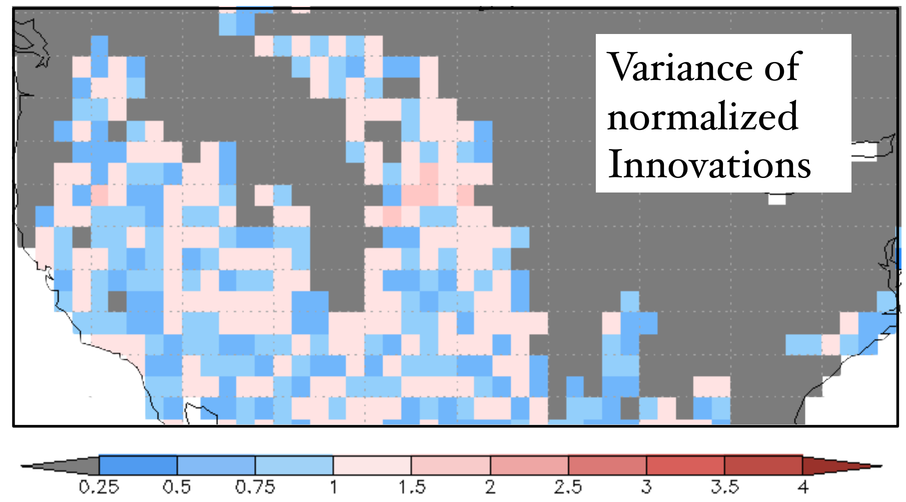
lvt.config

```
Apply external mask:                                0
External mask directory:                            OBSMASK.bin
Compute information theory metrics:                 0
Compute ensemble metrics:                           0
Metrics attributes file:                            ./FLUXNET/METRICS.TBL
Observation count threshold:                        0
Temporal averaging interval:                        "1mo"
Spatial averaging mode:                             "pixel-by-pixel"
Starting month if a shifted year definition is used in temporal averaging: 1
Stats output directory:                             ./STATS.FLUXNET
Stats output interval:                              "1mo"
Time series location file:                          ./FLUXNET/TS_LOCATIONS.TXT
Variable-based stratification:                       0
Compute LSM diagnostics:                             0
Confidence interval (%):                             95
External data-based stratification:                  0
Stratification attributes file:                      none
Compute average seasonal cycle of error metrics:     0
Seasonal cycle minimum count threshold:              0
Seasonal cycle interval type:                        "monthly"
Average diurnal cycle minimum count threshold:       0
Apply temporal smoothing to obs:                     0
```

Supports external masks; A variety of metrics;
Pixel-by-pixel and basin-scale averaging and computation of metrics
Use of water years, temporal smoothing, lagged computations

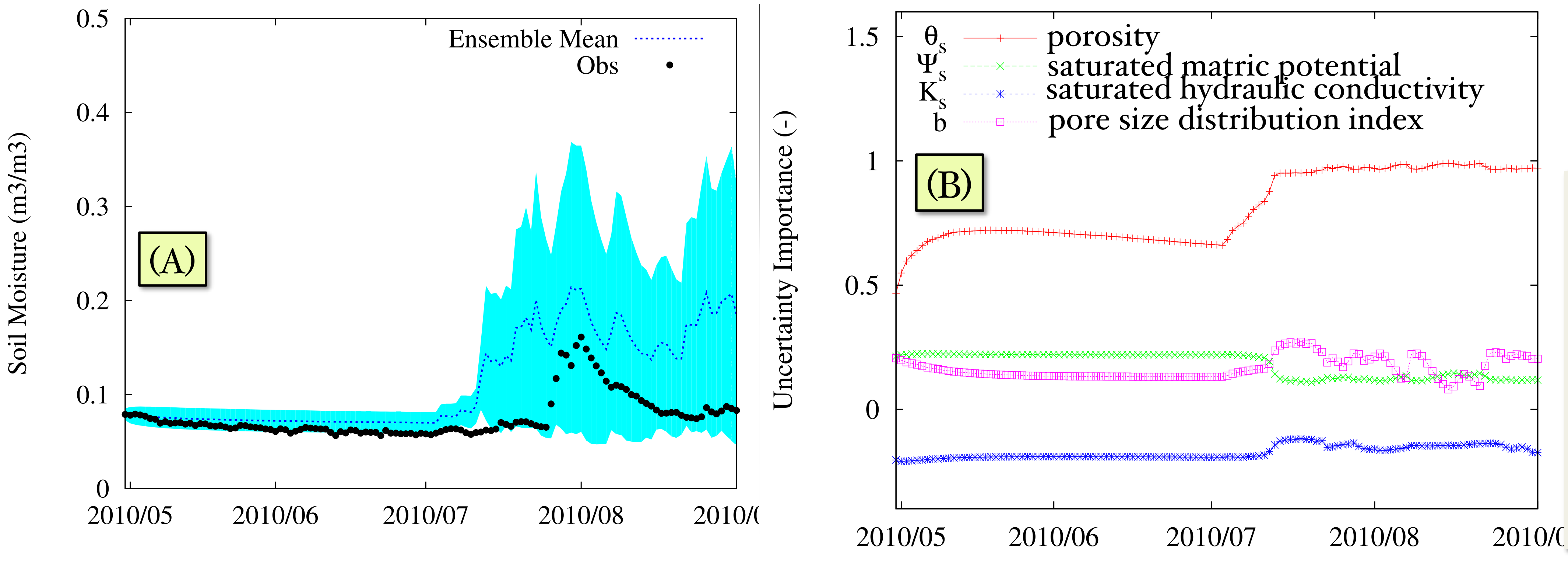
Analysis of LIS-DA outputs





- Deviations from the expected mean and standard deviations of the normalized innovation distribution is used as a measure of the optimality of the data assimilation configuration.

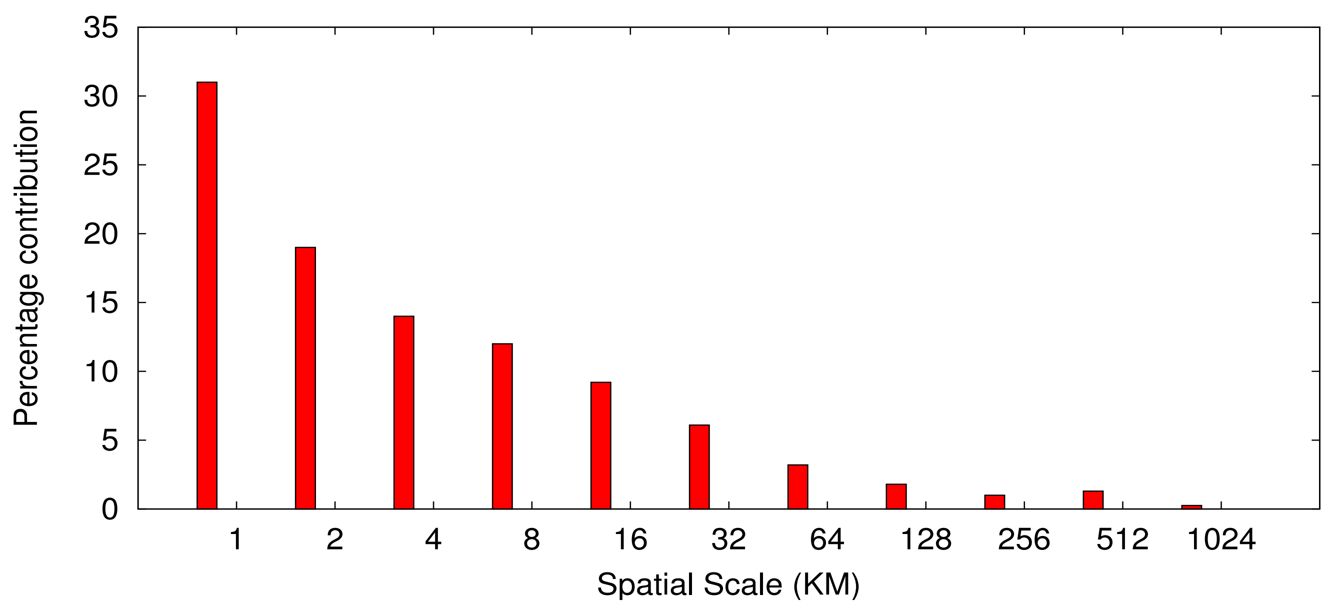
Analysis of LIS-UE outputs



- Uncertainty importance measure: An assessment of the relative contribution of each parameter to the ensemble spread, computed as the correlation between the simulated variable and the the parameter, across the ensemble.

Scale decomposition features

- Tools to characterize the impact of spatial scale on different process variables
- E.g. Discrete Wavelet transforms, spatial similarity measures



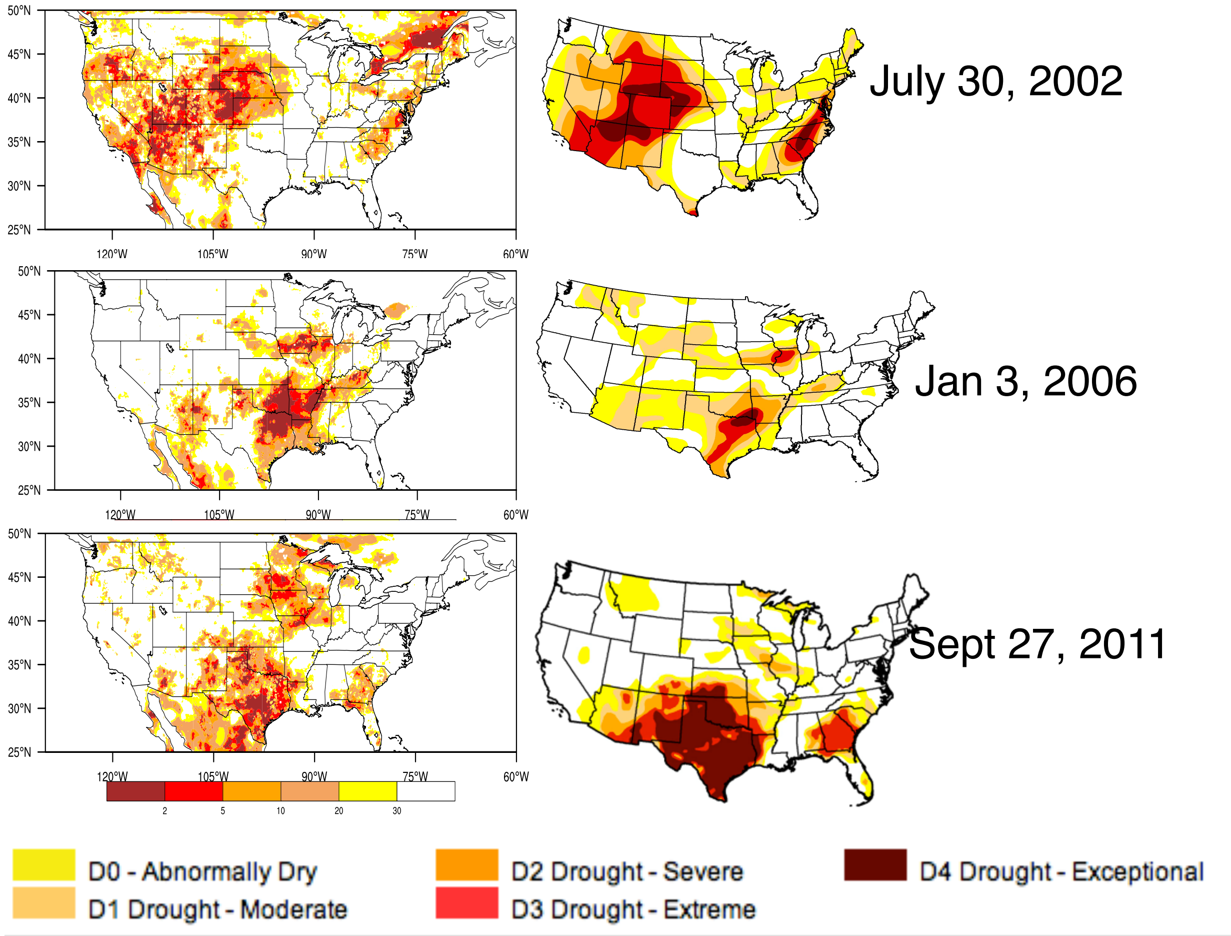
- Percentage contribution to the total improvement in snow covered area POD at different spatial scales, generated by a two-dimensional discrete Haar wavelet analysis.

Hydrological Products development

- A suite of common, normalized indicators used for drought monitoring has been developed in LVT (e.g. Standardized precipitation index (SPI), Standardized Runoff Index (SRI), Standardized Soil Water Index (SSWI), Percentiles

Root zone soil moisture based drought percentiles generated by LVT from a LIS simulation

U.S. Drought monitor estimate



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

Benchmarking

- Integration with PALS (Protocol for the Analysis of Land Surface Models) Land Model Benchmarking Evaluation Project (PLUMBER; Best et al. 2015) concepts
- LVT is being modified with a number of data analysis/fusion methods (regression, neural networks) that can generate benchmarks are purely based on specified datasets.
- These benchmarks can then be used for model intercomparisons (comparisons against a priori expectations of performance) and can be released to the community.
- LIS supports model outputs in 'PALS' formats. Direct use of PALS infrastructure is also possible using LIS outputs.

Summary

- An environment for the systematic, comprehensive and integrated verification of land surface models with a large suite of metrics.
- LVT supports the outputs from various LIS subsystems including DA, OPT, UE, RTM etc.
- Extensible features for incorporating new metrics and observation sources.
- A conduit for developing hydrological products (e.g. drought/ flood indicators).