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

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Model/reanalysis outputs</th>
<th>Measurement variables</th>
<th>In-situ measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural Meteorology</td>
<td>Water and energy fluxes, Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature,</td>
<td>Water and energy fluxes, soil moisture, soil temperature</td>
</tr>
<tr>
<td>Model (AGRMET) from the Air Force Weather Agency (AFWA)</td>
<td>Snow conditions, meteorology</td>
<td>Snow conditions, meteorology</td>
<td></td>
</tr>
<tr>
<td>NLDAS model outputs</td>
<td>Water and energy fluxes, Soil moisture, soil temperature,</td>
<td>Snow conditions, meteorology</td>
<td>Water and energy fluxes</td>
</tr>
<tr>
<td>Mitchell et al. (2004)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLDAS model outputs</td>
<td>Water and energy fluxes, Soil moisture, soil temperature,</td>
<td>Snow conditions, meteorology</td>
<td>Water and energy fluxes</td>
</tr>
<tr>
<td>Rodell et al. (2004b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canadian Meteorological Center (CMC) snow depth analysis Brown and Brasnett (2010)</td>
<td>Snow depth</td>
<td>Snow depth, precipitation,</td>
<td>Snow depth, precipitation,</td>
</tr>
<tr>
<td>Snow Data Assimilation System (SNODAS; Barrett (2003)</td>
<td>Snow depth, snow water equivalent</td>
<td>land surface temperature</td>
<td>land surface temperature</td>
</tr>
<tr>
<td>Satellite and remote sensing data</td>
<td>Snow cover, snow depth, snow water equivalent</td>
<td>Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature</td>
</tr>
<tr>
<td>AFWA NASA Snow Algorithm ANSA; Foster et al., 2011</td>
<td>Snow cover, snow depth, snow water equivalent</td>
<td>Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature</td>
</tr>
<tr>
<td>GlobSnow; Pulliainen (2006) (<a href="http://www.globsnw.info">www.globsnw.info</a>)</td>
<td>Snow cover, snow water equivalent</td>
<td>Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature</td>
</tr>
<tr>
<td>International Satellite Cloud Climatology Project; ISCCP; Rossow and Schiffer (1991) (isccp.nasa.gov)</td>
<td>Land surface temperature</td>
<td>Snow depth</td>
<td>Snow depth</td>
</tr>
<tr>
<td>MODIS/Terra Snow cover 500 m MOD10A1; Hall et al. (2006)</td>
<td>Snow cover</td>
<td>Snow depth, snow water equivalent</td>
<td>Snow depth, snow water equivalent</td>
</tr>
<tr>
<td>MODIS Evapotranspiration product MOD16; Mu et al. (2007)</td>
<td>Evapotranspiration</td>
<td>Snow depth, snow water equivalent</td>
<td>Snow depth, snow water equivalent</td>
</tr>
<tr>
<td>NASA Level-3, soil moisture retrieval from AMSR-E (AE_Land3) Njoku et al. (2003)</td>
<td>Soil moisture</td>
<td>Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature</td>
</tr>
<tr>
<td>Land Parameter Retrieval Model (LPRM) from NASA GSFC and VU Amsterdam Owe et al. (2008)</td>
<td>Soil moisture</td>
<td>Soil moisture, soil temperature,</td>
<td>Soil moisture, soil temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>In-situ measurements</th>
<th>Water and energy fluxes, soil moisture, soil temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMMA (database.amma-international.org/)</td>
<td>Water and energy fluxes, soil moisture, soil temperature</td>
</tr>
<tr>
<td>Atmospheric Radiation Measurement (ARM) (<a href="http://www.arm.gov">www.arm.gov</a>)</td>
<td>Water and energy fluxes, soil moisture, soil temperature, meteorology</td>
</tr>
<tr>
<td>Ameriflux (public.ornl.gov/ameriflux/)</td>
<td>Water and energy fluxes</td>
</tr>
<tr>
<td>Coordinated Energy and water cycle Observations Project (CEOP) (<a href="http://www.ceop.net/">www.ceop.net/</a>)</td>
<td>Water and energy fluxes, soil moisture, soil temperature, meteorology</td>
</tr>
<tr>
<td>National Weather Service Cooperative Observer Program (COOP) (<a href="http://www.nws.noaa.gov/com/coop/">www.nws.noaa.gov/com/coop/</a>)</td>
<td>Snow depth, precipitation, land surface temperature</td>
</tr>
<tr>
<td>NOAA CPC unified Higgins et al. (1996)</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Gridded FLUXNET Jung et al. (2009)</td>
<td>Water and energy fluxes</td>
</tr>
<tr>
<td>Finnish Meteorological Institute FMI/SYKE; <a href="http://www.environment.fi/syke">www.environment.fi/syke</a></td>
<td>Snow water equivalent</td>
</tr>
<tr>
<td>Global Summary of the Day (GSOD)</td>
<td>Snow depth</td>
</tr>
<tr>
<td>International Soil Moisture Network (<a href="http://www.ipf.tuwien.ac.at/insitu/">www.ipf.tuwien.ac.at/insitu/</a>)</td>
<td>Soil moisture</td>
</tr>
<tr>
<td>Soil Climate Analysis Network (SCAN; <a href="http://www.wcc.nrcs.usda.gov/scan/">www.wcc.nrcs.usda.gov/scan/</a>)</td>
<td>Soil moisture</td>
</tr>
<tr>
<td>WMO synoptic observations</td>
<td>Snow depth</td>
</tr>
<tr>
<td>NRCS SN0wpack TELemetry network (SN0TEL; <a href="http://www.wcc.nrcs.usda.gov/snow/">www.wcc.nrcs.usda.gov/snow/</a>)</td>
<td>Snow water equivalent</td>
</tr>
<tr>
<td>Surface Radiation Network (SURFRAD) (<a href="http://www.srhe.noaa.gov/surfrad/">www.srhe.noaa.gov/surfrad/</a>)</td>
<td>Downwelling shortwave, downwelling longwave</td>
</tr>
<tr>
<td>Southwest Watershed Research Center (SWRC; <a href="http://www.tucson.ars.ag.gov/dap/">www.tucson.ars.ag.gov/dap/</a>)</td>
<td>Soil moisture, soil temperature</td>
</tr>
<tr>
<td>USGS water data (waterdata.usgs.gov/inw)</td>
<td>Streamflow</td>
</tr>
<tr>
<td>AMSR-E radiances (mrain.atmos.colostate.edu/LEVEL1C)</td>
<td>Brightness temperature for different channels</td>
</tr>
</tbody>
</table>
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.

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

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
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.

---

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"

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

LVT supports both upscaling and downscaling of the LIS outputs.

The attributes file specifies the variables included in the analysis.

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

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.
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 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

**Figure 8.** Percentage contribution to the total improvement in snow covered area POD at different spatial scales, generated by a two-dimensional discrete Haar wavelet analysis.

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).