→ 8th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

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University of Leicester | United Kingdom

Measuring the surface temperatures of the earth from space

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Contents

Background

Challenges of measuring Land Surface Temperature

Applications

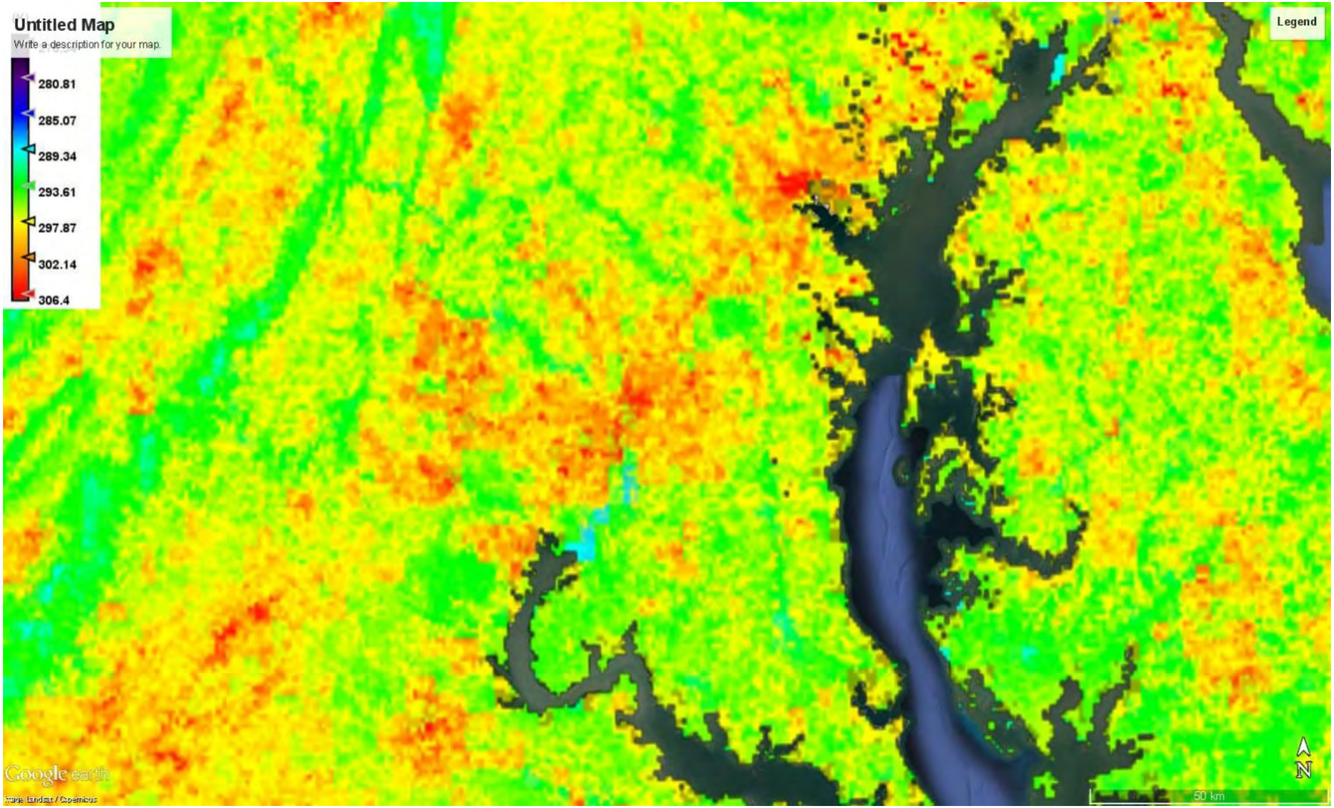
Current capability

What is Land Surface Temperature

- Land Surface Temperature (LST) is a measure of how hot or cold the surface of the Earth would feel to the touch
- For ground-based, airborne, and spaceborne remote sensing instruments it is the aggregated radiometric surface temperature of the ensemble of components within the sensor field of view
- LST is an independent temperature data set for quantifying climate change complementary to the near-surface air temperature ECV based on in situ measurements and reanalyses
- From a climate perspective, LST is important for:
    - evaluation of land surface and land-atmosphere exchange processes
    - constraint of surface energy budgets and flux variations
    - global and regional observations of surface temperature variations
- LST can be determined from thermal emission at wavelengths in either infrared (IR) or microwave (MW) atmospheric windows

Sentinel-3 Land Surface Temperature

Sentinel-3 Land Surface Temperature



Importance of LST for climate

LST increasingly recognised as an essential parameter for diagnosing Earth System behaviour and evaluating Earth System Models:

- provides a globally consistent record from satellite of radiative temperatures of the Earth's surface
- provides a crucial constraint on surface energy budgets, particularly in moisture-limited states - the LST record contains the imprint of climate events related to water stress and availability
- provides a metric of surface state when combined with vegetation parameters and soil moisture, and is related to the driving of vegetation phenology.
- an important source of information for deriving surface air temperature in regions with sparse measurement stations, such as parts of Africa and the Arctic
- A long, stable record of LST is particularly useful for model evaluation in regions where few in situ measurements of surface air temperature exist and for attribution of observed changes in such regions to their possible causes

The climate user community already use and need LST data.

How we measure Surface Temperature

How is it measured?

- Planck Function Radiation Curves
- Radiative Transfer Equation
- Thermal Infrared (TIR) atmospheric Window (~8-13μm)
- Split-Window and/or Dual angle Algorithms
- Mean radiative temperature over pixel area

$$L^{sat} = L^{ground} + L^{atm} + L^{atm\_reflected}$$

- L^{sat} is the radiance measured by the satellite sensor
- L^{ground} is the upwelling radiance emitted by the ground
- L^{atm} is the upwelling radiance emitted by the atmosphere
- $L^{atm\_reflected}$ is the down-welling radiance emitted by the atmosphere and reflected by the ground

A Simple Radiative Transfer Approach

$$B_i\left(T_{sensor}\right) = \left[\varepsilon B_i\left(LST\right) + \left(1-\varepsilon\right)L_i^{\downarrow}\right]\tau + L_i^{\uparrow}$$

BT measured by the sensor channel

Surface emissivity

Atmospheric effects

- Radiometers are used to measure the top-of-atmosphere brightness temperature (BT).
- To obtain *ST* from infrared satellite measurements, we need to correct for the effects of the atmosphere and non-unity of surface emissivity.
- Sea: The surface emissivity is very well behaved. The atmosphere tends to be spatially homogeneous except for some aerosol advection/broken cloud.
- A split-window algorithm is used (11/12 µm with addition of 3.7 µm channel at night for SST). Atmospheric effects and emissivity correction are implicitly handled through a coefficient approach.

Infrared or Microwave Retrievals?

- Microwaves are able to penetrate clouds and so offer a more continuous source of data
- However:
  - The signal originating from Earth is stronger at IR wavelengths
    - The Planck function peaks in the IR
    - Higher surface emissivity of terrestrial materials in IR

Rate of change of radiance is lower in the microwave

- A higher radiometric resolution is required to obtain the same precision

Measurements from microwave instruments are at a lower spatial resolution

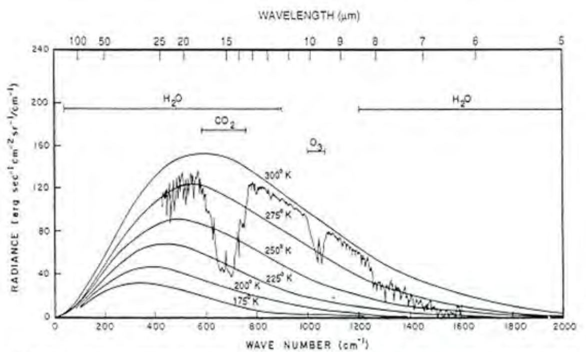


Figure 8.5 Spectrum of outgoing LW radiation over (215° W, 15° N) observed by Nimbus-4 IRIS, as a function of wavenumber λ^{-1}. Blackbody spectra for different temperatures and individual absorbing species indicated. Adapted from Liou (1980).

Atmospheric effects

- Even in the atmospheric window of high transmission attenuation is still significant
- Most attenuation at these wavelengths is due to water vapour absorption
- Stratospheric and tropospheric aerosols also depress infrared radiances
- Both atmospheric effects and emissivity variability need to accounted for to avoid retrieval errors of up to 12K (Sobrino and Raissouni, IJRS, 2000; Sobrino *et al., IJRS, 2003)*
- Most common approach is the Generalised Split-Window (GSW) algorithm
- GSW corrects the atmospheric effects based on the differential absorption in adjacent channels
- Transmission is highest in the 8-13μm window

Thermal infra-red Emissivity

Emissivity is the relative ability of the surface to emit radiation

It is quantified as the ratio of energy radiated by the surface with respect to the energy radiated by a black body ($\varepsilon = 1$) at the same temperature

Surface emissivities can be highly variable owing to the heterogeneity of the land. Factors influencing emissivity include:

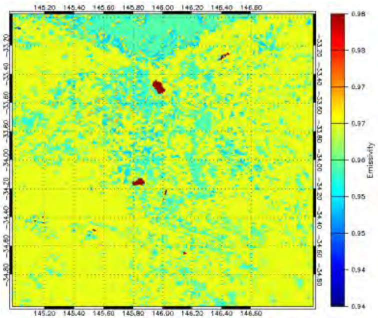
- Surface type
- Fractional vegetation cover
- Soil moisture

Can range from less than 0.94 for some sandy soils to over 0.99 for some regions of inland water or snow and ice

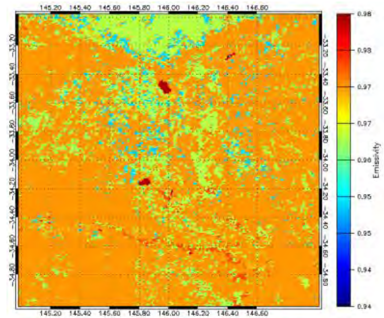
Variability of surface emissivities is amplified in regions of high topographic variance and for larger viewing angles.

Need to accurately deal with uncertainties otherwise biases can occur in LST retrieval of several degrees (Schaadlich *et al., RSE, 2001).*

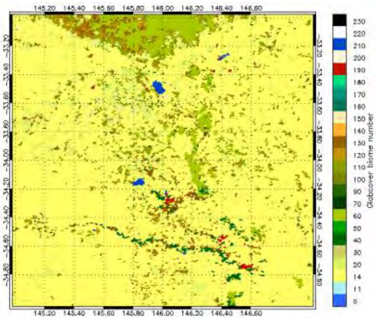
Thermal infra-red Emissivity



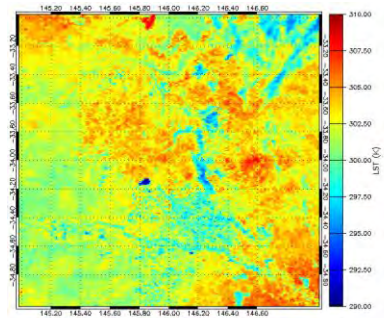
Emissivity 11μm channel



Emissivity 12μm channel



Biome - Globcover



LST

Long-term multi-channel IR LST

AATSR

ENVISAT, Polar Orbiting

Sun-Synchronous (~10.00a.m. descending)

Launched 2001, EOL 08/04/2012

Mission Series (ATSR-1 and ATSR-2) since 1991

SST derived from TIR channels: 3.7, 11 and 12 μm

High Spatial Resolution (1 km^2)

Narrow swath width (512 km)

Exceptional radiometric calibration; dual-view

AVHRR

NOAA + METOP, Polar Orbiting

Sun-Synchronous (a.m. descending)

Mission Series stretching back to 1979.

SST derived from TIR channels: 11 and 12μm

High Spatial Resolution (1 km^2)

Wide swath width (~2500 km)

MODIS

2 Polar Orbiting satellites: Terra and Aqua

Terra: Sun-Synchronous (~10.30a.m. descending)
Launched 1999

Aqua: Sun-Synchronous (~13.30a.m. descending)
Launched 2002

SST derived from TIR channels: 11 and 12μm

High Spatial Resolution (1 km^2)

Wide swath width (2330km)

SEVIRI

Meteosat9/MSG2

Geostationary (0° latitude, 0° longitude)

Launched 2005, EOL 2015

SST derived from TIR channels: 10.8 and 12 μm

High Temporal Resolution (15mins)

Coverage within +/- 60°

Spatial Resolution: 3km at nadir; +6km above 60°

How does LST compare with T_{air}

- Strong diurnal cycle
- Differences of as much as 20K for same scene
- Stronger non-uniformity within a landscape

Comparison example:

- GlobTemperature MODIS (Aqua) – GHCN/D

  (results coutesy of L. Good, Hadley Centre in framework of EU H2020 EUSTACE Project)
- LST_{min} – T_{min} [range between -0.13 K (MAM) and 0.79 K (JJA)]
- LST_{max} – T_{max} [range between -2.56 K (DJF) and 1.76 K (JJA)]
- LST_{ngt} often reasonable proxy for T_{min}

LST Split Window Algorithm

AATSR / SLSTR

Nadir retrievals only (dual angle only for SST)

$$LST = a_{f,i,pw} + b_{f,i}(T_{11} - T_{12})^{p(\theta)} + (b_{f,i} + c_{f,i})\, T_{12}$$

T_{11} and T_{12} are 11 and 12 μm channel brightness temperatures (BT)

a, *b*, *c* – retrieval coefficients dependent on:

- Surface/vegetation type (*i*) - biome
- Vegetation fraction (*f*) – seasonally dependent
- Precipitable water (*pw*) – seasonally dependent
- Satellite zenith view pointing angle ($p(\theta)$)

Emissivity dependence encapsulated in biome and fractional vegetation factors

Contents

Validation

Category A: Comparison of satellite LST with in situ measurements

This is the traditional and most straightforward approach to validating LST. It involves a direct comparison of satellite-derived LST with collocated and simultaneously acquired LST from ground-based radiometers.

Category B: Radiance-based validation

This technique uses top-of-atmosphere (TOA) brightness temperatures (BTs) in conjunction with a radiative transfer model to simulate ground LST using data of surface emissivity and a atmospheric profiles of air temperature and water vapour content.

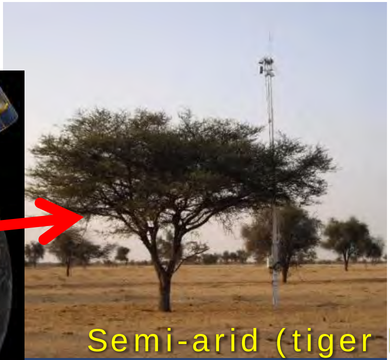
Category C: Inter-comparison with similar LST products

A wide variety of airborne and spaceborne instruments collects thermal infrared data and many provide operational LST products. An inter-comparison of LST products from different satellite instruments can be very valuable for determining LST.

Category D: Time series analysis

Analysing time series of satellite data over a temporally stable target site allows for the identification of potential calibration drift or other issues of the instrument that manifest themselves over time. Furthermore, problems associated with cloud contamination for example may be identified from artefacts evident in the time series. Care must be taken in distinguishing between instrument-related issues such as calibration drift and real geophysical changes of the target site or the atmosphere.

In-situ Validation Stations



- Large, homogeneous sites
- Well characterised
- Different climates & biomes
- Dedicated to LST validation

Validation challenges

- Geolocation accuracy and overpass timing

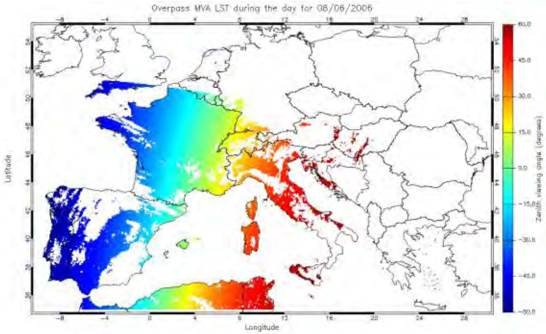
- Landscape heterogeneity
  - Simultaneous measurements of each surface class (‘endmember’)

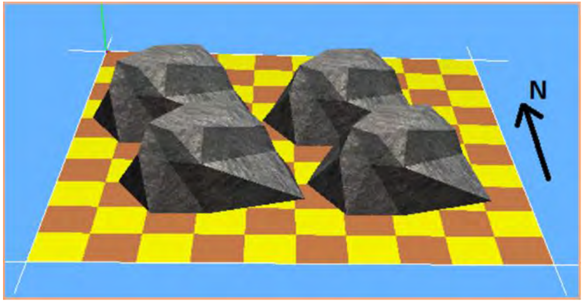
- LST from satellite depend upon angle of observation
  - Upscaling of nadir in situ measurements biased towards sunlit scenes
  - Angularly anisotropic surface emissivity at the microscopic scale
  - Requires measurements of shadow scenes and geometric projection modelling

- Upscaling assumptions:
  - precise geolocation and surface area of a satellite pixel can be guaranteed
  - for each pixel validated the same generic land cover classes can be reliably classified
  - within and between each pixel the thermal behaviour of each land cover class remains invariant

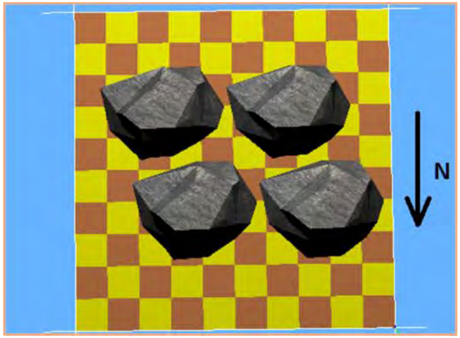
Validation challenges

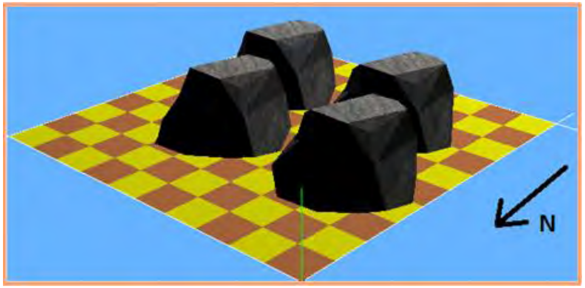
Challenges: Sensor Intercomparison





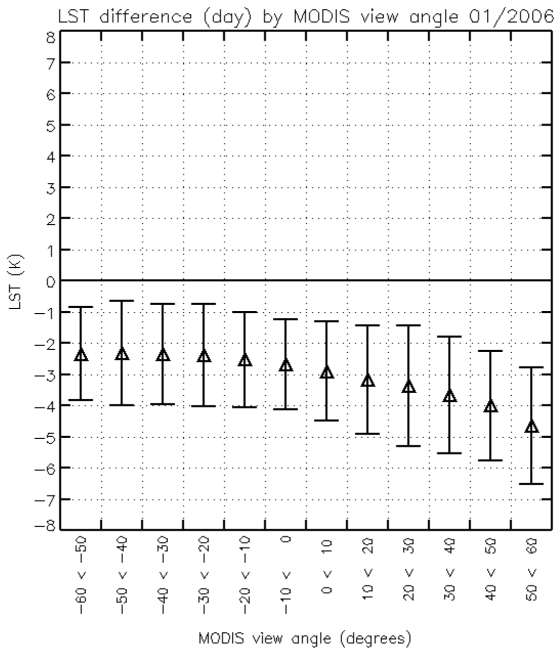
Daytime SEVIRI view

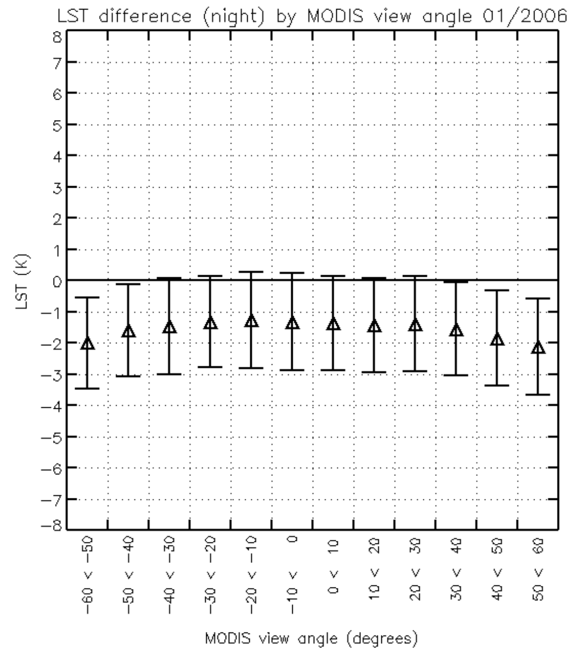




Daytime MODIS view for nadir viewing angles (left) and for positive viewing angles (right)

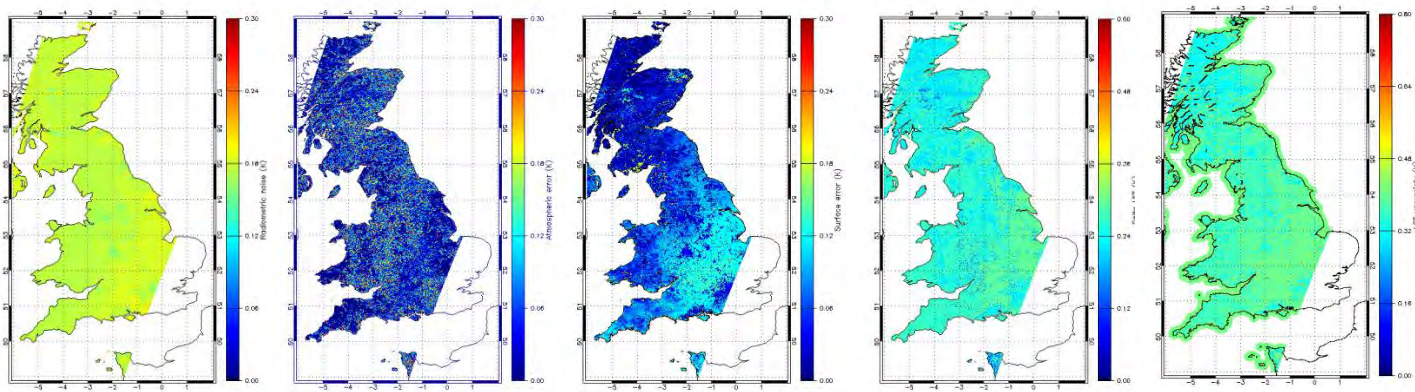
Challenges: Sensor Intercomparison





LST differences between MODIS and SEVIRI as a function of zenith viewing angle by day and night

Challenges: Uncertainty Budgets



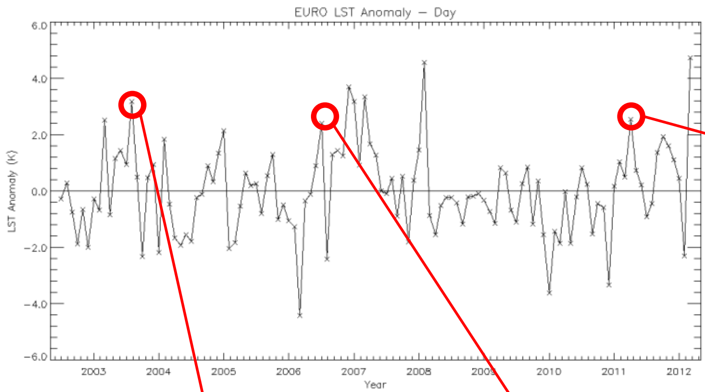
Radiometric noise | **Geolocation** | **Surface component** | **Atmosphere component** | **Total**

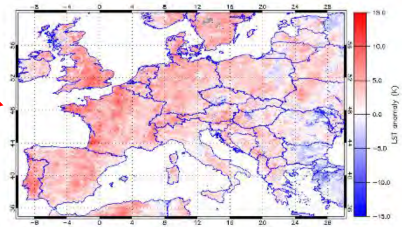
Contents

Applications for LST Data

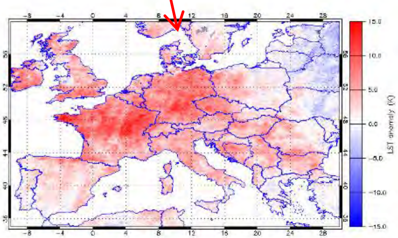
- Climate change
  - Urban heat islands, land/atmosphere coupling, surface energy balance
- Modelling studies
  - Model validation, data assimilation
- Land cover change
  - Desertification, change detection
- Crop management
  - Irrigation, drought stress
- Water management
  - Evapotranspiration, soil moisture retrievals
- Fire monitoring
  - Burned area mapping, fuel moisture content
- Geological applications
  - Geothermal anomalies, volcanic activity

Applications - Heat Waves

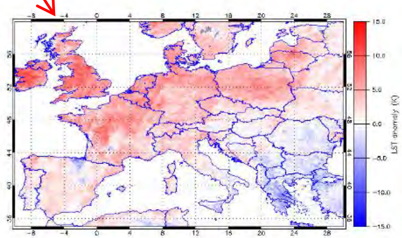




Apr 2011 anomaly



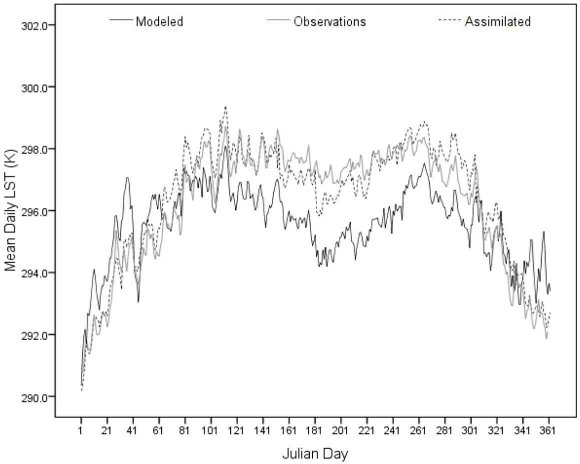
Aug 2003 anomaly



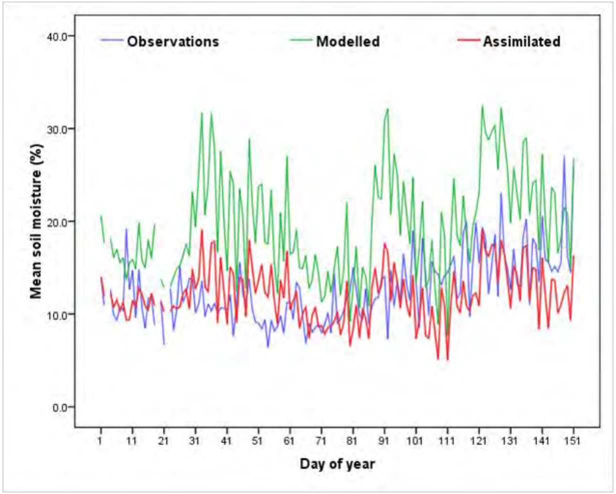
Jul 2006 anomaly

AATSR LST daytime anomalies during relative heatwaves

Applications - Data Assimilation



Modelled vs. assimilated mean daily LST compared with NCEP skin temperature



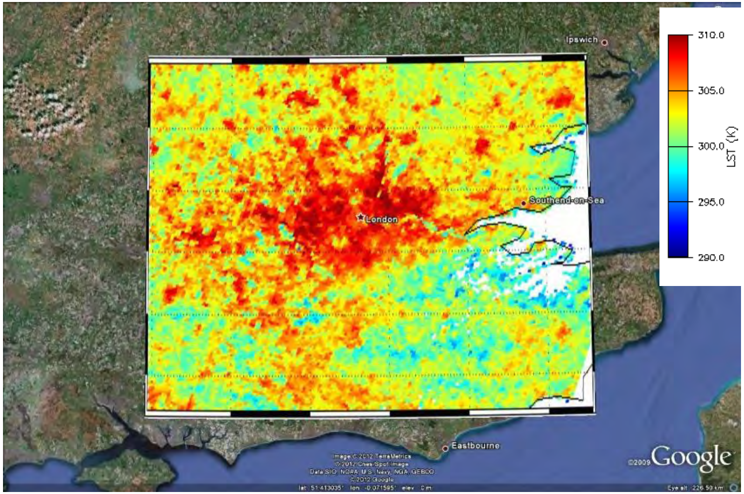
Time series of mean daily surface soil moisture in the top 5cm of the soil profile with and without LST data assimilation for values over West Africa from 1st January – 31st May 2007. ERS scatterometer surface soil moisture observations are plotted for comparison.

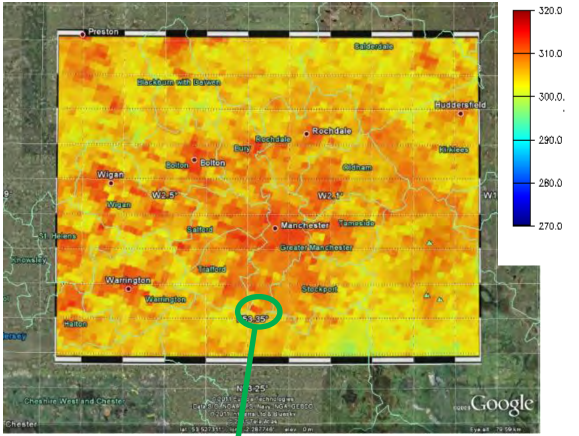
Applications - Hydrology

Why is accurate LST data important in hydrological applications?

- For non-vegetated surfaces water shortage at the surface of the soil causes the temperature to rapidly increase, with more energy partitioned into sensible heat. For vegetated surfaces root zone water shortage leads to stomatal closure, reduced transpiration, and higher canopy temperatures
- 0.5K LST error can result in a 10% error in sensible heat flux (Brutsaert *et al.*, 1993)
- 1.0K LST error can lead to a 10% error in ET (Moran and Jackson, 1991)
- LST Errors between 1.0K and 3.0K can lead to errors as much as 100Wm^{-2} in heat fluxes (Kustas and Norman, 1996)

Applications - Urban Heat

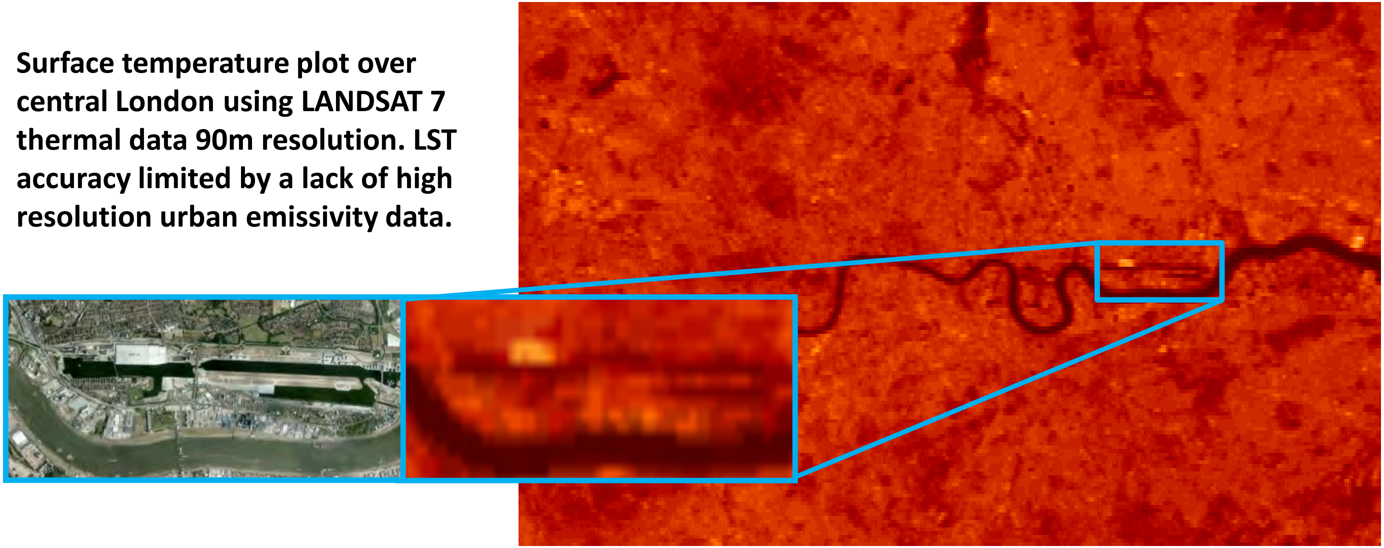




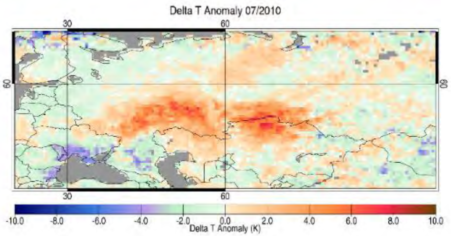
Applications - Urban Heat

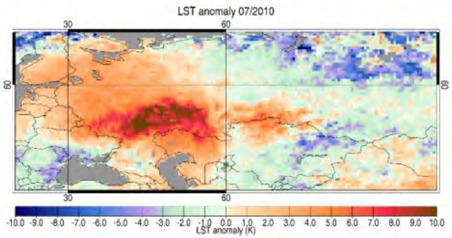
The high spatial resolution of LANDSAT comes at the cost of temporal resolution, with 16 day image separations and the accuracy with which temperatures can be established given the need for additional input variables

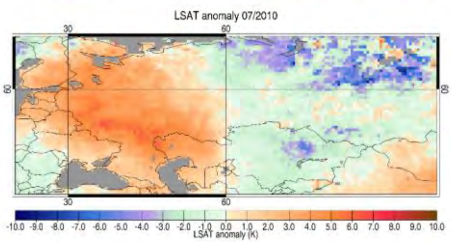
Surface temperature plot over central London using LANDSAT 7 thermal data 90m resolution. LST accuracy limited by a lack of high resolution urban emissivity data.

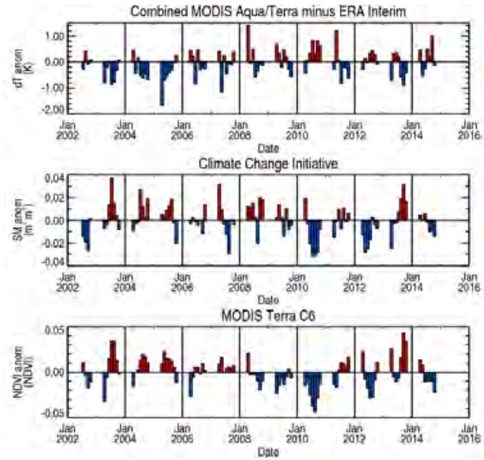


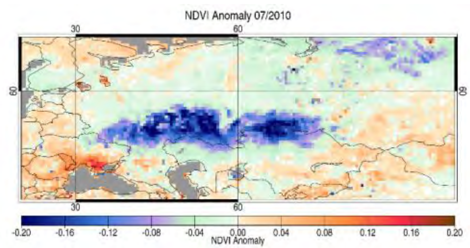
LST applications: Drought mapping



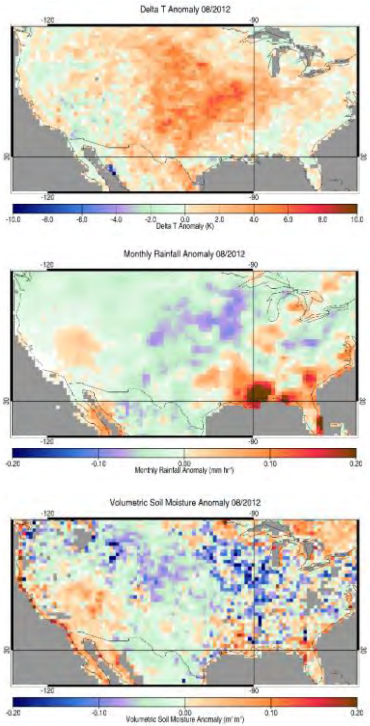


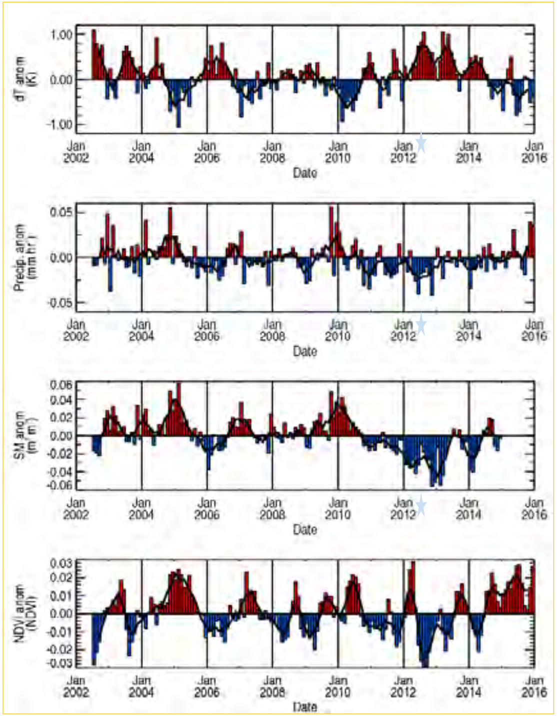






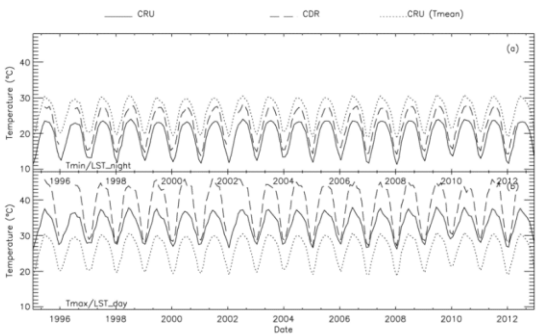
LST applications: Drought mapping





Improving LST representations

- Comparisons of LST and near-surface air temperature provide information on surface energy budget where coincident measurements are available
- LST delivers unique information on surface temperatures in sparsely observed regions for near-surface air temperature
- Consistent representations of surface temperature from LST can inform historical reconstructions.
- LST from IR is currently used more for climate studies



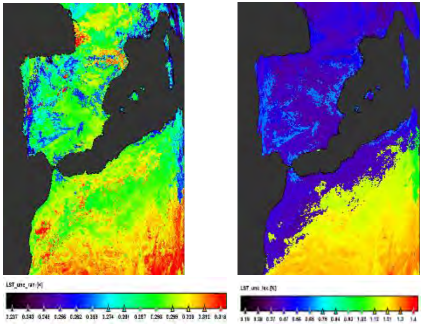
Time series from ATSR LST CDR vs. CRU for North Africa (E. Good, Met Office)

Contents

Current capability I (products)

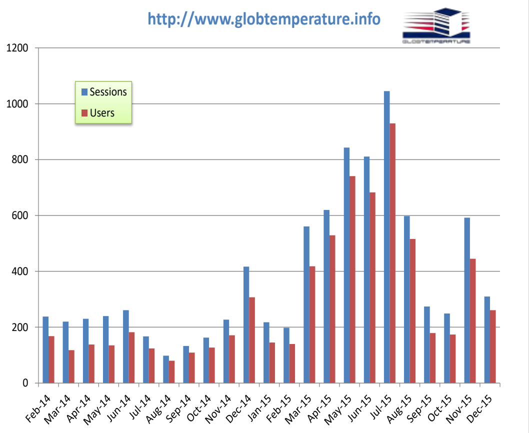
Single-sensor IR LST data-products from satellite have greatly improved:

- High accuracy of IR LST data:
  - validation shows LST biases < 1.0 K from AATSR (eg Coll et al., 2012)
  - emissivity accuracy < 0.015 (1.5%) from MODIS and ASTER (eg Hulley et al., 2012)
- Advances in cloud detection (dynamic probabilistic approaches)
- Approach to uncertainties consistent with Sea Surface Temperature (SST) including validation



Random   Locally correlated

ESA GlobTemperature MODIS uncertainties

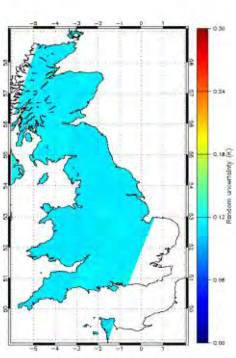


Current capability I (uncertainties)

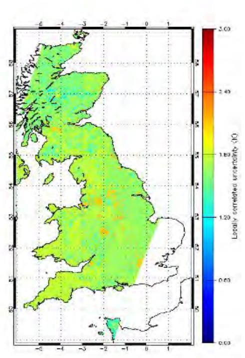
Uncertainties categorised by effects whose errors have distinct correlation properties:

- Random
- locally systematic
- (large-scale) systematic

Random



Locally correlated



This three-component model applies to all processing levels and LST products

Propagation of uncertainties:

- L1 → L2 → L3 → L4 (Merged Product)

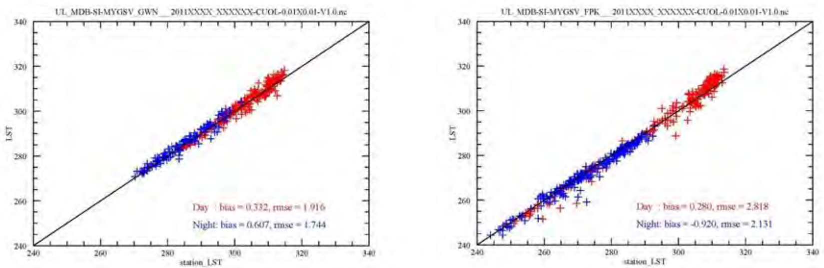
Current capability II (quality)

LST data, particularly I/R, are of much higher quality than previously:

- Demonstrated against accurate and highly stable in situ instruments
- Biases against in situ are stable, small (often < 1 K) and well documented.
- Standardised protocols
- Validation of LST uncertainties

Complementing IR LST with MW LST:

- Retrievals in the IR are generally more accurate than MW retrievals due to smaller variation of surface emissivities
- However, MW LST is complementary to IR LST due to their lower sensitivity to clouds and therefore helps us quantify the clear-sky bias

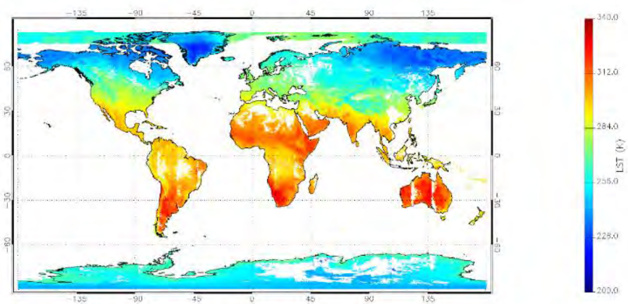


GlobTemperature MODIS LST Validation

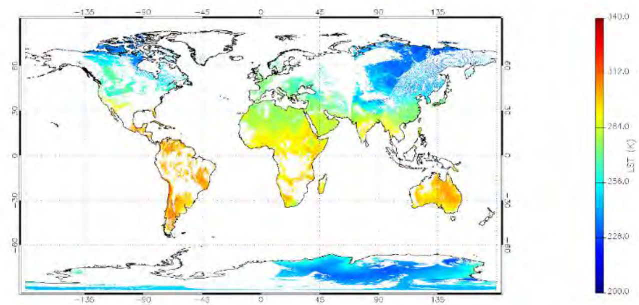
Current capability III (diurnal cycle)

Global LST data which resolve the diurnal cycle becoming available:

- Merged geostationary (GEO) and low earth orbit (LEO) data giving high spatial resolution, sub-diurnal sampling; estimates of cloud-bias.
- Intercalibrated LST using SEVIRI as a reference sensor
- 15-day LEO composite product at local solar time
- Combined GEO+LEO 3-hourly product at UTC



15-day Merged LEO composite LST Product from 1st Jan to 15th Jan 2012

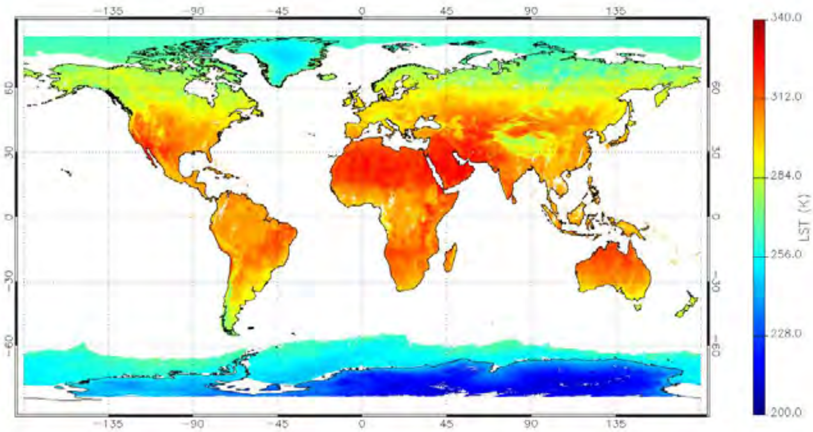


Merged GEO (SEVIRI, GOES, MTSAT) + LEO (ATSR, MODIS) LST Product at 21:00 UTC on 1st January 2013

Current capability IV (CDRs)

Increasing confidence in traceability and stability of LST

- Traceability of globally robust algorithm coefficients and uncertainties
- Quantitative assessments of biases between consecutive instruments such as ATSR-2/AATSR and MODIS/VIIRS
- Homogenisation of BTs and aerosol detection within ATSR Climate Data Record (CDR)

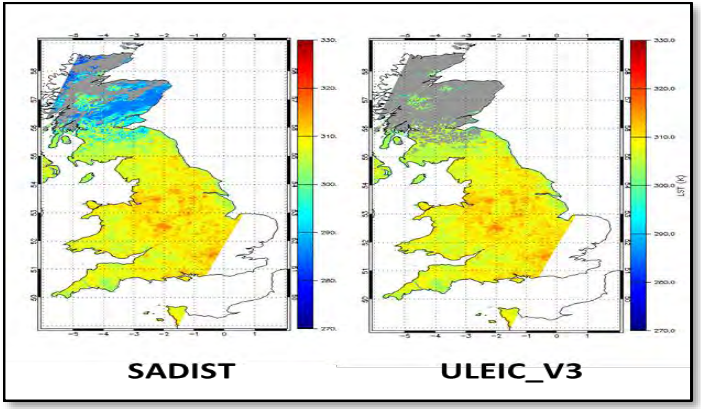


ATSR LST CDR (September 2002)

Towards a CDR from the ATSRs I

Increasing confidence in observations of LST

- Cloud clearing is the largest unknown in the retrieval of LST from IR
- Limitations with threshold-based approaches have been improved with dynamic, probabilistic methods
- These methods are adaptable to other instruments

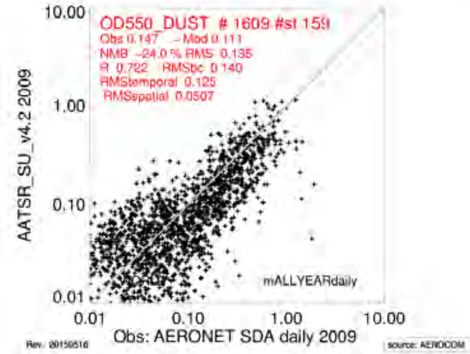


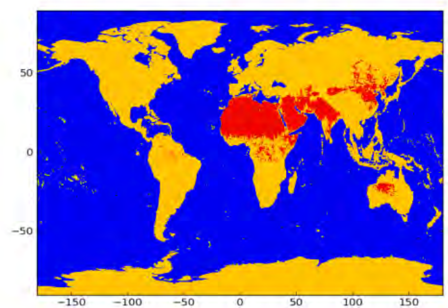
Example of the improved probabilistic approach for ATSR (right) compared to the existing operational approach (left)

Towards a CDR from the ATSRs II

Increasing confidence in observations of LST

- The retrieval of LST is usually performed under the assumption of clear-sky conditions
- In the thermal infrared window region the effect of aerosols is not negligible and will have impact on the observed LST.
- Within the ATSR CDR an aerosol flag (created from Swansea University CCI aerosol product Grey et al. 2006) informs users of possible aerosol contamination





Comparison of SU OD550_DU with Aeronet (left); CDR aerosol flag created form the dust optical depth product from U. Swansea (right). Credit http://aerocom.met.no/cgi-bin/aerocom/surfobs_annualrs.pl

CDR Assessment

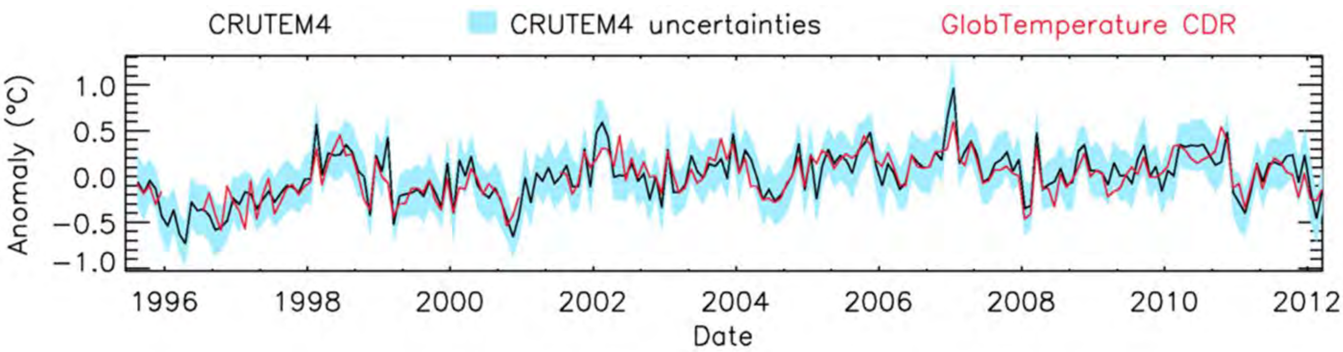
Explore using satellite LST retrievals to augment information from meteorological stations

CDR shows consistent and strong relationship with 2m air temperature.

Very good agreement between CDR anomalies and CRUTEM4 anomalies

- Day: ATSR-2 warmer than AATSR - likely non-optimal temporal adjustment
- Night: Much smaller difference

Independent confirmation of CRUTEM4 monthly anomaly variation.



Good et al., 2017, JGR-Atmospheres

User requirements for Climate

Climate users require LST data

Baseline requirements have been determined by user survey (ESA DUE GlobTemperature Requirements Baseline Document http://www.globtemperature.info/)

➢ Horizontal resolution -	Threshold	0.05°
➢ Temporal resolution -	Threshold:	Day-night
	Target:	≤ 3-hourly
➢ Accuracy -	Threshold	<1 K
➢ Precision -	Threshold	<1 K
➢ Stability -	Threshold:	<0.3 K per decade
	Target:	<0.1 K per decade
➢ Length of record -	Threshold:	20 years
	Target:	>30 years

LST is now an ECV in the GCOS 2016 Implementation Plan

ESA Climate Change Initiative (LST CCI)

12 international partners

UK lead (U. Leicester) with other UK partners (U. Reading, Met Office)

Algorithm development

- Retrieval algorithm consistency across LST ECV products

Ensure consistency of uncertainty approach

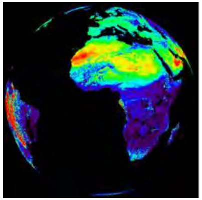
- Components separated according to correlation properties

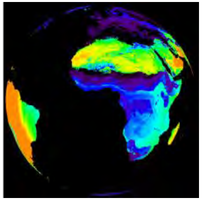
Optimisation of best cloud clearing detection

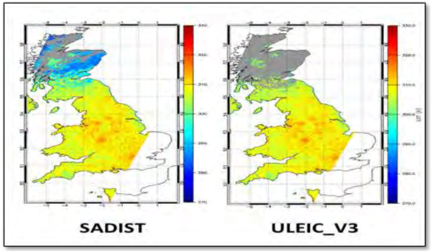
- Best cloud clearing approaches for IR CDRs

Long-term CDRs

- 25 years (1995 to 2020) from ATSR to Sentinel-3 IR CDR
- 22 years (1998 to 2020) for Passive microwave time series
- 10 years (2010 to 2020) for Merged IR CDR







Website: [cci.esa.int/lst](cci.esa.int/lst)

Current capability (operational data)

The next generation of LST observations has begun with Sentinel-3

Sentinel-3A:

Launch 16 February 2016

LST operational 5 July 2017

Sentinel-3B

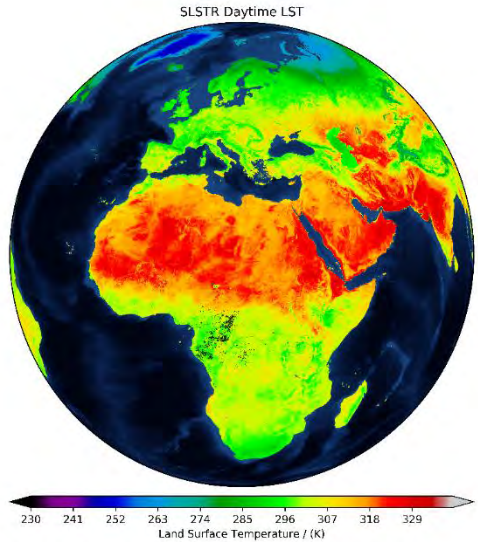
Launch 25 April 2018

LST to be operational autumn 2018

Achieving its mission requirements

LST accuracy < 1K

U. Leicester lead the LST activities for Sentinel-3



Sentinel-3A daytime LST for May 2018

An international effort

NCEO are coordinating The International Land Surface Temperature and Emissivity Working Group (ILSTE):

- Represents the best available expertise in LST & Emissivity data techniques and LST-related science, sharing best practice amongst providers, experts and users
- Act as an international forum for regular interactions between LST Measurement Teams, enabling improvements in data algorithms and data quality, and increased understandings of user requirements
- Delivers a range of user-provider meetings and workshops, increasing links across the community
- Supports the alignment of LST best practice with the planned activities and data provision of operational agencies
- Agrees standardised protocols for data formats and access to data, appropriate to key sectors of the LST user community
- Supports a dedicated validation group, supporting a consistent approach to data validation, in line with CEOS-LPV Best Practices

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

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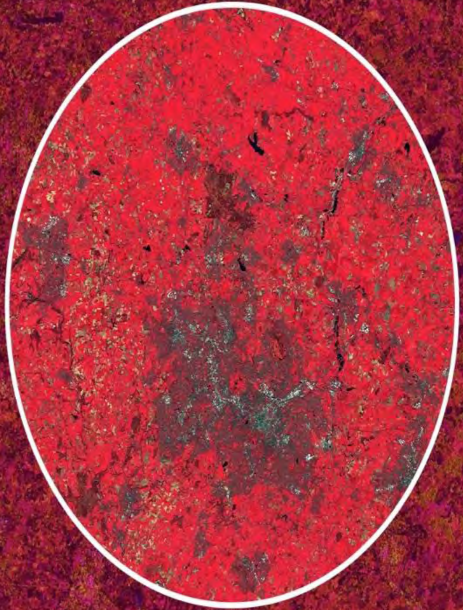
esa

→ 8th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

10–14 September 2018
University of Leicester | United Kingdom



Thank you

Questions?