1. **Name / brief description of recommended Earth System Data Record (ESDR) or Climate Data Record (CDR)**

Land Surface Temperature and Emissivity Earth System Data Record (LSTE-ESDR)

Land surface temperature (LST) and emissivity are key variables for explaining the biophysical processes which govern the balances of water and energy at the land surface. Table 1 summarizes the science requirements for the LSTE-ESDR.

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 GOES MSG	CrIS GOES MSG
Regional	1-5 km	2-4 times daily	0.5-1.0K	0.1-0.3K	MODIS AVHRR ATSR	VIIRS AVHRR ATSR
Local	30–100 m	Once every 8-16 days	0.5-1.0K	0.1-0.3K	ASTER Landsat	
Emissivity	1% or better (in 8-12.5μm) and 3% or better (in 3.6-4.2μm) all resolutions.					

Table 1 Science requirements for the Land Surface Temperature and Emissivity Earth System Data Record (LSTE-ESDR). Requirements for accuracy and precision are taken from the Algorithm Theoretical Basic Documents for the ASTER and MODIS land surface temperature and emissivity products and represent current state of the art. Typically more than one data source is required to provide the necessary resolution for a Subproduct.

The LSTE-ESDR is derived from satellite radiance at-sensor data and the requirements for those data must meet and preferably exceed the requirements for the LSTE data. In order to recover LSTE to the required accuracy two or more spectral bands are required in the 8-12 um region with three or more bands desired. The primary issues facing the LSTE measurement community in producing the LSTE record are:

- Possibly no high spatial resolution follow-on to ASTER and Landsat (pending LDCM design selection)
- Data sources vary in their radiometric calibration and validation
- Data are provided in multiple formats with different algorithms and no attempt to reconcile differences
- No common source for data
- Large uncertainties in high spatial resolution emissivity data, needed to convert observed brightness temperatures to skin kinetic temperatures.

- Inconsistent observation times and sun-view geometries lead to non-normalized data products

2. List of all authors of White Paper

(see end of document)

3.0 Scientific rationale and importance of measurement and expected end uses (both basic and applied science)

3.1 What are the science questions or applications drivers that the product will be used to address?

Science Questions

1. What are the temperatures of the land surface of the Earth, including soils, vegetation, snow, ice and inland water bodies? How are these temperatures spatially distributed, and how do they change at short and long time scales?
2. What are the evaporative flux rates and partitioning between surface-emitted LW radiation, sensible heat and latent heat at the land surface of the Earth and how are they spatially distributed and how are they changing?
3. How is land use changing and what are the consequences of any changes on the water, energy, and carbon cycles?
4. What is the chemistry of the Earth's surface and how is it changing?
5. How do volcanic eruptions affect weather and climate?
6. How do changes in land surface temperature and energy flux affect weather and climate?
7. How do changes in surface temperature affect snowpack evolution and melting, glacial retreat, spatial and temporal extent of seasonally snow-covered ground?

Applications

Hazard prediction and mitigation:

- Wildfire risk assessment
- Burned area mapping and hazard assessment
- Earthquake precursor detection and monitoring
- Detection and monitoring of the onset and progression of volcanic activity, including airborne volcanic ash plumes and low temperature thermal anomalies.
- Aquatic thermal plume detection (e.g., associated with power plants and shallow undersea volcanic eruptions)
- Locating and monitoring underground coal fires
- Assessment and monitoring of urban heat island impacts
- Detecting, tracking, and assessing airborne dust clouds—their transport mechanisms, destinations, and sources.

Water management

- Assessment of agricultural/urban water consumption
- Negotiation and monitoring of water rights/inter-state compacts
- Assessment of water losses from riparian areas and reservoirs
- Assessment of aquifer depletion rates
- Assessment of alternative water management practices

- Monitoring of sediment transport within rivers and into estuaries
- Water quality assessments

Crop management

- Drought/crop stress detection
- Irrigation scheduling
- Crop yield mapping/forecasting

Non-renewable resource management

- Differentiation of rock lithologies (important for mineral exploration and geotechnical engineering)
- Geothermal resource exploration

3.2 Why is the product important to a NASA Earth Science Focus Area(s)?

Carbon Cycle and Ecosystems Focus Area: Assessing land-cover/land-use change, modeling flux rates.

Earth Surface and Interior Focus Area: Understanding volcanic/earthquake processes, predicting eruptions, assessing volcanic hazards.

Climate Variability and Change Focus Area: Quantifying the effect of climate change.

Water and Energy Cycle Focus Area: Understanding water and energy cycles and how they are affected by climate change.

Applications:(Agricultural productivity and sustainability, Aviation, Disaster Management, Ecological Forecasting, Energy Management, Water Resources Management, Air Quality)

3.3 Which user communities need the product?

- Geologists and geophysicists – for volcano, earthquake, and geological studies.
- Hydrologists/Ecologists for characterizing surface temperatures, fluxes, managing water and carbon resources.
- Agronomists and engineers for monitoring crops, estimating water requirements and actual water consumption and predicting yields at farm to continental scales.
- Modelers for input into climate and weather models.
- Federal Agencies involved in water resource allocation (DOI), crop yield assessment (NASS, FAS) and drought and flood monitoring (USDA/NOAA, US Bureau of Reclamation)
- Urban and regional planners for mitigating heat island effects.
- Glaciologists for ice sheet and sea ice studies – to determine seasonal and interannual melt and to monitor trends in ice-surface temperature.

4.0 Scientific requirements for the measurement (background)

Requirements vary depending on science question being answered. At least two bands per instrument desired to facilitate atmospheric correction. At least three bands for temperature-emissivity separation.

4.1 What are the documented or implied requirements for the product?

Stable, periodically-calibrated multi-band mid and thermal infrared detectors. Atmospheric profile data and procedures for extracting temperature and emissivity from mid and thermal infrared observations.

4.2 What accuracy, precision, and uncertainty are needed?

Temperature Requirements

10-20 km: accuracy=0.5K, precision=0.1-0.3K
1-5 km: accuracy=0.5-1.0K, precision=0.1-0.3K
30-100 m: accuracy=0.5-1.0K, precision=0.1-0.5K

Emissivity Requirements

1% or better (in 8-12.5µm) and 3% or better (in 3.6-4.2µm) all resolutions.

4*.3 What are the needed temporal and spatial resolutions?*

10-20 km: global land surface coverage multiple times per day
1-5 km: global land surface coverage two or more times per day
30-100m: global land surface coverage every 8-16 days, preferably with coverage every 8 days to increase the likelihood of producing cloud-free images each 16 to 24 days. More frequent targeted acquisitions (every 2-3 days) desired for rapidly evolving thermal phenomena (e.g., volcanic eruptions and their precursors). Less frequent complete coverage is preferred over targeting for certain applications, e.g. evapotranspiration.

4.4 What is the required length of record?

Record length varies depending on science or application requirement. Hydrological and agricultural applications require data in perpetuity, i.e. land surface temperature data should be collected with the same priority as for meteorological data sets. Climate change studies desire minimum record length of 10 years.

5.0 Approach to generating the measurement (i.e., data product)

5.1 Feasibility, reliability of measurement

Measurement is feasible with current technology. Measurement reliability depends on successful cloud detection and atmospheric correction.

5.2 Algorithm(s) / concept to be applied and brief description

The radiation emitted from a surface at a given wavelength in the mid infrared (MIR) between 3 and 5 µm and thermal infrared (TIR) between 8 and 12 µm is a function of its temperature and emissivity. As a result, if the radiance is measured in n spectral channels, the system of equations describing the spectrum will have at least n+1 unknowns: n emissivities (one per channel) and a single unknown surface temperature. Four main approaches have been developed to recover land surface temperature and emissivity from space and each approach is continually being modified and improved.

The first approach uses a radiative transfer model to correct the at-sensor radiance to surface radiance followed by an emissivity model to separate the surface radiance into temperature and emissivity. This approach requires atmospheric profiles from either satellite sounding or conventional radiosondes for the atmospheric model and an emissivity model which is typically based on laboratory and field measurements. This approach has been adopted for the recovery of LST from the Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) (Gillespie et al. 1998).

The second approach involves extending the Sea Surface Temperature (SST) split-window approach to land surfaces (Wan, 1999). In this second approach the emissivity of the surface is assumed to be known based on an *a priori* classification of the Earth surface into a selected number of cover types and a dual or multi-channel split window algorithm is used in much the same way as with the oceans. This approach has been adopted by the MODIS and VIIRS instruments.

The third approach requires very high spectral resolution data and utilizes atmospheric information within the spectrum to simultaneously solve for the atmosphere, surface temperature and surface emissivity. This approach is being evaluated with data from the AIRS instrument.

The fourth approach uses a day/night pair to obtain a duplicate set of radiances for a given pixel at a different temperatures but fixed emissivity to obtain the necessary over-determination to extract temperature and emissivity. This approach has also been adopted by the MODIS instrument.

5.3 Measurement / algorithm heritage and maturity

Measurement and algorithm approaches are mature but undergoing continuous refinement with experience. Ancillary emissivity data, required for LST determination in some approaches, have high uncertainties. Standard temperature and emissivity products are produced by ASTER and MODIS. Validation of these products is underway.

5.4 Required inputs products and their traceability (including dependencies on other products)

a) Radiance at sensor in MIR and TIR bands
b) Atmospheric profiles of water vapor and ozone
c) Cloud mask
d) Georegistration data
e) Land use classifications or emissivity maps

Required inputs vary with algorithm used. Input may be derived from data themselves. For example AIRS data could be used to produce an atmospheric profile and derive emissivity.

5.5 Processing / reprocessing requirements

Depends on algorithm generation approach, some systems “on demand” e.g. ASTER, while other systems have periodic reprocessing of entire dataset e.g. MODIS. Computational complexity ranges from simple split window algorithms to multi-observation staged composite techniques.

5.6 Calibration / validation

On-board blackbodies and deep-space observations for calibration and post launch monitoring of at-sensor radiance and derived temperature and emissivity products with *in situ* measurements from permanent sites and periodic validation campaigns and Lunar cross-calibration. In situ measurements should produce equivalent data provided by satellite. Post-launch monitoring may identify calibration error necessitating product re-calibration. Rigorous pre-launch instrument characterization is critical to LSTE product quality.

5.7 Product accuracy, consistency, spatial and temporal resolutions, precision in terms of satisfying science requirements

The product requirements stated above (in 4.2) need characterization of data quality in metadata and pixel QA flags.

6.0 Intended sources for the measurement

6.1 Which instruments will be used?

10-20 km (AIRS, MSG, TOVS CrIS)
1-5 km (AVHRR, MODIS,VIIRS,ATSR, GOES, MSG)
30-100 m (ASTER, Landsat ETM+)

6.2 What in situ data, if any, is needed?

Continuous and standardized periodic measurements of surface skin temperature and emissivity from long-term monitoring sites for post-launch calibration and validation. Skin temperature measurements are required to be better than 0.1K absolute. Meteorological data from assimilation models and local balloon launches.

7.0 Necessary supporting activities, tasks

a) Periodic data reduction algorithm refinements.
b) Long-term cal/val monitoring sites with periodic cal/val campaigns,
c) Data at all scales should be easily and affordably accessible to entire thermal community.
d) Higher level data products may require additional inputs e.g. short wave (SW) reflectance vegetation cover amount for evapo-transpiration models.
e) Development of an accurate moderate resolution emissivity database(variable in time and space)

8.0 Relationships to other products and programs (of other agencies, international, etc.)

High spatial resolution data only available from ASTER/Landsat, with no identified future data source (pending LDCM instrument design selection).
Moderate spatial resolution data (~1km) will be available from AVHRR managed by NOAA, VIIRS managed by IPO and ATSR managed by European Space Agency
Low spatial resolution data will be available from MSG managed by EUMETSAT, GOES managed by NOAA, CrIS managed by IPO.

9.0 Key citations (<5; not a literature review)

Overviews

D. Quattrochi & J. Luvall (Eds). Thermal Remote Sensing in Land Surface Processes. CRC, Boca Rutan, Fl., 2004.

Temperature and Emissivity in Surface Energy Budgets

Diak, G.R., Mecikalski, J.R., Anderson, M.C., Norman, J.M., Kustas, W.P., Torn, R.D., and R. L. DeWolf, 2004. Estimating land-surface energy budgets from space: Review and current efforts at the University of Wisconsin-Madison and USDA-ARS, Bull. Amer. Meteorol. Soc. 85(1):65-78.

Temperature and Emissivity in Climate Studies

Sun, D., R. T. Pinker, and Menas Kafatos, 2006. Diurnal temperature range over the United States: A satellite view. Geophysical Research Letters, vol. 33 (10)

Temperature and Emissivity in Land Surface Models

Wang, K., Z. Wan, P. Wang, M. Sparrow, J. Liu, X. Zhou, and S. Haginoya, 2005. Estimation of Surface Long Wave Radiation and Broadband Emissivity using Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature/Emissivity Products, J. Geophys. Res. Atmosphere, 110, D11109.

Zhou, L., R.E. Dickinson, Y. Tian, M. Jin, K. Ogawa, H. Yu and T. Schmugge 2003. A sensitivity study of climate and energy balance simulations with use of satellite derived emissivity data over Northern Africa and the Arabian Peninsula, J. Geophys. Res. Atmosphere, 108, D24, 4795.

Zhou, L., Dickinson, R.E., Ogawa, K., Tian, Y., Jin, M., Schmugge, T., and Tsvetsinskaya, E., Relations Between Albedos and Emissivities from MODIS and ASTER Data Over North African Desert. Geophy. Res. Lett., 30 (20), 2026, doi:10.1029/2003GL018069, 2003.

Land-Surface Temperature for Drought Monitoring

Wan, Z., P. Wang, and X. Li, 2004, Using MODIS land surface temperature and normalized difference vegetation index for monitoring drought in the southern Great Plains, USA, Int. J. Remote Sens., vol. 25, pp. 61-72.

Temperature and Emissivity in Hydrologic Studies (Inland)

Steissberg; T. E., S. J. Hook and S. G. Schladow, 2005. Measuring Surface Currents in Lakes with High Spatial Resolution Thermal Infrared Imagery. Geophysical Research Letters, 32 (11).

Temperature and Emissivity in Snow/Ice Studies

Kay, J.E., A.R. Gillespie, G.B. Hansen and E.C. Pettit, Spatial relationships between snow contaminant content, grain size, and surface temperature from multispectral images of Mt. Rainier, Washington (USA) Remote Sensing of Env, 86 (2) pp. 216-231, 2003.

Temperature and Emissivity in Volcanology

Pieri, D. and M. Abrams, 2005. ASTER observations of thermal anomalies preceding the April 2003 eruption of Chikurachki volcano, Kurile Islands, Russia, Remote Sensing of Environment, 99: 84-94.

Vaughan, R. G., S. J. Hook, M. S. Ramsey, V. J. Realmuto and D. J. Schneider, 2005. Monitoring eruptive activity at Mount St. Helens with TIR image data, Geophysical Research Letters, 32 (19).

Temperature and Emissivity in Urban Heat Islands

Voogt, J.A., and T.R. Oke, 2003. Thermal remote sensing of urban climates. Remote Sensing of Environment, 86, pp. 370-384.

Temperature and Emissivity Extraction Algorithms

Gillespie, A., Rokugawa, S. Matsunaga, T., Cothern, S, Hook, S. and A. Kahle, 1998. A Temperature and Emissivity Separation Algorithm for Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Images. IEEE Transactions on Geoscience and Remote Sensing, vol. 36 pp. 1113-1126.

Wan, Z. 1999. MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD) ver. 3.3.

Sun, Donglian, R. T. Pinker, and Jeffrey B. Basara, 2004. Land surface temperature estimation from the next generation of Geostationary Operational Environmental Satellites GOES M-Q. J. Appl. Meteor., 43, 363-372.

Instrument Calibration and Validation

Ohring, G., Wielicki, B., Spencer, R., Emery, B and R. Datla, 2005. Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop. Bulletin of the American Meteorological Society, vol. 86, Issue 9, pp.1303-1313.

Acronyms

AIRS: Atmospheric Infrared Sounder
ATSR: Along Track Scanning Radiometer
AATSR: Advanced ATSR
ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR: Advanced Very High Resolution Radiometer
BLM: Bureau of Land Mangement
CDR: Climate Data Record
CrIS: Cross-track Infrared Sounder
ESDR: Earth System Data Record
ETM: Enhanced Thematic Mapper
FAS: Foreign Agricultural Service
GOES: Geostationary Operational Environmental Satellites
IPO: Integrated Program Office
LSTE: Land Surface Temperature and Emissivity
MIR: Mid Infrared
MODIS: Moderate Resolution Imaging Spectroradiometer
MSG: Meteosat Second Generation
NASS: National Agricultural Statistics Service
SST: Sea Surface Temperature
TIR: Thermal Infrared
TOVS: TIROS Operational Vertical Sounder
VIIRS: Visible Infrared Imager / Radiometer Suite

Author List

Simon Hook, JPL (lead)
Rick Allen, U of Idaho (confirmed)
Michael Abrams, JPL (confirmed)
Martha Anderson, USDA (confirmed)
Bob Knuteson, U of Wisconsin (confirmed)
Julia Barsi, GSFC (confirmed)
Wendy Calvin, UNR (confirmed)
Philip Christensen, ASU (confirmed)
Jim Crowley, USGS (confirmed)
Gayle Dana, DRI (confirmed)
Robert Dickinson, GATECH (confirmed)
Andrew French, USDA (confirmed)
Alan Gillespie, U of Washington (confirmed)
Dorothy Hall, GSFC (confirmed)
Brad Henderson, LANL (confirmed)
Chris Justice, UMD (confirmed)
James Irons, GSFC (confirmed)
Jeff Luvall, MSFC (confirmed)
Hugh Kieffer, USGS (confirmed)
William Kustas, USDA (confirmed)
Shunlin Liang, UMD (confirmed)
Brian Markham, GSFC (confirmed)
Susan Moran, USDA (confirmed)
John Norman, U of Wisconsin (confirmed)
David Pieri, JPL (confirmed)
Ana Pinheiro, GSFC (confirmed)
Rachel Pinker, UMD (confirmed)
Jeffrey Privette, GSFC (confirmed)
Dale Quattrochi, MSFC (confirmed)
Michael Ramsey, U of Pittsburgh (confirmed)
Nina Raqueno, RIT (confirmed)
Vince Realmuto, JPL (confirmed)
Hank Revercomb, U of Wisconsin (confirmed)
Geoffrey Schladow, UCD (confirmed)
Thomas Schmugge, New Mexico State (confirmed)
John Schott, RIT (confirmed)
Will Stefanov, JSC (confirmed)
Jim Taranik, UNR (confirmed)
M. Tasumi, U of Idaho (confirmed)
Susan Ustin, UCD (confirmed)
Greg Vaughan, JPL (confirmed)
Zhengming Wan, UCSB (confirmed)
Rick Wessels, USGS (confirmed)
Liming Zhou, GATECH (confirmed)