# International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps

**Summary Report**

*The Scientific Committee*
October 2008

## 1. Introduction

The *International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps* was held at NOAA's National Climatic Data Center (NCDC), Asheville, on 7-9 April 2008.

The workshop was co-sponsored by the GEWEX Radiation Panel and NOAA's NCDC, in partnership with NASA. More than 50 participants from 29 different institutions, representing eight different countries, participated. The participants included remote sensing specialists, modelers and members from the land surface temperature (LST) user community.

## 2. Workshop Objectives

The workshop was designed to foster dialogue between the research and user communities on the retrieval and use of land surface temperature products. The specific goals were to:

1) Review the state of the science of land surface temperature (LST) estimates from remote sensing platforms, models, and in situ approaches;
2) Specify the requirements for LST products from the different user communities (climate research, weather forecast, water management, other); and ultimately,
3) Identify the gaps between state of the science and the user community requirements, and discuss solutions to bridge these gaps.

## 3. Workshop Chairpersons

Pinheiro, Ana (NOAA's National Climatic Data Center, Asheville, NC, ana.pinheiro@noaa.gov)
Prigent, Catherine (Observatoire de Paris, Paris, France, Catherine.Prigent@obspm.fr)
Rossow, William (Chair, GEWEX Radiation Panel, City College of New York, New York City, NY, wbrossow@ccny.cuny.edu)

## 4. Scientific Organizing Committee (in alphabetical order of last name)

Michael Bosilovich (NASA Goddard Space Flight Center, USA)
Simon Hook (NASA Jet Propulsion Laboratory, USA)
Robert Knuteson (University of Wisconsin, USA)

Ana Pinheiro (NOAA National Climatic Data Center, USA)
Catherine Prigent (Observatoire de Paris, France)
William Rossow (The College City of New York, USA)
Pedro Viterbo (Instituto de Meteorologia, Portugal)

## 5. Workshop Structure

The agenda (see appendix A) included four sessions based to the following respective themes:
Theme 1: Remote Sensing of LST
Theme 2: Modeling of LST
Theme 3: Validation and Evaluation of LST
Theme 4: Community Requirements for LST

The first two days of the workshop included theme overview presentations by members of the scientific committee, followed by several selected presentations from other participants. A panel discussion was conducted at the conclusion of each session. The third day (morning) focused on breakout sessions (by theme), followed by brief summary presentations of the main issues highlighted in the panel discussions and breakout sessions. Scientific committee members served as session chairs and *rapporteurs*, and subsequently coauthored this Summary Report.

A questionnaire was given to the participants to identify existing LST products available to the community and the current limitation of those products. The questionnaire and the associated responses are summarized in Appendix B.

## 6. Top Issues For the LST Community Research Agenda (not in priority order)

I. Build a compendium of LST and emissivity products (as well as ancillary data like cloud masks, water vapor, etc).
II. Thoroughly assess the accuracy of selected LST products, especially over arid and semi-arid areas where errors can be large due to improper characterization of surface emissivity.
III. Intercompare different RS, model and *in situ* LST products, at the global scale, to assess level of agreement of the data for a full year, at different spatial resolutions. Investigate causes for disagreement (e.g., cloud mask, calibration issues, atmospheric correction, etc). Define time periods, areas of study and characteristics to be analyzed. Coordinate task with GEWEX Radiation Panel, EUMETSAT Land SAF, NOAA NCDC, ESA/GEWEX WACMOS and NASA.
IV. Characterize angular dependency of different RS products and investigate correction/normalization approaches.
V. Standardize *in situ* LST data collection procedures and metadata.
VI. Standardize RS and model LST metadata fields.
VII. Improve compatibility/consistency between land surface models physical parameterization of LST and remotely sensed products.

VIII. Create a web portal dedicated to the LST community where datasets are compiled, publications are shared, a discussion forum is available, etc.
IX. Continue routine generation of the MODIS Collection 4 LST products until Collection 5 problems are fully evaluated and corrected (see below)
X. Estimate LST over all pixels (all sky conditions) and provide cloud mask as separate product or layer.
XI. Develop calibration protocols or guidelines for *in situ* measurements. Such protocols should include detailed instrument information, rigorous error budgets and site characterize.
XII. Demonstrate the usefulness of LST versus air temperature for operational systems. Identify what additional information is provided by LST compared to Tair.
XIII. Evaluate the relationship between air temperature and surface temperature for different land surface types in terms of their diurnal cycle, diurnal range, monthly and annual averages, etc.

## 7. Summary of Thematic Sessions

### 7.1. Theme 1: Remote Sensing of LST

The Remote Sensing of LST session began with an overview of the state of the science by W. Rossow (Session Chair), followed by four contributed papers by Z. Wan, D. Hall, F. Prata and C. Prigent. The session ended with a panel discussion. A subsequent breakout session summarized issues and suggested some actions that might be undertaken to resolve them.

#### 7.1.1. Summary of Oral Presentations

Land surface radiometric temperature can be determined from satellite measurements of thermal emission at wavelengths in either infrared or microwave atmospheric “windows”; its accuracy is determined by how well several factors are accounted for. Estimated uncertainties associated with radiance calibration and correction for clear atmosphere absorption/emission are about 1-2K in both wavelength ranges; this is the estimate given in a previous workshop in 1993 (Gillies *et al*, 1995).

Thermal infrared (TIR) -based LST retrievals are less uncertain (1-2K) than microwave based ones because of the smaller range of variation of surface emissivities in the TIR domain and the stronger dependence of the radiance on temperature (almost to the fifth power in the infrared window). The range of surface emissivities in the microwave is much larger (many tenths) and the temperature dependence is essentially linear leading to LST uncertainties that can be as large as 10's of degrees. Infrared measurements are very much more sensitive to cloud contamination than are microwave measurements. Strict cloud detection can reduce the uncertainty of infrared temperature determinations to 2-3K (cf. Rossow and Garder 1993, Prigent et al. 2003), whereas the remaining cloud effects on microwave determinations are similar though much less frequent. However, the need for a strict cloud detection severely limits the space-time sampling of infrared measurements; in fact, the “clear-sky” bias of infrared results is significant (of order 4K rms) and varies systematically with location, time of day and season. In fact, the correlation of temperature variations and cloudiness in weather events precludes an accurate determination of the synoptic variations as well. Microwave measurements are much less limited in this regard but are much more uncertain because of the complex and large variations of surface emissivity (including angle dependence). Other issues raised, especially with regard to using infrared and microwave measurements to determine other properties of the land surface besides temperature, are the need for better information about small-scale (< 10 km) heterogeneity and the wavelength dependence of surface emissivity as a function of surface properties. Much progress on these problems would seem possible if the whole satellite constellation is used (both infrared and microwave instruments, high and low resolution measurements) and the measurements systematically processed using physically rigorous analysis methods.

Two different "split-window" LST retrieval algorithms being used to analyze MODIS data were discussed in detail: the split-window algorithm, where the surface emissivity is specified (as a function of a land surface classification), and the physically based day-night algorithm, where the day-night contrast at each location is used to separate temperature and emissivity values. Results comparing these two approaches show that there is too much variation in the retrieved emissivities from the latter method. Although the coefficients for this type of algorithm are determined from radiative model simulations of atmospheric effects, ancillary atmospheric data are not used explicitly. Evaluation of these products, such as the new ones based on MODIS, remains difficult because of the lack of *in situ* datasets covering a comprehensive range of regimes. A specific example of this difficulty was illustrated for Greenland ice sheet surface temperatures. Evaluation of the satellite surface temperatures was possible in this case but required determination of a good statistical relationship with near-surface air temperatures being measured at the surface. Uncertainty was associated not only with use of this relationship but with the comparison of point to area measurements. Another example uses the nighttime air temperature, which is generally very close to the LST value, as an evaluation of ATSR products. The ATSR version of the split-window technique uses specified land-class emissivities; estimated uncertainties are in the range of 1-3K.

A combined analysis of infrared and microwave measurements was presented that tries to overcome some of the limitations of the separate measurements. Conceptually, infrared and microwave measurements of the same clear-sky scenes provide LST and microwave emissivity values that are then employed as first guesses in a neural network analysis of microwave for cloudy scenes. Since this approach reduces the clear-sky biases for infrared-only products and the emissivity uncertainties for microwave-only methods, the final uncertainty in the LST values is less than 2K. Because of current satellite orbits, this approach does not yet provide complete diurnal coverage for cloudy scenes.

### 7.1.2. Panel and Breakout Group Discussions

Three different purposes for land surface temperature measurements were outlined: climate monitoring of temperature changes, study of land-atmosphere interactions as reflected in the variability of temperatures on a range of time scales from diurnal to annual, and inference of properties of the land surface from the variations of temperature (and emissivity). It was also emphasized that, in analyses of a combination of different kinds of measurements, the differences should be retained as indicative of the land surface properties. Discussion focused on several points concerning surface heterogeneity and instrument resolution, how these factors affect the results and their evaluation from *in situ* measurements. It was noted that, given the wide range of satellite instruments now available (very large range of spatial resolutions, multi-spectral to spectrometer, multi-angle and infrared-microwave), many of these questions could be tackled directly using combinations of these measurements. For example, ASTER and MODIS data from TERRA could be used to examine the role of small-scale spatial variability; ATSR and MERIS data on Envisat could be used to examine angle-dependence; MODIS and AIRS on AQUA could be used to examine spectral dependence. One goal of these analyses would be to develop “good enough” statistical-physical models of the land surface properties to allow for systematic processing of satellite observations to produce an accurate global record of LST. An accuracy goal is set by the desire to determine the land-atmosphere energy (water) fluxes to better than 10 $Wm^2$, which leads to an accuracy requirement for LST of about 1K.

### 7.1.3. Summary of Issues

The breakout session consider six questions:

1) Why are there such large and structured disagreements among the available LST products?
2) Can ASTER and MODIS be used in combination to understand surface heterogeneity and provide a parameterization for use by lower resolution remote sensing analyses and models?
3) How can we “boot-strap” the LST analysis from polar orbiting temperature infrared and microwave sounding systems to polar orbiting infrared and microwave imagers, to geostationary infrared imagers to provide a systematic, global, high-time-resolution (diurnal) LST product?
4) Should the split-window technique be improved (more physical, more input data) as the observation operator for assimilation systems?
5) What can the WCRP/WMO/CEOS Coordinated Energy and Water Cycle Observation Project - 2 (CEOP-2) do to help evaluate LST products?
6) What is the need for emissivity information at wavelengths other than the ones used to determine LST?

Specific issues under Question 1 and satellite instruments that could be used to investigate are: (a) AATSR could be combined with MERIS to survey the angle dependence of land surface emissivity over a range of angles and develop site-specific correction. (b) the emissivity products from AIRS, ASTER and MODIS could be compared to reconcile land infrared emissivities, (c) combined analysis of coincident IR and microwave LST retrievals can be used to evaluate cloud contamination effects in both, (d) IR and microwave instruments need to be calibrated to a common standard to produce long time records (there are projects underway to do this), (e) ancillary datasets used in the various LST products, such as land classifications, laboratory data and topography, should be compared to eliminate them as contributors of product differences, (f) more *in situ* data are needed to evaluate satellite products, joint evaluations for different instruments would be especially useful.

Discussion of Question 2 indicated that similar angle dependence studies could be carried out combining AMSR-E and AMSU. Analysis of multi-angle data from AATSR (not yet done) is important for study of those locations where the vegetation canopy is expected to exhibit vertical temperature variations, and where structure induced effects (sunlit versus shaded components) may play a role. Discussion of Question 3 highlighted the idea to exploit the differences among instruments to learn more about the properties of the land surface. Under Question 4, it was suggested that the split-window approach might be improved by better regression approaches than simple linear fits and by making the coefficients explicit functions of atmospheric properties provided by ancillary datasets (already used in some versions) There would be value in publication of the library of coefficients used for various versions of this algorithm. CEOP could provide a baseline set of LST evaluation data by standardizing procedures for measuring "skin" surface temperatures *in situ* as well as the ancillary data needed (complete meteorology including cloudiness and surface site characterization) for such evaluations and then collecting the required datasets. Finally, under Question 6, although such information is not too important for radiative flux purposes (because the atmosphere is nearly opaque outside the window wavelengths used for retrievals), it would be important as part of the characterization of surface properties if it could be determined from satellites.

#### 7.1.4. Suggested Recommendations/Actions

To address at least some of the issues discussed, an international collaboration could be organized to carry out a detailed comparison and evaluation of the available LST products. This should be done for a full year of data (at highest available space-time resolution); an initial proposal is that the year be 2003, when products from both older and newer instruments are available and some CEOP observations for evaluation are available (this choice will be refined after surveying data availability). In addition to collecting all of the products for this common year, their ancillary datasets should also be collected, especially surface emissivity (specified or retrieved) and atmospheric temperature and humidity. Model outputs for the same time period should also be gathered and compared with the satellite products and the in situ available measurements. This effort would be sponsored by the GEWEX Radiation Panel but should also be coordinated with plans/activities at the EUMETSAT Land SAF for its product development, at NOAA NCDC for development of a surface temperature climate data record, and within the recent ESA/GEWEX WACMOS initiative.

#### 7.1.5. Summary of Poster Presentations

- *A dynamic cloud masking and filtering algorithm for MSG retrieval of land surface temperature* (Fausto Barboncini and Fabio Castelli): The algorithm, applied to a surface energy balance model, uses a modified Kalman Filter to separate the non-Gaussian error due to clouds from the reference cloud-free LST retrieval error. The method leads to a more consistent identification of cloud-free LST data and a substantial increase in the quantity of final LST estimates.

- *The GHRSST pilot project: Benefits and lessons learned that are of interest to the LST community* (Gary Corlett, and Craig Donlon): The Global Ocean Data Assimilation Experiment (GODAE)

High-resolution SST Pilot Project (GHRSST-PP) http://www.ghrsst-pp.org provides near-real time SST data products from several different satellite sensors and *in situ* observations.

- *Estimating hourly, 1 km Land Surface Temperatures by combining MODIS and GOES data* (Andrew N. French and Anand Inamdar): This project combines MODIS and GOES LST estimates to take advantage of the high spatial resolution of the first sensor, and the high temporal resolution of the second sensor. The scheme has three main components: cloud-clearing, diurnal temperature modeling, and 5-1 km LST disaggregation. The resulting data sets are modeled LST values constrained by MODIS and GOES LST observations, diurnal temperature functions, and 20 day LST running averages.

- Hook, S., *HyspIRI-TIR - A new high spatial thermal infrared multispectral scanner recommended by the National Research Council.* Currently known as HyspIRI, this mission is in the conceptual design phase at NASA. It consists of an imaging spectrometer in the visible to shortwave infrared regions of the electromagnetic spectrum and a multispectral imager in the thermal infrared portion of the electromagnetic spectrum.

- *The ASTER Land Surface Temperature and Emissivity Database for California and Nevada* (Glynn Hulley, Simon Hook): This project generates gridded LST&E datasets from clear-sky ASTER data with the output product consisting of mean, seasonal, land surface emissivity and temperature values on grid-boxes of 1.0º x 1.0º at 100 m spatial resolution. This approach was used to produce a winter-time and summer-time emissivity dataset for California and Nevada, USA derived from 3,102 ASTER summer scenes.

- *Data sets available at NCDC for LST research* (Ken Knapp, Hilawe Semunegus): Several data sets (*in situ* and remotely-sensed) archived at NOAA's National Climatic Data Center may be used to further the ability to understand and retrieve both historical and present-day land surface temperature. Those include the Climate Reference Network (CRN), the International Satellite Cloud Climatology Project (ISCCP), global infrared observations data sets from geostationary satellites, and the DMSP Special Sensor Microwave Imager (SSMI).

- *Analysis of land surface thermal-IR emissivity products and applications* (Shunlin Liang): In this study, multi-year MODIS and ASTER emissivity products are evaluated for their temporal profiles and spatial patterns in conjunction with land cover types. Their application to calculation of upwelling thermal radiation and evaluation of land surface temperature is presented.

- *Directional effects in a daily AVHRR land surface temperature dataset over Africa* (Ana C. Pinheiro, Jeffrey L. Privette, Robert Mahoney, Compton J. Tucker): Describes the methodology for developing a six-year daily (day and night) NOAA-14 AVHRR LST dataset over continental Africa. It demonstrates through correlation, that some of the AVHRR LST variability can be attributed to angular effects imposed by AVHRR orbit and sensor characteristics, in combination with vegetation structure.

- *Climate Data Records of Satellite Based Land Surface Temperature* (Ana C.T. Pinheiro, Jeff L. Privette and John Bates): Identifies the main challenges in developing a land surface temperature (LST) Climate Data Records (CDR) from NOAA-AVHRR. These include the orbital drift effects, the observation/illumination directional dependency and its relation to variable surface structural characteristics, the emissivity variability and its uncertainty, and the limited availability of ground validation data. Efforts underway at NOAA to address these challenges for AVHRR, MODIS and VIIRS data are presented.

- *Estimation of the land surface microwave emissivities over the globe from satellite observations* (Catherine Prigent, Filipe Aires, Bill Rossow): Proposes a parameterization of microwave emissivities that accounts for frequency, incidence angle, and polarization dependences using ancillary data (IR satellite observations and meteorological reanalysis) to remove the contribution from the atmosphere, clouds and rain to the measured satellite signal, and separate surface temperature from emissivity variations. For each location and time of the year, it provides realistic first guess estimates of the microwave emissivities from 19 to 100 GHz, for all scanning conditions.

- *Restoration of NPOESS Climate Capabilities: Climate Data Records* (Jeffrey L. Privette, Bruce Barkstrom, John Bates, and Thomas Karl, Bryant Cramer and Jack Kaye, Wayne Cecil, David Young, Koblinsky, Michael Tanner, Gary Davis, Michael F. Bonadonna, and Kandis Boyd): Describes the joint-agency program between NOAA, NASA and USGS to create Climate Data Records (CDRs) and Climate Information Records (CIRs) from NPOESS. The proposed program is jointly managed by the responsible agencies, but its execution relies extensively on community activities. The result will be a comprehensive set of CDRs and CIRs useful for spatio-temporal detection, analysis and prediction of environmental change, and for development of a coherent environment for climate model execution.

## 7.2. Theme 2: Modeling of LST

### 7.2.1. Summary of Oral Presentations

Presentations providing an overview of the issues in modeling and assimilating land surface temperature were given by M. Bosilovich (Session Chair), R. Reichle, X. Zeng, W. Zheng and D. Entekhabi.

The surface temperature in global and regional models is crucially important because of its relevance to the computations of the turbulent heat fluxes as well as the terrestrial radiation. In addition, modeled LST provides a first guess for some retrievals and observation based radiative flux data sets. It is important to understand that the surface temperature calculation comes down to solving a budget or balance equation, and that a multitude of parameterizations ultimately affect the resulting values of temperature, including the surface and boundary layer parameterizations, vegetation and heterogeneity, quality of clouds (both in quantity and optical properties) and soil moisture through antecedent precipitation. Global observations of some of these properties are not available, and so isolating the sources of uncertainty in the models are difficult. Each model has its own parameterization and land specification data, and usually its own grid structures. In addition, the gradients of temperature between the surface and the atmosphere are a parameterized component of the surface turbulent fluxes, and also need to be validated.

Results were presented, comparing the LST from eiht different atmospheric analyses, where atmospheric data are assimilated, but not land surface data, and the range of monthly mean LST among the group can be as large as 12K. When comparing any one modeling system with satellite retrieved LST, monthly differences can be as large as 15-20K. However, comparing a group of model data to ISCCP clear-sky satellite based LST seems to show more similarity among the models than to the satellite data. It is easily shown that substantial uncertainties persist across models.

While surface temperature assimilation has been studied for many years, there still exist numerous limitations in implementing LST assimilation to the best possible capability. Data assimilation assumes that the differences between the model and observation are not biased. However, systematic uncertainties exist among LST remote sensing products (due to variable observation angles, cloud clearing and retrieval algorithms). Models tend to project temperature vertically, while the satellite observations are angle dependent . Satellites observe real surfaces while heterogeneity is parameterized in models (if at all). These inconsistencies add uncertainty to the comparison of model and remotely sensed LST for data assimilation purposes. While some inconsistencies are likely not to be eliminated completely, data assimilation must account for them as a matter of practice. Furthermore, biases of LST may have diurnal components, so that assimilation of LST requires observations that resolve the diurnal cycle, in order to function properly. Nonetheless, recent studies have shown that some positive impact on the surface states and energy budgets can be obtained across the globe by including surface temperature assimilation. Many techniques have been tested, but broad global use of the observations still faces the challenges outlined above.

One goal of stand-alone model simulations is to use the available observations to prescribe forcing for the land states, and thereby derive both surface states and fluxes. However, given the relationship between surface temperature and the turbulent fluxes, a reasonable approach may be to use the most requisite portions of models to derive fluxes from the fewest input observing systems (and so keeping the model component elementary). LST, being integral to the surface energy budget, is the immediate and most readily available choice. While results of such methods are indeed promising, further constraints from soil moisture, vegetation and other characteristics and conditions (e.g. snow cover) are also important.

### 7.2.2. Panel and Breakout Group Discussion

In coupled land/atmosphere modeling there are many formulations of the land surface temperature, depending on the complexity of the physical parameterizations and the purpose of each model. For example, surface temperature can be computed separately for vegetation and bare surfaces, or combined in a bulk computation. The inherent differences of the approaches are not well known. In some cases, models may not have enough documentation to discern subtlety in the formulations. While the land parameterizations affect the simulated data, equally important is the forcing. For example, there are wide variations in the amount and properties of clouds produced in models, which greatly affect LST. Uncertainty in the simulated LST can then feedback into the near surface air temperature and boundary layer (or vice versa). Even relatively homogeneous regions, such as arid deserts and glacial surfaces, can show large differences compared with remotely sensed LST.

High quality observations provide a constraint on the model development. Data assimilation ultimately confronts the model with the observations. In regards to surface temperature, there are numerous difficulties in attaining the needed quantity and quality from existing data. The large amplitude of the diurnal cycle of temperature implies that reasonable time resolution (3 hourly at a minimum) and spatial information is needed in observations, for example from polar orbiting platforms. With this, the output from the model can be compared as closely as possible to the observations, a requisite for data assimilation. In addition, many LST data sets are for cloud-free conditions only. While clear-sky data are useful, the strong effects of clouds on the surface temperature are not linear and all-sky conditions need to be considered for unambiguous results. Also useful from an observed data set would be uncertainty estimates derived for each observation given the conditions (space, time and environment) of the observation.

### 7.2.3. Suggested Recommendations/Actions

In moving forward, there has been tremendous progress in the development of instruments, calibration and high level data products. Yet, an essentially interdisciplinary collaboration between those developing the models and observation data sets could yield significant improvement in both fields. From the models, output diagnostics, more closely representing the data recorded from remote sensing could be derived. Since model data exists through clear and cloudy conditions, there may be utility in referencing to a model while comparing IR and microwave LST observations. Also, some commonality in benchmarking for both remotely sensed data and model data, through existing long term field experiments or “super stations”, would provide a venue for more clearly ascertaining the differences among the many different measurements and models.

### 7.2.5. Summary of Poster Presentations

- *Variational Estimation of Energy Balance Partitioning and Soil Heat Diffusion Using Remotely Sensed Land Surface Temperature Data* (S. Mohyeddin Bateni, Dara Entekhabi and Fabio Castelli): Presents a method to estimate parameters of the surface energy balance that control the partitioning of available energy into sensible, latent, and ground heat fluxes based on a variational data assimilation (VDA) approach. This method minimizes the estimated soil surface temperature against observations. Sequences of radiometric surface temperature measurements are the only input data source. The one dimensional parabolic heat diffusion equation is used as a physical constraint (the adjoint method).

- *Estimation of Land Surface Water and Energy Balance Closure Relation Using Conditional Sampling of Land Surface Temperature* (Leila Farhadi, Dara Entekhabi,and Guido Salvucci): This work proposes a new approach for estimating the functional form for the water and energy closure relationship. The approach is scalable to diverse climates and land surface conditions using remotely sensed measurements. Parameters of the system (water balance and energy balance) are estimated by developing objective functions that link atmospheric forcing, surface state and unknown parameters. This approach is based on conditional averaging of heat and moisture balance equations. Conditioning states are land surface temperature and moisture states which will ultimately be obtained from global remote sensing measurements.

- *Skin temperature data assimilation in the Land Information System (LIS) (*Sujay Kumar, Rolf Reichle and Christa Peters-Lidard): Describes the Land Information System (LIS; http://lis.gsfc.nasa.gov) as a hydrologic modeling system that integrates various community land surface models, ground and satellite-based observations, and high performance computing and data management tools to enable assessment and prediction of hydrologic conditions at various spatial and temporal scales. In addition, introduces the capabilities for sequential data assimilation that were recently implemented in LIS, enabling the use of multiple observational sources, multiple data assimilation algorithms, and multiple land surface models.

- *Utility of Thermal-based One-source versus Two-source Land Surface Schemes for Surface Energy Balance Modeling* (William P. Kustas, Martha C. Anderson, and John M. Norman): Compares bulk transfer (one-source) with multi-source canopy (two-source) modeling approaches, and evaluates simplified methods to accommodate radiometric-aerodynamic temperature differences in one-source approaches. The results suggest that two-source schemes with reliable estimates of component soil and canopy temperatures, and associated resistances, are much more likely to accommodate variability in the radiometric-aerodynamic relation for a wider range in vegetated canopy cover conditions than are one-source schemes.

- *Assimilating satellite data over land for NWP applications* (T.R. Sreerekha, Ed Pavelin, S. English): Describes the approach used by the MetOffice, based on monthly mean emissivity atlases at AMSU-B window channel frequencies, to provide background emissivity information and help improve the analysis of skin temperature. The impact of this approach on forecast accuracy is presented and evaluated. In addition, it describes the recent efforts on assimilating infrared data from AIRS and IASI over land, and introduces its future plans.

- *Estimation of Evaporation fields at regional scale based on the assimilation of remotely sensed LST* (F. Sini, G. Boni, F. Caparrini, D. Entekhabi): Introduces a model for surface energy fluxes estimation based on the assimilation of land surface temperature from satellite. The assimilation scheme adopted takes advantage of the synergy of multisensor-multiplatform observations in order to obtain estimations of surface fluxes, fluxes partitioning and surface characteristics. The model is based on the surface energy balance and bulk transfer formulation coupled with a simplified soil wetness model,t hat is a filter of antecedent precipitation. The latter is introduced in order to develop a more robust estimation scheme.

### 7.3. Theme 3: Validation and Evaluation of LST

The session began with an overview of the state of the science for the Evaluation and Validation of LST by Simon Hook (Session Chair) followed by four contributed papers by J. Moncet, I. Trigo, R. Knuteson and E. Noyes. The presentations by Moncet and Noyes were given by P. Liang and G. Corlette respectively. The session ended with a panel discussion. A subsequent breakout session summarized issues and suggested some actions that might be undertaken to resolve them.

### 7.3.1. Summary of Oral Presentations

The overview presentation summarized the different validation and evaluation approaches. The main validation approaches were 1) Using *in situ* data from radiometers, 2) Using *in situ* proxy data and 3) Using airborne data. Proxy data are similar data to Land Surface Temperature (LST) such as air temperature and bulk temperature which are not directly measured by the satellite but under some conditions are a proxy for what the satellite measures. Evaluation approaches included comparisons between LST datasets derived from different instruments as well as comparisons between LST datasets and modeled LST. The comparisons between datasets from different instruments included ASTER, ATSR, MODIS and AIRS as well as differences between versions for a given instrument.

The validation overview highlighted several key points including 1) the need for accurate field radiometers, 2) the need for some field sites with long (multi-decadal) validation records and expected measurement continuity 3) the danger of using sites that were unsuitable for validation but were used simply because they either had radiometer or proxy data and 4) The value of airborne data for providing coverage over a large area than could normally be achieved with field data provided the instrument was well calibrated.

The evaluation overview identified problems between products derived from different instruments and especially between recent version changes of the MODIS LST product. The overview emphasized the potential of validating emissivity rather than temperature which does not require time coincidence and highlighted the challenges as well as potential of developing a land surface temperature that was derived through assimilation of different instrument LST's into a model.

The first session presentation compared LST from land surface models, microwave and infrared satellite retrievals. Pan Liang presented comparisons between MODIS, ISCCP, AMSR-E, AGRMET, AIRS and NCEP. Liang showed that large biases exist between the MODIS and ISCCP products and the bias at night is about half the size of the bias during the day. In particular the ISCCP LST is higher than MODIS LST during both day and night, over arid and semi-arid areas, and daytime difference is larger than nighttime difference. These two LST products were then compared with the AMSR-E product. The MODIS product showed better agreement than the ISCCP product. The reason for the better agreement is still unknown. The AMSR-E product was very useful providing data for times when the site was cloudy. AMSR-E data are very sensitive to emissivity changes which is useful for change mapping but can result in large temperature errors in dynamic regions. The MODIS product was then compared with the AGRMET (NOAH-LSM), AIRS and NCEP. The best agreement was with the AIRS product. There was strong disagreement between the NCEP product during the day and the MODIS product.

The second presentation evaluated Land Surface Temperature from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat. SEVRI is a 12-channel imaging sensor with repeat cycles of 15 minutes in nominal mode and five minutes in rapid-scanning mode at high resolution (one kilometer for the High Resolution Channel from geostationary orbit). LST is generated from SEVIRI data using a generalized split-window technique. The SEVIRI-LST was compared with the MODIS-LST product (MOD11A1). Since the MOD11A1 product is also generated with a generalized split-window it was expected these would be in good agreement. While the agreement was generally good (+/- 2K) there was a clear bias in the MODIS-LST due to directional viewing of the canopy and the SEVIRI-LST's were generally warmer than the MODIS-LST's during the day.

The LST products were then compared to *in situ* measurements at a permanent site in Evora, Portugal. Comparison with the *in situ* data indicated that the nighttime temperatures from both MODIS and SEVIRI were underestimates. This underestimation could be explained by either an error in the assumed emissivity in the split window algorithm or an error in the assumed emissivity for the *in situ* radiometer measurements.

The third presentation compared LST and Emissivity from AIRS and MODIS on the EOS AQUA platform. It was shown that AIRS retrievals (water vapor) are dependent on surface emissivity and also that the radiance at sensor measured by both sensors (AIRS and MODIS) are in good agreement. The remainder of the presentation concerned the large differences in the LST product between MODIS collection 004 and MODIS collection 005. MODIS Clear-sky Day/Night algorithm collection 004 and AIRS (version 5) cloud-cleared multi-channel regression retrieval temperatures were in good agreement, within 0.5 K at night, and between 0 and -1.5 K during the Day, excluding snow/ice covered land. MODIS collection 005 Clear Land Classification algorithm was found to be 0.5 to 3 degrees colder than collection 004 (and colder than AIRS v5).

This change was due to a stronger dependence of the day/night algorithm on the split-window algorithm. This demonstrates that estimating surface emissivity from land cover classification in the split-window algorithm may lead to large systematic biases in barren areas. For example differences of up to 8 degrees were observed in the collection 005 MODIS LST product and the AIRS product over barren areas. This comparison may be complicated by different footprints, uncertainties in the AIRS cloud fraction and the MODIS saturation in bands 20 and 22."

The last presentation in the session provided an accuracy assessment of AATSR LST data using Empirical and Theoretical Methods. The (A)ATSR LSTs show quite good agreement with collocated *in situ* LST data. The estimated accuracies are close to the target accuracies (1.0 K night, 2.5 K day). There were biases in the retrievals and these appear to be seasonal: warm in summer and cold in winter. This is particularly apparent over the Oklahoma test site. Correlation of both empirical and theoretical biases with factors that influence AATSR BTs demonstrate that the bias increases with both water vapor and LST.

### 7.3.2. Panel and Breakout Group Discussions

The panel discussion focused around the following items:

a) *In situ* networks with proxy data, e.g., air temperature

b) *In situ* networks with radiometer data, e.g., radiometers
c) Radiometers in use (COTS [commercial-off-the-shelf] vs Custom)
d) Procedures for calibration and validating radiometers, required accuracy and precision (protocols)
e) Cross calibration of field radiometers - upcoming experiments
f) Methods used for spatial and temporal sampling and implications for future measurements and models
g) Satellite LST products – what/where
h) Model LST products – what/where
i) Cloud clearing/masking issues
j) Validation approaches for Model data
k) What is missing:
Spectral libraries? Accurate radiometers? Field radiometric measurements – which cover types? Accurate airborne radiometers – how accurate? Angular measurements?

### 7.3.3. Suggested Recommendations/Actions

The panel discussion resulted in a set of summary recommendations:

1) More validation is required over certain targets, in particular, low emissivity targets (e.g., barren lands)
2 ) More coordinated cross comparisons are required of field instruments and the use of a transfer standard should be considered.
3) More long-term comparisons are needed and more long-term measurement sites need to be developed.
4) Aircraft campaigns are needed to understand heterogeneity for scaling up.
5) Need to evaluate the use of Climate Reference Network (CRN) sites. This nearly-complete NOAA surface network (primarily U.S., but with some additional international sites) collects standard meteorological data, as well as LST and soil moisture, in a rigorous, systematic and continuous long-term approach. LST is collected with commercial off-the-shelf Apogee sensors. Can its data be corrected to research-sensor quality? CRN has wide variety sites. When complete in 2008, CRN will have 114 U.S. sites – necessary to evaluate their homogeneity (at the scale of the satellite footprint).
6) Need a clearing house to capture data and results that *have* been completed.
7) CDRs – major problems if keep changing algorithm e.g MODIS. Need better control.
8) Need to know when scene is clear for validation, cloud mask is major issue.
9) Need to deliver LST over all pixels and provide mask as separate product or layer that can be applied. MODIS LST varies with cloud mask – big problem.
10) Need a few well instrumented sites that capture largest possible range of conditions with v. strict quality control.
11) More effort is required to develop calibration protocols or guidelines. Such protocols should include detailed instrument information, rigorous error budgets and site characterization.

7.3.5. Summary of Poster Presentations

- *In situ measurements for validating land surface temperature derived from MODIS and AATSR data*, César Coll, Joan M. Galve, Vicente Caselles, Enric Valor, Juan M. Sánchez and Maria Mira. Describes a database of *in situ* measured LSTs collected in a large, flat and thermal homogeneous site of rice fields close to Valencia, Spain concurrently to EOS Terra/MODIS and Envisat/AATSR overpasses. The validation database includes 51 day-time, cloud-free concurrences of satellite and ground LSTs (23 for MODIS and 28 for AATSR). The *in situ* data is compared against MODIS and AATSR LSTs derived by means of two retrieval methods: split-window (SW) using the 11 and 12 μm bands, and single-channel (SC) using channel 11. The atmospheric profile information, in the latter method, was based on: (1) local radiosoundings, (2) NCEP global tropospheric analyses, and (3) EOS Aqua/AIRS atmospheric profile products. The best results were obtained by the SW method, both for MODIS and AATSR.

- *Providing ready access to multiple sources of land surface temperature*, Robert B. Cook, Jerry Pan, Ana Pinheiro, Glenn Rutledge, Steve Anthony, Dan Swank, Danny Brinegar, Jeff Privette, Suresh K. Santhana Vannan, Bruce E. Wilson, Introduces a pilot tool that provides access to surface temperature data from field observations, model output, and remote sensing records for in the United States. Current datasets available include MODIS, GOES, NOAA's RUC, CRN and AmeriFlux. Data request is based on the selection of a (network) site, time period and datasets of interest. Using Network Data Access Protocols, the tool will request an appropriate subset of surface temperature from these data sourcesthat can be vizualised as time-series plots. Those files can also be made available through download for further analysis by the user in his/her own desktop. Future developments will expand the numbers of parameters examined to include additional variables, as well as additional analysis and visualization tools.

- *All-weather estimates of the land surface skin temperatures from a combined analysis of microwave and infrared satellite observations (*Carlos Jimenez, Filipe Aires, Catherine Prigent, Bill Rossow): A neural network inversion scheme, including first guess information, has been developed to retrieve surface skin temperature ($T_{skin}$), along with atmospheric water vapor, cloud liquid water, and surface emissivities over land, from a combined analysis of Special Sensor Microwave /Imager (SSM/I) and International Satellite Cloud Climatology Project (ISCCP) data. The methodology is described, highlighting the role of the first guess emissivity and $T_{skin}$ estimates. The project aims at producing a synthetic data set that includes the full time record of Ts estimates, clear and cloudy, along with the coincident $T_{air}$ estimates.

- *Land Surface Temperature Validation Sites for MSG / SEVIRI* (Folke Olesen, Frank Göttsche, Ewa Kabsch): This work describes two valiadation station (Evora, Portugal; Gobabeb, Namibia)**,** created **w**ithin the framework of the Land Surface Analysis – Satellite Applications Facility (LSA-SAF), supported by Eumetsat, and set up by Forschungszentrum Karlsruhe**.** An additional set of radiometers was installed at an existing site operated by the University of Copenhagen (Dahra, Senegal). The main objective of the stations is to validate LST derived from Meteosat Second Generation's (MSG) Spinning Enhanced Visible and Infra Red Imager (SEVIRI). The technical features of the validation stations are highlighted and the characteristics of the sites in terms of surface cover and climatology are presented.

- *Evaluation of GOES-R Land Surface Temperature Algorithm Using SURFRAD Ground Measurements and GOES-8 and -10 Imager Data* (Yunyue Yu, Dan Tarpley, Konstantin Vinnikov): Compares collocated LST data from the SURFace RADiation (SURFRAD) budget network ground measurements and the GOES-8 and -10 satellite measurements. A stringent cloud filtering procedure was applied to minimize the effect of cloud contamination. The evaluation was performed by directly and indirectly comparing the SURFRAD and satellite LSTs of each site. The direct comparison was illustrated using scatter plots and histogram plots of the ground and the satellite LSTs, while the indirect comparison was performed using a method of "Comparing Two Sets of Noisy Measurements" developed by Flynn (2006).

## 7.4. Theme 4: Community Requirements for LST

The Community Requirements Panel Session started with an overview of the state of the science of the community requirements by Ana Pinheiro, followed by four contributed papers by C. Lorenzo, M. Anderson, M. Jin and F. Aires. The presentations were followed by a panel discussion. A subsequent breakout session, on Wednesday morning, tried to identify the main requirements for LST from the different user communities.

### 7.4.1. Summary of Oral Presentations

The requirements for LST for the different user communities are very different and have to be analyzed and considered separately. A compilation of the most common uses of LST is provided in the *NASA White Paper on LST and Emissivity Needs* (S. Hook, editor). This document describes the state of the science of remote sensing of LST (from thermal infrared sensors) and identifies the user communities for LST and their requirements for the product. It was developed to better understand the needs of the NASA's Earth Science Data records (ESDRs) and Climate Data Records (CDRs), and was compiled by Simon Hook (lead author) and 44 co-authors in May 2006. It is currently available at http://lcluc.umd.edu/Documents/land-esdr.asp.

This document was used in this workshop as a baseline for what had been identified as the state of the science in this area. Specific application areas identified by that document included: a) hazard prediction and mitigation (including wild fire risk assessment, detection and monitoring of onset and progression of volcanic activity, etc), b) water management (assessment of agricultural/urban water consumption assessment of water losses from riparian areas and reservoirs, etc), c) Crop management (drought/crop stress detection, irrigating scheduling, crop yield mapping /forecasting), d) non-renewable resource management (geothermal resource exploration, differentiation of rock-lithologies). In this workshop we focused on a few specific areas of applications that are more closely aligned with NOAA's mission and the GEWEX goals. Those include climate/weather, modeling of surface fluxes, drought monitoring, agricultural/crop health monitoring, and water management.

The LST product requirements for different applications identified by the white paper were presented to the community (Table 1):

Table 1: LST and emissivity product requirements (*source: NASA White Paper for LST&E*).

| Land Surface Temperature and Emissivity Earth System Data Record (LSTE-ESDR) | | | | | | |
|---|---|---|---|---|---|---|
| **Subproduct** | **Spatial Resolution** | **Temporal Resolution** | **Accuracy** | **Precision** | **Current Data Sources** | **Future Data Source** |
| Global | 10-20 km | Hourly | 0.5K | 0.1-0.3K | AIRS<br>GOES<br>MSG | CrIS<br>GOES<br>MSG |
| Regional | 1-5 km | 2-4 times daily | 0.5-1.0K | 0.1-0.3K | MODIS<br>AVHRR<br>ATSR | VIIRS<br>AVHRR<br>ATSR |
| Local | 30–100 m | Once every 8-16 days | 0.5-1.0K | 0.1-0.3K | ASTER<br>Landsat | |
| Emissivity | 1% or better (in 8-12.5μm) and 3% or better (in 3.6-4.2μm) all resolutions. | | | | | |

An additional document, specific to the water management community, was summarized in this session: "*Progress on utilizing space borne high resolution thermal radiometer in water resources research and management*, Bastiaanssen *et al.,* 2003." This document identified what are seen as the specific needs from this community (mostly representing a team from the Netherlands).

1) Multiple observation angles to derive the surface temperatures of plant leaves and soil separately, useful for partitioning between transpiration and evaporation.
2) Multiple TIR channels to aid the emissivity-temperature separation
a. Aids atmospheric correction for those models requiring LST (vs. top-of-atmosphere TIR)
3) A TIR pixel size of 30 to 90 m to provide adequate definition between adjacent fields and crop types.
4) An overpass time between 11 a.m. and 2 p.m.
5) A constellation of TIR satellites to reduce the large time gap between successive cloud free images.
6) Collocated shortwave observations to characterize vegetation (*e.g.,* vegetation fraction) and full energy balance.
7) Swath comparable or larger then Landsat ETM+ for efficiency in processing over large areas.

The community was asked to revisit those requirements on behalf of the water resources community outside of that specific working group.

Several limitations to the use of LST within the applications domain were identified. Despite these challenges and limitations, the use of LST products for applications has been increasing. LST products have been extensively used as inputs into assimilation routines to help improve the estimate of model state and prognostic variables. These are in turn used to improve the understanding and quantifications of surface fluxes, water availability, to aid resources management and improve weather forecasts. Through improved estimates of soil moisture and evapotranspiration, LST products are also used outside of assimilation schemes to monitor drought at continental and regional scales. Four examples were given of different applications using remotely sensed LST products.

The first presentation (Campo *et al*, presented by F. Castelli), demonstrated the use of satellite-derived observations of land surface temperature (LST), from the SEVRI sensor, as inputs in a data assimilation scheme, aimed at retrieving parameters that describe the energy balance at the land surface. The approach uses a parsimonious 1-D multiscale variational assimilation procedure. This assimilation scheme has been coupled with the non-hydrostatic limited area atmospheric model RAMS, in order to improve the quality of the energy budget at the surface in RAMS by replacing the lower boundary condition of the atmospheric domain. Comparisons between model results with and without coupling with the assimilation scheme were discussed, both in terms of reconstruction of surface variables and of vertical characterization of the atmosphere. Particular attention was given to the effects of the coupling on the moisture feedback between surface and atmosphere.

The second presentation (Anderson *et al*) demonstrated the use of thermal infrared (TIR) data as a valuable remote indicator of both evapotranspiration (ET) and the surface moisture status. Using thermal-infrared imagery from the Geostationary Operational Environmental Satellites (GOES), a fully automated inverse model of Atmosphere-Land Exchange (ALEXI) is used to model daily ET and surface moisture stress over a 10-km resolution grid covering the continental United States. Monthly anomalies in the ALEXI moisture stress fields show good spatiotemporal correspondence with standard drought metrics such as the Palmer Drought Severity Index, and with patterns of antecedent precipitation, but at significantly higher spatial resolution due to ALEXI's limited reliance on ground observations. In a disaggregation mode (DisALEXI), the model generates moderate to high-resolution flux maps at $10^0$-$10^3$ meter resolution over targeted scenes using thermal images from platforms like Landsat, ASTER and MODIS or from airborne imaging systems.

The third presentation (Jin and Dickinson) used LST products as an indicator for surface climate change. The study relies on seven-year MODIS and 18-year AVHRR of LST estimates to examine land surface climatology, skin temperature change, and the mechanisms responsible for such changes. Correlations between LST and land cover, albedo, vegetation, as well as atmosphere observations including rainfall, clouds, and aerosol were also evaluated.

The fourth and final presentation (Aires *et al*, presented by C. Prigent), investigated a method to reconstruct the diurnal cycle of LST based on the 3-hourly surface skin temperature estimated by the International Satellite Cloud Climatology Project (ISCCP) from the infrared measurements collected by the polar and geostationary meteorological satellites. The diurnal cycle of surface skin temperature is analyzed almost globally (60N-60S snow-free areas), using Principal Component Analysis (PCA). A new temporal interpolation algorithm, designed to work when only a few measurements of surface temperature are available, is developed based on the PCA representation and an iterative optimization algorithm. This method is very flexible: only temperature measurements are used (no ancillary data), no surface model constraints are used, and the time and number of measurements are not fixed.

7.4.2. Panel and Breakout Group Discussions

Several issues where identified and were presented as charges to the panel for discussion.

1) Identify the land surface temperature products (model, remote sensing and/or in situ) currently used and produced, and their primary user communities.
2) Identify the main limitations of these products.
3) State the ideal characteristics of an LST product for the respective user communities.
4) Review the specifications for the NPP/NPOESS operational LST product (accuracy: 2.4K; precision: 0.5; dynamic range: 213-343) and assess their adequacy for the respective user communities
5) Review the stated product requirements from the NASA White Paper and the Water Management Community White Paper for obsolescence and/or validity.
6) Identify the primary avenues of communication between LST producers and users, and assess their adequacy.
7) Identify the critical metadata and QA information needed in LST products.
8) Assess the relative merits of the following:
   a) A product where LST estimates are created for all pixels (clear and cloudy) and a separate cloud mask is provided. The product is continuous in space.
   b) A product where LST estimates are only produced for pixels identified as cloud free (with a given level of confidence). The product is discontinuous in space.

Additional questions and concerns were discussed in the panel.

Satellite LST products are, in general, generated only for clear sky conditions. However, models estimate LST under all-sky conditions. It would be beneficial to have satellite LST produced for all pixels, as long as a cloud mask is provided with the LST product.

When LST is assimilated into models, often the process leads to inconsistencies in the estimated fluxes. Therefore, the fluxes need to be balanced to yield reasonable results. It would be beneficial to have observable flux related variables to better assess the performance of the models. To just compare the skin temperature related variables between models is not sufficient. One should look at fluxes, profiles, etc. Also, it is necessary to evaluate that performance over sites that were not included in the tuning of the model. It was recommended that the community looks at larger areas, outside of those sites, using flux towers.

Regarding the NASA White Paper for LST and Emissivity, from the perspective of GEWEX and quantifying the weather-scale variations of the global energy and water cycle, the global requirements for LST would be stated as 10-20 km spatial and 3 hourly time sampling intervals. The review also noted that the white paper table listing of data sources, both current and future, is incomplete: to meet the GEWEX requirements requires use of the whole constellation of satellites, operational and research, imagers and sounders, infrared and microwave, to produce a unified product for all conditions.

The concern that the community is losing aircraft capabilities was expressed by several. The group recognized that it is harder to obtain funding for such campaigns since they are not very useful for operational problems and there are less and less airborne instruments available.

Currently, most operational systems rely on air temperature to provide information about the energy state of the surface. The community needs to evaluate and demonstrate that LST can provide additional (better) information than air temperature to these systems. Otherwise there is no reason for these operational systems to adopt LST in their metrics. For drought monitoring this has been demonstrated already. Analysis of thermal inertia, and how it relates to the diurnal cycle of LST, can be a good indicator of the type of information provided by LST. In most cases it is useful to have both variables ($T_{air}$ and LST) since if their patterns do not show some consistent behavior then it gives us some insight about possible problems. Ideally we should analyze those two variables together.

The relationship between air temperature and surface temperature needs to be better understood. Are the averages over days, weeks and months similar for both variables, over different types of surfaces? The discussion was inconclusive regarding this subject.

It is more useful for the application community to have access to temporal variations of LST than instantaneous observations. However, higher accuracy of the LST product is more desirable than high temporal frequency (e.g., hourly data).

It is necessary to better assess the different LST datasets available to build more confidence in the products. Need a Round Robin assessment exercise.

During the breakout session a table was generated expanding on Table 1 from the white paper. This table focuses on applications requirements for spatial and temporal resolution of TIR imagery, while the white paper table concentrates on current and future (planned) capabilities. In Table 2, a partial listing of this table is provided which includes the application, an associated ideal or target pixel resolution, and a range for required temporal resolution. Naturally, for many of the applications, current and future satellite platforms will not meet the requirements. However, this table is provided to emphasize the need for administrators in regulatory, natural resources and research agencies, and government officials and policy makers to seriously consider the benefits of having the necessary LST capabilities to address many of the environmental and resource problems faced in the U.S. and worldwide.

In addition, we propose to revise the list of seven needs/requirements from the water management community (listed above) based on the requirements listed in Table 2 and the potential for what might be provided by future satellite systems:

1) A minimum of three (3) TIR channels for temperature-emissivity separation.
2) LST pixel size of <90m in order to adequately resolve fields
3) An overpass time between ~1000 and 1400 to capture highest ET rates and vegetation stress
4) At a minimum a weekly revisit time at the high resolution (<90 m), and once/twice daily coverage at the coarser resolutions (~500 m – 1 km).
5) Collocated multispectral (preferably hyperspectral) observations that can complement TIR for capturing moisture and vegetation states and stress.

Table 2 Applications and Associated LST Target Pixel and Temporal Resolution

| Application | Resolution [m] | Temporal Sampling | Specific Requirements |
|---|---|---|---|
| National Drought Assessment | 1000 | 1 hr | Co-located veg cover info |
| Regional Drought Monitoring | 50 | 1-7 day | Co-located veg cover info |
| Agriculture Yield and Water Use | 50 | 1-7 day | Co-located veg cover info |
| Weather NWP | 1000 | 1-3 hr | |
| Soil Moisture and Runoff | 50 | 0.5-7 day | One obs near peak or diurnal range |
| Climate Science | 5000 | 1-3 hr | Sensors overlap |
| Watersheds and Ecological Services | 50 | 1-7 day | |
| Landuse and Urban Heat Island | 50 | 0.5-30 day | Diurnal range useful |
| Fire | 50 | 0.5-7 day | High temperatures sensitivity |
| Lithology and Geological Hazards | 50 | 0.5-7 day | Diurnal range useful; High temperatures sensitivity |
| Cryosphere | 100 | 0.5-7 day | |

### 7.4.3. Summary of Issues

The main challenges associated with the use of LST products for applications were identified. Those include:

1) Limited number of products available
2) Difficult to ascertain exactly what is available
3) No comprehensive "catalog" of all products – though the University of Maryland (UMD) is developing a new land product "portal". As a result of this workshop we expect to put together a LST/Emissivity Compendium.

In addition, for those products available:

4) Not many are operational (systematic; long-term continuation assured)
5) The majority is insufficiently validated (stratification approaches required: land cover types, climate regimes, day vs night…)
6) Show discontinuous in space and time (clouds, orbital characteristics)
7) Insufficiently long term records
8) Inadequate latency
9) Spatial resolution/temporal resolution dichotomy
10) May be sensor- or algorithm-specific

Specifically, when the application involves the use of models, additional challenges are:

11) Remote Sensing products and model state variables are inherently inconsistent (vertical scale): satellite sees "*skin*" temperature in thin layer, whereas model "*surface*" temperature is typically a mixture of temperatures of thicker layers.
12) Satellite *skin* temperature and model *surface* temperature may be inherently inconsistent (horizontal scale): Satellite "sees" a great variety of spatial heterogeneity, whereas a model is limited in the spatial variability it can represent.
13) $T_{skin}$ is different from $T_{aerodynamic}$ (needed for energy balance calculations).

### 7.4.4. Suggested Recommendations/Actions

1) Expand Table 2 to include the other criteria/requirements/issues and reach a final agreement on what are the acceptable requirements
2) Determine the feasibility of generating satellite LST products for all-sky conditions.
3) Demonstrate the usefulness of LST versus air temperature for operational systems. Identify what additional information is provided by LST compared with Tair?
4) How can we reliably accommodate differences between LST ($T_{skin}$) and the aerodynamic temperature ($T_{aerodynamic}$) for energy balance calculations and to compare with land surface model simulations?
5) Evaluate the relationship between air temperature and surface temperature for different land surface types: their diurnal cycle, the diurnal range, the monthly and annual averages, etc.

### 7.4.5. Summary of Poster Presentations

- *Ensemble filters and LST assimilation in basin-scale hydrologic models for flood forecasting* (*Fausto* Barboncini, Fabio Castelli and Dara Entekhabi): This study evaluates the fundamental differences (threshold processes , preferential trajectories for convection and diffusion, low observability of the main state variables and high parametric uncertainty) between distributed hydrologic models an other geo-fluid-dynamics models, and explores them through some numerical experiments on an continuous hydrologic model, MOBIDIC. In the numerical experiments, two different sub-optimal filtering techniques are tested: the first is a simple rank reduction of the complete filter error covariance and the second is a more exceed filter on a complementary reduced space.

- *Operational regional-scale soil moisture monitoring with assimilation of satellite LST.* (G. Boni (1), L. Campo, F. Caparrini, F. Castelli, L. Ferraris, L. Rossi, R. Rudari): Describes the operational implementation over the Italian territory of an experimental operational system of soil moisture monitoring, based on the assimilation of LST and other satellite-derived products. The assimilation scheme is based on the surface energy balance. It is forced using satellite products such as incoming radiation (shortwave and longwave), cloud mask, LST and ground observations. The model is used to derive EF, turbulent conductivity for energy fluxes and heat and moisture fluxes at national scale. The model has been recently implemented in DROPS, the experimental monitoring system of the Italian Civil Protection Department.

- *Near-real time retrievals of land surface temperature within the MODIS Rapid Response System* (A.C.T. Pinheiro, J, Decloitres, J. Schmaltz, J.L. Privette , J. Susskind, L. Iredell ): Describes the implementation of the MODLAND Land Surface Temperature Product within the MODIS Rapid Response System. The implementation of this algorithm, in a near-real time system, required several modifications to the code to remove any dependencies on upstream MODIS products. Differences between the official LST product the one implemented are compared and characterized globally.

- *Vegetation monitoring through retrieval of NDVI and LST time series from NOAA-AVHRR historical databases* (José A. Sobrino*, Yves Julien): In this paper the annual evolutions of

NDVI and LST have been analyzed simultaneously, with the purpose of a better mapping of the vegetation than when only NDVI parameter is used. To this end, three parameters have been retrieved to describe the whole NDVI/LST yearly cycle. These three parameters are related to the local relationship between NDVI and LST values and the amplitude of the annual cycle. The use of these parameters allows for an adequate differentiation of distinct biomes.

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*International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps*

**AGENDA**

**MON April 7 2008**

8:00 - 8:30 Check in (breakfast provided)

8:30 - 8:40 Welcome and Introduction toWorkshop (Ana. Pinheiro)

8:40 - 8:50 Welcome by NOAA's National Climatic Data Center Director (Tom Karl)

8:50 - 9:05 Welcome by NCDC Remote Sensing and Applications Division (RSAD) Chief (John Bates)

9:05 - 9:20 The GEWEX LANDFLUX Context (William Rossow)

**Panel: Remote Sensing of LST** *Moderator:* William Rossow *Rapporteur:* Bob Knuteson

9:20 - 10:05 Remote Sensing of LST -- State of the Science Overview (William Rossow)

10:05 - 10:25 Zhengming Wan (UCSB, USA), *Current Status of the MODIS Land-Surface Temperature /Emissivity products*.

10:25 - 10:45 Dorothy Hall (NASA GSFC, USA), J. C. Comiso , C.A. Shuman, W. Abdalati, *Development of a Satellite-Derived Climate-Data Record of the Surface Temperature of the Greenland Ice Sheet, 1981 – present*.

10:45 - 11:00 Coffee Break

11:00 - 11:20 Fred Prata (NILU, Norway), *Land surface temperatures from the ATSR-family of instruments-–An assessment of the accuracy and usefulness of 15 years of global measurements.*

11:20 - 11:40 F. Aires, Catherine Prigent (CRNS, France) and C. Jimenez, *All-weather estimates of the land surface skin temperatures from a combined analysis of microwave and infrared satellite observations.*

11:40 - 12:30 Remote Sensing of LST Panel Discussion

12:30 - 1:30 Lunch Break (lunch provided)

**Panel: Modeling of LST** *Moderator:* Michael Bosilovich *Rapporteur:* Catherine Prigent

1:30 - 2:15 Modeling of LST -- State of the Science Overview (Michael Bosilovich)

2:15 - 2:35 Rolf H. Reichle (NASA GSFC, USA) and M. G. Bosilovich, *Issues regarding the assimilation of satellite retrievals of land surface temperature into land surface models.*

2:35 - 2:55 Weizhong Zheng (NOAA NCEP, USA), J. Meng and K. Mitchell, *Analysis and Assimilation of Land Surface Skin Temperature in NCEP Operational NWPModels.*

2:55 - 3:15 Xubin Zeng (University of Arizona, USA) and Z. Wang, *Improving the coupling of land surface temperature modeling and remote sensing.*

3:15 - 3:30 Coffee Break

3:30 - 3:50 Dara Entekhabi (MIT, USA), F. Castelli, F. Caparrini and G. Boni, *Estimation of Surface Fluxes Based on Assimilation of Land Surface Temperature Data.*

3:50 - 4:40 Modeling of LST Panel Discussion

4:40 - 5:20 Poster Session I

5:20 Adjourn

7:00 - 9:30 Group dinner at *Windows on the Park* (*pre-registration required*)

**TUE April 8 2008**

| **Panel:** ***Validation and Evaluation of LST*** | *Moderator:* Simon Hook | *Rapporteur:* William Rossow |
|---|---|---|

09:00 - 9:45 Validation and Evaluation of LST -- State of the Science Overview (Simon Hook)

09:45 - 10:05 J. Moncet, Pan Liang (AER, USA), A. Lipton and J. Galantowicz, *Intercomparison of land surface temperature products from models and microwave and IR satellite retrievals.*

10:05 - 10:25 Isabel F. Trigo (IM, Portugal), I. T. Monteiro, F. Olesen and E. Kabsch, *Land Surface Temperature from SEVIRI/Meteosat.*

10:25 - 10:40 Coffee Break

10:40 - 11:00 Robert O. Knuteson (University of Wisconsin, USA), L. Moy, H.E. Revercomb and D.C. Tobin, *Comparison of NASA AIRS and MODIS Land Surface Temperature and Infrared Emissivity Measurements from the EOS AQUA platform.*

11:00 - 11:20 E. Noyes, Gary Corlett (University of Leicester, UK), J. Remedios, X. Kong and D. Llewellyn-Jones, *An Accuracy Assessment of AATSR LST Data using Empirical and Theoretical Methods.*

11:20 - 12:10 Validation and Evaluation of LST Panel Discussion

12:10 - 1:45 Lunch Break

| **Panel:** ***Community Requirements for LST*** | *Moderator:* Dara Entekhabi | *Rapporteur:* Simon Hook |
|---|---|---|

1:45 - 2:30 Community Requirements for LST -- State of the Science Overview (Ana Pinheiro)

2:30 - 2:50 C. Lorenzo, Fabio Castelli (Universita de Firenze), D. Entekhabi and F. Caparrini, *Land-Atmosphere Interactions in an High Resolution Atmospheric Simulation Coupled with a Surface Data Assimilation Scheme*.

2:50 - 3:10 Martha C. Anderson (USDA ARS, USA) and W.P. Kustas, *Mapping evapotranspiration and drought at local to continental scales using thermal remote sensing.*

3:10 - 3:25 Coffee Break

3:25 - 3:45 Menglin Jin (University of Maryland, USA) and R.E. Dickinson, *Using Land Skin Temperature for Climate Change Study and Evaluating Climate/Land-Surface Model.*

3:45 - 4:05 F. Aires, Catherine Prigent (CRNS, France) and W. Rossow, *Global Analysis of Surface Skin Temperature Diurnal Cycle Over Land.*

| | |
|---|---|
| 4:05 - 4:55 | Community Requirements for LST Panel Discussion |
| 4:55 - 5:45 | Poster Session II |
| 5:45 | Adjourn |

**WED April 9 2008**

08:30 - 09:30 Summary of two previous days (Moderators)

09:30 - 10:15 Breakout Sessions (discussion)

Theme 1 – Remote Sensing of LST (Room 400);
*Moderator*: William Rossow; *Rapporteur*: Catherine Prigent

Theme 2 – Modeling of LST (Room 411);
*Moderator:* Xubin Zeng; *Rapporteur:* Mike Bosilovich

Theme 3 – Evaluation and Validation of LST (Room 504);
*Moderator*: Simon Hook *Rapporteur:* Bob Knuteson

Theme 4 – Community Requirements for LST (Room 541)
*Moderator:* Dara Entekhabi *Rapporteur:* Bill Kustas

10:15 - 10:30 Coffee Break

10:30 - 11:30 Breakout Sessions (writing assignments)

11:30 - 12:15 Group discussion (all)

12:15 - 12:30 Closing remarks (William Rossow, Catherine Prigent and Ana Pinheiro)

12:30 Adjourn

12:30 - 2:00 Scientific Organizing Committee Meeting

2:00 Guided tour of the NCDC facilities (please register on April 7th)

**Poster Session I – Mon April 7th 2008 (4:40 pm - 5:20 pm)**

## Theme 1: Remote Sensing of Land Surface Temperature

1. Barboncini, F. and F. Castelli, *A dynamic cloud masking and filtering algorithm for MSG retrieval of land surface temperature.*
2. Corlett , G. and C. Donlon, *The GHRSST pilot project: Benefits and lessons learned that are of interest to the LST community.*
3. French, A.N. and A. Inamdar, *Estimating hourly, 1 km Land Surface Temperatures by combining MODIS and GOES data.*
4. Hook, S., *HyspIRI-TIR - A new high spatial thermal infrared multispectral scanner recommended by the National Research. Council.*
5. Hulley, G. and S. Hook, *The ASTER Land Surface Temperature and Emissivity Database for California and Nevada.*
6. Knapp, K. and H. Semunegus, *Data sets available at NCDC for LST research.*
7. Liang, S., *Analysis of land surface thermal-IR emissivity products and applications.*
8. Pinheiro, A.C.T., J.L. Privette, R. Mahoney, and C.J. Tucker, *Directional effects in a daily AVHRR land surface temperature dataset over Africa*.
9. Pinheiro, A.C.T., J.L. Privette and J.L. Bates, *Challenges for Climate Data Records of Satellite Based Land Surface Temperature.*
10. Prigent, Catherine, Filipe Aires, William Rossow, *Estimation of the land surface microwave emissivities over the globe from satellite observations.*
11. Privette, Jeffrey L., Bruce Barkstrom, John Bates, and Thomas Karl, Bryant Cramer and Jack Kaye, Wayne Cecil, David Young,Chet Koblinsky, Michael Tanner, Gary Davis, Michael F. Bonadonna, and Kandis Boyd, *Restoration of NPOESS Climate Capabilities: Climate Data Records.*

## Theme 2: Modeling of Land Surface Temperature

1. Bateni, S. M., D. Entekhabi and F. Castelli , *Variational Estimation of Energy Balance Partitioning and Soil Heat Diffusion Using Remotely Sensed Land Surface Temperature Data.*
2. Farhadi, L., D. Entekhabi and G. Salvucci, *Estimation of Land Surface Water and Energy Balance Closure Relation Using Conditional Sampling of Land Surface Temperature.*
3. Kumar, S., R. Reichle and C. Peters-Lidard, *Skin temperature data assimilation in the Land Information System (LIS).*

4. Kustas, W. P., M. C. Anderson and J. M. Norman, *Utility of Thermal-based One-source versus Two-source Land Surface Schemes for Surface Energy Balance Modeling.*

5. Ravindranathan Sreerekha (MetOffice, UK), E. Pavelin and S. English, *Assimilating satellite data over land for NWP applications.*

6. Sini, F., G. Boni, F. Caparrini and D. Entekhabi, *Estimation of evaporation fields at regional scale based on the assimilation of remotely sensed LST.*

**Poster Session II – Tue April 8th 2008 (4:55 pm - 5:45 pm)**

## Theme 3: Validation and Evaluation of Land Surface Temperature

1. Coll, C., J.M. Galve, V. Caselles, E. Valor, J. M. Sánchez and M. Mira, *In situ measuremnts for validating land surface temperatures derived from MODIS and AATSR data.*
2. Cook , R.B., J. Pan, A.C.T. Pinheiro, G. Rutledge, S. Anthony, D. Swank, D. Brinegar, J.L. Privette, S. K. Santhana Vannan, B. E. Wilson, *Providing ready access to multiple sources of land surface temperature.*
3. Jimenez, C., F. Aires, C. Prigent, P. Liang, J. Moncet, B. Rossow, *A comparison of satellite and modeled land surface temperatures: global analysis for selected months in 2003.*
4. Meyers, T., J. Augustine and B. Baker, *Observations of Land Surface Temperature from NOAA's U.S. Climate Reference Network and the Surface Energy Balance Network (SEBN).*
5. Olesen , F., F. Göttsche and E. Kabsch,, *Land Surface Temperature Validation Sites for MSG / SEVIRI,*
6. Pinker, R. T., D. Sun, Y. Ma and C. Li, *A test-bed for evaluating LST algorithms over the United States.*
7. Yu, Y. D. Tarpley, K. Vinnikov, *Evaluation of GOES-R Land Surface Temperature Algorithm Using SURFRAD Ground Measurements and GOES-8 and -10 Imager Data.*

## Theme 4: Community Requirements for Land Surface Temperature

1. Allen, R, G., W. Bastiaanssen, J. Hendrickx, M. Tasumi, *Concepts for Relaxing Accuracy Requirements for Land Surface Temperature in Satellite-based Energy Balances for Evapotranspiration.*
2. Barboncini, F., F. Castelli and D. Entekhabi, *Ensemble filters and LST assimilation in basin-scale hydrologic models for flood forecasting.*
3. Boni, G., L. Campo, F. Caparrini, F. Castelli, L. Ferraris, L. Rossi and R. Rudari, *Operational regional-scale soil moisture monitoring with assimilation of satellite LST.*
4. Pinheiro, A.C.T., Descloitres, J., Privette, J.L., Schmaltz, J., and Susskind, J., *Near-real time retrievals of MODIS Surface Temperature within the MODIS Rapid Response System.*
5. Sobrino, J.A., and Y. Julien, *Vegetation monitoring through retrieval of NDVI and LST time series from NOAA-AVHRR historical databases.*

# APPENDIX B

*International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps*

**Questionnaire**

**Total number of responses received: 21**

*Name and affiliation:*______________________________________________________

1. Please select the one(s) that better define(s) you:
- Remote sensing LST product developer: __10__
- LST modeler: __5__
- LST product user: __11___
- Other (specify): Validation: _3

2. Have you (or your institution) developed any LST (RS, model or in situ) or emissivity products? If so, please identify its characteristics, and provide a point of contact (This list will support the creation of an LST/emissivity compendium).

Product characteristics:

POC:
Name: __________________________________
Institution: _______________________________
Phone: __________________________________
E-mail:__________________________________

a. **RS LST retrieval algorithms (IR, split-window, MODIS, AATSR)**
   Cesar Coll, University of Valencia, Spain
   +34 96 354 3247; Cesar.coll@uv.es
b. **LST product from AATSR**
   Fred Prata, NILU, Norway
   +47 63898156; Fred.prata@nilu.no
c. **All weather LST estimates from combined IR and MW**
   Catherine Prigent, Observatoire de Paris, France
   +33 140 512018; Catherine.prigent@obspm.fr
d. **LST estimates using support vector machines and IR Tb observations**
   Bruno S. Serpico, University of Genova, Italy
   Sebastiano.serpico@unige.it
e. **Diurnal cycle of LST at 1 km scale by combining GOES and MODIS data over Southwest US**
   Andrew French, ALARC/ARS/USDA
   520-316-6371; Andrew.French@ARS.USDA.GOV
f. **LST from SEVERI/Meteosat (15 min) and IR emissivity**
   **LST AVHRR/Metop (2x/day; 1km)**
   Isabel Trigo; IM/Land-SAF
   Isabel.trigo@meteo.pt

g. **Single-channel LST using ANN**
   **Validation data**
   **Diurnal temperature cycle model**
   Frank Goettsche, Forschungszentrum Karlsruhe, Germany
   0048 7247 82 3821; frank.goettsche@imkafzk.de
h. **AVHRR long term LST dataset (5 degrees)**
   Menglin Jin, University of Maryland, College Park, USA
   301-405-5337, mjin@atmos.umd.edu
i. **CERES Surface and Atmosphere Radiation Budget (SARB)**
   **Emissivity mapped globally using IGBP surface types**
   **Blended LST using ISCCP and GOES**
   Paul Stackhouse, NASA Langley
   757-864-5368; paul.w.stackhouse@nasa.gov
j. **LST over Africa and Europe based on Metosat from 1999-2005 (neural network atmospheric correction with ECMWF atmospheric data)**
   Folke Olesen, Forschungszentrum Karlsruhe, Germany
   +49-7247-822109; folke.olesen@imk.fzk.de
k. **CDR for Greenland (not yet available)**
   Dorothy Hall, NASA GSFC
   301-614-5771; Dorothy.k.hall@nasa.gov
l. **Global, 25 km, 3 hr, IR based (clear sky) LST for 24 years (e=1)**
   **Global, 25 km, 3 hr, IR based estimates (all sky but clear sky biased) LST for 24 years (e=variable)**
   **Global, 25 km, 3 hr, IR-microwave (all sky) LST for 24 years**
   **Global, 25 km, 3 hr, LST and Tair merged for 24 years**
   William Rossow, NOAA CREST at City Colleae at New York
   212-650-5389, wbrossow@ccny.cuny.edu

3. What are the main limitations of the current LST products available to the community?

   a. Poor accuracy and precision
   b. The accuracy claimed for products is often better than the difference between different products (limits confidence in existing products)
   c. Limited availability of some products
   d. Cloud contamination
   e. Revisit time vs spatial resolution
   f. Lack of validated products and difficulty of validation exercises
   g. Limited number of validation ground observations
   h. Inconsistency between products. More intercomparison with other estimates from models, remote sensing and in situ data are required
   i. Poor reliability
   j. Angular dependency (directional character of products)
   k. Algorithm dependency
   l. Inadequate spatial resolution (need less than 100 m for local/regional applications)
   m. Inadequate temporal resolution (need 5-10 days revisit)

n. Emissivity uncertainty
o. Lack of long term datasets with moderate resolution
p. Limited number of operational products
q. Use of old/non-standard formats
r. Use of different algorithm – which is best?
s. Lack of products that resolve the diurnal cycle
t. Lack of products for all sky conditions
u. Lack of estimates under clouds
v. Unresolved spatial heterogeneity in complex topography /mountainous regions.

4. **(For LST Users)** Do you believe that the specifications for the NPP/NPOESS operational LST product (accuracy: 2.4K; precision: 0.5; dynamic range: 213-343) will meet your user needs? If not, please explain.

    a. Inadequate precision for climate studies (0.1 K or less). Dynamic range should be 190-360 K
    b. LST accuracy < 2 K and higher resolution for applications in agriculture
    c. Errors in accuracy of 2.4 K will lead to surface flux errors in the order of 20-30 W/M2. Errors in the order of 10 W/m2 are desired.
    d. Not adequate: accuracy < 1 K; precision < 0.3 K; dynamic range 213-350K
    e. It will be a very useful product
    f. If these specifications can be met over all places then the product would be useful. However, it would be preferable to have accuracy within 2 K
    g. Inadequate to measure changes in ice temperatures – should have accuracy of 1 K or less (particularly important in the southern half of Greenland ice sheet that is already near melting during summer)
    h. Precision and dynamic range are good enough
    i. What is the radiance requirement?

5. What are the ideal characteristics of an LST product that would match your needs?
Identify need: ____________________________________________________

| | Threshold (required) | Objective (desired) |
|---|---|---|
| a. Spatial resolution: | __________________ | _________________ |
| b. Temporal resolution: | __________________ | _________________ |
| c. Accuracy (bias): | __________________ | _________________ |
| d. Precision (STD): | __________________ | _________________ |
| e. Uncertainty (*): | __________________ | _________________ |
| f. Latency: | __________________ | _________________ |
| g. Longevity: | __________________ | _________________ |
| h. Projections: | __________________ | _________________ |
| i. Data format (e.g., HDF, binary): | __________________ | _________________ |

j. Swath format ☐ or gridded ☐
k. Aggregates ☐ or subsets ☐
l. Diurnal cycle resolved? yes ☐ no ☐

m. Other: ______________________________________

Given the disparity of requests from the different users, it is not possible to compile the information into categories, even assuming different types of users (climate studies, agricultural. etc). The specifications for accuracy, spatial and temporal resolution, precision and uncertainty vary greatly from user to user. There was a general request for data projections to include UTM and geographical lat/lon, and for the HDF, NetCDF and binary formats to be made available.

Users tend to have a preference for gridded data (over swath data, although some requests for swath data were made). The need for data aggregation to regional and national scales was referred. Also, all users requested that the diurnal cycle be resolved.

6. What are your main concerns regarding the LST products that will/will not become available in the future (next 10 years)?

Concerns:

a. Lack of longevity and consistency of products
b. Lack of adequate cover of diurnal cycle
c. Lack of intercalibrated data from satellite to satellite to get uniform long term global data
d. Inadequate spatial resolution (high resolution required)
e. Limited availability of products
f. Existence of systematic biases in products
g. Lack of consistency of instrument or spectral channels across platforms
h. Inadequate accuracy to meet user needs
i. Most products are clear-sky biased
j. Inadequate cloud mask

Opportunities:

k. Combination of polar orbiters and geostationary provides real opportunities.
l. Feasibility of multi-sensor multi-platform LST products.

7. **(For LST Users)** As a user of LST products, how much interaction, and what type (e.g., collaboration, clarification through literature only, data center contacts), do you have with the LST product development community (none, some, a lot)?

Most users reported little or no interaction with the product development community. The few interactions are mostly done through literature search, contact with data centers, and to a lesser extend, direct contact with individuals in conferences and workshops. Some users requested more additional workshops that bring the developers and user community together.

8. Based on your experience and applications, what is the critical metadata and QA information needed in LST products:

a. Satellite:
    i. cloud mask and error estimates for cloudy pixels
    ii. product accuracy and precision, and error bars
    iii. pixel geolocation information
    iv. observation and illumination geometries
    v. exact acquisition time
    vi. type of instrument, instrument error, and instrument precision
    vii. calibration information (including coefficients)
    viii. radiance statistics
    ix. transmissivity and Ldown,
    x. adopted emissivity,
    xi. algorithm details and assumptions regarding atmosphere
    xii. surface classification
    xiii. original resolution of data
    xiv. quality flags
    xv. satellite ID

b. Models:
    i. geolocation information;
    ii. land model details,
    iii. atmospheric forcing data details (for offline) and atmospheric boundary layer formulations

c. *In situ*:
    i. Accuracy and precision
    ii. Precise geolocation
    iii. Exact time of acquisition
    iv. Instrument information: precision, accuracy, bandwidth, etc
    v. Calibration information
    vi. Radiometric skin temperature
    vii. Cloud information
    viii. Downwelling radiance
    ix. Emissivity adopted
    x. Collocated (time and space) ancillary data: surface fluxes, LAI, meteorological conditions, etc

    xi. Existing LST networks;

9. Which type of product do you tend to consider more useful:
    a. A product where LST estimates are created for all pixels (clear and cloudy) and a separate cloud mask is provided. The product is continuous in space: **15**
    b. A product where LST estimates are only produced for pixels identified as cloud free (with a given level of confidence). The product is discontinuous in space: **3**

Thank you!